JG|U

SFB 1044
Institut für Kernphysik

Parity Violating Electron Scattering Experiments for an Ultra Precise Determination of the Weak Mixing Angle $\sin^2 \theta_W$ at Low Energies

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(Helmholtz Institute Mainz,
PRISMA cluster of excellence,
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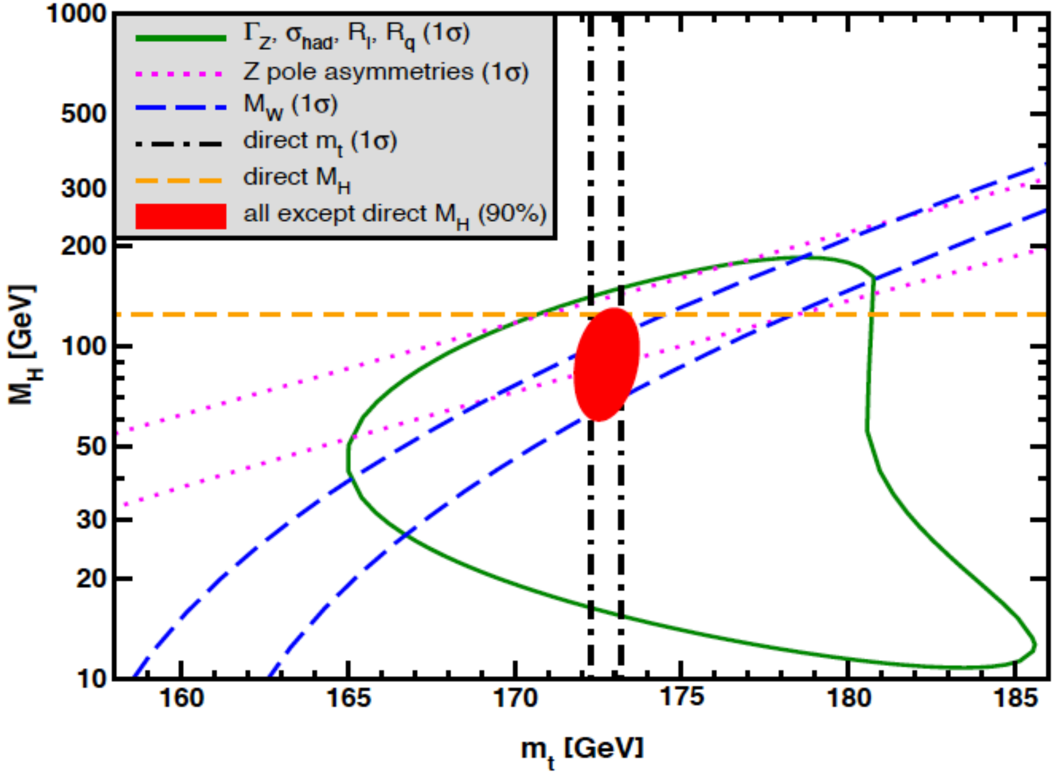
CIPANP 2018 - Thirteenth Conference on the Intersections of Particle and Nuclear Physics, 29 May 2018 - 3 June 2018, Hyatt Regency Indian Wells Conference Center

SFB 1044 HIM PRISMA

Direct observation versus precision measurements: top-quark, Higgs

Erler '18



Direct measurements:

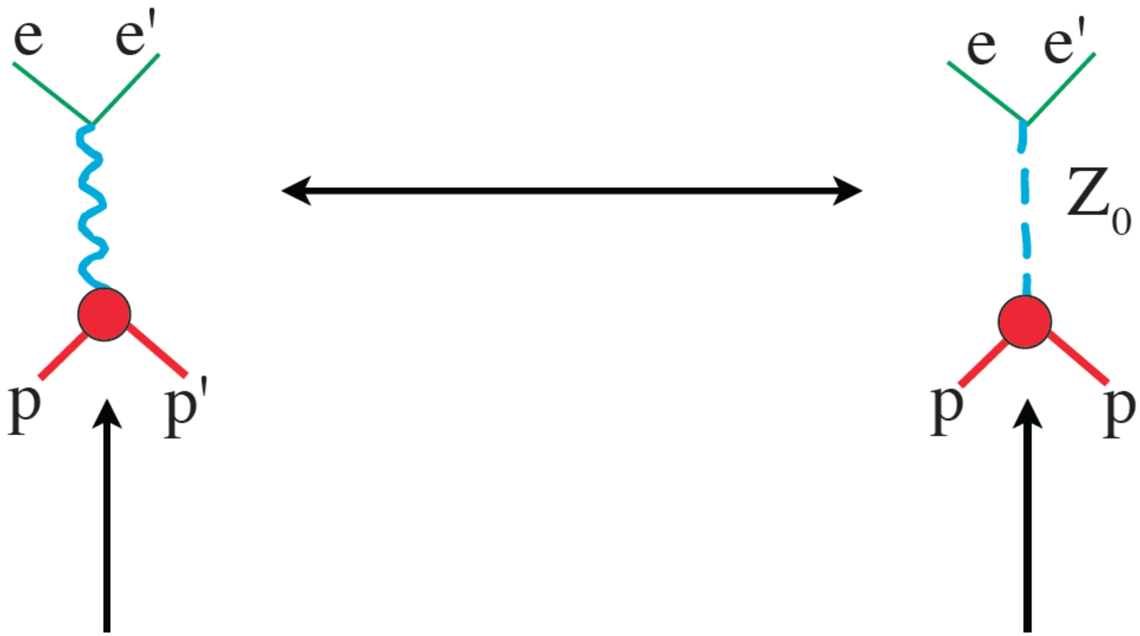
$$M_H = 125.14 \pm 0.15 \text{ GeV}$$
$$m_t = 172.74 \pm 0.46 \text{ GeV}$$

Indirect prediction:

$$M_H = 90^{+17}_{-16} \text{ GeV}$$
$$m_t = 176.4 \pm 1.8 \text{ GeV}$$

The role of the weak mixing angle

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

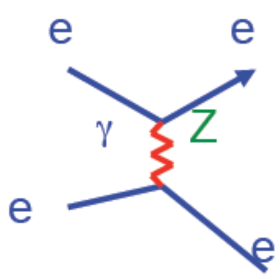


$Q_e(p) = +e$
electric charge of the proton

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

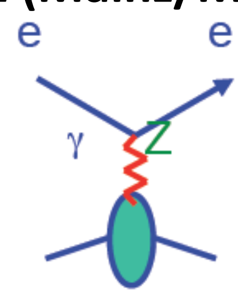
$\sin^2 \theta_W$: a central parameter of the standard model

Møller Scattering



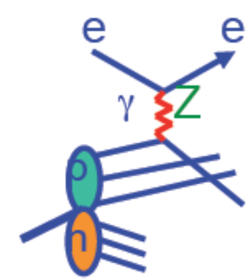
- Purely Leptonic

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



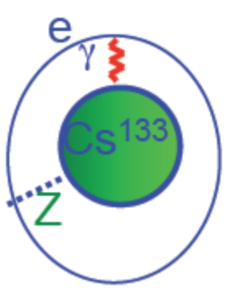
- Coherent quarks in p
- in operation now
- $2(2C_{1u}+C_{1d})$

e-DIS



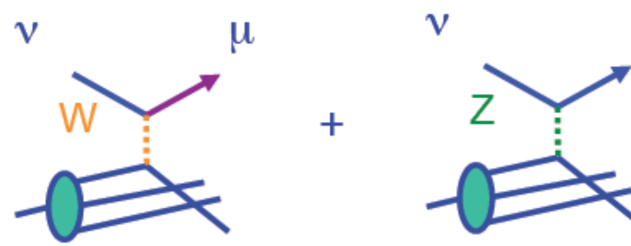
- Isoscaler quark scattering
- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

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

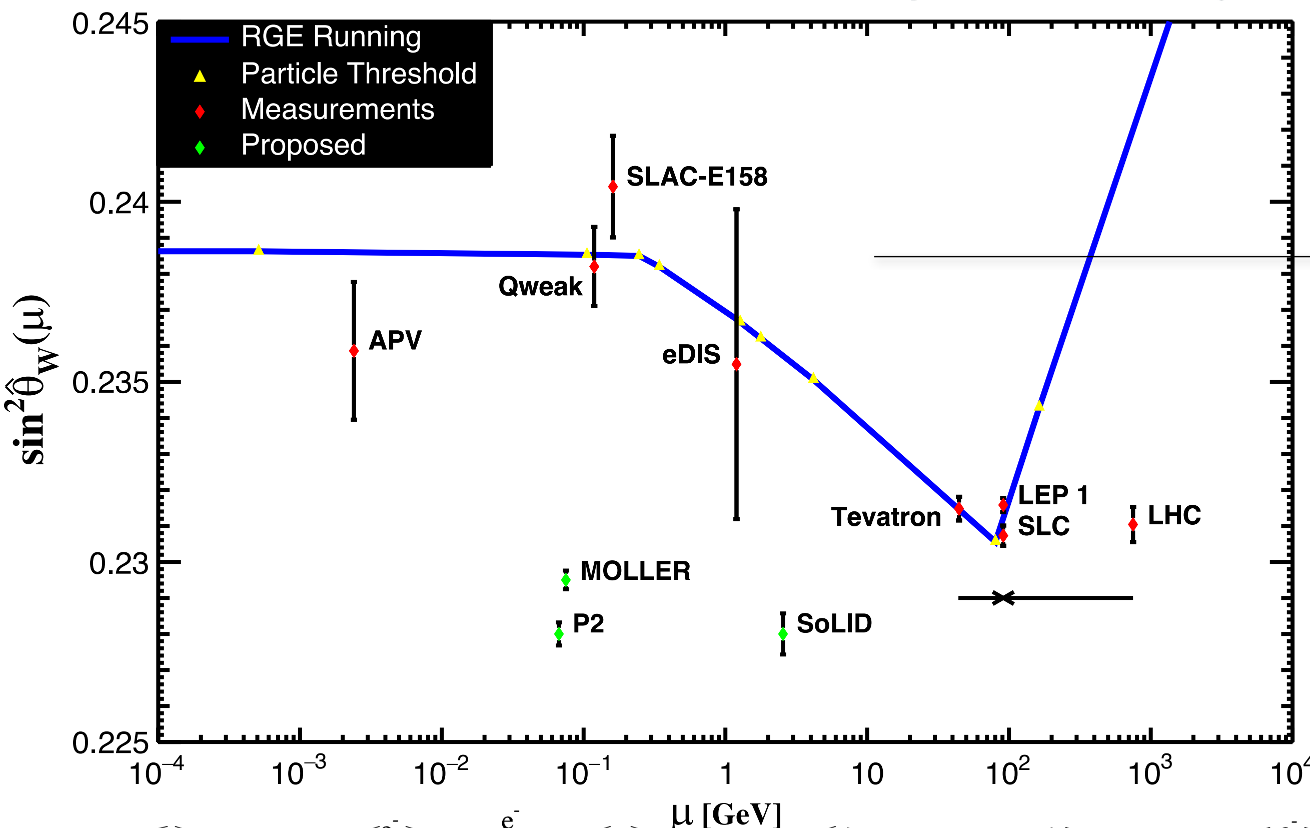
Courtesy of P. Reimer and R. Arnold

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

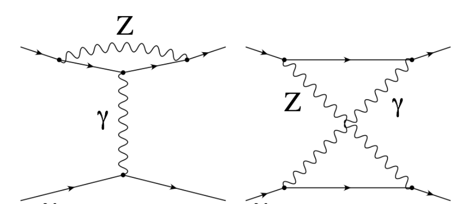
On Z resonance: A_Z is imaginary

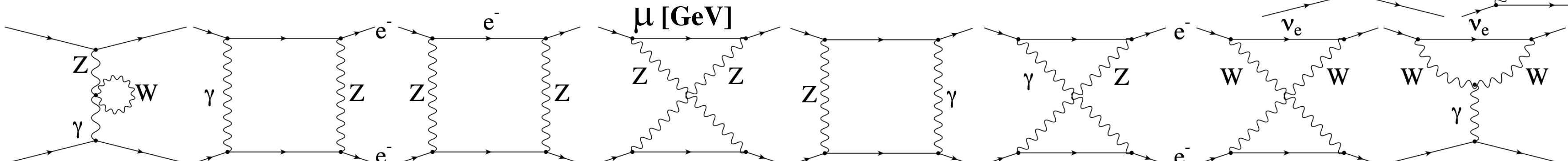
$$\left|A_Z + A_{new}\right|^2 \rightarrow A_Z^2\left[1+\left(\frac{A_{new}}{A_Z}\right)^2\right]$$

No interference term



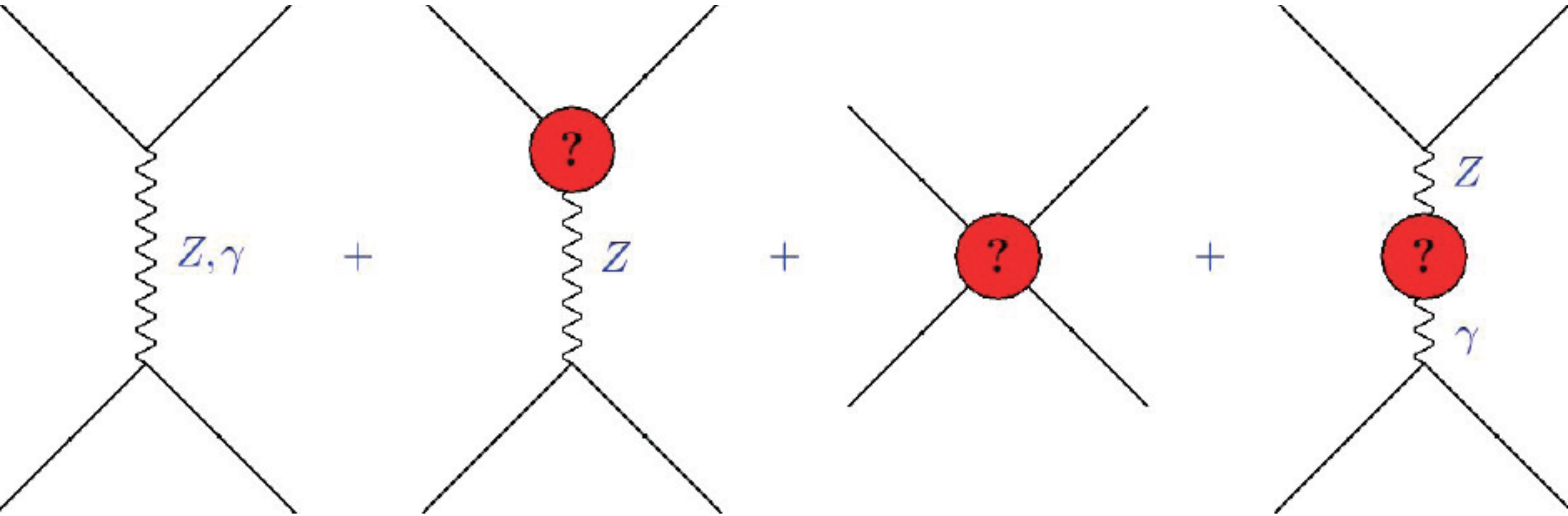
3 %





Sensitivity to new physics beyond the Standard Model

Sensitivity to new physics beyond the Standard Model



Extra Z

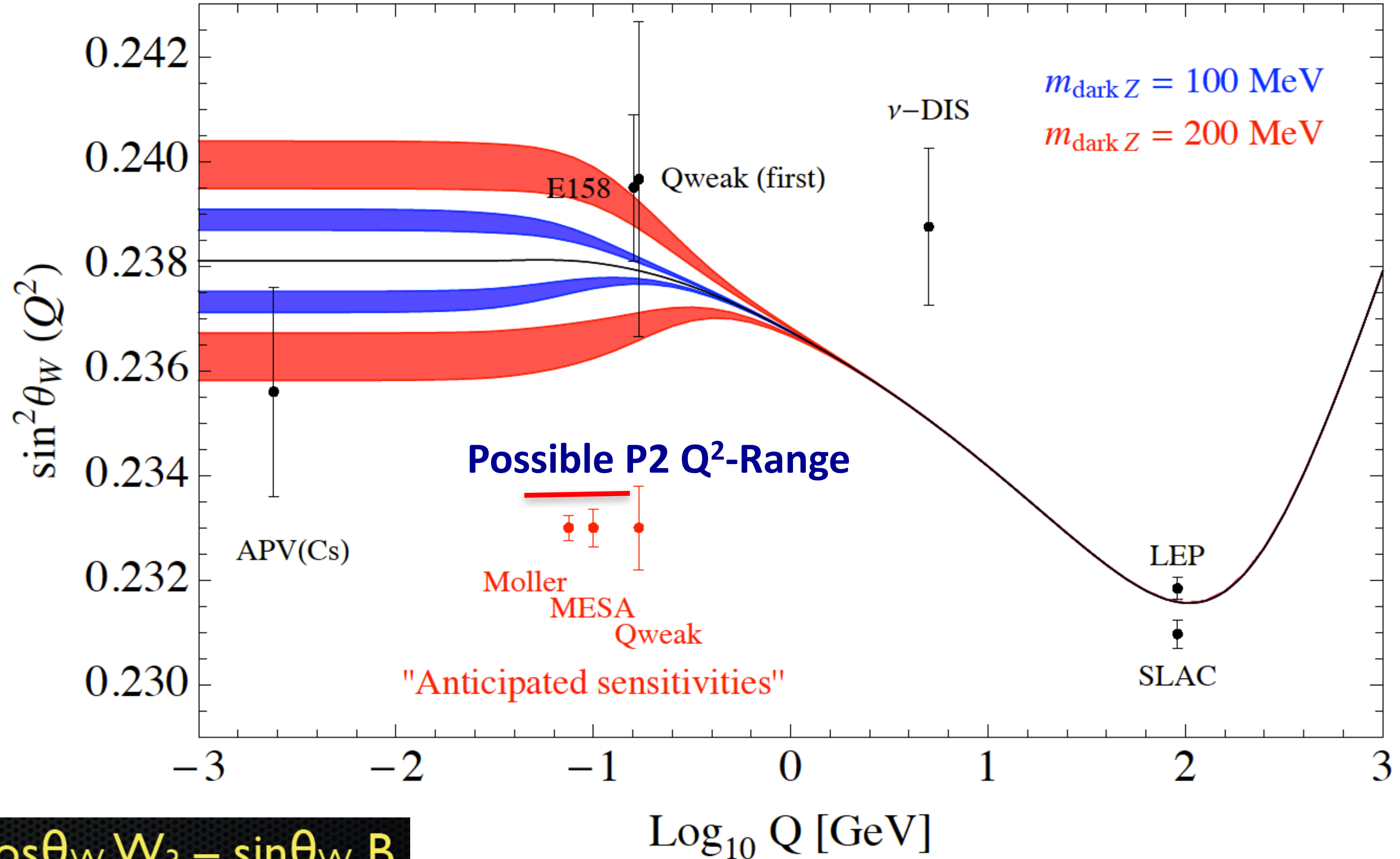
Mixing with Dark photon or Dark Z

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

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

Weak Charge Of Electron:
MOELLER (JLAB)

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

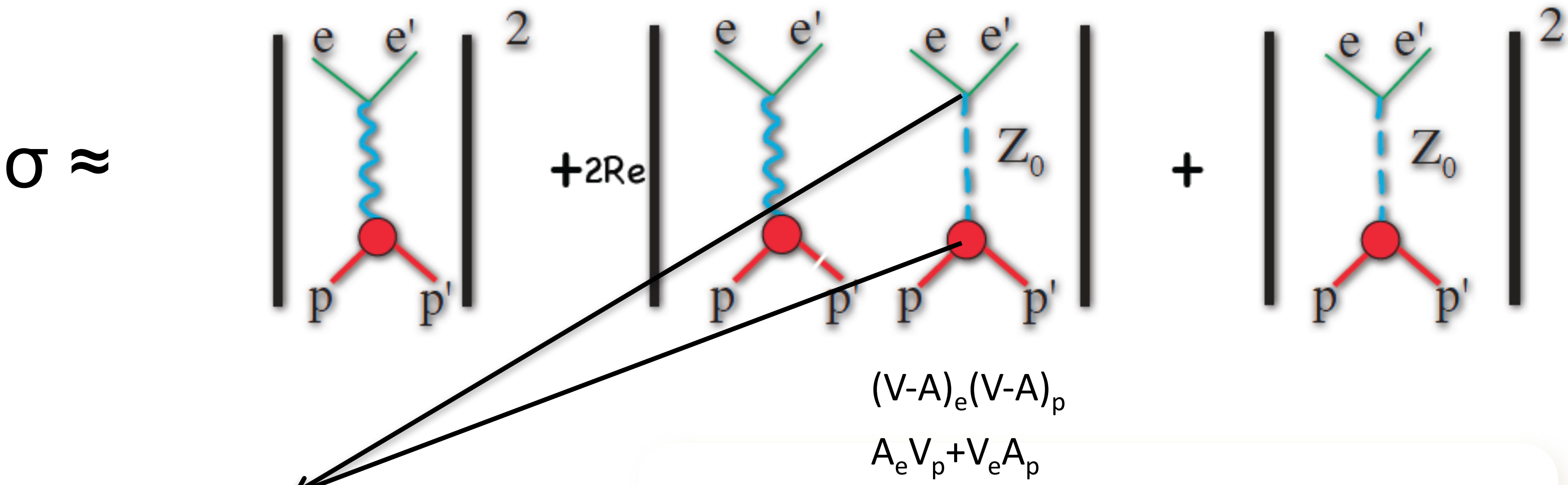
Physics sensitivity from contact interaction (LEP2 convention, $g^2 = 4pi$)

	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

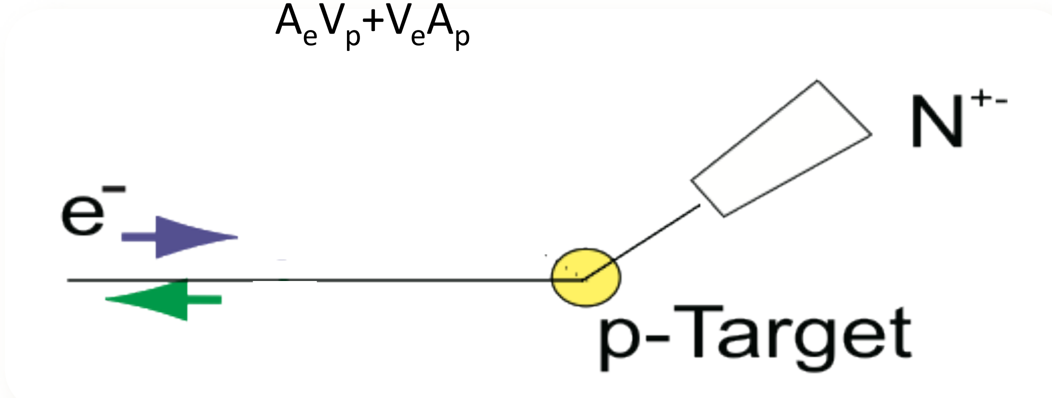
Jens Erler

Experimental Method:
Parity Violating Electron Scattering

Parity Violating Asymmetry in elastic electron electron/proton scattering



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



P2@MESA: Parity violating cross section asymmetry

tracking system

weak charge

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

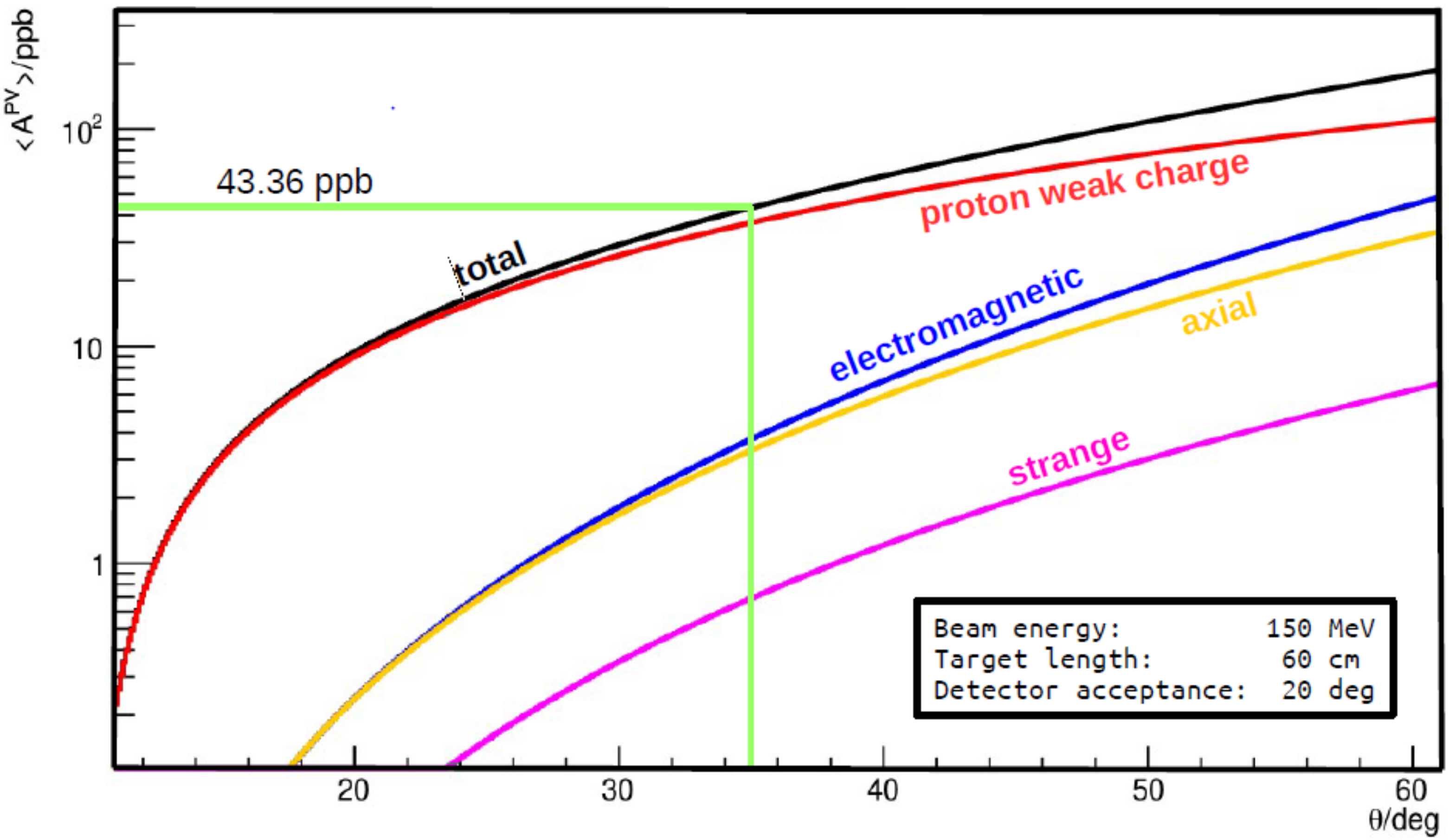
polarisation measurement

hadron structure

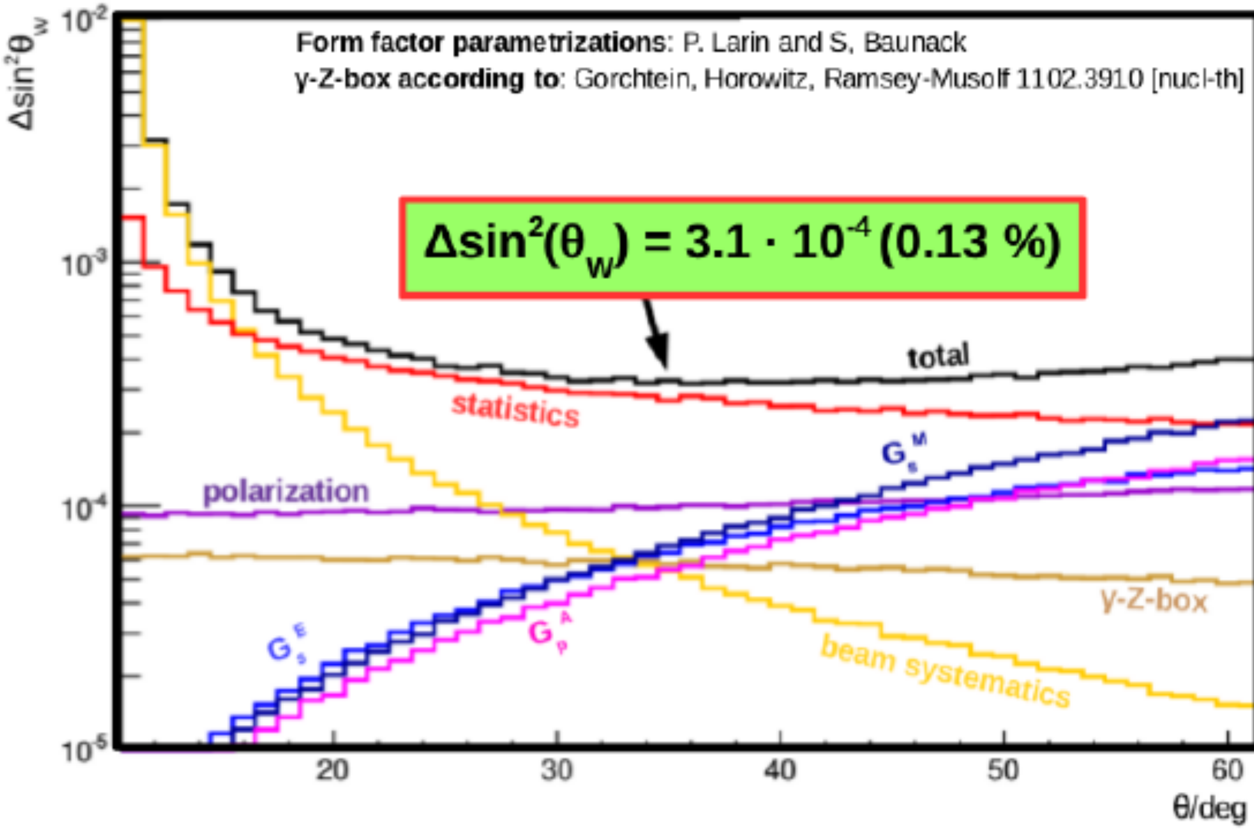
$$Q_W = 1 - 4\sin^2\theta_W(\mu)$$

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

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



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



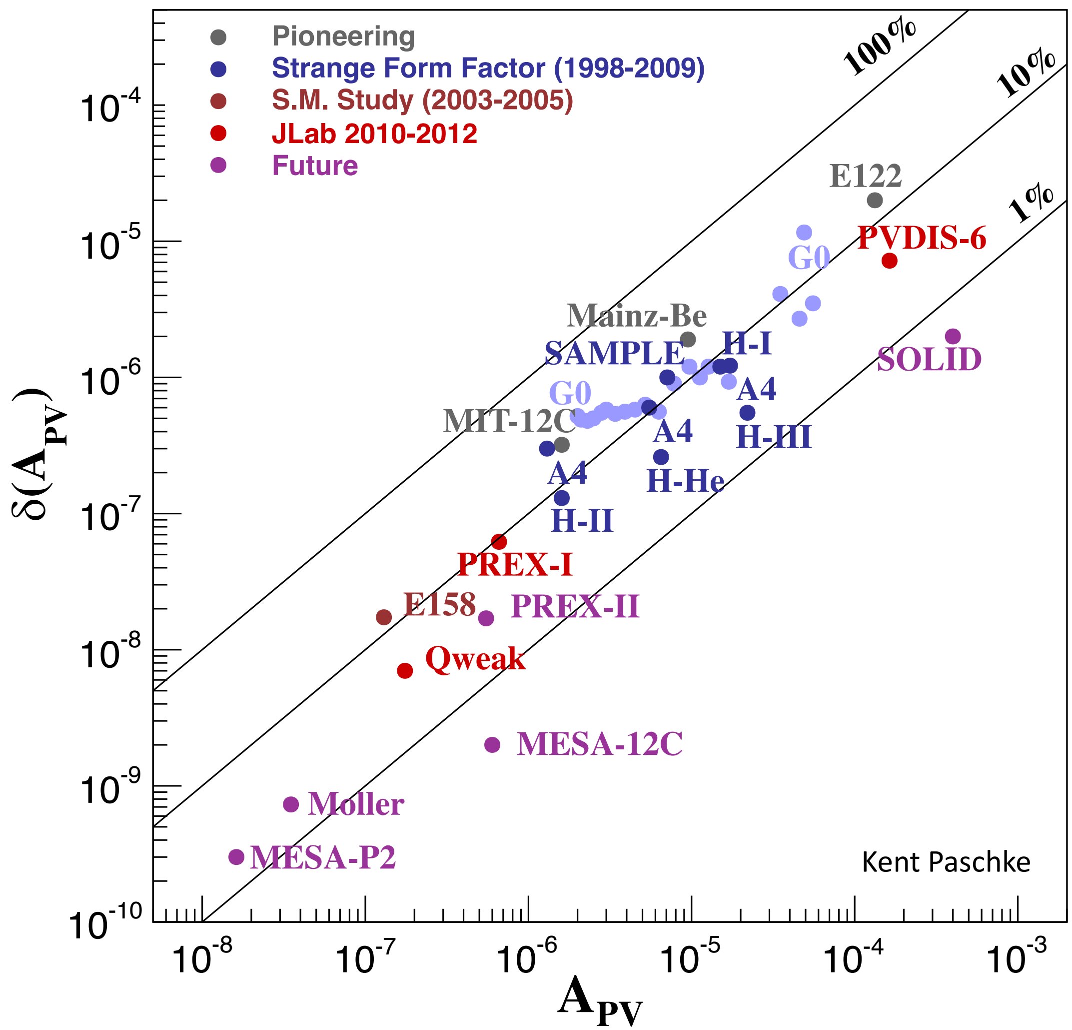
- Beam energy: 155 MeV
- Beam current: 150 μA
- Polarization: (85±0.5)%
- Target: 60 cm lH2
- Acceptance: 2π·(35°±10°)
- Rate: 0.5 THz
- Runtime: 10000 h
- ΔA^{app}: 0.1 ppb

	Total	Statistics	Polarization	Apparative	FF	Re($\Box_{\gamma ZA}$)
$\Delta \sin^2(\theta_w)$	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 %)

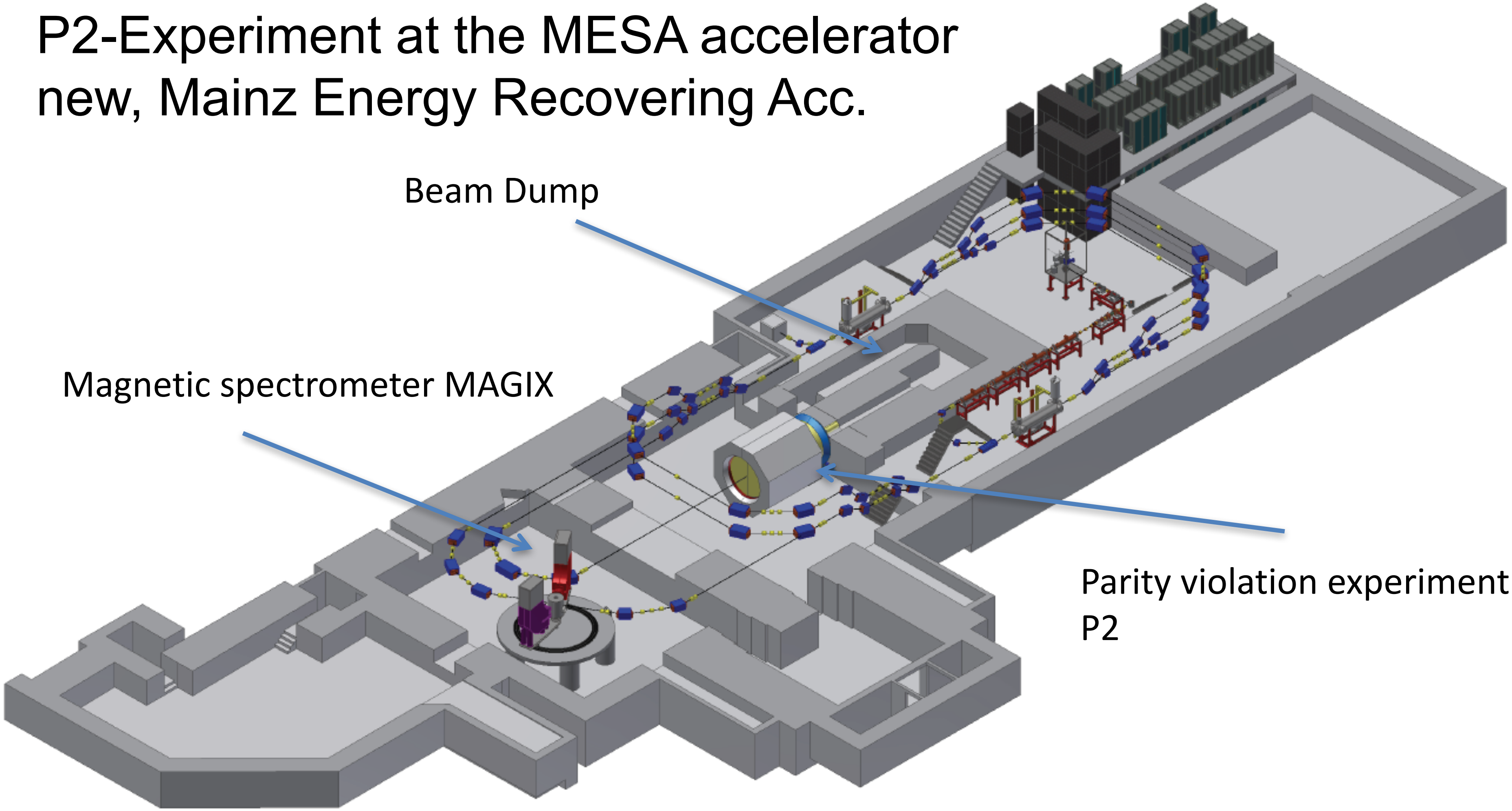
P2 Parameter

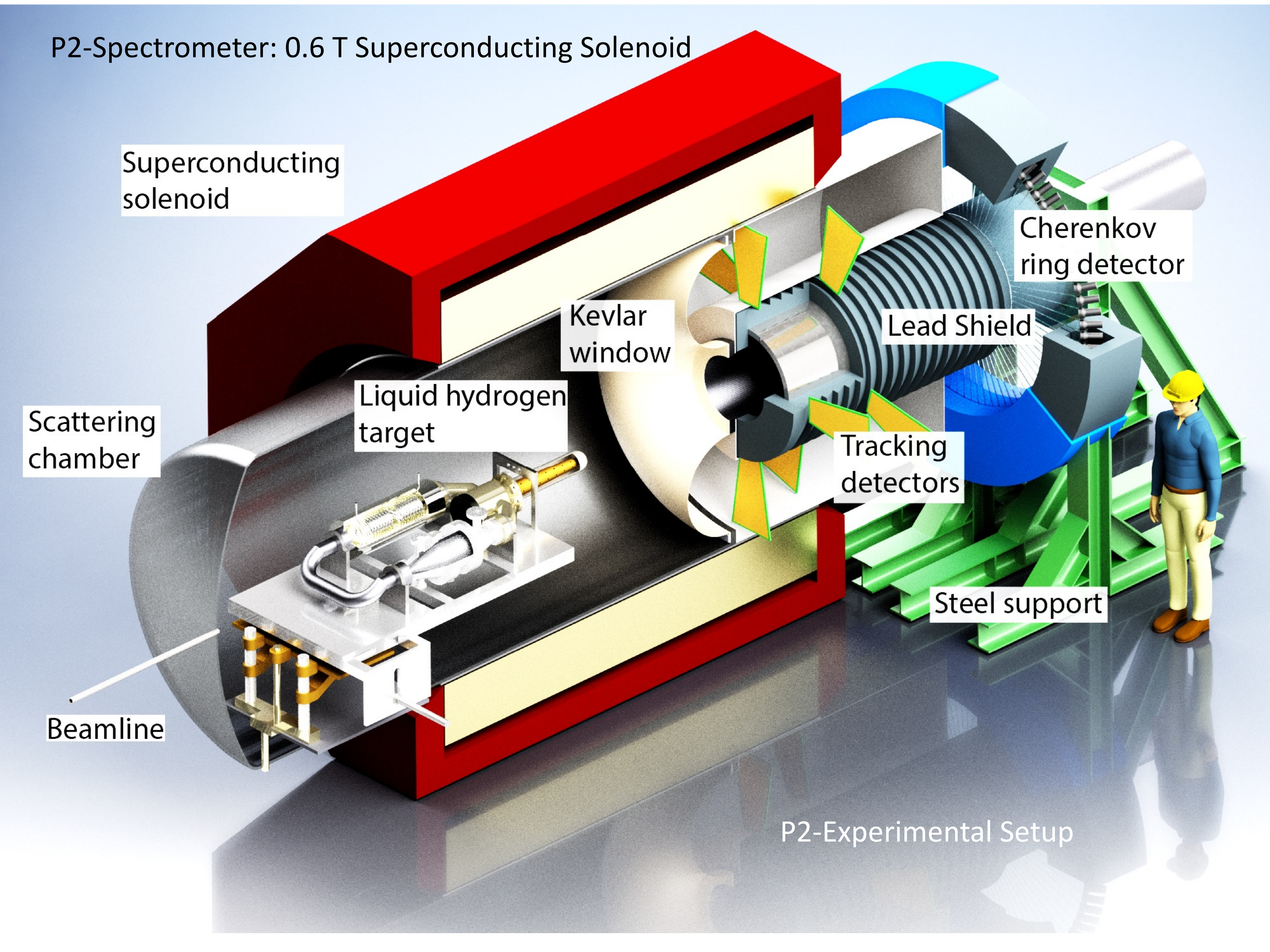
E_{beam}	155 MeV
$\bar{\theta}_{\text{f}}$	35°
$\delta\theta_{\text{f}}$	20°
$\langle Q^2 \rangle_{L=600\,\text{mm},\ \delta\theta_{\text{f}}=20°}$	6×10^{-3} (GeV/c)^2
$\langle A^{\text{exp}} \rangle$	−39.94 ppb
$(\Delta A^{\text{exp}})_{\text{Total}}$	0.56 ppb (1.40 %)
$(\Delta A^{\text{exp}})_{\text{Statistics}}$	0.51 ppb (1.28 %)
$(\Delta A^{\text{exp}})_{\text{Polarization}}$	0.21 ppb (0.53 %)
$(\Delta A^{\text{exp}})_{\text{Apparative}}$	0.10 ppb (0.25 %)
$\langle s^2_{\text{W}} \rangle$	0.231 16
$(\Delta s^2_{\text{W}})_{\text{Total}}$	3.3×10^{-4} (0.14 %)
$(\Delta s^2_{\text{W}})_{\text{Statistics}}$	2.7×10^{-4} (0.12 %)
$(\Delta s^2_{\text{W}})_{\text{Polarization}}$	1.0×10^{-4} (0.04 %)
$(\Delta s^2_{\text{W}})_{\text{Apparative}}$	0.5×10^{-4} (0.02 %)
$(\Delta s^2_{\text{W}})_{\Box_{\gamma Z}}$	0.4×10^{-4} (0.02 %)
$(\Delta s^2_{\text{W}})_{\text{nucl. FF}}$	1.2×10^{-4} (0.05 %)
$\langle Q^2 \rangle_{\text{Cherenkov}}$	4.57×10^{-3} (GeV/c)^2
$\langle A^{\text{exp}} \rangle_{\text{Cherenkov}}$	−28.77 ppb

PVeS Experiment Summary



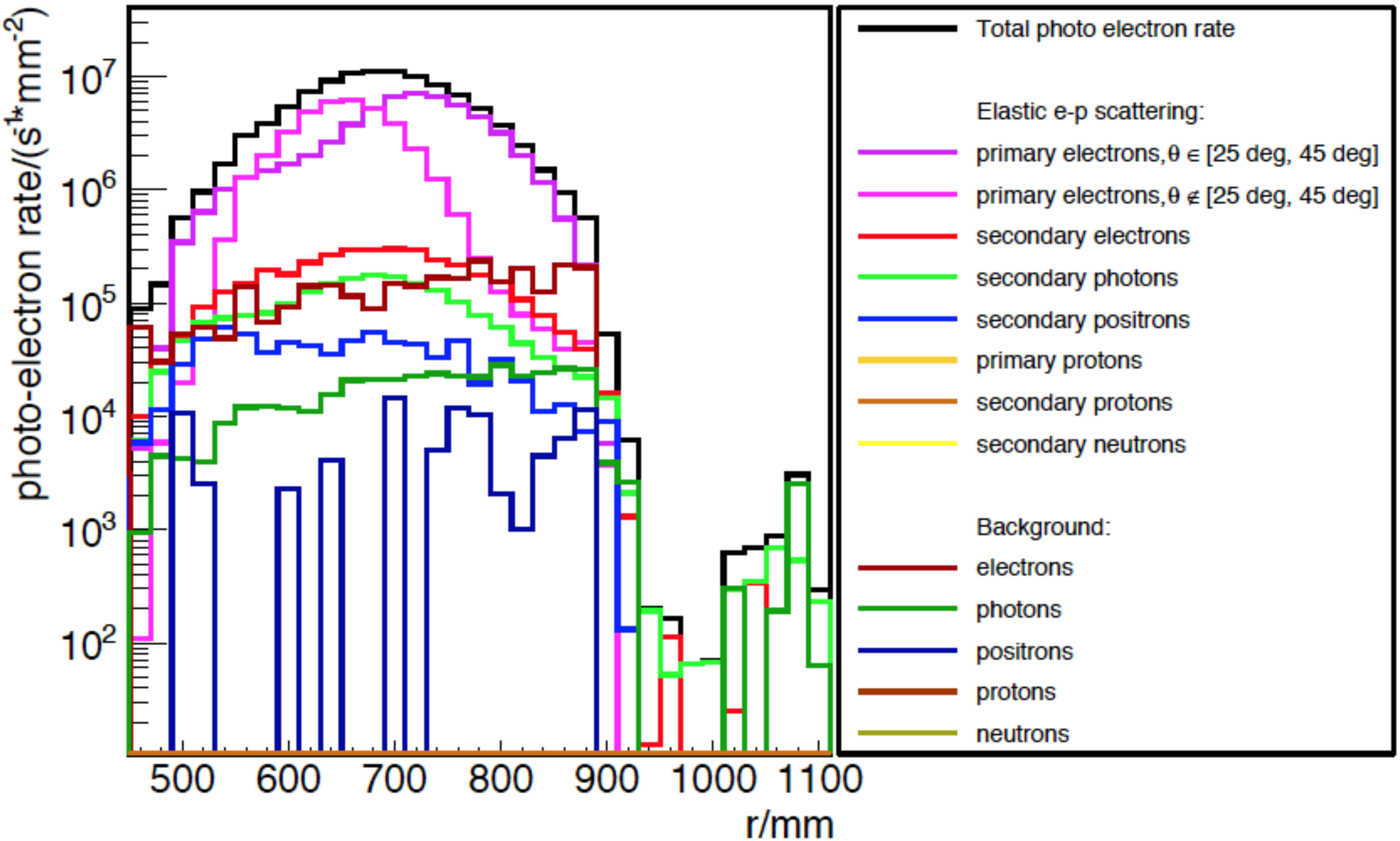
P2-Experiment at the MESA accelerator
new, Mainz Energy Recovering Acc.

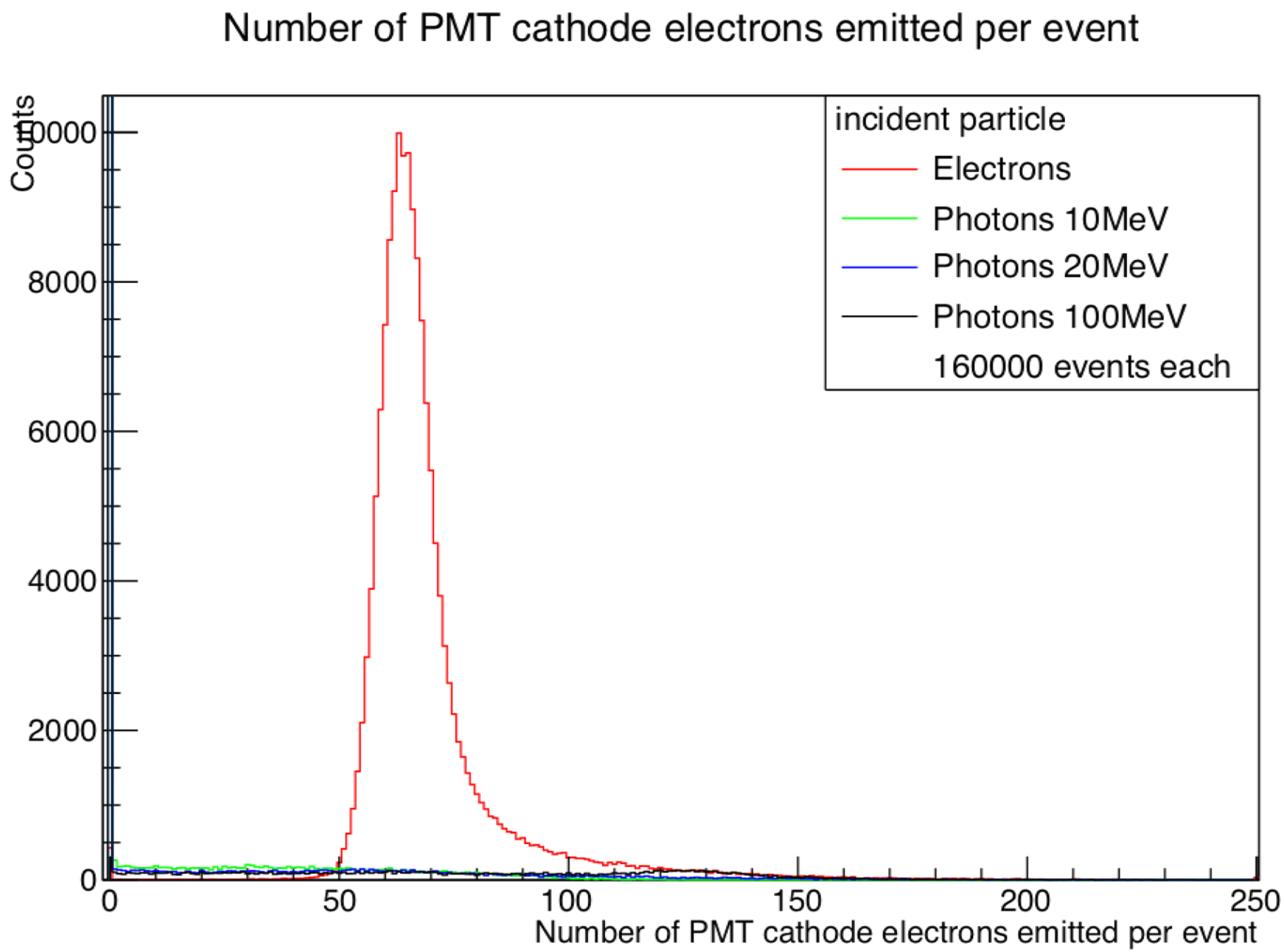



P2-Spectrometer: 0.6 T Superconducting Solenoid
Superconducting solenoid
Cherenkov ring detector
Kevlar window
Lead Shield
Liquid hydrogen target
Scattering chamber
Tracking detectors
Steel support
Beamline
P2-Experimental Setup

P2-Detector response

Full GEANT4 simulation




Number of PMT cathode electrons emitted per event
Counts
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
Number of PMT cathode electrons emitted per event
incident particle
Electrons
Photons 10MeV
Photons 20MeV
Photons 100MeV
160000 events each

The P2 Experiment arXiv:1802.04759

A future high-precision measurement of the electroweak mixing angle at low momentum transfer

Dominik Becker[1,2], Razvan Bucoveanu[1,3], Carsten Grzesik[1,2], Ruth Kempf[1,2], Kathrin Imai[1,2], Matthias Molitor[1,2], Alexey Tyukin[1,2], Marco Zimmermann[1,2], David Armstrong[4], Kurt Aulenbacher[1,2,5], Sebastian Baunack[1,2], Rakitha Beminiwattha[6], Niklaus Berger[1,2], Peter Bernhard[1,7], Andrea Brogna[1,7], Luigi Capozza[1,2,5], Silviu Covrig Dusa[8], Wouter Deconinck[4], Jürgen Diefenbach[1,2], James Dunne[17], Jens Erler[9], Ciprian Gal[10], Boris Gläser[1,2], Boxing Gou[1,2,5], Wolfgang Gradl[1,2], Michael Gericke[11], Mikhail Gorchtein[1,2], Yoshio Imai[1,2], Krishna S. Kumar[12], Frank Maas[1,2,5,a], Juliette Mammei[11], Jie Pan[11], Preeti Pandey[11], Kent Paschke[10], Ivan Perić[13], Mark Pitt[14], Sakib Rahman[11], Seamus Riordan[15], David Rodríguez Piñeiro[1,2,5], Concettina Sfienti[1,2,3,7], Iurii Sorokin[1,2], Paul Souder[16], Hubert Spiesberger[1,3], Michaela Thiel[1,2], Valery Tyukin[1,2], and Quirin Weitzel[1,7]

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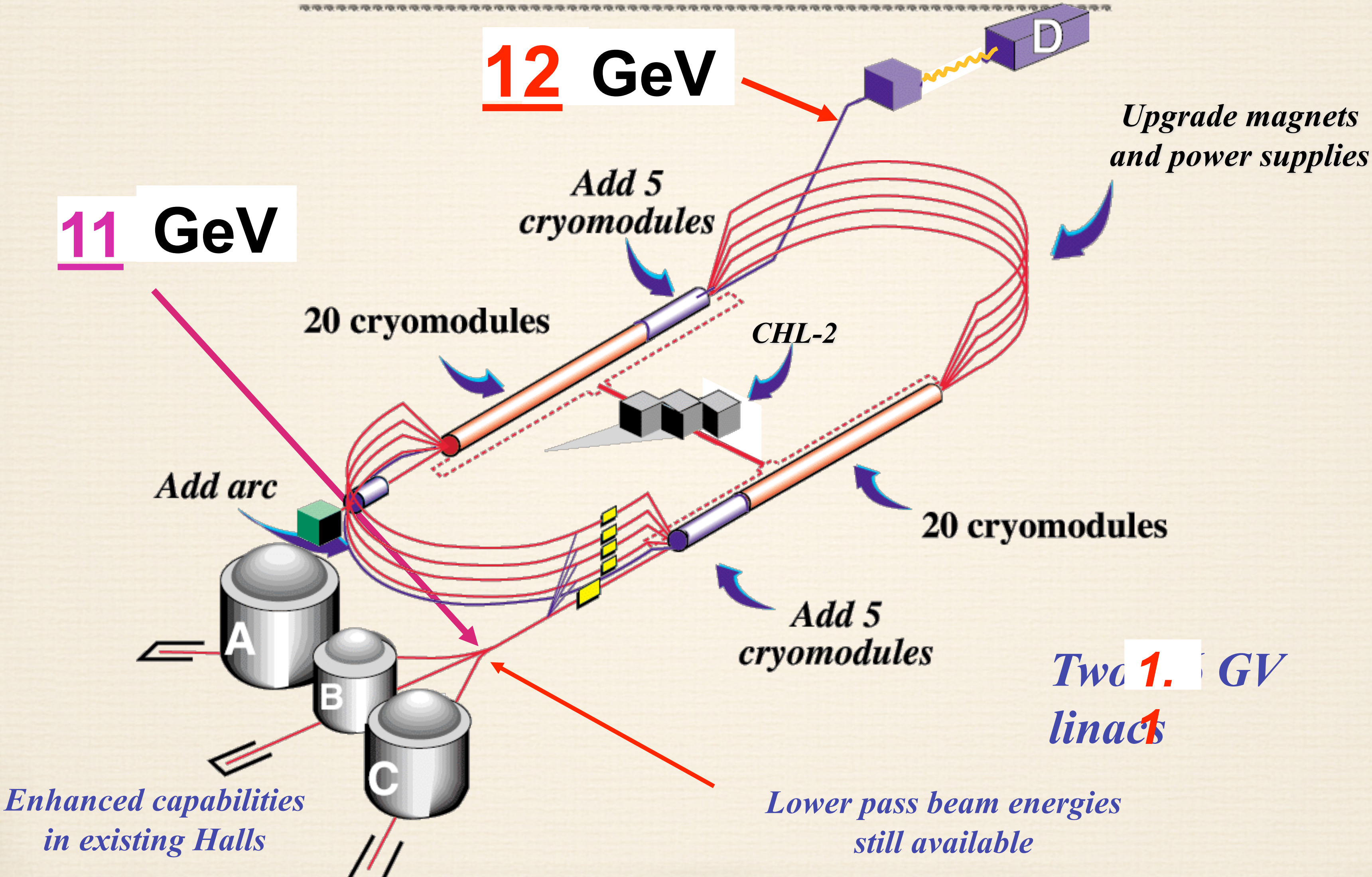
[17] Mississippi State University, Mississippi State, MS, USA

The 12 GeV Upgrade of JLab



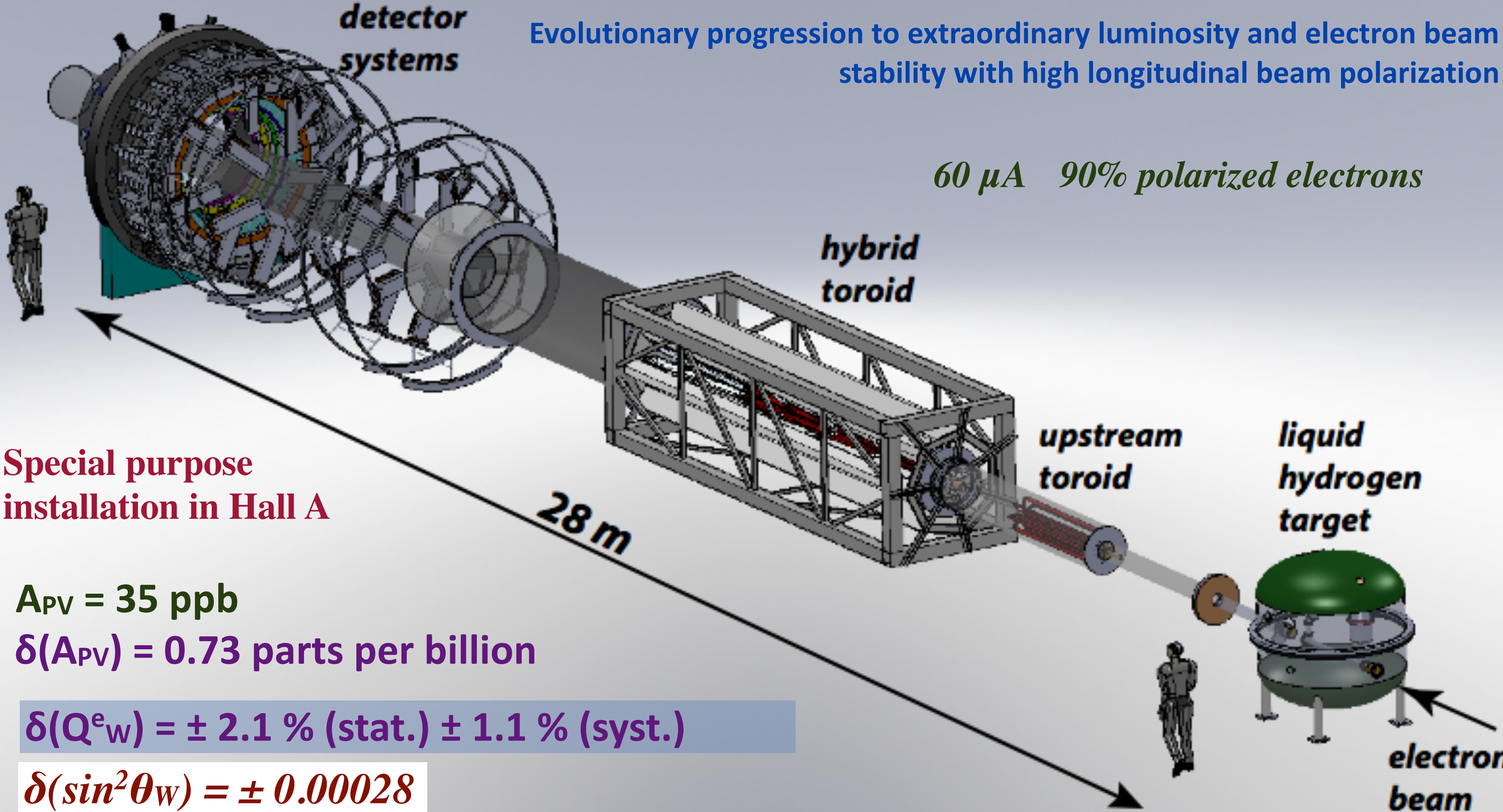
Parity-Violating Fixed Target 11 GeV electron-electron (Møller) scattering

MOLLER at JLab

Unique opportunity leveraging the 12 GeV Upgrade investment

Evolutionary progression to extraordinary luminosity and electron beam stability with high longitudinal beam polarization

60 µA   90% polarized electrons



Special purpose installation in Hall A

A_{PV} = 35 ppb

$\delta(A_{PV})$ = 0.73 parts per billion

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

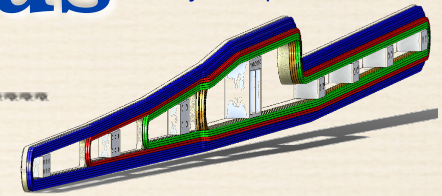
$\delta(\sin^2\theta_W) = \pm 0.00028$

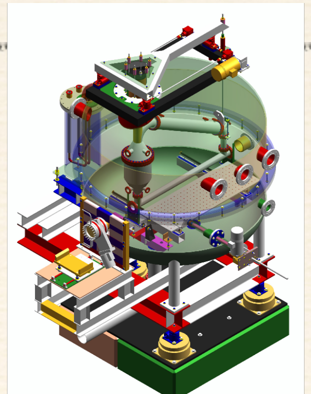
MOLLER Apparatus

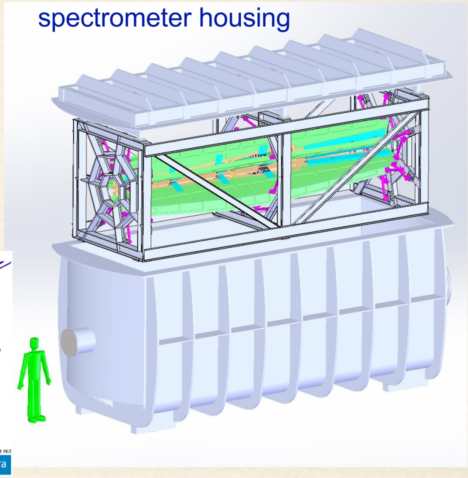
Technical Challenges

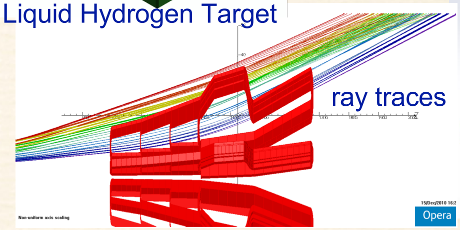
Evolutionary Improvements from Technology of Third Generation Experiments

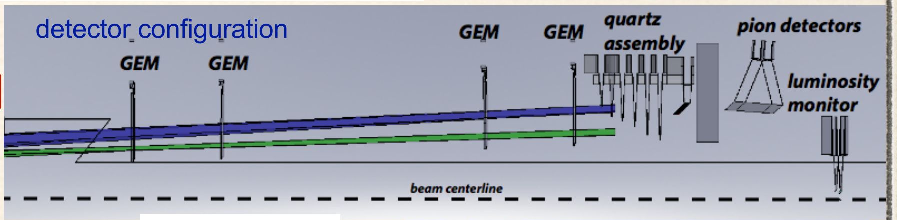
- ~ 150 GHz scattered electron rate
- 1 nm control of beam centroid on target
- > 10 gm/cm^2 liquid hydrogen target
  - 1.5 m: ~ 5 kW @ 85 μA
- Full Azimuthal acceptance w/ θ_{lab} ~ 5 mrad
  - novel toroidal spectrometer pair
  - radiation hard, highly segmented integrating detectors
- Robust & Redundant 0.4% beam polarimetry

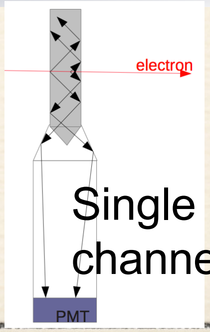


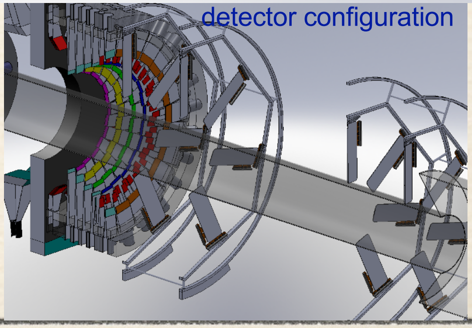






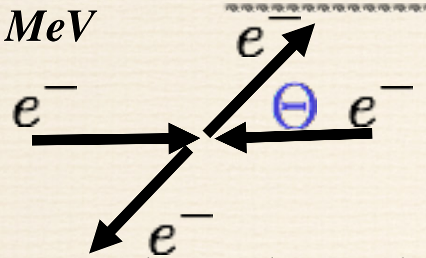




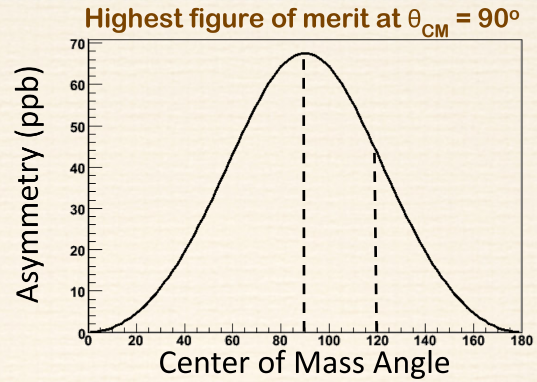


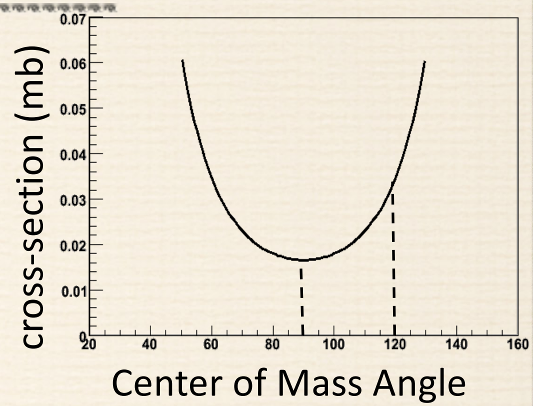
Møller Kinematics

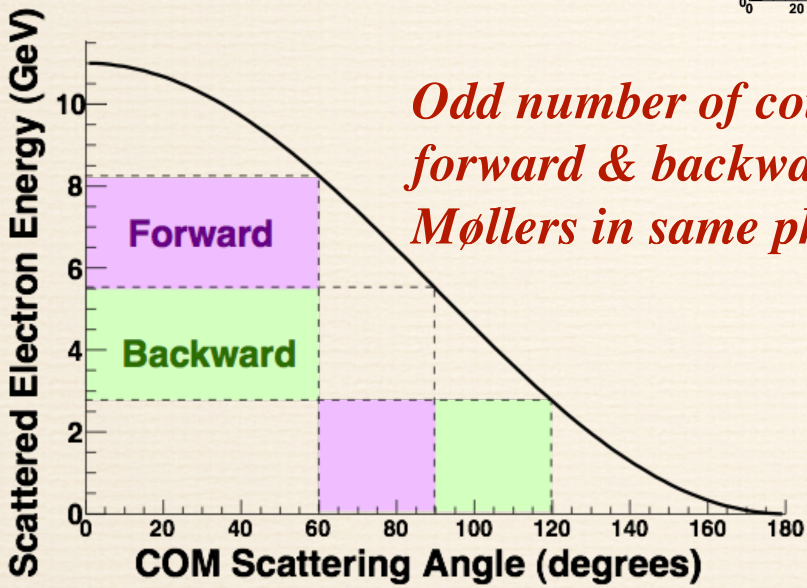
E_{COM} = 53 MeV



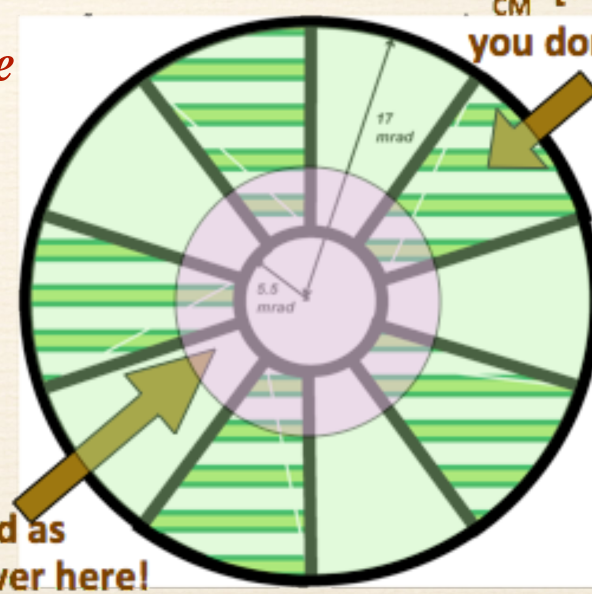
identical particles!







Odd number of coils: both forward & backward Møllers in same phi-bite



MOLLER Uncertainty Table

Beam Property	Assumed Sensitivity	Accuracy of Correction	Required 2 kHz random fluctuations	Required cumulative helicity-correlation	Systematic contribution
Intensity	1 ppb / ppb	$\sim$1%	$<$ 1000 ppm	$<$ 10 ppb	$\sim$ 0.1 ppb
Energy	-1.4 ppb / ppb	$\sim$10%	$<$ 108 ppm	$<$ 0.7 ppb	$\sim$ 0.05 ppb
Position	0.85 ppb / nm	$\sim$10%	$<$ 47 μm	$<$ 1.2 nm	$\sim$ 0.05 ppb
Angle	8.5 ppb / nrad	$\sim$10%	$<$ 4.7 μrad	$<$ 0.12 nrad	$\sim$ 0.05 ppb

Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Normalization of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \to e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \to e + p(+\gamma)$	0.3
$\gamma^{(*)} + p \to (\pi, \mu, K) + X$	0.3
Transverse polarization	0.2
Neutral background (soft photons, neutrons)	0.1
Total systematic	**1.1**

All systematics required at sub-1% level

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:

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

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

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

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

AA, Grilli Di Cortona, Tabrizi
1802.08296

AA, Gonzalez-Alonso
in progress

- Parity violating electron/electron and electron/proton scattering: "Low energy frontier" comprises a sensitive test of the standard model complementary to LHC
- If LHC sees ANY anomaly in Runs 2 or 3 (~2025), parity violating electron scattering with its unique discovery space will become a pressing need, like other sensitive probes (e.g. g-2 anomaly)
- Determination of $\sin^2(\theta_W)$ with high precision (similar to Z-pole) but far off Z-Pole tests BSM up to a mass scale of 50 TeV
- P2-Experiment (proton weak charge) in Mainz under preparation New MESA energy recovering accelerator at 155 MeV, target precision is 2 % in weak proton charge i.e. 0.15% in $\sin^2(\theta_W)$,
- Start P2-commissioning in 2022, MOLLER commissioning in 2023
- Much more physics from PV electron scattering
- P2@MESA, Moeller@Jlab and SOLID@Jlab very sensitive test of Standard Model Extension