Low-Energy determination of the Electroweak Mixing Angle with high accuracy: the P2 experiment

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PREN 2023 (Proton Radius European Network - STRONG 2020) & µASTI (Muonic Atom Spectroscopy Theory Initiative)

26.–30. Juni 2023

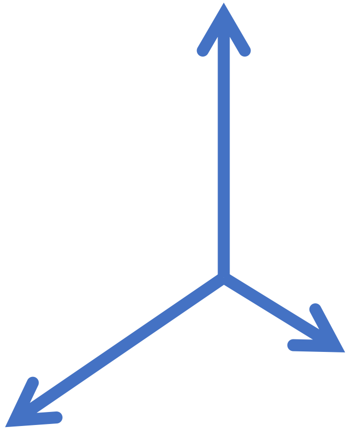
JG|U

HIM

PRiSMA+

Search for physics beyond the standard model

Direct: High Energy (LHC)

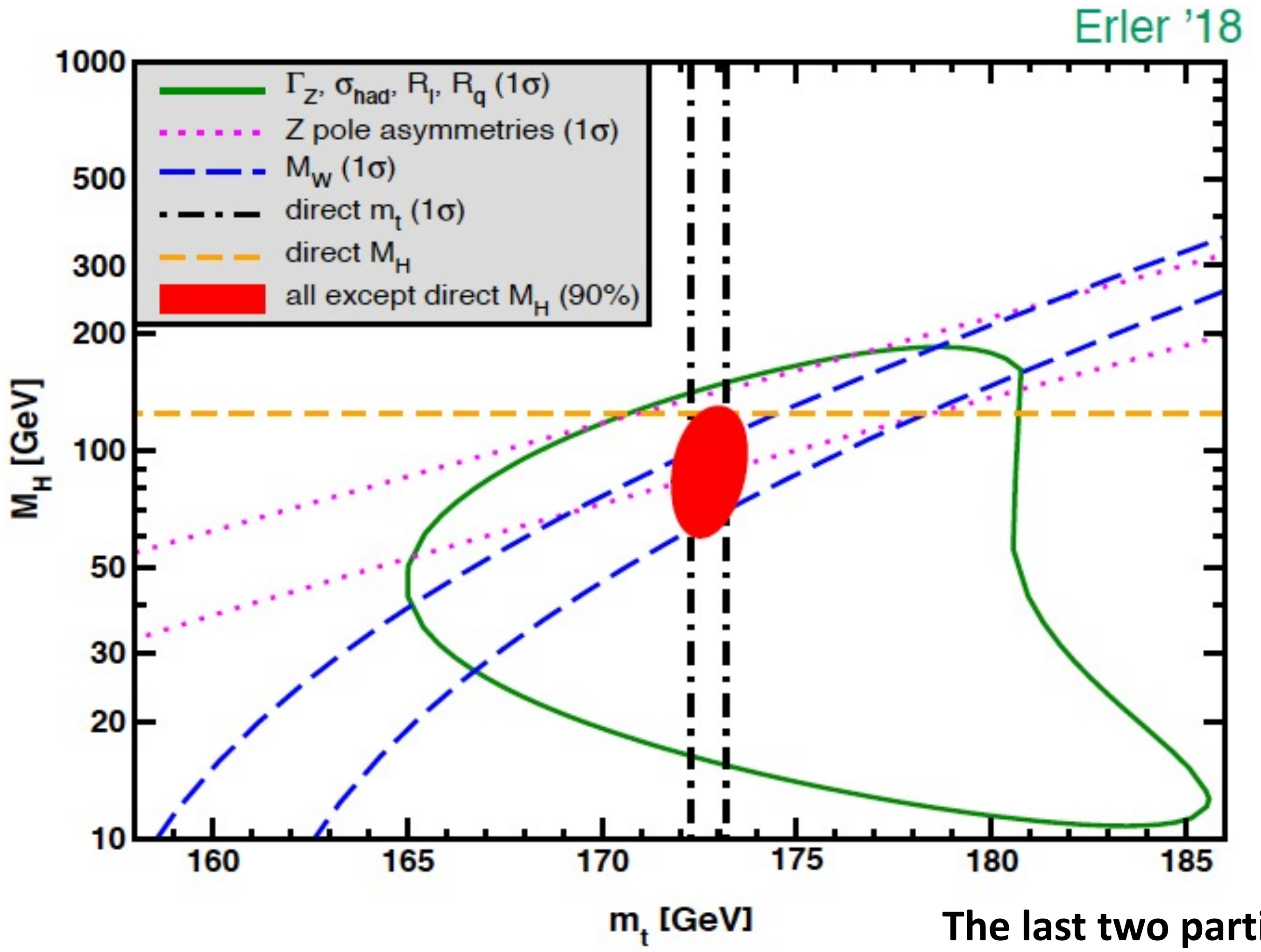


Indirect: High Precision
Anom. Mag. Moment
$(g\text{-}2)_{\mu,e}$, EDM, $\sin^2\theta_W$, …

Indirect: High Intensity
Rare B-decays
R_{D*}

- at low energy
- accurate theory needed

Direct observation versus precision measurements: top-quark, Higgs



Direct measurements:

$$M_H = 125.14 \pm 0.15 \text{ GeV}$$

$$m_t = 172.74 \pm 0.46 \text{ GeV}$$

Indirect prediction:

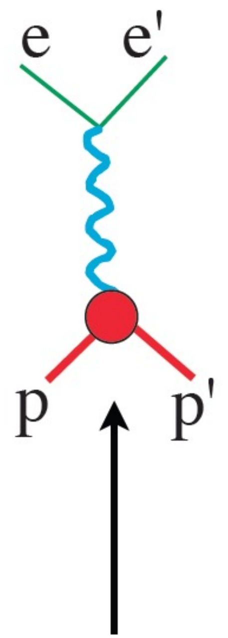
$$M_H = 90^{+17}_{-16} \text{ GeV}$$

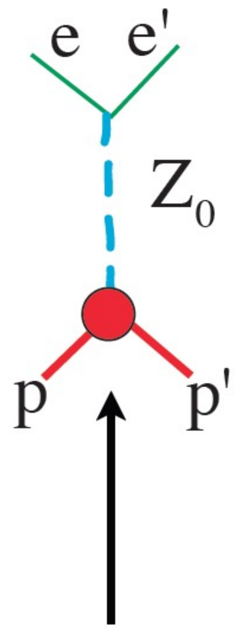
$$m_t = 176.4 \pm 1.8 \text{ GeV}$$

The last two particles of the standard model have been seen in indirect searches before their direct production

The role of the weak mixing angle

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





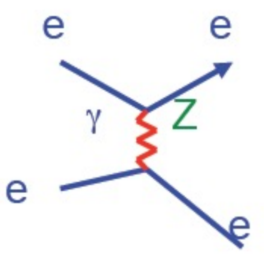
$Q_e(p) = +e$
electric charge of the proton

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

$\sin^2 \theta_W$: a central parameter of the standard model accessible through the weak charge

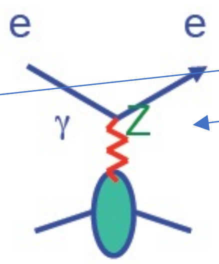
Access to the weak mixing angle at low energy

MOLLER (Jlab)
Møller Scattering



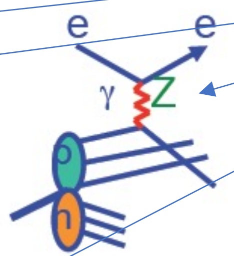
- Purely Leptonic

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



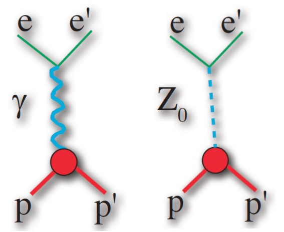
- Coherent quarks in p

SOLID (Jlab)
e-DIS

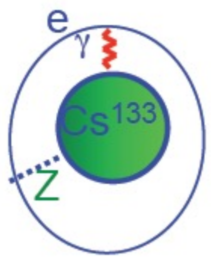


- Isoscaler quark scattering
- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

Interference between electromagnetic and weak neutral current amplitude: Parity violating asymmetries



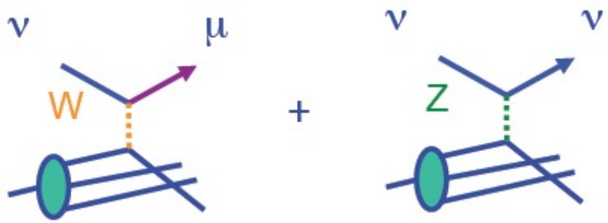
Yb,Dy,Sm (HIM/Mainz)
Atomic Parity Violation



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

Neutrino Scattering

CEvNS (Jlab)

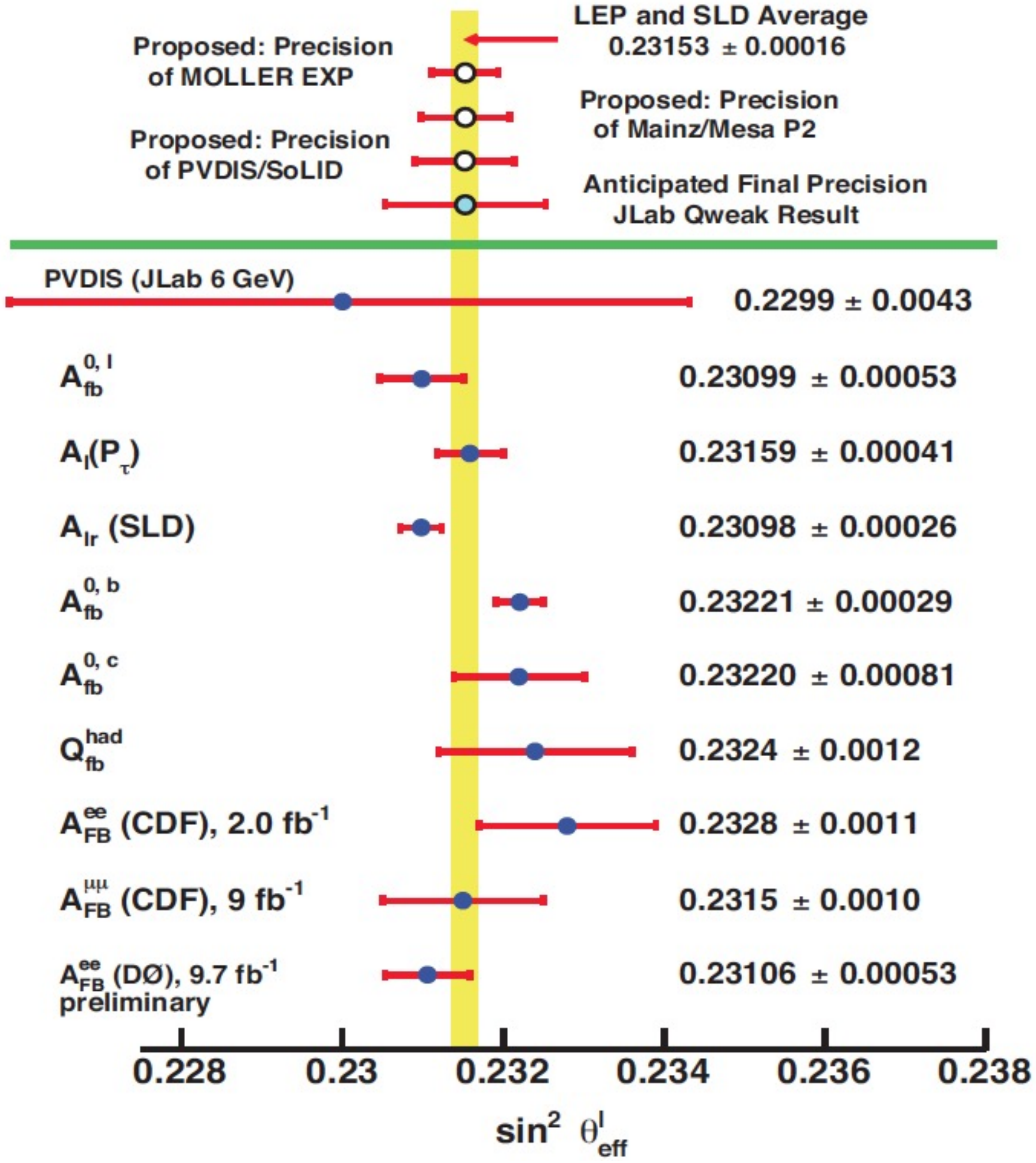


- Quark scattering (from nucleus)
- Weak charged and neutral current difference

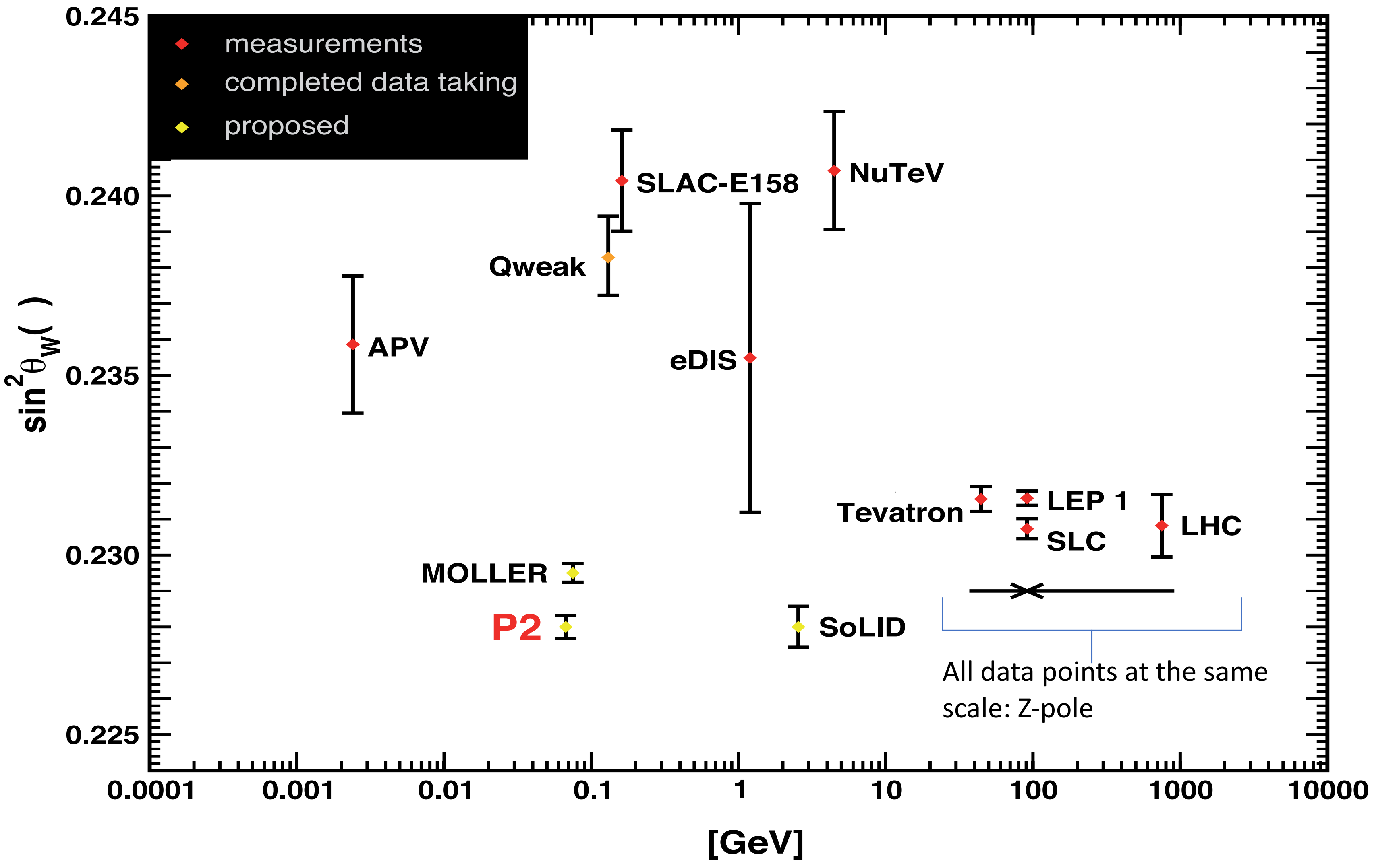
Cross section measurements

Access to the weak mixing angle at high energy (Z-pole)

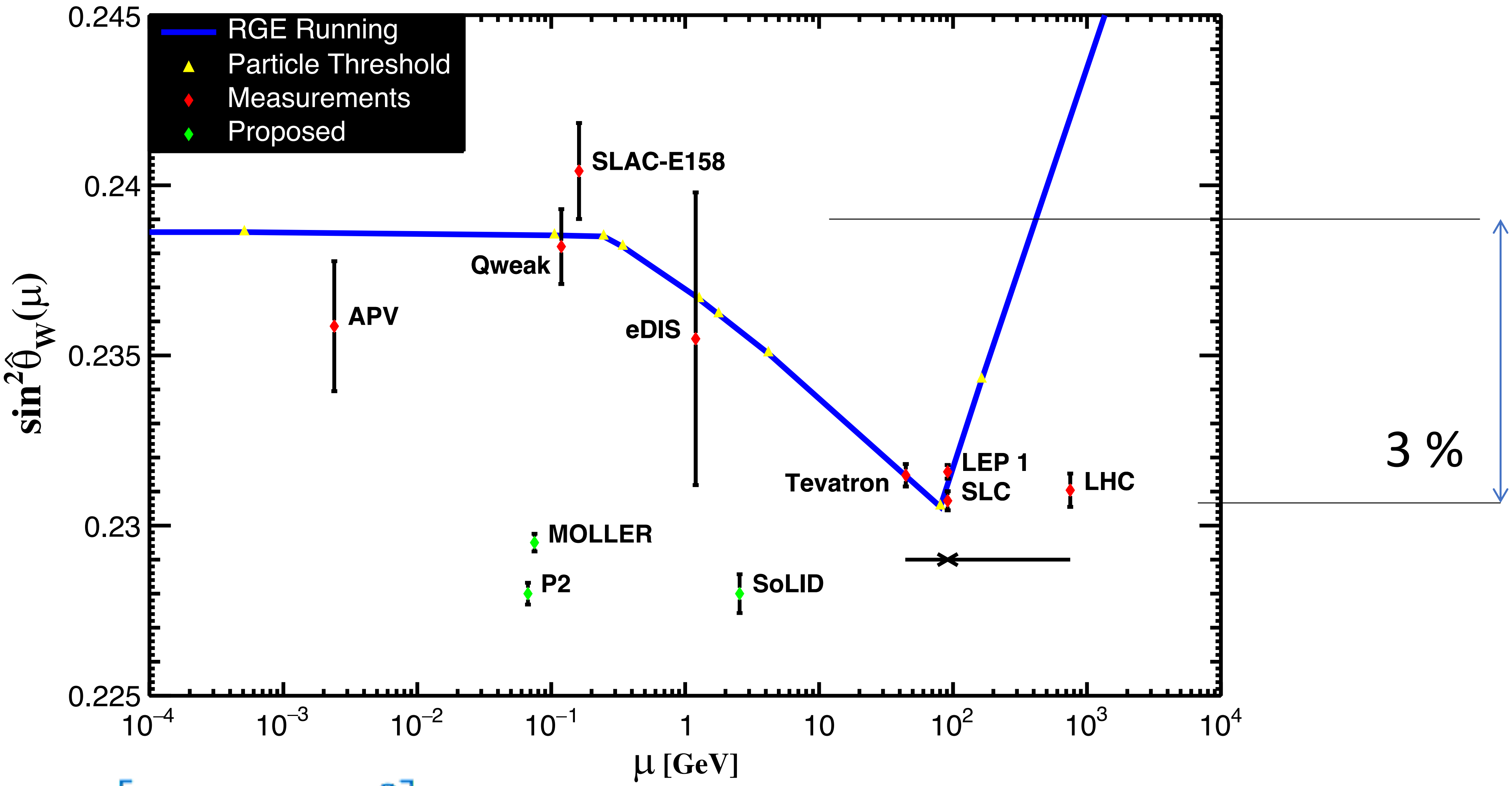
Summary: Measurements of $\sin^2\theta_{W(effective)}$



Measurements of the weak mixing angle



Running of the weak mixing angle



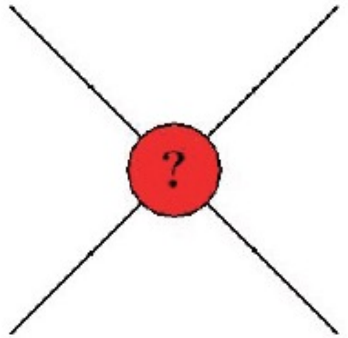
$$\left|A_Z + A_{new}\right|^2 \rightarrow A_Z^2\left[1 + \left(\frac{A_{new}}{A_Z}\right)^2\right]$$

On the Z-resonance A_Z imaginary and very large, largely reduced sensitivity to new physics

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

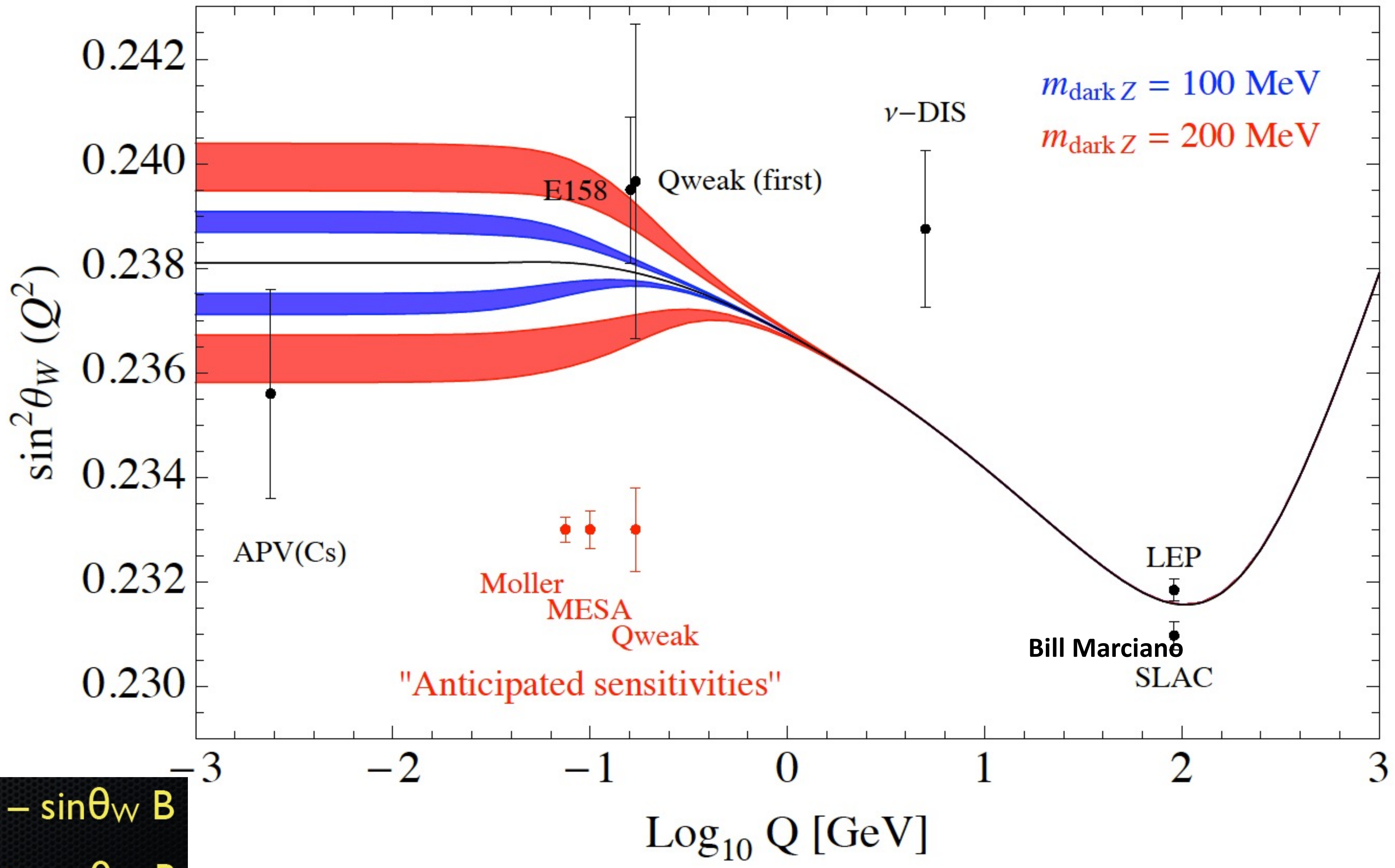
	precision	$\Delta \sin^2\bar{\theta}_W(0)$	Λ_{new} (expected)
APV Cs	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
Qweak final	4.5 %	0.0008	33 TeV
PVDIS	4.5 %	0.0050	7.6 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3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

Effective field theory approach (EFT)



Jens Erler

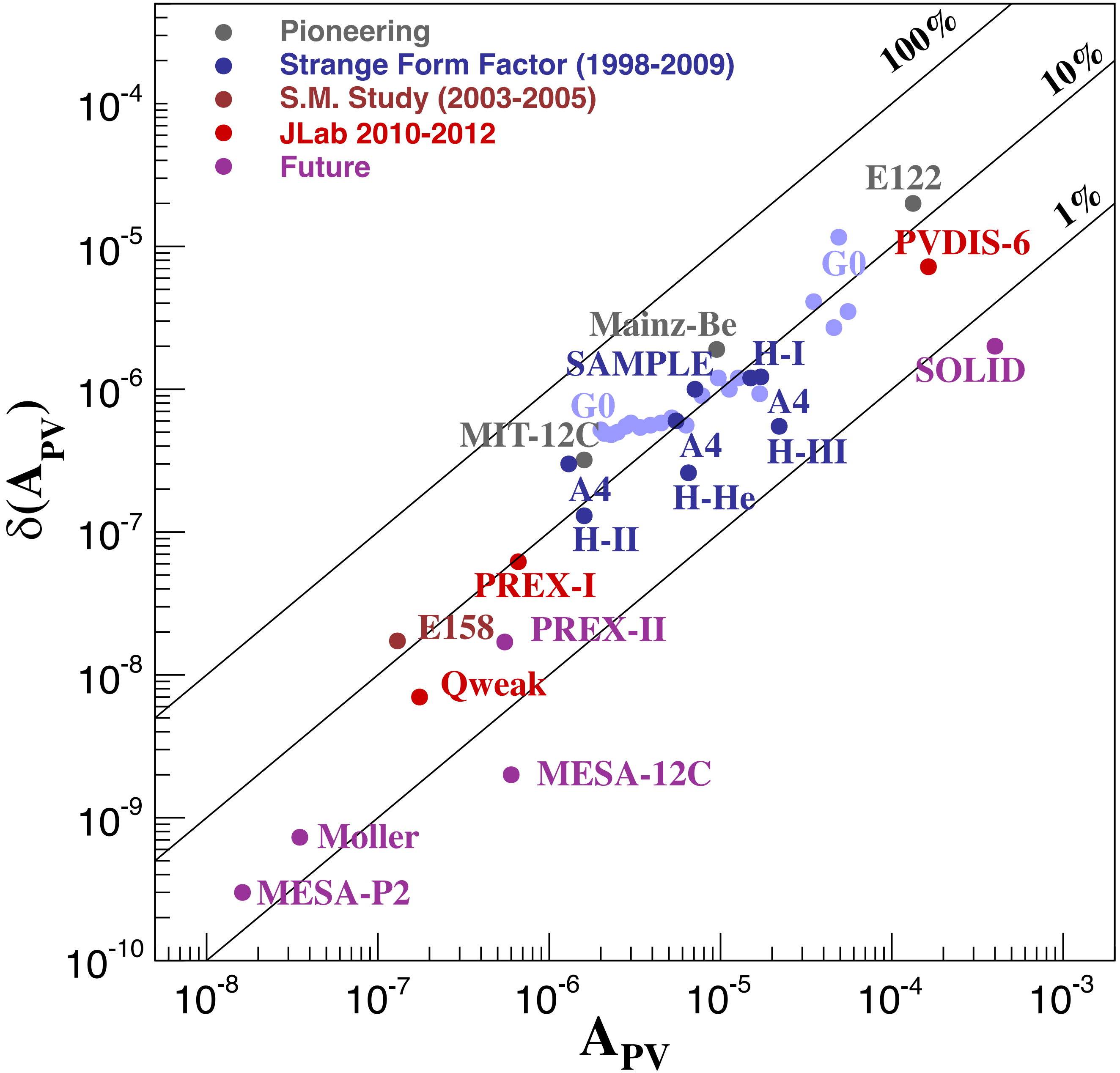
Running $\sin^2\theta_W$ and Dark Parity Violating Z



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

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

PVeS Experiment Summary

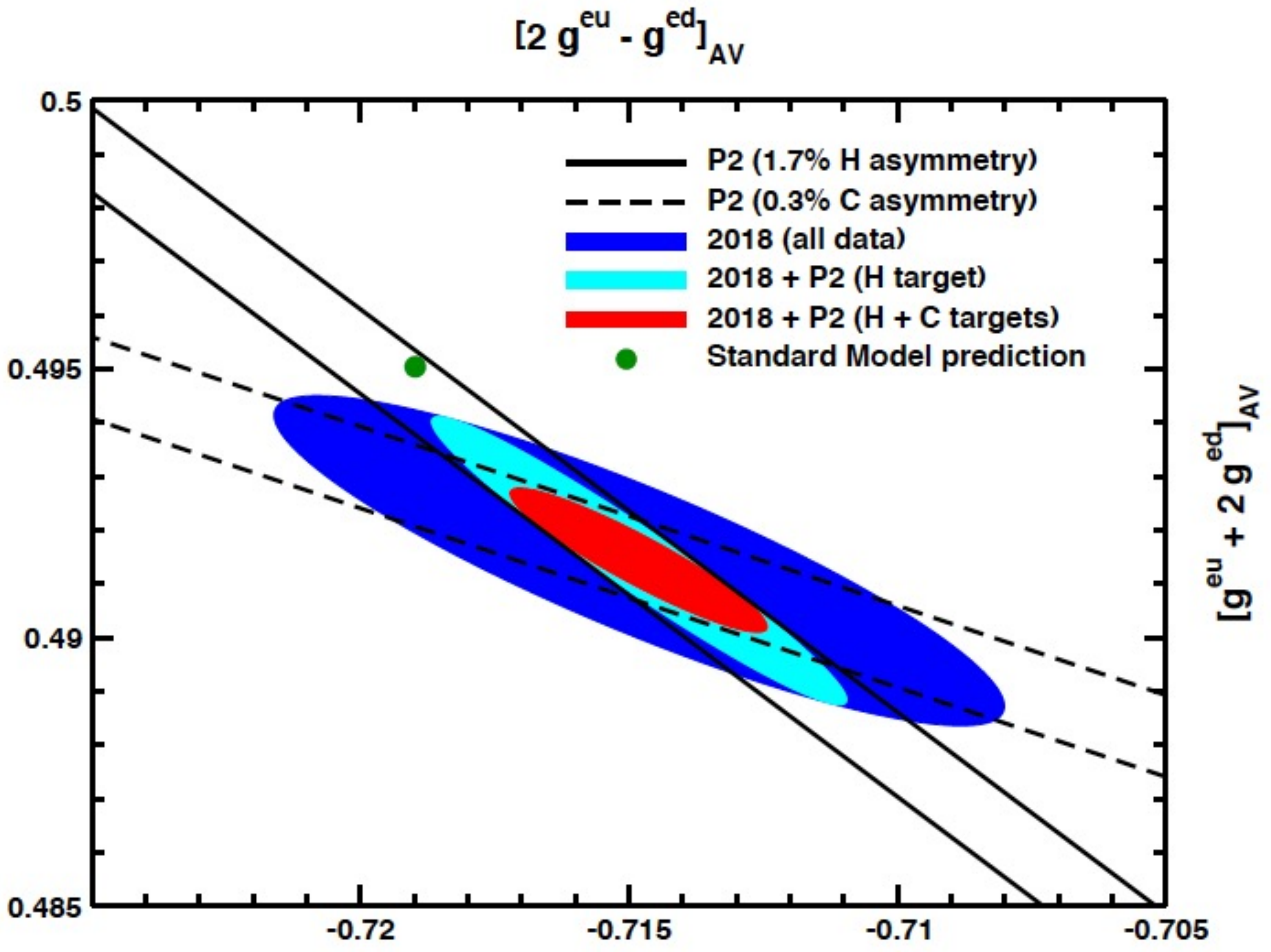


P2 parity violation experiment in Mainz: program

Qweak@Jlab	P2@MESA hydrogen	P2@MESA carbon	P2@MESA Lead, Transverse A
A_{ep}=-226.5 ppb	A_{ep}=-28 ppb	A_{ep}= 416.3 ppb	Neutron skin measurement
ΔA_{ep}= 9.3 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	Two-Photon exchange
$\Delta A_{ep}/A_{ep}$= 4.2 %	$\Delta A_{ep}/A_{ep}$= 1.8 %	$\Delta A_{ep}/A_{ep}^{stat}$= 0.6 % (0.2 %) Polarimetry!	
$\Delta \sin^2\theta_W/\sin^2\theta_W$= 0.46 %	$\Delta \sin^2\theta_W/\sin^2\theta_W$= 0.15 %	$\Delta \sin^2\theta_W/\sin^2\theta_W$= 0.6 %	
	Aux. measurem. backward angle	Aux. measurem. backward angle	

Improvement by high luminosity, long measurement time, small systematics, lower Q^2

Constraints from PVES at MESA



- Quark-vector-electron-axial vector couplings
- Sensitivity down to masses of 70 MeV and up to masses of 50 TeV

Future wEFT constraints from APV and PVES

Adam Falkowski at Mainz MITP workshop: Impact on low energy measurements

Current QWEAK, PVDIS, and APV cesium experiments:

$$\begin{pmatrix} \delta g^{eu}_{AV} \\ \delta g^{ed}_{AV} \\ 2\delta g^{eu}_{VA} - \delta g^{ed}_{VA} \end{pmatrix} = \begin{pmatrix} 0.74 \pm 2.2 \\ -2.1 \pm 2.5 \\ -39 \pm 54 \end{pmatrix} \times 10^{-3}$$

Projections from combined P2, SoLID, and APV radium experiments:

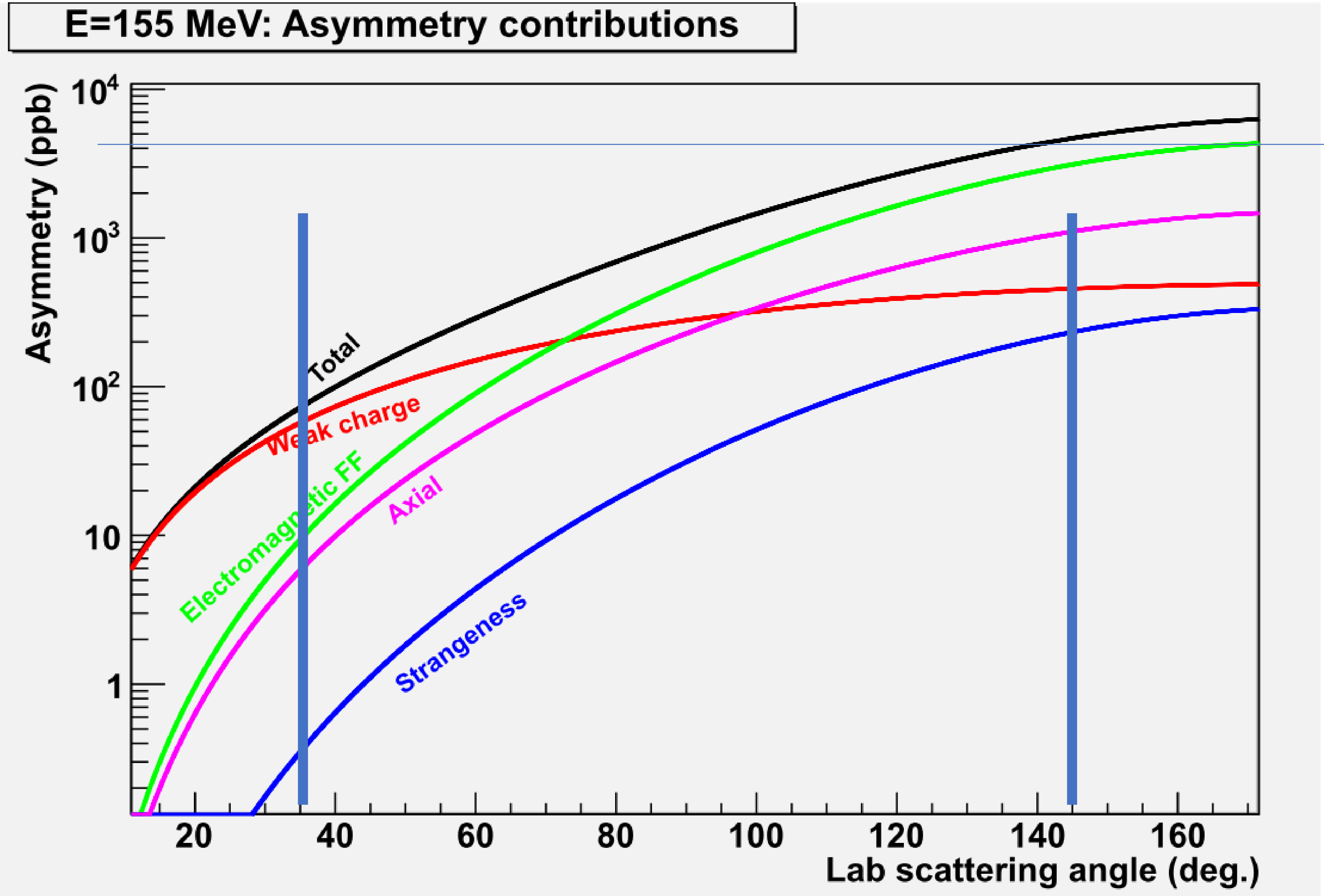
$$\begin{pmatrix} \delta g^{eu}_{AV} \\ \delta g^{ed}_{AV} \\ 2\delta g^{eu}_{VA} - \delta g^{ed}_{VA} \end{pmatrix} = \begin{pmatrix} 0 \pm 0.70 \\ 0 \pm 0.97 \\ 0 \pm 7.4 \end{pmatrix} \times 10^{-3}$$

$$\mathcal{L}_{\rm wEFT} \supset -\frac{1}{2v^2}\sum_{q=u,d} g^{eq}_{AV}(\bar{e}\,\bar{\sigma}_\rho e - e^c\sigma_\rho \bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q + q^c\sigma^\rho\bar{q}^c)$$
$$-\frac{1}{2v^2}\sum_{q=u,d} g^{eq}_{VA}(\bar{e}\,\bar{\sigma}_\rho e + e^c\sigma_\rho \bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q - q^c\sigma^\rho\bar{q}^c)$$

AA, Grilli Di Cortona, Tabrizi
1802.08296

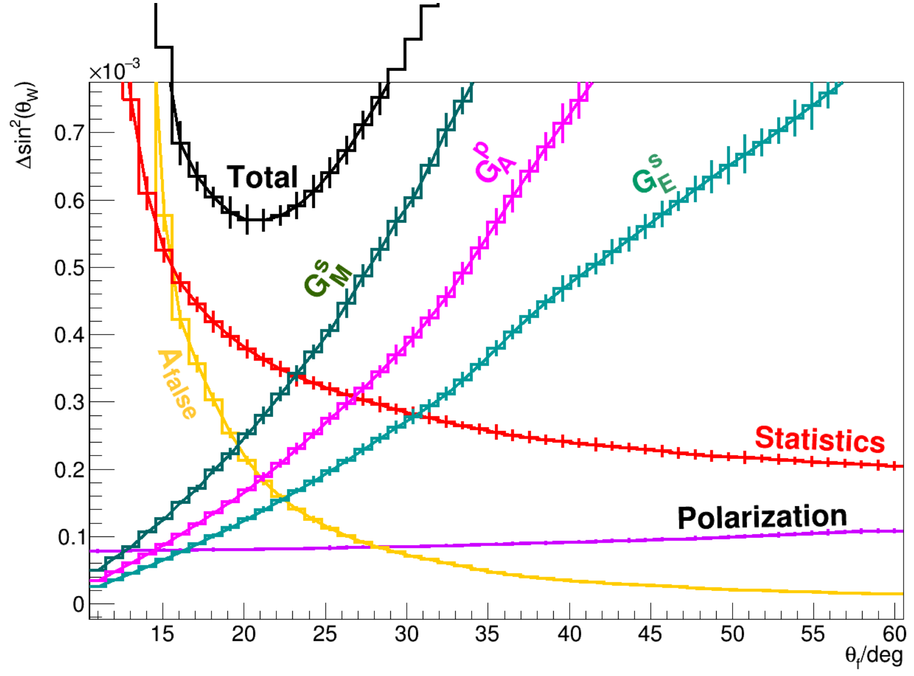
AA, Gonzalez-Alonso
in progress

P2 parity violation experiment in Mainz: forward and backward angle measurements



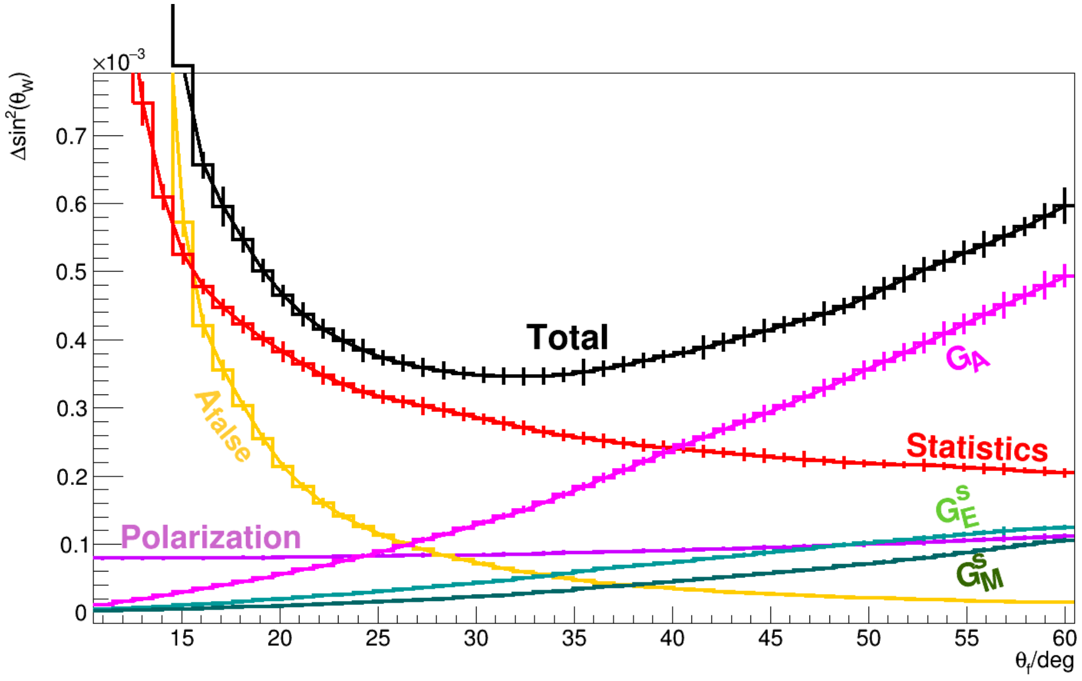
Auxiliary measurements at backward angles

Strange FF and axial FF from present data



Present status (accuracy) of electric and magnetic strangeness form factor and axial form factor

Strange FF from lattice, axial FF with uncertainty/3

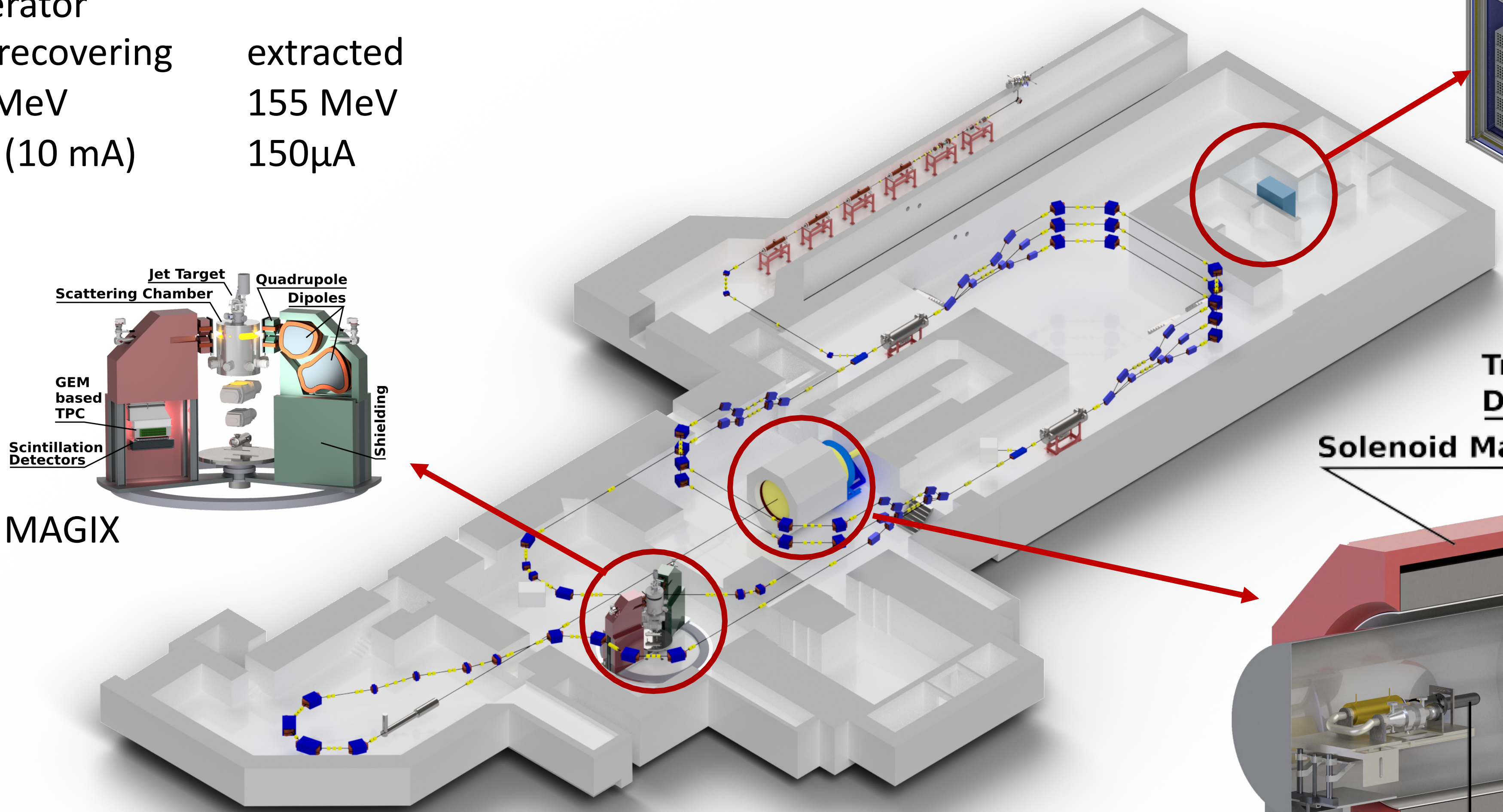


Accuracy of electric and magnetic strangeness form factor from recent lattice QCD calculations and axial form factor from backward angle measurement

Mainz Energy recovering Superconducting Accelerator: MESA

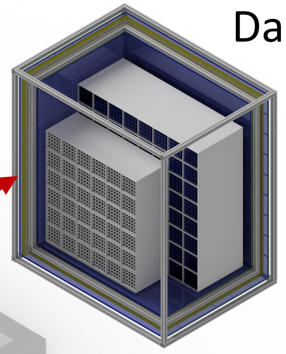
Electron accelerator

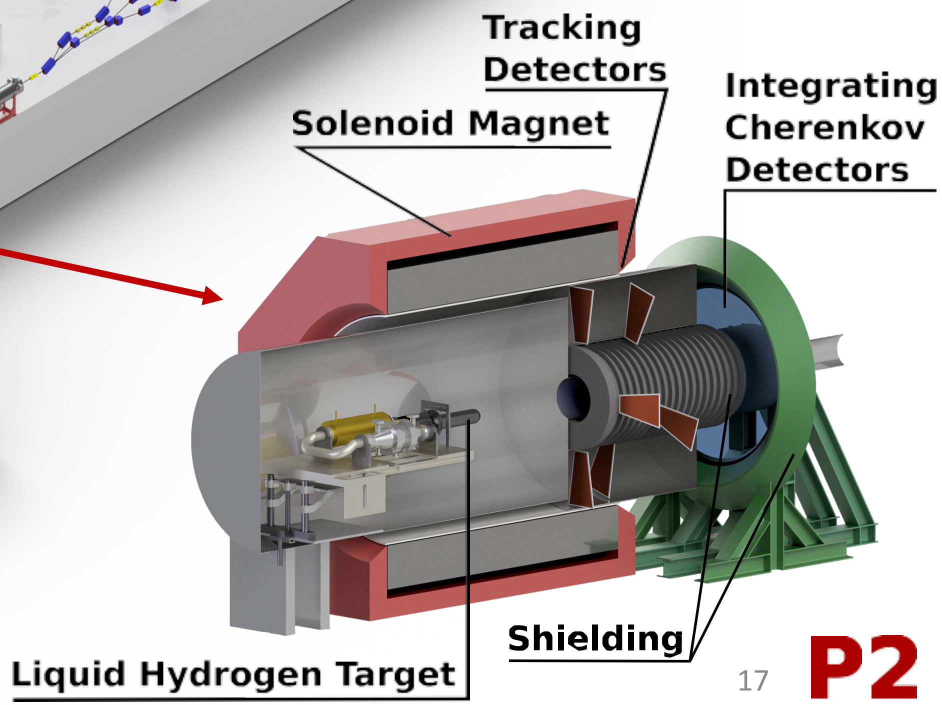
Mode:	energy recovering	extracted
Energy:	105 MeV	155 MeV
Current:	1mA (10 mA)	150µA



MAGIX

Dark MESA

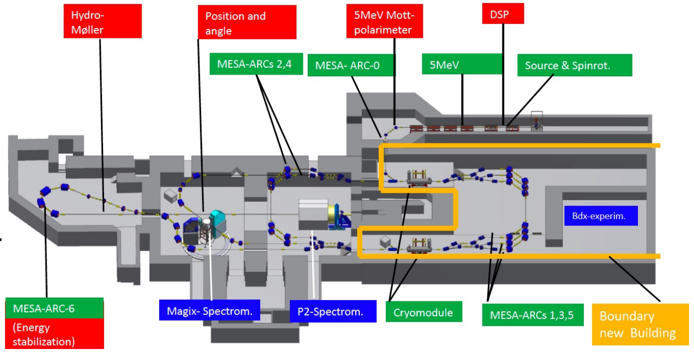




P2

See talk in session new facilities

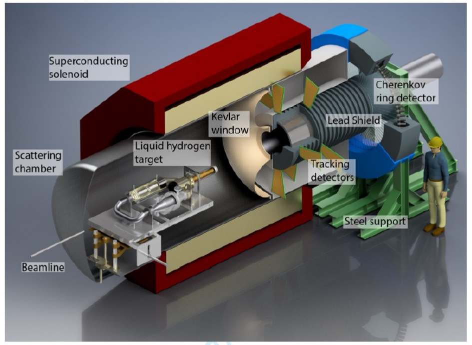
P2: Parity violating electron proton scattering at MESA/Mainz



$$A_{LR}^{exp} = \frac{\sigma(\vec{e}p) - \sigma(\overleftarrow{e}p)}{\sigma(\vec{e}p) + \sigma(\overleftarrow{e}p)} + A_F = -P\,\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(p) - F(Q^2)\right)$$

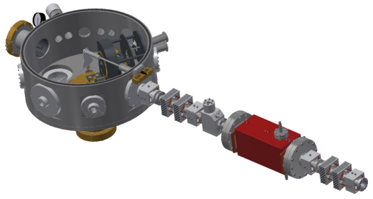
False asymmetries: control of target and accelerator

Measurement:
Cross section asymmetry A_{LR}^{exp}

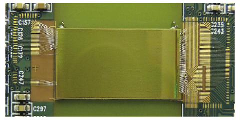


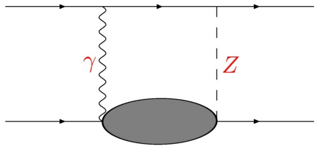
Magnetic spectrometer
Cherenkov detector
Read-out electronics
Data acquisition

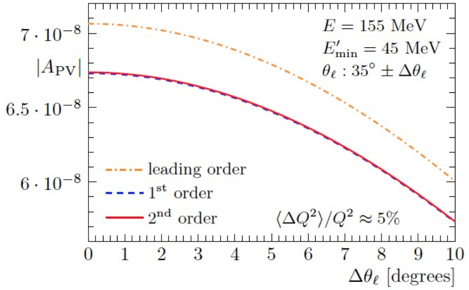
Beam polarisation
P
Polarimetry



Momentum transfer $< Q^2 >$
Tracking system

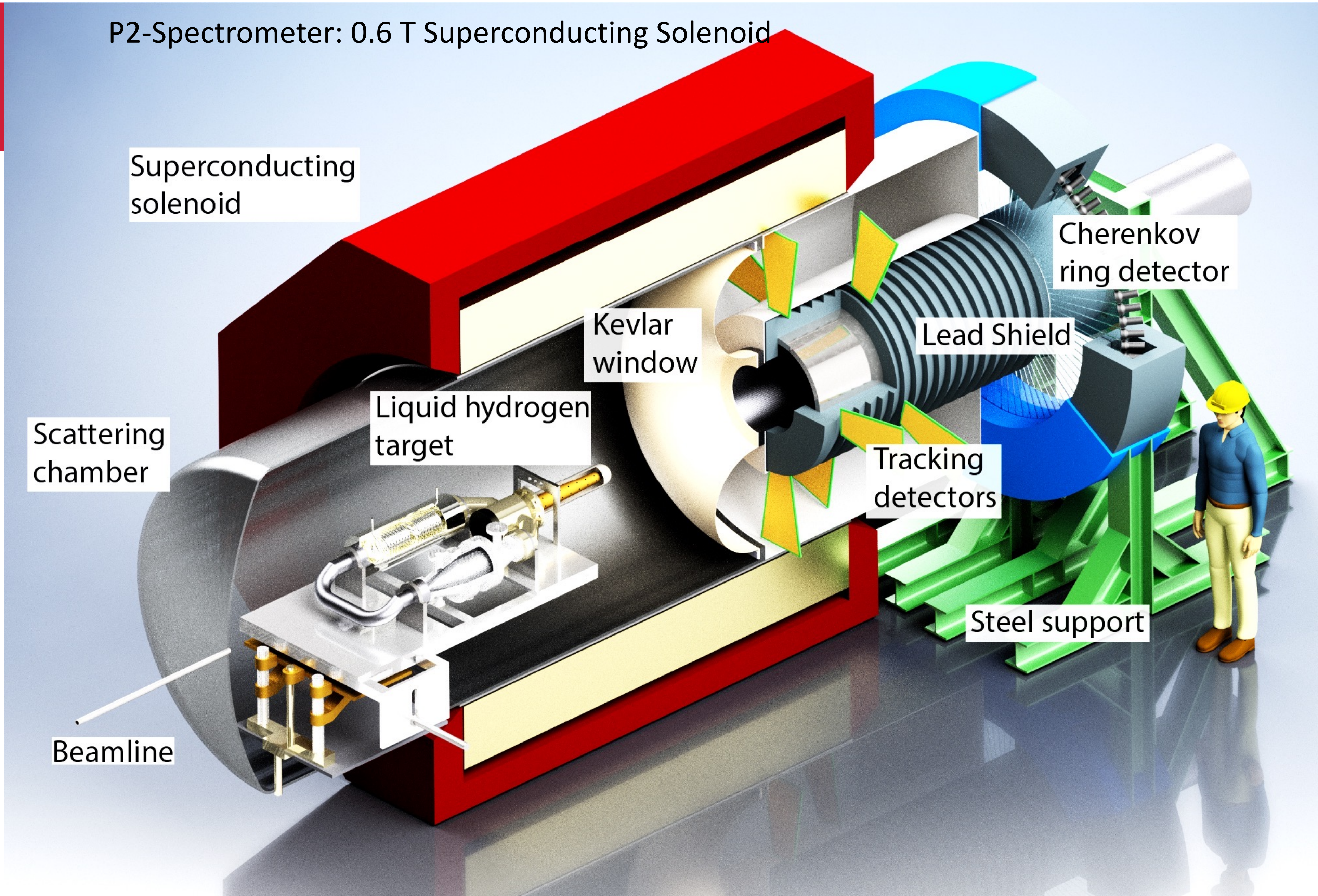






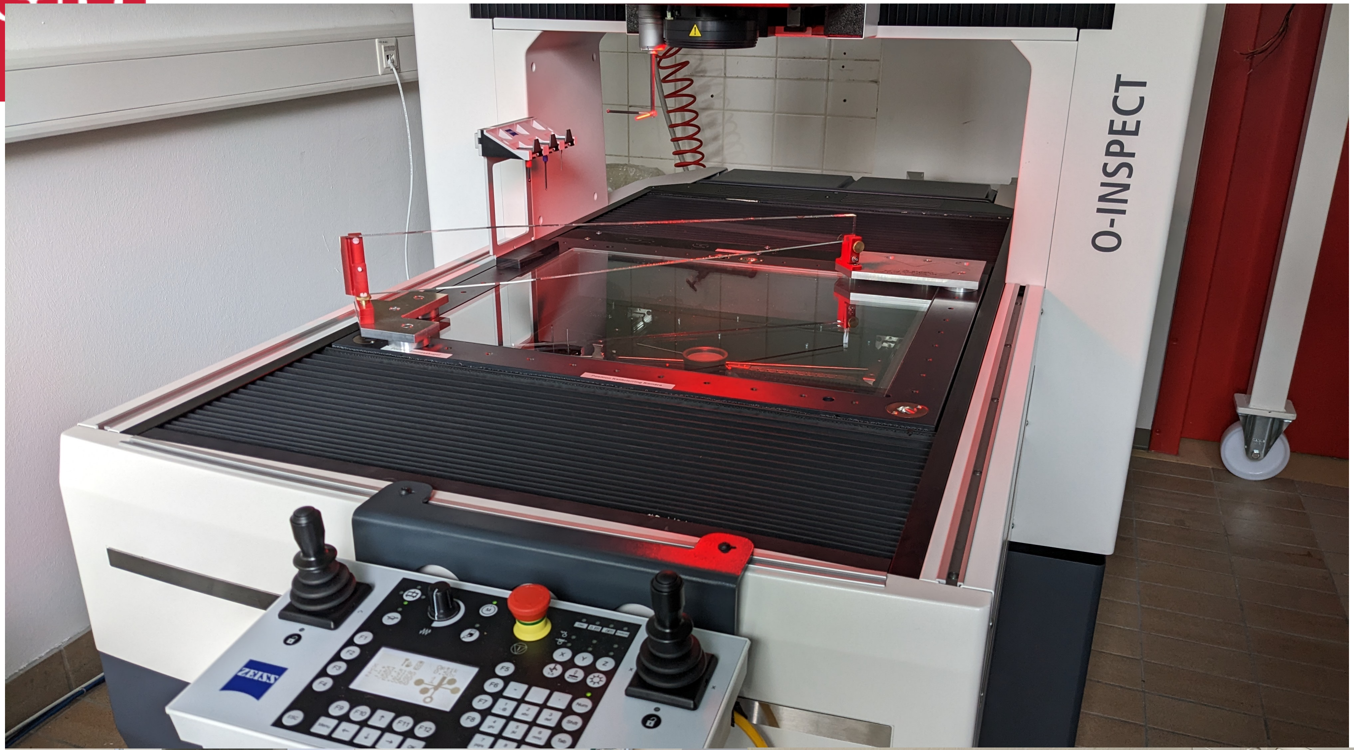
Theory:
QED corrections
EW corrections (two loop, three loop)
Hadron structure $F(Q^2)$,
Strangeness form factors
Merasure:
Axial form factor

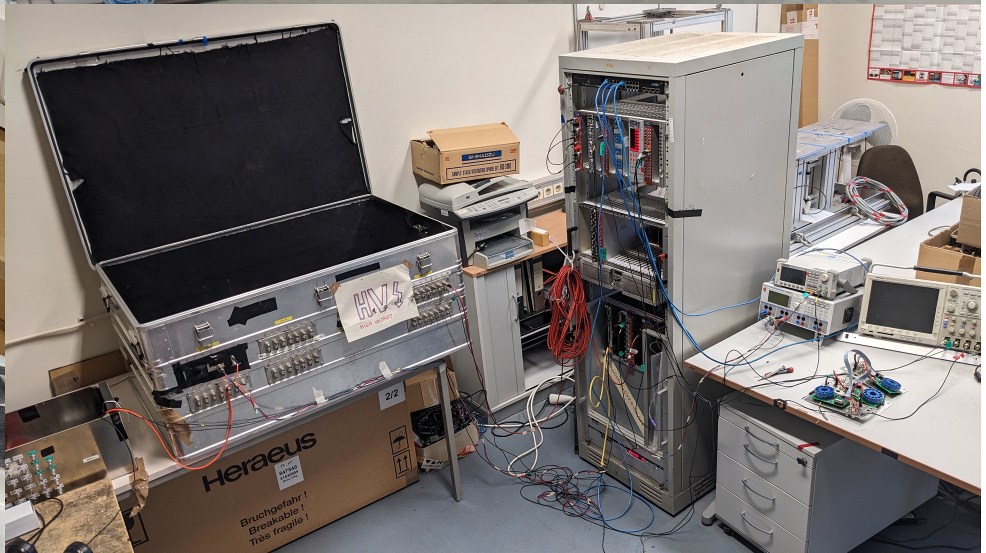
P2-Spectrometer: 0.6 T Superconducting Solenoid



First time use of a solenoid in a parity violating electron scattering experiment

JG|U PRiSMA+


O-INSPECT
ZEISS


Heraeus
Bruchgefahr !
Breakable !
Très fragile !

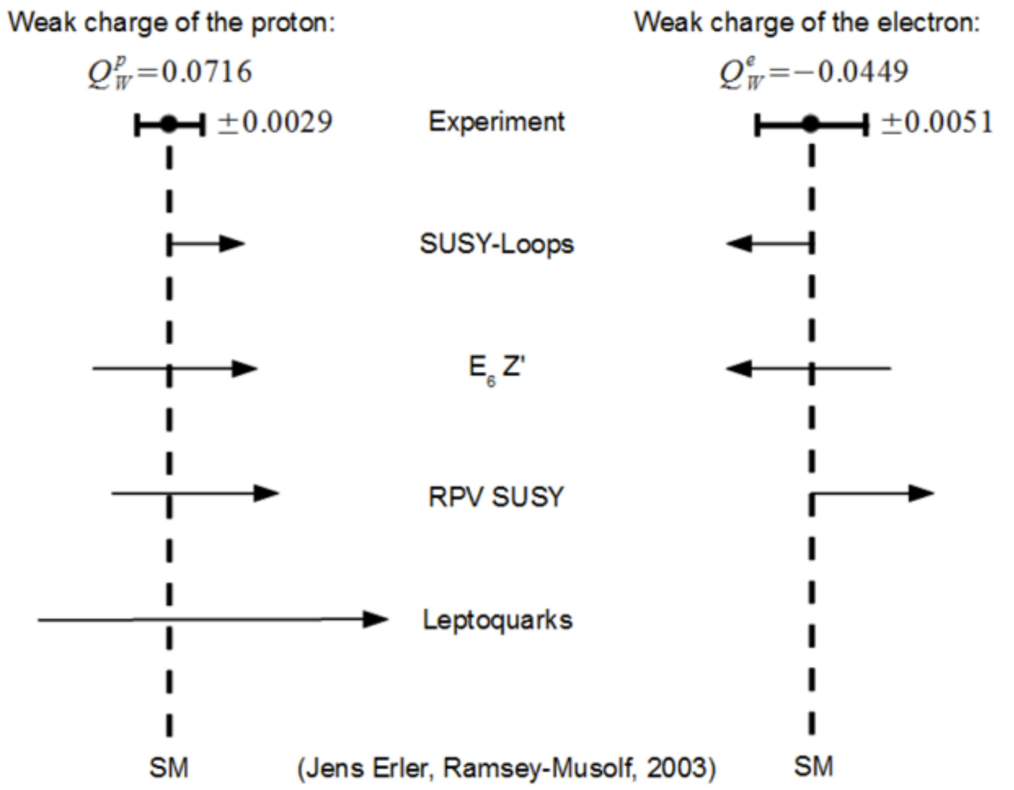
Three PV experiments with three different probes for new physics

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

Weak Charge Of Electron: MOLLER (JLAB)

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

- Complementary access by weak charges of proton and electron



Summary

- **Parity violating electron scattering:**
  "Low energy frontier" comprises a sensitive test of the standard model complementary to LHC up to 50 TeV
- **Determination of $\sin^2(\theta_W)$ with highest precision 0.15% (similar to Z-pole)**
- **P2-Experiment (proton weak charge) at MESA**
- **Solenoid delivery in December 2023, all critical components delivered, start commissioning P2 in 2025**
- **New MESA energy recovering accelerator at 155 MeV, target precision is 2 % in weak proton charge i.e. 0.15% in $\sin^2(\theta_W)$,**
- **Sensitivity to new physics at a scale from 70 MeV up to 50 TeV**
- **Strategic series of measurements from large asymmetries to ultimate precision**
- **Final accuracy corresponds to a factor 4 improvement over Qweak-experiment**
- **Much more physics from PV electron scattering: Neutron Skin in heavy nuclei, weak charge in light nuclei**