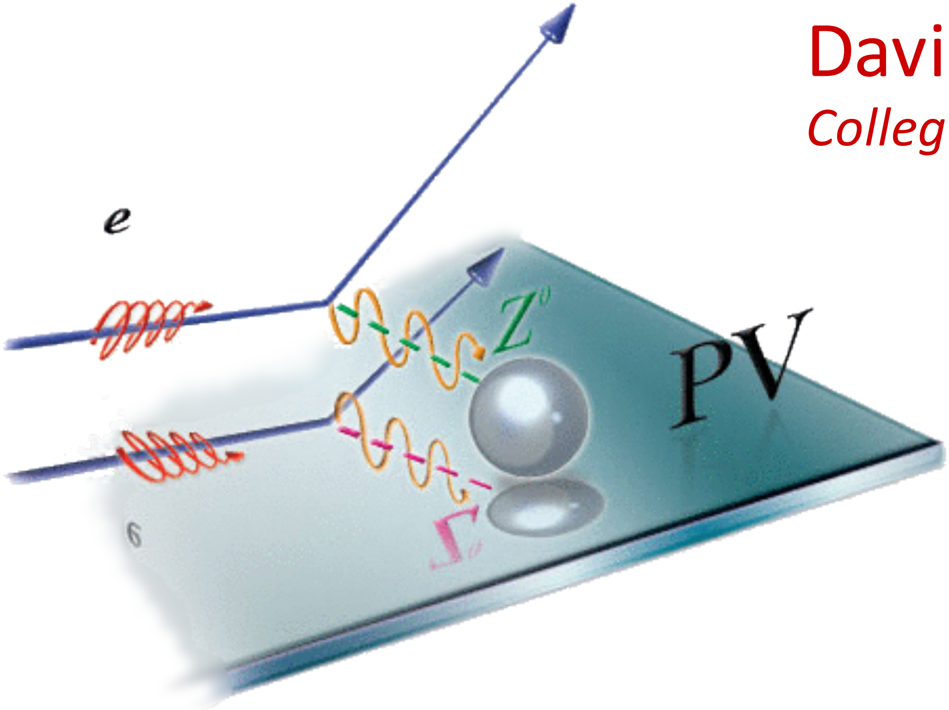
Parity-Violating Electron Scattering and Q_{weak}



David S. Armstrong

College of William & Mary

Symmetry Tests in Nuclei and Atoms
Kavli Institute for Theoretical Physics, UCSB
Sept 19-23 2016

NSF
WILLIAM & MARY
CHARTERED 1693
Jefferson Lab

Outline

1) Intro to Parity-Violating Electron Scattering (PVES)

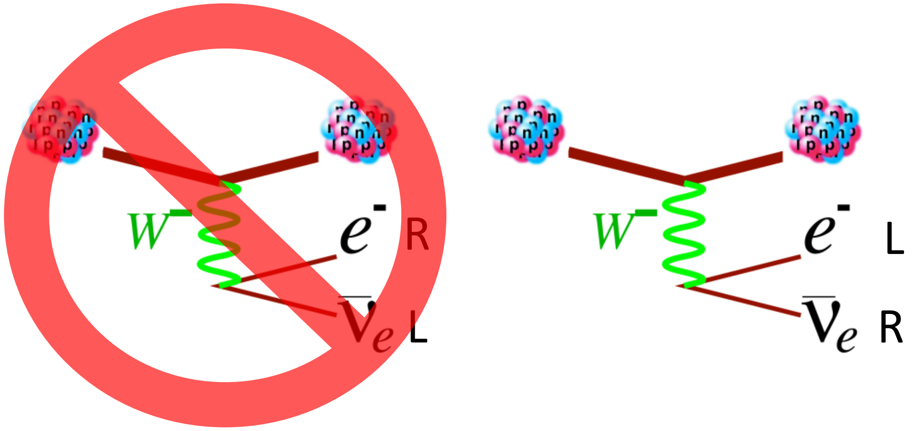
2) Qweak:
    - first results on the proton's weak charge
    - prospects for final result
    - Sensitivity to new physics

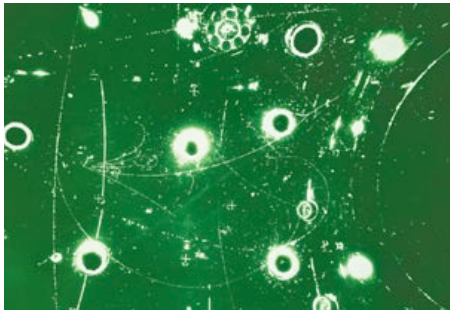
3) Further Standard Model Tests with PVES:
    Plans at JLab-12 GeV

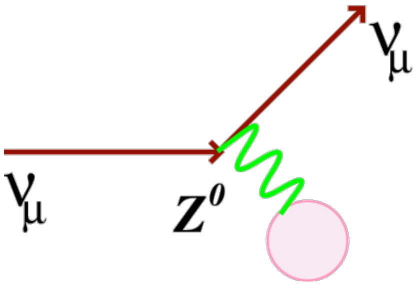
A brief history of parity violation

1930s – weak interaction needed to explain nuclear β decay

1950s – parity violation in weak interaction;
V-A theory to describe ^{60}Co decay



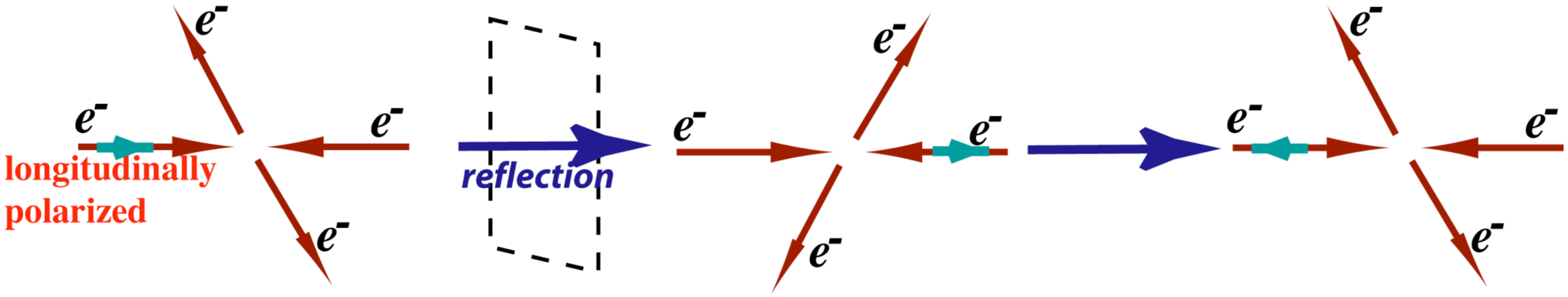




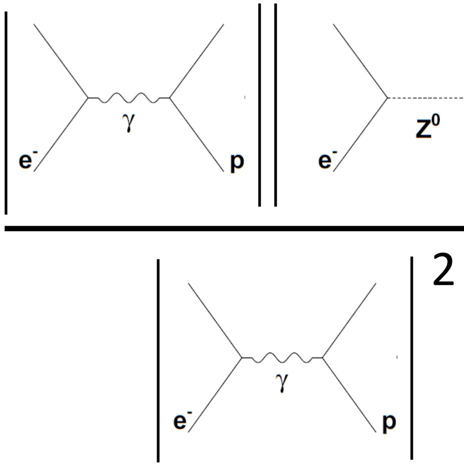
1970s – neutral weak current observed
at Gargamelle

late 1970s – parity violation observed in electron scattering - SLAC E122

Parity-violating electron scattering



Proposed by Ya. B. Zeldovich   JETP 36 (1959)



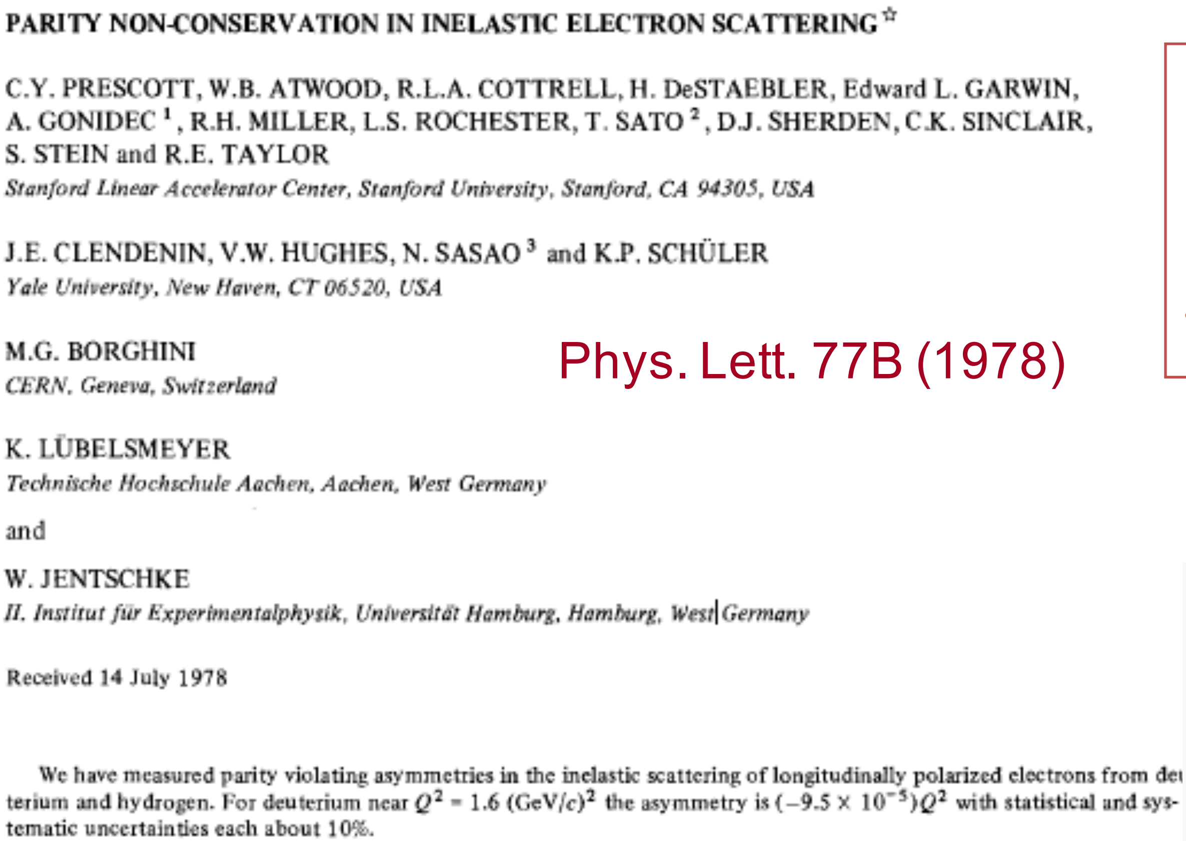
$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \propto \qquad \propto \frac{|M_Z|}{|M_\gamma|}$$

Electroweak interference

$$A_{PV} \propto \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left(g_A^e g_V^T + \beta g_V^e g_A^T\right) \sim 10^{-4} Q^2 \left[\mathrm{GeV}^2\right]$$

Pioneering Experiment

SLAC E122



PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING ☆

C.Y. PRESCOTT, W.B. ATWOOD, R.L.A. COTTRELL, H. DeSTAEBLER, Edward L. GARWIN,
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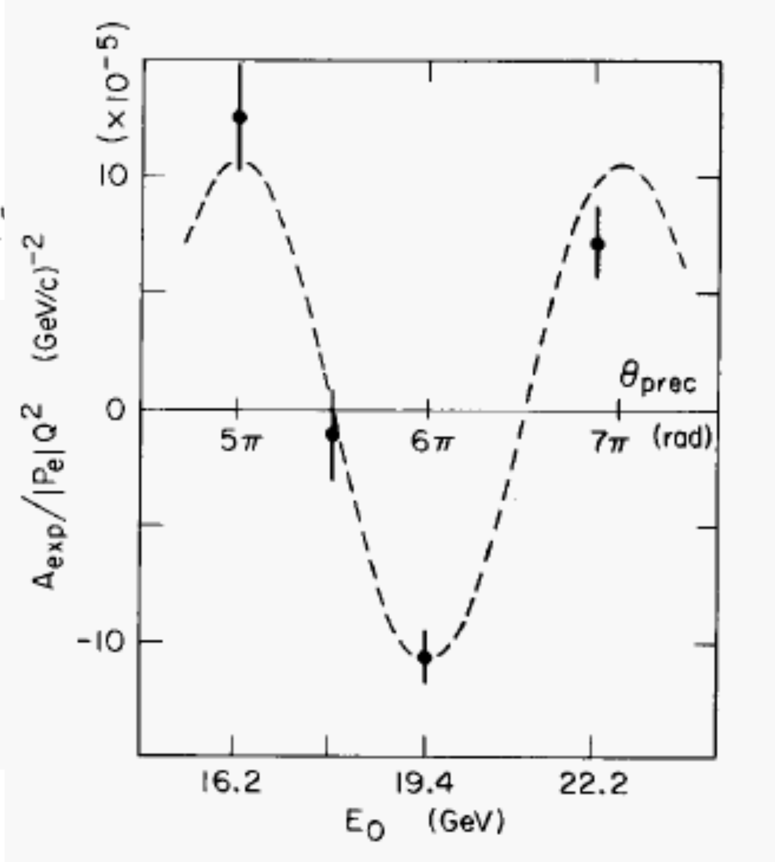
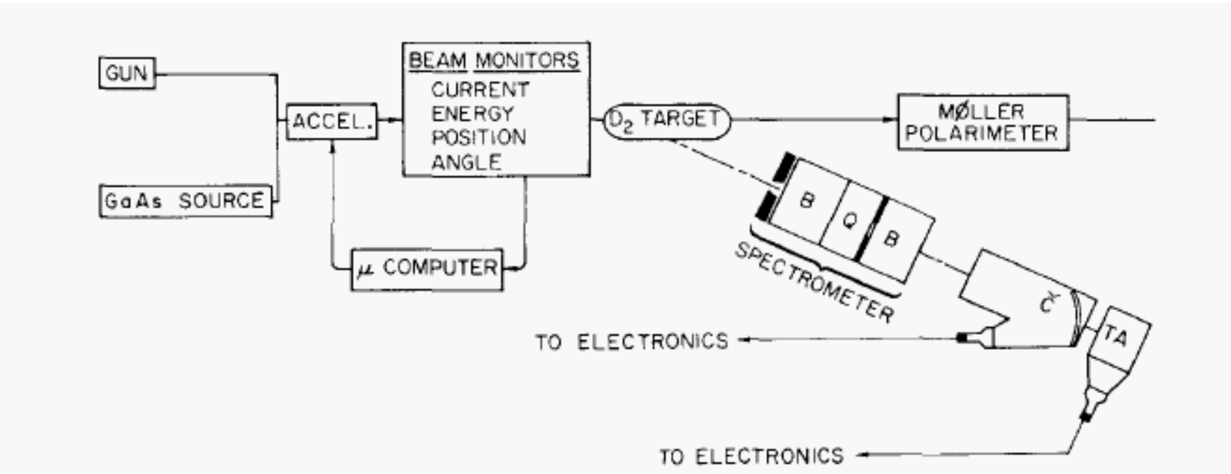
Received 14 July 1978

We have measured parity violating asymmetries in the inelastic scattering of longitudinally polarized electrons from de
terium and hydrogen. For deuterium near $Q^2 = 1.6\ (\mathrm{GeV}/c)^2$ the asymmetry is $(-9.5 \times 10^{-5})Q^2$ with statistical and systematic uncertainties each about 10%.

Phys. Lett. 77B (1978)

Deep-inelastic scattering from isoscalar target





Textbook Physics: High Energy Physics (D.H. Perkins)

SLAC E122 *cont'd*

Pivotal to establishing Weinberg-Salam-Glashow SU(2)×U(1) gauge theory

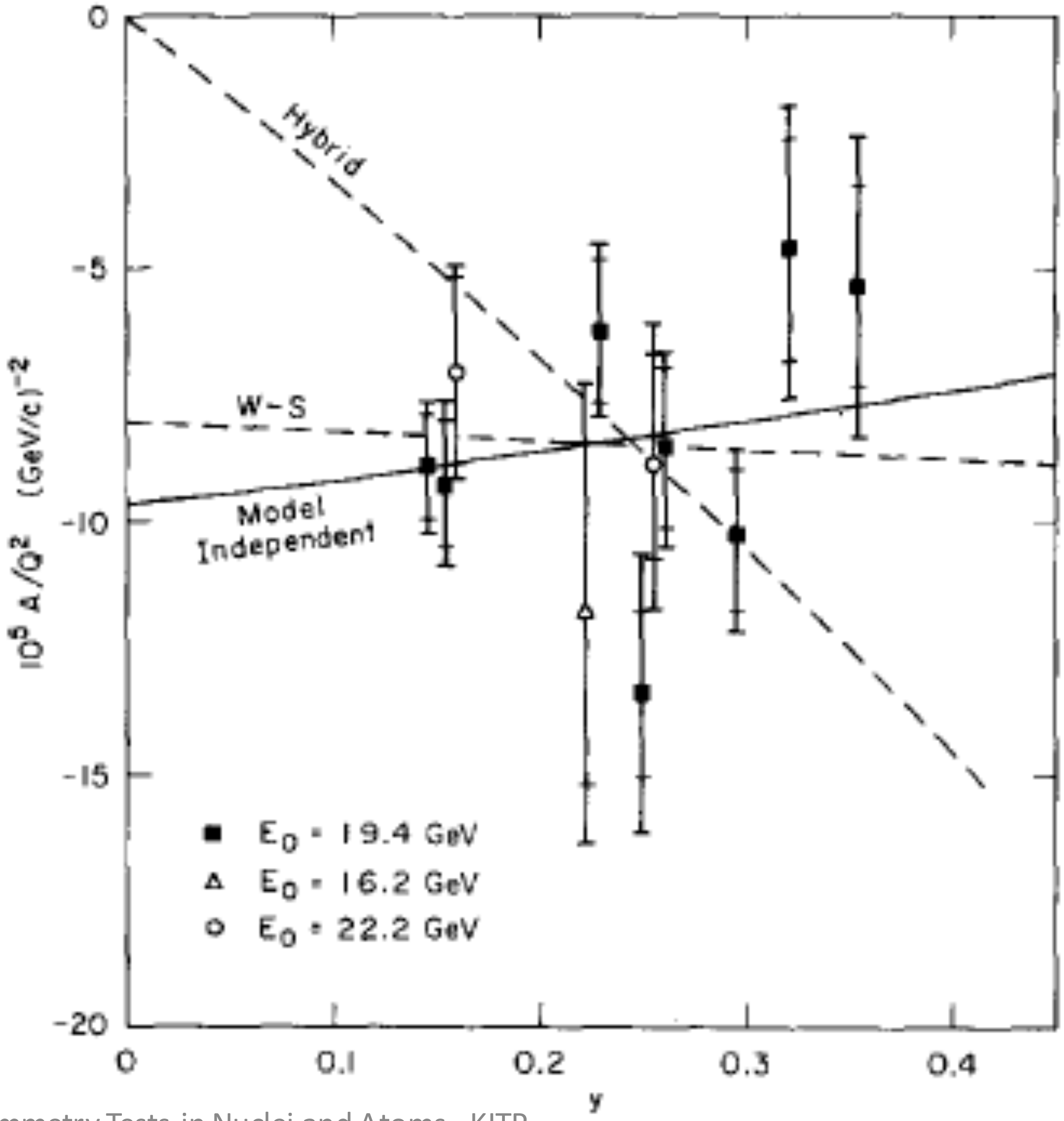
Also critical test of parton model

Techniques

Optically pumped electron source: rapid helicity reversal,

integrate scattered flux

monitor & feedback to control electron beam fluctuations



Followed by:

1989: Mainz ^{9}Be
W. Heil et al.

1990: MIT/Bates ^{12}C
P.A. Souder et al.

SLAC Experiments

SLAC E122 – crucial confirmation of **WSG electroweak model**

- Electron-deuteron deep inelastic scattering
- High luminosity: photoemission from NEA GaAs cathode
- Rapid helicity-flip (sign of e- polarization)
- Polarimetry to determine beam polarization
- Magnetic spectrometer: backgrounds and kinematic separation

A_{PV} ~ 100 ± 10 ppm

$\boxed{\sin^2\theta_W=0.20\pm0.03}$

SLAC E158 – 1999

- electron-electron scattering - purely leptonic interaction
- electron-electron weak attractive force had never before been measured!

A_{PV} ~ -131 ± 14 ± 10 ppb

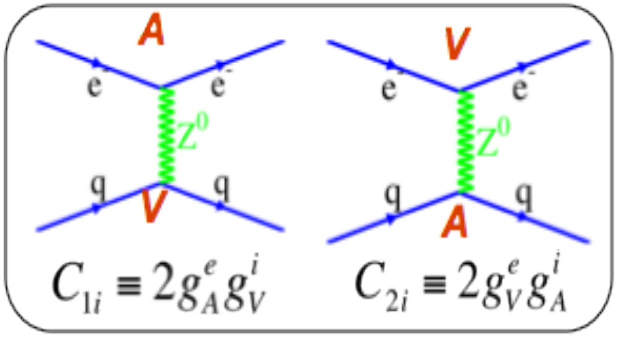
$\boxed{\sin^2\theta_W=0.2403\pm0.0013}$

Weak Charges

Electroweak Lagrangian → Parity-Violating electron-quark term:

$$\mathcal{L}_{PV}^{EW} = \frac{G_F}{\sqrt{2}}\left[g_A^e(\bar{e}\gamma_\mu\gamma_5 e)\cdot\sum_q g_V^q(\bar{q}\gamma^\mu q) + g_V^e(\bar{e}\gamma_\mu e)\cdot\sum_q g_A^q(\bar{q}\gamma^\mu\gamma_5 q)\right]$$

$$C_{1q} = 2g_A^e g_V^q$$



$C_{1i} \equiv 2g_A^e g_V^i$ $C_{2i} \equiv 2g_V^e g_A^i$

Small θ Large θ

-Electroweak Charges-

Particle	Electric Charge	Weak Vector Charge ($\sin^2\theta_W \approx \frac{1}{4}$)
u	$+\frac{2}{3}$	$-2C_{1u} = +1 - \frac{8}{3}\sin^2\theta_W \approx +\frac{1}{3}$
d	$-\frac{1}{3}$	$-2C_{1d} = -1 + \frac{4}{3}\sin^2\theta_W \approx -\frac{2}{3}$
p(uud)	$+1$	$Q_W^p = 1 - 4\sin^2\theta_W \approx 0$
n(udd)	0	$Q_W^n = -1$

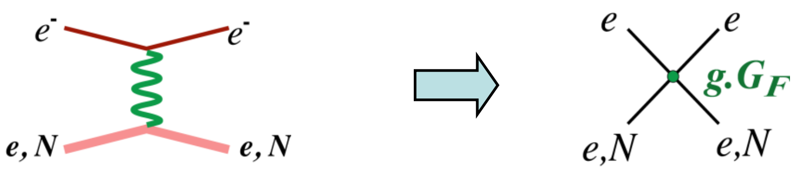
← Proton's Weak Charge ("accidental" suppression: enhanced sensitivity to new physics)

Qweak: Proton’s weak charge

For forward angle scattering at low Q^2 :
A_{PV} accesses Q_W^p

$$A_{\rm PV} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \to \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} Q_W^p$$

Use four-fermion contact interaction to parameterize the effective PV electron-quark couplings (mass scale and coupling)



$$\frac{1}{Q^2 - M^2} \xrightarrow{Q^2 \ll M^2} \frac{1}{M^2}$$

New physics:

$$\sigma \propto |M_\gamma + M_{\rm Z} + M_{\rm new}|^2$$
$$\sim |M_\gamma|^2 + 2M_\gamma M_{\rm Z}^* + 2M_\gamma M_{\rm new}^*$$

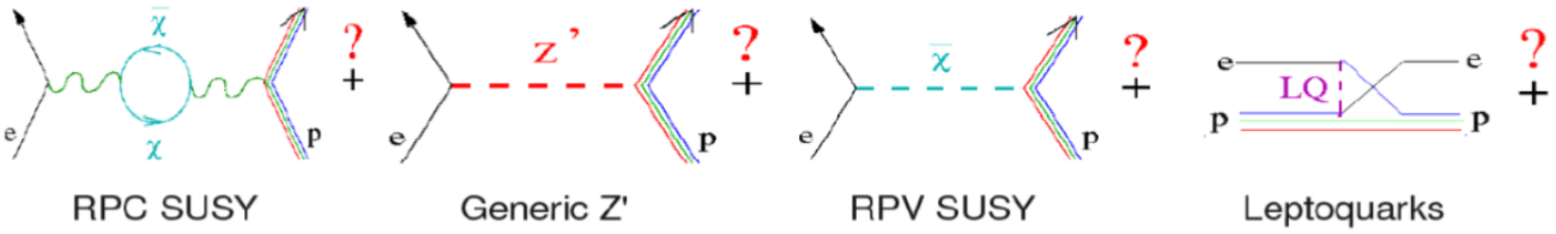
Planned 4% measurement of proton’s weak charge - probes TeV-scale new physics

$$\frac{\Lambda}{g} \sim \left(\sqrt{2} G_F \Delta Q_W^p\right)^{-\frac{1}{2}} \sim O(\rm TeV)$$

Erler, Kurylov, and Ramsey-Musolf, PRD 68, 016006 2003

Qweak: Proton’s weak charge

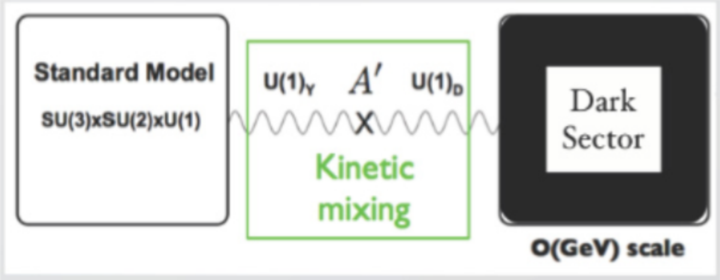
Examples of TeV scale new physics that Q_{weak} would be sensitive to are:



Q_{weak} is also sensitive to MeV-GeV scale mediators such as:

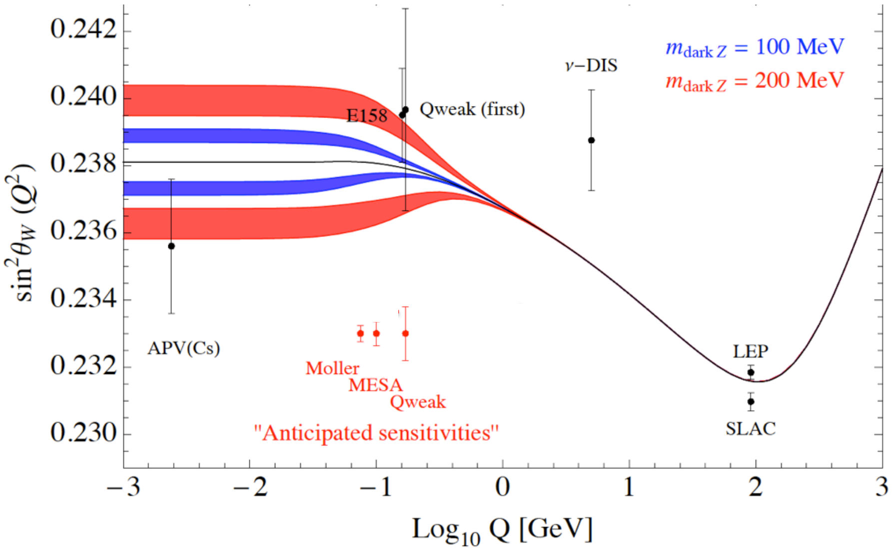
Dark Photon:

- Astrophysical motivation, observed in positron data
- Might be linked to muon g-2 anomaly

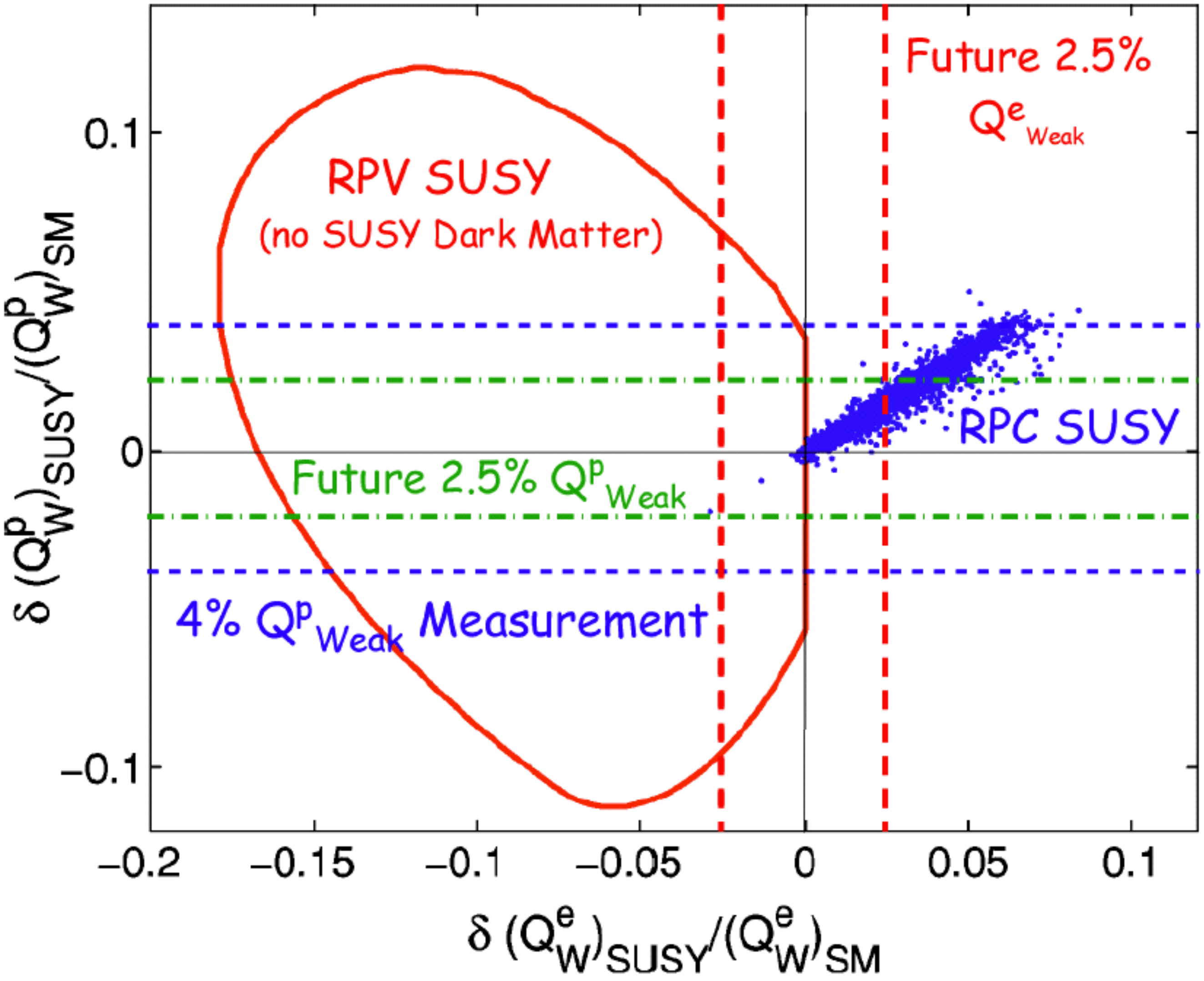


Dark Parity Violation: (Davoudiasl, Lee, Marciano, arXiv 1402.3620)

- New source of low energy PV via mass mixing between Z and Z_d with observable consequences
- Complementary to direct search for heavy dark photons



SUSY "phase space"



Kurylov, Ramsey-Musolf, Su (2003)

Extracting the weak charge

$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[Q_w^p + B(\theta, Q^2)Q^2\right]$$

Hadron structure enters here: electromagnetic and electroweak form factors…

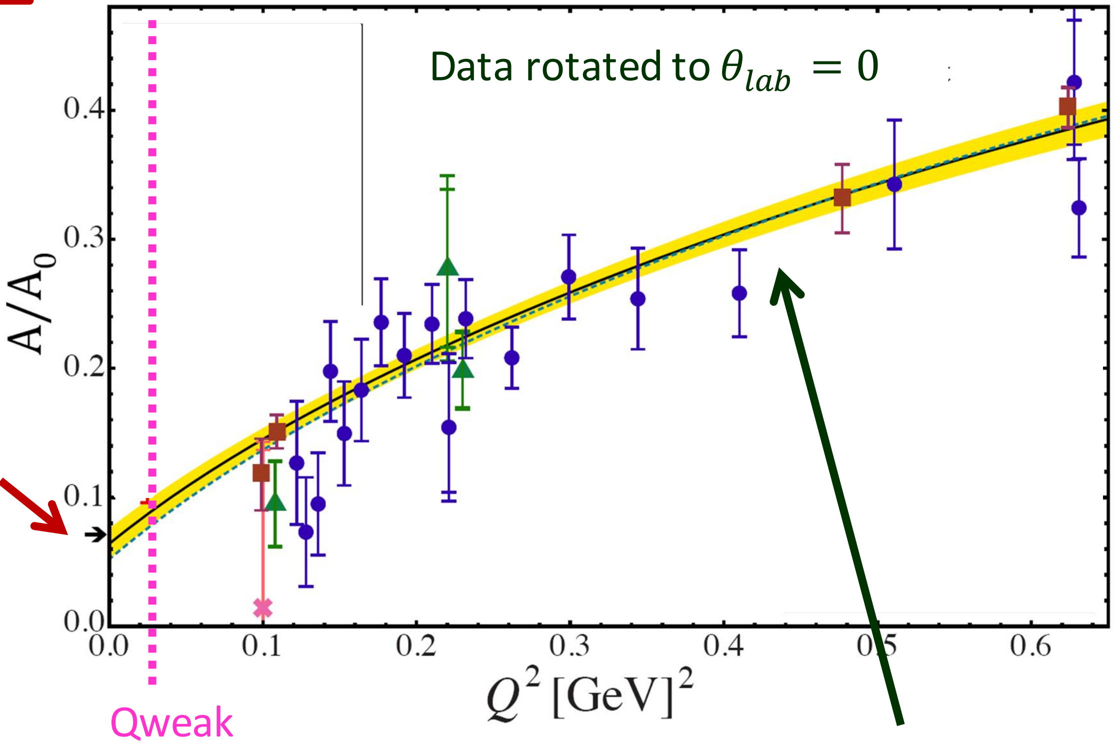
Reduced asymmetry more convenient:

$$A_{red} = \frac{A_{PV}}{A_0} \qquad A_0 = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}$$

One must extrapolate to $Q^2 = 0$.

We measure A_{phys}^{PV}

at $Q^2 = 0.025\ GeV^2$.



Data rotated to $\theta_{lab} = 0$

SM

Qweak kinematics

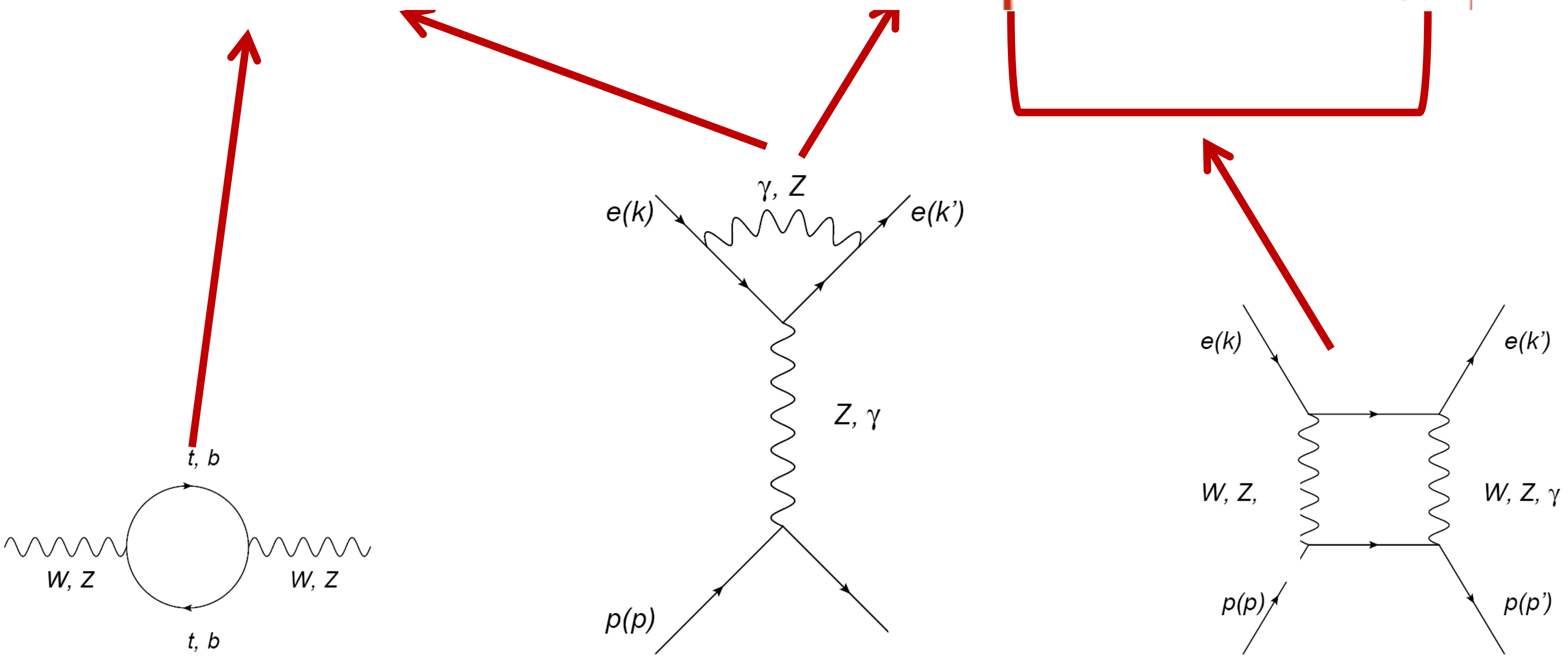
Hadronic term extracted from fit

The previous strange form factor program (experiments at MIT/Bates, JLab and MAMI) allow us to subtract our hadronic contribution

Electroweak Radiative Corrections

In the Standard Model, the weak charge is *defined* at $Q^2 = 0, E = 0.$

$$Q_W^p = [\rho_{NC} + \Delta_e][1 - 4\sin^2\hat{\theta}_W(0) + \Delta'_e] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$



Full expression for Q_W^p has energy dependent corrections – need precise calculations

The $\Box_{WW}$ and $\Box_{ZZ}$ are well determined from pQCD ($\propto \frac{1}{q^2 - M^2_{W(Z)} + i\epsilon}$)

The $\Box_{\gamma Z}$ isn't pQCD friendly due to the photon leg ($\propto \frac{1}{q^2 + i\varepsilon}$)

Electroweak Radiative Corrections

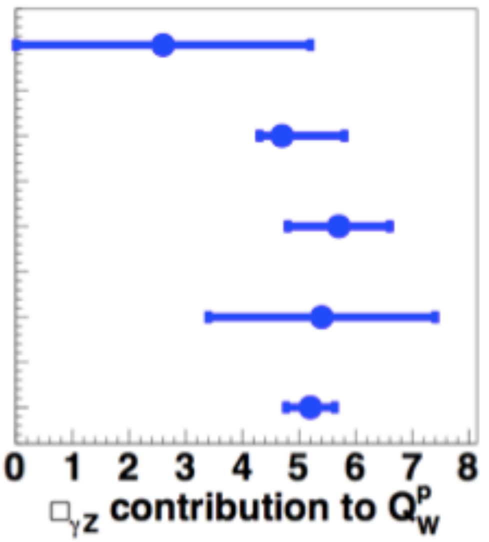
In the Standard Model, the weak charge is *defined* at $Q^2 = 0, E = 0$.

$$Q_W^p = [\rho_{NC} + \Delta_e][1 - 4\sin^2\hat{\theta}_W(0) + \Delta_e'] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

Uncertainty from these corrections on *current* results is irrelevant.

$\Box_{\gamma Z}$ contribution to Q_W^p (Qweak kinematics)

Gorchtein & Horowitz *PRL 102, 091806 (2009)*	0.0026 ± 0.0026
Sibirtsev, Blunden & Melnitchouk, Thomas *PRD 82, 013011 (2010)*	$0.0047^{+0.0011}_{-0.0004}$
Rislow & Carlson *PRD 83, 13007 (2011)*	0.0057 ± 0.0009
Gorchtein, Horowitz & Ramsey-Muslof *PRC 84, 015502 (2011)*	0.0054 ± 0.0020
Hall, Blunden, Melnitchouk, Thomas & Young *arXiv:1304:7877 (2013)* (calculation constrained by PVDIS data)	0.0052 ± 0.00043



Calculations are primarily dispersion theory type

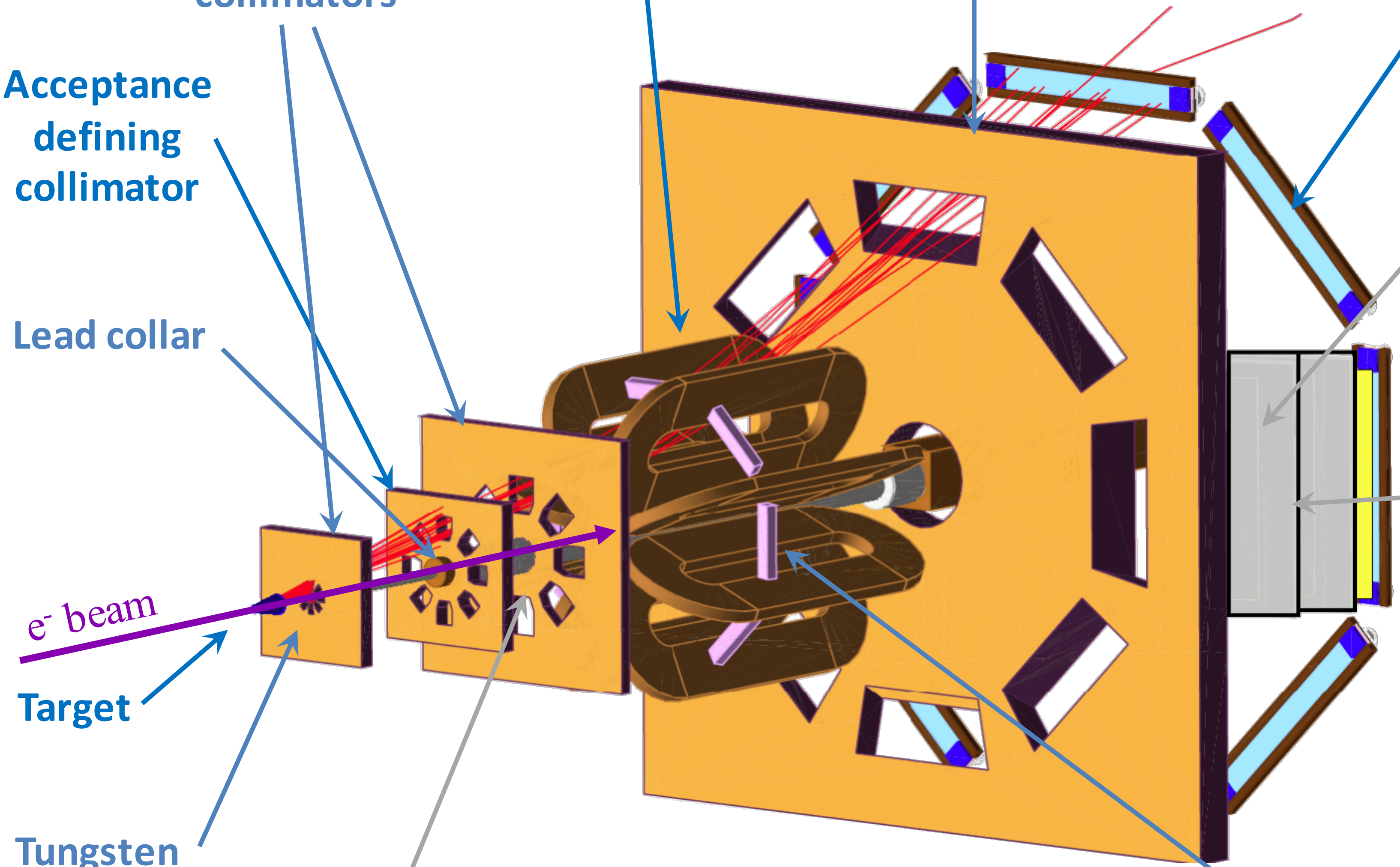
error estimates can be firmed up with data!

Qweak: inelastic asymmetry data taken at W ~ 2.3 GeV, $Q^2 = 0.09$ GeV^2

Meeting PVES Challenges

- 180 μA beam current (JLab record)
- High power cryogenic target
- Rapid helicity reversal (960 Hz)
- Small scattering angle: toroidal magnet, large acceptance
- 6 GHz detected rates: data-taking in integrating mode
- Radiation hard detectors
- Low noise 18-bit ADCs
- Exquisite control of helicity-correlated beam parameters
- Four different kinds of helicity reversal:
  - Rapid (Pockels cell at source)
  - Slow (insertable λ/2 plate)
  - Ultra slow (Wien-reversal, g-2 spin flip)
- Two independent high-precision beam polarimeters
- High resolution Beam Current monitors
- Dedicated Tracking system for kinematics determination

The Q_{weak} Apparatus



Cleanup collimators

QTOR

Shield wall

Main detectors 8-fold symmetry

Acceptance defining collimator

Trigger scintillator

Lead collar

Vertical drift chambers (VDC) (rotate)

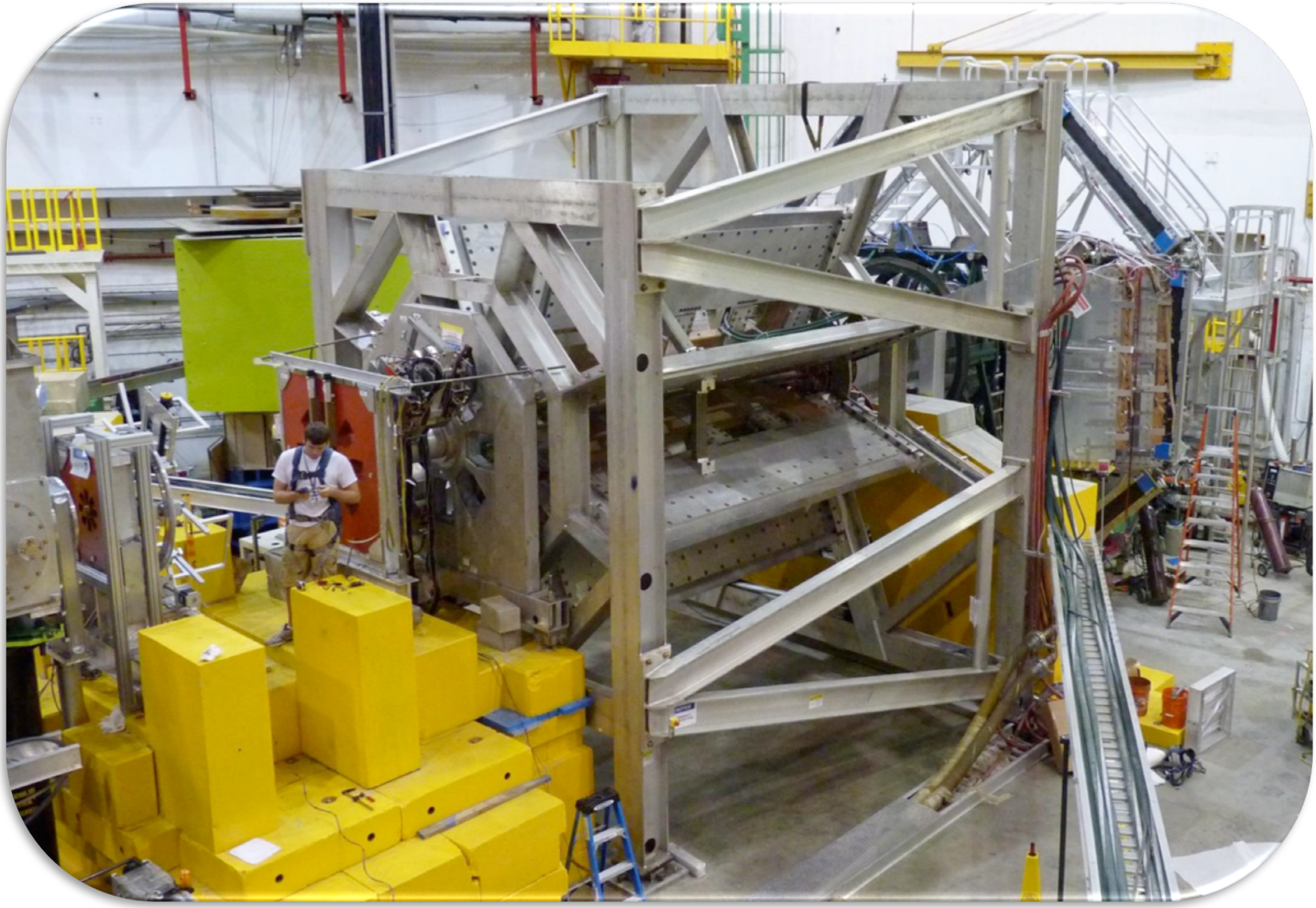
Target

Tungsten plug

Horizontal drift chambers (HDC) (rotate)

Lintels

The Q_{weak} Apparatus



First result

Q_{weak} ran from Fall 2010 – May 2012 (Hall C at JLab)

Four distinct running periods:

- Hardware checkout (Fall 2010-January 2011)
- Run 0 (Jan-Feb 2011)
- Run 1 (Feb – May 2011)
- Run 2 (Nov 2011 – May 2012)

We have completed and unblinded the analysis of “Run 0” (about 1/25th of our total dataset).

D. Androic *et al.* Phys. Rev. Lett. 111 (2013)141803.

$A_{PV}^{p} = -279 \pm 35(stat) \pm 29\ (sys)$ ppb

$\langle Q^2 \rangle = 0.0250 \pm 0.0006\ \mathrm{GeV}^2$

$\langle E_{beam} \rangle = 1155\ \mathrm{MeV}$

$\theta_{eff} = 7.90\,°$

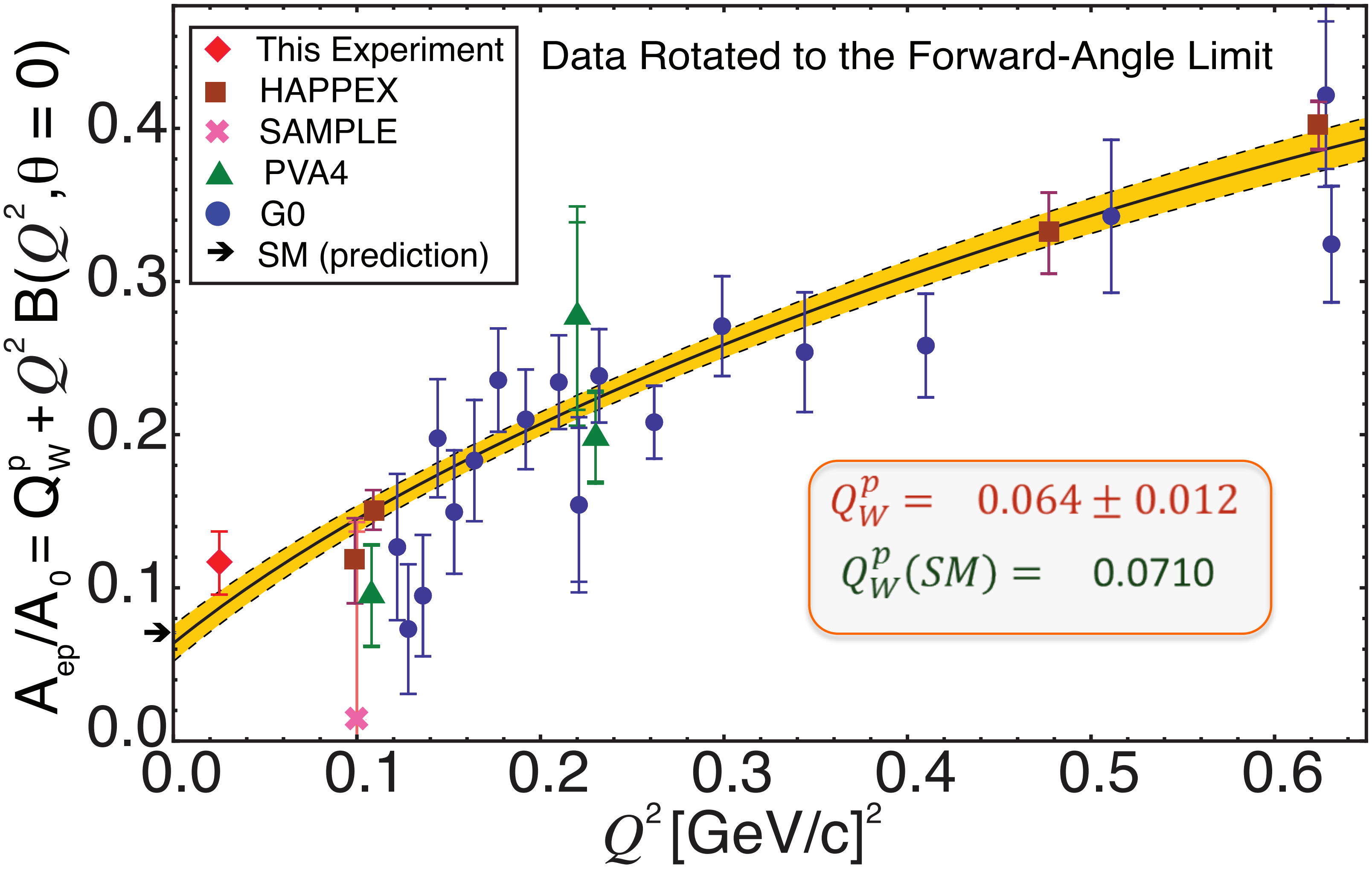
Good agreement with Standard Model prediction

Reduced Asymmetry

4% of total data

in the forward-angle limit (θ=0)

$$A_0 = -\frac{Q^2 G_F}{4\sqrt{2}\pi\alpha} \qquad \overline{A^p_{\mathrm{LR}}} = \frac{A_{LR}}{A_0} \xrightarrow{\theta\to 0} [Q^p_W + \boxed{Q^2 B(Q^2)}]$$

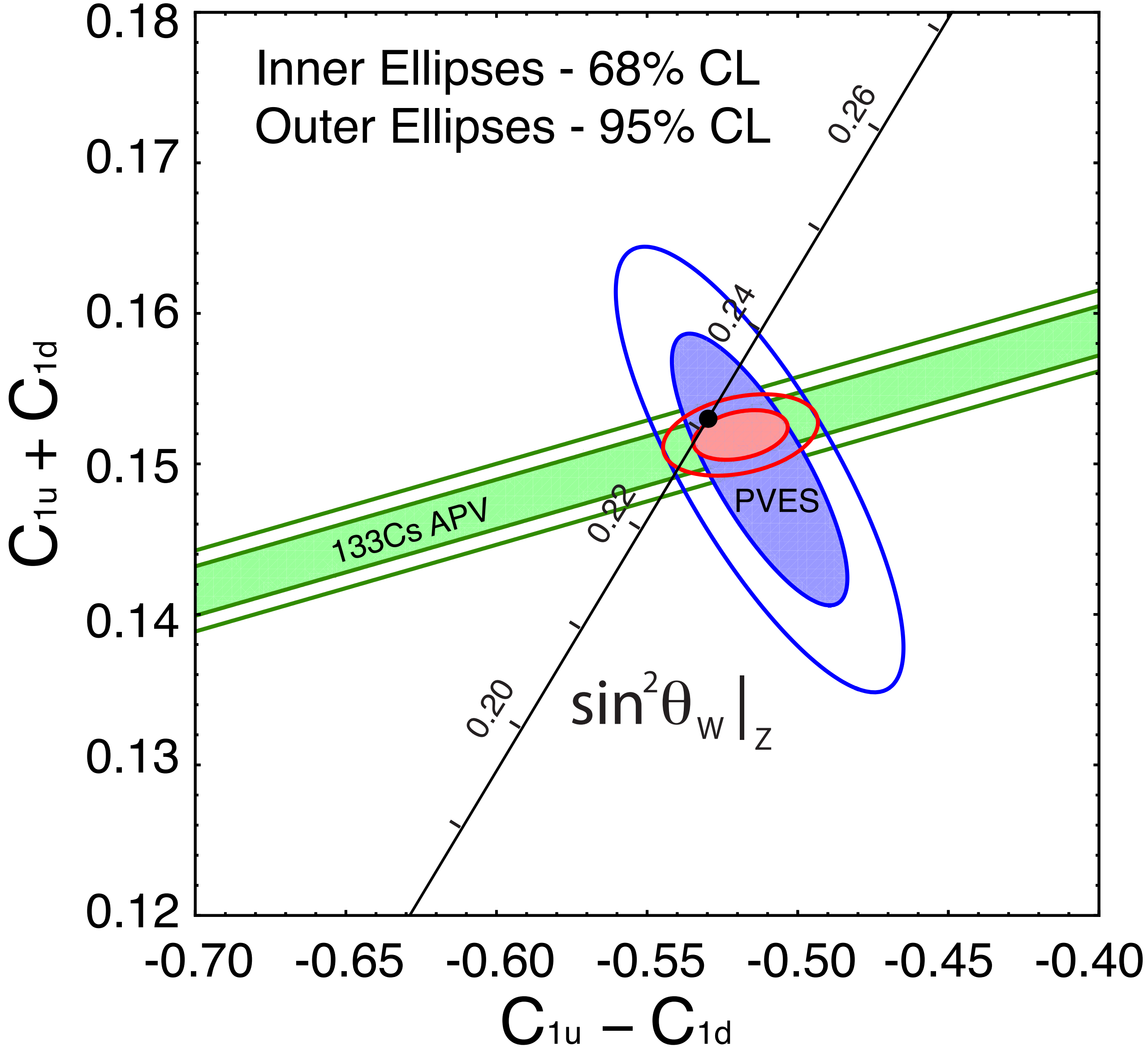


$Q^p_W = \quad 0.064 \pm 0.012$

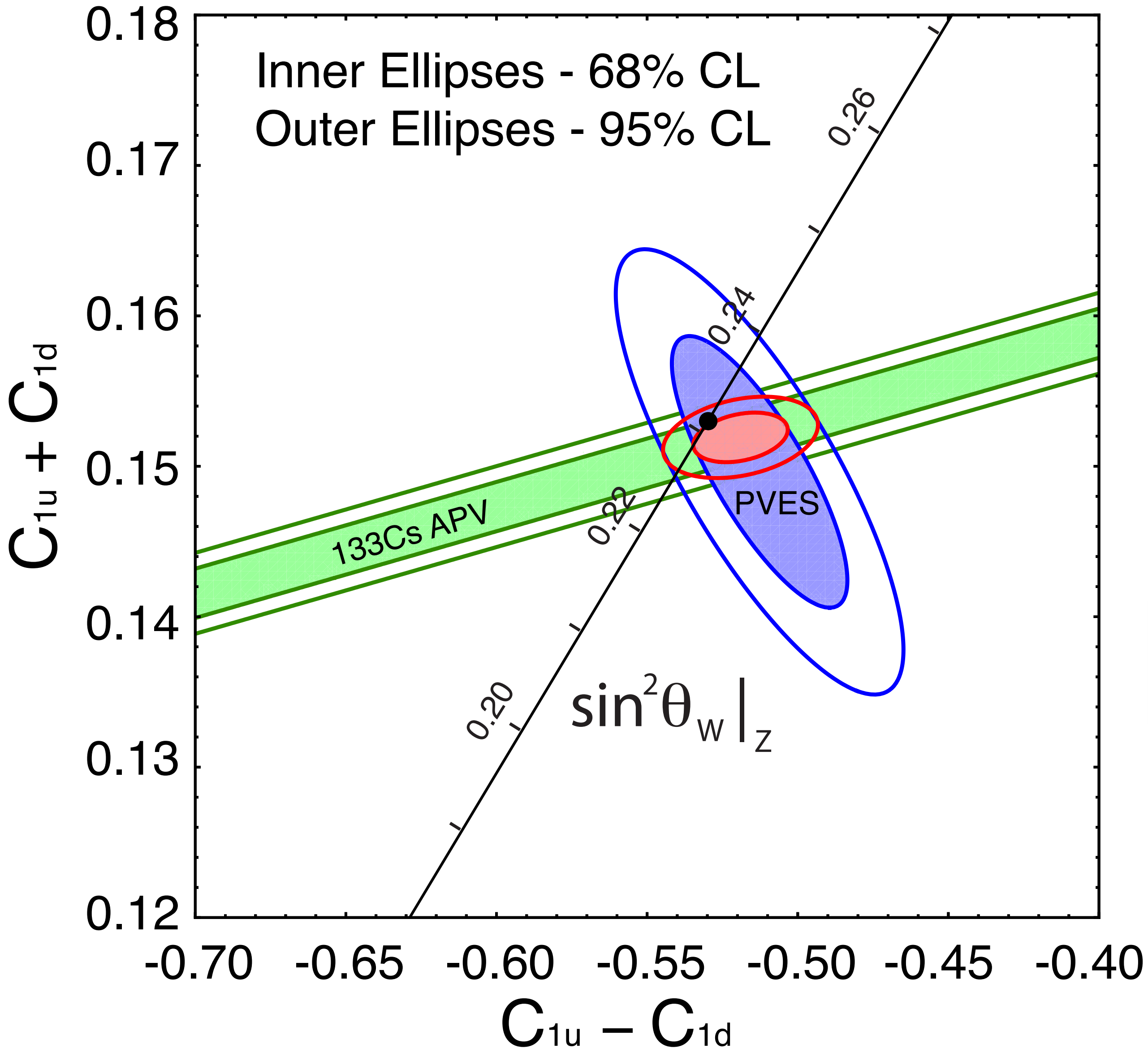
$Q^p_W(SM) = \quad 0.0710$

Hadronic part extracted through global fit of PVES data.

The C_{1q} & the neutron's weak charge



The C_{1q} & the neutron's weak charge



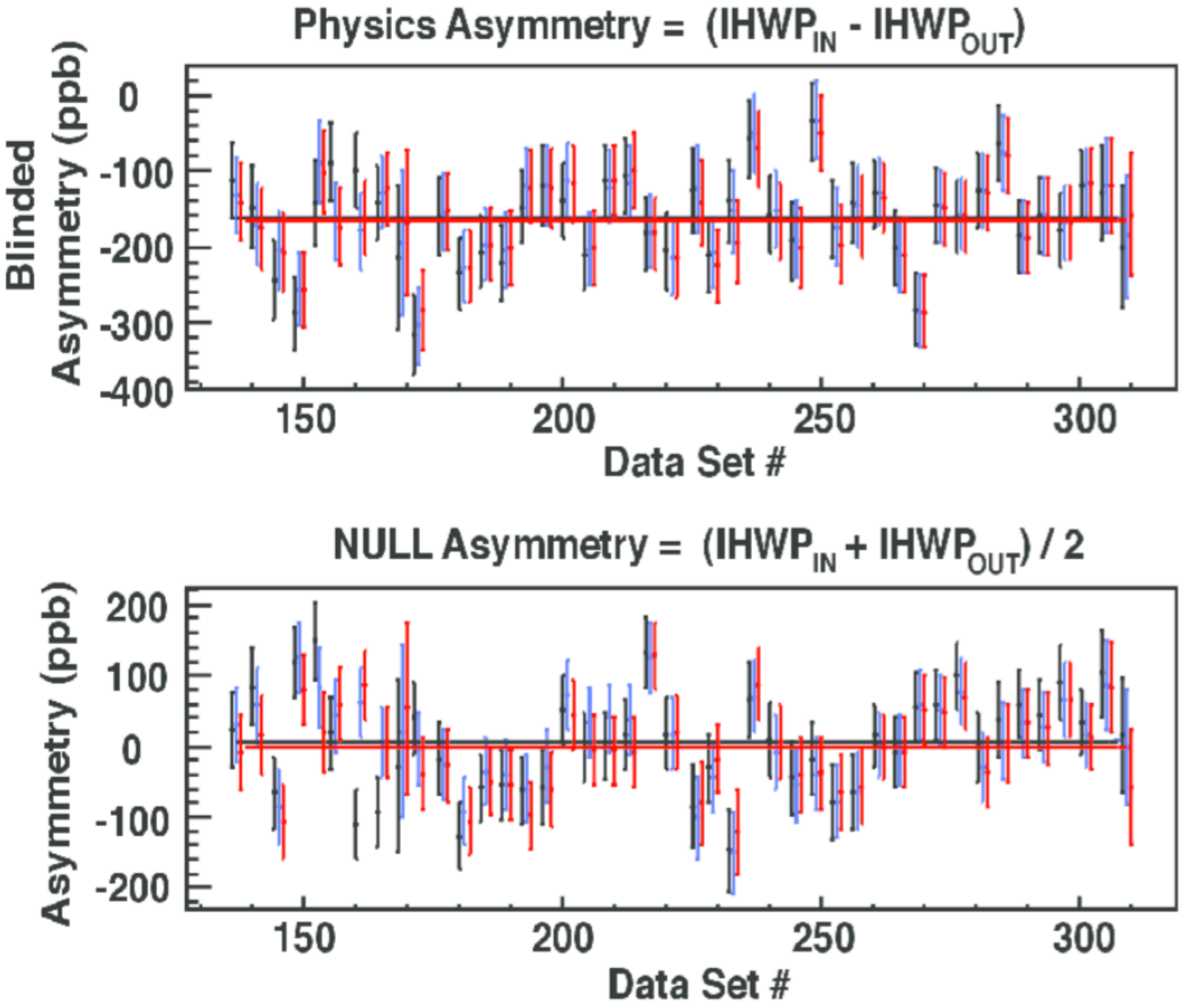
Combining this result with the most precise atomic parity violation experiment we can also extract, for the first time, the neutron's weak charge:

$$Q_W^n = -0.975 \pm 0.010$$

$$Q_W^n(SM) = -0.9890$$

Qweak Run 2 – Quality of Data

(statistics only - not corrected for beam polarization, Al target windows, ΔQ^2, etc.)



Raw = -161.8 ± 7.6

(χ^2/ NDF = 1.40, Prob = 0.043)

Regressed = -160.9 ± 7.6

(χ^2/ NDF = 1.19, Prob = 0.18)

Beamline Bkgd Corrected = -164.5 ± 7.6

(χ^2/ NDF = 1.08, Prob = 0.33)

Raw = 4.7 ± 7.7

(χ^2/ NDF = 1.84, Prob = 0.001)

Regressed = 7.9 ± 7.7

(χ^2/ NDF = 1.38, Prob = 0.048)

Beamline Bkgd Corrected = -1.4 ± 7.7

(χ^2/ NDF = 1.29, Prob = 0.097)

Expect final result early next year; will be statistics-limited

PVDIS at 6 GeV

Repeat of SLAC E122
to 5x higher precision (JLab, Hall A)

Sensitive to: C_{2u} & C_{2d}
(axial quark – vector electron)

Two kinematic settings:

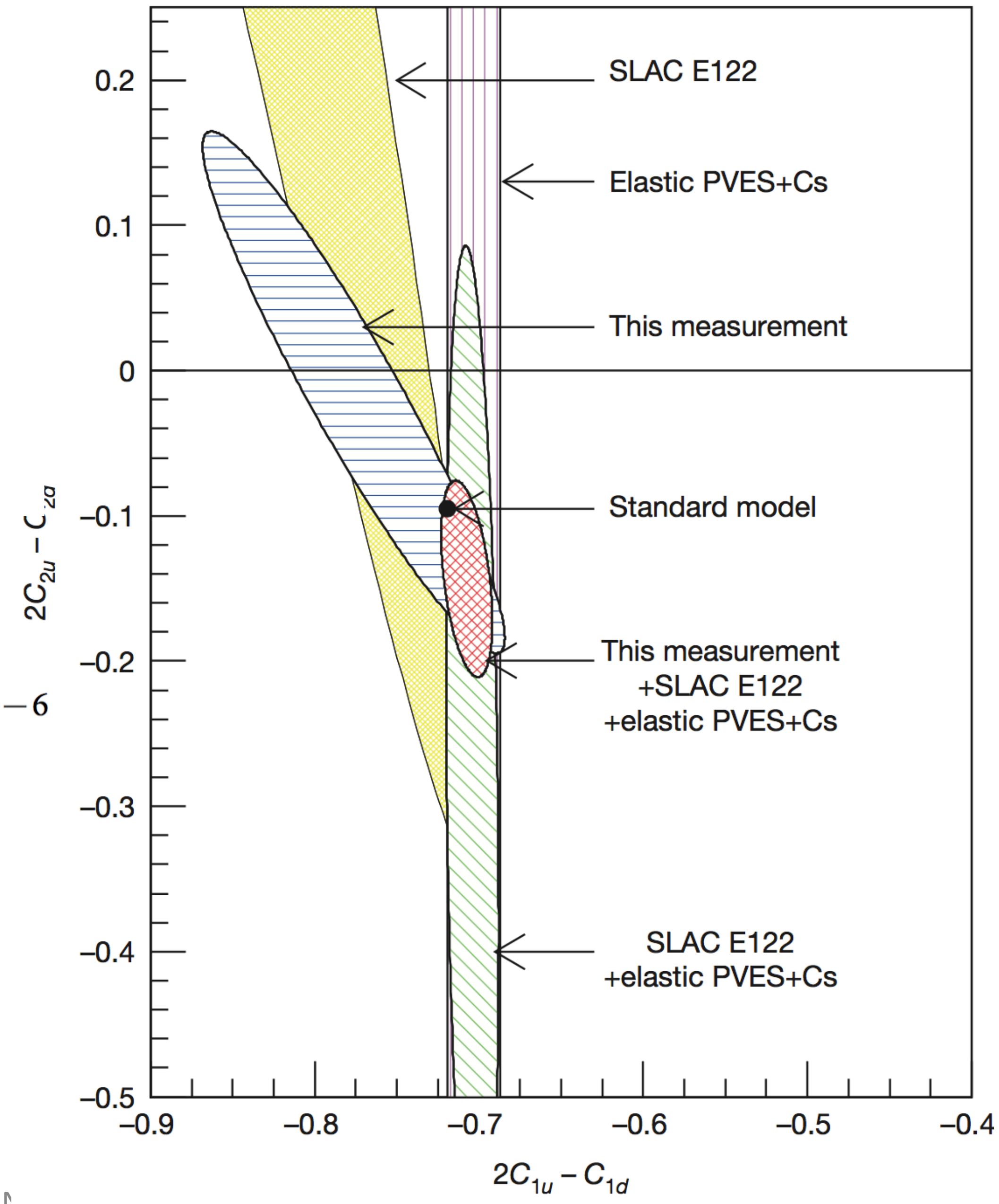
$$A_{\text{exp}} = [-91.1 \pm 3.1(\text{stat.}) \pm 3.0(\text{syst.})] \times 10^{-6}$$

$$A_{\text{SM}} = -87.7 \times 10^{-6}$$

$$A_{\text{exp}} = [-160.8 \pm 6.4(\text{stat.}) \pm 3.1(\text{syst.})] \times 10^{-6}$$

$$A_{\text{SM}} = (-158.9 \pm 1.0) \times 10^{-6}$$

D. Wang *et al.* Nature **506** (2014)67



Qweak and PVDIS combined

Electron & quark compositeness or contact interaction limits*:

$$\Lambda^{\pm} = \mathrm{v}\left[\frac{8\sqrt{5}\pi}{\left|(2C_{2u}-C_{2d})_{Q^2=0}\right|^{\pm}}\right]^{1/2}$$

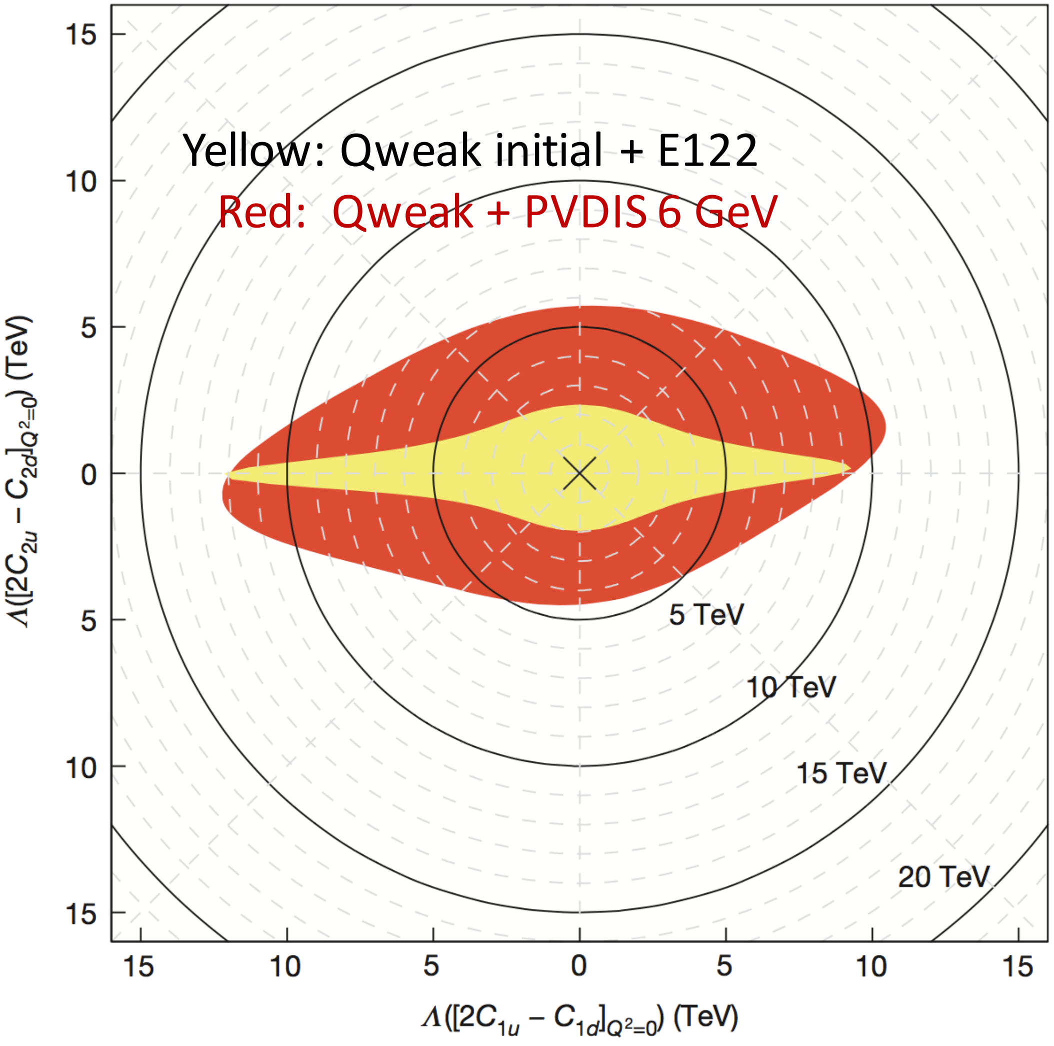
$$v = \sqrt{\sqrt{2}/(2G_F)} = 246.22\ \text{GeV}$$

>5.8 TeV & >4.6 TeV
(constructive & destructive int. with SM)

c.f. HERA (ZEUS & H1) limits
>3.2 & >3.8 TeV on e_V-q_A term

c.f. ATLAS, PRD **87** 015010(2013)
>9.5 TeV & >12.1 TeV
in left-left isoscalar model

(need to assume all other contact interactions are zero; PVES does not need this assumption)



Yellow: Qweak initial + E122

Red: Qweak + PVDIS 6 GeV

*convention of Eichten, Lane & Peskin
PRL **50**, 811 (1983)

Future: PVES at JLab in 12 GeV era

MOLLER - precision Standard Model test by measuring weak charge of electron in PV electron-electron scattering (revisit SLAC E158)

SOLID - precision Standard Model test by measuring PV DIS on deuteron: improved access to quark weak axial couplings C_{2q}

Large kinematic coverage: disentangle CSV and higher-twist effects

Elsewhere: P2 experiment at Mainz/MAMI (→ *Kurt Aulenbacher's talk*)
improve Qweak by factor of 2-3 at lower Q^2

MOLLER at 12 GeV

Parity-violating electron-electron scattering:
weak charge of electron
Update SLAC E158

A_{PV} = 35 ppb
Luminosity: 3x10^{39} cm^2/s
75 μA 80% polarized beam

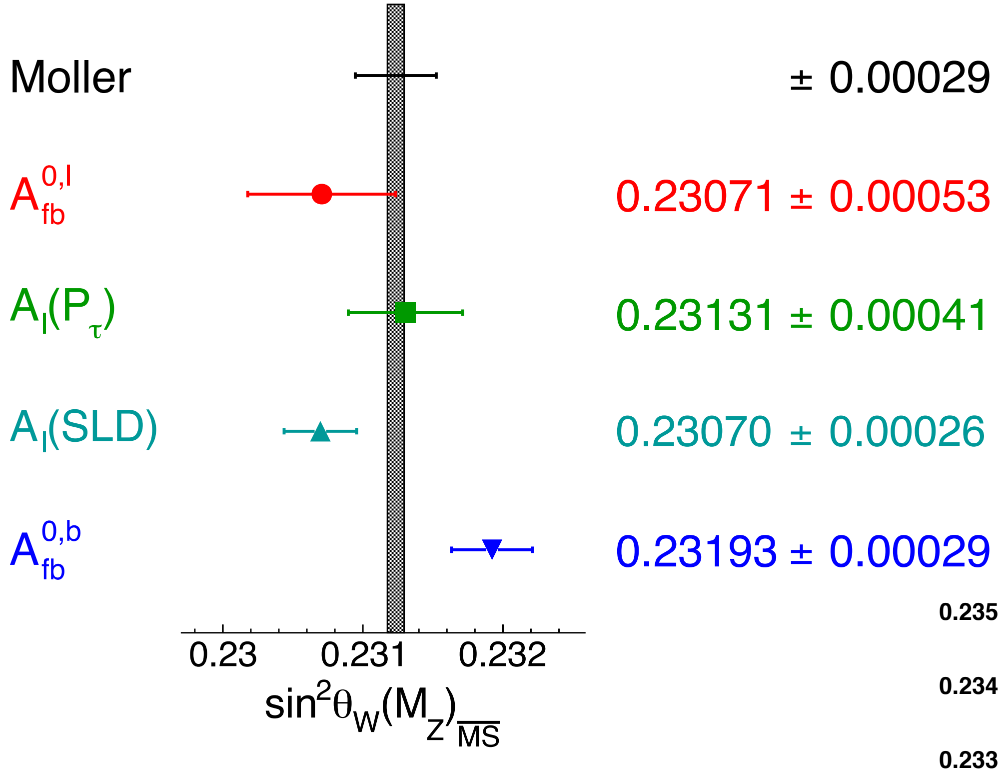
δ(A_{PV}) = 0.73 ppb
δ(Q_e^W) = ± 2.1 % (stat.) ± 1.1 % (syst.)

$$\mathcal{L}_{e_1 e_2} = \sum_{\mathbf{i,j=L,R}} \frac{\mathbf{g_{ij}^2}}{\mathbf{2\Lambda^2}} \bar{\mathbf{e}}_\mathbf{i}\gamma_\mu \mathbf{e}_\mathbf{i}\bar{\mathbf{e}}_\mathbf{j}\gamma^\mu \mathbf{e}_\mathbf{j} \Rightarrow \frac{\boldsymbol{\Lambda}}{\sqrt{|\mathbf{g_{RR}^2} - \mathbf{g_{LL}^2}|}} = \mathbf{7.5}\ \mathrm{TeV}$$

LEP2 (g_{LR} and sum) mass scale sensitivity: ~5.2 and 4.4 TeV

MOLLER: Lepton compositeness (strong coupling) – 47 TeV
Sensitivity to: Doubly-charged scalar, heavy Z', SUSY, dark Z…

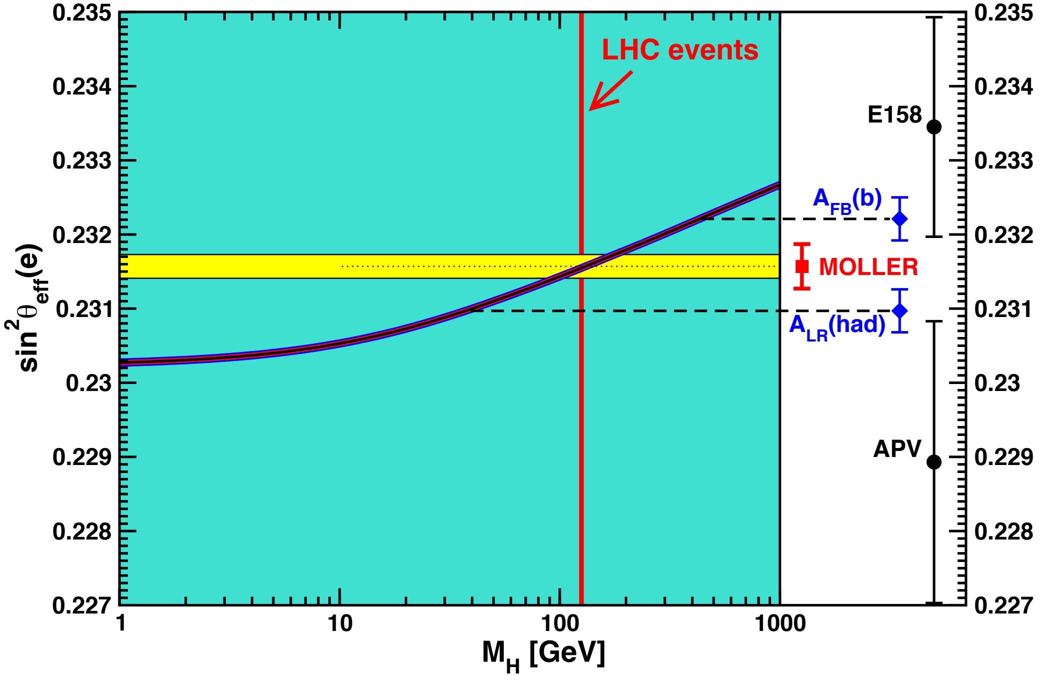
MOLLER and weak mixing angle



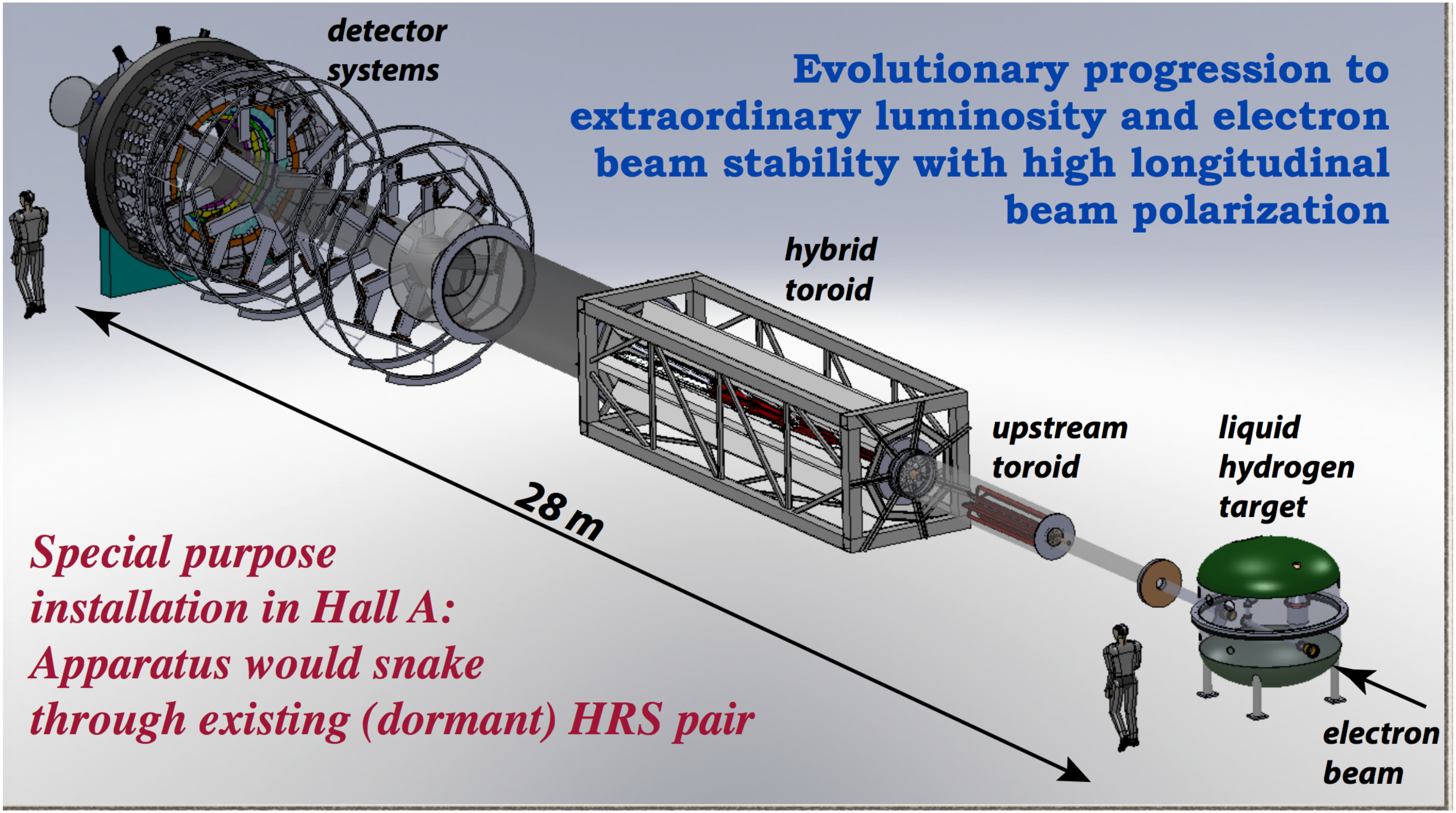
Reminder: at tree-level

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

Higgs discovery at LHC allows firm prediction of MOLLER asymmetry in Standard Model

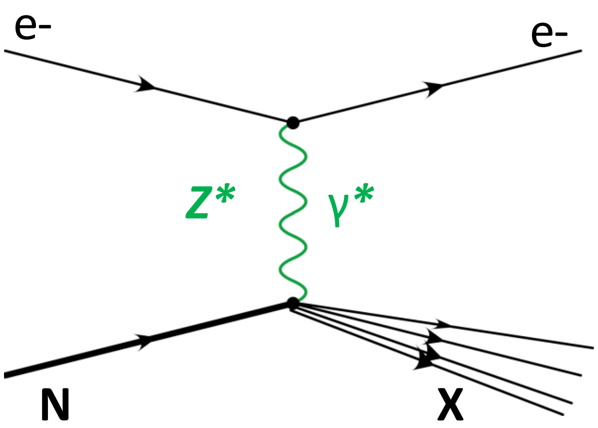


MOLLER apparatus



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

Special purpose installation in Hall A: Apparatus would snake through existing (dormant) HRS pair



SOLID – accessing the C_{2q}'s

$$\begin{aligned} A_{\rm iso} &= \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \\ &= -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{2C_{1u} - C_{1d}\,(1+R_s) + Y\,(2C_{2u} - C_{2d})\,R_v}{5+R_s} \end{aligned}$$

Cahn and Gilman, PRD **17** 1313 (1978) polarized electrons on deuterium

$$\begin{aligned} R_s(x) &= \frac{2S(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 0 \\ R_v(x) &= \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1 \end{aligned}$$

$$\begin{aligned} C_{1u} &= -\tfrac{1}{2}+\tfrac{4}{3}\sin^2\theta_W &\approx& -0.19 \\ C_{1d} &= \tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W &\approx& 0.35 \\ C_{2u} &= -\tfrac{1}{2}+2\sin^2\theta_W &\approx& -0.04 \\ C_{2d} &= \tfrac{1}{2}-2\sin^2\theta_W &\approx& 0.04 \end{aligned}$$

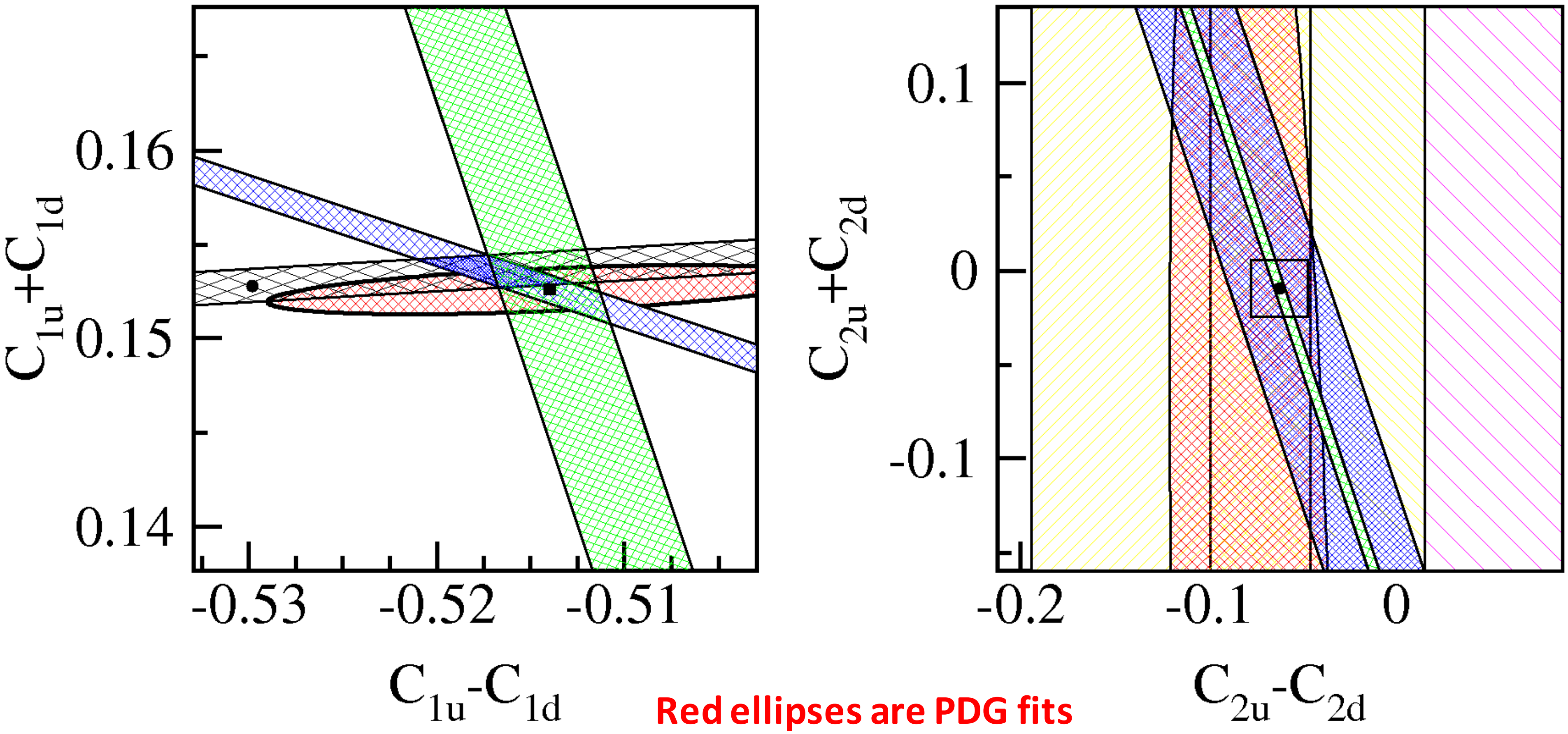
$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\frac{R}{R+1}}$$

$$R(x,Q^2) = \sigma^l/\sigma^r \approx 0.2$$

$x \equiv x_{Bjorken}$

$y \equiv 1 - E'/E$

SOLID – accessing the C_{iq}'s

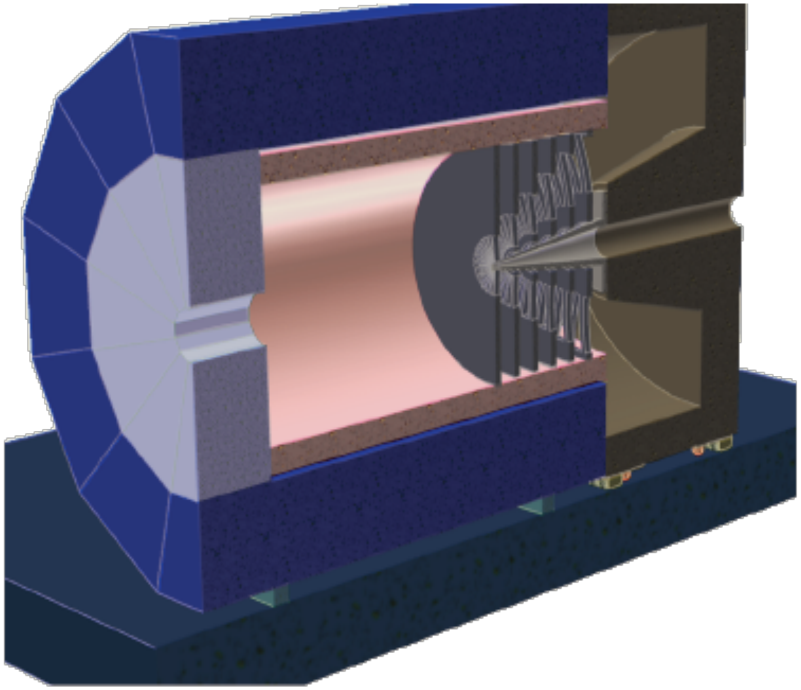


Red ellipses are PDG fits

Blue bands represent expected data:
Qweak (left) and PVDIS-6GeV (right)

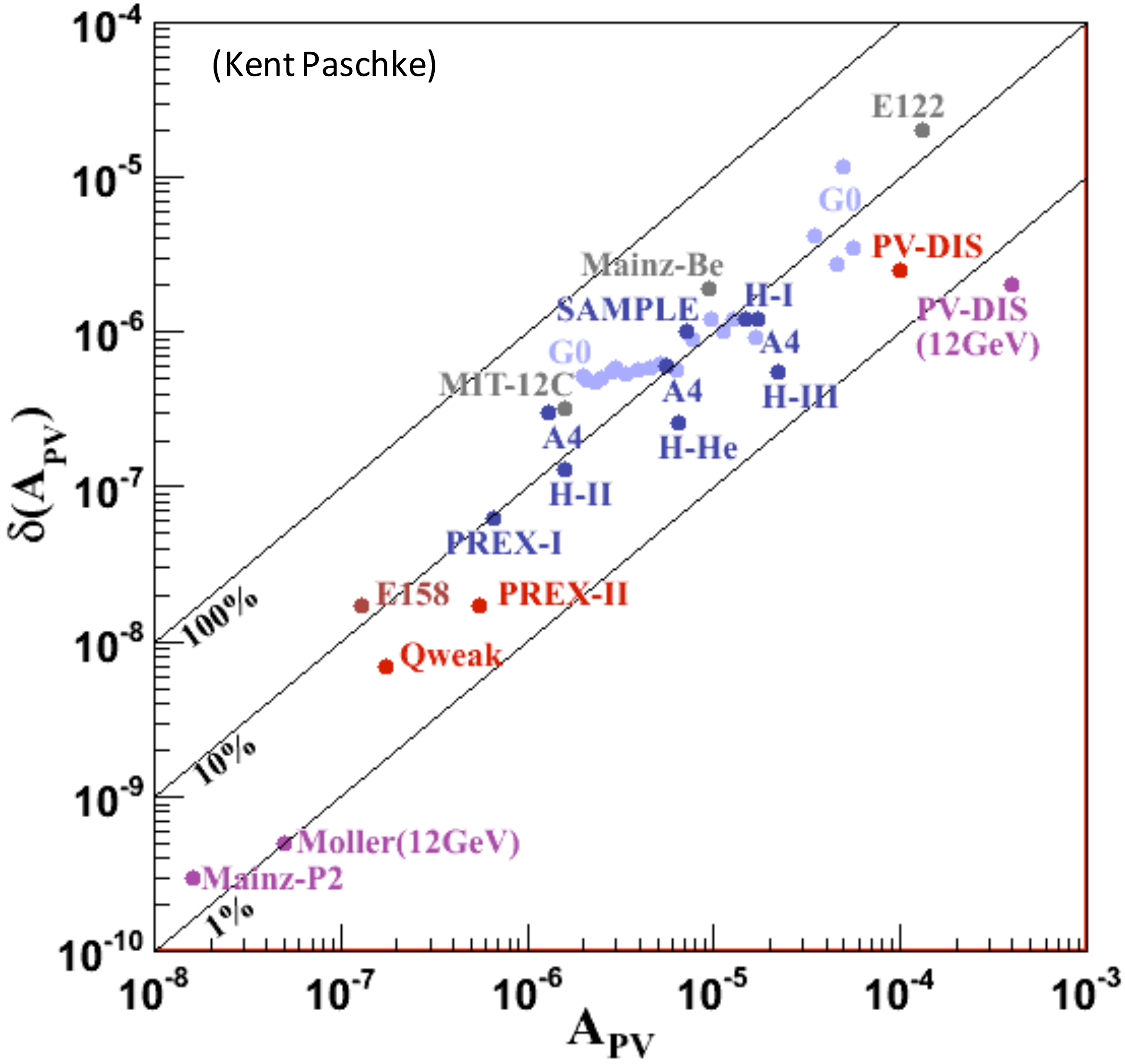
Green bands are proposed SOLID PVDIS

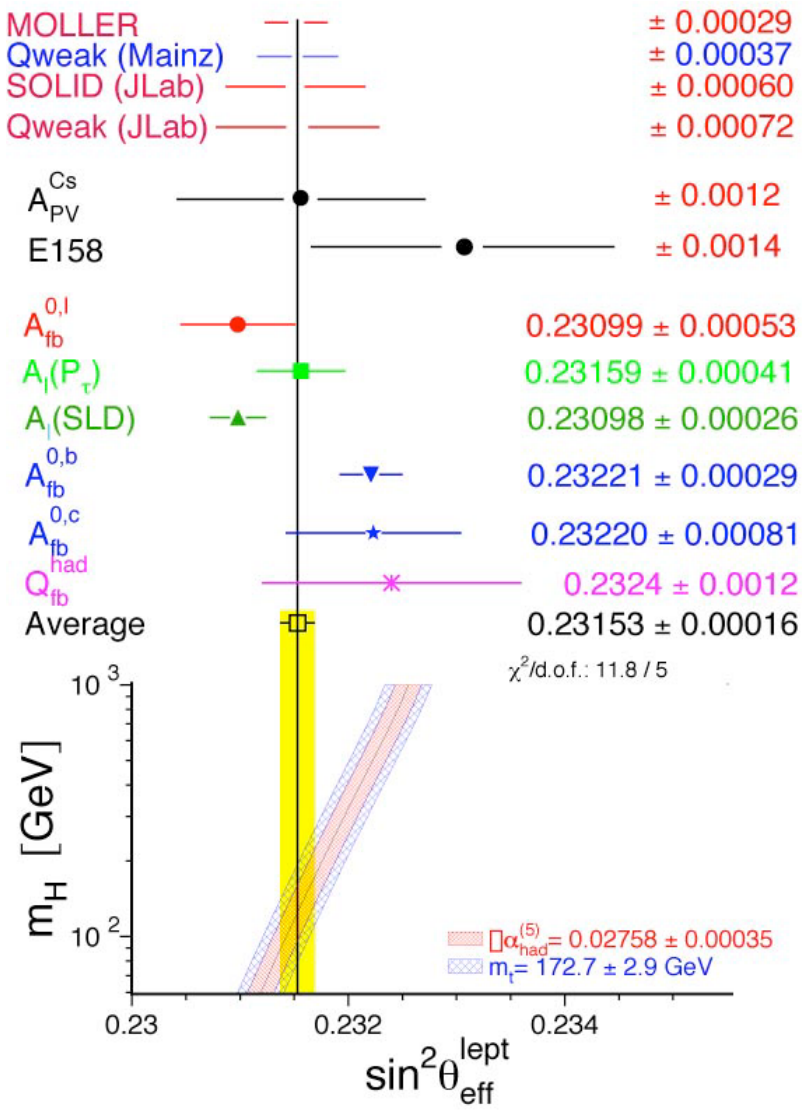
SOLID – Large Acceptance Device



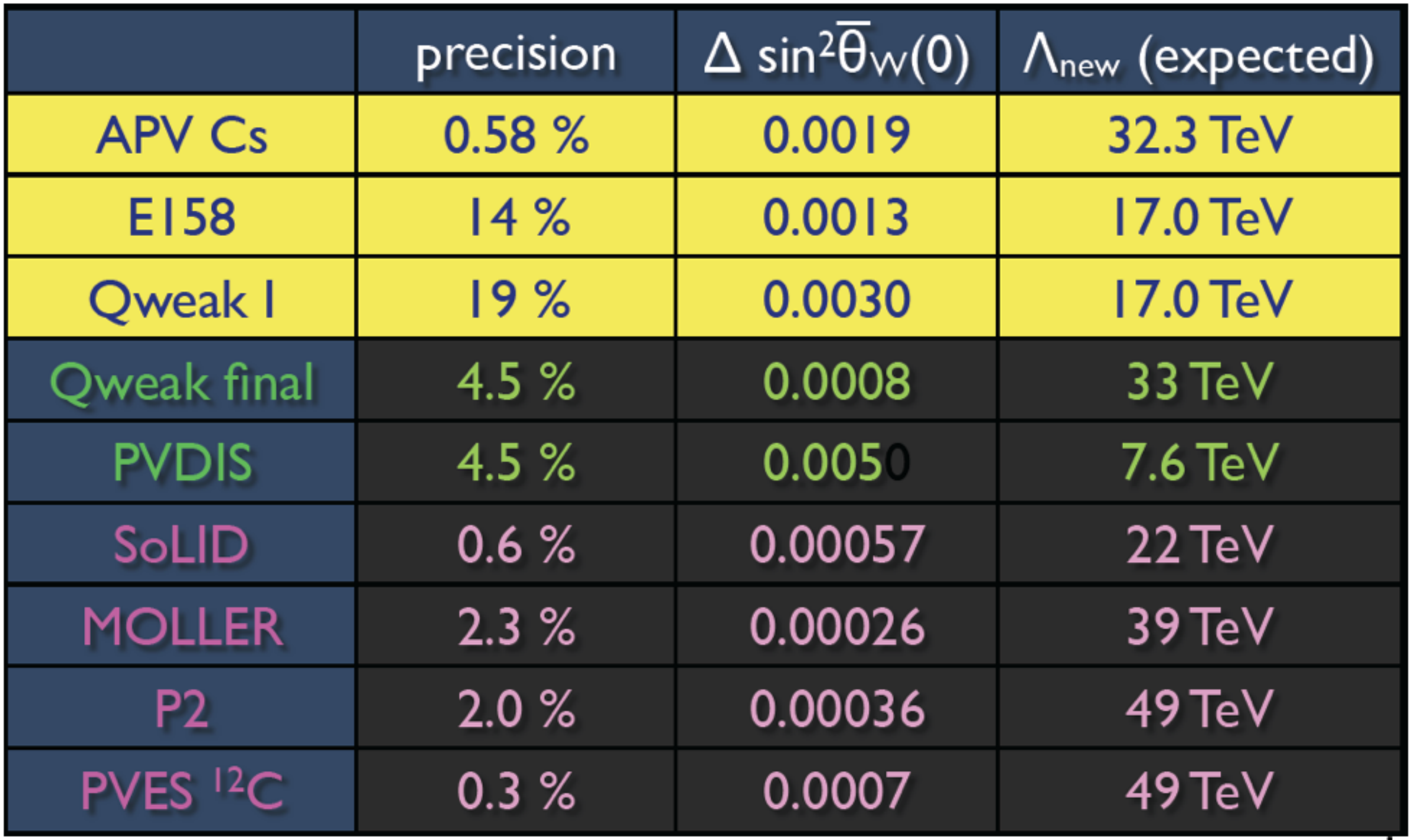
- Moderate running times
  - Large Acceptance
  - High Luminosity on LH2 & LD2
- Better than 1% errors for small bins
- Kinematics:
  - Large Q^2 coverage
  - x-range 0.25-0.75
  - $W^2 > 4$ GeV^2
- Requirements:
  - Solenoid contains low energy backgrounds (Møller, pions, etc)
  - Baffling to cut backgrounds
  - Trajectories measured after baffles
  - Fast tracking—GEM, particle ID, calorimetry, and pipeline electronics
  - Precision polarimetry (0.4%) Compton and atomic hydrogen Moller

PVES Experiment Summary


(Kent Paschke)



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

The Qweak Collaboration

97 collaborators 23 grad students
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[14] Southern University at New Orleans
[15] Idaho State University
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[17] University of Connecticut
[18] University of Northern British Columbia
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A SEARCH FOR NEW PHYSICS
Qweak

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Jefferson Lab

Spokespersons Project Manager Grad Students

Summary

- Qweak: First measurement of proton’s weak charge, consistent with Standard Model, 25x more data soon to be released
- Qweak and PVDIS at 6 GeV: constraints on new physics
- MOLLER and SOLID: major programs after JLab upgrade
  two complementary Standard Model tests.

Thanks to the organizers for the kind invitation!
And thanks to you who stayed for my talk rather than….