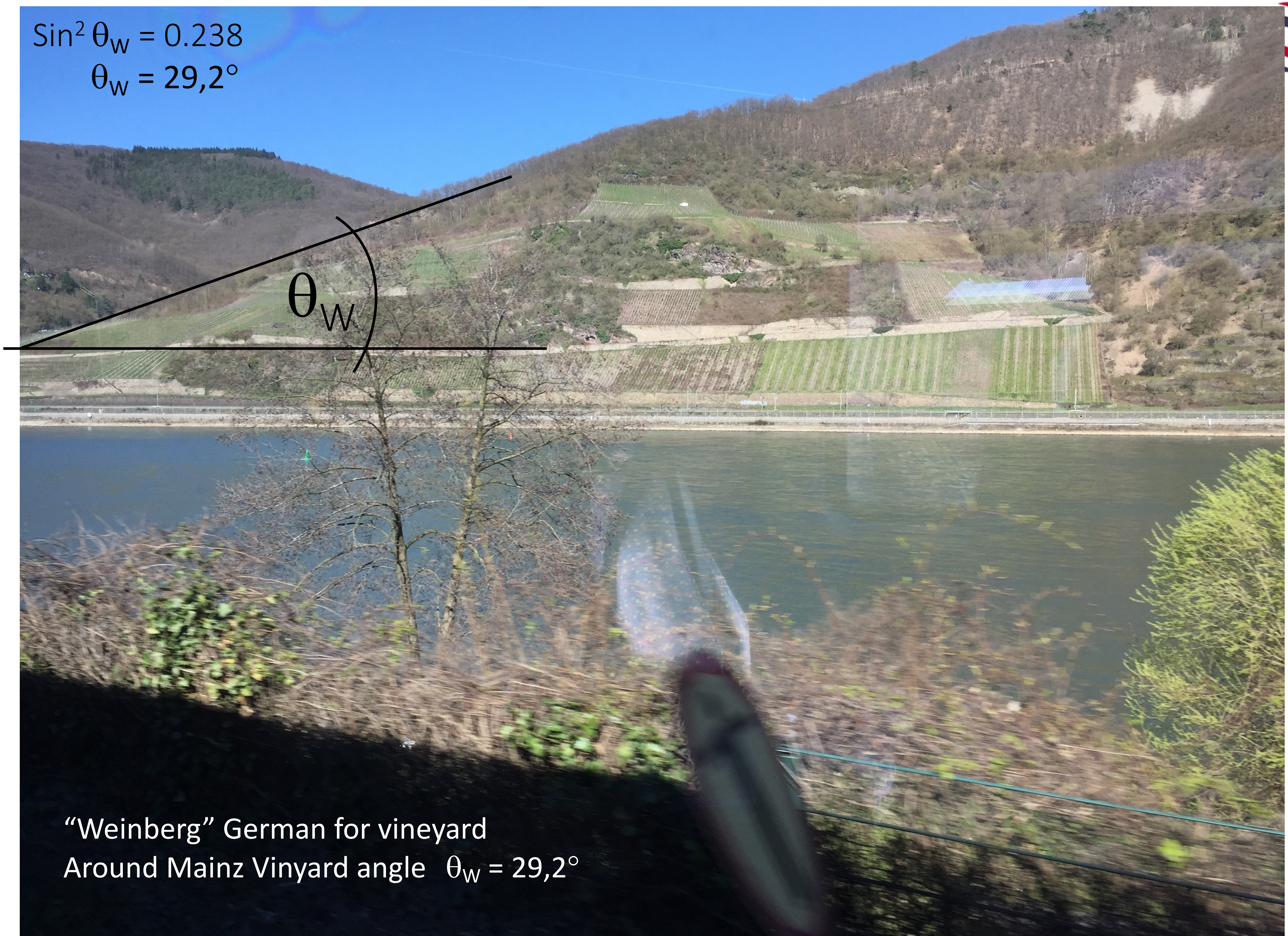
Low-Energy Experiments for the determination of the Electroweak Mixing Angle

Frank Maas, Institut für Kernphysik and Helmholtz-Institut Mainz

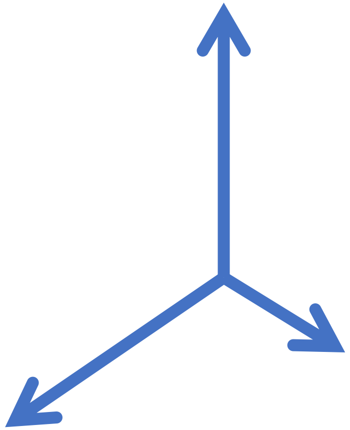
2023 EIC User Group Early Career Workshop, 23.–24. Juli 2023
Faculty of Physics, Warsaw University, Warsaw, Poland



$\sin^2 \theta_W = 0.238$
$\theta_W = 29{,}2°$
θ_W
“Weinberg” German for vineyard
Around Mainz Vinyard angle $\theta_W = 29{,}2°$

Search for physics beyond the standard model

Direct: High Energy (LHC)



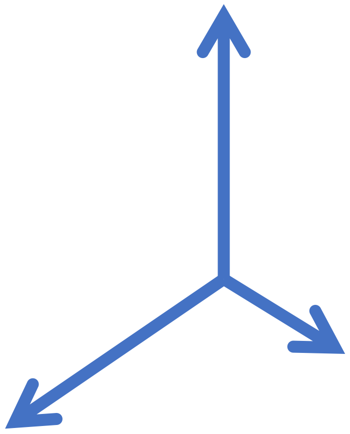
Indirect: High Precision

Indirect: High Intensity

- at low energy
- accurate theory needed

Search for physics beyond the standard model

Direct: High Energy (LHC)



Indirect: High Precision

Anom. Mag. Moment

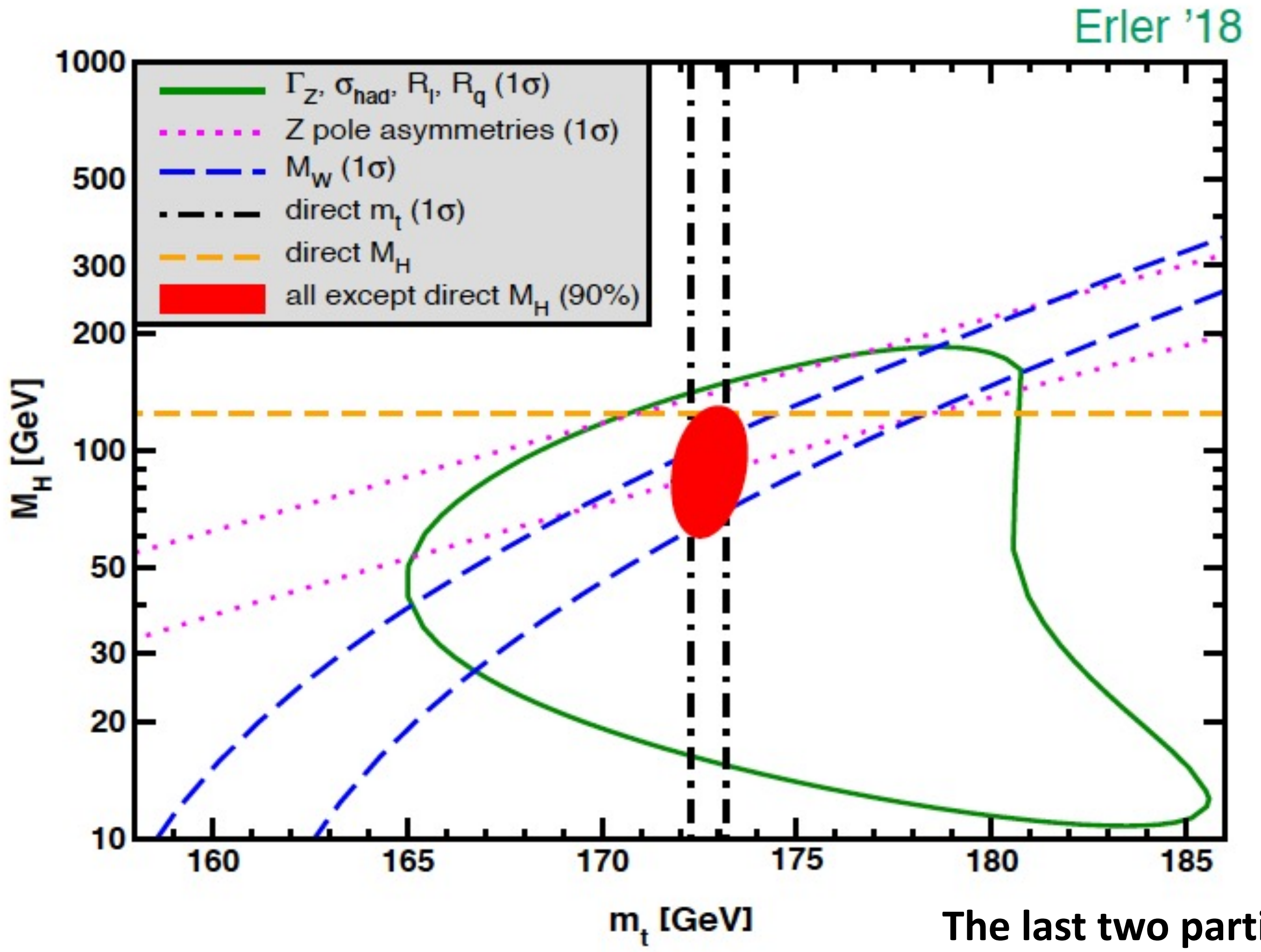
$(g\text{-}2)_{\mu,e}$, EDM, $\sin^2\theta_W$, …

Indirect: High Intensity

Rare B-decays

- at low energy
- accurate theory needed

Direct observation versus precision measurements: top-quark, Higgs



Direct measurements:

$M_H = 125.14 \pm 0.15$ GeV

$m_t = 172.74 \pm 0.46$ GeV

Indirect prediction:

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

$m_t = 176.4 \pm 1.8$ 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

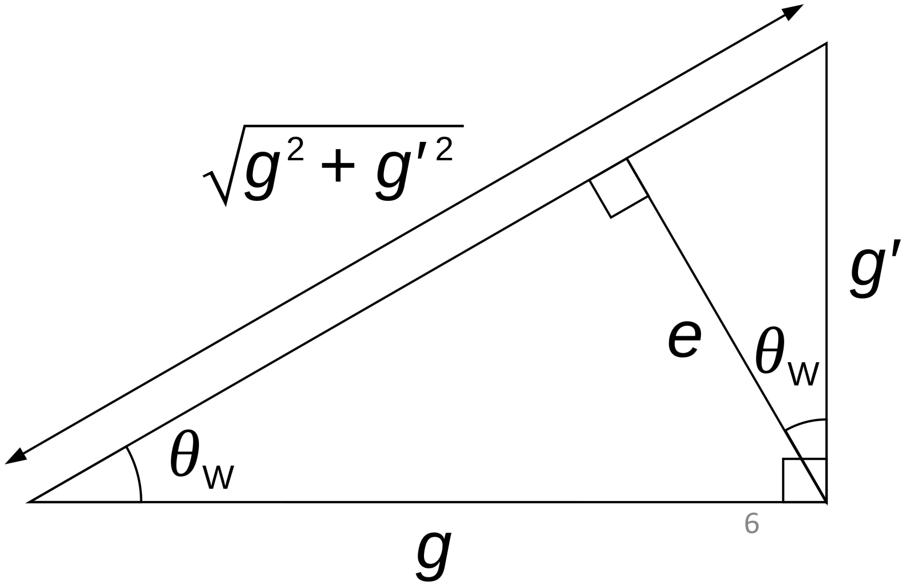
- Key parameter in Electroweak sector of the Standard Model.

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

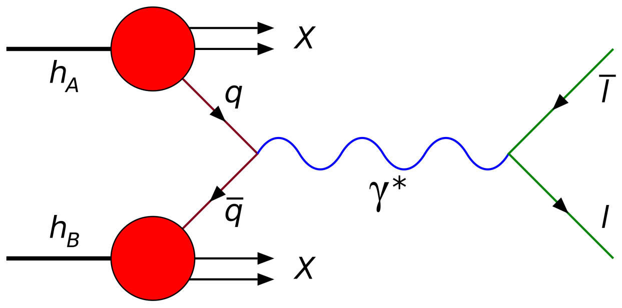
$$\sin^2(\theta_W) = (1 - \frac{m_W^2}{m_Z^2}) \qquad m_Z = \frac{m_W}{\cos\theta_W}$$

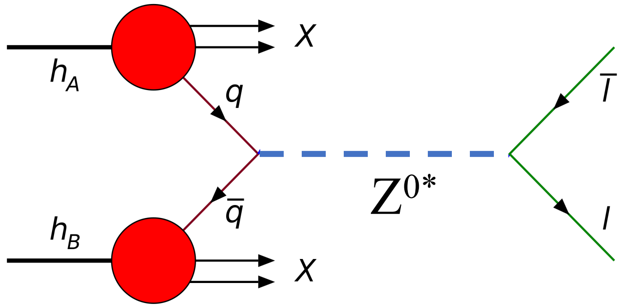
$$\cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \qquad \sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$

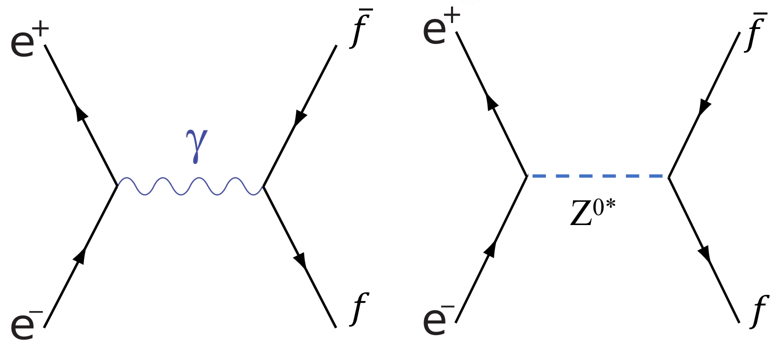
$$e = g \sin\theta_W = g' \cos\theta_W$$

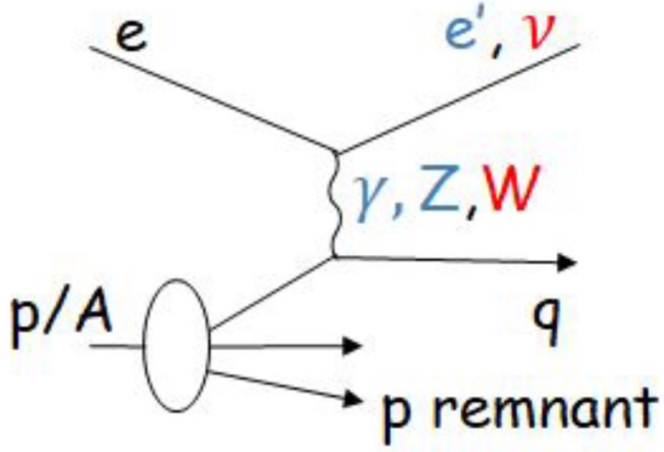


Access to the weak mixing angle at high energy



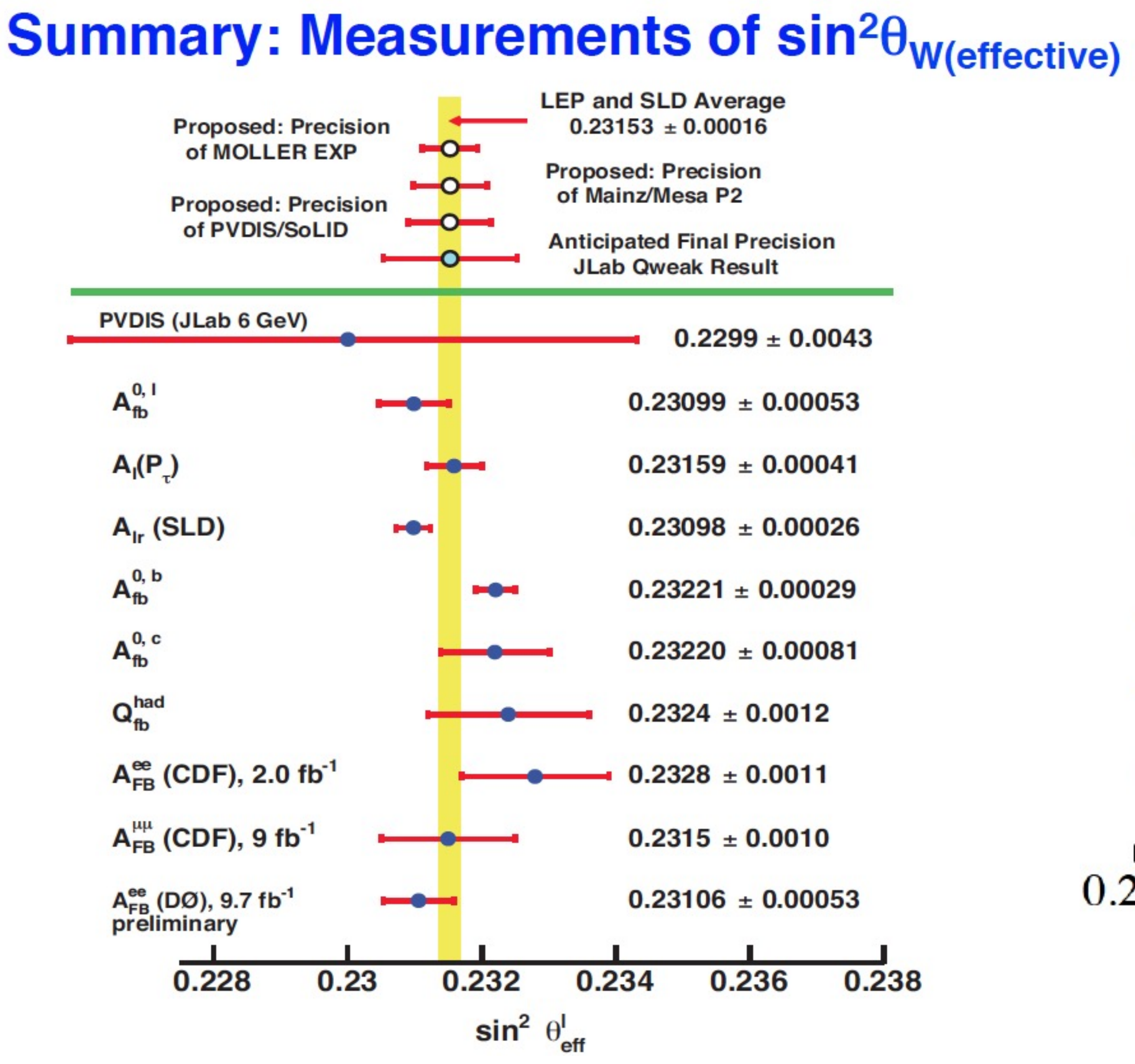


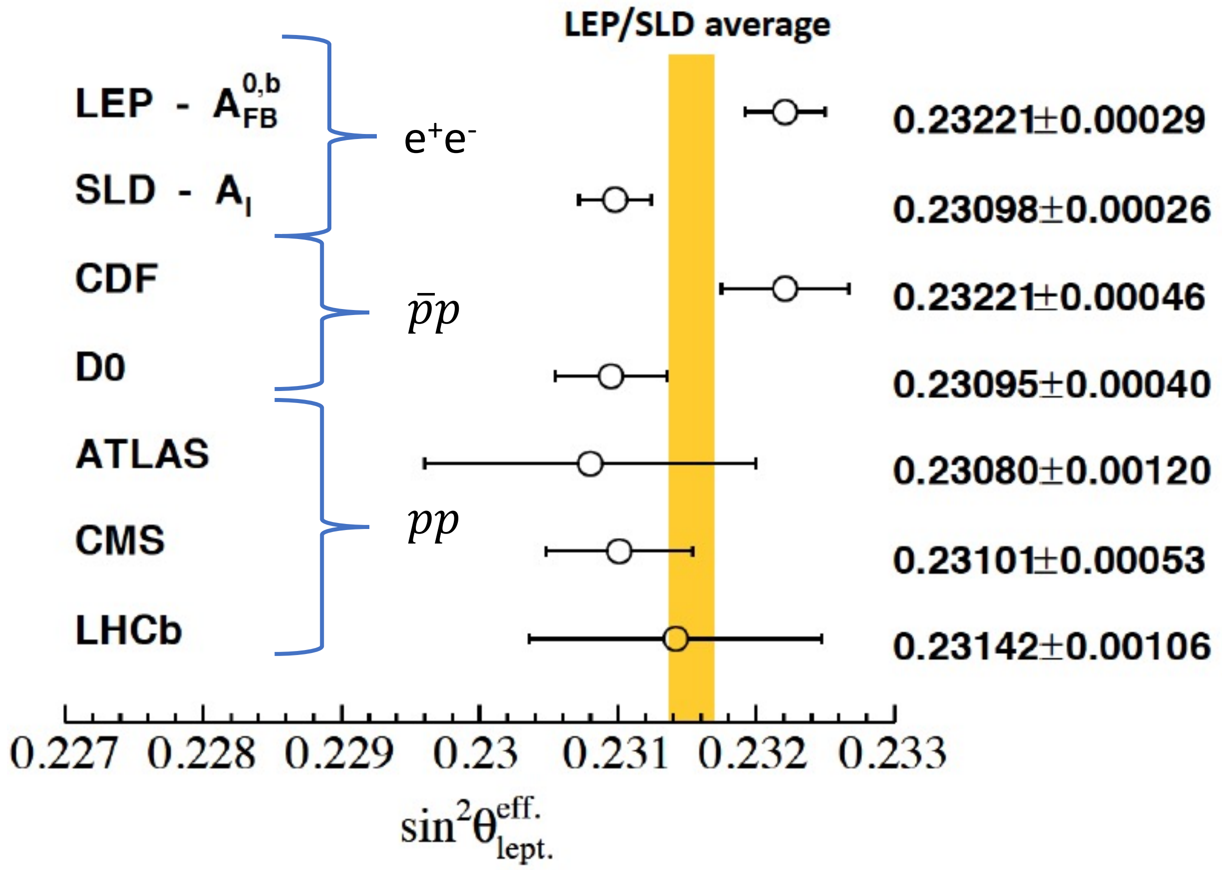




- e^+e^- collider: final state fermions
- $\bar{p}p$,pp collider: Drell-Yan process, PDFs needed
- EIC: deep inelastic scattering, PDFs needed
- Interference between photon exchange and neutral current process
- Cross section dominated by the Z-resonance
- Parity Violating Observables are large at Z-pole
- Imaginary part is large at the Z-pole, sensitivity to new physics suppressed

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

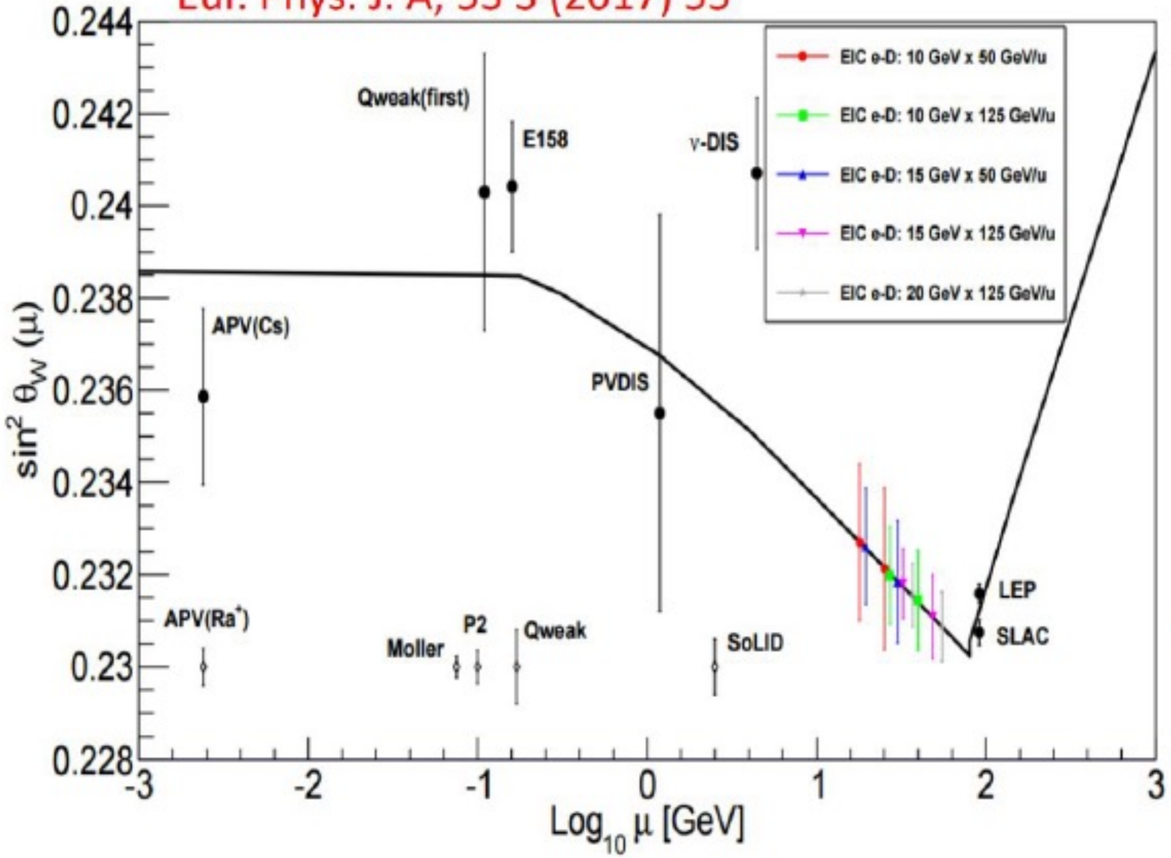


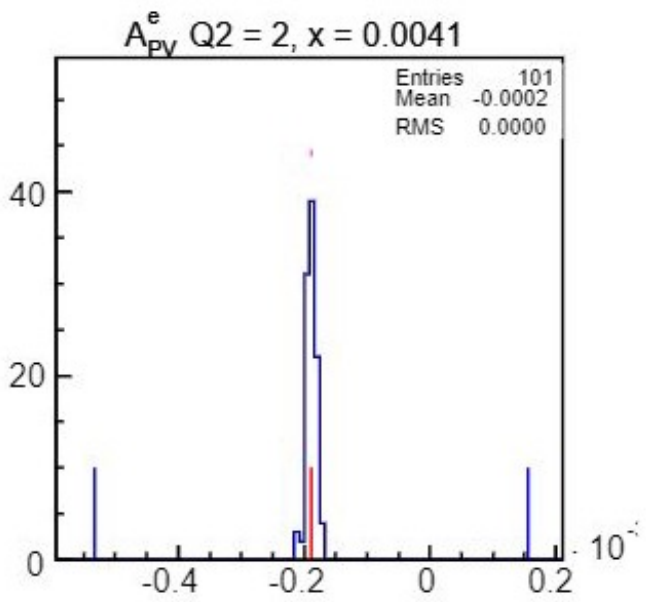


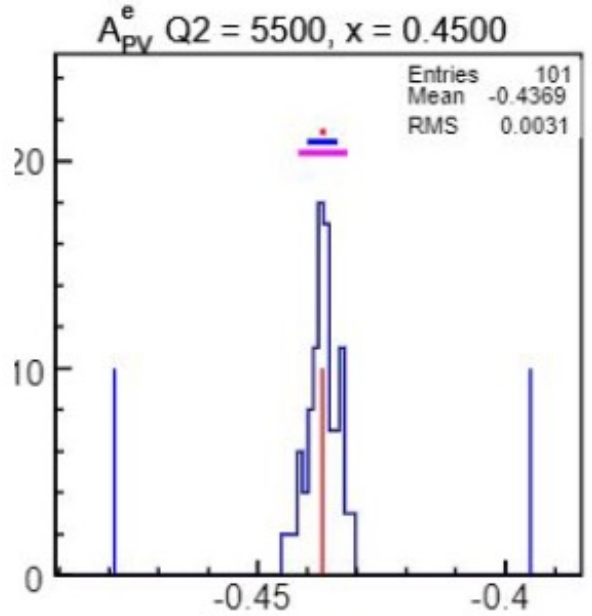
NC extractions

Jinlong Zhang

Eur. Phys. J. A, 53 3 (2017) 55







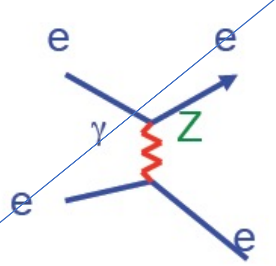
- PDF uncertainties are fairly small compared to the statistical precision of the data
- We are working to understand if we can use the proton data to extract the weak mixing angle on top of the deuteron result published by Yuxiang
- This data should allow us to get larger statistical precision and have a larger reach in Q

Access to the weak mixing angle at low energy

This session

MOLLER (Jlab)

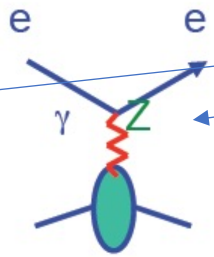
Møller Scattering



- Purely Leptonic

P2 (MESA/Mainz)

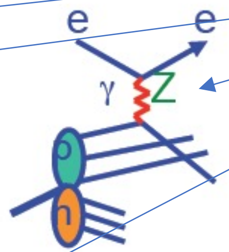
Q-Weak (JLab)



- Coherent quarks in p

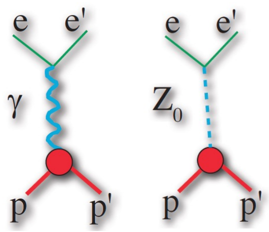
SOLID (Jlab)

e-DIS



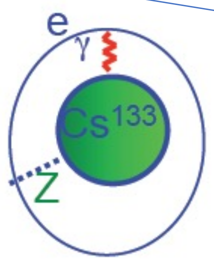
- Isoscaler quark scattering
- $(2C_{1u}\text{-}C_{1d})+Y(2C_{2u}\text{-}C_{2d})$

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



Yb,Dy,Sm (HIM/Mainz)

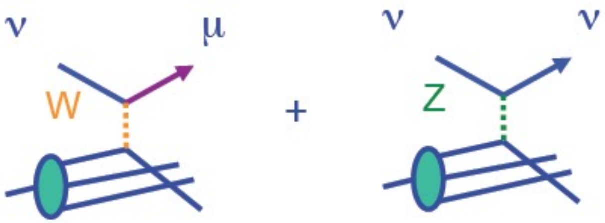
Atomic Parity Violation



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

Neutrino Scattering

CEvNS (Jlab)

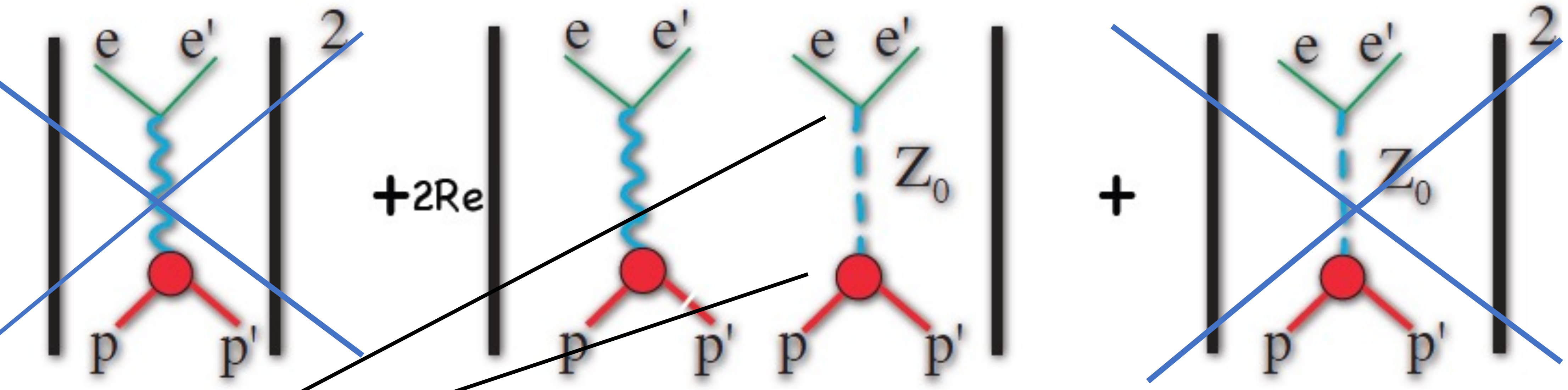


- Quark scattering (from nucleus)
- Weak charged and neutral current difference

Cross section measurements

Parity Violating in elastic electron proton scattering

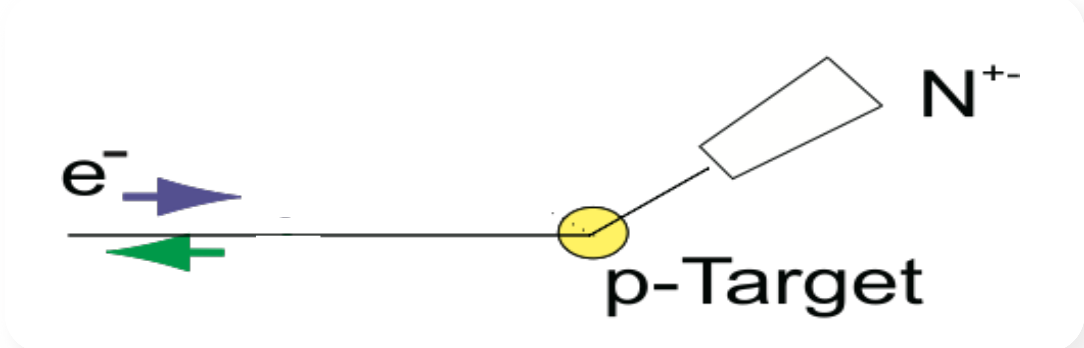
$\sigma \approx$

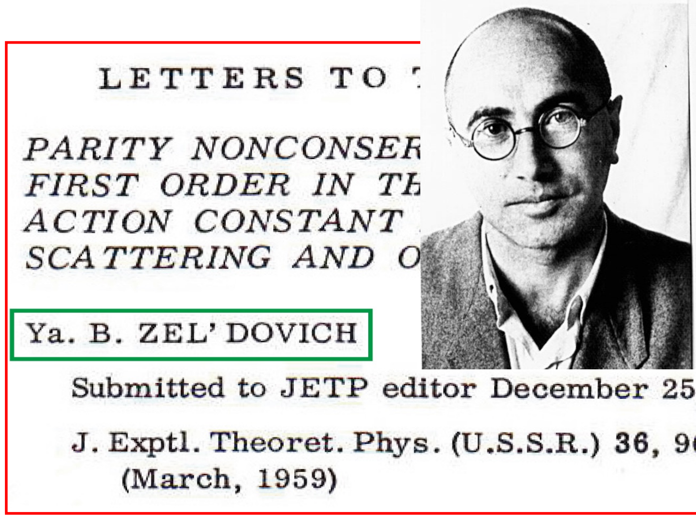


V-A coupling:
parity-violating
cross section asymmetry A_{LR}
longitudinally pol. electrons
unpolarised protons

$(V\text{-}A)_e(V\text{-}A)_p$

$A_eV_p+V_eA_p$

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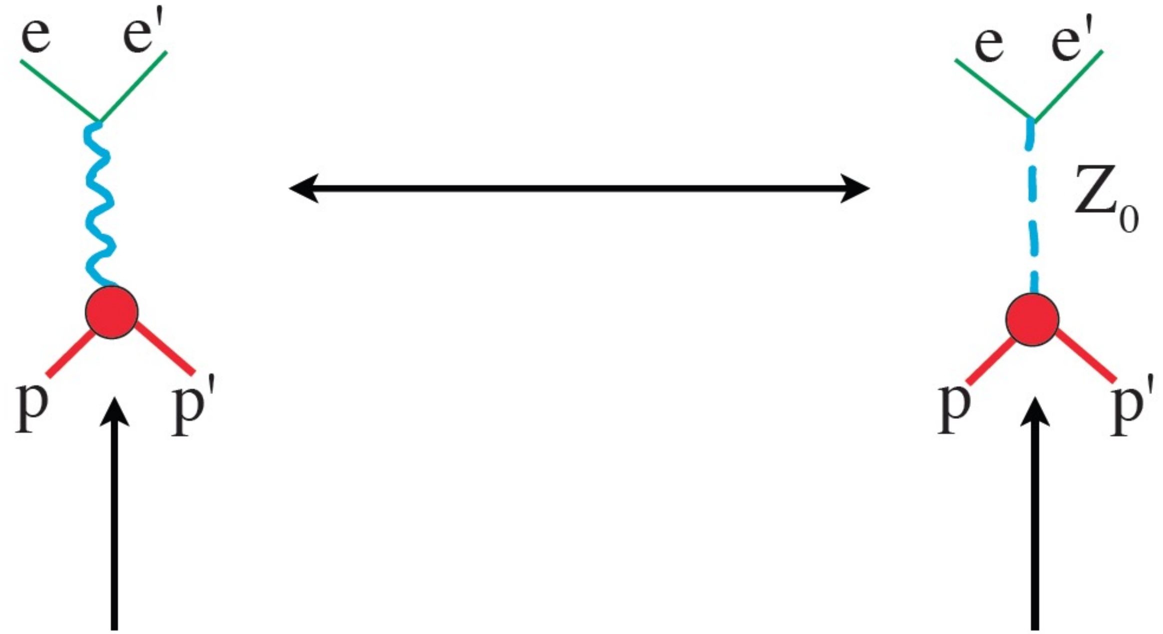
Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25

J. Exptl. Theoret. Phys. (U.S.S.R.) 36, 9
(March, 1959)

The role of the weak mixing angle

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

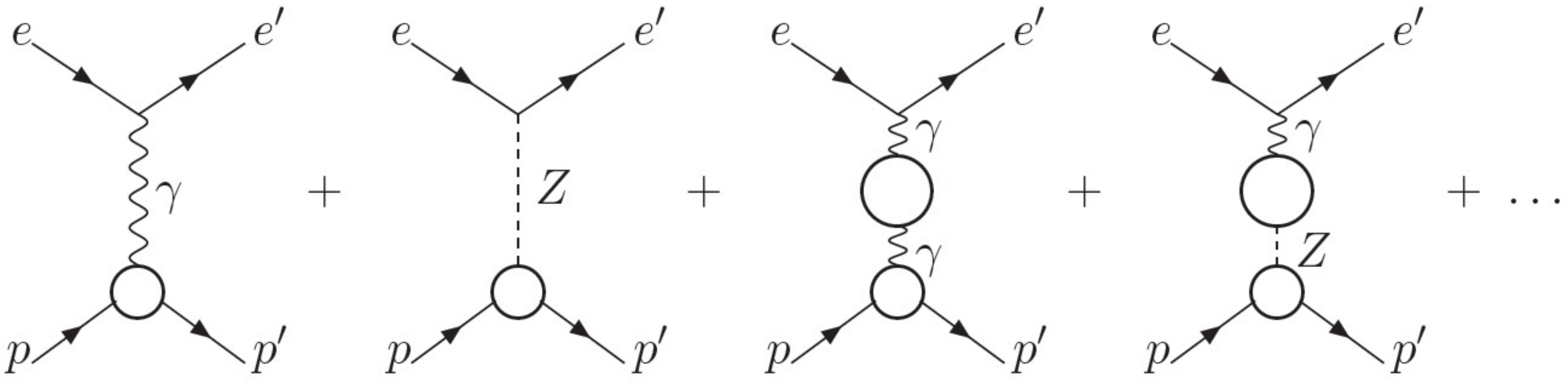


$Q_e(p) = +e$
electric charge of the proton

$Q_W(p) = 1 – 4 \sin^2 \theta_W$
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

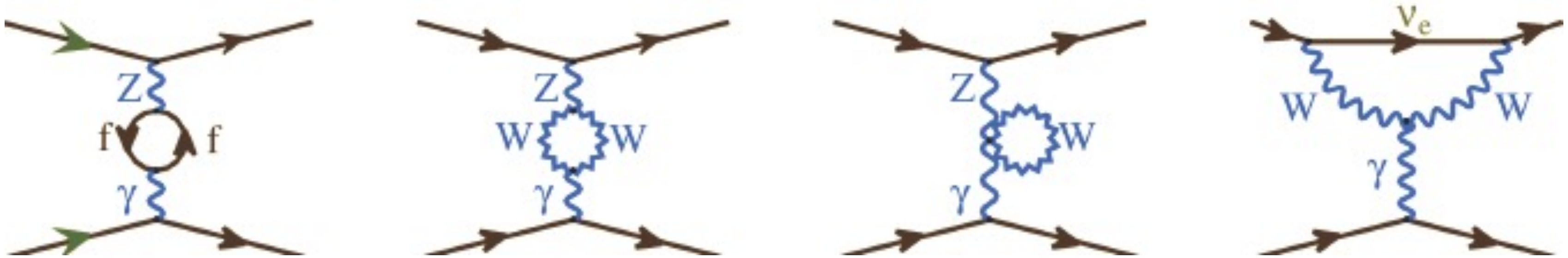
Precision measurements and quantum corrections:



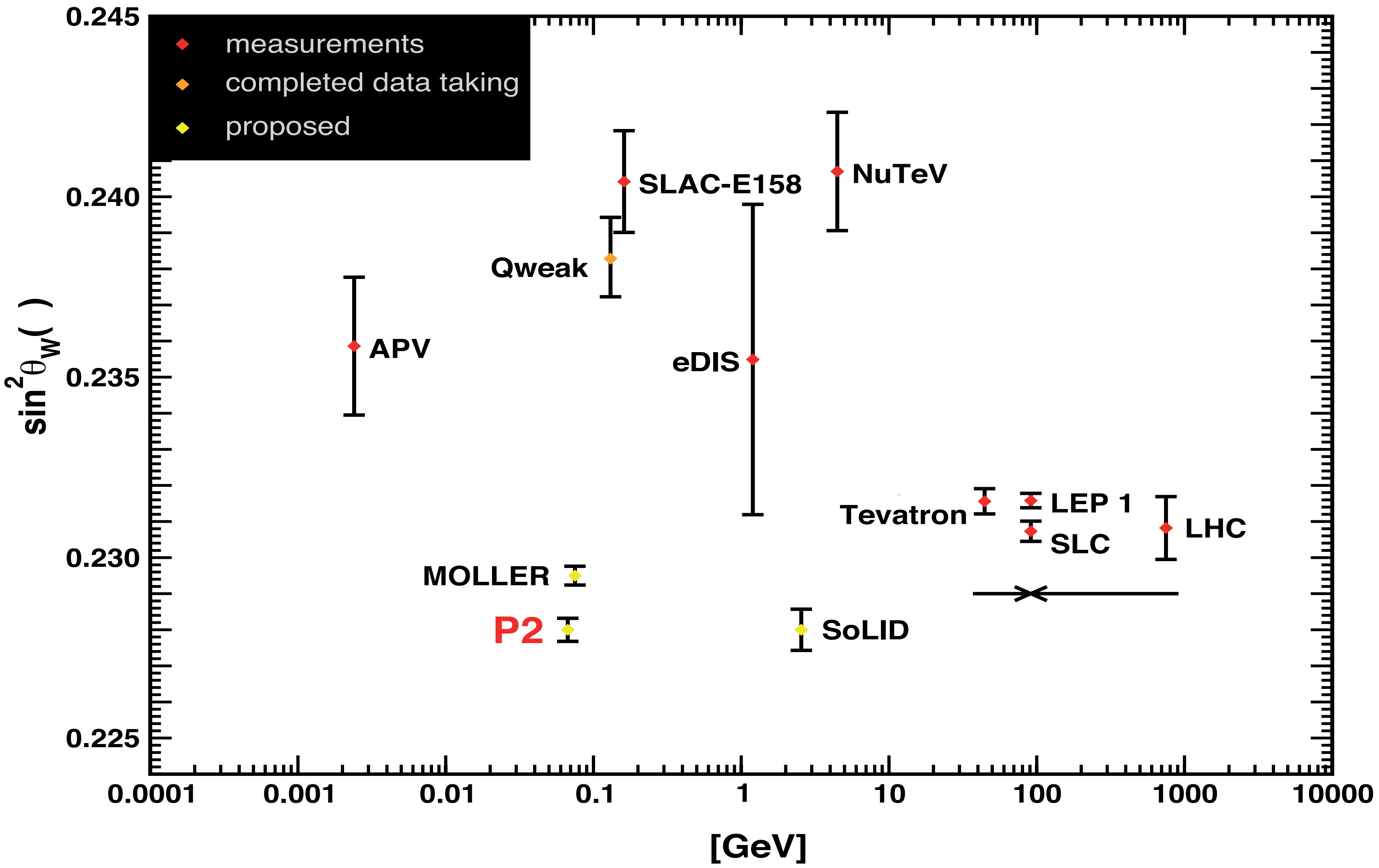
running α

running $\sin^2\theta_W(\mu)$
(P2)

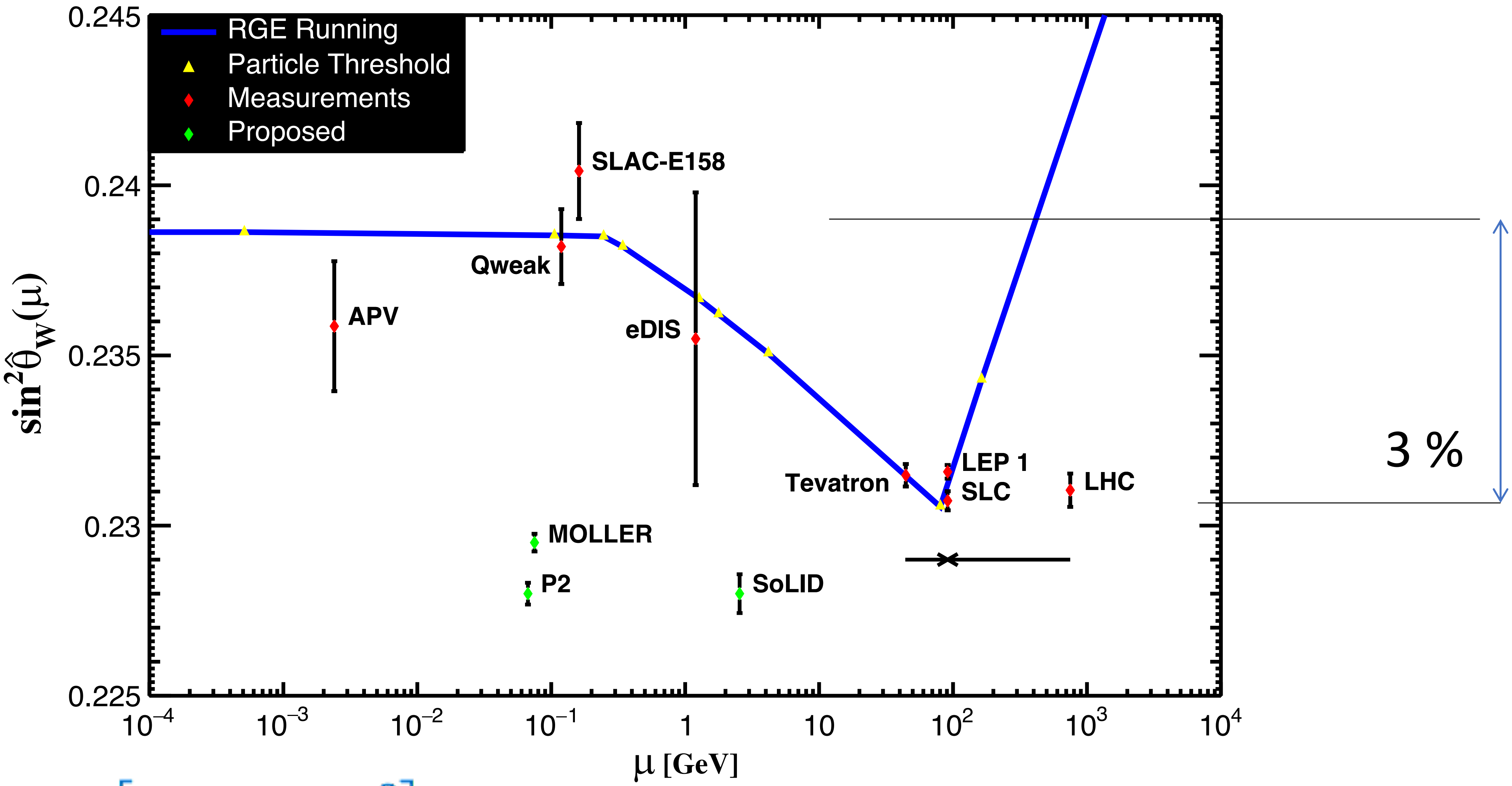
Universal quantum corrections: can be absorbed into a **scale dependent, „running“** **$\sin^2\theta_{eff}$ or $\sin^2\theta_W(\mu)$**



Measurements of the weak mixing angle



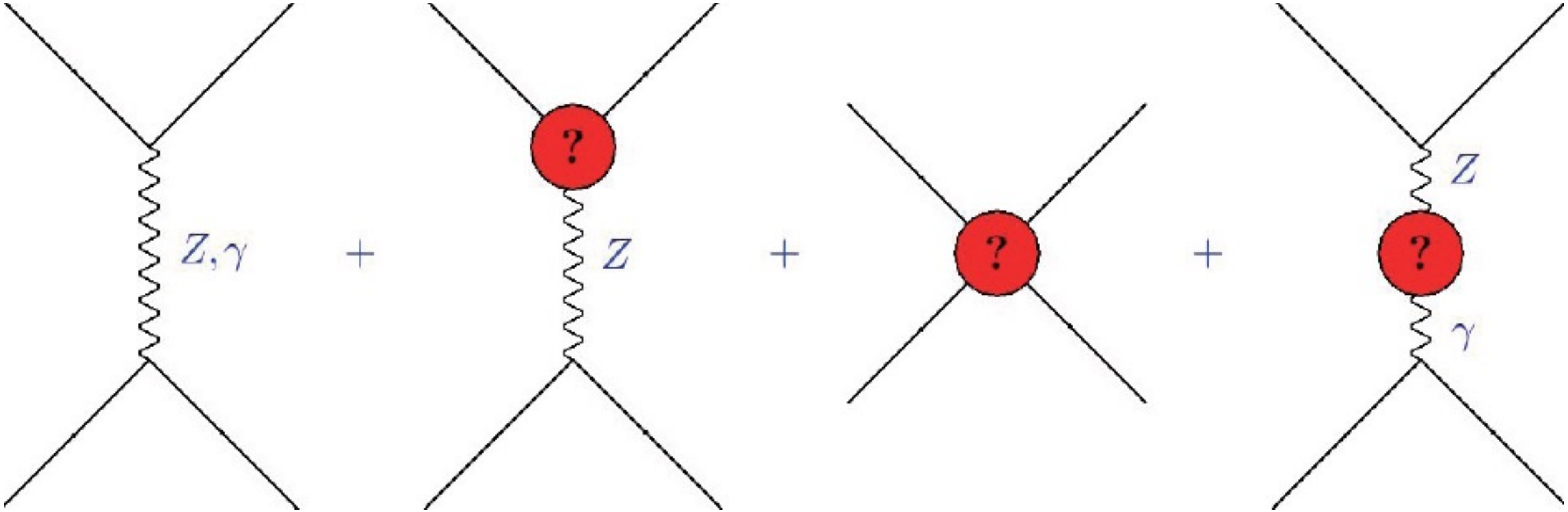
Running of the weak mixing angle



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

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

Sensitivity to new physics beyond the Standard Model



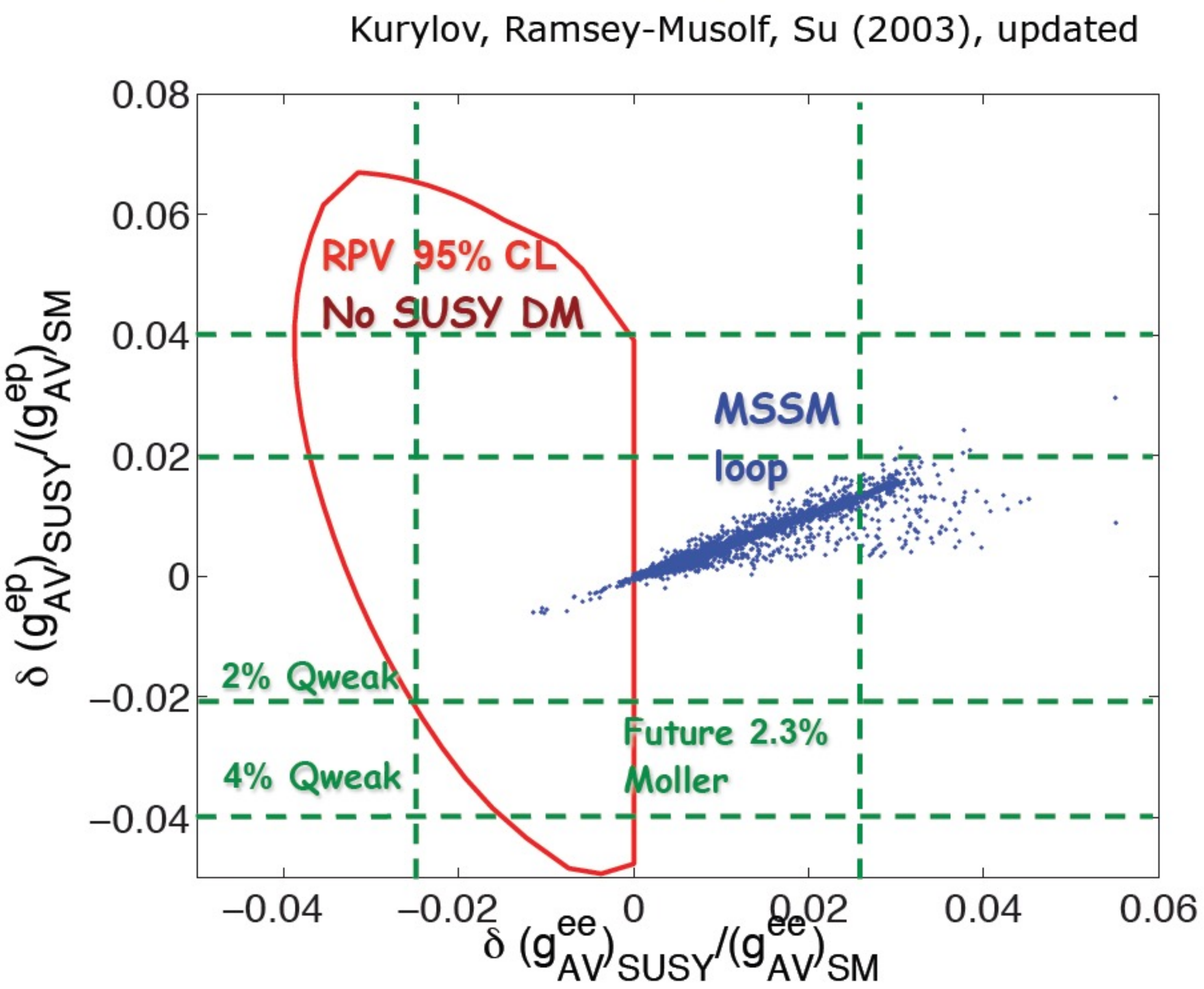
Extra Z

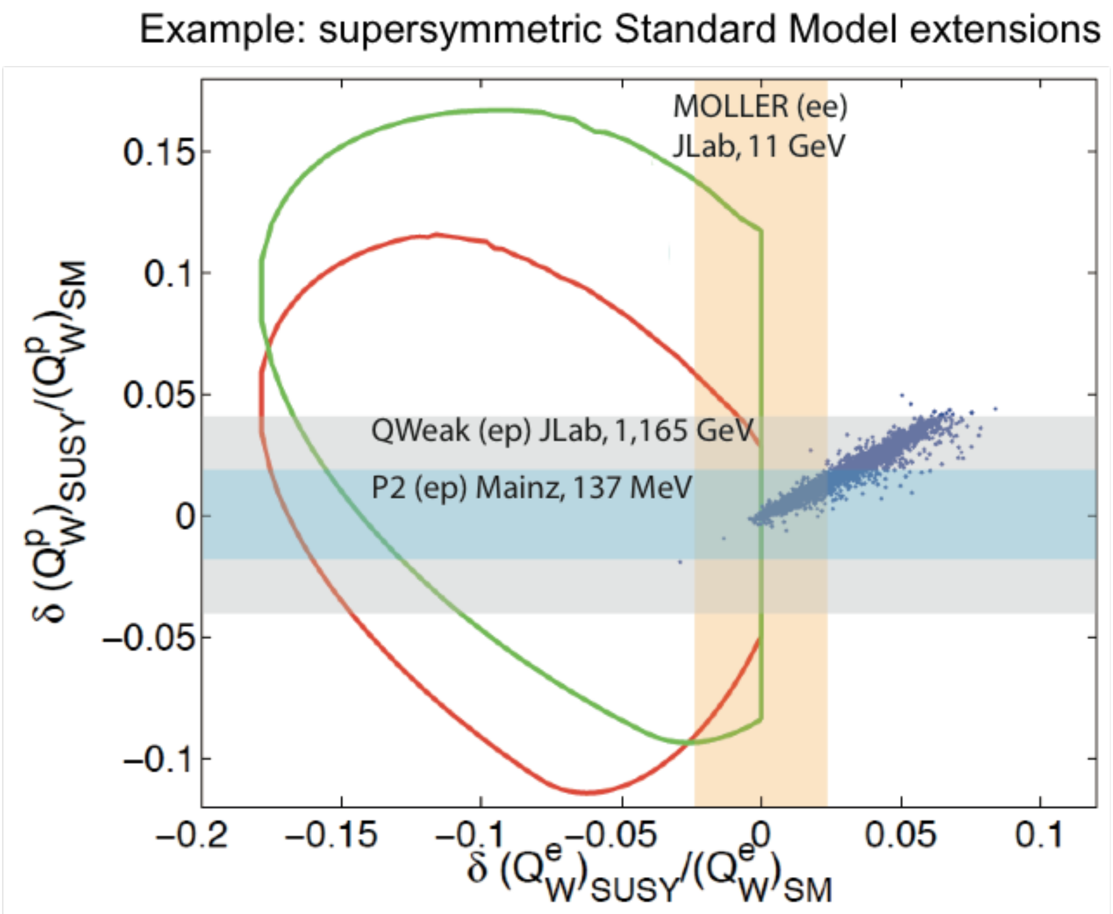
Mixing with
Dark photon or
Dark Z

Contact interaction

New
Fermions

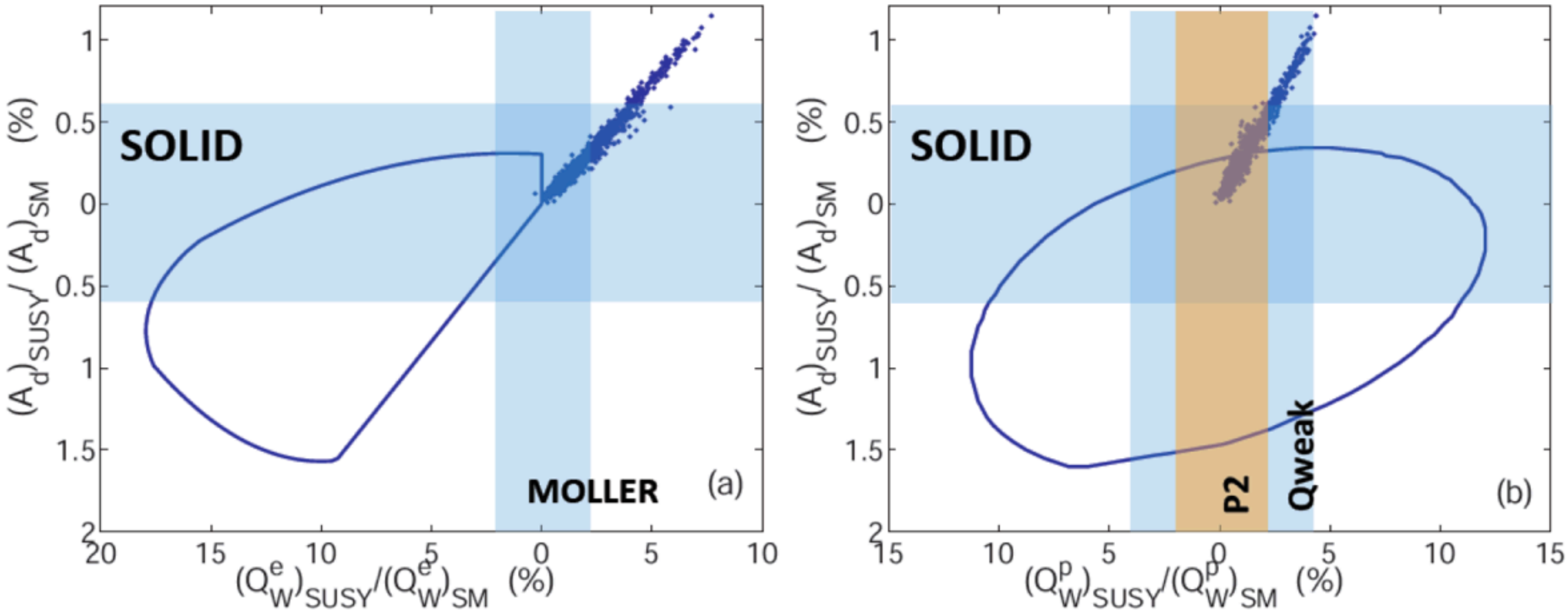
Example: Supersymmetric standard model extensions





Example: Supersymmetric standard model extensions

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



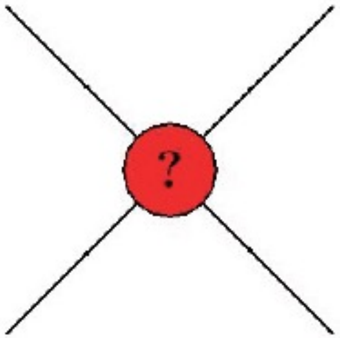
Proton: special case

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:	$\Delta Q_W(p)/Q_W(p)$	=	$4/\left((1/\sin^2\theta_W) - 4\right)\ (\Delta\sin^2\theta_W/\sin^2\theta_W)$
Rel. error	$\Delta\sin^2\theta_W/\sin^2\theta_W$	=	$\left((1/\sin^2\theta_W) - 4\right)/4\ \ \Delta Q_W(p)/Q_W(p)$
Example:	$\sin^2\theta_W$ (50 MeV)	=	0.238
	$4/\left((1/\sin^2\theta_W) - 4\right)$	~	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:	$\Delta Q_W(p)/Q_W(n)$	=	$\Delta\sin^2\theta_W/\sin^2\theta_W$

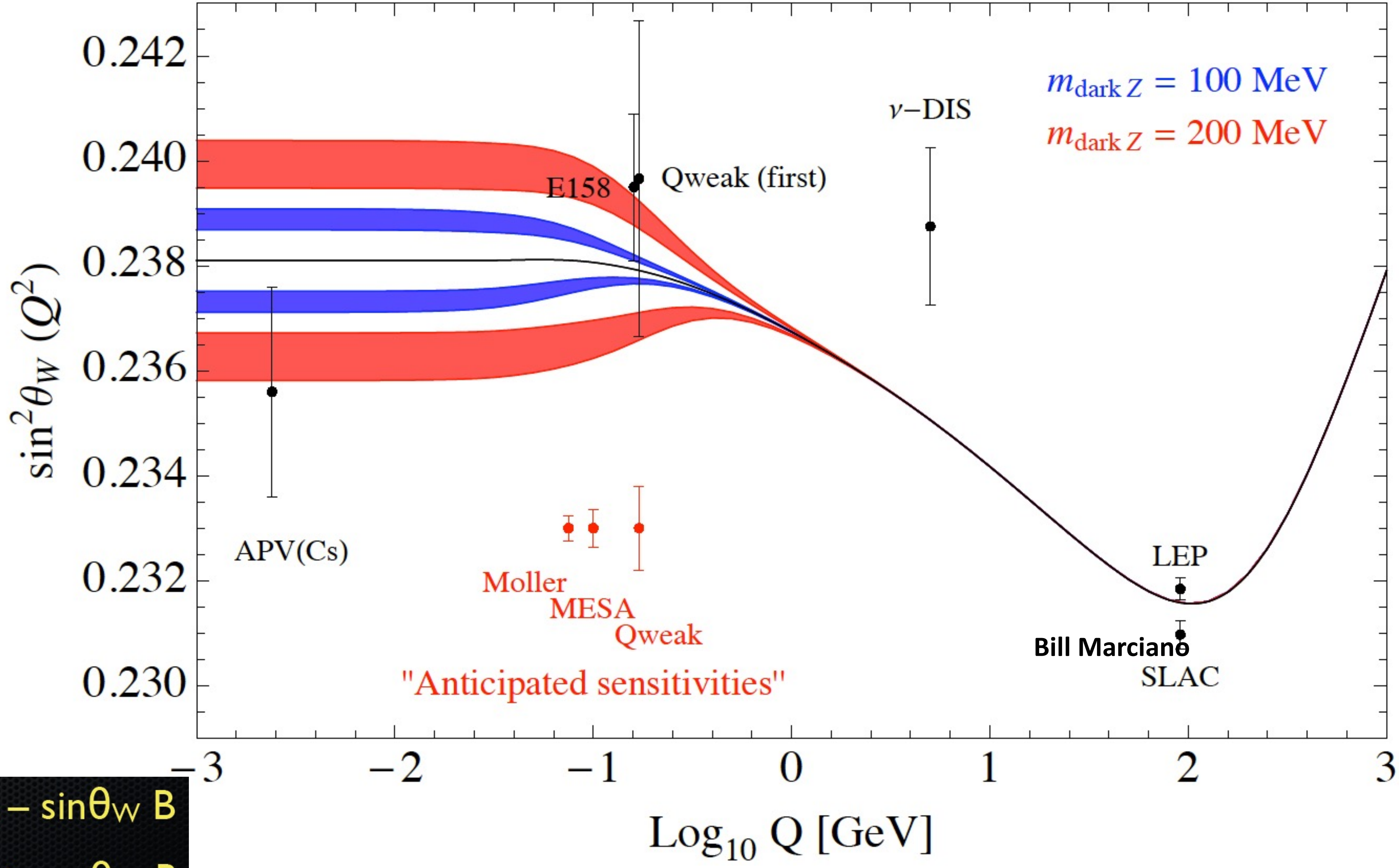
Physics sensitivity from contact interaction (LEP2 convention, g^2= 4pi)

	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

Effective field theory approach (EFT)



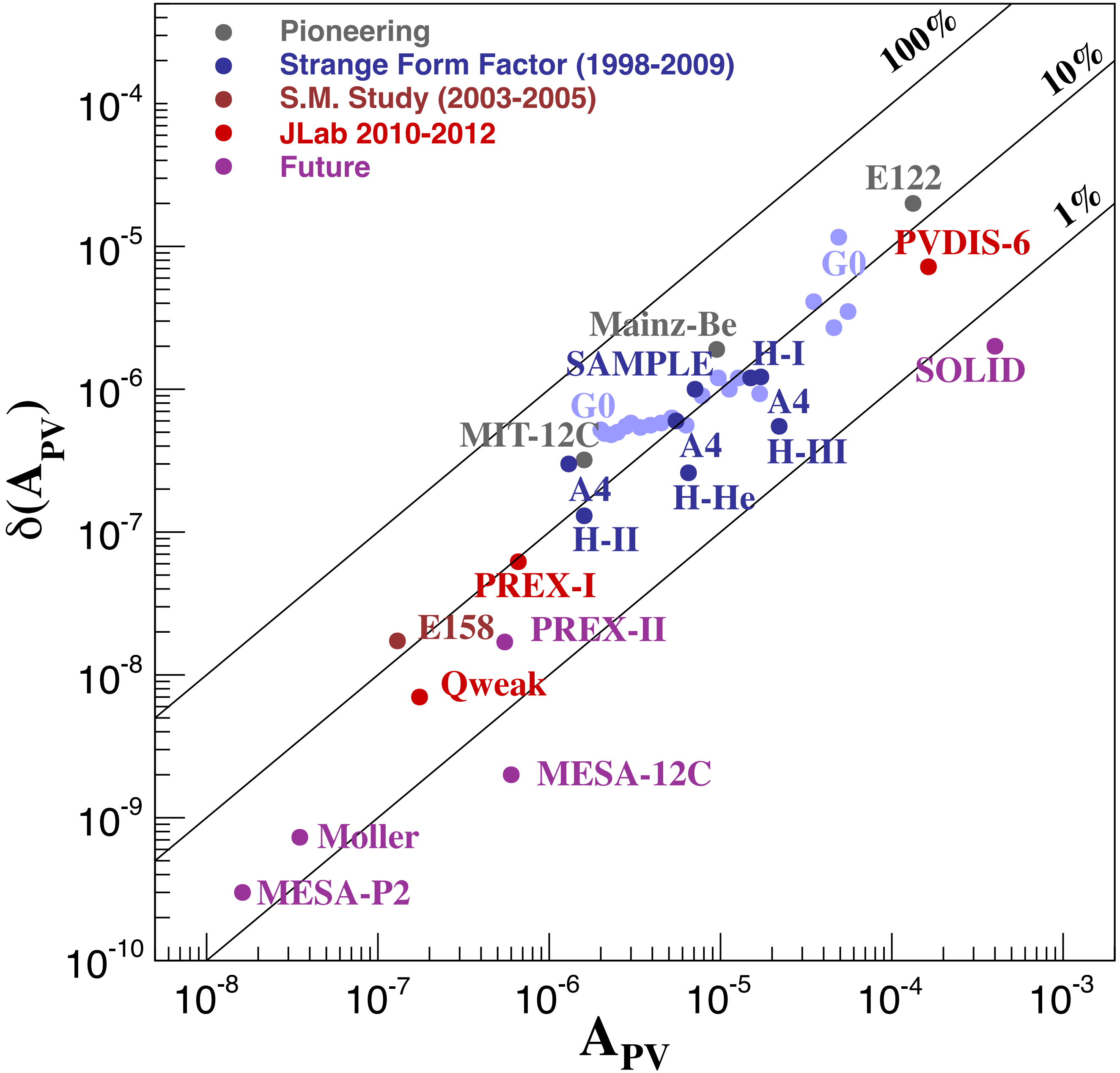
Running $\sin^2\theta_W$ and Dark Parity Violating Z



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

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

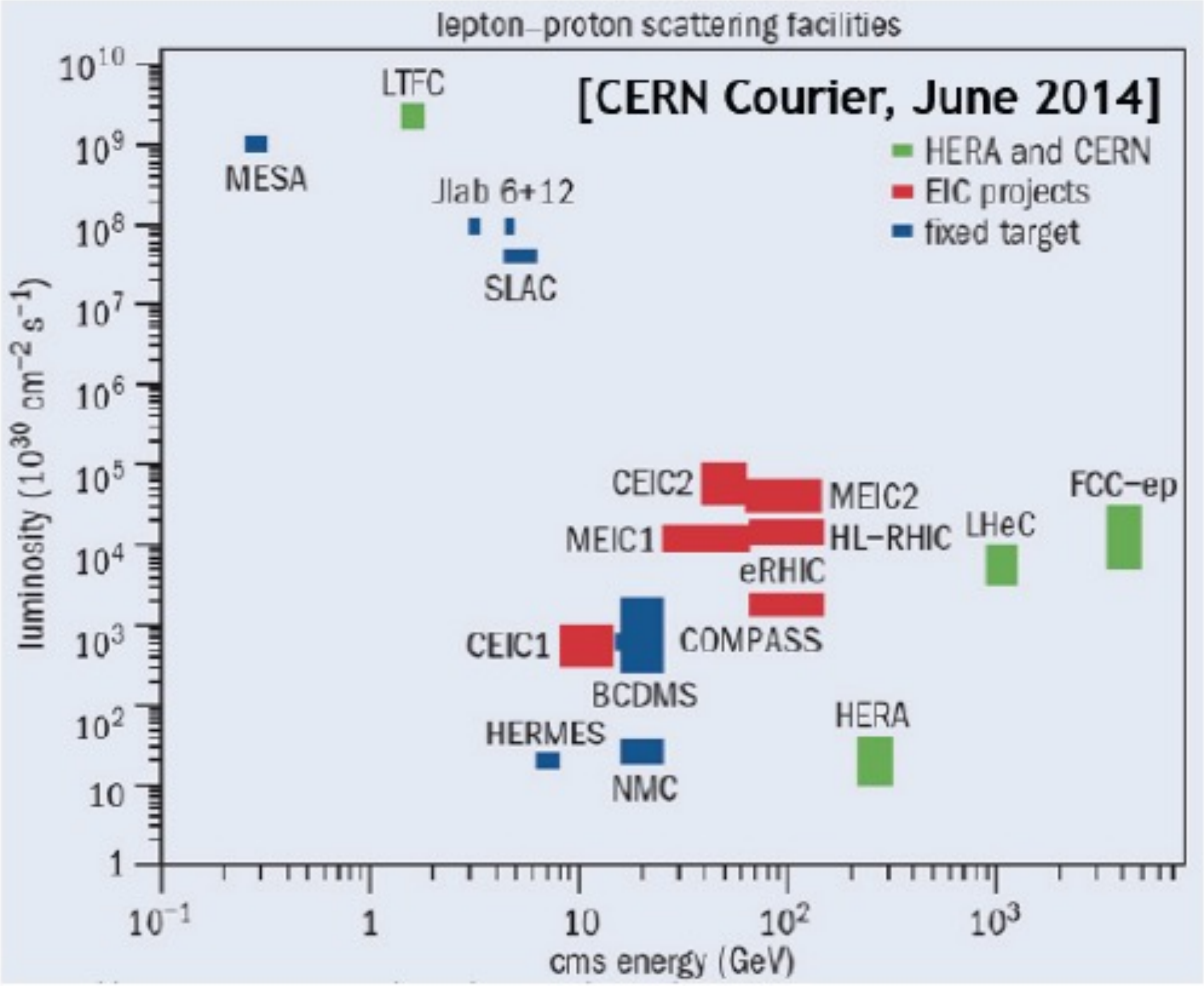
PVeS Experiment Summary



Parity Violation experiments need very high luminosity

(10,000 h)
data taking ➜

$\int \mathcal{L} dt \simeq 8.6\ \mathrm{ab}^{-1}$



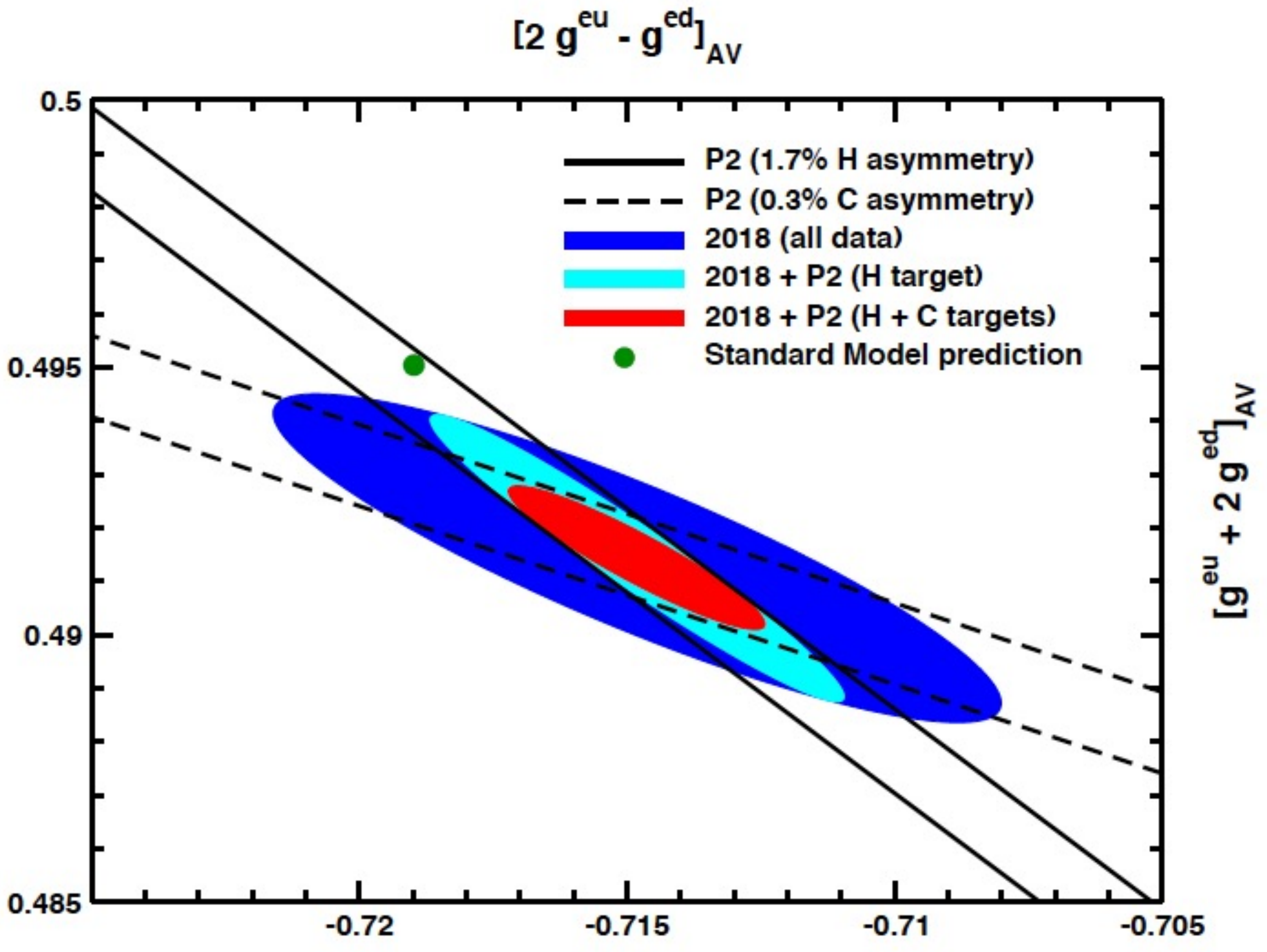
P. Newman

P2 parity violation experiment in Mainz: program

Qweak@Jlab	P2@MESA hydrogen	P2@MESA carbon	P2@MESA lead
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	
$\Delta A_{ep}/A_{ep}$= 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:

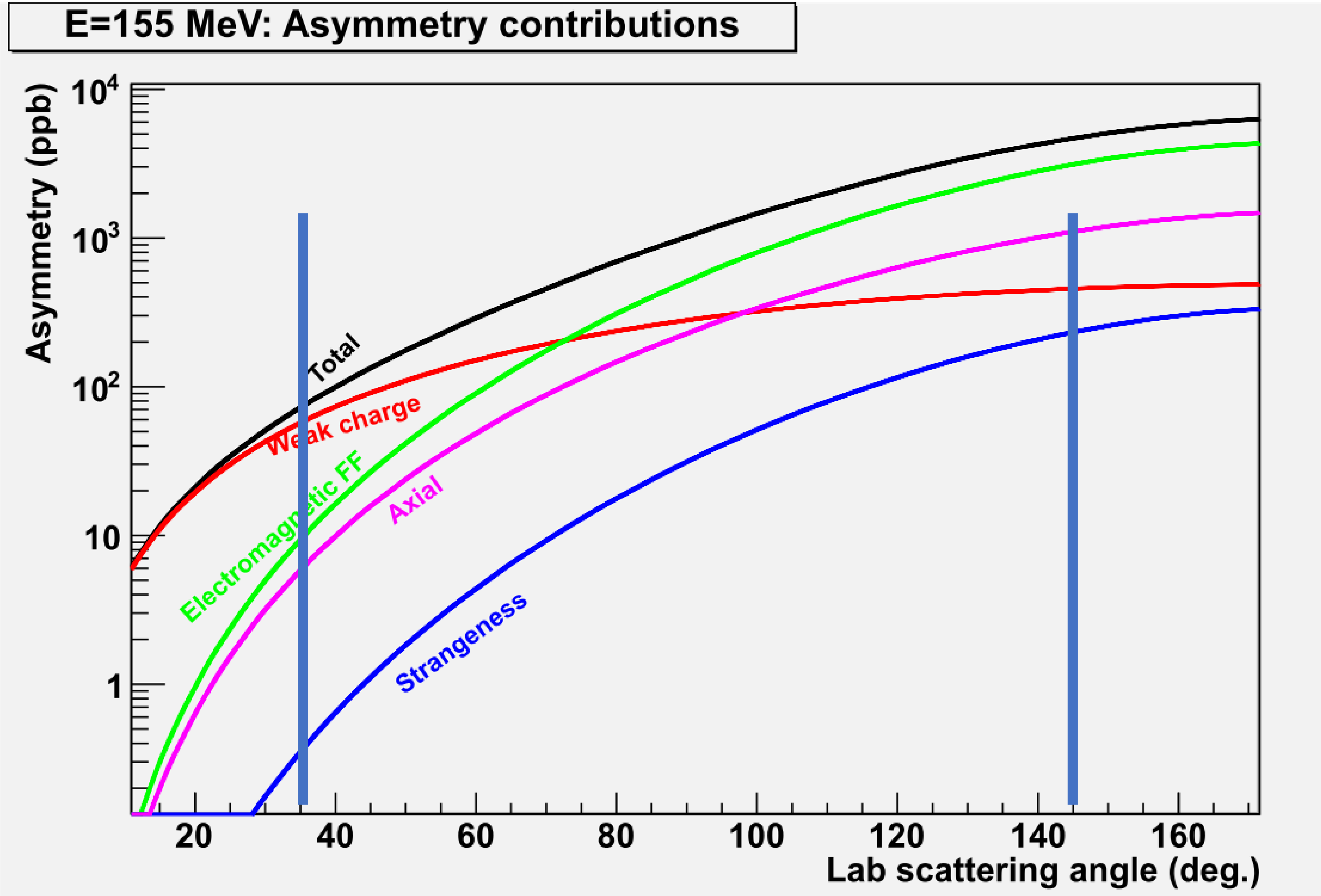
$$\begin{pmatrix} \delta g^{eu}_{AV} \\ \delta g^{ed}_{AV} \\ 2\delta g^{eu}_{VA} - \delta g^{ed}_{VA} \end{pmatrix} = \begin{pmatrix} 0 \pm 0.70 \\ 0 \pm 0.97 \\ 0 \pm 7.4 \end{pmatrix} \times 10^{-3}$$

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

AA, Grilli Di Cortona, Tabrizi 1802.08296

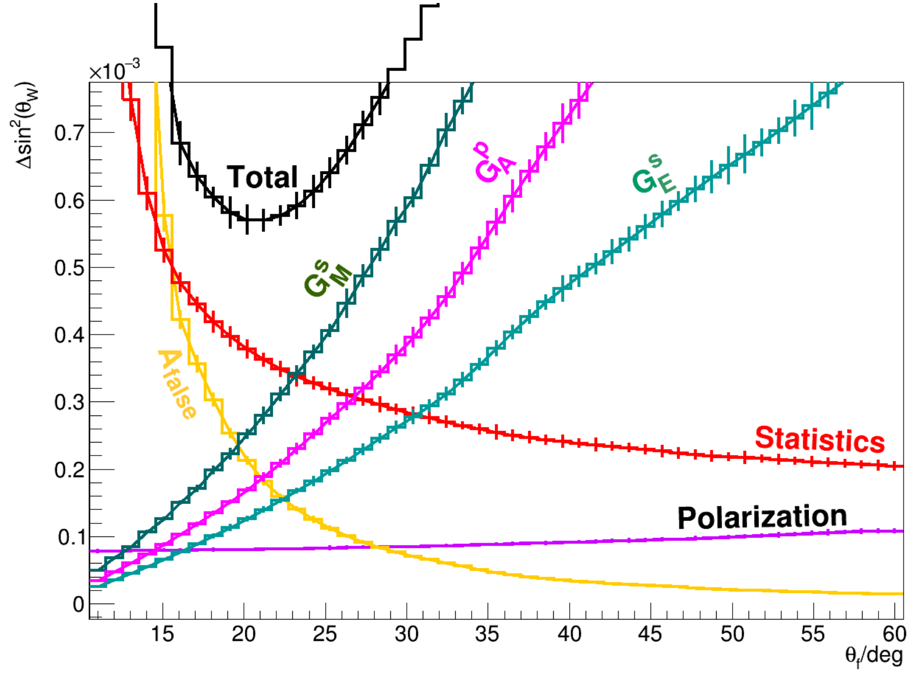
AA, Gonzalez-Alonso in progress

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



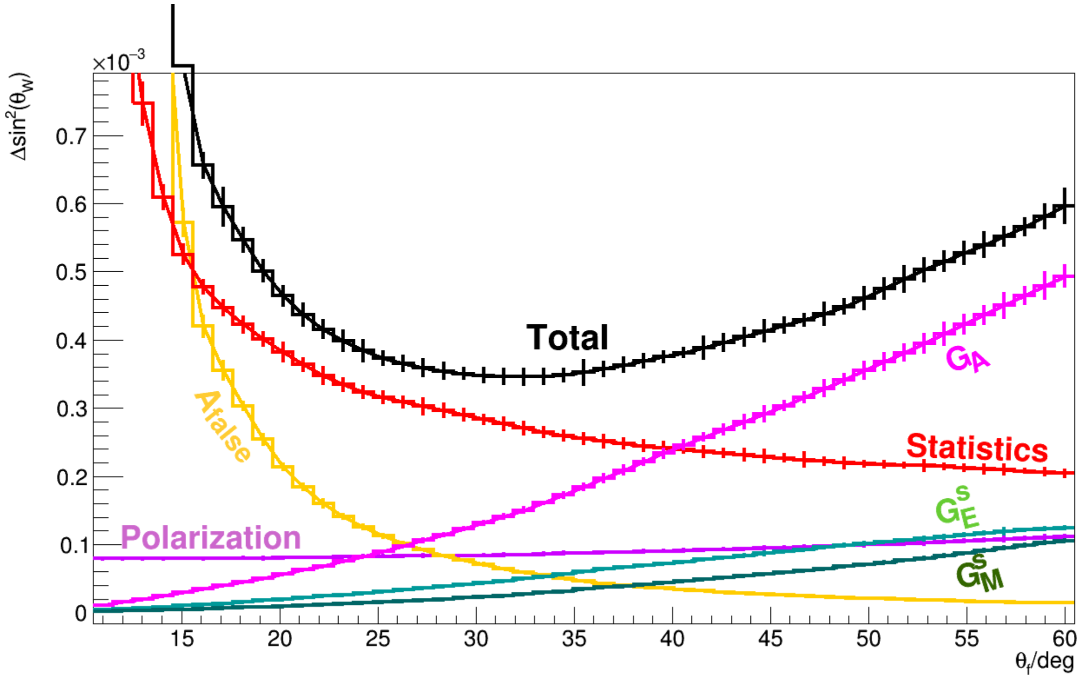
Auxiliary measurements at backward angles

Strange FF and axial FF from present data



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

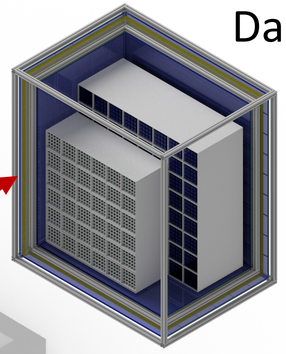
Strange FF from lattice, axial FF with uncertainty/3

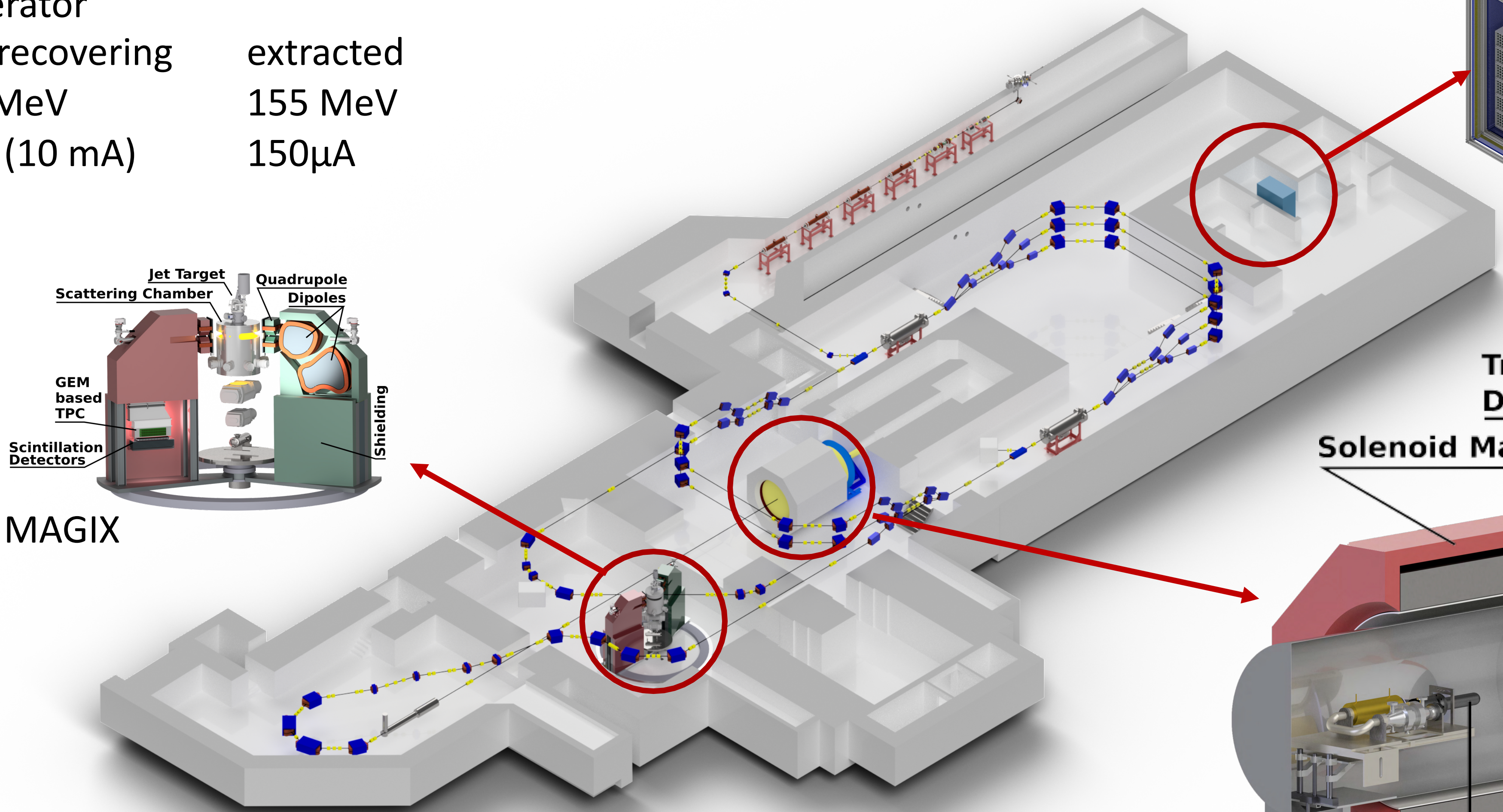


Accuracy of electric and magnetic strangeness form factor from recent lattice QCD calculations and axial form factor from backward angle measurement

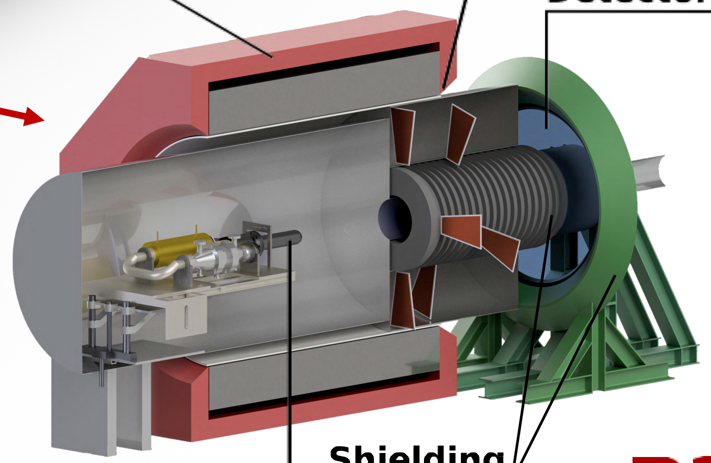
Mainz Energy recovering Superconducting Accelerator: MESA

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



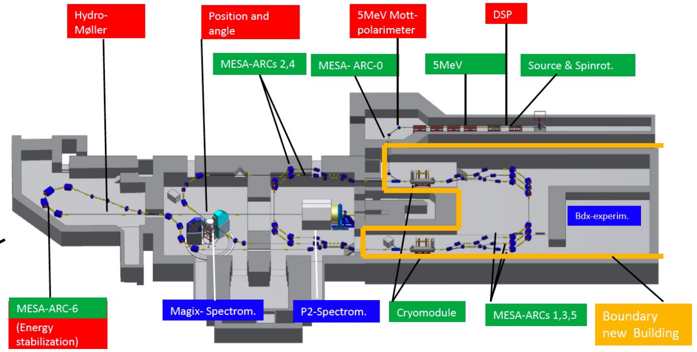


MAGIX



See talk in session new facilities

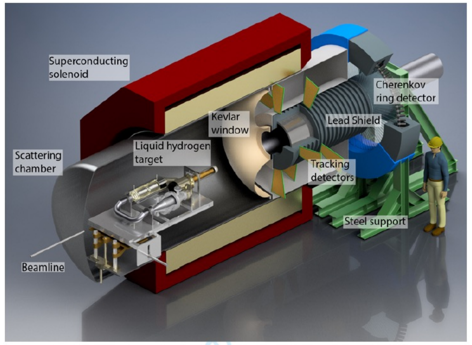
P2: Parity violating electron proton scattering at MESA/Mainz



False asymmetries: control of target and accelerator

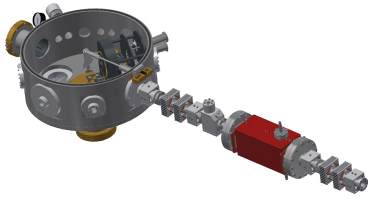
$$A_{LR}^{exp} = \frac{\sigma(\vec{e}p)-\sigma(\overleftarrow{e}p)}{\sigma(\vec{e}p)+\sigma(\overleftarrow{e}p)} = -P\,\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\underbrace{\left(Q_W(p) - F(Q^2)\right)} + A_F$$

Cross section asymmetry A_{LR}^{exp}

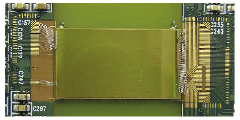


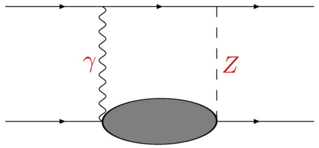
Magnetic spectrometer
Cherenkov detector
Read-out electronics
Data acquisition

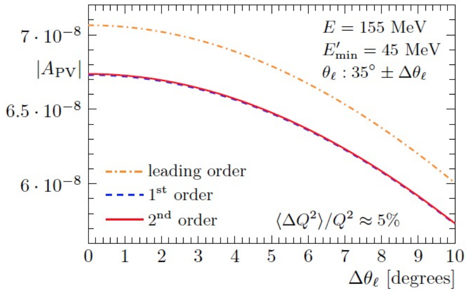
Beam polarisation
P
Polarimetry



Momentum transfer $< Q^2 >$
Tracking system







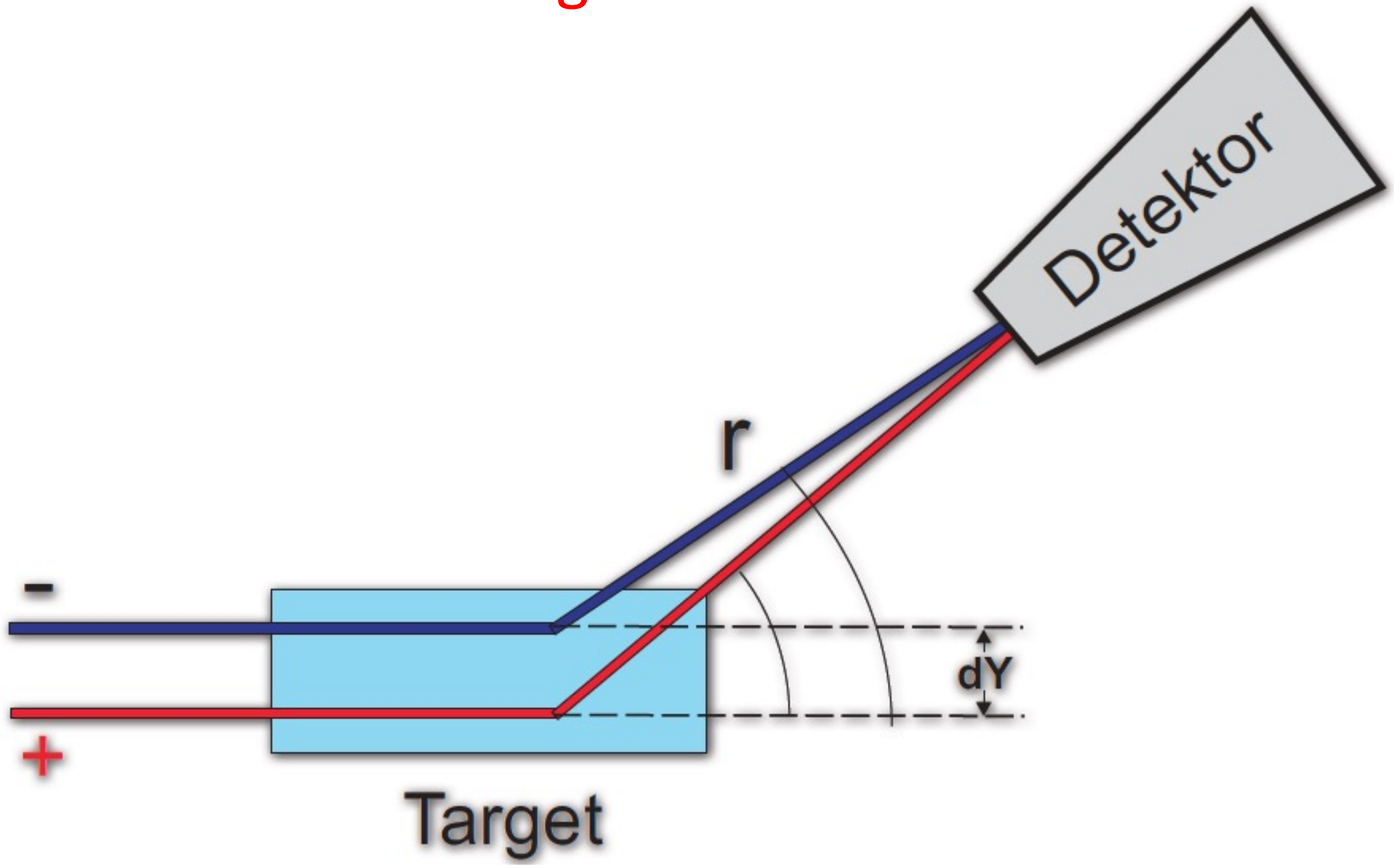
Theory:
QED corrections
EW corrections (two loop)
Hadron structure $F(Q^2)$,
Strangeness form factors
Merasure:
Axial form factor

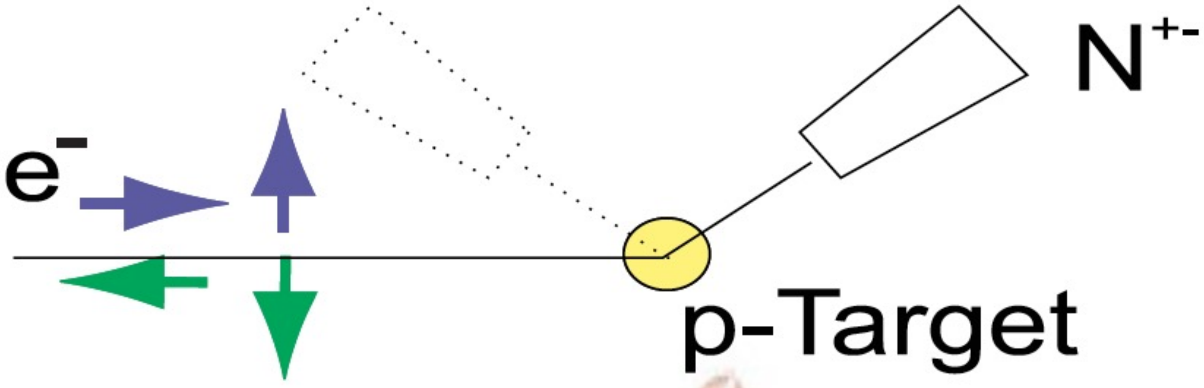
Systematic effects: detector related (false) asymmetries:

Extreme good control of beam and target

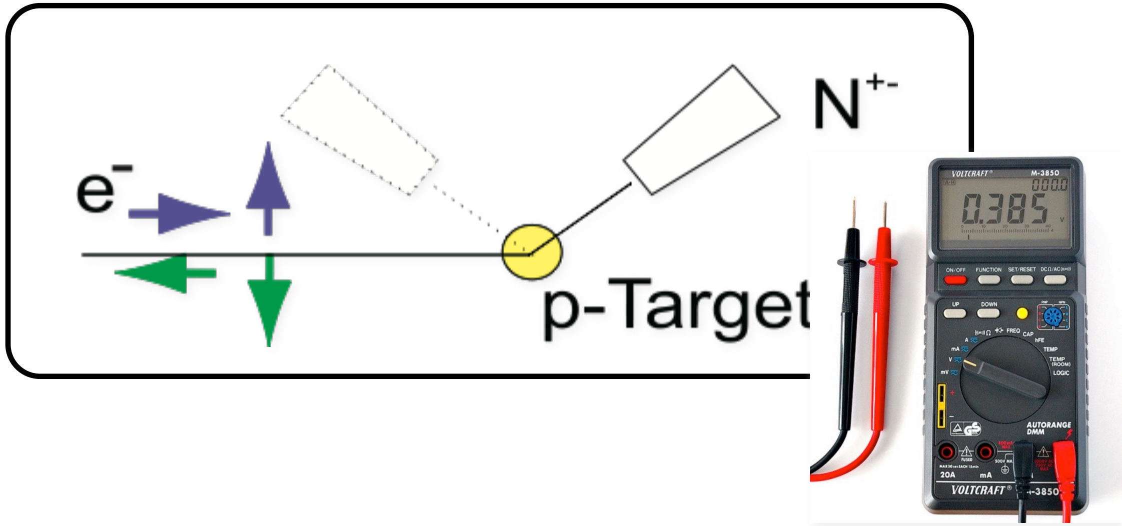
Flip Helicity fast

Extra spin flip





Analogue Technique

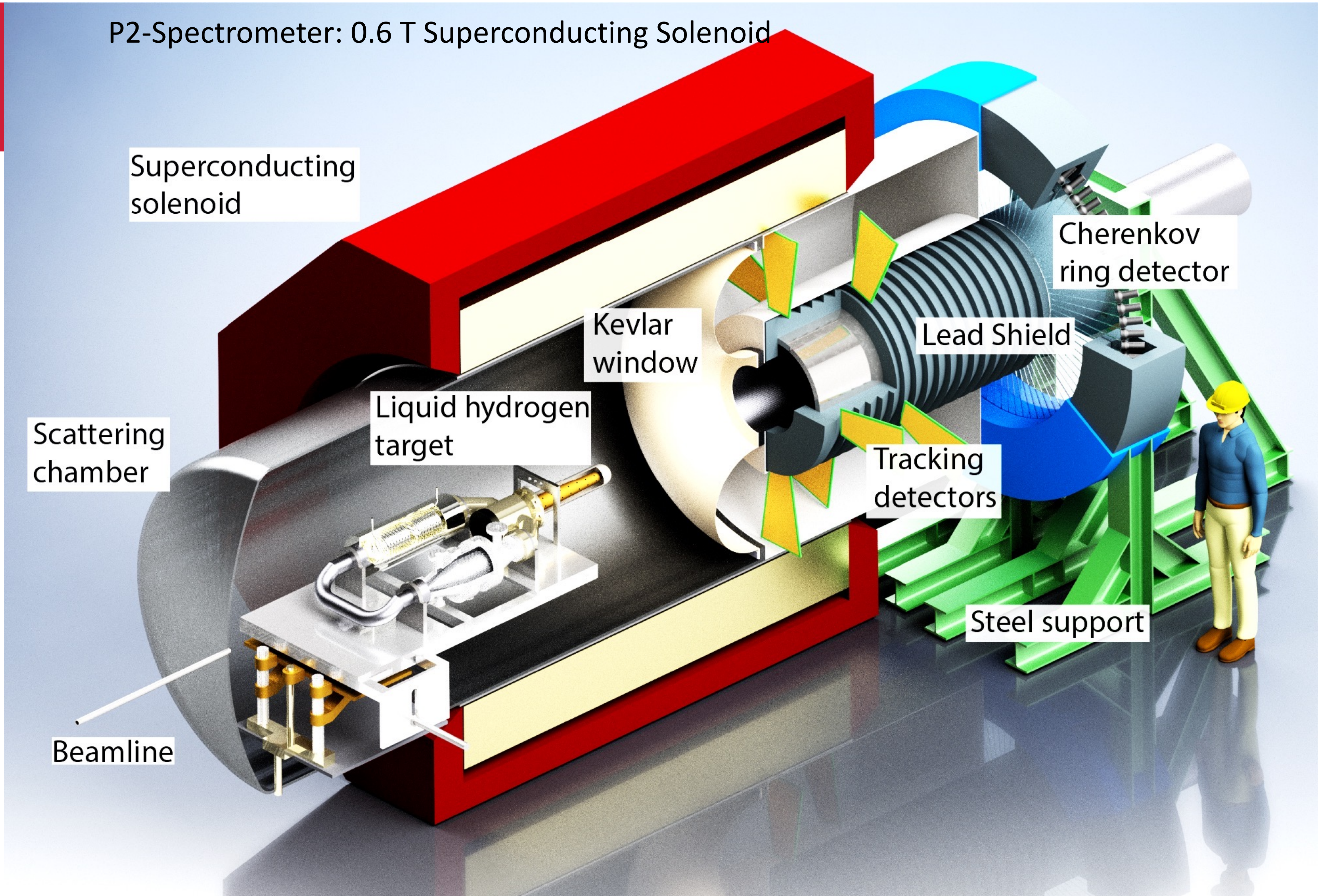


Counting Technique

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

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

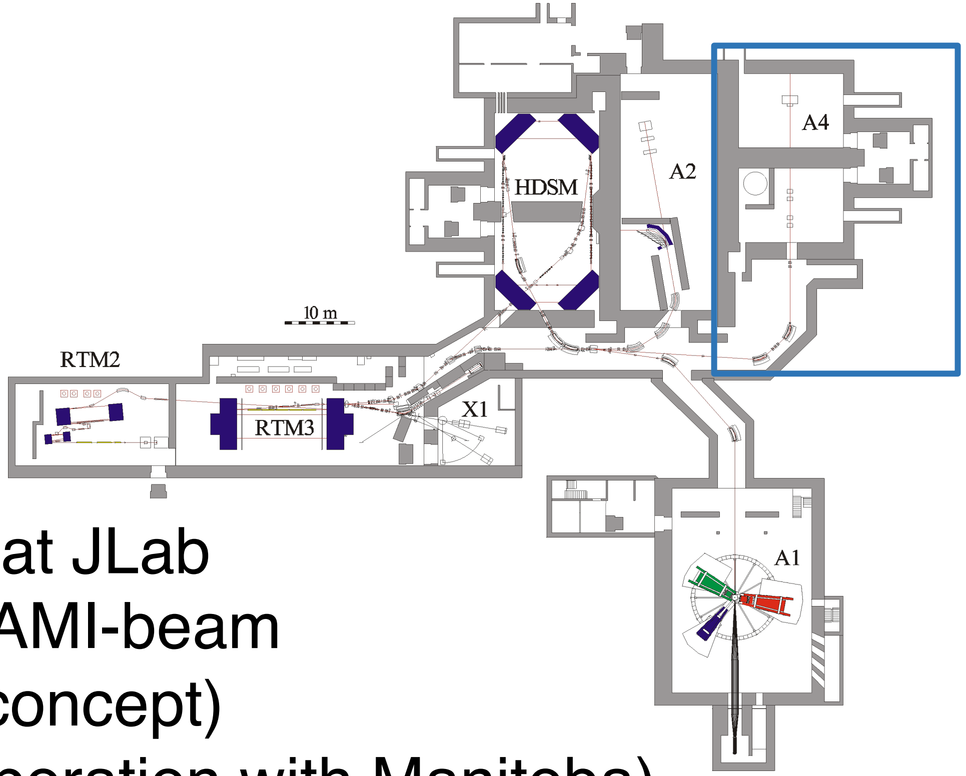
P2-Spectrometer: 0.6 T Superconducting Solenoid



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

Parity violating electron scattering

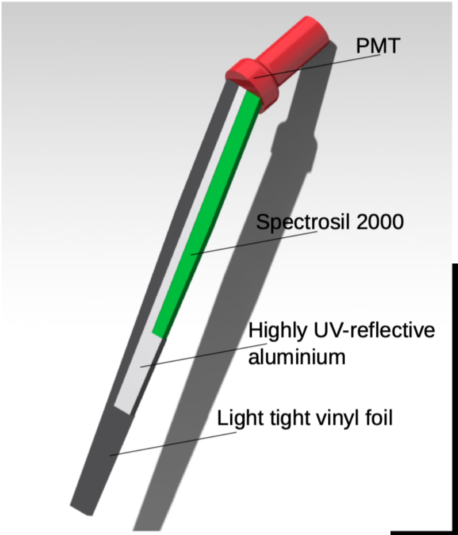
- 20 years of experience with previous parity violating electron scattering experiment (A4)
- 10000 h of beam and detector data
- 36 beam stabilisation systems
- Polarimetry, fast electronics, target

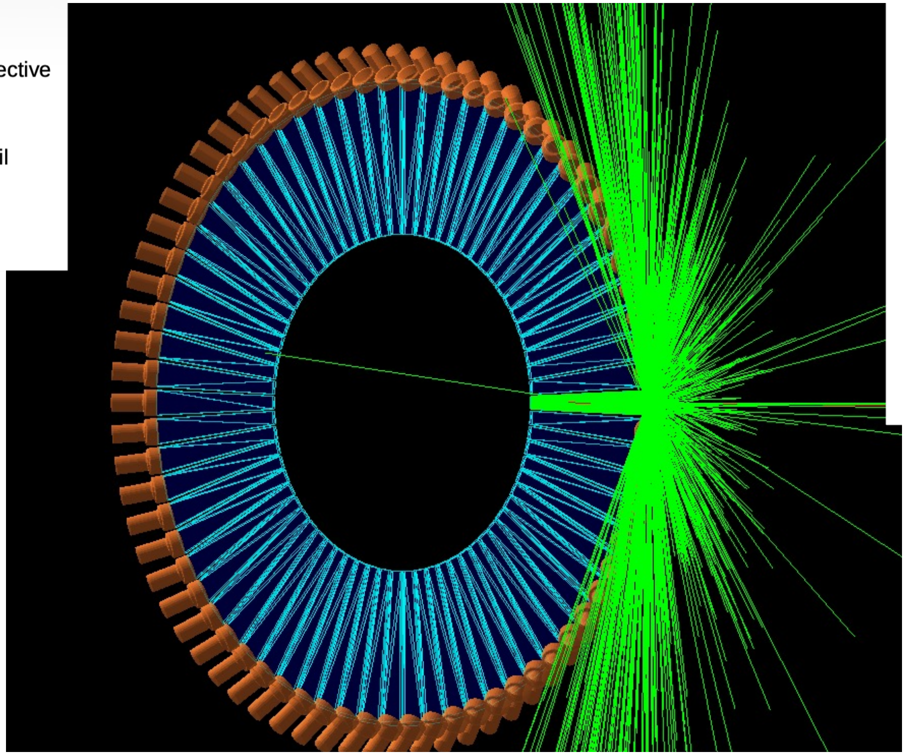


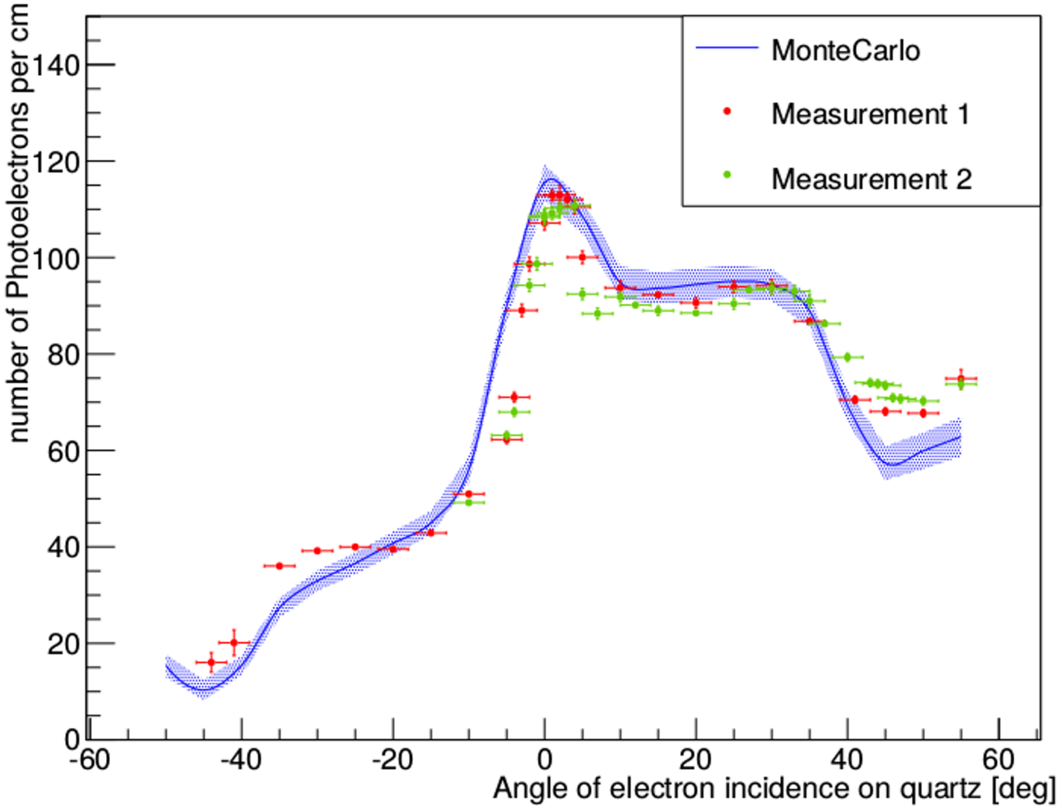
- MAMI accelerator in operation
- Large synergy with MOLLER experiment at JLab
- Prototypes of all components tested in MAMI-beam
    - Integrating detectors and PMTs (new concept)
    - Electronics and data acquisition (collaboration with Manitoba)
    - Luminosity monitors
    - Accelerator components, new concept position monitors
    - Polarimetry

Quartz glas detector concept

- Cherenkov detector ring consisting of **72 fused silica bars**
  - Covering **full azimuth 25° - 45° polar angle**
  - **Integrating detector**

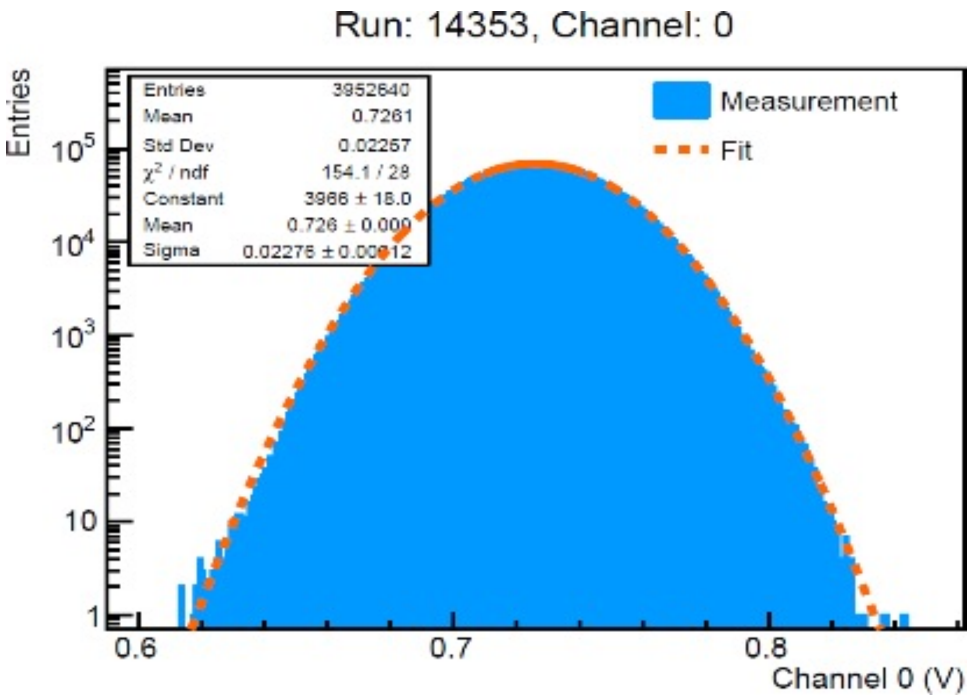


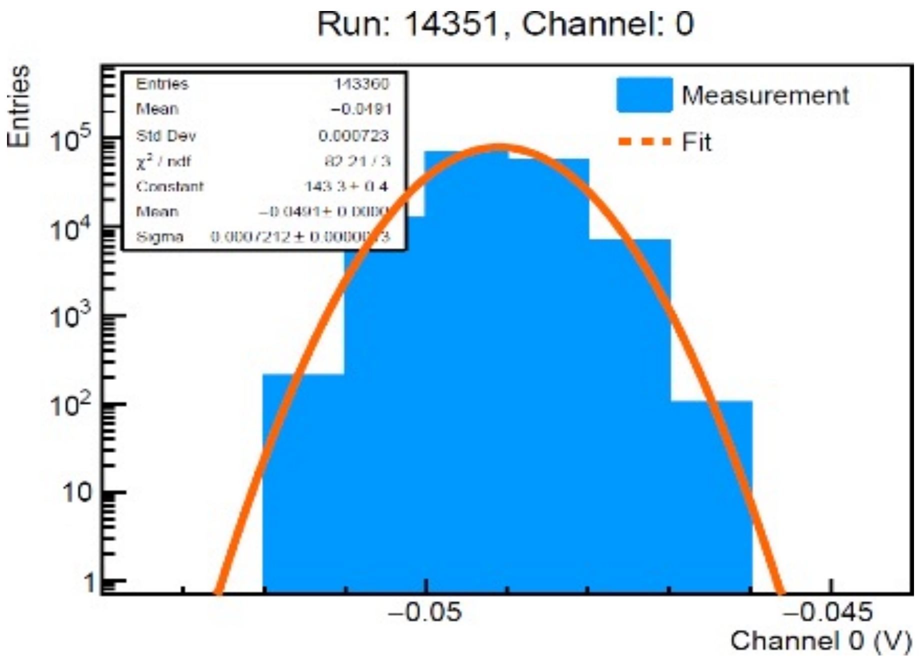




- Extended experimental study
- Quartz glas, PMTs, reflector
- Radiation hardness
- 500 h with MAMI beam

Test of analogue integrating detector and readout

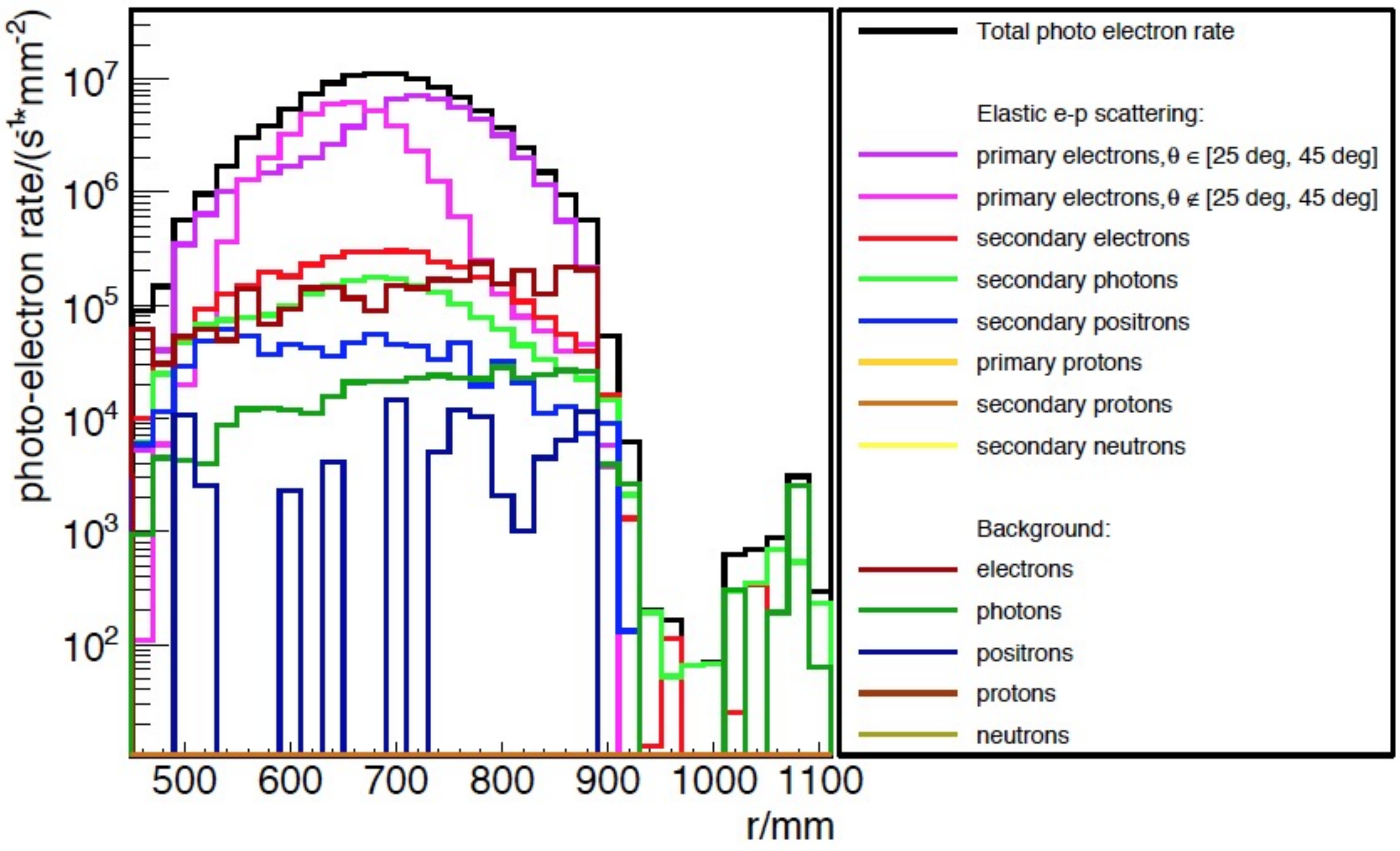




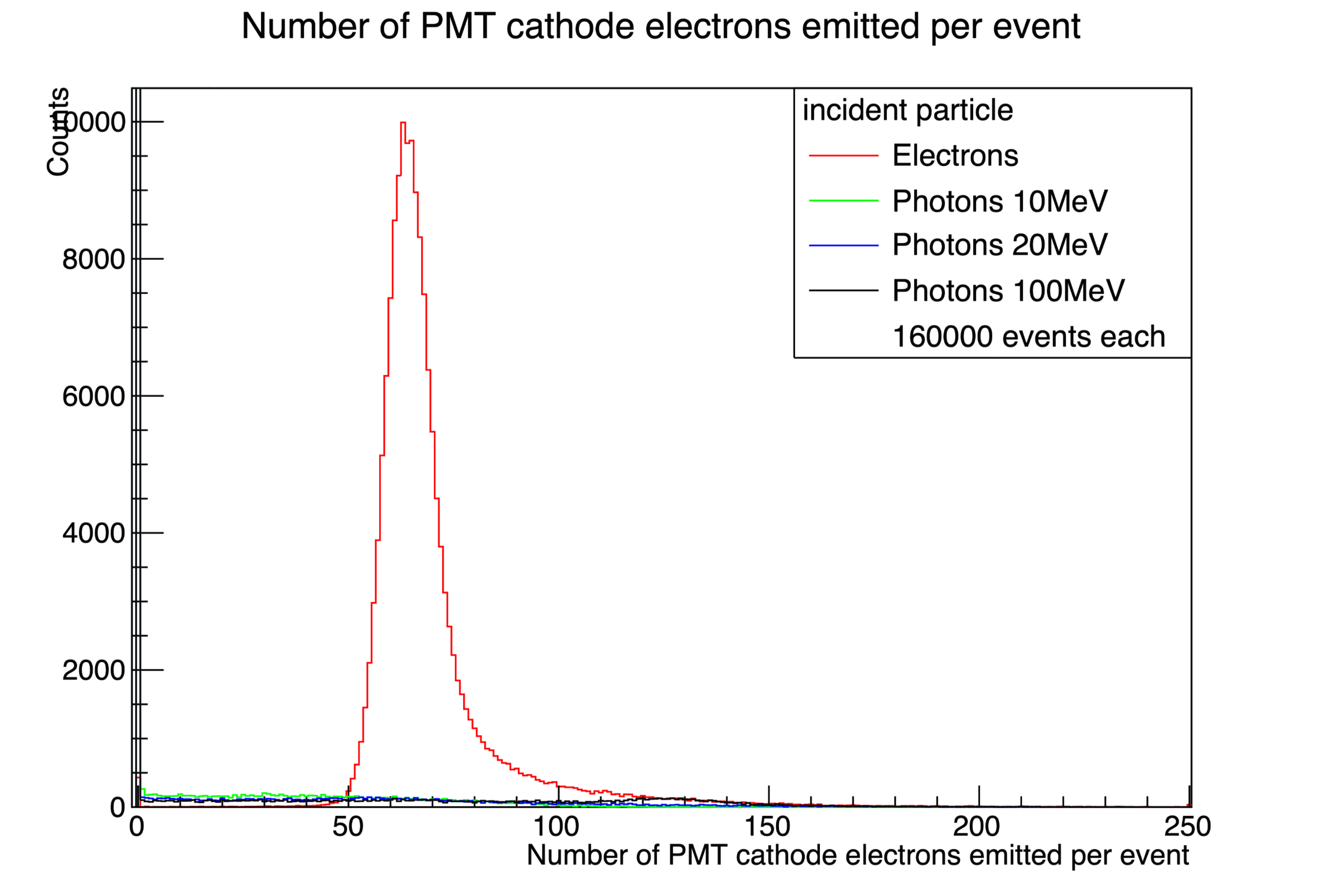
- Analogue signal from electrons in quartz Cherenkov, 274pA=1.7 GHz electrons on detector
- Electronics from U Manitoba
- Response of detector and width as expected
- System is ready to be used in the experiment

P2-Detector response

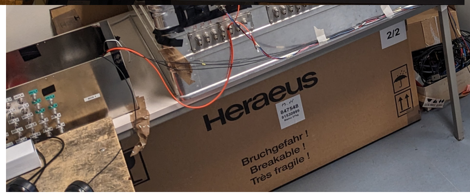
Full GEANT4 simulation

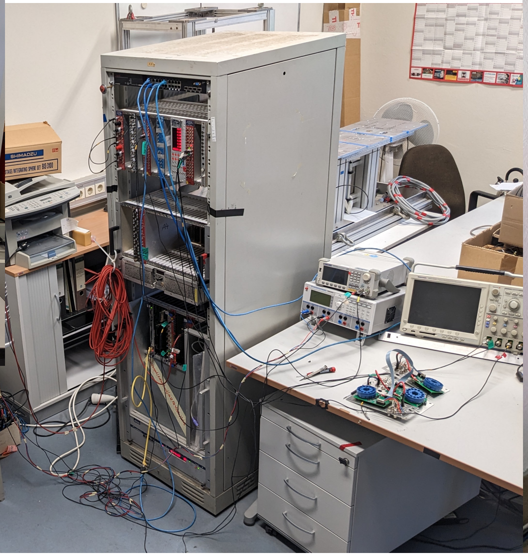


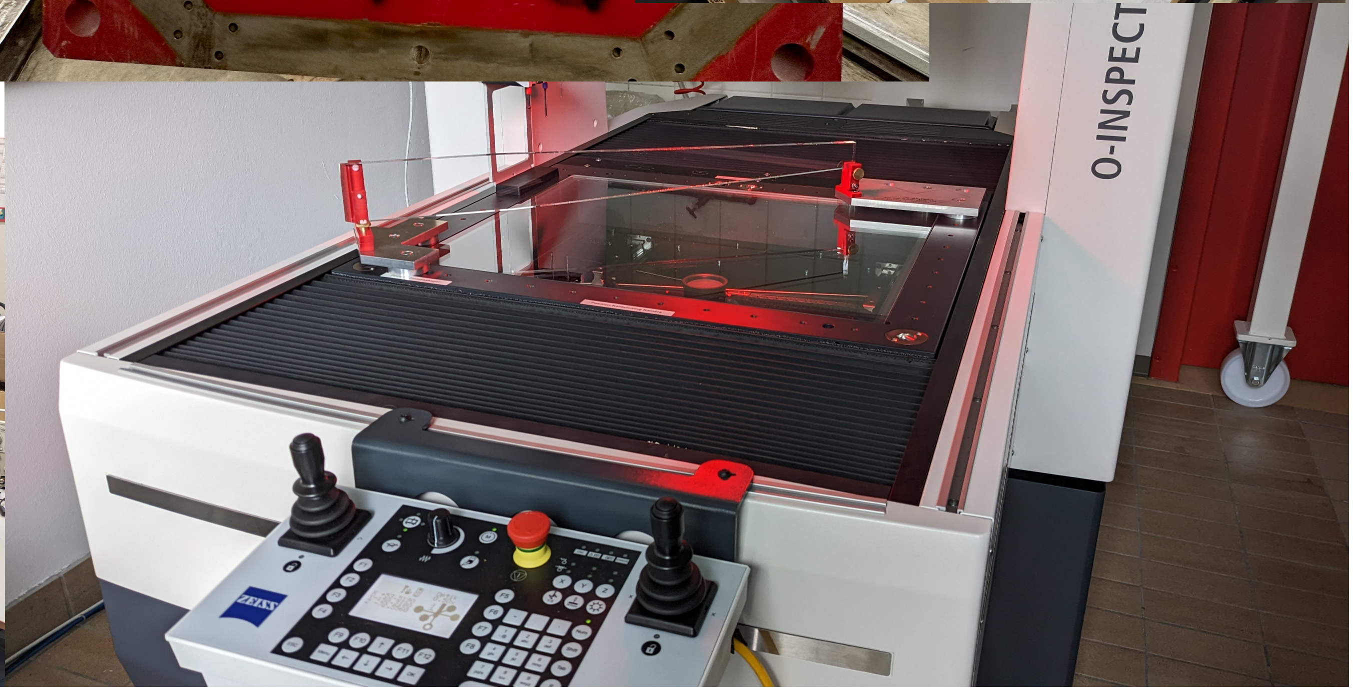
P2-Detector response



PRISMA+


Heraeus
Bruchgefahr!
Breakable!
Très fragile!



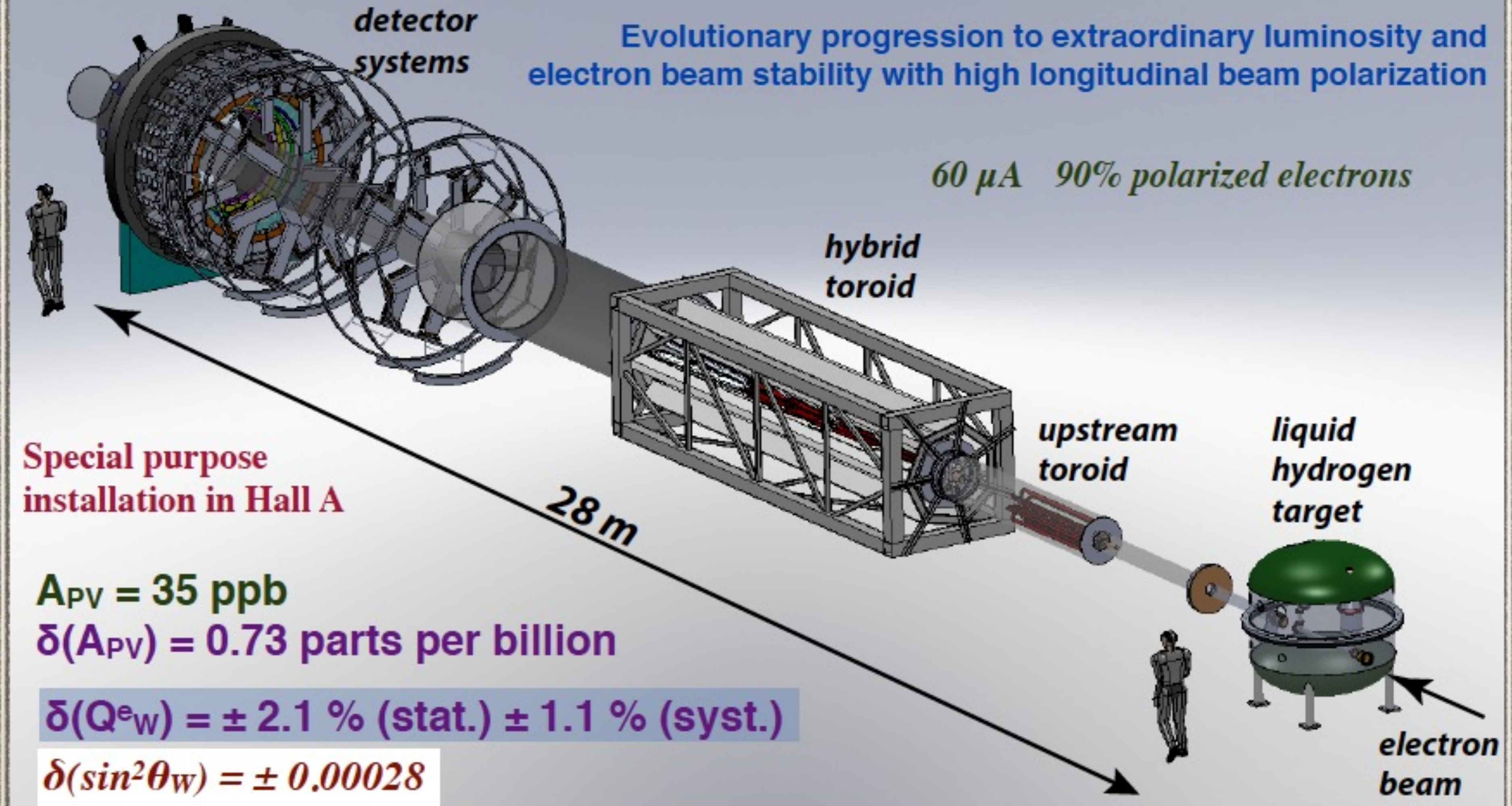

O-INSPECT
ZEISS

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



Special purpose installation in Hall A

$A_{PV} = 35$ ppb

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

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

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

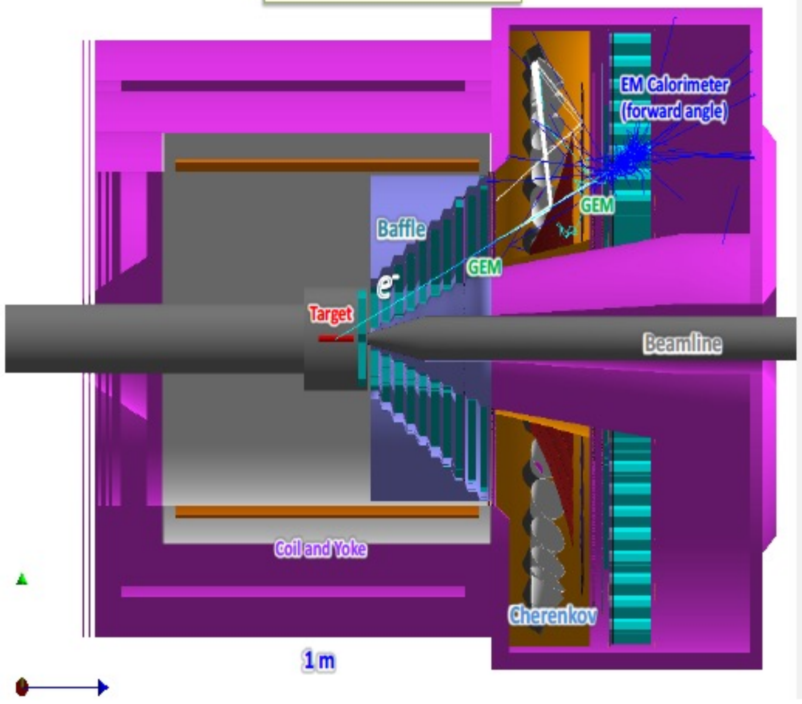
PVDIS @ SoLID

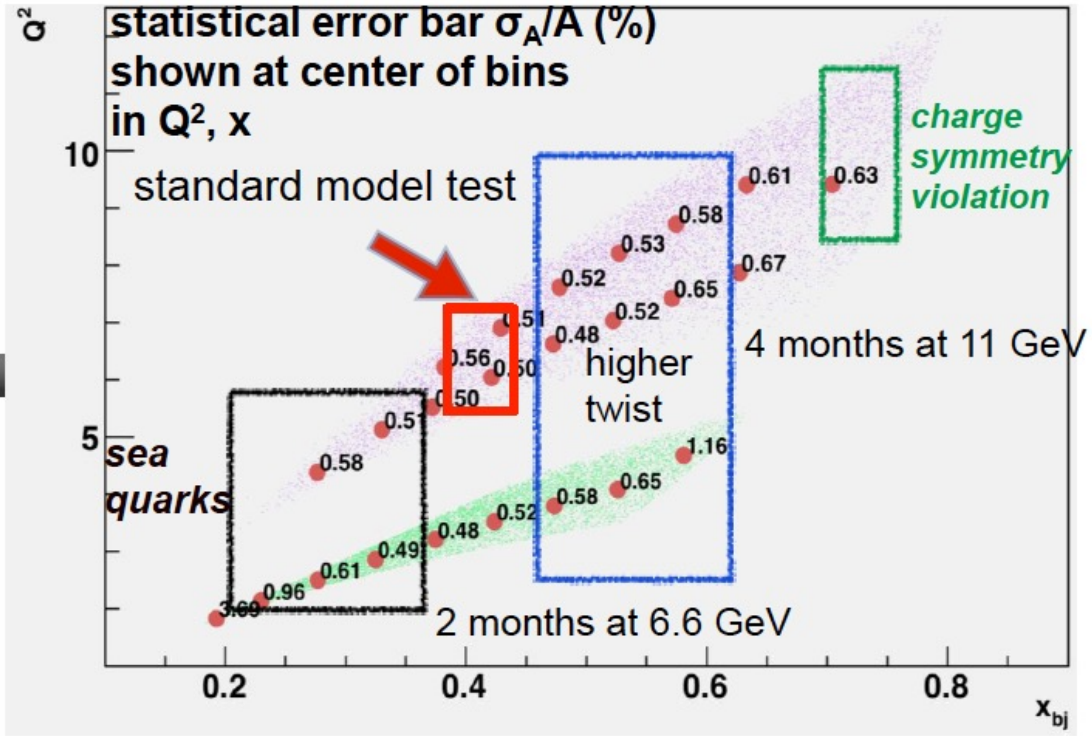
PRiSMA+

JLab 12 GeV: Extraordinary opportunity to do the ultimate PVDIS Measurement

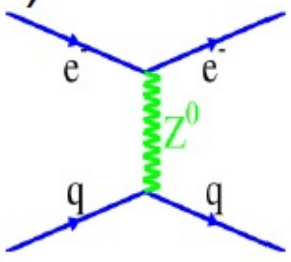
Strategy: **sub-1% precision** over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**

JLab





$g^{eq}_{VA}(\sin^2\theta_W)$



Only SoLID can measure g^{eq}_{VA}

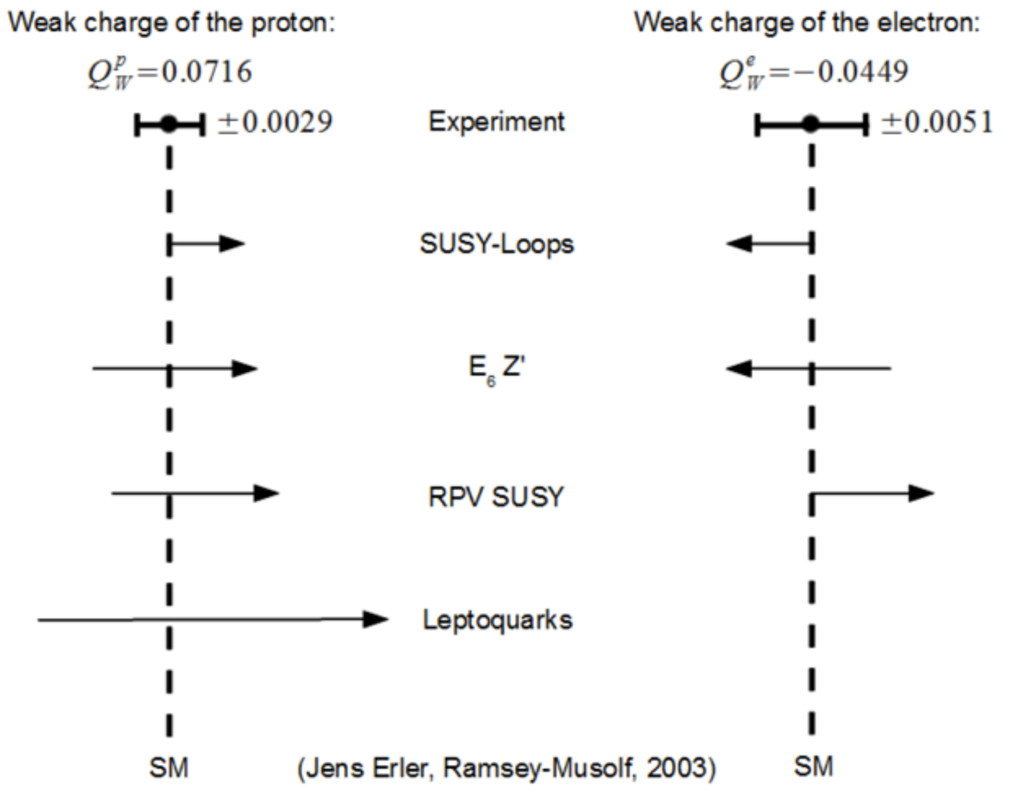
Three PV experiments with three different probes for new physics

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 with a sensitivity to new physics 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, installation of magnet yoke started, start commissioning 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