JG|U

SFB 1044
Institut für Kernphysik

# Fundamental weak interaction studies with electron beams

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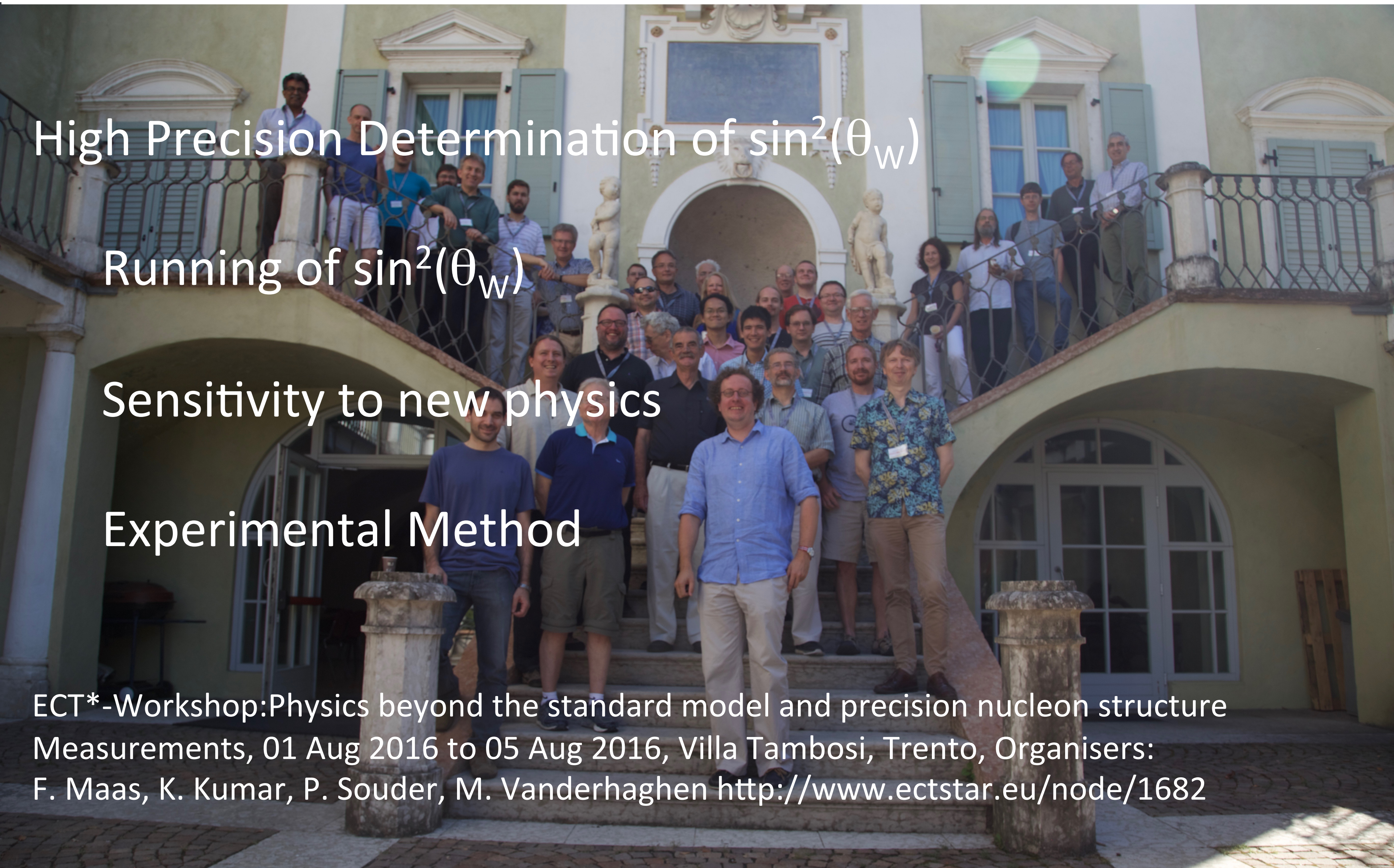
GSI Darmstadt and
Johannes Gutenberg University Mainz)

**Physics of fundamental Symmetries and Interactions - PSI2016**

SFB 1044

HIM

PRISMA



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

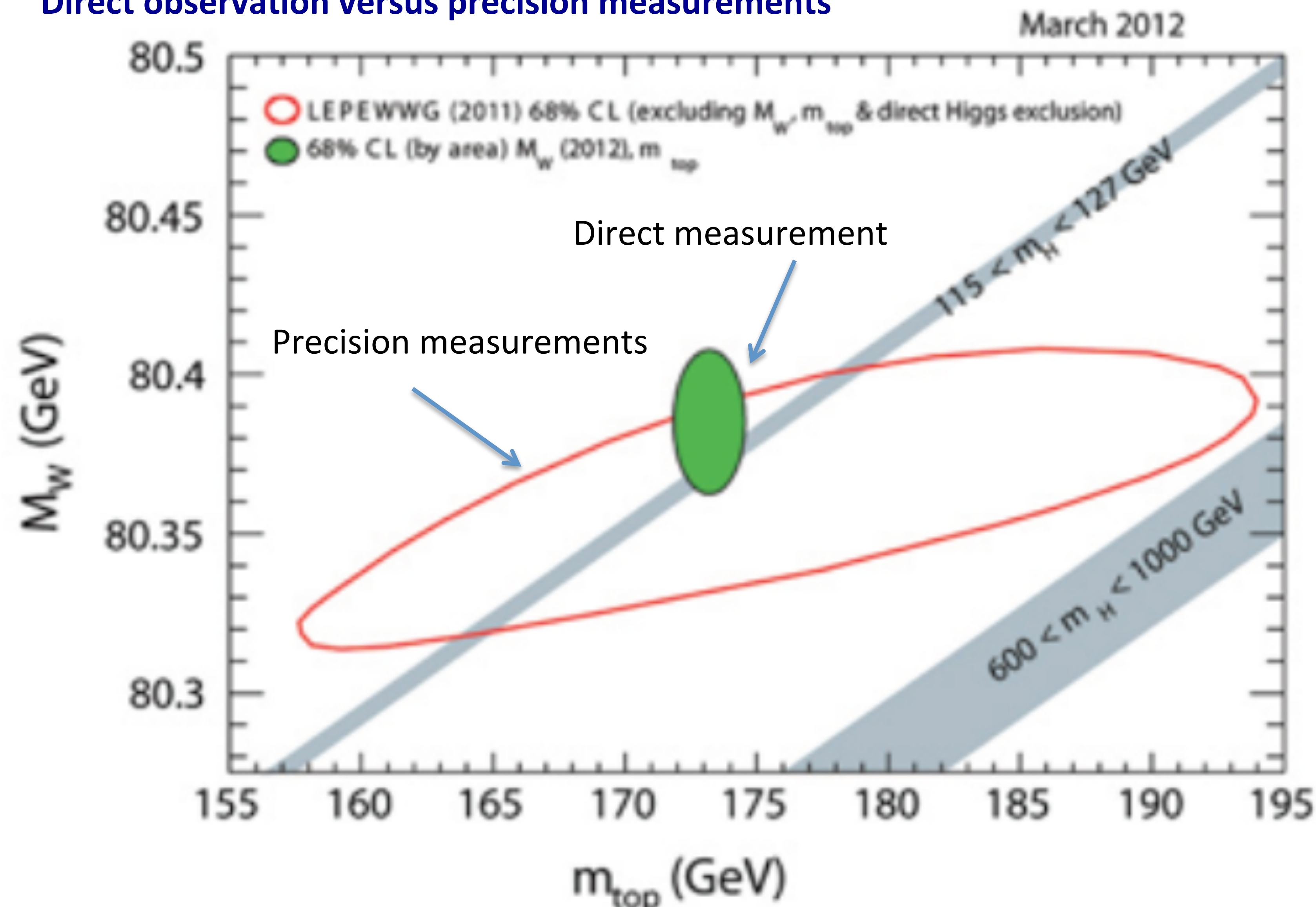
Running of $\sin^2(\theta_W)$

Sensitivity to new physics

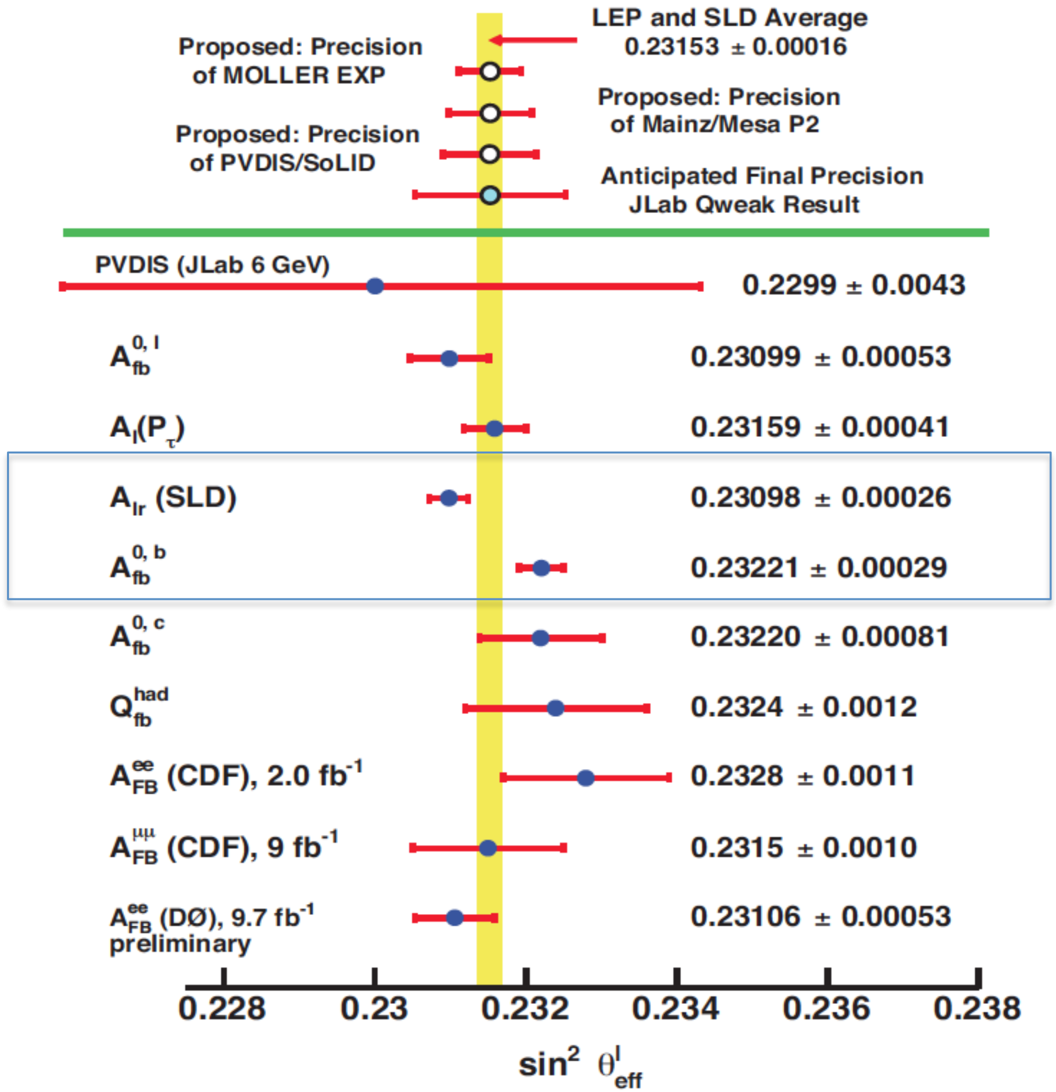
Experimental Method

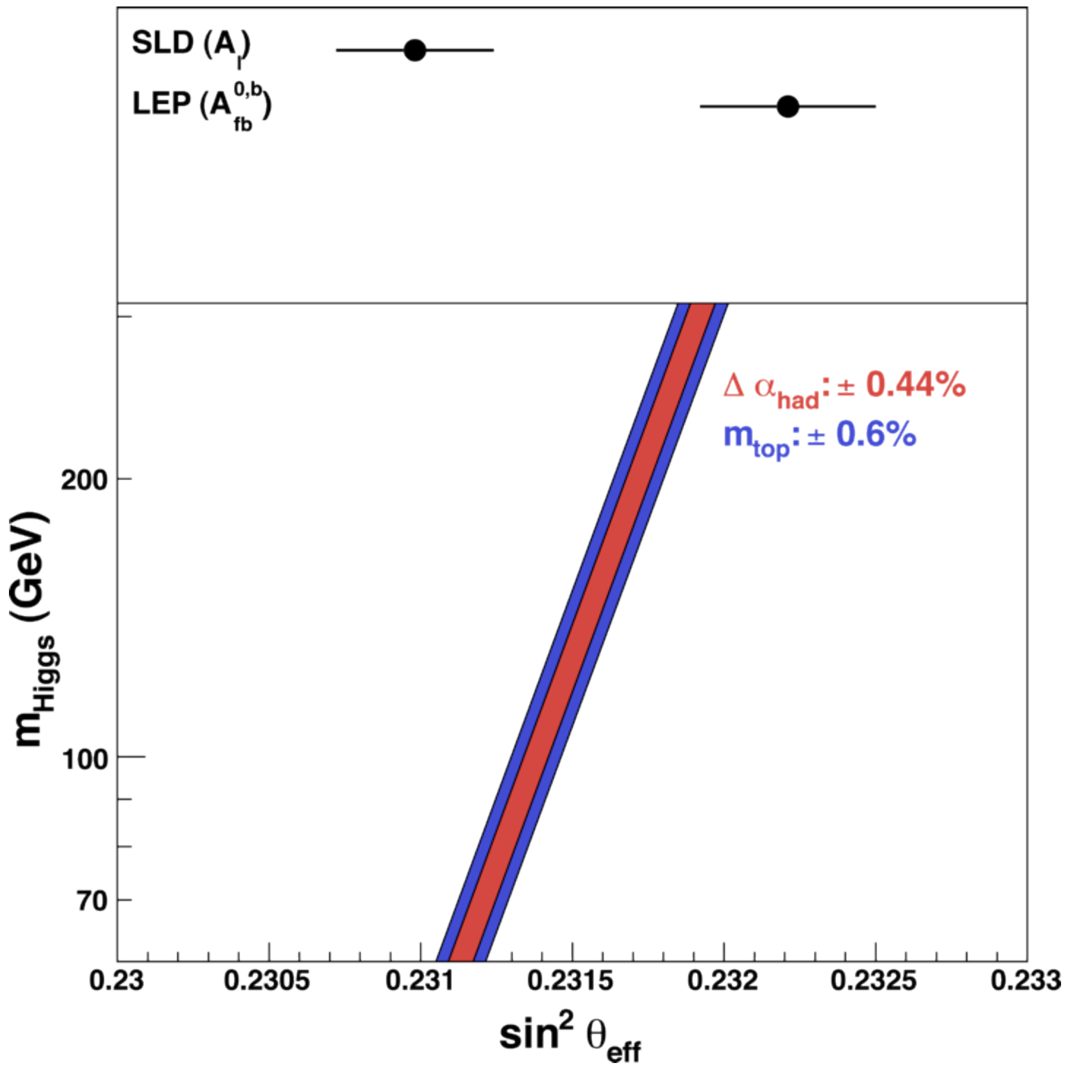
ECT*-Workshop:Physics beyond the standard model and precision nucleon structure Measurements, 01 Aug 2016 to 05 Aug 2016, Villa Tambosi, Trento, Organisers: F. Maas, K. Kumar, P. Souder, M. Vanderhaghen http://www.ectstar.eu/node/1682

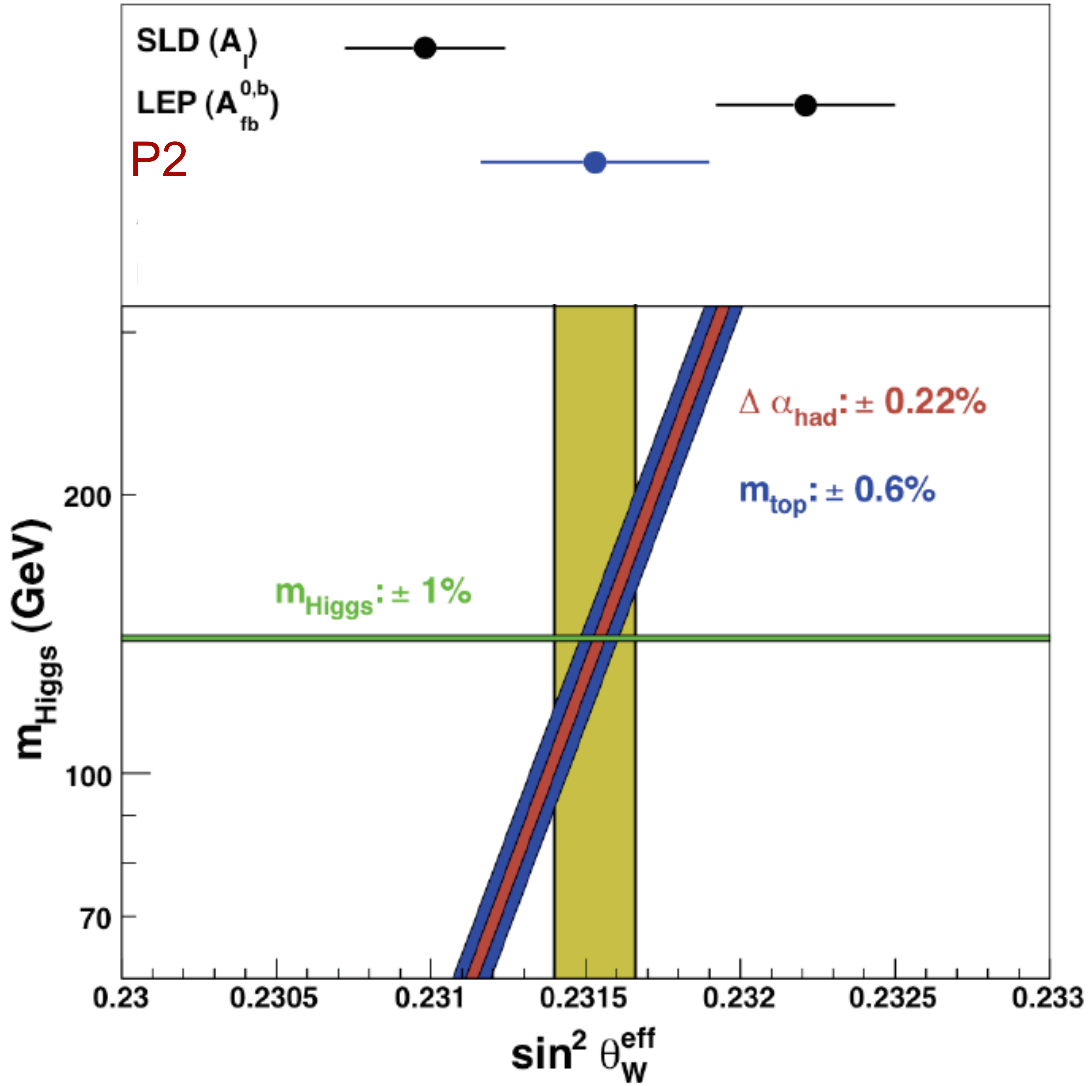
## Direct observation versus precision measurements



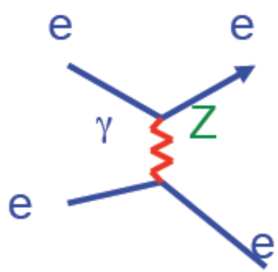
# Summary: Measurements of $\sin^2\theta_{W(\text{effective})}$




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
$\sin^2\theta_{eff}$

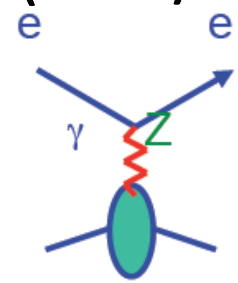

SLD ($A_l$)
LEP ($A_{fb}^{0,b}$)
P2
$\Delta\ \alpha_{had}$: ± 0.22%
$m_{top}$: ± 0.6%
$m_{Higgs}$: ± 1%
200
100
70
$m_{Higgs}$ (GeV)
0.23
0.2305
0.231
0.2315
0.232
0.2325
0.233
$\sin^2 \theta_W^{eff}$

## Møller Scattering



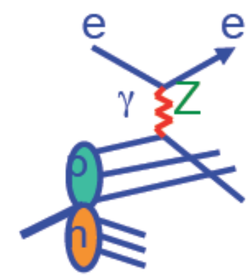

- Purely Leptonic

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



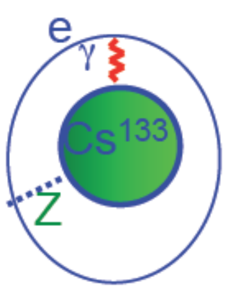

- Coherent quarks in p
- in operation now
- $2(2C_{1u}+C_{1d})$

## e-DIS



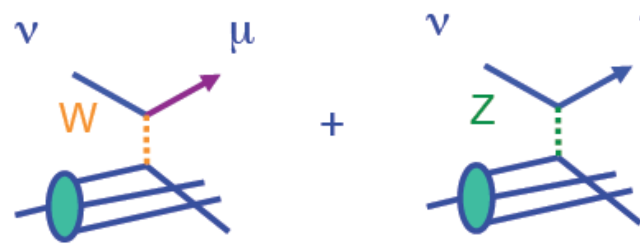

- Isoscaler quark scattering
- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

## Atomic Parity Violation




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

## Neutrino Scattering



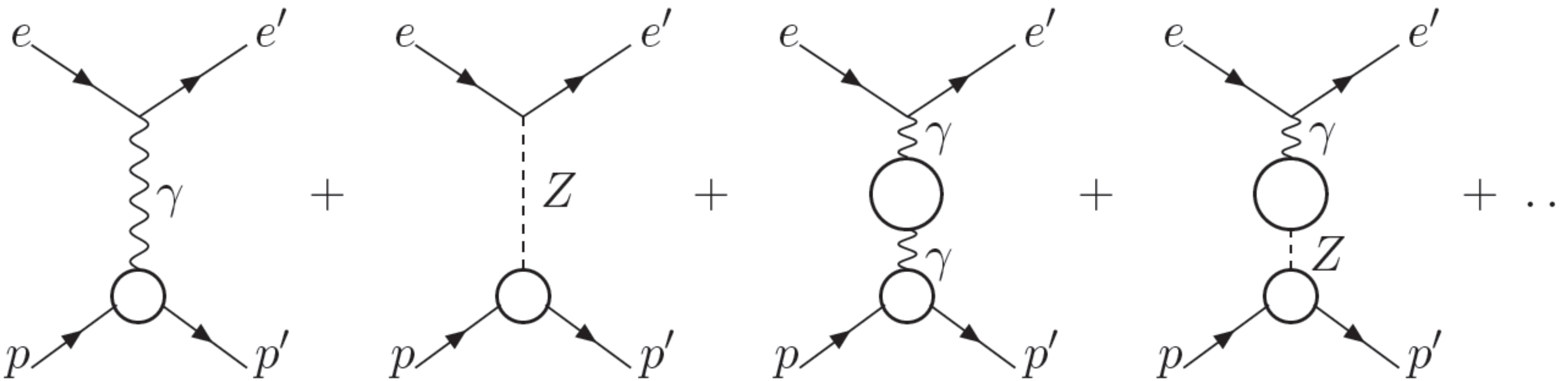

- Quark scattering (from nucleus)
- Weak charged and neutral current difference



Courtesy of P. Reimer and R. Arnold

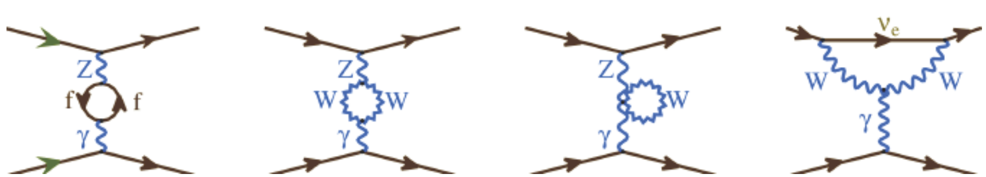
„running“ $\sin^2 \theta_{eff}$ or $\sin^2 \theta_W(\mu)$

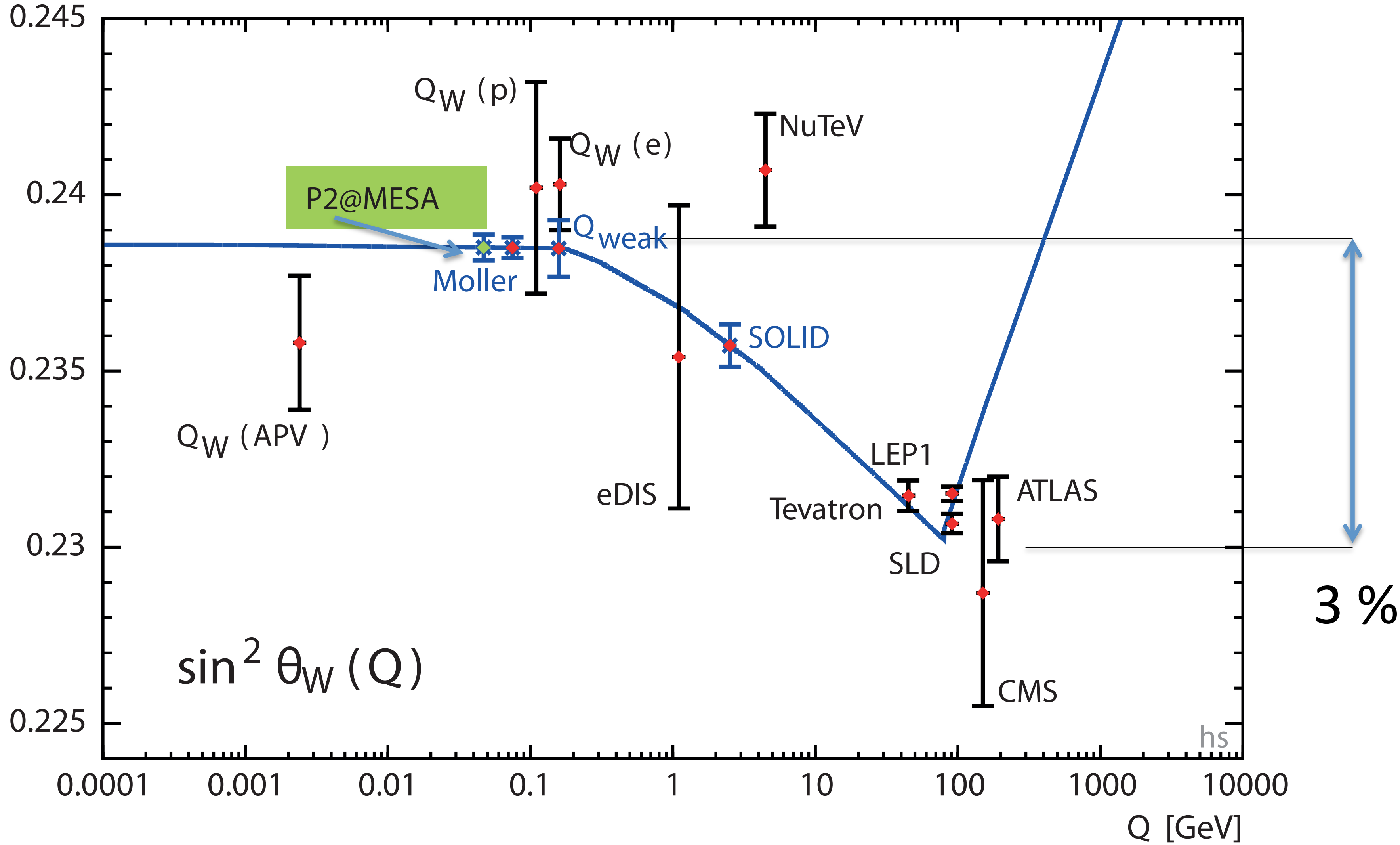
# Precision measurements and quantum corrections:




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

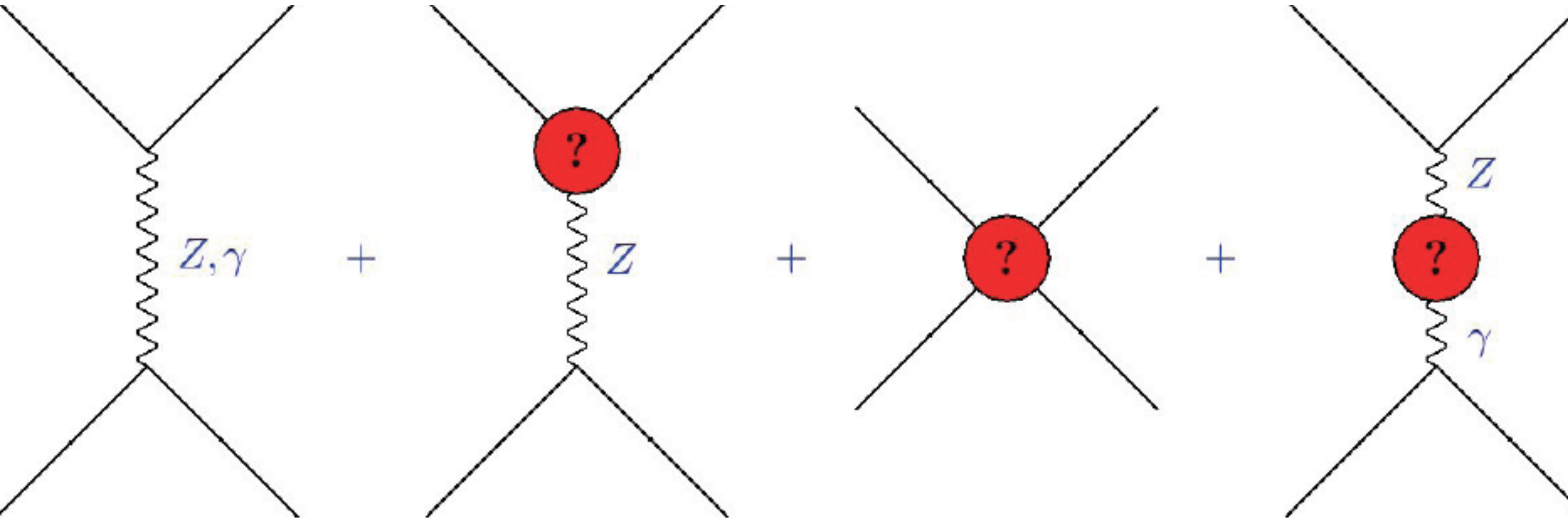
**Universal quantum corrections: can be absorbed into a**
**scale dependent, „running“ $\sin^2\theta_{eff}$ or $\sin^2\theta_W(\mu)$**




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
$\sin^2\theta_W(Q)$
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

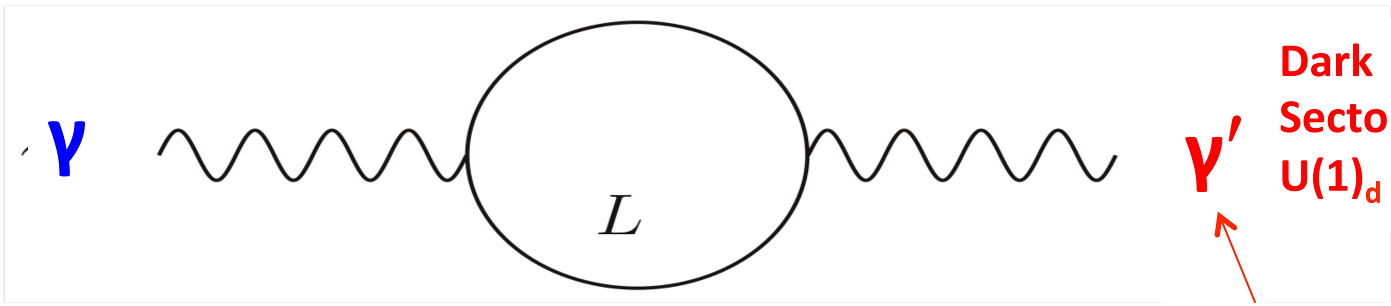
New Fermions

# Dark Photon, Z-Boson

Holdom 86

## A portal to relate the dark sector to the SM world (coupling ~ $\varepsilon^2$)

**Standard Model Sector U(1)**




**Dark Sector $U(1)_d$**

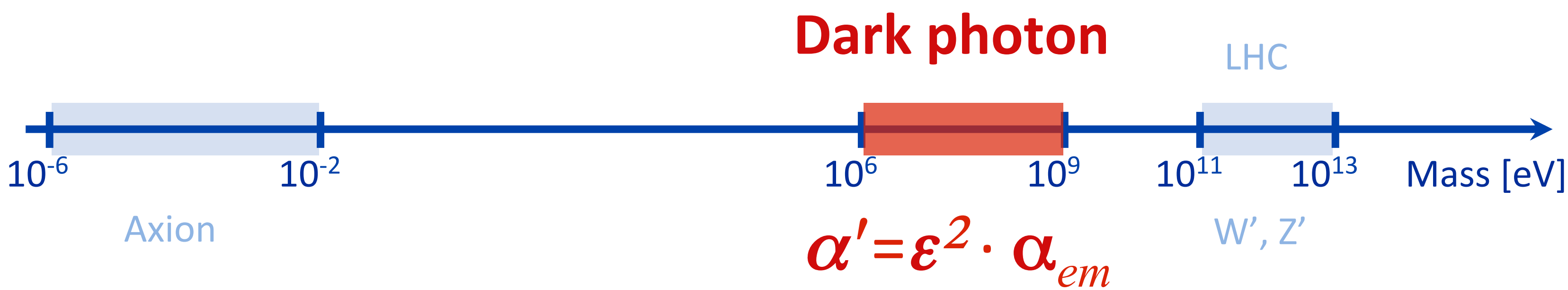
Heavy Charged Leptons *L*
(carry $U(1)_d$ charge)

**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**



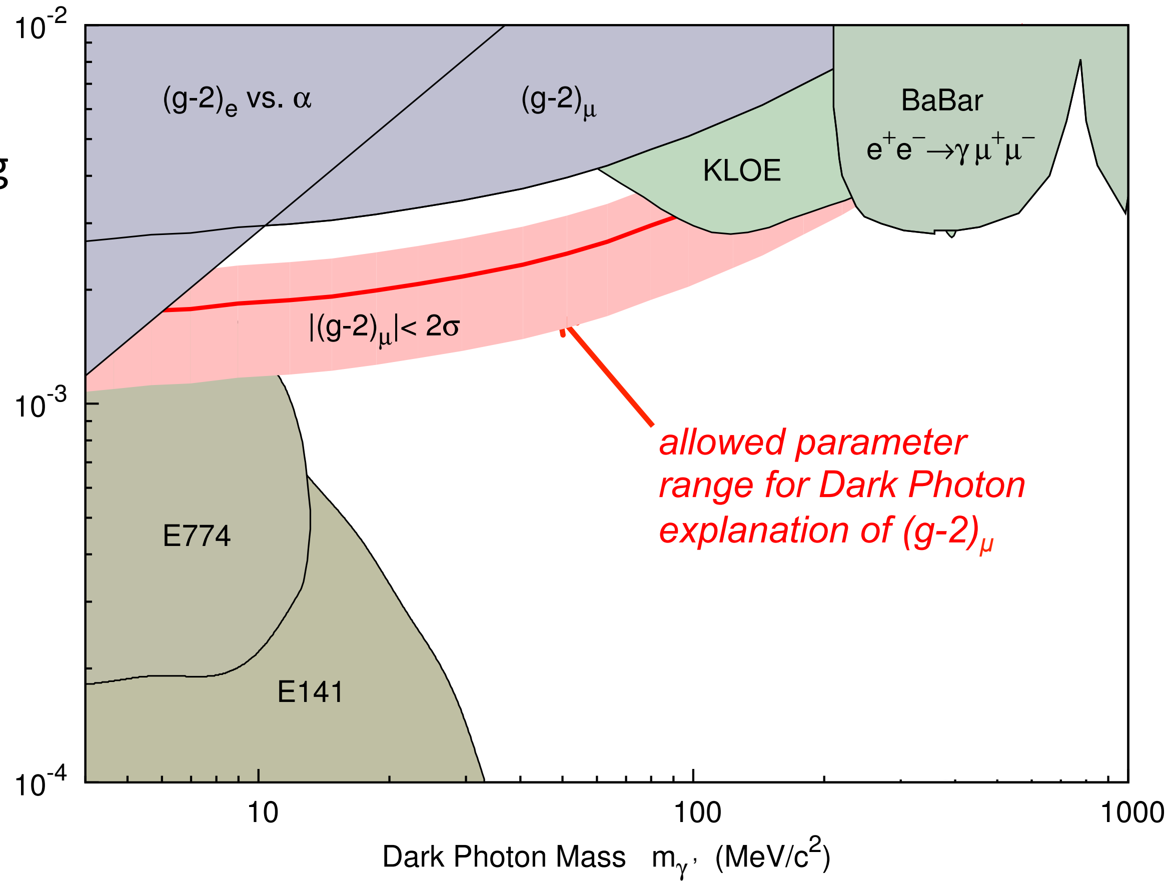

## Search for the O(GeV/$c^2$) mass scale in a world-wide effort

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

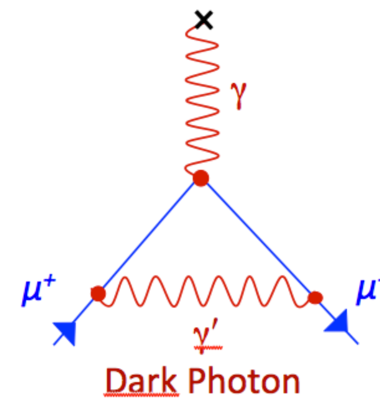
- Could explain presently seen **deviation of >3σ** between **$(g\text{-}2)_\mu$** Standard Model prediction and direct $(g\text{-}2)_\mu$ measurement
  Pospelov(2008)

**Status 2011**

Coupling



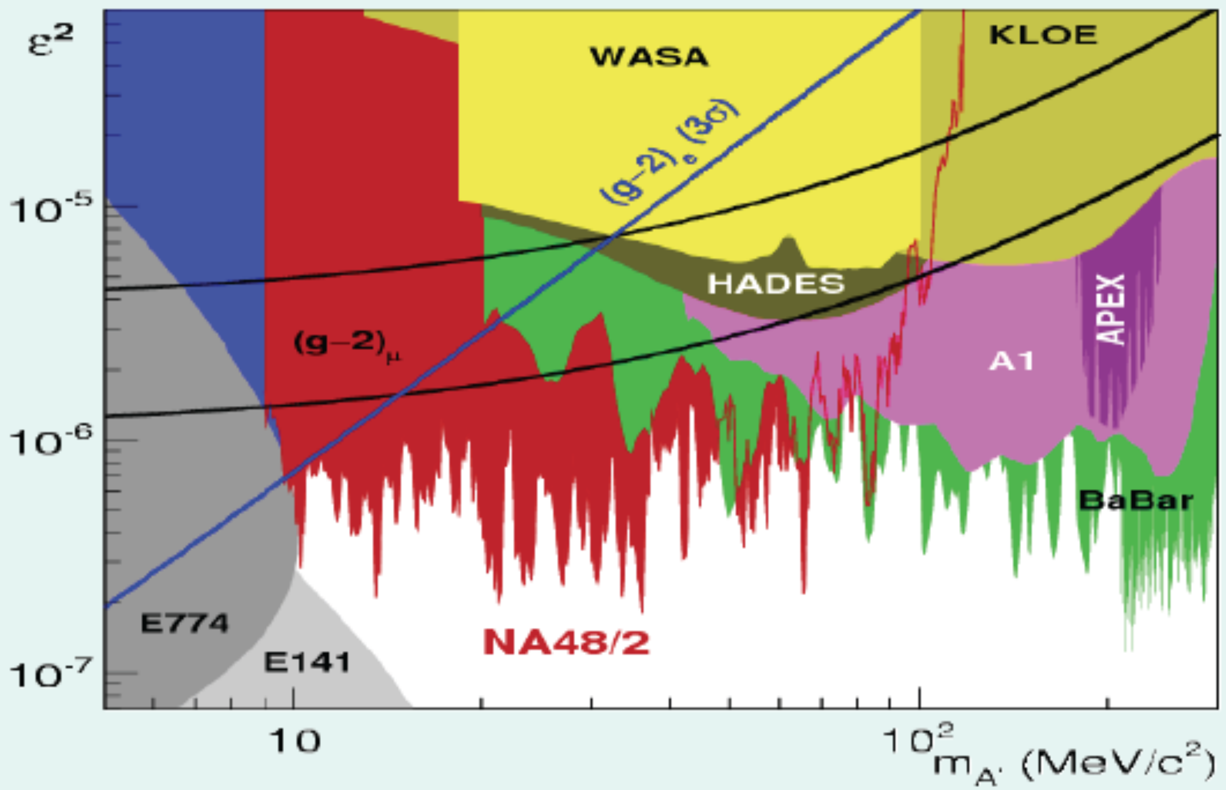

Mass



NA48/2 Updated Bounds on Dark Photon

**$g_\mu$-2 discrepancy solution ruled out**

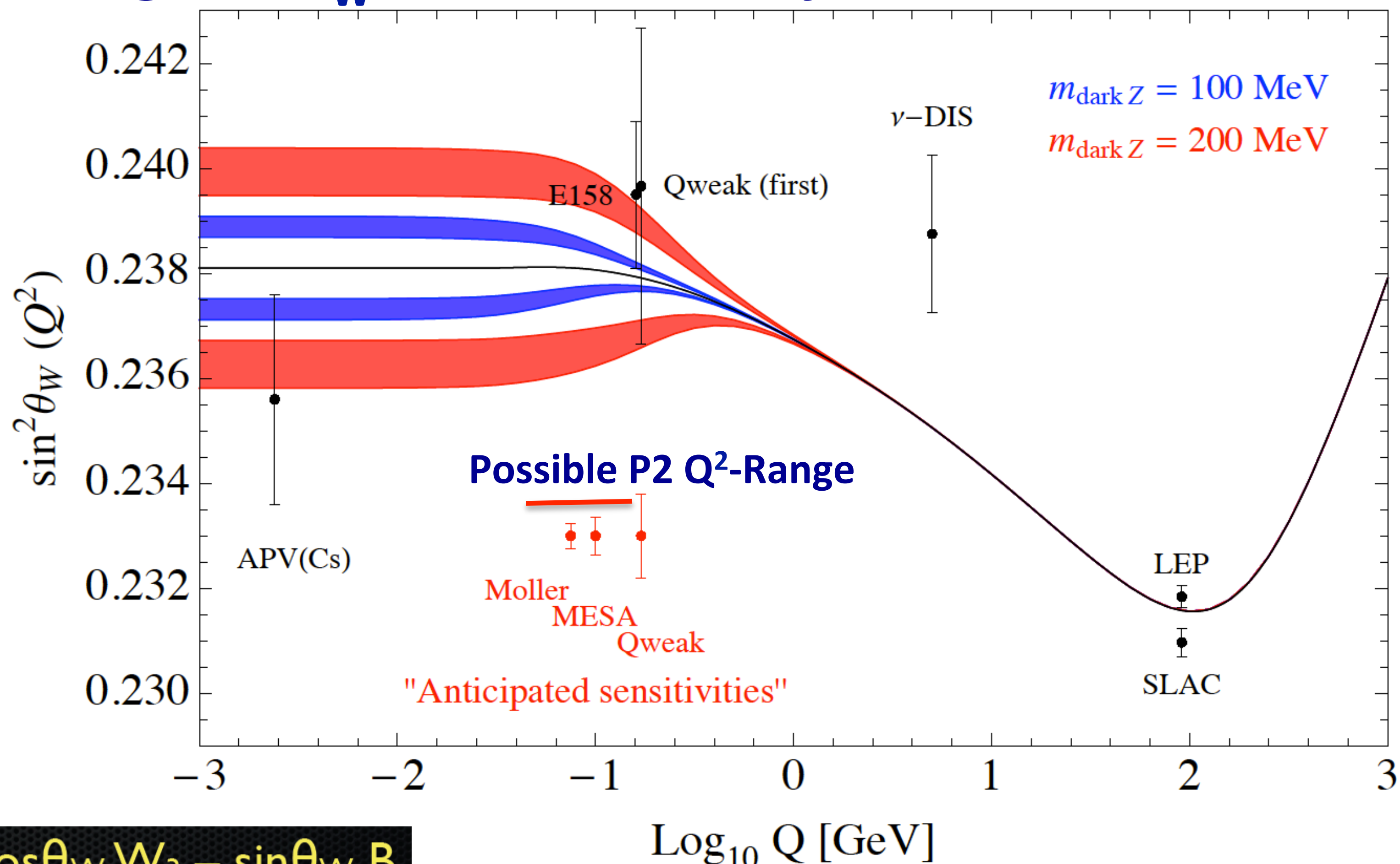
Assumes BR($Z_d$→ e+e-) ~1






H. Davoudiasl, W. Marciano

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

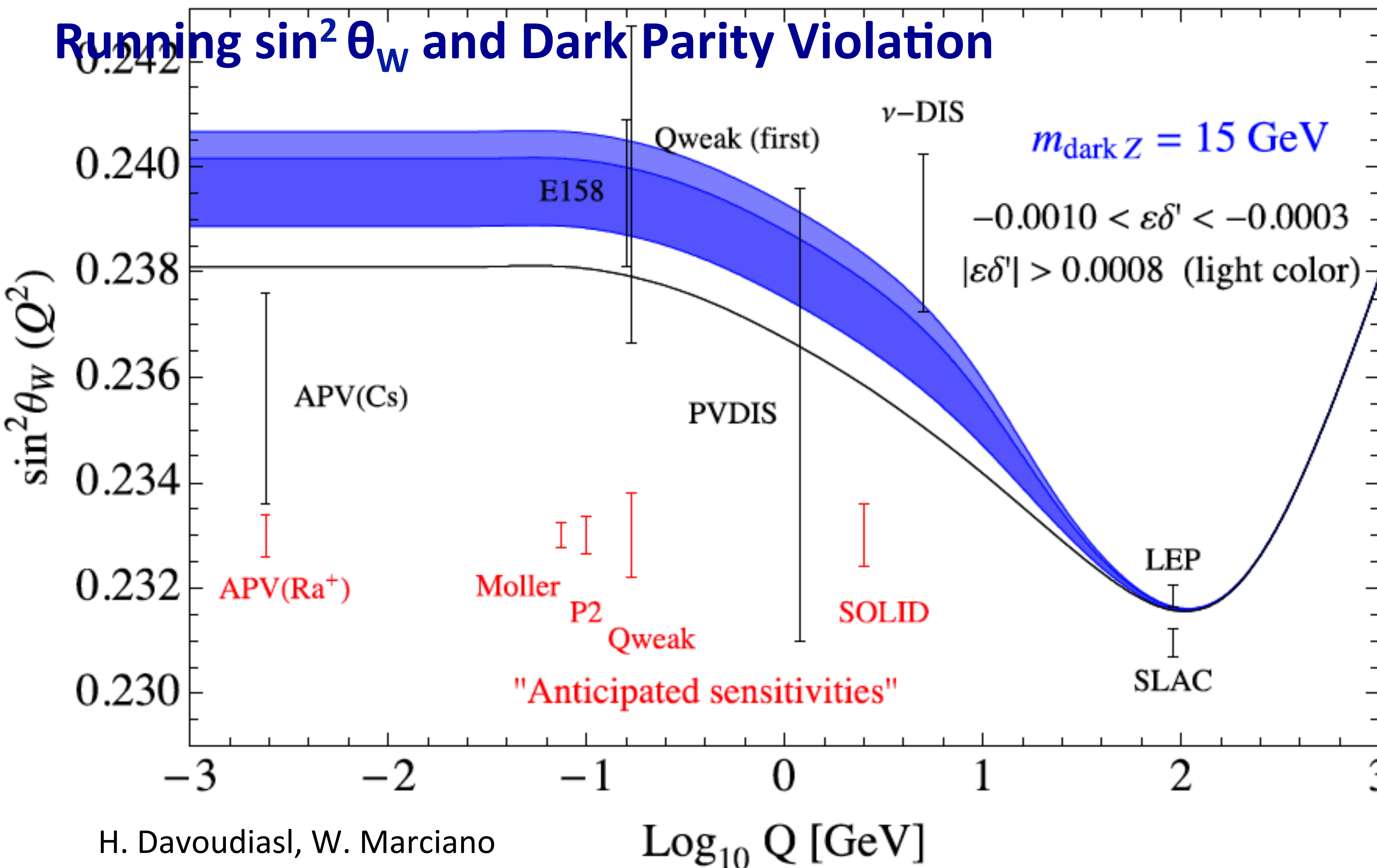



$Z = \cos\theta_W W_3 - \sin\theta_W B$

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

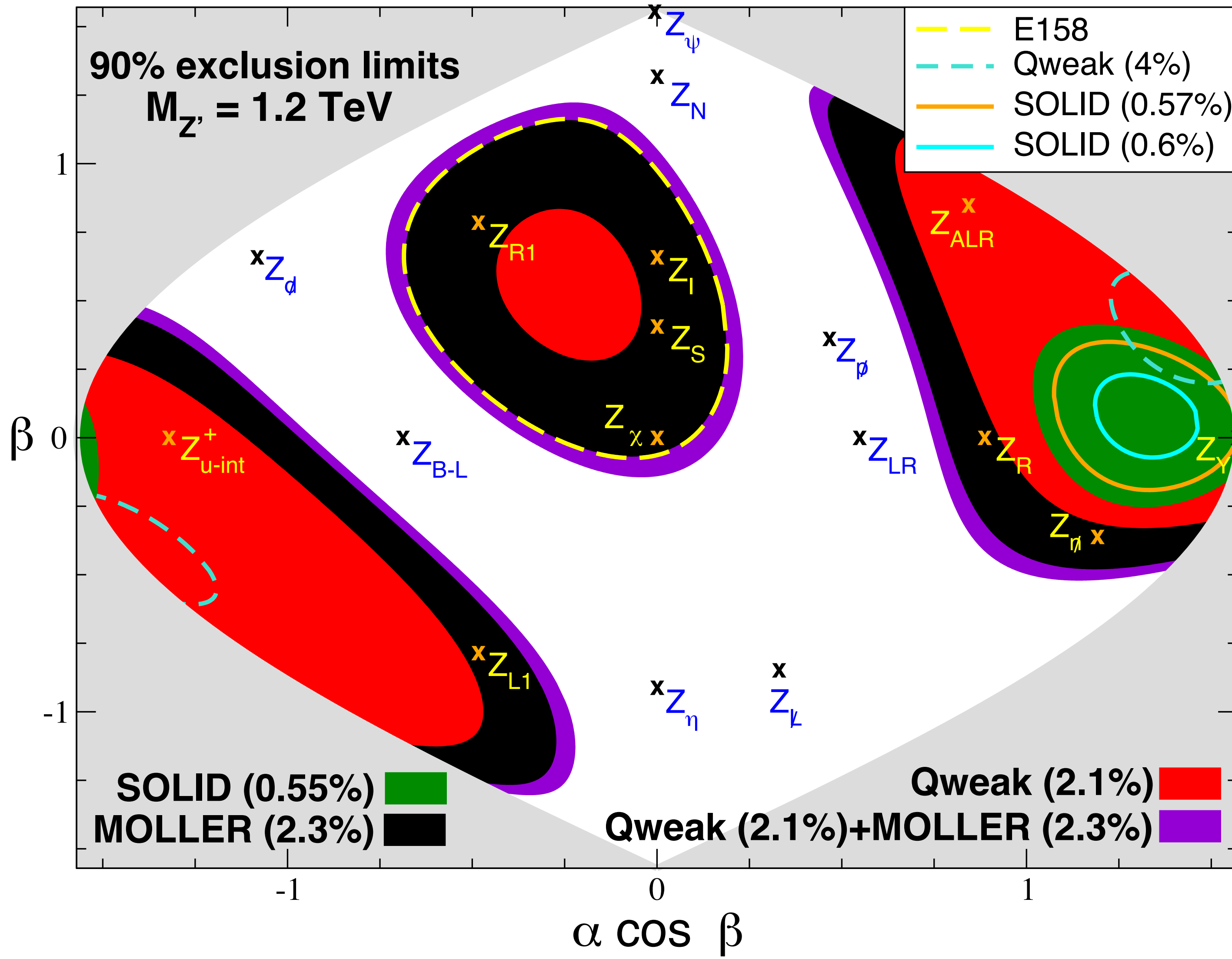
Bill Marciano

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




H. Davoudiasl, W. Marciano

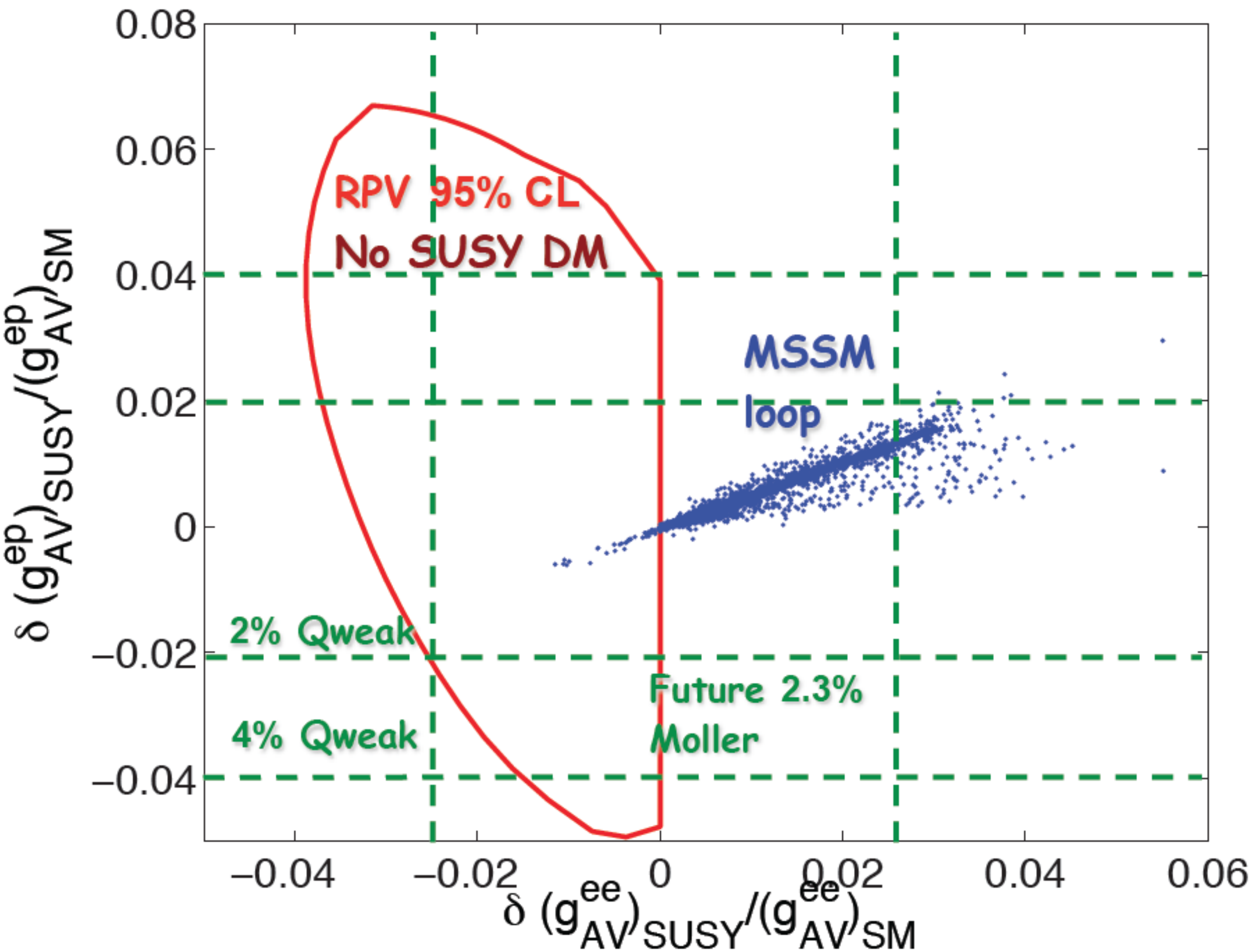
# Extra Z-Boson


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

# Supersymmetry

Example: Supersymmetric standard model extensions

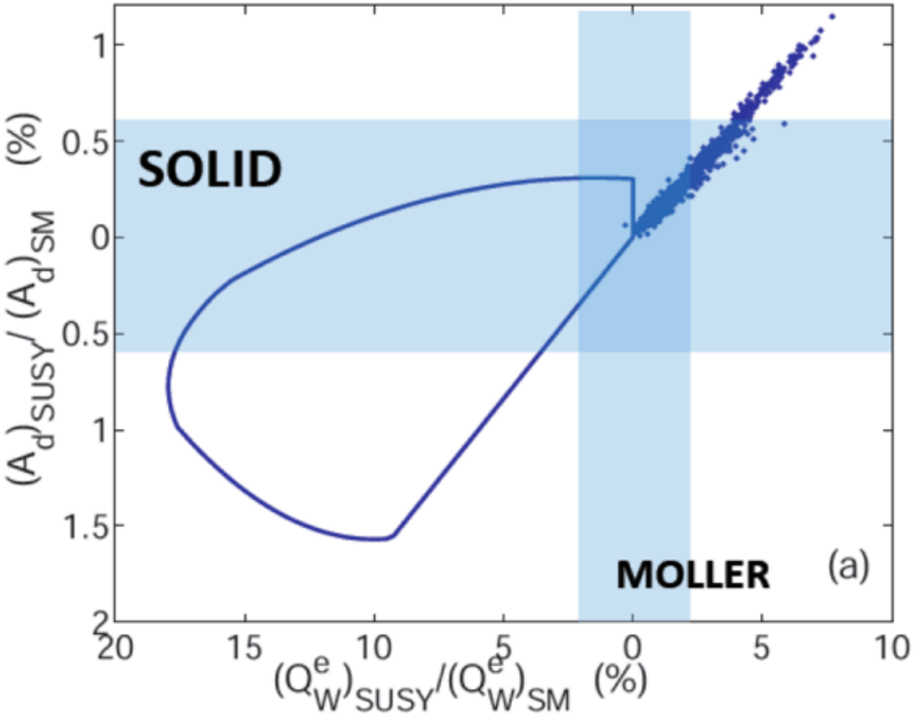
Kurylov, Ramsey-Musolf, Su (2003), updated

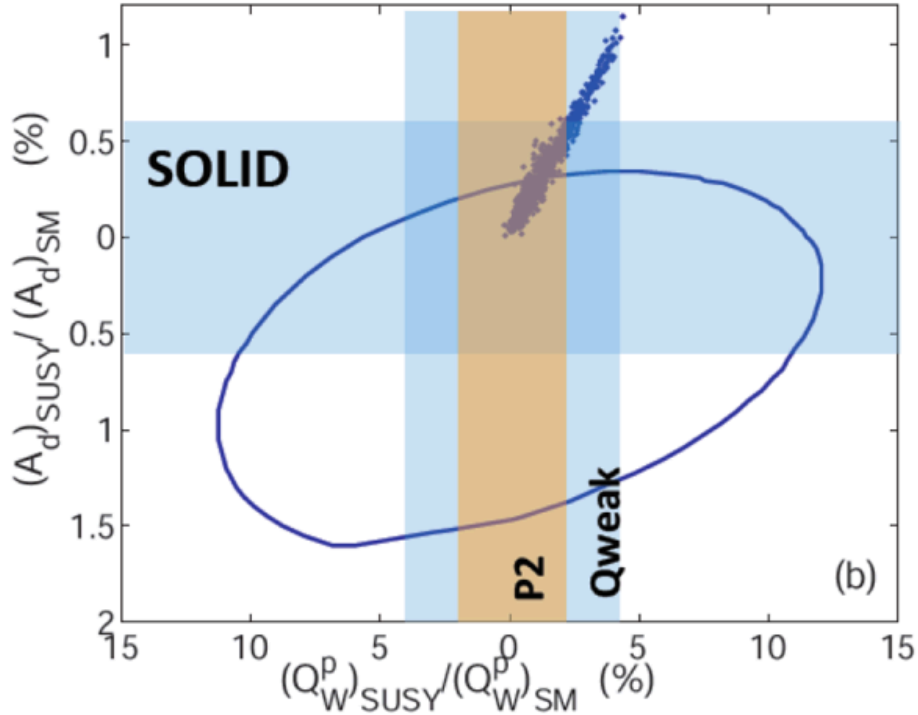



After LHC
Run 1

X. Su

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

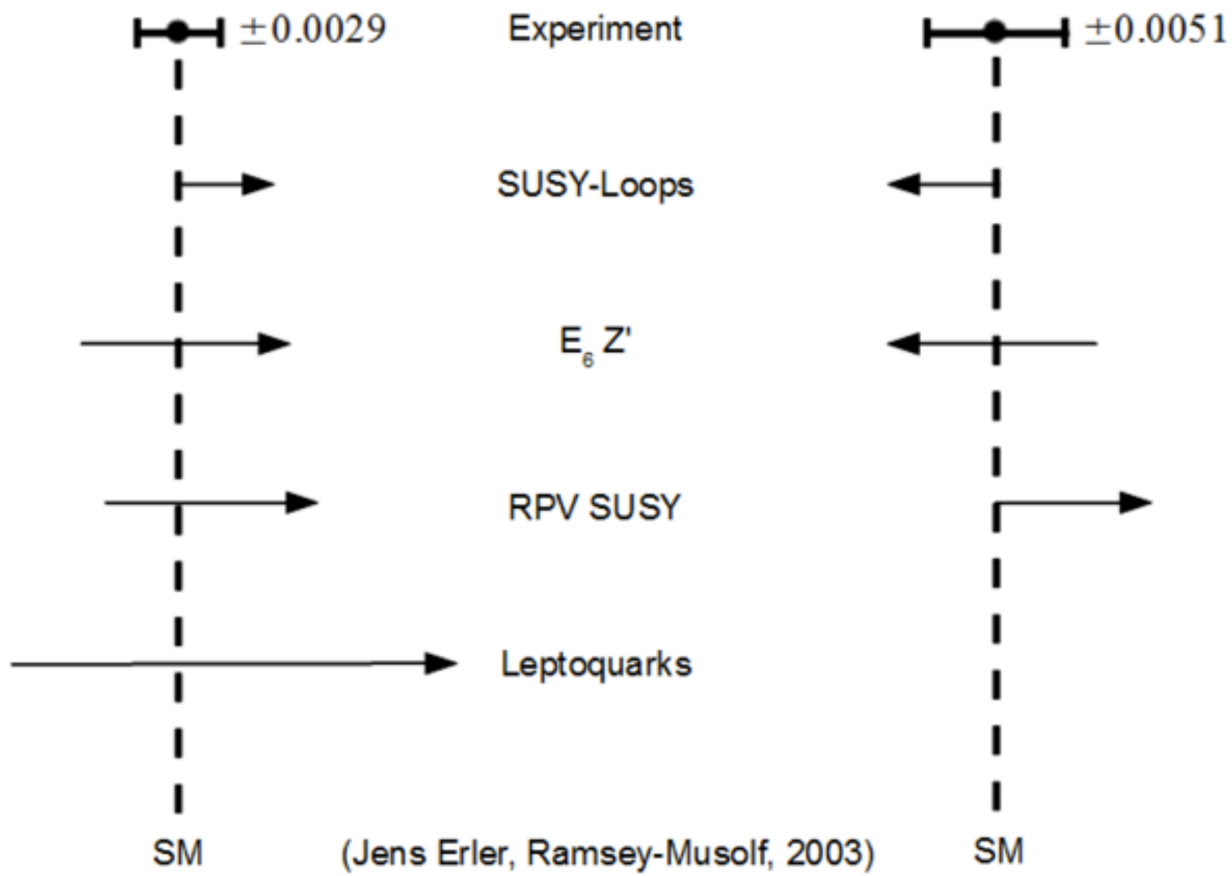


- Complementary access by weak charges of proton and electron

Weak charge of the proton: $Q_W^p = 0.0716$

Weak charge of the electron: $Q_W^e = -0.0449$



**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, $g^2 = 4pi$)

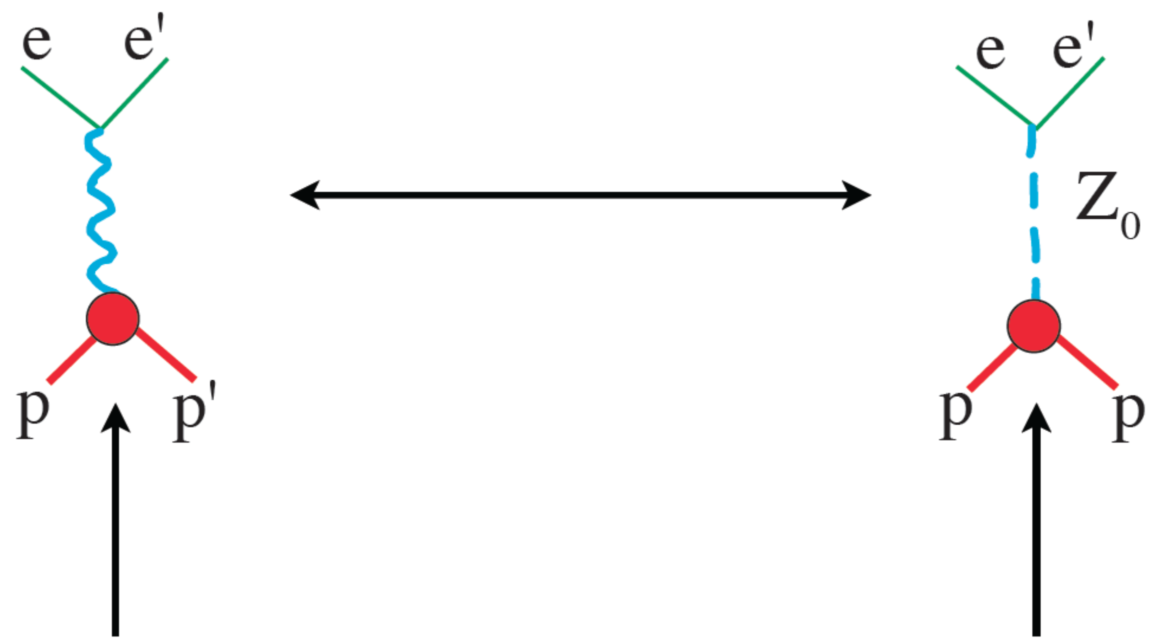
| | precision | $\Delta \sin^2\overline{\theta}_W(0)$ | $\Lambda_{new}$ (expected) |
|---|---|---|---|
| APV Cs | 0.58 % | 0.0019 | 32.3 TeV |
| E158 | 14 % | 0.0013 | 17.0 TeV |
| Qweak I | 19 % | 0.0030 | 17.0 TeV |
| Qweak final | 4.5 % | 0.0008 | 33 TeV |
| PVDIS | 4.5 % | 0.0050 | 7.6 TeV |
| SoLID | 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

# 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

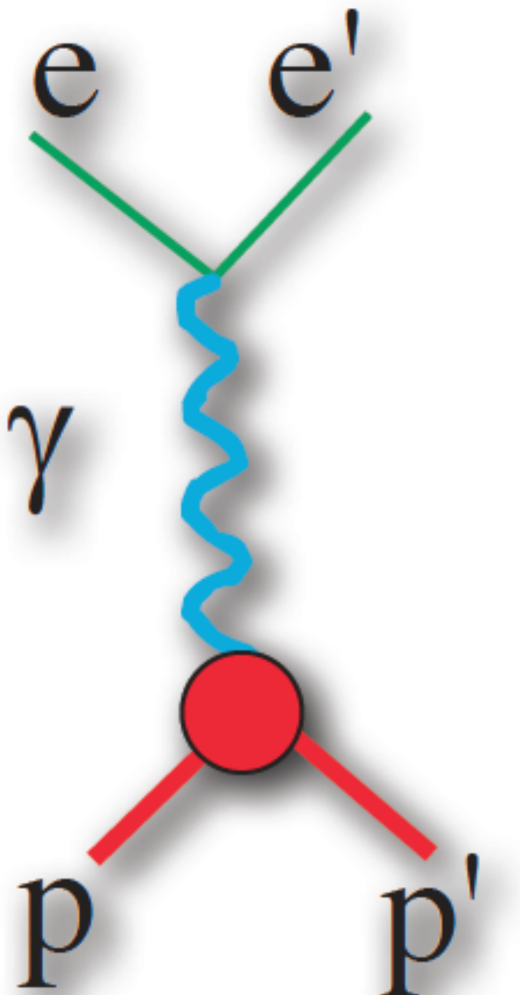
$\sin^2\theta_W$: a central parameter of the standard model

# 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: | $\Delta Q_W(p)/Q_W(p)$ | = | $4/\left(\,(1/\sin^2\theta_W) - 4\,\right)\quad(\Delta\sin^2\theta_W/\sin^2\theta_W)$ | |
| Rel. error | $\Delta\sin^2\theta_W/\sin^2\theta_W$ | = | $\left(\,(1/\sin^2\theta_W) - 4\,\right)/4\quad\Delta Q_W(p)/Q_W(p)$ | |
| Example: | $\sin^2\theta_W\,(50\text{ MeV})$ | = | 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:

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



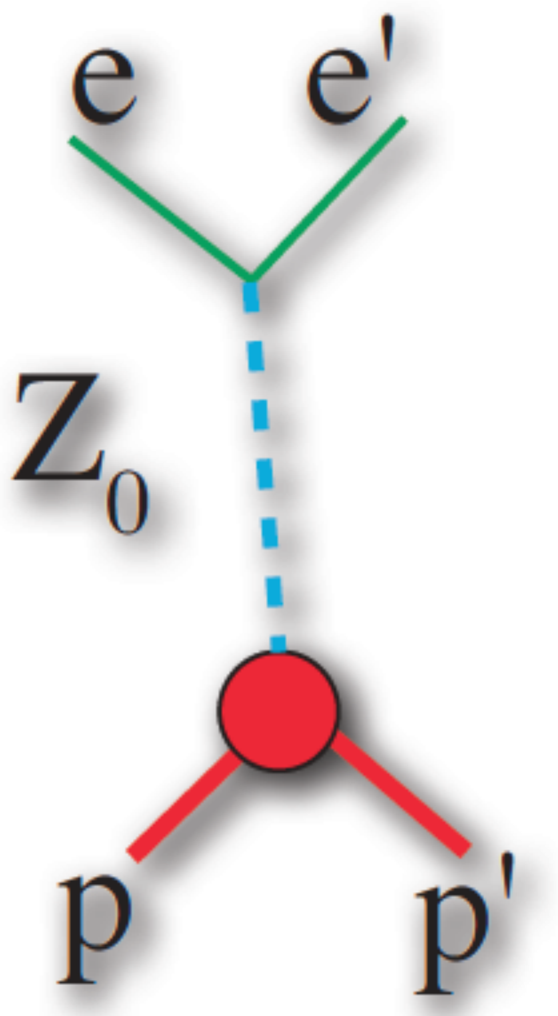

$$\sigma \sim \mathcal{M}\,\mathcal{M}^{*}\ \text{Phasespace}$$

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

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

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

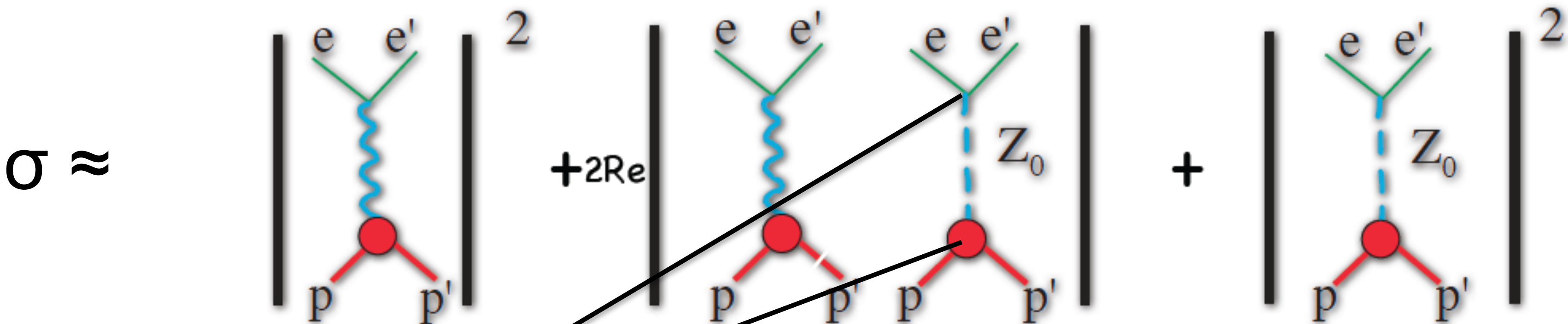
$$= \overline{\mathcal{P}}\left[\gamma^\mu F_1 - i\sigma^{\mu\nu} q_\nu \frac{\kappa_p}{2M_N} F_2\right]\mathcal{P}$$




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

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

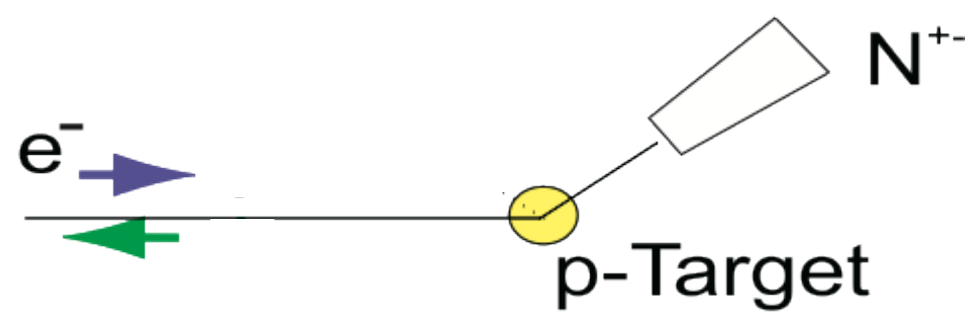
Parity Violating Asymmetry in elastic electron proton scattering



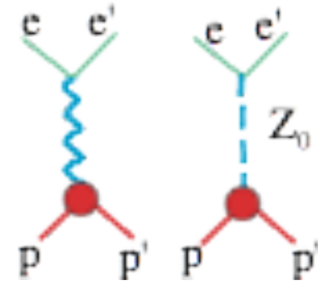

$(V\text{-}A)_e(V\text{-}A)_p$

$A_eV_p+V_eA_p$

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



# Parity violating cross section asymmetry




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

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

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

# Parity violating cross section asymmetry

tracking system

weak charge

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

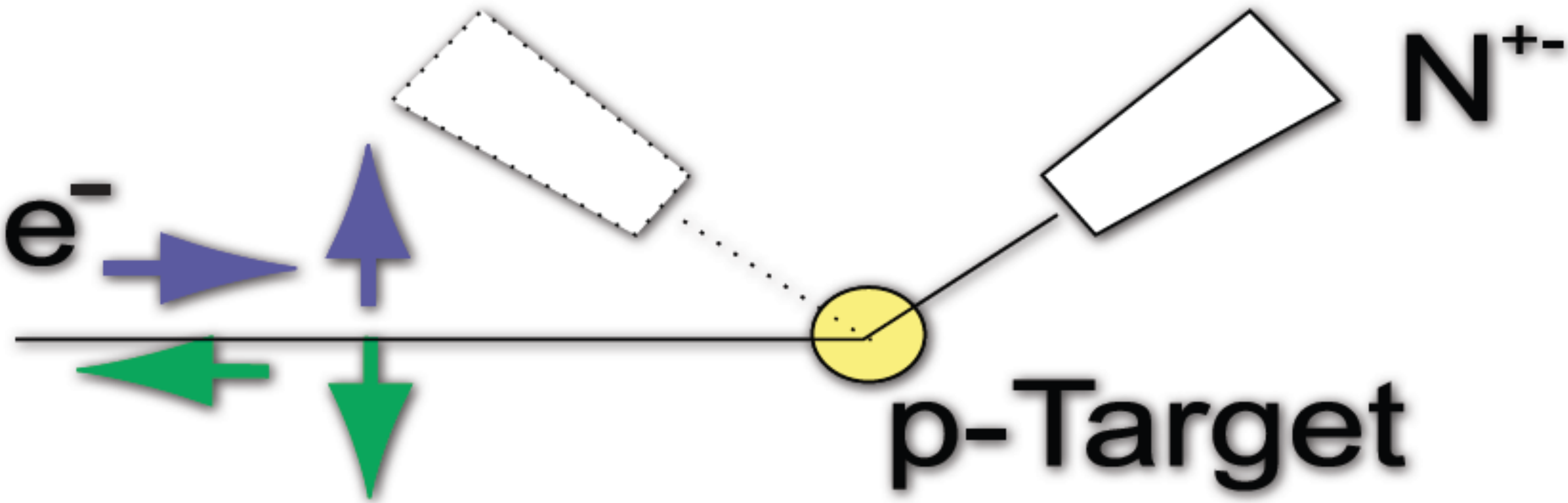
polarisation measurement

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

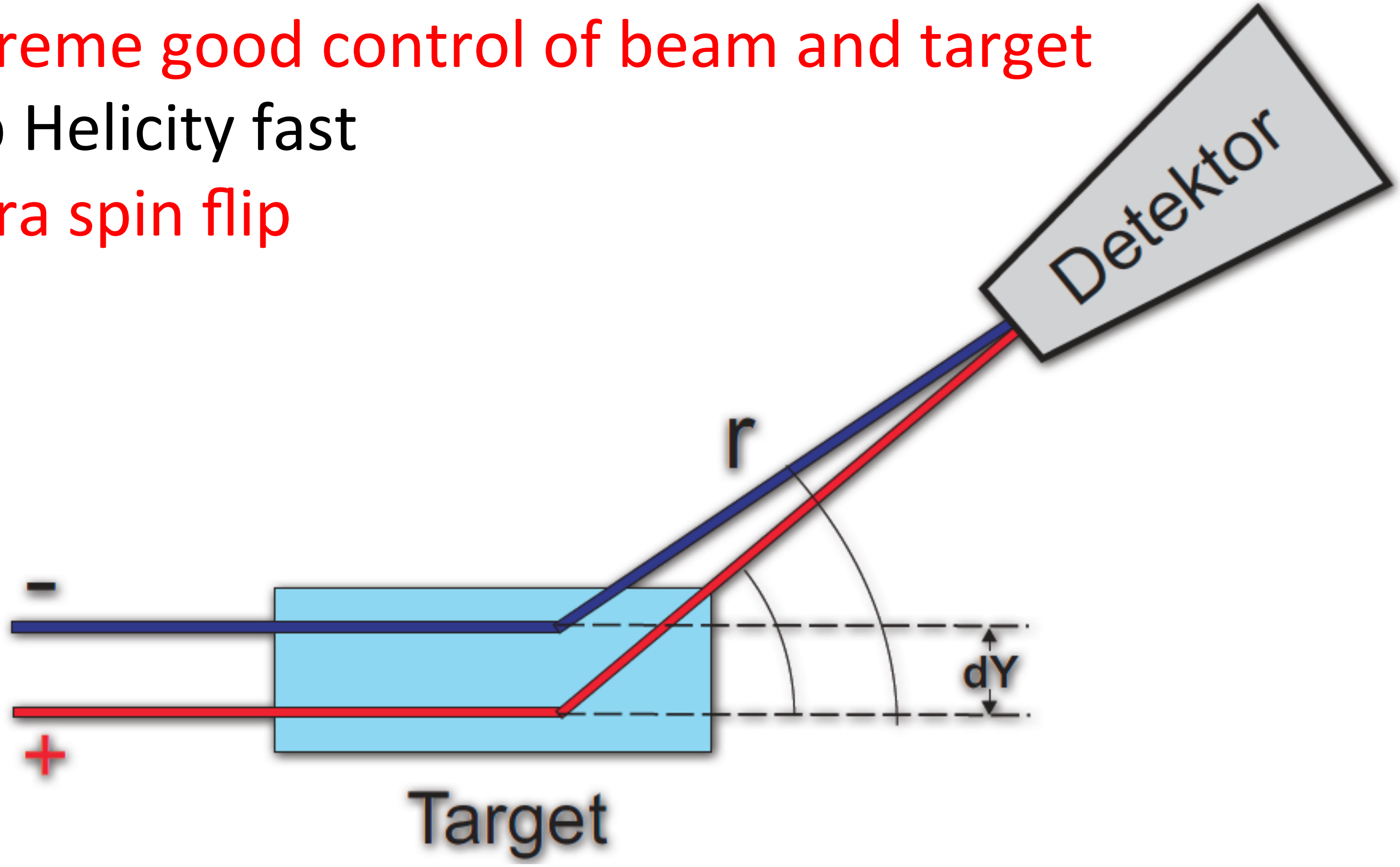
Highest rate, measure $Q^2$: Large Solid Angle Spectrometers

Apparative (false) asymmetries:

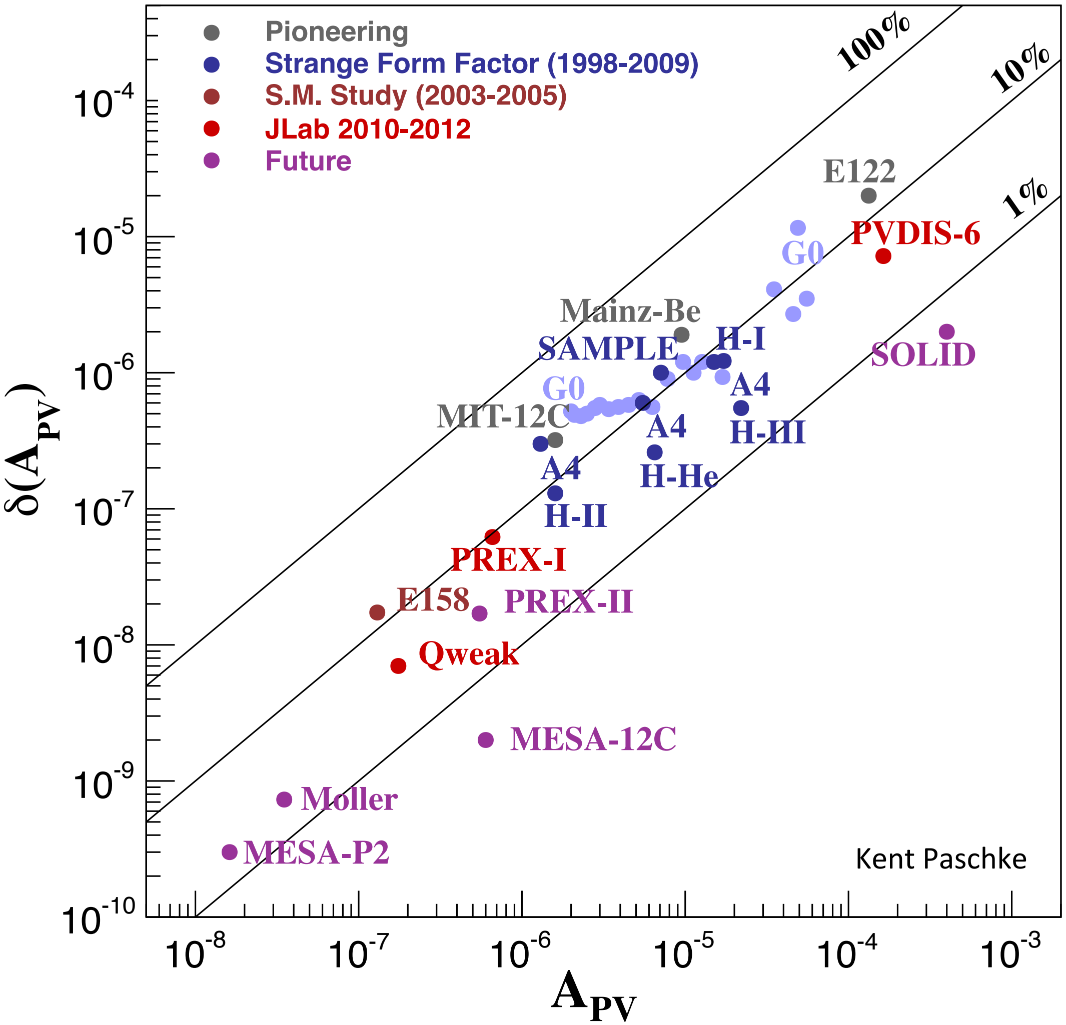
Extreme good control of beam and target

Flip Helicity fast

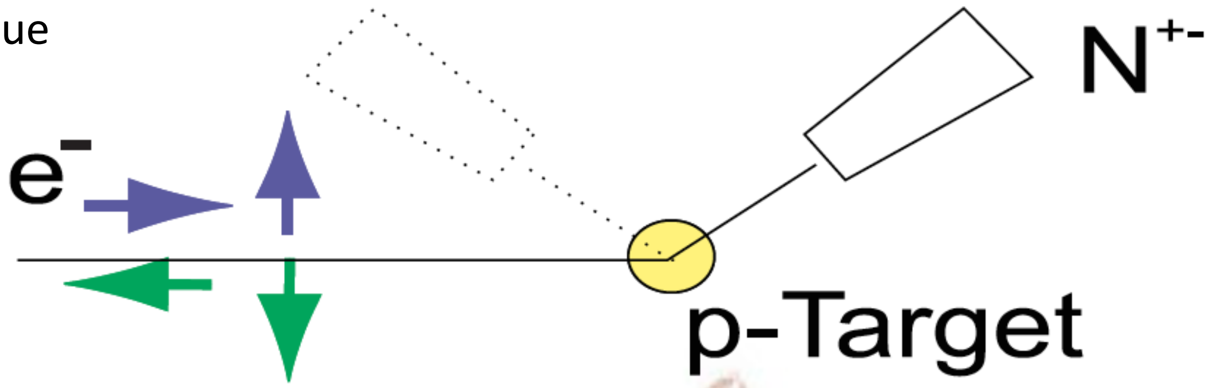
Extra spin flip



# PVeS Experiment Summary



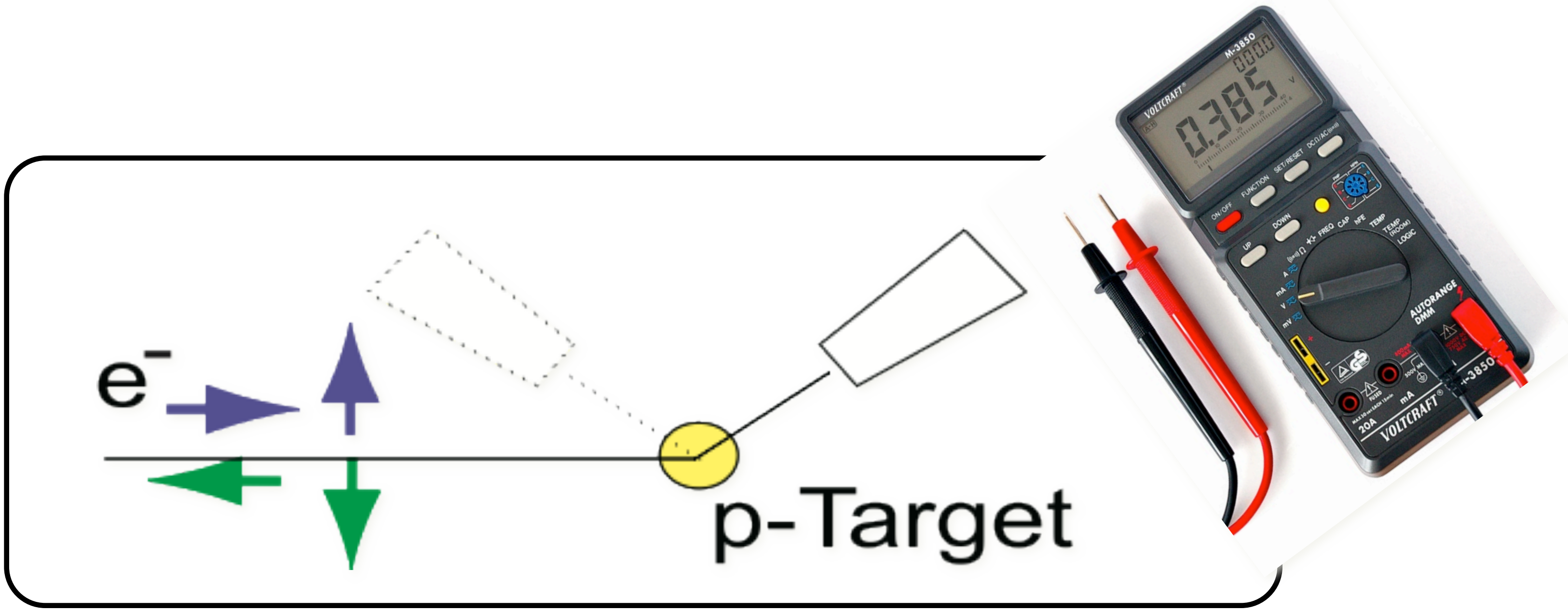
Counting Technique





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

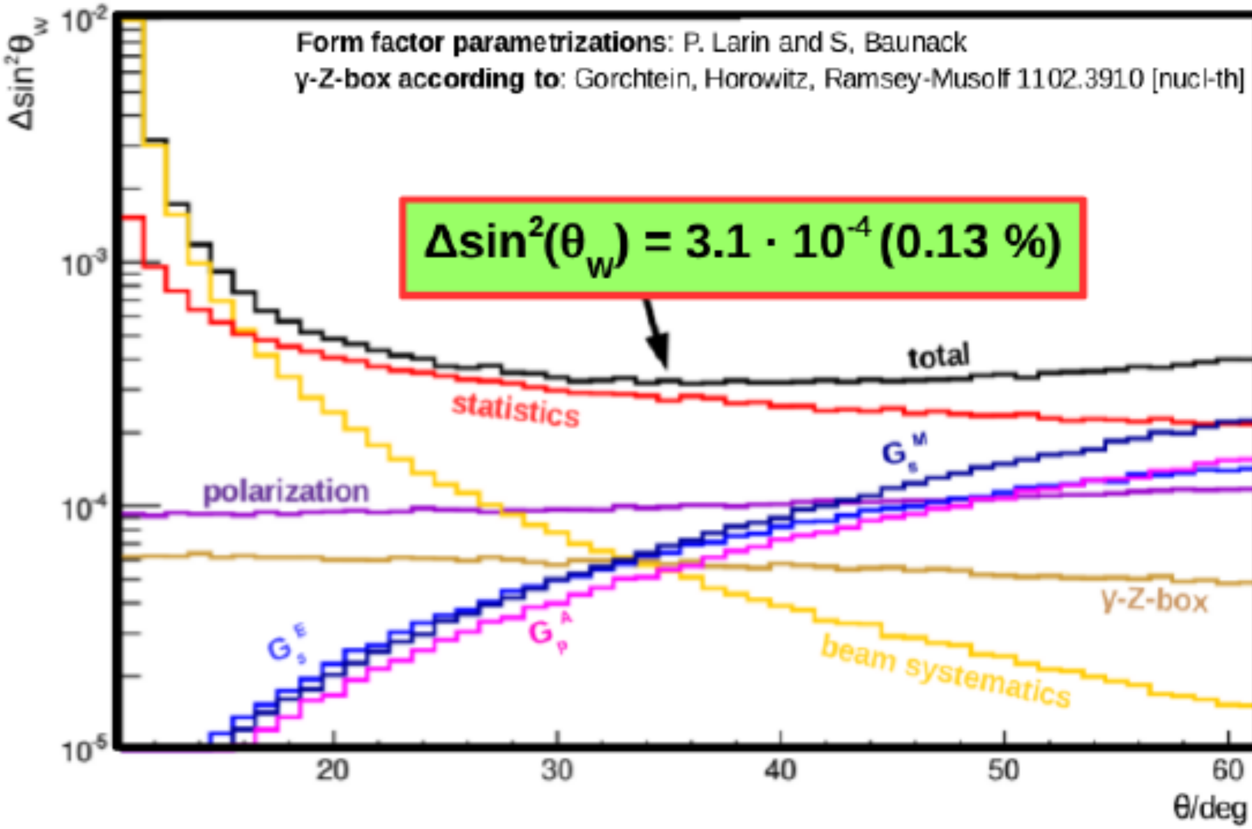
## Analogue Technique




Measure Flux of Scattered electrons:

- no pile-up (double count losses)
- sensitive to small electr. fields.
- no separation of phys. process

# P2-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

$\Delta A^{app}$: 0.1 ppb

| | Total | Statistics | Polarization | Apparative | FF | Re(□$_{\gamma ZA}$) |
|---|---|---|---|---|---|---|
| $\Delta\sin^2(\theta_w)$ | 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 %) |
| $\Delta A^{exp}$/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-Kollaboration

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

Hubert Spiesberger
Razvan Bucoveanu
Stephan Wezorke
Frank Maas
Sebastian Baunack
Dominik Becker
Kathrin Gerz
Thomas Jennewein
Kurt Aulenbacher
Dr. Valery Tioukine

Matthias Molitor
Niklaus Berger
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Alexey Tyukin
Marco Zimmermann
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Paul Souder
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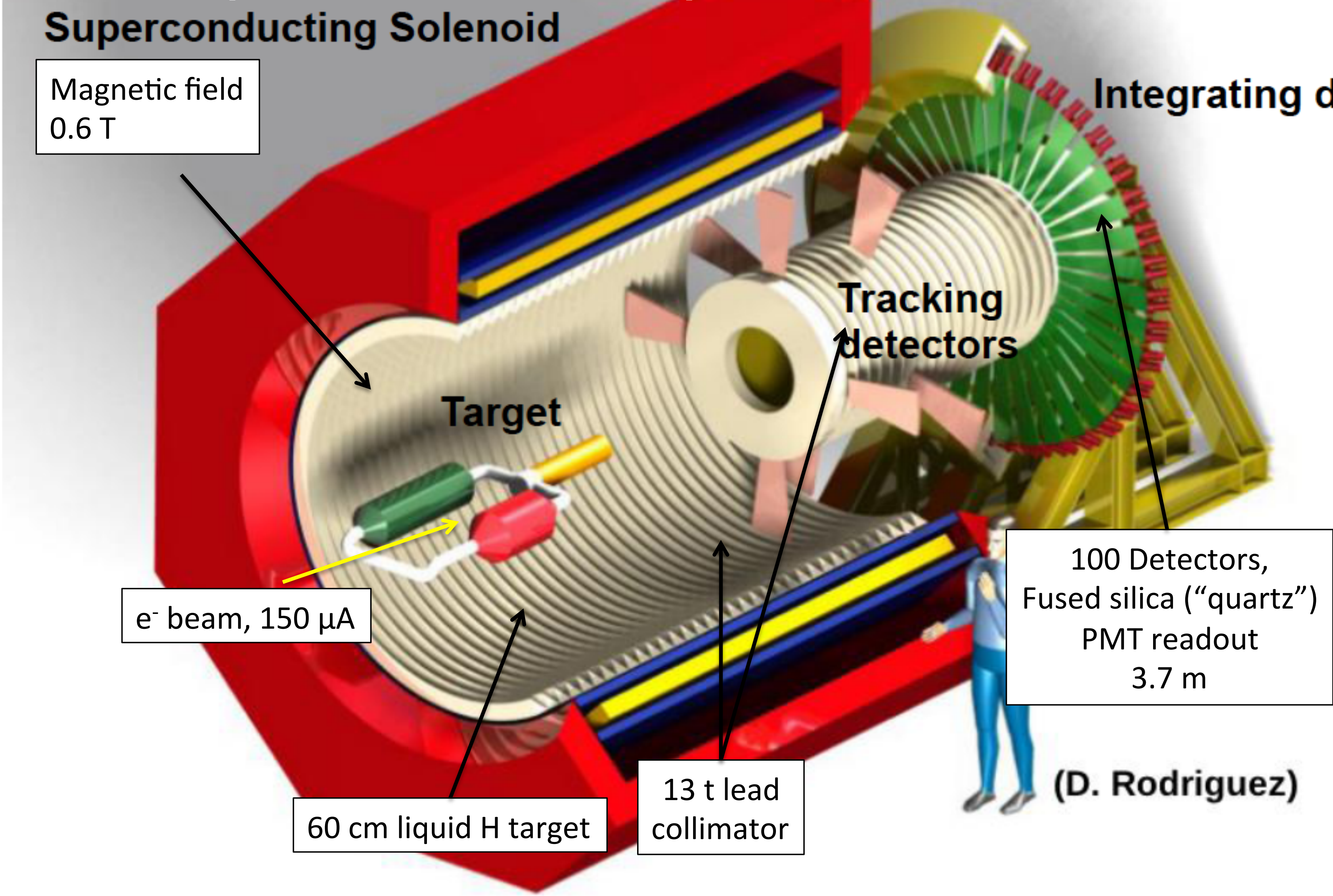
**Syracuse University, Syracuse, NY**

PRISMA

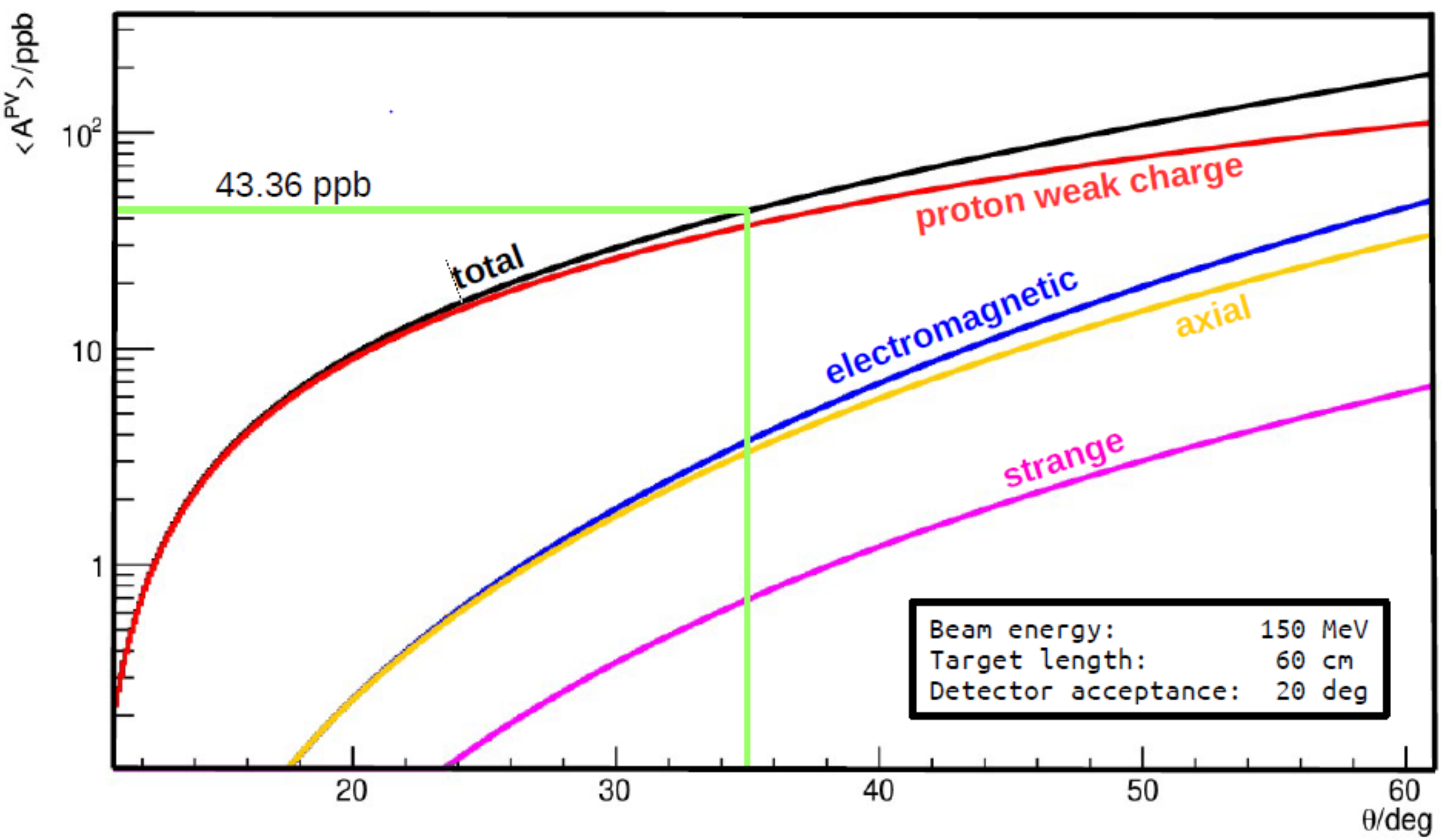
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

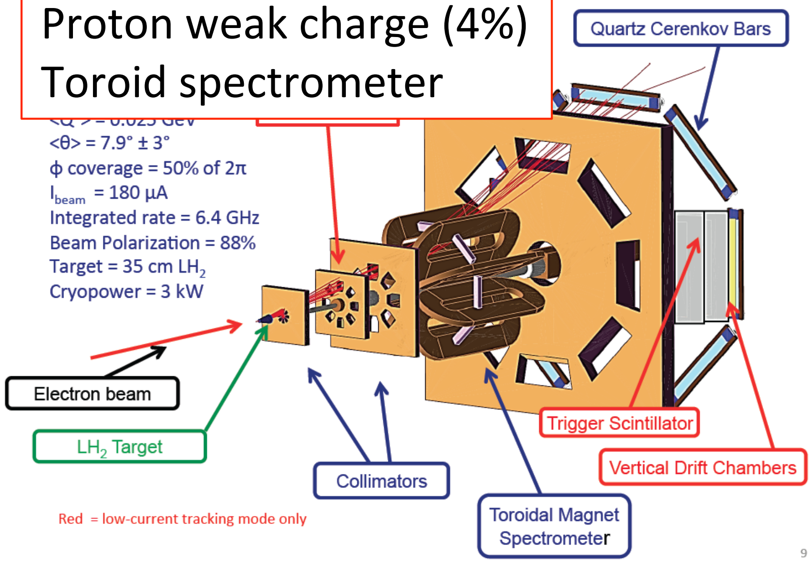
# P2-experimental setup



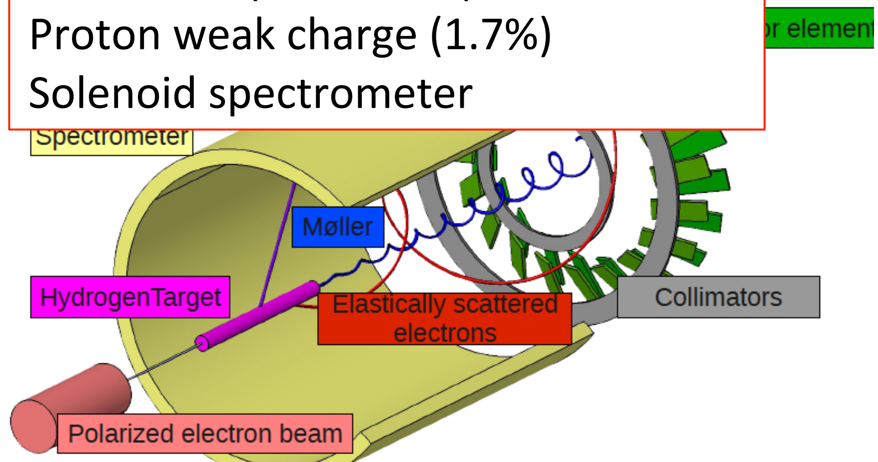
- Contributions to $\Delta\sin^2\Theta_W$ for 35° central scattering angle, E=150 MeV, 10000 h of data taking



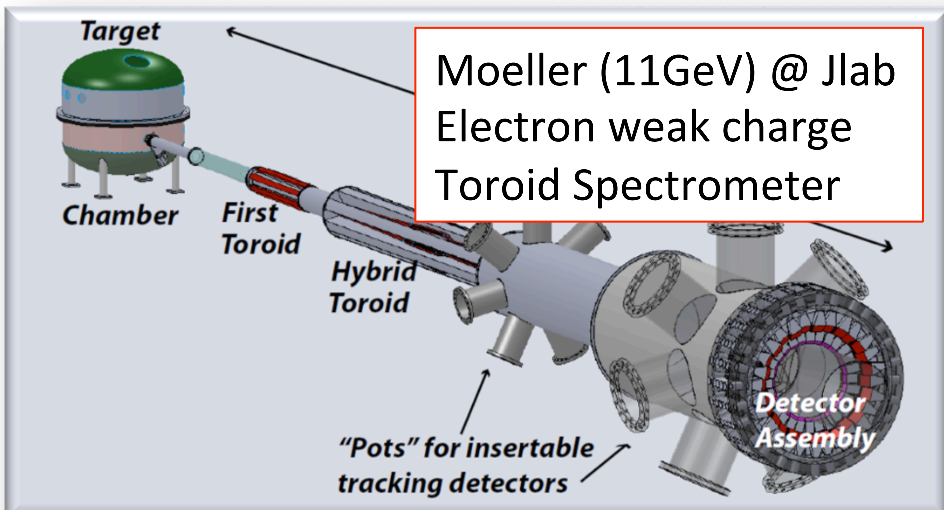

Qweak (1GeV) @ Jlab
Proton weak charge (4%)
Toroid spectrometer



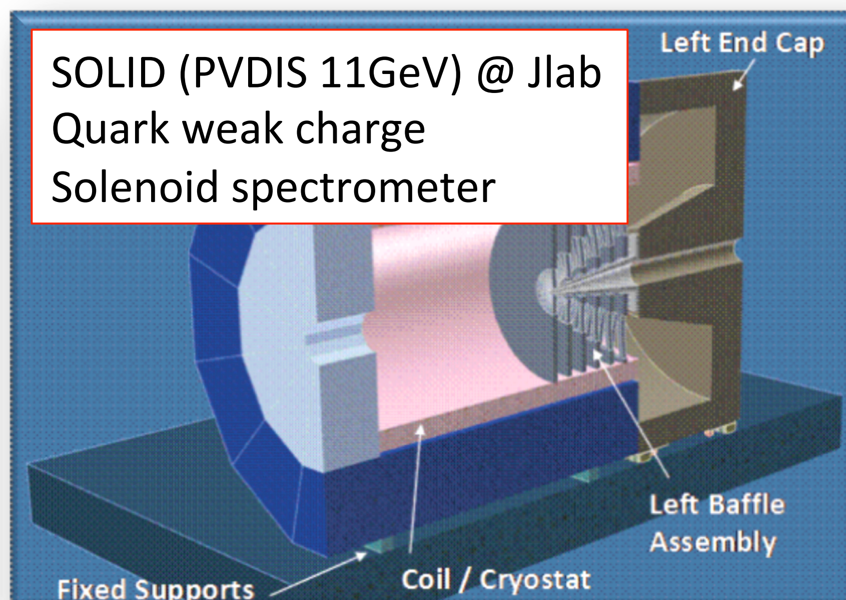

P2@MESA (0.150 GeV) @ Mainz
Proton weak charge (1.7%)
Solenoid spectrometer



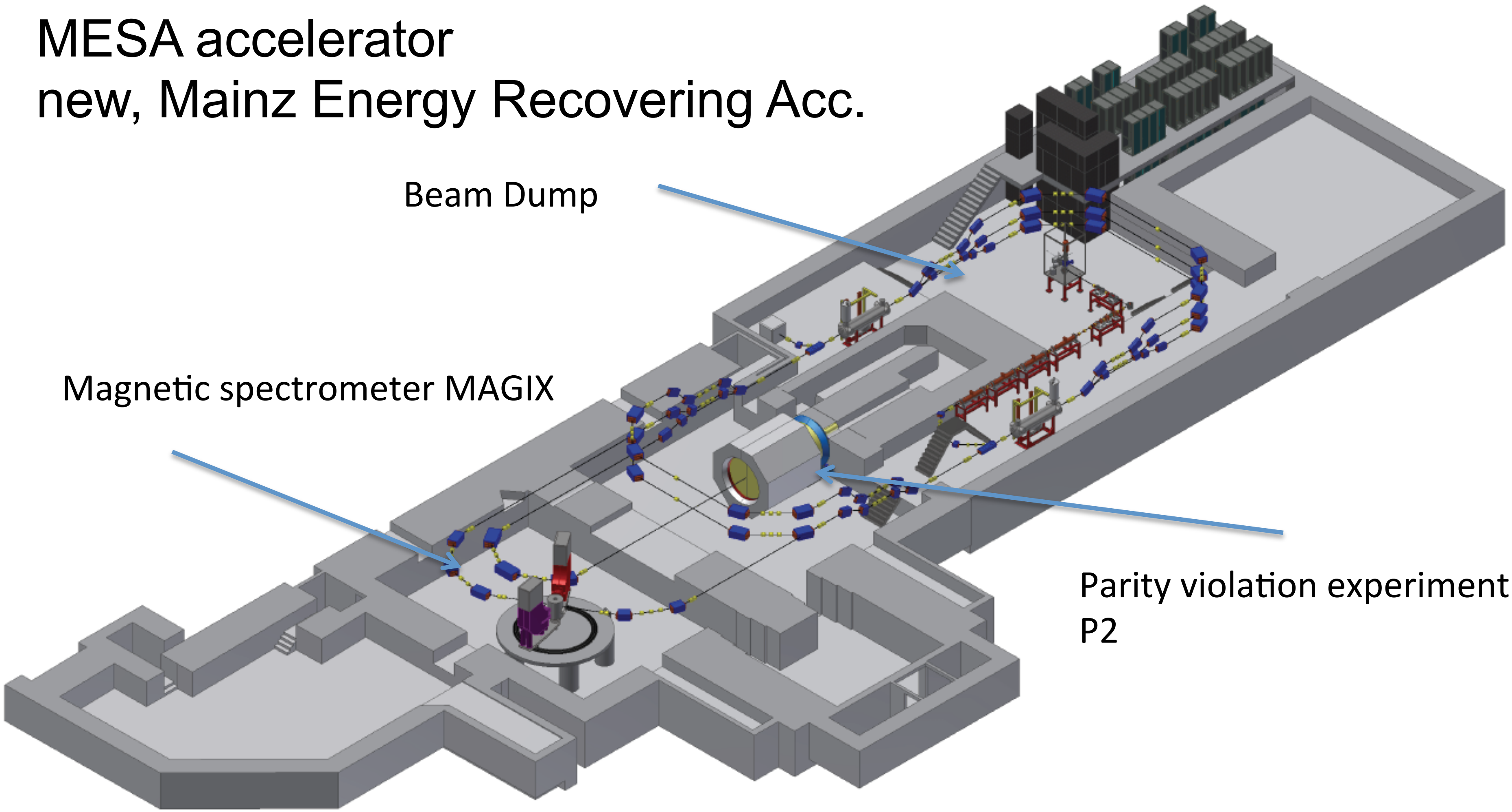

Moeller (11GeV) @ Jlab
Electron weak charge
Toroid Spectrometer




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



# MESA accelerator
# new, Mainz Energy Recovering Acc.



# MESA: Beam parameter

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Institut für Kernphysik

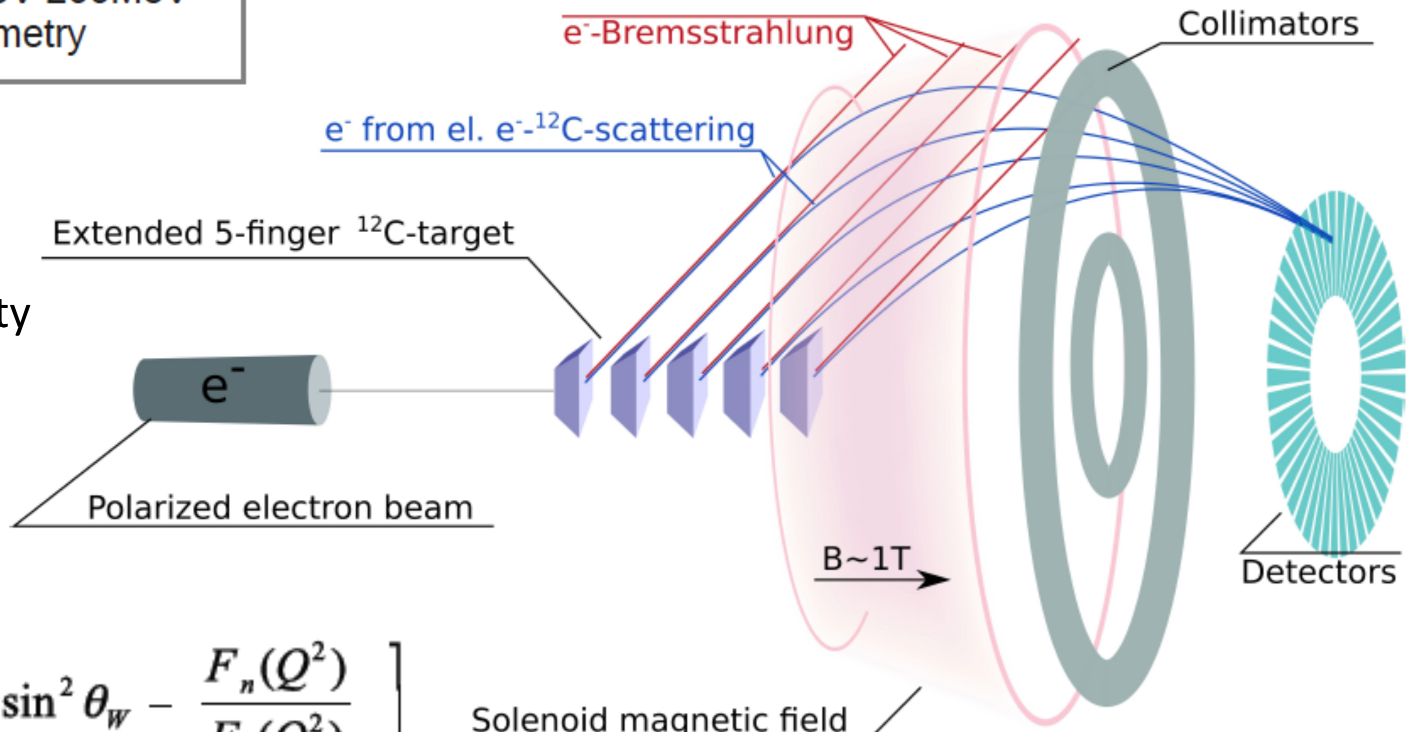
| | |
|---|---|
| Beam Energy ERL/EB [MeV] | 105/155 (105/205) |
| Operation mode | 1300 MHz, c.w. |
| Elektron-sources | 1.) Polarised : NEA GaAsP/GaAs superlattice , 200keV (?)<br>2.) unpolarised KCsSb, 200keV |
| Bunch Charge EB/ERL [pC]<br>7.7pC=10mA@1300MHz | 0.15/0.77 (0.15/7.7) |
| Norm. Emittance 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) |

# Other Measurements:
# Carbon, Lead

# EXPERIMENTAL REALIZATION

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

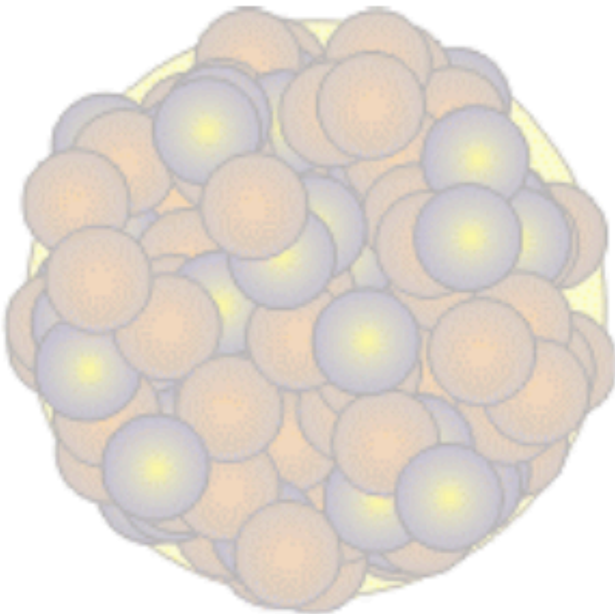
Enhanced sensitivity
To new physics

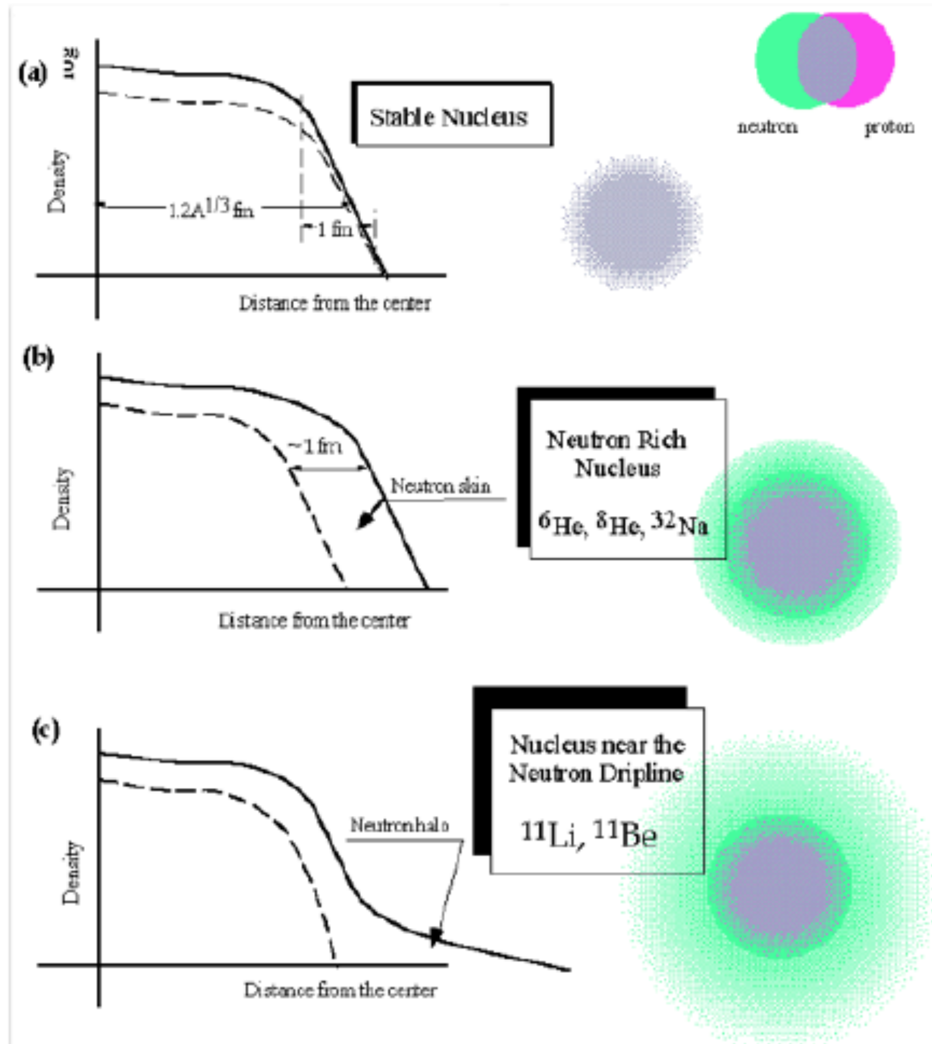



$$-N = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

# Neutron Skin for beginner

## Where do the neutrons go?

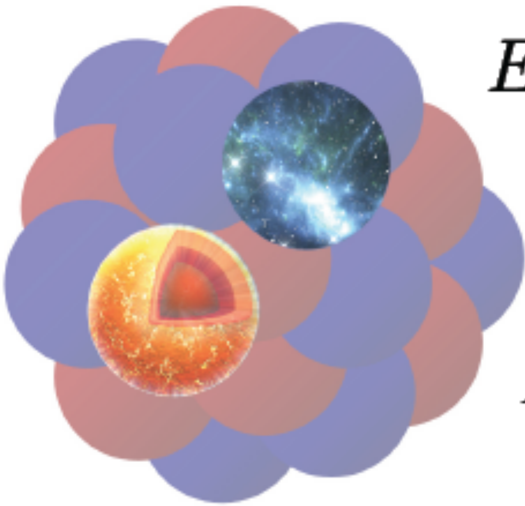





**Pressure forces neutrons out against surface tension**

→ **EOS**

# Measurement of neutron distribution in nuclei deceisive for Neutron star properties

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

**symmetry energy**

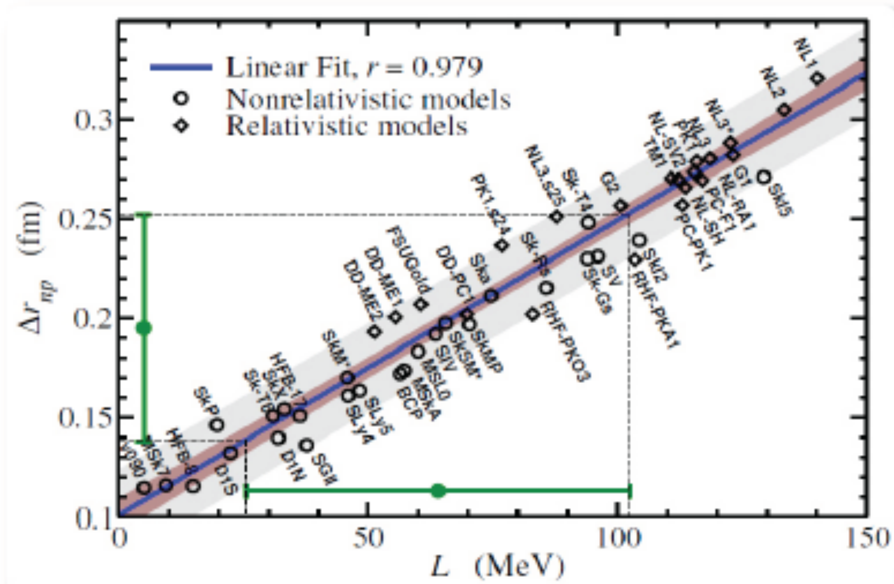
$$E_{sym}(\rho) = \left[S_v + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2\right] + \ldots$$

**slope parameter**

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

**curvature parameter**

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



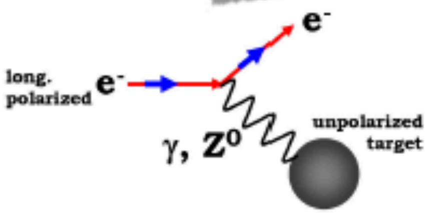

X. Roca-Maza et al., PRL 106 (2011) 252501

M. Thiel

# MREX

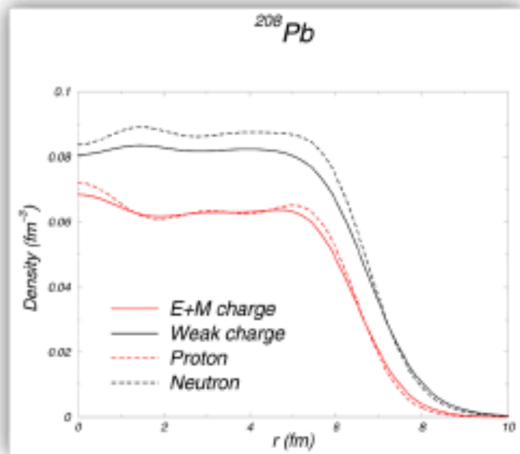
Enormously Clean …
Extraordinarily Expensive!

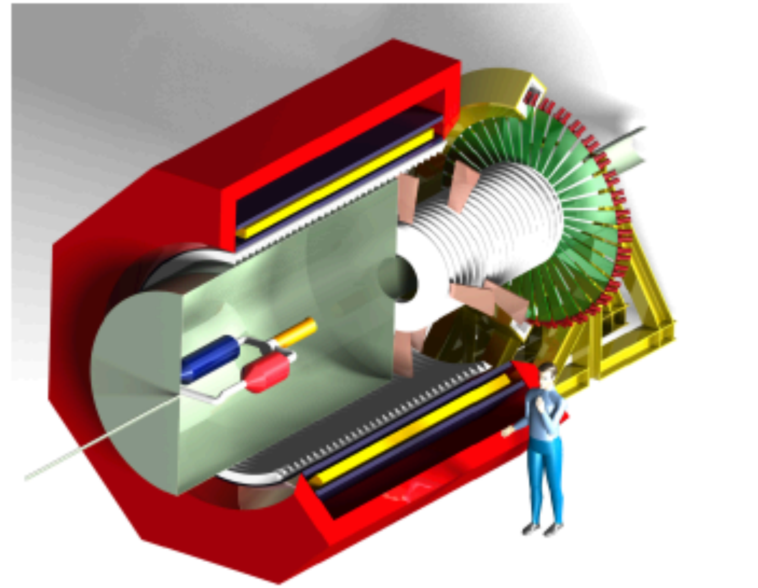
## PVES



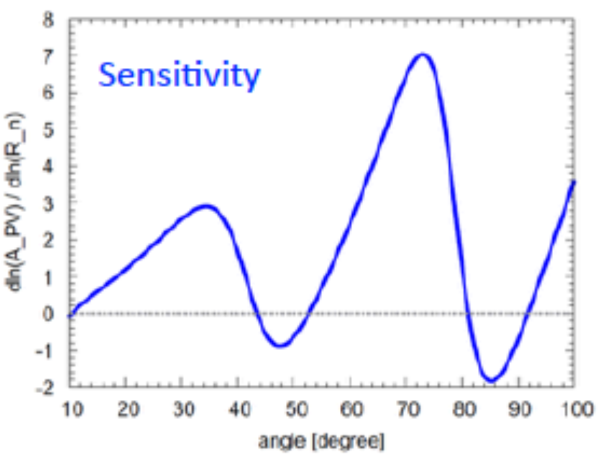

$$A_{PV} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{1-4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

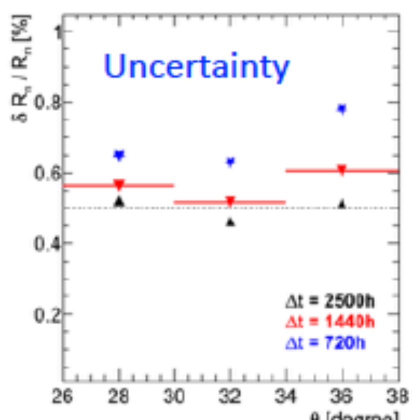
$$F_{n,p}(Q^2) = \frac{1}{4\pi}\int d^3r\; j_0(qr)\;\rho_{n,p}(r)$$



Full azimuthal coverage⇔4xstat



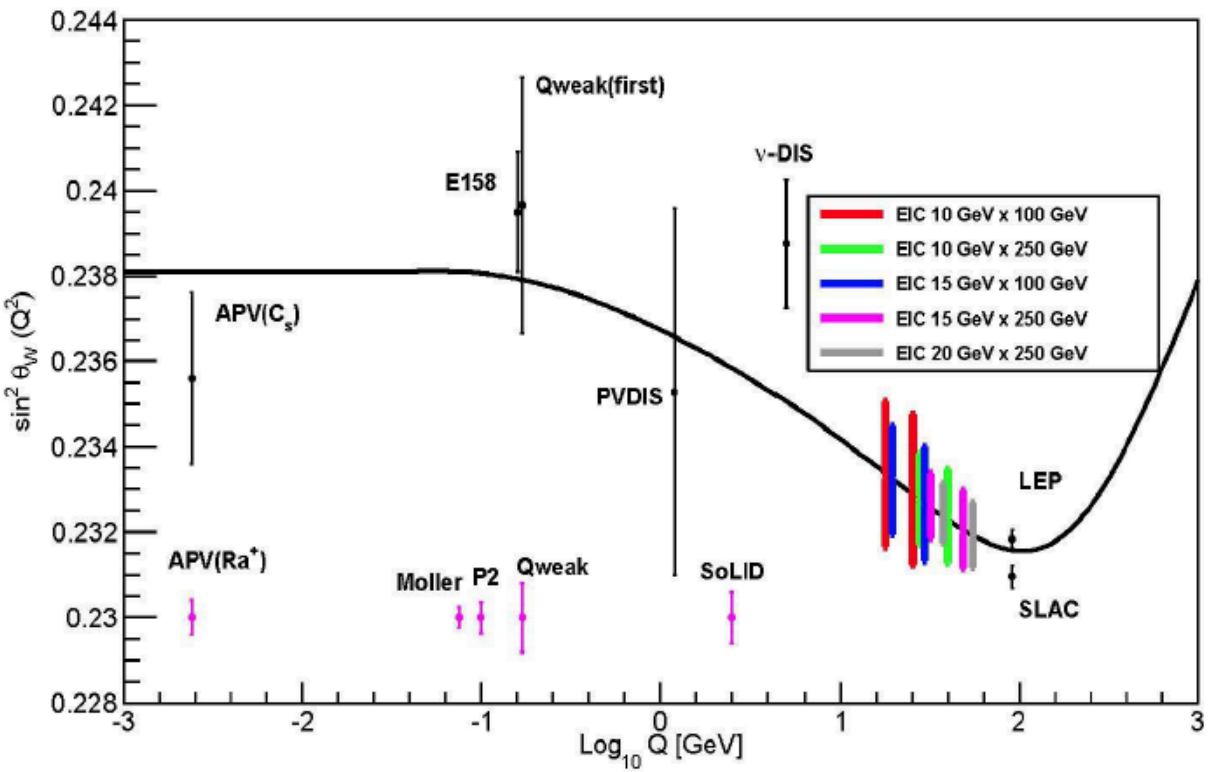

**Assuming same PREX luminosity:**

**Δθ=4° : 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)**
- **Qweak results from Jlab**
- **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**