Acknowlegements:
The E158, HAPPEX, PREX, CREX, MOLLER, SOLID, P2 and MREX Collaborations

Many thanks to numerous collaborators for ideas, photos, slides, text….

Parity Violating Electron Scattering

Recent Results and Future Plans

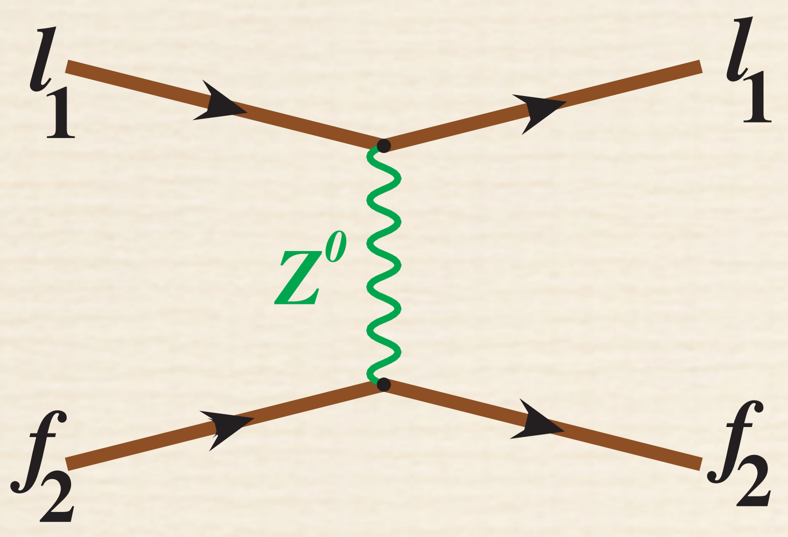
Krishna Kumar
University of Massachusetts, Amherst

MENU 2023, Mainz, Germany
October 19, 2023

Outline

- **Introduction to Parity-Violating Electron Scattering**
  - ***Historical Perspective on Neutral Weak Interactions***
- **Elastic Scattering off Doubly Magic Nuclei**
  - ***Results PREX and CREX Experiments at Jefferson Laboratory***
  - ***Broader Implications and the Future: MREX at MESA***
- **Scattering off electrons, protons and quarks**
  - ***Program to Search for New Neutral Current Interactions Beyond the Standard Model***
  - ***Motivation, Complementarity and Brief Review of Past Measurements***
  - ***The Future: MOLLER and SOLID at JLab, P2 and C-12 at MESA, and the EIC***
- **Summary and Outlook**

Semi-Leptonic and Leptonic Weak Neutral Currents at $Q^2 \ll M_Z^2$

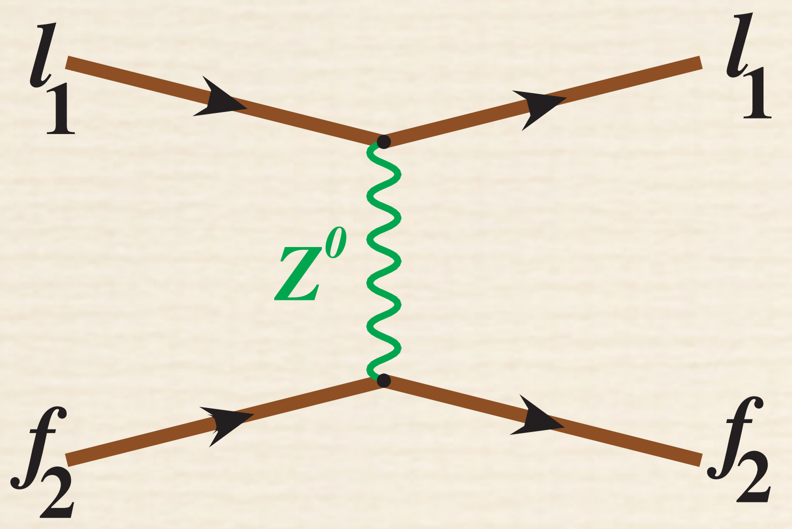


✦Neutrino Scattering

✦Weak-Electromagnetic Interference with Electrons

- *opposite parity transitions in heavy atoms*
- *Spin-dependent electron scattering*

Semi-Leptonic and Leptonic Weak Neutral Currents at $Q^2 \ll M_Z^2$

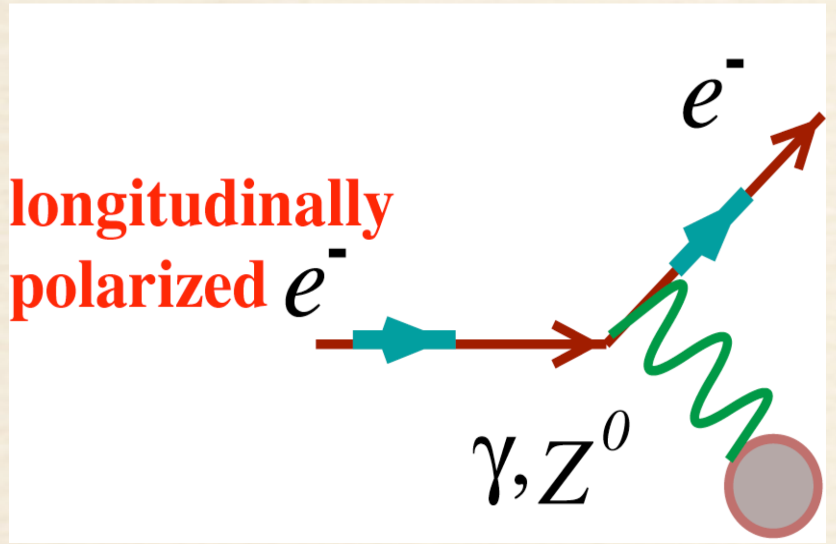


✦Neutrino Scattering

✦Weak-Electromagnetic Interference with Electrons

- *opposite parity transitions in heavy atoms*
- *Spin-dependent electron scattering*

Parity-violating Electron Scattering (PVES)

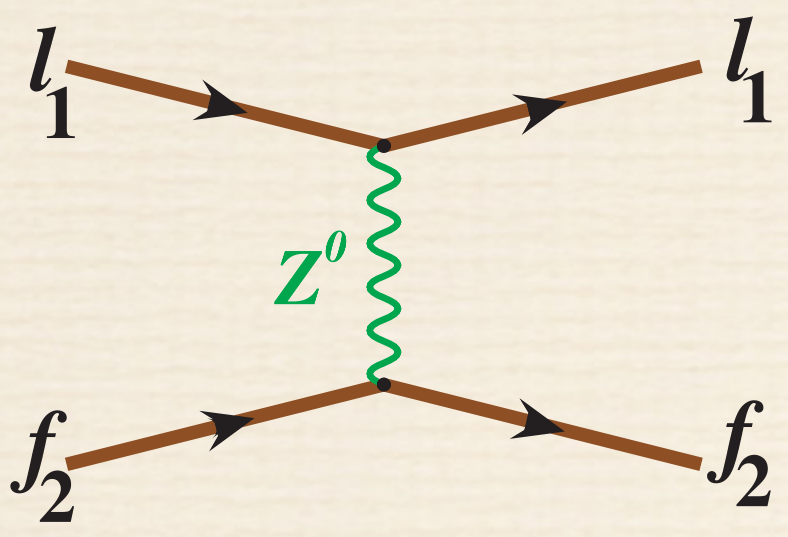


g_V's are functions of $\sin^2\theta_W$

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e g_V^T + \beta g_V^e g_A^T\right)$$

$$A_{PV} \sim 10^{-5}\cdot Q^2 \ \textit{to}\ 10^{-4}\cdot Q^2$$

Semi-Leptonic and Leptonic Weak Neutral Currents at $Q^2 \ll M_Z^2$



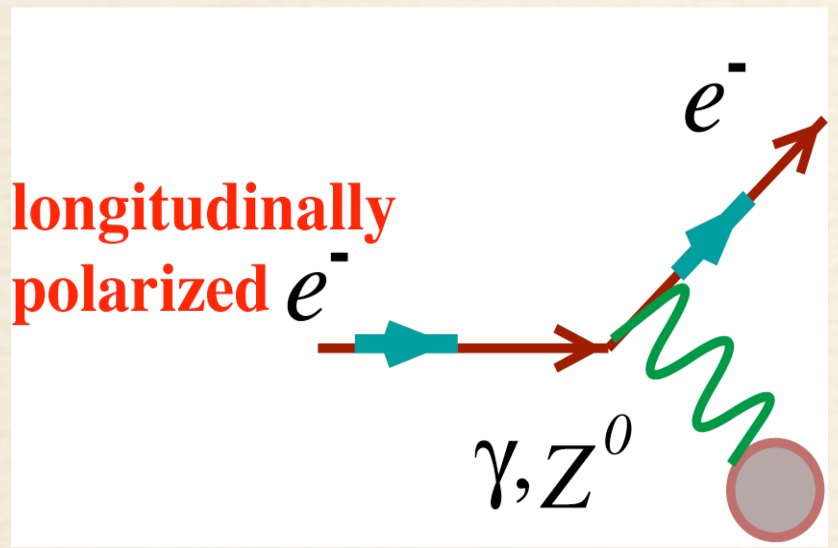
✦Neutrino Scattering

✦Weak-Electromagnetic Interference with Electrons

- *opposite parity transitions in heavy atoms*
- *Spin-dependent electron scattering*

Parity-violating Electron Scattering (PVES)

Weak Charge Q_W

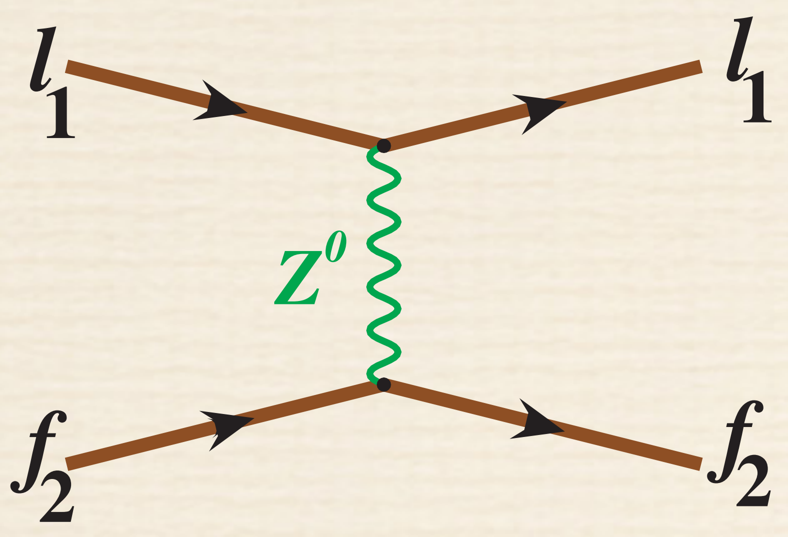


g_V's are functions of $\sin^2\theta_W$

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e g_V^T + \beta\, g_V^e g_A^T\right)$$

$$A_{PV} \sim 10^{-5} \cdot Q^2 \ \textit{to}\ 10^{-4} \cdot Q^2$$

Semi-Leptonic and Leptonic Weak Neutral Currents at $Q^2 \ll M_Z^2$

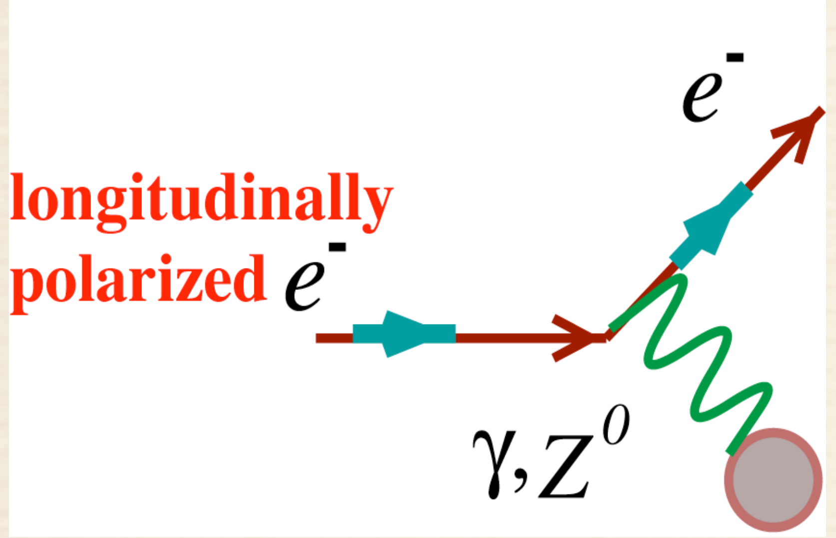


✦Neutrino Scattering

✦Weak-Electromagnetic Interference with Electrons

- *opposite parity transitions in heavy atoms*
- *Spin-dependent electron scattering*

Parity-violating Electron Scattering (PVES)



g_V's are functions of $\sin^2\theta_W$

Weak Charge Q_W

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e g_V^T + \beta\, g_V^e g_A^T\right)$$

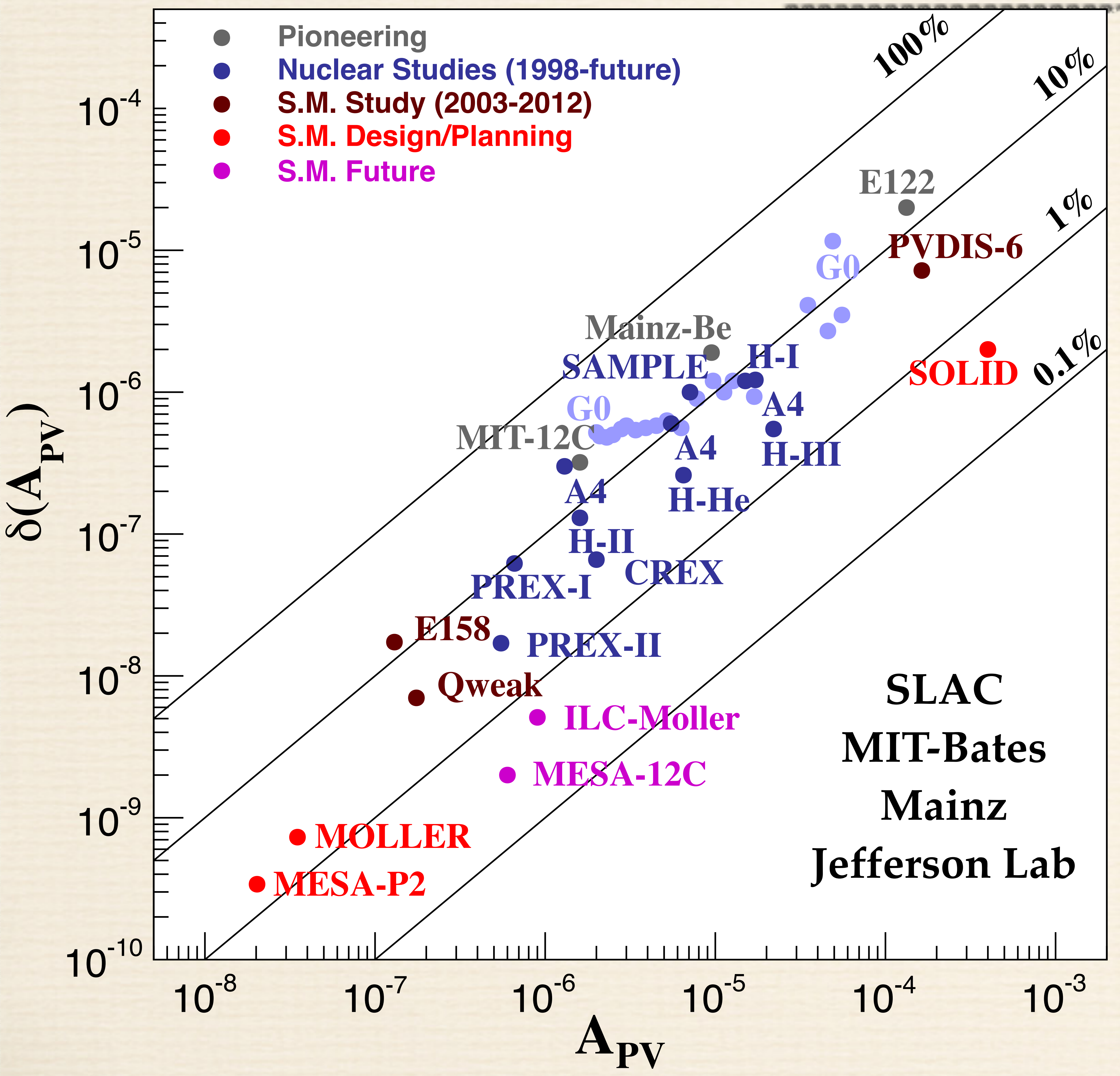
$$A_{PV} \sim 10^{-5} \cdot Q^2 \;\; \textit{to} \;\; 10^{-4} \cdot Q^2$$

Specific choices of kinematics and target nuclei probe different physics:

- ***Mid-70s to late-80's, goal was to show $\sin^2\theta_W$ was the same as in neutrino scattering***
- ***Since early 90's: target couplings probe novel aspects of hadron structure***
  - ✦ ***strange quark form factors, neutron RMS radius of heavy nuclei***
- ***Since late 90's: precision measurements with carefully chosen kinematics can probe physics at the multi-TeV scale***

Continuous interplay between probing hadron structure and electroweak physics

Four Decades of PVES

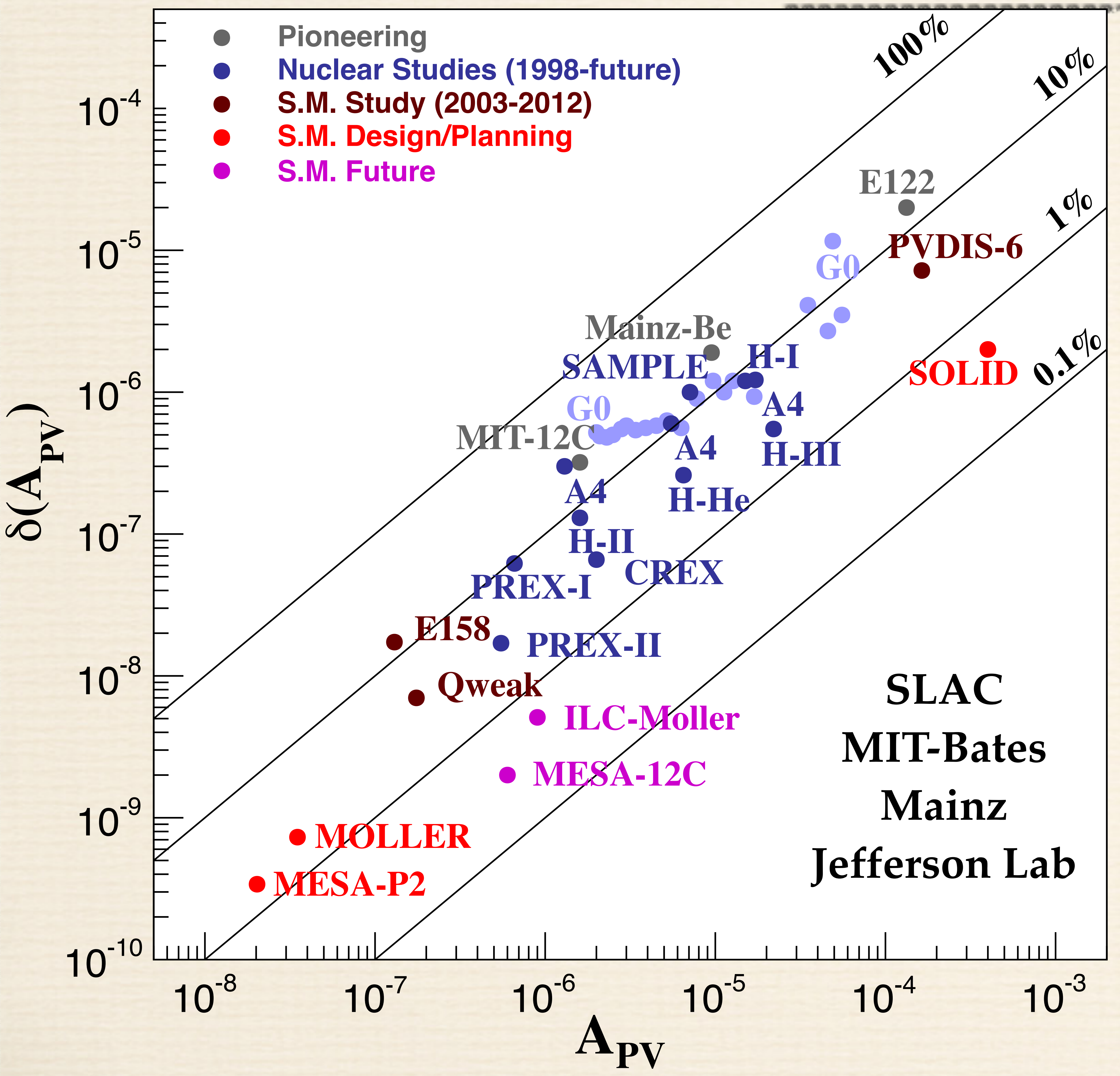


Parity-violating electron scattering has become a precision tool

- *Beyond Standard Model Searches*
- *Strange quark form factors*
- *Neutron skin of a heavy nucleus*
- *QCD structure of the nucleon*

Continuous interplay between probing hadron structure and electroweak physics

Four Decades of PVES



Parity-violating electron scattering has become a precision tool

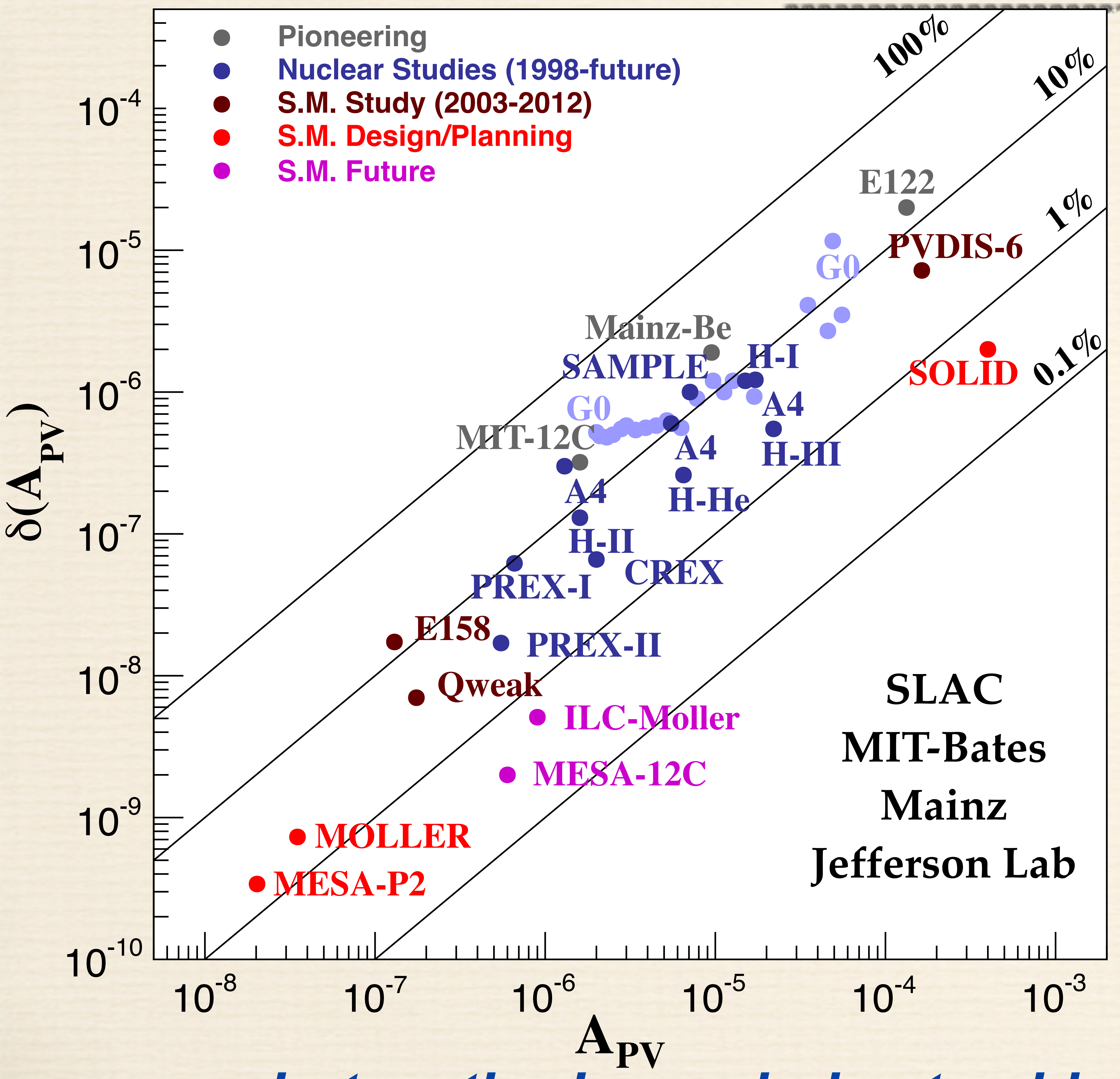
- *Beyond Standard Model Searches*
- *Strange quark form factors*
- *Neutron skin of a heavy nucleus*
- *QCD structure of the nucleon*

State-of-the-art:

- ***sub-part per billion statistical reach and systematic control***
- ***sub-1% normalization control***

Continuous interplay between probing hadron structure and electroweak physics

Four Decades of PVES



Parity-violating electron scattering has become a precision tool

- *Beyond Standard Model Searches*
- *Strange quark form factors*
- *Neutron skin of a heavy nucleus*
- *QCD structure of the nucleon*

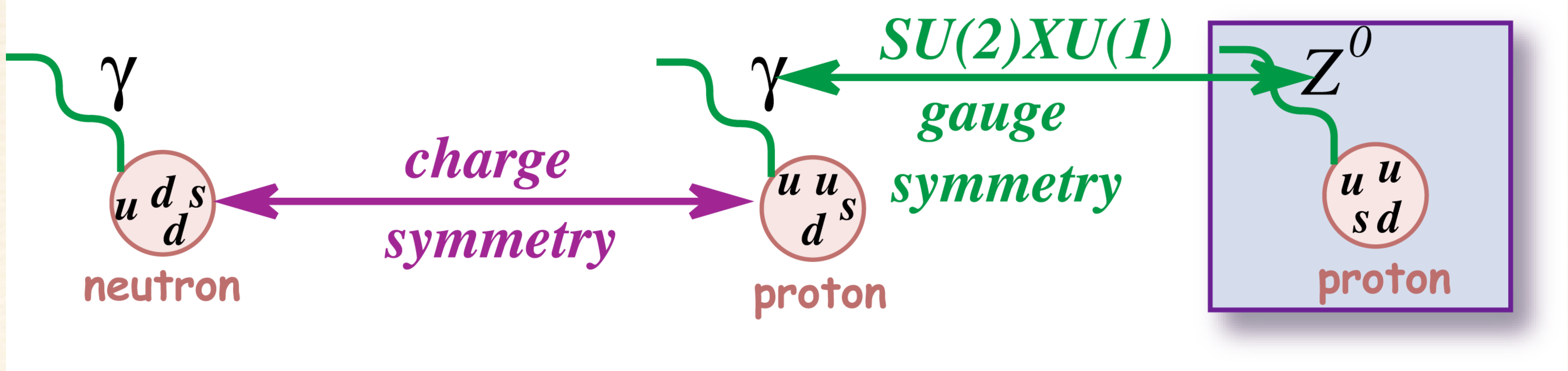
State-of-the-art:

- ***sub-part per billion statistical reach and systematic control***
- ***sub-1% normalization control***

photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors

1990 - 2010

PV Electron-Nucleon Elastic Scattering: Nucleon Strange Quark Form Factors

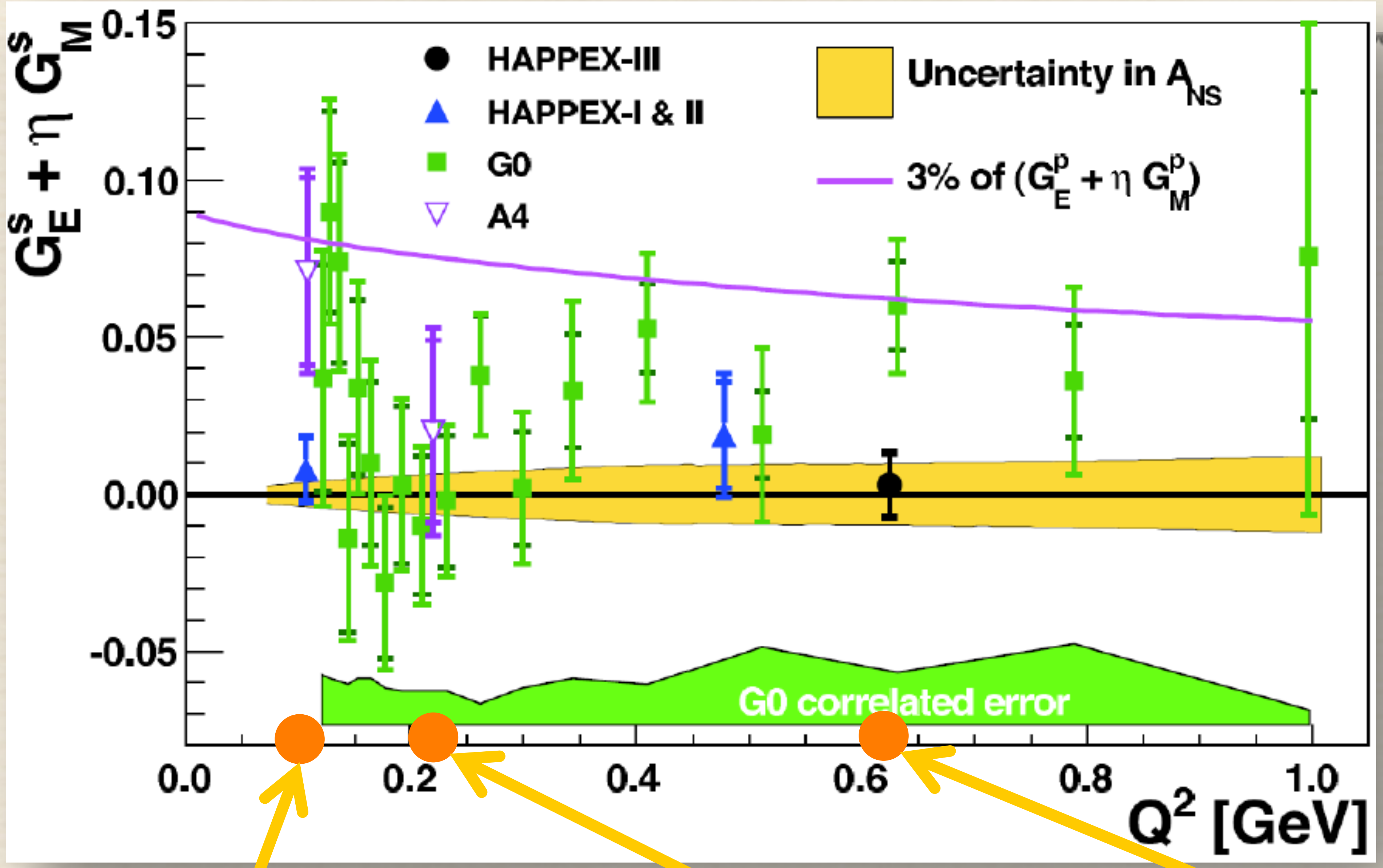


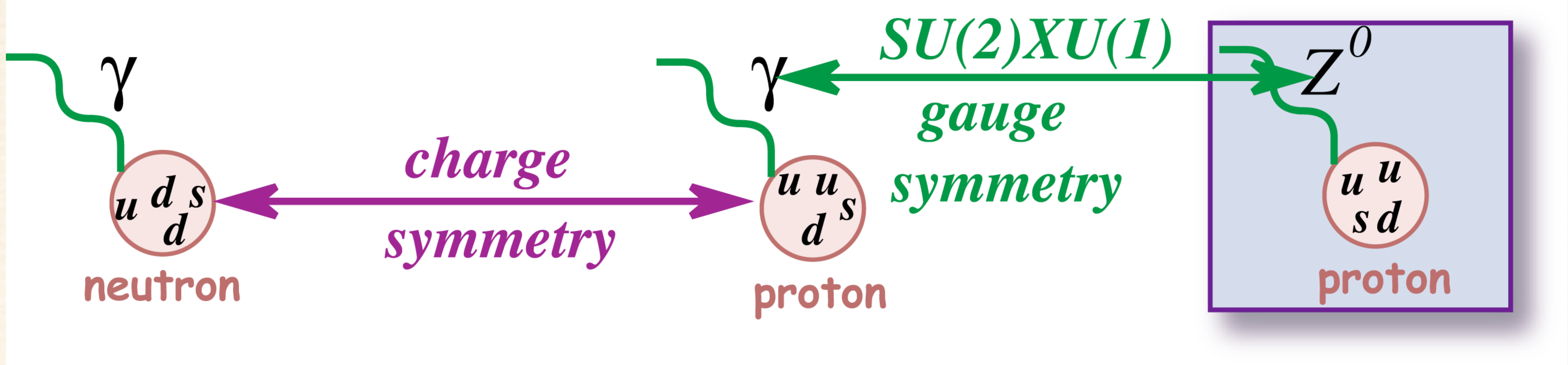
$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s$$

$\Rightarrow$ $G_E^s(Q^2), G_M^s(Q^2)$

PV Electron-Nucleon Elastic Scattering: Nucleon Strange Quark Form Factors

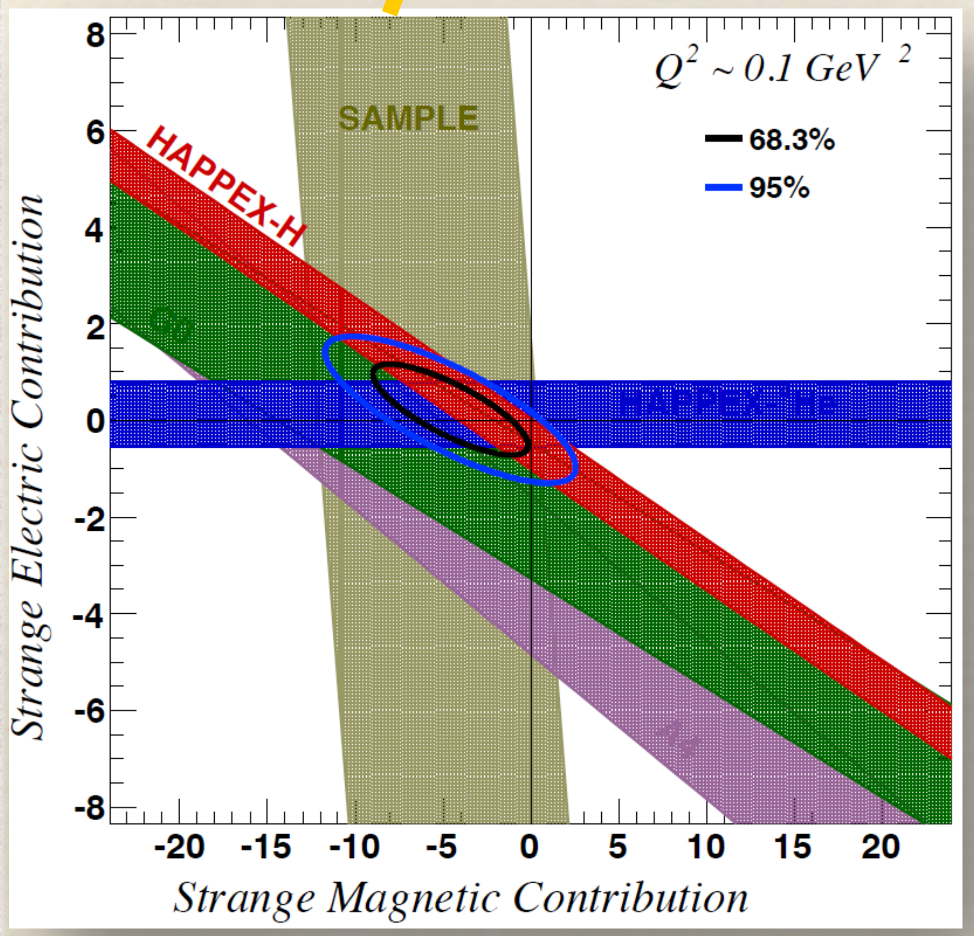
1990 - 2010

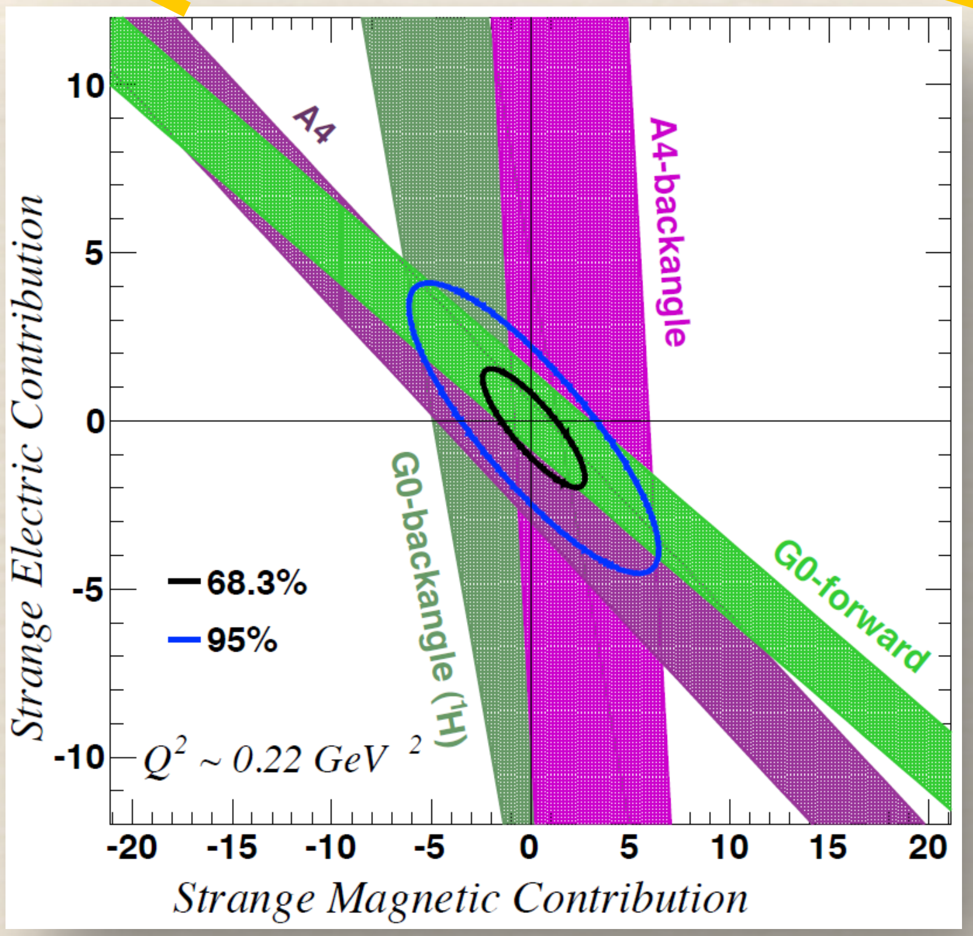


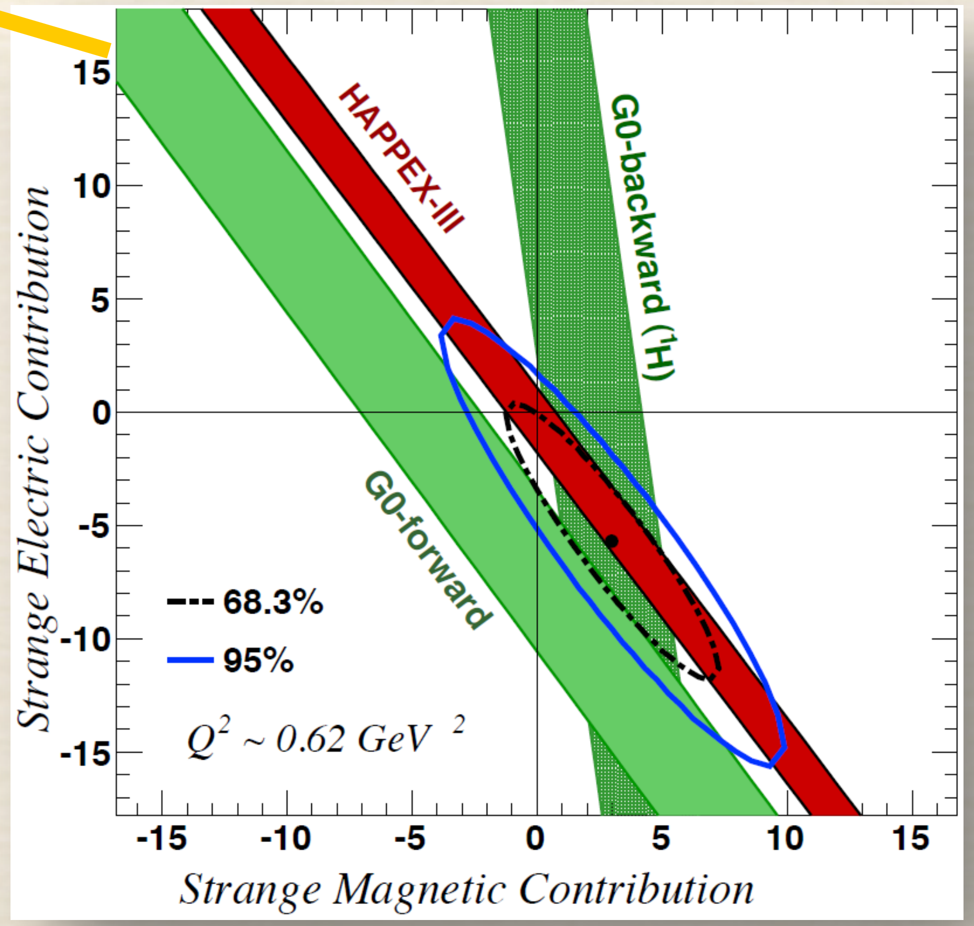


$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s$$

$\Rightarrow$ $G_E^s(Q^2), G_M^s(Q^2)$

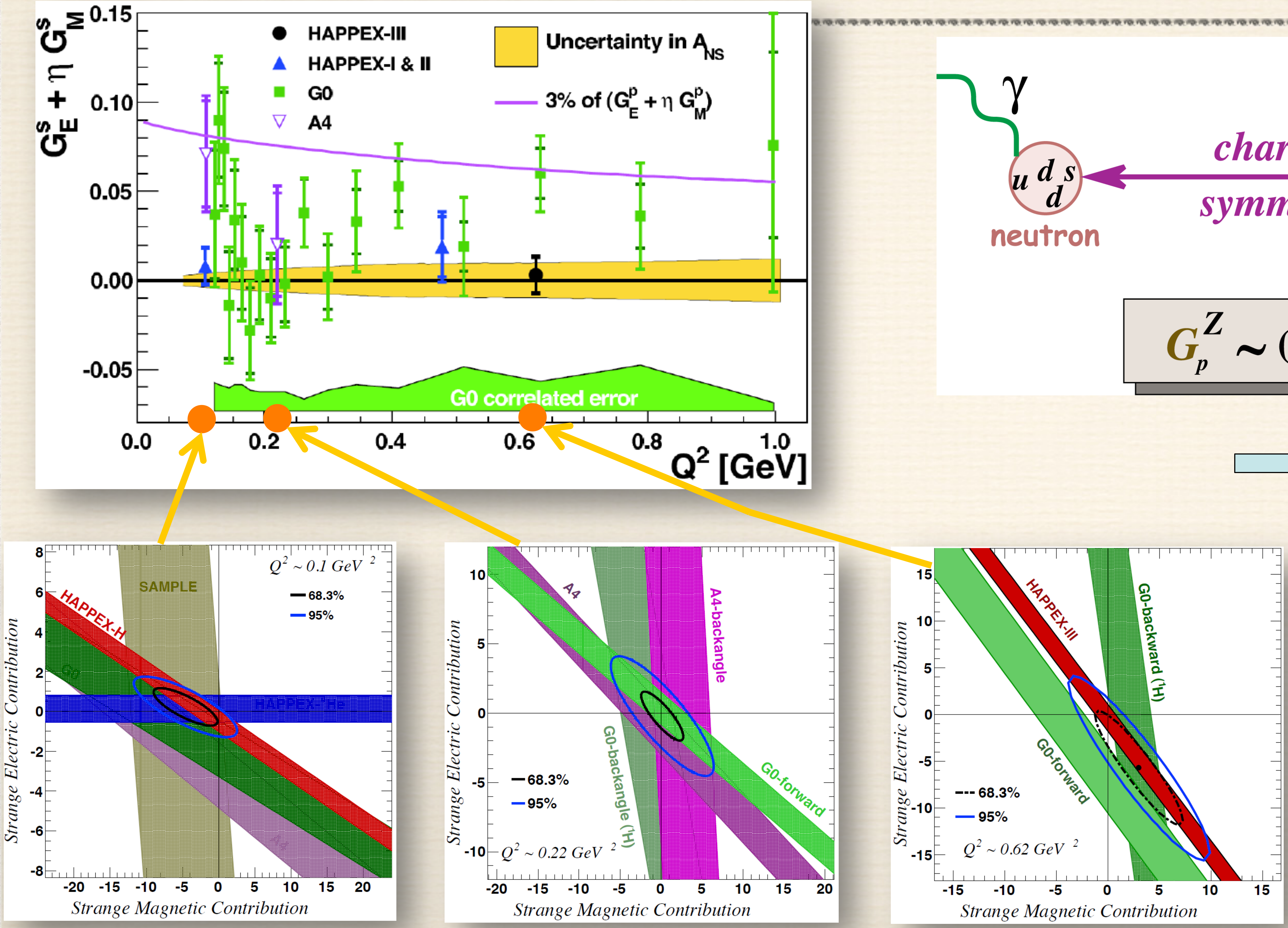


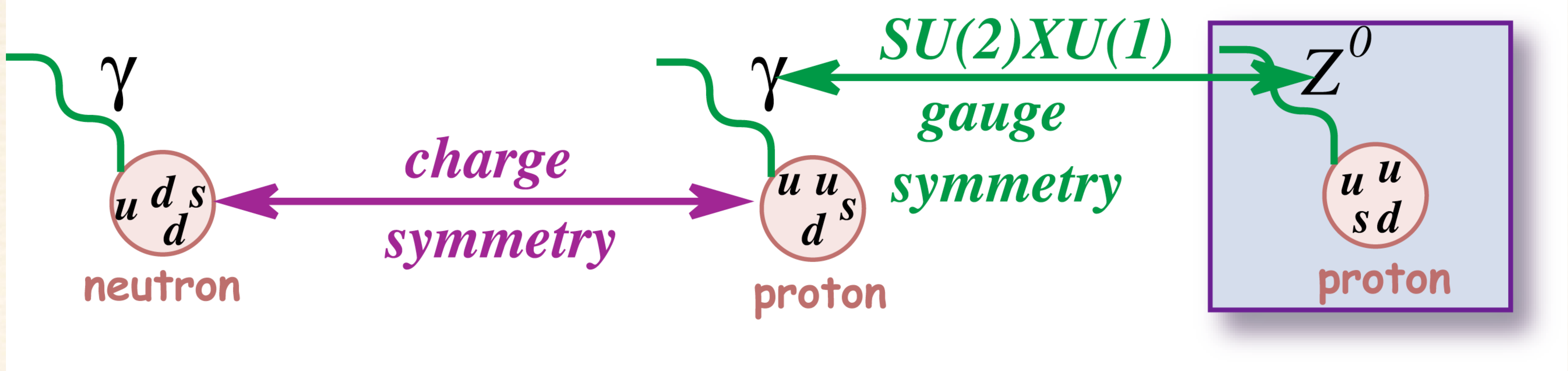




1990 - 2010

PV Electron-Nucleon Elastic Scattering: Nucleon Strange Quark Form Factors





$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s$$

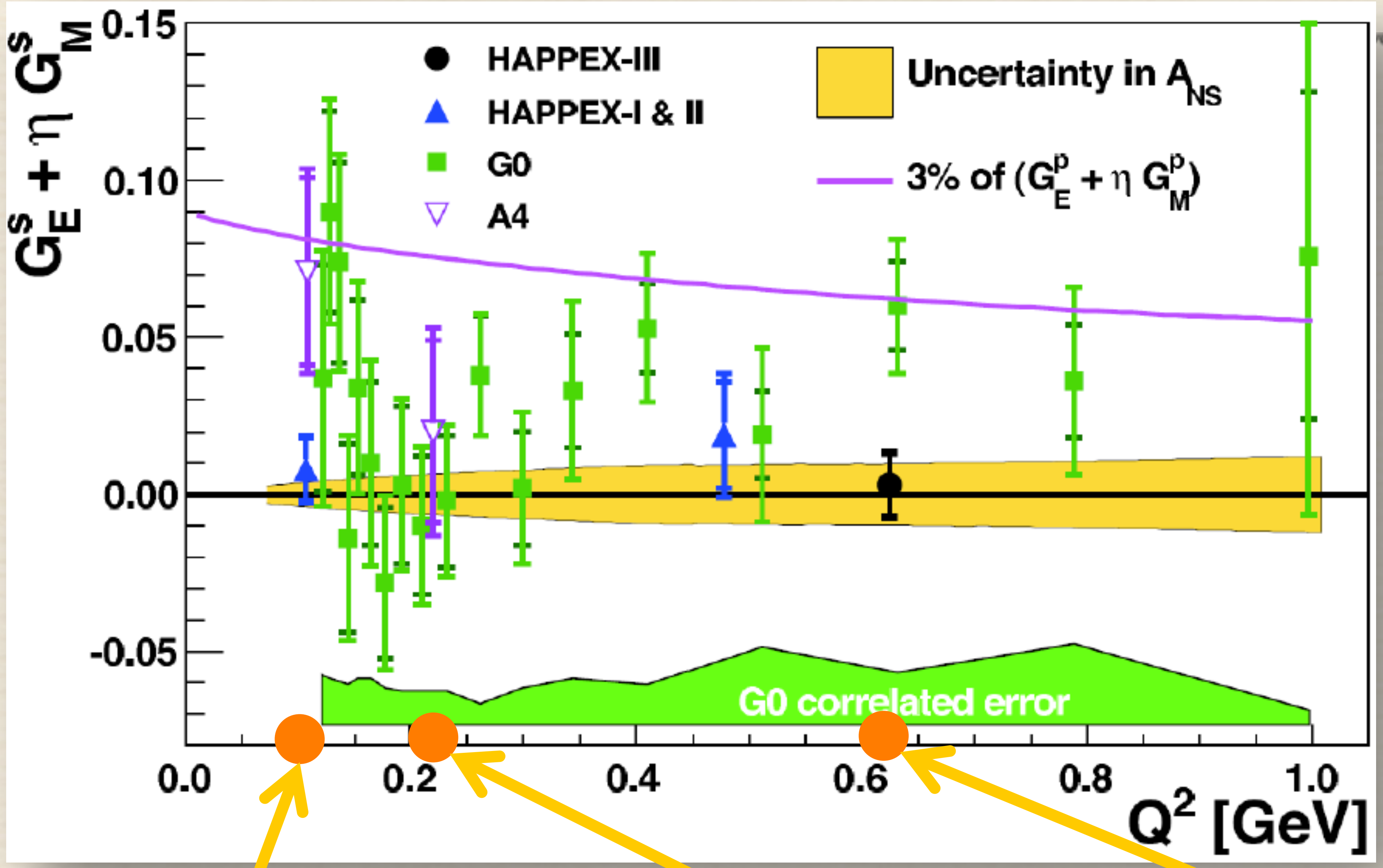
⇒ $G_E^s(Q^2), G_M^s(Q^2)$

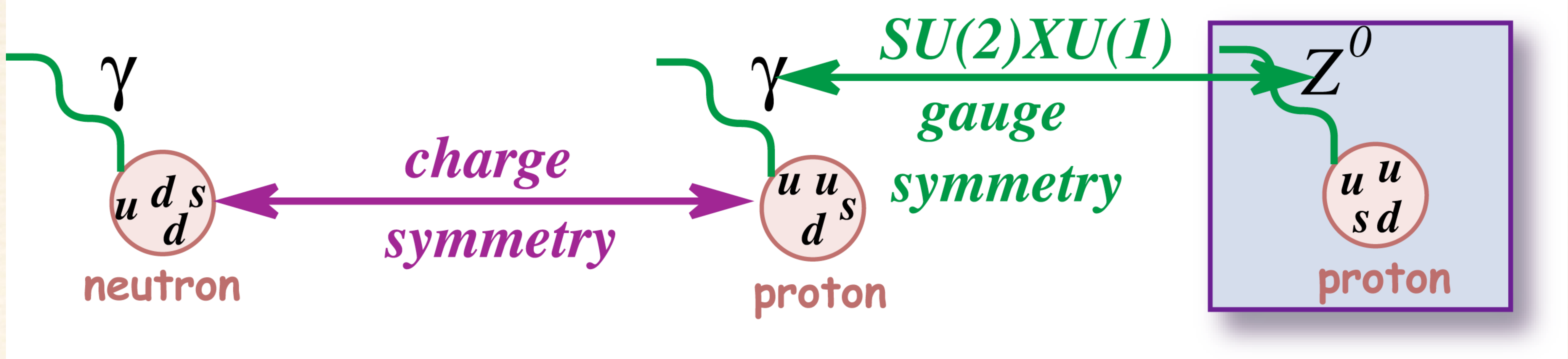
- Sensitive Flavor separation at three Q² values
- Strange quarks are no more than a few % of EM structure
- Modern lattice QCD results are in agreement

1990 - 2010

PV Electron-Nucleon Elastic Scattering: Nucleon Strange Quark Form Factors

Still could learn more about axial form factors and strange quark contribution to the magnetic moment

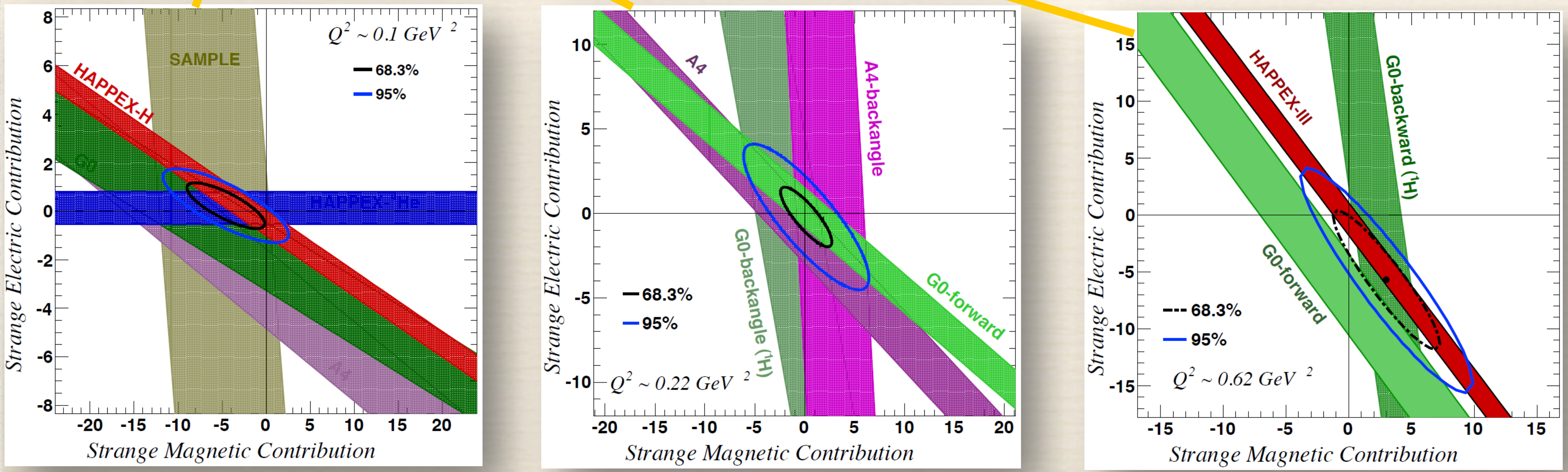


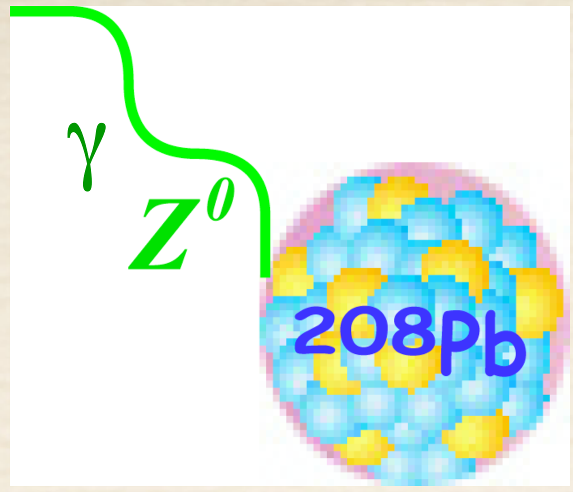


$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s$$

$\Rightarrow$ $G_E^s(Q^2), G_M^s(Q^2)$

- Sensitive Flavor separation at three Q^2 values
- Strange quarks are no more than a few % of EM structure
- Modern lattice QCD results are in agreement





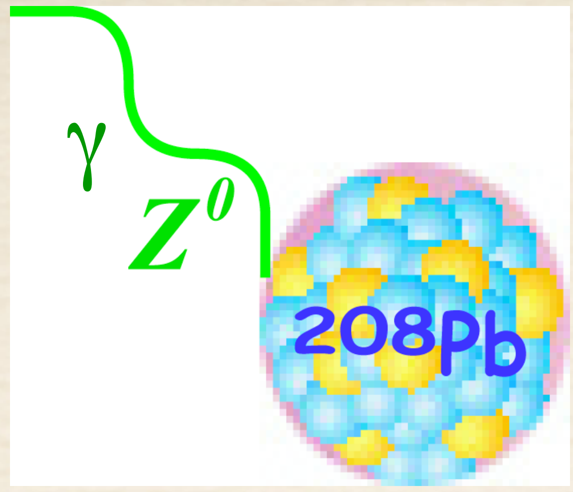
PV Elastic Scattering off Heavy Nuclei: Neutron Densities

2010 -

$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

$$M^{NC}_{PV} = \frac{G_F}{\sqrt{2}}\left[\left(1-4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$



PV Elastic Scattering off Heavy Nuclei: Neutron Densities

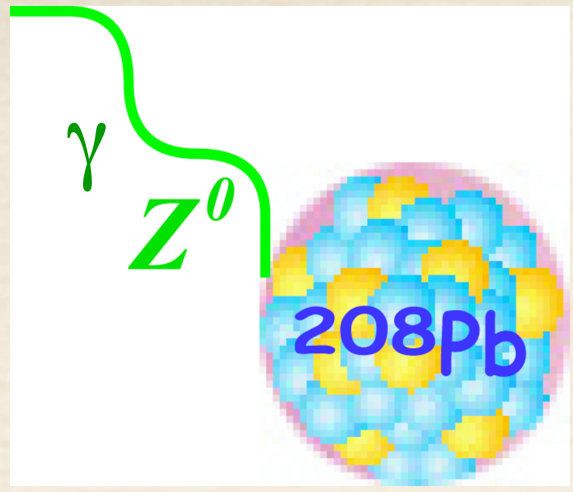
2010 -

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

$$M^{NC}_{PV} = \frac{G_F}{\sqrt{2}}\left[\left(1-4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$



PV Elastic Scattering off Heavy Nuclei: Neutron Densities

2010 -

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

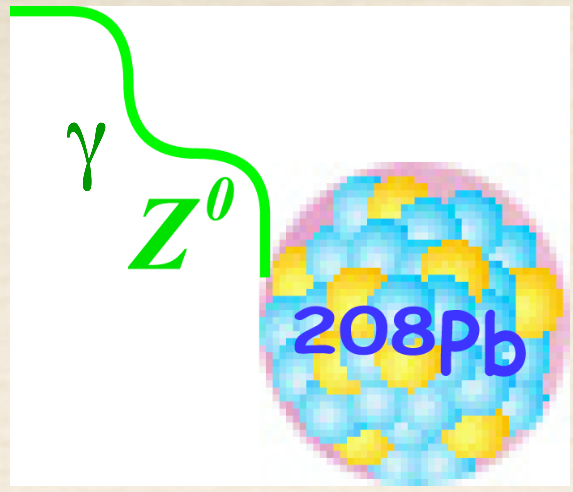
$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

$$M_{PV}^{NC} = \frac{G_F}{\sqrt{2}}\left[\left(1 - 4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

$\delta(A_{PV})/A_{PV} \sim 3\%$

$\delta(R_n)/R_n \sim 1\%$

$\delta(R_n)$: $\pm$ 0.07 fm (^{208}Pb)
$\pm$ 0.03 fm (^{48}Ca)



PV Elastic Scattering off Heavy Nuclei: Neutron Densities

2010 -

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

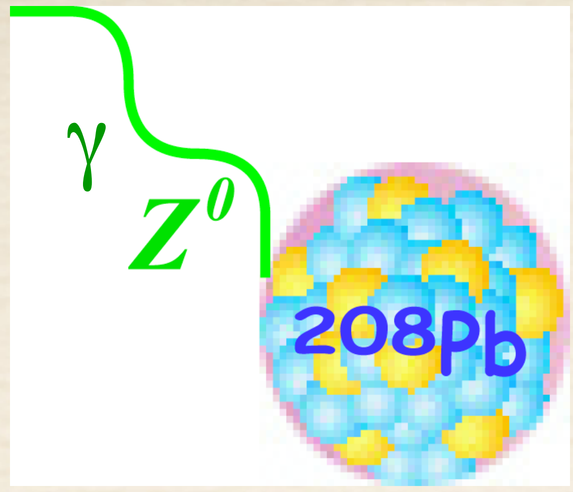
$$M^{NC}_{PV} = \frac{G_F}{\sqrt{2}}\left[\left(1-4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

$\delta(A_{PV})/A_{PV} \sim 3\%$
$\delta(R_n)/R_n \sim 1\%$

$\delta(R_n)$: $\pm$ 0.07 fm (^{208}Pb)
$\pm$ 0.03 fm (^{48}Ca)

PREX
&
CREX

PV Elastic Scattering off Heavy Nuclei: Neutron Densities



2010 -

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

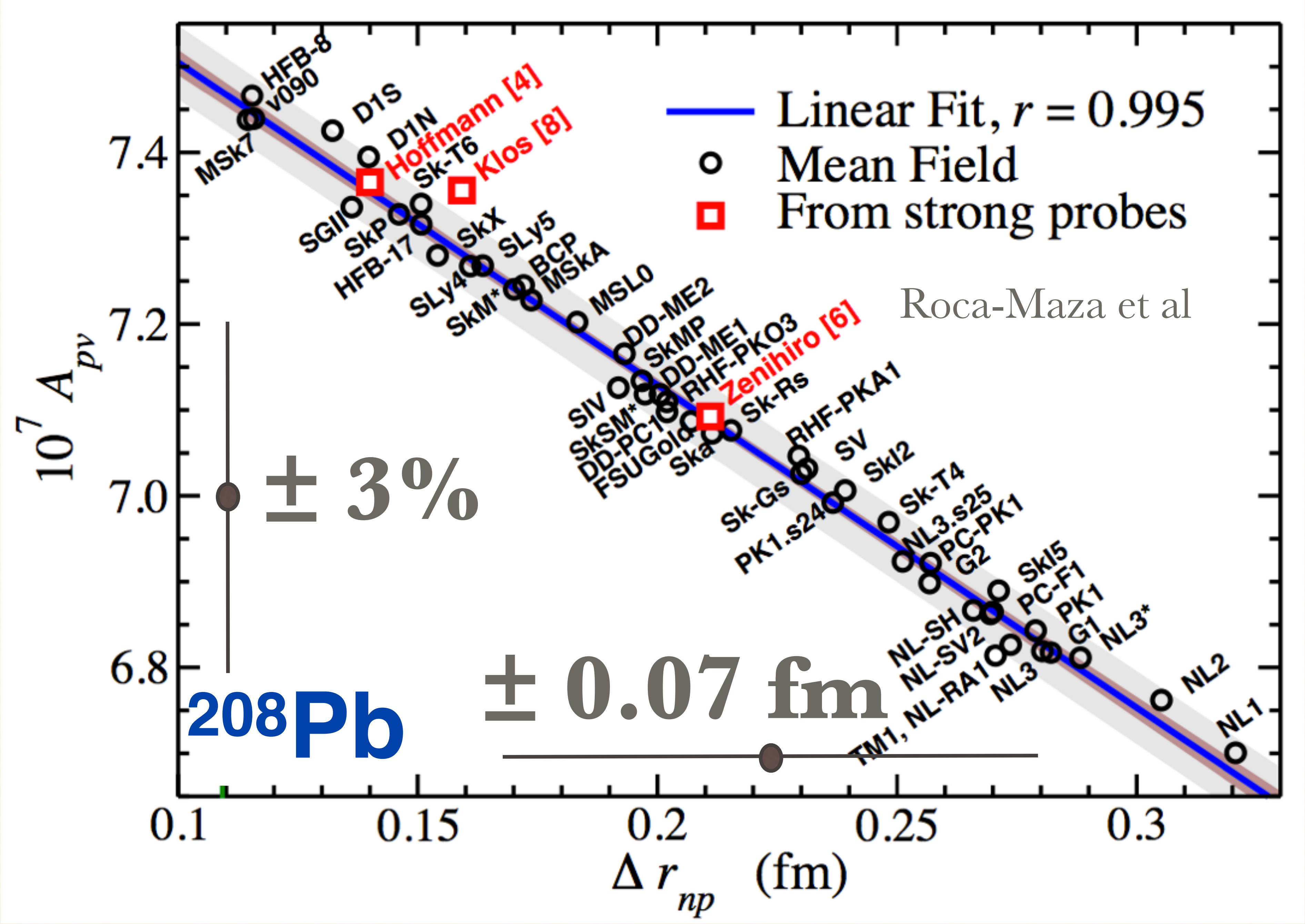
$$M^{NC}_{PV} = \frac{G_F}{\sqrt{2}}\left[\left(1 - 4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

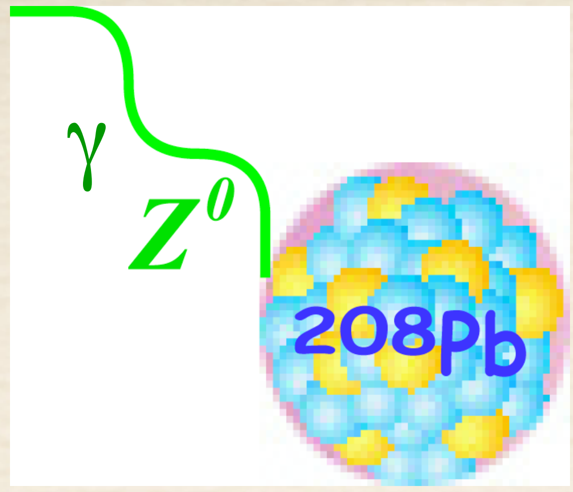
$\delta(A_{PV})/A_{PV} \sim 3\%$

$\delta(R_n)/R_n \sim 1\%$

$\delta(R_n)$: ± 0.07 fm (^{208}Pb)
± 0.03 fm (^{48}Ca)

PREX
&
CREX





PV Elastic Scattering off Heavy Nuclei: Neutron Densities

2010 -

$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

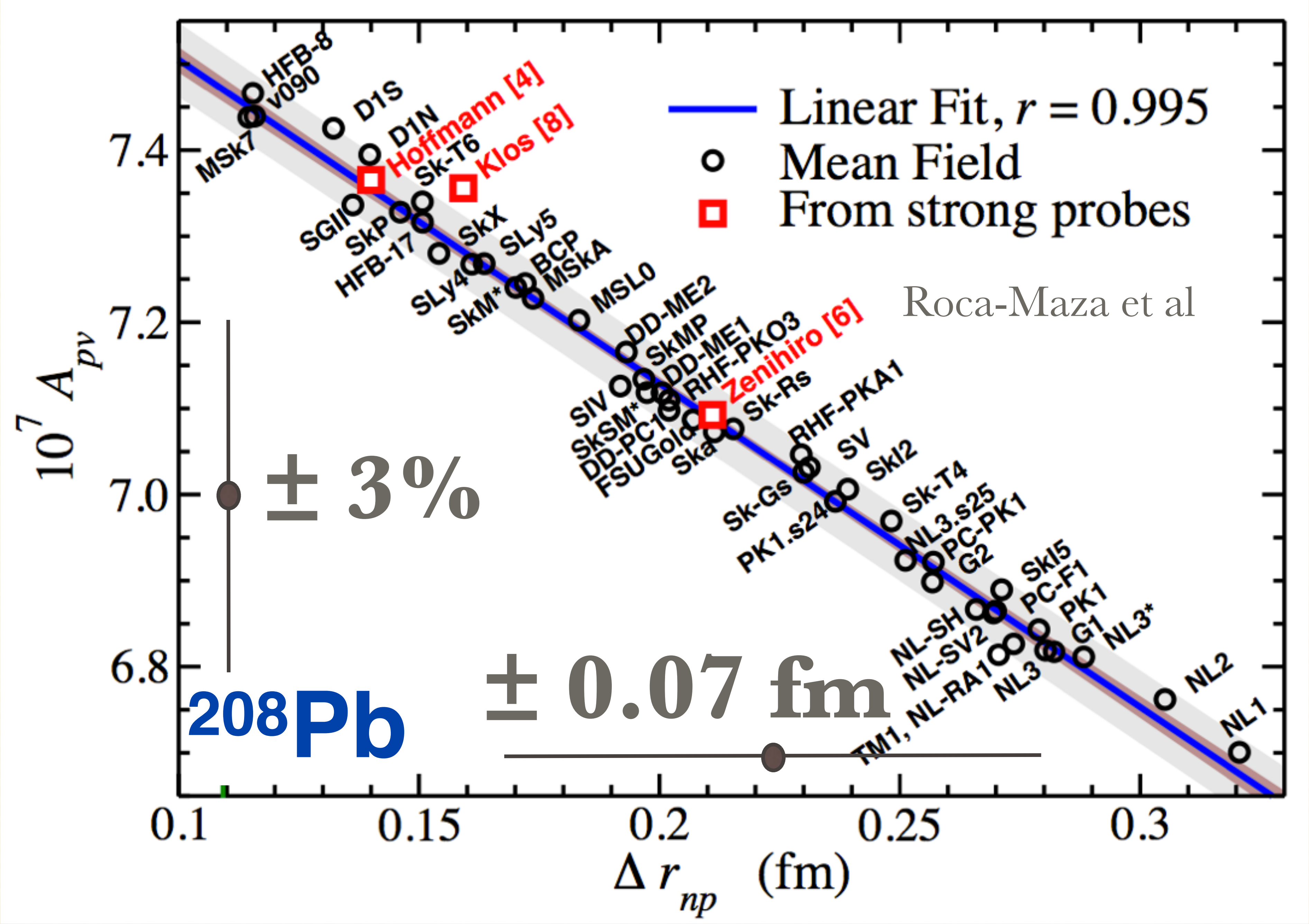
$$M^{NC}_{PV} = \frac{G_F}{\sqrt{2}}\left[\left(1-4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

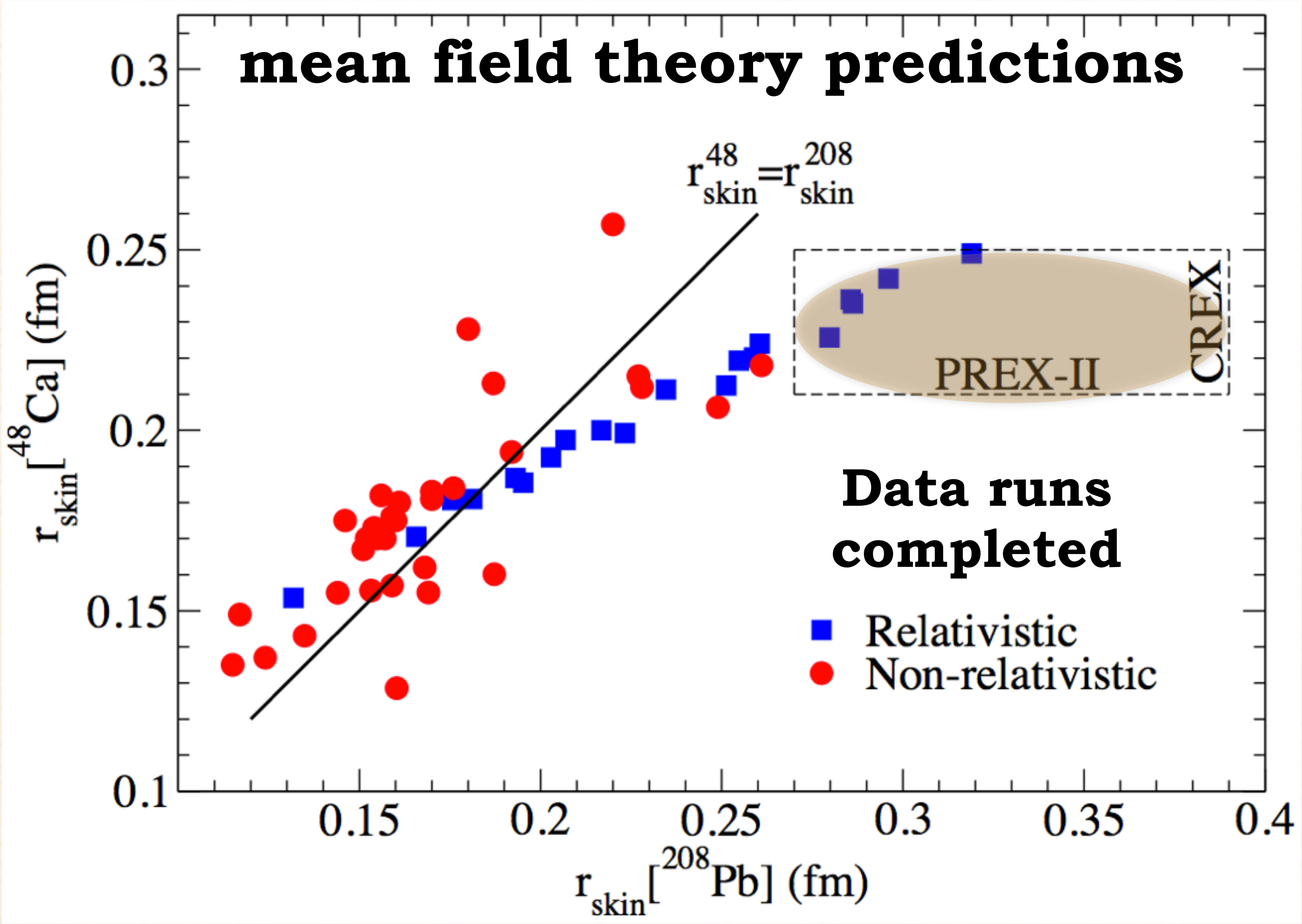
$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

$\delta(A_{PV})/A_{PV} \sim 3\%$

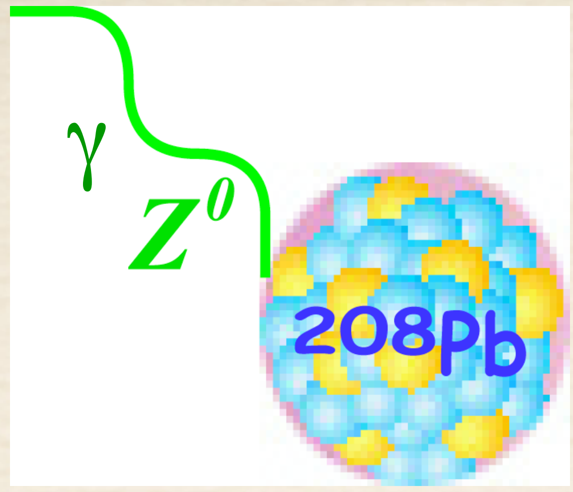
$\delta(R_n)/R_n \sim 1\%$

$\delta(R_n)$: ± 0.07 fm (^{208}Pb)
± 0.03 fm (^{48}Ca)





PREX & CREX



PV Elastic Scattering off Heavy Nuclei: Neutron Densities

2010 -

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

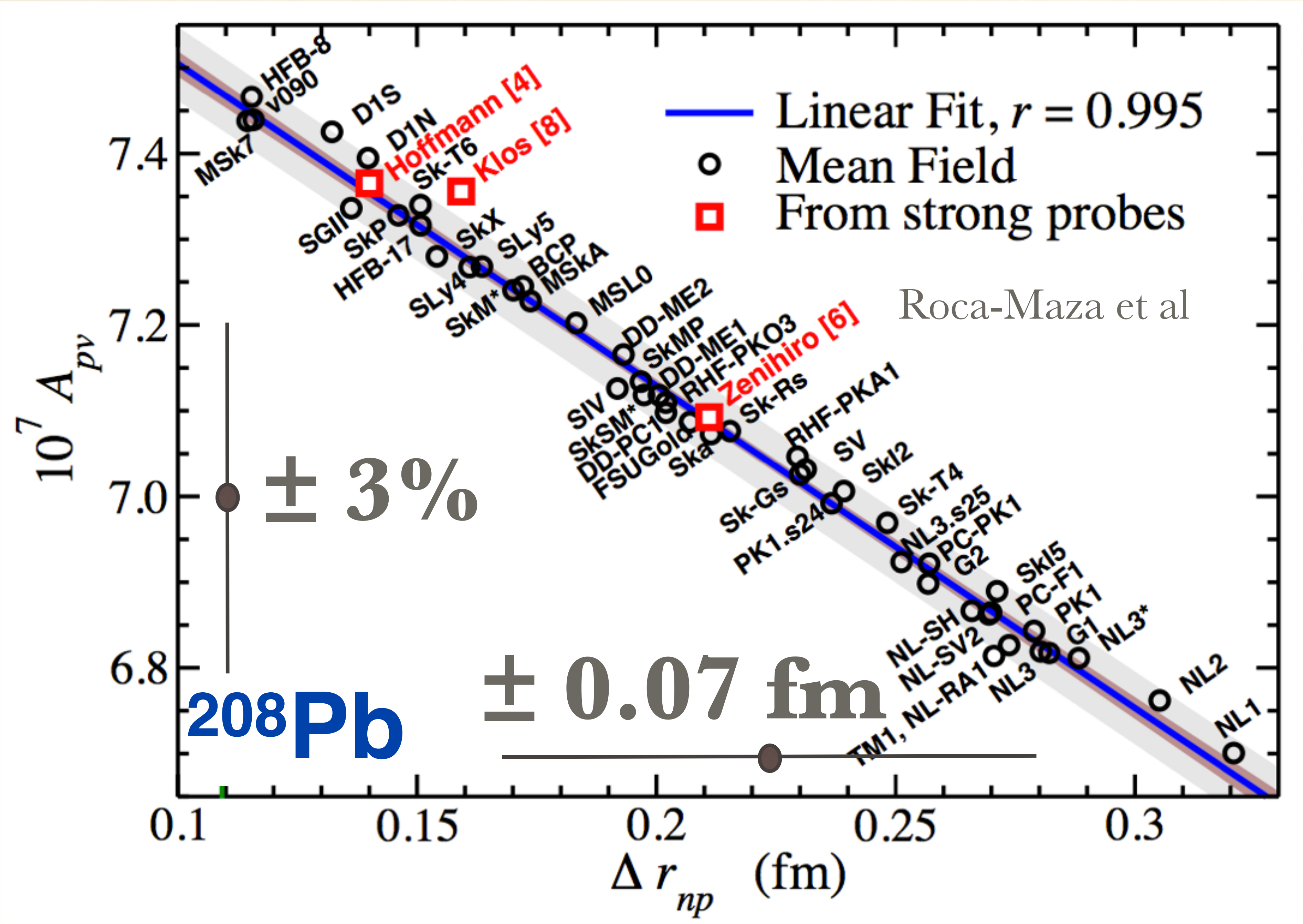
$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

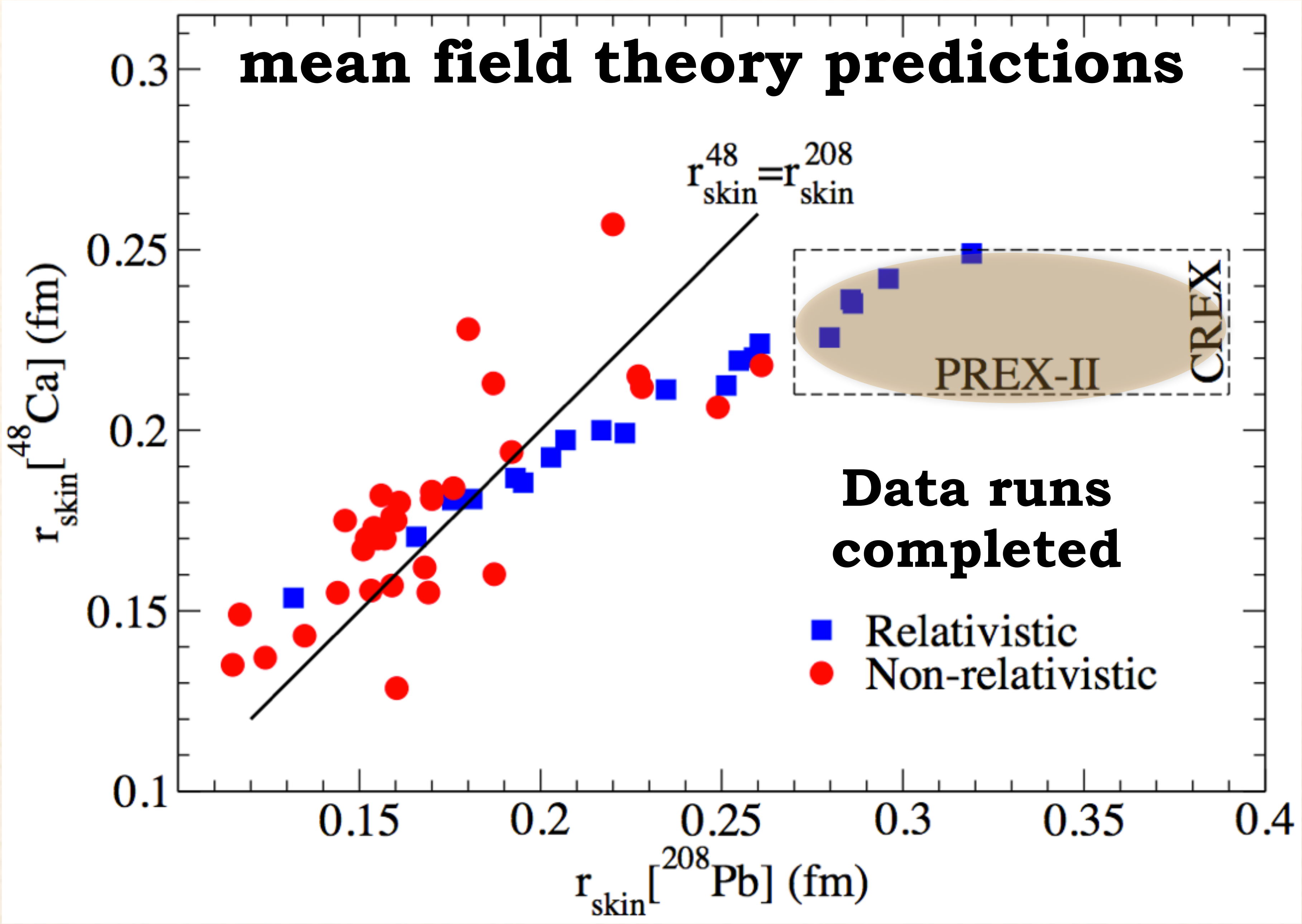
$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

$$M^{NC}_{PV} = \frac{G_F}{\sqrt{2}}\left[\left(1-4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

$\boxed{\delta(A_{PV})/A_{PV} \sim 3\% \quad \delta(R_n)/R_n \sim 1\%}$

$\delta(R_n)$: ± 0.07 fm (^{208}Pb)
± 0.03 fm (^{48}Ca)





PREX & CREX

PREX-2 Run: Summer 2019

CREX runs: Dec 19 to Sep 20 (Despite lockdowns!)

^{208}Pb PREX/CREX Overview and Data ^{48}Ca

$Q^2 \sim 0.006$ GeV^2

$A_{PV} \sim 0.6$ ppm

Rate ~ 4 GHz

$\Delta(A_{PV}) \sim 16$ ppb

$\Delta(R_n) \sim 0.07$ fm

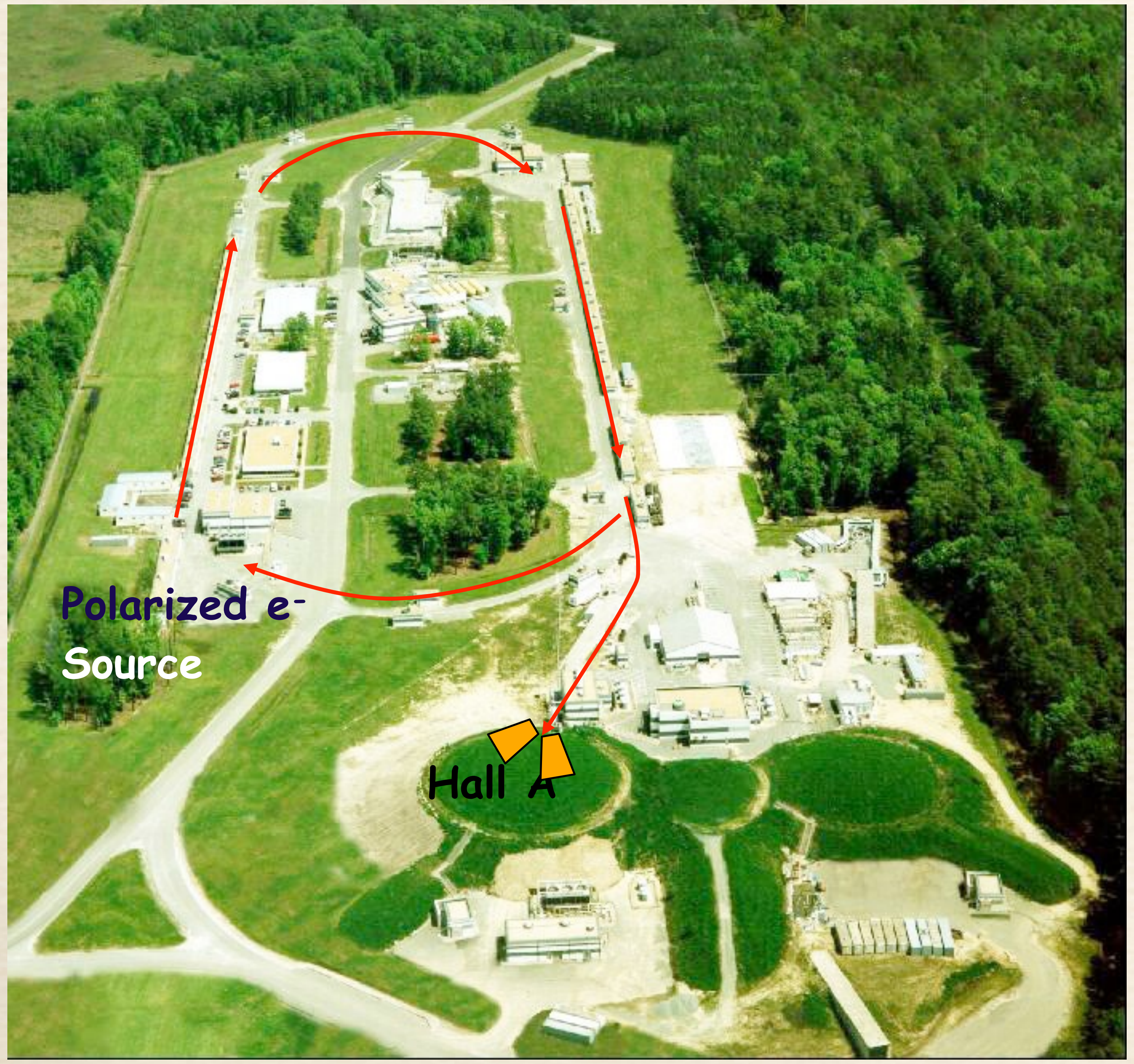
$Q^2 \sim 0.03$ GeV^2

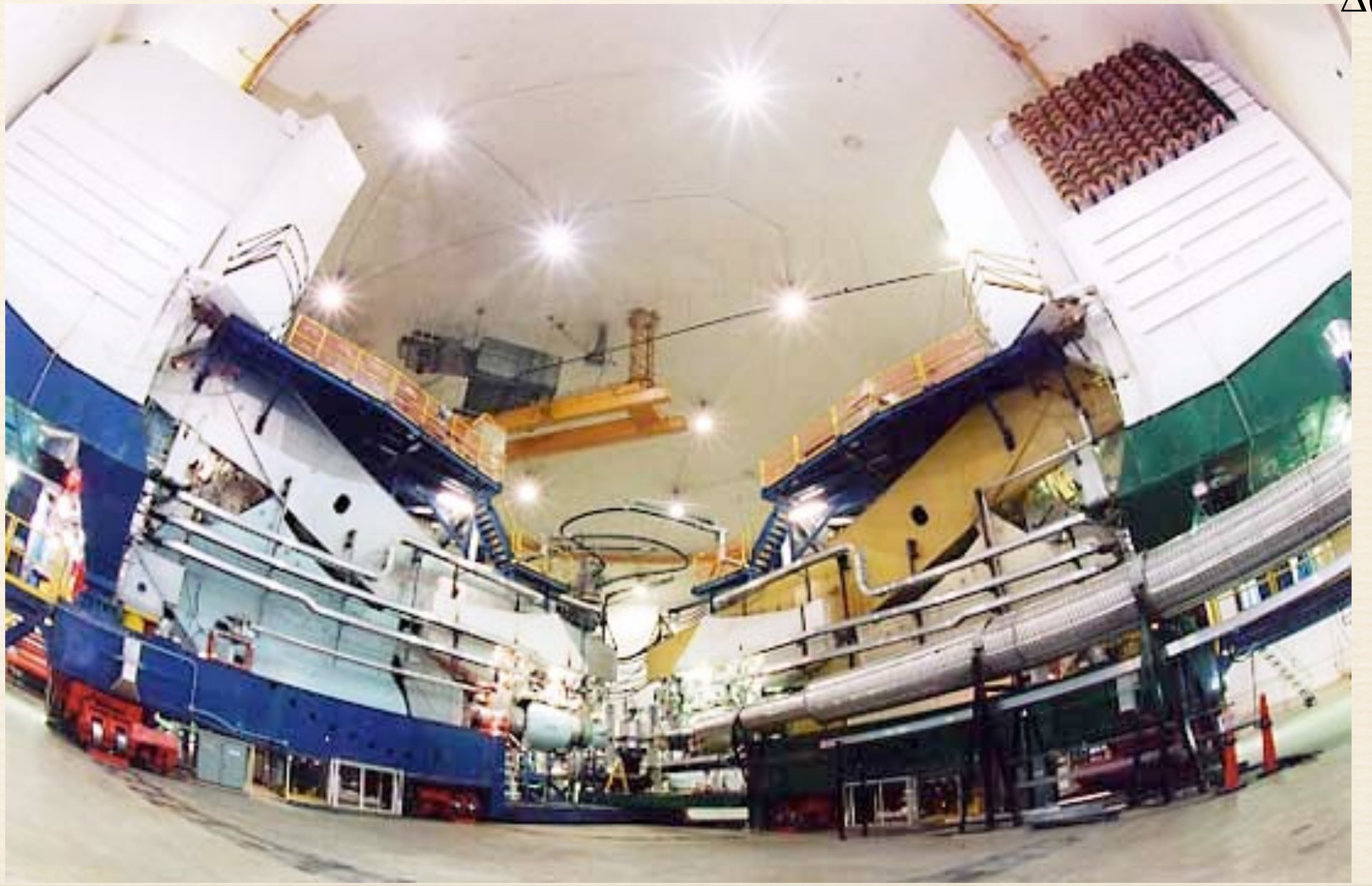
$A_{PV} \sim 2$ ppm

Rate ~ 56 MHz

$\Delta(A_{PV}) \sim 100$ ppb

$\Delta(R_n) \sim 0.03$ fm





^{208}Pb PREX/CREX Overview and Data ^{48}Ca

$Q^2 \sim 0.006$ GeV^2

$A_{PV} \sim 0.6$ ppm

Rate ~ 4 GHz

$\Delta(A_{PV}) \sim 16$ ppb

$\Delta(R_n) \sim 0.07$ fm

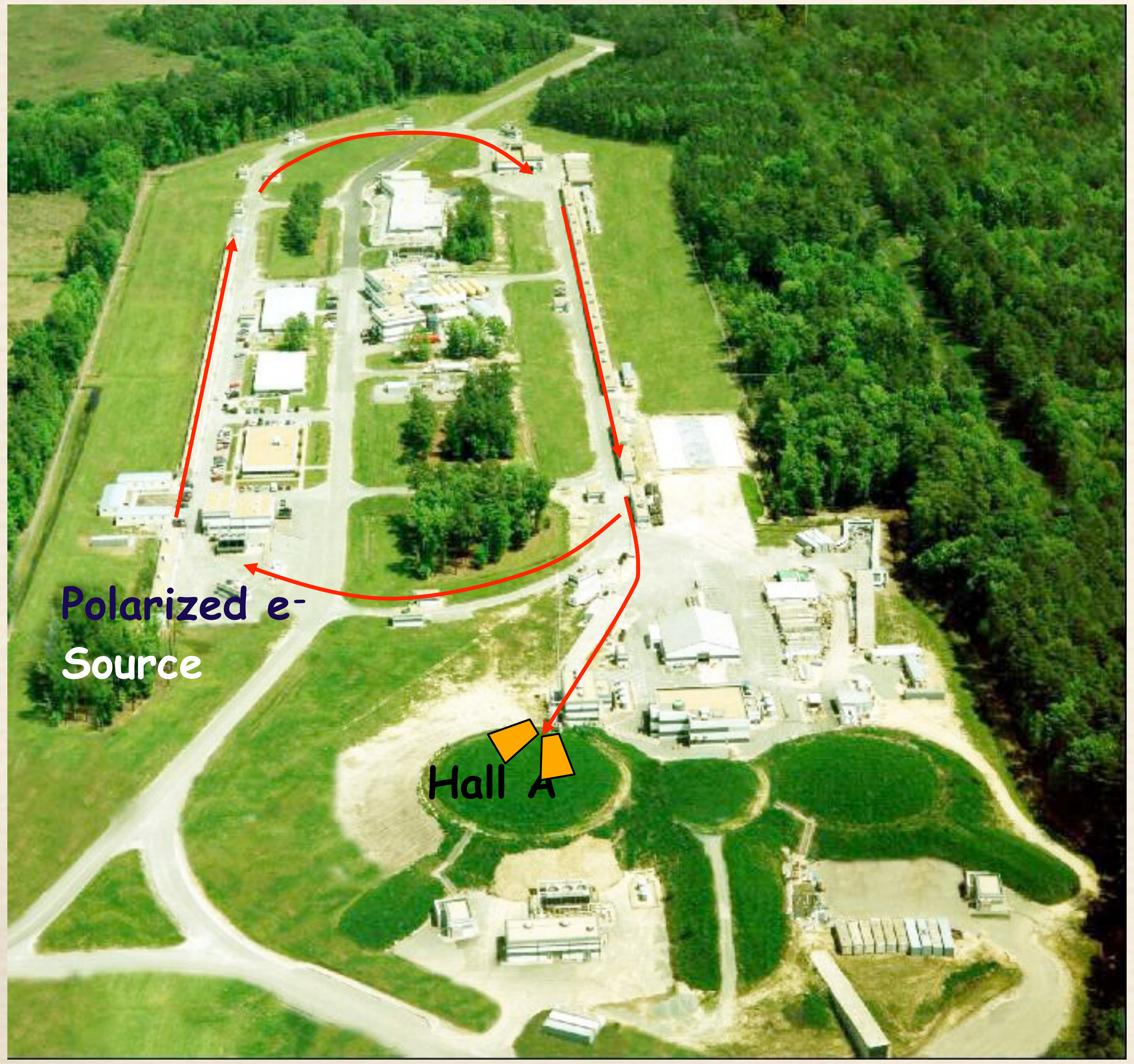
$Q^2 \sim 0.03$ GeV^2

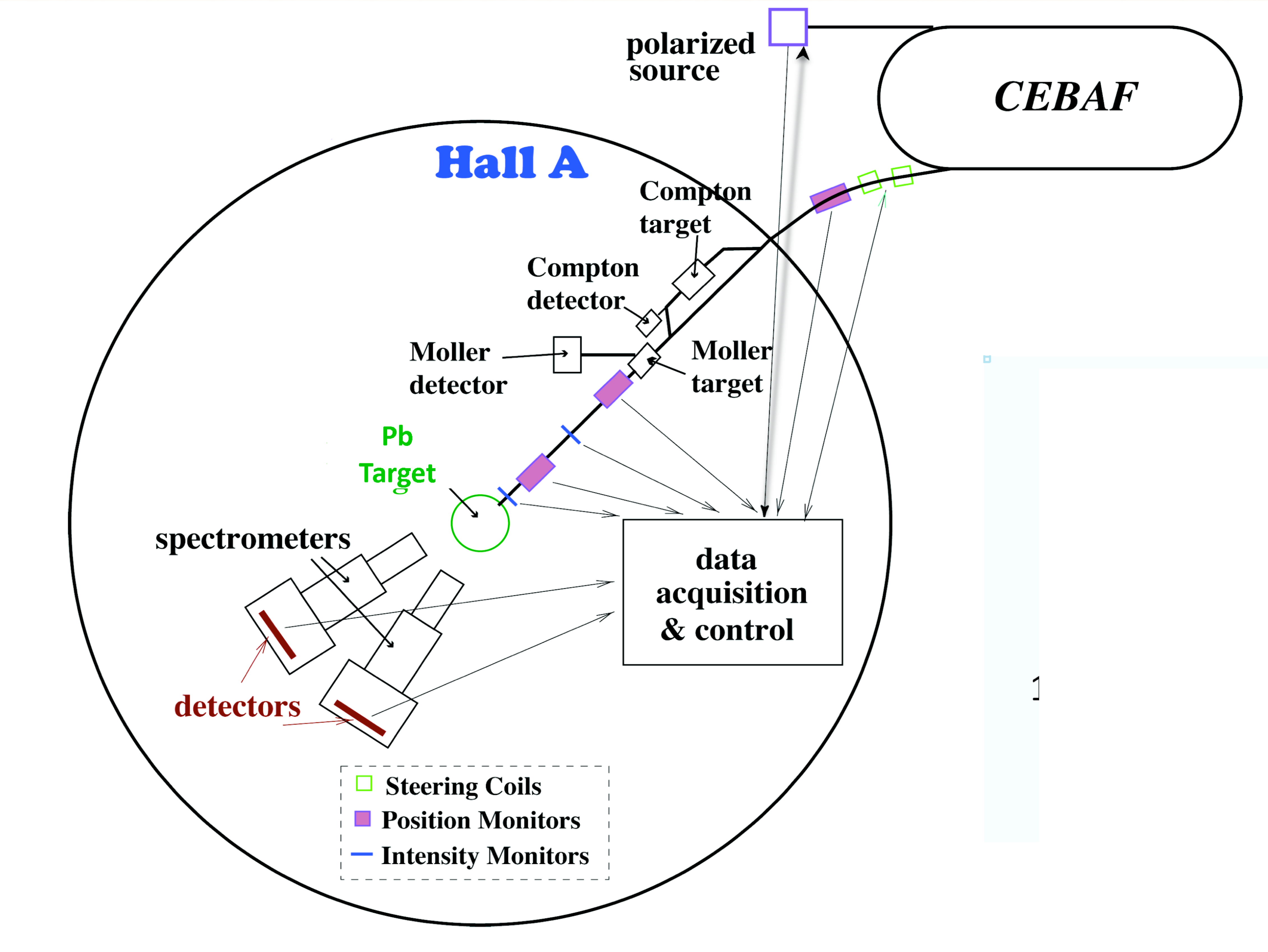
$A_{PV} \sim 2$ ppm

Rate ~ 56 MHz

$\Delta(A_{PV}) \sim 100$ ppb

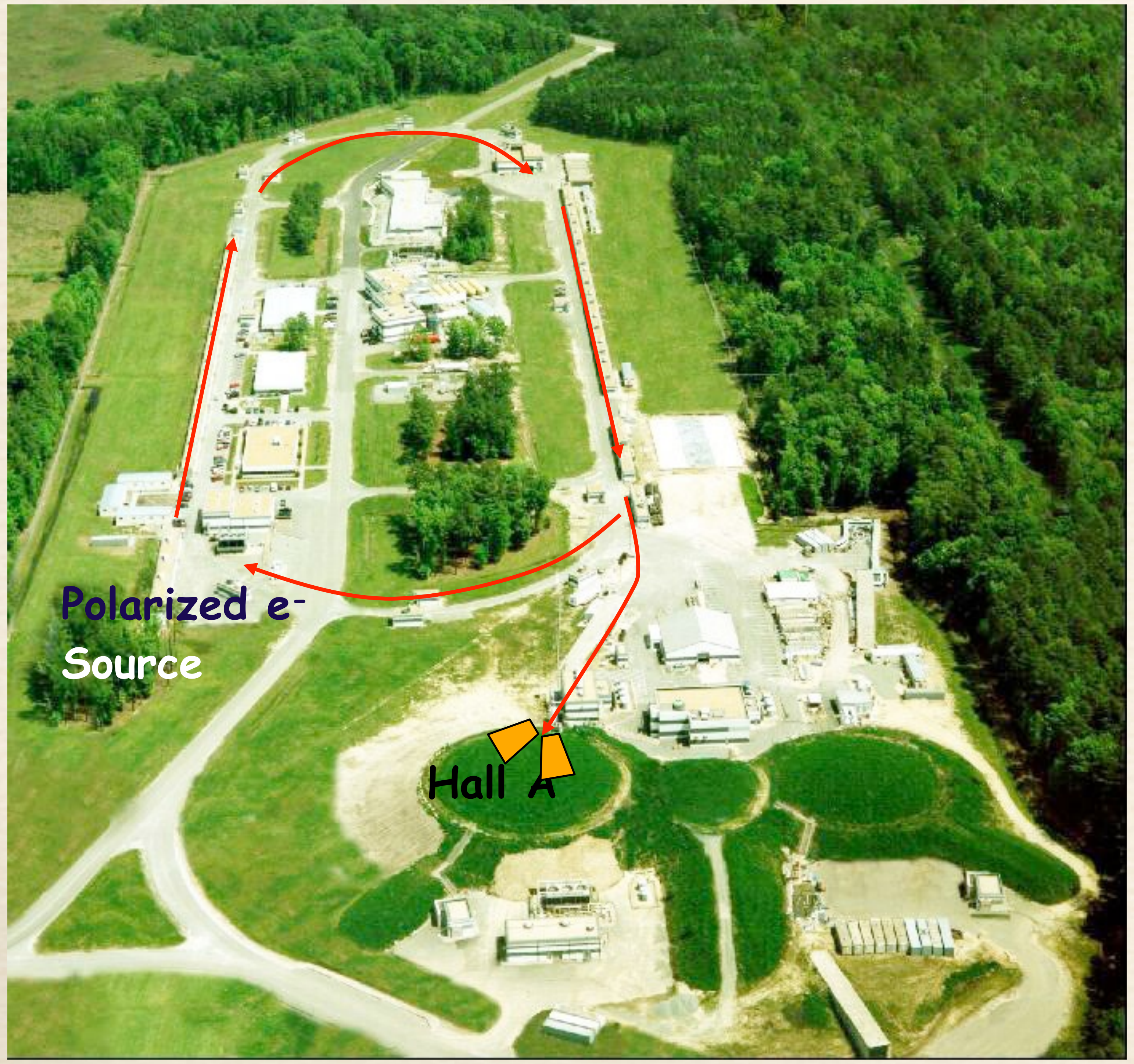
$\Delta(R_n) \sim 0.03$ fm

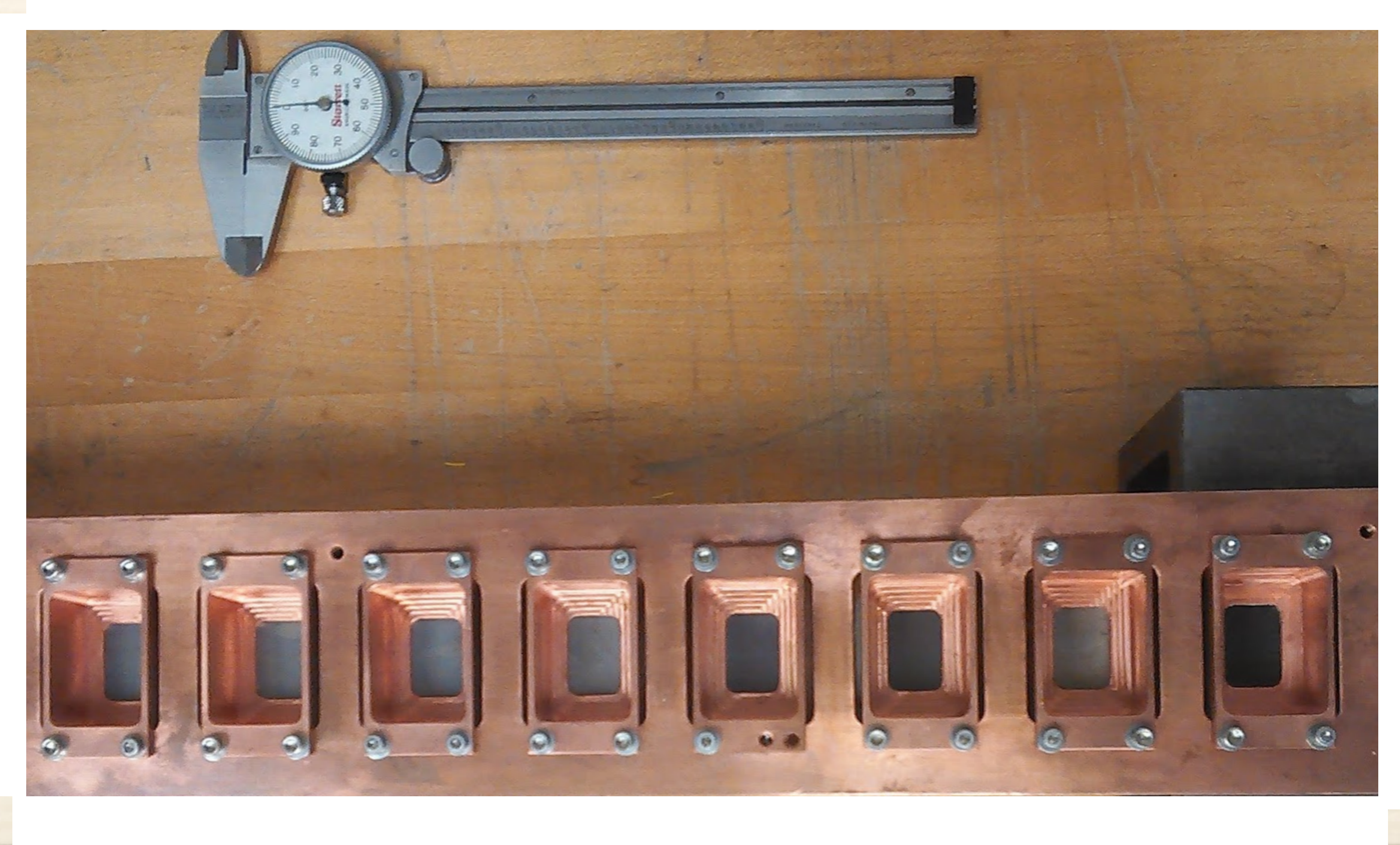


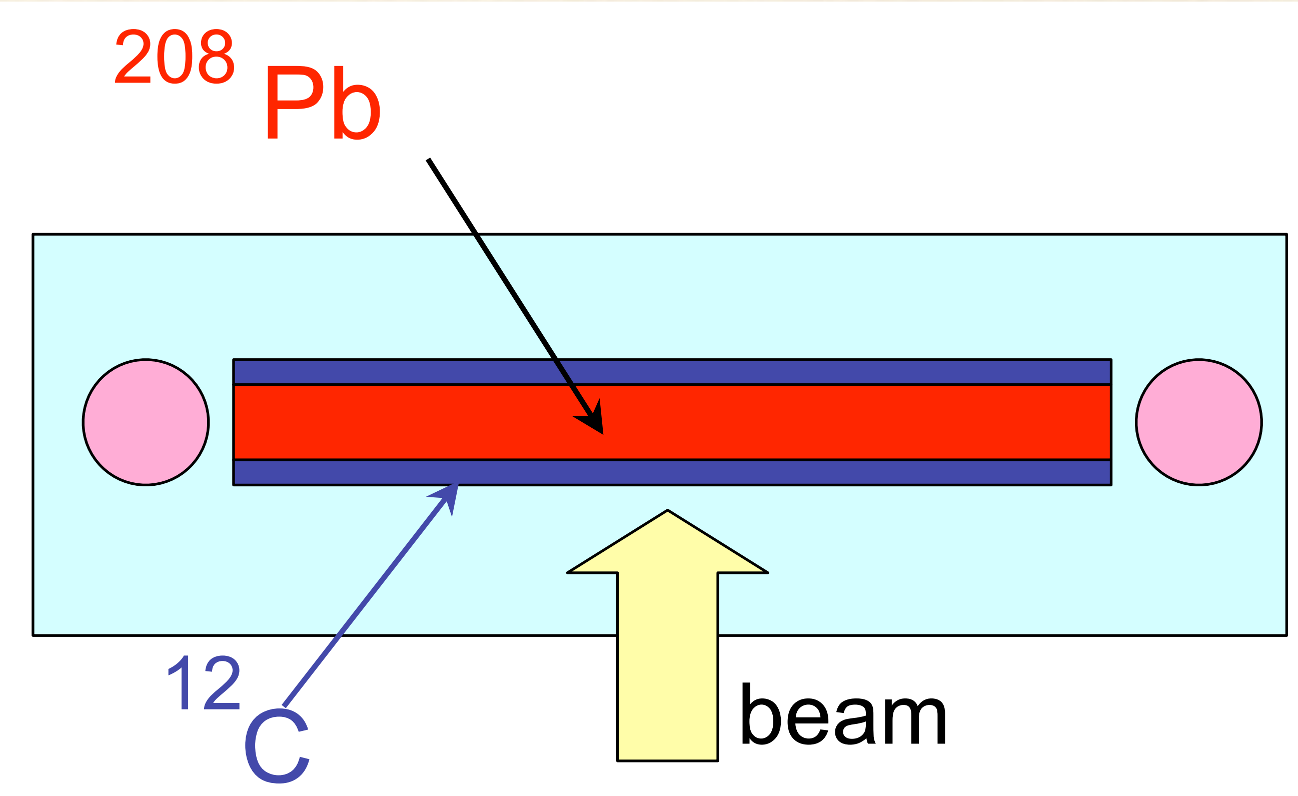


^{208}Pb PREX/CREX Overview and Data ^{48}Ca

^{208}Pb	^{48}Ca
$Q^2 \sim 0.006$ GeV^2	$Q^2 \sim 0.03$ GeV^2
$A_{PV} \sim 0.6$ ppm	$A_{PV} \sim 2$ ppm
Rate ~ 4 GHz	Rate ~ 56 MHz
$\Delta(A_{PV}) \sim 16$ ppb	$\Delta(A_{PV}) \sim 100$ ppb
$\Delta(R_n) \sim 0.07$ fm	$\Delta(R_n) \sim 0.03$ fm







^{208}Pb PREX/CREX Overview and Data ^{48}Ca

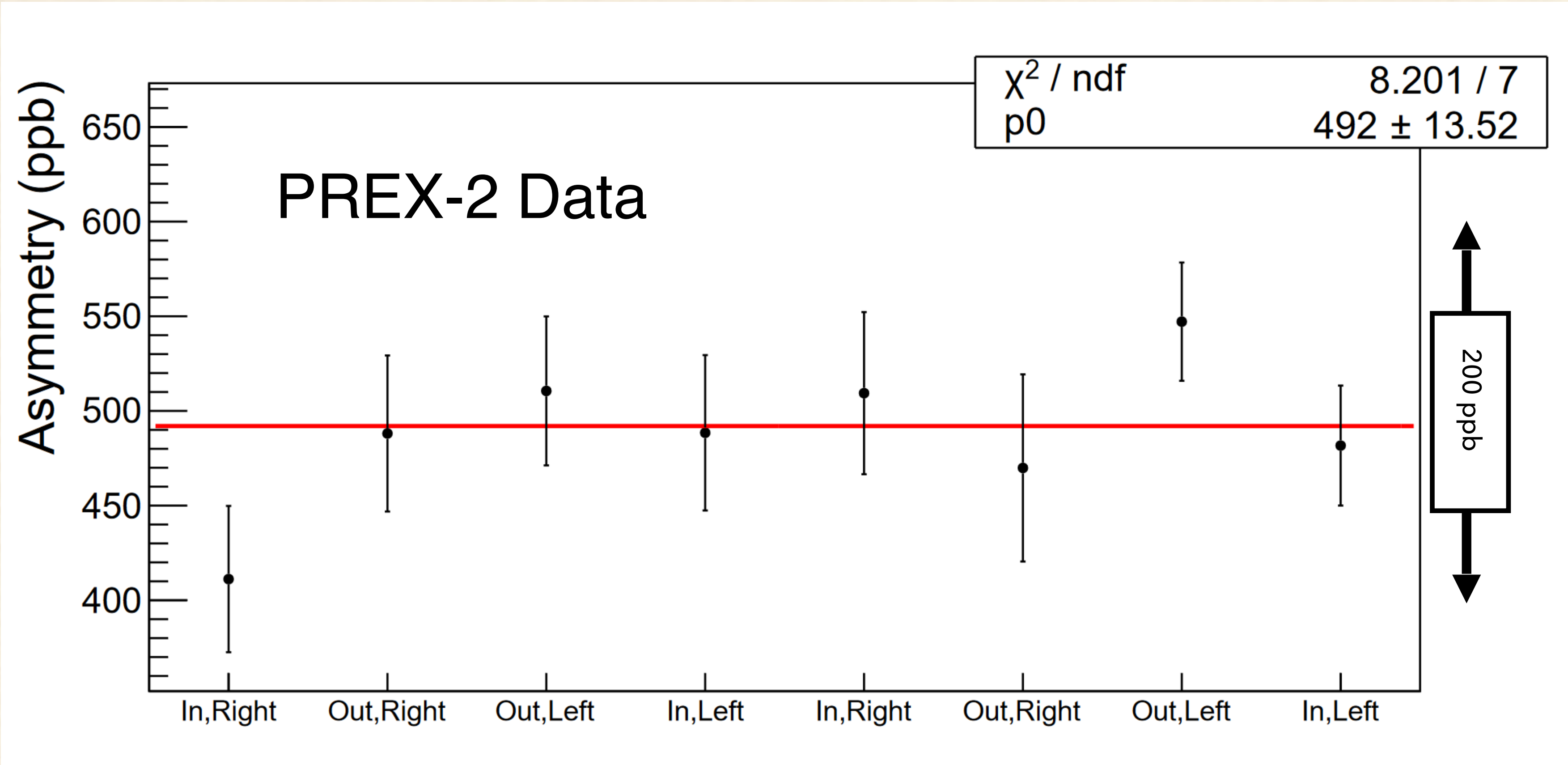
$Q^2 \sim 0.006$ GeV^2

$A_{PV} \sim 0.6$ ppm

Rate ~ 4 GHz

$\Delta(A_{PV}) \sim 16$ ppb

$\Delta(R_n) \sim 0.07$ fm



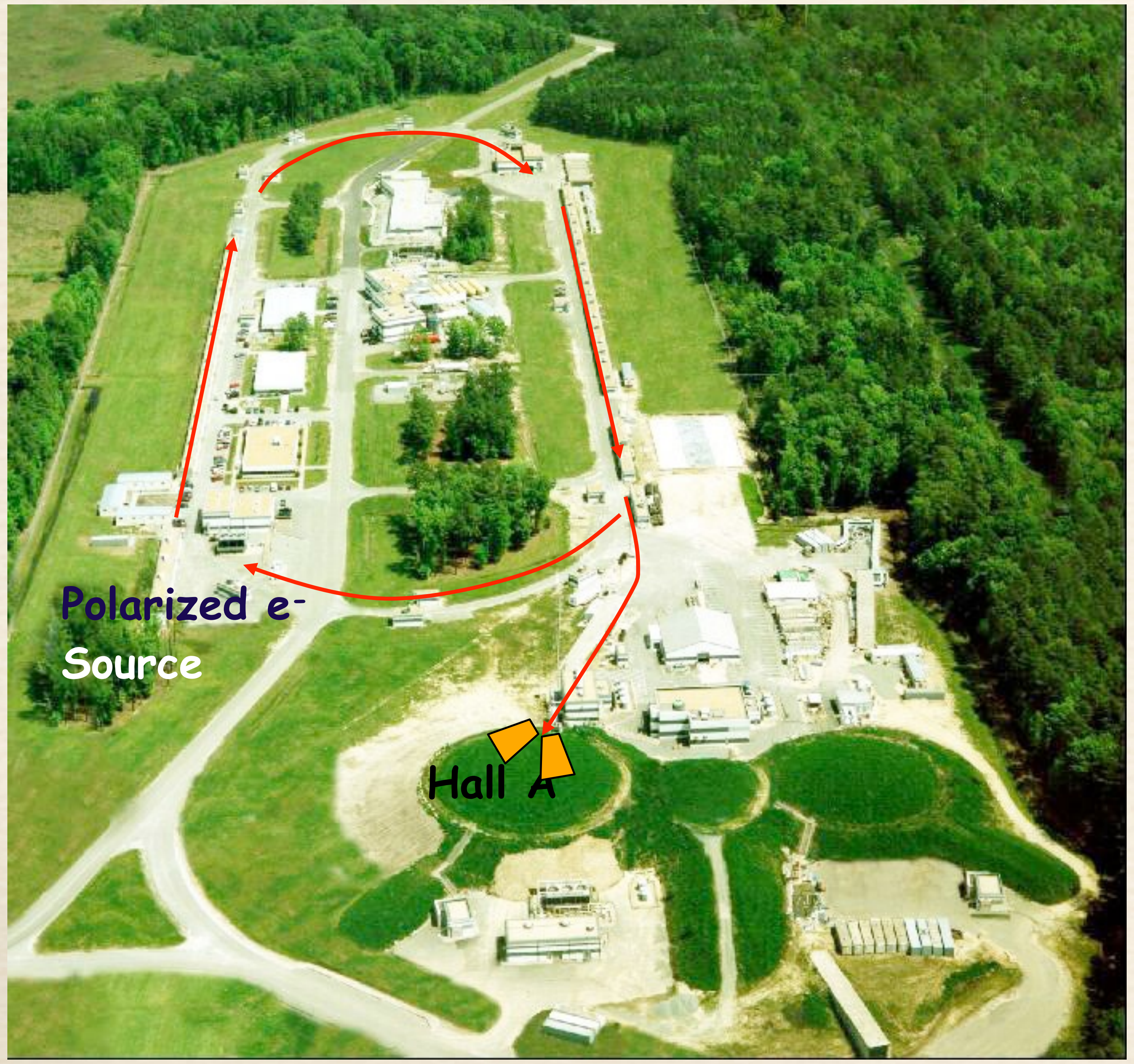
$Q^2 \sim 0.03$ GeV^2

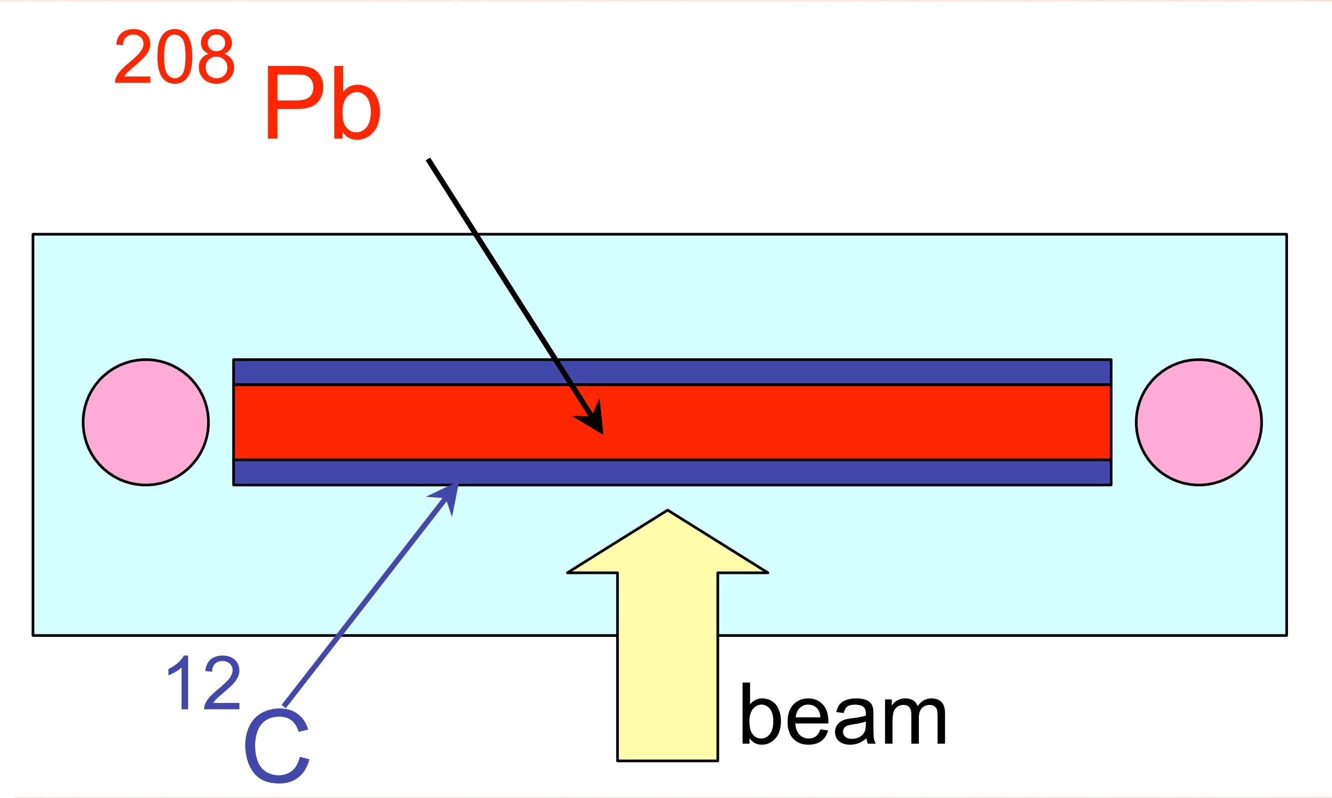
$A_{PV} \sim 2$ ppm

Rate ~ 56 MHz

$\Delta(A_{PV}) \sim 100$ ppb

$\Delta(R_n) \sim 0.03$ fm





^{208}Pb PREX/CREX Overview and Data ^{48}Ca

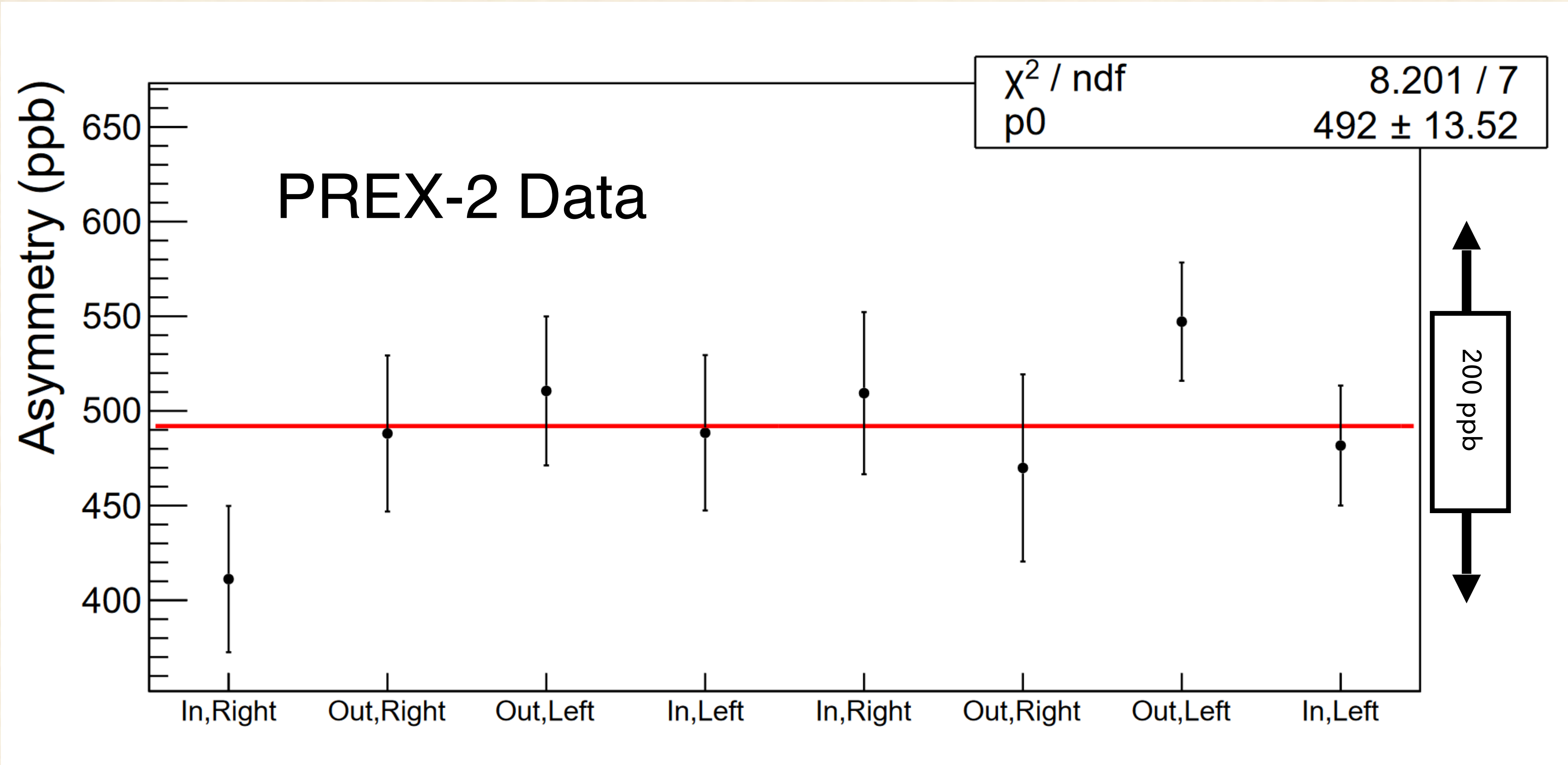
$Q^2 \sim 0.006$ GeV^2

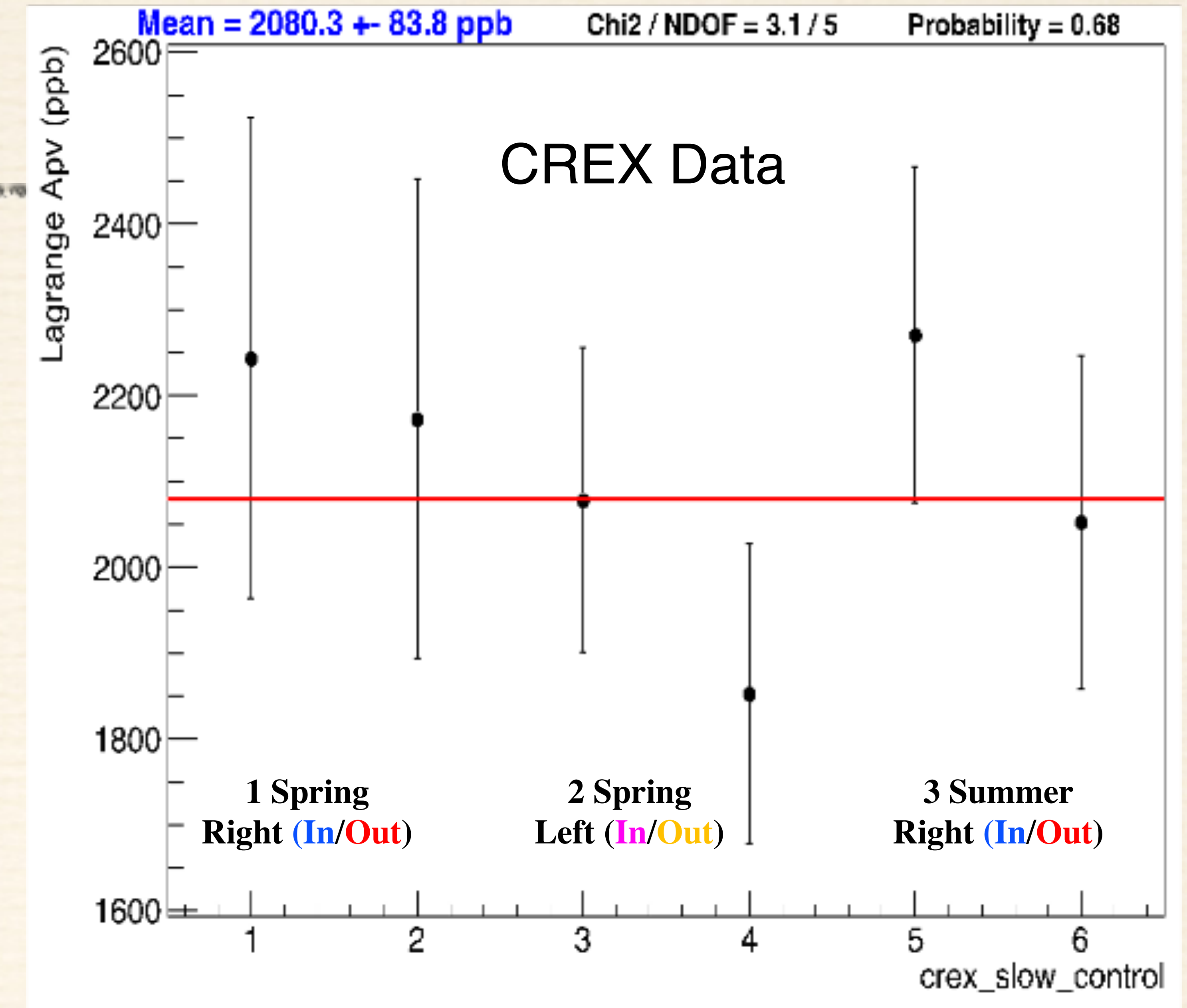
$A_{PV} \sim 0.6$ ppm

Rate ~ 4 GHz

$\Delta(A_{PV}) \sim 16$ ppb

$\Delta(R_n) \sim 0.07$ fm





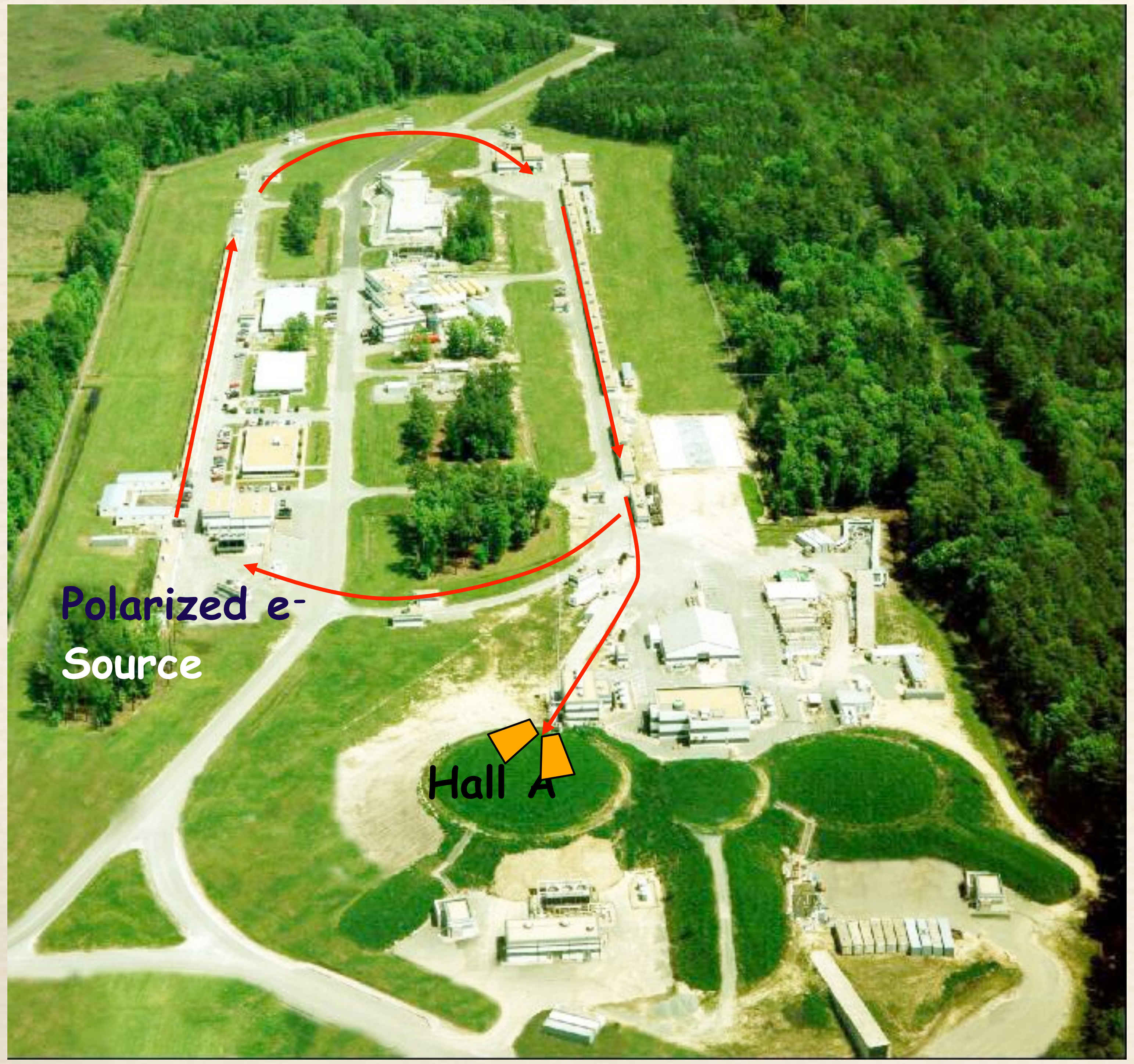
$Q^2 \sim 0.03$ GeV^2

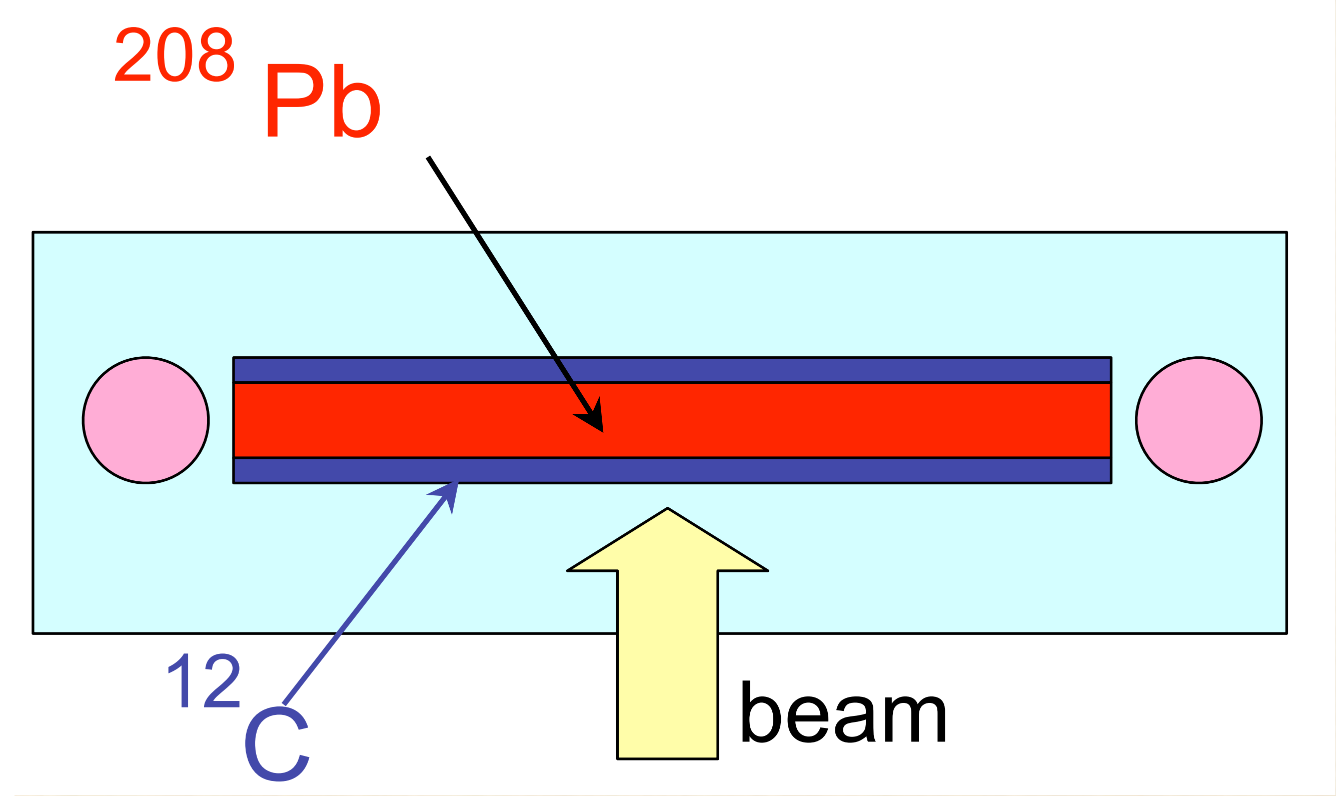
$A_{PV} \sim 2$ ppm

Rate ~ 56 MHz

$\Delta(A_{PV}) \sim 100$ ppb

$\Delta(R_n) \sim 0.03$ fm





PREX and CREX Final Results

334 citations

^{208}Pb

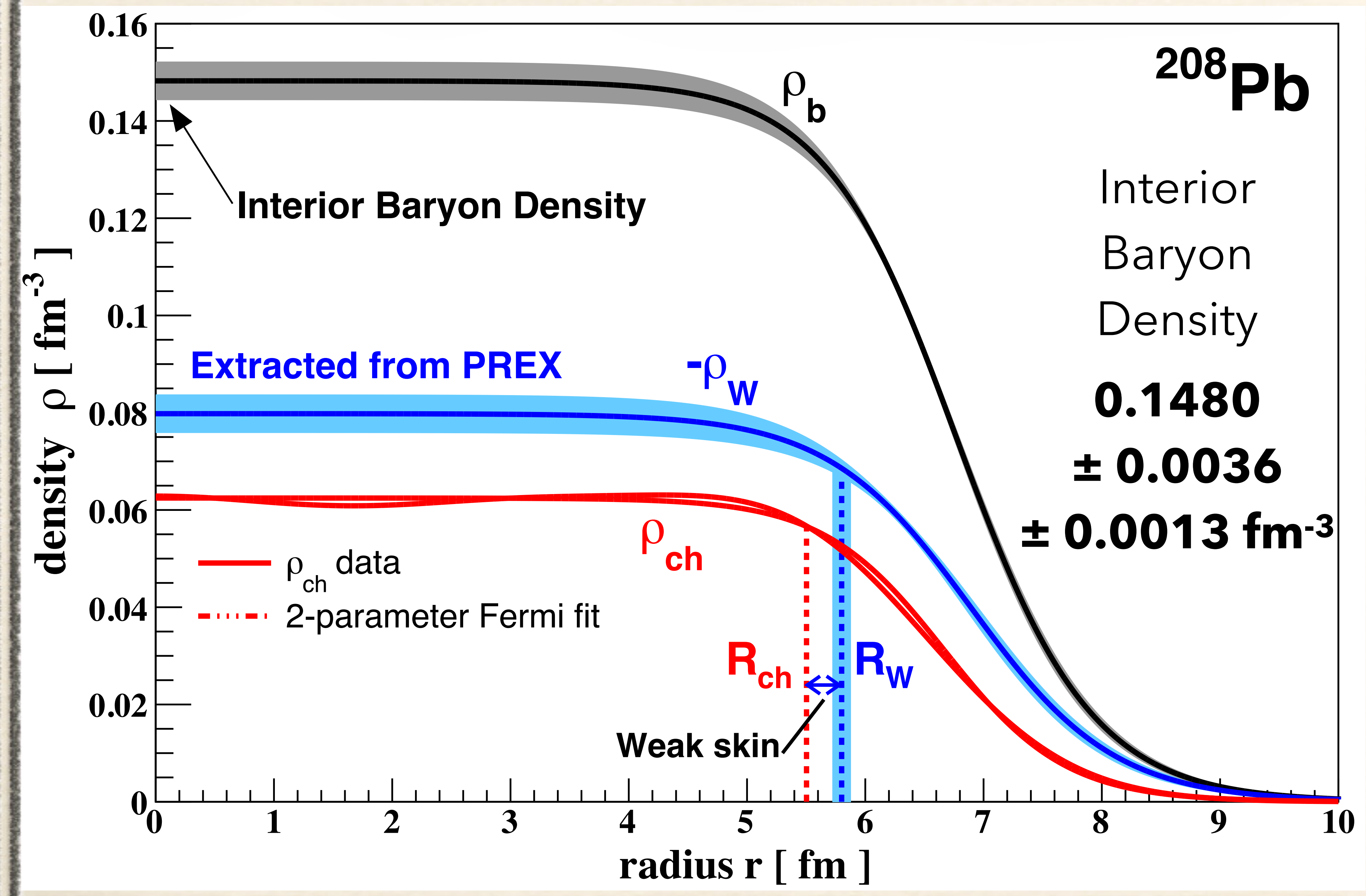
Phys.Rev.Lett. 126 (2021) 17, 172502

$$A_{\rm PV} = 550 \pm 16(\mathrm{stat}) \pm 8\ (\mathrm{syst})\, \mathrm{ppb}$$

$\boxed{F_W(Q^2 = 0.00616\ \mathrm{GeV}^2) = 0.368 \pm 0.013}$

Implied neutron skin thickness PREX-1 and PREX-2

$$R_n - R_p = 0.283 \pm 0.071\ \ \mathrm{fm}$$



PREX and CREX Final Results

^{208}Pb

334 citations

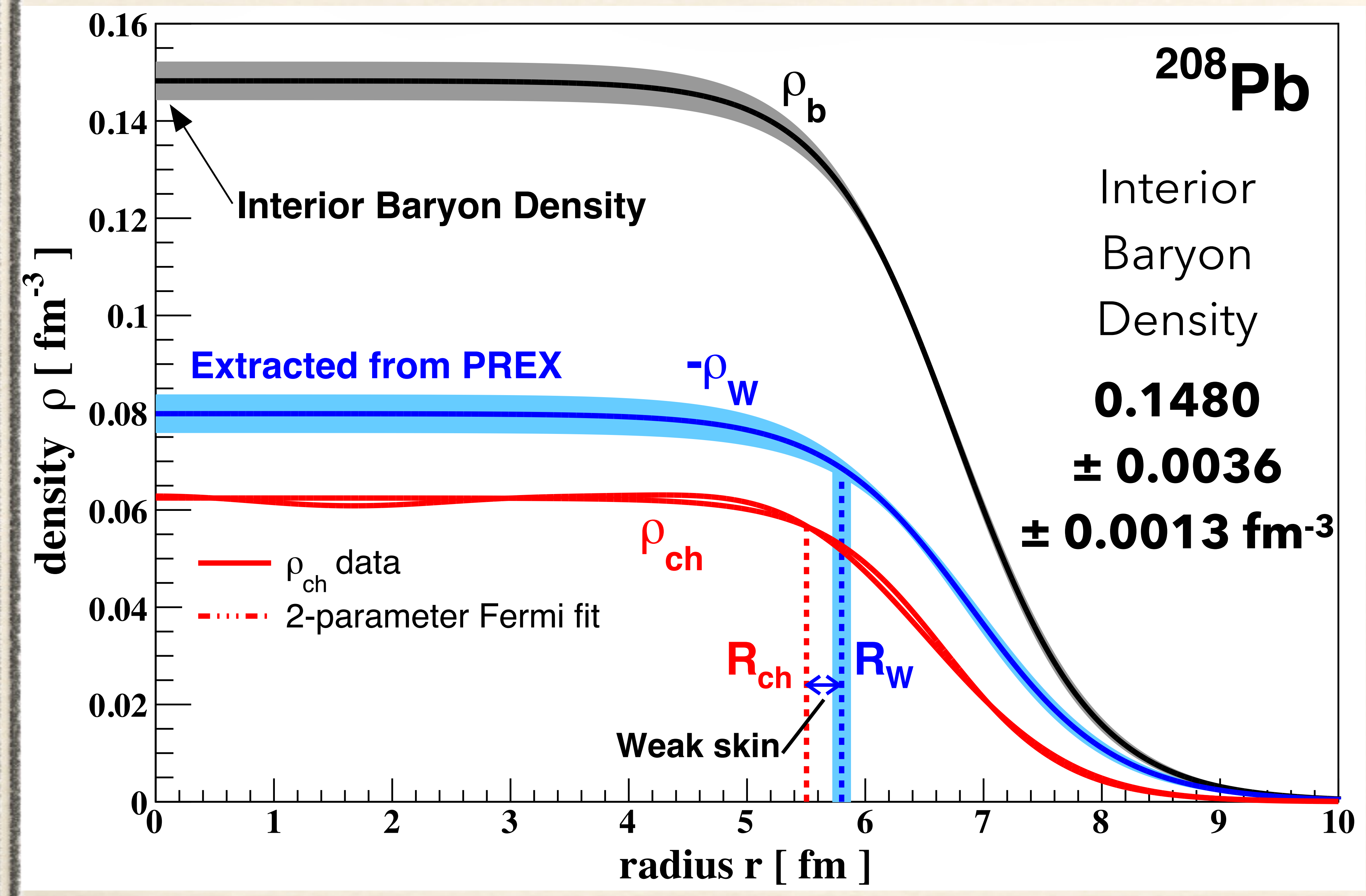
Phys.Rev.Lett. 126 (2021) 17, 172502

$$A_{PV} = 550 \pm 16(\text{stat}) \pm 8\ (\text{syst})\ \text{ppb}$$

$F_W\,(Q^2 = 0.00616\ \text{GeV}^2) = 0.368 \pm 0.013$

Implied neutron skin thickness PREX-1 and PREX-2

$$R_n - R_p = 0.283 \pm 0.071\ \text{fm}$$



^{48}Ca

98 citations

Phys.Rev.Lett. 129 (2022) 4, 042501

$$A_{PV} = 2668 \pm 106\ (\text{stat}) \pm 40\ (\text{sys})\ \text{ppb}$$

$F_W\,(Q^2 = 0.0297\ \text{GeV}^2) = 0.1304 \pm 0.0055$

Implied neutron skin thickness from CREX

$$R_n - R_p = 0.121 \pm 0.026\ (\text{exp}) \pm 0.024\ (\text{model})$$

PREX and CREX Final Results

334 citations

98 citations

^{208}Pb

Phys.Rev.Lett. 126 (2021) 17, 172502

Phys.Rev.Lett. 129 (2022) 4, 042501

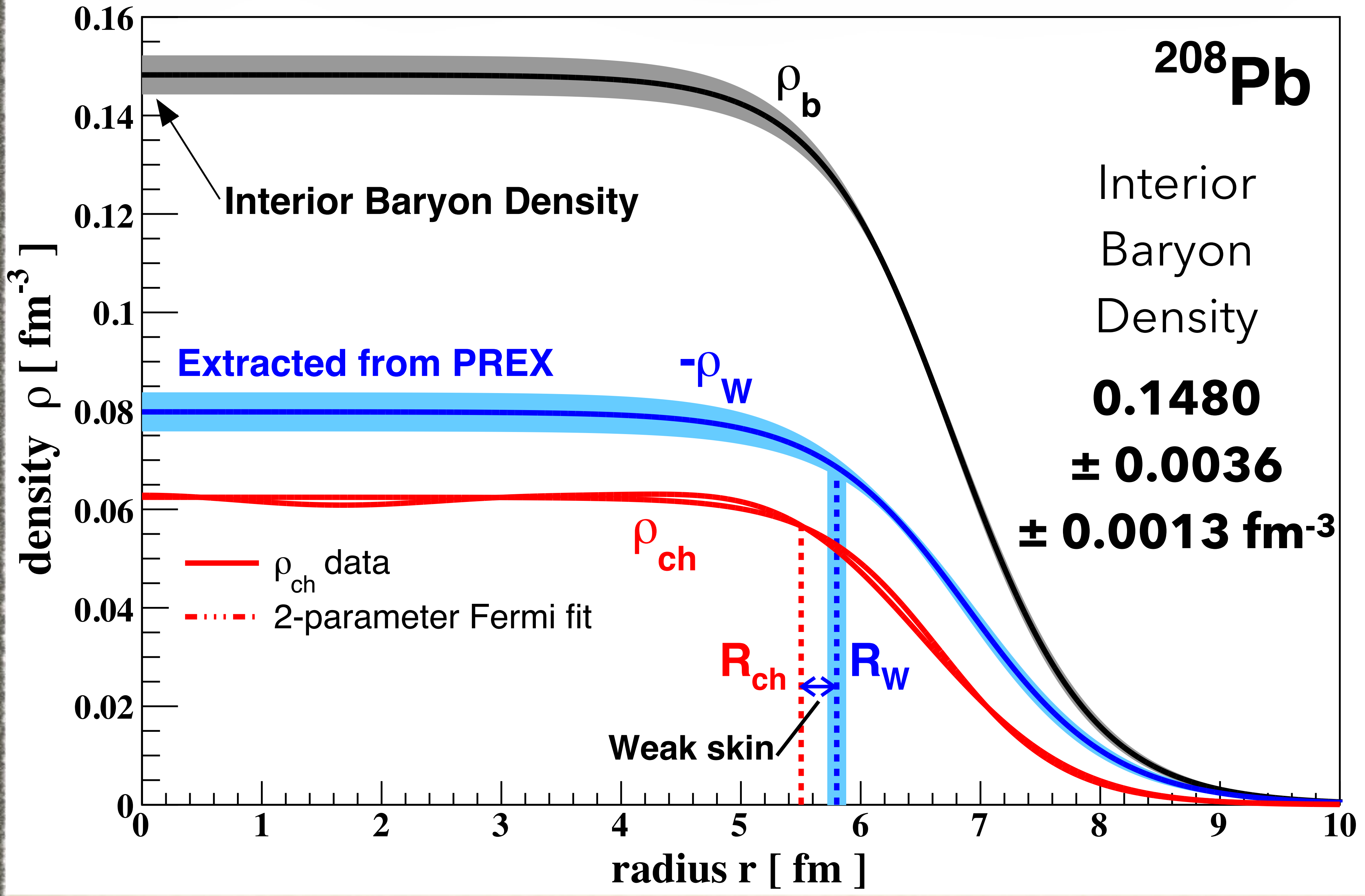
^{48}Ca

$$A_{PV} = 550 \pm 16(\text{stat}) \pm 8\ (\text{syst})\ \text{ppb}$$

$F_W\ (Q^2 = 0.00616\ \text{GeV}^2) = 0.368 \pm 0.013$

Implied neutron skin thickness PREX-1 and PREX-2

$$R_n - R_p = 0.283 \pm 0.071\ \text{fm}$$

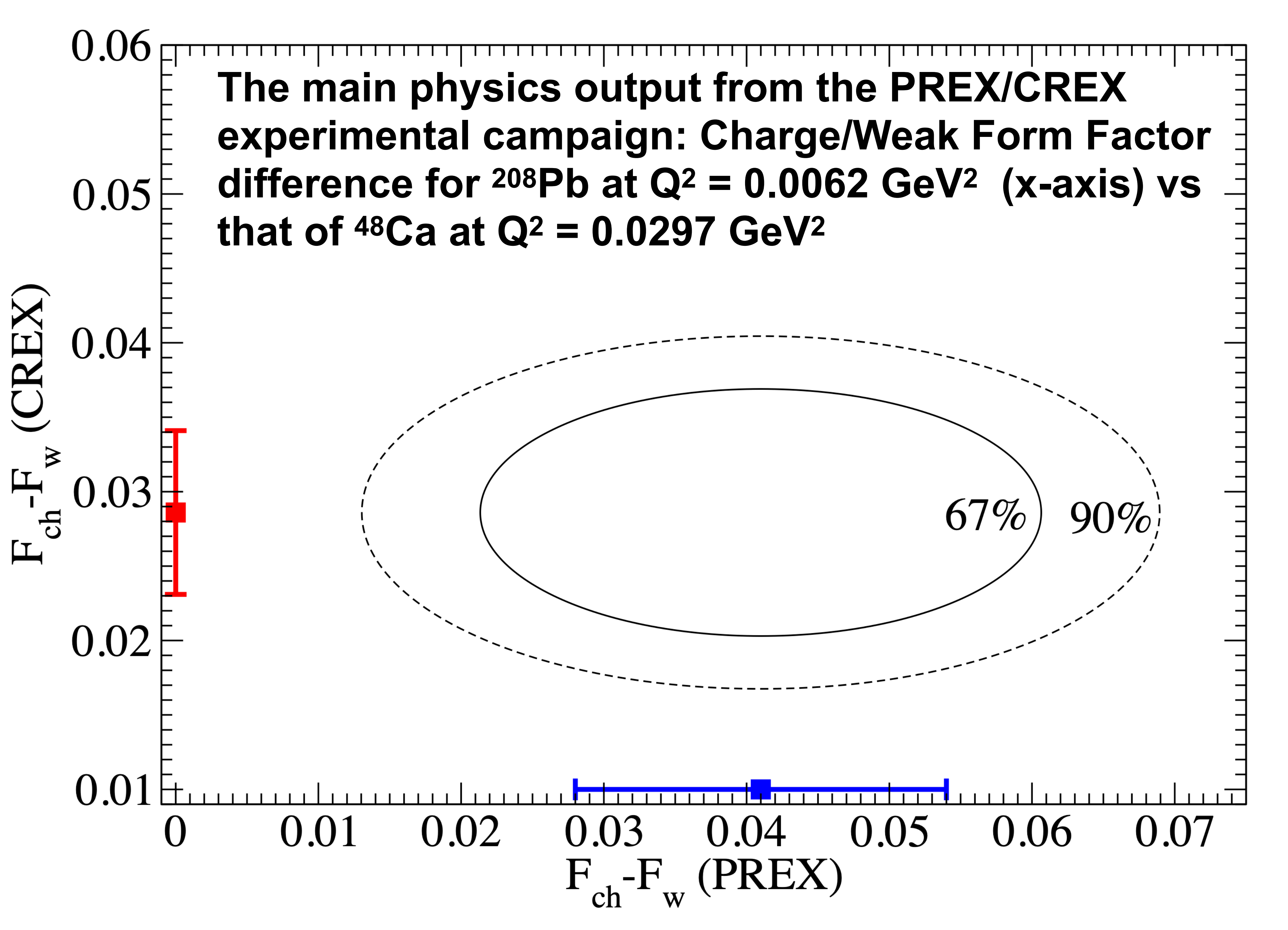


$$A_{PV} = 2668 \pm 106\ (\text{stat}) \pm 40\ (\text{sys})\ \text{ppb}$$

$F_W\ (Q^2 = 0.0297\ \text{GeV}^2) = 0.1304 \pm 0.0055$

Implied neutron skin thickness from CREX

$$R_n - R_p = 0.121 \pm 0.026\ (\text{exp}) \pm 0.024\ (\text{model})$$



PREX and CREX Final Results

^{208}Pb

334 citations

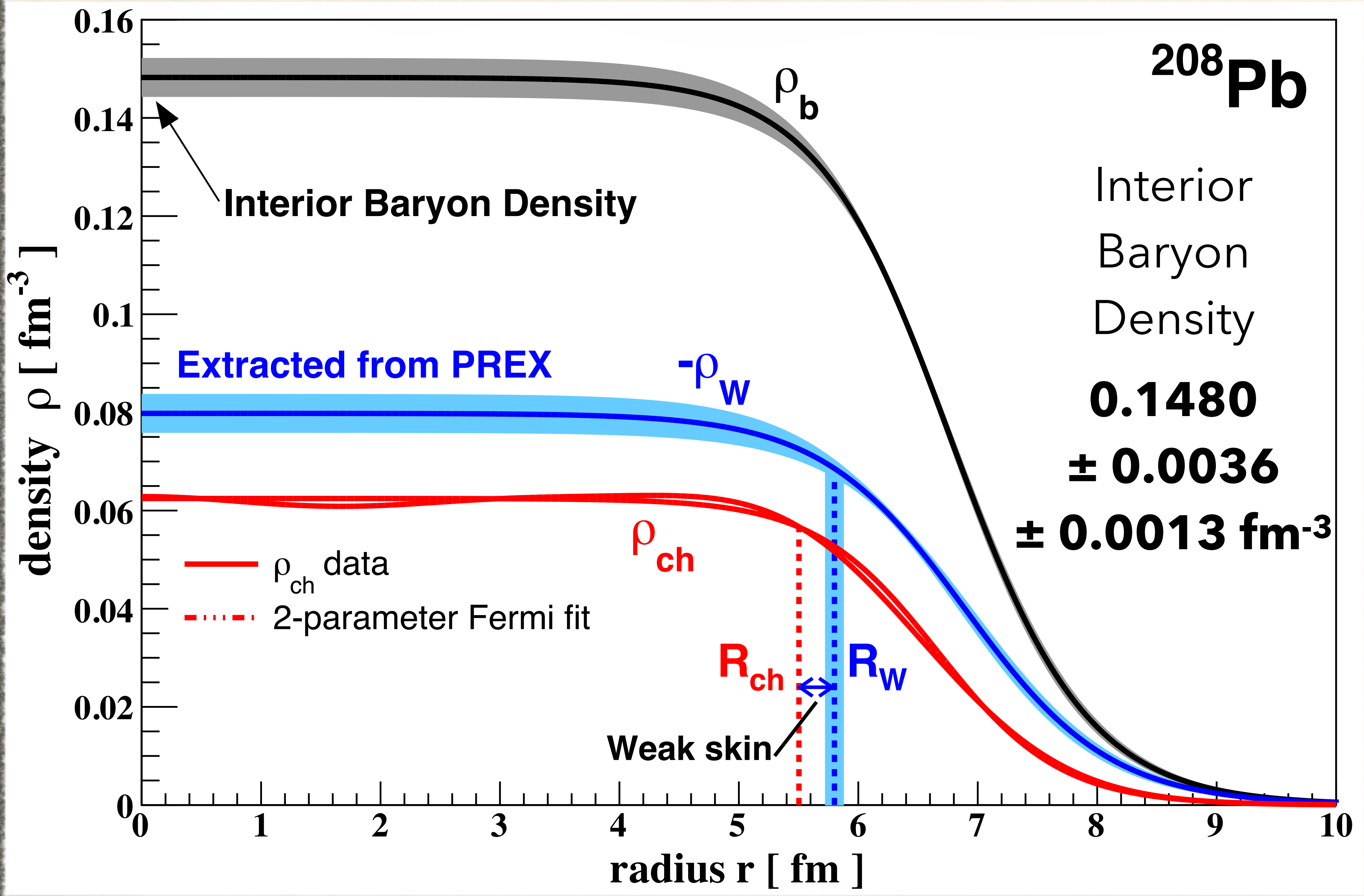
Phys.Rev.Lett. 126 (2021) 17, 172502

$$A_{PV} = 550 \pm 16(\text{stat}) \pm 8\ (\text{syst})\ \text{ppb}$$

$F_W\ (Q^2 = 0.00616\ \text{GeV}^2) = 0.368 \pm 0.013$

Implied neutron skin thickness PREX-1 and PREX-2

$$R_n - R_p = 0.283 \pm 0.071\ \text{fm}$$



^{48}Ca

98 citations

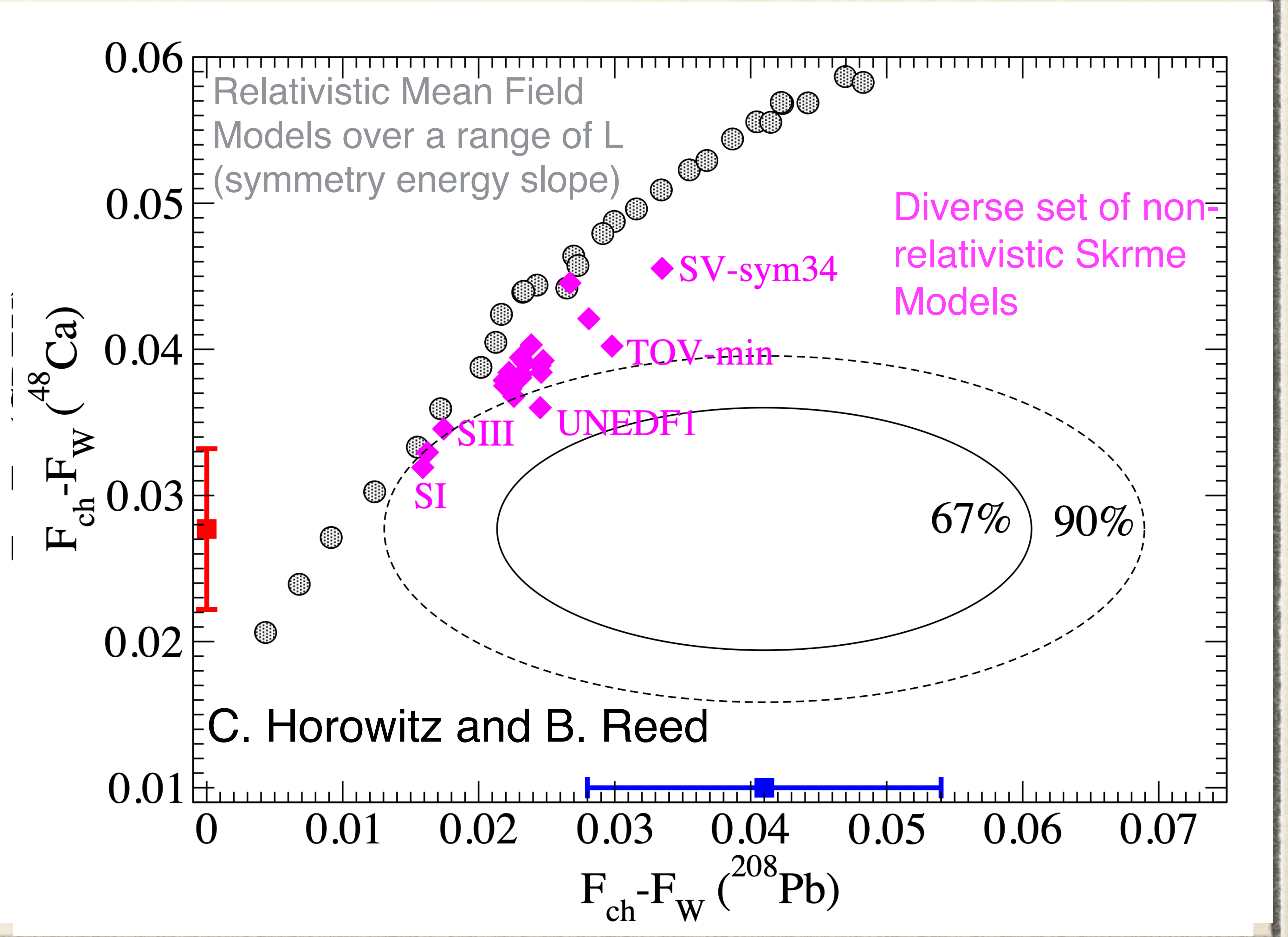
Phys.Rev.Lett. 129 (2022) 4, 042501

$$A_{PV} = 2668 \pm 106\ (\text{stat}) \pm 40\ (\text{sys})\ \text{ppb}$$

$F_W\ (Q^2 = 0.0297\ \text{GeV}^2) = 0.1304 \pm 0.0055$

Implied neutron skin thickness from CREX

$$R_n - R_p = 0.121 \pm 0.026\ (\text{exp}) \pm 0.024\ (\text{model})$$



PREX and CREX Final Results

^{208}Pb

334 citations

Phys.Rev.Lett. 126 (2021) 17, 172502

$$A_{PV} = 550 \pm 16(\text{stat}) \pm 8\ (\text{syst})\,\text{ppb}$$

$F_W\,(Q^2 = 0.00616\ \text{GeV}^2) = 0.368 \pm 0.013$

Implied neutron skin thickness PREX-1 and PREX-2

$$R_n - R_p = 0.283 \pm 0.071\ \text{fm}$$

^{48}Ca

98 citations

Phys.Rev.Lett. 129 (2022) 4, 042501

$$A_{PV} = 2668 \pm 106\ (\text{stat}) \pm 40\ (\text{sys})\ \text{ppb}$$

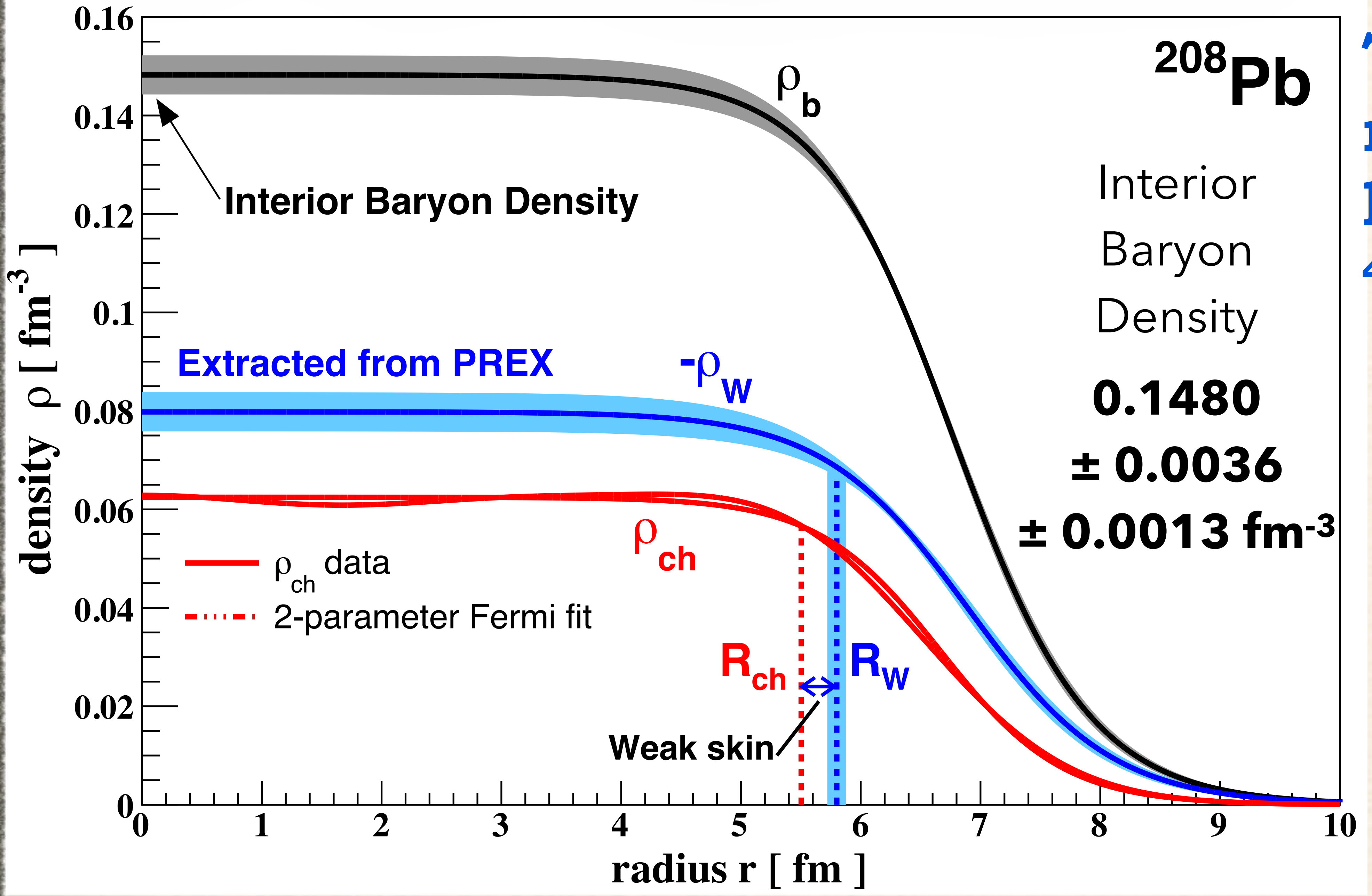
$F_W\,(Q^2 = 0.0297\ \text{GeV}^2) = 0.1304 \pm 0.0055$

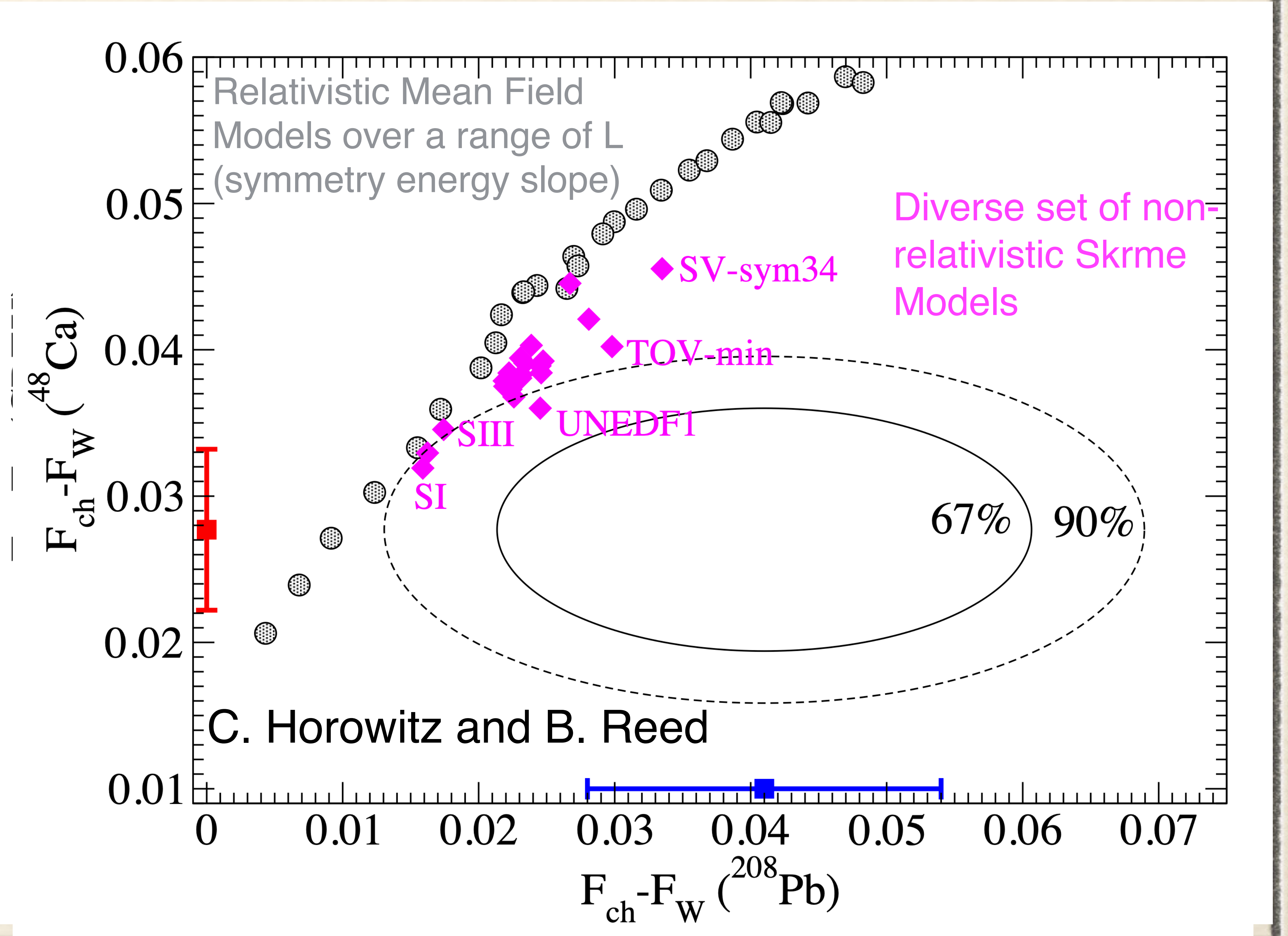
Implied neutron skin thickness from CREX

$$R_n - R_p = 0.121 \pm 0.026\ (\text{exp}) \pm 0.024\ (\text{model})$$

The PREX measurement of the neutron skin thickness of ^{208}Pb has very little model uncertainty

The CREX measurement is hard to improve for ^{48}Ca at the same Q^2





PREX and CREX Final Results

^{208}Pb

334 citations

Phys.Rev.Lett. 126 (2021) 17, 172502

$$A_{PV} = 550 \pm 16(\text{stat}) \pm 8\ (\text{syst})\ \text{ppb}$$

$$\boxed{F_W\ (Q^2 = 0.00616\ \text{GeV}^2) = 0.368 \pm 0.013}$$

Implied neutron skin thickness PREX-1 and PREX-2

$$R_n - R_p = 0.283 \pm 0.071\ \text{fm}$$

^{48}Ca

98 citations

Phys.Rev.Lett. 129 (2022) 4, 042501

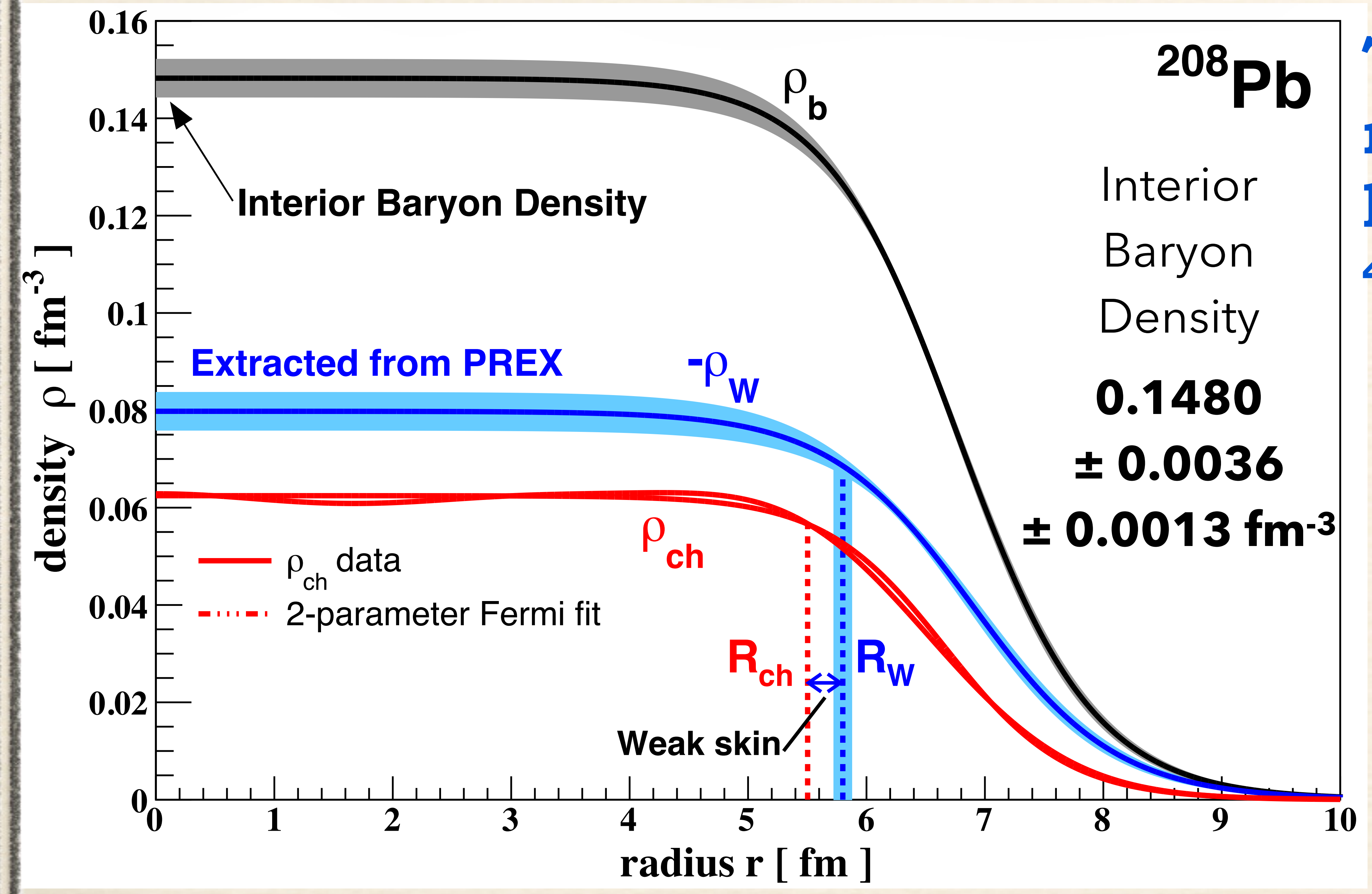
$$A_{PV} = 2668 \pm 106\ (\text{stat}) \pm 40\ (\text{sys})\ \text{ppb}$$

$$\boxed{F_W\ (Q^2 = 0.0297\ \text{GeV}^2) = 0.1304 \pm 0.0055}$$

Implied neutron skin thickness from CREX

$$R_n - R_p = 0.121 \pm 0.026\ (\text{exp}) \pm 0.024\ (\text{model})$$

The PREX measurement of the neutron skin thickness of ^{208}Pb has very little model uncertainty

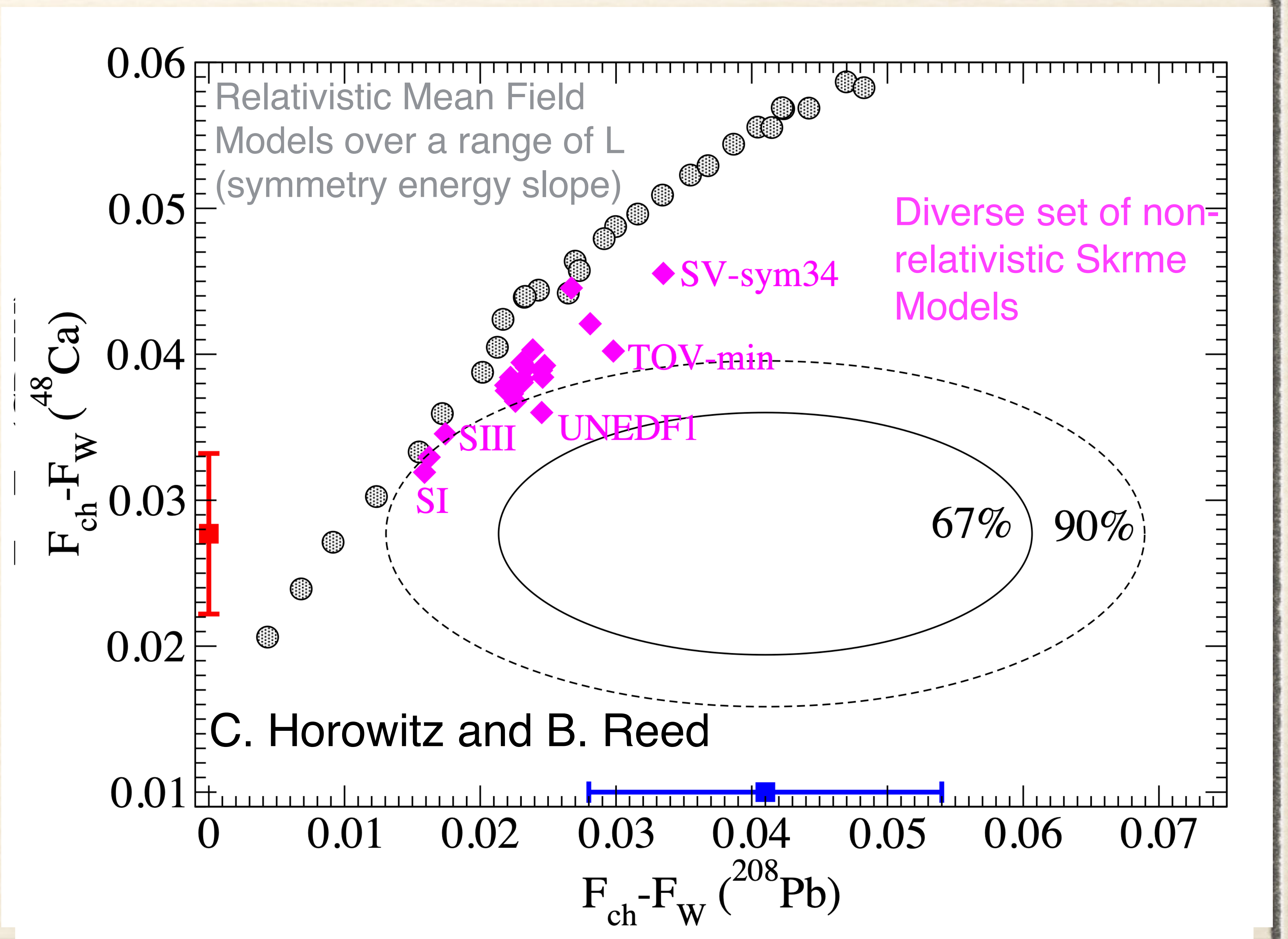


The CREX measurement is hard to improve for ^{48}Ca at the same Q^2

Community "Lore":

Ca-48 skin: "too thin"

Pb-208 skin: "too thick"



Broader Context

- *Nuclear Structure Physics*
- *Neutron Star Physics*
- *Atomic Parity Violation*
- *Coherent Neutrino Scattering*

Equation of state (EOS) of dense nuclear matter

$$E(\rho, \delta) = E_0(\rho, \delta = 0) + \boxed{S(\rho)}\delta^2$$

$$\delta = \frac{(\rho_n - \rho_p)}{\rho}$$

Symmetry Energy

Broader Context

- *Nuclear Structure Physics*
- *Neutron Star Physics*
- *Atomic Parity Violation*
- *Coherent Neutrino Scattering*

Equation of state (EOS)
of dense nuclear matter

$$E(\rho, \delta) = E_0(\rho, \delta = 0) + \boxed{S(\rho)}\delta^2$$

Symmetry Energy

size of neutron skin

$\Downarrow$

pressure $\Rightarrow$ density dependence of symmetry energy at subnuclear densities

Broader Context

- *Nuclear Structure Physics*
- *Neutron Star Physics*
- *Atomic Parity Violation*
- *Coherent Neutrino Scattering*

MREX at MESA: *Use of a solenoidal spectrometer makes it possible to increase solid angle of elastically scattered electrons by a factor of 4 compared to PREX-2 while rejecting inelastic background at a similar level*

⇒ $\delta(A_{PV})/A_{PV} \sim 1.5\%$ ⇒ $\delta(R_n)$: ± 0.03 fm

Equation of state (EOS) of dense nuclear matter

$$E(\rho, \delta) = E_0(\rho, \delta = 0) + \boxed{S(\rho)}\delta^2$$

Symmetry Energy

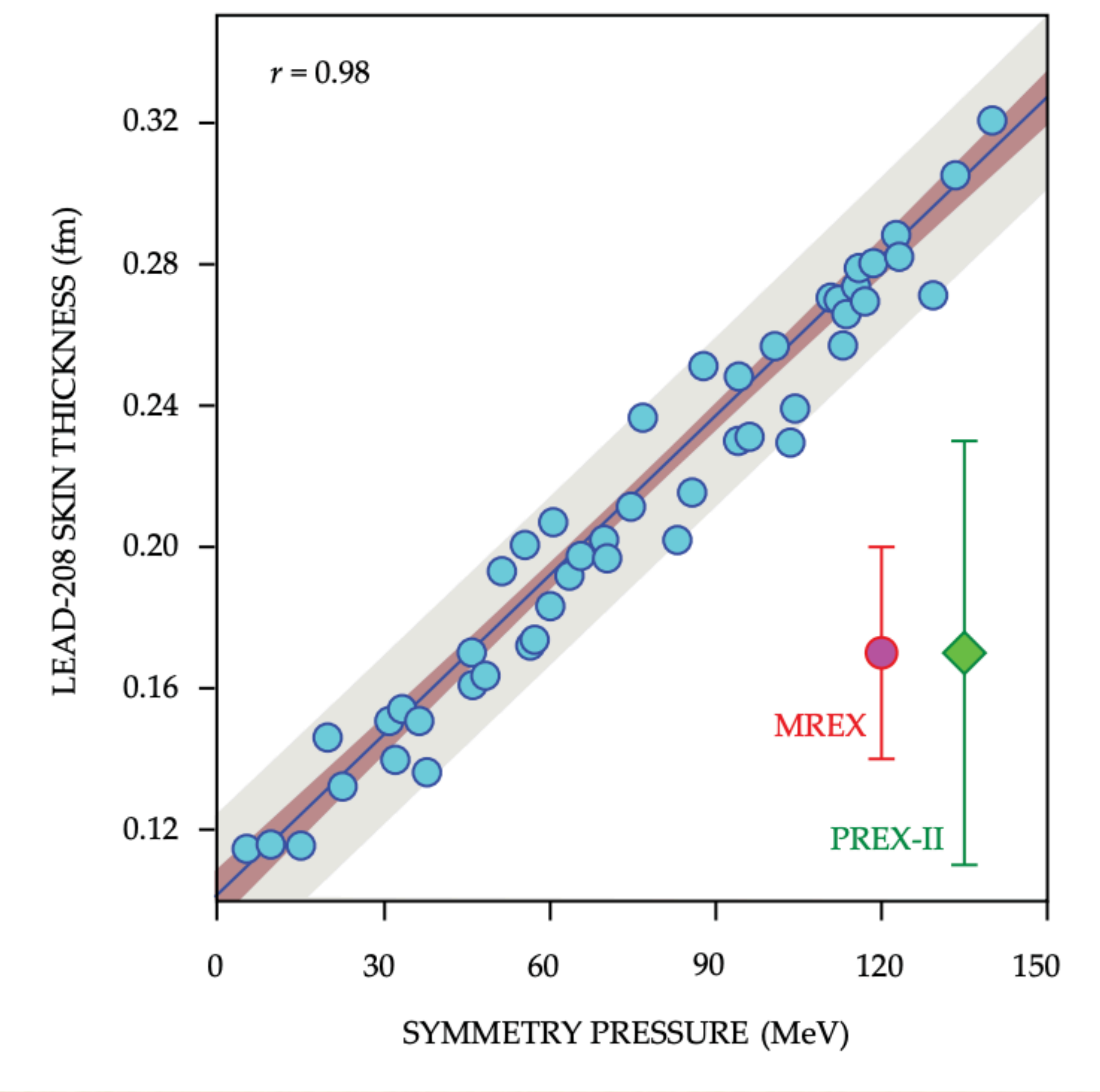
size of neutron skin

↓

pressure ⇒ density dependence of symmetry energy at subnuclear densities

Broader Context

- *Nuclear Structure Physics*
- *Neutron Star Physics*
- *Atomic Parity Violation*
- *Coherent Neutrino Scattering*



MREX at MESA: *Use of a solenoidal spectrometer makes it possible to increase solid angle of elastically scattered electrons by a factor of 4 compared to PREX-2 while rejecting inelastic background at a similar level*

$\delta(A_{PV})/A_{PV} \sim 1.5\%$

$\delta(R_n)$: ± 0.03 fm

Equation of state (EOS) of dense nuclear matter

$$E(\rho, \delta) = E_0(\rho, \delta = 0) + \boxed{S(\rho)}\delta^2$$

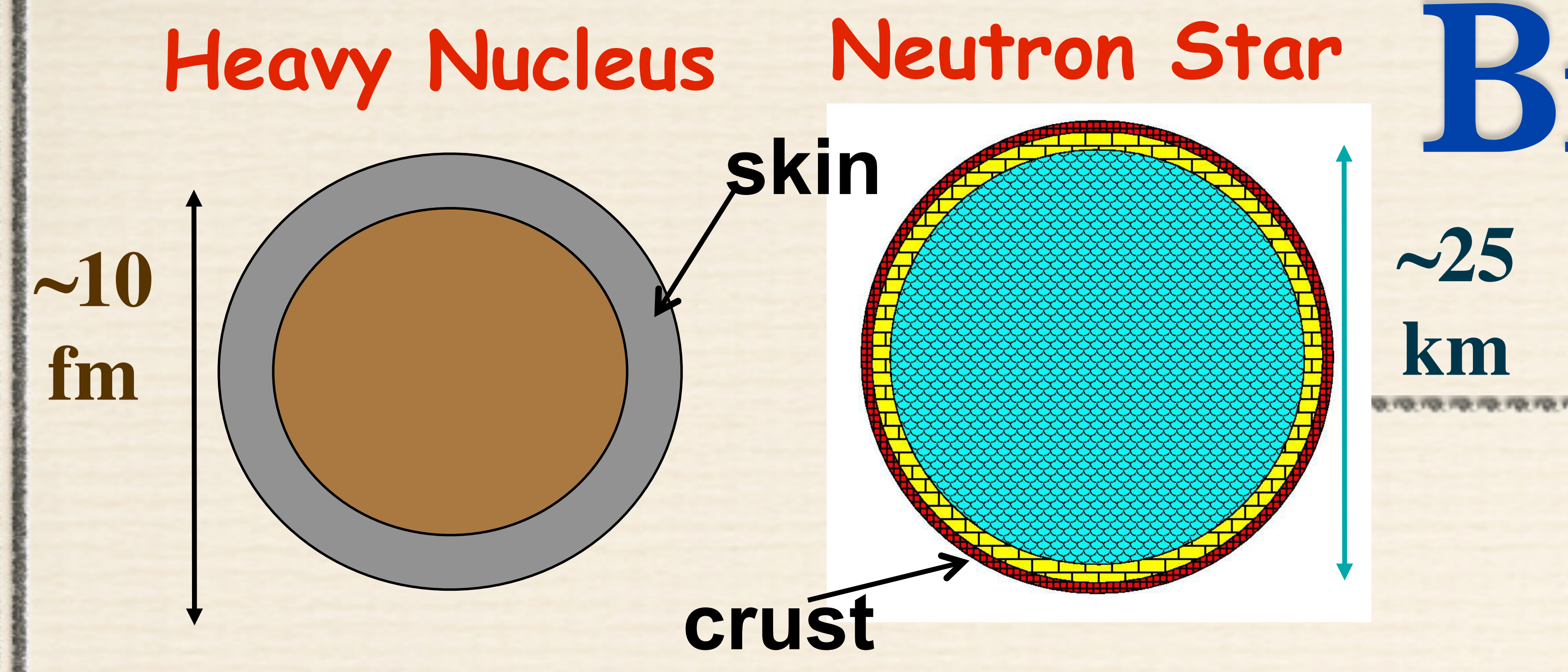
Symmetry Energy

size of neutron skin

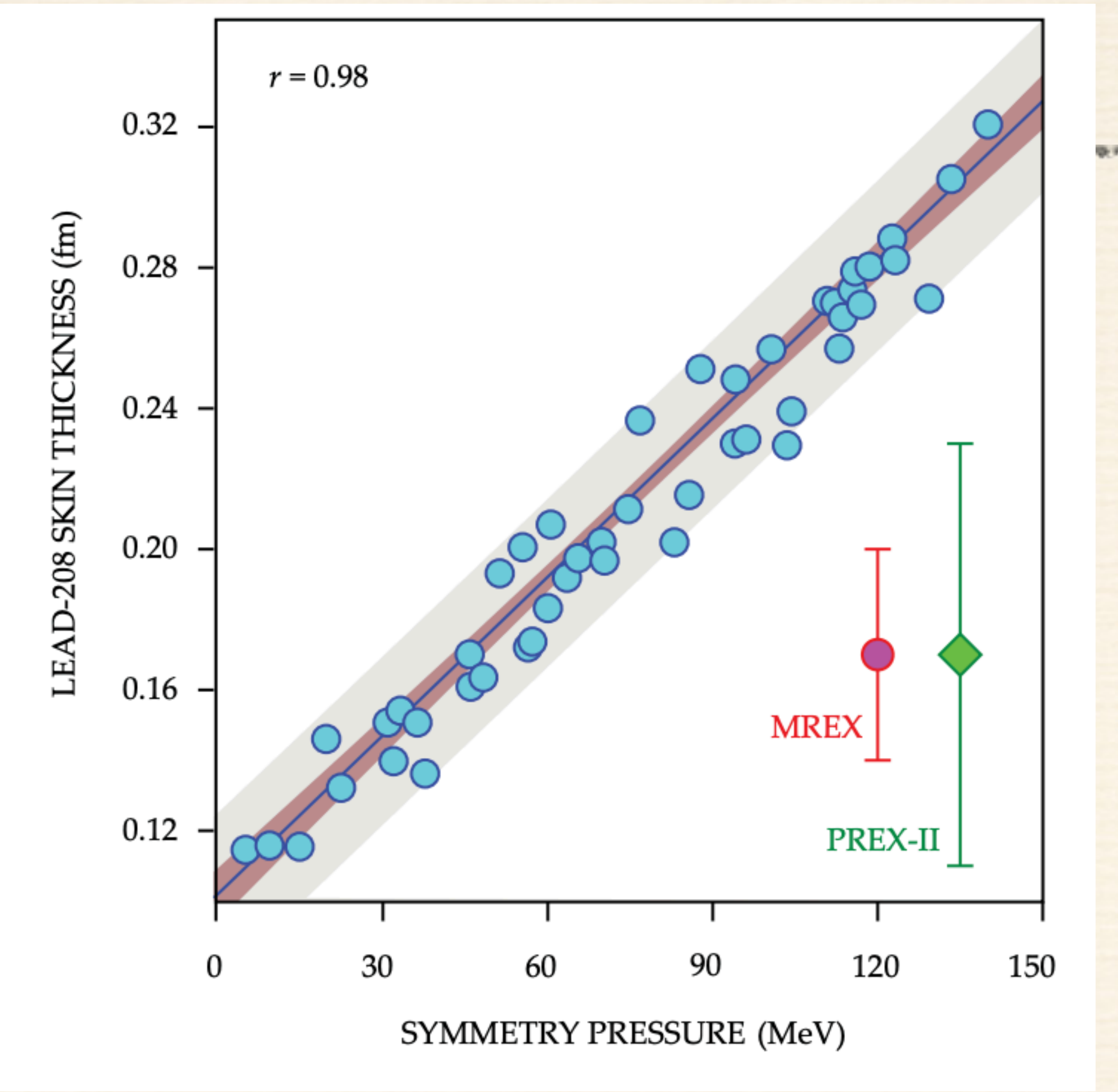
pressure

density dependence of symmetry energy at subnuclear densities

Broader Context



- *Nuclear Structure Physics*
- *Neutron Star Physics*
- *Atomic Parity Violation*
- *Coherent Neutrino Scattering*



MREX at MESA: *Use of a solenoidal spectrometer makes it possible to increase solid angle of elastically scattered electrons by a factor of 4 compared to PREX-2 while rejecting inelastic background at a similar level*

→ $\delta(A_{PV})/A_{PV} \sim 1.5\%$ → $\delta(R_n)$: ± 0.03 fm

Equation of state (EOS)
of dense nuclear matter

$$E(\rho,\delta) = E_0(\rho,\delta=0) + \boxed{S(\rho)}\delta^2$$

Symmetry Energy

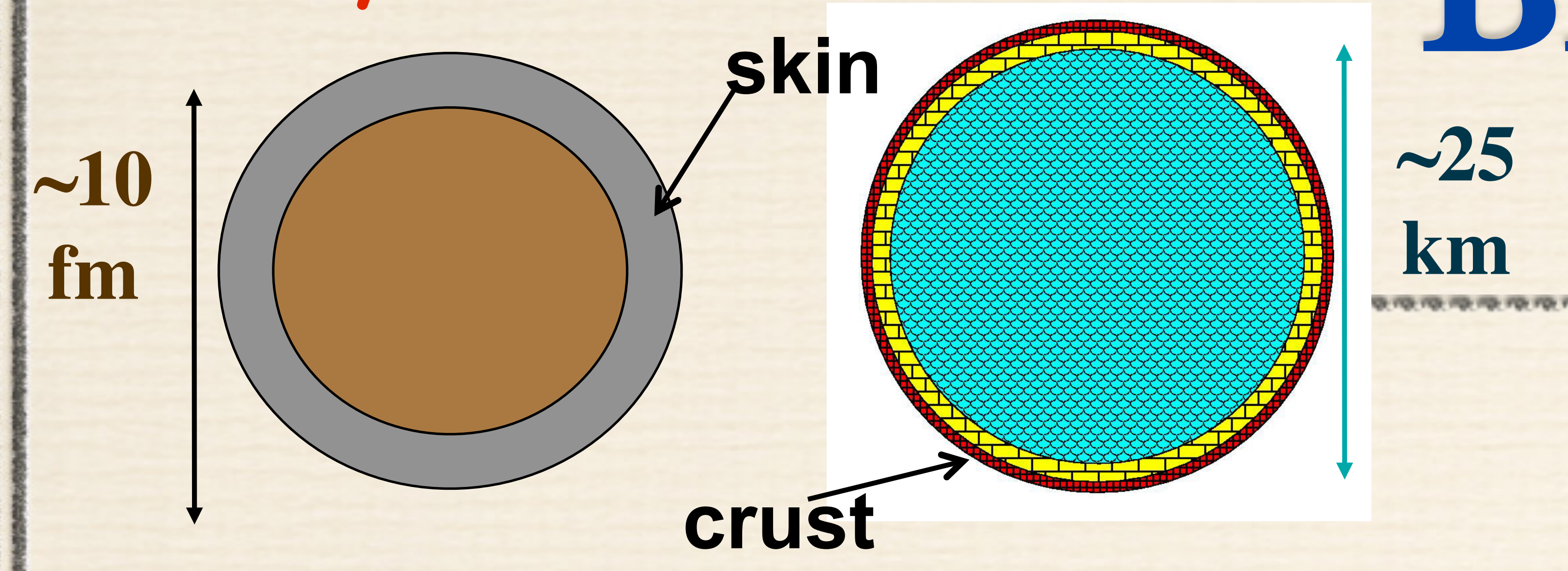
size of neutron skin

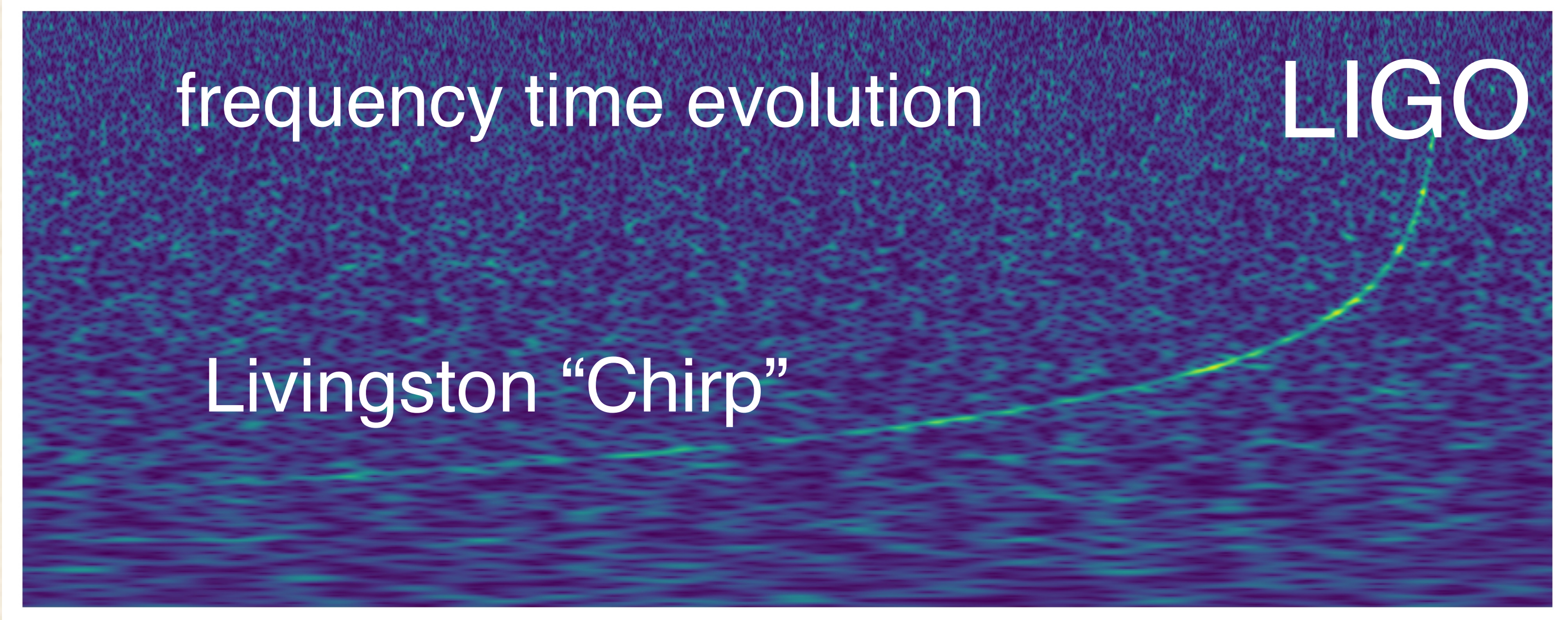
↓

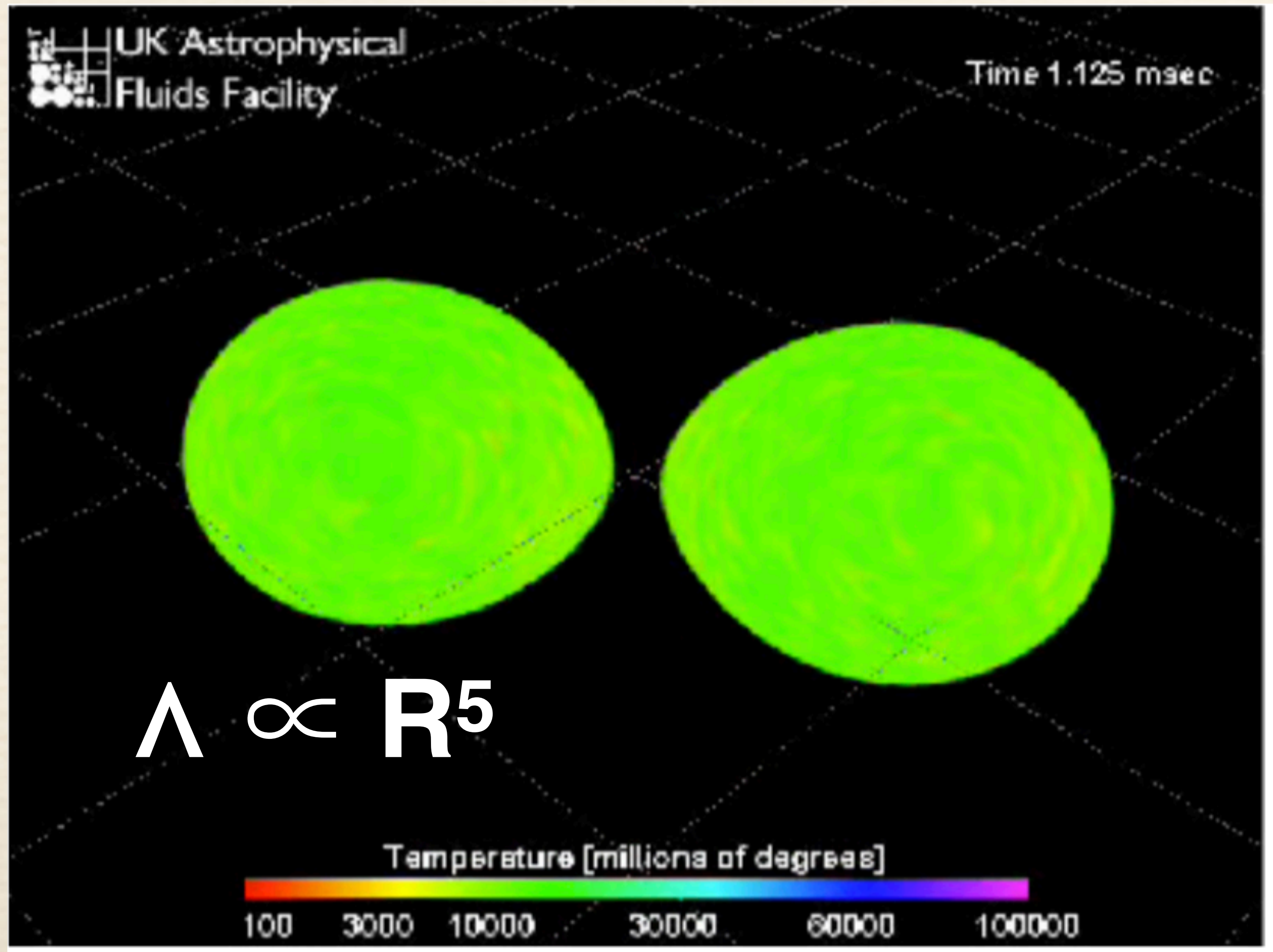
pressure → density dependence of symmetry energy at subnuclear densities

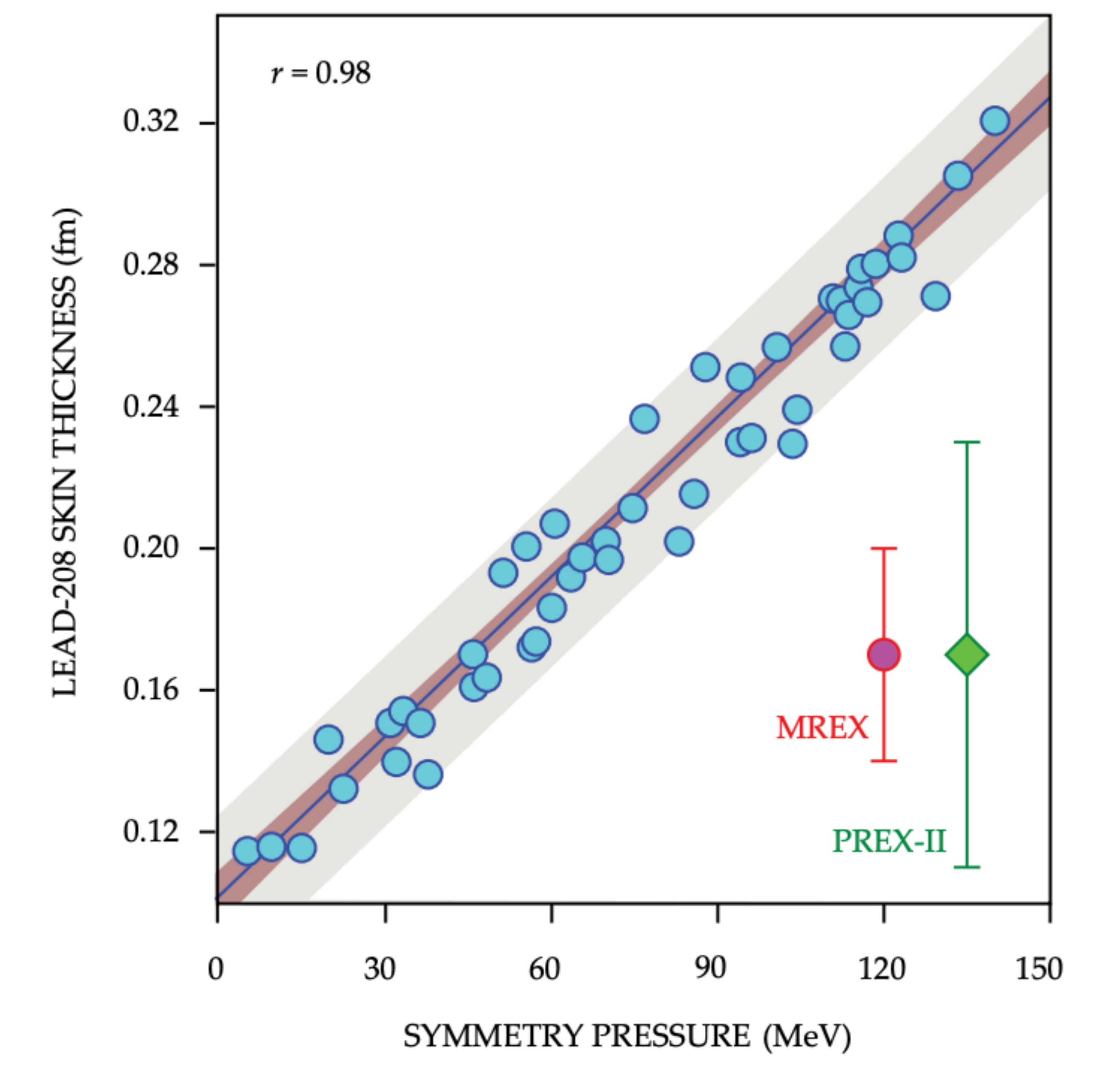
Broader Context

Heavy Nucleus Neutron Star









Equation of state (EOS)
of dense nuclear matter

$$E(\rho,\delta) = E_0(\rho,\delta=0) + \boxed{S(\rho)}\delta^2$$

Symmetry Energy

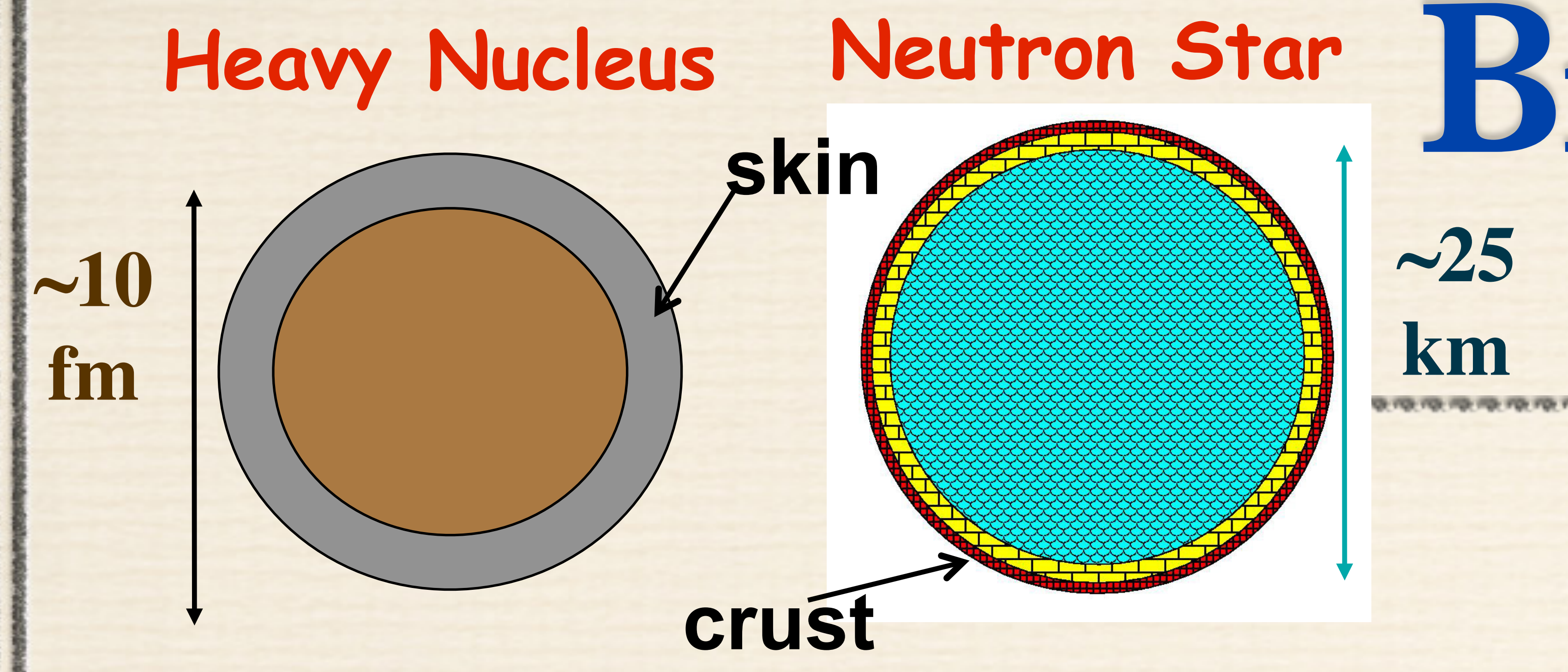
size of neutron skin → pressure → density dependence of symmetry energy at subnuclear densities

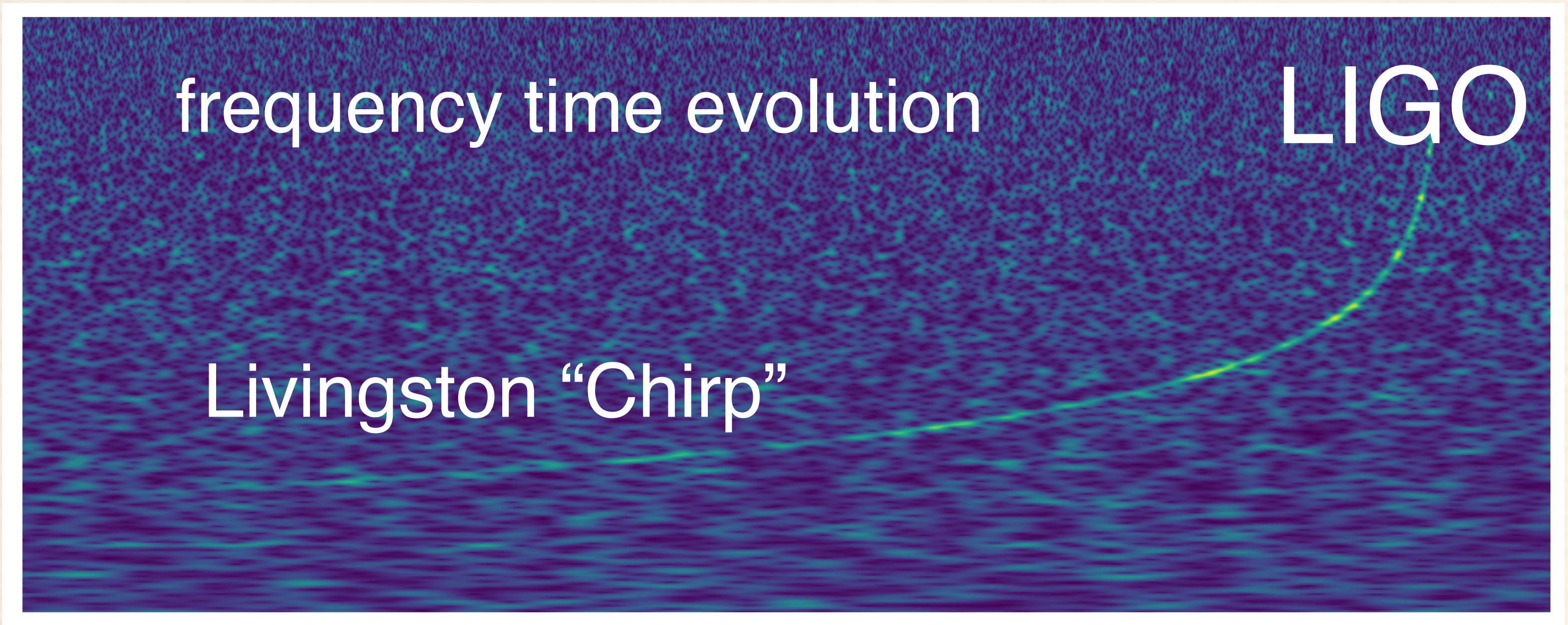
- *Nuclear Structure Physics*
- *Neutron Star Physics*
- *Atomic Parity Violation*
- *Coherent Neutrino Scattering*

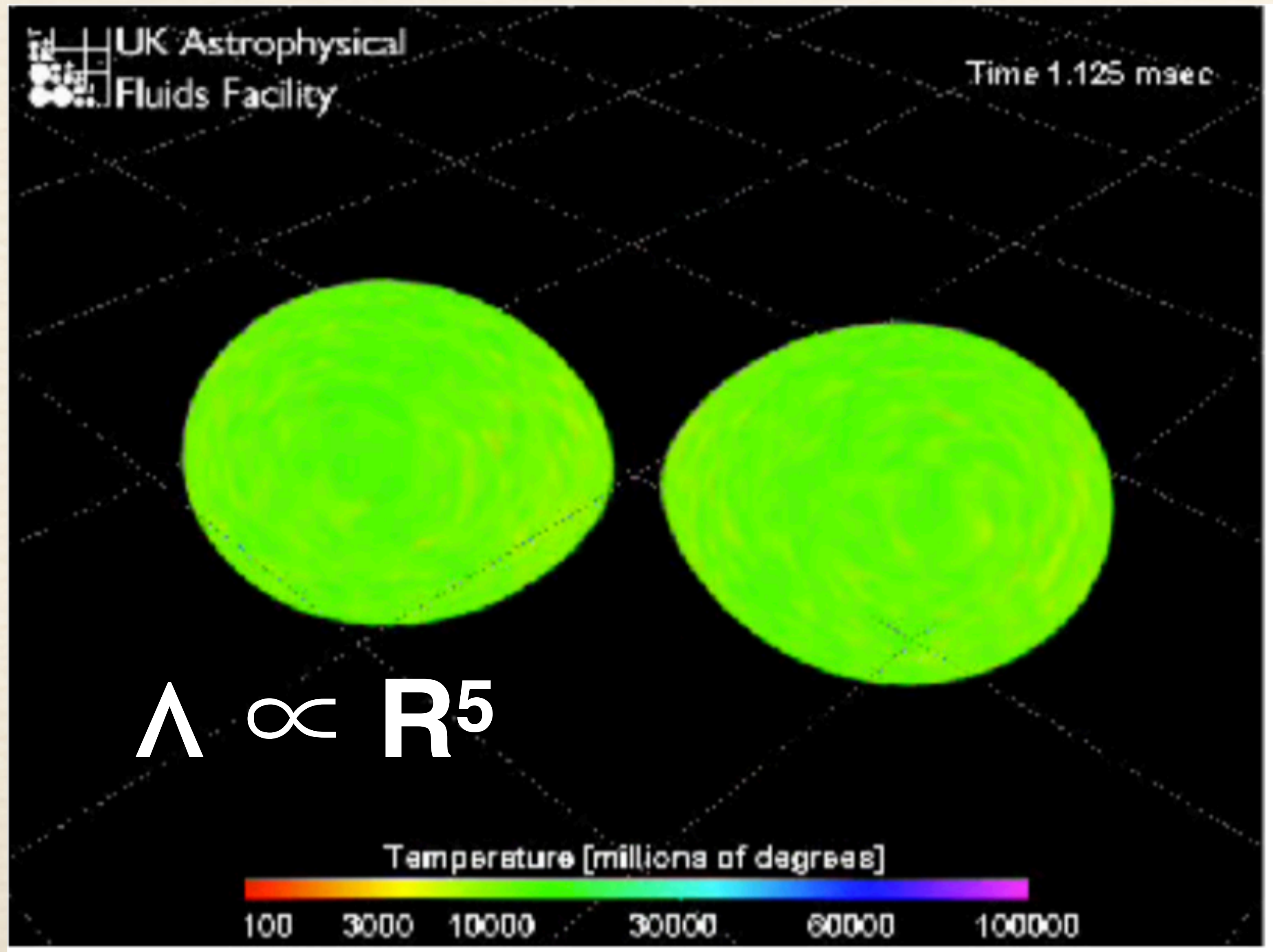
MREX at MESA: *Use of a solenoidal spectrometer makes it possible to increase solid angle of elastically scattered electrons by a factor of 4 compared to PREX-2 while rejecting inelastic background at a similar level*

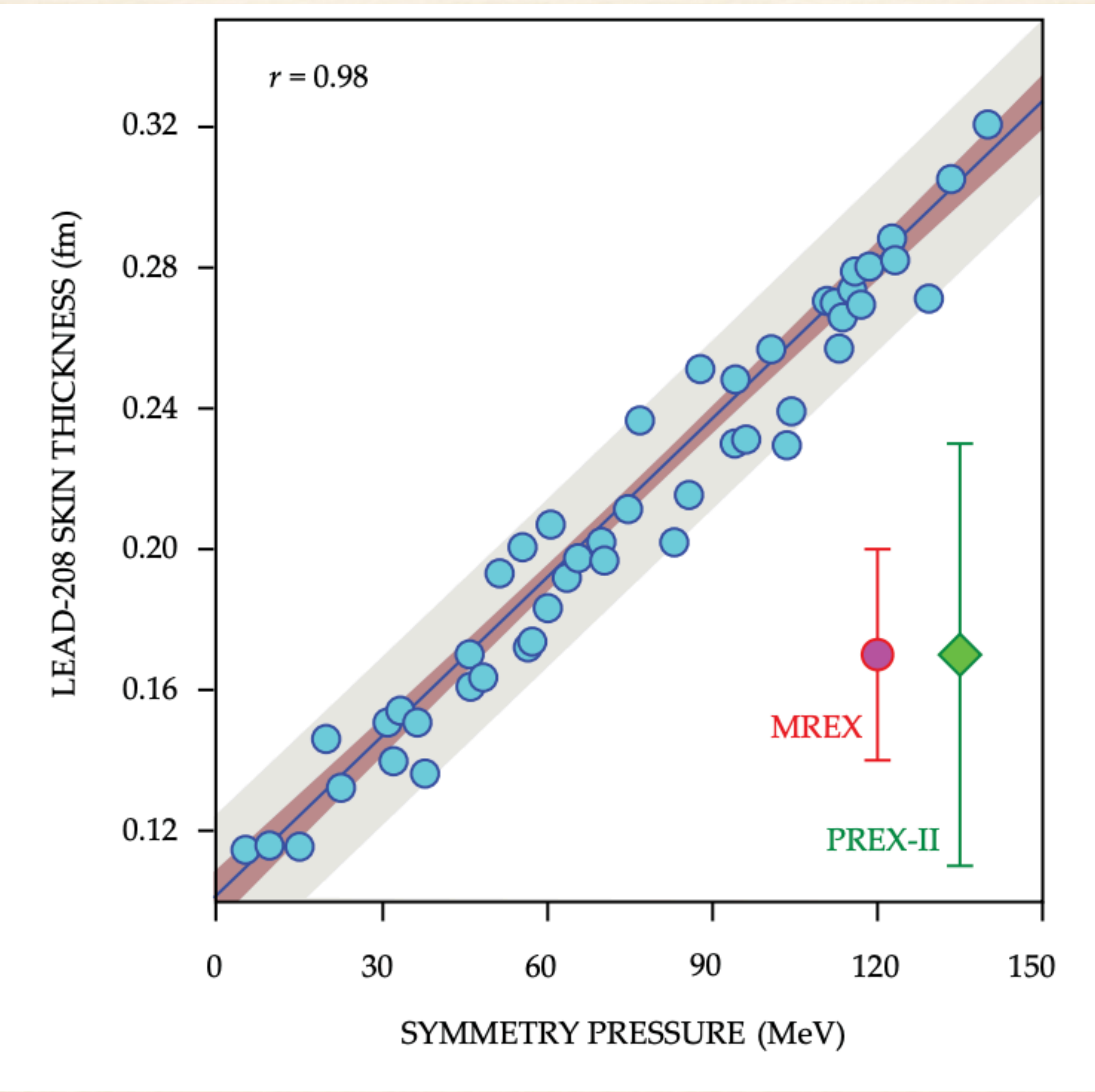
→ $\delta(A_{PV})/A_{PV} \sim 1.5\%$ → $\delta(R_n)$: ± 0.03 fm

Broader Context









- *Nuclear Structure Physics*
- *Neutron Star Physics*
- *Atomic Parity Violation*
- *Coherent Neutrino Scattering*

MREX at MESA: *Use of a solenoidal spectrometer makes it possible to increase solid angle of elastically scattered electrons by a factor of 4 compared to PREX-2 while rejecting inelastic background at a similar level*

$\Rightarrow$ $\delta(A_{PV})/A_{PV} \sim 1.5\%$ $\Rightarrow$ $\delta(R_n)$: $\pm$ 0.03 fm

Equation of state (EOS) of dense nuclear matter

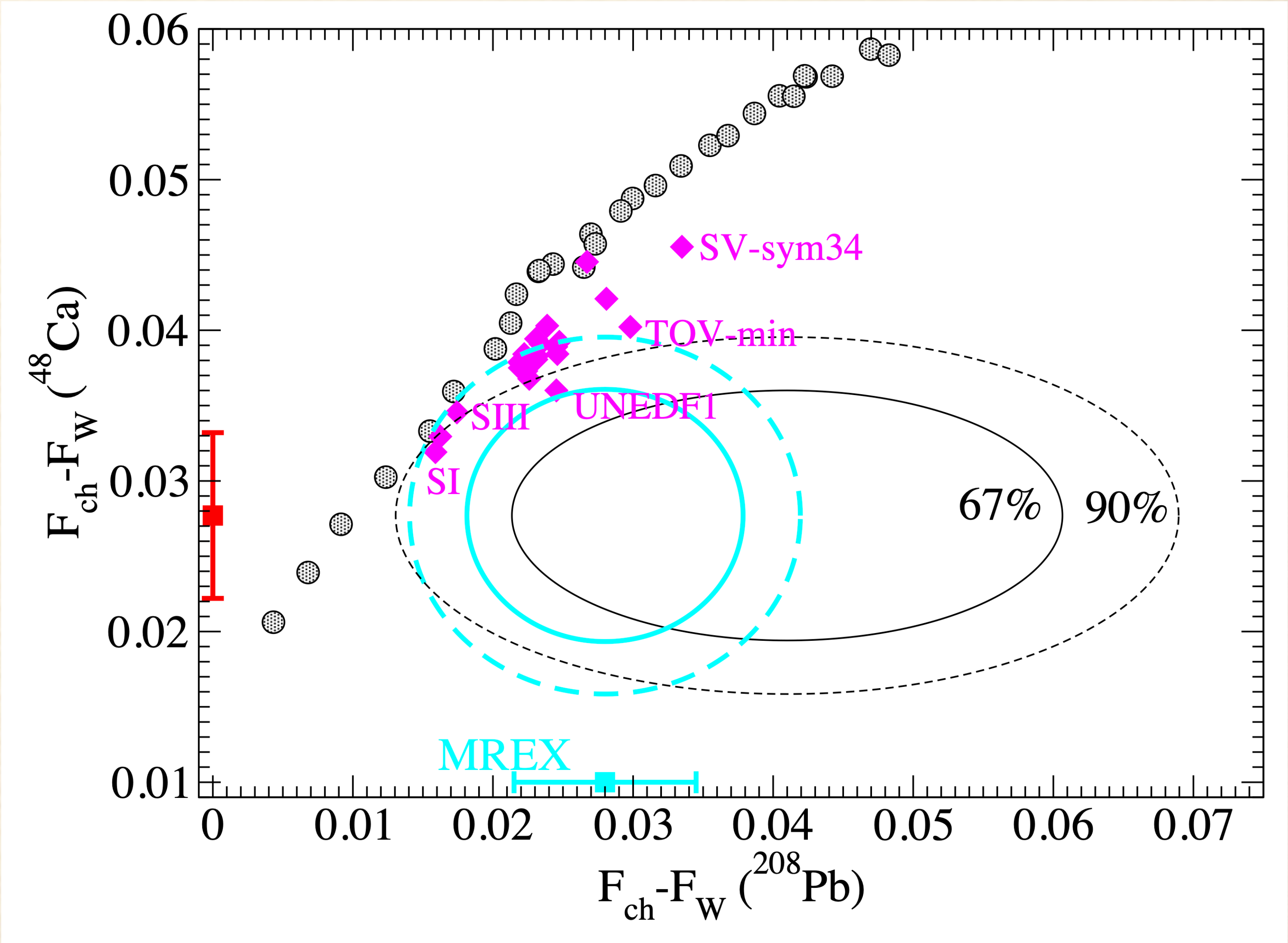
$$E(\rho,\delta) = E_0(\rho,\delta=0) + \boxed{S(\rho)}\delta^2$$

Symmetry Energy

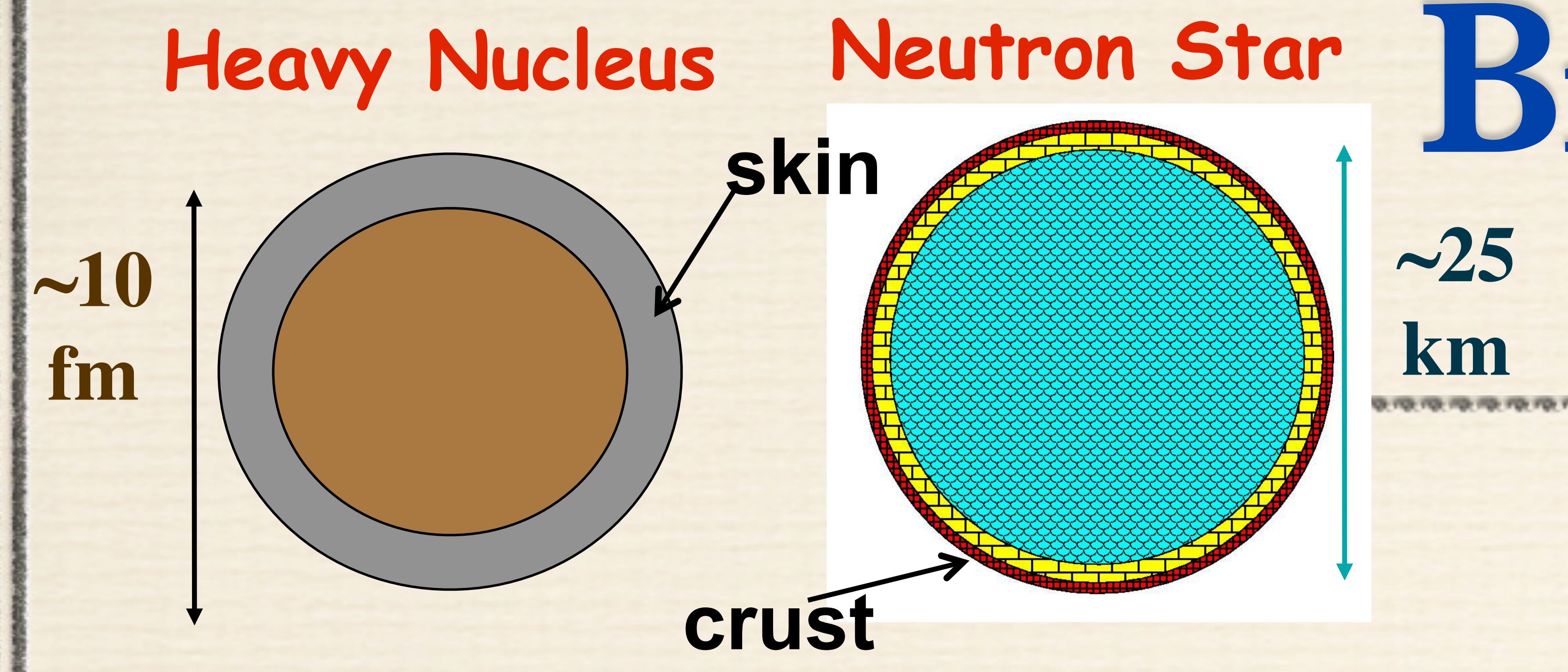
size of neutron skin

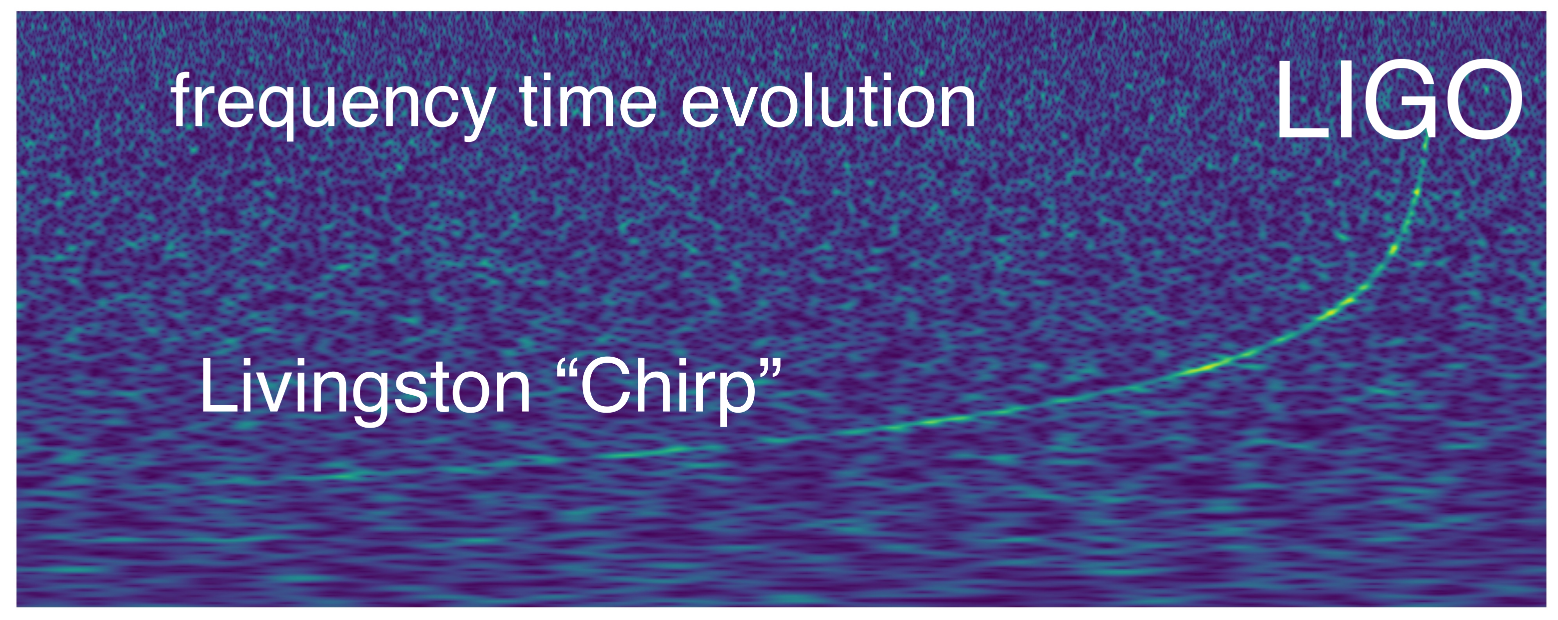
⇓

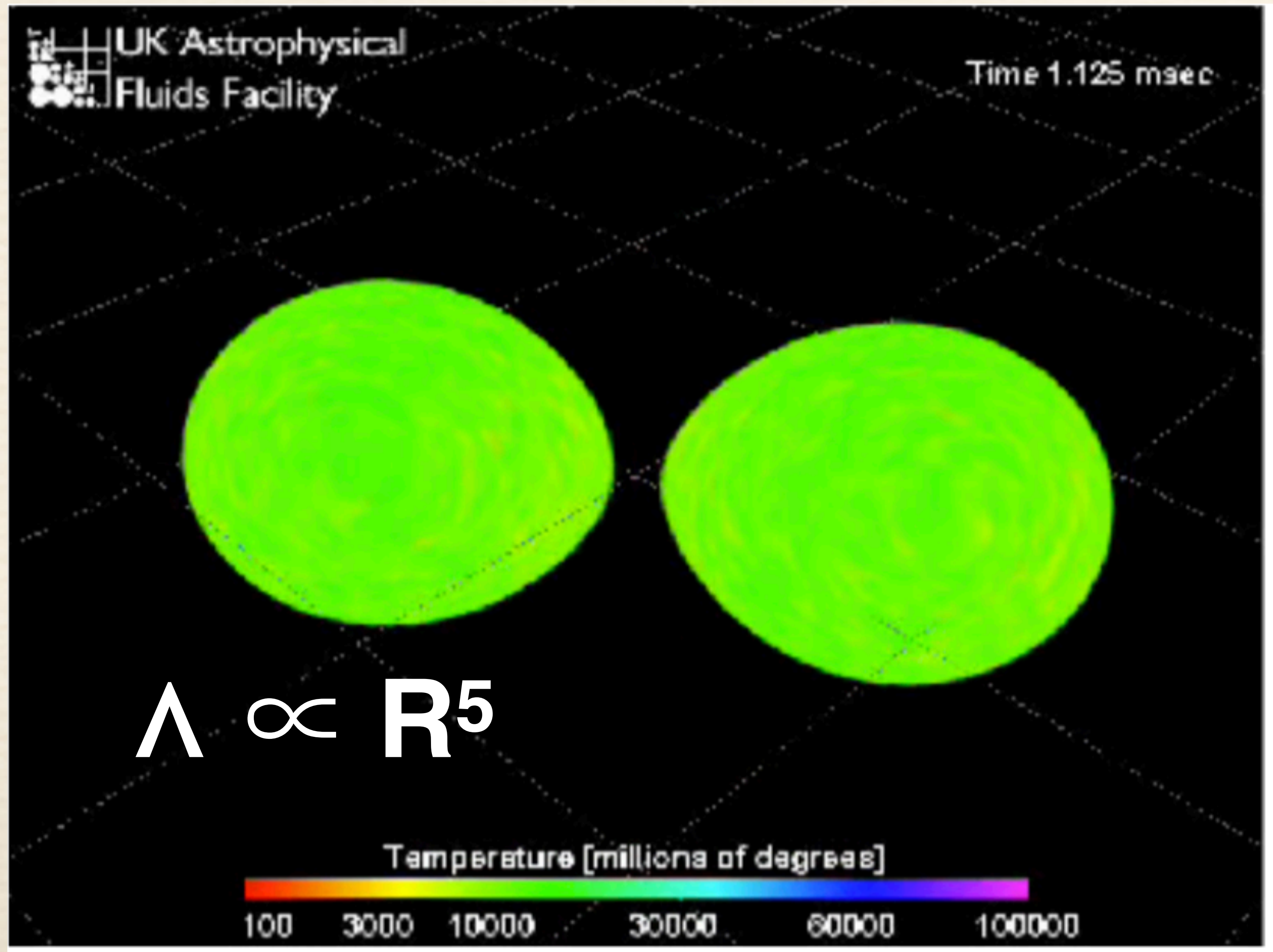
pressure ⇒ density dependence of symmetry energy at subnuclear densities

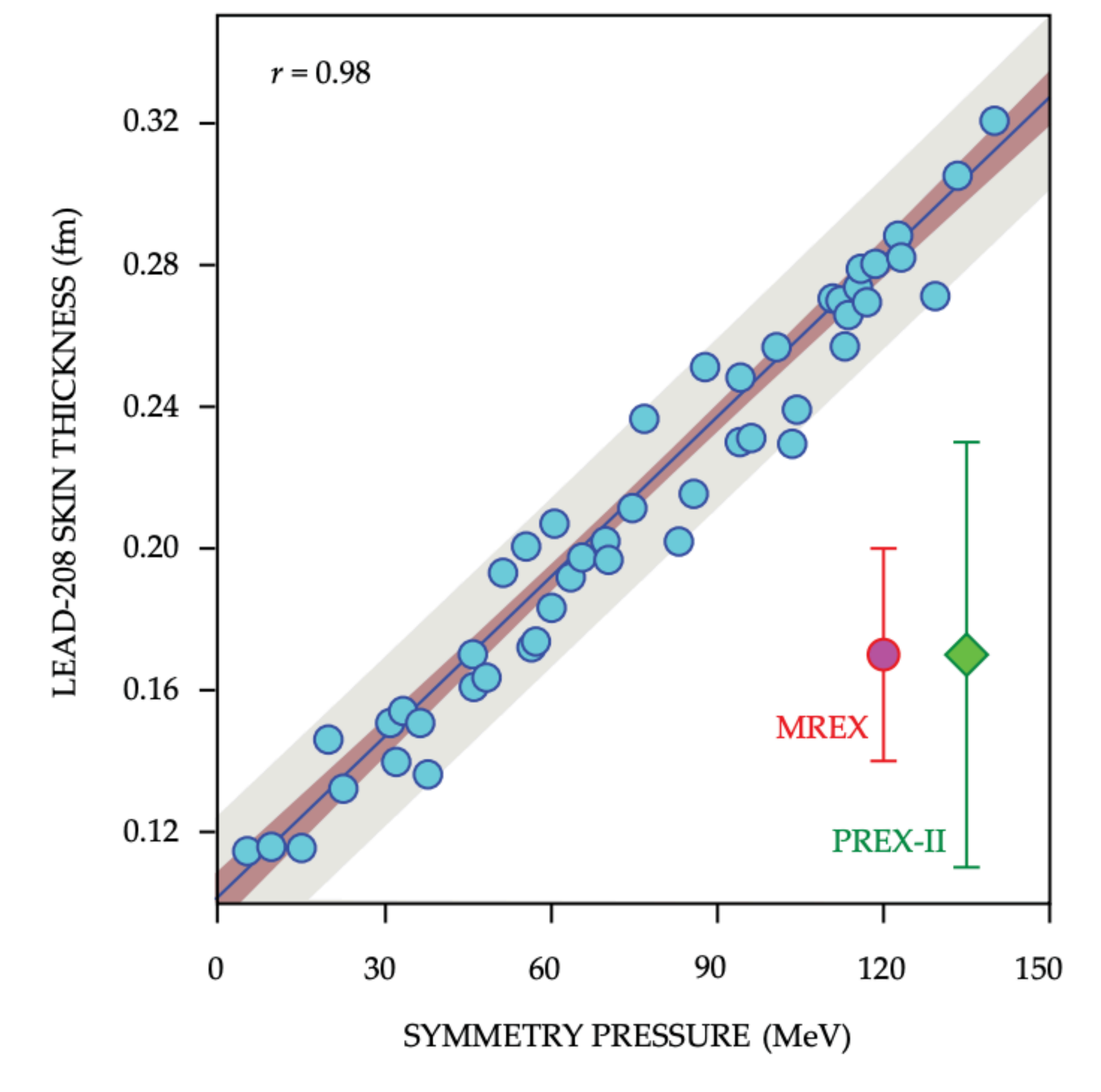


Broader Context









- *Nuclear Structure Physics*
- *Neutron Star Physics*
- *Atomic Parity Violation*
- *Coherent Neutrino Scattering*

MREX at MESA: *Use of a solenoidal spectrometer makes it possible to increase solid angle of elastically scattered electrons by a factor of 4 compared to PREX-2 while rejecting inelastic background at a similar level*

$\delta(A_{PV})/A_{PV} \sim 1.5\%$ → $\delta(R_n)$: ± 0.03 fm

Equation of state (EOS) of dense nuclear matter

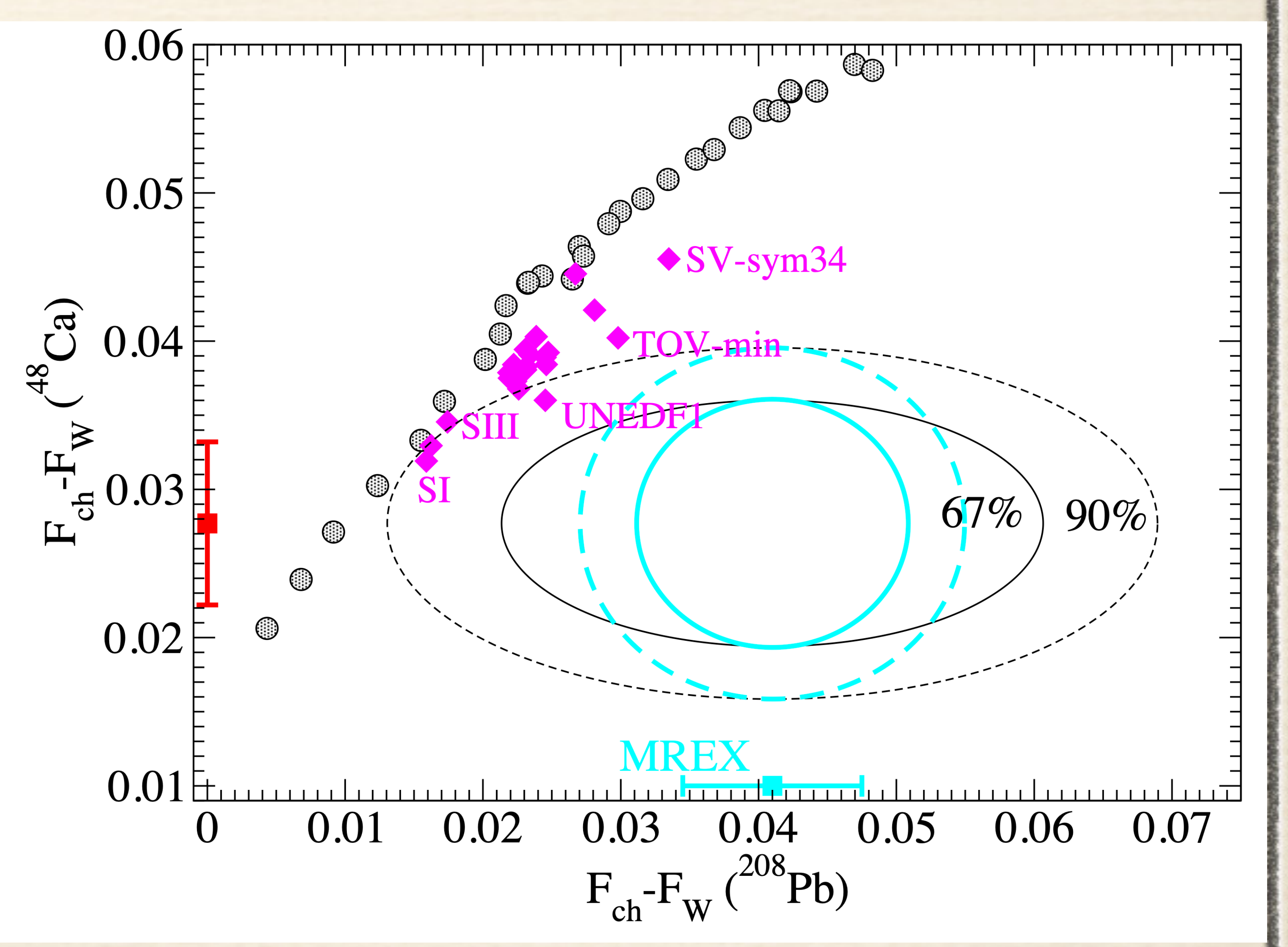
$$E(\rho,\delta) = E_0(\rho,\delta=0) + \boxed{S(\rho)}\delta^2$$

Symmetry Energy

size of neutron skin

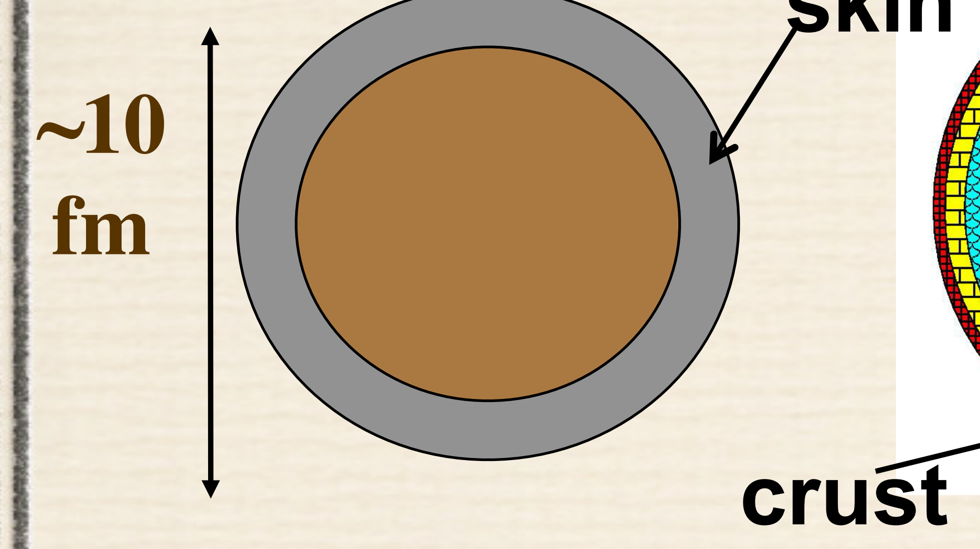
↓

pressure → density dependence of symmetry energy at subnuclear densities

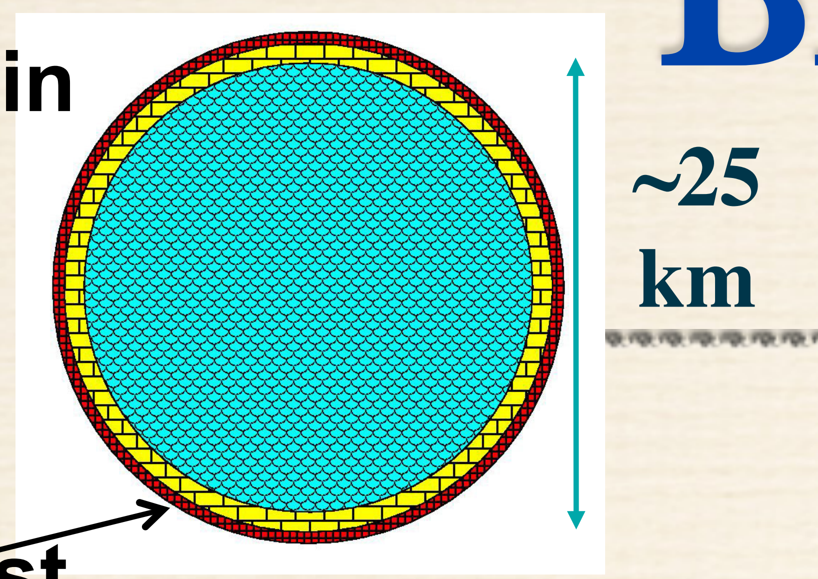


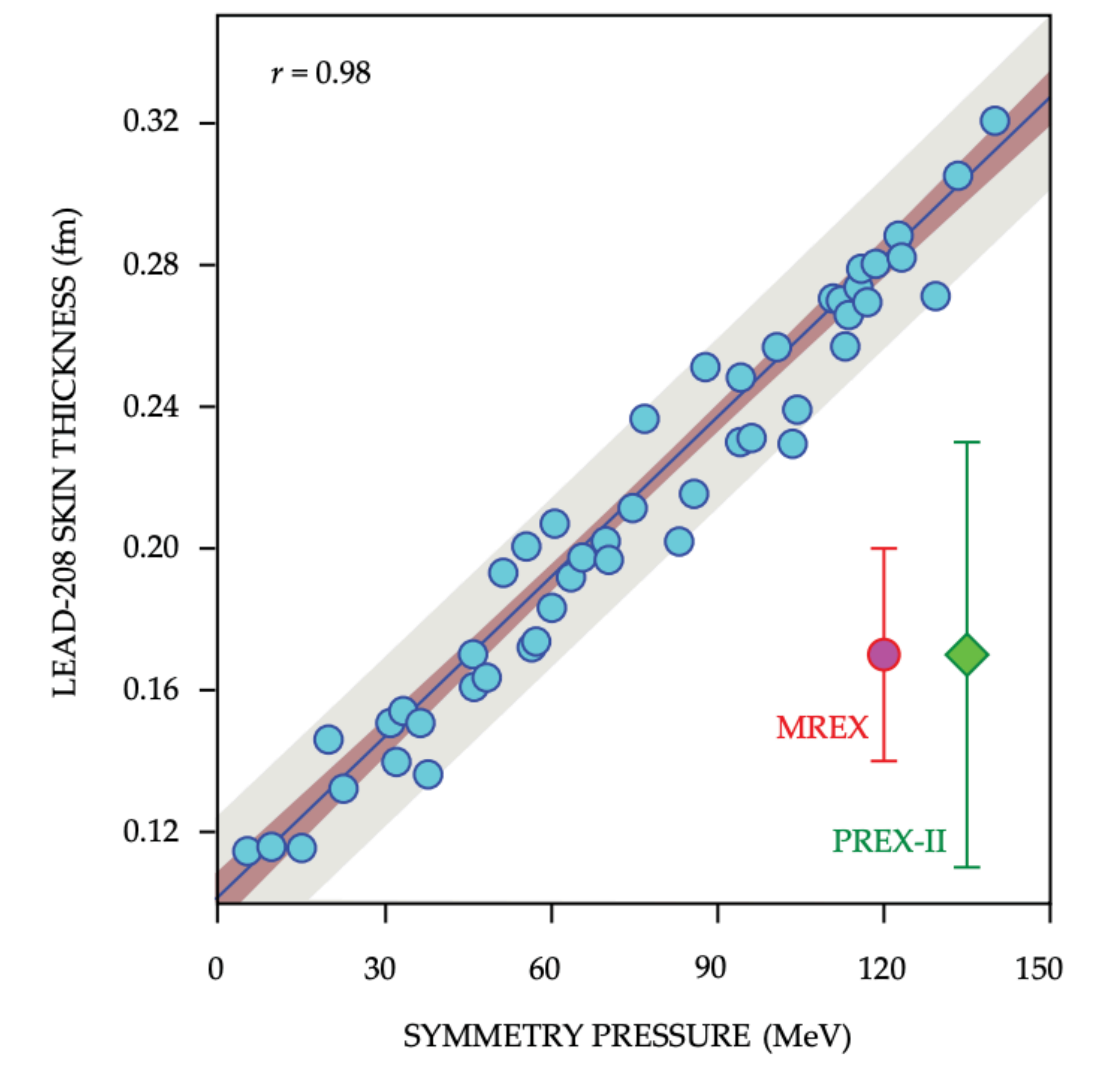
Broader Context

Heavy Nucleus



Neutron Star

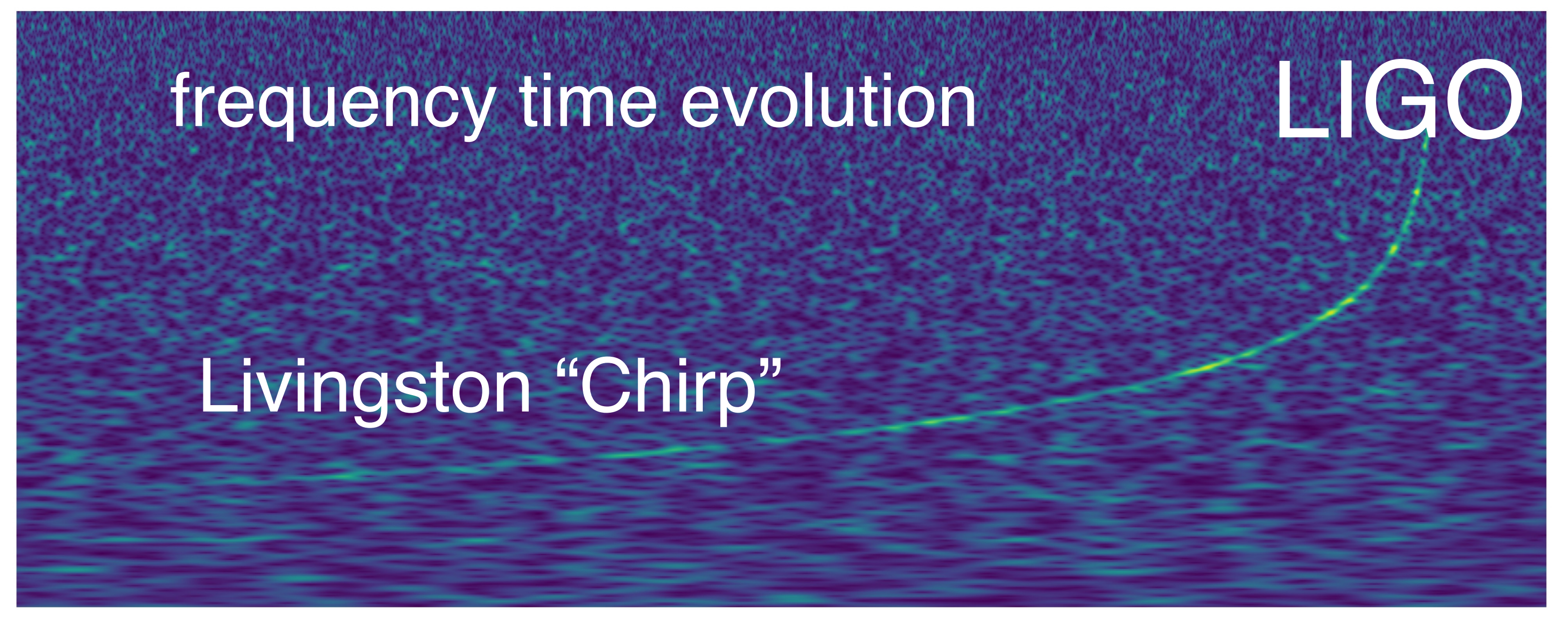


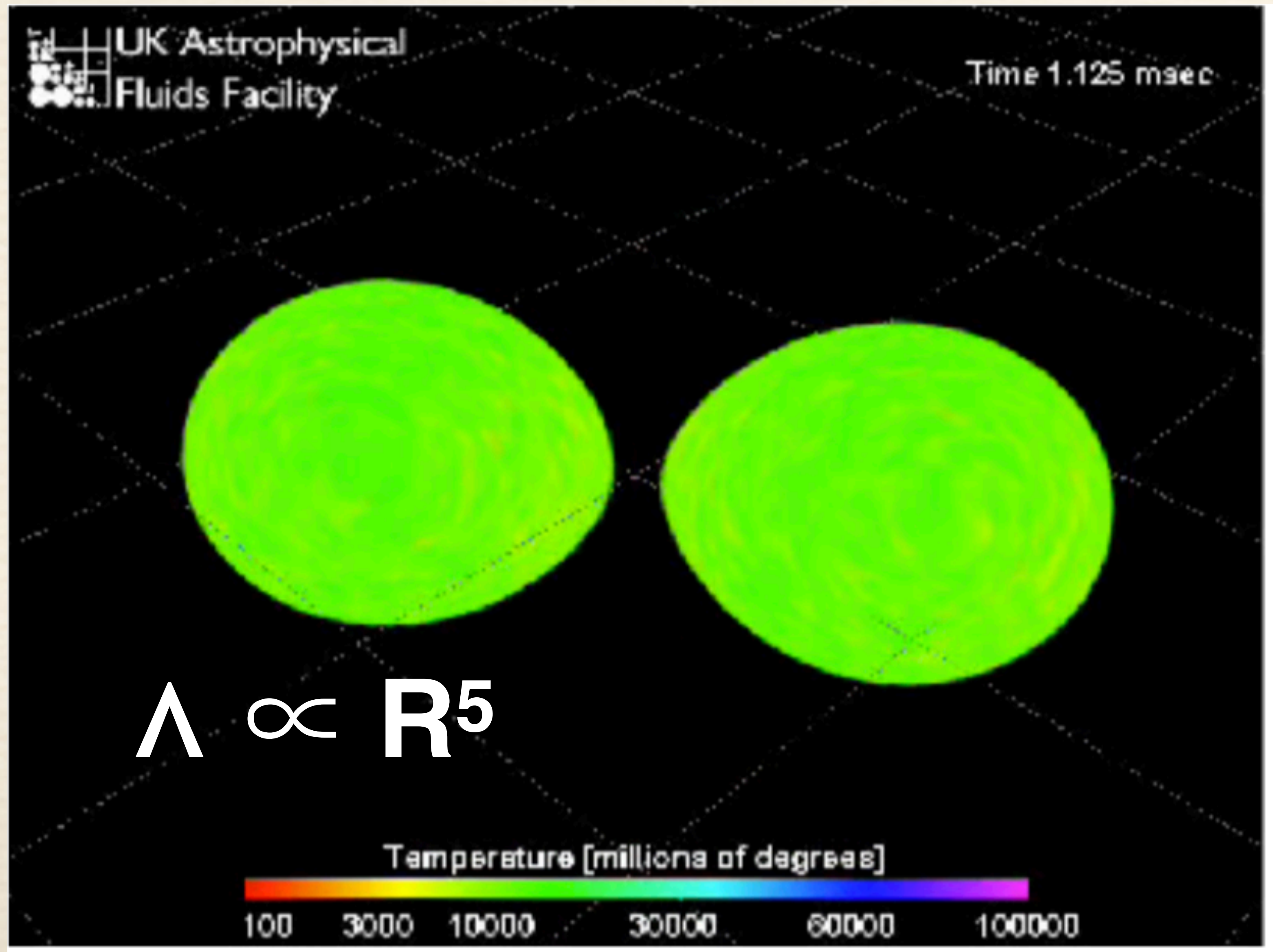


- *Nuclear Structure Physics*
- *Neutron Star Physics*
- *Atomic Parity Violation*
- *Coherent Neutrino Scattering*

MREX at MESA: *Use of a solenoidal spectrometer makes it possible to increase solid angle of elastically scattered electrons by a factor of 4 compared to PREX-2 while rejecting inelastic background at a similar level*

$\Rightarrow$ $\delta(A_{PV})/A_{PV} \sim 1.5\%$ $\Rightarrow$ $\delta(R_n)$: ± 0.03 fm





Equation of state (EOS)
of dense nuclear matter

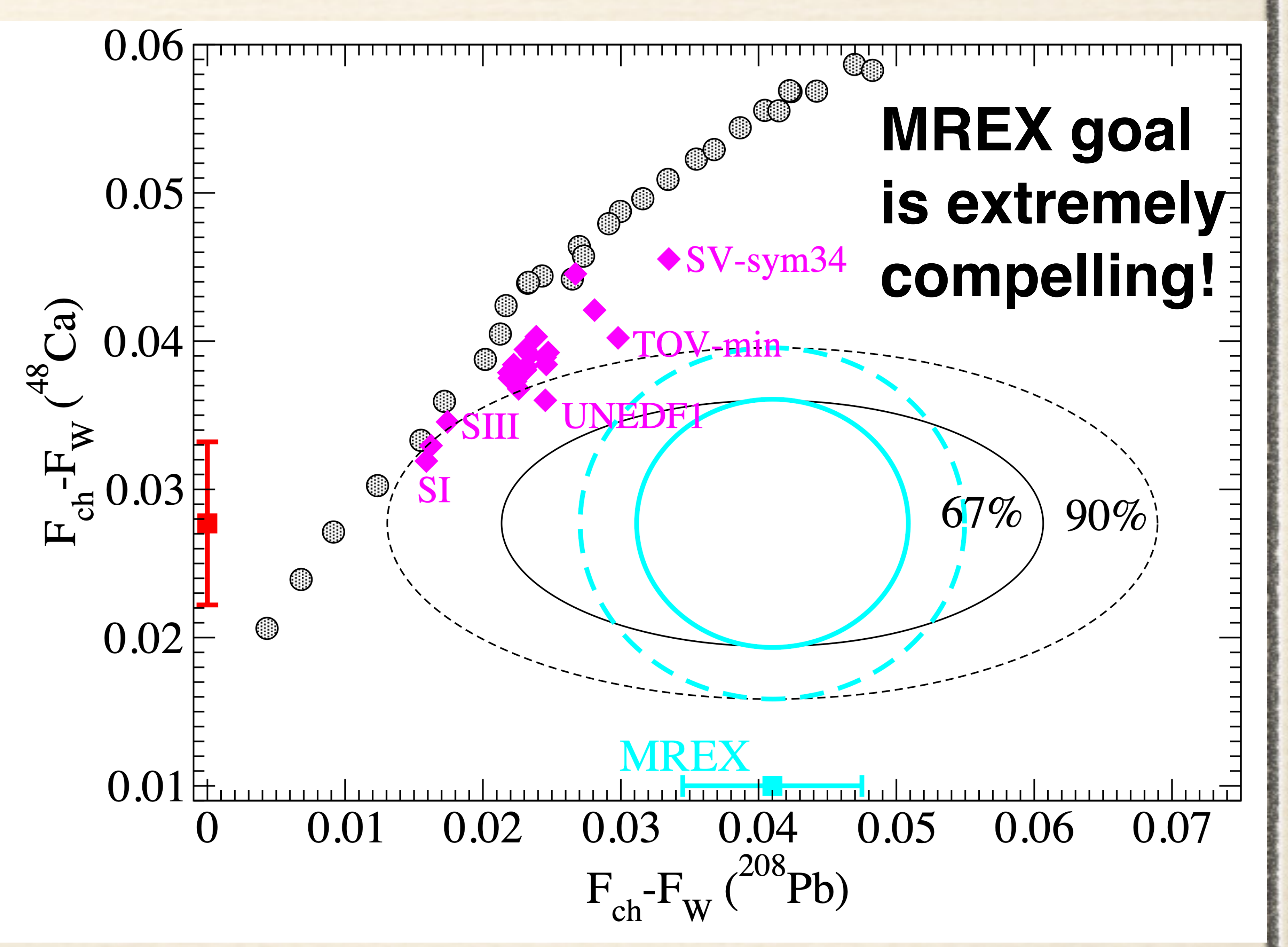
$$E(\rho,\delta) = E_0(\rho,\delta=0) + \boxed{S(\rho)}\delta^2$$

Symmetry Energy

size of neutron skin

$\Downarrow$

pressure $\Rightarrow$ density dependence of symmetry energy at subnuclear densities



MREX goal is extremely compelling!

Modern EW Physics

courtesy
V. Cirigliano,
H. Maruyama,
M. Pospelov

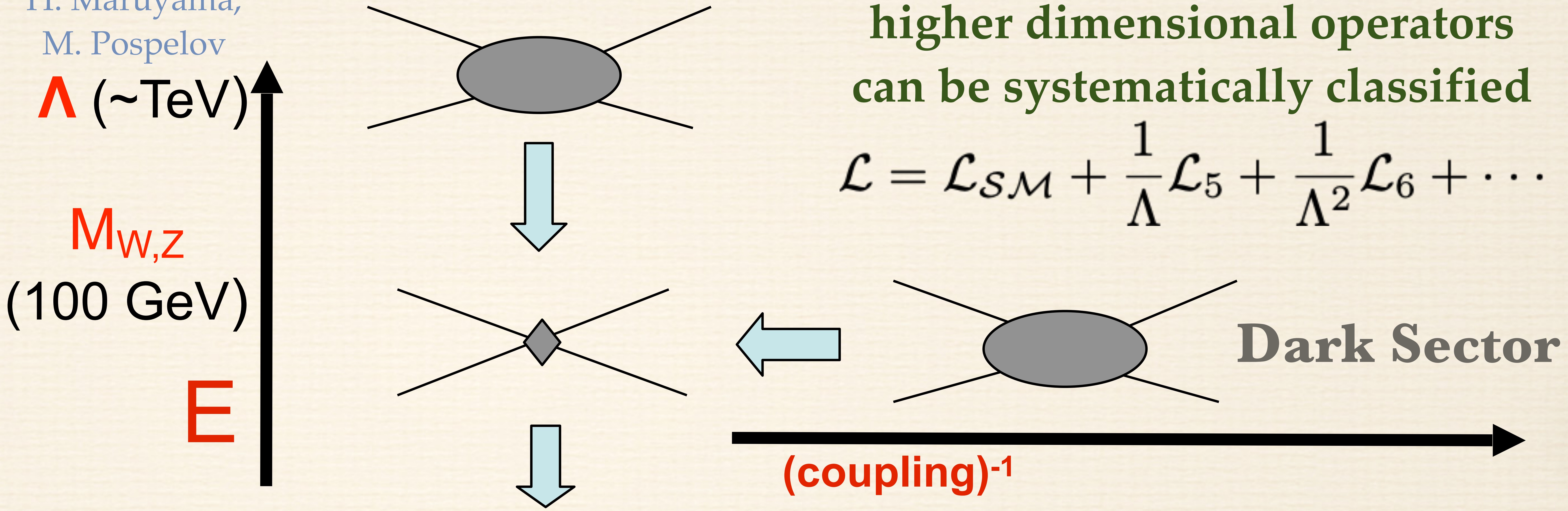
Unravelling "New Dynamics" in the Early Universe:
how did nuclear matter form and evolve?

Nuclear Physics Initiatives:
"Low" Energy: $Q^2 << M_Z^2$

High Energy Dynamics

higher dimensional operators can be systematically classified

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$



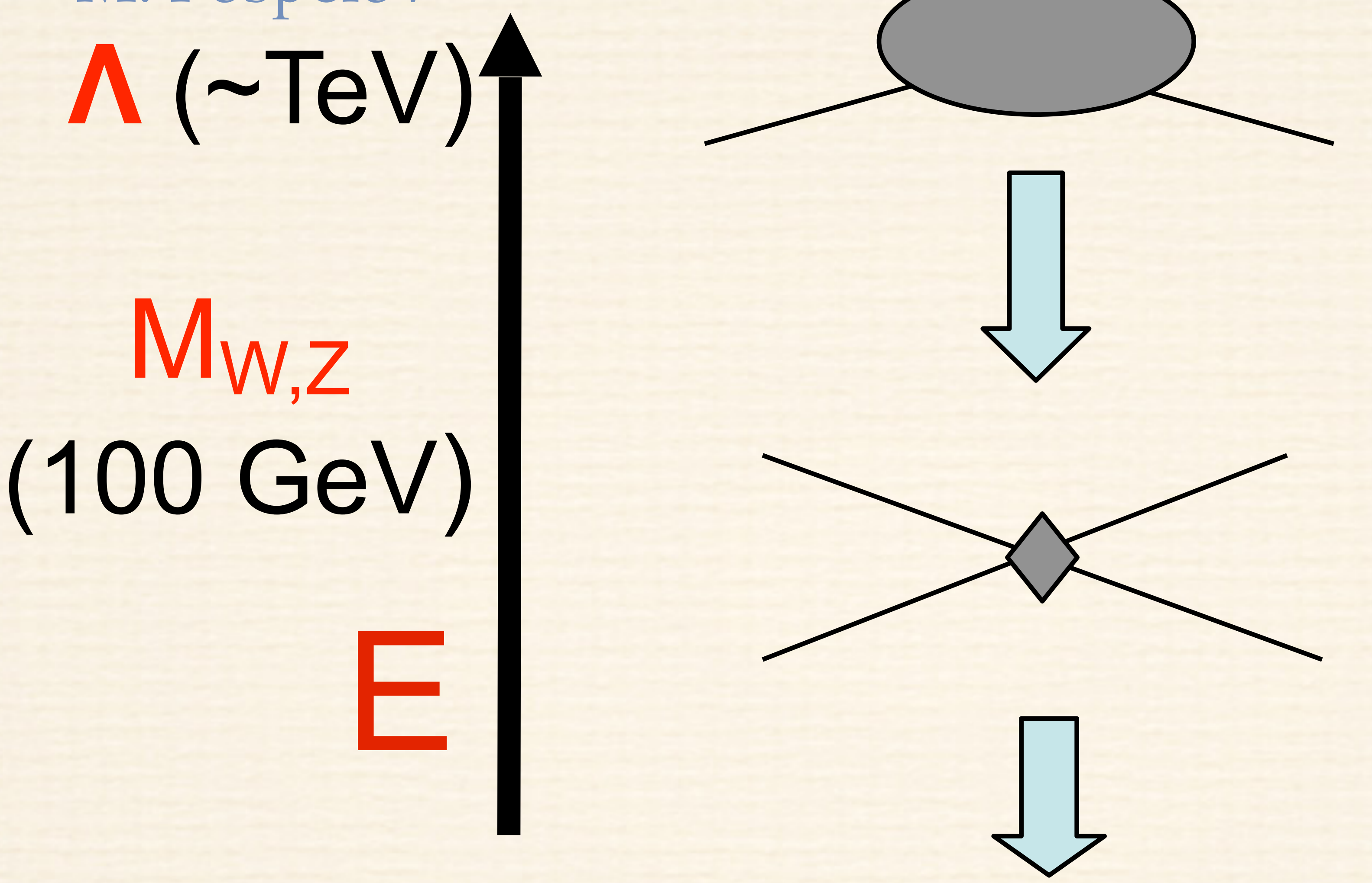
Modern EW Physics

Unravelling "New Dynamics" in the Early Universe:
how did nuclear matter form and evolve?

Nuclear Physics Initiatives:
"Low" Energy: $Q^2 \ll M_Z^2$

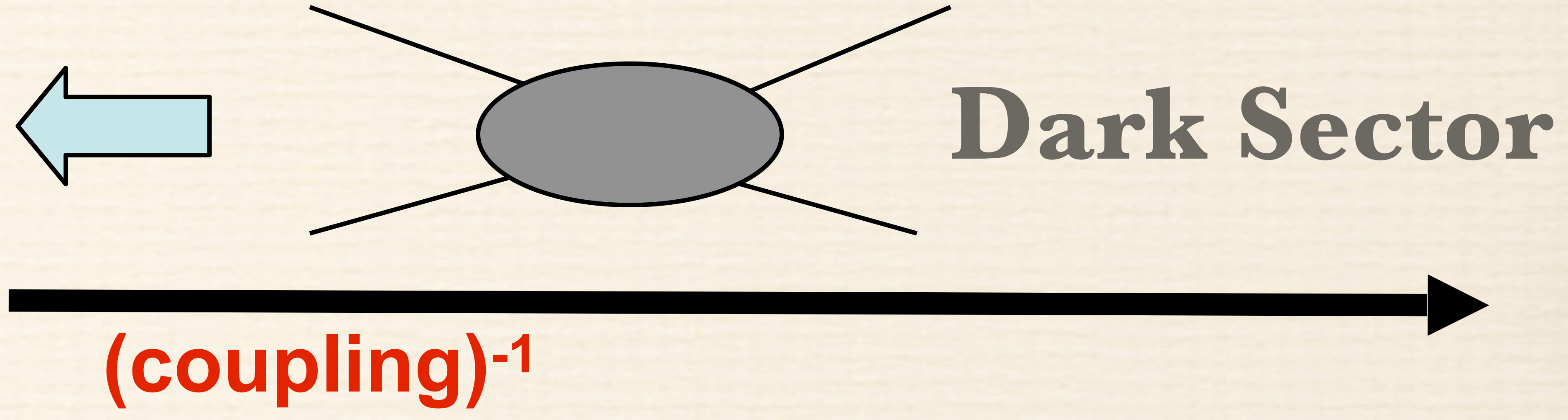
courtesy
V. Cirigliano,
H. Maruyama,
M. Pospelov

High Energy Dynamics

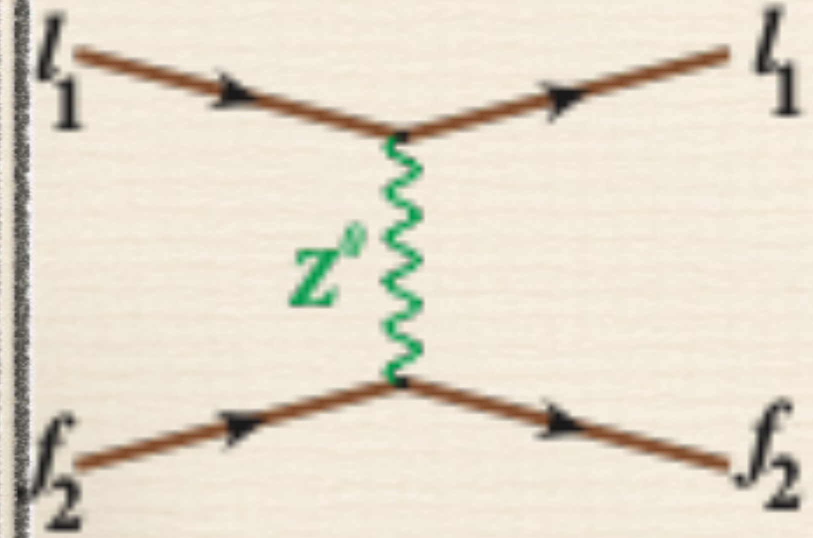


higher dimensional operators can be systematically classified

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$



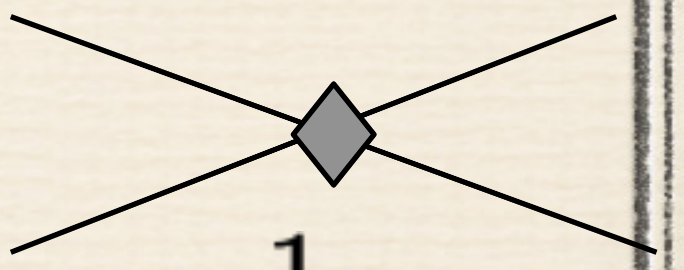
Leptonic and Semileptonic Weak Neutral Current Interactions



Search for new flavor diagonal neutral currents

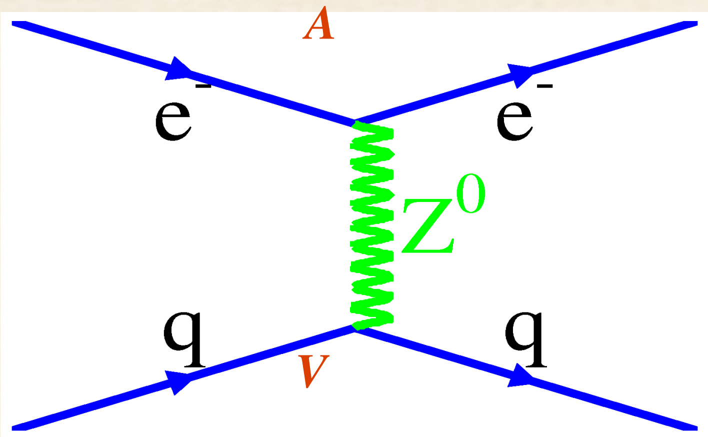
Tiny yet measurable deviations from precisely calculable SM processes

must reach Λ ~ 10 TeV

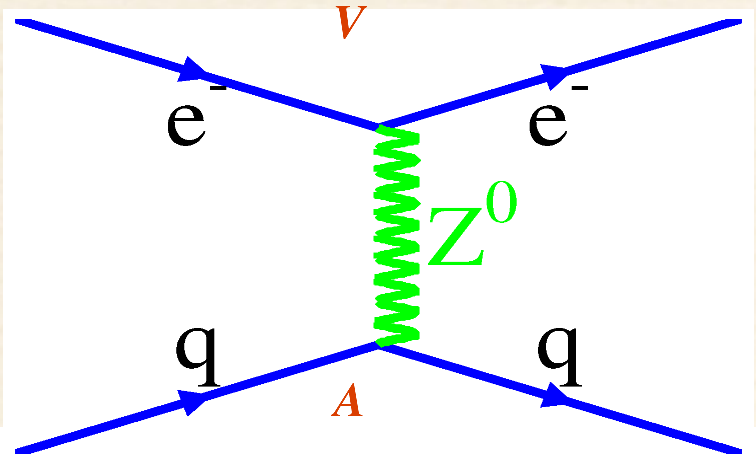


$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

Weak Neutral Current (WNC) Couplings



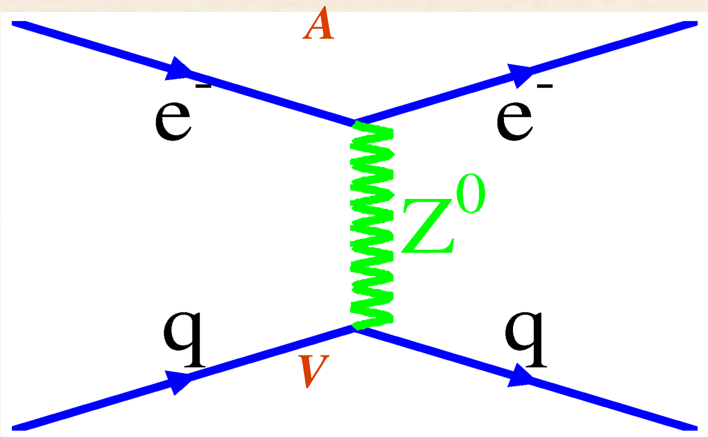
$C_{1i} \equiv 2 g_A^e g_V^i$



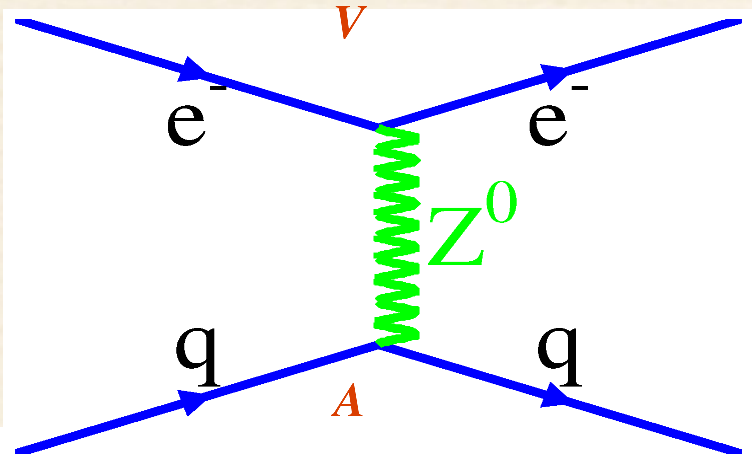
$C_{2i} \equiv 2 g_V^e g_A^i$

$$
\begin{aligned}
\mathcal{L}^{PV} &= \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) \\
&\quad +\bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)] \\
&\quad +C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)
\end{aligned}
$$

Weak Neutral Current (WNC) Couplings



$$C_{1i} \equiv 2 g_A^e g_V^i$$



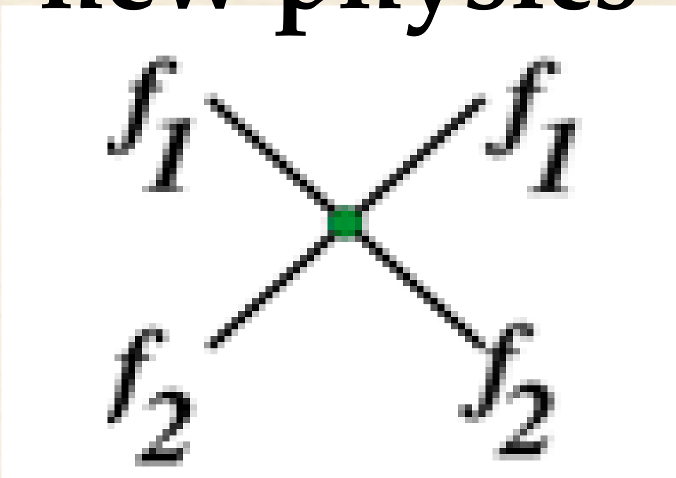
$$C_{2i} \equiv 2 g_V^e g_A^i$$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d)$$
$$+\bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$
$$+C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

C_{1u}	$=$	$-\frac{1}{2}+\frac{4}{3}\sin^2\theta_W$	$\approx$	-0.19
C_{1d}	$=$	$\frac{1}{2}-\frac{2}{3}\sin^2\theta_W$	$\approx$	0.35
C_{2u}	$=$	$-\frac{1}{2}+2\sin^2\theta_W$	$\approx$	-0.04
C_{2d}	$=$	$\frac{1}{2}-2\sin^2\theta_W$	$\approx$	0.04

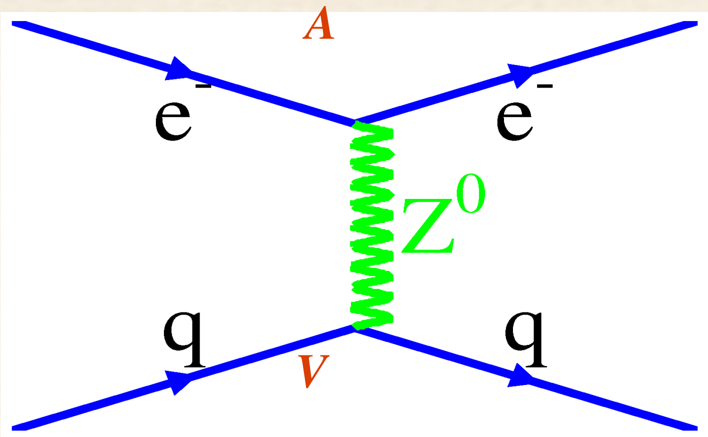
+

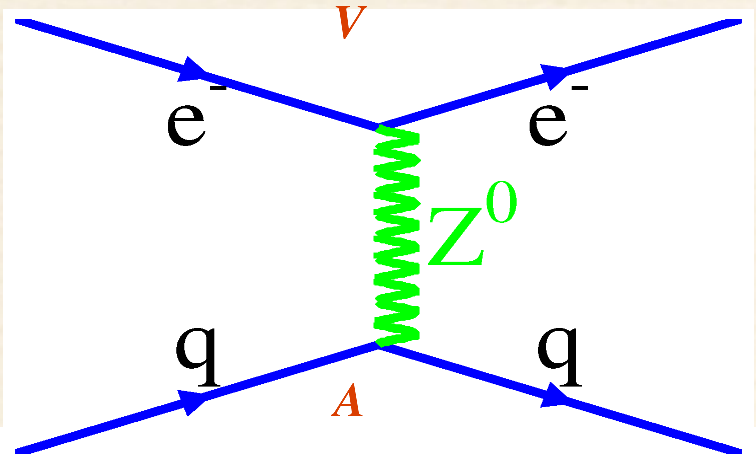
new physics



$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

Weak Neutral Current (WNC) Couplings



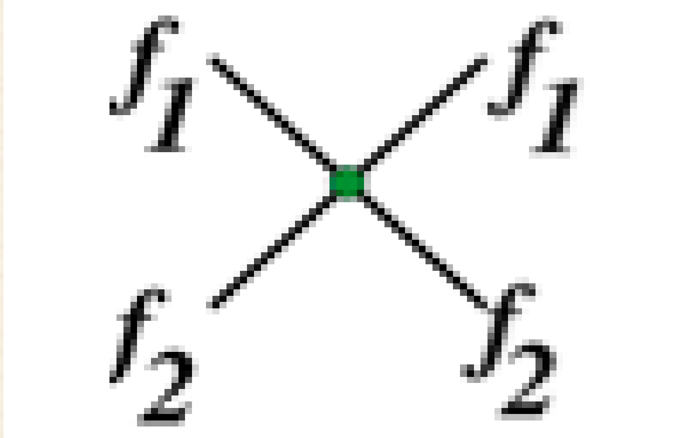


$C_{1i} \equiv 2g_A^e g_V^i$ $\quad C_{2i} \equiv 2g_V^e g_A^i$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)] + C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

$$\begin{array}{llll} C_{1u} & = & -\frac{1}{2}+\frac{4}{3}\sin^2\theta_W & \approx & -0.19 \\ C_{1d} & = & \frac{1}{2}-\frac{2}{3}\sin^2\theta_W & \approx & 0.35 \\ C_{2u} & = & -\frac{1}{2}+2\sin^2\theta_W & \approx & -0.04 \\ C_{2d} & = & \frac{1}{2}-2\sin^2\theta_W & \approx & 0.04 \end{array}$$

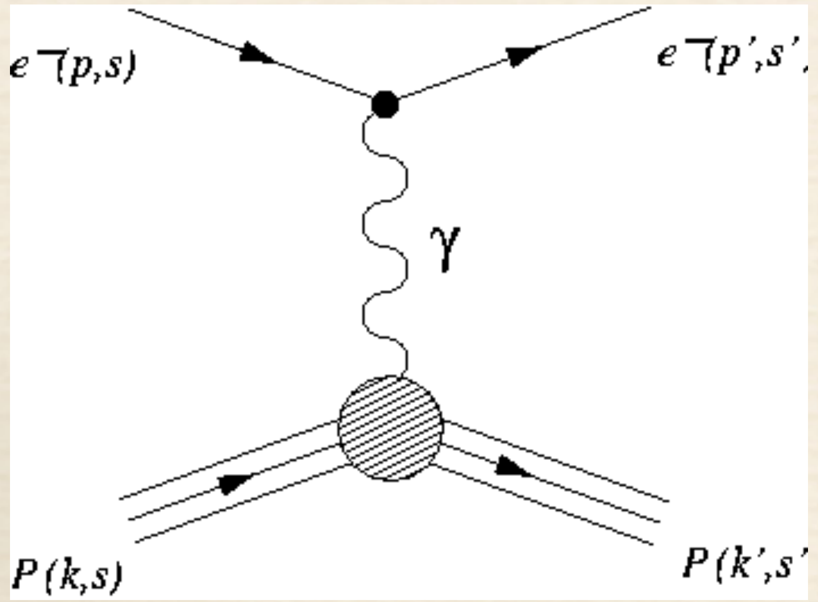
+ new physics



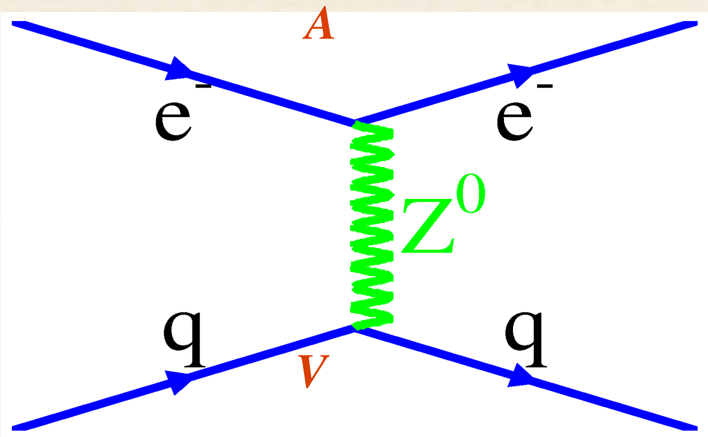
$$C_{1q} \propto (g^{eq}_{RR})^2 + (g^{eq}_{RL})^2 - (g^{eq}_{LR})^2 - (g^{eq}_{LL})^2$$

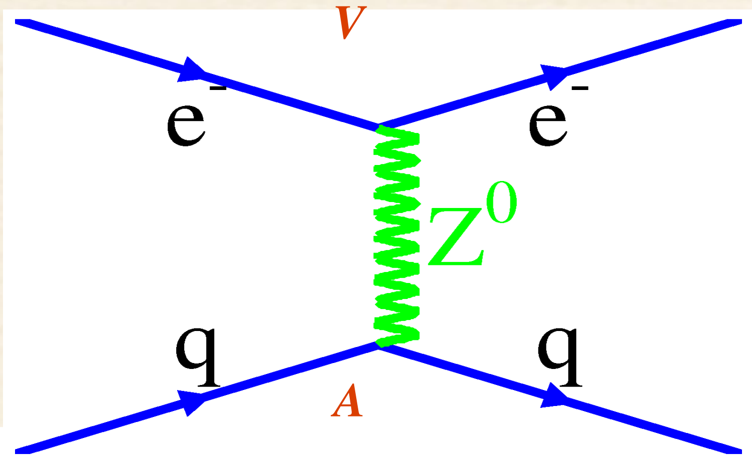
PV elastic e-N scattering, Atomic parity violation

$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g^{12}_{ij})^2}{\Lambda^2_{ij}} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$



Weak Neutral Current (WNC) Couplings





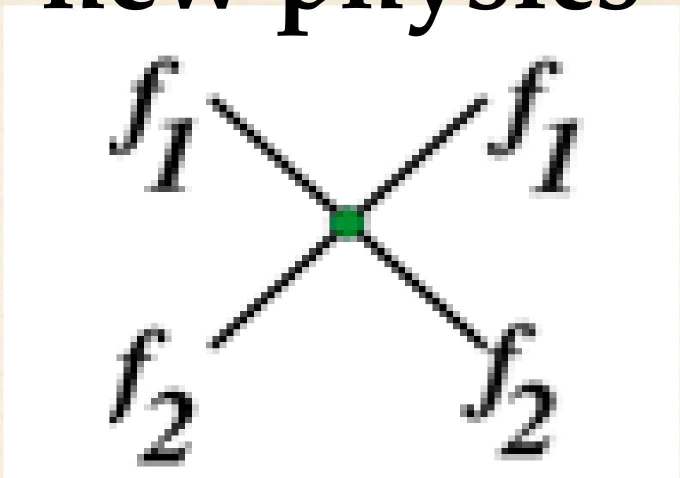
$C_{1i} \equiv 2 g_A^e g_V^i$ $\quad$ $C_{2i} \equiv 2 g_V^e g_A^i$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d)$$
$$+\bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$
$$+C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

$$\begin{aligned}
C_{1u} &= -\tfrac{1}{2}+\tfrac{4}{3}\sin^2\theta_W &\approx& -0.19\\
C_{1d} &= \tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W &\approx& 0.35\\
C_{2u} &= -\tfrac{1}{2}+2\sin^2\theta_W &\approx& -0.04\\
C_{2d} &= \tfrac{1}{2}-2\sin^2\theta_W &\approx& 0.04
\end{aligned}$$

+

new physics



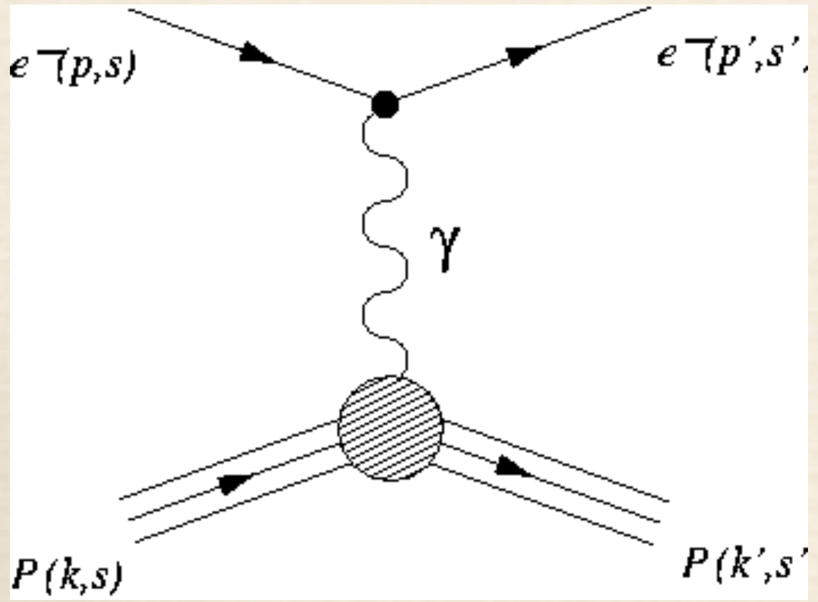
$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$

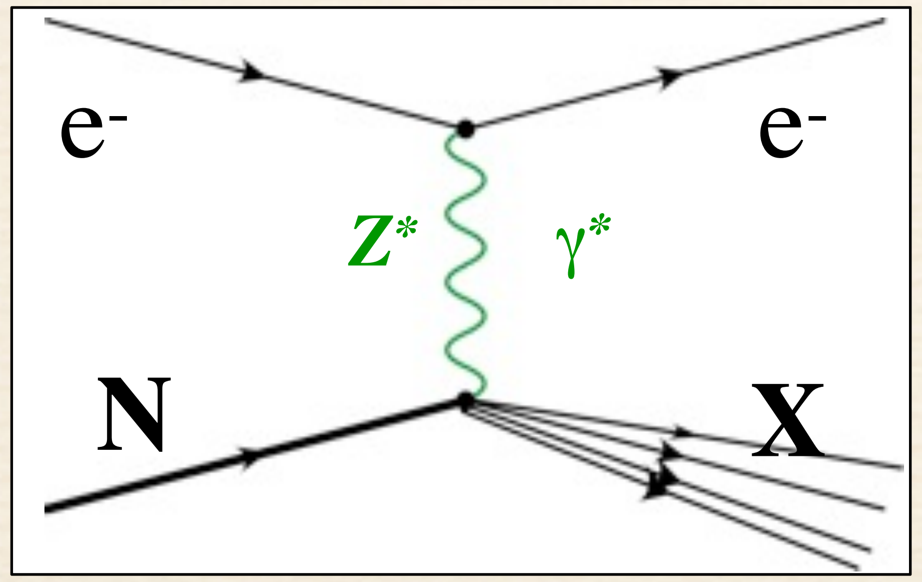
PV elastic e-N scattering, Atomic parity violation

$$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$

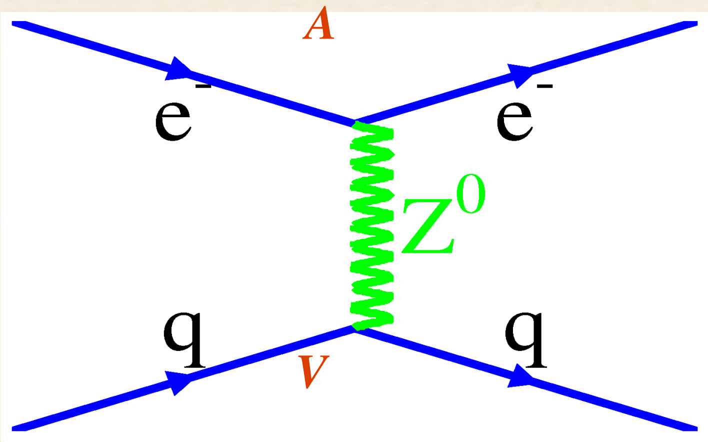
PV deep inelastic scattering

$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2}\bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

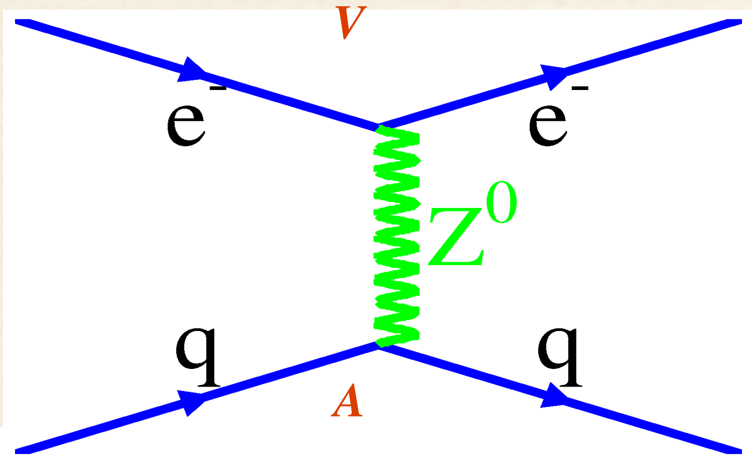




Weak Neutral Current (WNC) Couplings



$C_{1i} \equiv 2 g_A^e g_V^i$

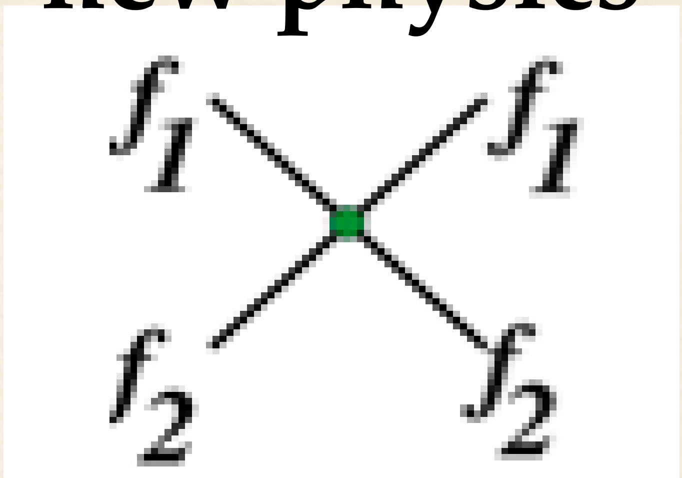


$C_{2i} \equiv 2 g_V^e g_A^i$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)] + C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

$$\begin{array}{lcrcr} C_{1u} & = & -\frac{1}{2}+\frac{4}{3}\sin^2\theta_W & \approx & -0.19 \\ C_{1d} & = & \frac{1}{2}-\frac{2}{3}\sin^2\theta_W & \approx & 0.35 \\ C_{2u} & = & -\frac{1}{2}+2\sin^2\theta_W & \approx & -0.04 \\ C_{2d} & = & \frac{1}{2}-2\sin^2\theta_W & \approx & 0.04 \end{array}$$

+ new physics

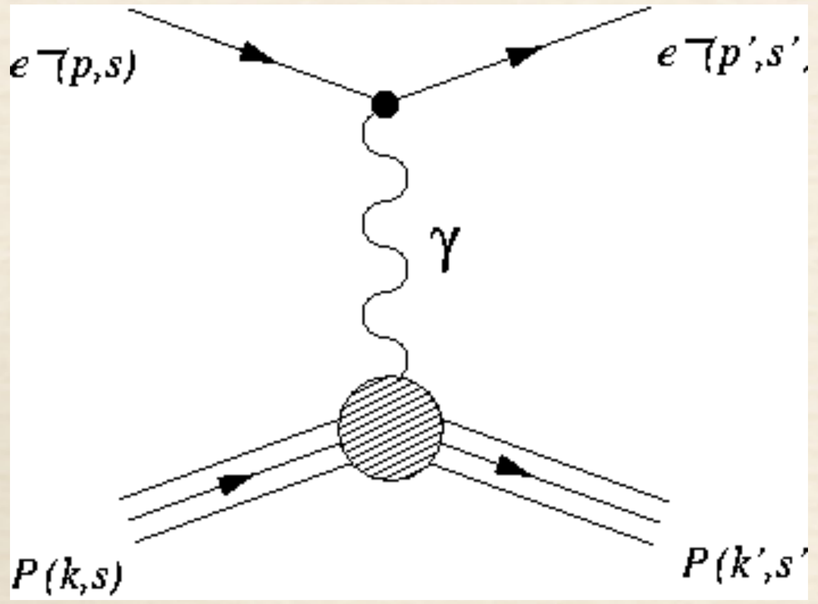


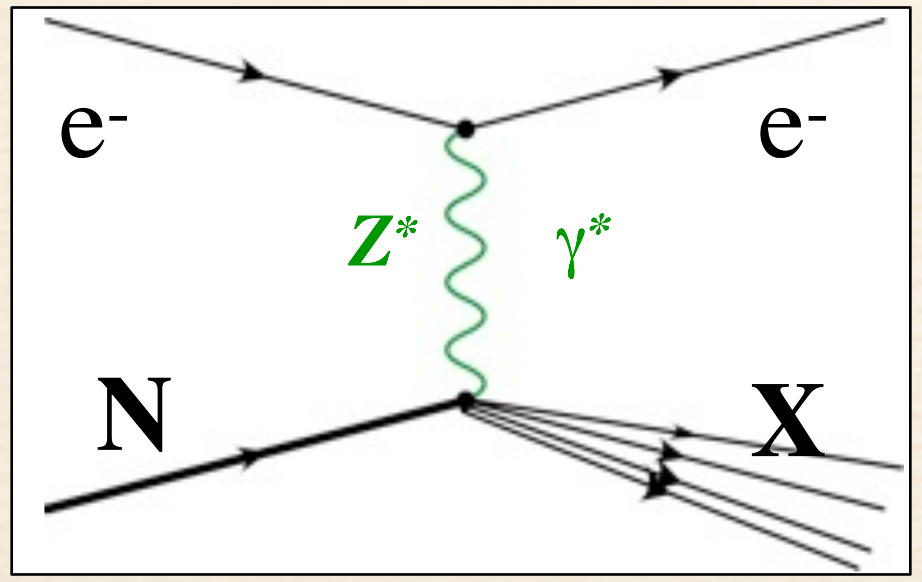
$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$ ***PV elastic e-N scattering, Atomic parity violation***

$$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$ ***PV deep inelastic scattering***

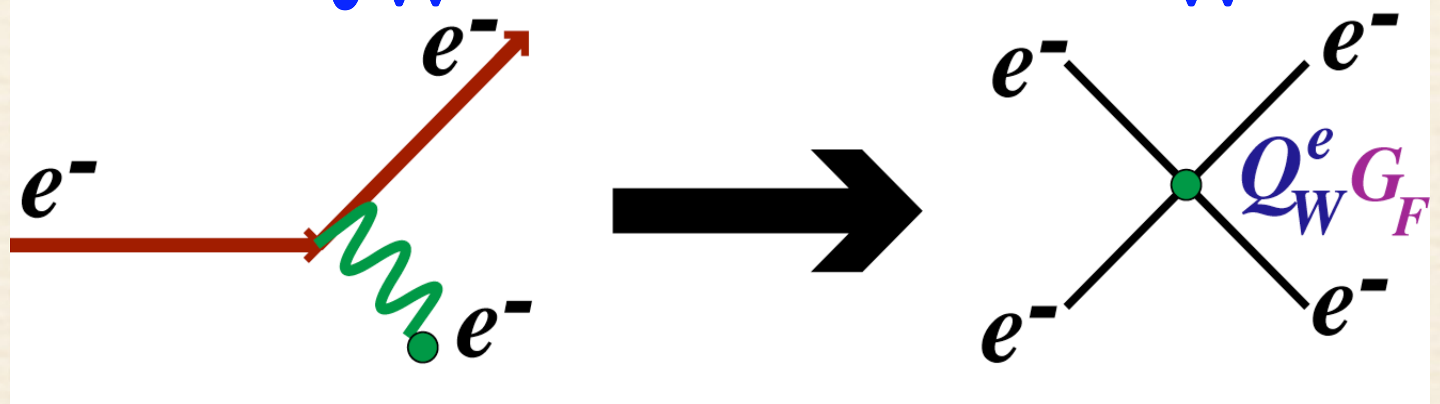
$$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2 \Rightarrow$$ ***PV Møller scattering***

$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$





$Q_W = 1 - 4\sin^2\theta_W$

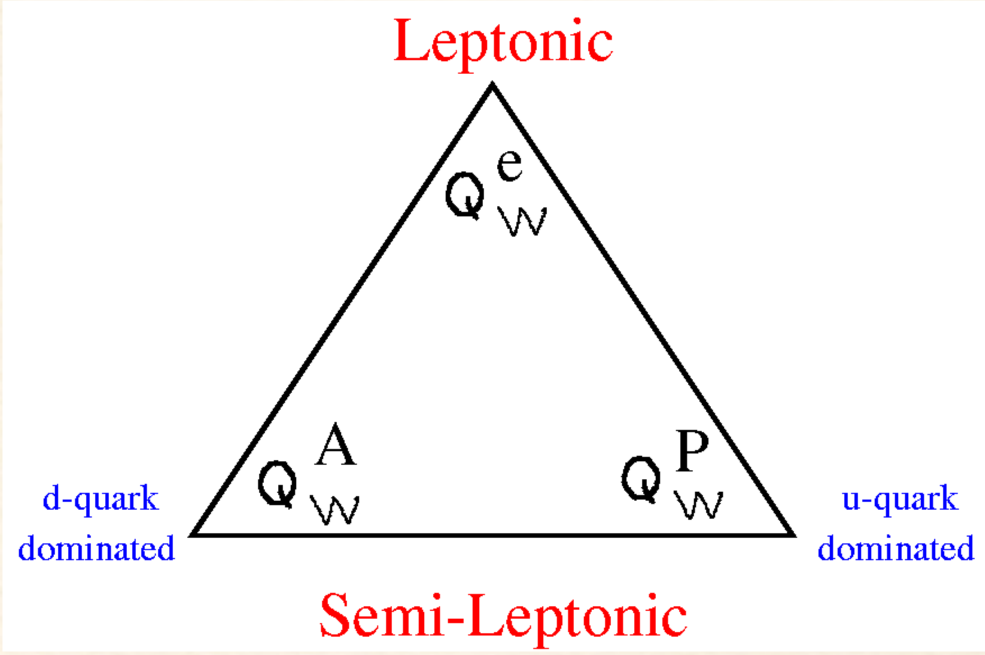


PVES New Physics Reach

Physics sensitivity from contact interaction (LEP2 convention, g^2= 4pi)

	precision	$\Delta \sin^2\bar{\theta}_W(0)$	Λ_{new} (expected)
APV Cs	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
Qweak final	4.5 %	0.0008	33 TeV
PVDIS	4.5 %	0.0050	7.6 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV

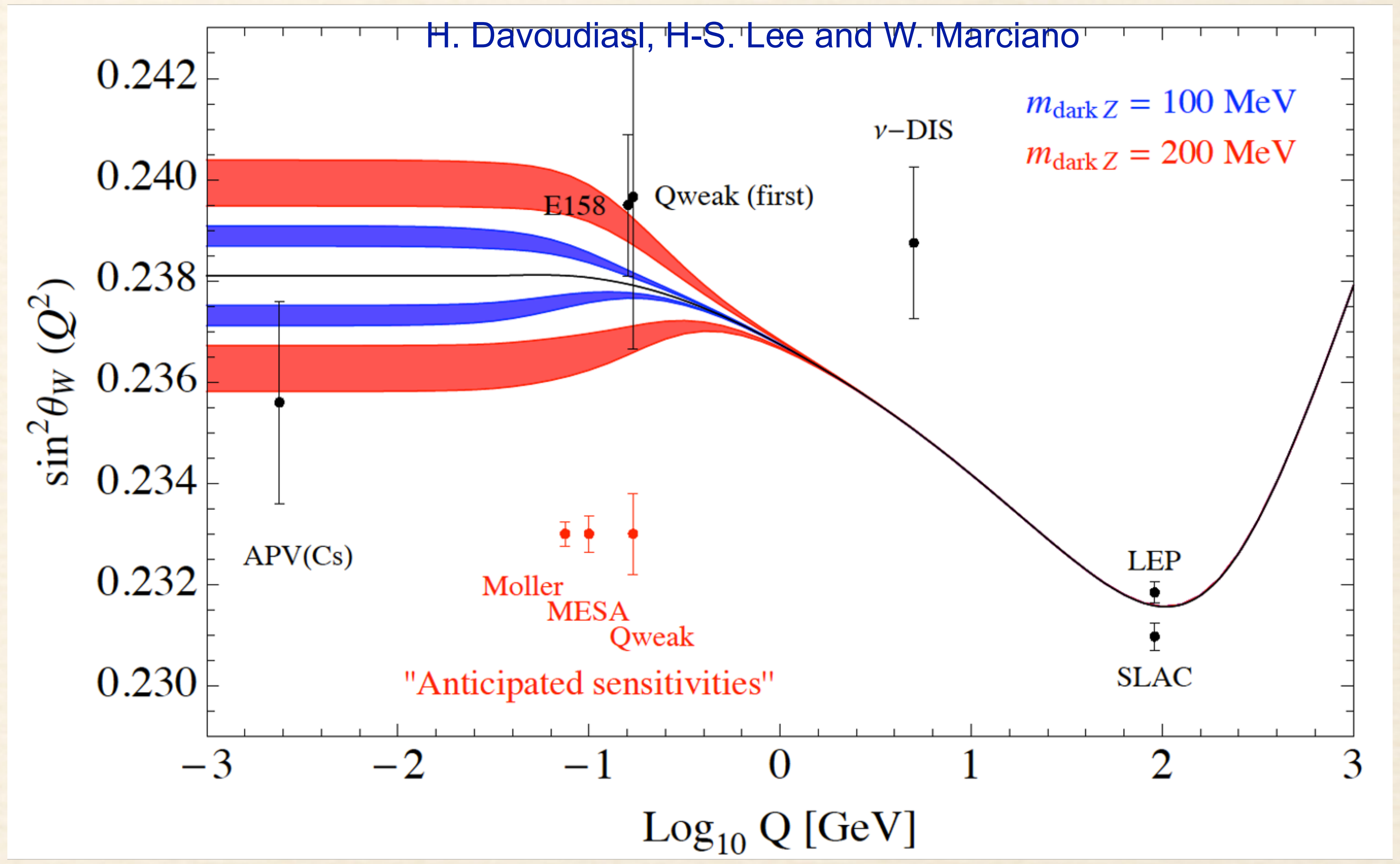
J. Erler



Courtesy: M. Ramsey-Musolf

$$[\mathbf{2C_{2u} - C_{2d}}]$$

axial-quark couplings



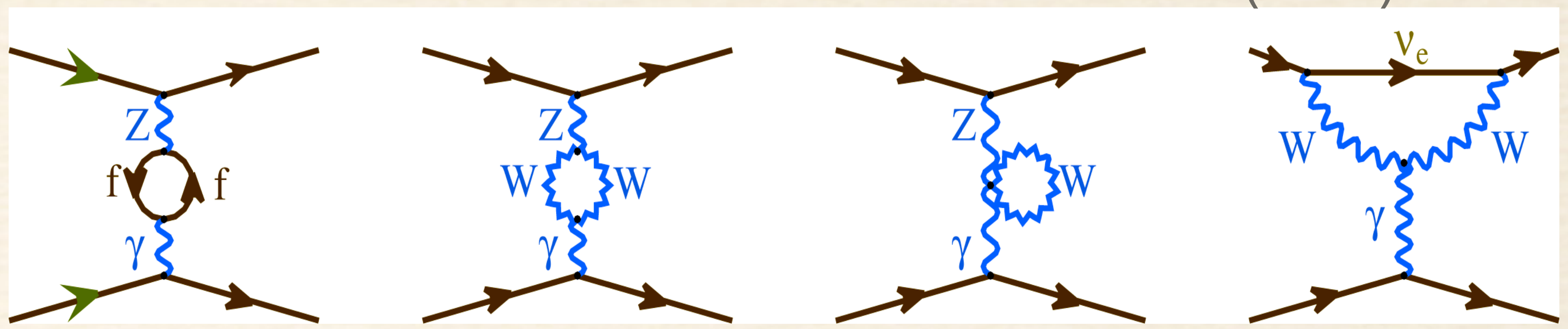
✦Complementary to collider Drell-Yan Searches
✦Unique sensitivity to low energy dark Z's

Thumb Rule: Weak mixing angle must be measured to sub-0.5% precision

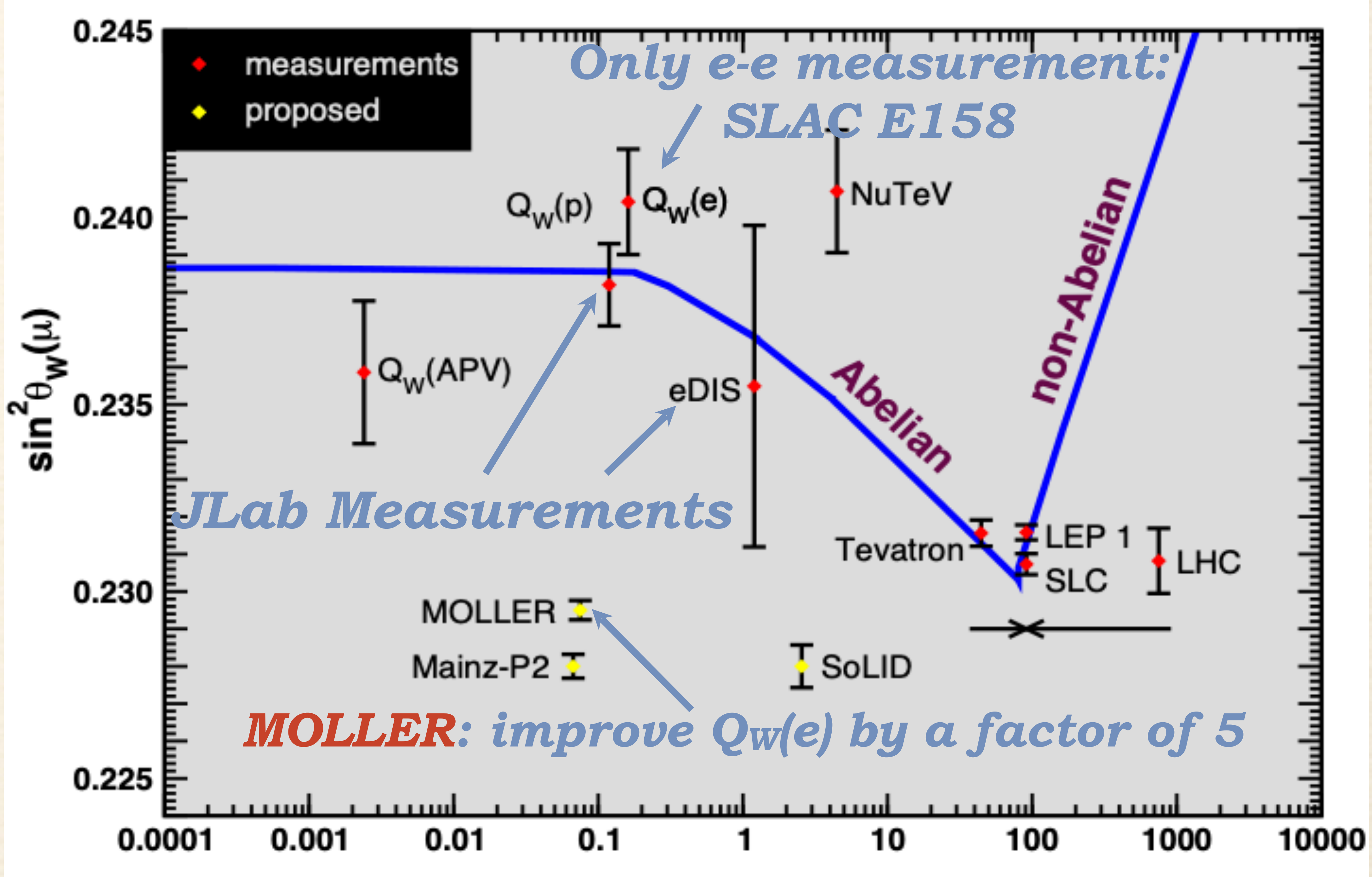
Neutral Current "Bookkeeping"

Electroweak Radiative Corrections causes weak mixing angle to "run"

Czarnecki and Marciano (1995)

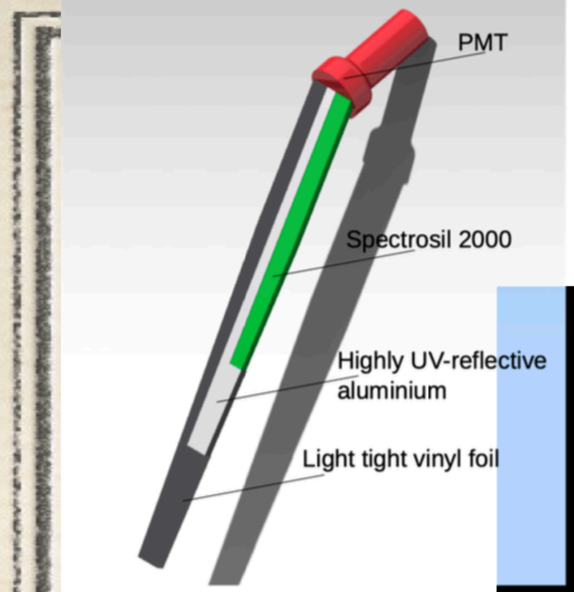


- ✦ **Atomic Parity Violation: Cs-133**
  - ✦ future measurements and theory challenging
- ✦ **Neutrino Deep Inelastic Scattering: NuTeV**
  - ✦ future measurements and theory challenging
- ✦ **PV Møller Scattering: E158 at SLAC**
  - ✦ statistics limited, theory robust
  - ✦ next generation: MOLLER (factor of 5 better)
- ✦ **PV elastic e-p scattering: Qweak**
  - ✦ theory robust at low beam energy
  - ✦ next generation: P2 (factor of 3 better)
- ✦ **PV Deep Inelastic Scattering: PVDIS**
  - ✦ theory robust for ²H in valence quark region
  - ✦ factor of 5 improvement: SOLID

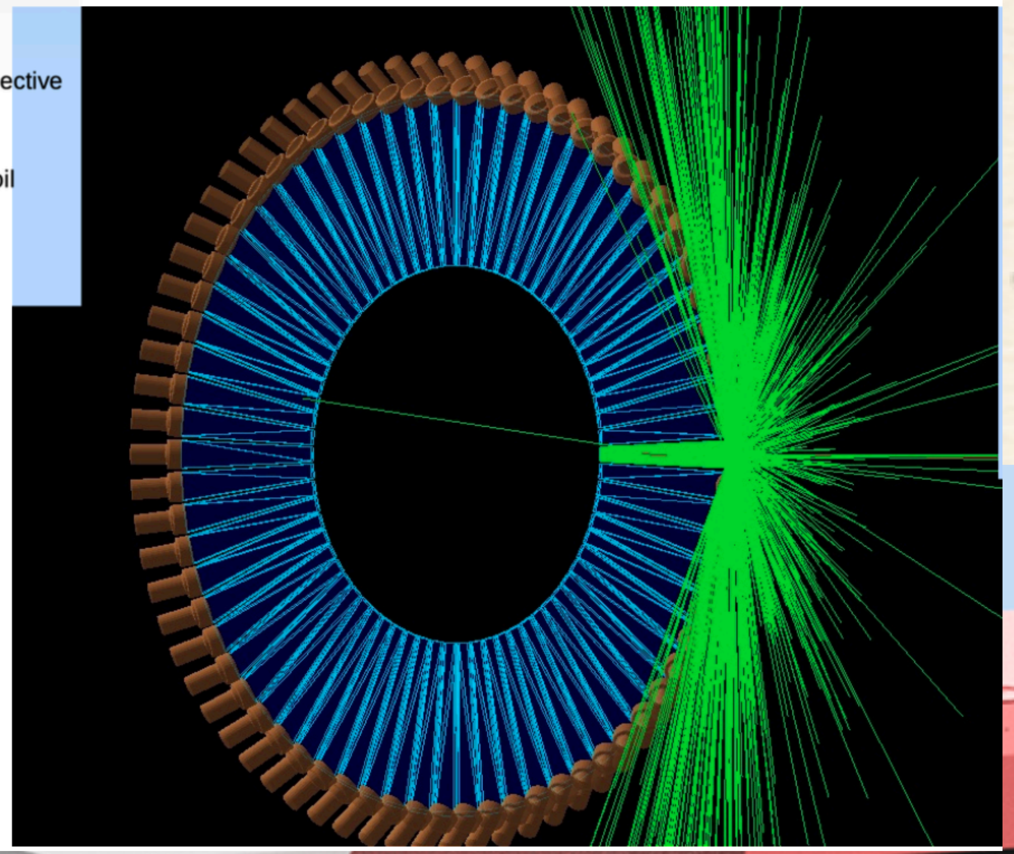


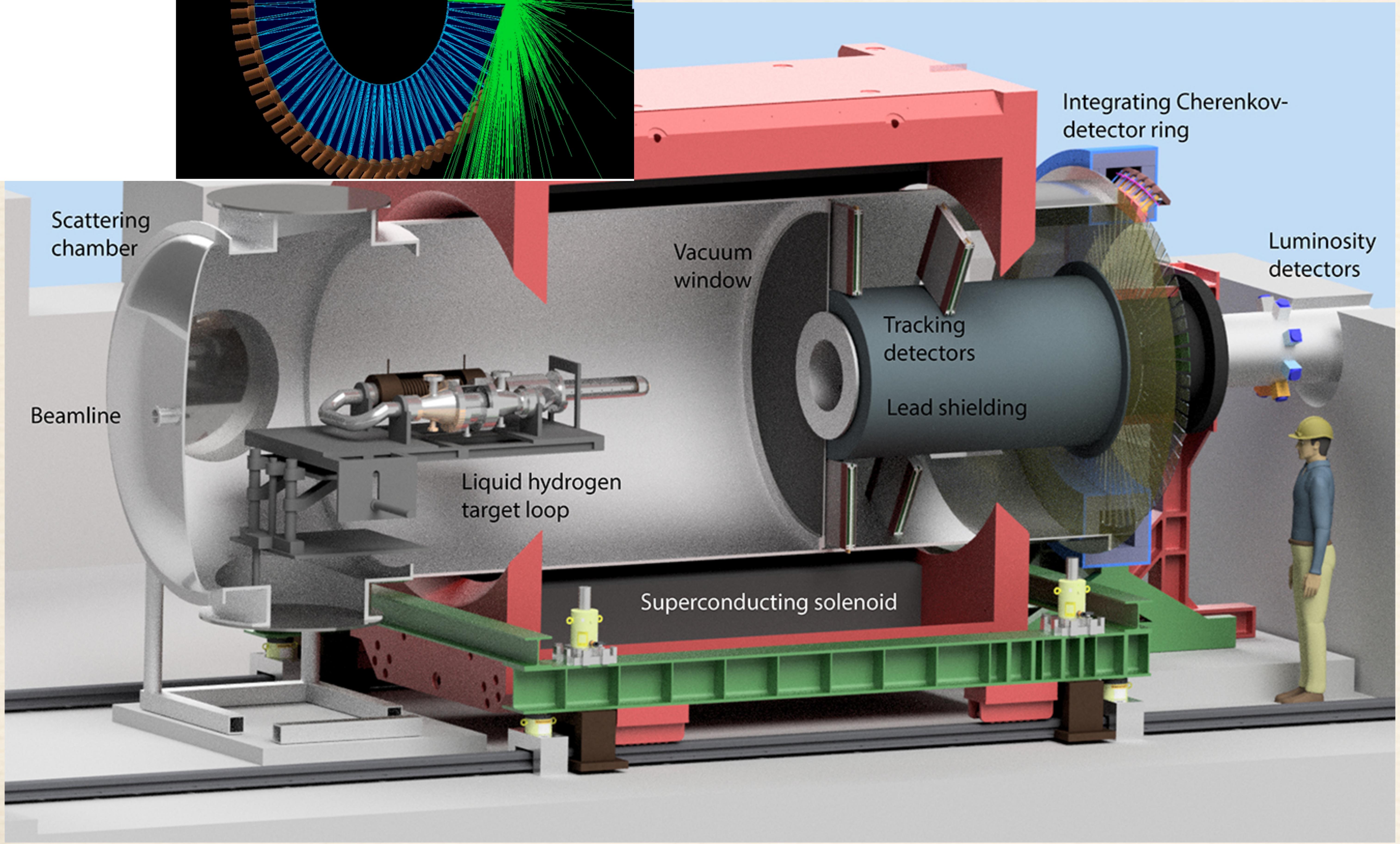
Erler and Ramsey-Musolf (2004)
Erler and Ferro-Hernandez (2018)

P2 at MESA



Radiation Hard
Fused Silica
Cherenkov detectors





60 cm LH2 target   155 MeV, 150 μA   90% beam polarization

P2@MESA hydrogen	P2@MESA carbon
A_{ep}=-28 ppb	A_{ep}= 416.3 ppb
ΔA_{ep}= 0.5 ppb ppb=1/√N Factor 19 After 11,000 h	ΔA_{ep}^{stat}= 2.7 ppb after 300 h ΔA_{ep}^{stat}= 0.9 ppb after 2500 h
$\Delta A_{ep}/A_{ep}$= 1.8 %	$\Delta A_{ep}/A_{ep}^{stat}$= 0.6 % (0.2 %) Polarimetry!
$\Delta \sin^2\theta_W/\sin^2\theta_W$= 0.15 %	$\Delta \sin^2\theta_W/\sin^2\theta_W$= 0.6 %
Aux. measurem. backward angle	Aux. measurem. backward angle

Physics Program 2025 onwards with proton, ^{12}C and ^{208}Pb targets

A Decade-Long Rich PVES Program at MESA!

- **Hydrogen** at **<u>forward</u> angles:**
  $A_{PV} \rightarrow Q_W(p) \rightarrow \sin^2\theta_W \rightarrow$ BSM physics?

$$\sin^2\theta_W \approx \frac{1-Q_W}{4}$$

Proton structure - << 1 at small Q²

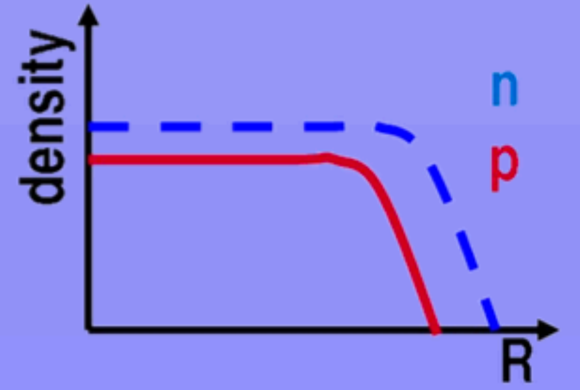
$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{em}}\left(Q_W - F(Q^2)\right)$$

Hadronic structure of proton sizable at not-so-small Q²

- **Hydrogen + Deuterium** at **<u>backward</u> angles:**
  $A_{PV} \rightarrow$ axial FF + strange contribution to magnetic FF

- **Carbon**:
  $A_{PV} \rightarrow Q_W(^{12}C) = -24 \sin^2\theta_W$
  Complementary sensitivity to BSM physics

- **Lead**:
  $A_{PV} \rightarrow F_{weak}(Q^2)$
  $\rightarrow$ neutron radius
  $\rightarrow$ neutron skin thickness
  related to the
  $\rightarrow$ symmetry energy - nuclear Equation of State,
  e.g., $\rightarrow$ modeling of neutron stars



MREX

See MESA details in previous talk by S. Schlimme

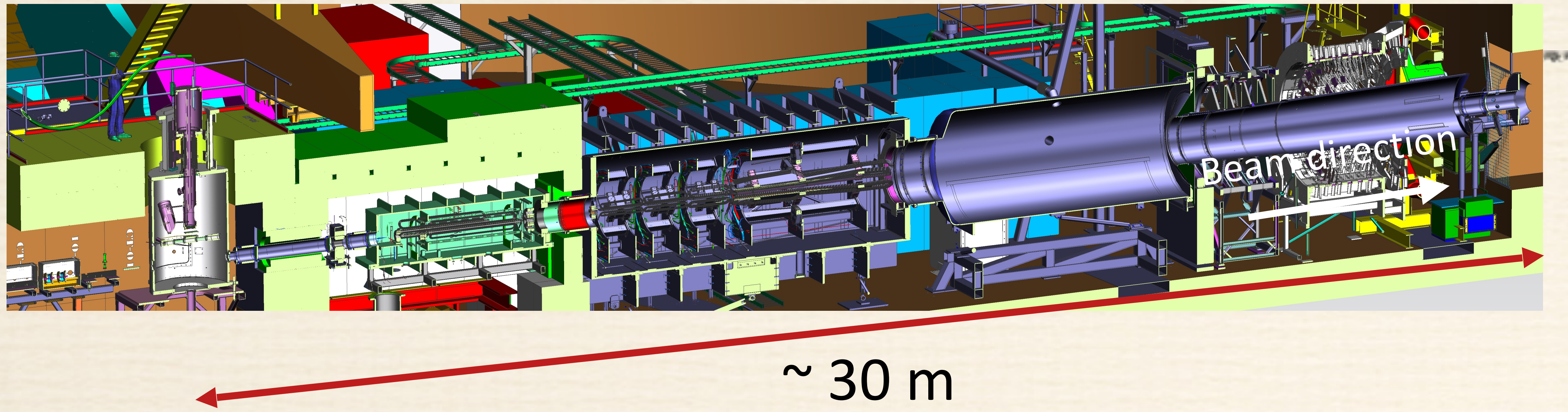
Notional Schedule of physics measurement campaign

2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035

- Beam line, detector, target, forward, backward (2024)
- Forward Si- tracker (2024)
- $\langle Q^2\rangle$, 55 MeV, $\Delta Q^2/Q^2$ = 4 % (2025–2026)
- $\langle Q^2\rangle$, 155 MeV, $\Delta Q^2/Q^2$ = 4 % (2025–2026)
- A_{PV}= -403 ppb, H_2 backward, 55 MeV 1000h, (ΔA/A=10%), G_A (2025–2026)
- A_{PV} = -28 ppb, H_2 forward, 155 MeV (ΔA/A=7%), $\sin^2\Theta_W$: 0.4% (2025–2026)
- Measurement and analysis, A_{PV} , A_n for carbon, aluminum and lead (common with N01) (2028–2035)
- Systematic studies, auxilliary measurements (2028–2033)
- $\langle Q^2\rangle$, 155 MeV $\Delta Q^2/Q^2$ = 2 % (2028–2030)
- $\langle Q^2\rangle$, 155 MeV $\Delta Q^2/Q^2$ = 1 % (2032–2033)
- Data taking and analysis 155 MeV, 1000 h beam Backw. angle, A_{PV}= -4510 ppb, (ΔA/A=1%), G_A (2028–2032)
- Data taking and analysis, 155 MeV, 11.000 h beam Forward angle, A_{PV}= -28 ppb, (ΔA/A=2%), $\sin^2\Theta_W$ (2028–2033)
- $\sin^2\Theta_W$: 0.3% accuracy (2028–2031)
- $\sin^2\Theta_W$: 0.14% accuracy (2031–2035)

MOLLER at JLab

Special purpose installation in Hall A



11 GeV, 65 μA 90% beam polarization

$A_{PV} \sim 32$ ppb $\delta(A_{PV}) \sim 0.8$ ppb

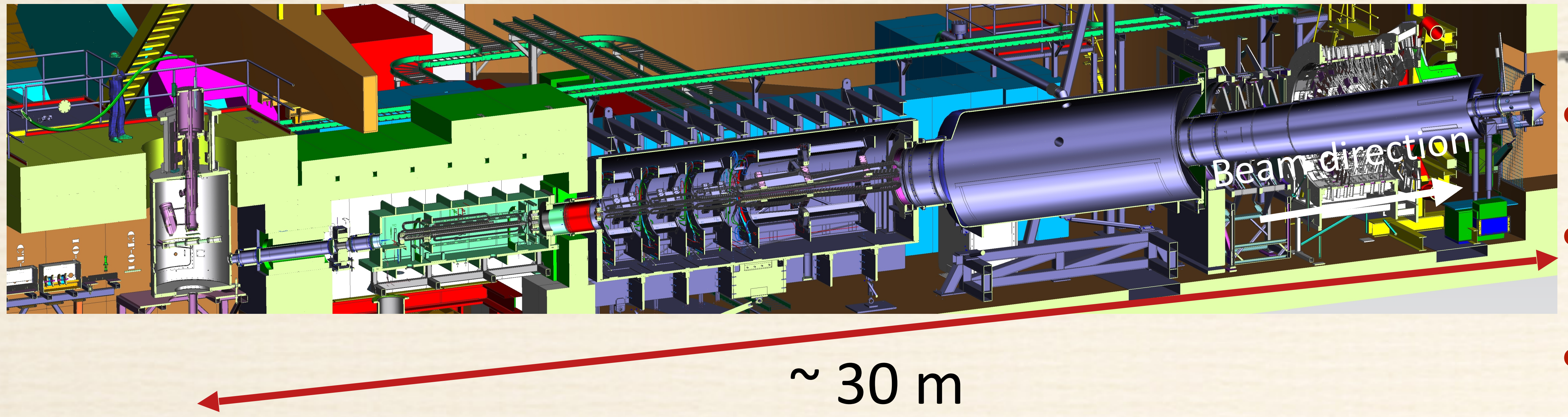
$\delta(Q^e_W) = \pm 2.1\ \%\ (stat.) \pm 1.1\ \%\ (syst.)$

$\delta(\sin^2\theta_W) = \pm 0.00023\ (stat.) \pm 0.00012\ (syst.)$

New purely leptonic interactions:
MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory

MOLLER at JLab

Special purpose installation in Hall A



11 GeV, 65 μA   90% beam polarization

A_{PV} ~ 32 ppb $\delta(A_{PV})$ ~ 0.8 ppb

$\delta(Q^e_W) = \pm 2.1\ \%\ (stat.) \pm 1.1\ \%\ (syst.)$

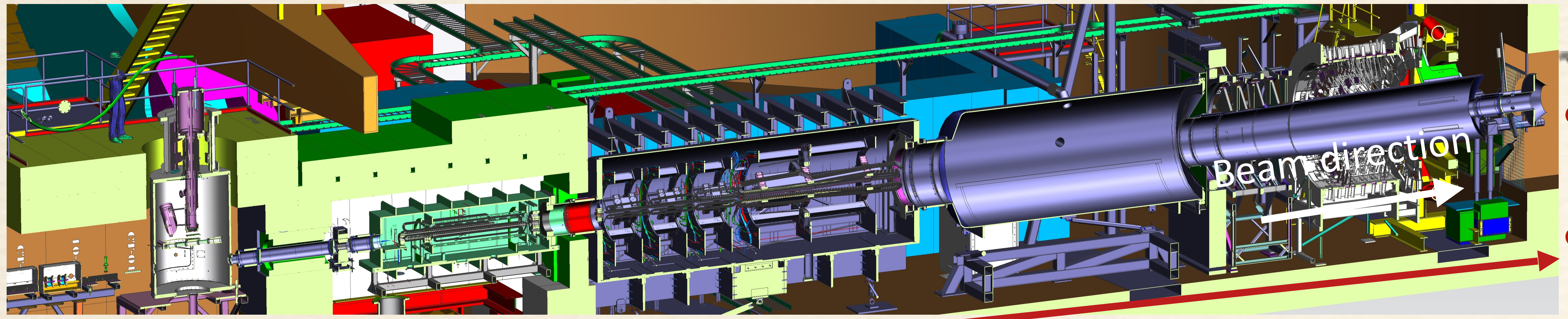
$\delta(\sin^2\theta_W) = \pm 0.00023\ (stat.) \pm 0.00012\ (syst.)$

- High intensity polarized electron source
- ~ 134 GHz scattered electron rate
- 1 nm control of beam centroid on target
- ~ 9 gm/cm² liquid hydrogen target
  - 1.25 m: ~ 3.7 kW @ 70 μA
- Full Azimuthal acceptance w/ θ_{lab} ~ 5 mrad
  - novel toroidal spectrometer assemblies
  - radiation hard, segmented integrating detectors
- Robust & Redundant 0.4% beam polarimetry

New purely leptonic interactions:
MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory

MOLLER at JLab

Special purpose installation in Hall A



11 GeV, 65 μA   90% beam polarization

A_{PV} ~ 32 ppb $\delta(A_{PV})$ ~ 0.8 ppb

$\delta(Q^e_W) = \pm 2.1\ \%\ (stat.) \pm 1.1\ \%\ (syst.)$

$\delta(\sin^2\theta_W) = \pm 0.00023\ (stat.) \pm 0.00012\ (syst.)$

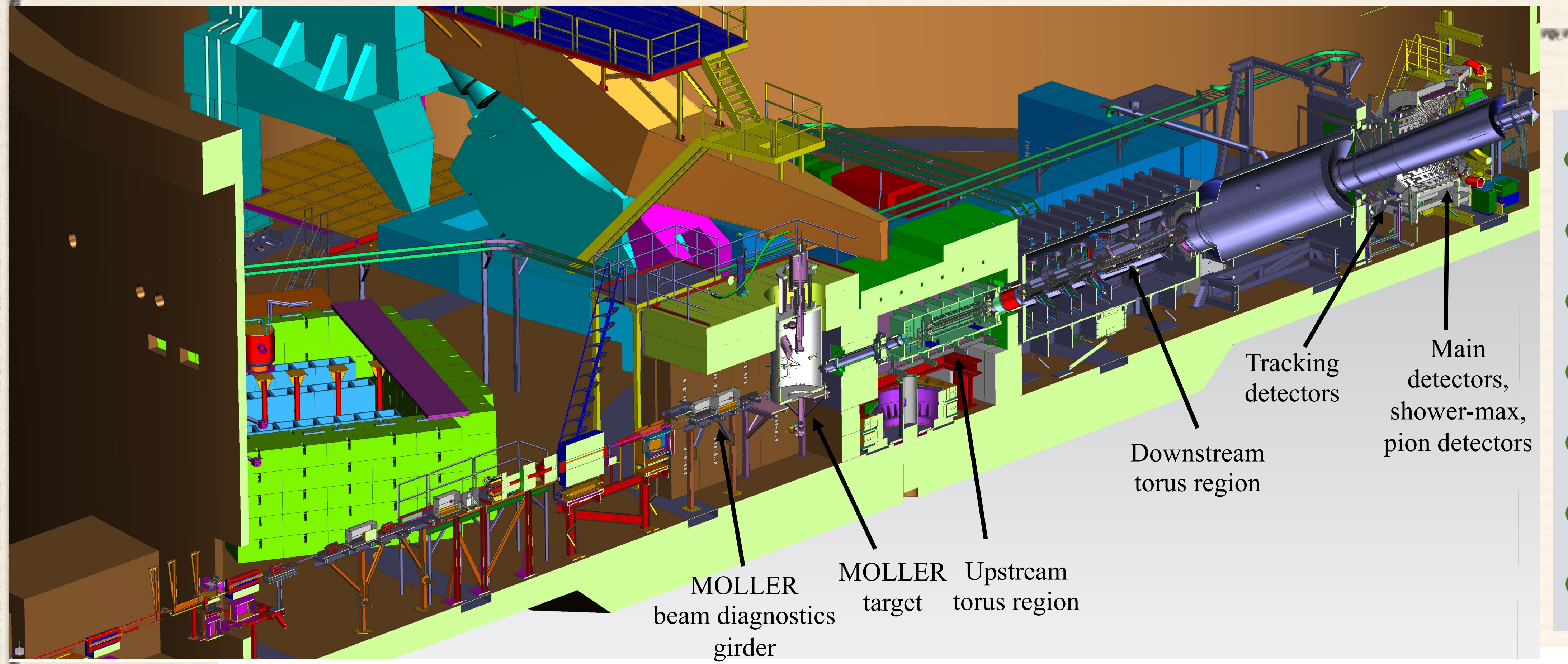
- High intensity polarized electron source
- ~ 134 GHz scattered electron rate
- 1 nm control of beam centroid on target
- ~ 9 gm/cm² liquid hydrogen target
  - •1.25 m: ~ 3.7 kW @ 70 μA
- Full Azimuthal acceptance w/ θ_{lab} ~ 5 mrad
  - •novel toroidal spectrometer assemblies
  - •radiation hard, segmented integrating detectors
- Robust & Redundant 0.4% beam polarimetry

New purely leptonic interactions:
MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory

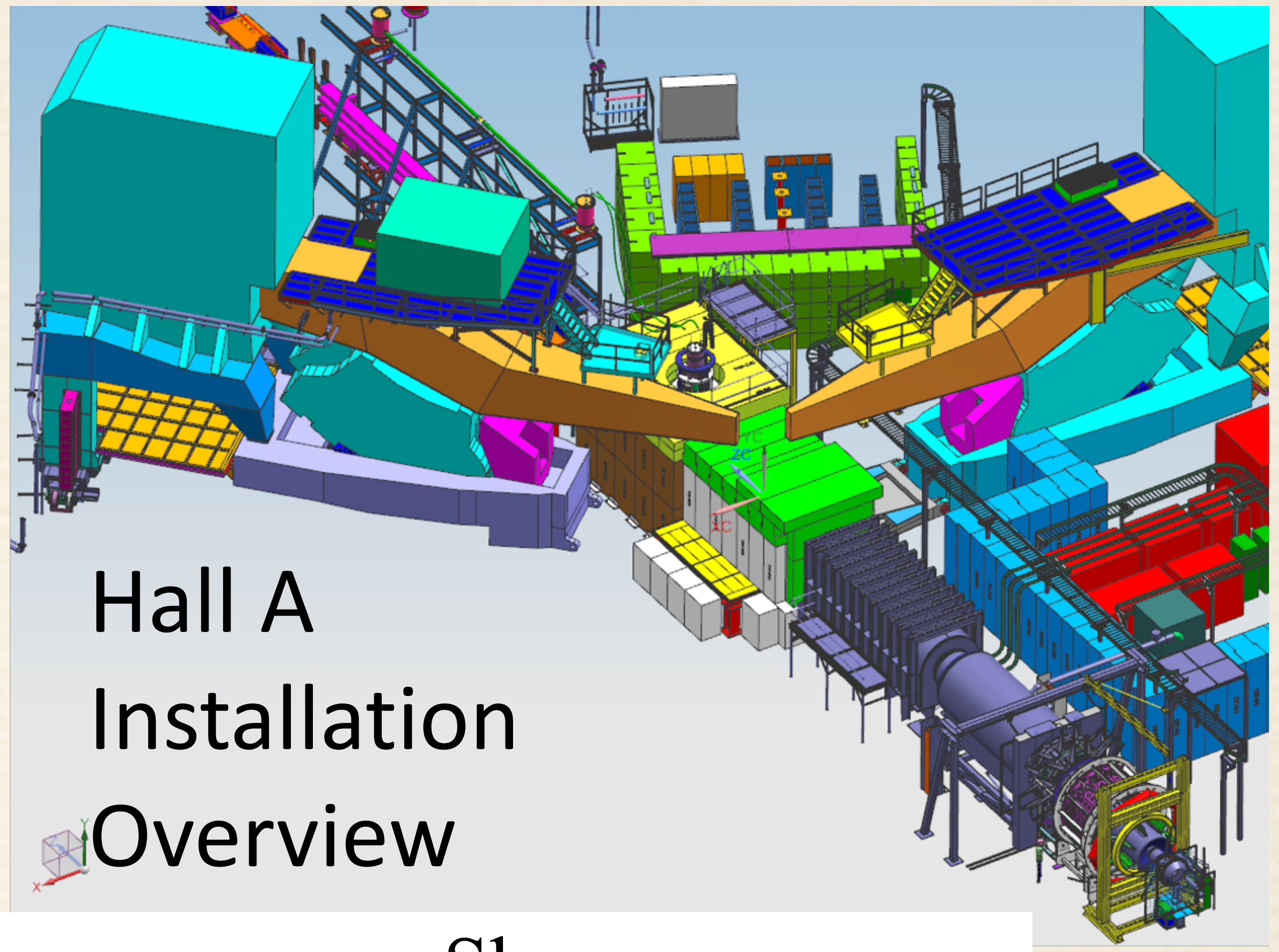
- **MOLLER Collaboration**
  - – 180 scientists, 34 institutions, 4 countries
  - – Experience from SAMPLE, A4, HAPPEX, G0, PREX, Qweak, E158
  - – Technical Design Report has been released and will be on ArXiv

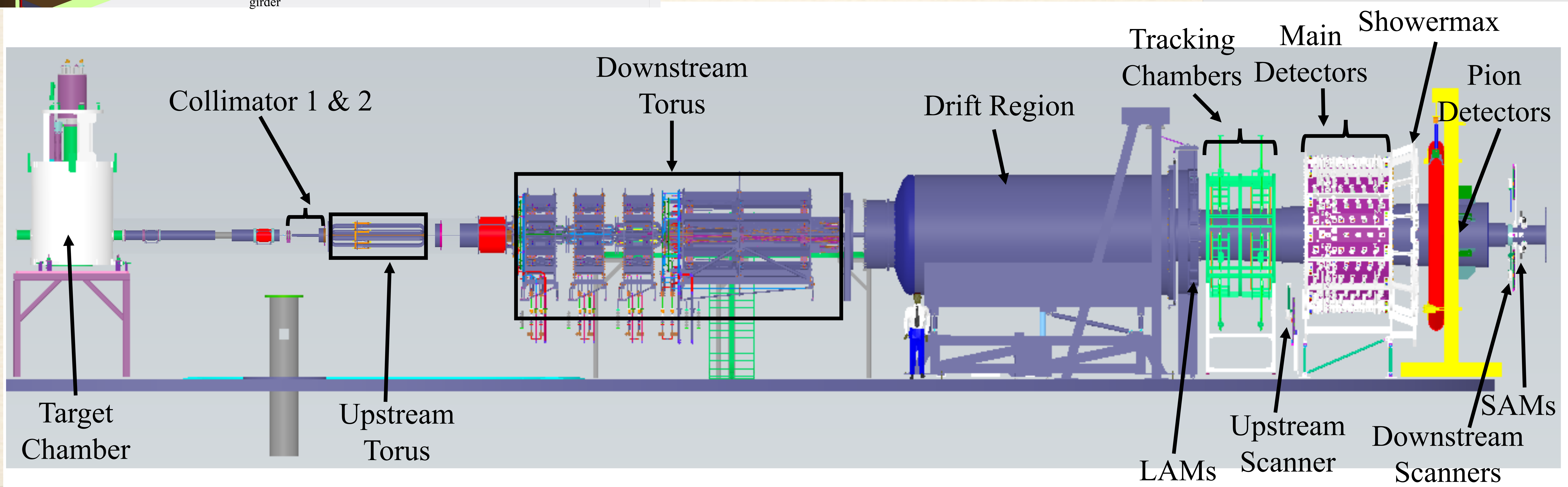
MOLLER Status

Engineering Design of all components of apparatus complete: Technical Design Report about to be put on ArXiv



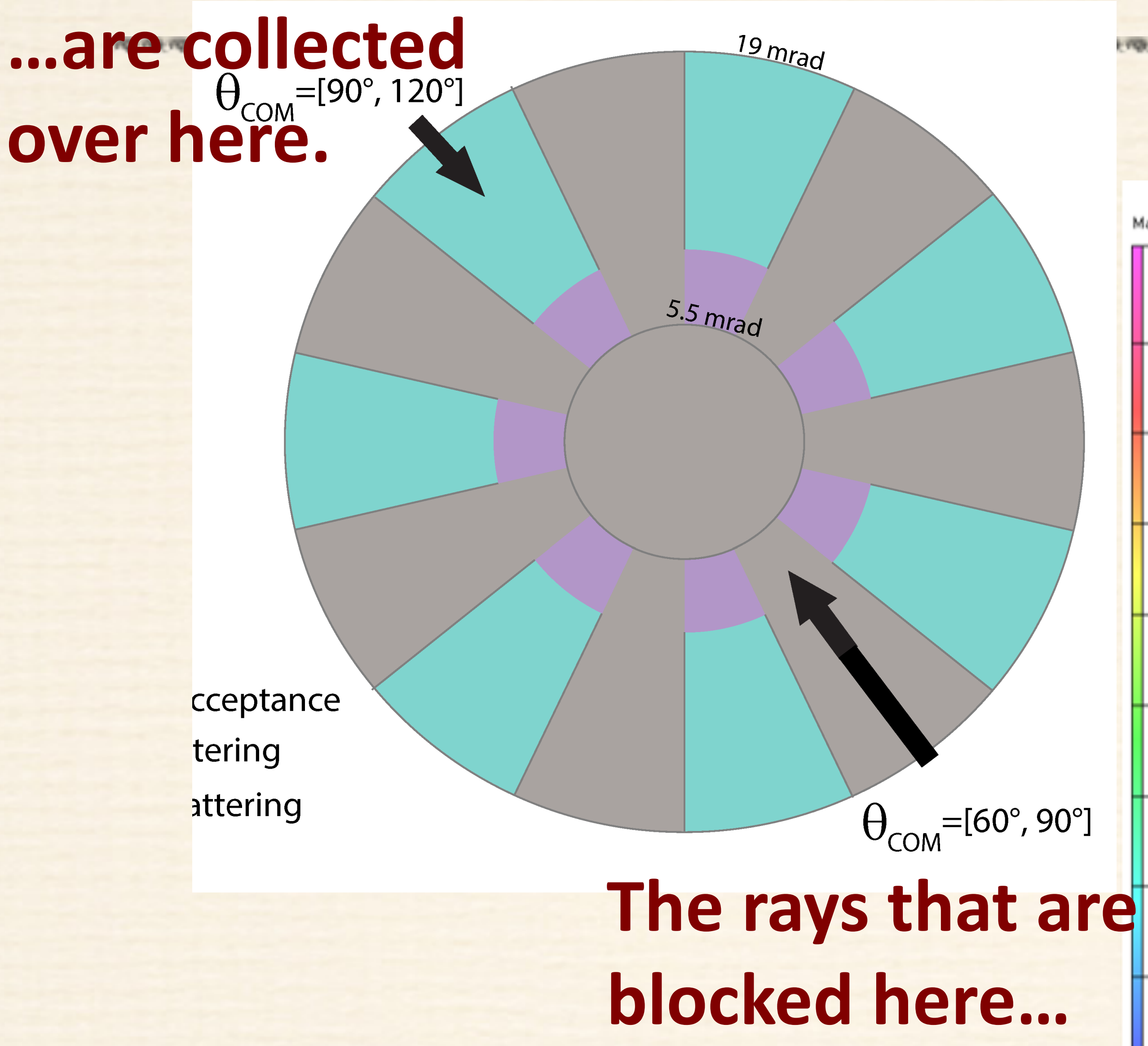
- ~ 50M$ MIE by US DOE
- CD-1 granted in Dec 2020
- CD-2/3 Review just completed
- Construction: 2024-25
- Installation 2025-26
- Commissioning: Summer 2026
- Physics thru 2028

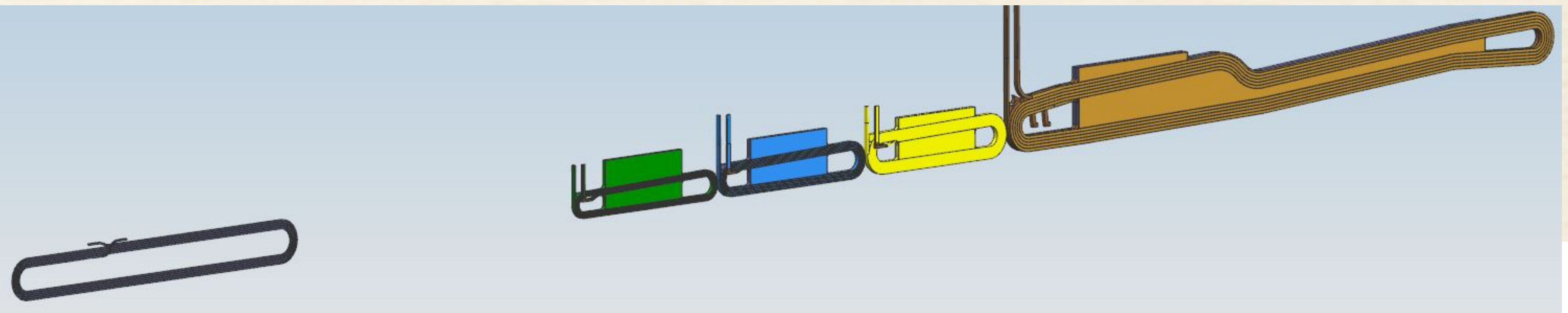


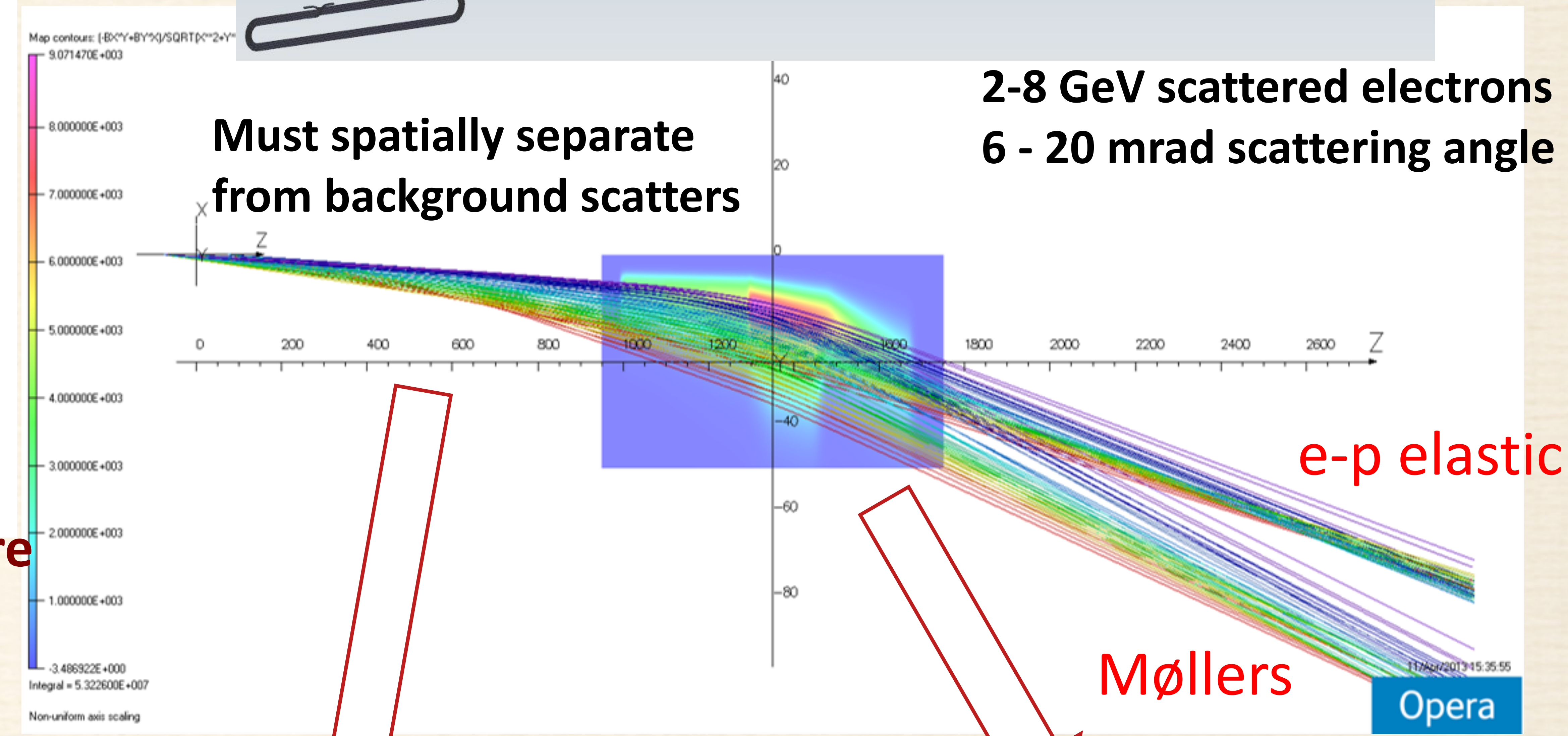


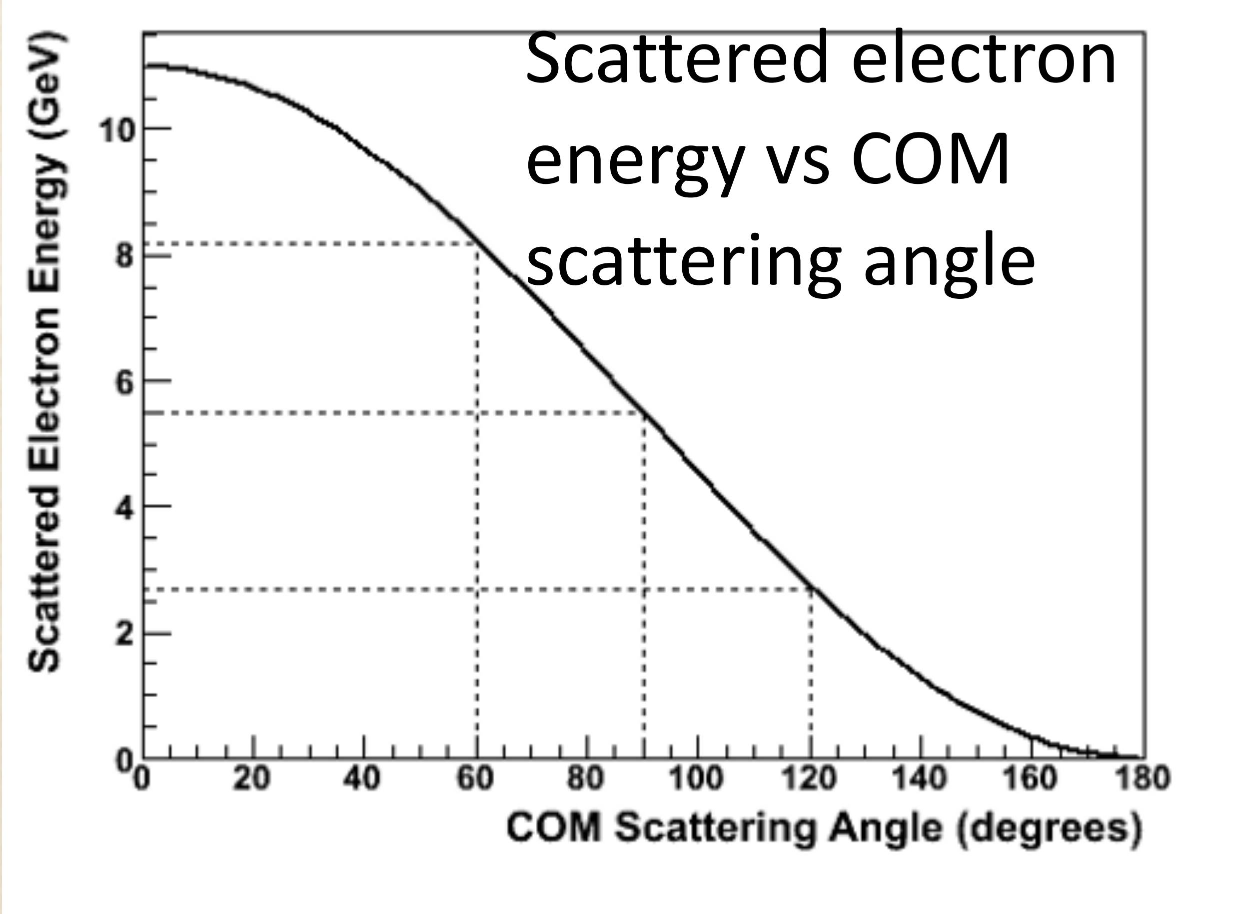
Spectrometer Acceptance and Collimation

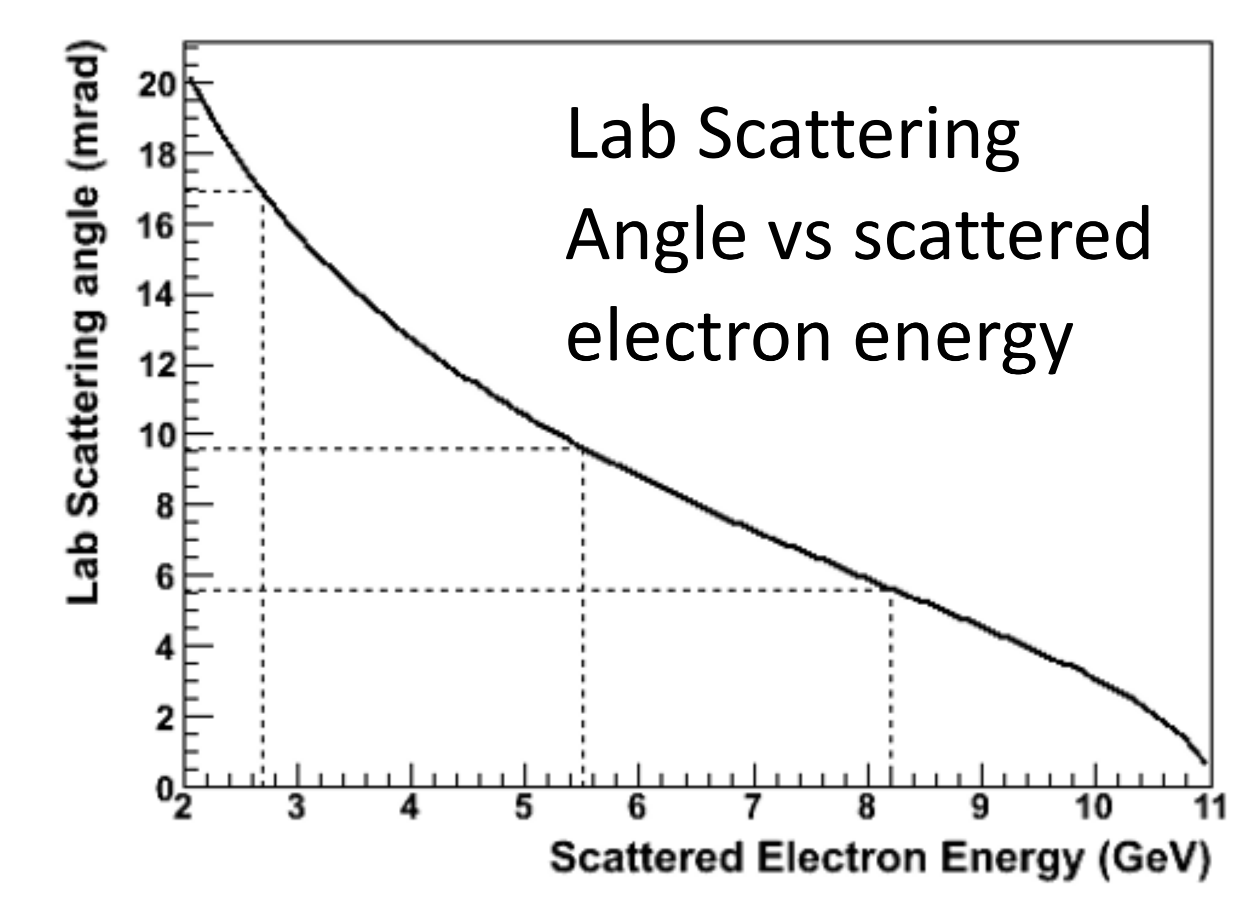
- Accept all Møller scattered electrons in range Θ_{CM} = 50^{o} – 130^{o}
- **Exploit identical particle nature for 100% azimuthal acceptance**; needs odd number of coils

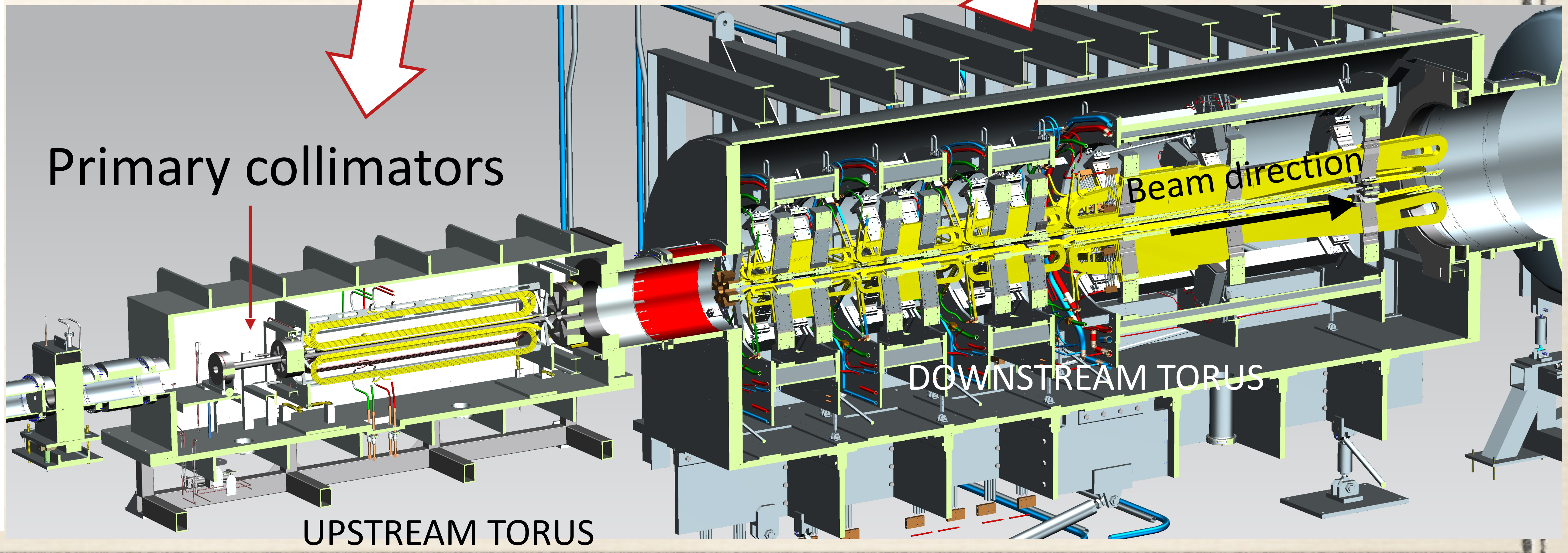




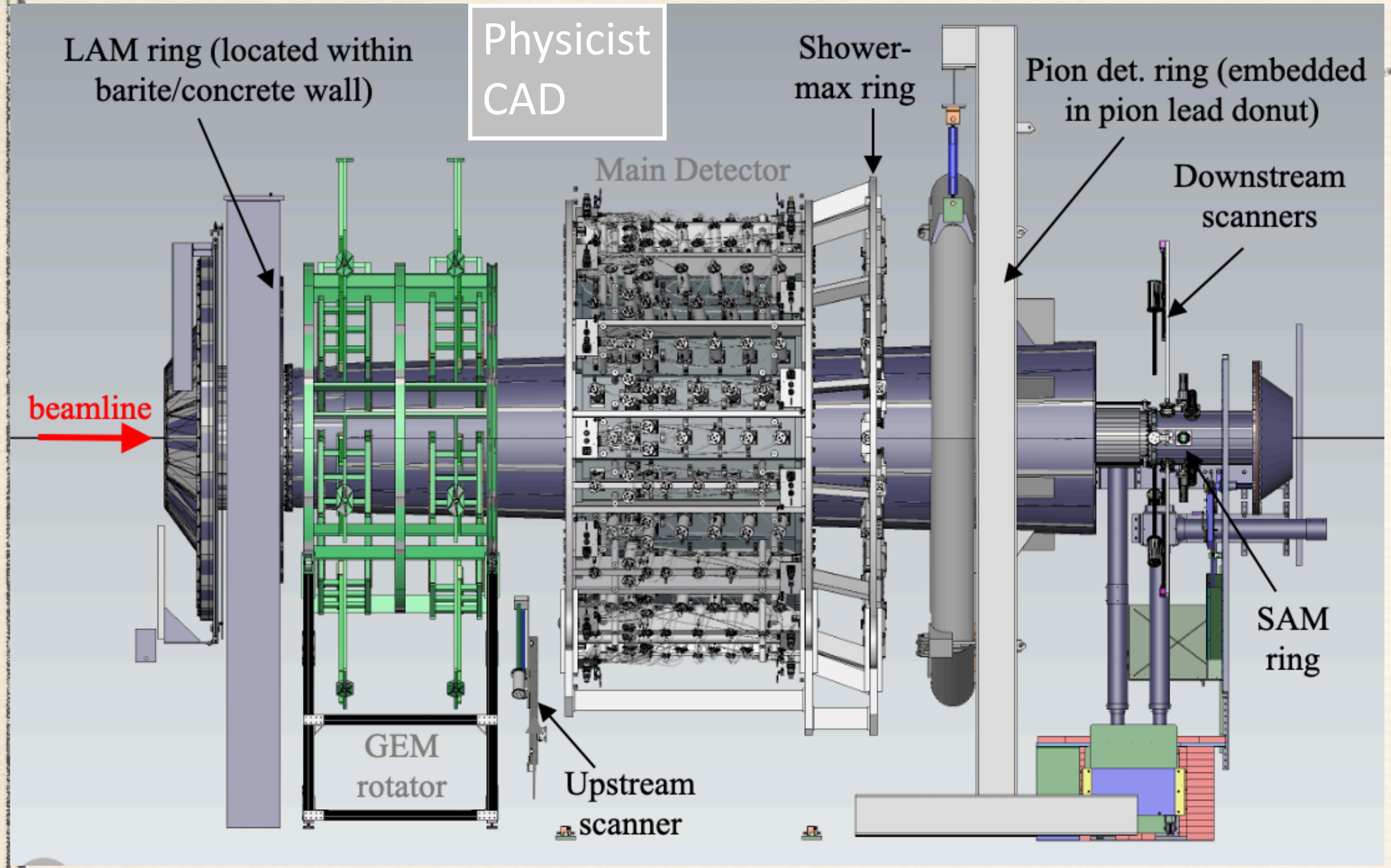




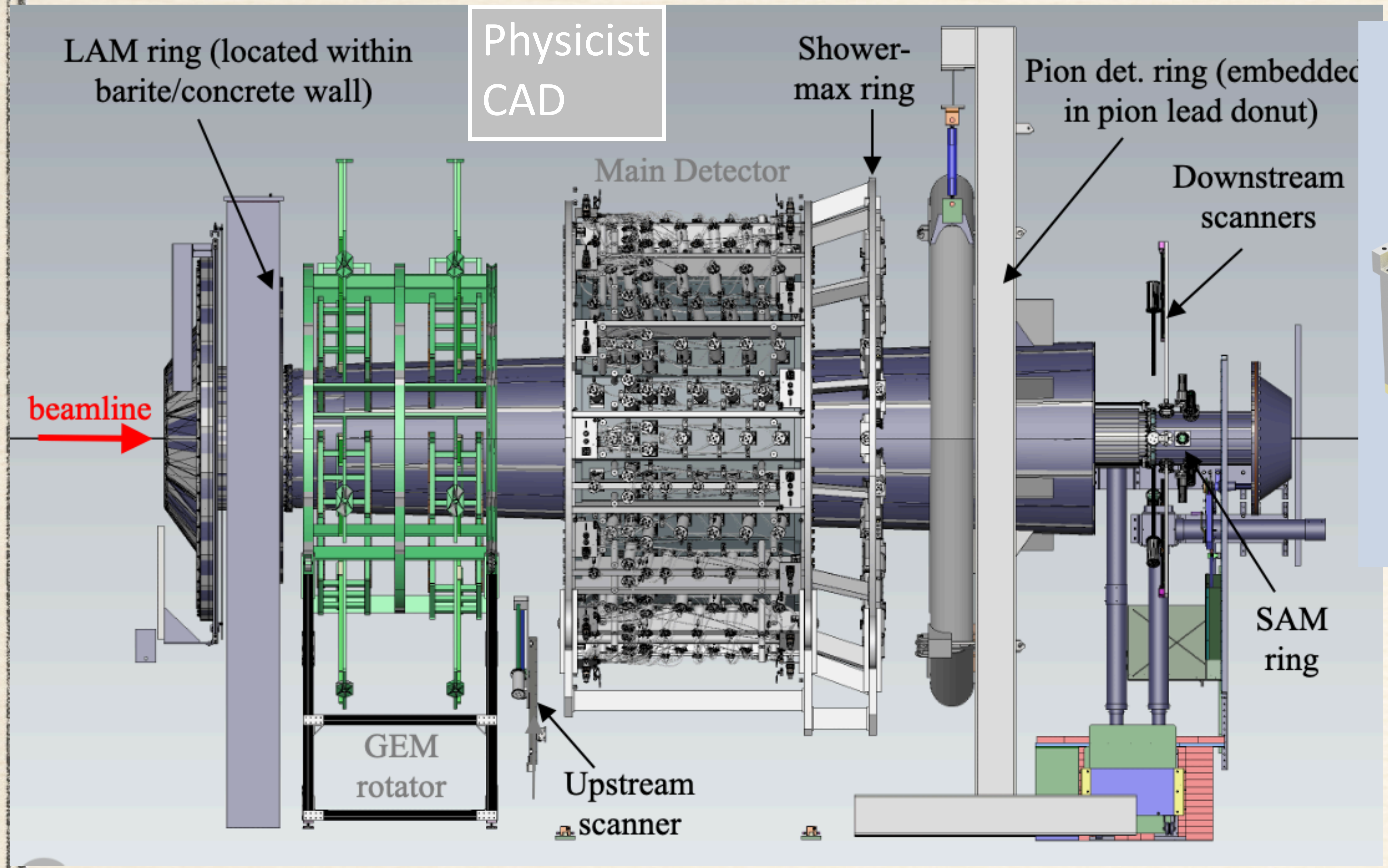


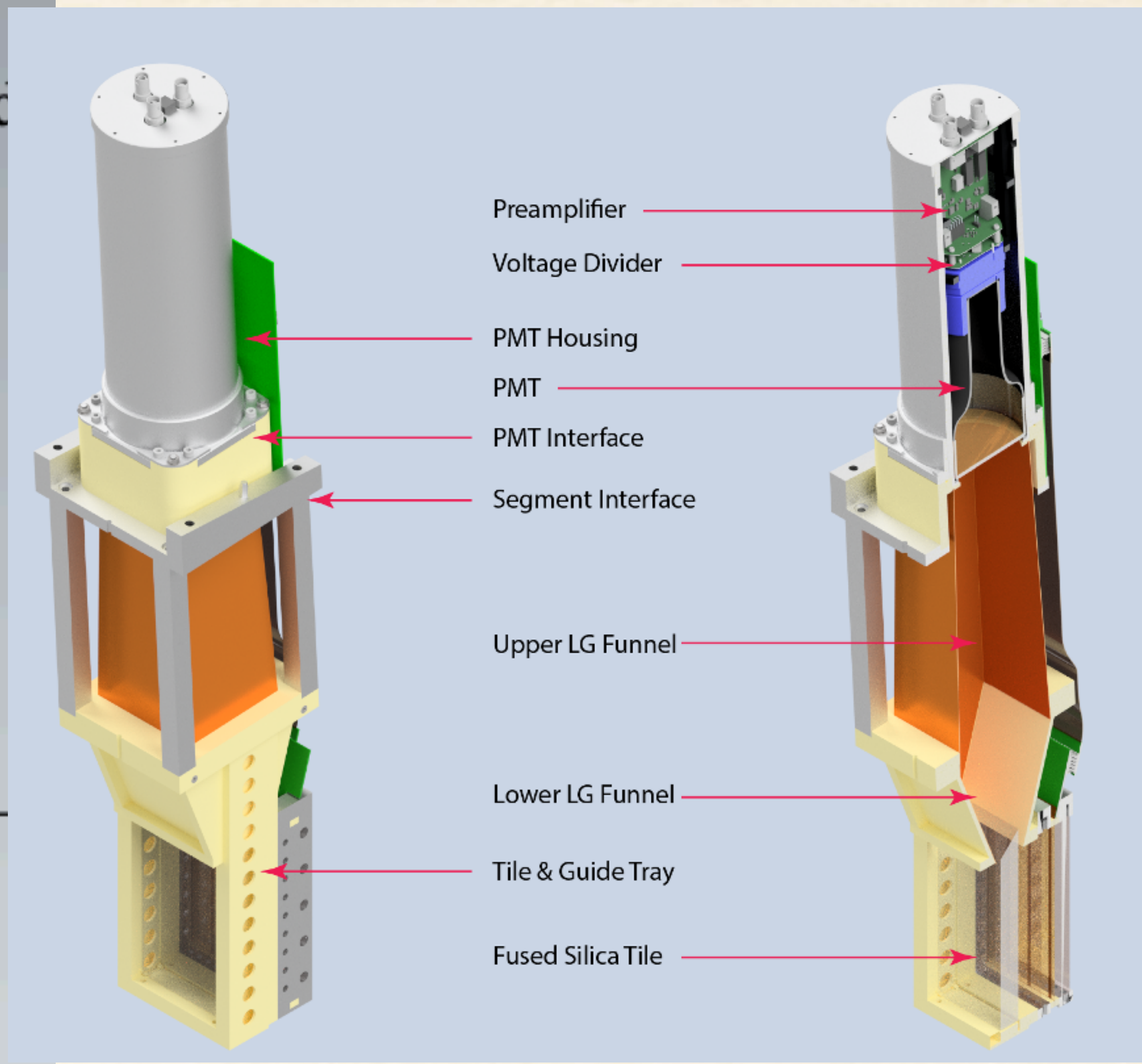


MOLLER Detectors



MOLLER Detectors

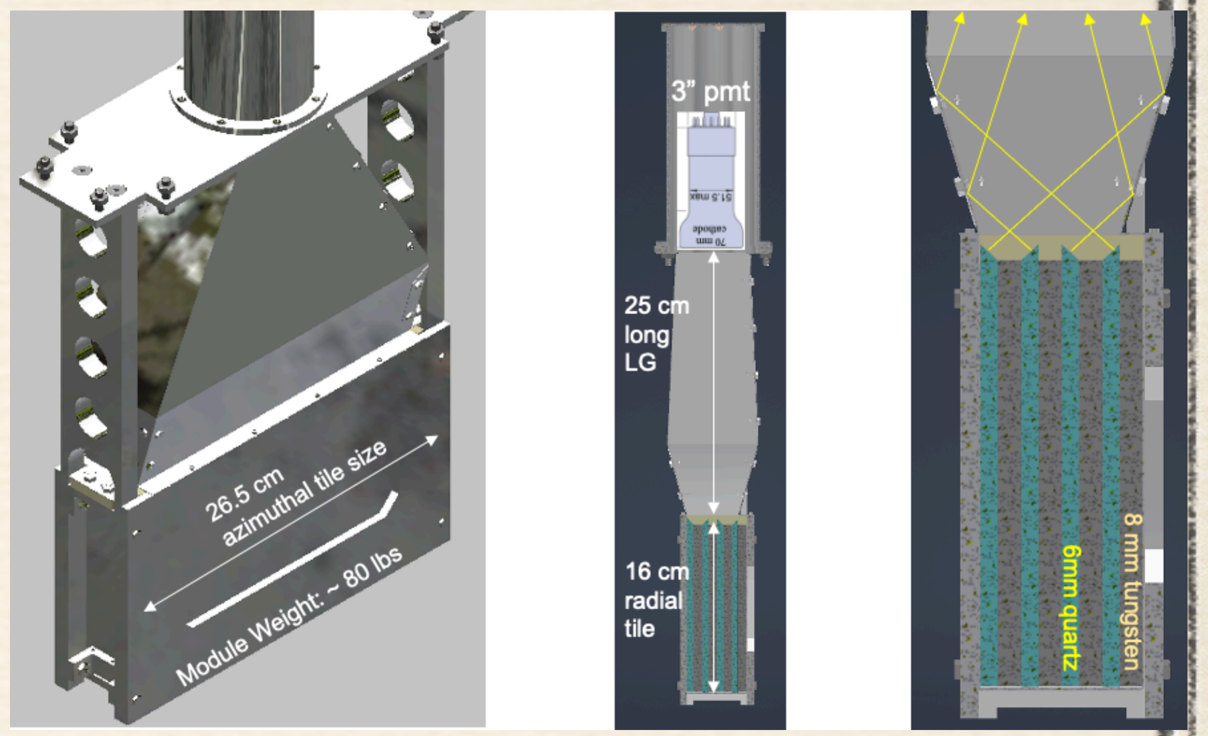




Requirement for Ring 5:

Detector resolution < 25%

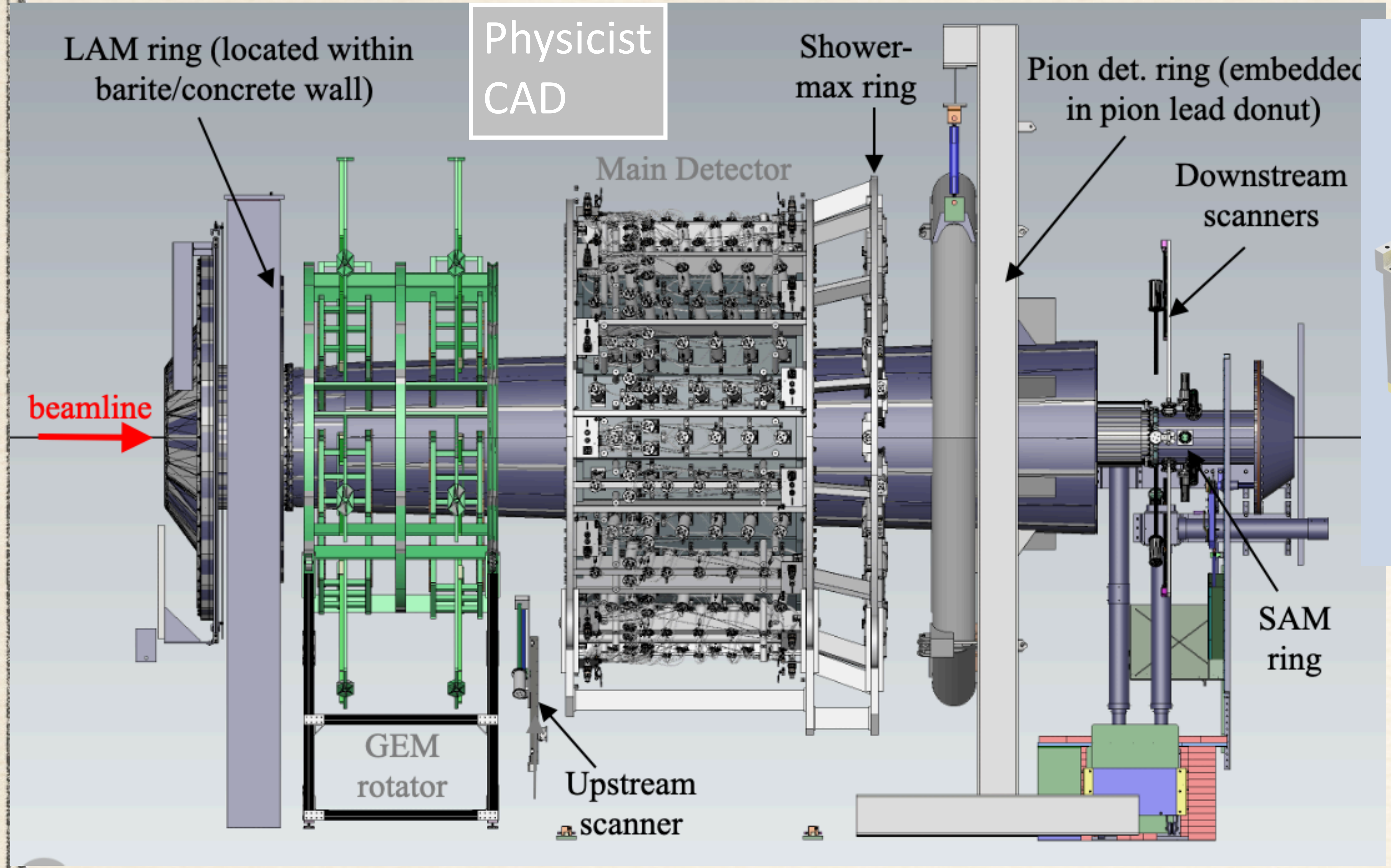
excess noise < 4%

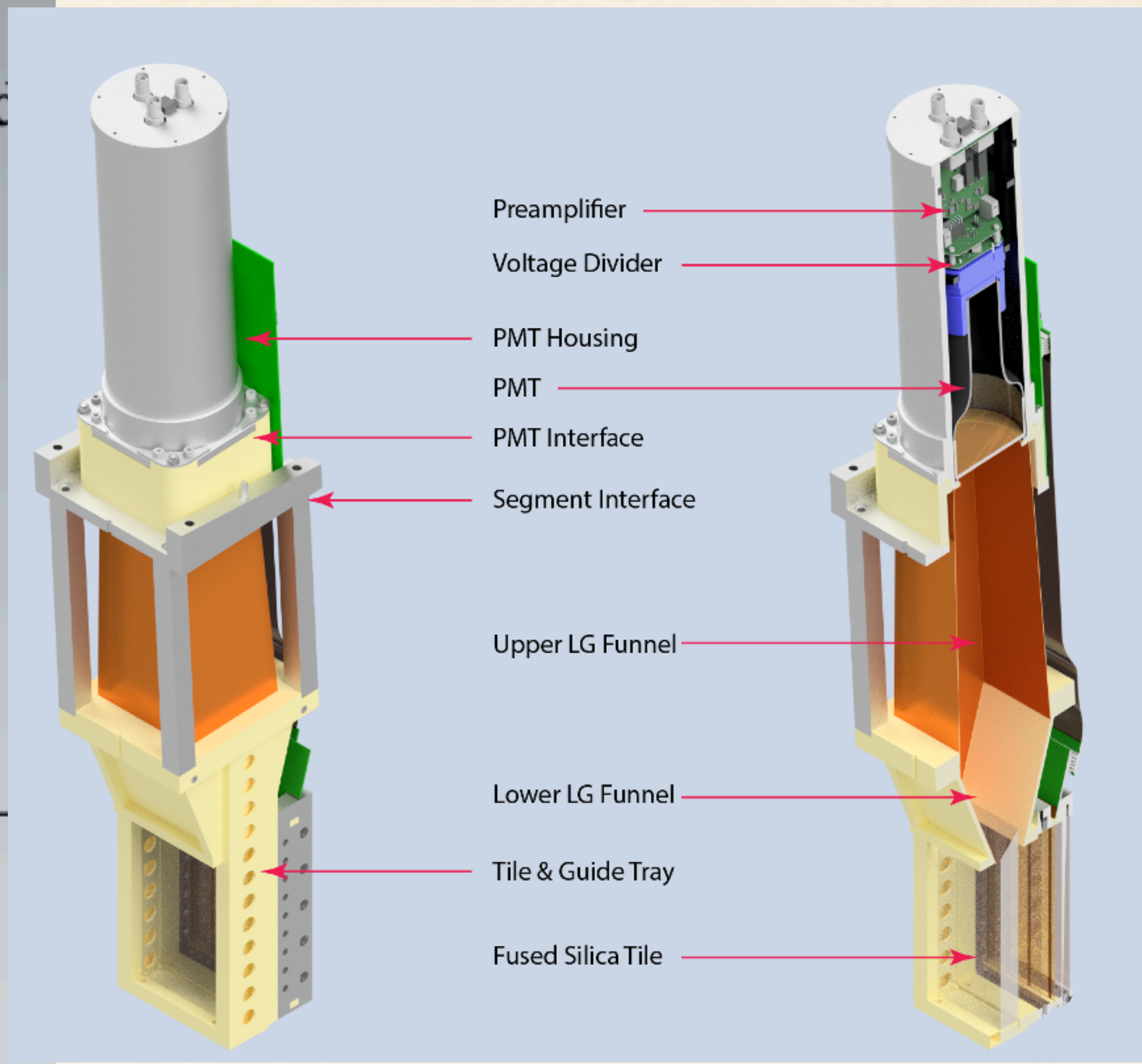


Integrating (current mode) detectors:

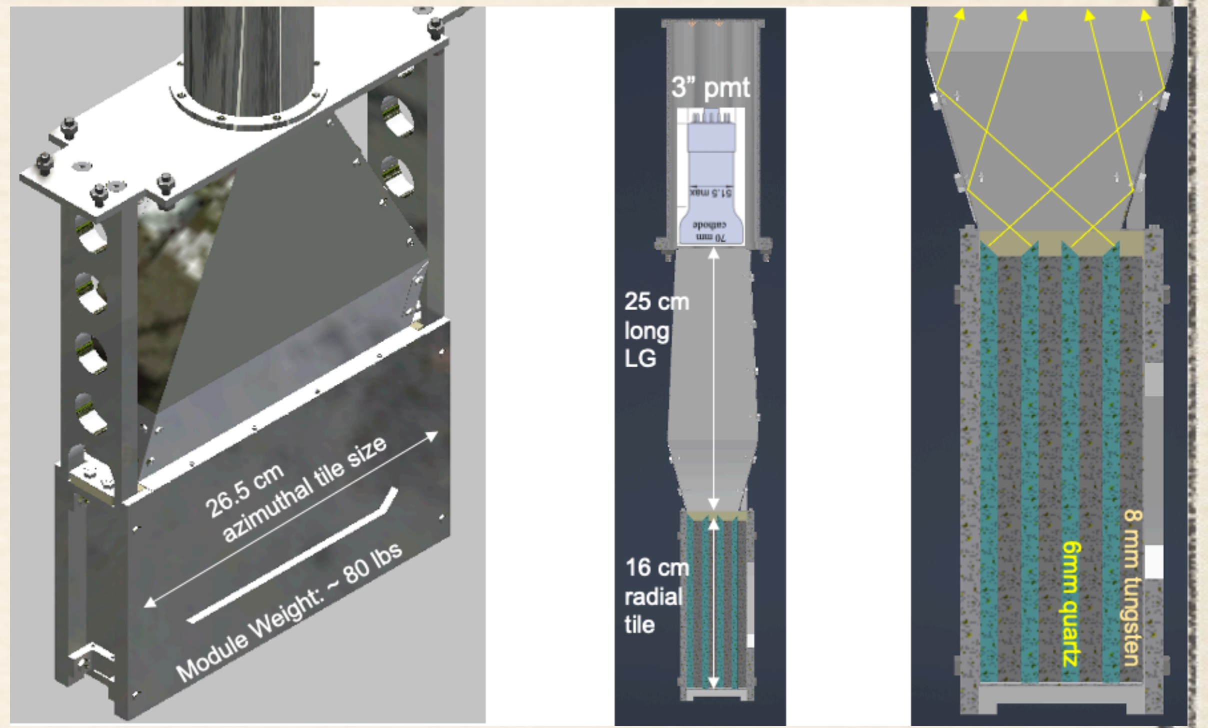
asymmetry measurements of both signal and background, and beam and target monitoring

MOLLER Detectors





Requirement for Ring 5:
Detector resolution < 25%
excess noise < 4%

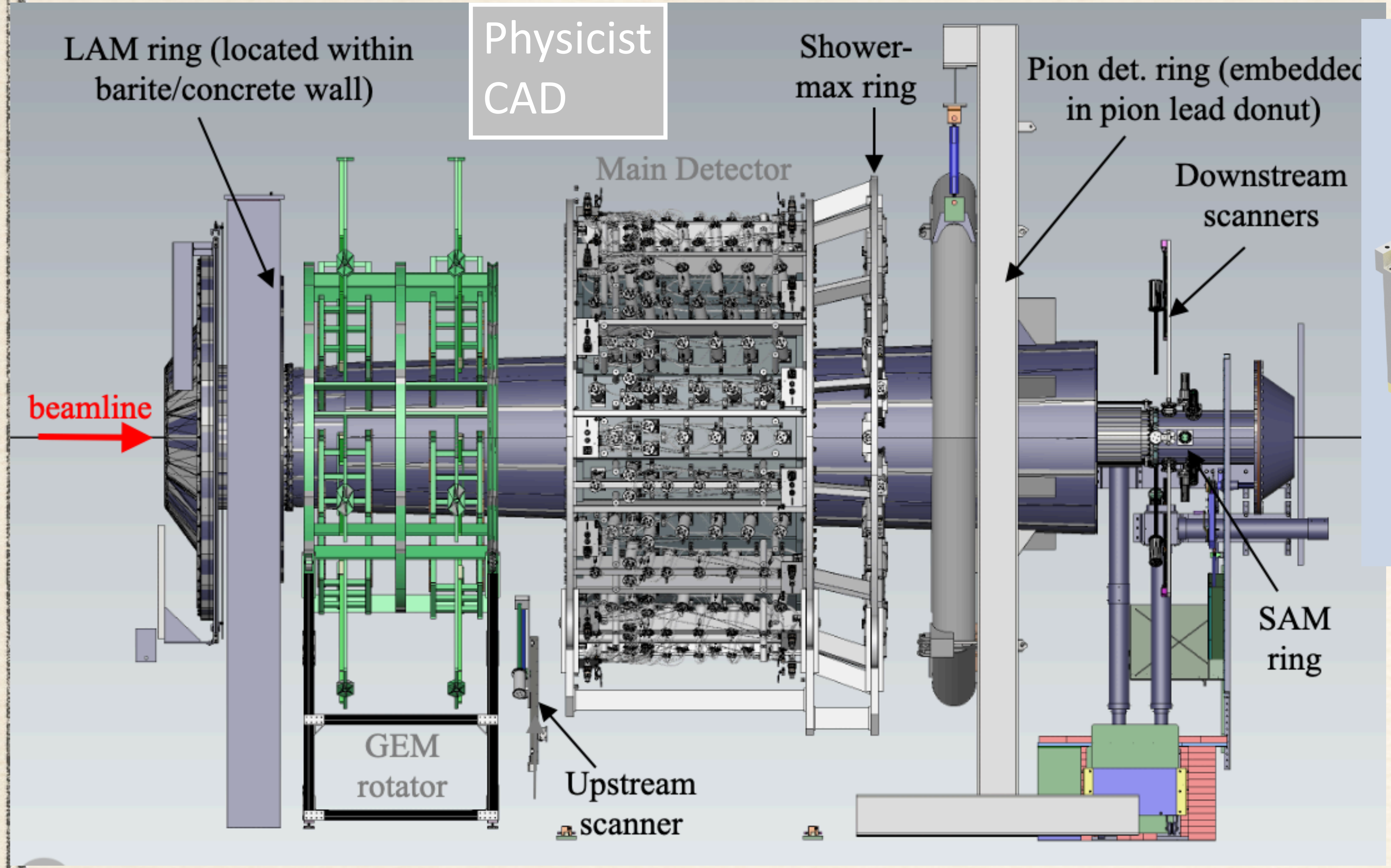


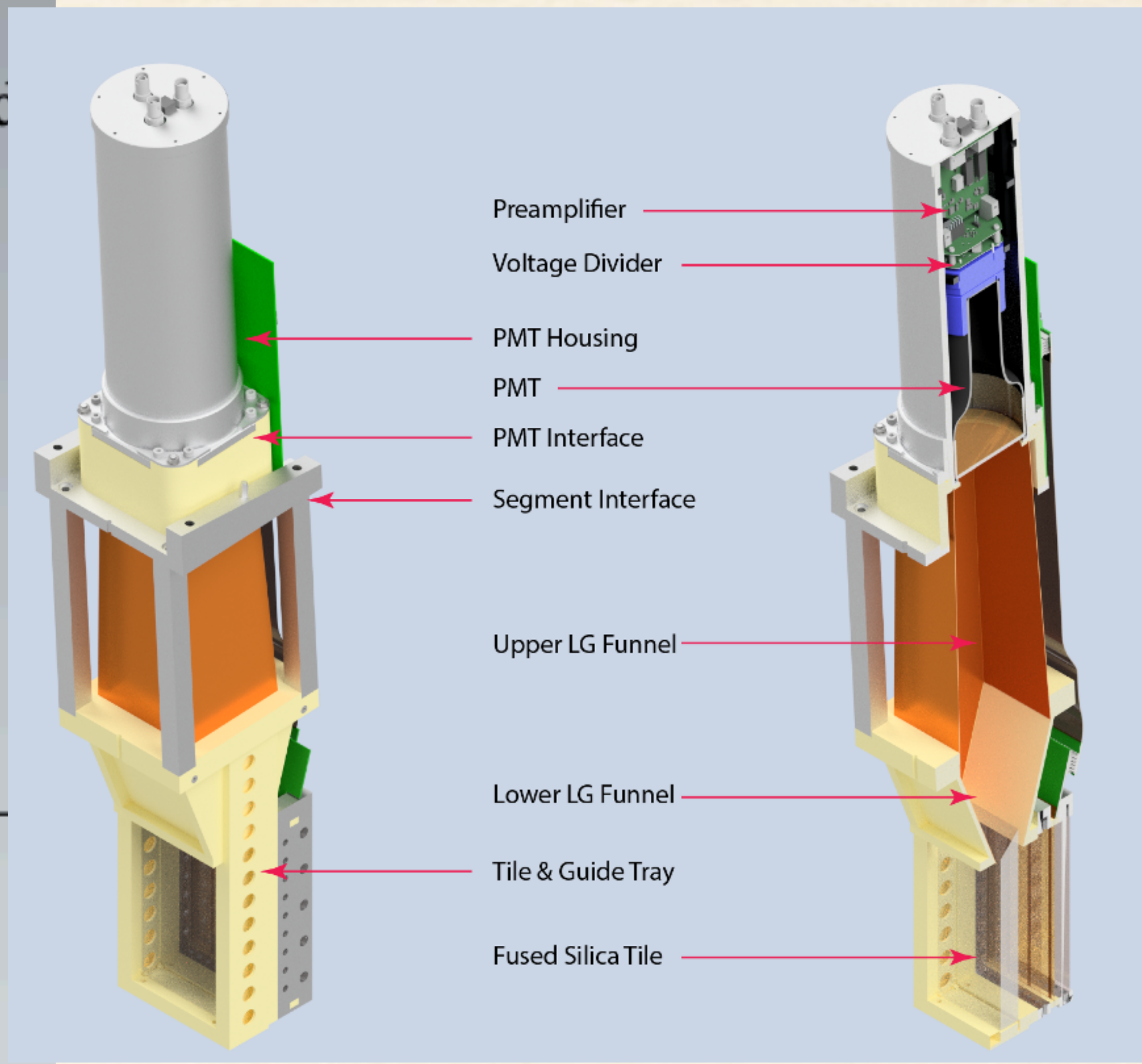
Integrating (current mode) detectors:
asymmetry measurements of both signal and background, and beam and target monitoring

Tracking (counting mode) detectors:
spectrometer calibration, electron scattering angle distribution, and background measurements

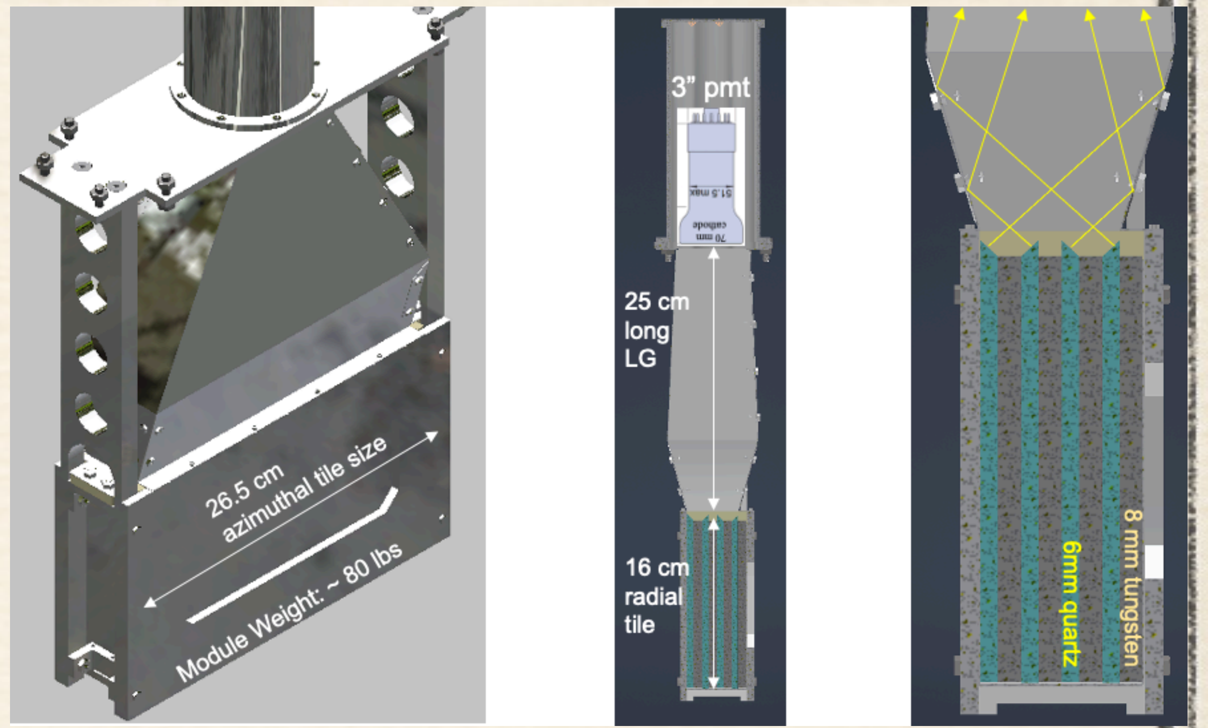
- Gas electron multipliers (GEM) detectors
- "Pion" acrylic Cherenkov detectors

MOLLER Detectors





Requirement for Ring 5:
Detector resolution < 25%
excess noise < 4%



Integrating (current mode) detectors:
asymmetry measurements of both signal and background, and beam and target monitoring

Tracking (counting mode) detectors:
spectrometer calibration, electron scattering angle distribution, and background measurements

- Gas electron multipliers (GEM) detectors
- “Pion” acrylic Cherenkov detectors

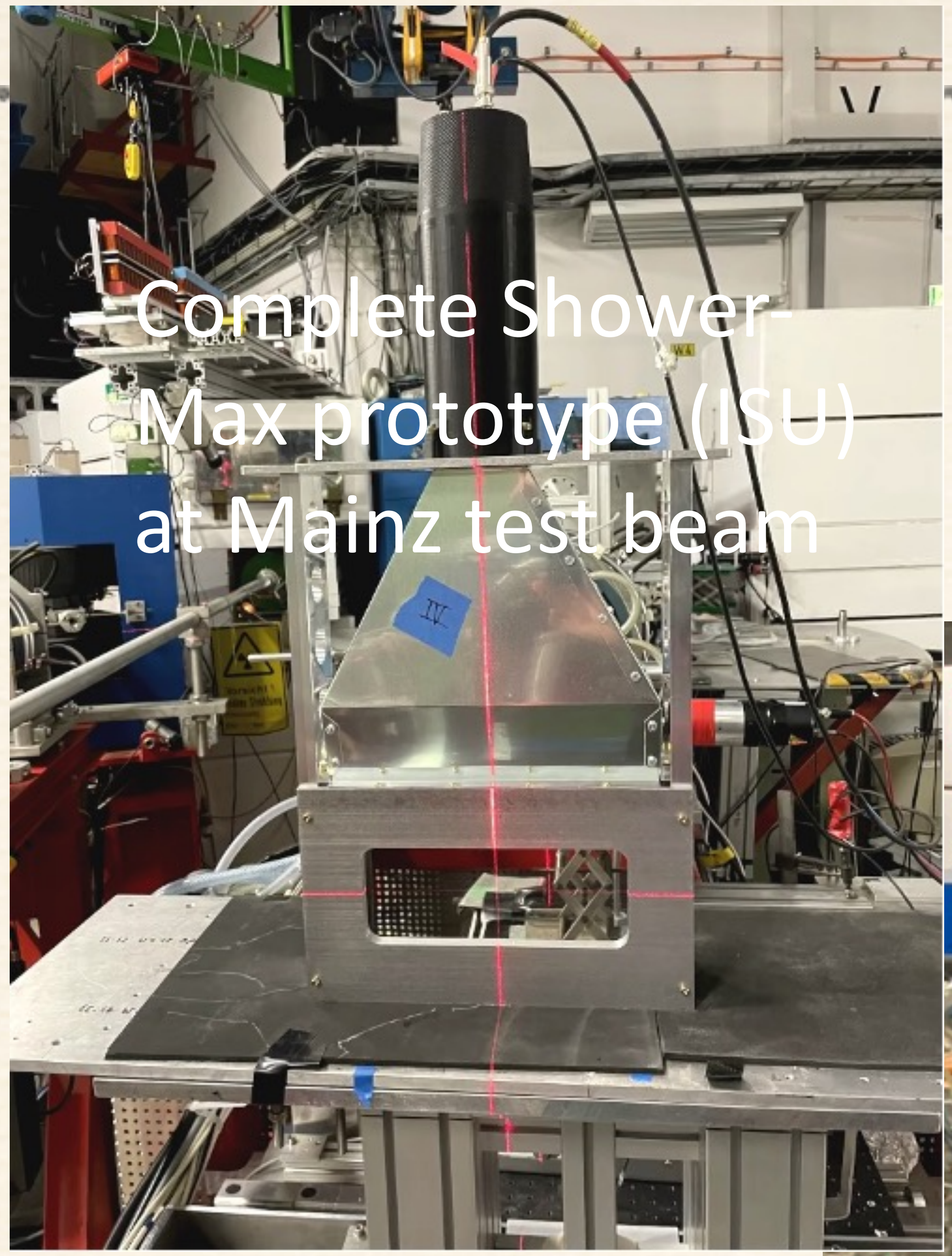
Readout Electronics:

- Integration mode DAQ & trigger
  - *Collect & analyaize100% of the helicity windows*
- Counting mode DAQ & trigger
  - *input rates between 10~kHz and 300~kHz*

P2 and MOLLER Prototyping

Prototype Frame for DS Magnet

Set of 4 downstream magnet coils fabricated; tests validate design/ fabrication process



Complete Shower Max prototype (ISU) at Mainz test beam

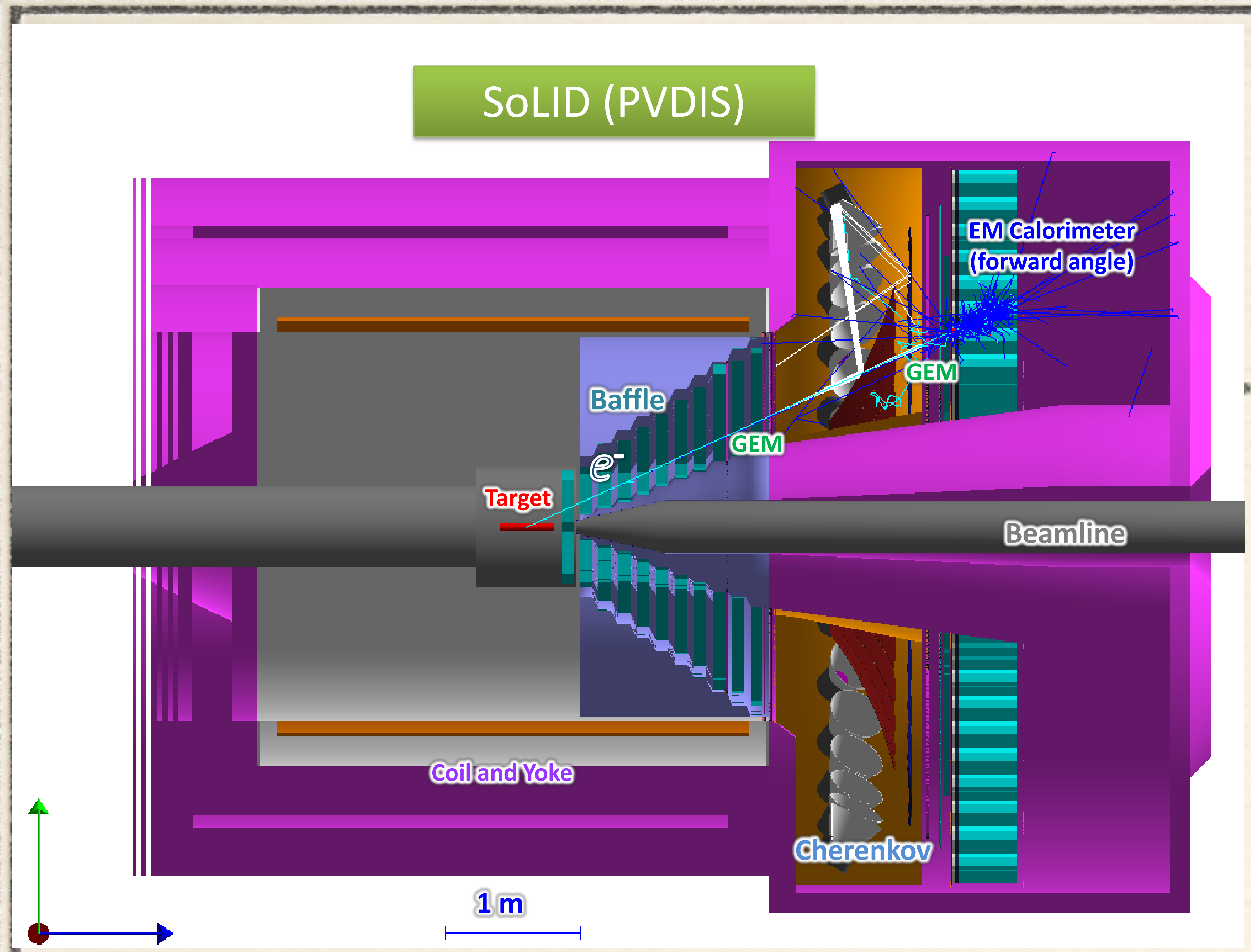
Full PMT/Base/ Preamplifier and container (Manitoba)

Main detector technology: fused silica, PMT, readout electronics the same for P2 and MOLLER: fully tested in both counting and integrate mode at full scattering rate

September 2023: Full MOLLER segment with 8 detector modules tested in MAMI test beam

MOLLER design and prototyping has greatly benefited from the availability of MAMI test beam time

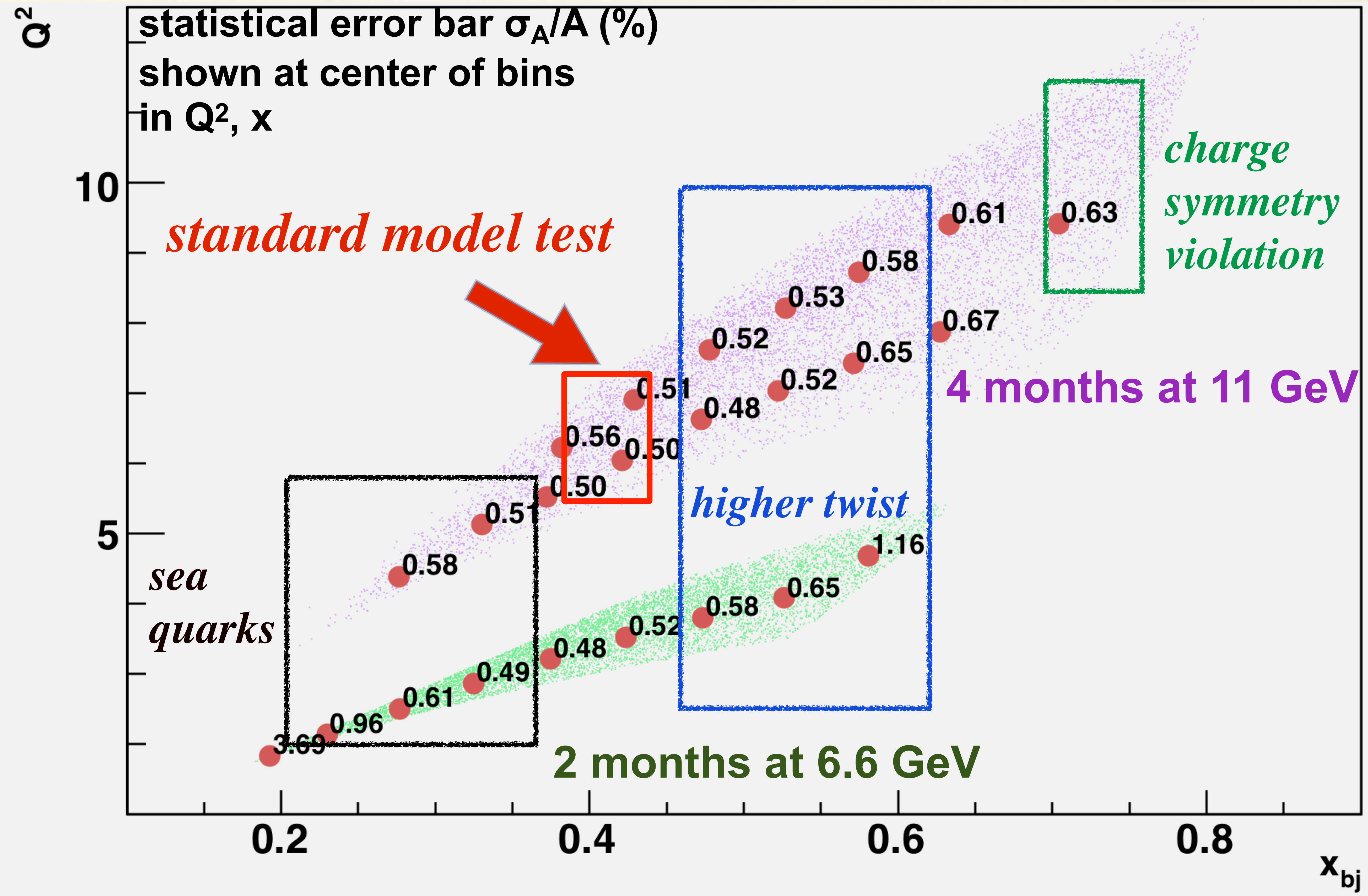
A very fruitful collaboration between P2 and MOLLER has resulted in a fully tested concept for very challenging detector designs



SOLID at Jlab

electron-deuteron parity-violating deep inelastic scattering

Strategy: sub-1% precision over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**



Requirements

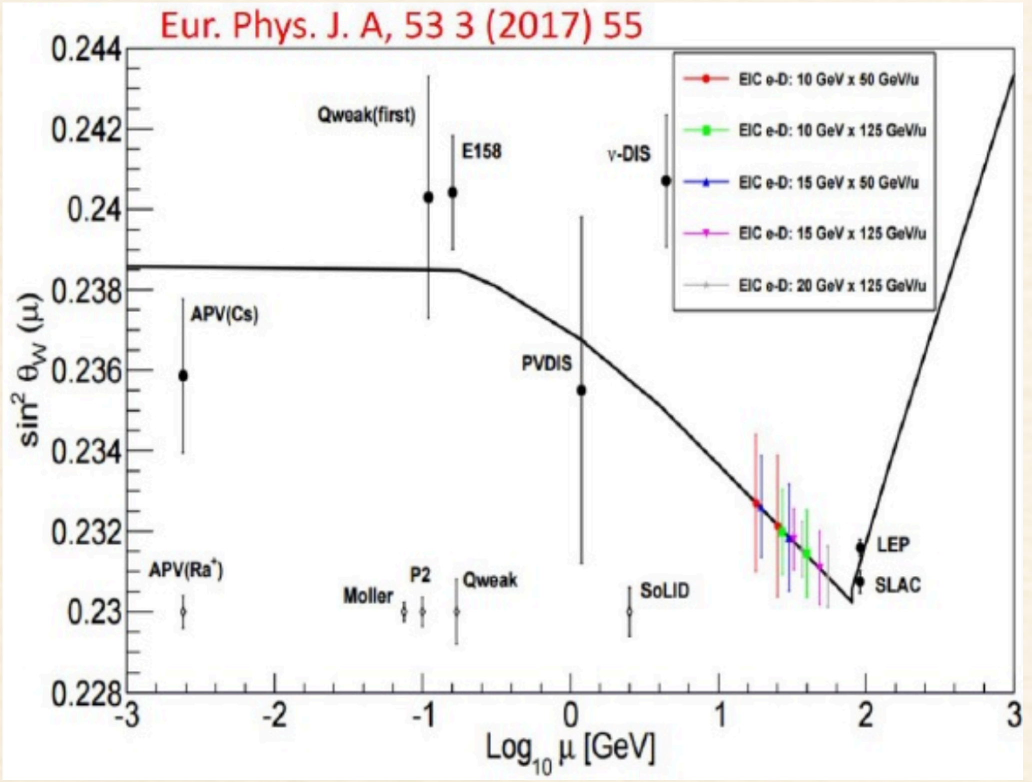
- *High Luminosity with E > 10 GeV*
- *Large scattering angles (for high x & y)*
- *Better than 1% errors for small bins*
- *x-range 0.25-0.75*
- *W^2 > 4 GeV^2*
- *Q^2 range a factor of 2 for each x*
  - (Except at very high x)
- *Moderate running times*

Parity Violation at the EIC

e^- → ← $^1H, ^2H, ^3He$

***polarized* electron, *unpolarized* hadron**

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$



***unpolarized* electron, *polarized* hadron**

$$A_{TPV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V \frac{g_5^{\gamma Z}}{F_1^{\gamma}} + g_A f(y)\frac{g_1^{\gamma Z}}{F_1^{\gamma}}\right]$$

$$\frac{1}{2m_N}W_{\mu\nu}^i = -\frac{g_{\mu\nu}}{m_N}F_1^i + \frac{p_\mu p_\nu}{m_N(p\cdot q)}F_2^i + i\frac{\epsilon_{\mu\nu\alpha\beta}}{2(p\cdot q)}\left[\frac{p^\alpha q^\beta}{m_N}F_3^i + 2q^\alpha S^\beta g_1^i - 4xp^\alpha S^\beta g_2^i\right] - \frac{p_\mu S_\nu + S_\mu p_\nu}{2(p\cdot q)}g_3^i + \frac{S\cdot q}{(p\cdot q)^2}p_\mu p_\nu g_4^i + \frac{S\cdot q}{p\cdot q}g_{\mu\nu}g_5^i$$

Ji, Vogelsang, Blümlein, ...
Anselmino, Efremov & Leader, Phys. Rep. **261** (1995)

proton	**deuteron**
$F_1^{\gamma Z} \propto u + d + s$	$F_1^{\gamma Z} \propto u + d + 2s$
$F_3^{\gamma Z} \propto 2u_v + d_v$	$F_3^{\gamma Z} \propto u_v + d_v$
$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$	$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$
$g_5^{\gamma Z} \propto 2\Delta u_v + \Delta d_v$	$g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v$

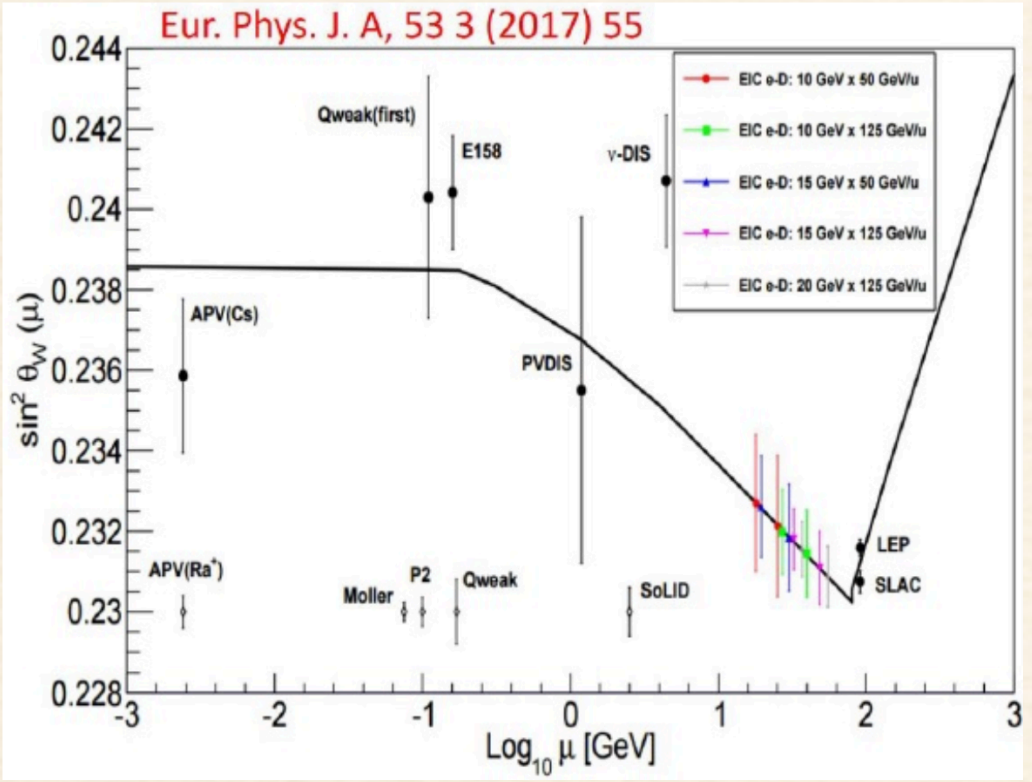
High luminosity: novel nucleon structure functions from PV observables

Parity Violation at the EIC

e⁻ → ← $^1H, ^2H, ^3He$

***polarized** electron, **unpolarized** hadron*

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$



***unpolarized** electron, **polarized** hadron*

$$A_{TPV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V \frac{g_5^{\gamma Z}}{F_1^{\gamma}} + g_A f(y)\frac{g_1^{\gamma Z}}{F_1^{\gamma}}\right]$$

$$\frac{1}{2m_N}W^i_{\mu\nu} = -\frac{g_{\mu\nu}}{m_N}F_1^i + \frac{p_\mu p_\nu}{m_N(p\cdot q)}F_2^i + i\frac{\epsilon_{\mu\nu\alpha\beta}}{2(p\cdot q)}\left[\frac{p^\alpha q^\beta}{m_N}F_3^i + 2q^\alpha S^\beta g_1^i - 4xp^\alpha S^\beta g_2^i\right] - \frac{p_\mu S_\nu + S_\mu p_\nu}{2(p\cdot q)}g_3^i + \frac{S\cdot q}{(p\cdot q)^2}p_\mu p_\nu g_4^i + \frac{S\cdot q}{p\cdot q}g_{\mu\nu}g_5^i$$

Ji, Vogelsang, Blümlein, ...
Anselmino, Efremov & Leader, Phys. Rep. **261** (1995)

proton	**deuteron**
$F_1^{\gamma Z} \propto u + d + s$	$F_1^{\gamma Z} \propto u + d + 2s$
$F_3^{\gamma Z} \propto 2u_v + d_v$	$F_3^{\gamma Z} \propto u_v + d_v$
$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$	$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$
$g_5^{\gamma Z} \propto 2\Delta u_v + \Delta d_v$	$g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v$

- **First measurements of novel electroweak spin structure functions**
- **6-flavor separation of polarized quark pdfs using *just inclusive* measurements**
- **exploit both polarized proton and deuteron (or helium-3)**
- **weak mixing angle (averaging over ion polarization) at high Q^2**

Summary & Outlook

- ✦ **Parity-Violating Electron Scattering**
  - ★ Enabled unique studies of the weak force
  - ★ Technical progress has enabled unprecedented precision
  - ★ flagship experiments at electron accelerators
- ✦ **Fundamental Nuclear/Nucleon Physics**
  - ★ Neutron RMS radii of heavy nuclei (PREX, CREX, MREX)
  - ★ Precision and Novel Nucleon Structure (P2, SOLID, EIC)
- ✦ **Precision Electroweak Physics**
  - ★ Search for new dynamics at the TeV scale (P2, MOLLER, SOLID)
    - *complementary to colliders; would help interpret potential anomalies*
    - *precision measurement of the weak mixing angle*

All of the physics and projects discussed in this talk are articulated in the recently released 2023 US Long Range Plan for Nuclear Science

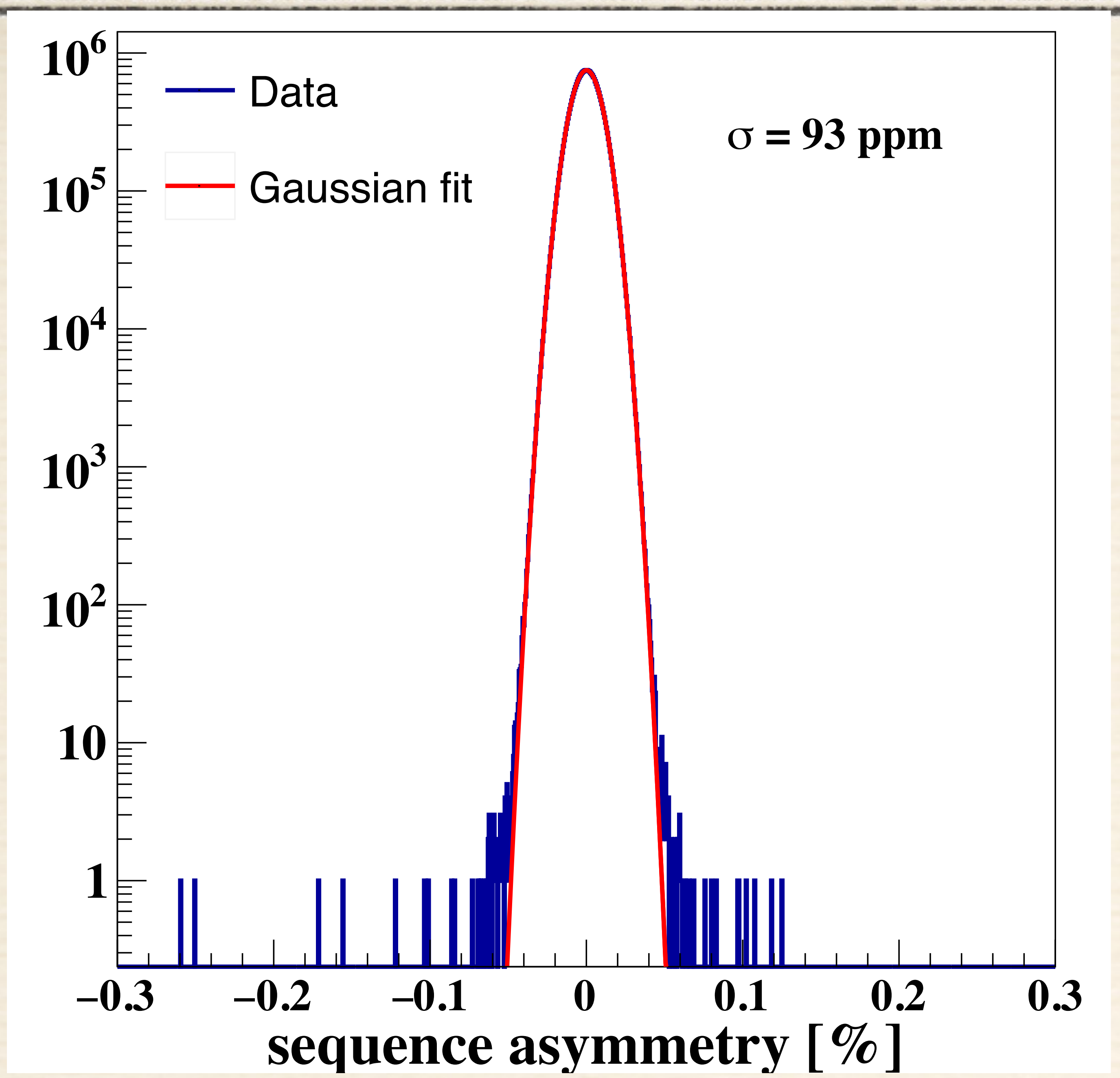
Summary & Outlook

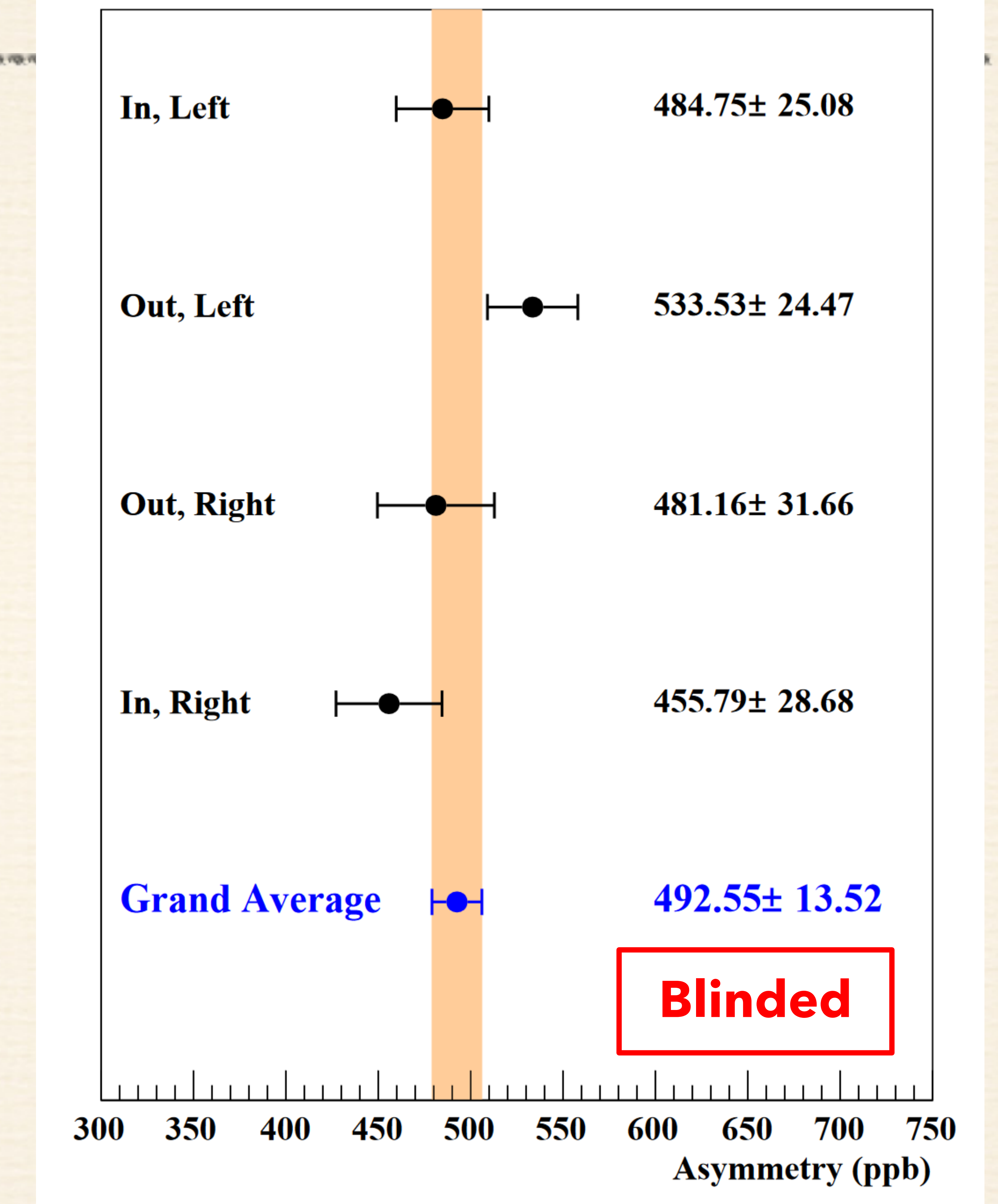
- **Parity-Violating Electron Scattering**
  - ★ Enabled unique studies of the weak force
  - ★ Technical progress has enabled unprecedented precision
  - ★ flagship experiments at electron accelerators
- **Fundamental Nuclear/Nucleon Physics**
  - ★ Neutron RMS radii of heavy nuclei (PREX, CREX, MREX)
  - ★ Precision and Novel Nucleon Structure (P2, SOLID, EIC)
- **Precision Electroweak Physics**
  - ★ Search for new dynamics at the TeV scale (P2, MOLLER, SOLID)
    - *complementary to colliders; would help interpret potential anomalies*
    - *precision measurement of the weak mixing angle*

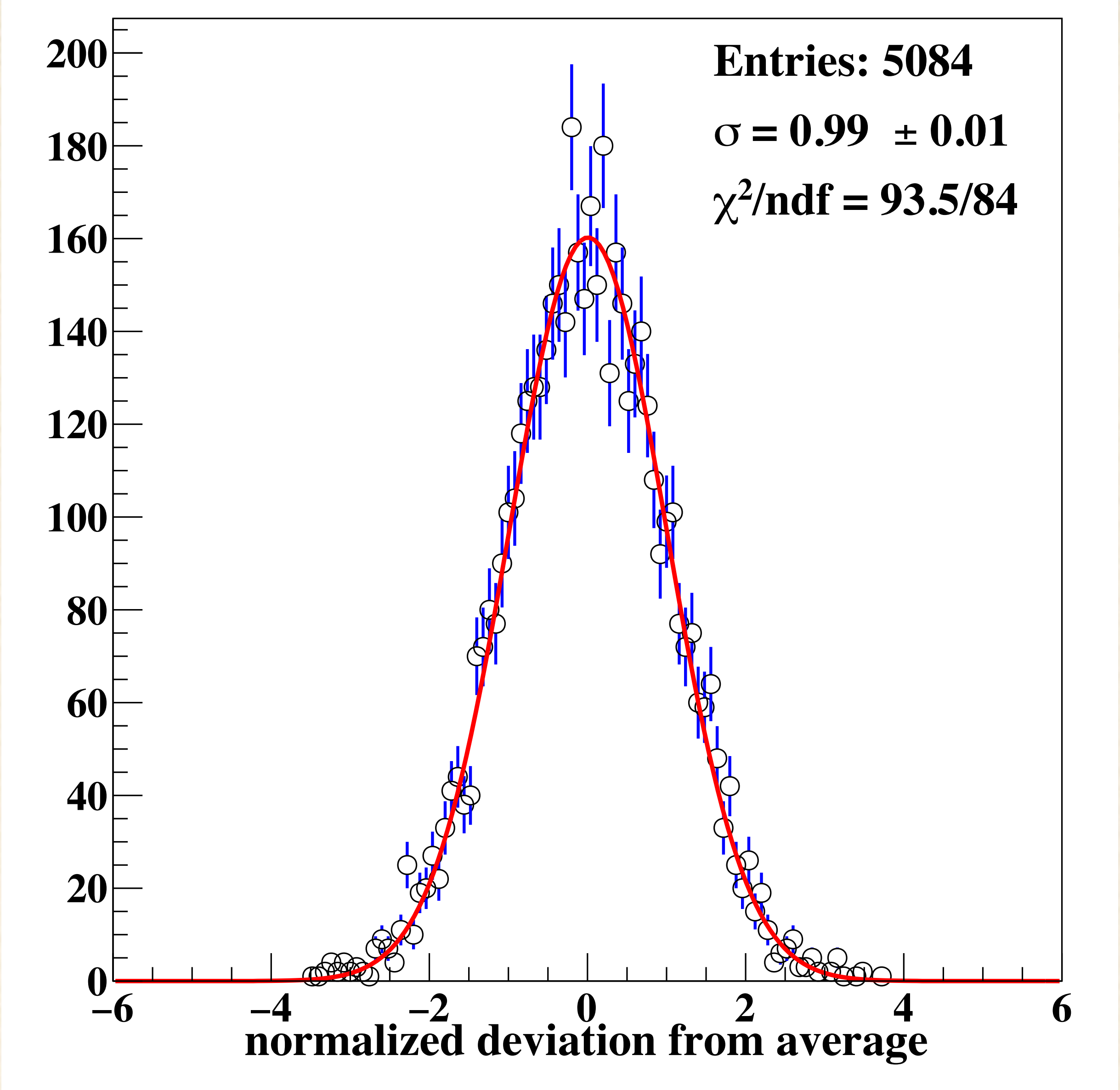
A remarkably productive research program that will continue to flourish over the next decade

PhysRevLett.126.172502

PREX Result





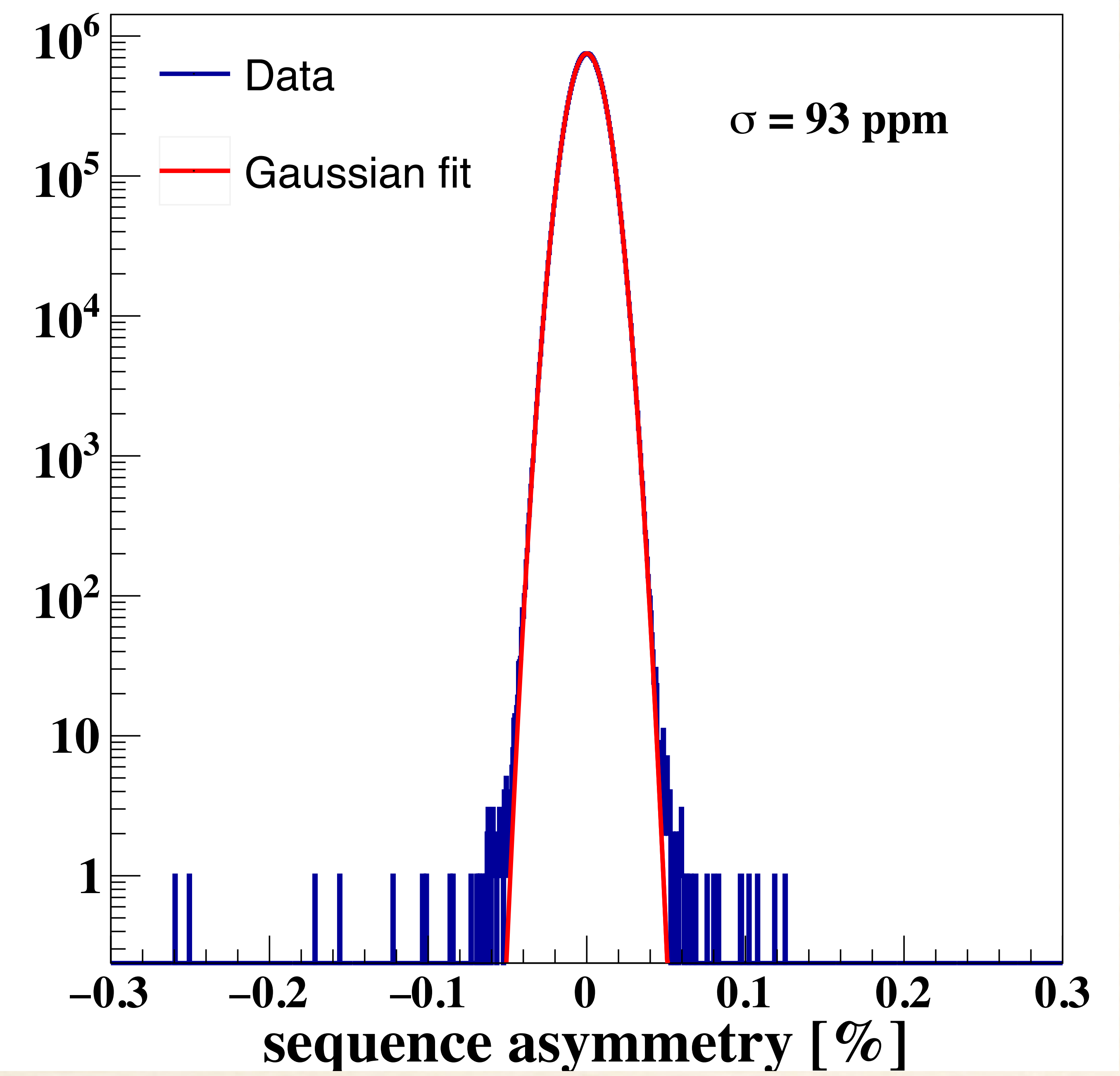


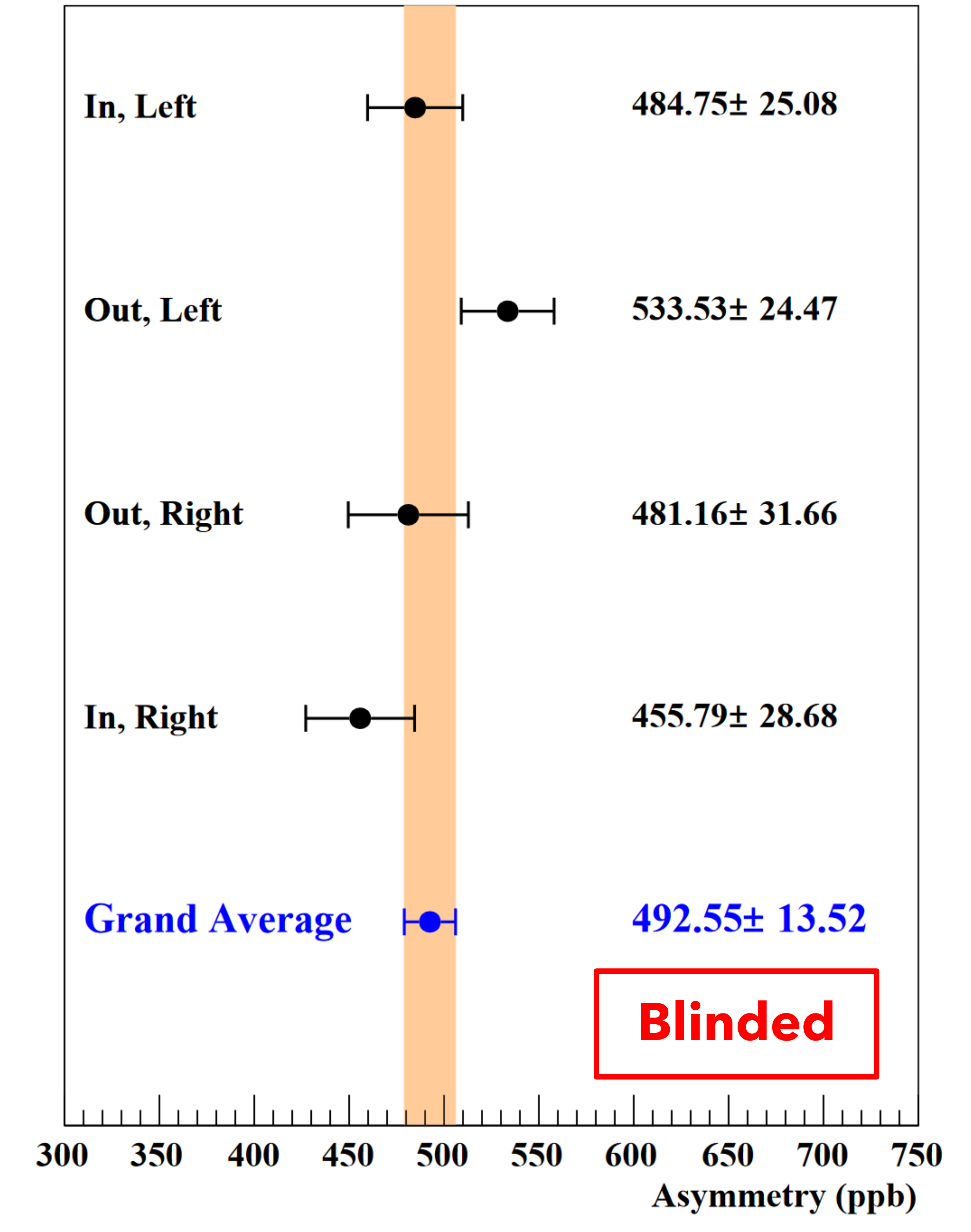
Unblinded A_{PV}:

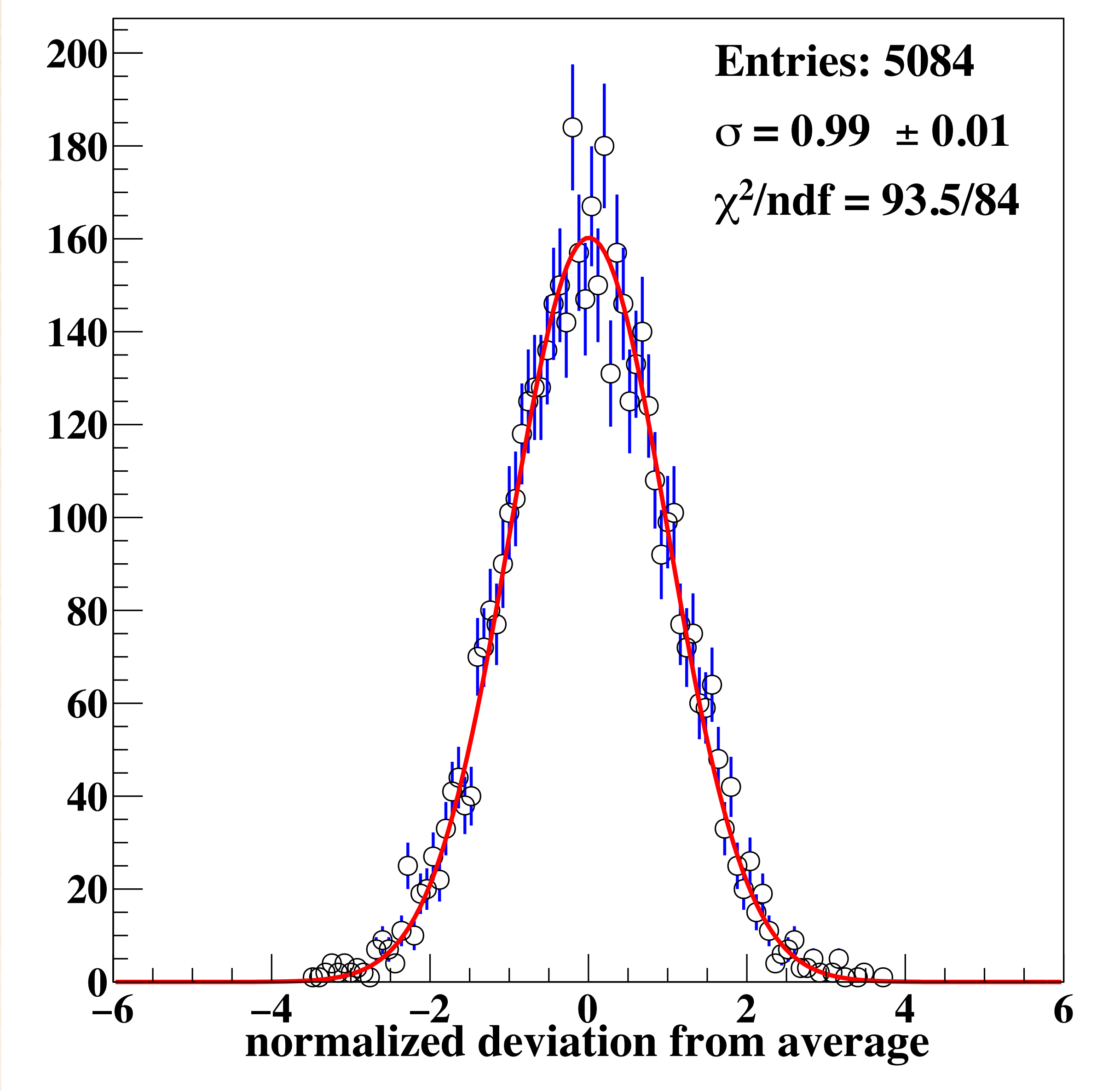
(550.0 ± 16.1)ppb

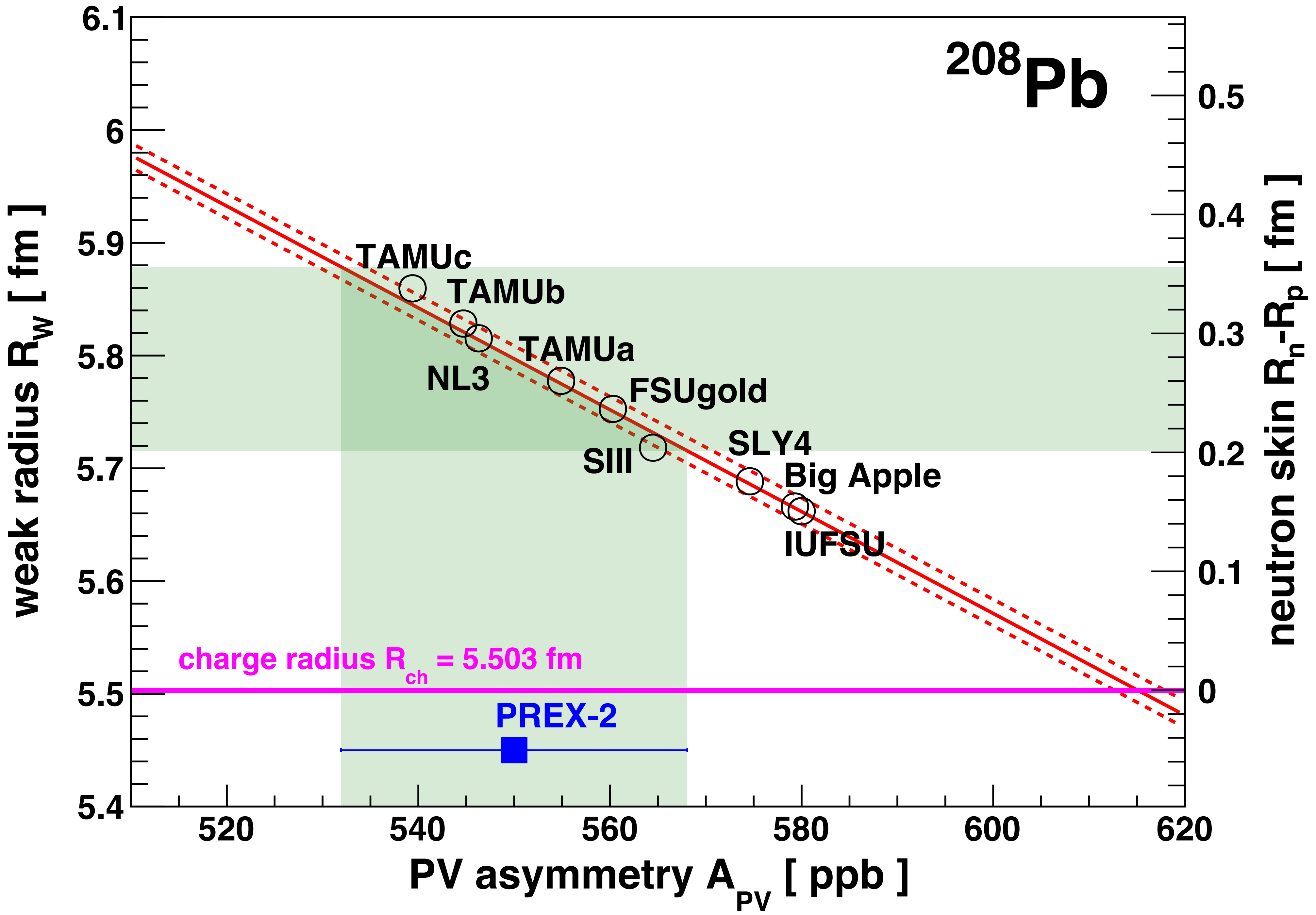
[PhysRevLett.126.172502](https://doi.org/10.1103/PhysRevLett.126.172502)

PREX Result







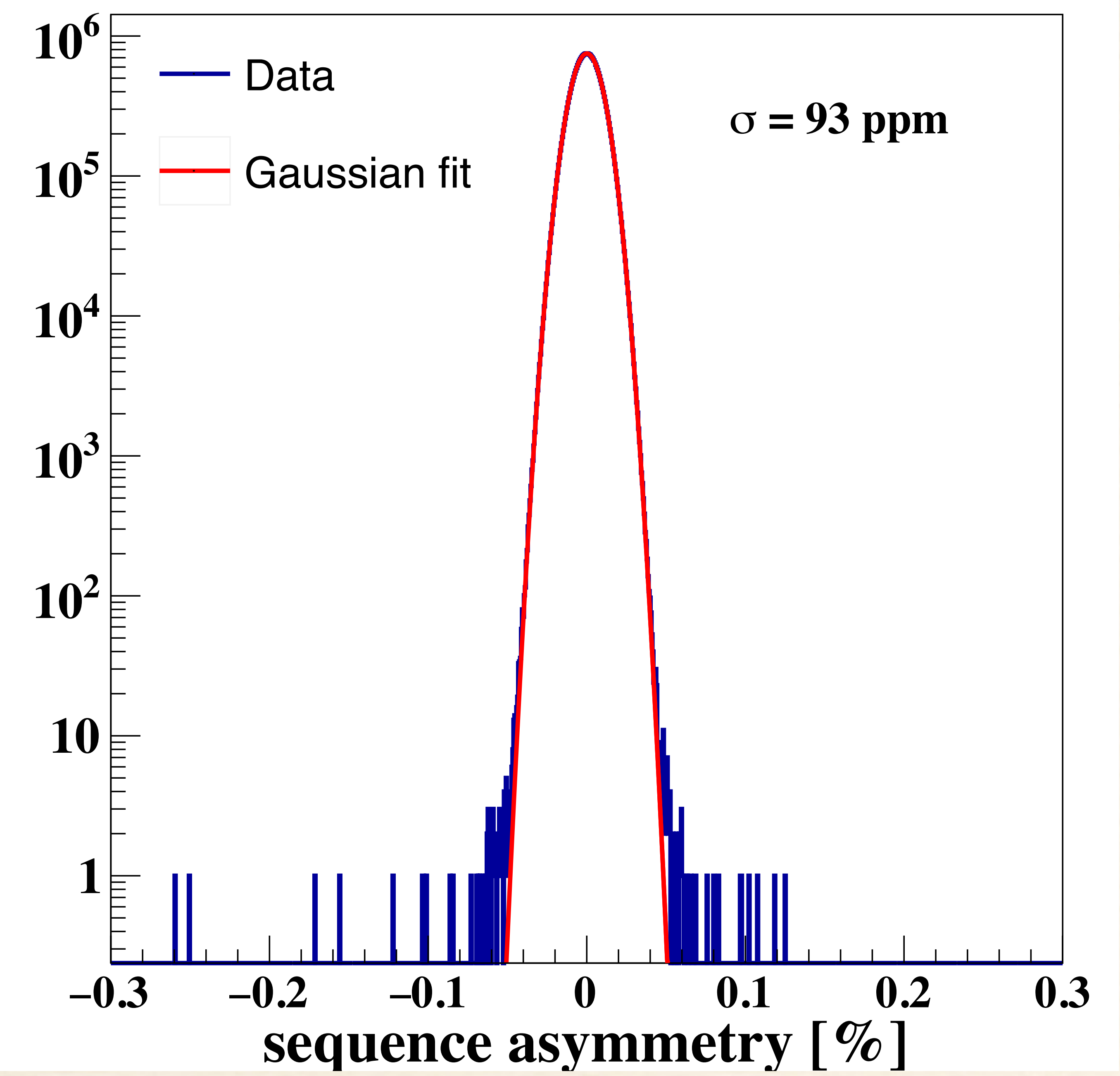


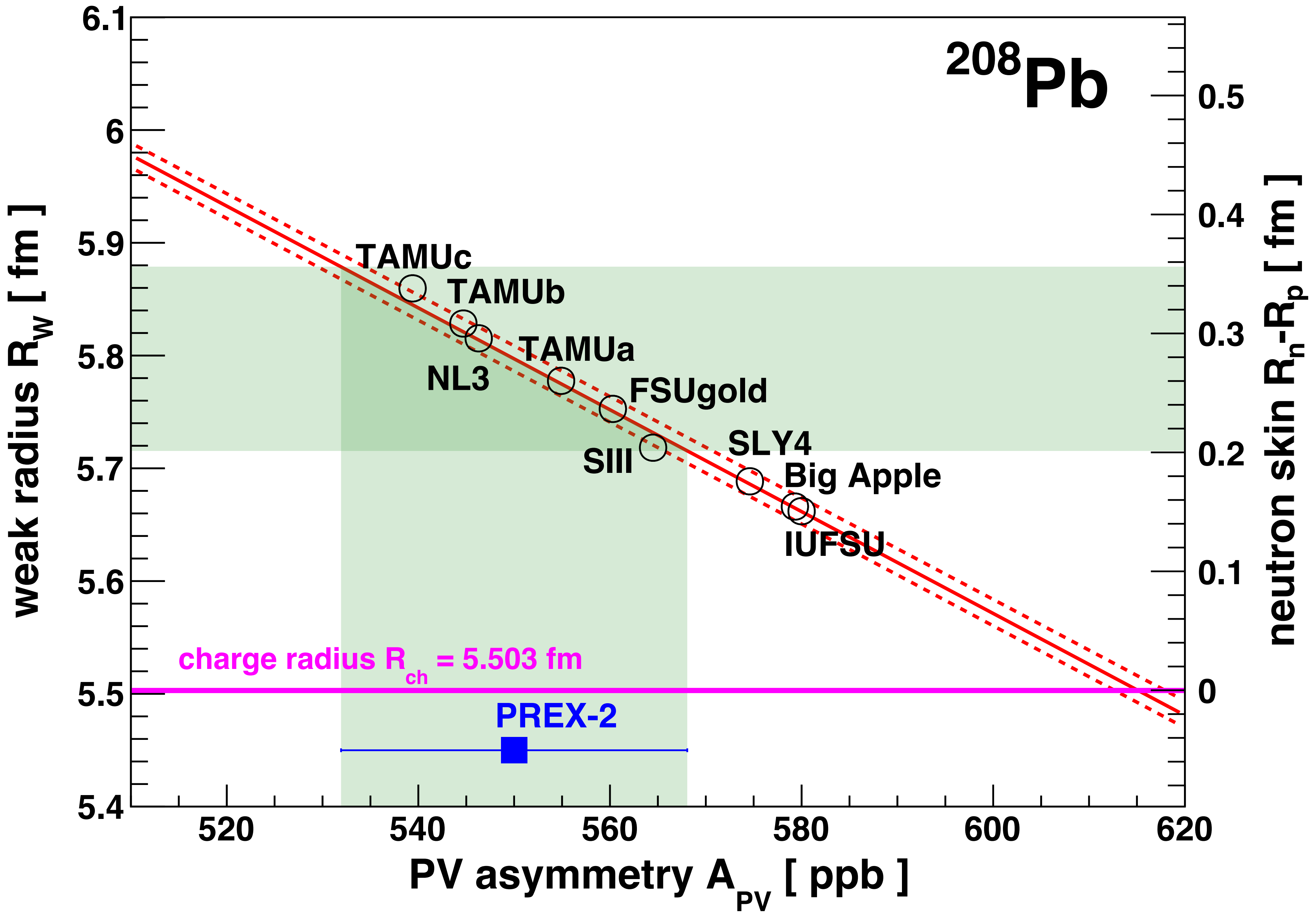
Unblinded A_{PV}:

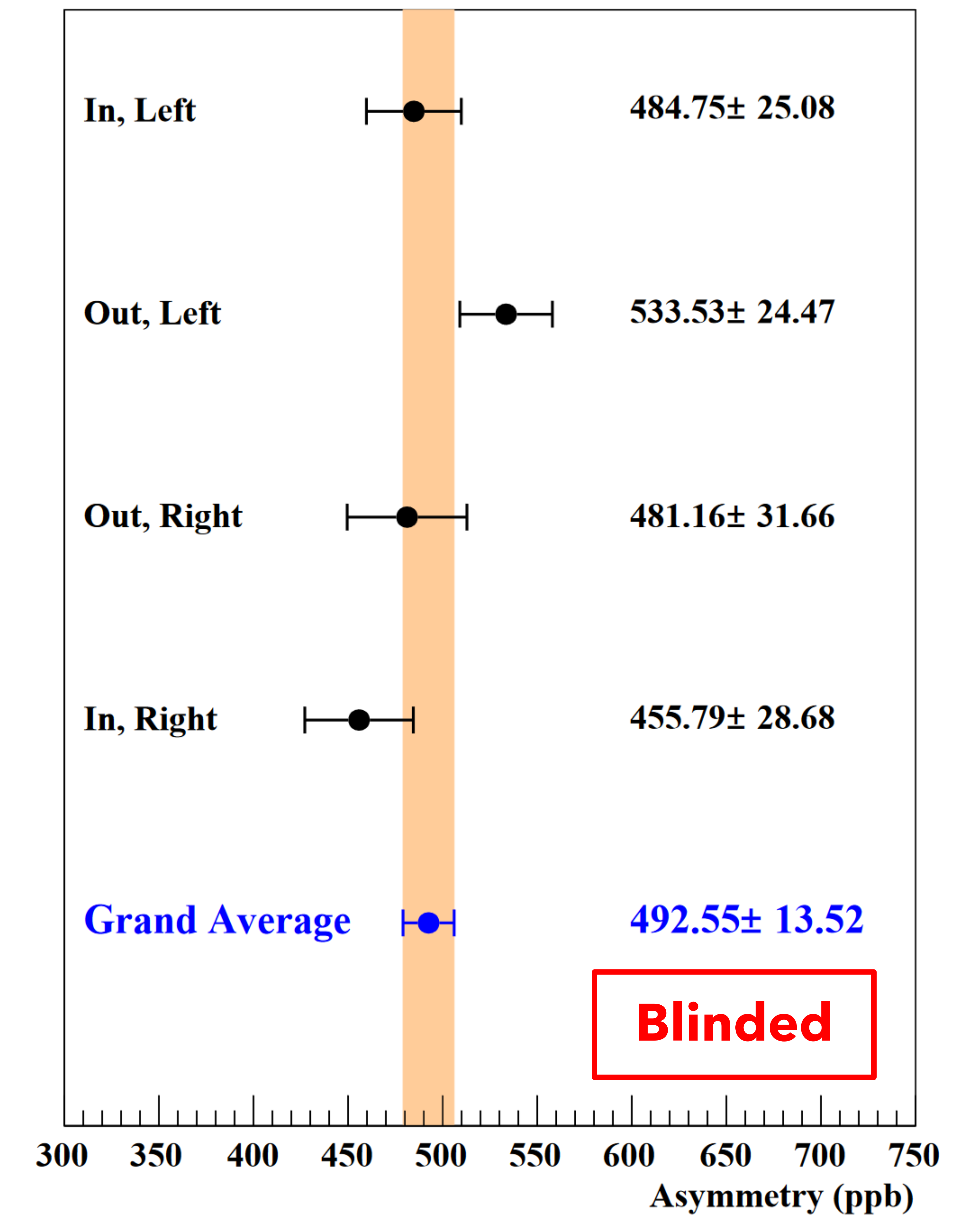
(550.0 ± 16.1)ppb

[PhysRevLett.126.172502](https://doi.org/10.1103/PhysRevLett.126.172502)

PREX Result

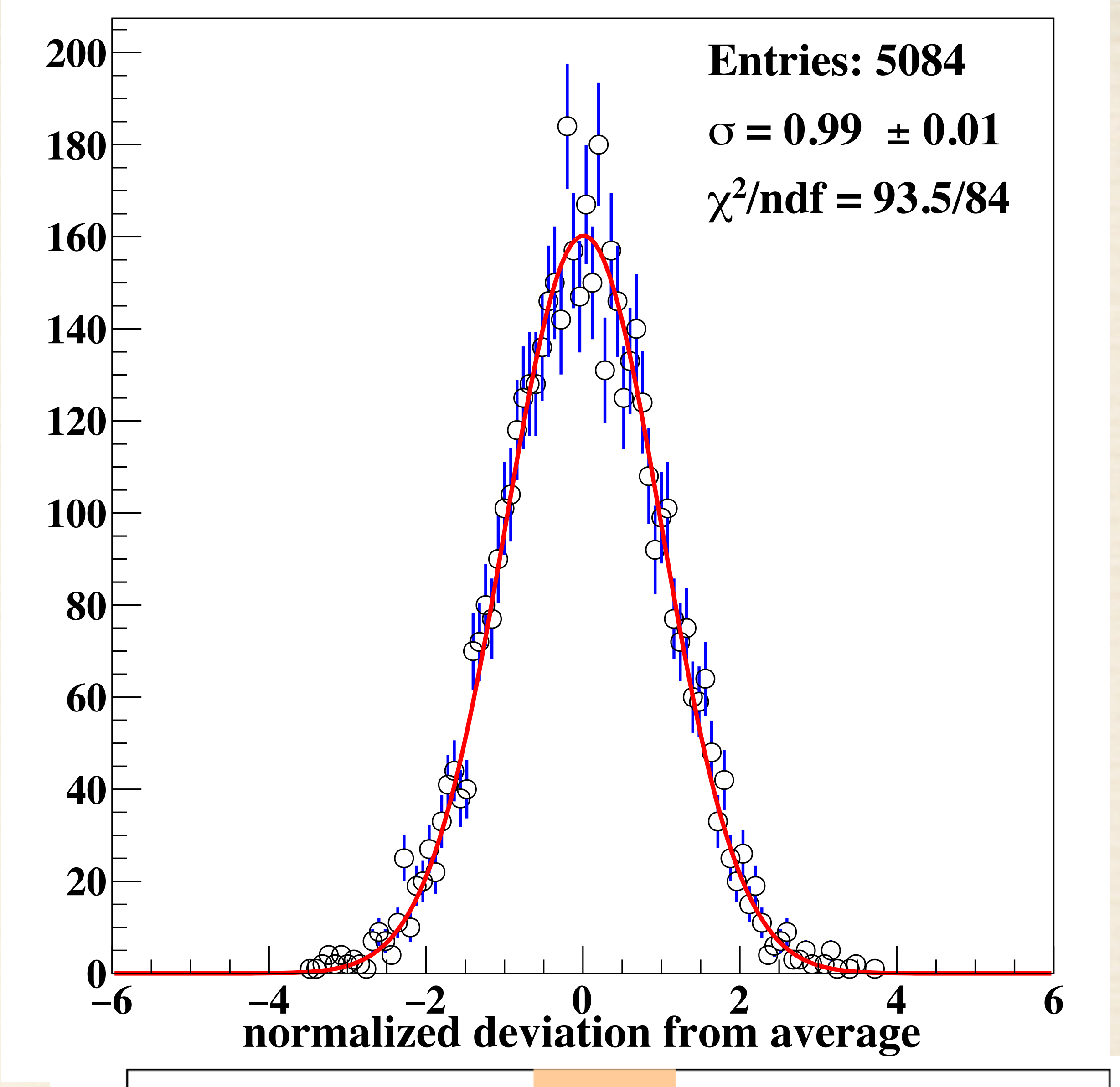


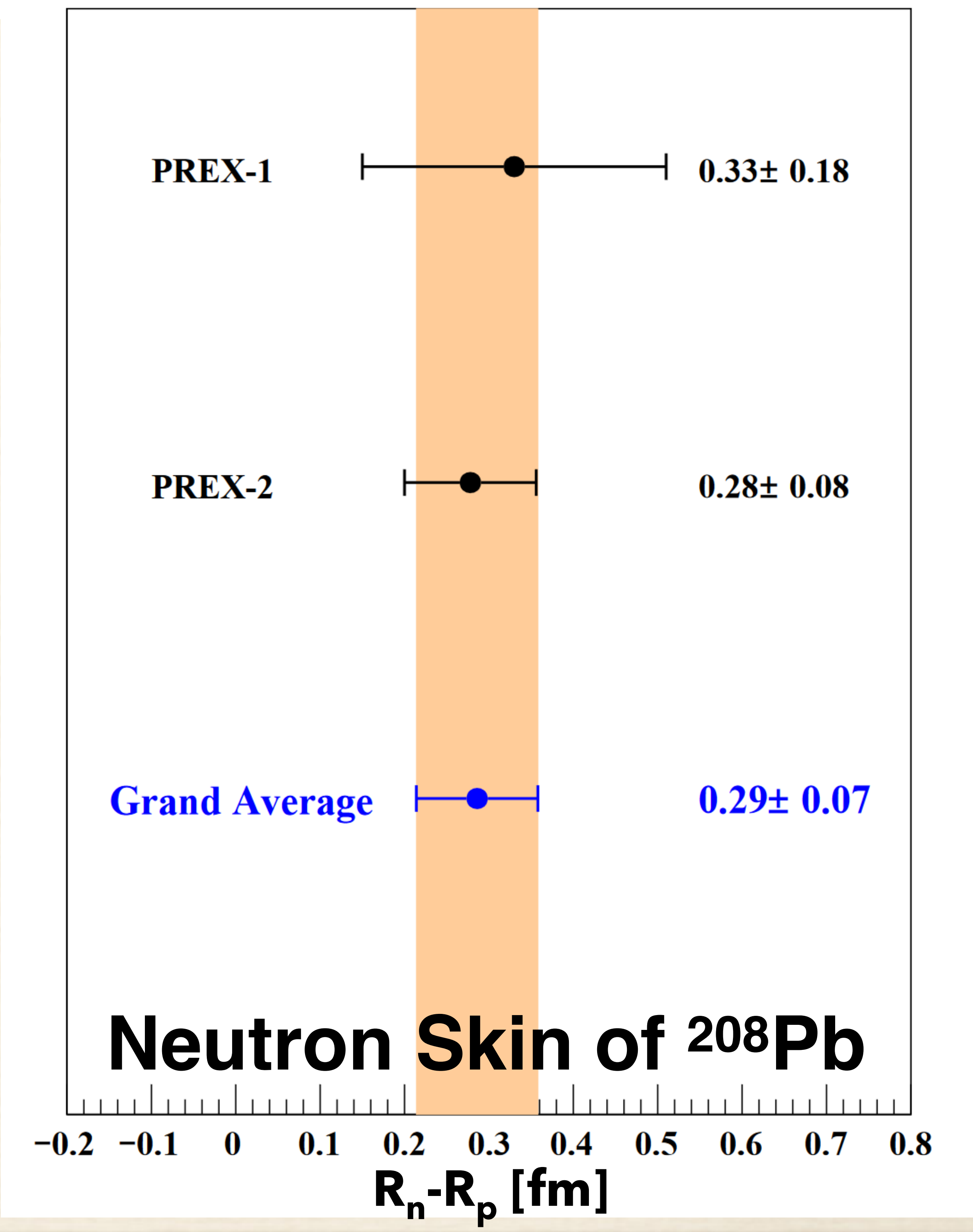




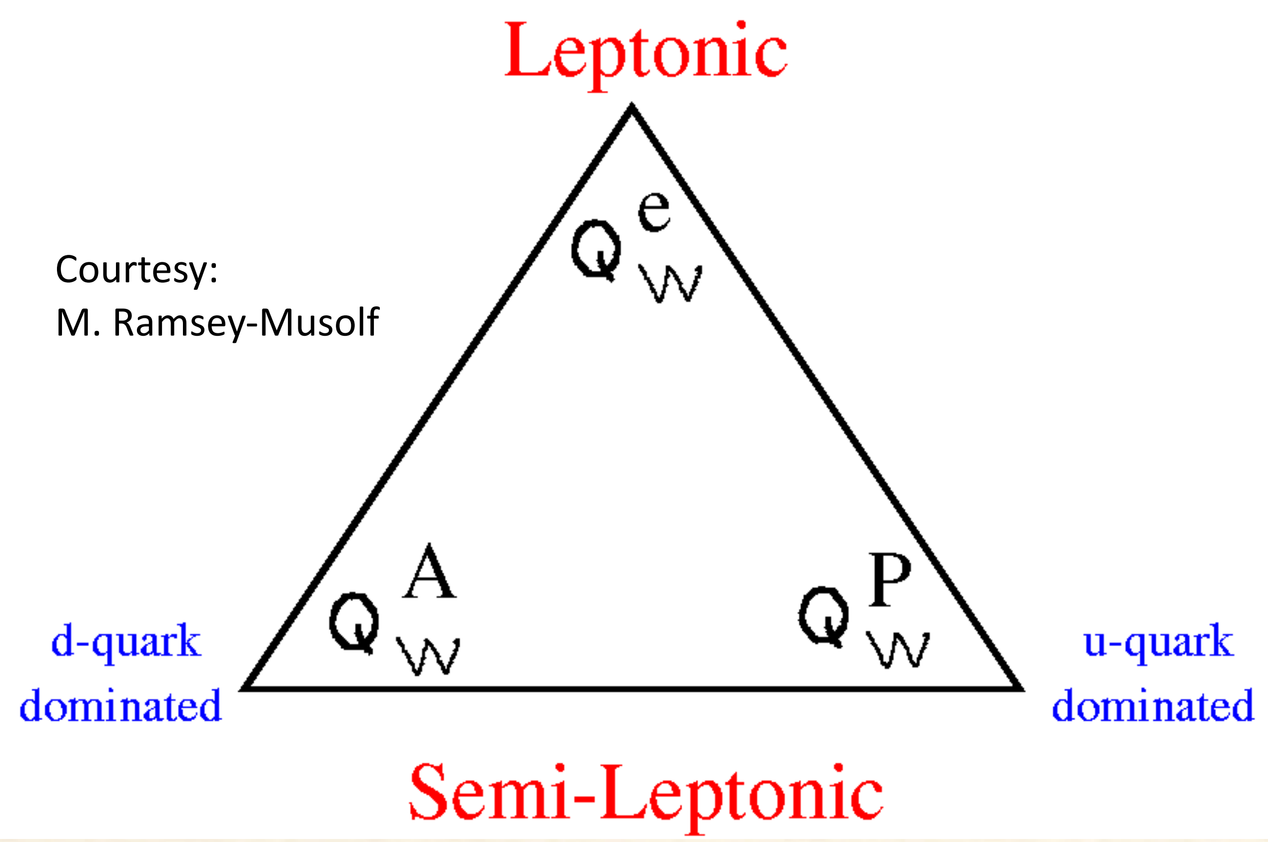
Unblinded A_{PV}:

(550.0 ± 16.1)ppb





PVES Standard Model Tests: Complementarity



$$[2C_{2u} - C_{2d}]$$

axial-quark couplings

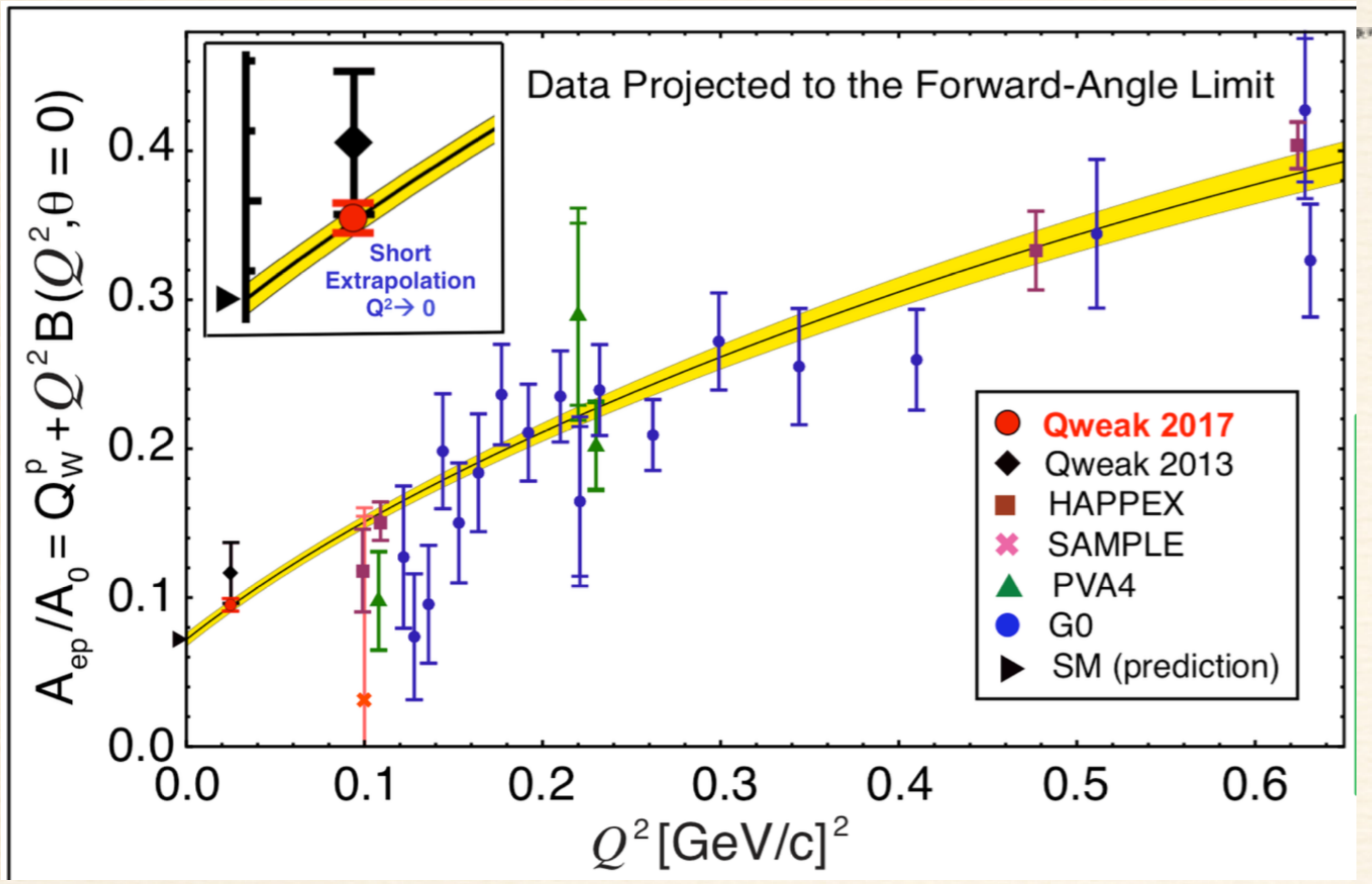
vector-quark couplings

SUSY Loops	➡	**Q_W^e and Q_W^p::same absolute shift, smaller for others**
GUT Z'	➡	**High for Q_w(Cs), Q_W^e(relative), smaller for others**
Leptophobic Z'	➡	**axial-quark couplings (C_2's) only**
RPV SUSY	➡	**Different for all four in sign and magnitude**
Leptoquarks	➡	**semi-leptonic only; different sensitivities**
Lepton Number Violation	➡	**Q_W^e only**

$$A_{ep} = -226.5 \pm 7.3(\text{stat}) \pm 5.8(\text{syst})\ \text{ppb at}\ \langle Q^2 \rangle = 0.0249\ (\text{GeV}/c)^2$$

Qweak and APV

Nature 557 (2018) no.7704, 207-211



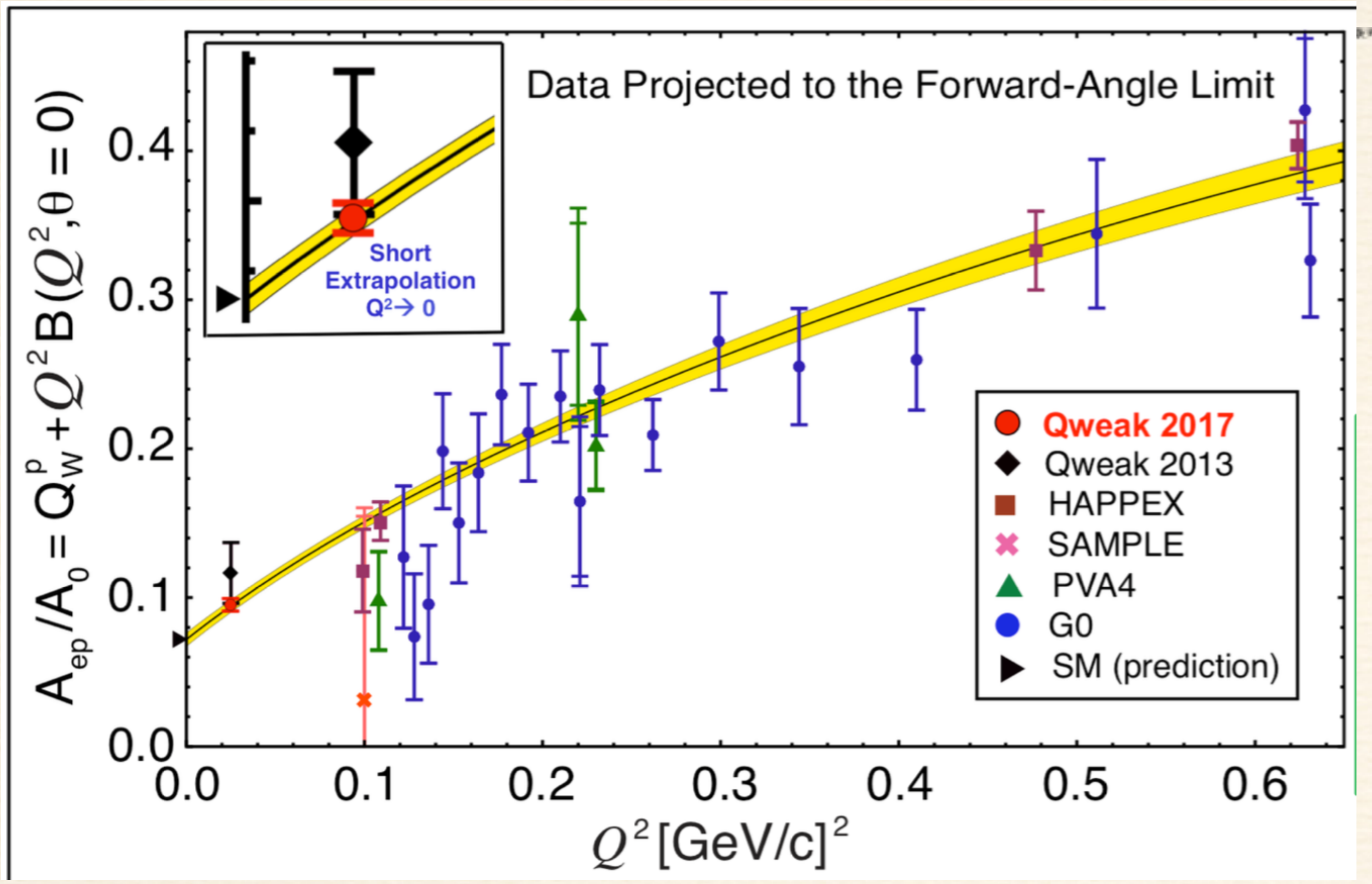
SM: 0.0708 ± 0.0003

Quantity	Value	Error
Q^p_W	0.0719	0.0045
$\sin^2\theta_W$	0.2382	0.0011
ρ_s	0.19	0.11
μ_s	-0.18	0.15
$G_A^{Z(T=1)}$	-0.67	0.33

$$A_{ep} = -226.5 \pm 7.3(\text{stat}) \pm 5.8(\text{syst})\ \text{ppb at}\ \langle Q^2 \rangle = 0.0249\ (\text{GeV}/c)^2$$

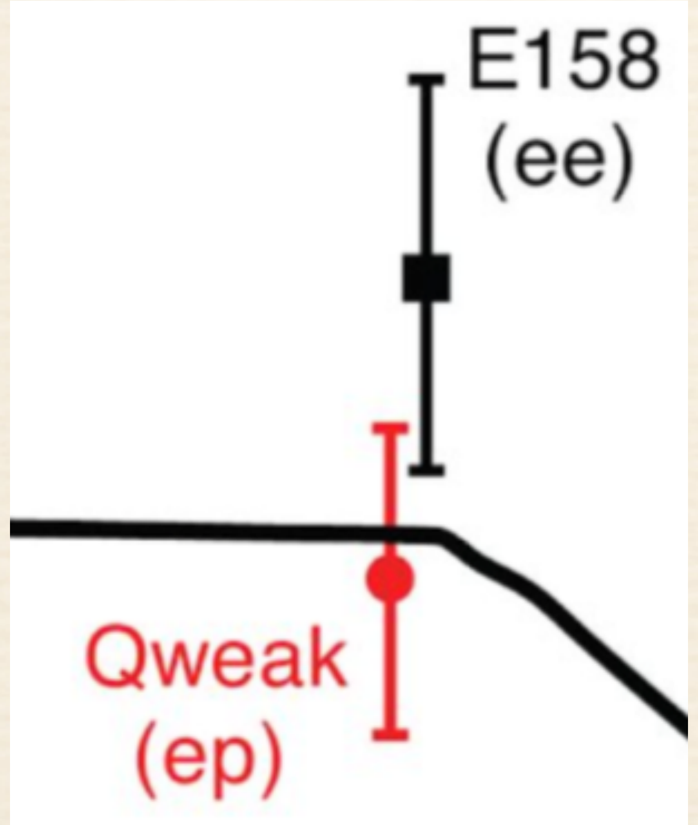
Qweak and APV

Nature 557 (2018) no.7704, 207-211



SM: 0.0708 ± 0.0003

Quantity	Value	Error
Q_W^p	0.0719	0.0045
$\sin^2\theta_W$	0.2382	0.0011
ρ_s	0.19	0.11
μ_s	-0.18	0.15
$G_A^{Z(T=1)}$	-0.67	0.33

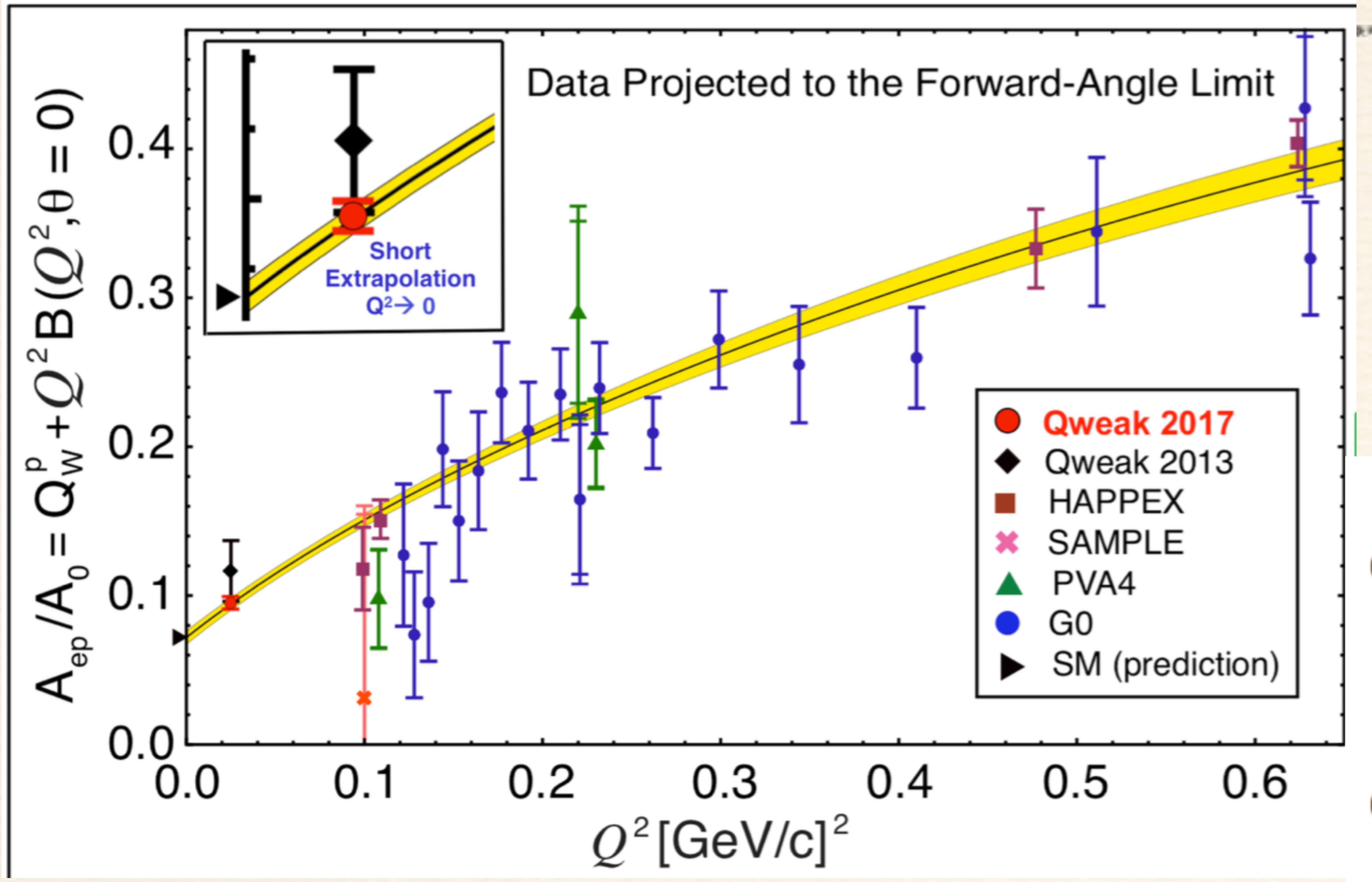


$$A_{ep} = -226.5 \pm 7.3(\mathrm{stat}) \pm 5.8(\mathrm{syst})\ \mathrm{ppb\ at}\ \langle Q^2 \rangle = 0.0249\ (\mathrm{GeV}/c)^2$$

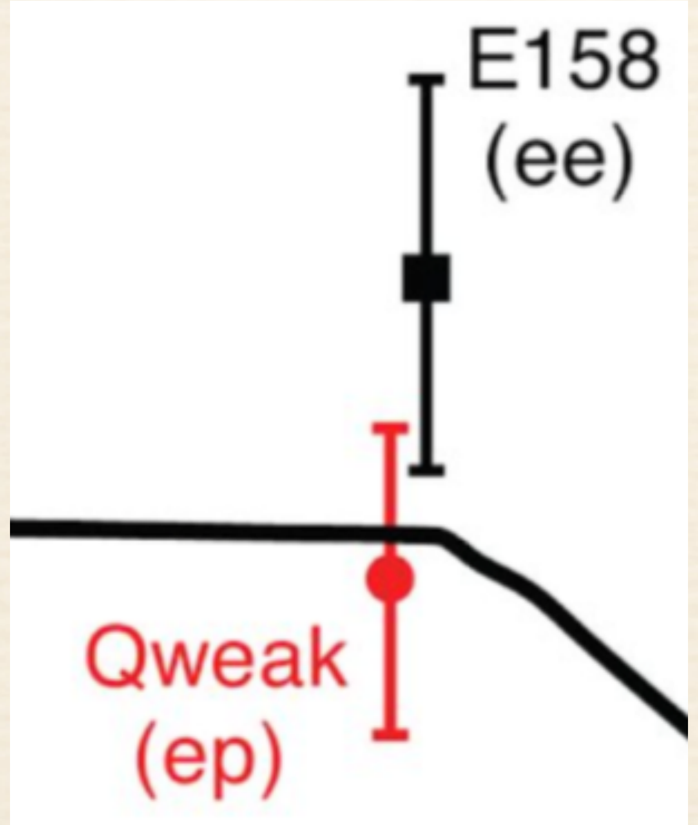
Qweak and APV

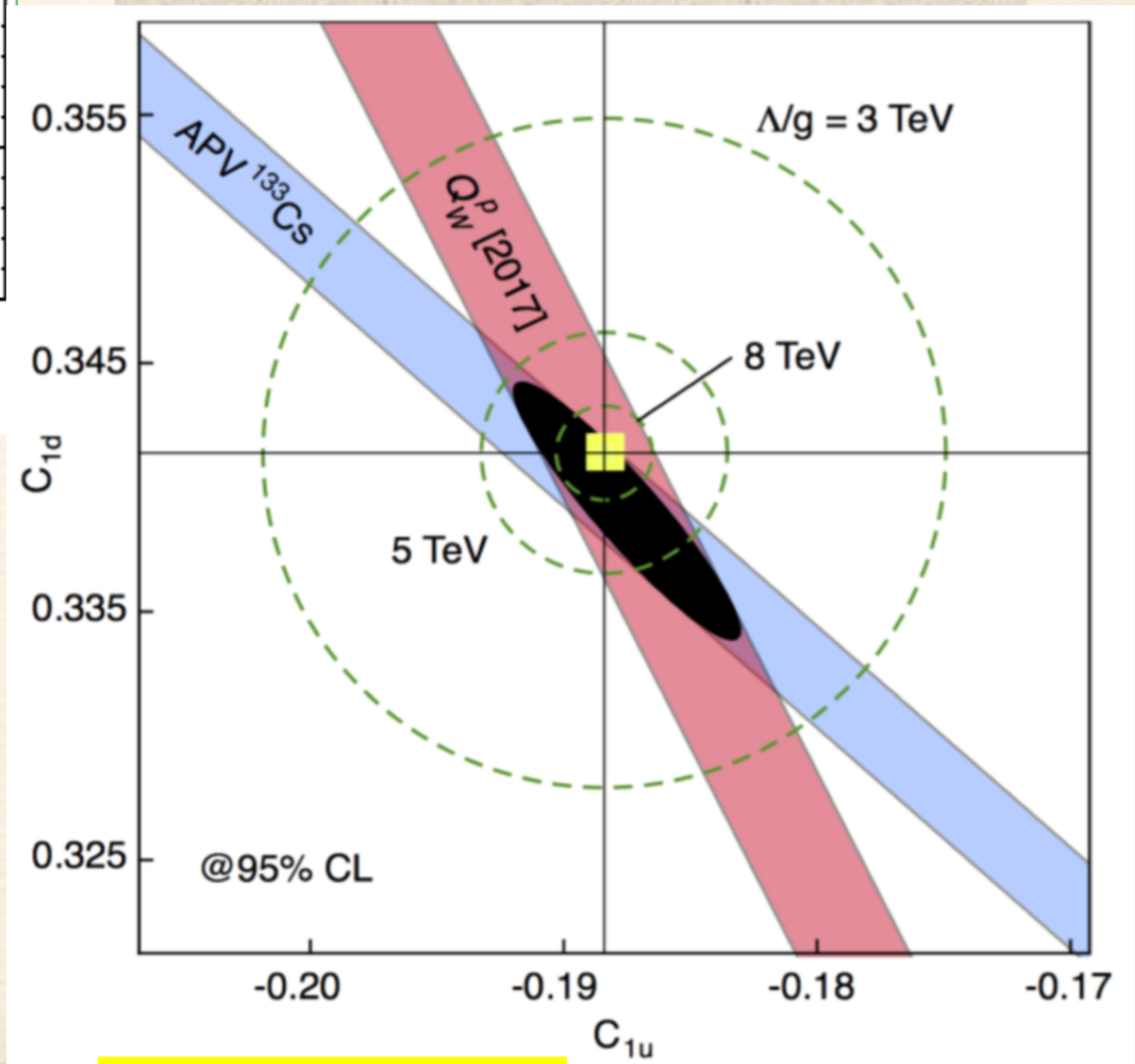
Nature 557 (2018) no.7704, 207-211

SM: 0.0708 ± 0.0003



Quantity	Value	Error
Q_W^p	0.0719	0.0045
$\sin^2\theta_W$	0.2382	0.0011
ρ_s	0.19	0.11
μ_s	-0.18	0.15
$G_A^{Z(T=1)}$	-0.67	0.33

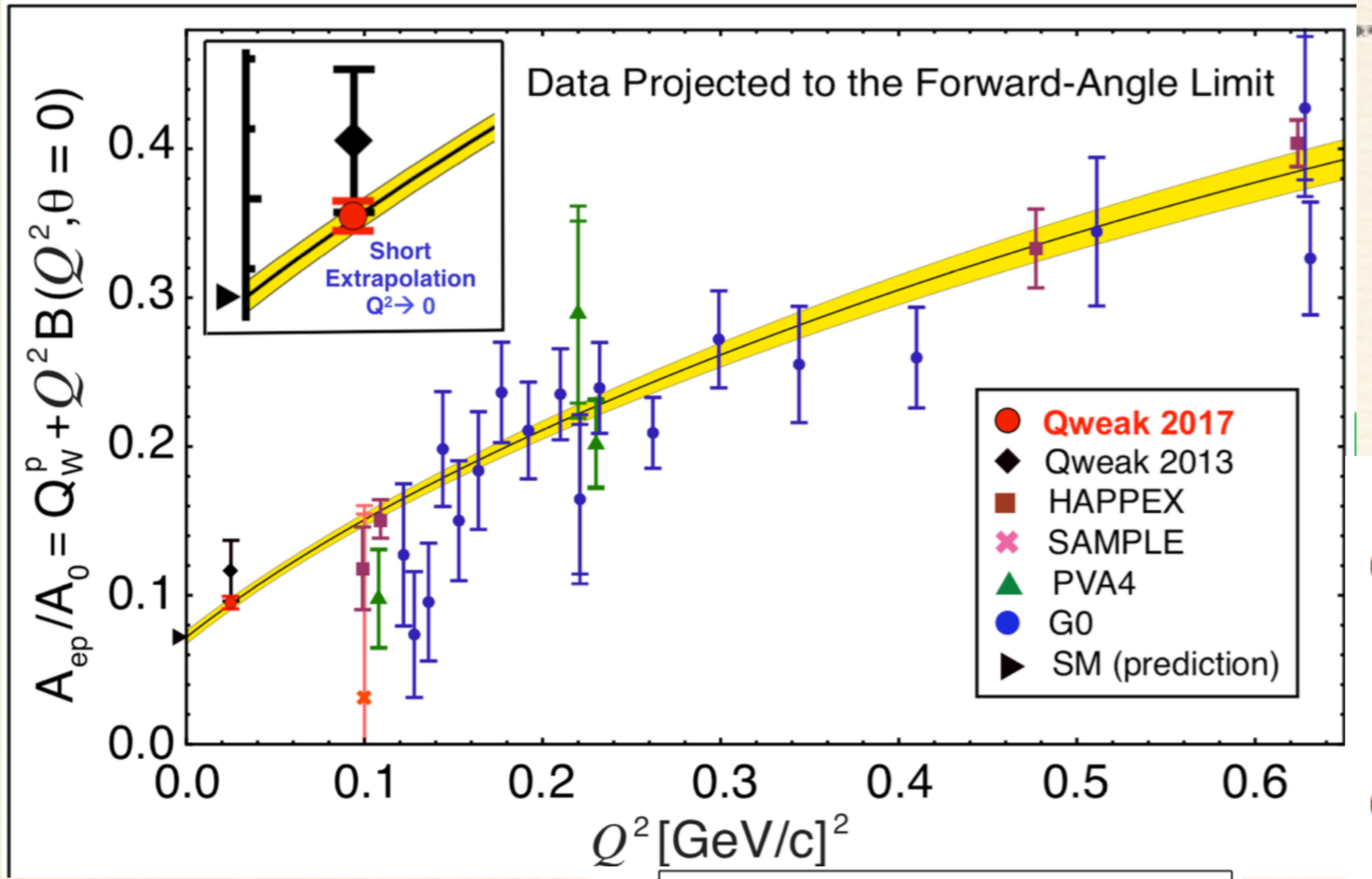




$$A_{ep} = -226.5 \pm 7.3(\mathrm{stat}) \pm 5.8(\mathrm{syst})\ \mathrm{ppb\ at}\ \langle Q^2 \rangle = 0.0249\ (\mathrm{GeV}/c)^2$$

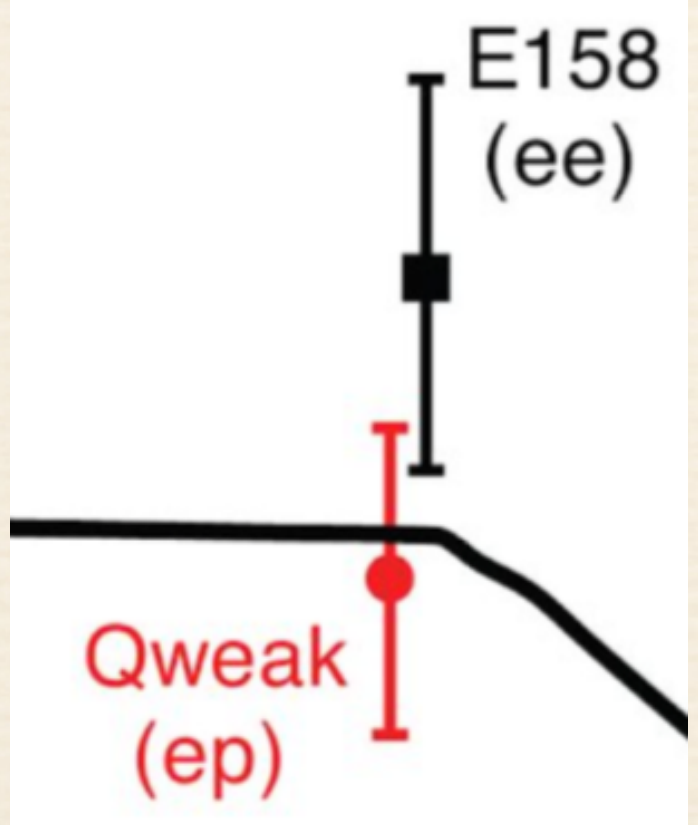
Qweak and APV

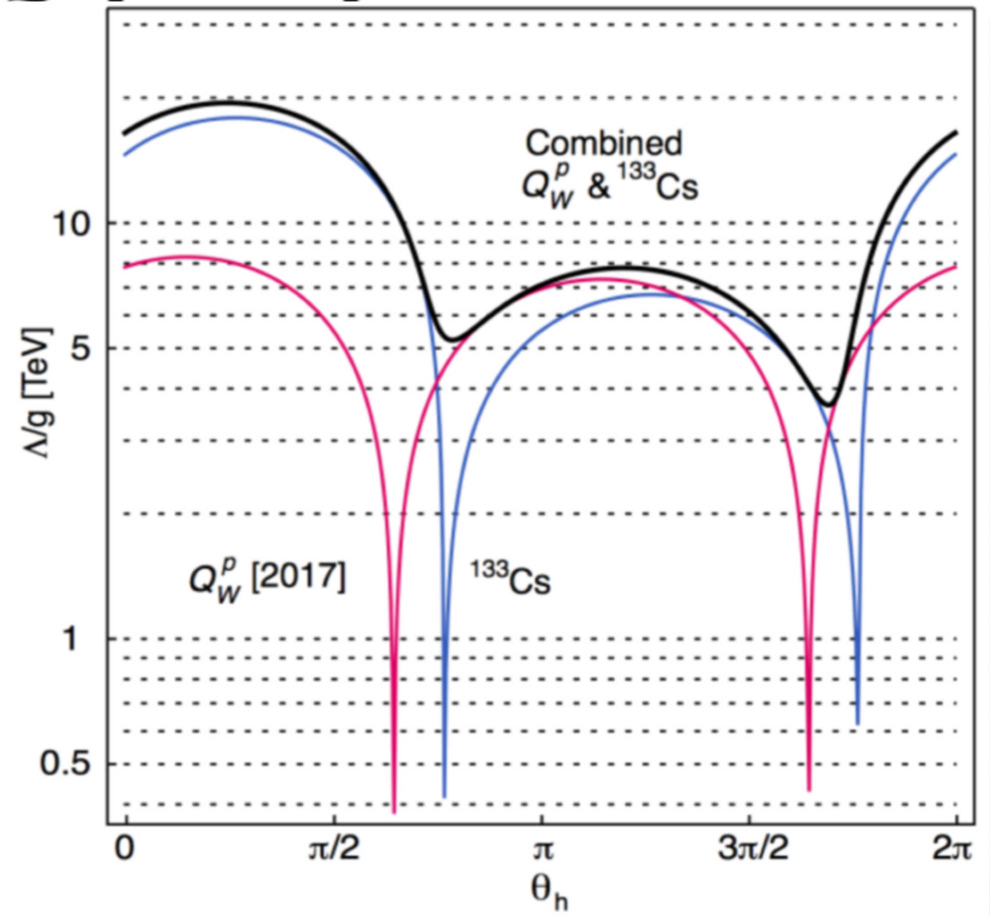
Nature 557 (2018) no.7704, 207-211

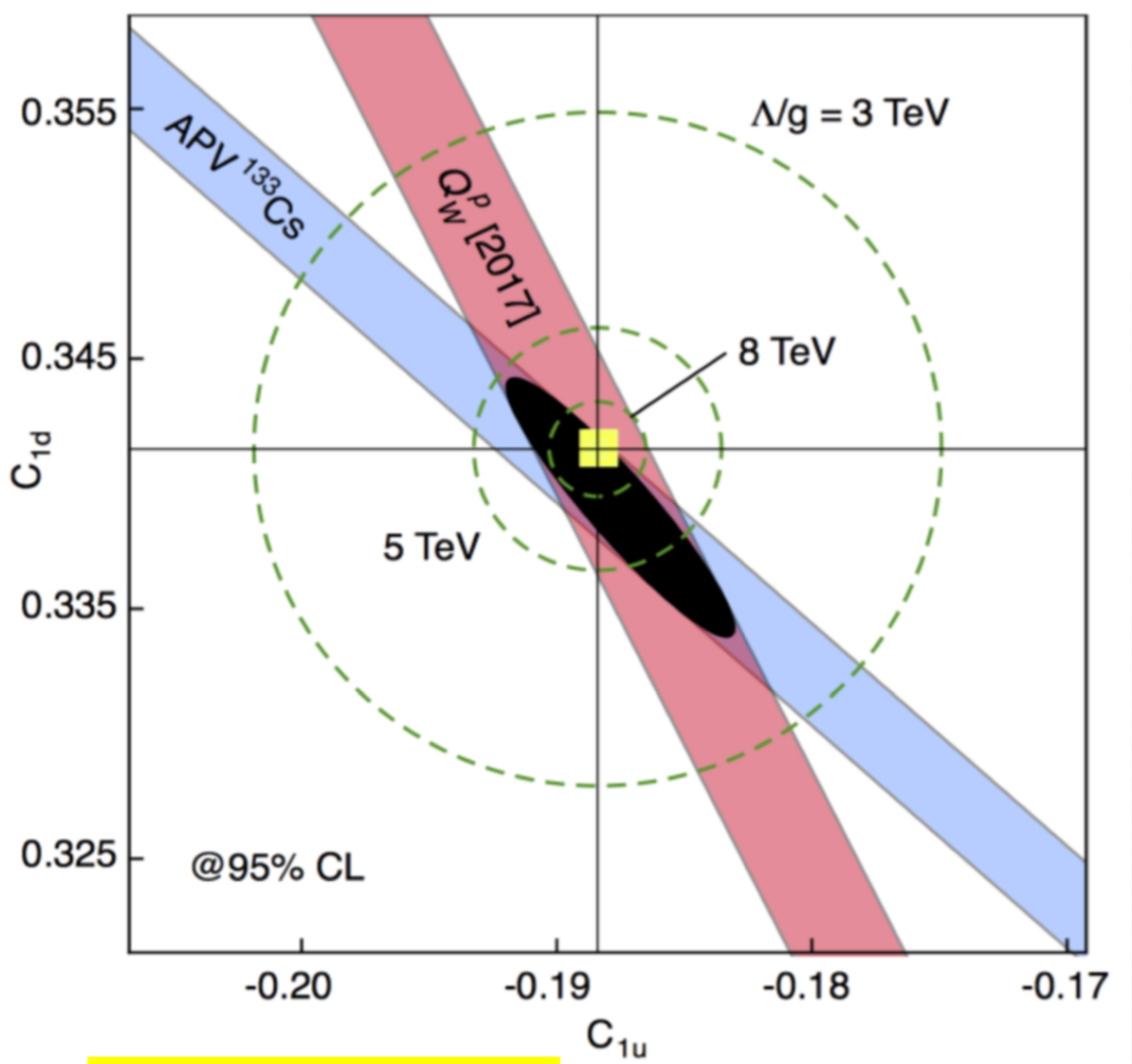


SM: 0.0708 ± 0.0003

Quantity	Value	Error
Q_W^p	0.0719	0.0045
$\sin^2\theta_W$	0.2382	0.0011
ρ_s	0.19	0.11
μ_s	-0.18	0.15
$G_A^{Z(T=1)}$	-0.67	0.33







Fixed Target vs Collider Complementarity

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q_W^e|}}$$

$$\simeq \frac{246.22\ \mathrm{GeV}}{\sqrt{0.023 Q_W^e}} = 7.5\ \mathrm{TeV}.$$

Model	η_{LL}^f	η_{RR}^f	η_{LR}^f	η_{RL}^f
$LL^\pm$	± 1	0	0	0
$RR^\pm$	0	± 1	0	0
$LR^\pm$	0	0	± 1	0
$RL^\pm$	0	0	0	± 1
$VV^\pm$	± 1	± 1	± 1	± 1
$AA^\pm$	± 1	± 1	∓ 1	∓ 1
$VA^\pm$	± 1	∓ 1	± 1	∓ 1

Conventional Collider Contact Interaction Analysis: $\Rightarrow$ $|g_{RR}^2 - g_{LL}^2| = 4\pi$

Simultaneous fits to cross-sections and angular distributions

LEP200

95% C.L. Limits

$\Lambda_{\rm LL}^{\rm ee} \sim 8.3$ TeV $\quad\quad$ $\Lambda_{\rm LL}^{\rm ll} \sim 12.8$ TeV

$\Lambda_{\rm RR}^{\rm ee} \sim 8.2$ TeV $\quad\quad$ $\Lambda_{\rm RR}^{\rm ll} \sim 12.2$ TeV

$\Lambda_{\rm VV}^{\rm ee} \sim 17.7$ TeV $\quad\quad$ $\Lambda_{\rm VV}^{\rm ll} \sim 22.2$ TeV

E158 Reach (actual limits asymmetric)

$\Lambda_{\rm LL}^{\rm ee} \sim 12$ TeV $\quad\quad$ $\Lambda_{\rm RR-LL}^{\rm ee} \sim 17$ TeV

LEP-200 insensitive

Fixed Target vs Collider Complementarity

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q_W^e|}}$$

$$\simeq \frac{246.22\text{ GeV}}{\sqrt{0.023 Q_W^e}} = 7.5\text{ TeV}.$$

Model	η_{LL}^f	η_{RR}^f	η_{LR}^f	η_{RL}^f
$LL^\pm$	±1	0	0	0
$RR^\pm$	0	±1	0	0
$LR^\pm$	0	0	±1	0
$RL^\pm$	0	0	0	±1
$VV^\pm$	±1	±1	±1	±1
$AA^\pm$	±1	±1	∓1	∓1
$VA^\pm$	±1	∓1	±1	∓1

Conventional Collider Contact Interaction Analysis: $\Rightarrow$ $|g_{RR}^2 - g_{LL}^2| = 4\pi$

Simultaneous fits to cross-sections and angular distributions

95% C.L. Limits

LEP200

$\Lambda_{LL}^{ee} \sim 8.3$ TeV $\quad$ $\Lambda_{LL}^{ll} \sim 12.8$ TeV

$\Lambda_{RR}^{ee} \sim 8.2$ TeV $\quad$ $\Lambda_{RR}^{ll} \sim 12.2$ TeV

$\Lambda_{VV}^{ee} \sim 17.7$ TeV $\quad$ $\Lambda_{VV}^{ll} \sim 22.2$ TeV

E158 Reach (actual limits asymmetric)

$\Lambda_{LL}^{ee} \sim 12$ TeV $\quad$ $\Lambda_{RR-LL}^{ee} \sim 17$ TeV

LEP-200 insensitive

MOLLER Reach

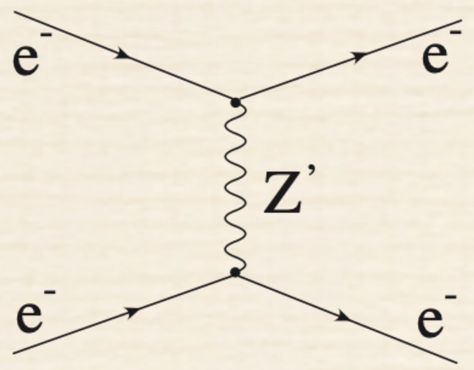
$\Lambda_{LL}^{ee} \sim 27$ TeV $\quad$ $\Lambda_{RR-LL}^{ee} \sim 38$ TeV

MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider

Unique Opportunity: Purely Leptonic Reaction at $Q^2 << M_Z^2$

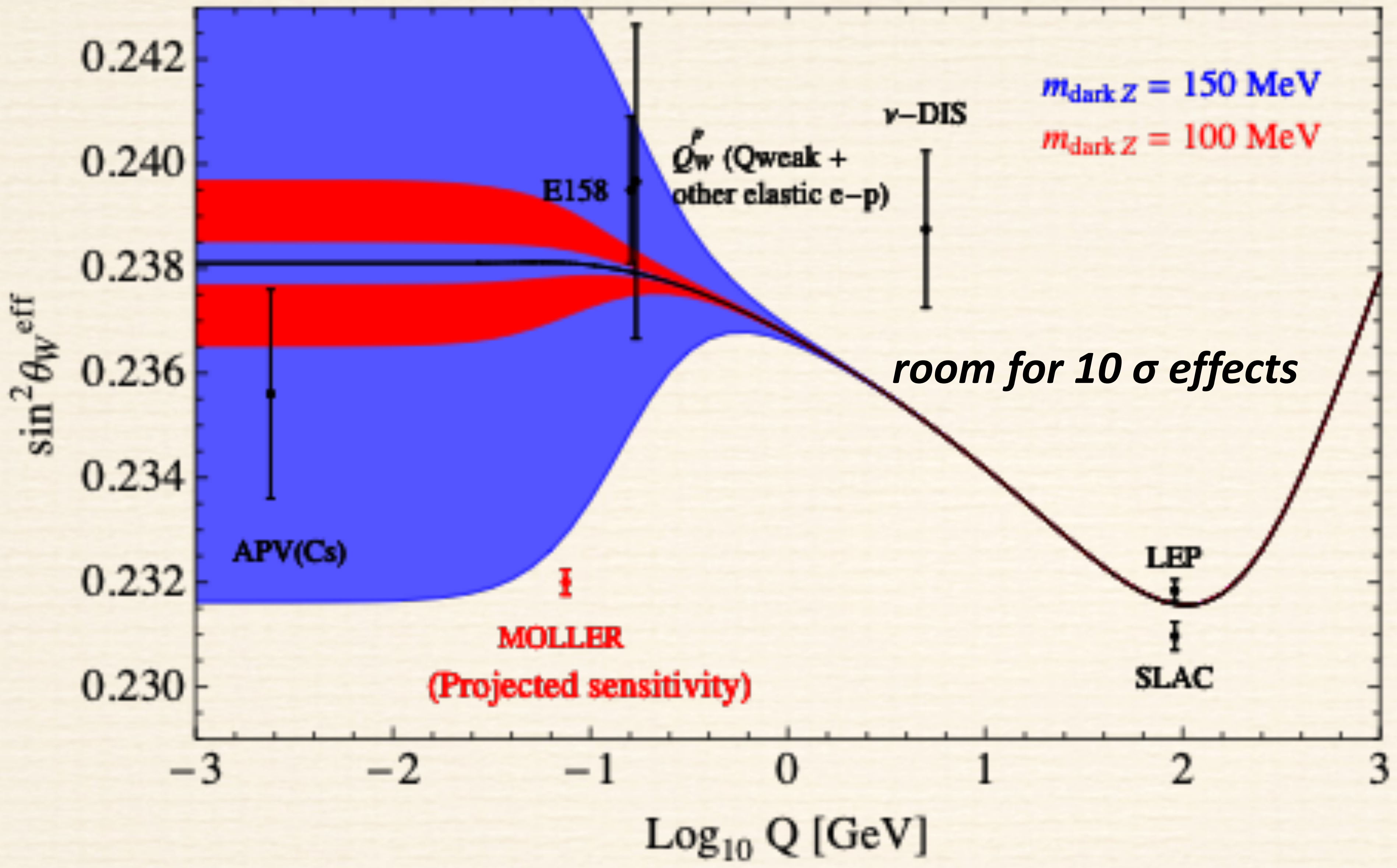
PV Møller Scattering: BSM Examples

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential



Heavy Photons (A' mixed with Z_0): The Dark Z

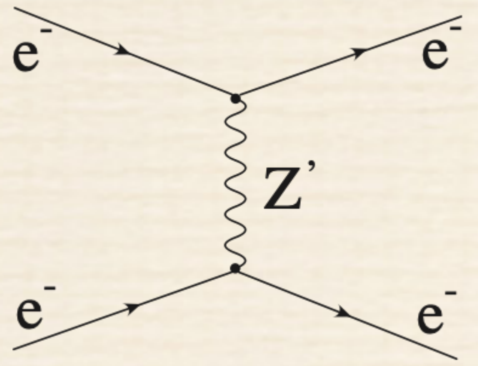
H. Davoudiasl, H-S. Lee and W. Marciano



Unique Opportunity: Purely Leptonic Reaction at $Q^2 << M_Z^2$

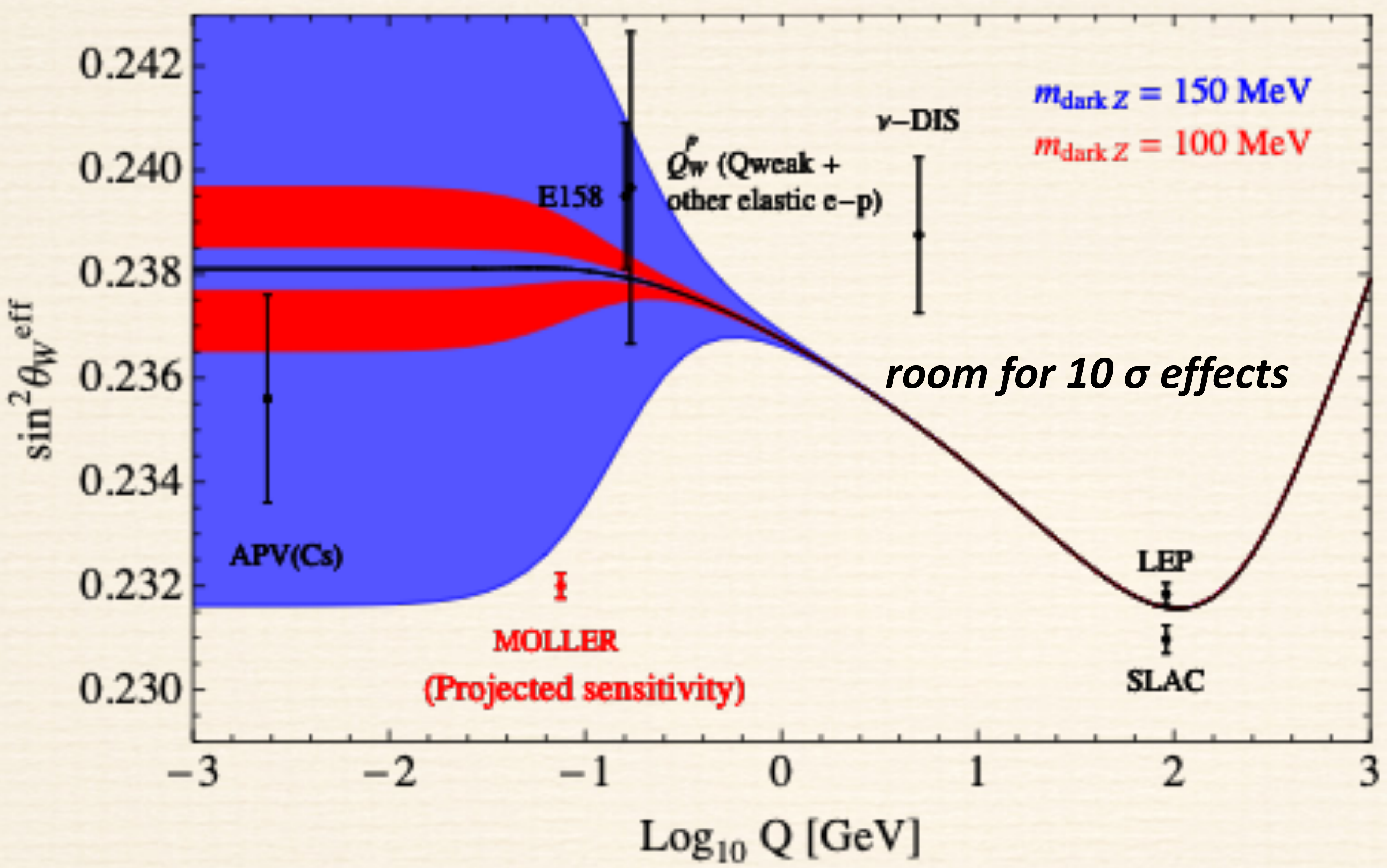
PV Møller Scattering: BSM Examples

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential



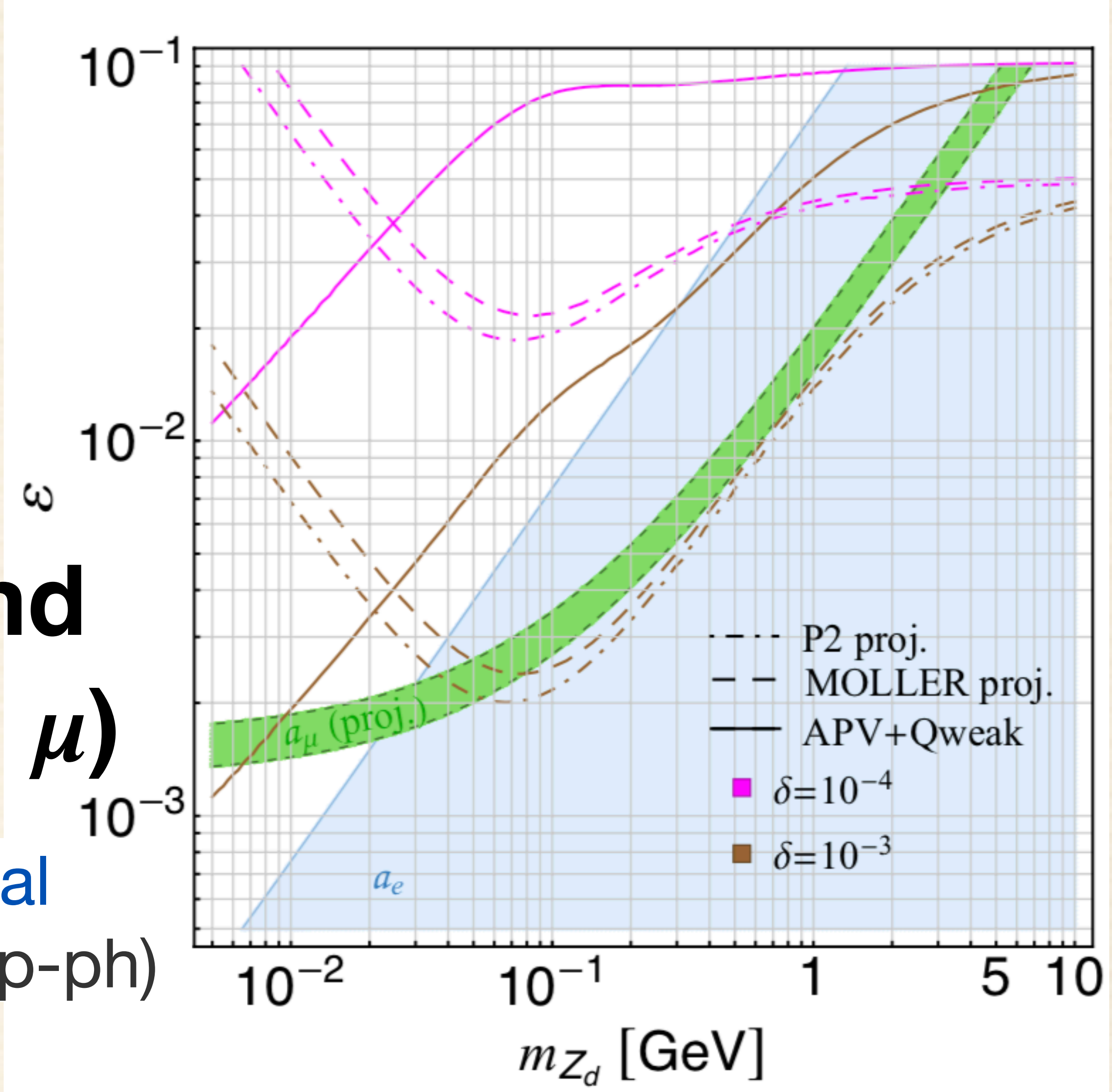
Heavy Photons (A' mixed with Z_0): The Dark Z

H. Davoudiasl, H-S. Lee and W. Marciano



Specific Scenario folding in Cs APV and g-2 (e and μ)

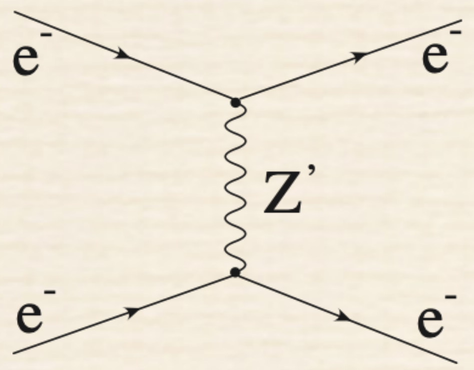
M. Caddedu et al 2104.03280 (hep-ph)



Unique Opportunity: Purely Leptonic Reaction at $Q^2 << M_Z^2$

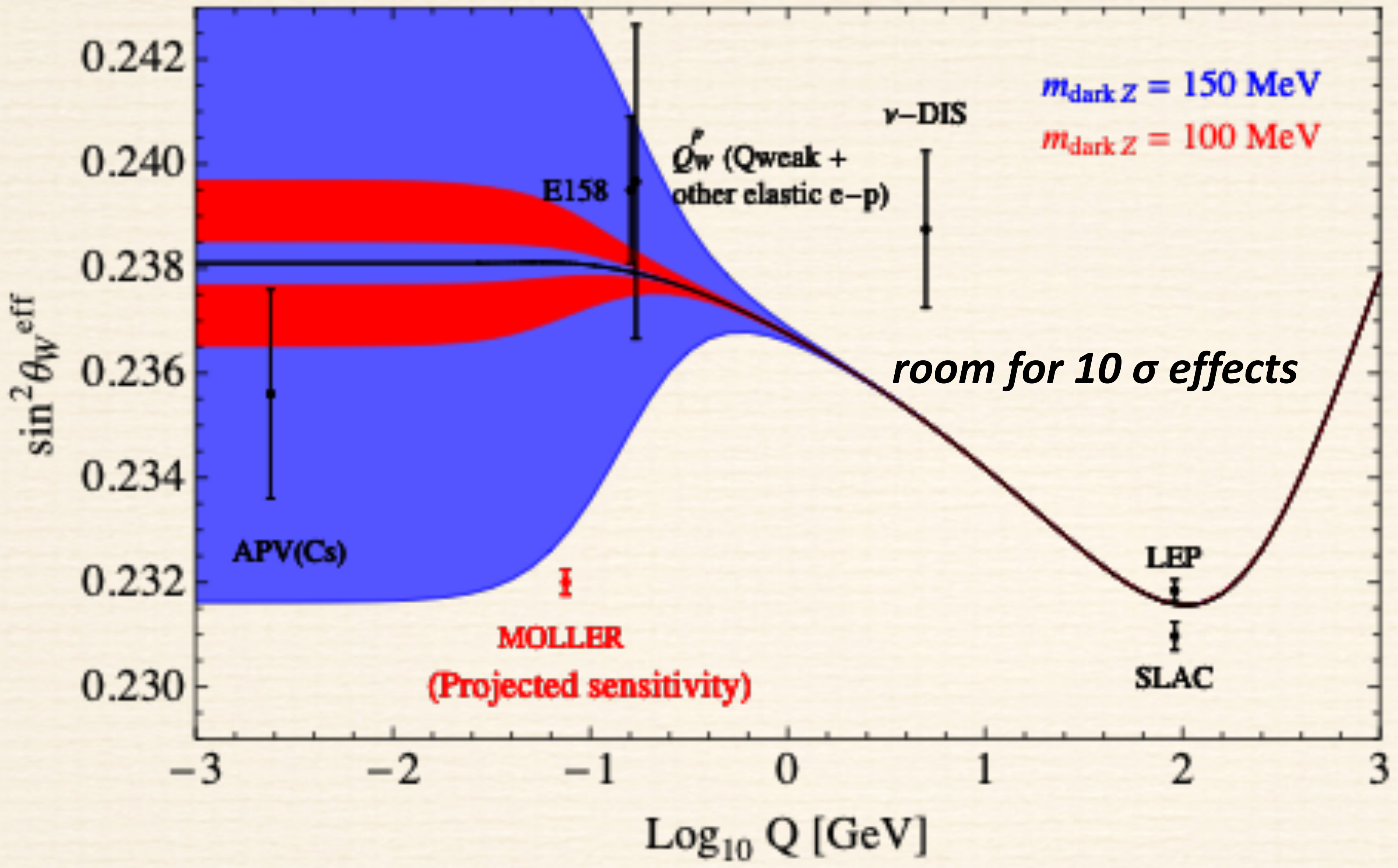
PV Møller Scattering: BSM Examples

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential



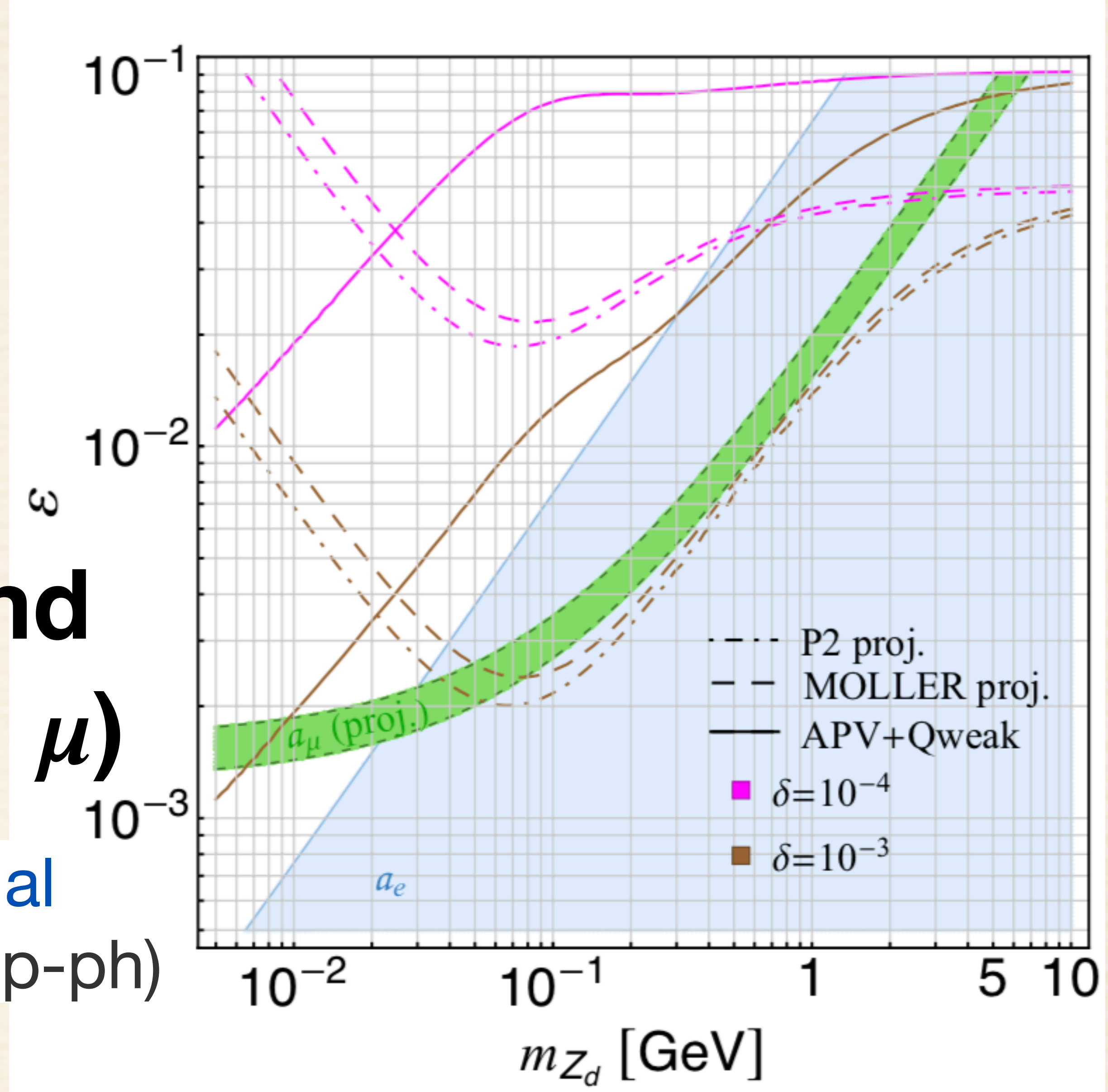
Heavy Photons (A' mixed with Z_0): The Dark Z

H. Davoudiasl, H-S. Lee and W. Marciano

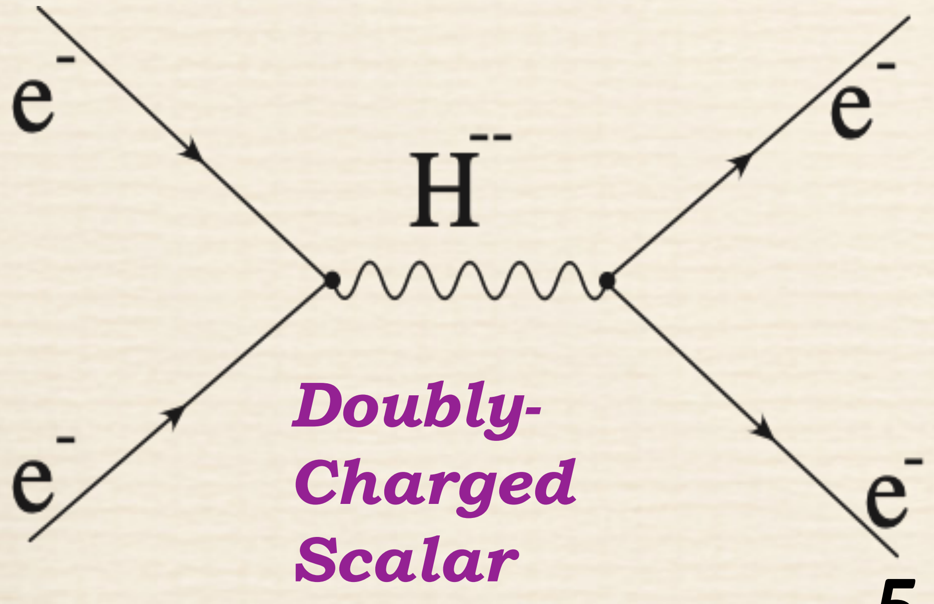


Specific Scenario folding in Cs APV and g-2 (e and μ)

M. Caddedu et al
2104.03280 (hep-ph)



Lepton Number Violation



$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14\frac{|h_{ee}|^2}{(M_\Delta/1\ \mathrm{TeV})^2}$$

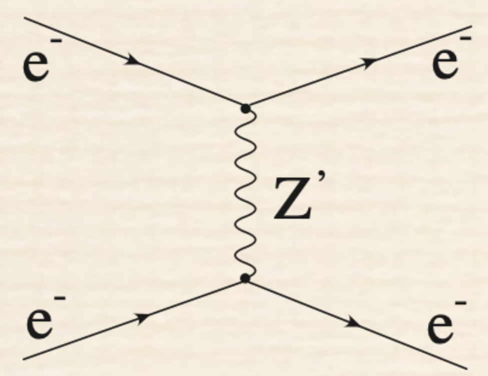
Cirigliano et al
Phys.Rev. D70 (2004) 075007

5 σ for h_{ee} ~ 1 and M_Δ ~ 1 TeV

Unique Opportunity: Purely Leptonic Reaction at $Q^2 << M_Z^2$

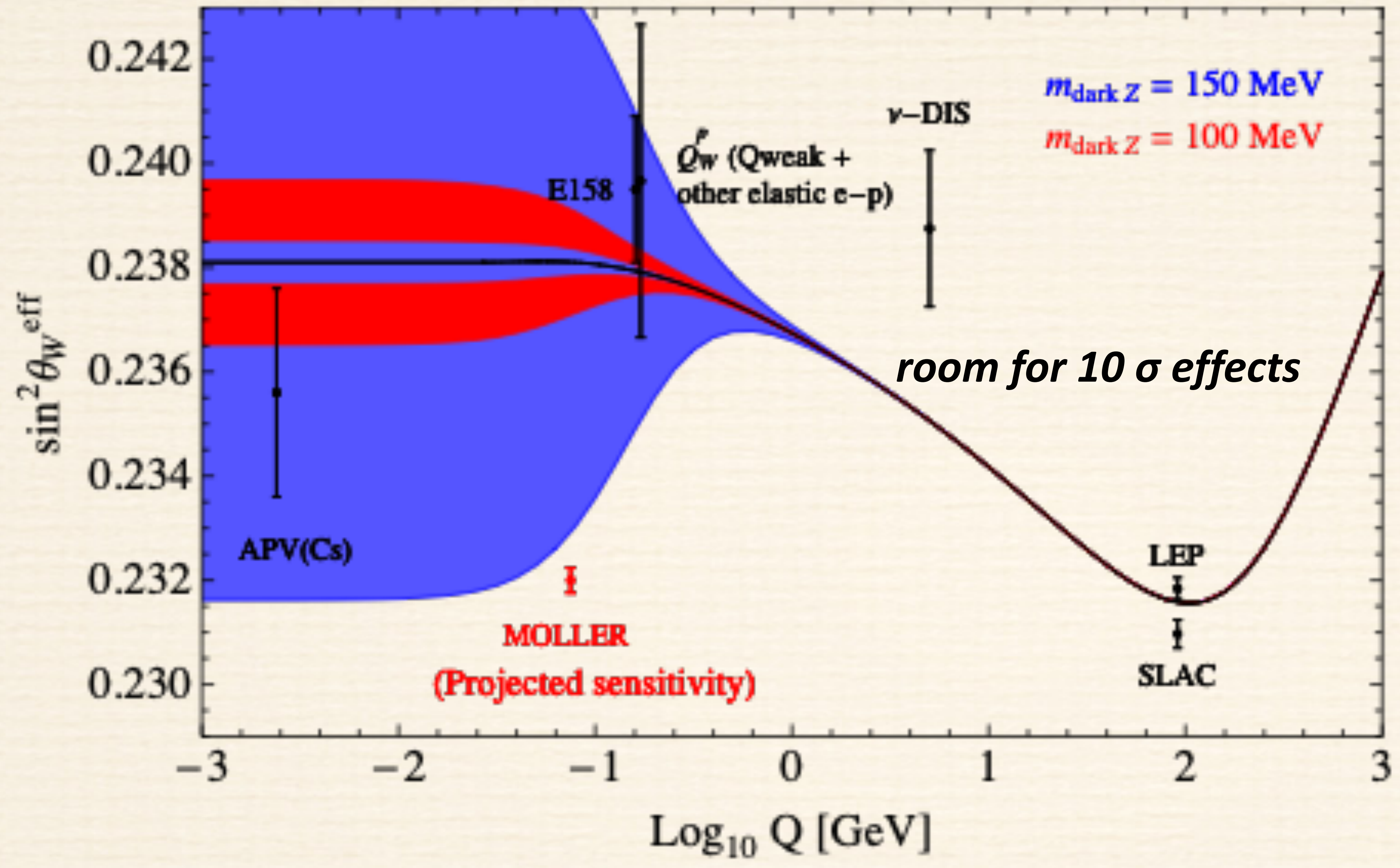
PV Møller Scattering: BSM Examples

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential



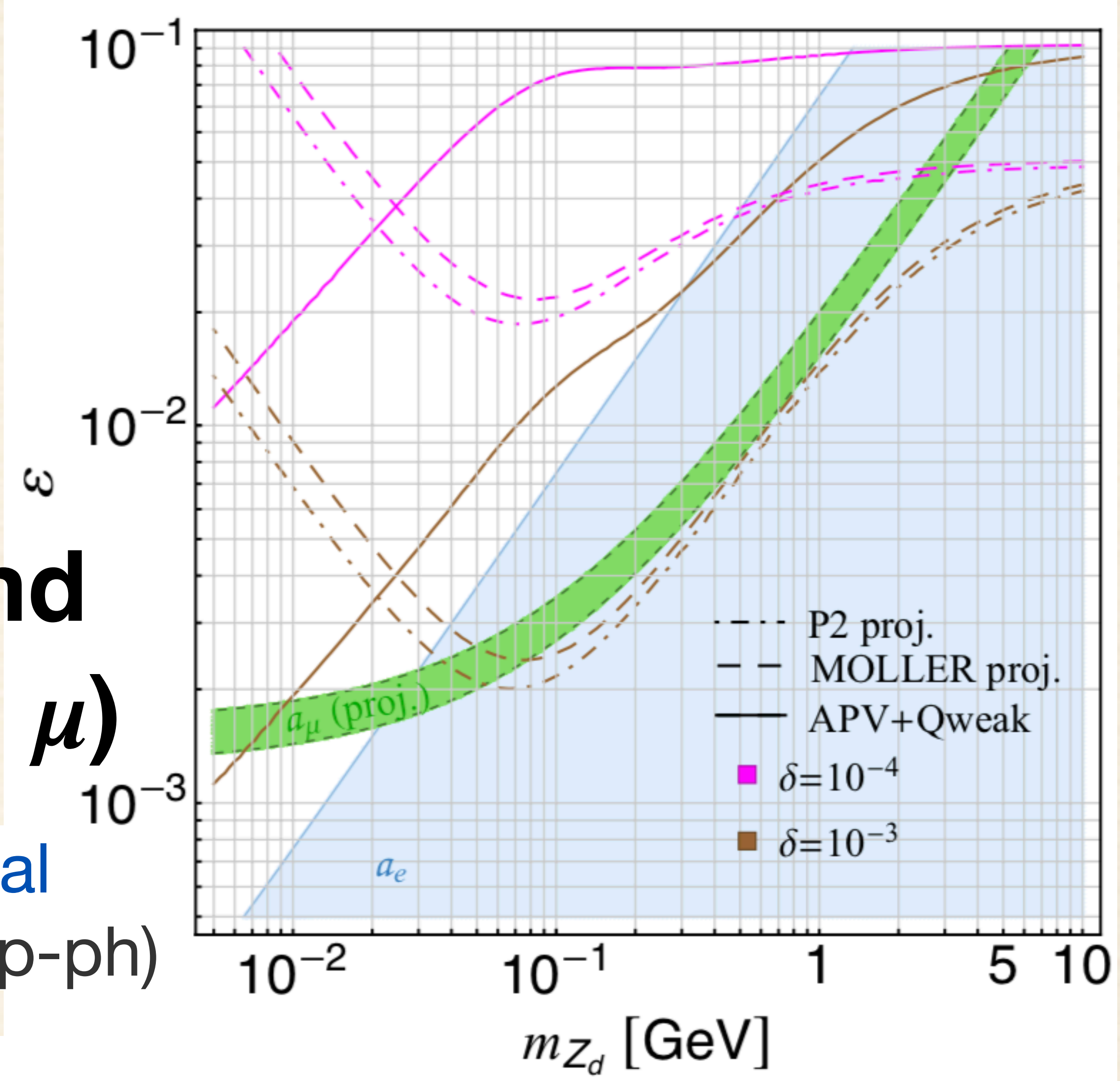
Heavy Photons (A' mixed with Z_0): The Dark Z

H. Davoudiasl, H-S. Lee and W. Marciano

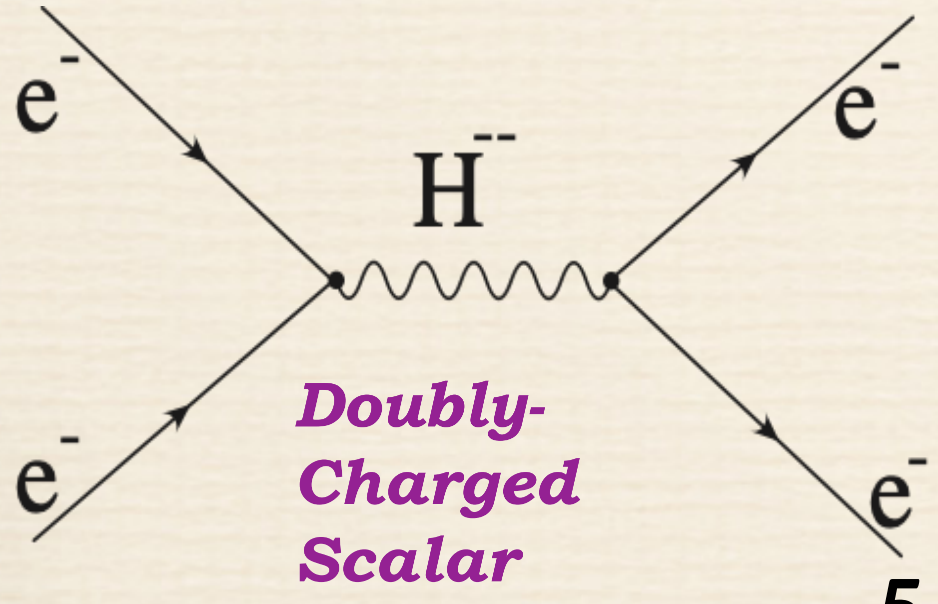


Specific Scenario folding in Cs APV and g-2 (e and μ)

M. Caddedu et al
2104.03280 (hep-ph)



Lepton Number Violation



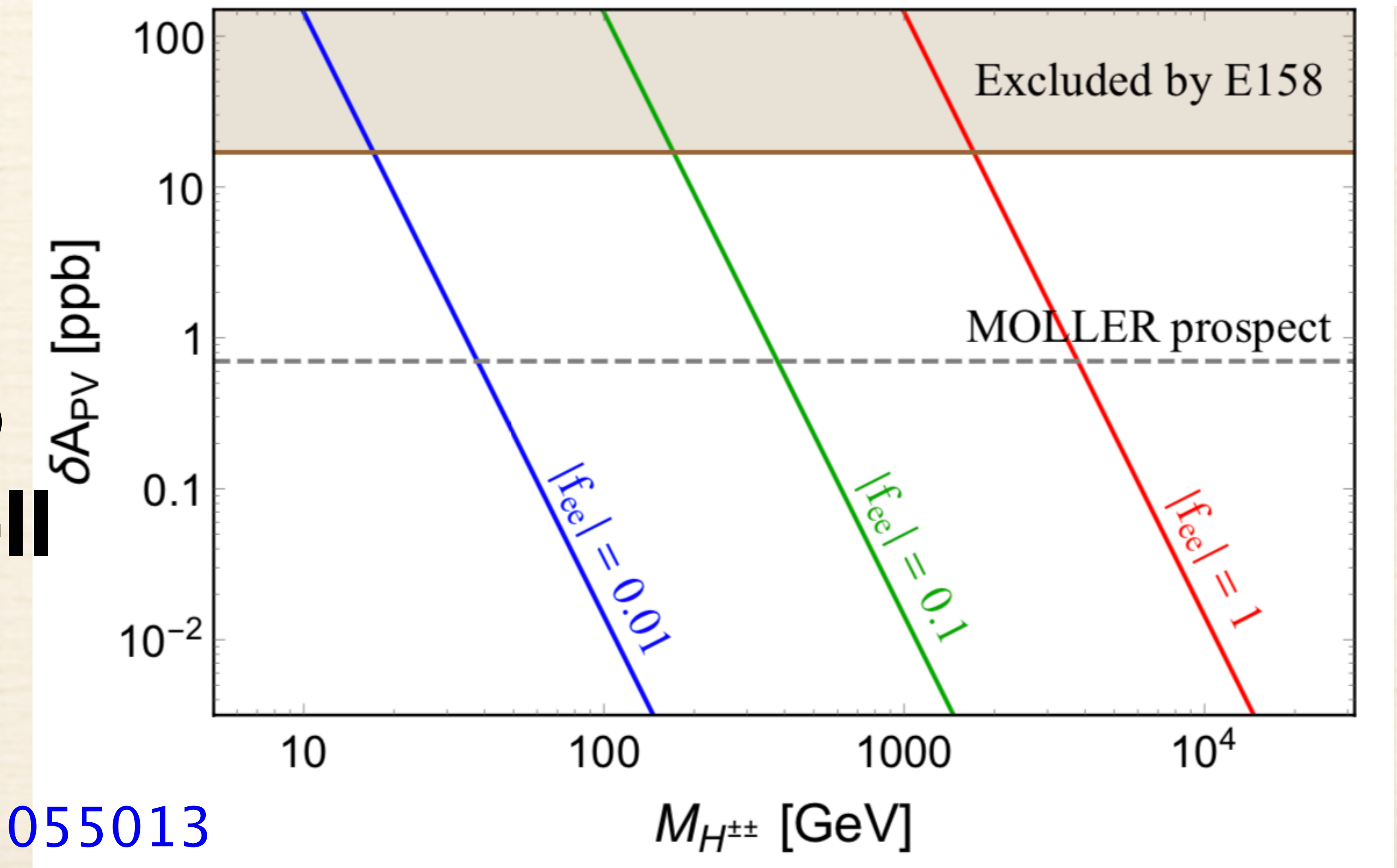
$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14\frac{|h_{ee}|^2}{(M_\Delta/1\ \mathrm{TeV})^2}$$

Cirigliano et al
Phys.Rev. D70 (2004) 075007

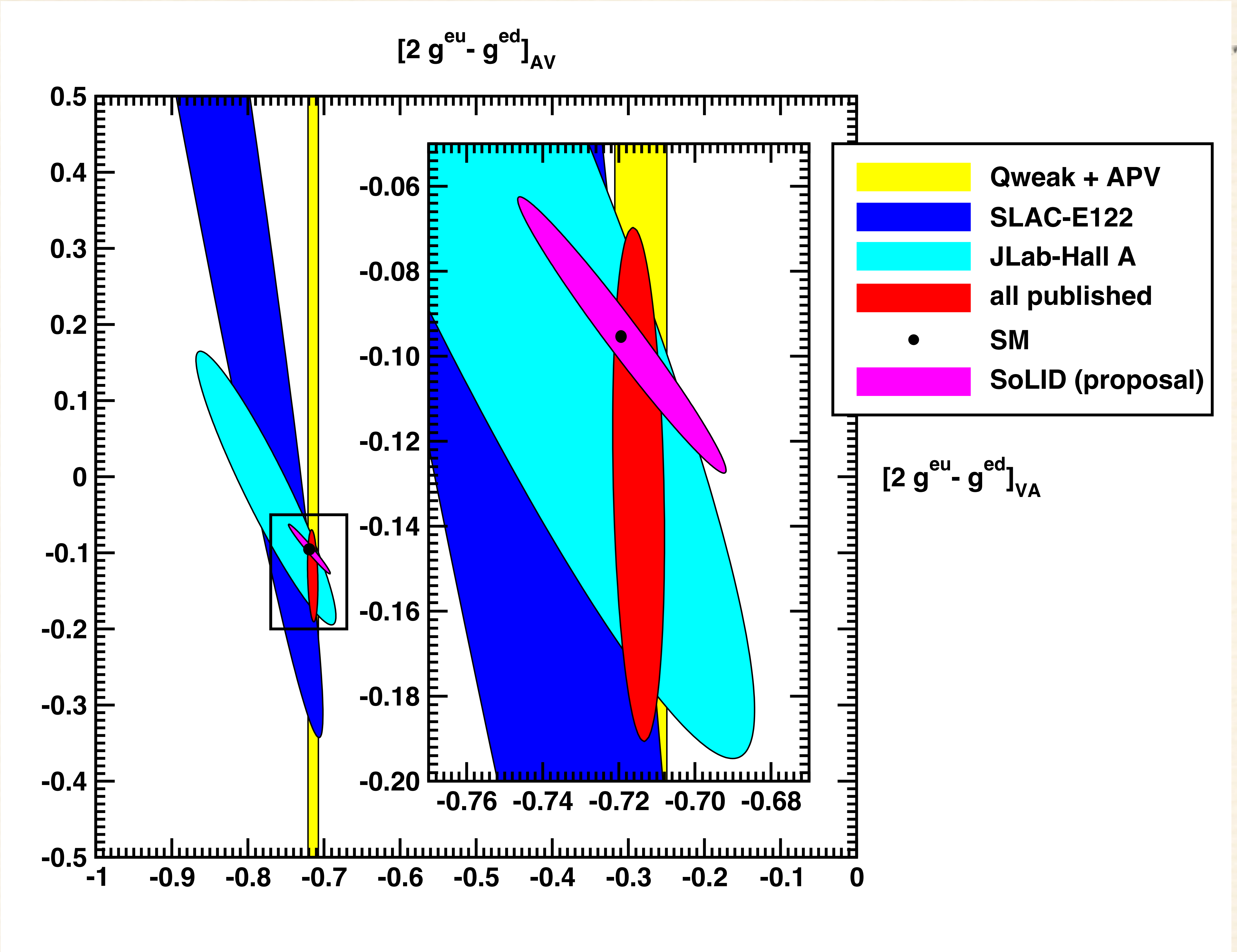
5 σ for h_{ee} ~ 1 and M_Δ ~ 1 TeV

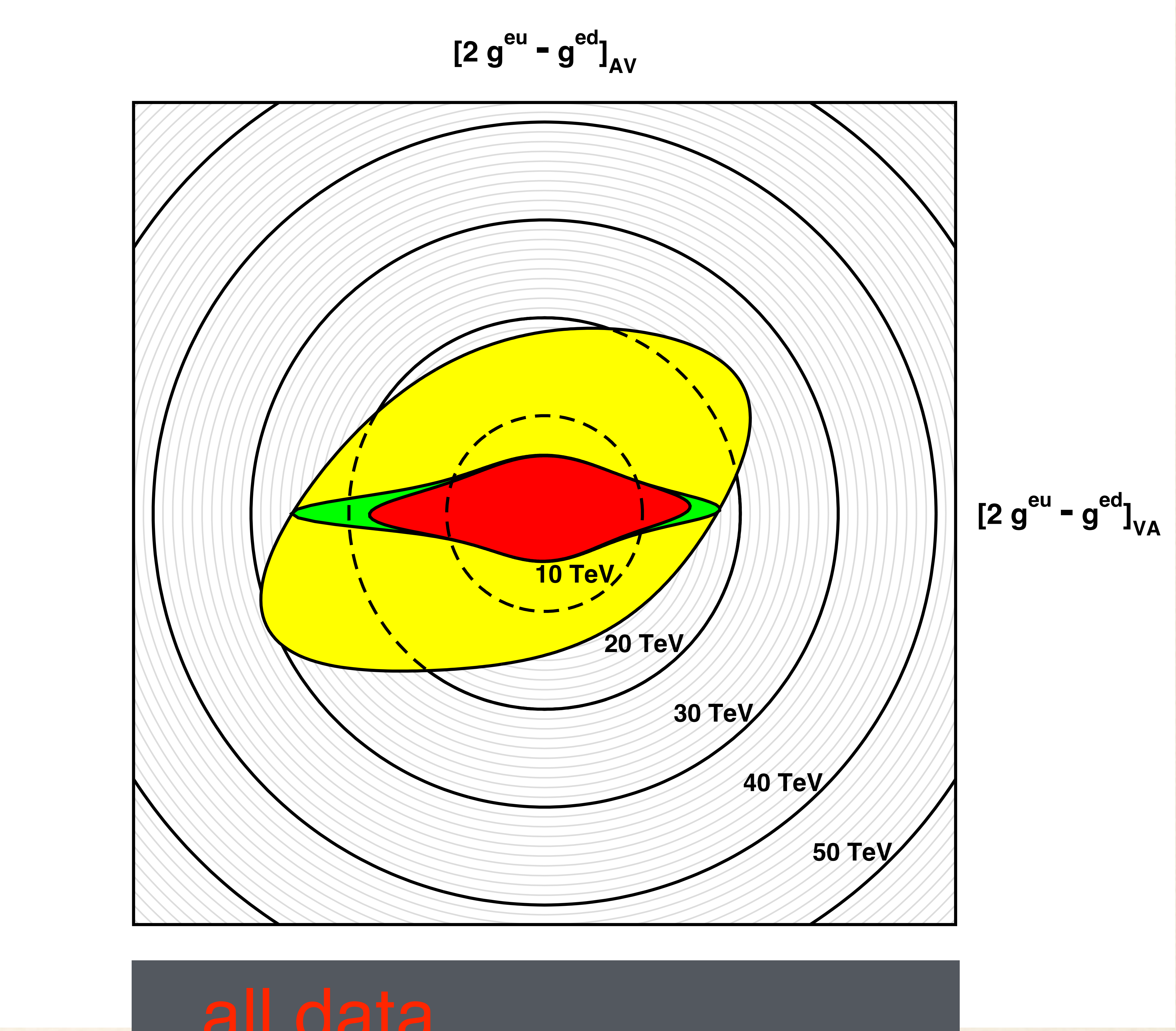
Specific Scenario for Type-II SeeSaw

B. Dev et al
PhysRevD.98.055013



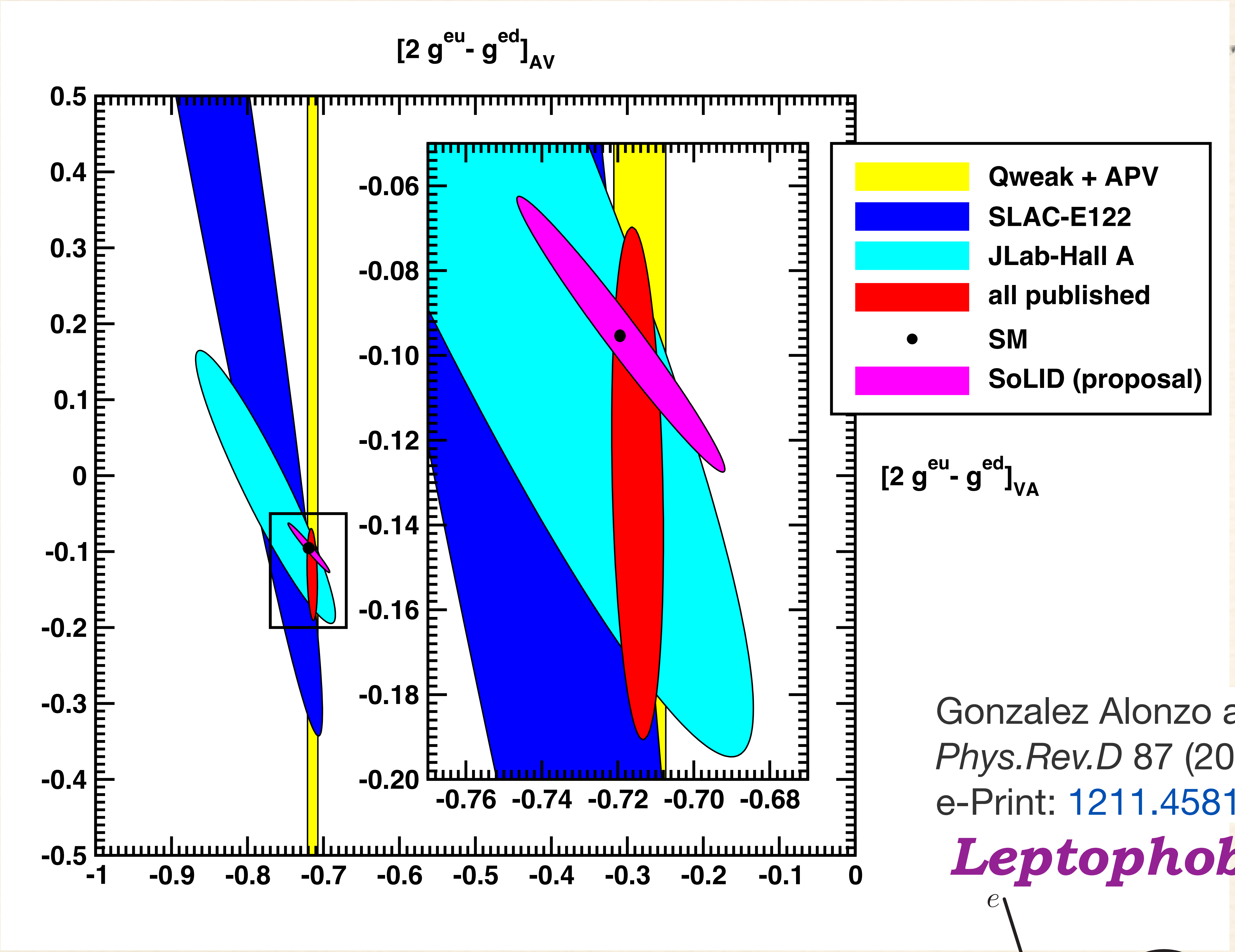
SOLID & P2: New Reach on e-q Couplings



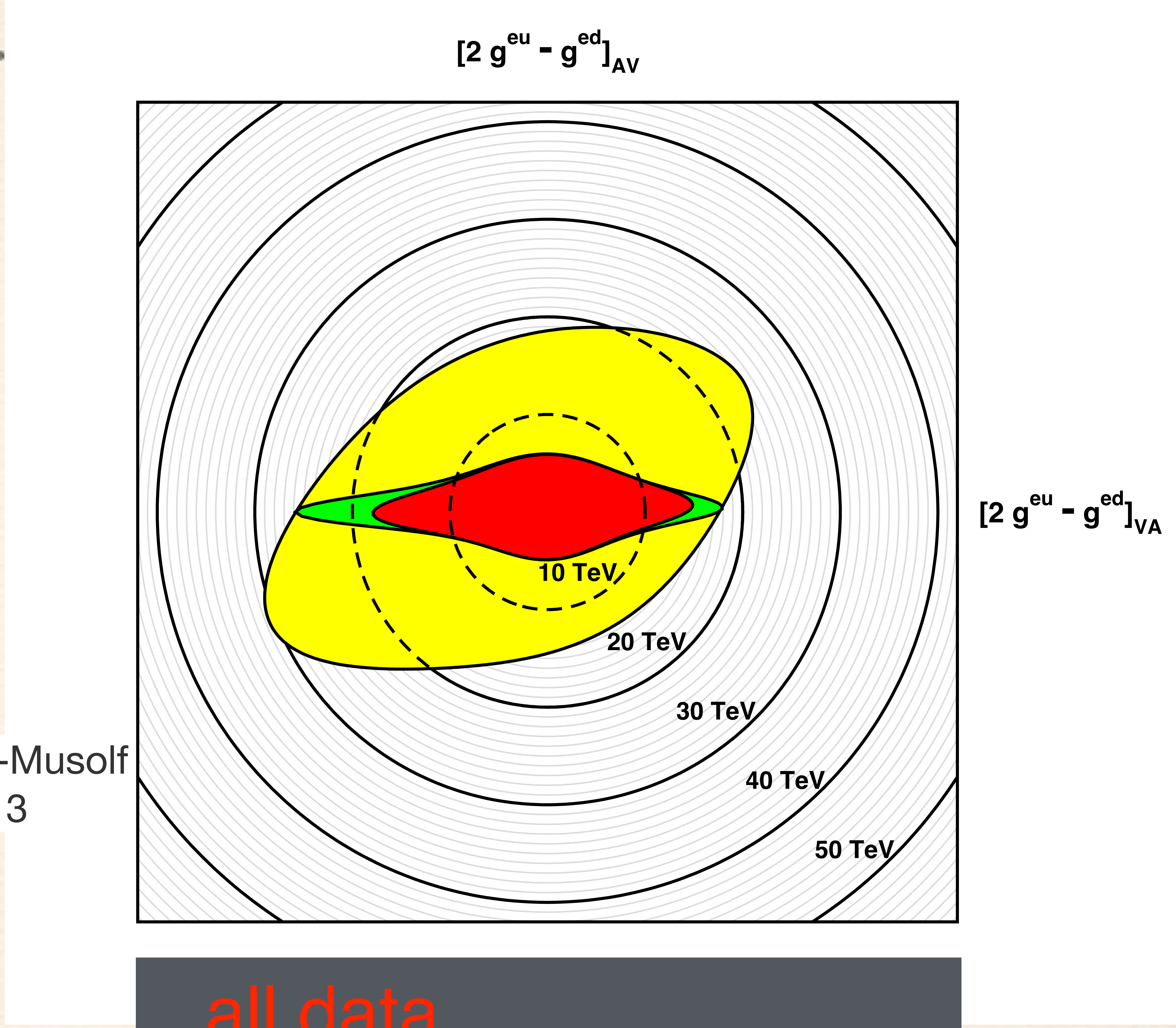


all data
all data + P2
all data + P2 + SoLID

SOLID & P2: New Reach on e-q Couplings

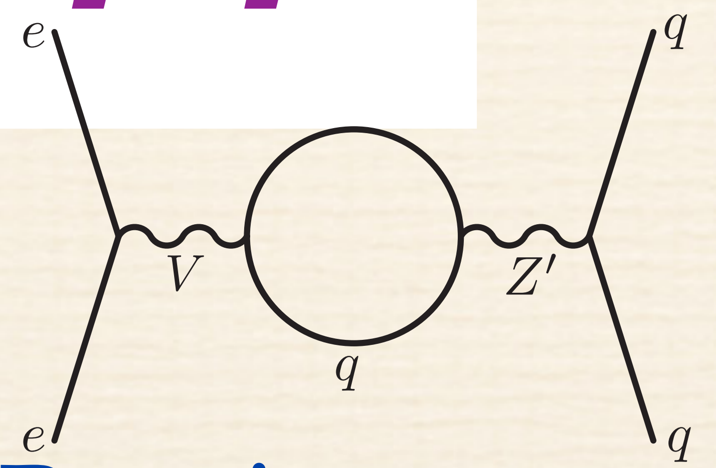


Gonzalez Alonzo and Ramsey-Musolf
Phys.Rev.D 87 (2013) 5, 055013
e-Print: 1211.4581



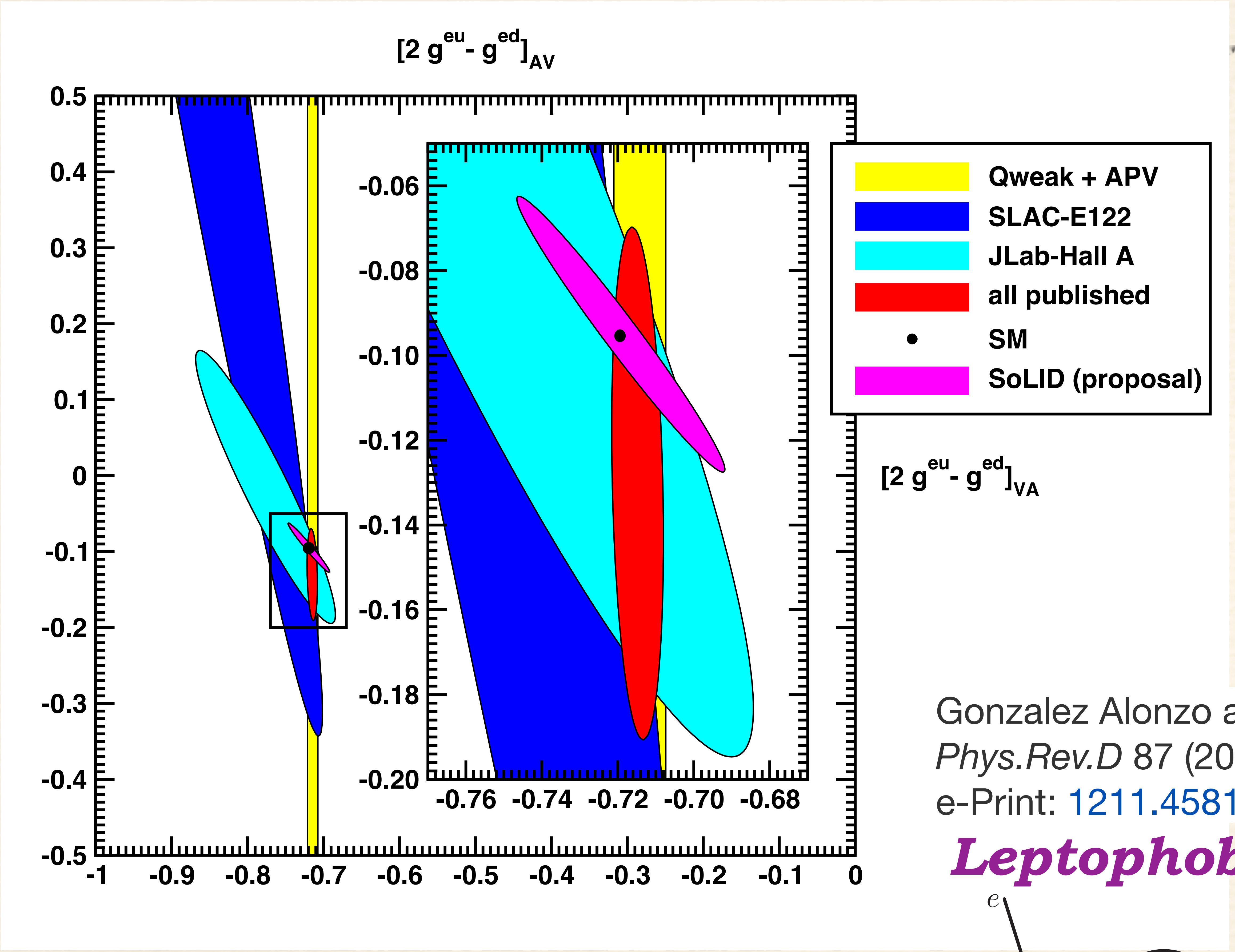
all data
all data + P2
all data + P2 + SoLID

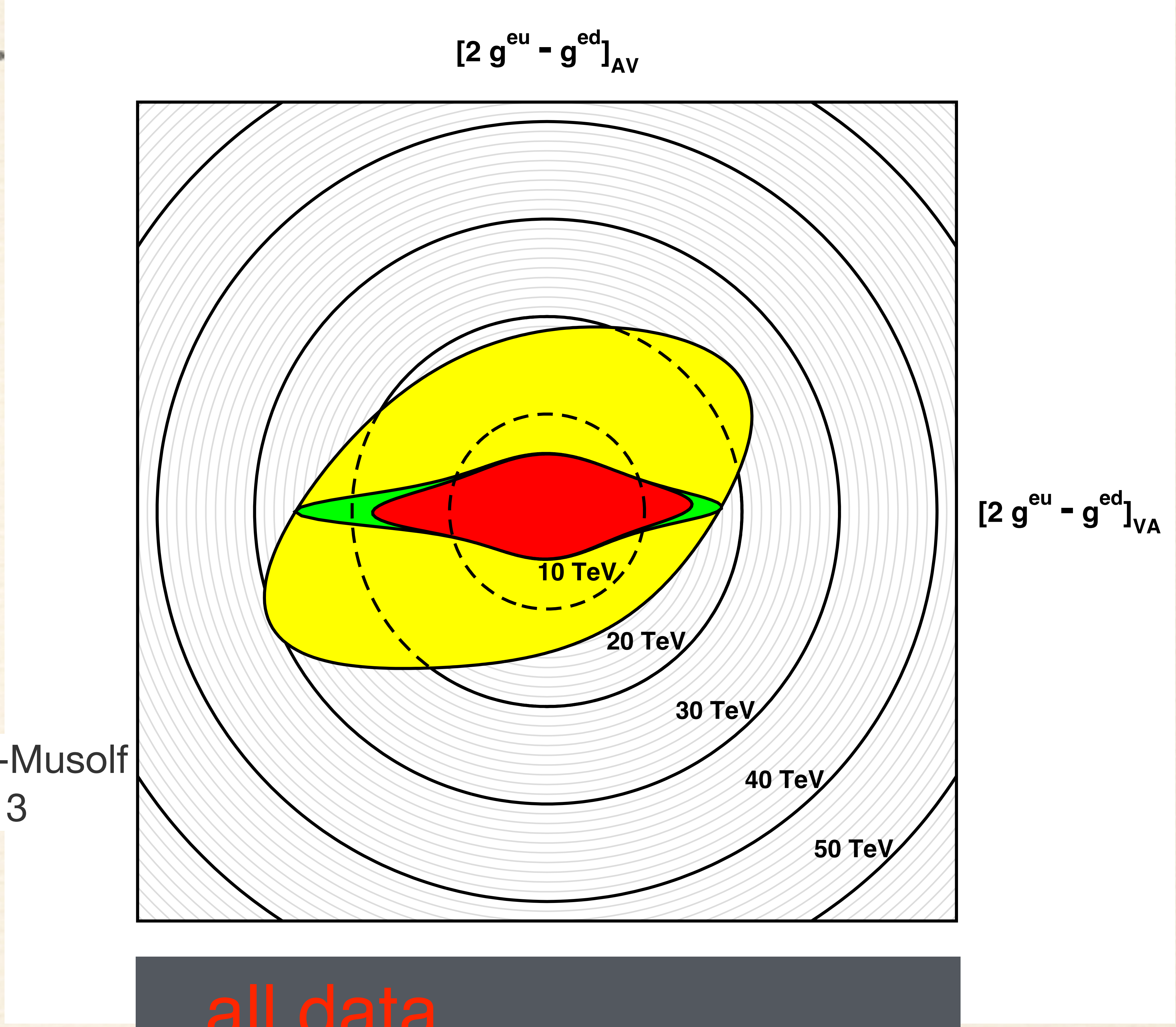
Leptophobic Z'



SOLID can improve sensitivity: 100-200 GeV range

SOLID & P2: New Reach on e-q Couplings

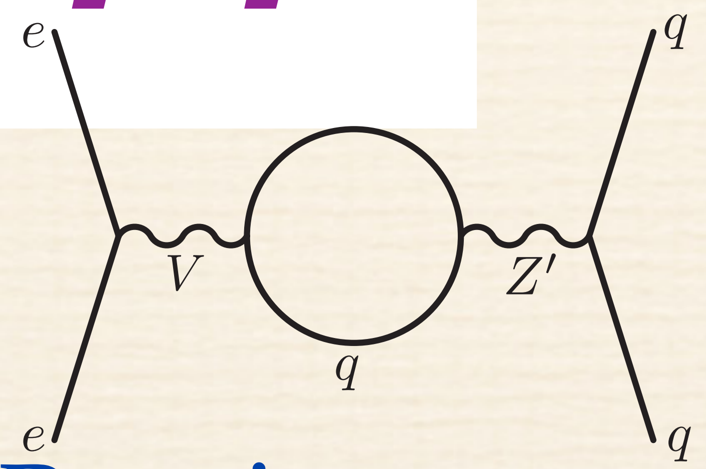




Gonzalez Alonzo and Ramsey-Musolf
Phys.Rev.D 87 (2013) 5, 055013
e-Print: 1211.4581

all data
all data + P2
all data + P2 + SoLID

Leptophobic Z'



Recent paper explores Z' sensitivity of P2 over a range of masses

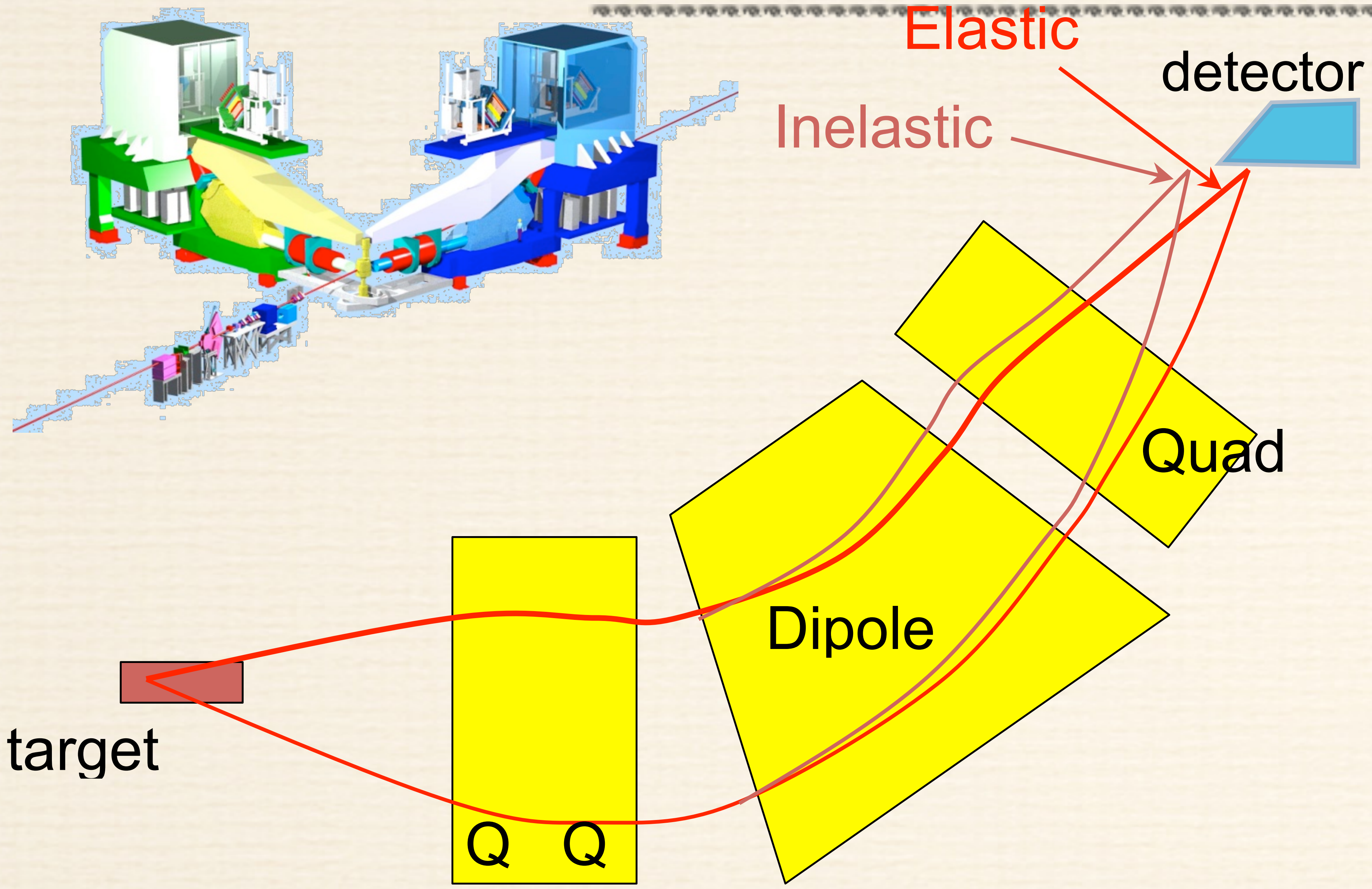
B. Dev et al: 2103.09067 [hep-ph

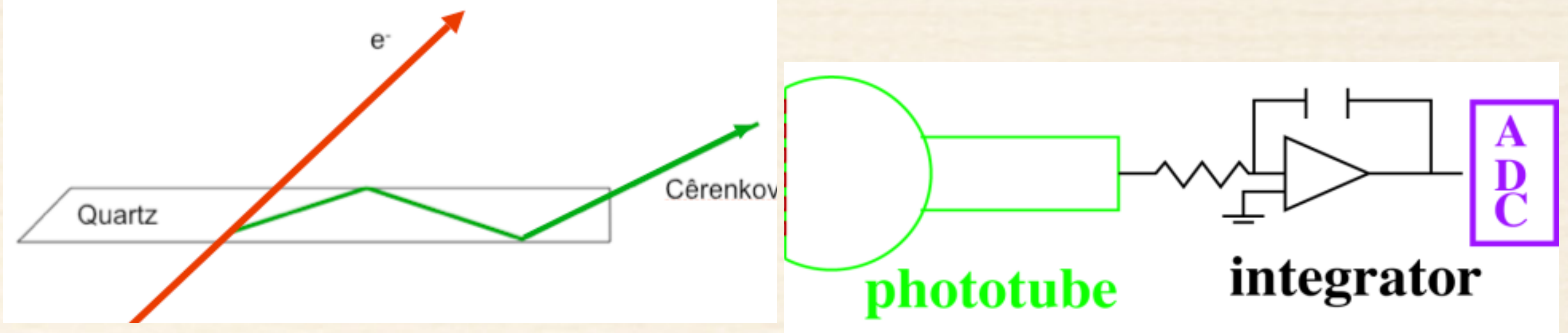
SOLID can improve sensitivity: 100-200 GeV range

second major SLAC E122 innovation: “flux integration”

High Flux, Low Background

Hall A High Resolution Spectrometers





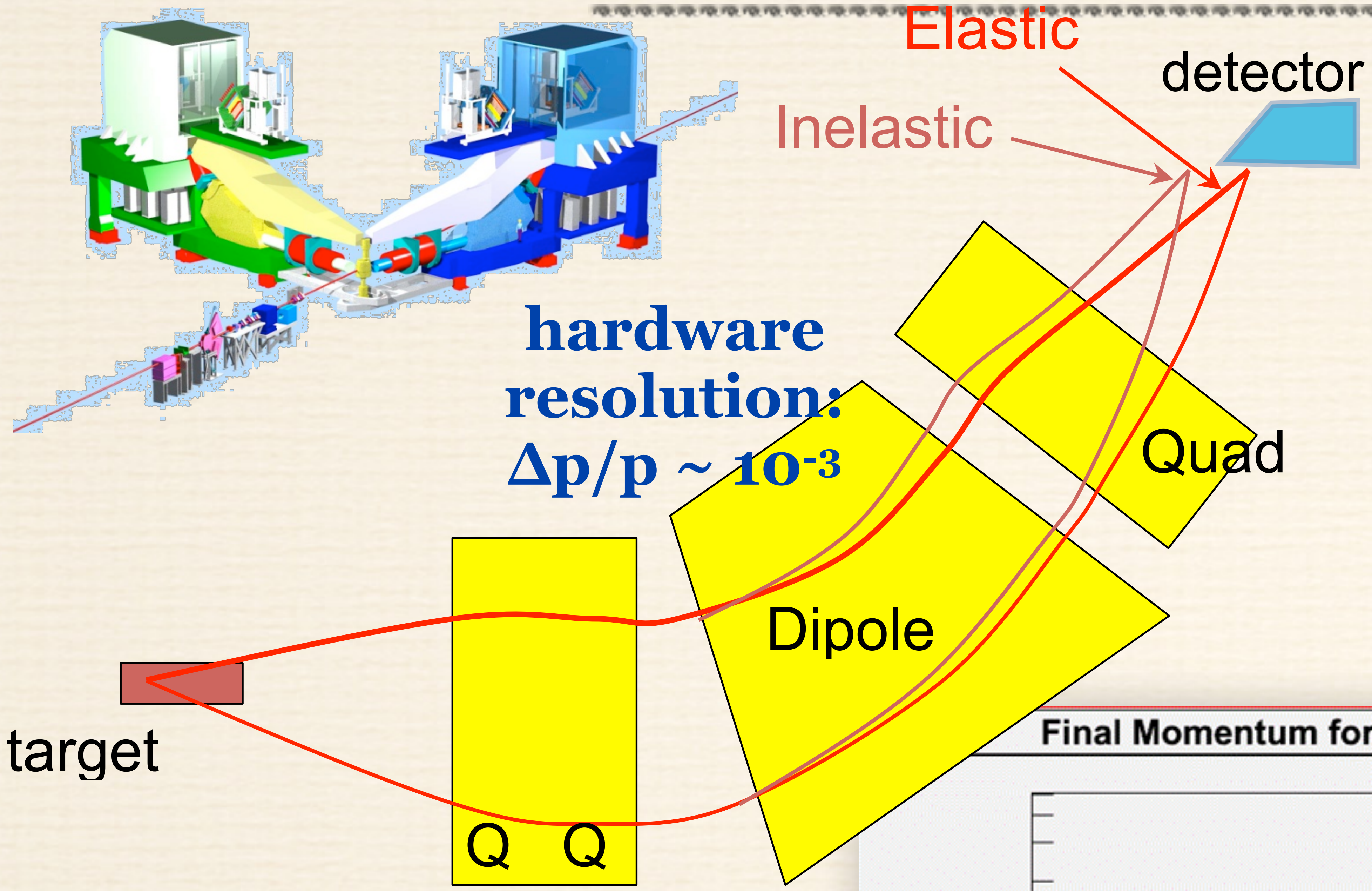
3 GHz scattered flux

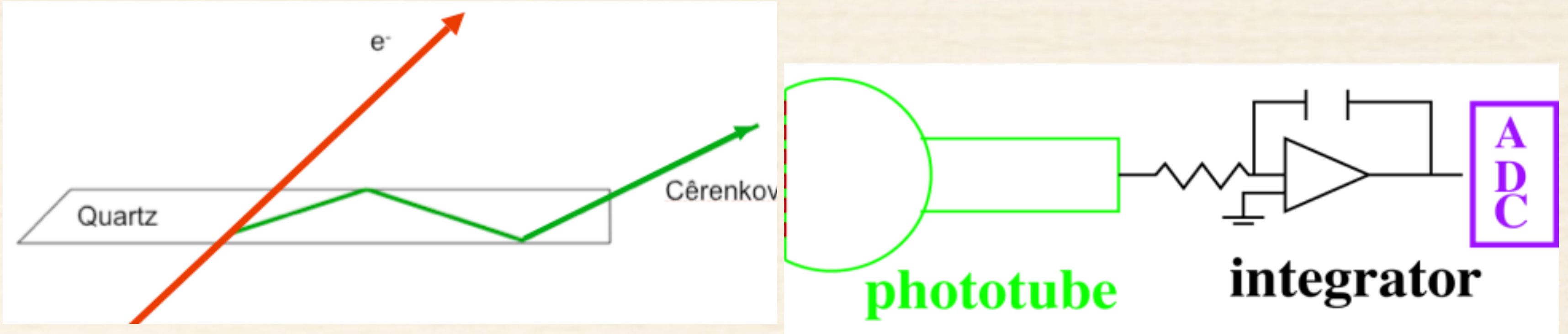
1 x 10^{-4} statistical uncertainty
30 times per second

second major SLAC E122 innovation: "flux integration"

High Flux, Low Background

Hall A High Resolution Spectrometers

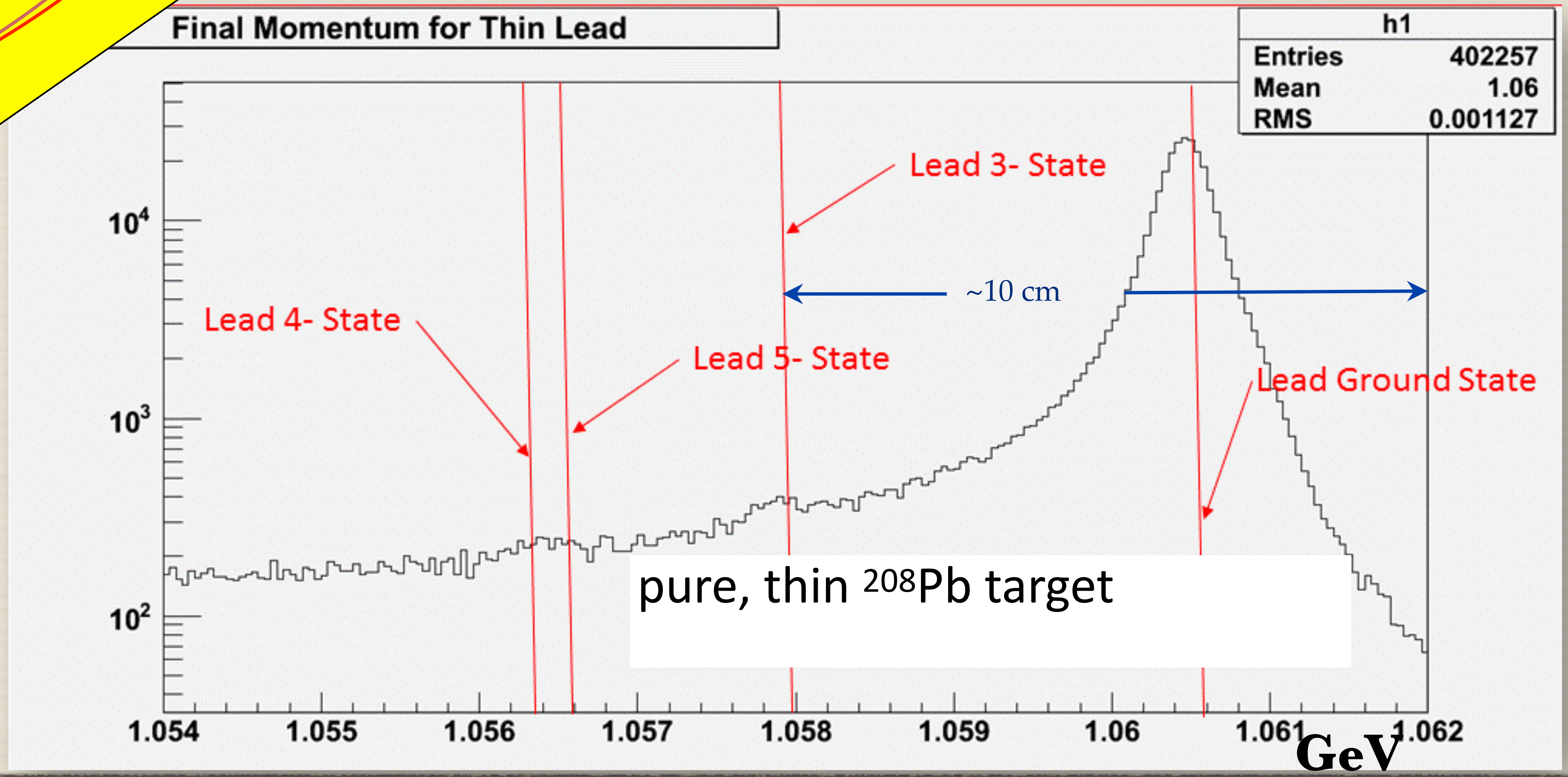




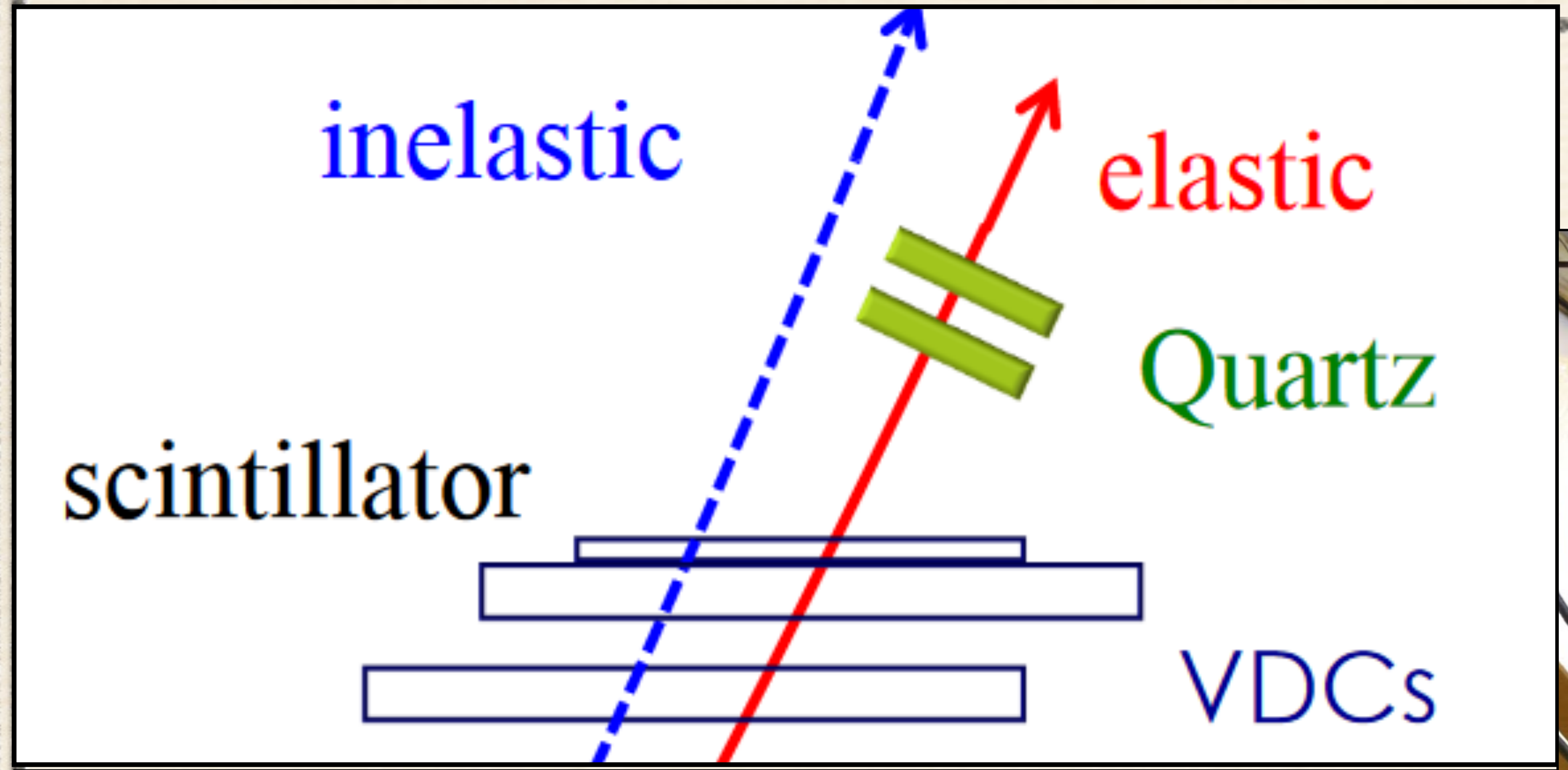
3 GHz scattered flux

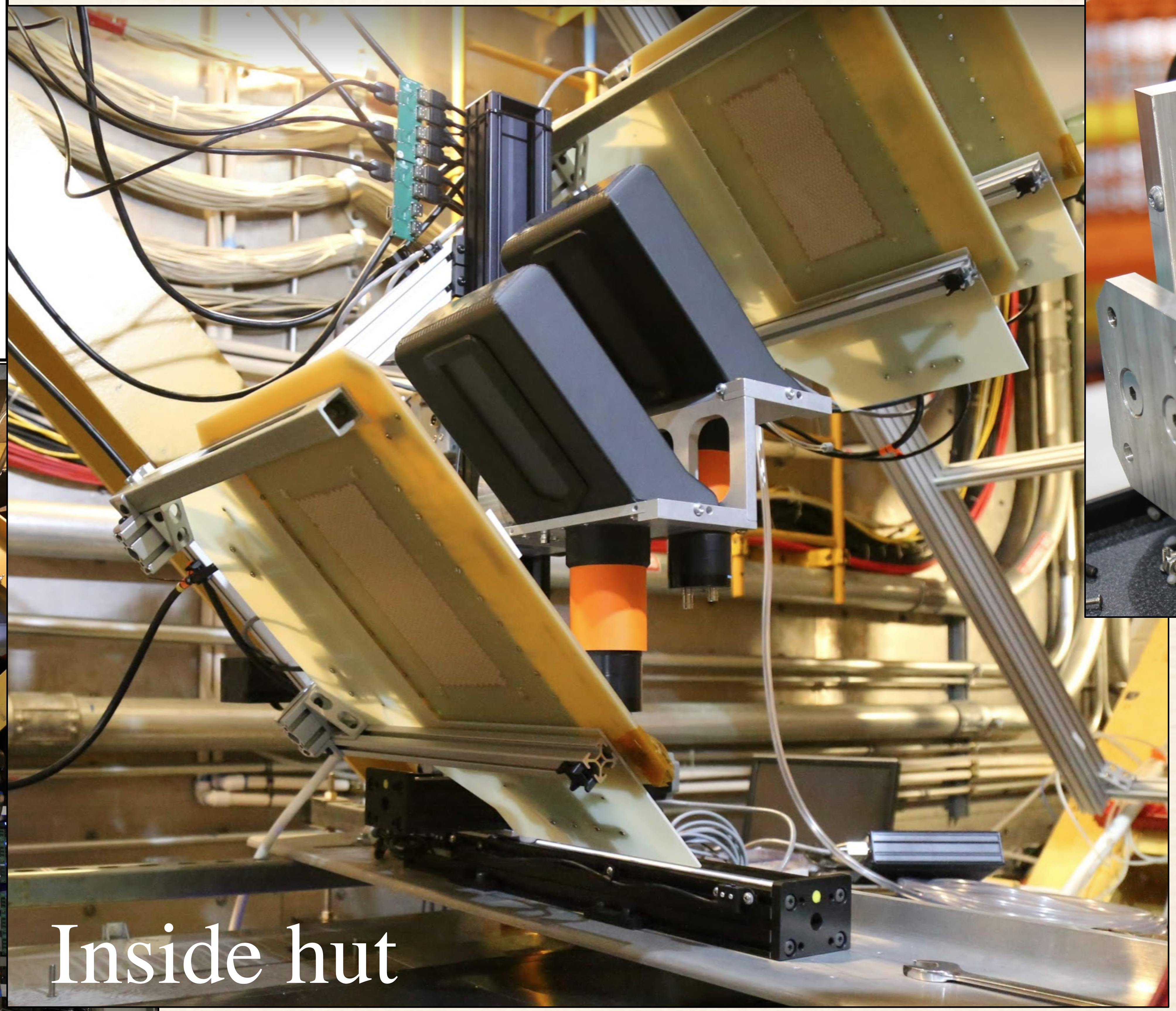
1×10^{-4} statistical uncertainty
30 times per second

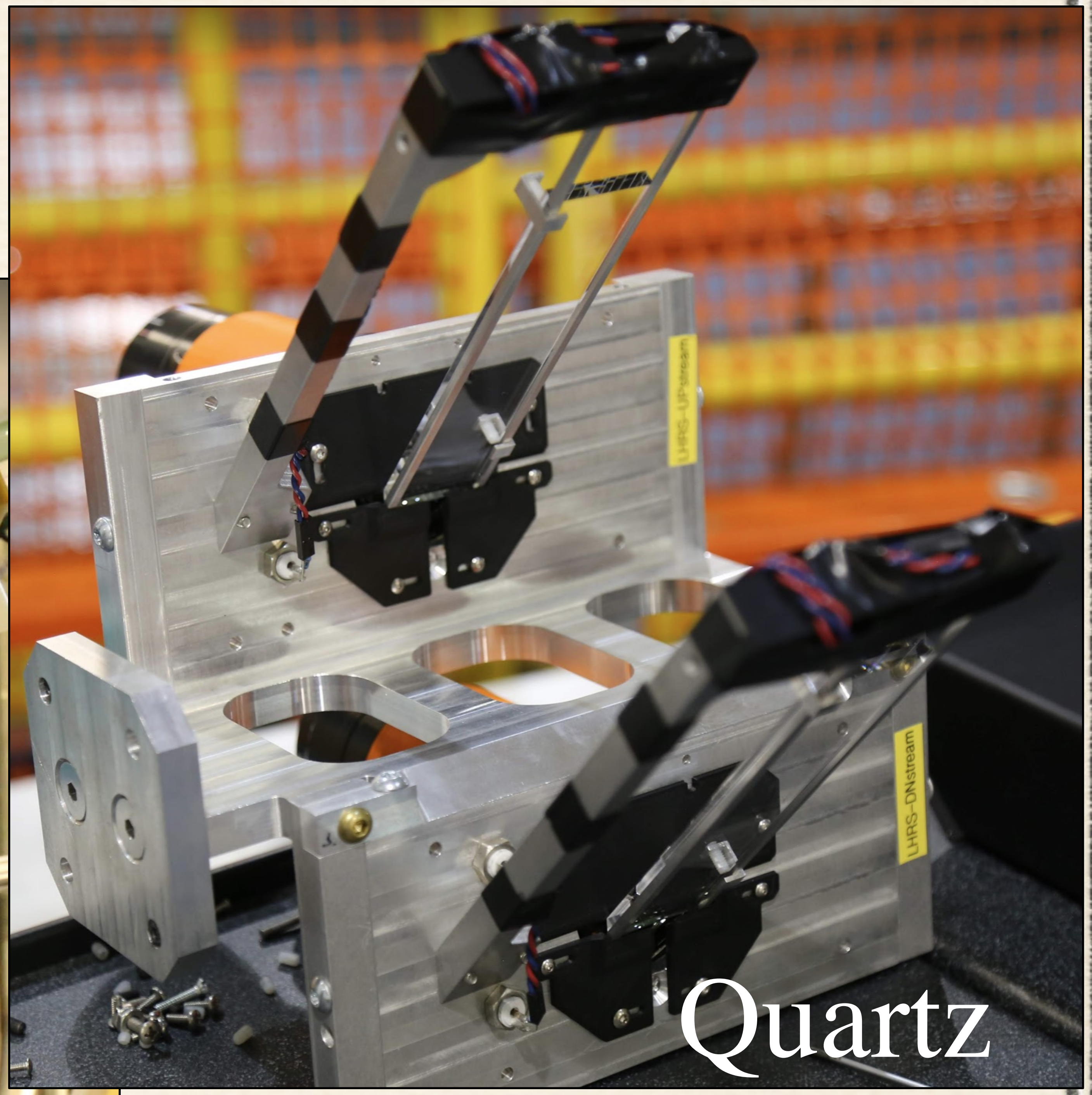
Inelastic backgrounds negligible



Inside the HRS "Counting Hut"



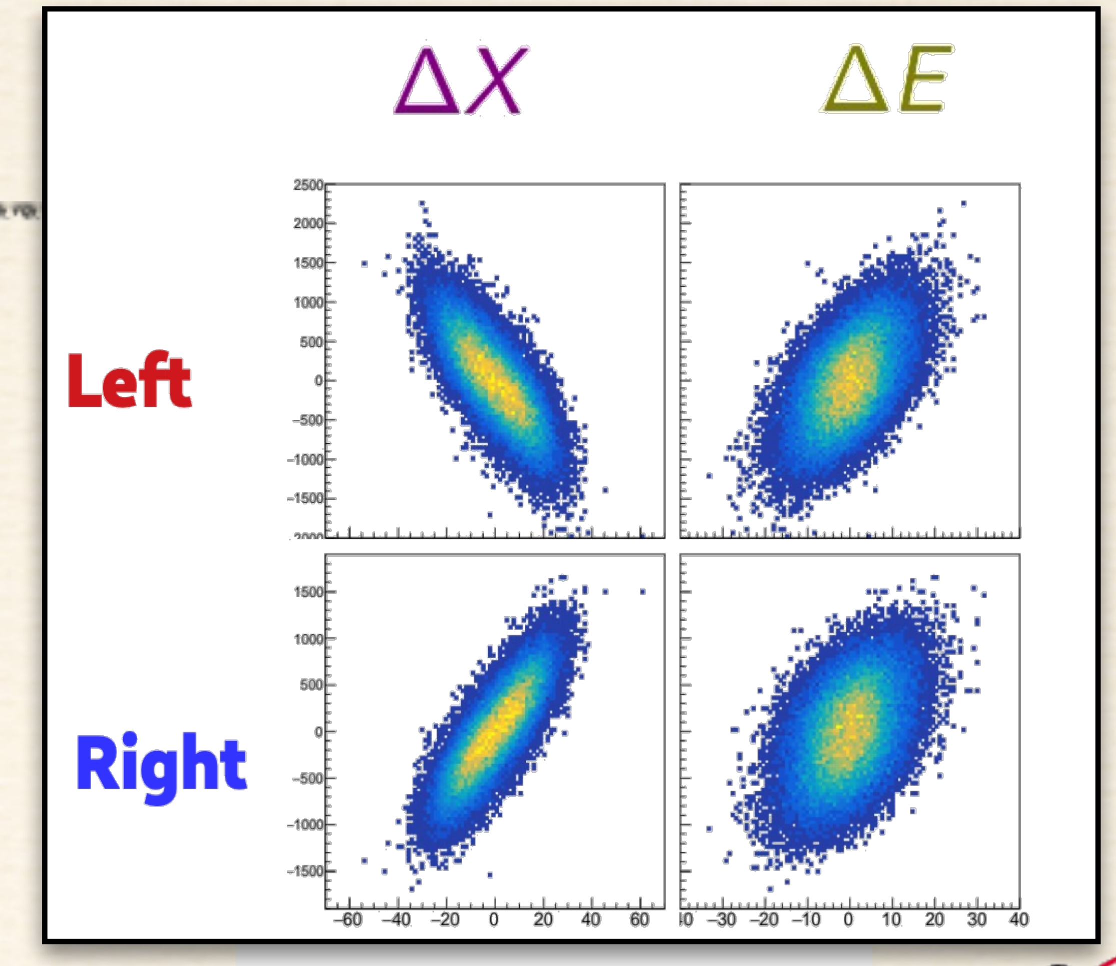




- Integrating detectors (reduce deadtime effects)
- Thick and thin quartz bars (different systematics)

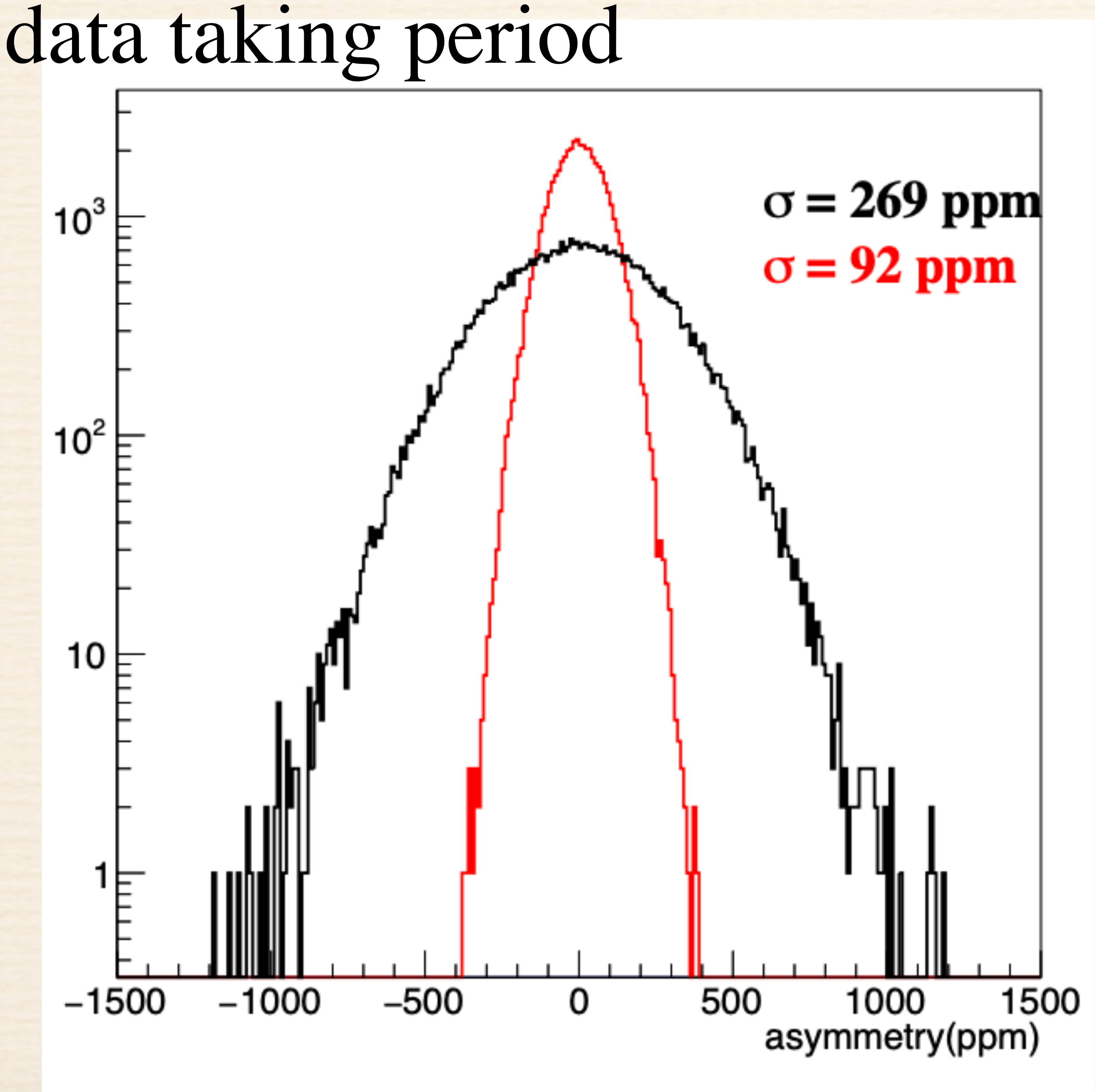
Corrections for Beam Fluctuations

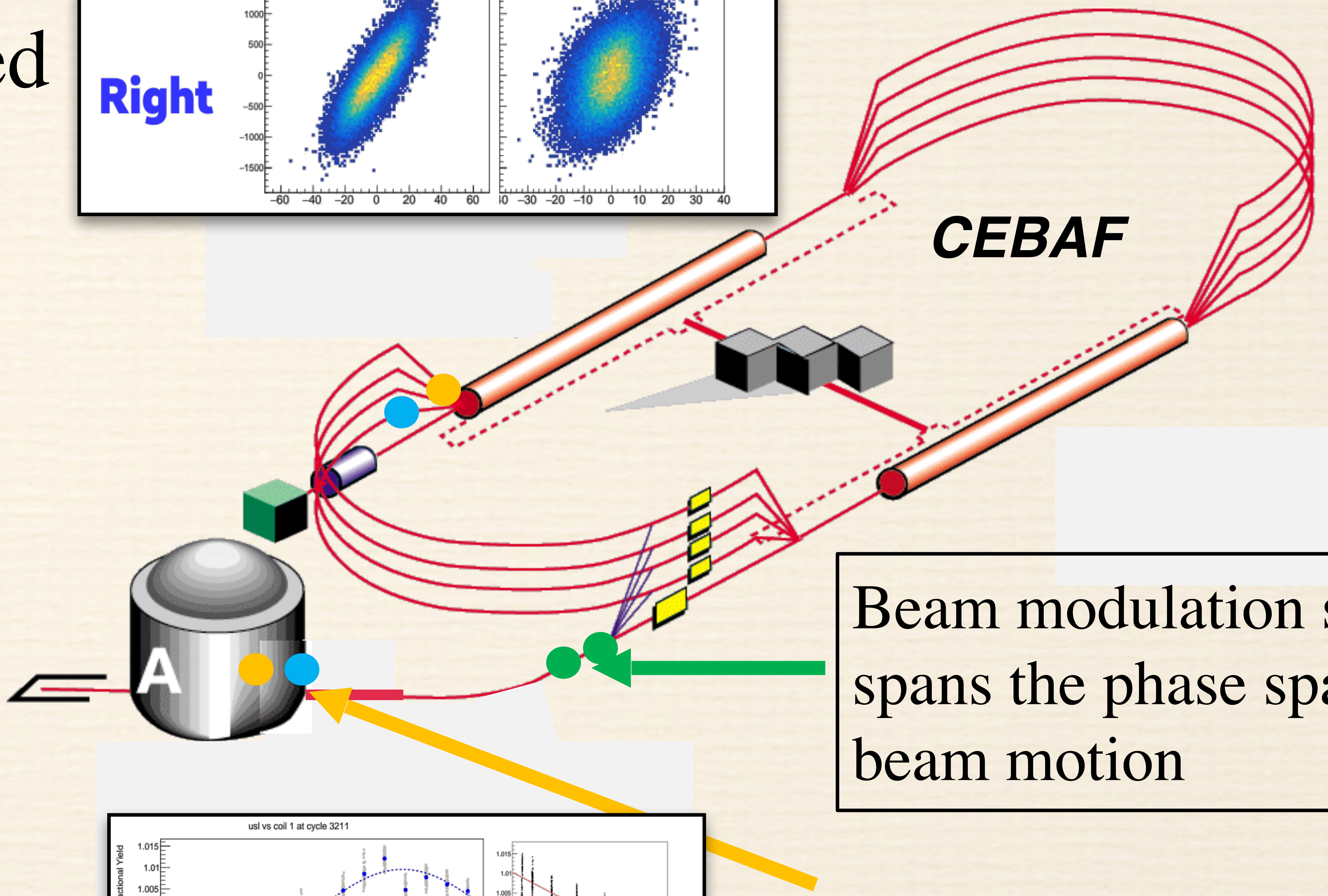
- To span the 5 dimension phase space of beam motion at the target (position, angle, energy) we made use of a set of 6 coils and an energy vernier
  - This modulation is automated and was performed throughout the data taking period



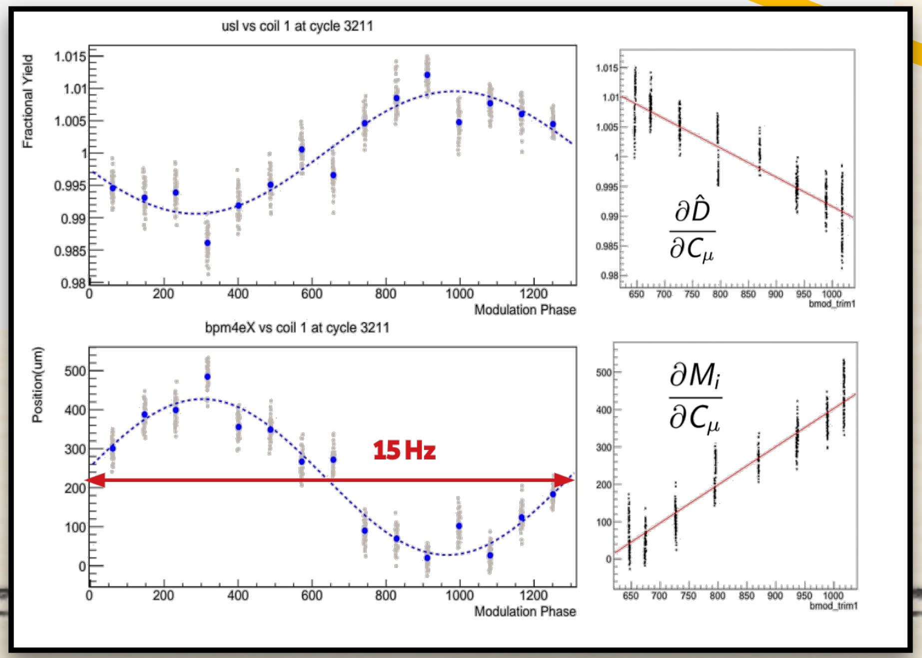
$$A_{corr} = A_{det} - A_Q + \alpha\,\Delta_E + \Sigma\beta_i\,\Delta x_i$$

$A_{corr} \sim$ **500 ppb**





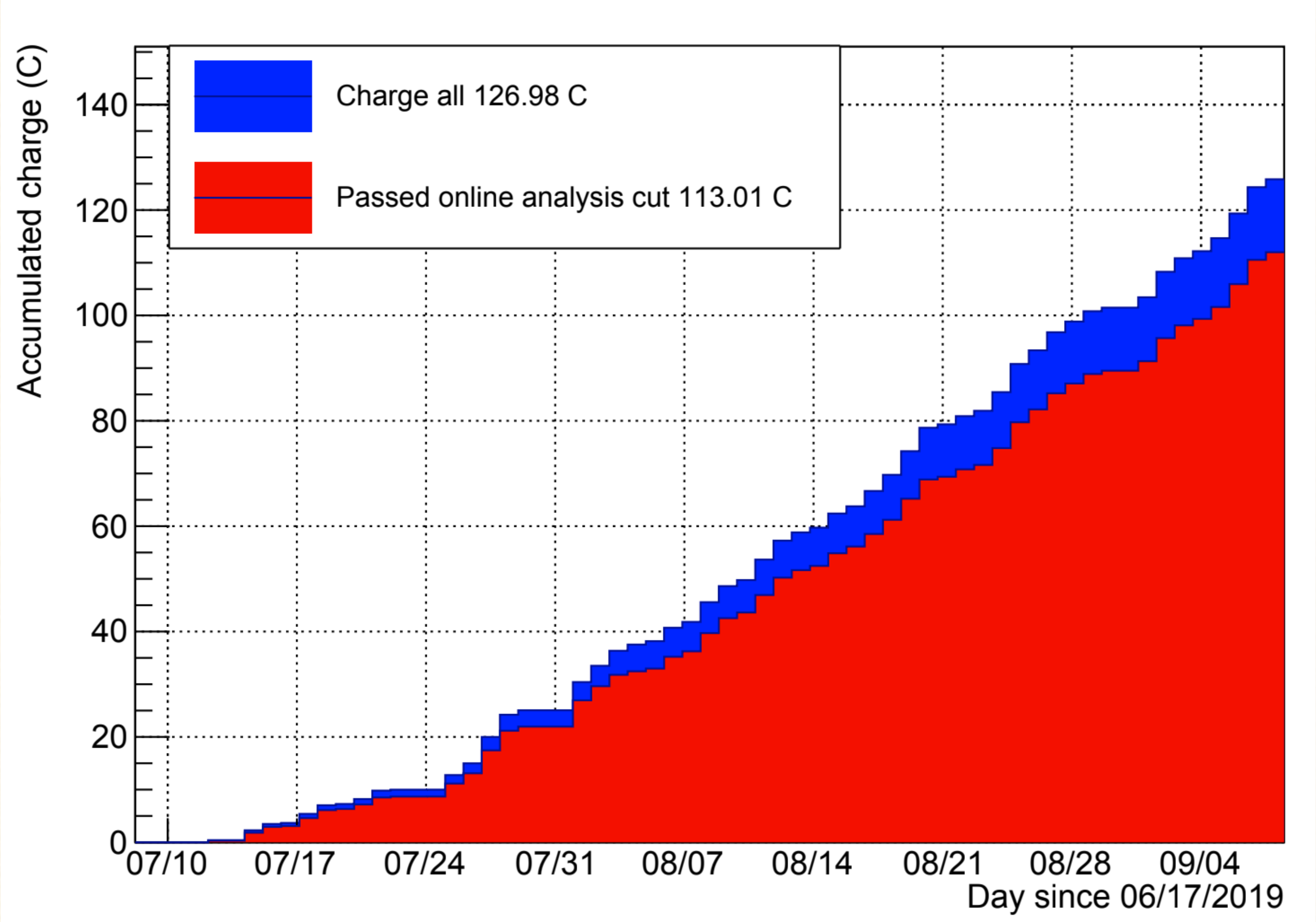
Beam modulation system spans the phase space of beam motion



Beam monitors determine trajectory and parameters onto target

PREX-2 Run: Summer 2019

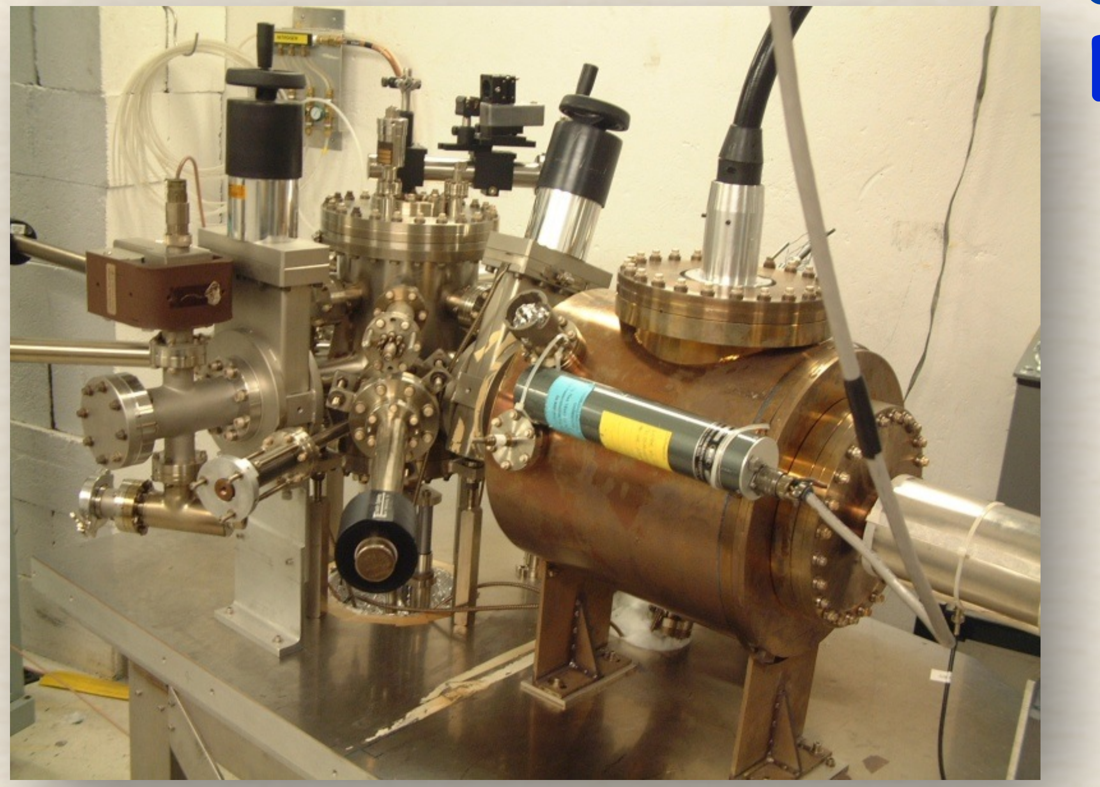
- 13 Ph.D. students, 7 postdocs, a total of about 80 scientists
- Very close watch on-line data stream - beam conditions, detector response, etc.
- Frequent contact with machine operators to maintain running conditions
- “prompt" analysis flagged subtle probe: review of beam performance by PhD students in weekly shifts



- At the end of the experiment after our realtime analysis we collected about 113 C of charge on target with only about 14 C being excluded in calibrations or due to poor beam conditions (mostly, trip recovery, beam excursions, or beam monitor issues)

PREX-2 ran from June to September 2019

Stability of Polarized Beam for PREX-2



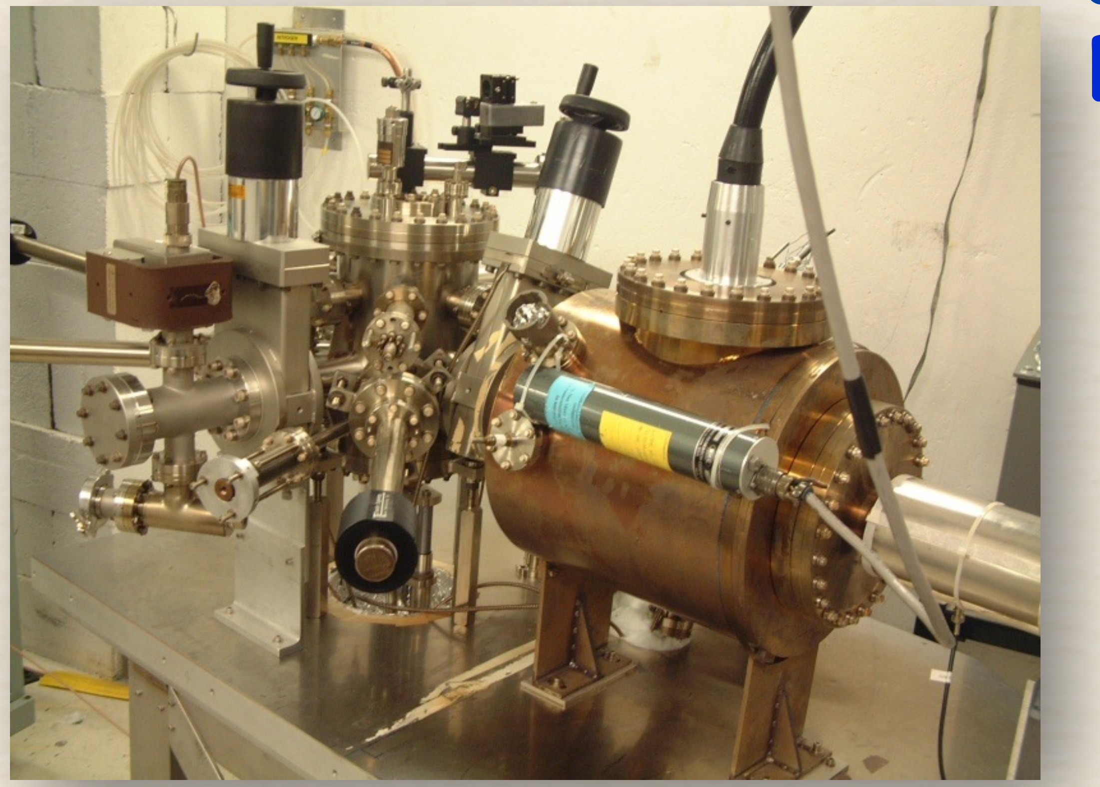
Beam helicity is chosen pseudo-randomly at multiple of 30 Hz

$A_{corr} \sim 500$ ppb

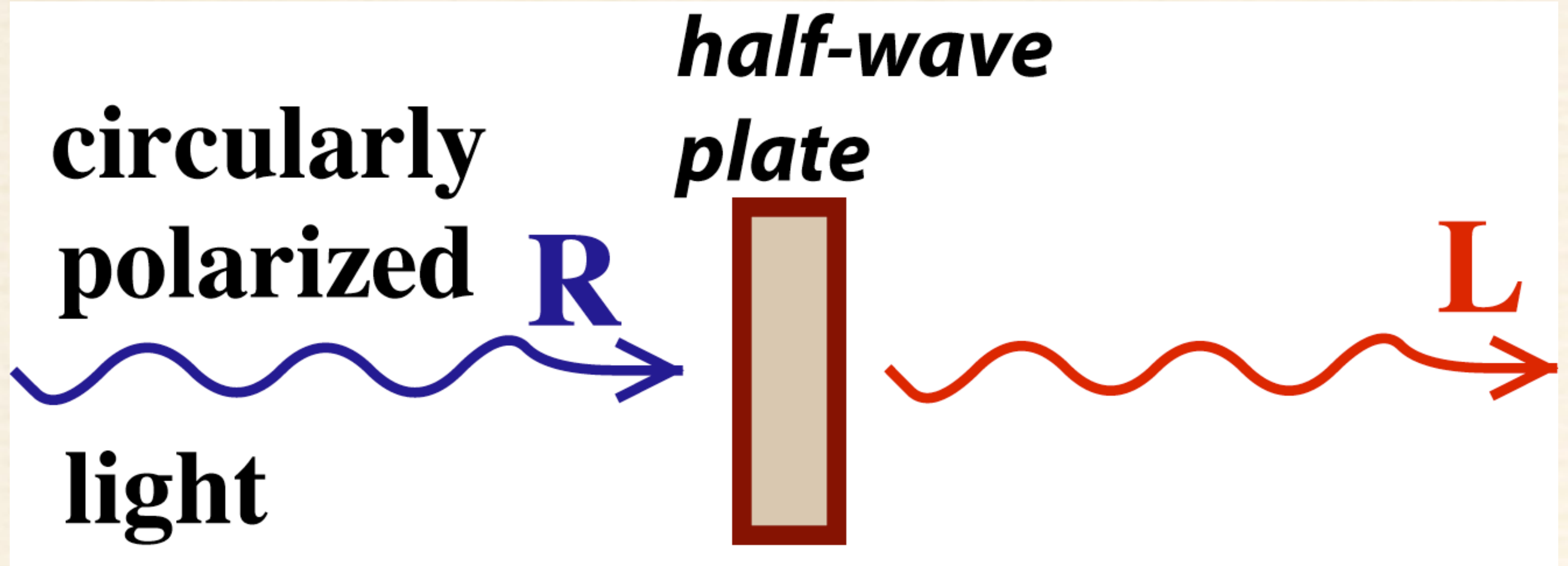
$$A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma \beta_i\, \Delta x_i$$

PREX-2 ran from June to September 2019

Stability of Polarized Beam for PREX-2



Beam helicity is chosen pseudo-randomly at multiple of 30 Hz

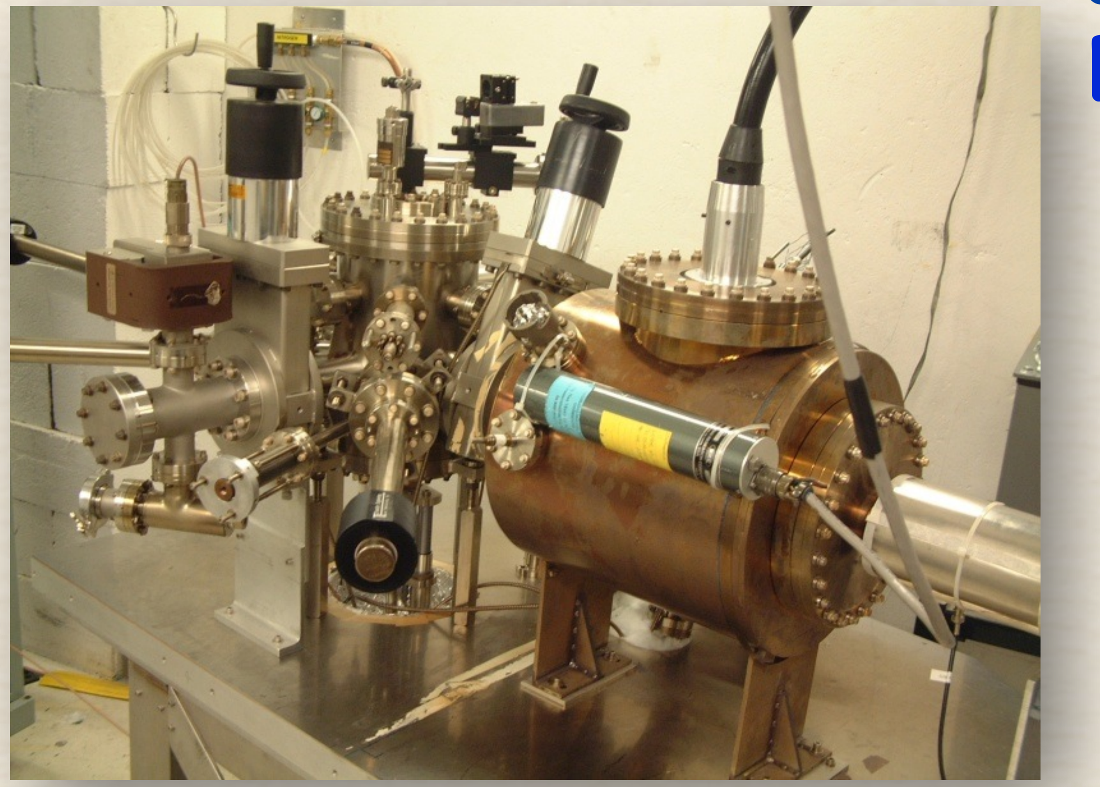


$A_{corr} \sim 500$ ppb

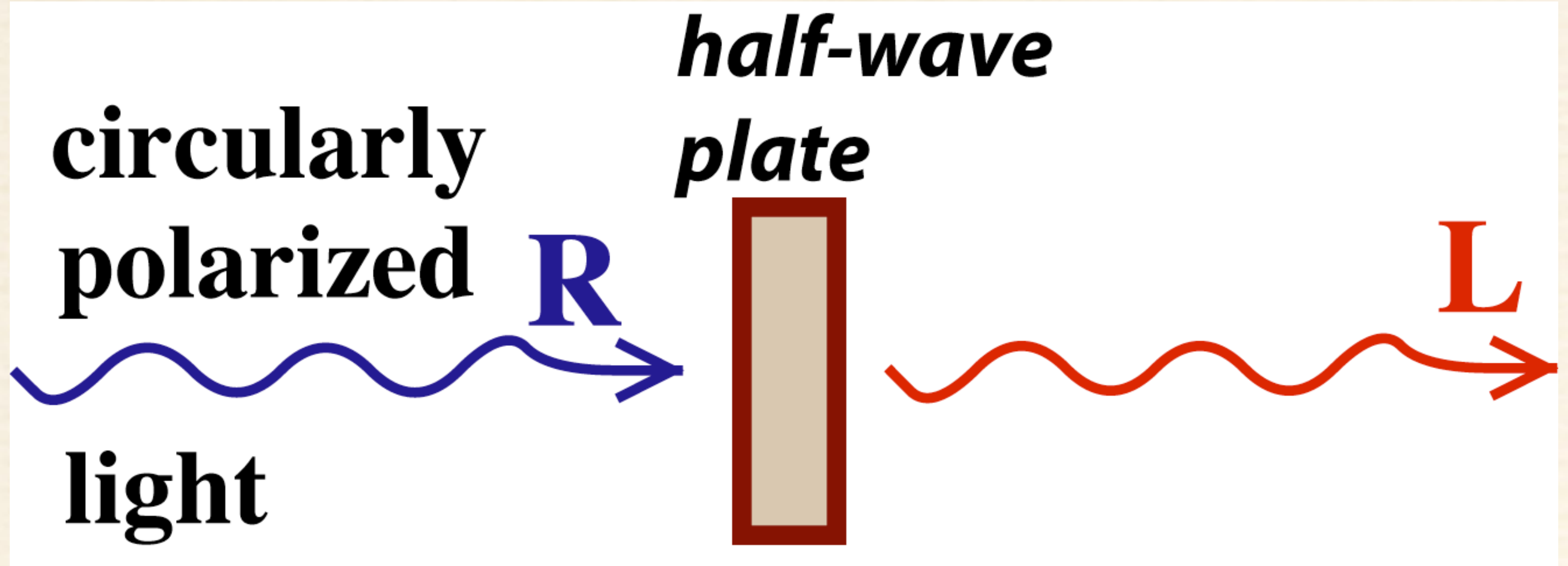
$$A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma\beta_i\, \Delta x_i$$

PREX-2 ran from June to September 2019

Stability of Polarized Beam for PREX-2



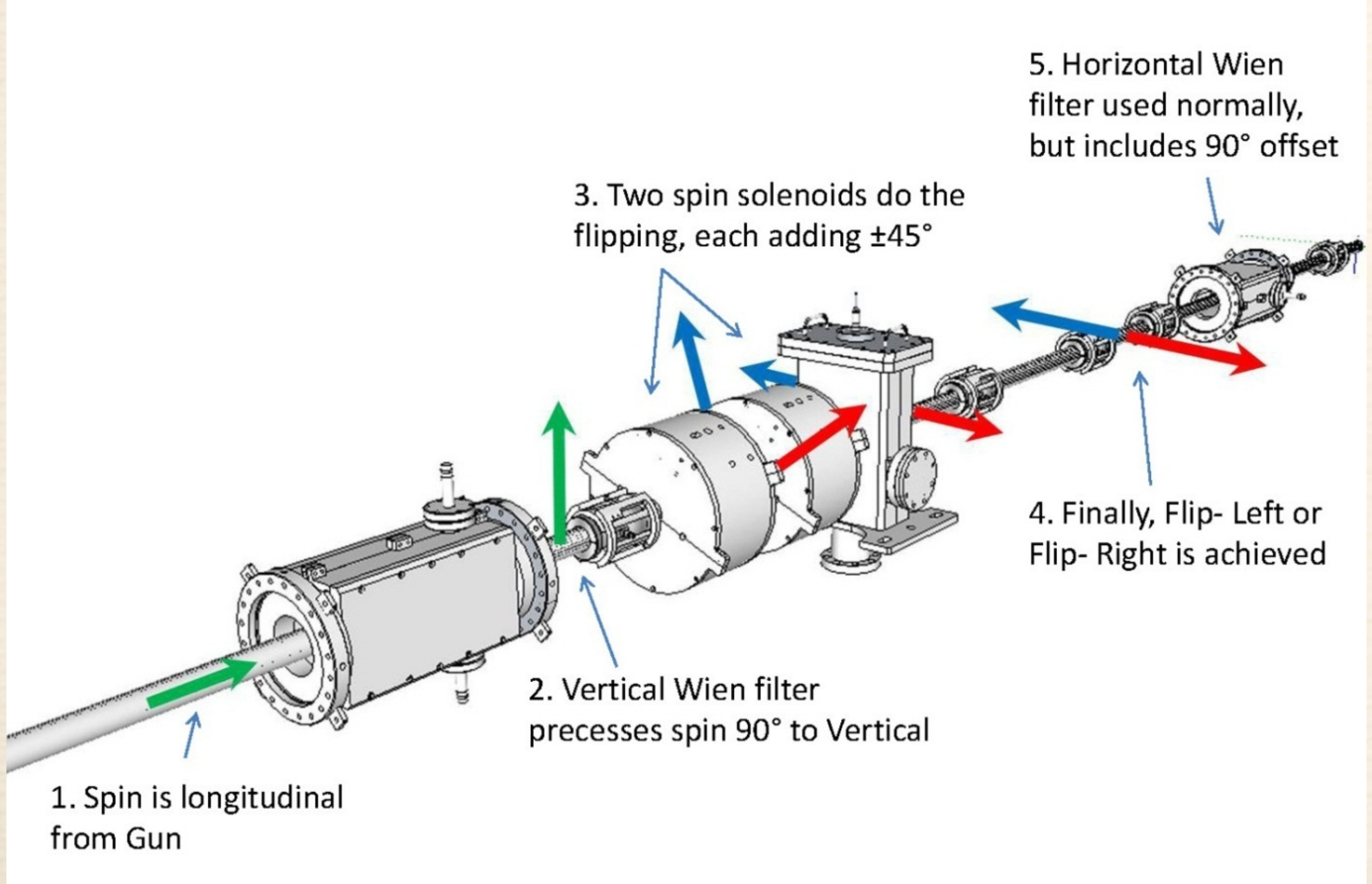
Beam helicity is chosen pseudo-randomly at multiple of 30 Hz



$A_{corr} \sim 500$ ppb

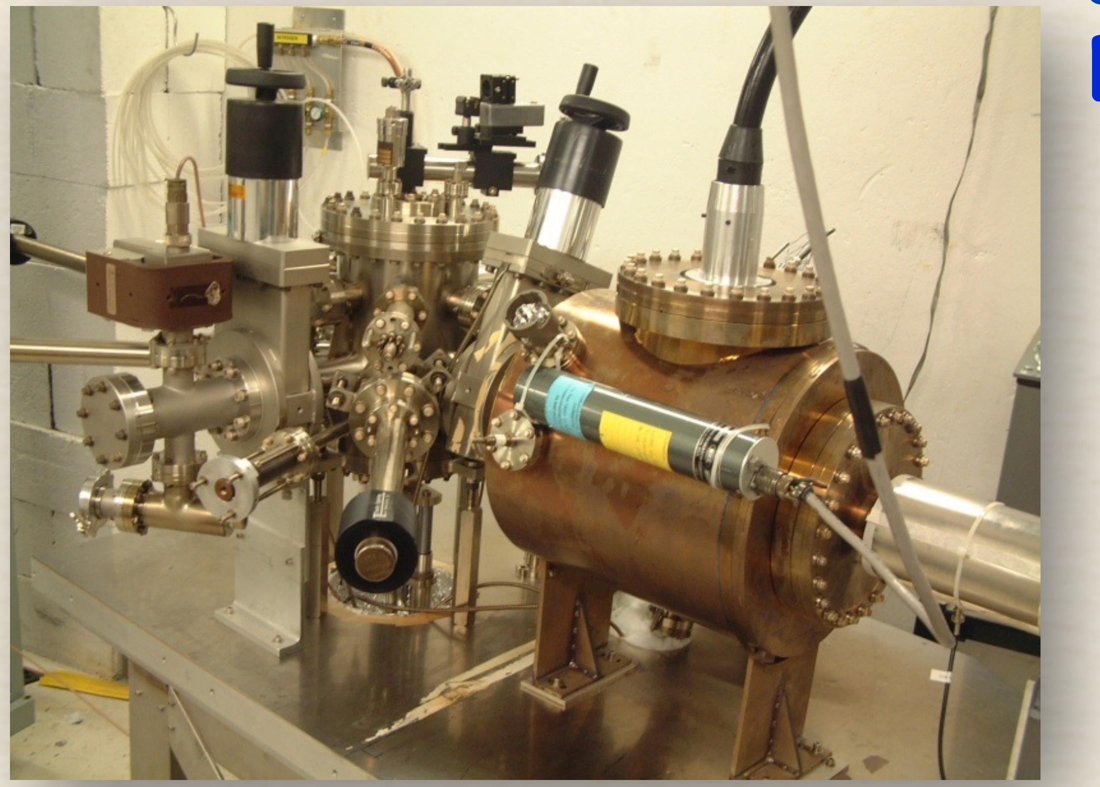
$$A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma\beta_i\, \Delta x_i$$

Injector Two Wien Flipper – QWeak setup (Nov-Dec, 2011) – J. Grames

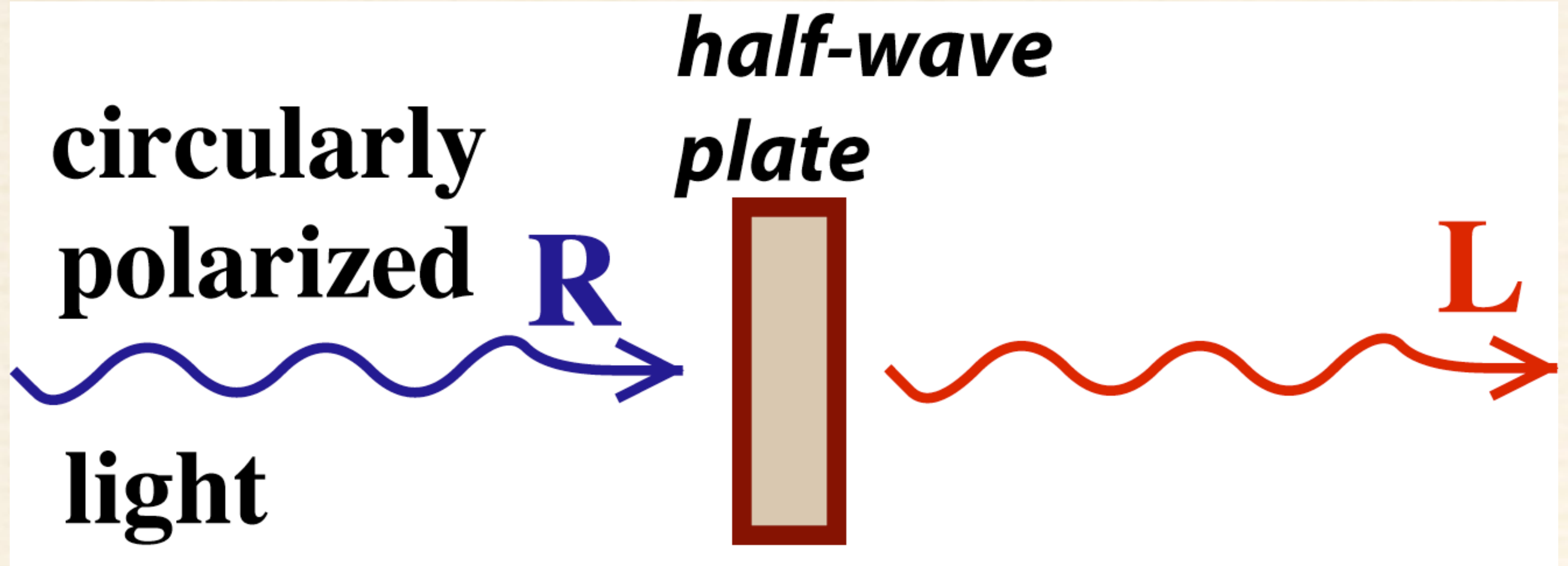


PREX-2 ran from June to September 2019

Stability of Polarized Beam for PREX-2



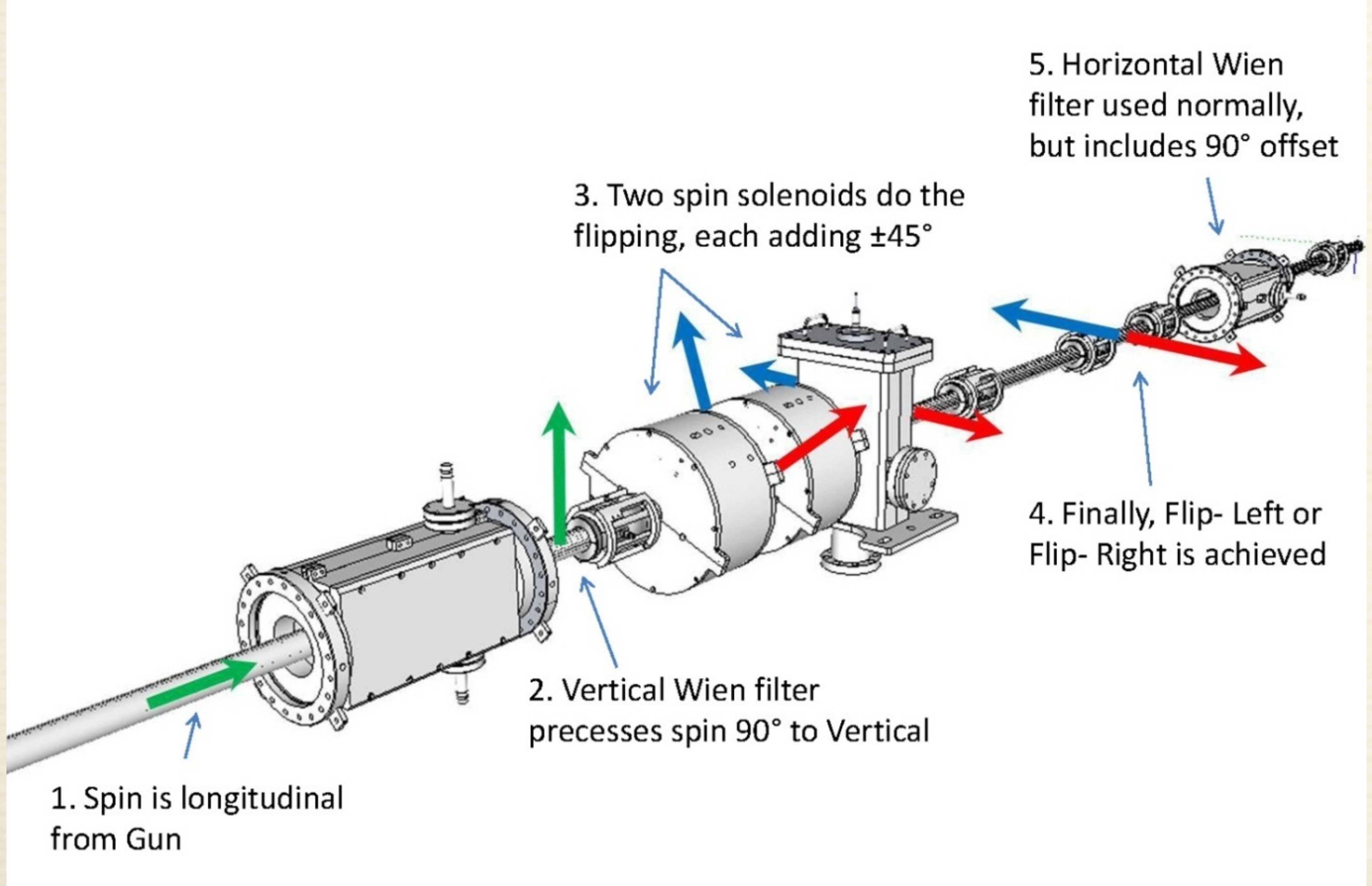
Beam helicity is chosen pseudo-randomly at multiple of 30 Hz



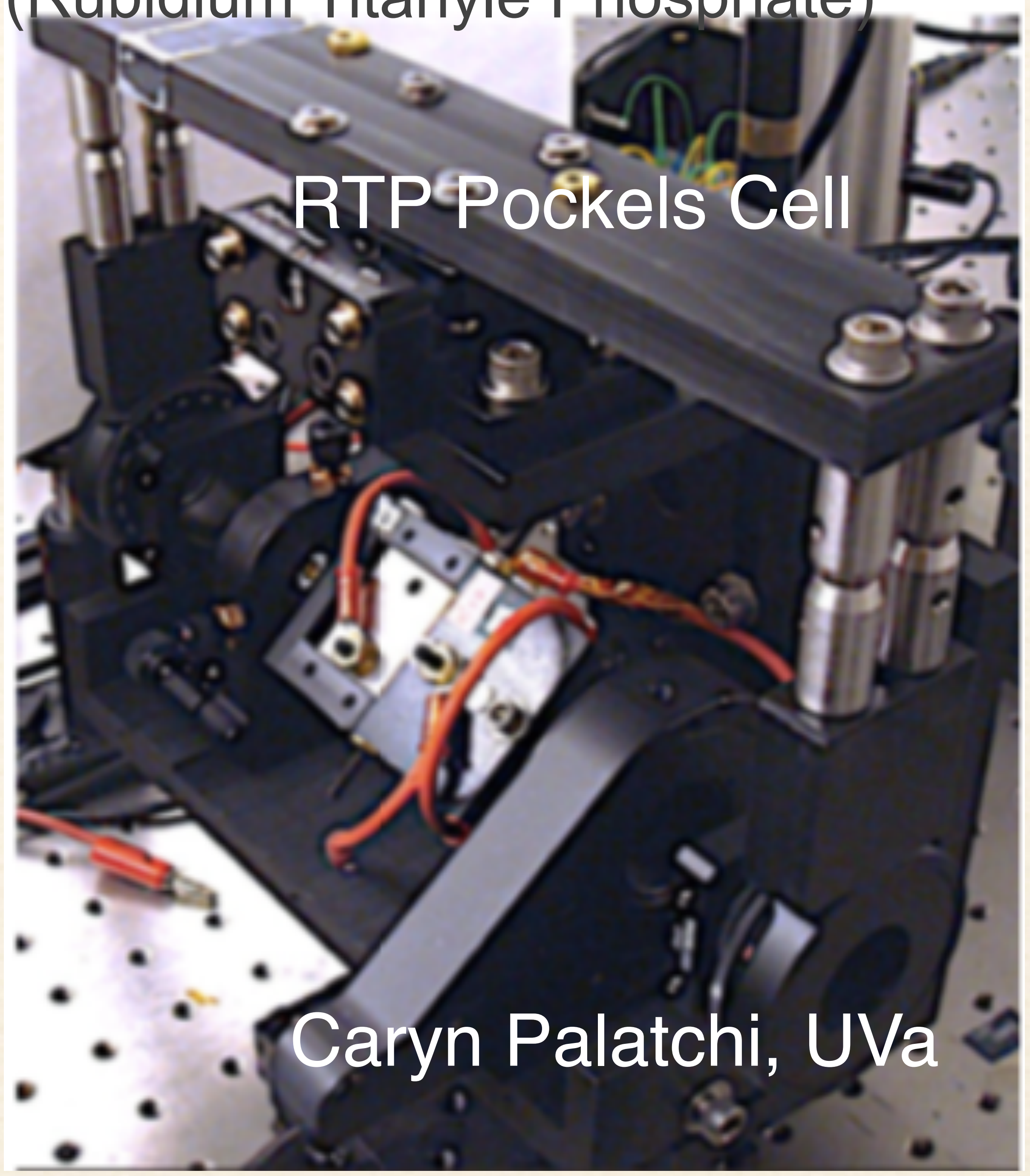
$A_{corr} \sim 500$ ppb

$$A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma\beta_i\, \Delta x_i$$

Injector Two Wien Flipper – QWeak setup (Nov-Dec, 2011) – J. Grames

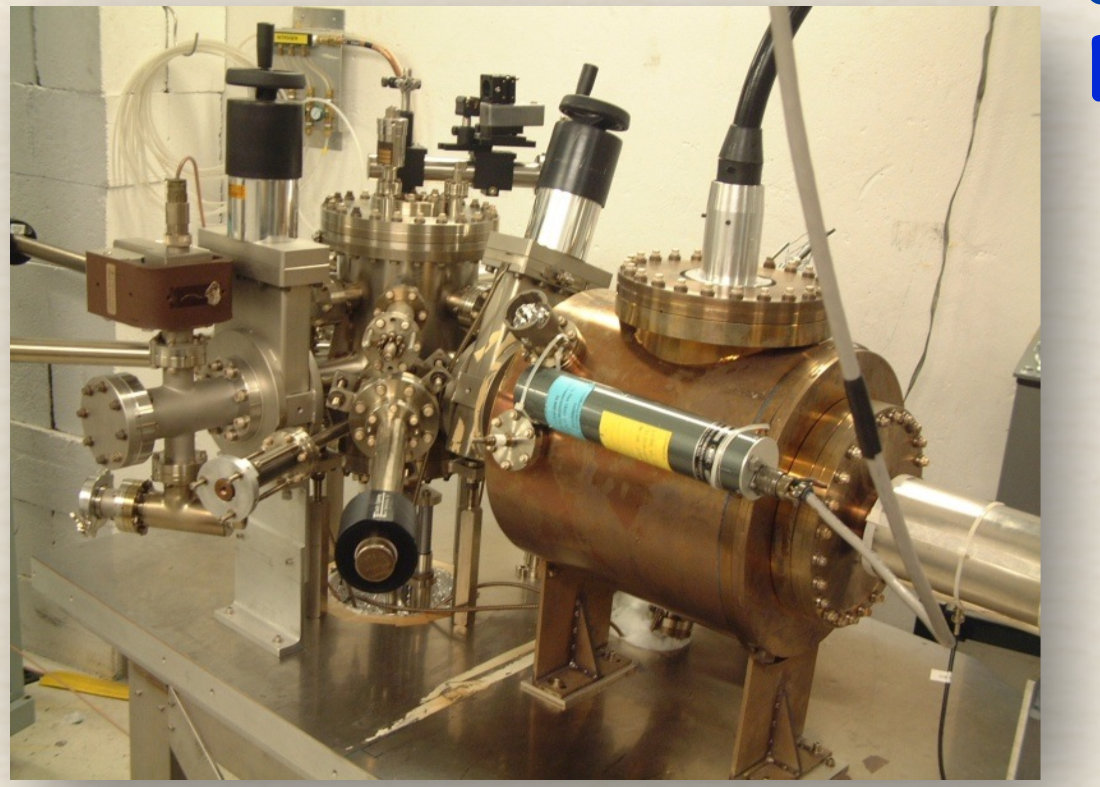


(Rubidium Titanyle Phosphate)

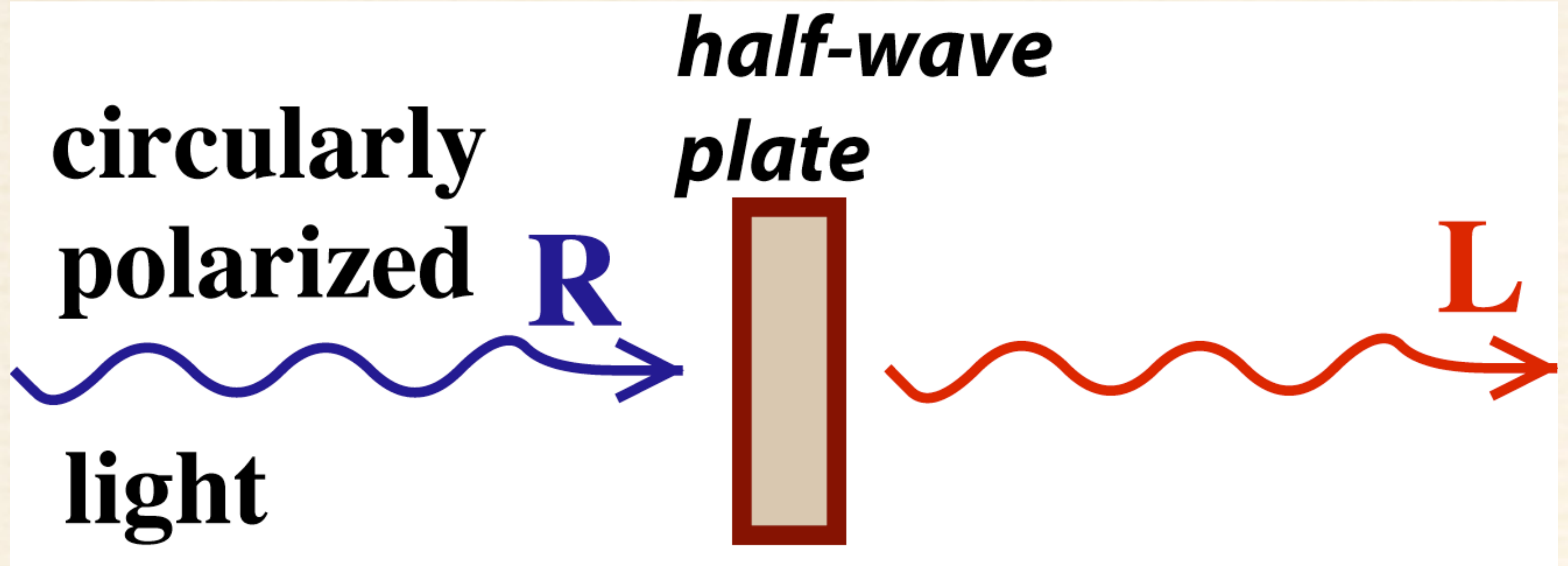


PREX-2 ran from June to September 2019

Stability of Polarized Beam for PREX-2

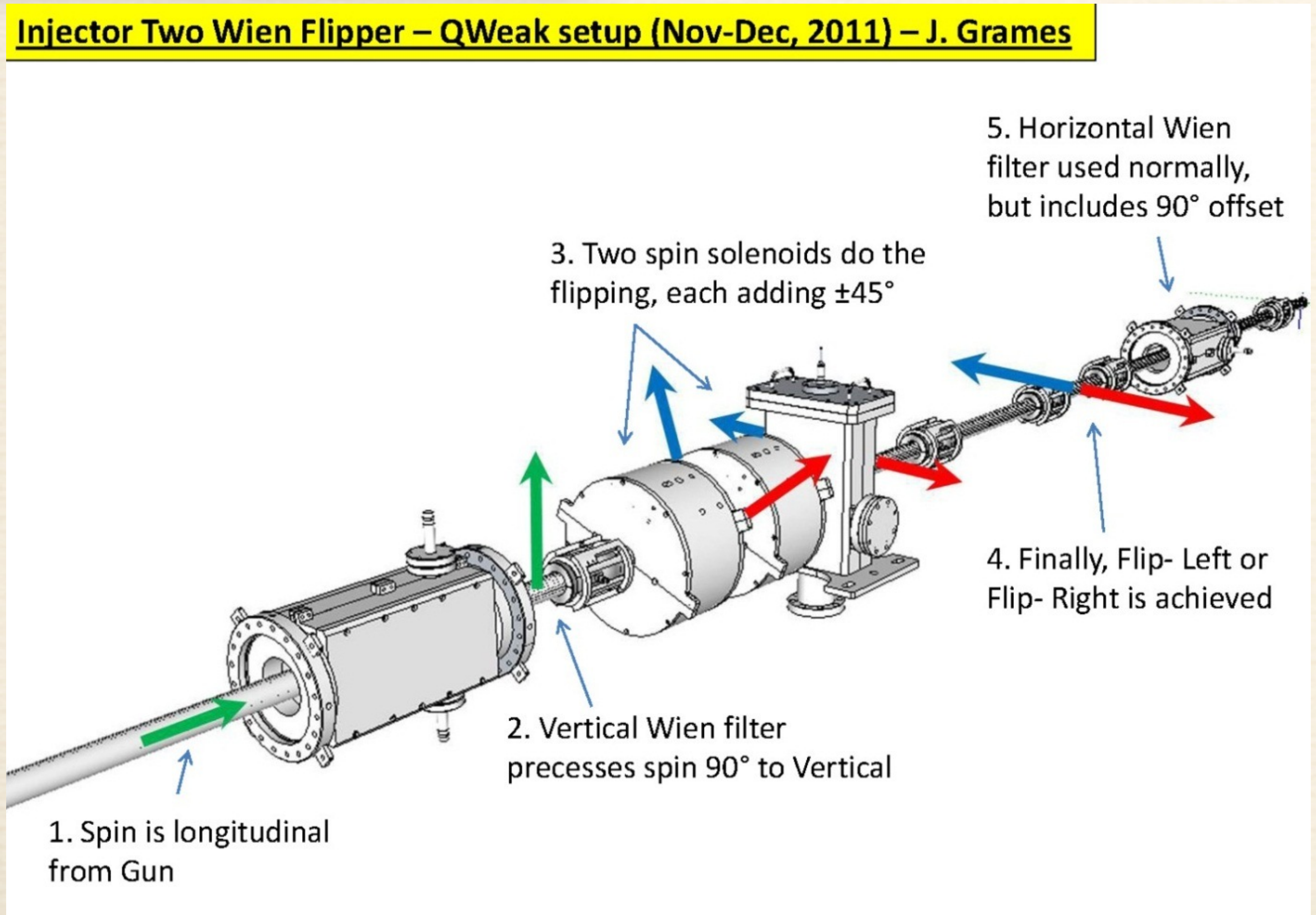


Beam helicity is chosen pseudo-randomly at multiple of 30 Hz

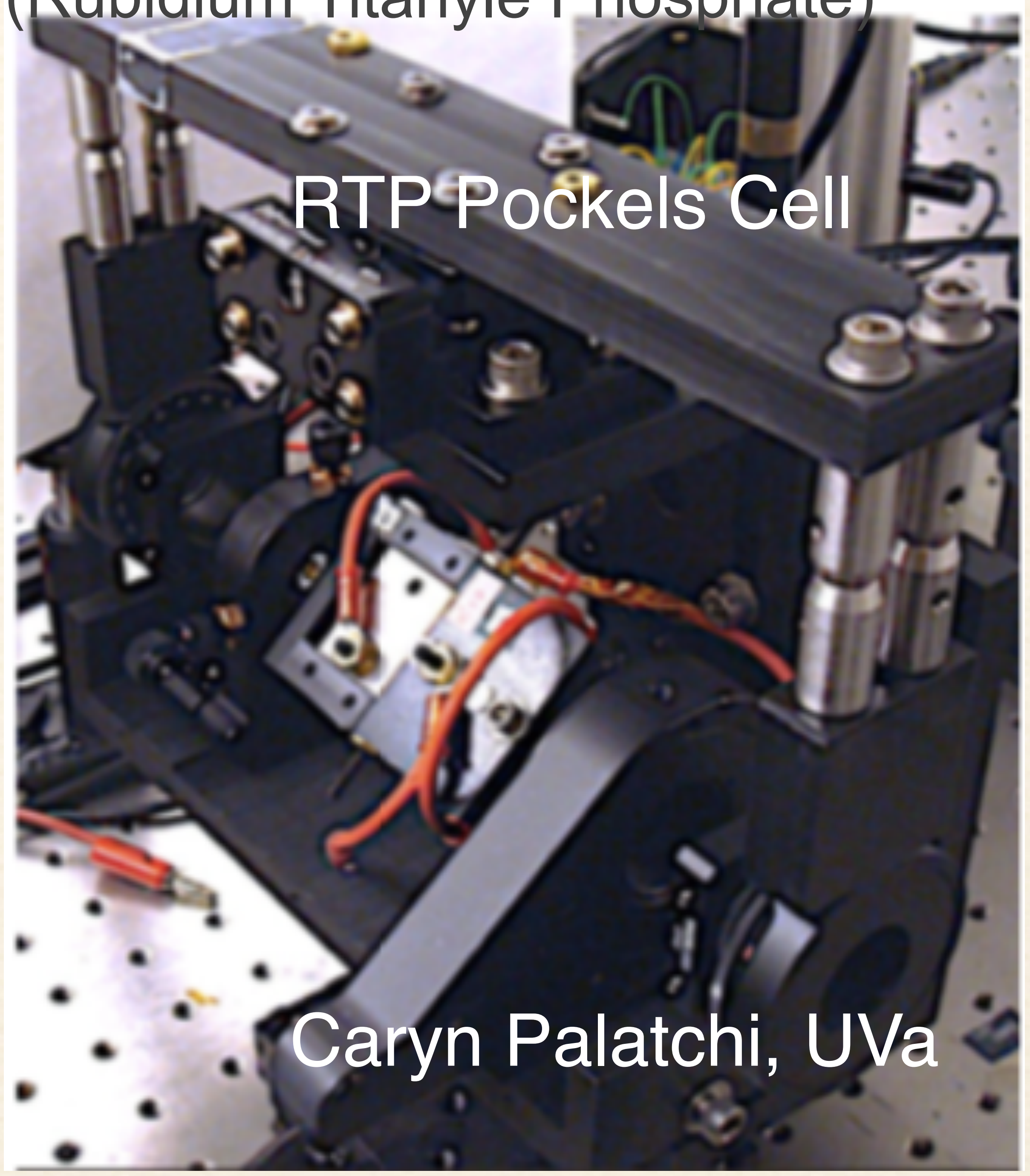


$A_{corr} \sim 500$ ppb

$$A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma \beta_i\, \Delta x_i$$



(Rubidium Titanyle Phosphate)

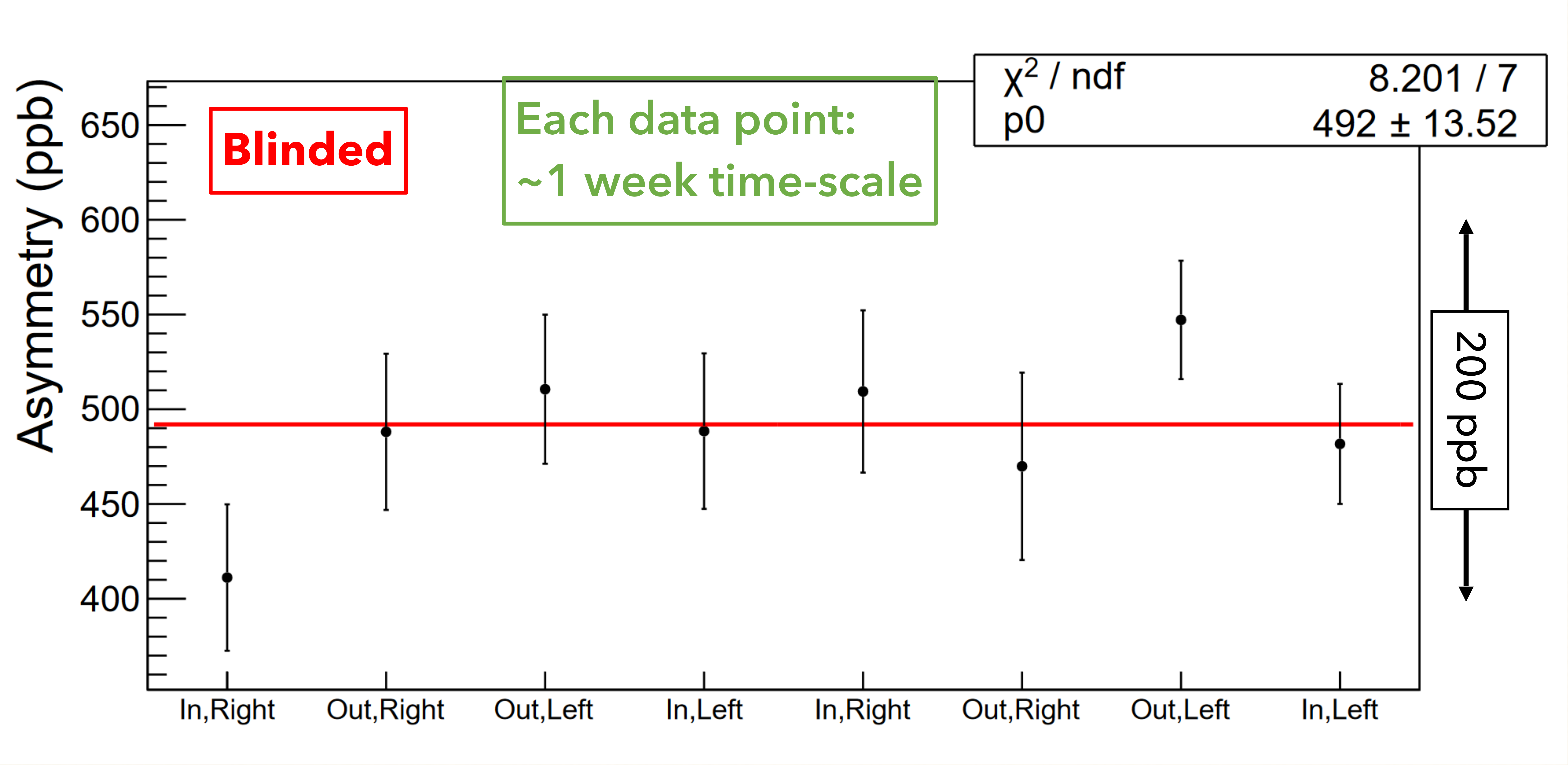


PREX-2 Run Grand Average

Parameter	Value
ΔX_t(nm)	0.15
ΔY_t(nm)	0.85
θx (nrad)	-0.2
θy (nrad)	0.02
ΔE/E (ppb)	0.5

Sub-nrad, nm, ppb level

Data Overview: Corrected Asymmetry



Half Wave Plate: IN/OUT

Wien: Left/Right

Raw Blinded Detector Asymmetry

492.0 ± 13.5 ppb

Total beam corrections:

(60.4 ± 2.5)ppb

- The corrected asymmetry removed effects from beam asymmetries and noise
- Still to come: polarization and background corrections

Beam Correction Analysis

Warning! Only interesting to parity experimentalists!

Multivariate Regression:

$$\chi^2 = \sum \left(A_{raw} - \sum_i \beta_i \Delta M_i \right)^2, \quad \frac{\partial \chi^2}{\partial \beta_i} = 0$$

- χ^2 minimization
- Variation in β_i dominated by **'strength sharing'**
- Bias by **(anti-)correlated electronic noise**
- Slope 'diluted' by **monitor resolution**

Beam Modulation:

- **Modulation amplitude** $\sim$ 100 um
  - beam random jitter 10 um
  - monitor resolution 0.4 um

Powerful new technique implemented exploiting the the advantages of two traditional methods while avoiding the potential pitfalls

Tau Ye (SBU)
Paul Souder
Kent Paschke
KK

Beam Correction Analysis

Warning! Only interesting to parity experimentalists!

Multivariate Regression:

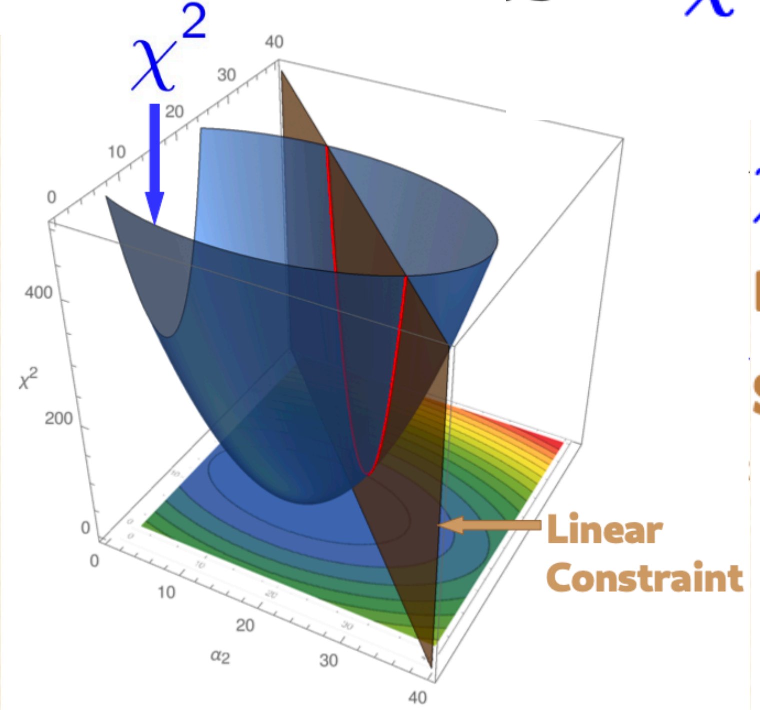
$$\chi^2 = \sum \left(A_{raw} - \sum_i \beta_i \Delta M_i\right)^2, \quad \frac{\partial \chi^2}{\partial \beta_i} = 0$$

- χ^2 minimization
- Variation in β_i dominated by **'strength sharing'**
- Bias by **(anti-)correlated electronic noise**
- Slope 'diluted' by **monitor resolution**

Beam Modulation:

- **Modulation amplitude** $\sim$ 100 um
  - beam random jitter 10 um
  - monitor resolution 0.4 um

Powerful new technique implemented exploiting the the advantages of two traditional methods while avoiding the potential pitfalls



Lagrange Multiplier

$$\mathcal{L} = \chi^2 + \sum_\mu \lambda_\mu \left(\frac{\partial D}{\partial C_\mu} - \sum_i \beta_i \frac{\partial M_i}{\partial C_\mu}\right)$$

χ^2 **minimization** with **beam modulation sensitivities constraints**:

$$\frac{\partial \mathcal{L}}{\partial \beta_i} = 0, \quad \frac{\partial \mathcal{L}}{\partial \lambda_\mu} = 0$$

Tau Ye (SBU)
Paul Souder
Kent Paschke
KK

Beam Correction Analysis

Warning! Only interesting to parity experimentalists!

Multivariate Regression:

$$\chi^2 = \sum \left(A_{raw} - \sum_i \beta_i \Delta M_i \right)^2, \quad \frac{\partial \chi^2}{\partial \beta_i} = 0$$

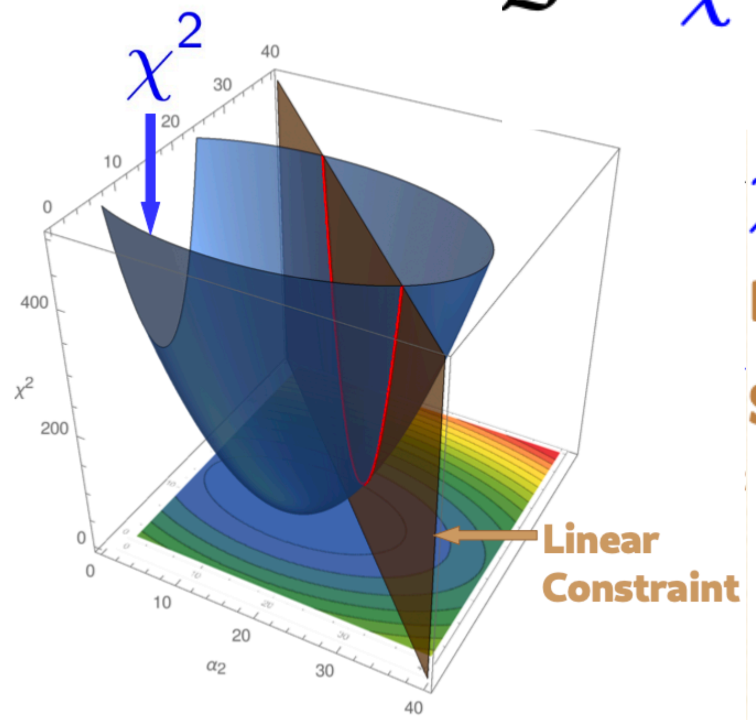
- χ^2 minimization
- Variation in β_i dominated by **'strength sharing'**
- Bias by **(anti-)correlated electronic noise**
- Slope 'diluted' by **monitor resolution**

Beam Modulation:

- **Modulation amplitude** $\sim$ 100 um
  - beam random jitter 10 um
  - monitor resolution 0.4 um

Lagrange Multiplier

$$\mathcal{L} = \chi^2 + \sum_\mu \lambda_\mu \left(\frac{\partial D}{\partial C_\mu} - \sum_i \beta_i \frac{\partial M_i}{\partial C_\mu} \right)$$



χ^2 **minimization** with **beam modulation sensitivities constraints**:

$$\frac{\partial \mathcal{L}}{\partial \beta_i} = 0, \quad \frac{\partial \mathcal{L}}{\partial \lambda_\mu} = 0$$

Ranking eigenvectors by eigenvalue $\lambda_1 > \lambda_2 > \lambda_3 ...$

	Mean(nm)	Error(nm)	RMS(um)
X1	-3.96	2.12	14.9
Y1	2.31	1.38	9.6
E	-1.83	1.01	7.0
Y2	-1.61	0.46	3.3
X2	-1.01	0.38	2.6
	0.16	0.2	1.3
	0.15	0.12	0.9
	0.02	0.11	0.7
	-0.08	0.07	0.4
	-0.02	0.06	0.3
	-0.04	0.05	0.3
	-0.01	0.04	0.3

Powerful new technique implemented exploiting the the advantages of two traditional methods while avoiding the potential pitfalls

Tau Ye (SBU)
Paul Souder
Kent Paschke
KK

Beam Correction Analysis

Warning! Only interesting to parity experimentalists!

Multivariate Regression:

$$\chi^2 = \sum \left(A_{raw} - \sum_i \beta_i \Delta M_i\right)^2, \quad \frac{\partial \chi^2}{\partial \beta_i} = 0$$

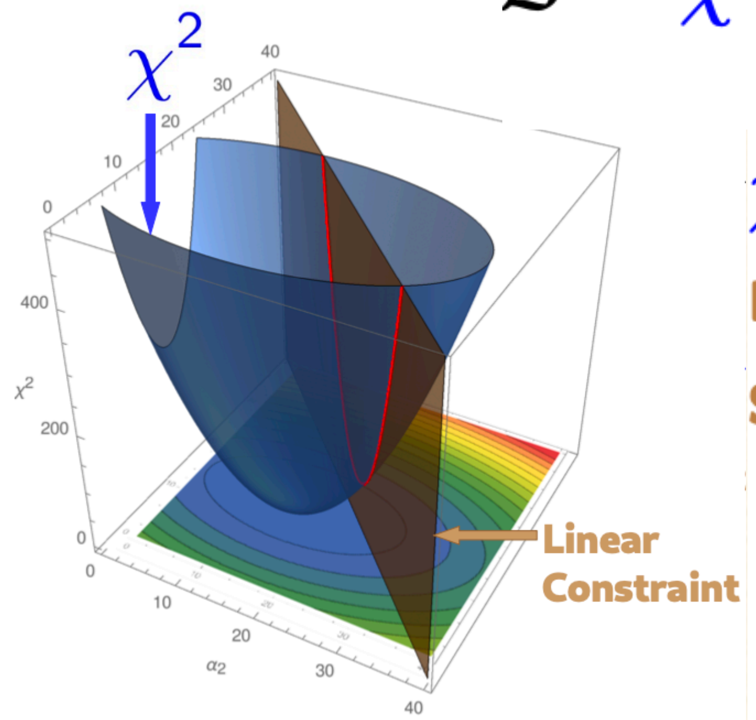
- χ^2 minimization
- Variation in β_i dominated by **'strength sharing'**
- Bias by **(anti-)correlated electronic noise**
- Slope 'diluted' by **monitor resolution**

Beam Modulation:

- **Modulation amplitude** $\sim$ 100 um
  - beam random jitter 10 um
  - monitor resolution 0.4 um

Lagrange Multiplier

$$\mathcal{L} = \chi^2 + \sum_\mu \lambda_\mu \left(\frac{\partial D}{\partial C_\mu} - \sum_i \beta_i \frac{\partial M_i}{\partial C_\mu}\right)$$



χ^2 **minimization** with **beam modulation sensitivities constraints**:

$$\frac{\partial \mathcal{L}}{\partial \beta_i} = 0, \quad \frac{\partial \mathcal{L}}{\partial \lambda_\mu} = 0$$

Powerful new technique implemented exploiting the the advantages of two traditional methods while avoiding the potential pitfalls

Tau Ye (SBU)
Paul Souder
Kent Paschke
KK

Ranking eigenvectors by eigenvalue $\lambda_1 > \lambda_2 > \lambda_3 \ldots$

	Mean(nm)	Error(nm)	RMS(um)
X1	-3.96	2.12	14.9
Y1	2.31	1.38	9.6
E	-1.83	1.01	7.0
Y2	-1.61	0.46	3.3
X2	-1.01	0.38	2.6
	0.16	0.2	1.3
	0.15	0.12	0.9
	0.02	0.11	0.7
	-0.08	0.07	0.4
	-0.02	0.06	0.3
	-0.04	0.05	0.3
	-0.01	0.04	0.3

	Mean(ppb)	Std.E.(ppb)	RMS(ppm)
X1	-22.33	16.46	191
Y1	22.5	10.5	88
E	-70.44	36.45	257
Y2	-2.84	4.46	36
X2	9.7	5.7	40
	1.27	0.95	7
	-0.01	1.33	12
	1.06	1.46	11
	0.26	0.61	5
	0.24	0.42	3
	0.18	0.54	5
	0.06	0.39	3
Total	-60.38		

Beam Correction Analysis

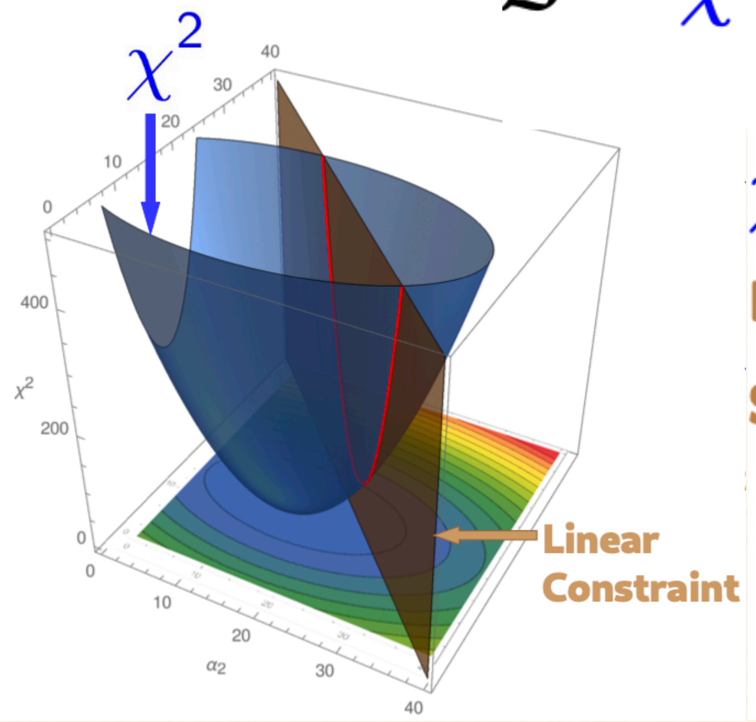
Warning! Only interesting to parity experimentalists!

Multivariate Regression:

$$\chi^2 = \sum \left(A_{raw} - \sum_i \beta_i \Delta M_i\right)^2, \quad \frac{\partial \chi^2}{\partial \beta_i} = 0$$

- χ^2 minimization
- Variation in β_i dominated by **'strength sharing'**
- Bias by **(anti-)correlated electronic noise**
- Slope 'diluted' by **monitor resolution**

Powerful new technique implemented exploiting the the advantages of two traditional methods while avoiding the potential pitfalls



Beam Modulation:

- **Modulation amplitude** $\sim$ 100 um
  - beam random jitter 10 um
  - monitor resolution 0.4 um

Lagrange Multiplier

$$\mathcal{L} = \chi^2 + \sum_\mu \lambda_\mu \left(\frac{\partial D}{\partial C_\mu} - \sum_i \beta_i \frac{\partial M_i}{\partial C_\mu}\right)$$

χ^2 **minimization** with **beam modulation sensitivities constraints**:

$$\frac{\partial \mathcal{L}}{\partial \beta_i} = 0, \quad \frac{\partial \mathcal{L}}{\partial \lambda_\mu} = 0$$

Ranking eigenvectors by eigenvalue $\lambda_1 > \lambda_2 > \lambda_3 \ldots$

	Mean(nm)	Error(nm)	RMS(um)
X1	-3.96	2.12	14.9
Y1	2.31	1.38	9.6
E	-1.83	1.01	7.0
Y2	-1.61	0.46	3.3
X2	-1.01	0.38	2.6
	0.16	0.2	1.3
	0.15	0.12	0.9
	0.02	0.11	0.7
	-0.08	0.07	0.4
	-0.02	0.06	0.3
	-0.04	0.05	0.3
	-0.01	0.04	0.3

	Mean(ppb)	Std.E.(ppb)	RMS(ppm)
X1	-22.33	16.46	191
Y1	22.5	10.5	88
E	-70.44	36.45	257
Y2	-2.84	4.46	36
X2	9.7	5.7	40
	1.27	0.95	7
	-0.01	1.33	12
	1.06	1.46	11
	0.26	0.61	5
	0.24	0.42	3
	0.18	0.54	5
	0.06	0.39	3
Total	-60.38		

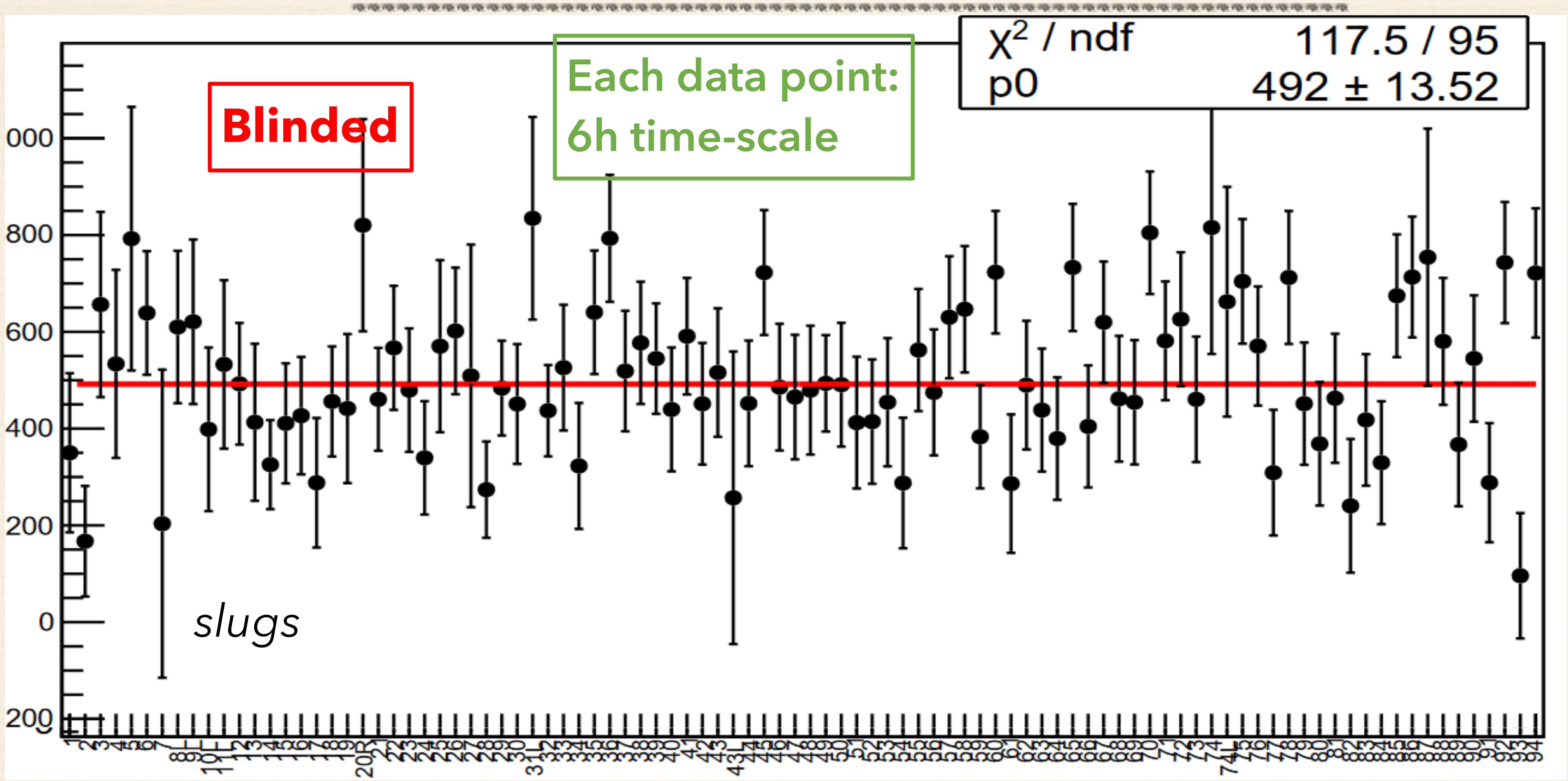
Tau Ye (SBU)
Paul Souder
Kent Paschke
KK

	ΔA (ppb)	$\sigma(\Delta A)$(ppb)	χ^2/ndf
dit vs Lagrange	2.2	3.5	86.4 / 95
Lagrange vs Reg	-1.0	1.2	91.2 / 95

Systematic Uncertainty in Beam Correction

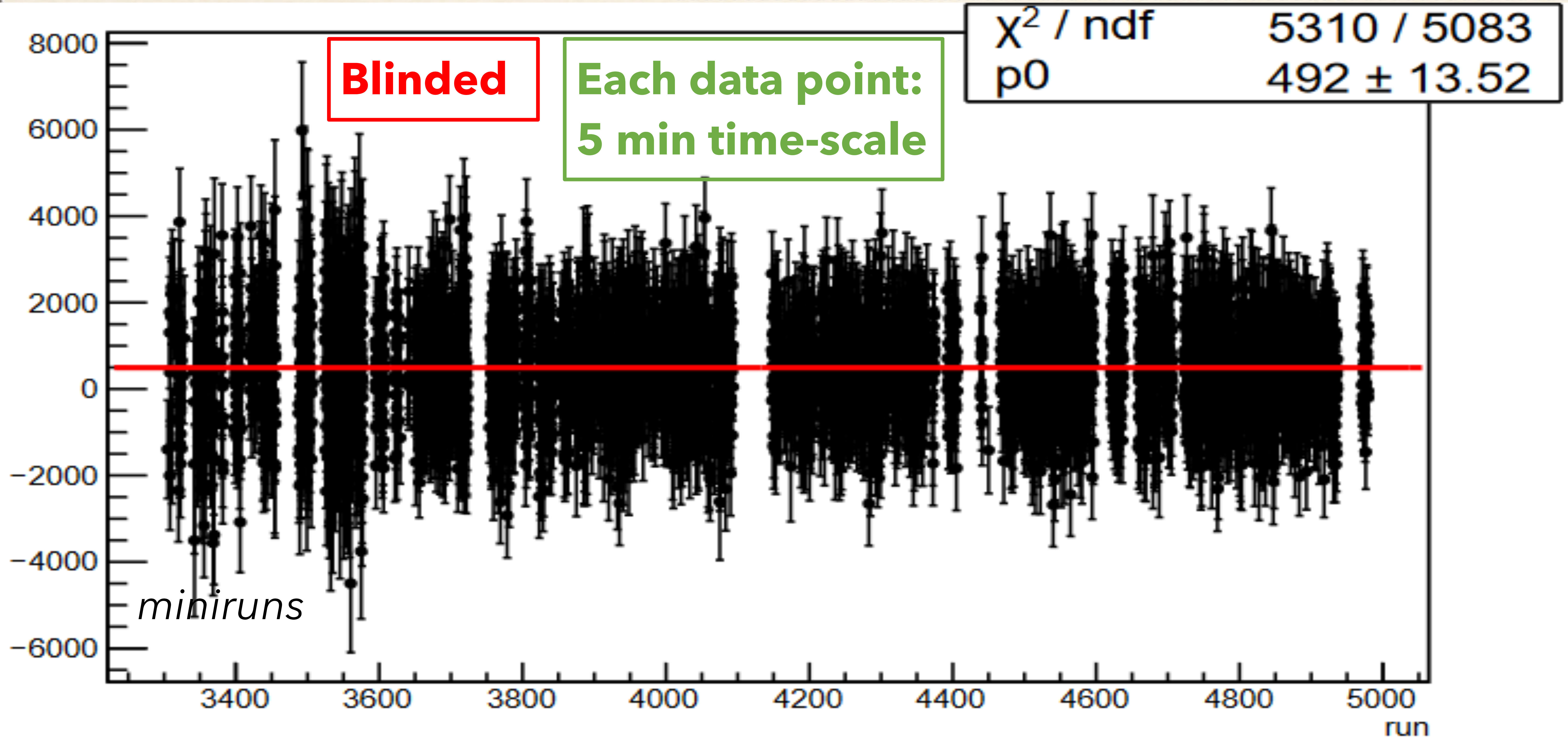
$$\boxed{A_{beam} = -60.38 \pm 2.5 \text{ ppb.}}$$

6 hour time scale

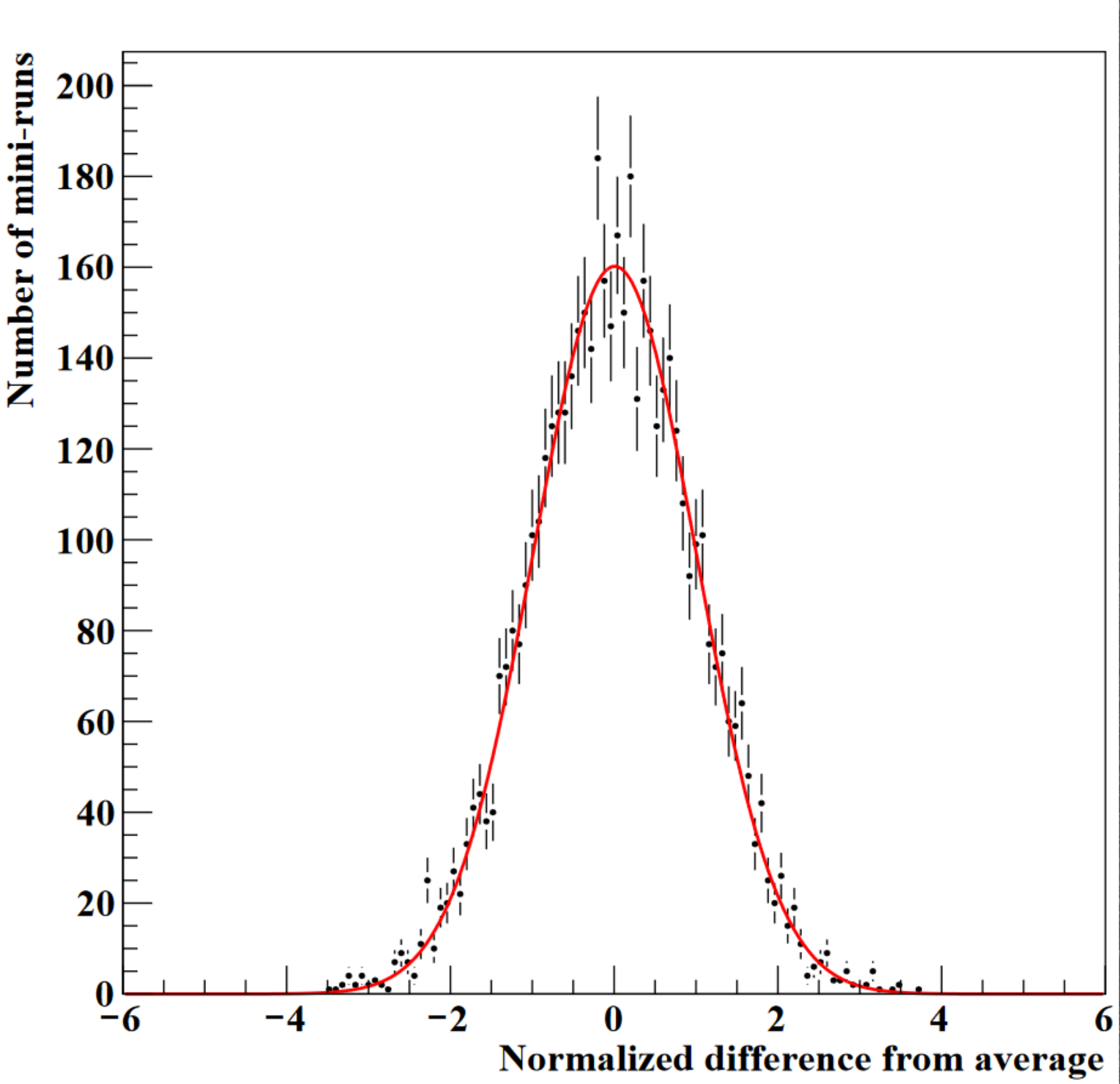


- The corrected asymmetry removed effects from beam asymmetries and noise
- Still to come: polarization and background corrections

5 minute time scale

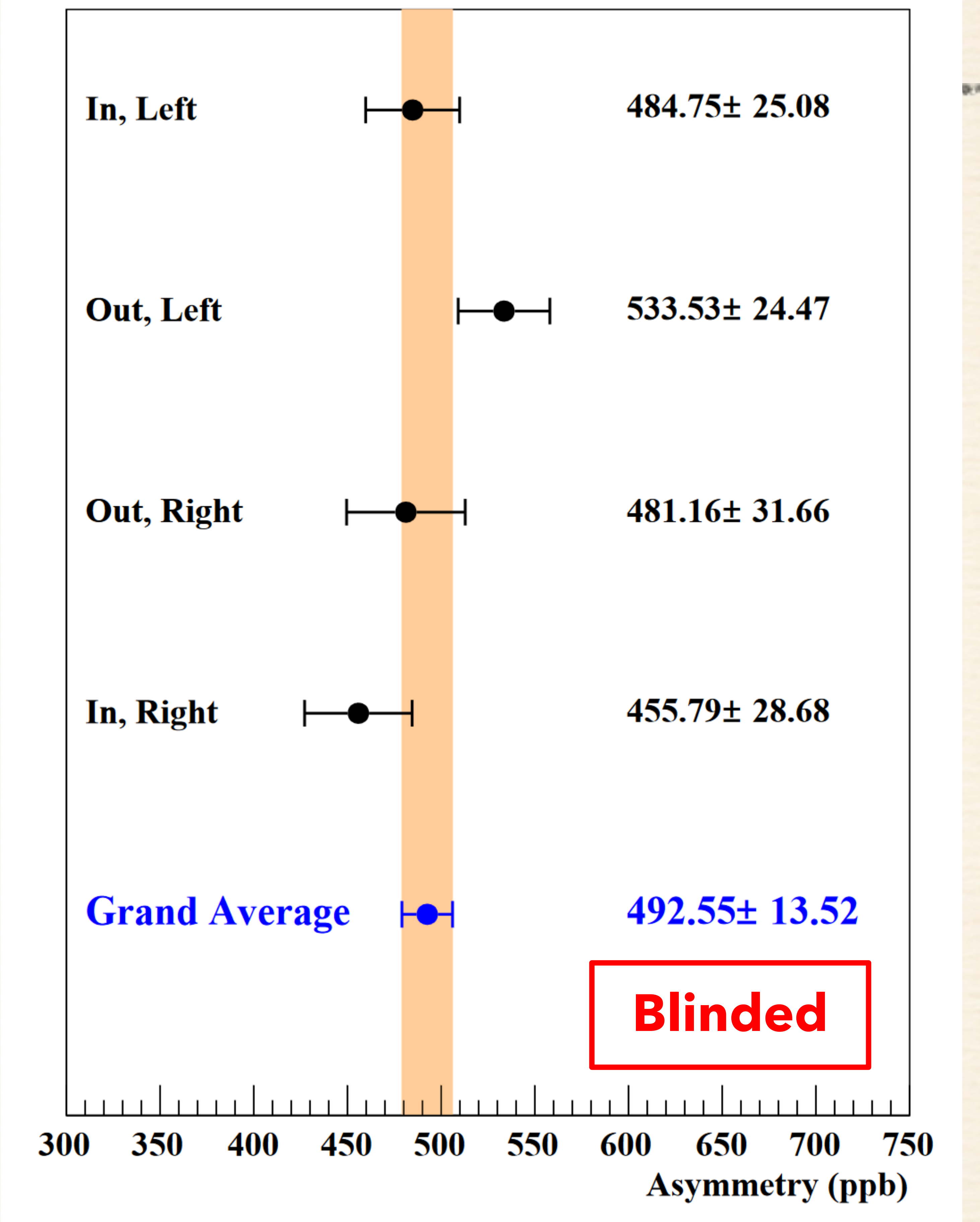


"pull" plot



- The corrected asymmetry removed effects from beam asymmetries and noise
- Still to come: polarization and background corrections

PREX Corrected Results



$$A_{PV} = R_{acceptNorm}\frac{A_{corr}/P_e - \sum_i A_i f_i}{1 - \sum_i f_i}$$

$$A_{corr} = A_{raw} + A_{beam} + A_{nonLin} - A_{blind}$$

Blinded A_{PV}:
(549.4 ± 16.1)ppb

	A_{PV} uncertainty contribution [ppb]	A_{PV} uncertainty contribution [%]
Polarization	5.23	0.95%
Acceptance normalization	4.56	0.83%
Beam correction	2.98	0.54%
Non-linear detector response	2.69	0.49%
Carbon dilution	1.45	0.26%
Charge correction	0.25	0.04%
Inelastic contamination	0.12	0.02%
Total	**8.16**	**1.48%**

When taken all into account the experimental systematic uncertainty comes to just shy of 1.5%

Compare and Combine with PREX-I

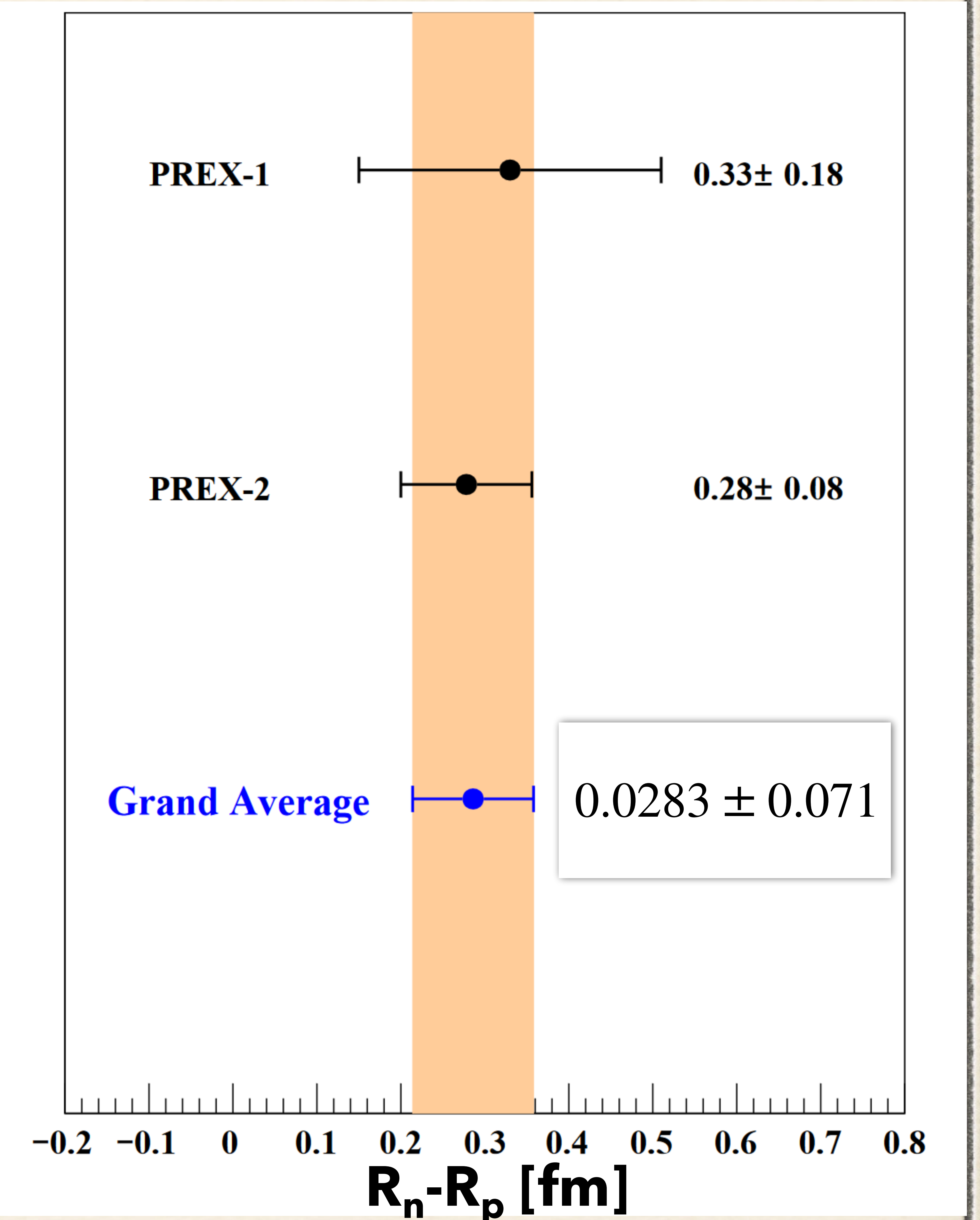
Measured at different angles, so different Q2 (and rather different sensitivities)

PREX-1 $Q^2 = 0.0088\text{GeV}^2$

$$A_{PV} = [656 \pm 60(\text{stat}) \pm 14(\text{syst})]\text{ppb} \rightarrow 9.4\%$$

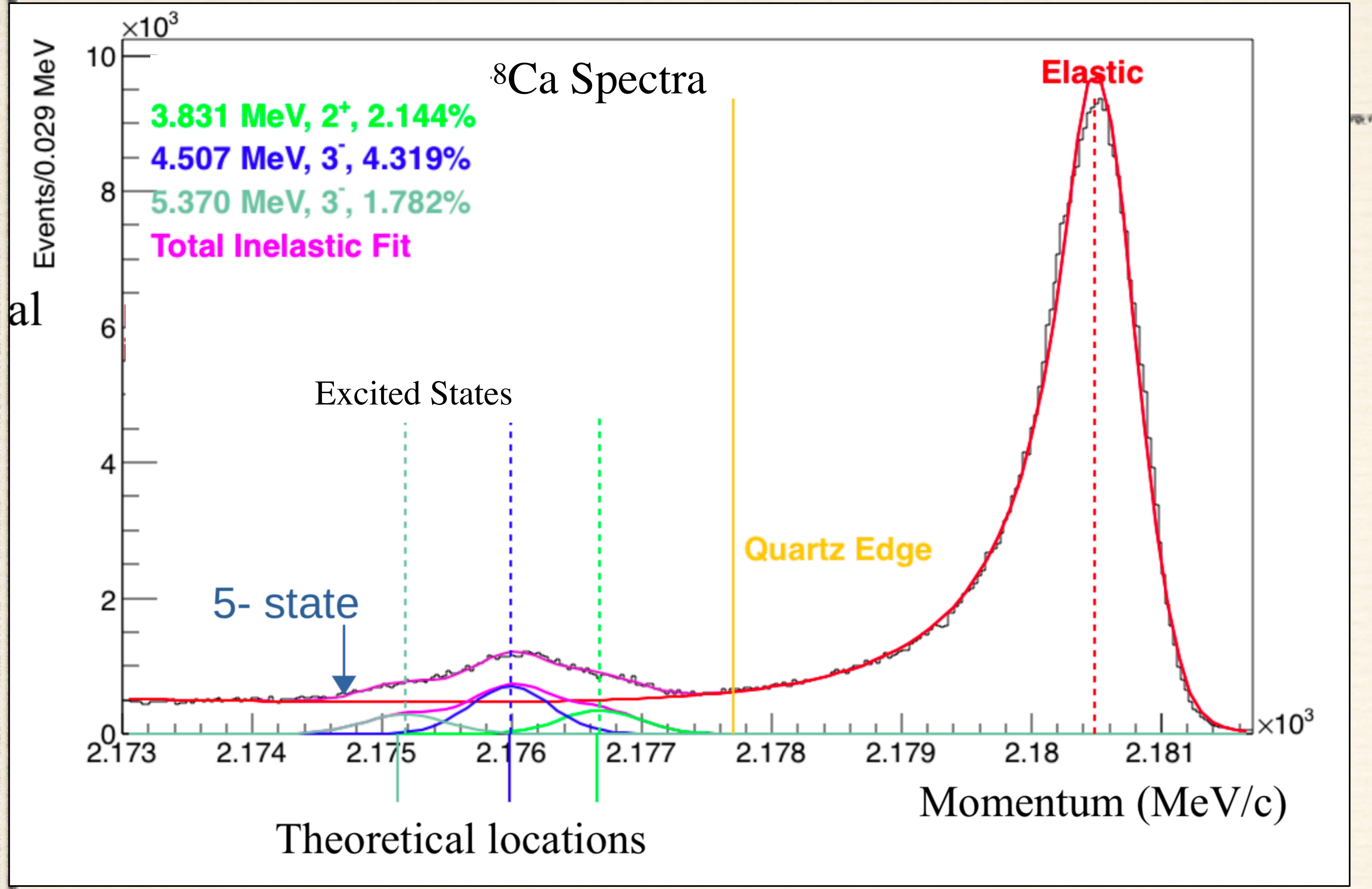
PREX-2 $Q^2 = 0.0062\text{GeV}^2$

$$A_{PV} = [550 \pm 16(\text{stat}) \pm 8(\text{syst})]\text{ppb} \rightarrow 3.3\%$$

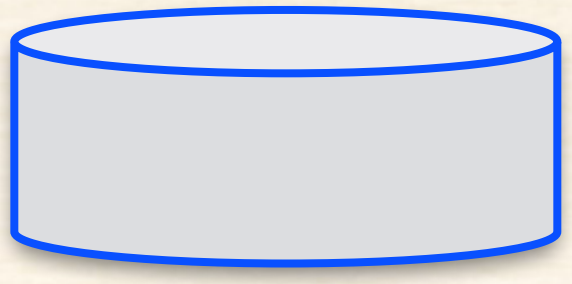


^{208}Pb Parameter	Value
Weak radius (R_W)	5.800 ± 0.075 fm
Interior weak density (ρ^0_W)	-0.0796 ± 0.0038 fm^{-3}
Interior baryon density (ρ^0_b)	0.1480 ± 0.0038 fm^{-3}
Neutron skin ($R_n - R_p$)	0.283 ± 0.071 fm

^{48}Ca Target



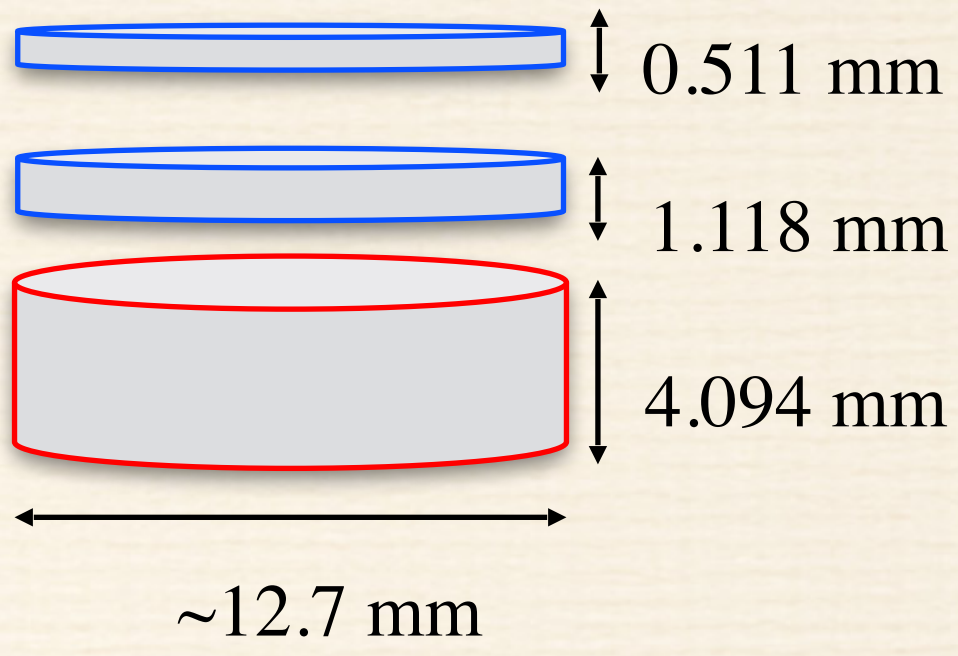
Target 1



Element:	Calcium
Symbol:	Ca
Isotope:	48
Series:	LO
Batch:	140042

- Single puck
- 5mm thick
- 96% ^{48}Ca
- 3.84% ^{40}Ca

Target 2



Element:	Calcium
Symbol:	Ca
Isotope:	48
Series:	
Batch:	900242

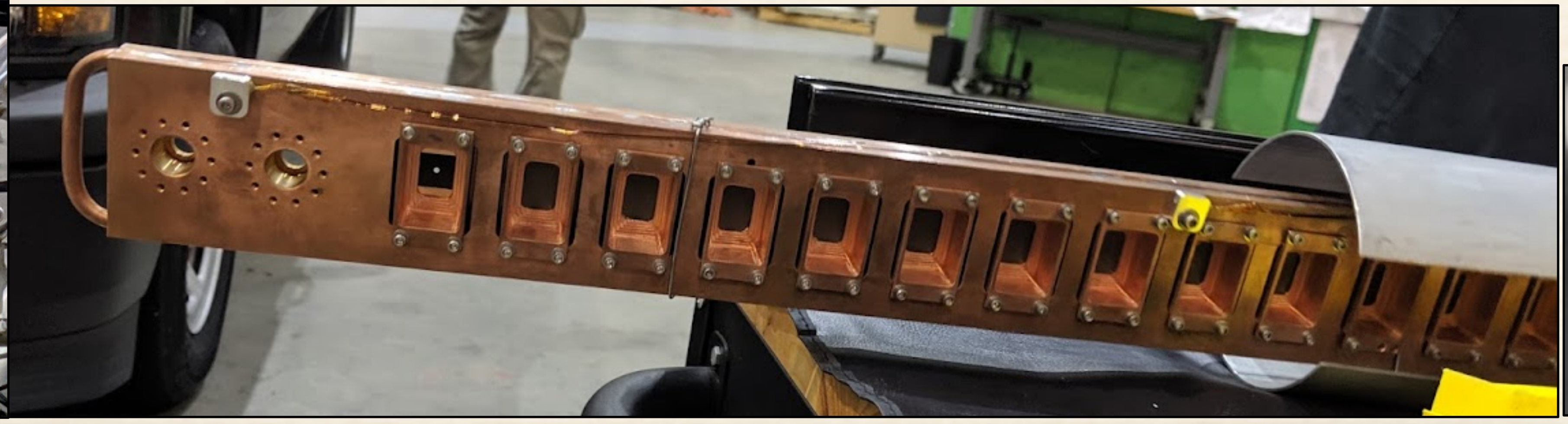
*Oak Ridge

- 1puck+2 foils sandwiched
- ~5.7mm thick total
- ~91.7% ^{48}Ca
- ~7.96% ^{40}Ca

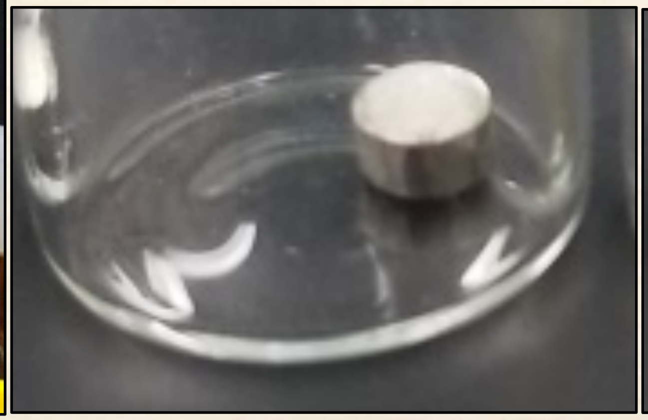
Stored in mineral oil until installed
Protected against oxidation

Delicate Installation

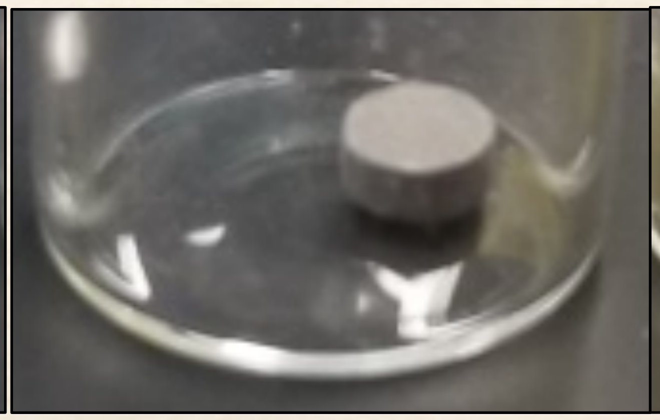
Cooled Copper Target Ladder



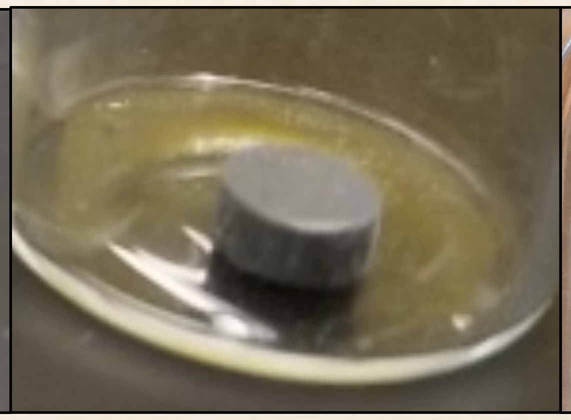
sanded



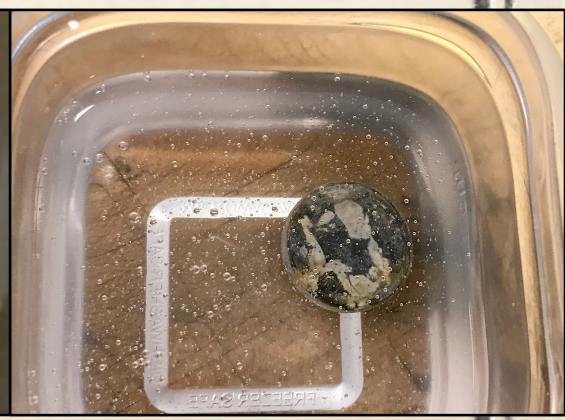
Oxidized 1hr



Oxidized 24hr



mineral oil



The CREX Physics Runs

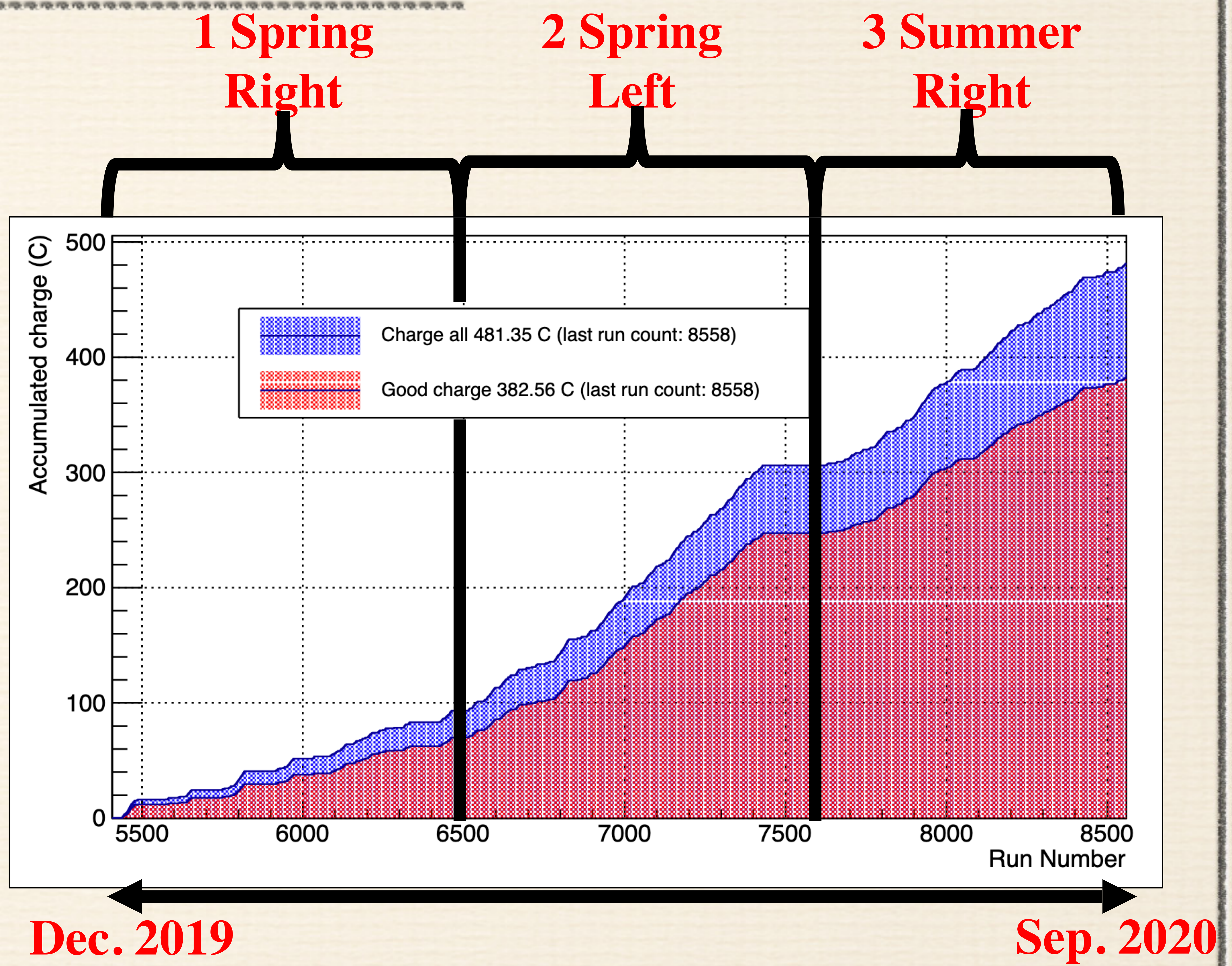
13 Ph.D. students, 7 postdocs, a total of about 80 scientists

Data Divided Into 3 Run Periods

- Part 1) Wien* Right Spring
- Part 2) Wien* Left Spring

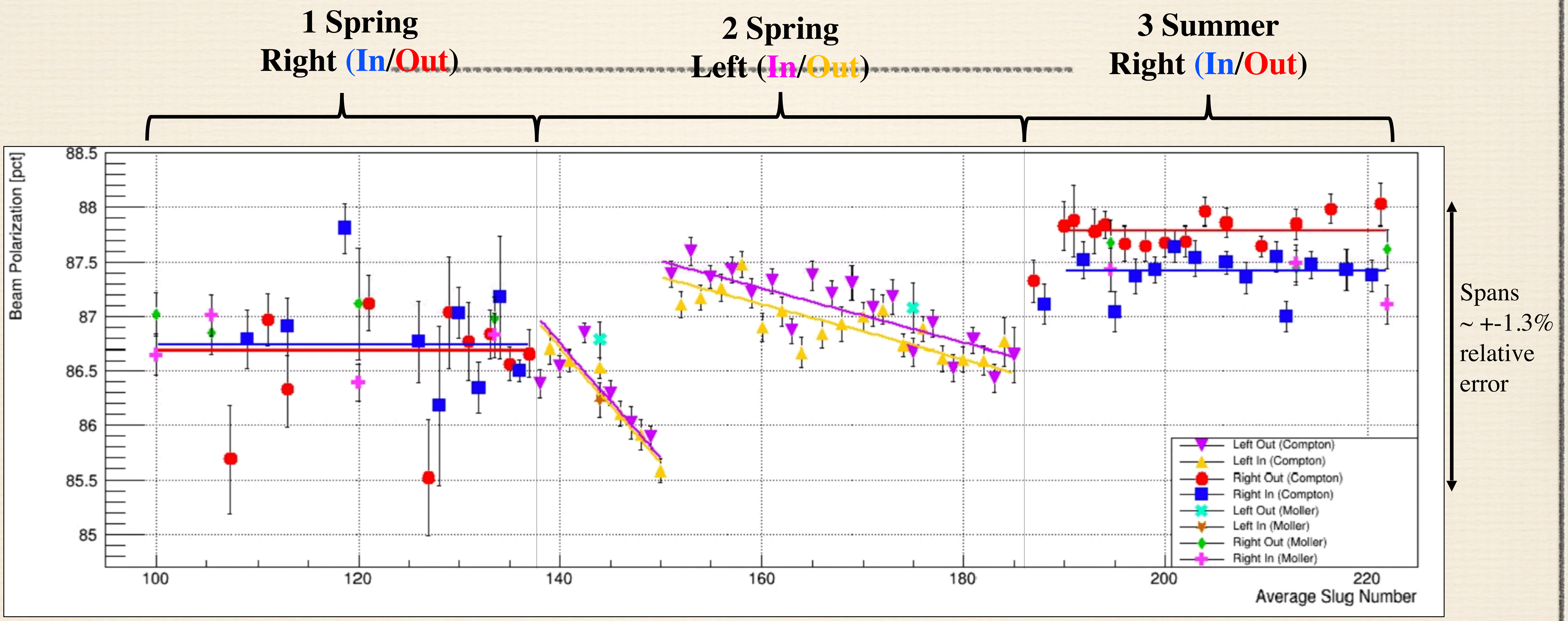
  …Covid hit….
- Part 3) Wien* Right Summer
- * "Wien" = Spin Manipulator

- Very close watch on-line data stream - beam conditions, detector response, etc.
- Frequent contact with MCC operators to maintain running conditions
- "prompt" analysis process flagged more subtle problems
- Daily grooming and review in "WAC" process
- (analysis development leader Paul King)



- **At the end of the experiment after our realtime analysis we collected about 383 C of charge on target which passed online analysis cuts(i.e. not excluded in calibrations or due to poor beam conditions, trip recovery, beam excursions, or beam monitor issues)**

Beam Polarimetry



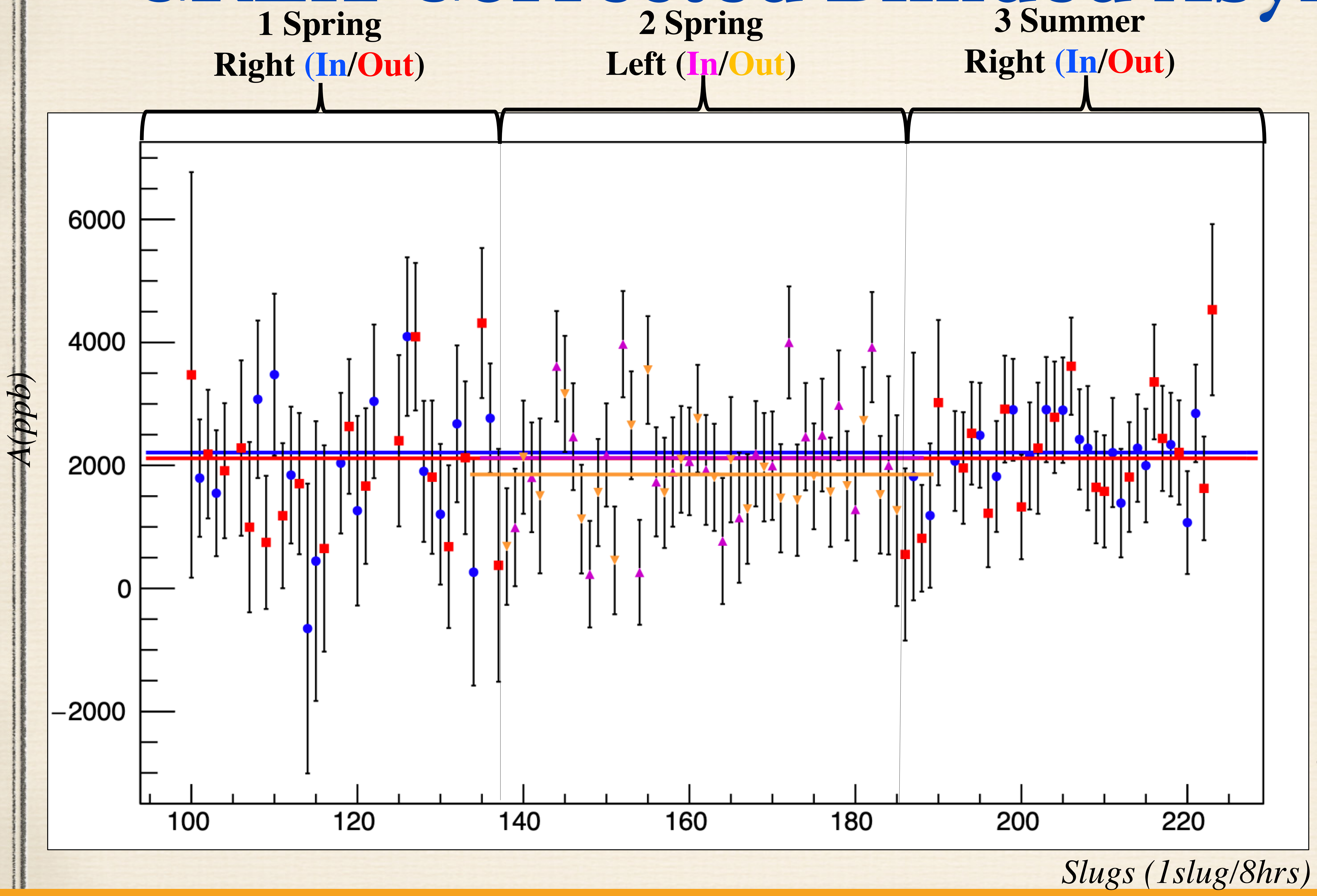
Acknowledgments: A.J. Zec, J. C. Cornejo, M. Dalton, C. Gal, D. Gaskell, C. Palatchi, K. Paschke, A. Premithilake, B. Quinn

Average Compton polarization:
87.10 ± (0.52% dP/P)

CREX Polarimetry Result:
P_e=87.09 +/- (0.44% dP/P)

Average Moller polarization:
87.06 ± (0.85% dP/P)

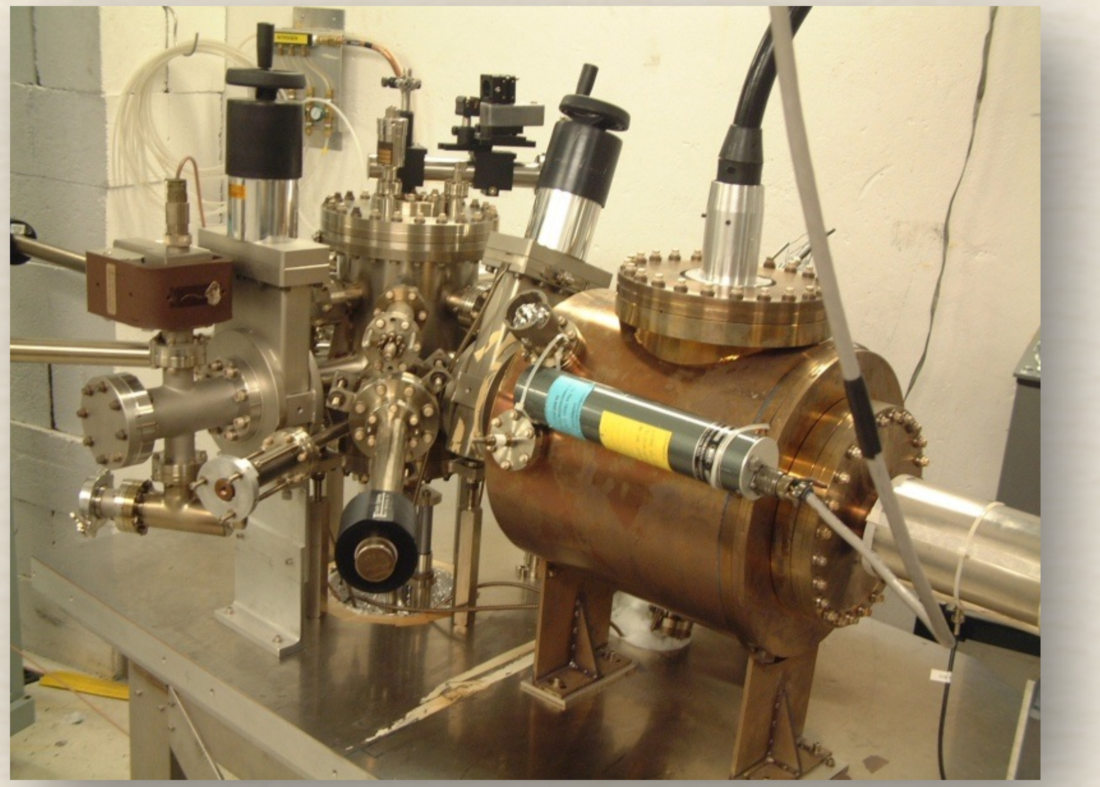
CREX Corrected Blinded Asymmetries



We were looking at the final data set after carefully removing unstable run periods with multiple checks on log books by about the middle of Summer 2021

Statistical Uncertainty: 80 to 90 parts per billion

Stability of Polarized Beam for CREX



Beam helicity is chosen pseudo-randomly at 30 Hz

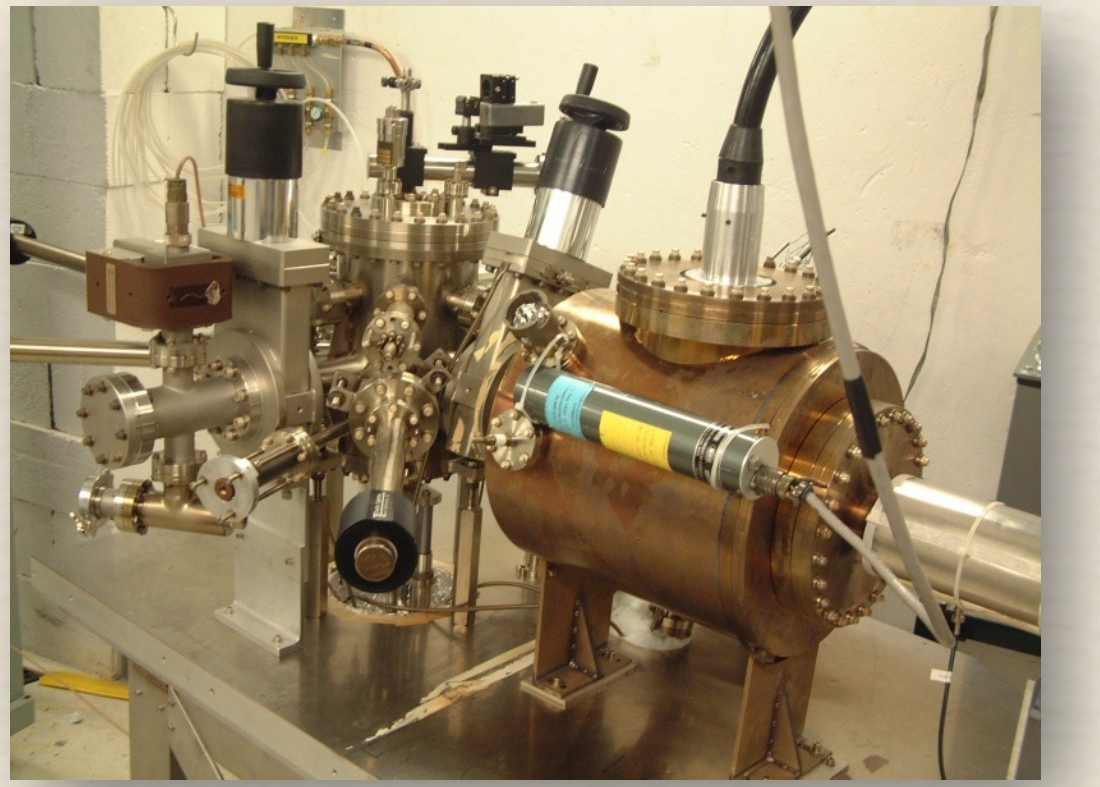
$A_{corr} \sim 2000$ ppb

$$A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma \beta_i\, \Delta x_i$$

Wien	Weight	X (nm)	Y (nm)	θ X (nrad)	θ Y (nrad)	E dpp
R 1	18.0%	1.6 $\pm$ 3.7	-2.4 $\pm$ 2.0	-0.26 $\pm$ 0.17	-0.11 $\pm$ 0.12	$-2.0 \pm 2.0e^{-9}$
Left	45.2%	-4.1 $\pm$ 1.6	0.3 $\pm$ 1.1	0.08 $\pm$ 0.04	-0.024 $\pm$ 0.10	$0.32 \pm 1.5e^{-9}$
R 2	36.9%	-2.8 $\pm$ 4.1	-0.2 $\pm$ 1.7	-0.06 $\pm$ 0.09	-0.28 $\pm$ 0.17	$0.84 \pm 1.9e^{-9}$
	Avg	-2.6 $\pm$ 1.8	-0.4 $\pm$ 0.9	-0.03 $\pm$ 0.05	-0.13 $\pm$ 0.08	$0.09 \pm 1.0e^{-9}$

- Three independent techniques agree across 3-parts of data set
- For beam correction, decided to use 12 BPM Lagrange Multiplier 3-part eigenvector correction, 5% slope uncertainty
- Left/right symmetric detectors, so correction dominated by E

Stability of Polarized Beam for CREX



Beam helicity is chosen pseudo-randomly at 30 Hz

$A_{corr} \sim 2000$ ppb

$$A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma \beta_i\, \Delta x_i$$

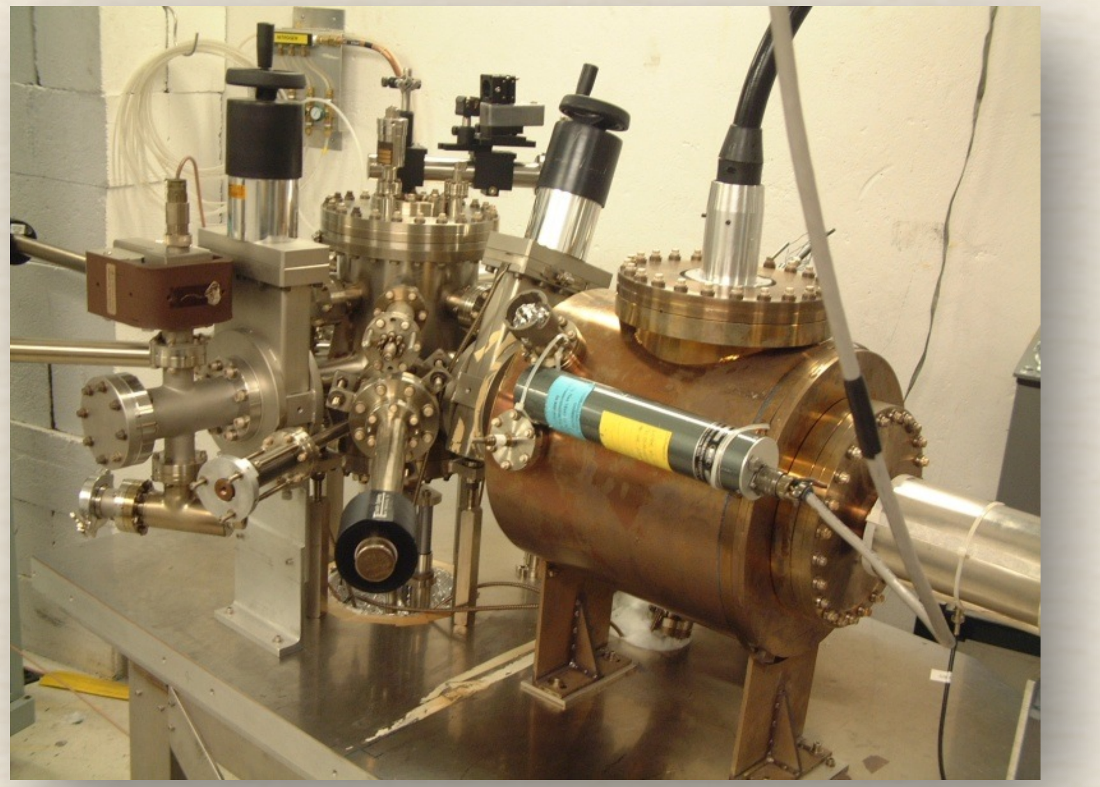
Wien	Weight	X (nm)	Y (nm)	θ X (nrad)	θ Y (nrad)	E dpp
R 1	18.0%	1.6 $\pm$ 3.7	-2.4 $\pm$ 2.0	-0.26 $\pm$ 0.17	-0.11 $\pm$ 0.12	$-2.0 \pm 2.0e^{-9}$
Left	45.2%	-4.1 $\pm$ 1.6	0.3 $\pm$ 1.1	0.08 $\pm$ 0.04	-0.024 $\pm$ 0.10	$0.32 \pm 1.5e^{-9}$
R 2	36.9%	-2.8 $\pm$ 4.1	-0.2 $\pm$ 1.7	-0.06 $\pm$ 0.09	-0.28 $\pm$ 0.17	$0.84 \pm 1.9e^{-9}$
	Avg	-2.6 $\pm$ 1.8	-0.4 $\pm$ 0.9	-0.03 $\pm$ 0.05	-0.13 $\pm$ 0.08	$0.09 \pm 1.0e^{-9}$

12BPM Eigenvector Lagrange Analysis ($\frac{\delta \text{slope}}{\text{slope}} = 5\%$)

Monitor	Part 1	Part 2	Part 3
evMon 0 (E)	-482.8	61.8	-0.9
evMon 1 (X)	22.3	3.8	164.0
evMon 2 (Y)	52.2	-7.3	-46.7
evMon 3	65.4	9.1	49.4
evMon 4	9.6	-1.2	4.4
evMon 5	162.9	-10.9	-9.3
evMon 6	-0.1	1.5	2.4
evMon 7	5.4	1.5	-15.4
evMon 8	7.1	-2.1	0.0
evMon 9	-12.4	-3.0	-9.2
evMon 10	-2.0	-1.6	9.3
evMon 11	-7.3	0.2	6.2
Net Corrections	-179.6	51.9	154.4
Local corrections' err	25.9	3.2	9.0
Avg Correction's weight	15.6%	47.5%	36.9%
Avg Correction (ppb)	53.5	5.4	

- Three independent techniques agree across 3-parts of data set
- For beam correction, decided to use 12 BPM Lagrange Multiplier 3-part eigenvector correction, 5% slope uncertainty
- Left/right symmetric detectors, so correction dominated by E

Stability of Polarized Beam for CREX



Beam helicity is chosen pseudo-randomly at 30 Hz

$$A_{corr} \sim 2000 \text{ ppb}$$

$$A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma \beta_i\, \Delta x_i$$

12BPM Eigenvector Lagrange Analysis ($\frac{\delta\text{slope}}{\text{slope}} = 5\%$)			
Monitor	Part 1	Part 2	Part 3
evMon 0 (E)	-482.8	61.8	-0.9
evMon 1 (X)	22.3	3.8	164.0
evMon 2 (Y)	52.2	-7.3	-46.7
evMon 3	65.4	9.1	49.4
evMon 4	9.6	-1.2	4.4
evMon 5	162.9	-10.9	-9.3
evMon 6	-0.1	1.5	2.4
evMon 7	5.4	1.5	-15.4
evMon 8	7.1	-2.1	0.0
evMon 9	-12.4	-3.0	-9.2
evMon 10	-2.0	-1.6	9.3
evMon 11	-7.3	0.2	6.2
Net Corrections	-179.6	51.9	154.4
Local corrections' err	25.9	3.2	9.0
Avg Correction's weight	15.6%	47.5%	36.9%
Avg Correction (ppb)	53.5	5.4	

Wien	Weight	X (nm)	Y (nm)	θ X (nrad)	θ Y (nrad)	E dpp
R 1	18.0%	1.6 $\pm$ 3.7	-2.4 $\pm$ 2.0	-0.26 $\pm$ 0.17	-0.11 $\pm$ 0.12	$-2.0 \pm 2.0e^{-9}$
Left	45.2%	-4.1 $\pm$ 1.6	0.3 $\pm$ 1.1	0.08 $\pm$ 0.04	-0.024 $\pm$ 0.10	$0.32 \pm 1.5e^{-9}$
R 2	36.9%	-2.8 $\pm$ 4.1	-0.2 $\pm$ 1.7	-0.06 $\pm$ 0.09	-0.28 $\pm$ 0.17	$0.84 \pm 1.9e^{-9}$
	Avg	-2.6 $\pm$ 1.8	-0.4 $\pm$ 0.9	-0.03 $\pm$ 0.05	-0.13 $\pm$ 0.08	$0.09 \pm 1.0e^{-9}$

- Three independent techniques agree across 3-parts of data set
- For beam correction, decided to use 12 BPM Lagrange Multiplier 3-part eigenvector correction, 5% slope uncertainty
- Left/right symmetric detectors, so correction dominated by E

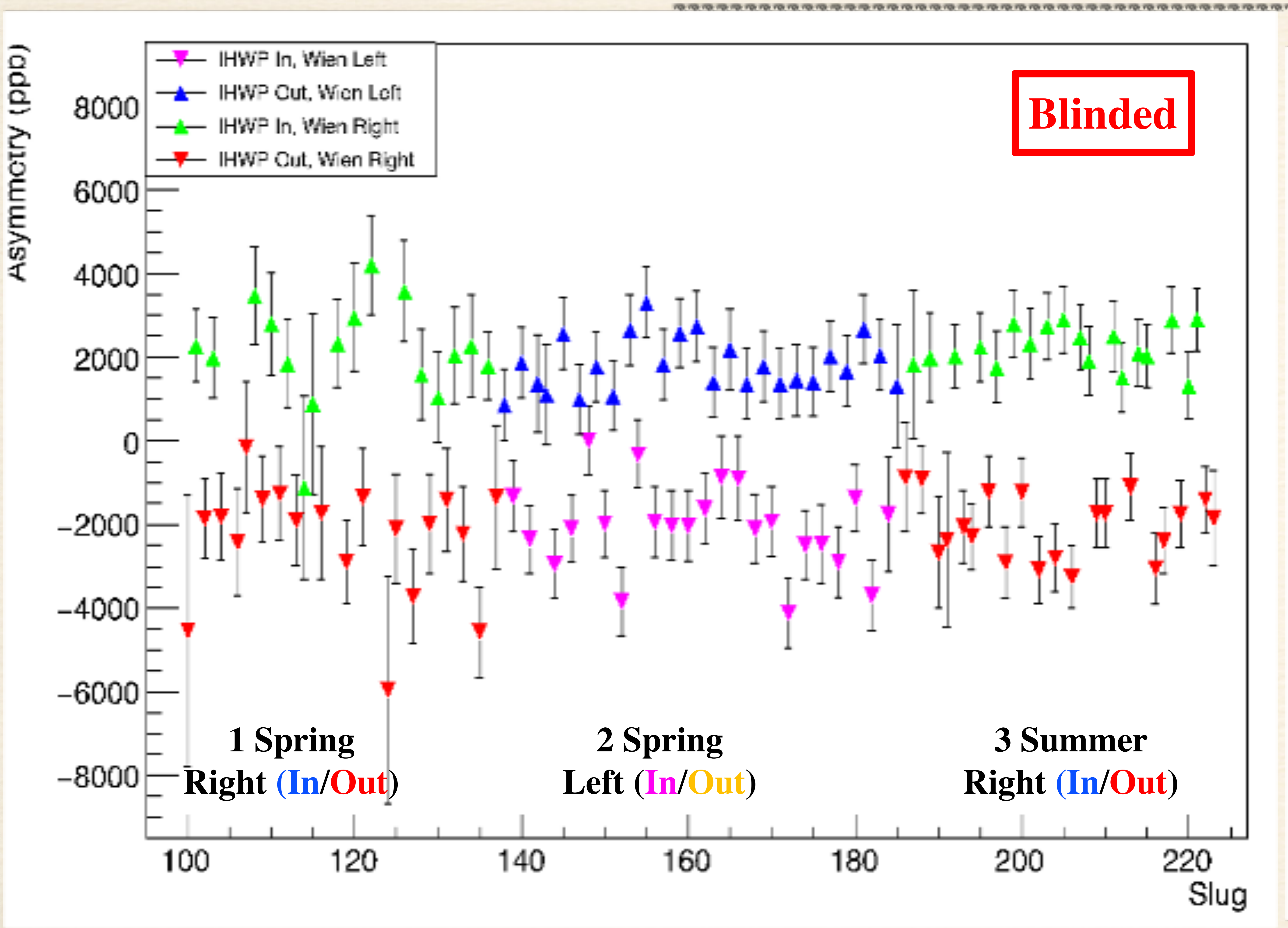
Total beam corrections:

$$A_{beam} = (53.5 \pm 5.4) \text{ ppb}$$

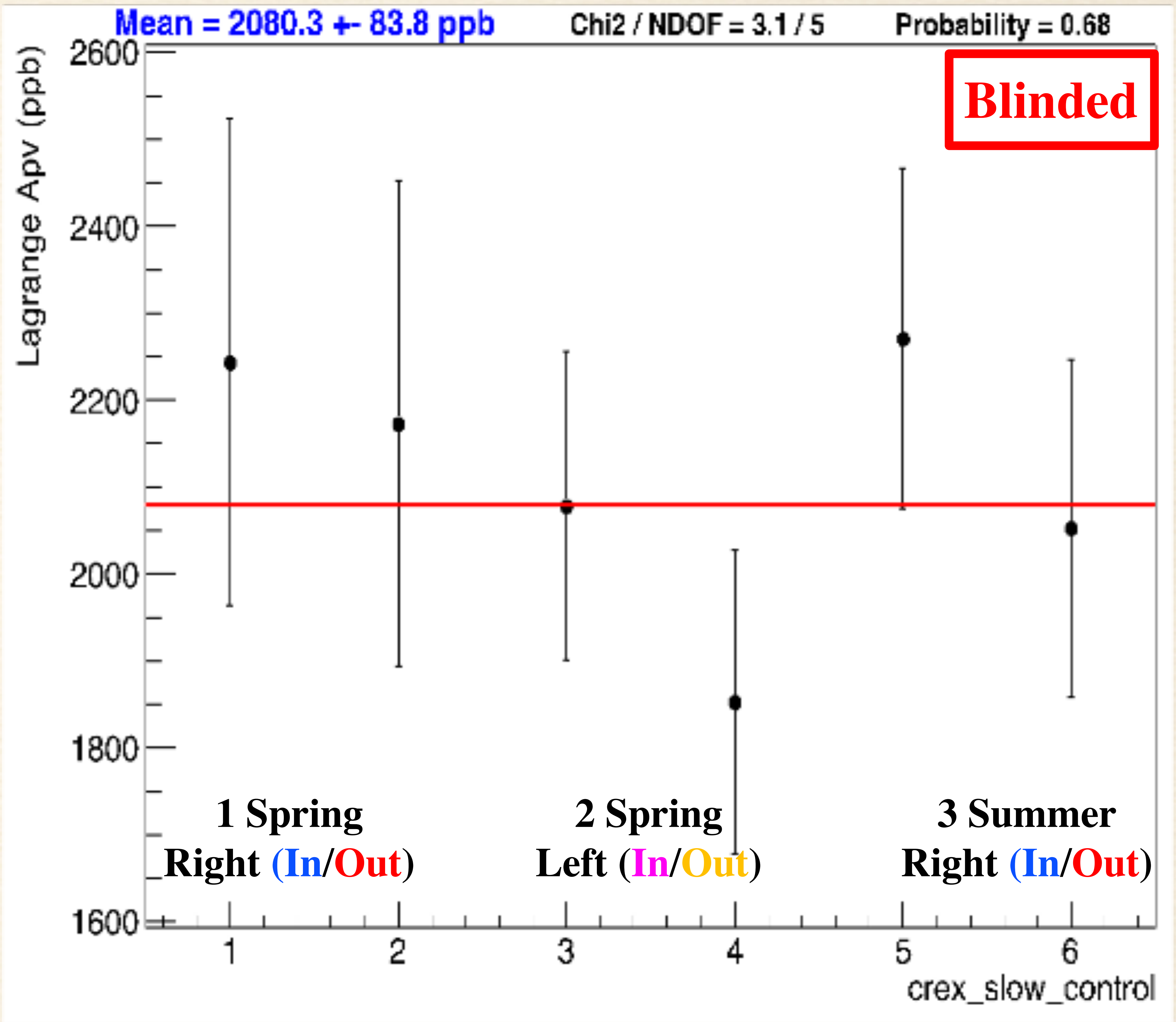
Half Wave Plate: IN/OUT Wien(Spin Manipulator): Left/Right

Demonstration of Systematic Control

Sign-uncorrected, Each point: 8h time-scale



Sign-corrected, Each point: ~1week time-scale



- Entire data set! 6 colors on left correspond to 6 points on the right (zoomed in y-scale)
- Measuring continuously flipping sign by 2 methods (IHWP, Wien)
- The corrected asymmetry removed effects from beam asymmetries and noise

CREX Grand Corrected Asymmetry

Final result averaging over all IHWP
and 3 Part Wien flip configurations

C. Clarke

1 Right (In/Out)
2 Left (In/Out)
3 Right (In/Out)

Wien	Weight	A_{raw} (ppb)	A_{det} (ppb)	A_Q (ppb)
Right 1	17.9%	2460.15 ± 391.95	2207.90 ± 197.69	-94.1 ± 69.6
Left	45.2%	1871.06 ± 278.39	1963.65 ± 124.64	148.1 ± 40.1
Right 2	36.9%	2006.57 ± 335.29	2160.94 ± 137.95	-376.3 ± 38.7
Weighted Average		2026.81 ± 189.88	2080.26 ± 83.77	-88.8 ± 26.2

Blinded Corrected Asymmetry A_{corr}:
2080.3 ± 83.8ppb

CREX Grand Corrected Asymmetry

Final result averaging over all IHWP
and 3 Part Wien flip configurations

C. Clarke

1 Right (In/Out)
2 Left (In/Out)
3 Right (In/Out)

Wien	Weight	A_{raw} (ppb)	A_{det} (ppb)	A_Q (ppb)
Right 1	17.9%	2460.15 ± 391.95	2207.90 ± 197.69	-94.1 ± 69.6
Left	45.2%	1871.06 ± 278.39	1963.65 ± 124.64	148.1 ± 40.1
Right 2	36.9%	2006.57 ± 335.29	2160.94 ± 137.95	-376.3 ± 38.7
Weighted Average		2026.81 ± 189.88	2080.26 ± 83.77	-88.8 ± 26.2

Blinded Corrected Asymmetry A_{corr}:
2080.3 ± 83.8ppb

Careful and painstaking analyses by multiple students on each of the small corrections to extract the physics asymmetry

$$A_{corr} = A_{det} - A_{beam} - A_{trans} - A_{nonlin} - A_{blind}$$

$$A_{phys} = R_{radcorr}\, R_{accept}\, R_{Q^2} \frac{A_{corr} - P_L \sum_i f_i A_i}{P_L(1 - \sum_i f_i)}$$

CREX Grand Corrected Asymmetry

Final result averaging over all IHWP
and 3 Part Wien flip configurations

C. Clarke

	Wien	Weight	A_{raw} (ppb)	A_{det} (ppb)	A_Q (ppb)
1 Right (In/Out)	Right 1	17.9%	2460.15 ± 391.95	2207.90 ± 197.69	-94.1 ± 69.6
2 Left (In/Out)	Left	45.2%	1871.06 ± 278.39	1963.65 ± 124.64	148.1 ± 40.1
3 Right (In/Out)	Right 2	36.9%	2006.57 ± 335.29	2160.94 ± 137.95	-376.3 ± 38.7
	Weighted Average		2026.81 ± 189.88	2080.26 ± 83.77	-88.8 ± 26.2

Blinded Corrected Asymmetry A_{corr}:
2080.3 ± 83.8ppb

Careful and painstaking analyses by multiple students on each of the small corrections to extract the physics asymmetry

$$A_{corr} = A_{det} - A_{beam} - A_{trans} - A_{nonlin} - A_{blind}$$

$$A_{phys} = R_{radcorr}\, R_{accept}\, R_{Q^2} \frac{A_{corr} - P_L \sum_i f_i A_i}{P_L(1 - \sum_i f_i)}$$

CREX Result Summary

Unblinded Detector Asymmetry A_{corr}:

2336.0 ± 84.8 ppb

$$A_{phys} = R_{radcorr}\, R_{accept}\, R_{Q^2} \frac{A_{corr} - P_L \sum_i f_i A_i}{P_L(1 - \sum_i f_i)}$$

$$A_{corr} = A_{det} - A_{beam} - A_{trans} - A_{nonlin} - A_{blind}$$

Unblinded A_{PV}:

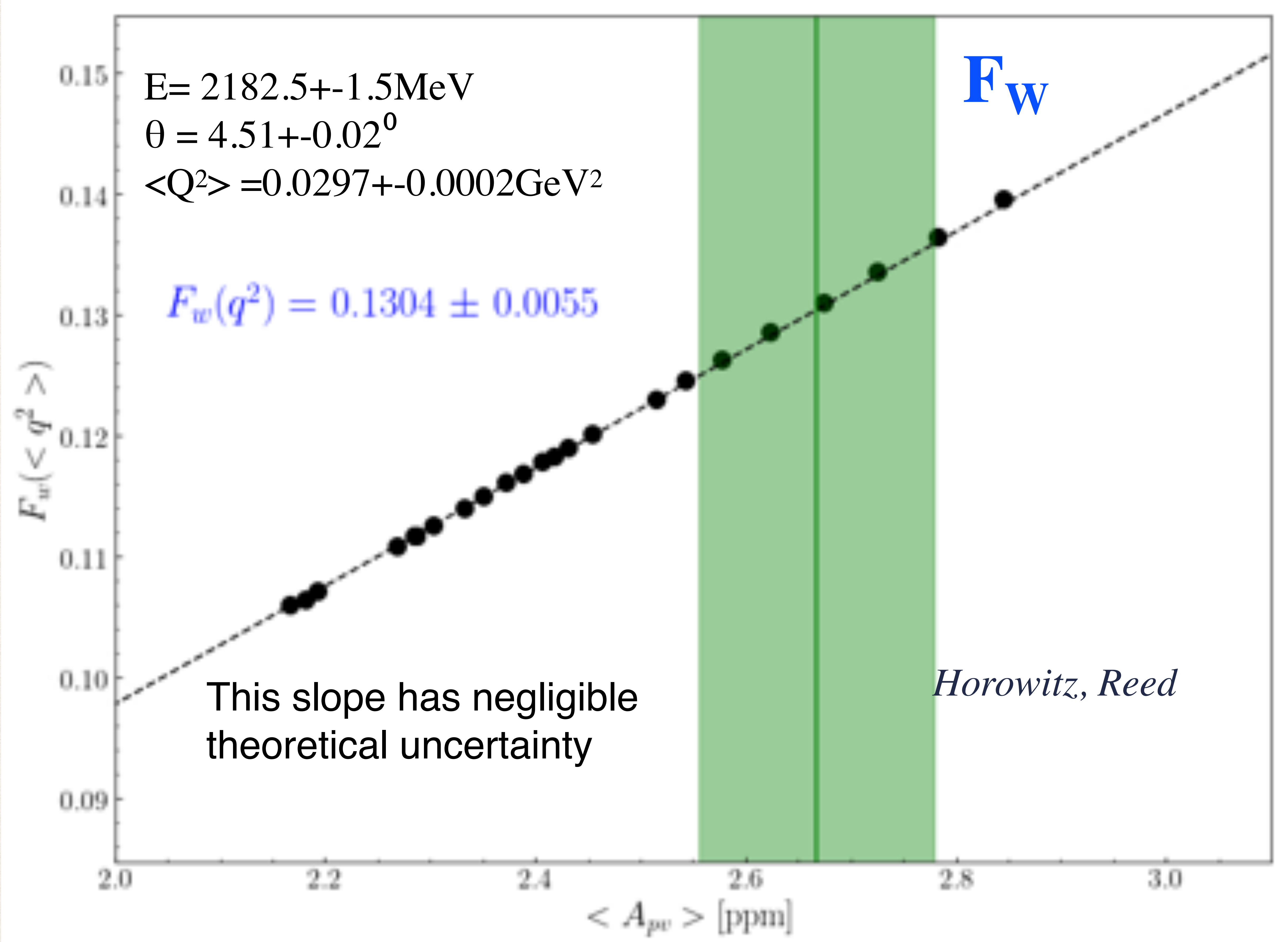
2668 ± 106 (stat) ± 40 (sys)ppb

[± 113.3 ppb (tot) (4.3%)]

	A_{PV} uncertainty contribution [ppb]	A_{PV} uncertainty contribution [%]
Polarization	13.1	0.49%
Horizontal Polarization	12.7	0.48%
Vertical Polarization	0.9	0.03%
Acceptance normalization	23.9	0.90%
Beam correction	6.9	0.26%
Non-linear detector response	6.7	0.25%
Ca40 background	3.0	0.10%
Charge correction	1.1	0.04%
Inelastic contamination 2+	18.9	0.71%
Inelastic contamination 3-(1)	10.2	0.38%
Inelastic contamination 3-(2)	3.6	0.13%
Rescattering	0.5	0.02%
Total	**39.6**	**1.5%**

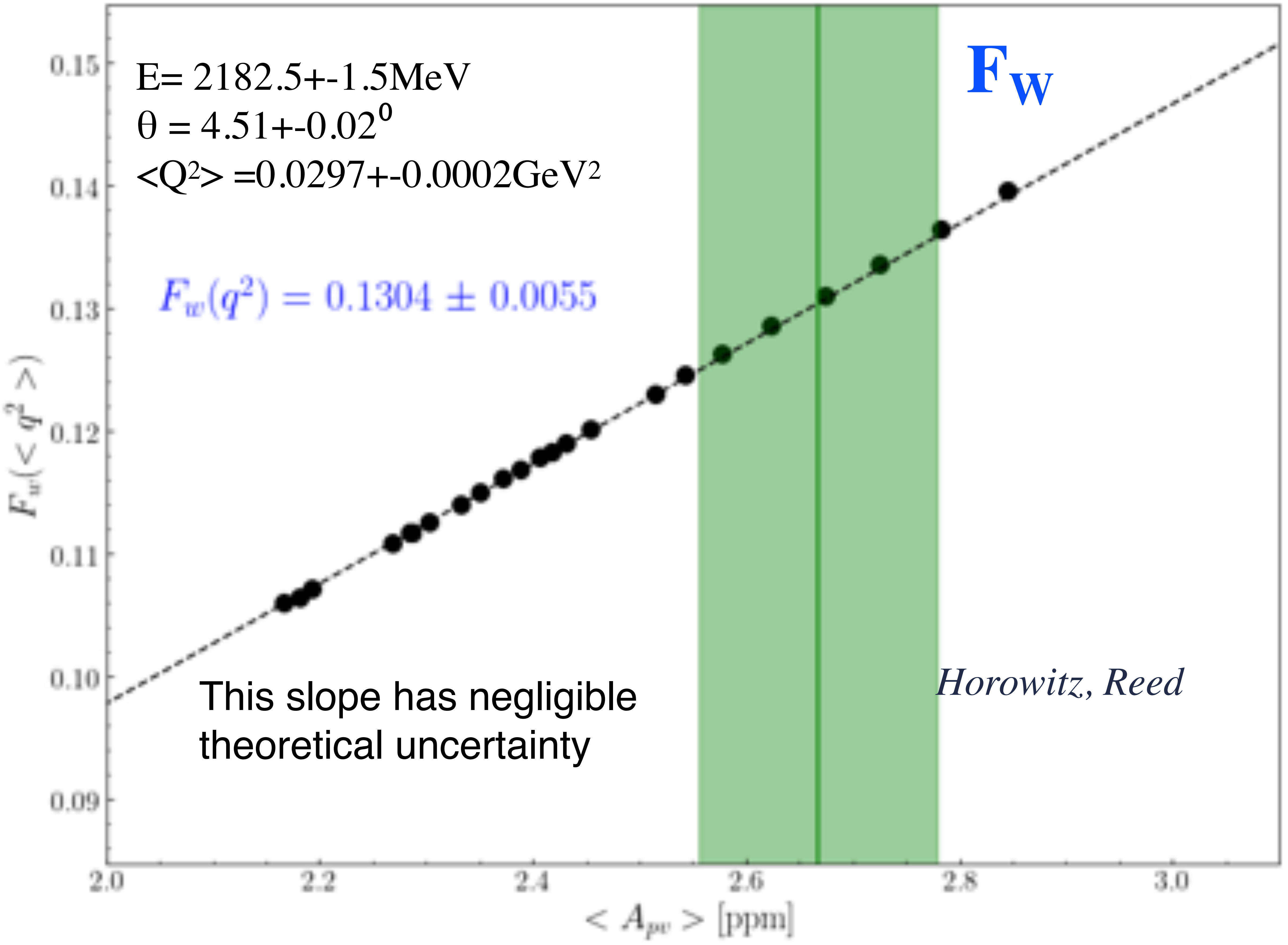
- When taken all into account the experimental systematic uncertainty comes to 1.5%, less than half the 4.0% statistical uncertainty
- Total uncertainty of is 113.3ppb (4.3%)

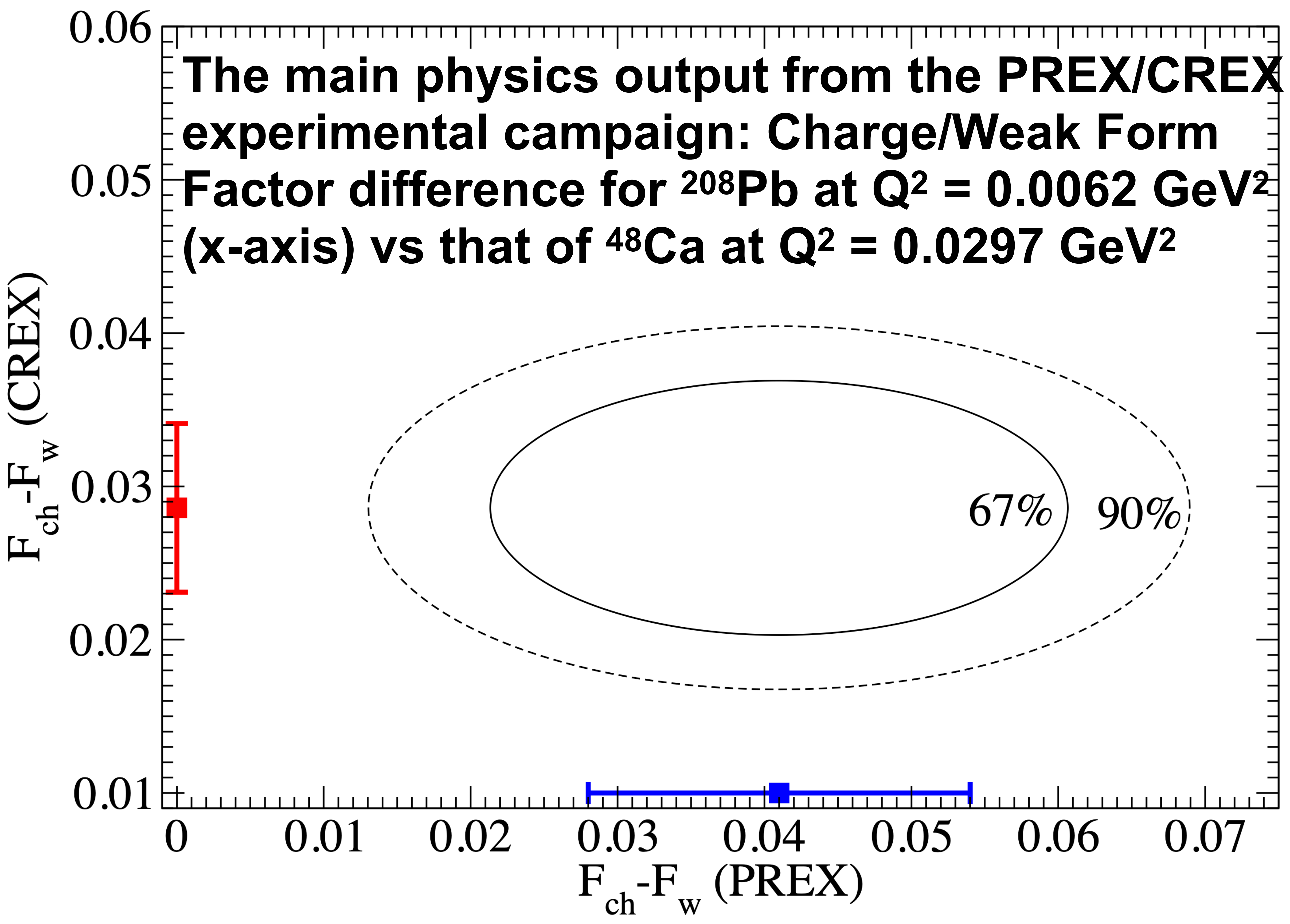
Main Derived Parameter:
The Weak Form Factor at Q^2 = 0.0297 GeV^2



F_W: 0.1304 ± 0.0055

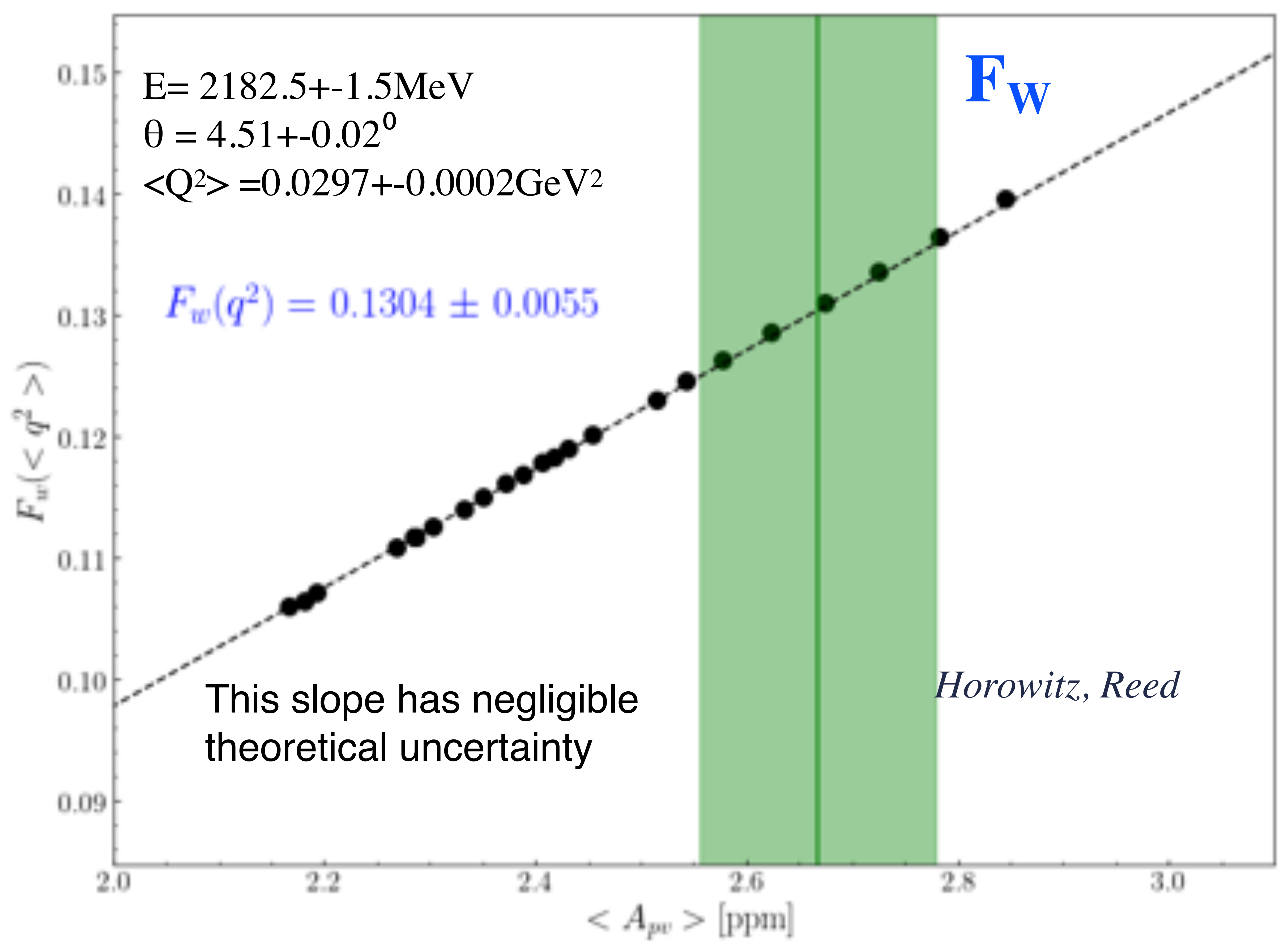
Main Derived Parameter: The Weak Form Factor at $Q^2 = 0.0297$ GeV^2

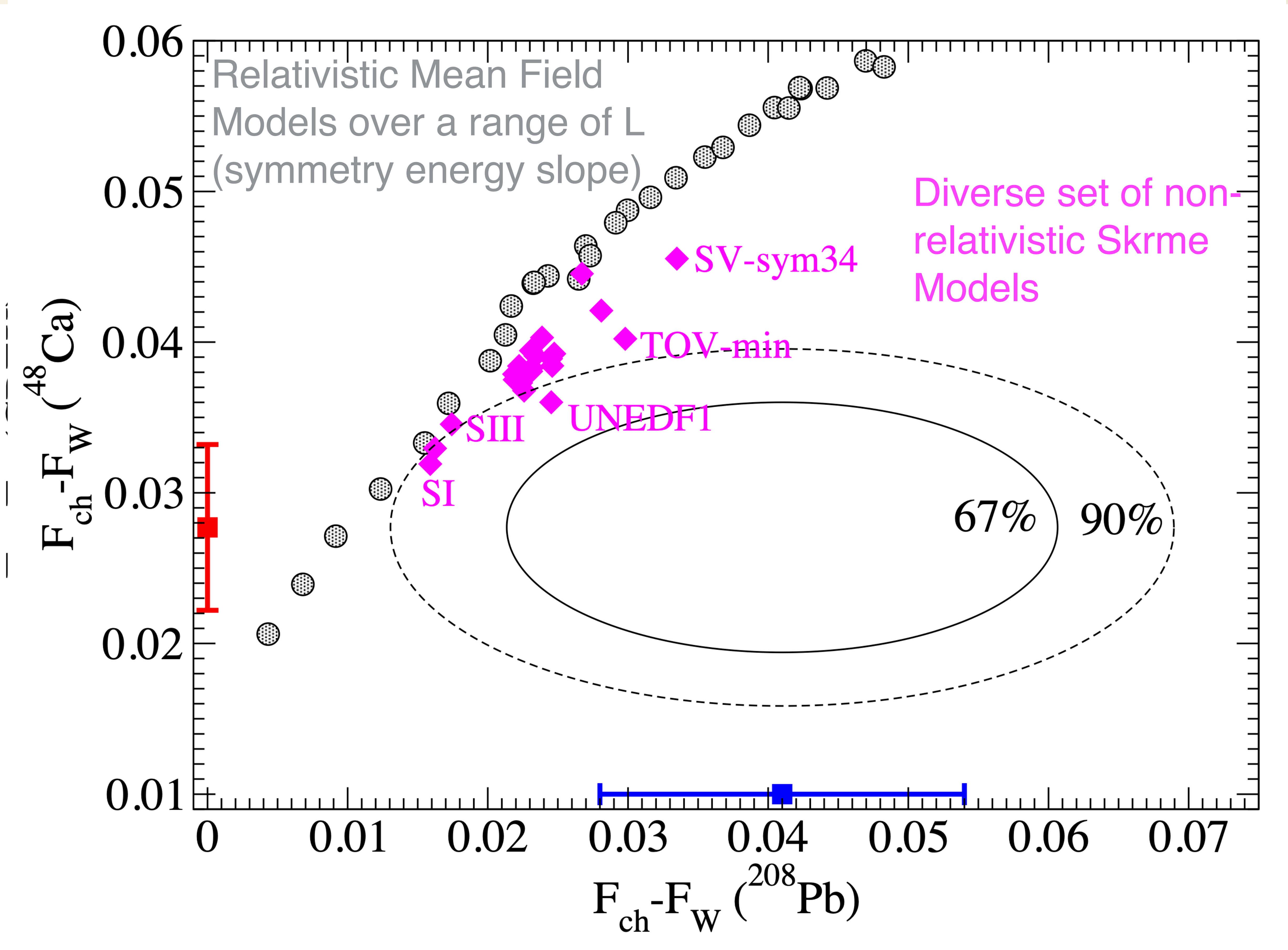




F_W: 0.1304 ± 0.0055

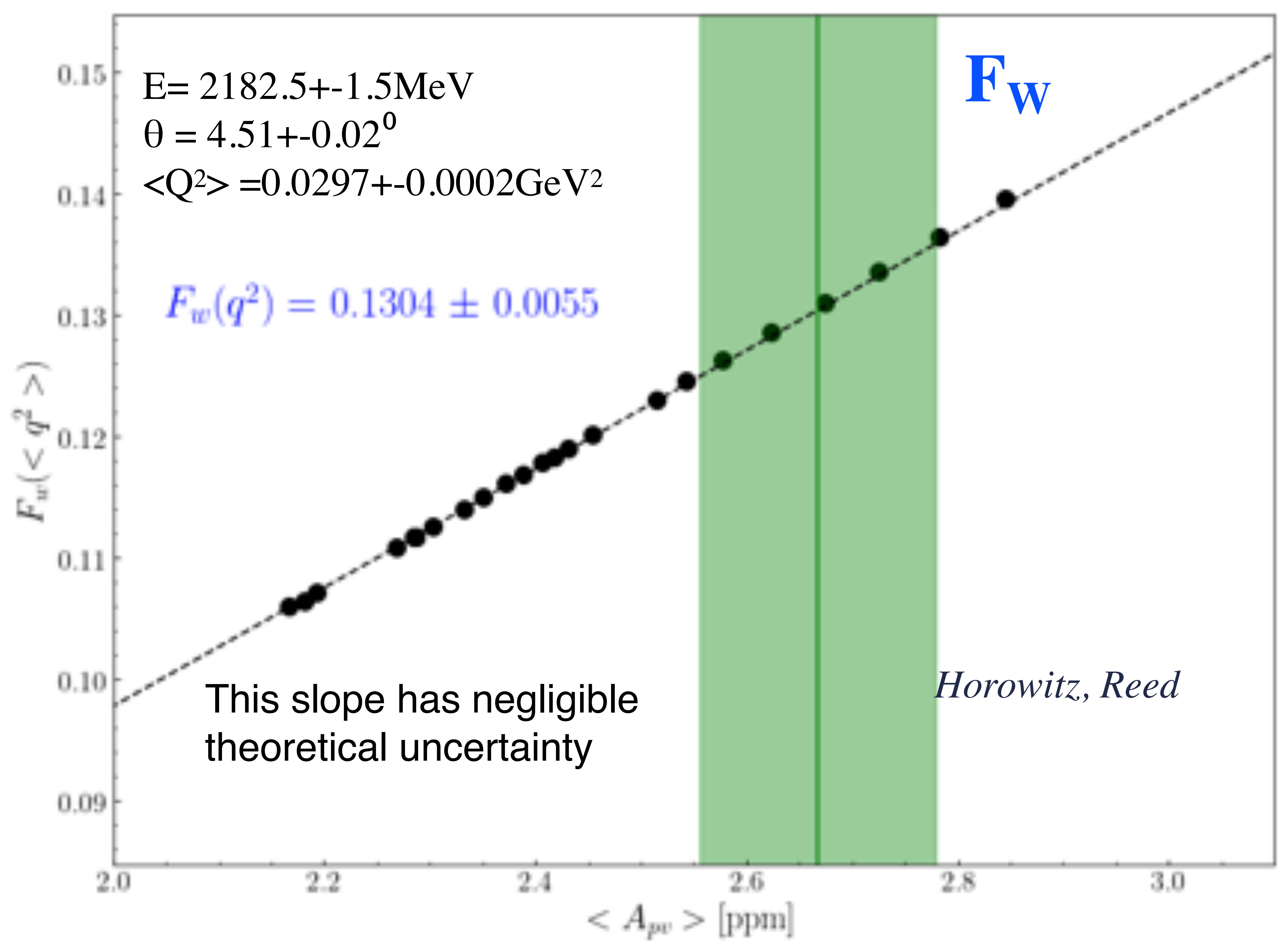
Main Derived Parameter: The Weak Form Factor at $Q^2 = 0.0297$ GeV^2

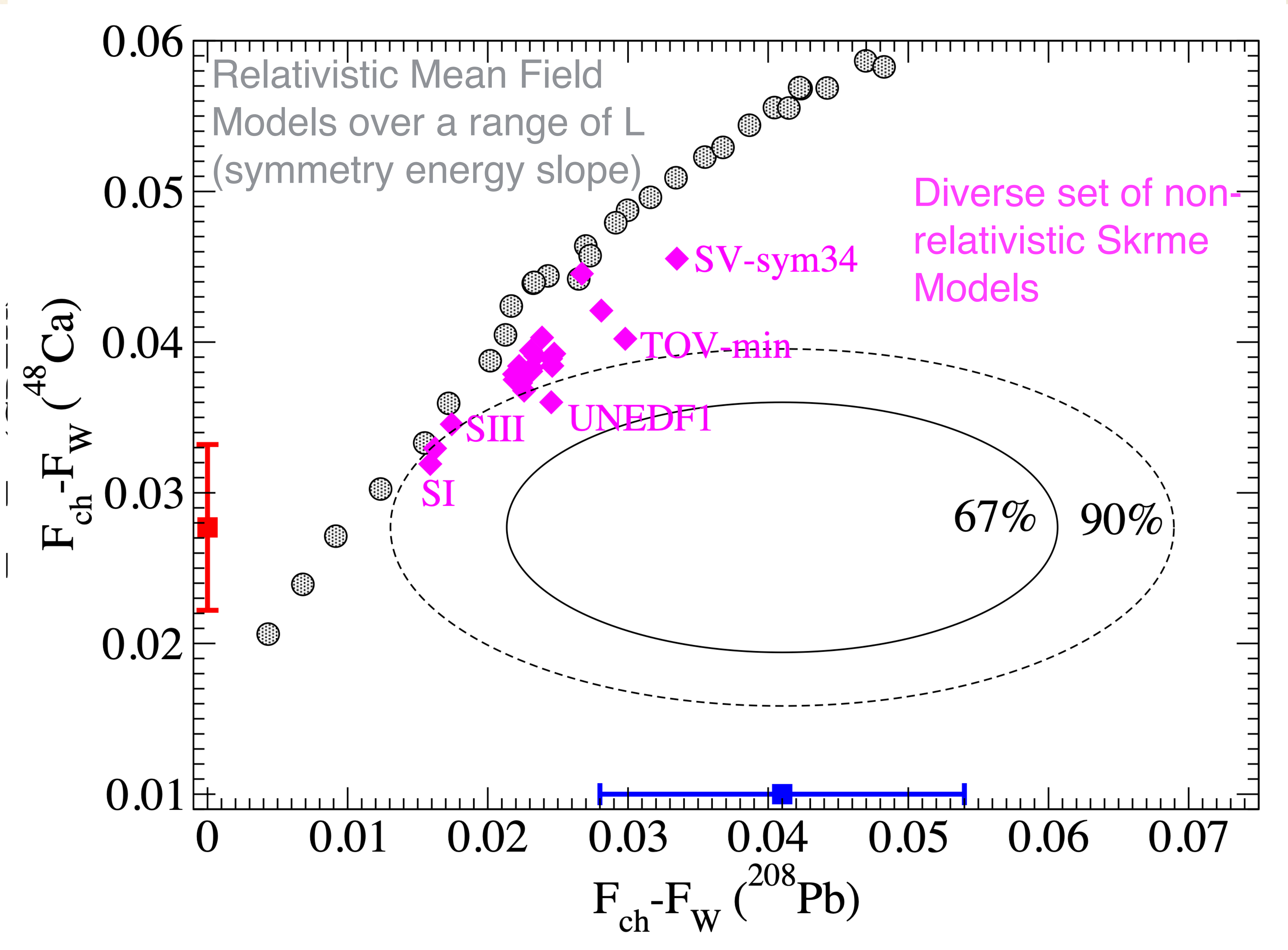




F_W: 0.1304 ± 0.0055

Main Derived Parameter: The Weak Form Factor at $Q^2 = 0.0297\ GeV^2$



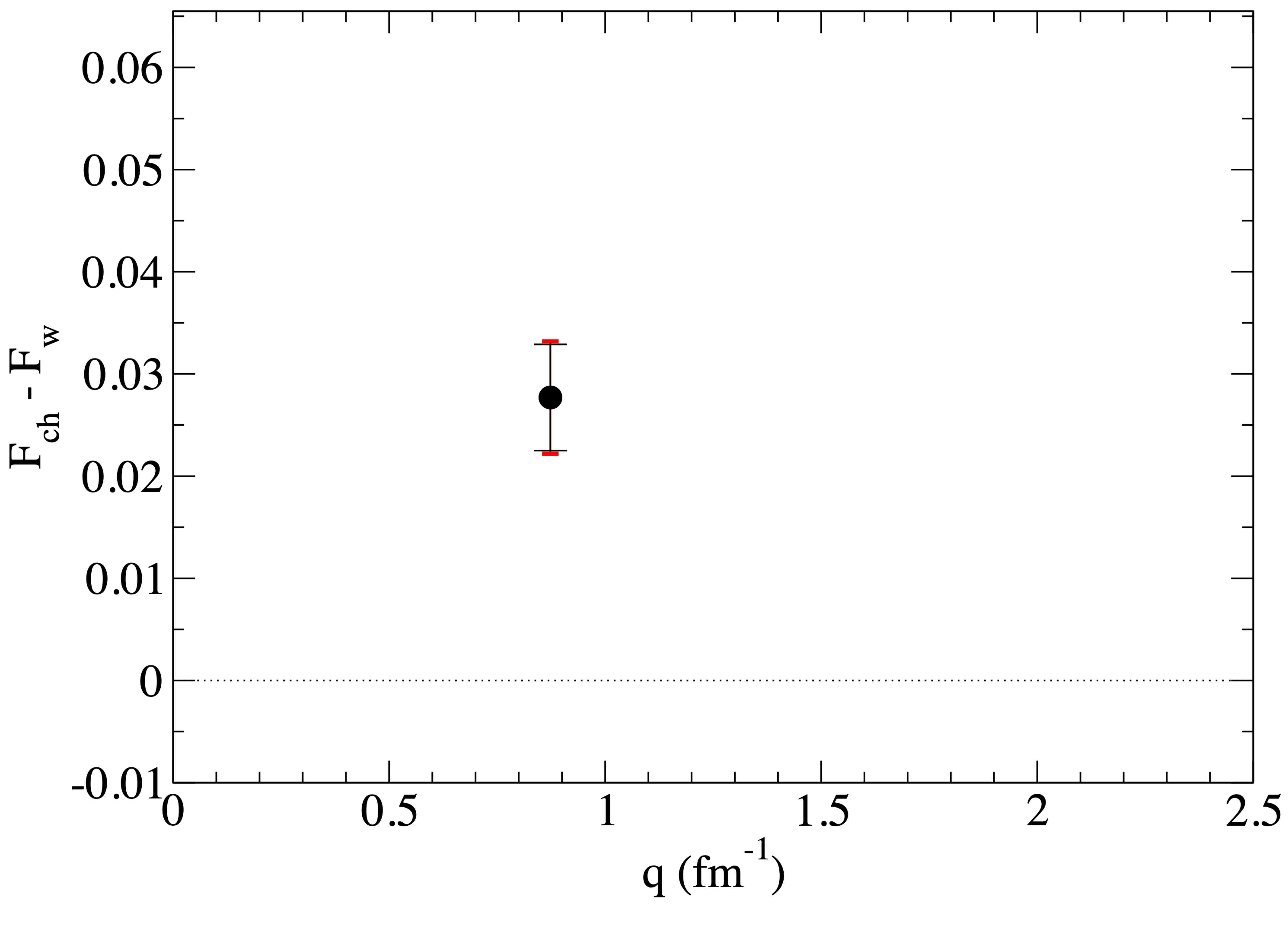


F_W: 0.1304 ± 0.0055

Observation:
CREX result is consistent with a thin neutron skin prediction (e.g. coupled cluster calculations) and is strongly inconsistent with predictions of a very thick skin

CREX Result Discussion and Plans

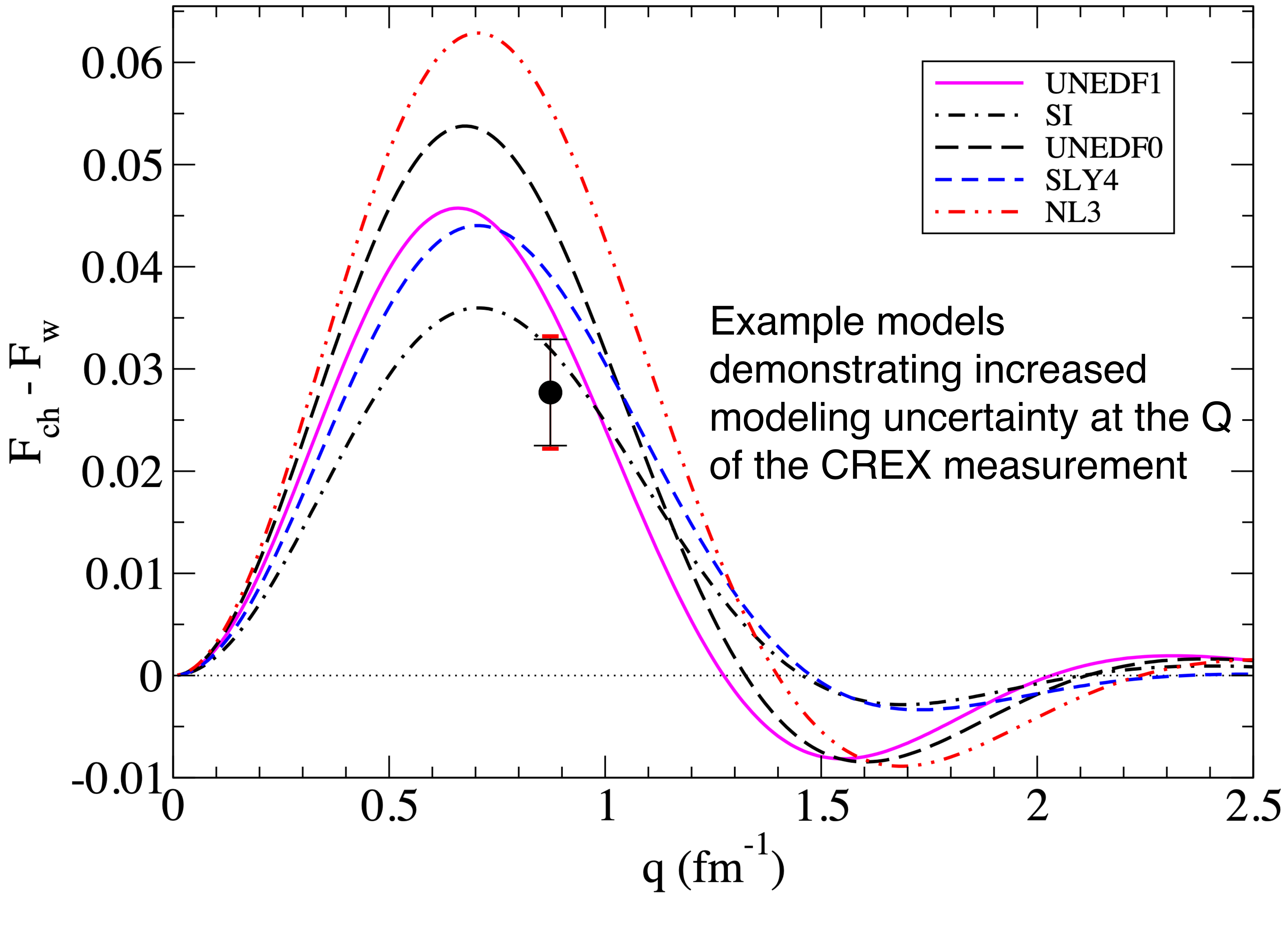
^{48}Ca: Form Factor Difference vs Q



- **Publication on final CREX results just approved by collaboration TODAY**
  - ★ A_{PV} and Weak Form Factor
  - ★ Neutron Skin Thickness with an uncertainty of ~ +/- 0.035 fm
- **Community Discussion of Implications Beginning**
  - ★ Interplay between ^{208}Pb and ^{48}Ca underscores rich dynamics
  - ★ Full implications for symmetry energy slope L will require continued collaboration between various theoretical and experimental groups

CREX Result Discussion and Plans

^{48}Ca: Form Factor Difference vs Q



- **Publication on final CREX results just approved by collaboration TODAY**
  - ★ A_{PV} and Weak Form Factor
  - ★ Neutron Skin Thickness with an uncertainty of ~ +/- 0.035 fm
- **Community Discussion of Implications Beginning**
  - ★ Interplay between ^{208}Pb and ^{48}Ca underscores rich dynamics
  - ★ Full implications for symmetry energy slope L will require continued collaboration between various theoretical and experimental groups

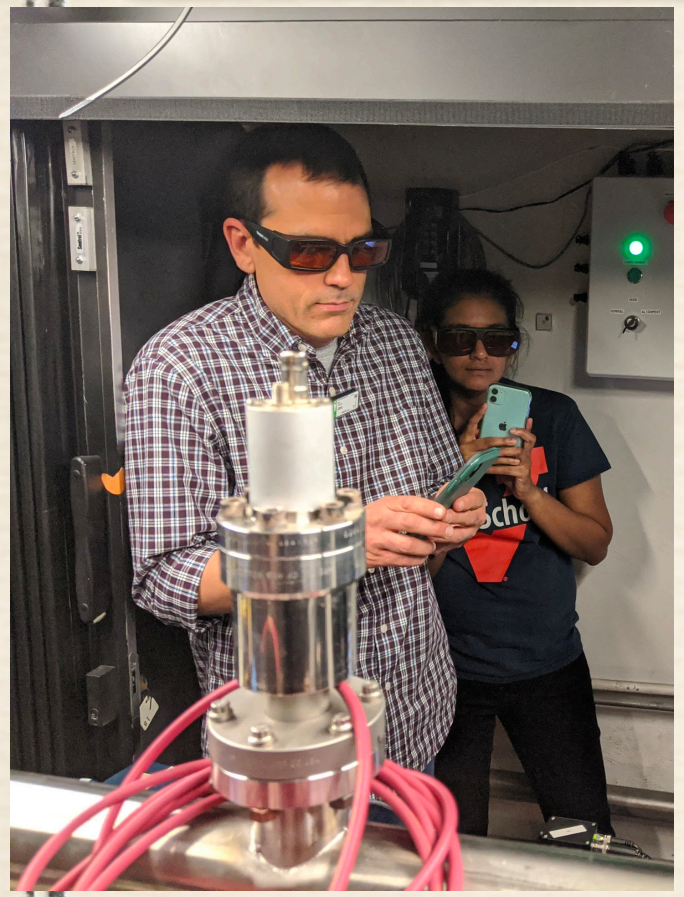
Outlook from PREX & CREX Campaigns

- ✦ **The PREX measurement of the neutron skin thickness of ^{208}Pb has very little model uncertainty**
  - ★ There is a clear and transparent line from the statistical uncertainty in the experimental observable (A_{PV}) to the uncertainty in the neutron skin thickness and then on to slope of the symmetry energy: unique among all measurement techniques!
  - ★ Given the above, improved A_{PV} uncertainty is desirable; MREX at Mainz, targeting an uncertainty of +/- 0.04 fm, has become extremely compelling
- ✦ **The CREX measurement is the final statement from JLab for ^{48}Ca**
  - ★ Before extracting information on slope of the symmetry energy, the community must collaborate to carefully evaluate modeling uncertainties
  - ★ Along with new NSCL and FRIB measurements on a range of nuclei of similar A, reliable neutron skin estimates could be made across the Periodic Table
  - ★ If found compelling, it might be feasible to devise a new A_{PV} measurement on ^{48}Ca at a different Q value at Mainz, or maybe Hall C at JLab

Our Crew

PhD Student

Students: Devi Adhikari, Devaki Bhatta Pathak, Quinn Campagna, Yufan Chen, Cameron Clarke, Catherine Feldman, Iris Halilovic, Siyu Jian, Eric King, Carrington Metts, Marisa Petrusky, Amali Premathilake, Victoria Owen, Robert Radloff, Sakib Rahman, Ryan Richards, Ezekiel Wertz, Tao Ye, Allison Zec, Weibin Zhang





Post-docs and Run Coordinators: Rakitha Beminiwattha, Juan Carlos Cornejo, Mark-Macrae Dalton, Ciprian Gal, Chandan Ghosh, Donald Jones, Tyler Kutz, Hanjie Liu, Juliette Mammei, Dustin McNulty, Caryn Palatchi, Sanghwa Park, Ye Tian, Jinlong Zhang

Spokespeople: D. McNulty, J. Mammei, P. Souder, S. Covrig Dusa, R. Michaels, K. Paschke, S. Riordan, K. Kumar

Thanks to the Hall A techs, Machine Control, Yves Roblin, Jay Benesch and other Jefferson Lab staff

Special thanks to: Charles Horowitz and Jorge Piekarewicz for support and insightful conversations
Especially Chuck and grad student Brendan Reed who have worked to help us interpret our results

Experiments developed at around the same time as the Haeberli/Simonius pp Experiment

Standard Model Tests in the 80's

Elastic scattering from $(J^\pi, T) = (0^+, 0)$ *nuclei* *Feinberg (1975)*

For a simple nucleus like ^{12}C, A_{PV} in elastic scattering at forward angle insensitive to nuclear structure: clean measurement of $\sin^2\theta_W$

^{12}C at MIT-Bates: $A_{PV} = (1.69 \pm 0.39 \pm 0.06) \times 10^{-6}$ *Souder (1990)*

Experiments developed at around the same time as the Haeberli/Simonius pp Experiment

Standard Model Tests in the 80's

Elastic scattering from $(J^\pi, T) = (0^+, 0)$ ***nuclei*** *Feinberg (1975)*

For a simple nucleus like ^{12}C, A_{PV} in elastic scattering at forward angle insensitive to nuclear structure: clean measurement of $\sin^2\theta_W$

^{12}C at MIT-Bates: $A_{PV} = (1.69 \pm 0.39 \pm 0.06) \times 10^{-6}$ *Souder (1990)*

Quasi-elastic backward angle scattering from ^{9}Be

^{9}Be at Mainz: $A_{PV} = (-9.4 \pm 1.8 \pm 0.5) \times 10^{-6}$ *Heil (1989)*

Experiments developed at around the same time as the Haeberli/Simonius pp Experiment

Standard Model Tests in the 80's

Elastic scattering from $(J^\pi, T) = (0^+, 0)$ ***nuclei*** *Feinberg (1975)*

For a simple nucleus like ^{12}C, A_{PV} in elastic scattering at forward angle insensitive to nuclear structure: clean measurement of $\sin^2\theta_W$

^{12}C at MIT-Bates: $A_{PV} = (1.69 \pm 0.39 \pm 0.06) \times 10^{-6}$ *Souder (1990)*

Quasi-elastic backward angle scattering from ^{9}Be

^{9}Be at Mainz: $A_{PV} = (-9.4 \pm 1.8 \pm 0.5) \times 10^{-6}$ *Heil (1989)*

- ***First measurements of electron-nuclear weak interactions***
- ***Pushed experimental technology***
- ***Spawned a new generation of experimenters and experiments***

Standard Model Tests in the 80's

Elastic scattering from $(J^\pi, T) = (0^+, 0)$ ***nuclei*** *Feinberg (1975)*

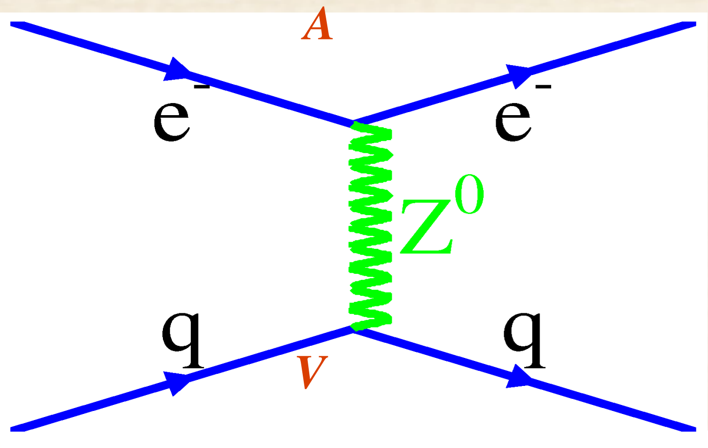
For a simple nucleus like ^{12}C, A_{PV} in elastic scattering at forward angle insensitive to nuclear structure: clean measurement of $\sin^2\theta_W$

^{12}C at MIT-Bates: $A_{PV} = (1.69 \pm 0.39 \pm 0.06) \times 10^{-6}$ *Souder (1990)*

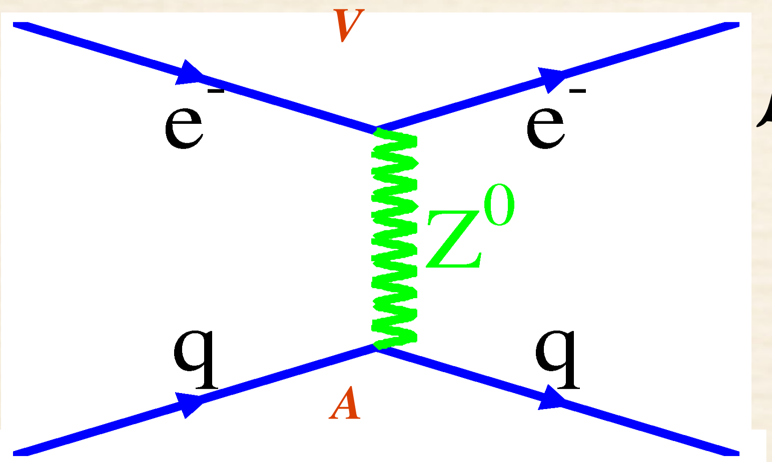
Quasi-elastic backward angle scattering from ^{9}Be

^{9}Be at Mainz: $A_{PV} = (-9.4 \pm 1.8 \pm 0.5) \times 10^{-6}$ *Heil (1989)*

- *First measurements of electron-nuclear weak interactions*
- *Pushed experimental technology*
- *Spawned a new generation of experimenters and experiments*



$C_{1i} \equiv 2g_A^e g_V^i$



$C_{2i} \equiv 2g_V^e g_A^i$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$

Standard Model Tests in the 80's

Elastic scattering from $(J^\pi, T) = (0^+, 0)$ ***nuclei*** *Feinberg (1975)*

For a simple nucleus like ¹²C, A_{PV} in elastic scattering at forward angle insensitive to nuclear structure: clean measurement of $\sin^2\theta_W$

^{12}C at MIT-Bates: $A_{PV} = (1.69 \pm 0.39 \pm 0.06) \times 10^{-6}$ *Souder (1990)*

Quasi-elastic backward angle scattering from ^{9}Be

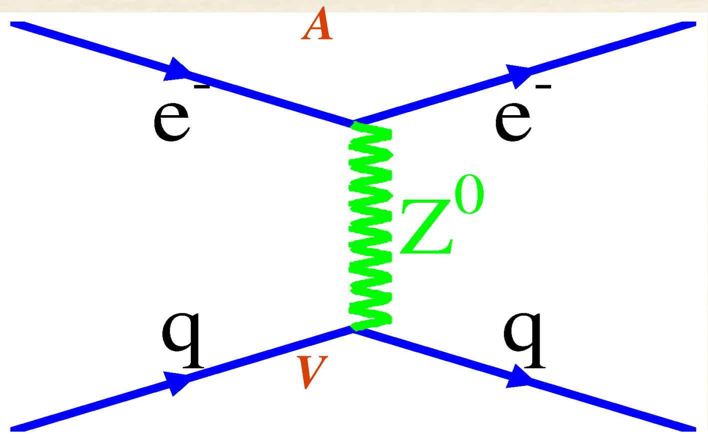
^{9}Be at Mainz: $A_{PV} = (-9.4 \pm 1.8 \pm 0.5) \times 10^{-6}$ *Heil (1989)*

Electron Scattering

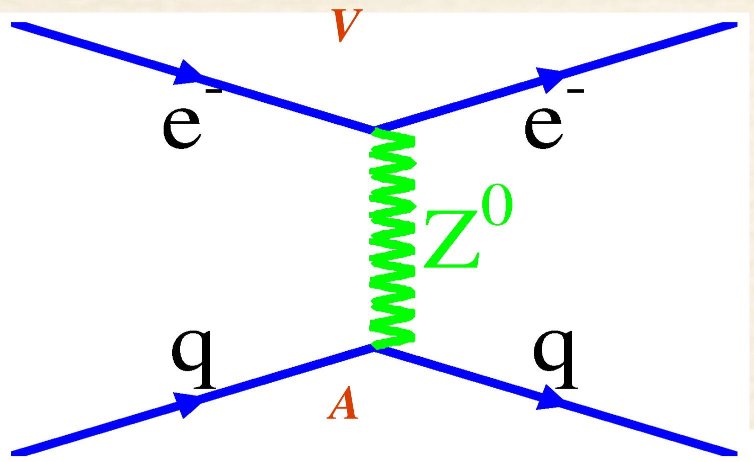
100 ppb systematics

100's of MHz rates

- *First measurements of electron-nuclear weak interactions*
- *Pushed experimental technology*
- *Spawned a new generation of experimenters and experiments*



$C_{1i} \equiv 2 g_A^e g_V^i$



$C_{2i} \equiv 2 g_V^e g_A^i$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$

Standard Model Tests in the 80's

Elastic scattering from $(J^\pi, T) = (0^+, 0)$ ***nuclei*** *Feinberg (1975)*

For a simple nucleus like ^{12}C***,*** A_{PV} ***in elastic scattering at forward angle insensitive to nuclear structure: clean measurement of*** $\sin^2\theta_W$

^{12}C at MIT-Bates: $A_{PV} = (1.69 \pm 0.39 \pm 0.06) \times 10^{-6}$ *Souder (1990)*

Quasi-elastic backward angle scattering from ^{9}***Be***

^{9}Be at Mainz: $A_{PV} = (-9.4 \pm 1.8 \pm 0.5) \times 10^{-6}$ *Heil (1989)*

- ***First measurements of electron-nuclear weak interactions***
- ***Pushed experimental technology***
- ***Spawned a new generation of experimenters and experiments***

Electron Scattering

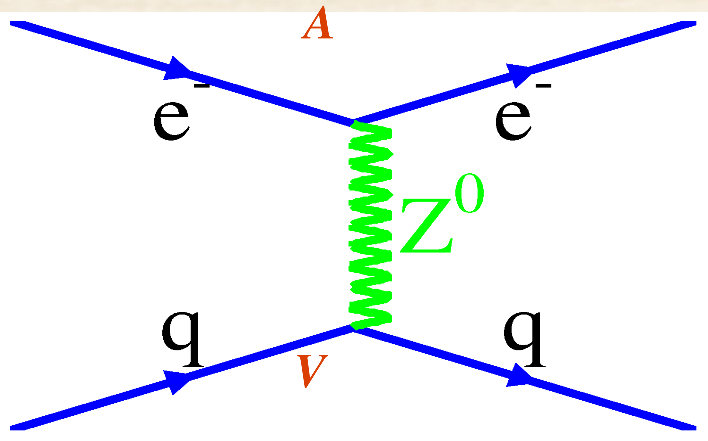
100 ppb systematics

100's of MHz rates

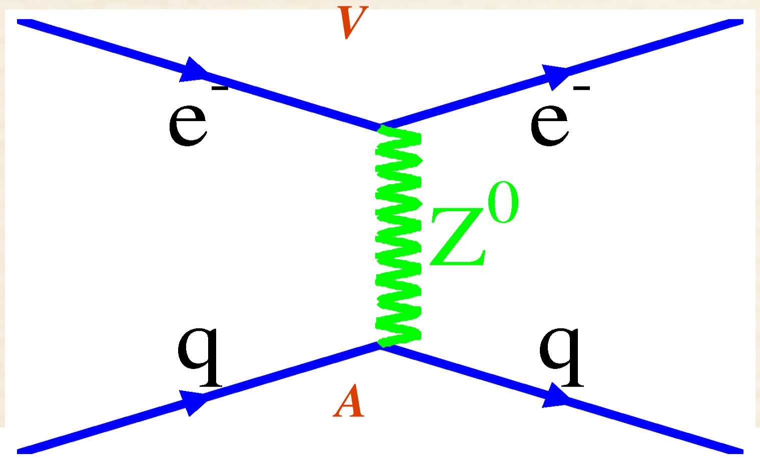
Proton Scattering

10 ppb systematics

10's of GHz rates



$C_{1i} \equiv 2 g_A^e g_V^i$



$C_{2i} \equiv 2 g_V^e g_A^i$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}} [\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$

QCD Dynamics with Precision
LD_2 PVDIS

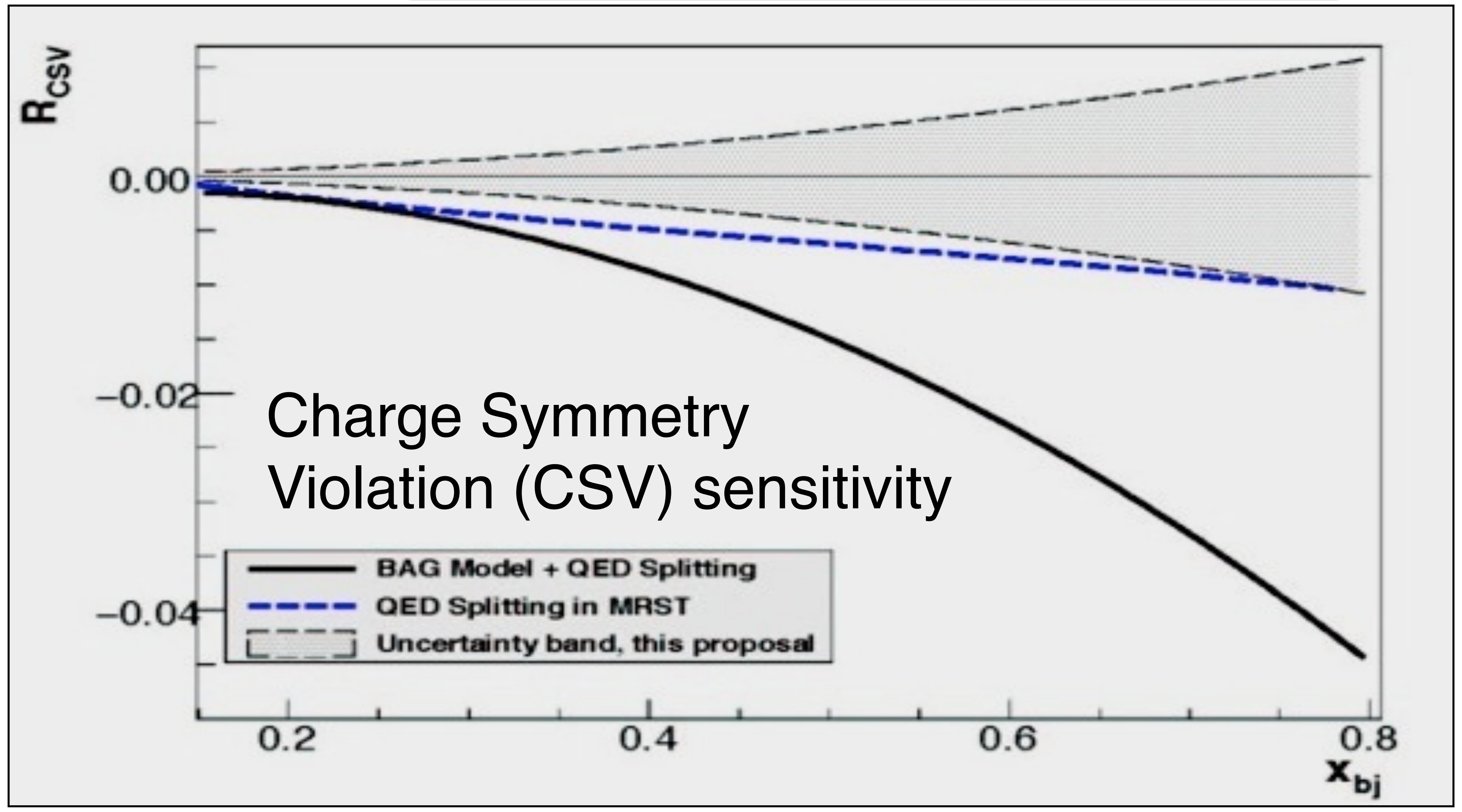
$$u^p(x) \stackrel{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$
$$d^p(x) \stackrel{?}{=} u^n(x) \quad \Rightarrow \quad \delta d(x) \equiv d^p(x) - u^n(x)$$

$$R_{CSV} = \frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

We already know some CSV effects:

- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects

- **Direct sensitivity to parton-level CSV**
- **Important implications for PDF's**
- ***Could be* partial explanation of the NuTeV anomaly**



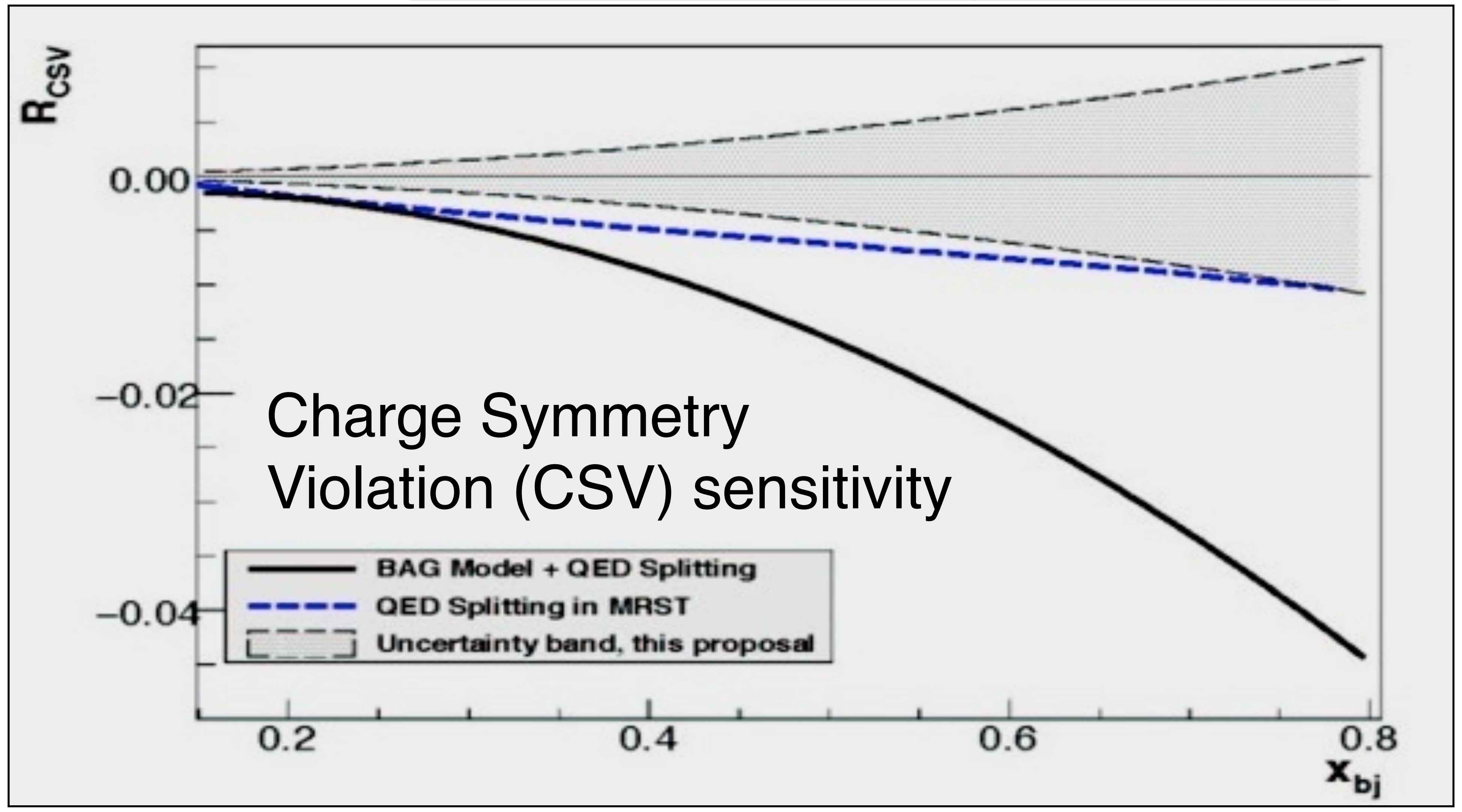
QCD Dynamics with Precision LD$_2$ PVDIS

$$u^p(x) \stackrel{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$
$$d^p(x) \stackrel{?}{=} u^n(x) \quad \Rightarrow \quad \delta d(x) \equiv d^p(x) - u^n(x)$$

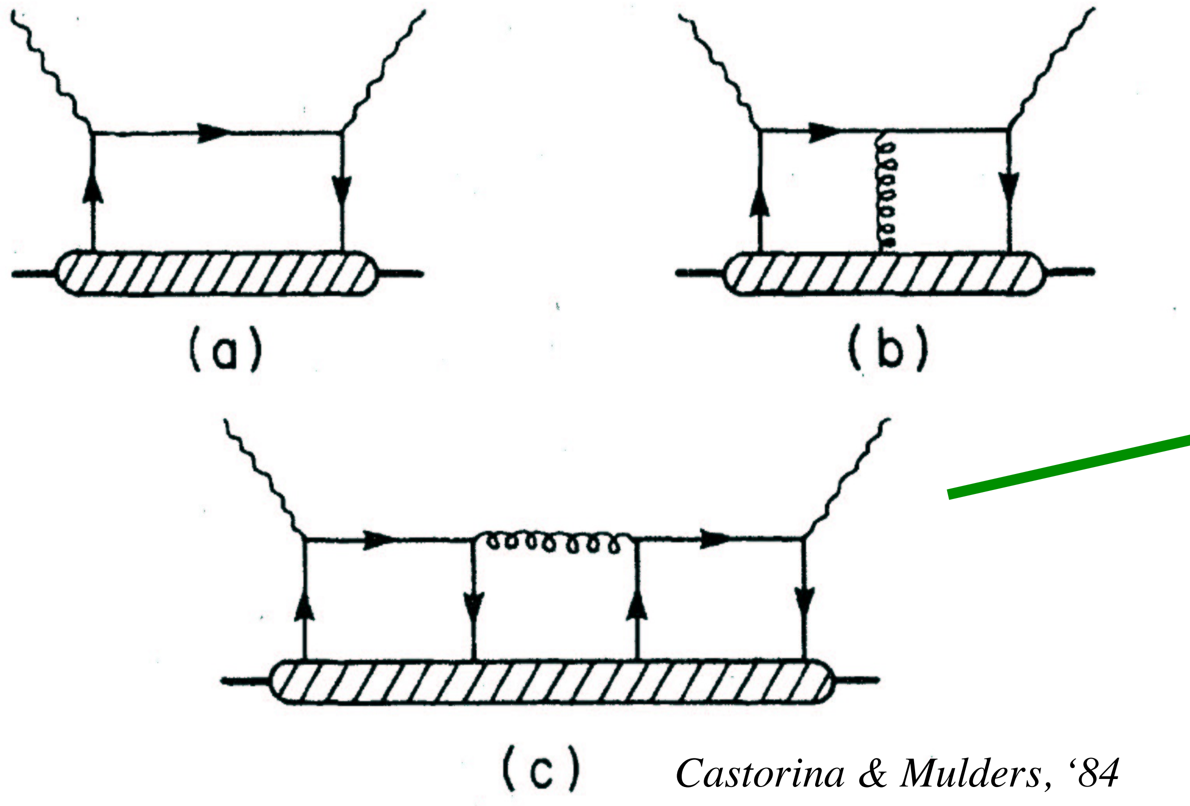
$$R_{CSV} = \frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

We already know some CSV effects:

- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects



- **Direct sensitivity to parton-level CSV**
- **Important implications for PDF's**
- ***Could be* partial explanation of the NuTeV anomaly**



Castorina & Mulders, '84

$$\langle VV\rangle - \langle SS\rangle = \langle (V-S)(V+S)\rangle \propto l_{\mu\nu} \int \langle D \,|\, \bar{u}(x)\gamma^{\mu} u(x) \bar{d}(0)\gamma^{\nu} d(0) \rangle e^{iqx} d^4x$$

Zero in quark-parton model

Higher-Twist valence quark-quark correlation

(c) type diagram is the only operator that can contribute to a(x) higher twist: theoretically very interesting!

σ_L contributions cancel

PVDIS with the Nucleon

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

first principles: using electroweak neutral current structure functions of the nucleon

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2} \frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

PVDIS with the Nucleon

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

first principles: using electroweak neutral current structure functions of the nucleon

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2} \frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

quark-parton model and pdfs

$$a(x) \approx \frac{3}{4}\left[\frac{6C_{1u}u(x) - 3C_{1d}d(x)}{u(x) + \frac{1}{4}d(x)}\right] \sim \left[\frac{u(x) + 0.912d(x)}{u(x) + 0.25d(x)}\right]$$

PVDIS with the Nucleon

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

first principles: using electroweak neutral current structure functions of the nucleon

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2} \frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

quark-parton model and pdfs

$$a(x) \approx \frac{3}{4}\left[\frac{6C_{1u}u(x) - 3C_{1d}d(x)}{u(x) + \frac{1}{4}d(x)}\right] \sim \left[\frac{u(x) + 0.912d(x)}{u(x) + 0.25d(x)}\right]$$

The Z vector coupling to u- and d-quarks approximately the same: for hydrogen, dominant a(x) piece is very sensitive to d/u

PVDIS with the Nucleon

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

first principles: using electroweak neutral current structure functions of the nucleon

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

quark-parton model and pdfs

$$a(x) \approx \frac{3}{4}\left[\frac{6C_{1u}u(x) - 3C_{1d}d(x)}{u(x) + \frac{1}{4}d(x)}\right] \sim \left[\frac{u(x) + 0.912d(x)}{u(x) + 0.25d(x)}\right]$$

The Z vector coupling to u- and d-quarks approximately the same: for hydrogen, dominant a(x) piece is very sensitive to d/u

NO Nuclear Corrections !!!

PVDIS with the Nucleon

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

first principles: using electroweak neutral current structure functions of the nucleon

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

quark-parton model and pdfs

$$a(x) \approx \frac{3}{4}\left[\frac{6C_{1u}u(x) - 3C_{1d}d(x)}{u(x) + \frac{1}{4}d(x)}\right] \sim \left[\frac{u(x) + 0.912d(x)}{u(x) + 0.25d(x)}\right]$$

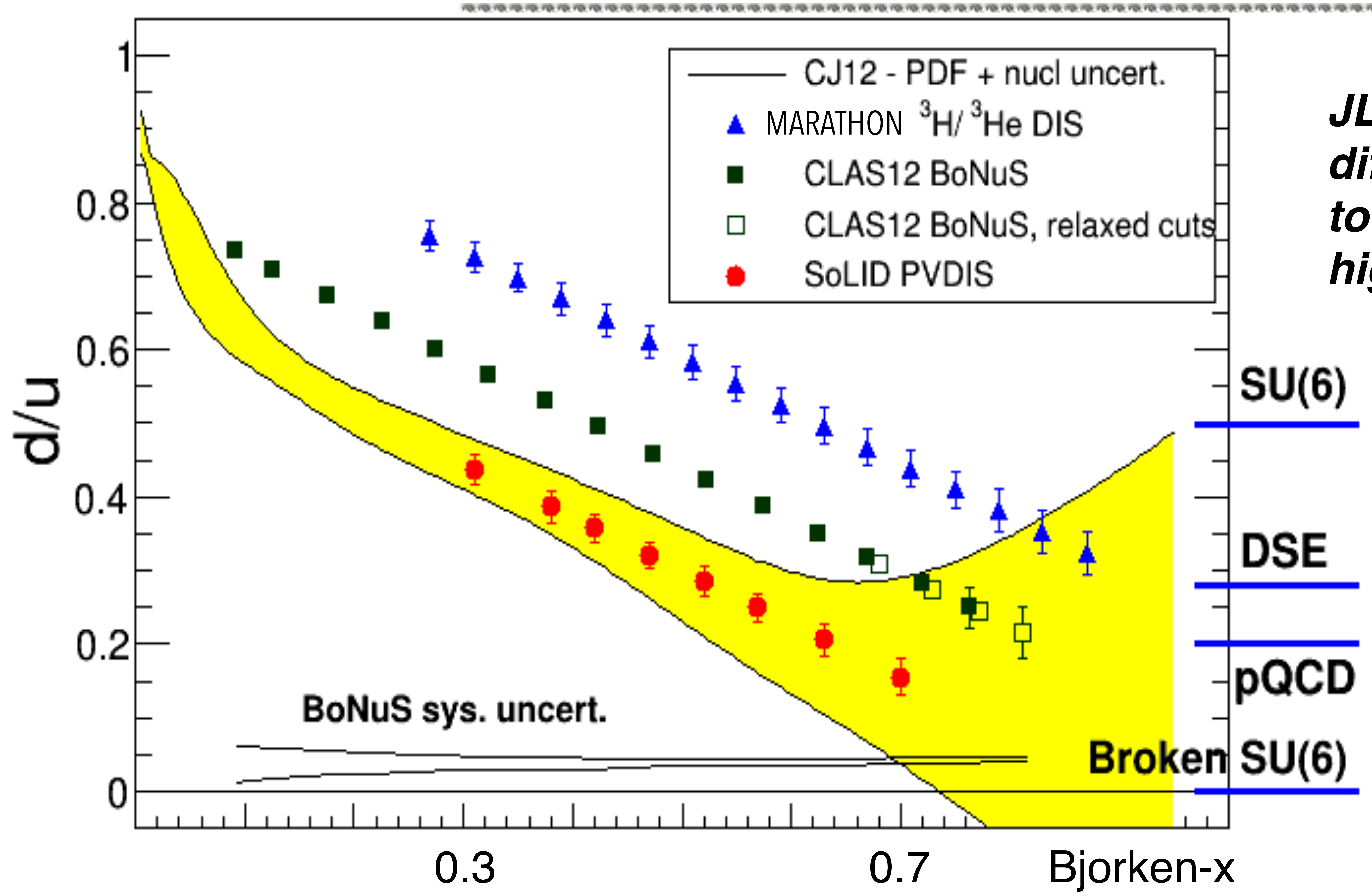
The Z vector coupling to u- and d-quarks approximately the same: for hydrogen, dominant a(x) piece is very sensitive to d/u

NO Nuclear Corrections !!!

SOLID makes possible the first measurements on LH_2 with sufficient statistical precision at high-x

Longstanding issue in nucleon structure: d(x) as x → 1

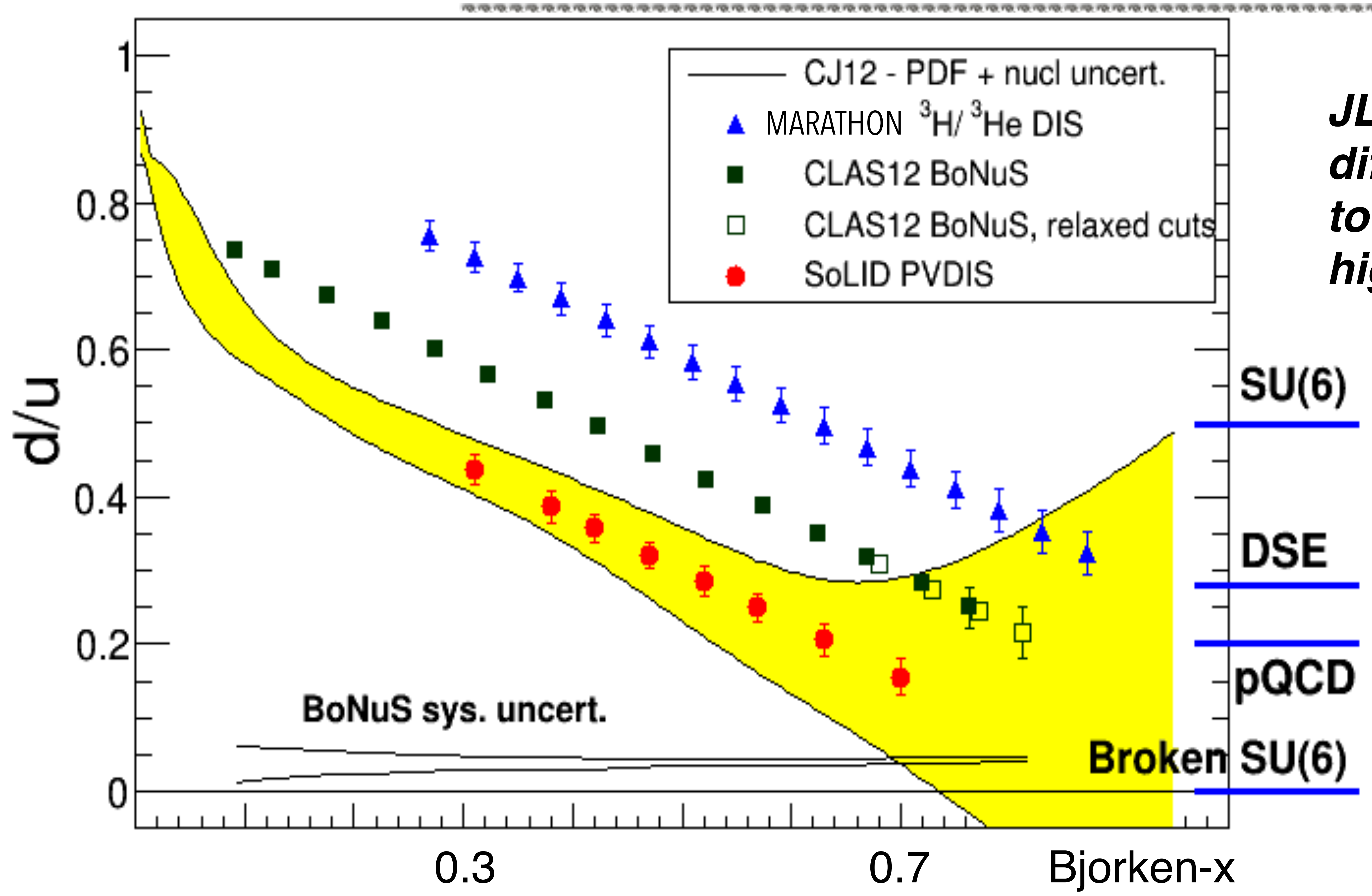
d/u with the Proton



JLab program has three different methods to extract d/u at high-x with high statistical precision

Longstanding issue in nucleon structure: d(x) as x → 1

d/u with the Proton

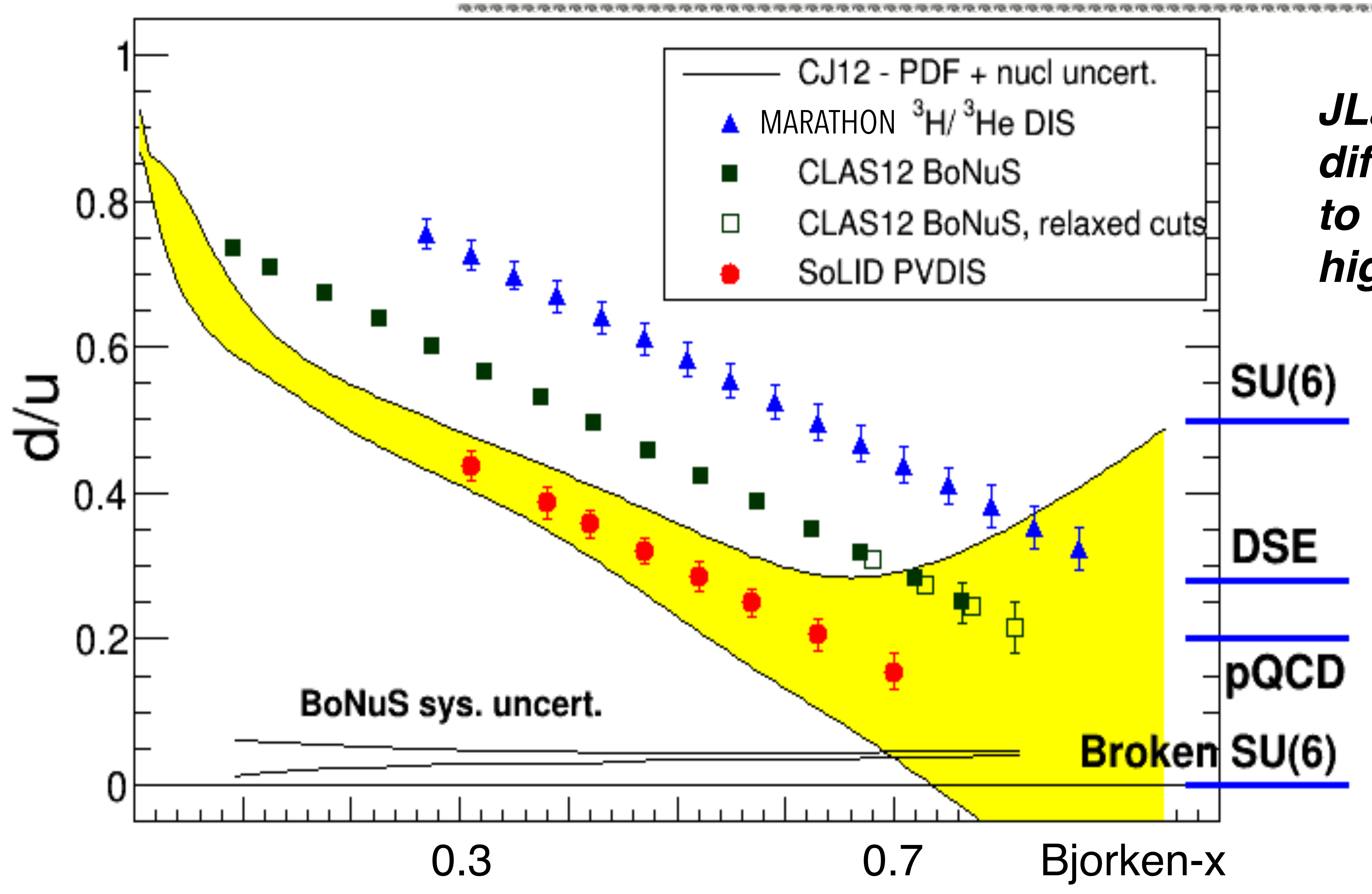


JLab program has three different methods to extract d/u at high-x with high statistical precision

- **Nucleon scattering**
- **Slightly lower-x**
- **Statistics-dominated!**
- **"For free": just replace LD2 with LH2**

Longstanding issue in nucleon structure: d(x) as x → 1

d/u with the Proton



JLab program has three different methods to extract d/u at high-x with high statistical precision

- ***Nucleon*** **scattering**
- **Slightly lower-x**
- **Statistics-dominated!**
- **"For free": just replace LD2 with LH2**

By comparing and contrasting the three methods:

- **Robust extraction of d/u from JLab**
- **Possible new Insights into higher twist effects**
- **Possibly disentangle charge symmetry violation**
- **Nuclear dynamics at high-x**

Cloet, Bentz, Thomas, arXiv 0901.3559

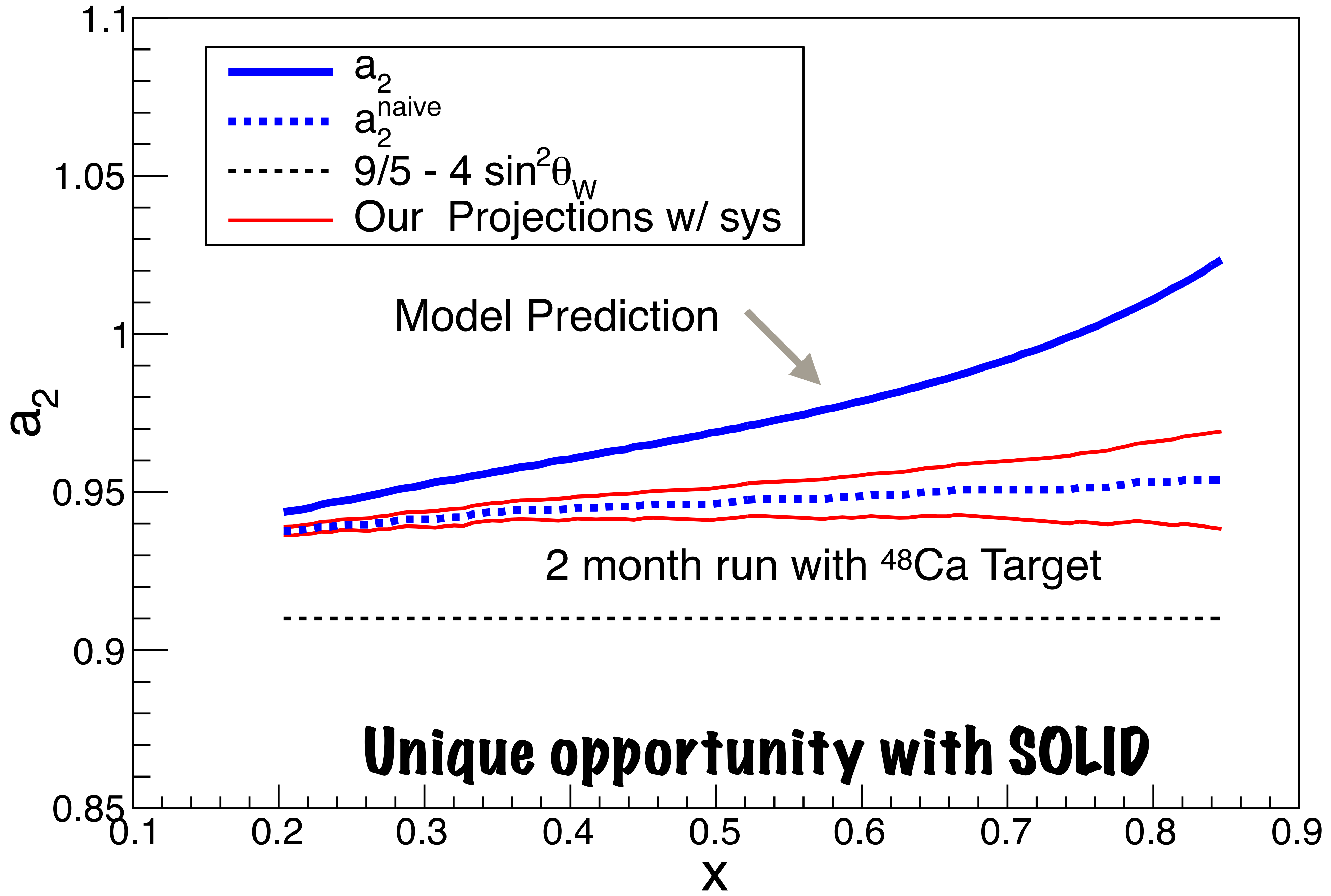
^{48}Ca PVDIS

Consider PVDIS on a heavy nucleus

- Neutron or proton excess in nuclei leads to a isovector-vector mean field (ρ exchange)
- shifts quark distributions: “apparent” charge symmetry violation
- Isovector EMC effect: could be responsible for at least 2/3 of NuTeV anomaly
    - **new insight into medium modification of quark distributions**

$$a_2 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + \dots$$

Great leverage for insight into isospin dependence of the EMC effect in an inclusive measurement



Cloet, Bentz, Thomas, arXiv 0901.3559

^{48}Ca PVDIS

Consider PVDIS on a heavy nucleus

- **Neutron or proton excess in nuclei leads to a isovector-vector mean field (ρ exchange)**
- **shifts quark distributions: "apparent" charge symmetry violation**
- **Isovector EMC effect: could be responsible for at least 2/3 of NuTeV anomaly**
  - **new insight into medium modification of quark distributions**

$$a_2 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + \ldots$$

Great leverage for insight into isospin dependence of the EMC effect in an inclusive measurement

- ***methods of flavor decomposition of medium modifications challenging***
- ***must disentangle small effects (theoretically and experimentally)***
- ***Precise isotope cross-section ratios in purely electromagnetic electron scattering: MUCH reduced sensitivity to the isovector combination***