SFB 1044
Institut für Kernphysik

$\sin^2 \theta_W = 0.238$

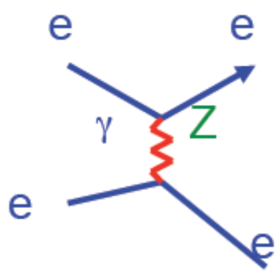
Precision measurement of the Weinberg angle

Frank Maas
(Helmholtz Institute Mainz,
Johannes Gutenberg University Mainz)

"The Future of Non-Collider-Physics", Mainz, April 27./28., 2017

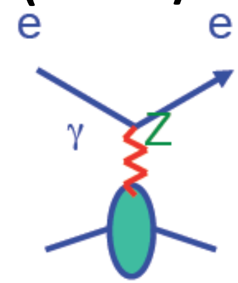
SFB 1044 HIM PRISMA

Møller Scattering



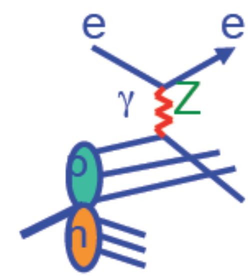
- Purely Leptonic

Q-Weak (JLab)
P2 (Mainz/MESA)



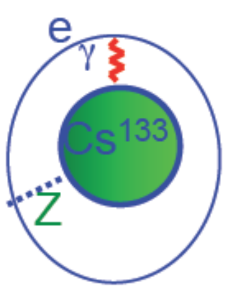
- Coherent quarks in p
- in operation now
- $2(2C_{1u}+C_{1d})$

e-DIS



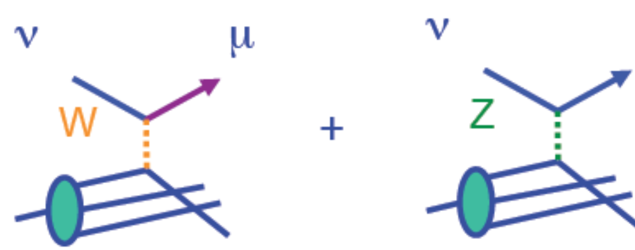
- Isoscaler quark scattering
- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

Atomic Parity Violation



- Coherent quarks in entire nucleus
- Nuclear structure uncertainties
- $-376\ C_{1u} - 422\ C_{1d}$

Neutrino Scattering



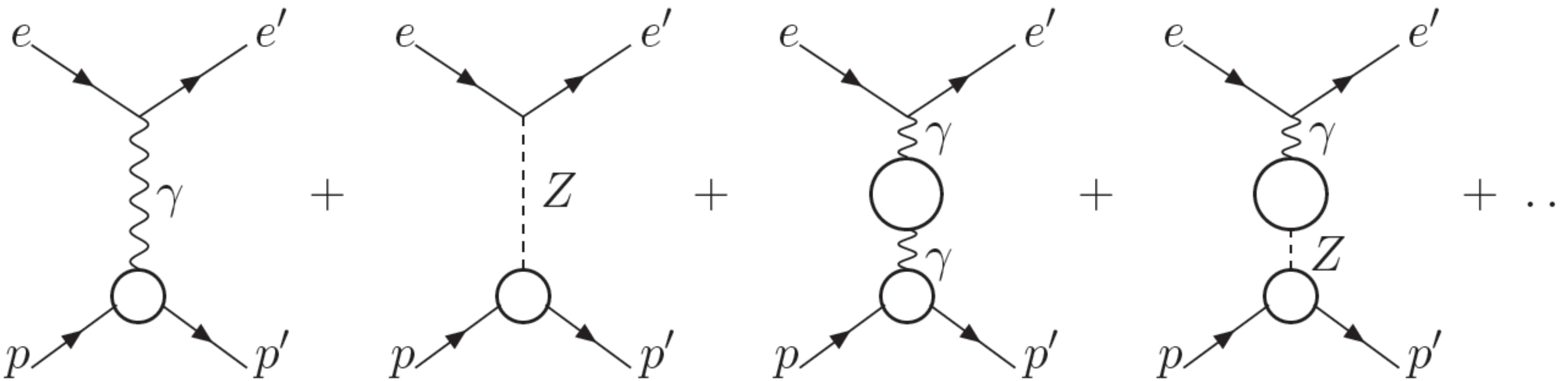
- Quark scattering (from nucleus)
- Weak charged and neutral current difference

S. Su

Courtesy of P. Reimer and R. Arnold

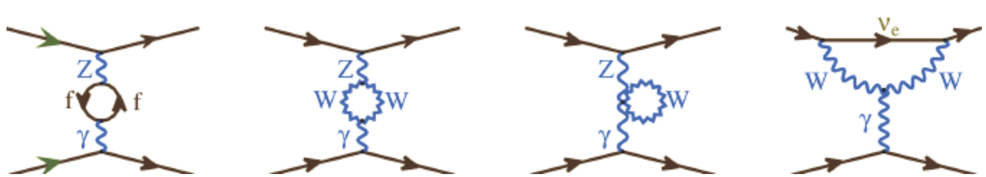
„running“ $\sin^2 \theta_{eff}$ or $\sin^2 \theta_W(\mu)$

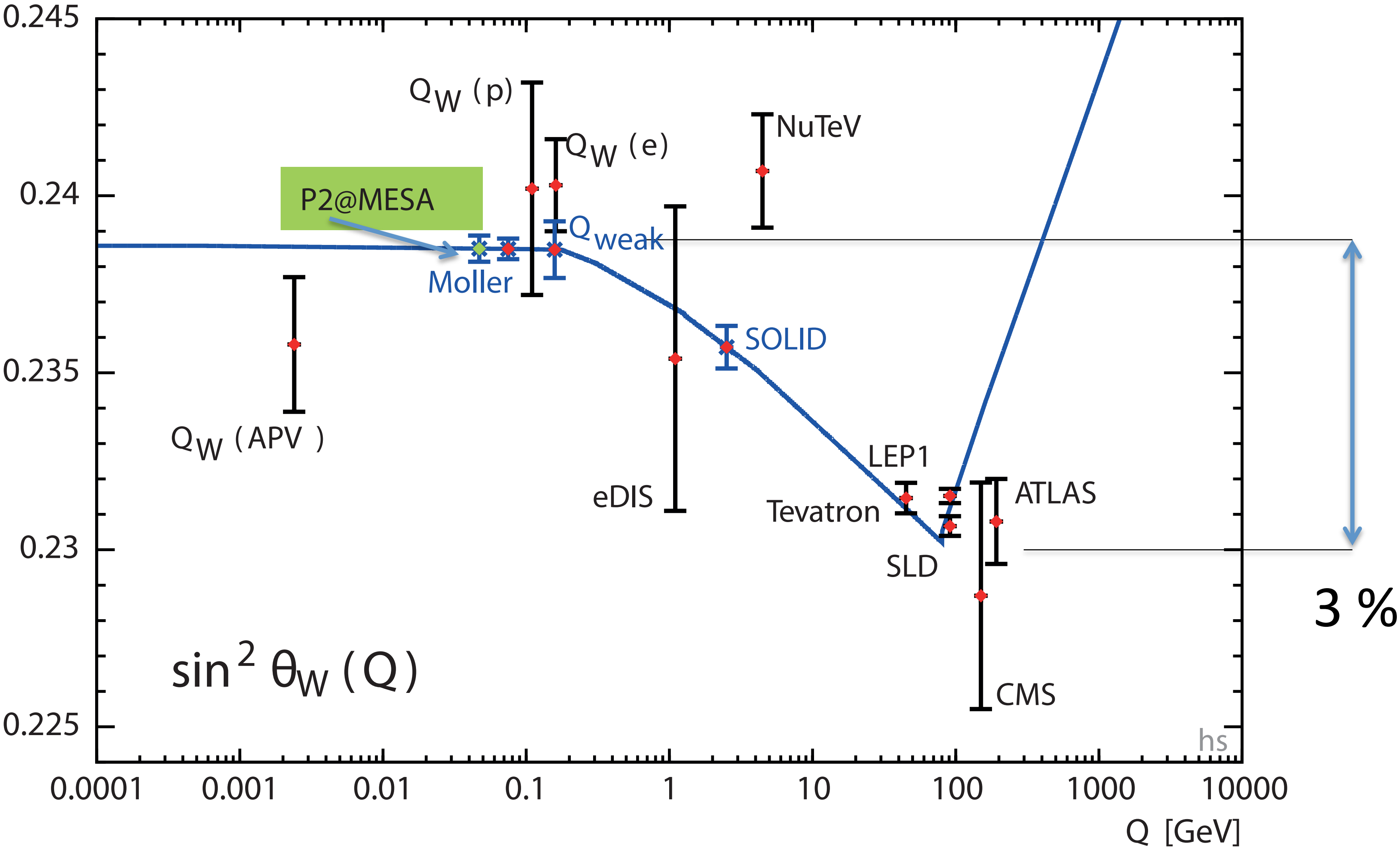
Precision measurements and quantum corrections:



running α **running $\sin^2 \theta_W(\mu)$**

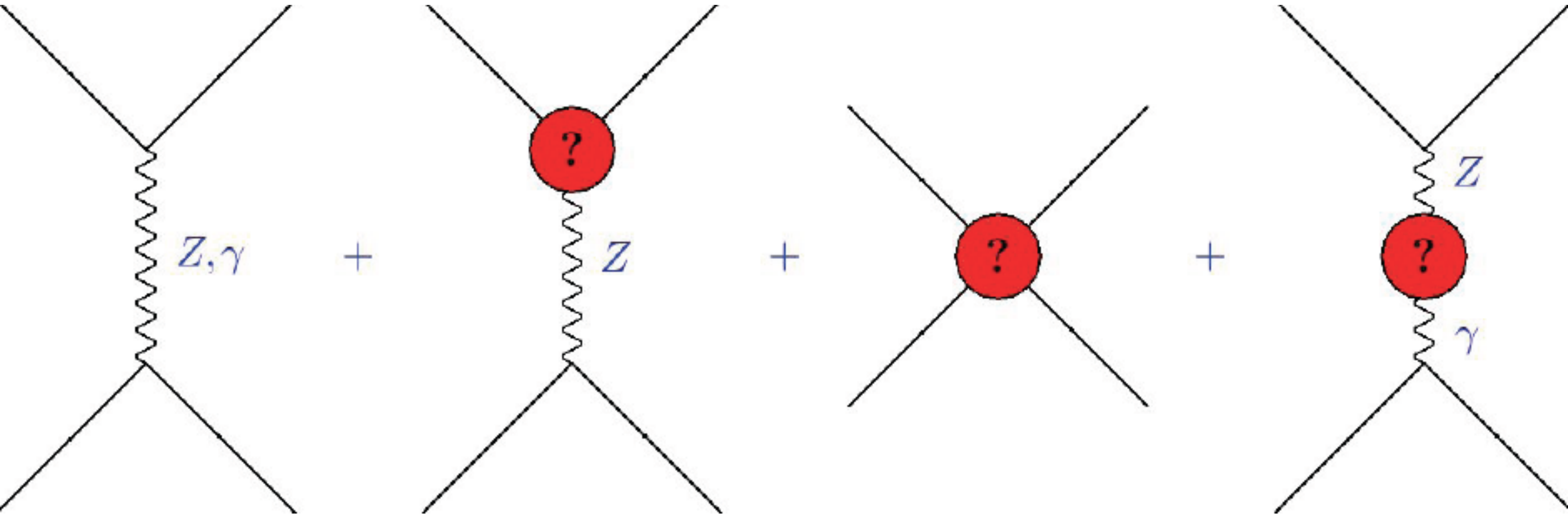
Universal quantum corrections: can be absorbed into a
scale dependent, „running“ $\sin^2 \theta_{eff}$ or $\sin^2 \theta_W(\mu)$




0.245
0.24
0.235
0.23
0.225
Q_W (p)
Q_W (e)
NuTeV
P2@MESA
Q_weak
Moller
SOLID
Q_W (APV)
eDIS
LEP1
Tevatron
ATLAS
SLD
CMS
sin² θ_W (Q)
hs
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
Q [GeV]
3 %

Sensitivity to new physics beyond the Standard Model

Sensitivity to new physics beyond the Standard Model



Extra Z

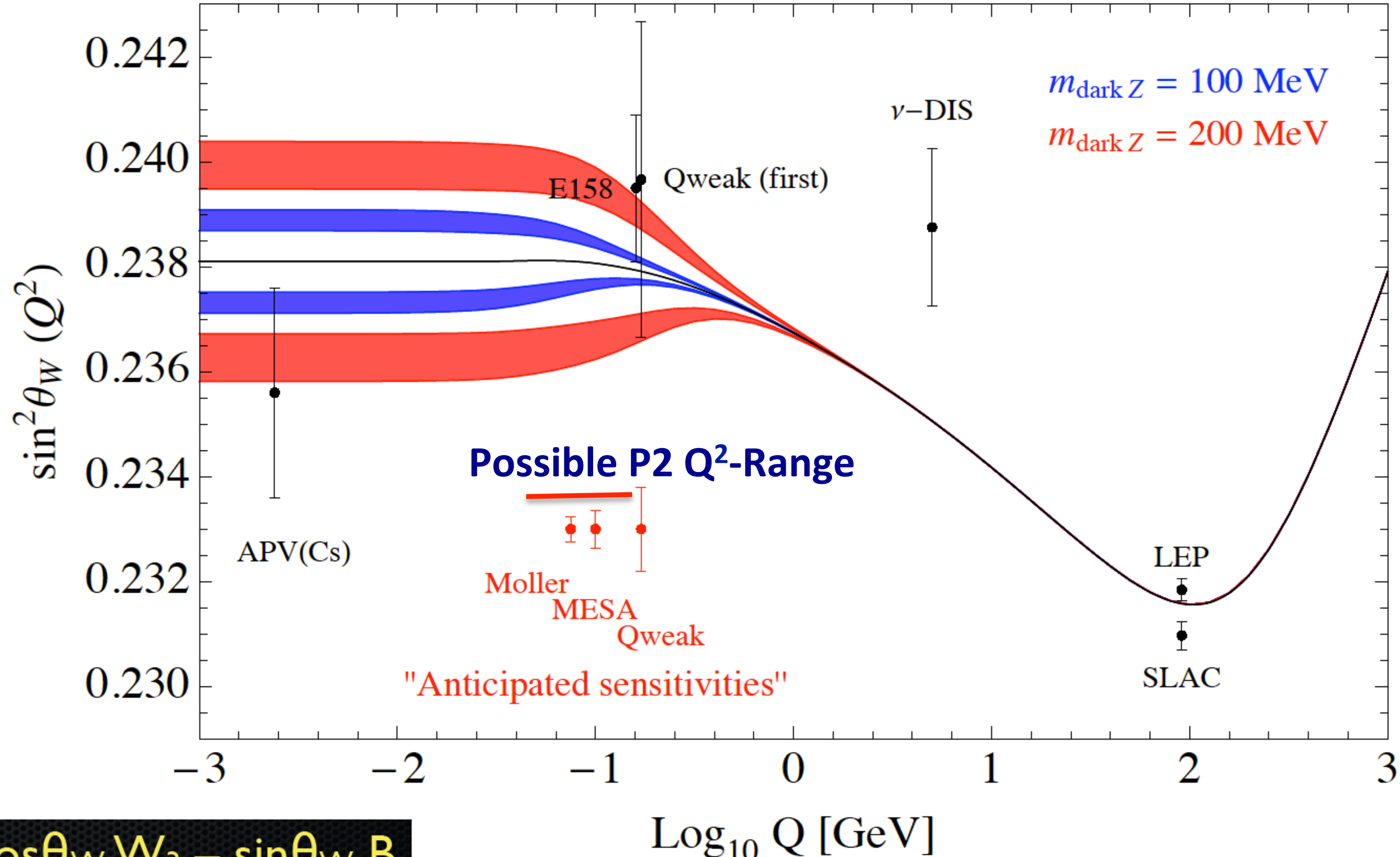
Mixing with Dark photon or Dark Z

Contact interaction

New Fermions

Dark Photon, Z-Boson

Running $\sin^2\theta_W$ and Dark Parity Violation

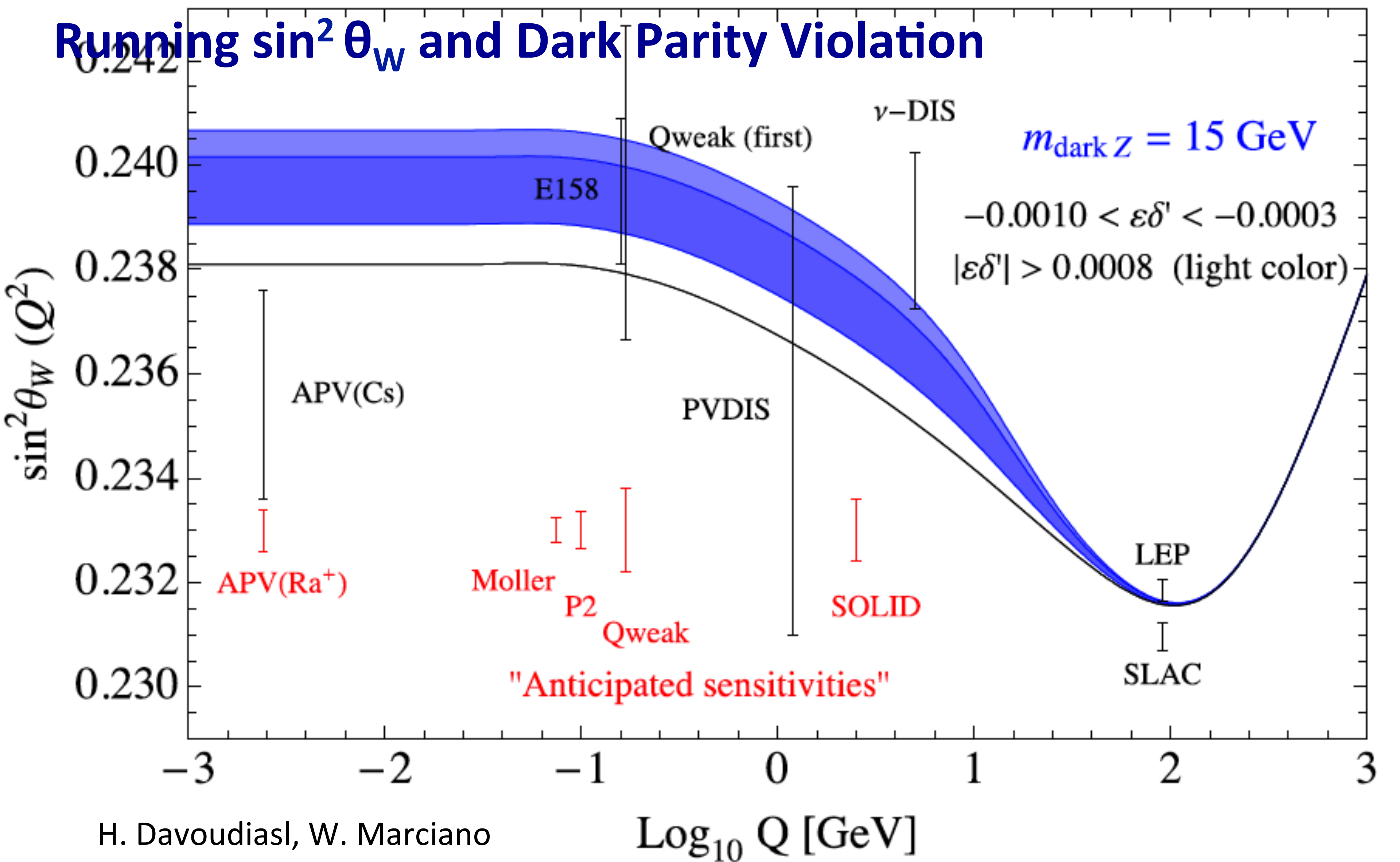


$Z = \cos\theta_W W_3 - \sin\theta_W B$

$A = \sin\theta_W W_3 + \cos\theta_W B$

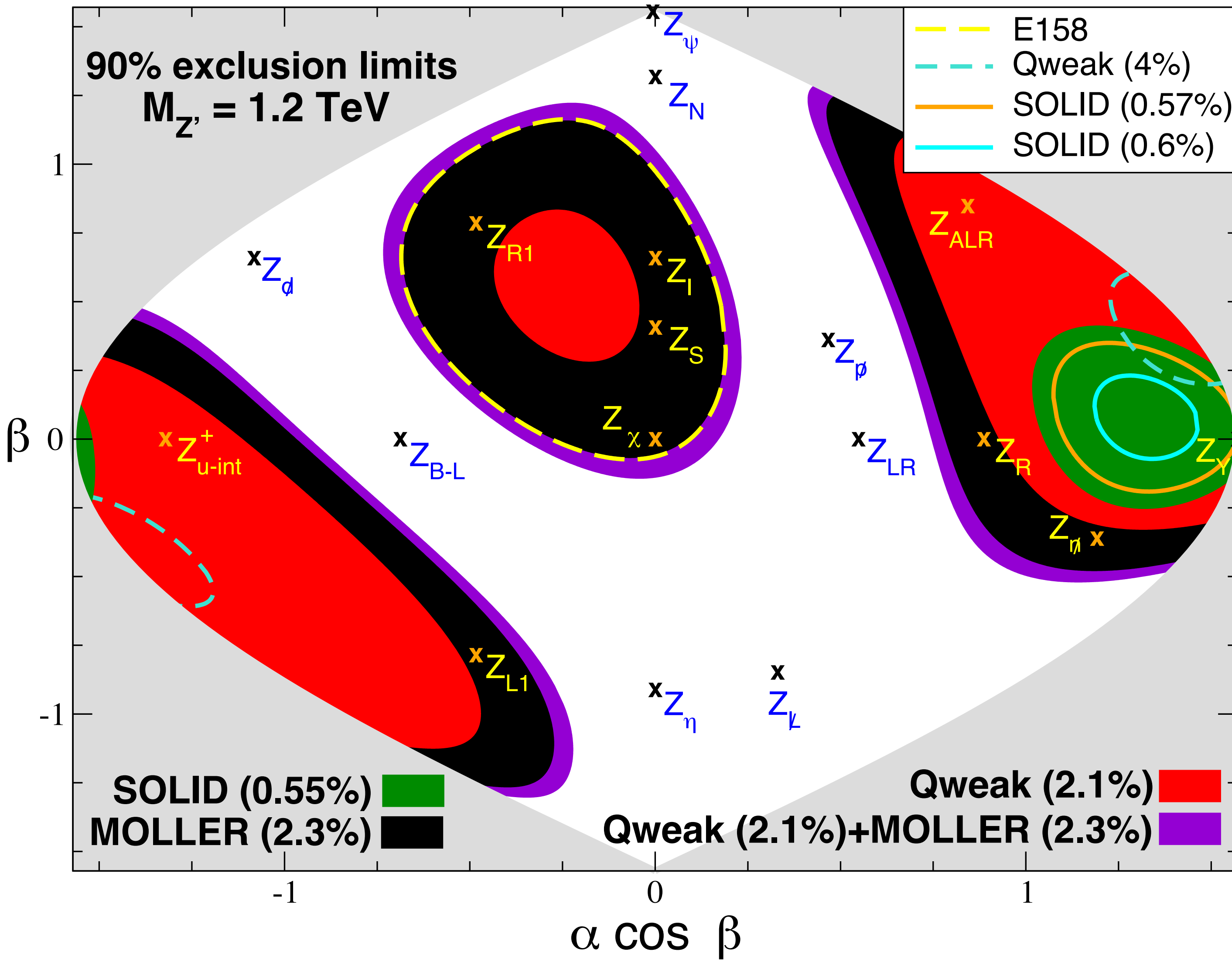
Bill Marciano

Running $\sin^2\theta_W$ and Dark Parity Violation



H. Davoudiasl, W. Marciano

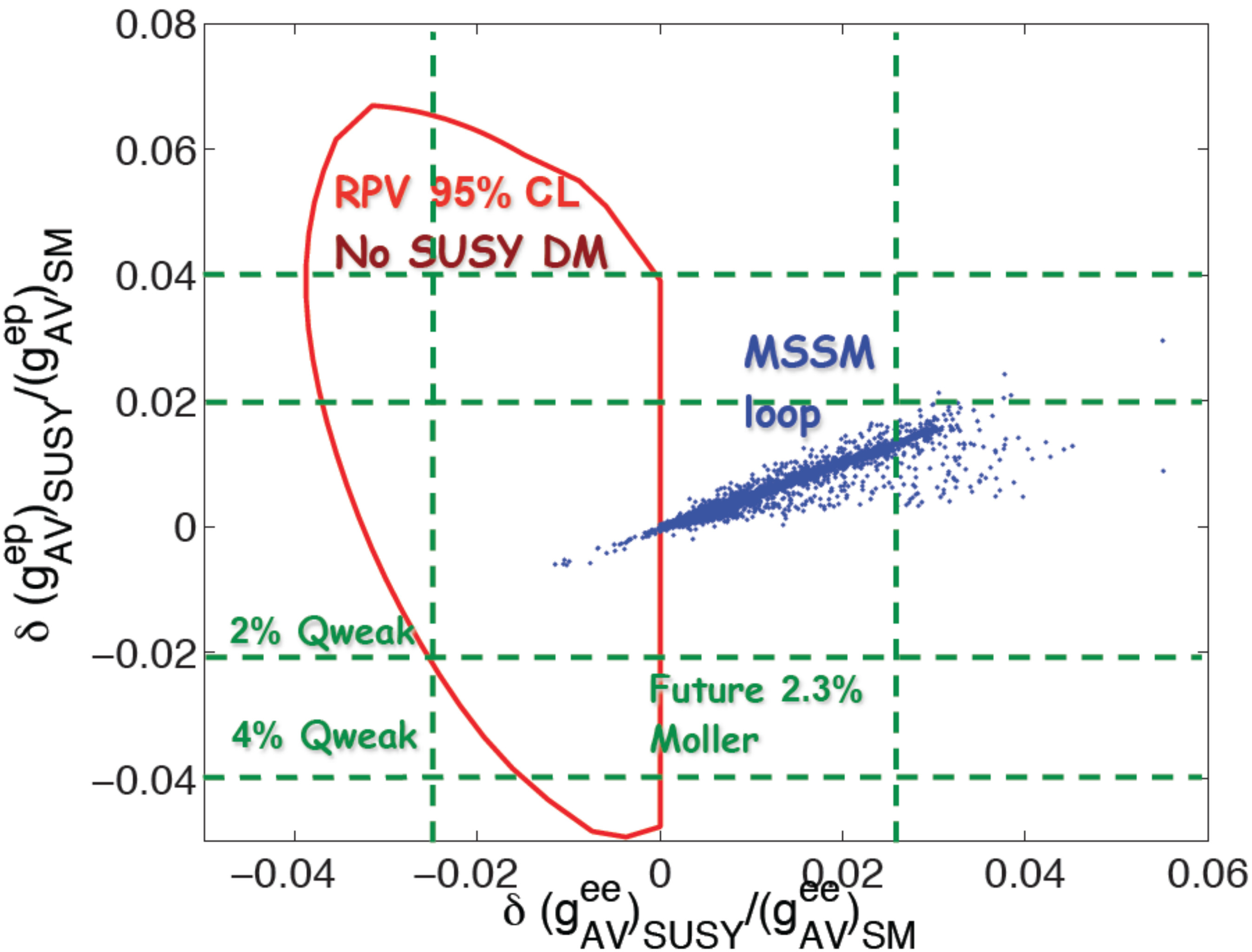
Extra Z-Boson


90% exclusion limits
$M_{Z'}$ = 1.2 TeV
E158
Qweak (4%)
SOLID (0.57%)
SOLID (0.6%)
Z_ψ
Z_N
Z_{R1}
Z_I
Z_S
Z_χ
Z_{ALR}
$Z_{u\text{-}int}^+$
$Z_{B\text{-}L}$
Z_{LR}
Z_R
Z_Y
Z_{L1}
Z_η
β
α cos β
1
0
-1
SOLID (0.55%)
MOLLER (2.3%)
Qweak (2.1%)
Qweak (2.1%)+MOLLER (2.3%)

Supersymmetry

Example: Supersymmetric standard model extensions

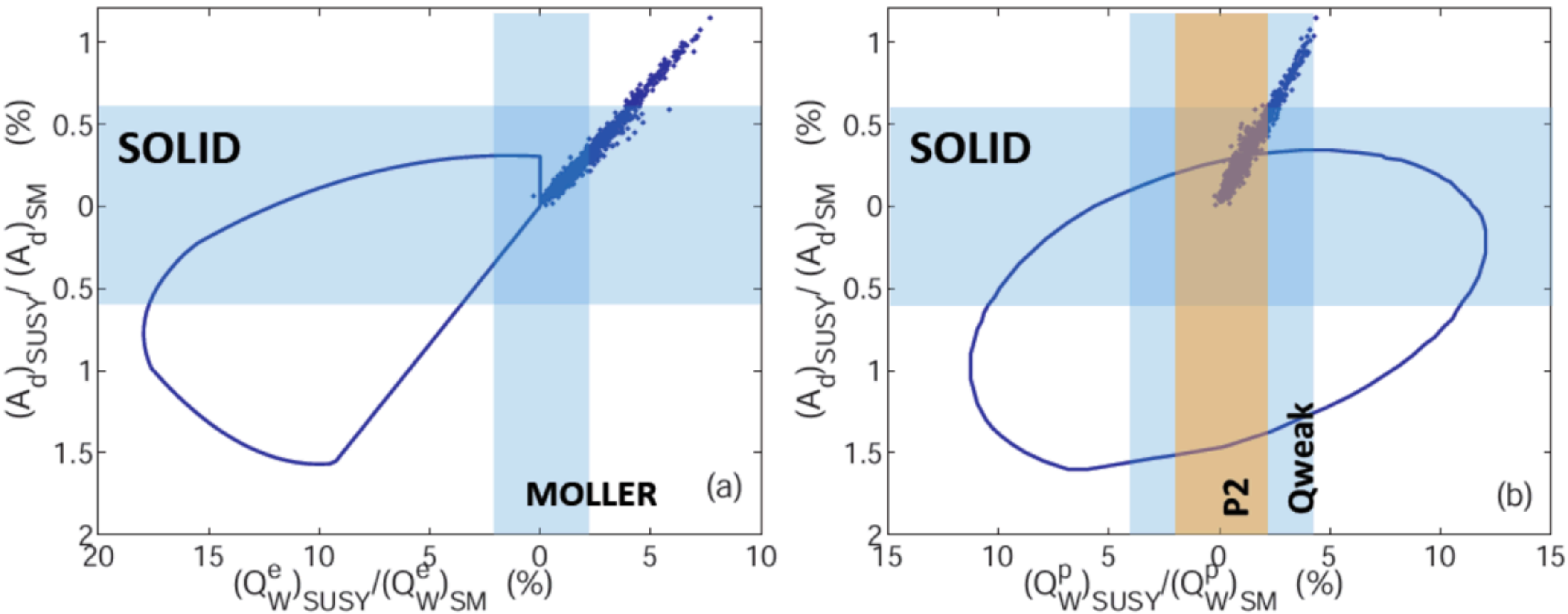
Kurylov, Ramsey-Musolf, Su (2003), updated



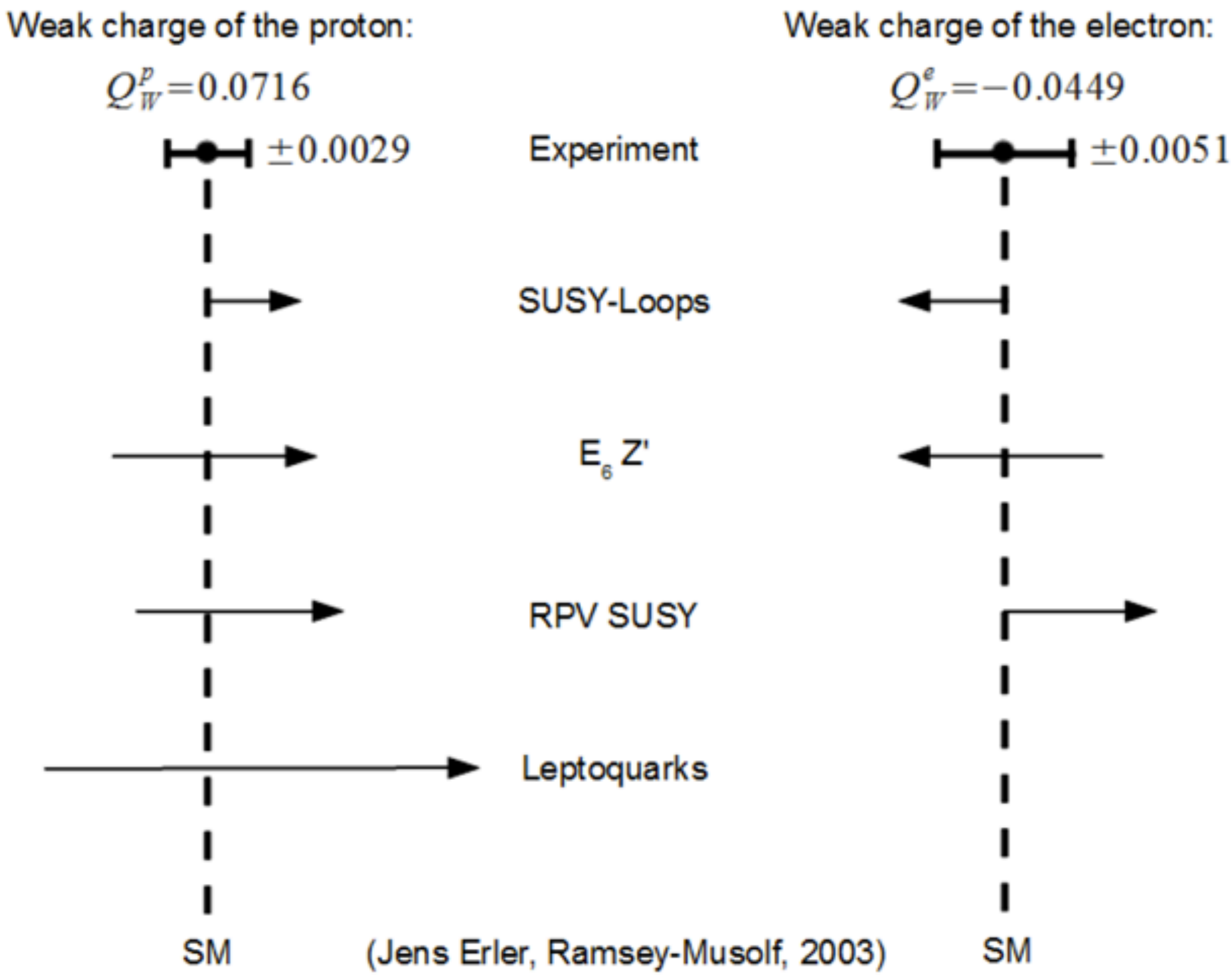
After LHC
Run 1

X. Su

Ramsey-Musolf and Su, ***Phys. Rep. 456 (2008)***



- Complementary access by weak charges of proton and electron



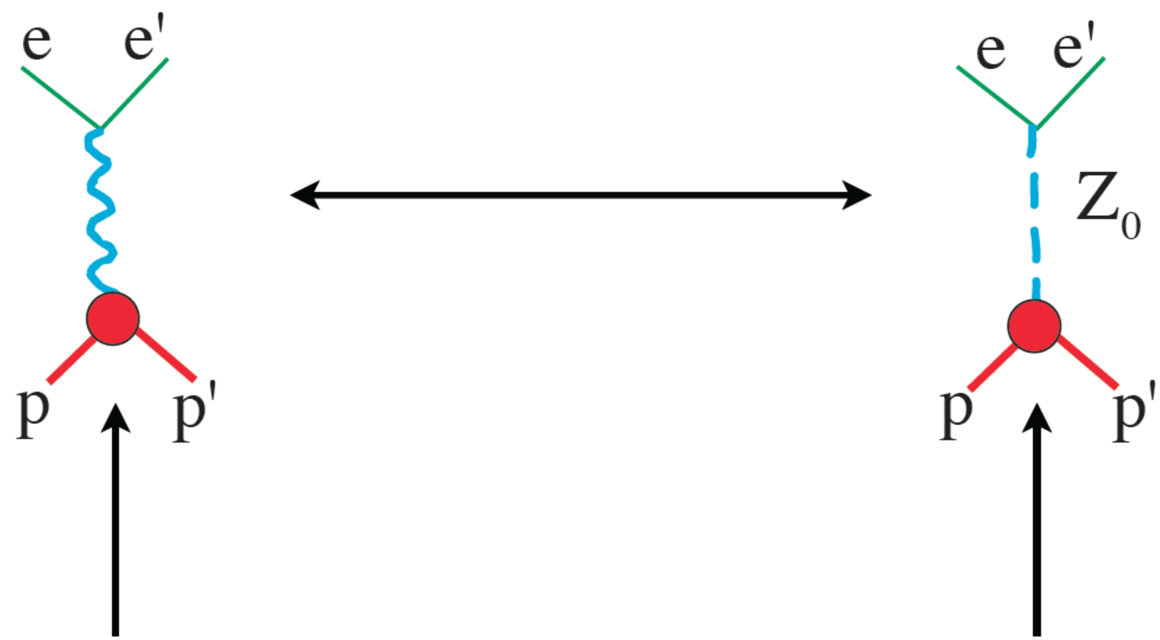
Weak Charge Of Proton:
Qweak (Jlab), P2 (MESA)

Weak Charge Of Electron:
MOELLER (JLAB)

Weak Charge Of Quarks:
SOLID (PVDIS) (JLAB)

The role of the weak mixing angle

The relative strength between the weak and electromagnetic interaction is determined by the weak mixing angle: $\sin^2(\theta_W)$



$Q_e(p) = +e$
electric charge of the proton

$Q_W(p) = 1 - 4\sin^2\theta_W$
weak charge of the proton

$\sin^2\theta_W$: a central parameter of the standard model

Proton: special case

Proton Weak charge:	$Q_W(p)$	=	$1 - 4 \sin^2\theta_W$	
Error:	$\Delta Q_W(p)$	=	$4\,\Delta\sin^2\theta_W$	
Rel. error:	$\Delta Q_W(p)/Q_W(p)$	=	$4/((1/\sin^2\theta_W) - 4)\;(\Delta\sin^2\theta_W/\sin^2\theta_W)$	
Rel. error	$\Delta\sin^2\theta_W/\sin^2\theta_W$	=	$((1/\sin^2\theta_W) - 4)/4\;\;\Delta Q_W(p)/Q_W(p)$	
Example:	$\sin^2\theta_W$ (50 MeV)	=	0.238	
	$4/((1/\sin^2\theta_W) - 4)$	~	20	
	$\Delta Q_W(p)/Q_W(p)$	=	2%	from Experiment
	$\Delta\sin^2\theta_W/\sin^2\theta_W$	=	0.1 %	same precision as LEP, SLAC

Neutron Weak charge:

$$\Delta Q_W(p)/Q_W(n) = \Delta\sin^2\theta_W/\sin^2\theta_W$$

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

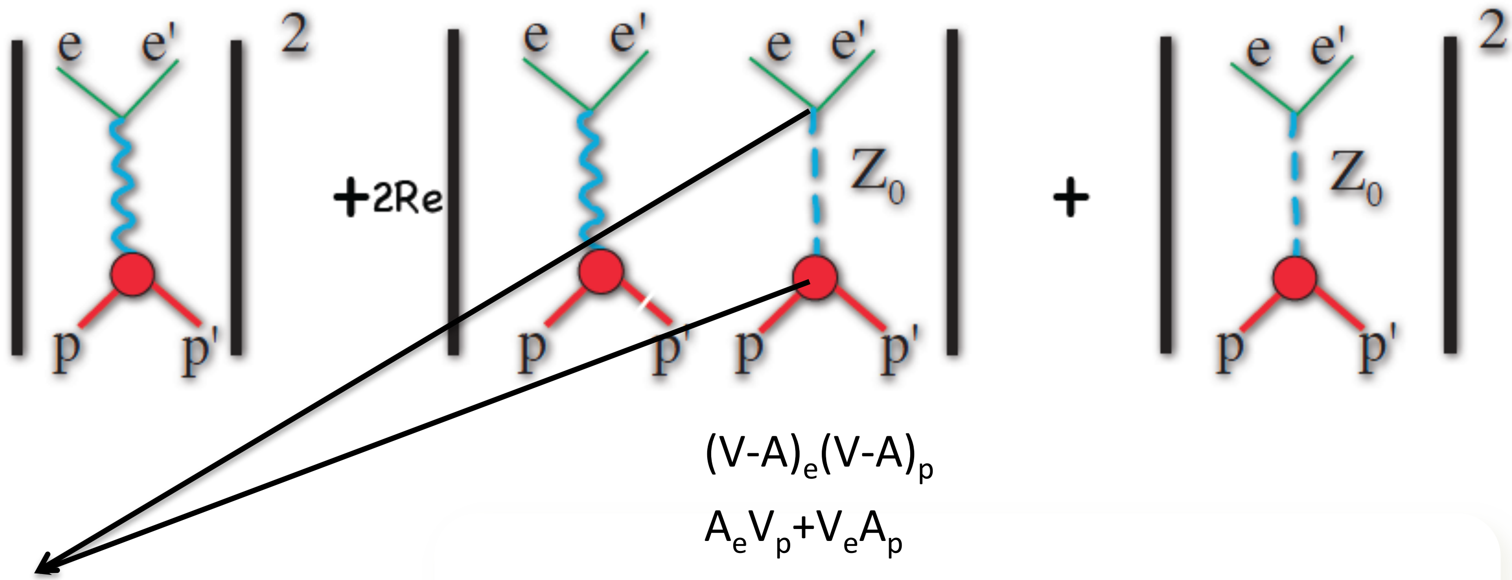
	precision	$\Delta \sin^2\overline{\theta}_W(0)$	Λ_{new} (expected)
APV Cs	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
Qweak final	4.5 %	0.0008	33 TeV
PVDIS	4.5 %	0.0050	7.6 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C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

Jens Erler

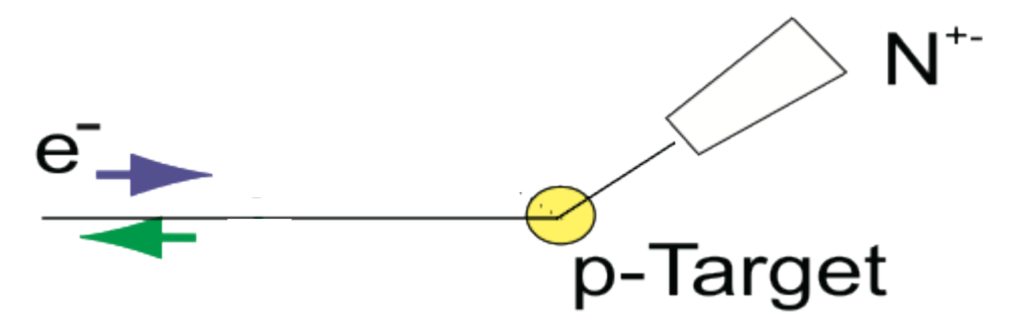
Experimental Method:
Parity Violating Electron Scattering

Parity Violating Asymmetry in elastic electron proton scattering

σ ≈



V-A coupling:
parity-violating
cross section asymmetry A_{LR}
longitudinally pol. electrons
unpolarised protons



Parity violating cross section asymmetry

tracking system

weak charge

$$A_{LR} = \frac{\sigma(e\uparrow) - \sigma(e\downarrow)}{\sigma(e\uparrow) + \sigma(e\downarrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W - F(Q^2)\right)$$

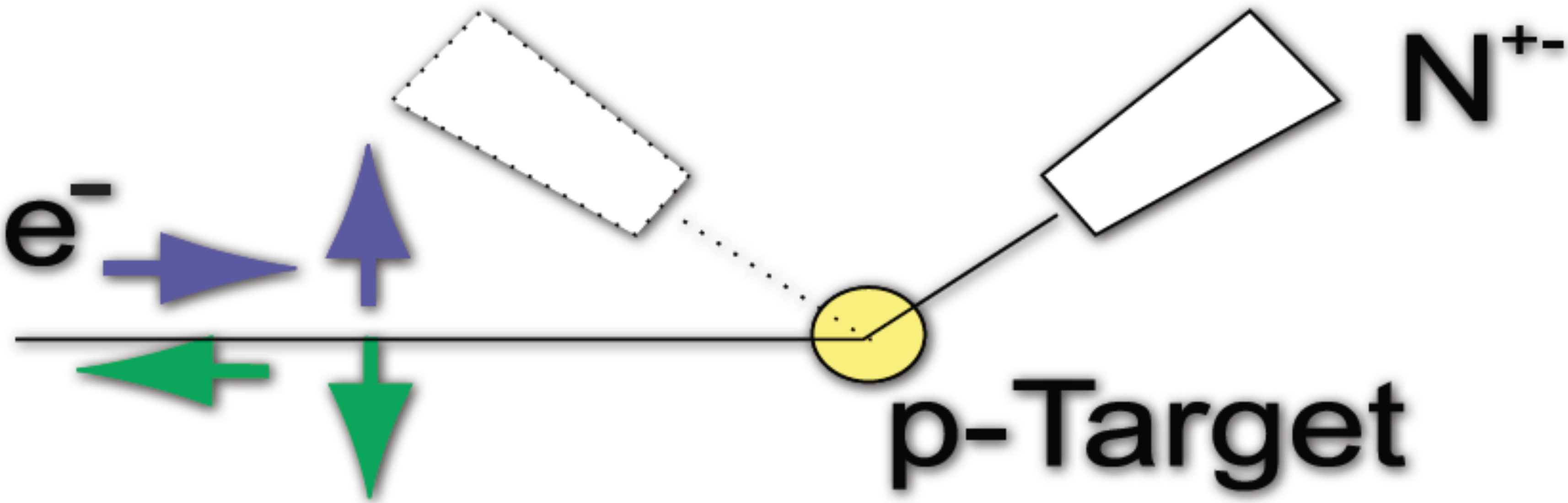
polarisation measurement

hadron structure

$$Q_W = 1 - 4\sin^2\theta_W(\mu)$$

$$F(Q^2) = F_{EM}(Q^2) + F_{Axial}(Q^2) + F_{Strange}(Q^2)$$

Conceptually very simple experiments



$A = (N^+ - N^-)/(N^+ + N^-)$ $\Delta A = (N^+ + N^-)^{-1/2} = N^{-1/2}$

$A = 20 \times 10^{-9}$ 2% Measurement $N = 6.25 \times 10^{18}$ events

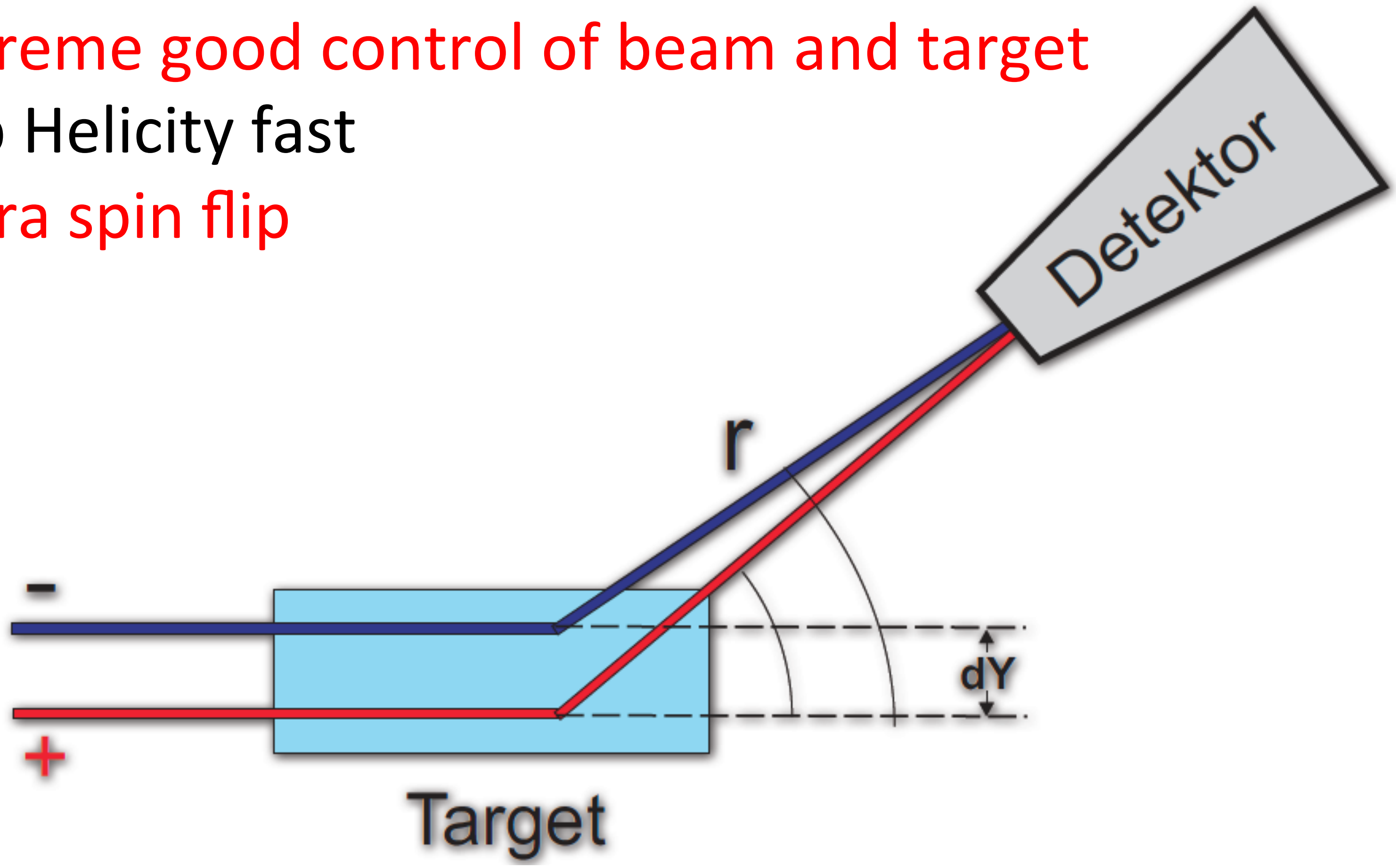
Highest rate, measure Q^2: Large Solid Angle Spectrometers

Apparative (false) asymmetries:

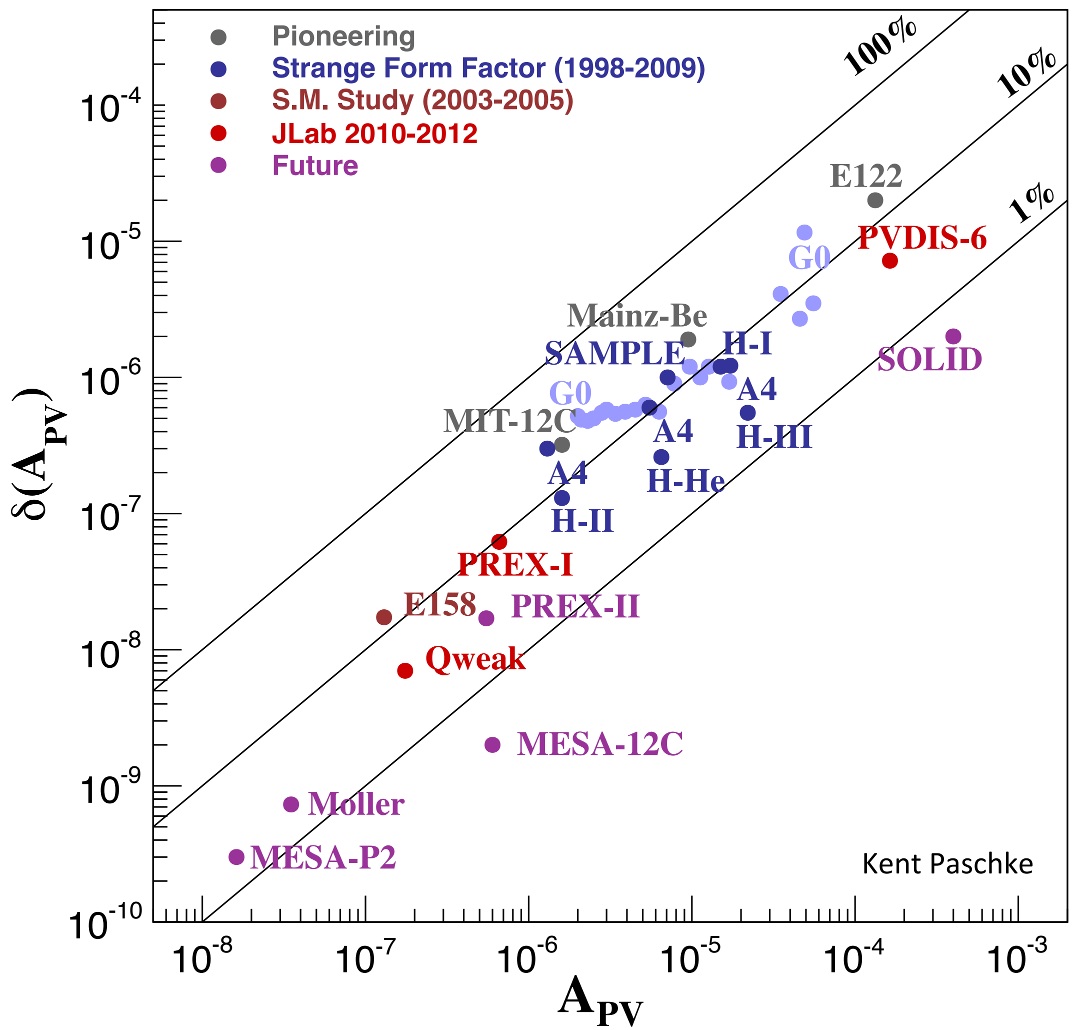
Extreme good control of beam and target

Flip Helicity fast

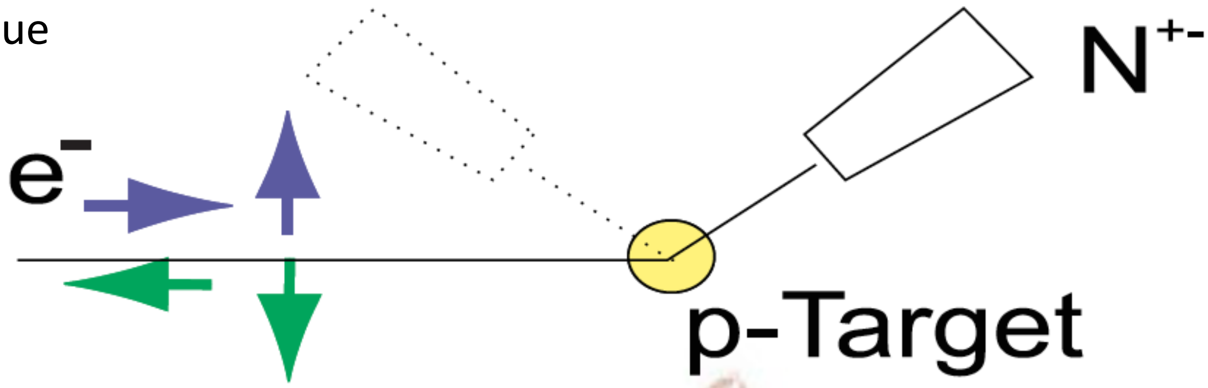
Extra spin flip



PVeS Experiment Summary

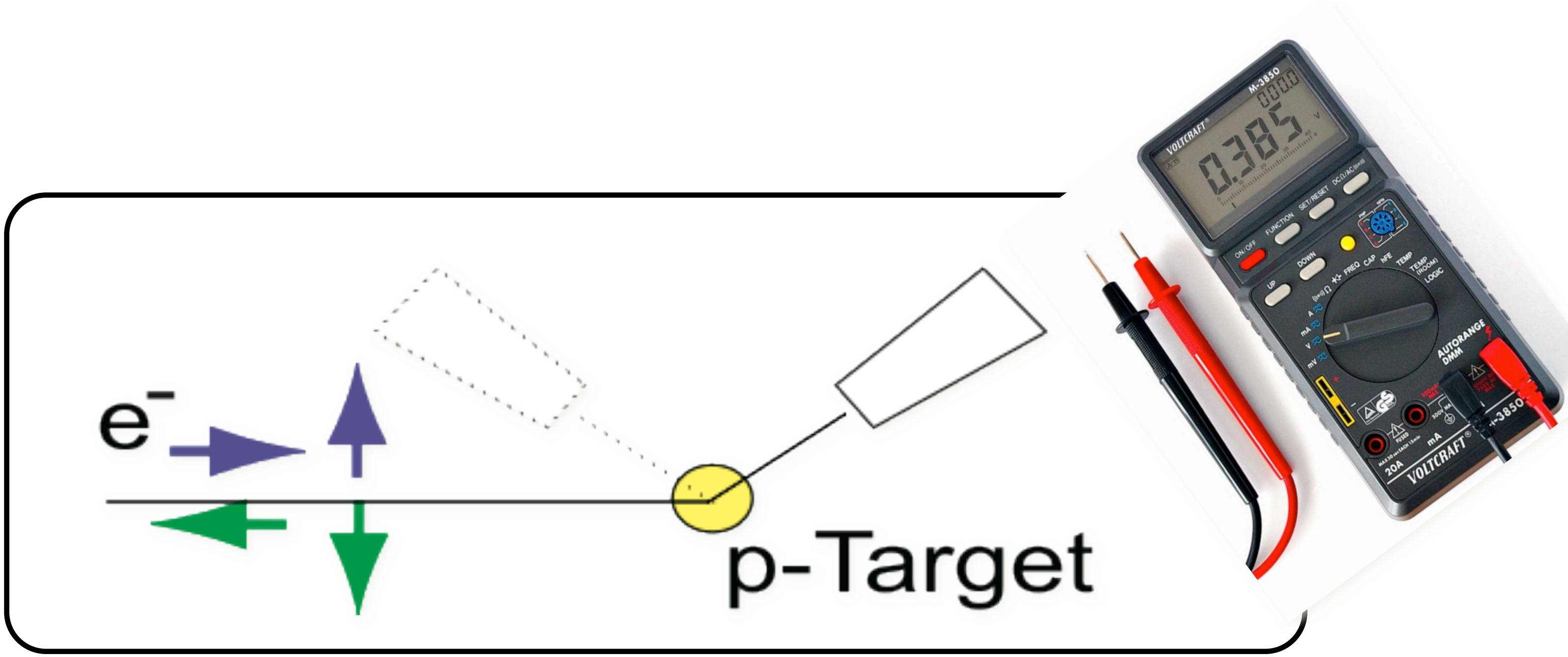


Counting Technique



Count scattered electrons:
- pile-up (double count losses)
- Background Asymmetry
- Very Fast Counting (MHz)
- Measure TOF or Energy

Analogue Technique



Measure Flux of Scattered electrons:
- no pile-up (double count losses)
- sensitive to small electr. fields.
- no separation of phys. process

P2-Kollaboration

- Collaboration was enlarged during the past years
- Integreating detectors, magnetic spectrometer, theory, elektronics, target, polarimetry

Hubert Spiesberger	Matthias Molitor
Razvan Bucoveanu	Niklaus Berger
Stephan Wezorke	Iurii Sorokin
Frank Maas	Alexey Tyukin
Sebastian Baunack	Marco Zimmermann
Dominik Becker	Silviu Covrig
Kathrin Gerz	Sandesh Gopinath
Thomas Jennewein	Krishna Kumar
Kurt Aulenbacher	Paul Souder
Dr. Valery Tioukine	Michael Gericke

Institut für Kernphysik, Universität Mainz
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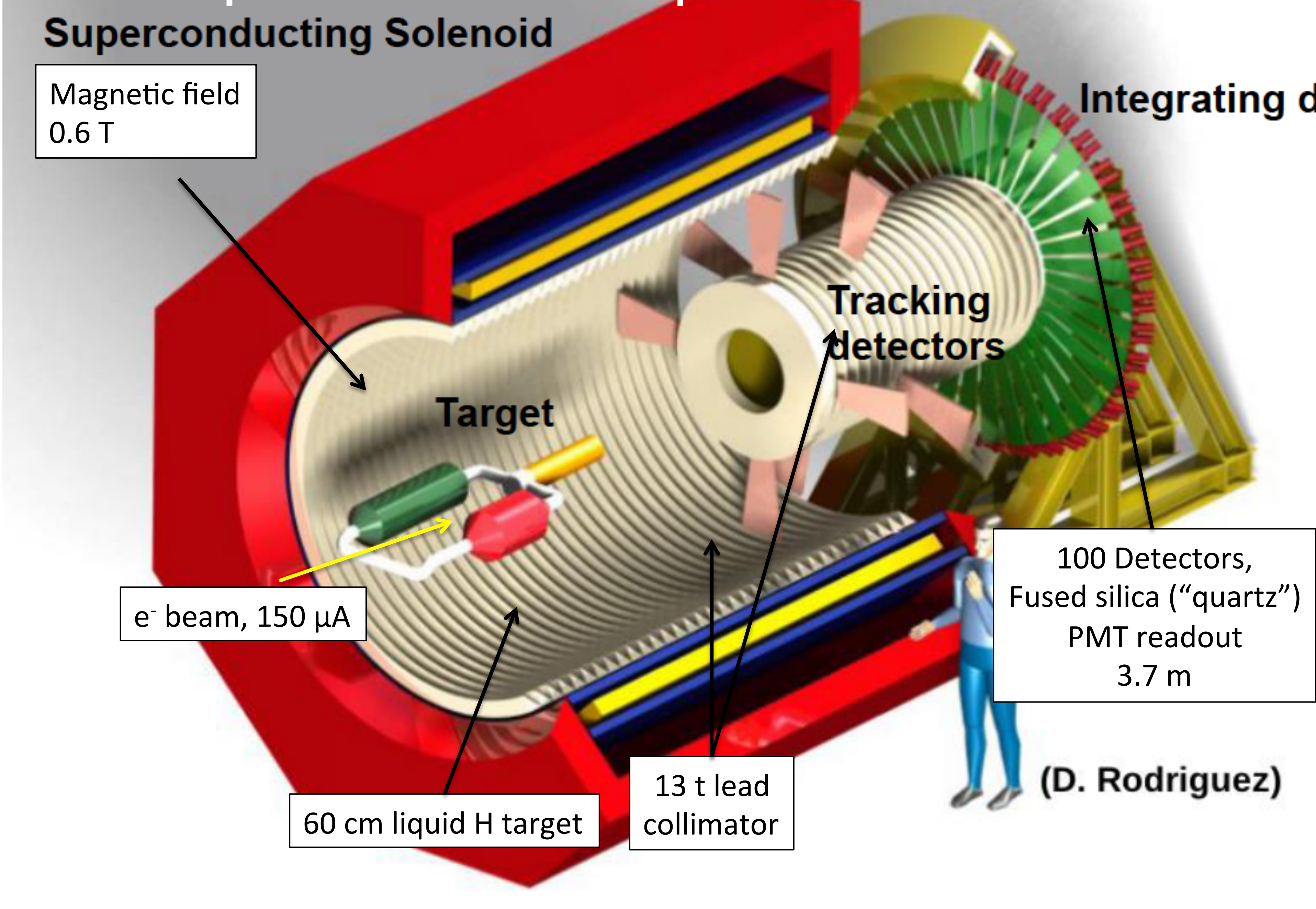
Department of Physics and Astronomy, Stony Brook, NY
Jefferson Lab, Newport News, VA
University of Manitoba, Winnipeg
Syracuse University, Syracuse, NY

PRISMA

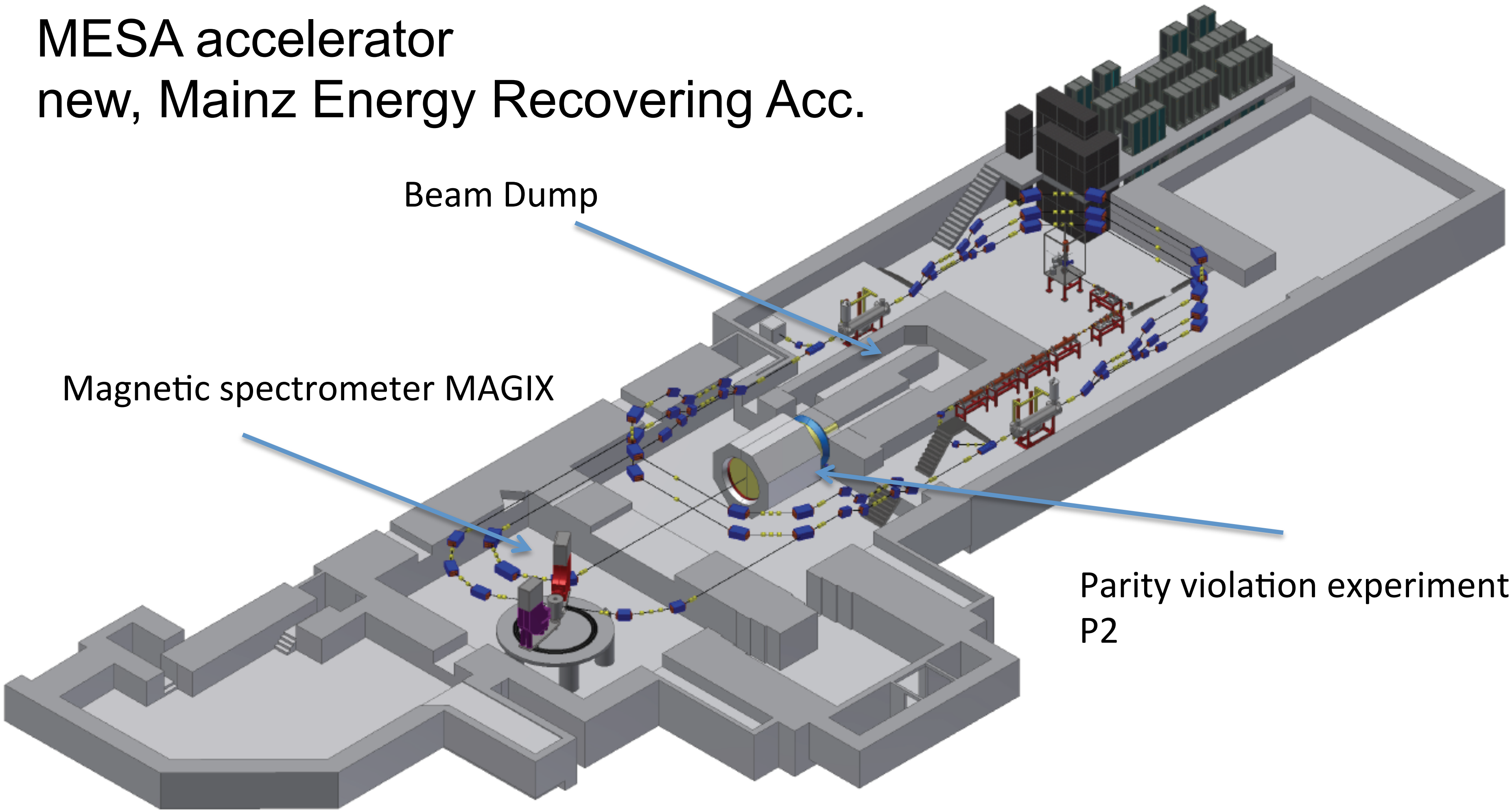
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

P2-experimental setup



MESA accelerator
new, Mainz Energy Recovering Acc.

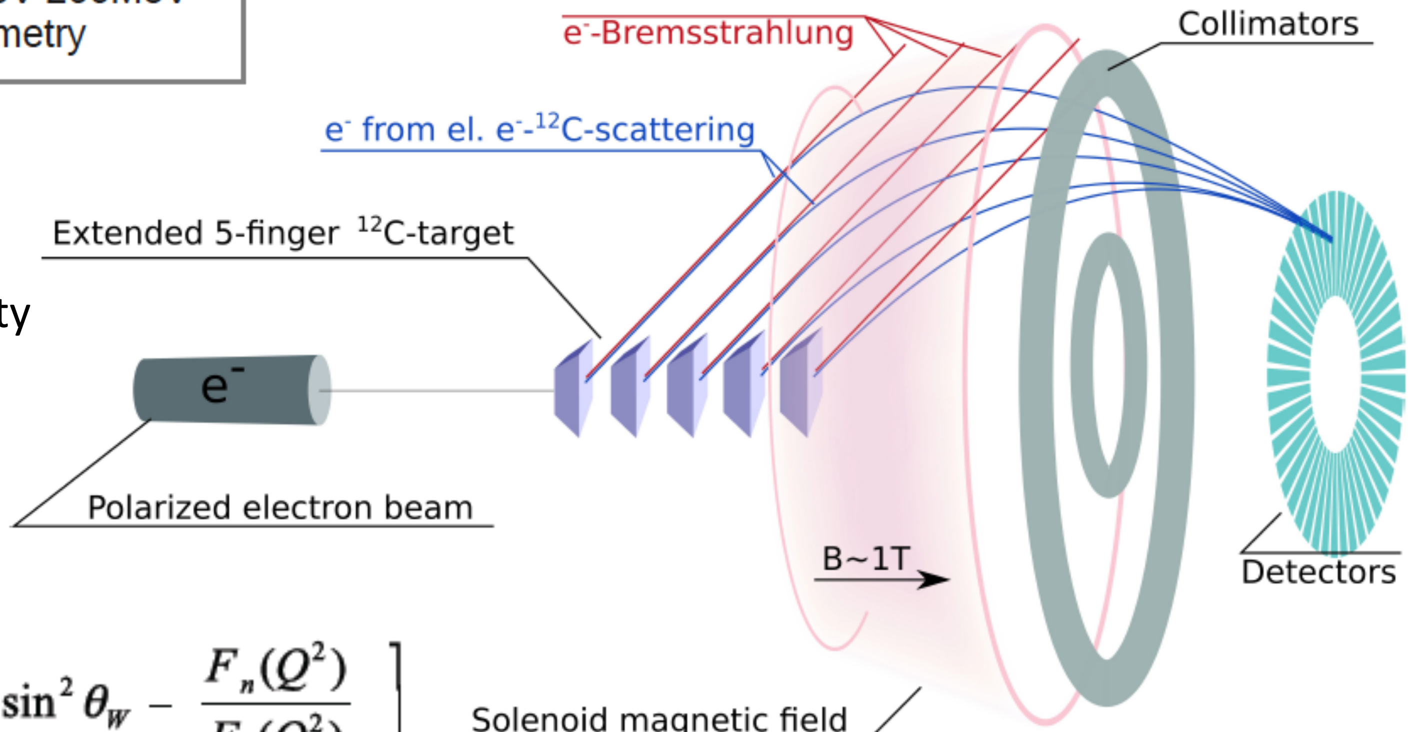


Other Measurements:
Carbon, Lead

EXPERIMENTAL REALIZATION

MESA:
- 150µA
- 150MeV-200MeV
- Polarimetry

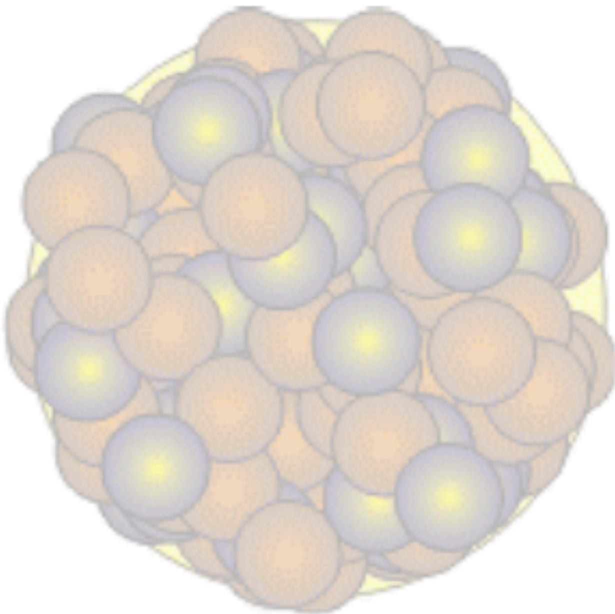
Enhanced sensitivity
To new physics

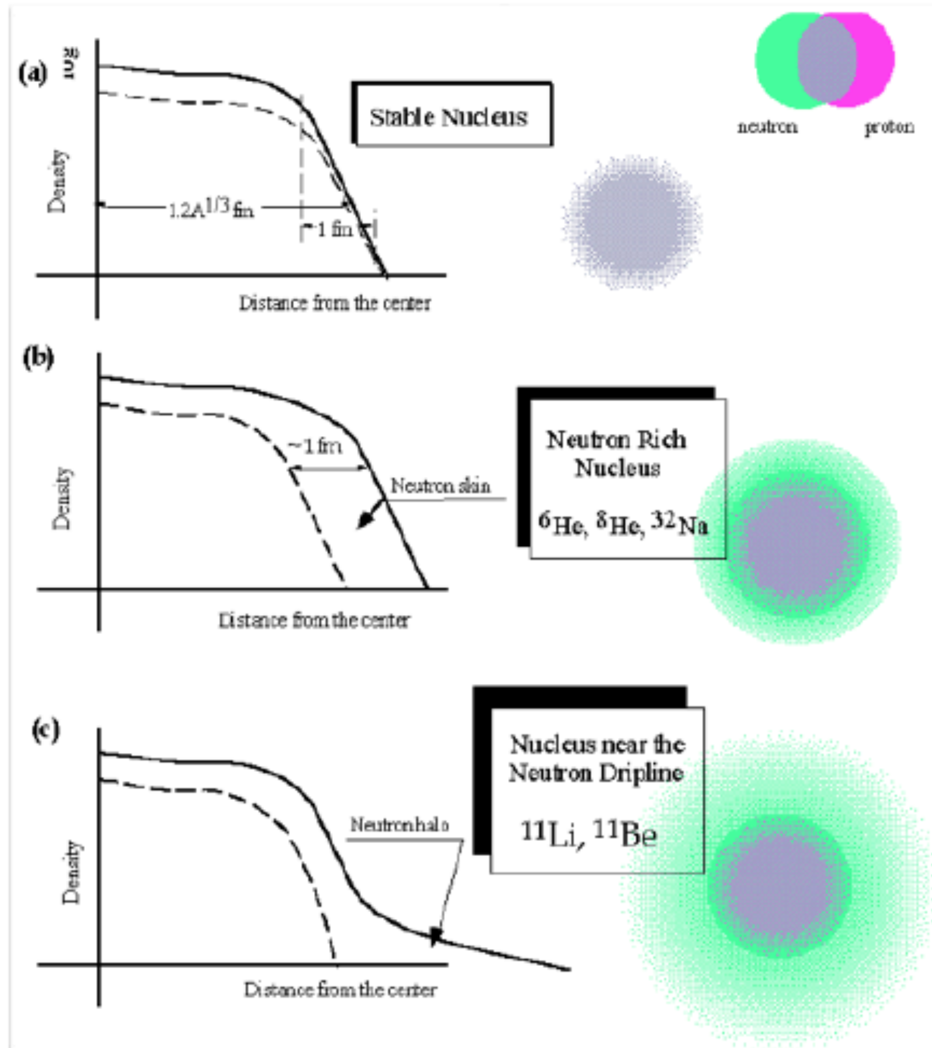


$$-N = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[\underbrace{\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)} \right]$$

Neutron Skin for beginner

Where do the neutrons go?

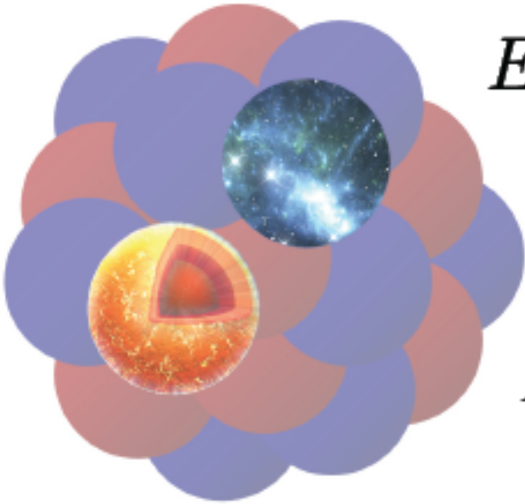




Pressure forces neutrons out against surface tension

→ **EOS**

Measurement of neutron distribution in nuclei deceisive for Neutron star properties



$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\,\delta^2 + \mathcal{O}(\delta)^4$$

symmetry energy

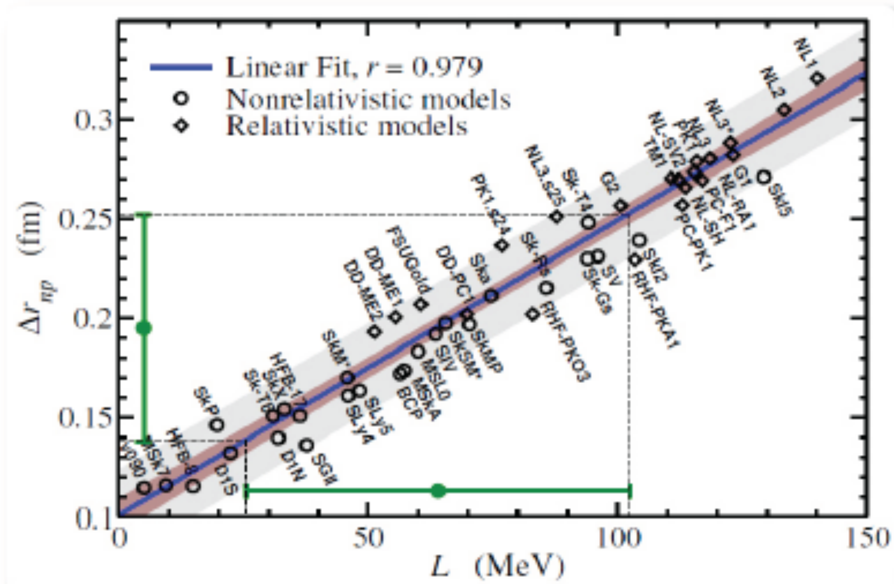
$$E_{sym}(\rho) = \left[S_v + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2\right] + \ldots$$

slope parameter

$$L = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho}\bigg|_{\rho_0}$$

curvature parameter

$$K_{sym} = 9\rho_0^2 \frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}\bigg|_{\rho_0}$$

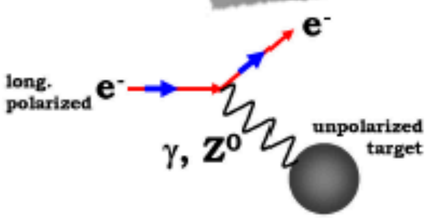


X. Roca-Maza et al., PRL 106 (2011) 252501

M. Thiel

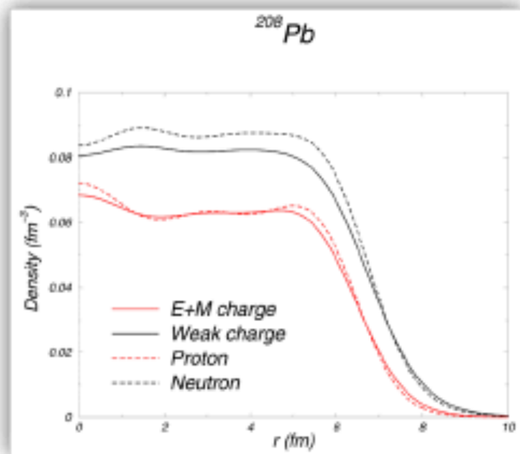
Enormously Clean …
Extraordinarily Expensive!

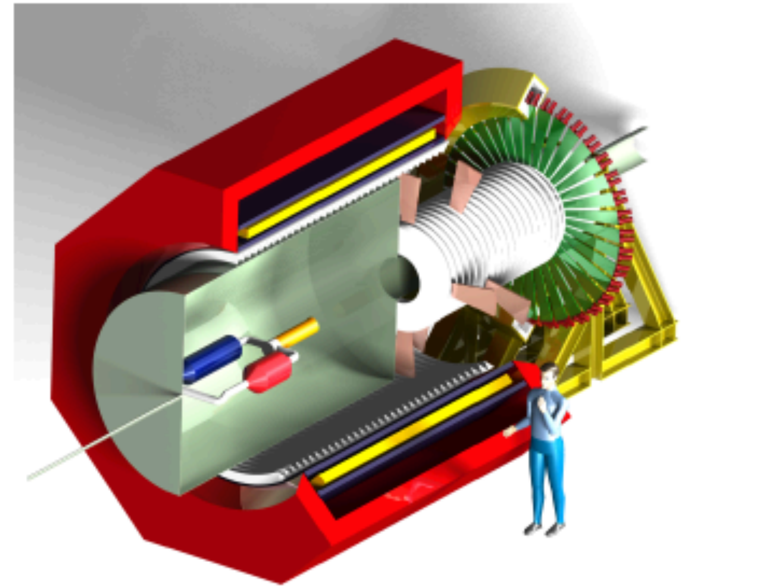
PVES



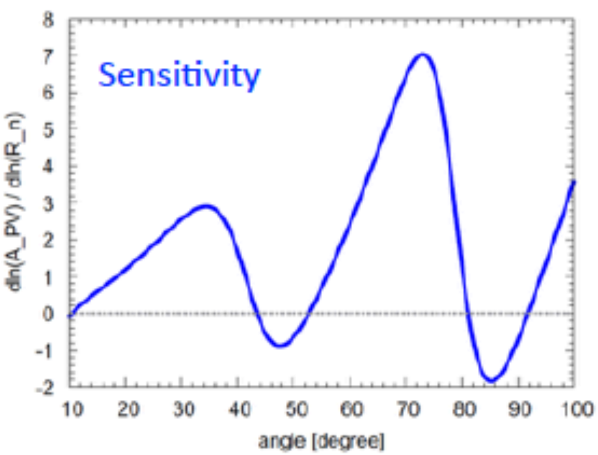
$$A_{PV} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

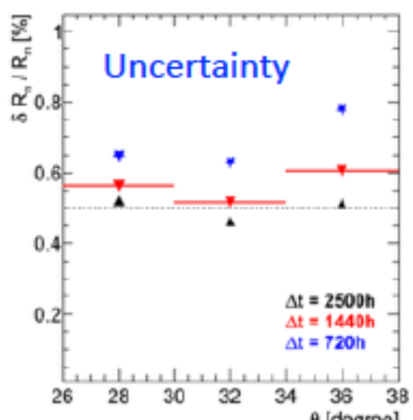
$$F_{n,p}(Q^2) = \frac{1}{4\pi}\int d^3r\; j_0(qr)\; \rho_{n,p}(r)$$





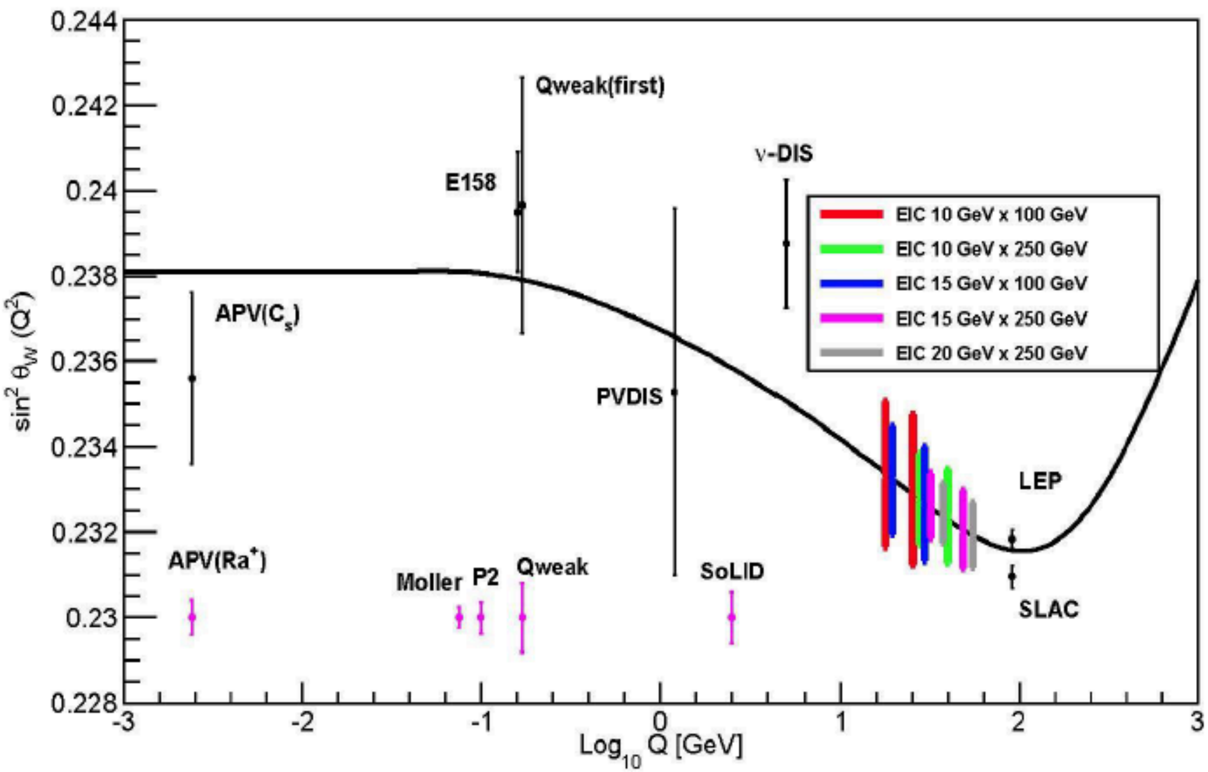
Full azimuthal coverage⇔4xstat





Assuming same PREX luminosity:
$\Delta\theta=4^o$: Rate=8.25 GHz, A_{PV}=0.66 ppm
1440h ➔ $\delta R_n/R_n$ = 0.5%
(assuming 1% syst. $\delta A_{PV}/A_{PV}$)

World data of $\sin^2\Theta_W$ including EIC projections



- 200 days of dedicated run
- Can reach similar precision to SoLID measurement
- Interesting Q^2 region never been measured or planned

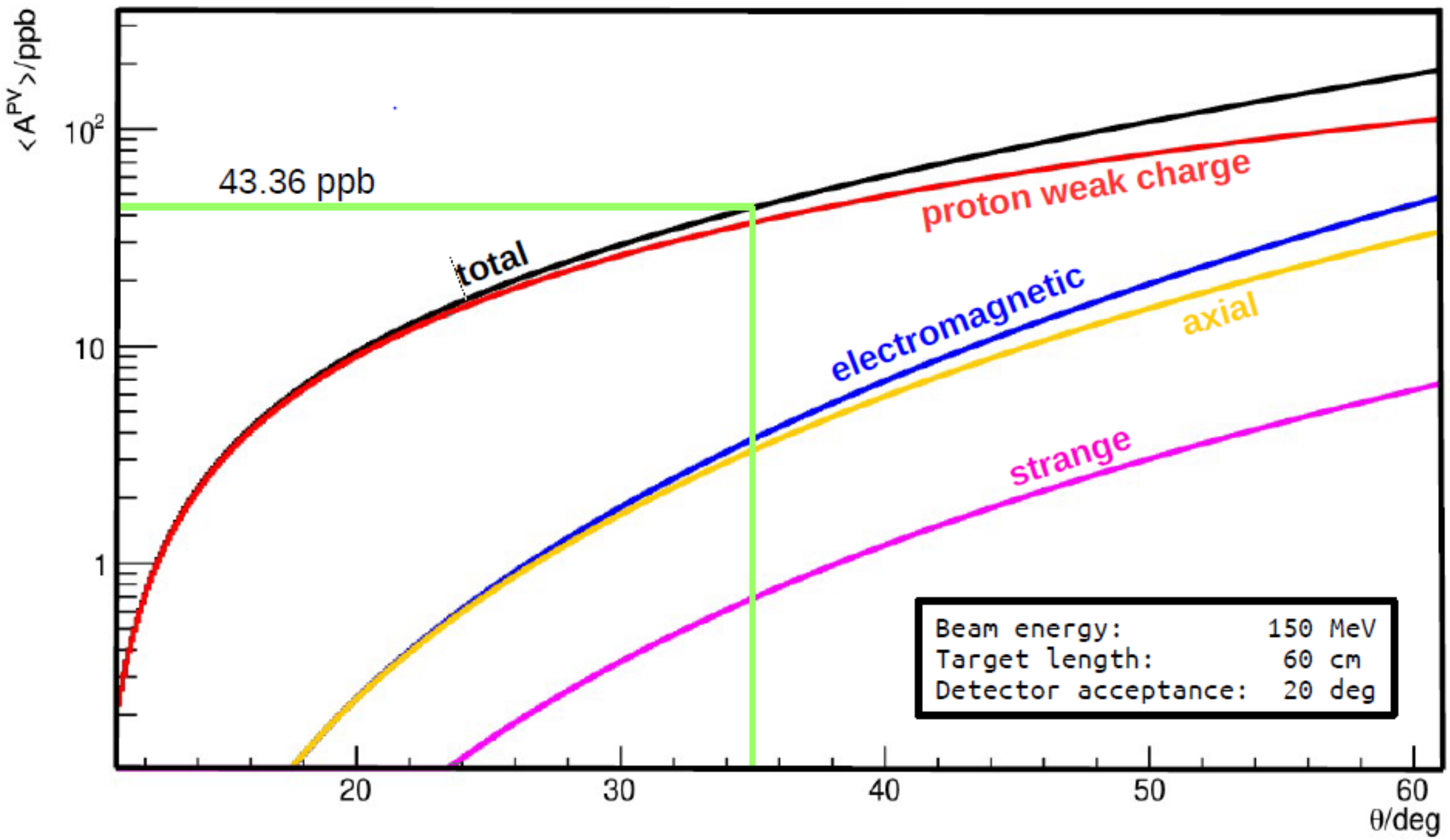
Yuxiang Zhao (SBU)

- **Parity violating electron scattering: “Low energy frontier” comprises a sensitive test of the standard model complementary to LHC**

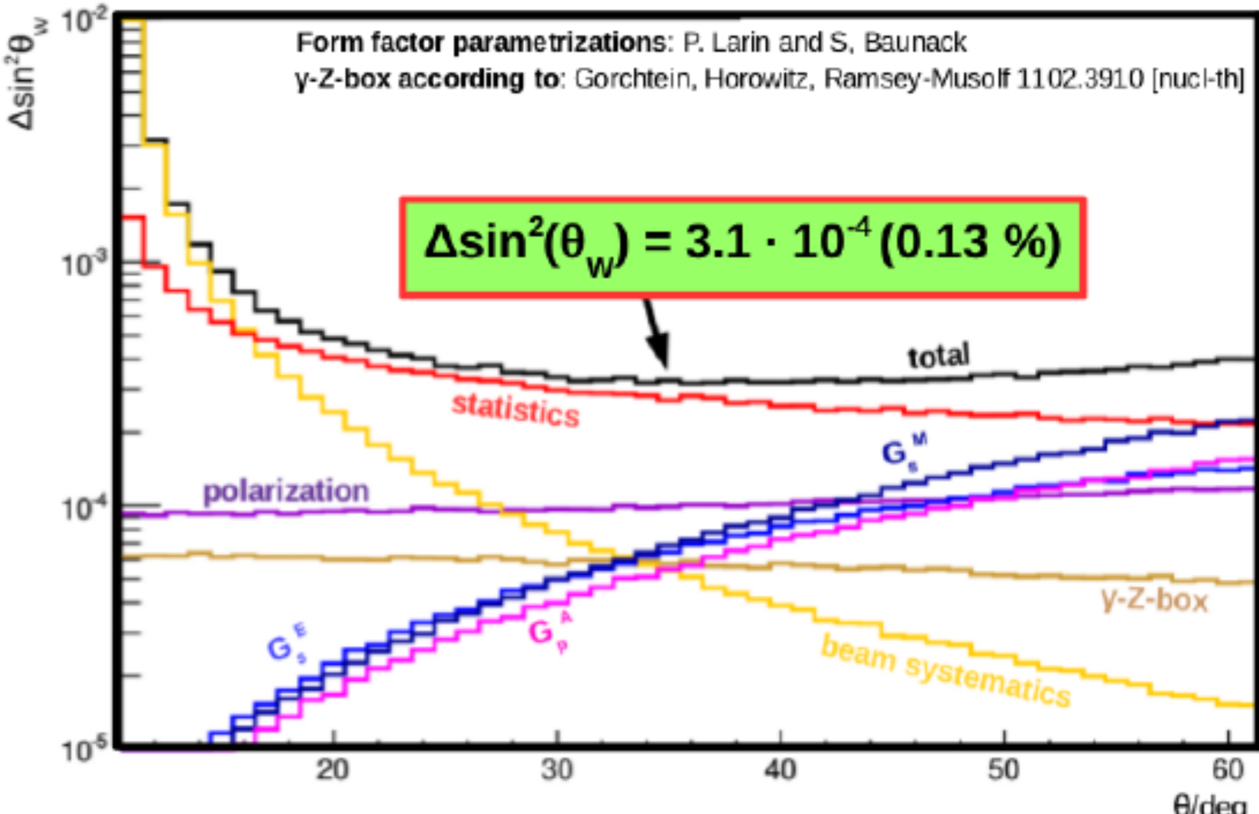
- **Determination of $\sin^2(\theta_W)$ with high precision (same as Z-pole)**

- **P2-Experiment (proton weak charge) in Mainz under preparation New MESA energy recovering accelerator at 155 MeV, target precision is 1.7% in Qweak i.e. 0.13% in $\sin^2(\theta_W)$, Sensitivity to new physics up to a scale of 49 TeV**
- **Much more physics from PV electron scattering**
- **Together with Moeller@Jlab (electron weak charge) and SOLID@Jlab (quark weak charge) very sensitive test of standard model and possibility to narrow in on Standard Model Extension**

- Contributions to $\Delta\sin^2\Theta_W$ for 35° central scattering angle, E=150 MeV, 10000 h of data taking



P2-Precision in $\sin^2 \theta_W$



Beam energy: 155 MeV

Beam current: 150 μA

Polarization: (85±0.5)%

Target: 60 cm lH2

Acceptance: 2π·(35°±10°)

Rate: 0.5 THz

Runtime: 10000 h

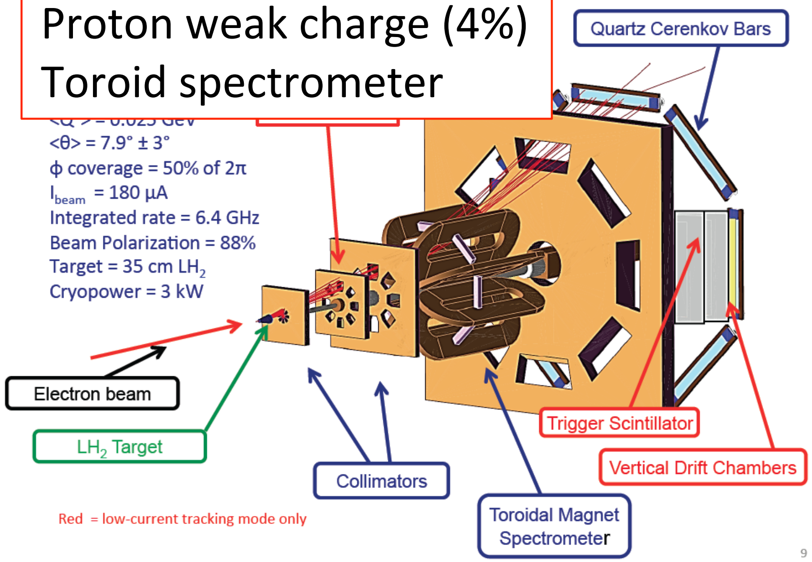
ΔA^{app}: 0.1 ppb

	Total	Statistics	Polarization	Apparative	FF	$Re(\square_{\gamma ZA})$
$\Delta\sin^2(\theta_w)$	3.1e-4 (0.13 %)	2.6e-4 (0.11 %)	9.7e-5 (0.04 %)	7.0e-5 (0.03 %)	1.4e-4 (0.04 %)	6e-5 (0.03 %)
ΔA^{exp}/ppb	0.44 (1.5 %)	0.38 (1.34 %)	0.14 (0.49 %)	0.10 (0.35 %)	0.11 (0.38 %)	0.09 (0.32 %)

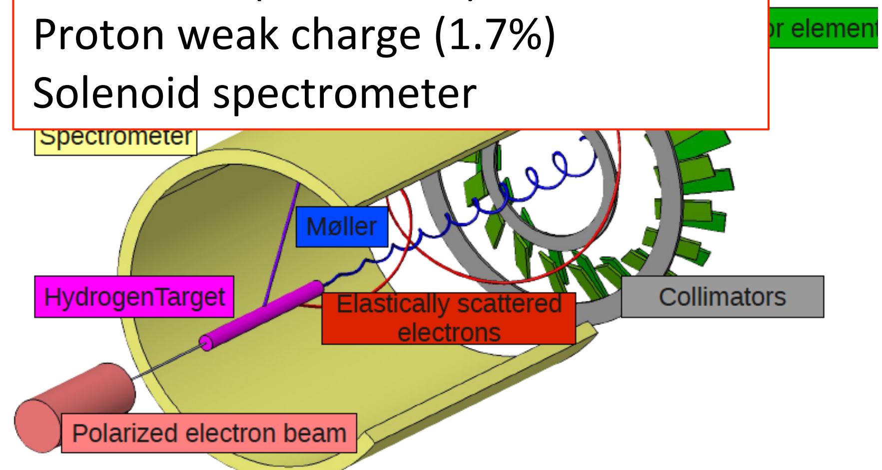
MESA: Beam parameter

Beam Energy ERL/EB [MeV]	105/155 (105/205)
Operation mode	1300 MHz, c.w.
Elektron-sources	1.) Polarised : NEA GaAsP/GaAs superlattice , 200keV (?) 2.) unpolarised KCsSb, 200keV
Bunch Charge EB/ERL [pC] 7.7pC=10mA@1300MHz	0.15/0.77 (0.15/7.7)
Norm. Emittance EB/ERL [μm]	0.1/<0.5 (0.1/<1)
Spin Polarisation (EB-mode only)	> 0.85
Recirculations	2 (3)
Beampower at Exp. ERL/EB [kW]	100/22.5 (1050/30)
R.f.-Power installed [kW]	140 (180)

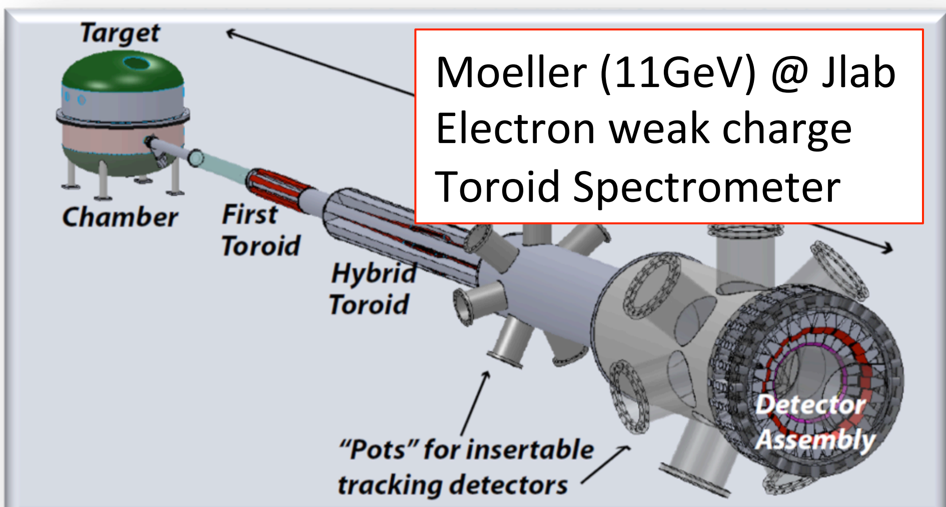
Qweak (1GeV) @ Jlab
Proton weak charge (4%)
Toroid spectrometer



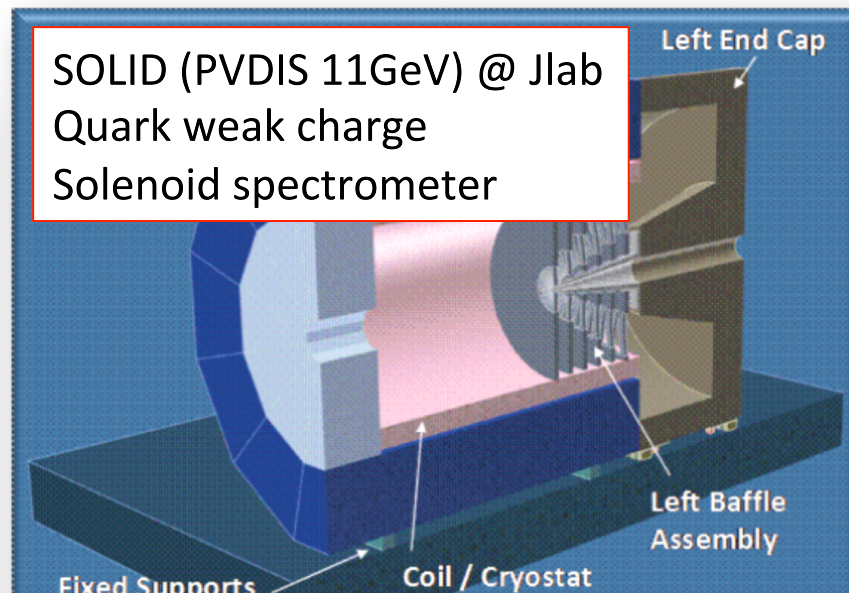
P2@MESA (0.150 GeV) @ Mainz
Proton weak charge (1.7%)
Solenoid spectrometer



Moeller (11GeV) @ Jlab
Electron weak charge
Toroid Spectrometer

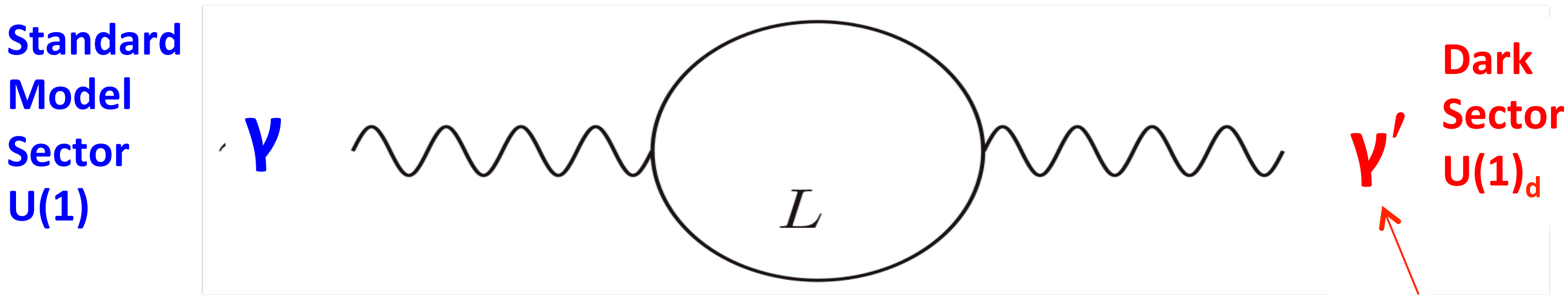


SOLID (PVDIS 11GeV) @ Jlab
Quark weak charge
Solenoid spectrometer



Holdom 86

A portal to relate the dark sector to the SM world (coupling ~ ε^2)



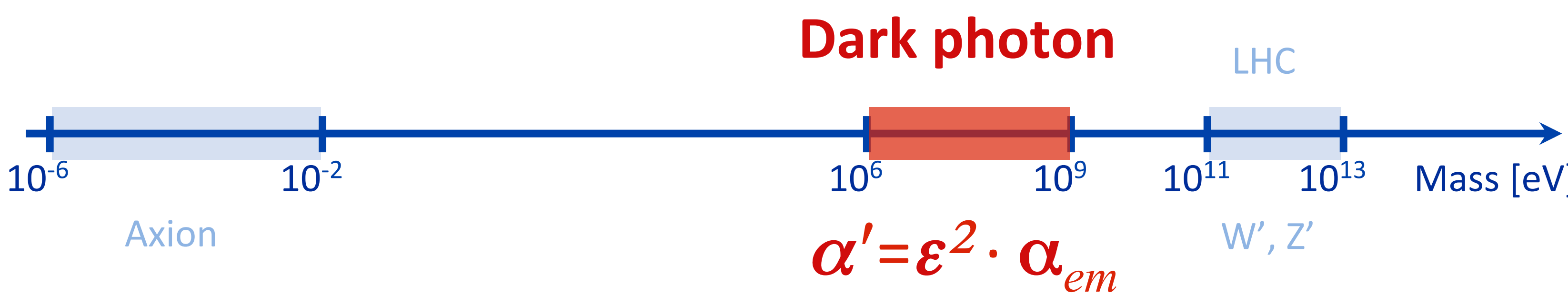
Heavy Charged Leptons *L*
(carry $U(1)_d$ charge)

Dark Photon
(aka A′, U, Z_d, ...)

Features à la Arkani-Hamed: A theory of Dark Matter

- More than one Dark Matter particle → Dark Sector
- dm + dm → e+e- explains positron excess
- Astrophysical anomalies (PAMELA, FERMI, DAMA/LIBRA, INTEGRAL, ...) suggest dark photon mass on GeV mass scala (and lighter than $2M_p$)

New massive force carrier of extra $U(1)_d$ gauge group; predicted in almost all string compactifications

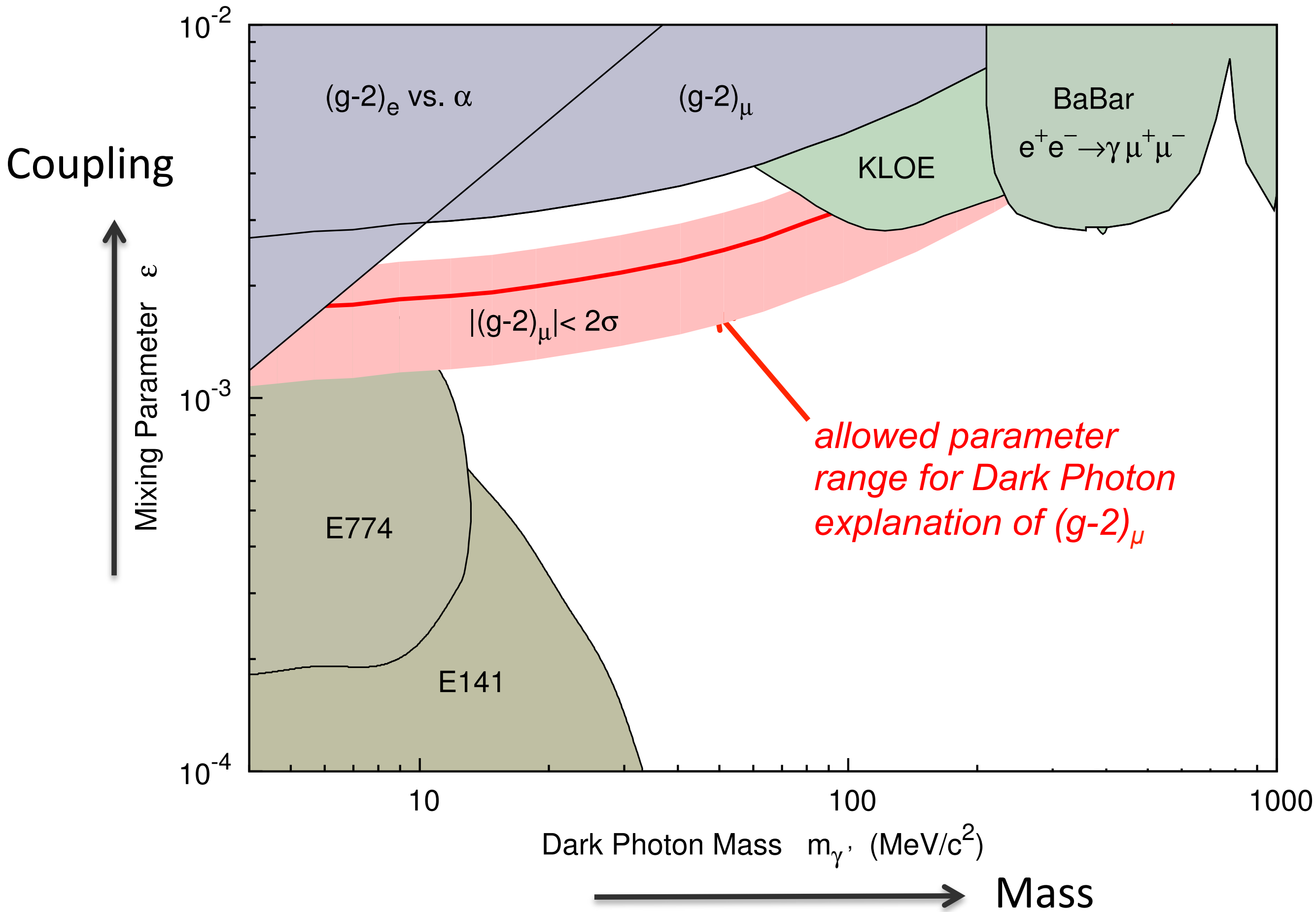


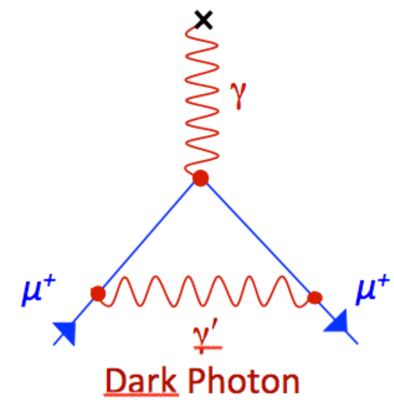
Search for the O(GeV/c²) mass scale in a world-wide effort

- Could explain large number of **astrophysical anomalies**
  Arkani-Hamed et al. (2009)
  Andreas, Ringwald (2010); Andreas, Niebuhr, Ringwald (2012)

- Could explain presently seen **deviation of >3σ** between **$(g-2)_\mu$** Standard Model prediction and direct $(g-2)_\mu$ measurement
  Pospelov(2008)

Status 2011

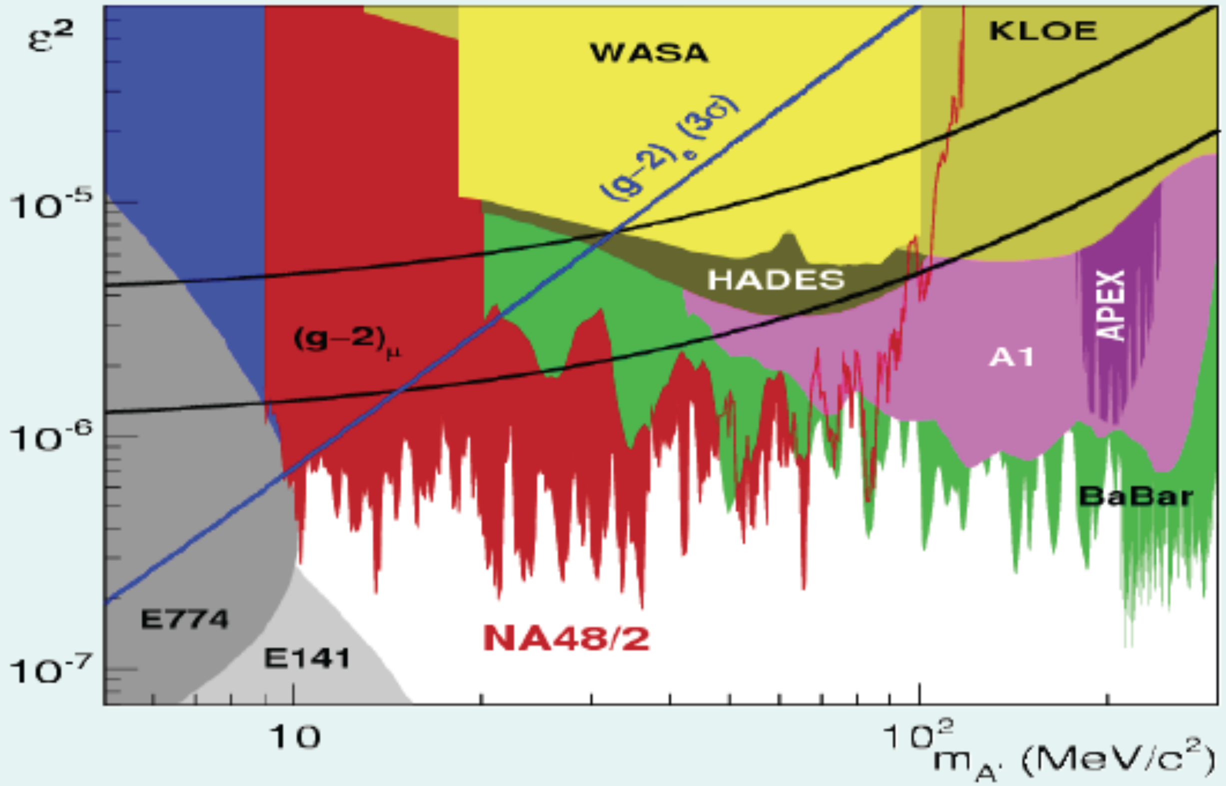

Coupling
Mixing Parameter ε
10^{-2}
10^{-3}
10^{-4}
(g-2)$_e$ vs. α
(g-2)$_\mu$
BaBar
$e^+e^- \to \gamma\mu^+\mu^-$
KLOE
|(g-2)$_\mu$|< 2σ
allowed parameter range for Dark Photon explanation of (g-2)$_\mu$
E774
E141
10
100
1000
Dark Photon Mass $m_{\gamma'}$ (MeV/c^2)
Mass


×
γ
μ^+
μ^+
γ′
Dark Photon

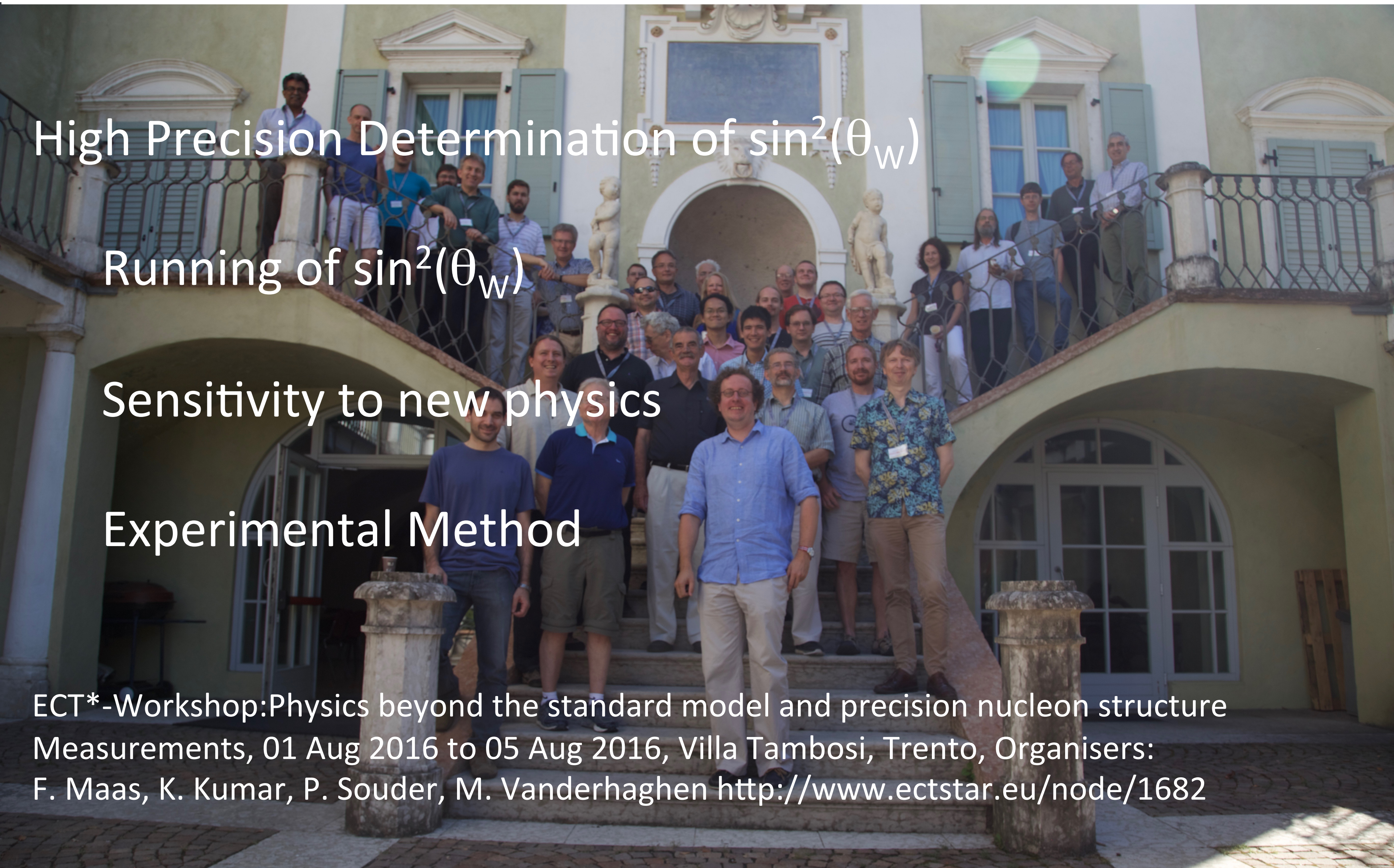
NA48/2 Updated Bounds on Dark Photon

g_μ-2 discrepancy solution ruled out

Assumes BR($Z_d \rightarrow$ e+e-) ~1



H. Davoudiasl, W. Marciano



High Precision Determination of $\sin^2(\theta_W)$

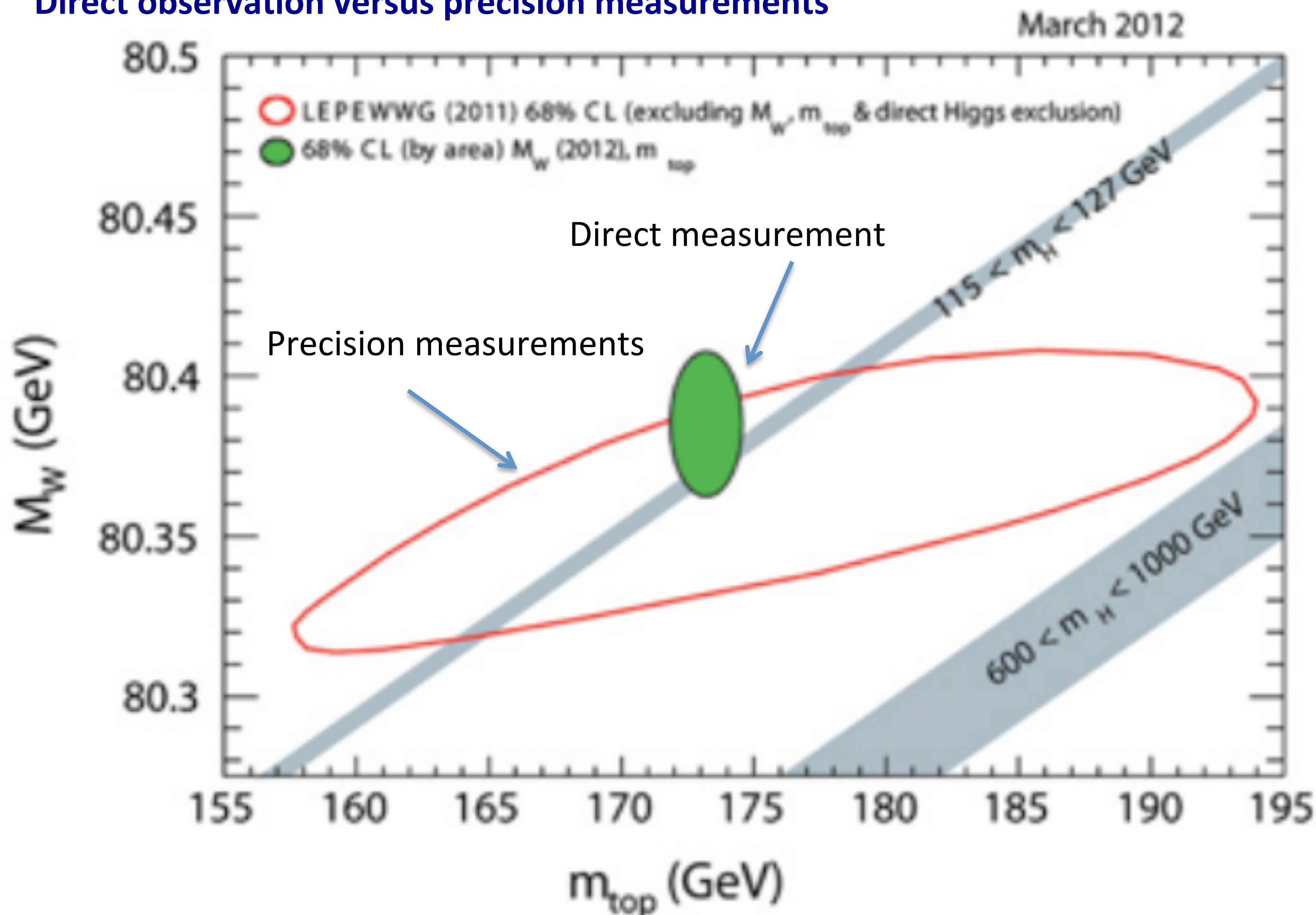
Running of $\sin^2(\theta_W)$

Sensitivity to new physics

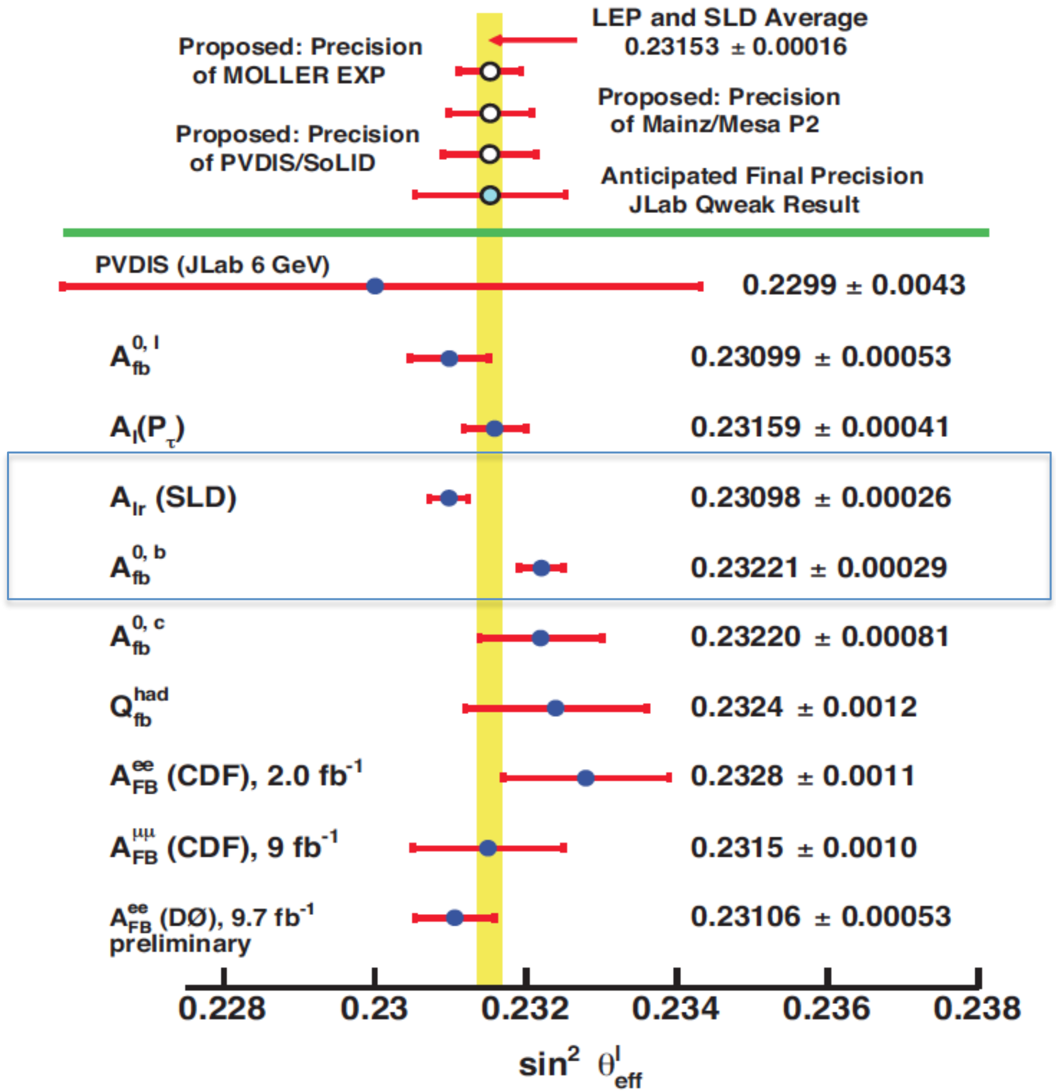
Experimental Method

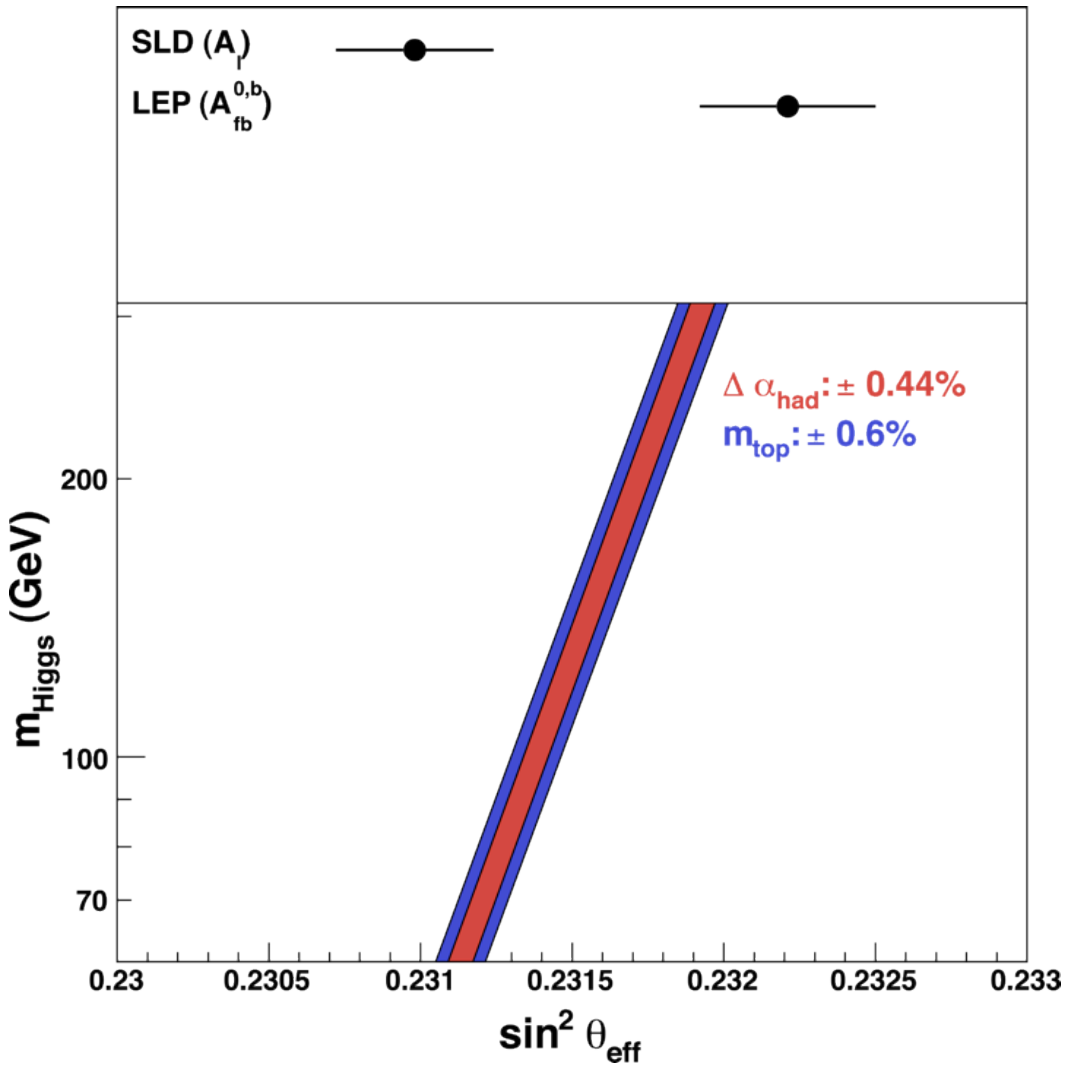
ECT*-Workshop:Physics beyond the standard model and precision nucleon structure Measurements, 01 Aug 2016 to 05 Aug 2016, Villa Tambosi, Trento, Organisers: F. Maas, K. Kumar, P. Souder, M. Vanderhaghen http://www.ectstar.eu/node/1682

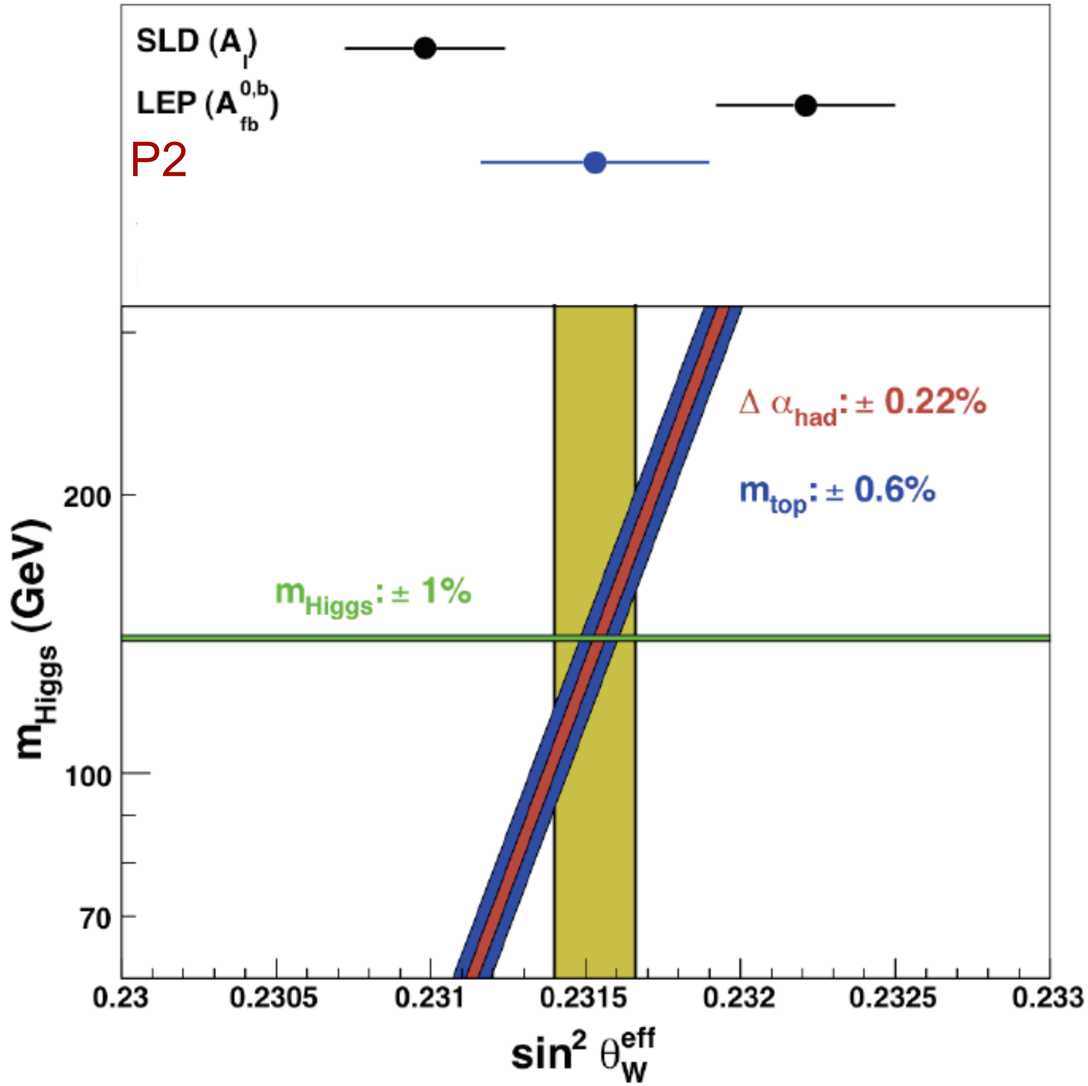
Direct observation versus precision measurements

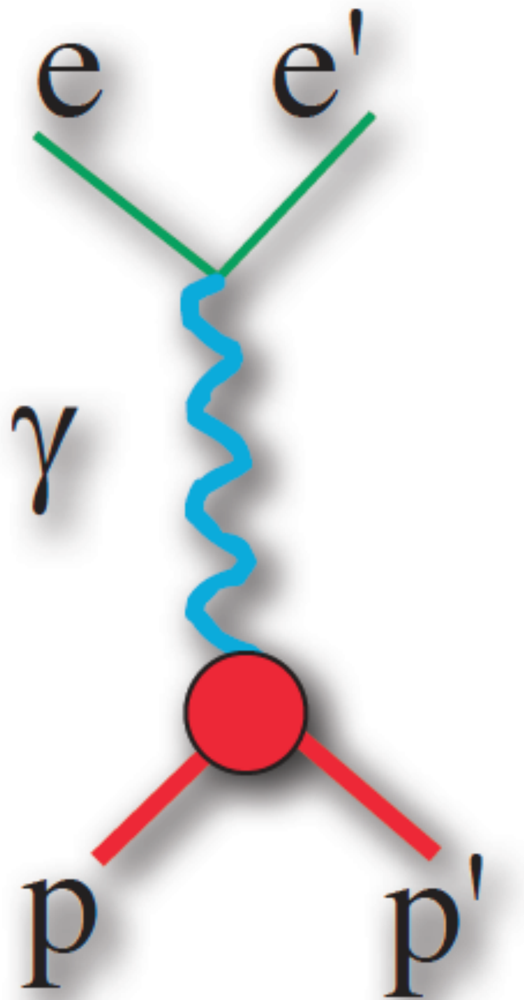


Summary: Measurements of $\sin^2\theta_{W(effective)}$




SLD (A_l)
LEP ($A_{fb}^{0,b}$)
$\Delta\ \alpha_{had}$: ± 0.44%
m_{top}: ± 0.6%
m_{Higgs} (GeV)
200
100
70
0.23
0.2305
0.231
0.2315
0.232
0.2325
0.233
$\sin^2\theta_{eff}$


SLD (A_l)
LEP ($A^{0,b}_{fb}$)
P2
$\Delta\ \alpha_{had}$: ± 0.22%
m_{top}: ± 0.6%
m_{Higgs}: ± 1%
m_{Higgs} (GeV)
200
100
70
0.23
0.2305
0.231
0.2315
0.232
0.2325
0.233
$\sin^2 \theta_W^{eff}$



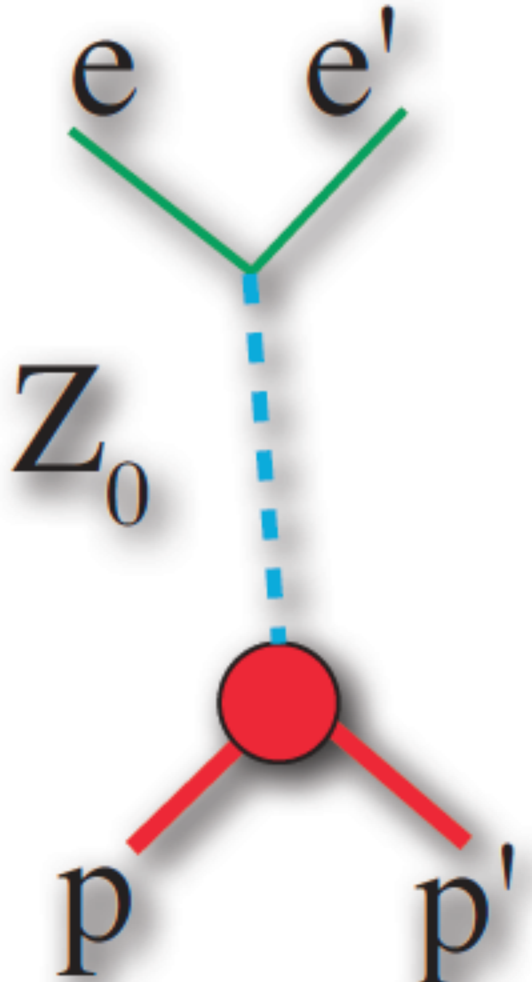
$$\sigma \sim \mathcal{M}\,\mathcal{M}^* \text{ Phasespace}$$

$$\sim \left(j_\mu \frac{1}{Q^2} J^\mu\right)\left(j_\mu \frac{1}{Q^2} J^\mu\right)^*$$

$$j_\mu \sim \overline{e}\,\gamma_\mu\, e \quad \text{Vector Current}$$

$$J^\mu_\gamma \sim \left\langle N \middle| q^u \overline{u}\,\gamma_\mu\, u + q^d \overline{d}\,\gamma_\mu d + q^s \overline{s}\,\gamma_\mu s \middle| N' \right\rangle$$

$$= \overline{\mathcal{P}}\left[\gamma^\mu F_1 - i\sigma^{\mu\nu} q_\nu \frac{\kappa_p}{2M_N} F_2\right]\mathcal{P}$$

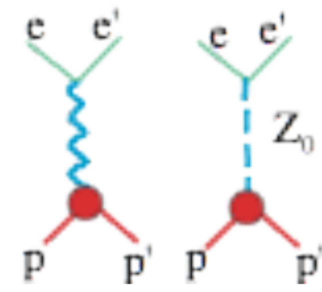


$$\tilde{q}^{d}{}_{V} \quad = \quad \tau_3 - 2q^{d}\,sin^2(\theta_W)$$

$$\begin{aligned} \tilde{J}^{\mu}_{Z} &\sim \left\langle N|\tilde{q}^{u}\overline{u}\,\gamma_\mu\, u + \tilde{q}^{d}\overline{d}\,\gamma_\mu d + \tilde{q}^{s}\overline{s}\,\gamma_\mu s|N'\right\rangle \\ &= \overline{\mathcal{P}}[\gamma^\mu \tilde{F}_1 - i\sigma^{\mu\nu} q_\nu \frac{\kappa_p}{2M_N}\tilde{F}_2]\mathcal{P} \end{aligned}$$

Parity violating cross section asymmetry

$$A_{ep} = \left[\frac{G_F\, Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{\epsilon G_E^{\gamma} G_E^{Z} + \tau G_M^{\gamma} G_M^{Z} - (1-4\sin^2\theta_w)\epsilon' G_M^{\gamma} G_A^{Z}}{\varepsilon (G_E^{\gamma})^2 + \tau (G_M^{\gamma})^2}$$



$$A_{\rm RL} = \underbrace{A_{\rm V} + A_{\rm A}}_{= A_0} + A_{\rm S} \begin{cases} A_{\rm V} = -a\rho'_{eq}\left[(1-4\sin^2\theta_W) - \dfrac{\epsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}\right] \\ A_{\rm A} = a\dfrac{(1-4\sin^2\theta_W)\sqrt{1-\epsilon^2}\sqrt{\tau(1+\tau)}G_M^p \tilde{G}_A^p}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} \\ A_{\rm S} = a\rho'_{eq}\dfrac{\epsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} \end{cases}$$

e

$$a = -G_F q^2/4\pi\alpha\sqrt{2}, \quad \tau = -q^2/4M_{\rm p}^2, \quad \epsilon = [1 + 2(1+\tau)\tan^2\theta/2]^{-1}$$