The Q_{Weak} Experiment

First Determination of the Weak Charge of the Proton

- Qweak basics and motivation
- Experimental design
- Preliminary results
- Outlook, summary

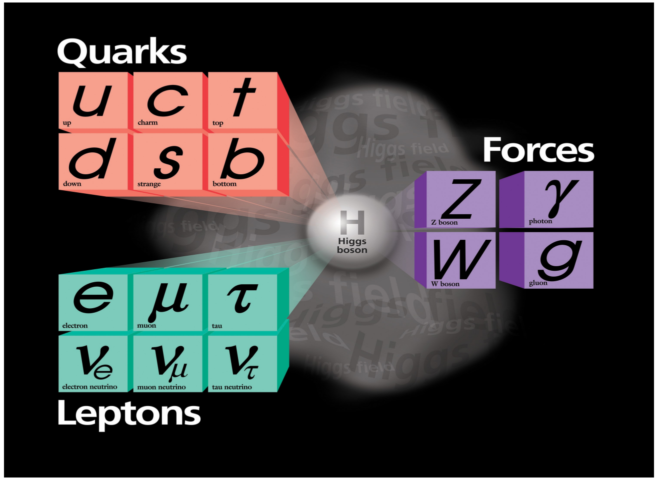
Manolis Kargiantoulakis

On behalf of the Q_{Weak} Collaboration

Les Rencontres de Physique de la Vallée d'Aoste

La Thuile 2014

Precision tests of the Standard Model



The Standard Model has been greatly successful, but thought to be just an effective low-energy theory of a more fundamental underlying structure.

Two complementary approaches to look for Physics *Beyond* the Standard Model :

- Energy frontier - direct searches, eg LHC, Tevatron
- Precision or Intensity frontier - indirect high-precision measurements at lower energies α_μ-2, 0νββ, atomic parity violation (APV), parity violating electron scattering (PVES)

Precision measurements focus on quantities that are precisely predicted or suppressed within the Standard Model.

The weak charge of the proton $Q_w(p)$

is both suppressed *and* precisely predicted in the SM

Weak charge of the proton, $Q_w(p)$

Charge / Particle	Electric	Weak (vector)
u	+2/3	$-2\ C_{1u} = +1 - 8/3\ \sin^2\theta_W$
d	-1/3	$-2\ C_{1d} = -1 + 4/3\ \sin^2\theta_W$
Proton uud	+1	$Q_w^p = 1 - 4\ \sin^2\theta_W \approx 0.07$
Neutron udd	0	$Q_w^n = -1$

Weak mixing angle

Suppressed

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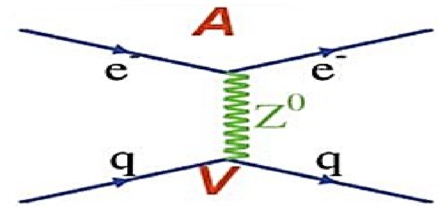
Vector weak quark couplings, defined in the effective 4-fermion contact interaction

Weak mixing angle

Suppressed

$$Q_W^p = -2\,(2C_{1u} + C_{1d})$$



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

$$\mathcal{L}_{e\text{-}q}^{NC} = \frac{G_F}{\sqrt{2}}\,\bar{e}\gamma_\mu\gamma^5 e \sum_q C_{1q}\bar{q}\gamma^\mu q$$

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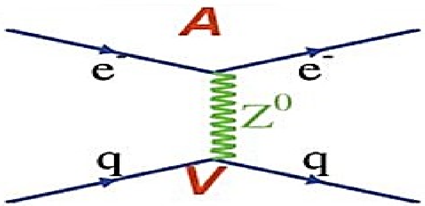

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The Q_{Weak} experiment proposes a 4% determination of $Q_w(p)$

Very important precision test of EW sector. $Q_w(p)$ suppression allows:

- Enhanced **TeV-scale** sensitivity to signatures of BSM physics
- A 0.3% extraction of $\sin^2\theta_w$, the weak mixing angle: most precise at low Q^2
- High-precision extraction of both C_{1u}, C_{1d}, in combination with APV data

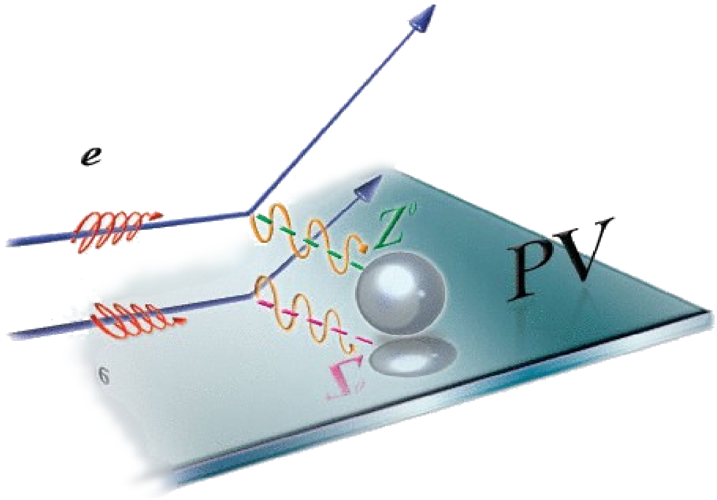
The Q_{Weak} Experiment in Jefferson Lab

The Jefferson Lab
e^- accelerator facility,
supporting a world-leading
Parity Violation program

Qweak was completed on May 2012 after 2 years of data-taking in Hall C of Jefferson Lab.

Elastic scattering of polarized e^- on proton target.

Parity-Violating asymmetry in e-p scattering



Electrons prepared in two “mirror” states of opposite helicity. The Parity-Violating asymmetry arises from interference of γ and Z exchange:

$$A_{ep}^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{|M_{weak}^{PV}|}{|M_{EM}|}$$

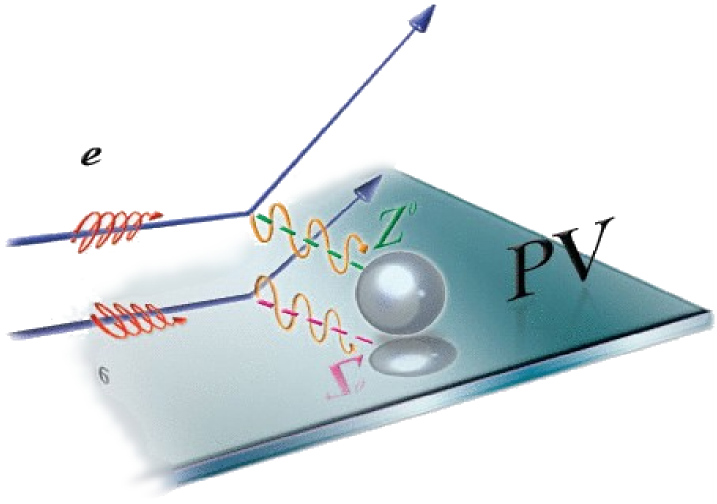
Tree-level expression in terms of EM and weak form factors

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

At forward angles and low Q^2, recast the reduced asymmetry: → $A_{ep}/A_0 = \mathbf{Q_W^p} + Q^2 B(Q^2,\theta)$, $A_0 = \left[\frac{-G_F Q^2}{4\sqrt{2}\pi\alpha}\right]$

Access to the neutral-weak charge of the proton

Parity-Violating asymmetry in e-p scattering



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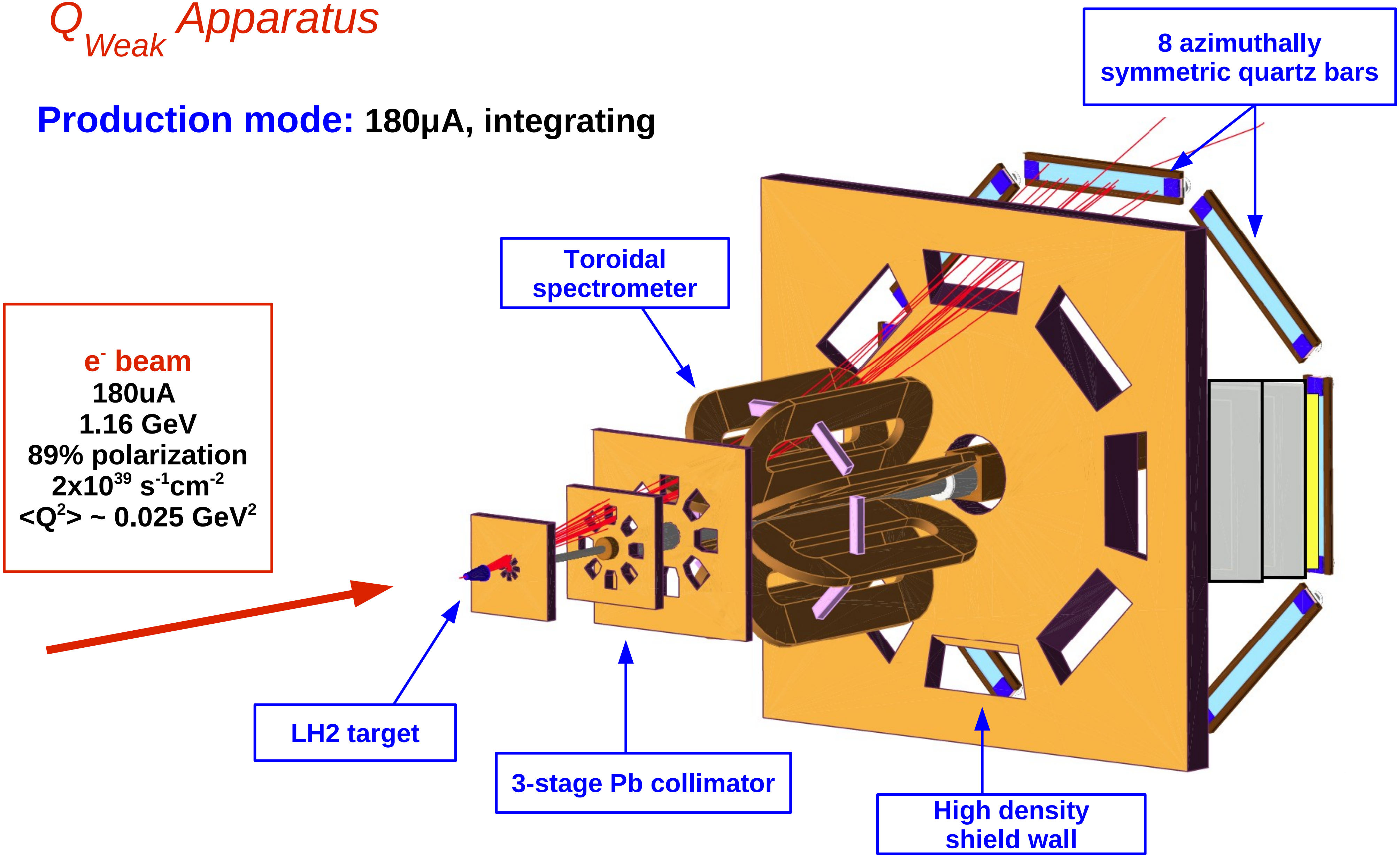
Access to the neutral-weak charge of the proton

Nuclear structure in terms of EM and weak FFs. Suppressed at low Q^2 and constrained experimentally by the world PVES data.

Q_{Weak} Apparatus

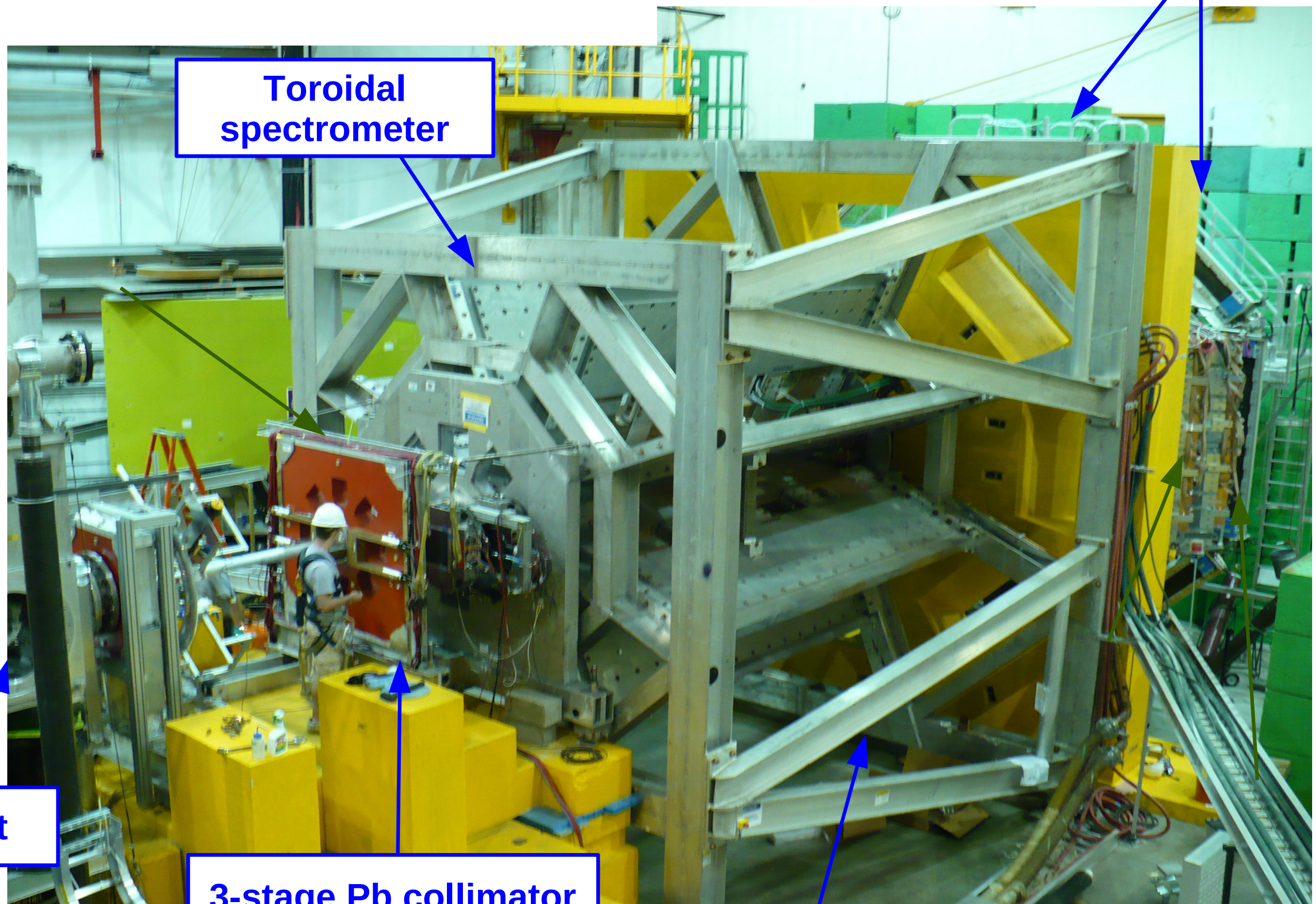
Production mode: 180μA, integrating



Q_{Weak} Apparatus

Production mode: 180μA, integrating

e⁻ beam
180uA
1.16 GeV
89% polarization
$2\times10^{39}\ s^{-1}cm^{-2}$
$\langle Q^2\rangle \sim 0.025\ GeV^2$



Q_{Weak} *Preliminary results*

Results from the commissioning run of the experiment.
Only ~4% of full dataset, but already competitive.

First Determination of the Weak Charge of the Proton

PRL 111, 141803 (2013)

Physical Review Letters
moving physics forward

Phys. Rev. Lett. 111, 141803 (2013) [7 pages]

First Determination of the Weak Charge of the Proton

D. Androic *et al.* (Q_{weak} Collaboration)
Show All Authors/Affiliations

Received 25 July 2013; published 2 October 2013

The $Q_{\rm weak}$ experiment has measured the parity-violating asymmetry in $\vec{e}p$ elastic scattering at $Q^2 = 0.025\,({\rm GeV}/c)^2$, employing 145 μA of 89% longitudinally polarized electrons on a 34.4 cm long liquid hydrogen target at Jefferson Lab. The results of the experiment's commissioning run, constituting approximately 4% of the data collected in the experiment, are reported here. From these initial results, the measured asymmetry is $A_{ep} = -279 \pm 35$ (stat) ± 31 (syst) ppb, which is the smallest and most precise

Preliminary results: A_{ep}

$$A_{ep} = R_{total} \left[\frac{\frac{A_{msr}}{P} - \sum_{i=1}^{4} A_i f_i}{1 - \sum_{i=1}^{4} f_i} \right]$$

A_{msr} : Includes corrections for helicity-correlated beam differences

P : Beam polarization

A_i, f_i : Background asymmetry and signal fraction

R_{total} : Radiative corrections and non-uniform Q^2

Corrections and contributions to uncertainty

	Correction Value (ppb)	Contribution to ΔA_{ep} (ppb)	
Normalization Factors Applied to A_{Raw}			
Beam Polarization $1/P$	-21	5	
Kinematics R_{tot}	5	9	
Bckgrnd Dilution $1/(1-f_{tot})$	-7	-	
Asymmetry corrections			
Beam Asymmetries κA_{reg}	-40	13	
Transverse Polarization κA_T	0	5	
Detector Linearity κA_L	0	4	
Backgrounds	$\kappa P f_i A_i$	$\delta(f_i)$	$\delta(A_i)$
Target Windows (b_1)	-58	4	8
Beamline Scattering (b_2)	11	3	23
Other Neutral bkg (b_3)	0	1	< 1
Inelastics (b_4)	1	1	< 1

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Preliminary Q_{Weak} result:

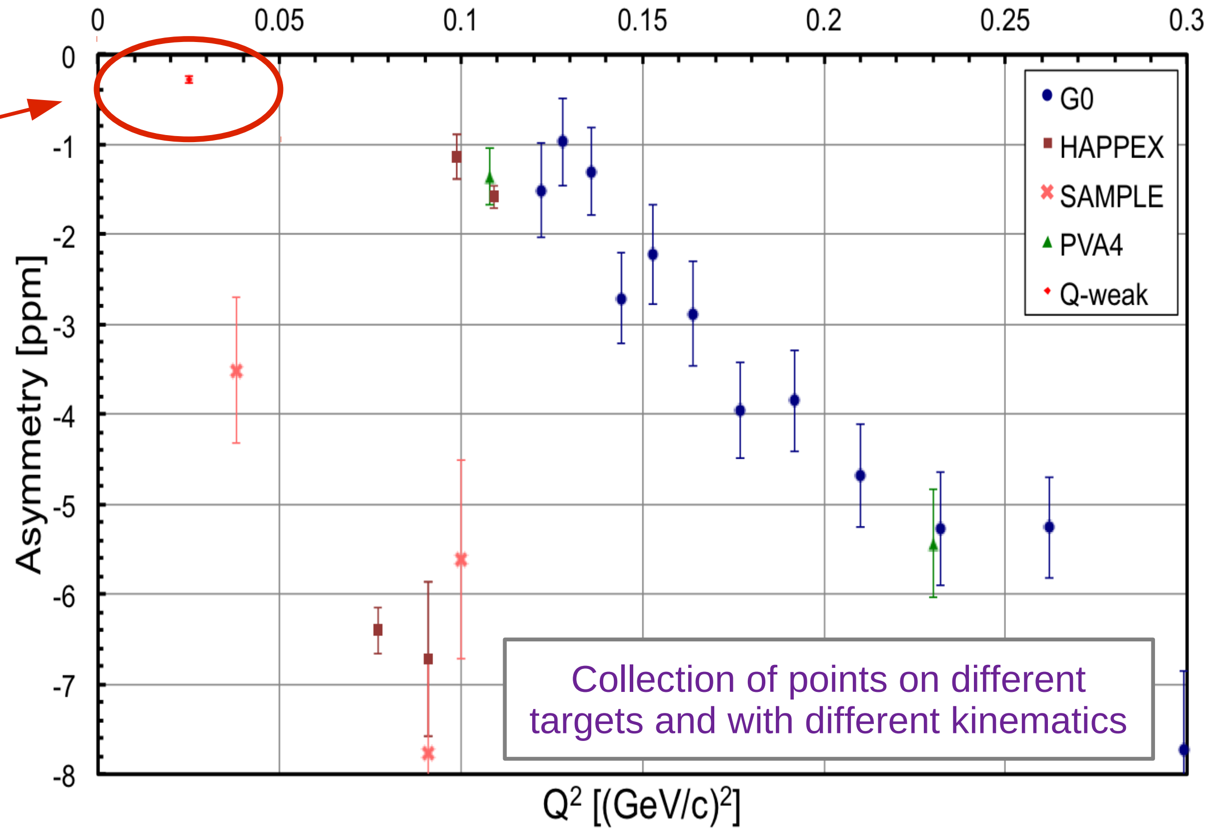
A_{ep} = −279 ± 35 (statistics) ± 31 (systematics) ppb

Preliminary results: A_{ep}

Q_{Weak} preliminary A_{ep}

Comparing to world data:

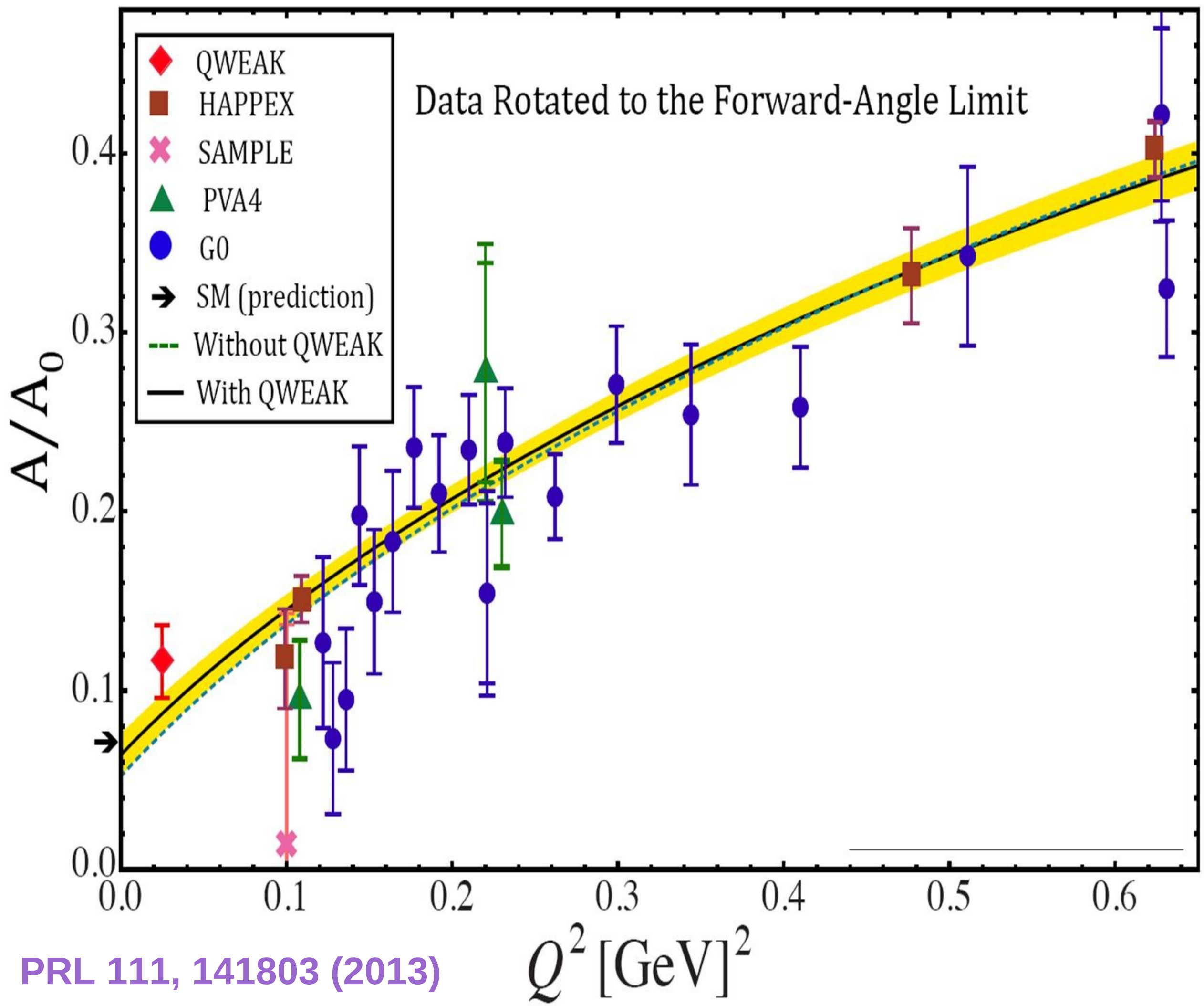
Smallest asymmetry and absolute error bar measured to date in PV electron scattering from nuclear targets



A_{ep} = −279 ± 35 (statistics) ± 31 (systematics) ppb

Preliminary results: Weak charge of the proton

$$A_{ep}/A_0 = \boldsymbol{Q_W^p} + Q^2 B(Q^2, \theta)$$



PRL 111, 141803 (2013)

Global fit of all PVES data on H, D, ^{4}He, similar to:
Young, Roche, Carlini, Thomas
PRL 97, 102002 (2006)
PRL 99, 122003 (2007)

Free fit parameters:
- weak couplings C_{1u}, C_{1d}
- ρ_s , μ_s
- iso-vector axial FF $G_A^{Z(T=1)}$

World PVES data constrain uncertainties of hadronic structure in the B-term.

Q_w(p) is the intercept of the fit

ée d'Aoste

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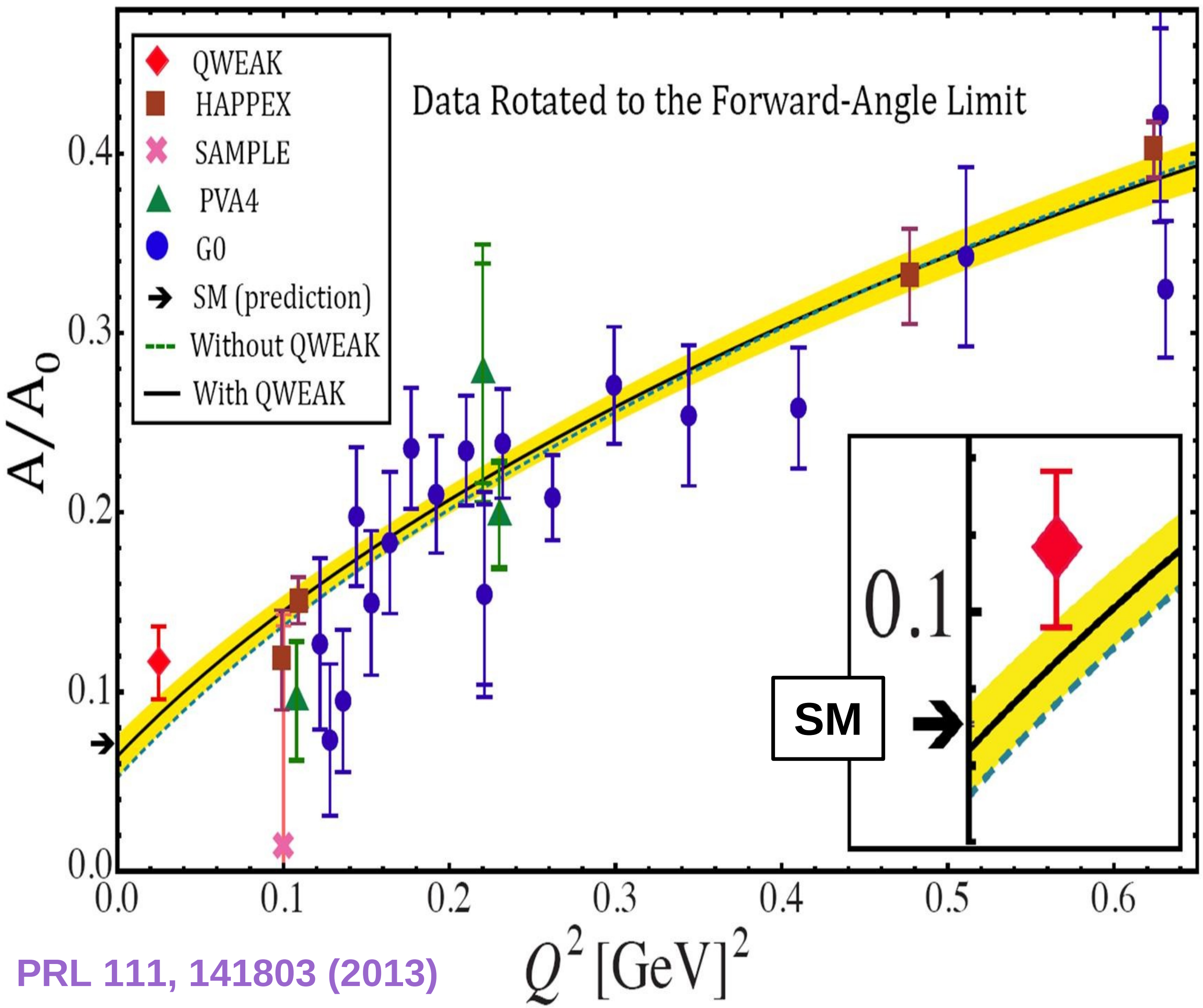

PRL 111, 141803 (2013)

Global PVES fit yields
first determination of the neutral-weak charge of the proton

$$Q_w^p = 0.064 \pm 0.012$$

(18.7% relative)

Consistency with SM prediction:

$$Q_w^p(SM) = 0.0710 \pm 0.0007$$

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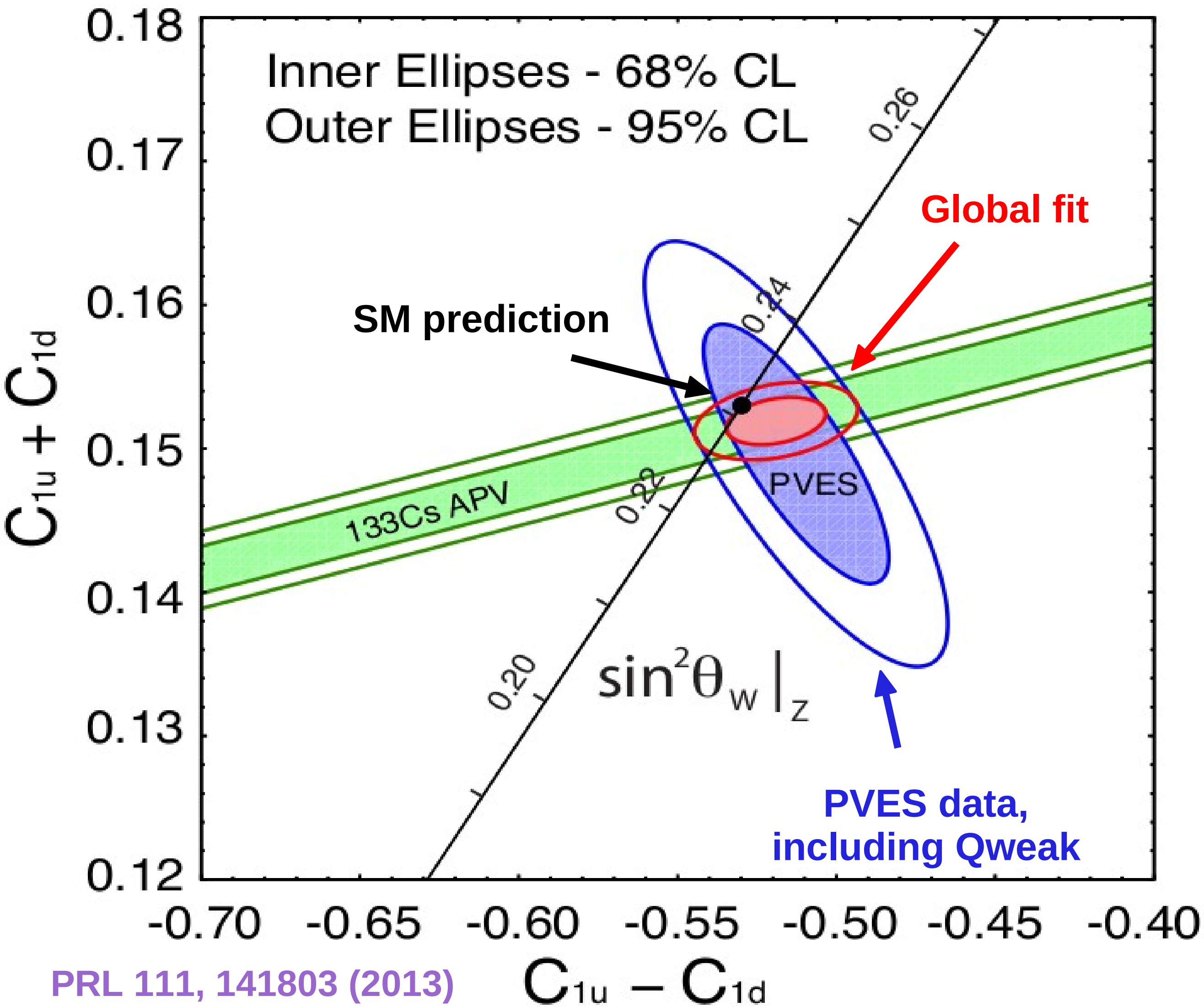
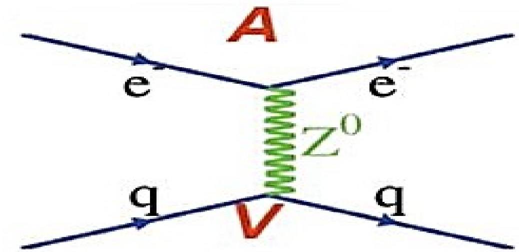
Constraints on C_{1q} couplings





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$$\mathscr{L}_{e\text{-}q}^{NC} = \frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu \gamma^5 e \sum_q \underline{C_{1q}} \bar{q}\gamma^\mu q$$

Excellent complementarity between PVES and APV allows high precision on both C_{1u}, C_{1d}

$$C_{1u} = -0.184 \pm 0.005$$

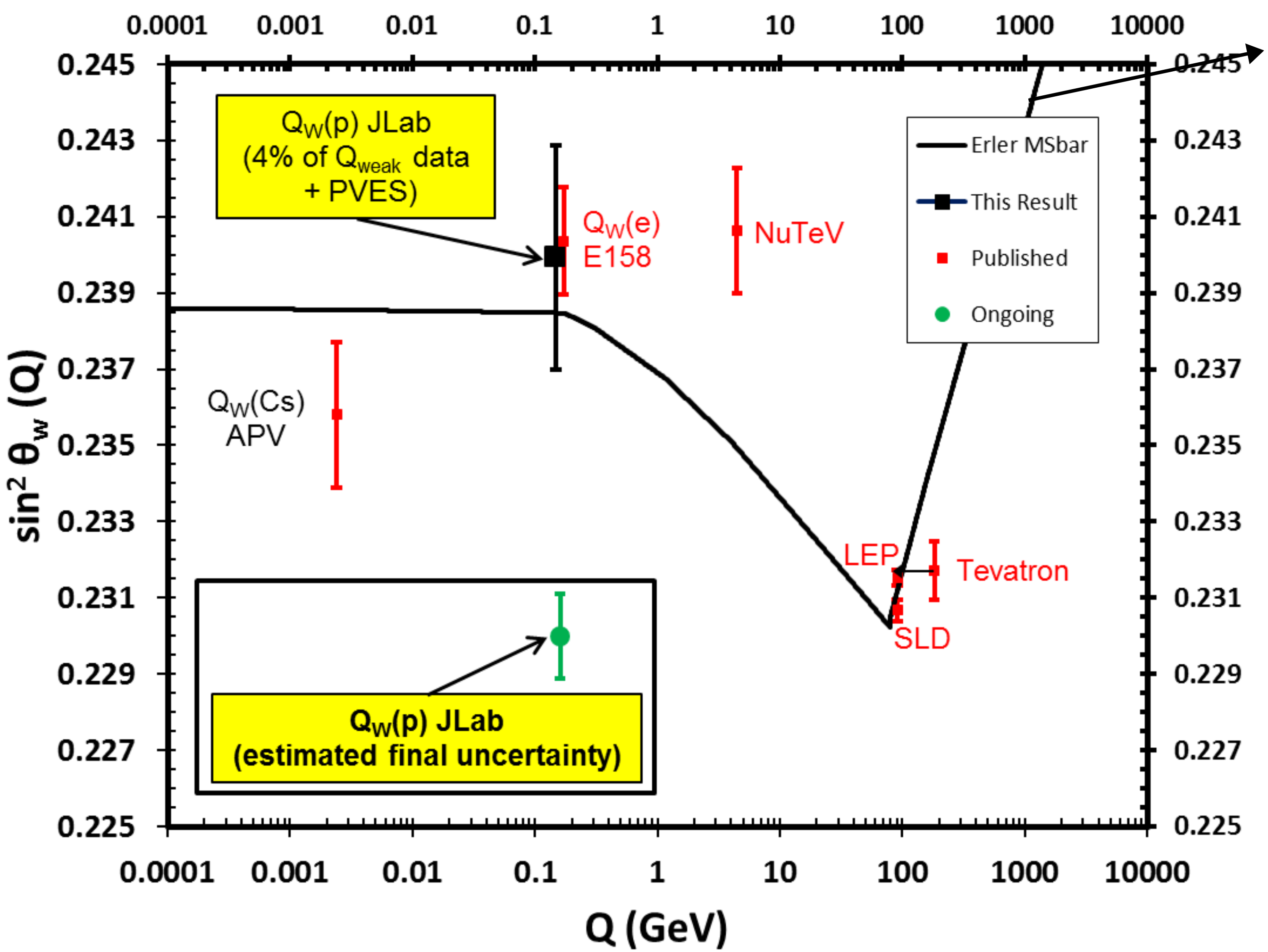
$$C_{1d} = 0.336 \pm 0.005$$

Agreement with SM at 1σ

PRL 111, 141803 (2013)

Preliminary results: Weak mixing angle

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



SM prediction for running in the $\overline{\rm MS}$ scheme, anchored by collider measurements at the Z-pole.

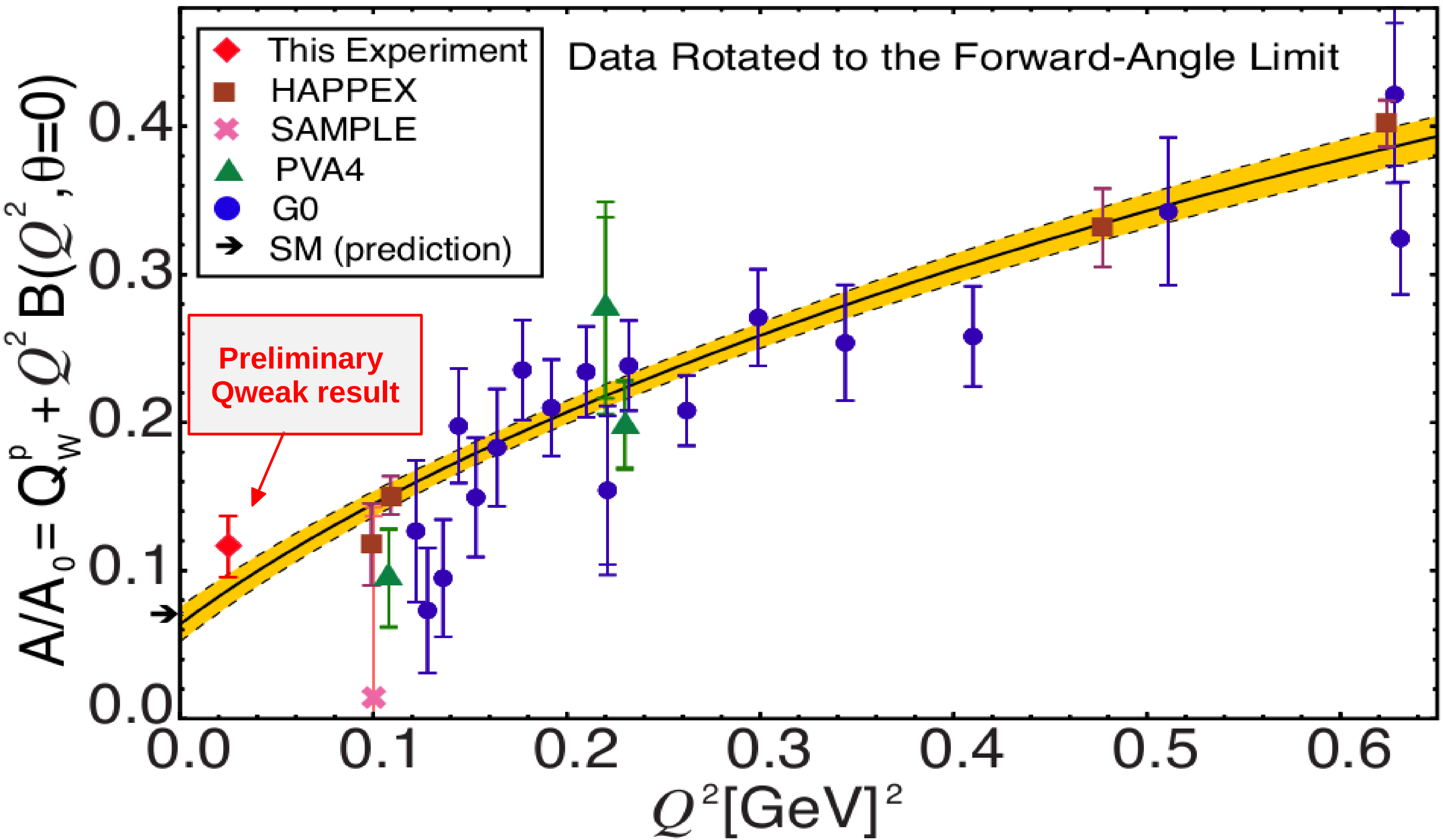
Precision measurements at lower energies test the SM prediction, complementary to collider searches (but many open issues).

The full Qweak measurement will offer the most precise determination below the Z-pole.

Outlook

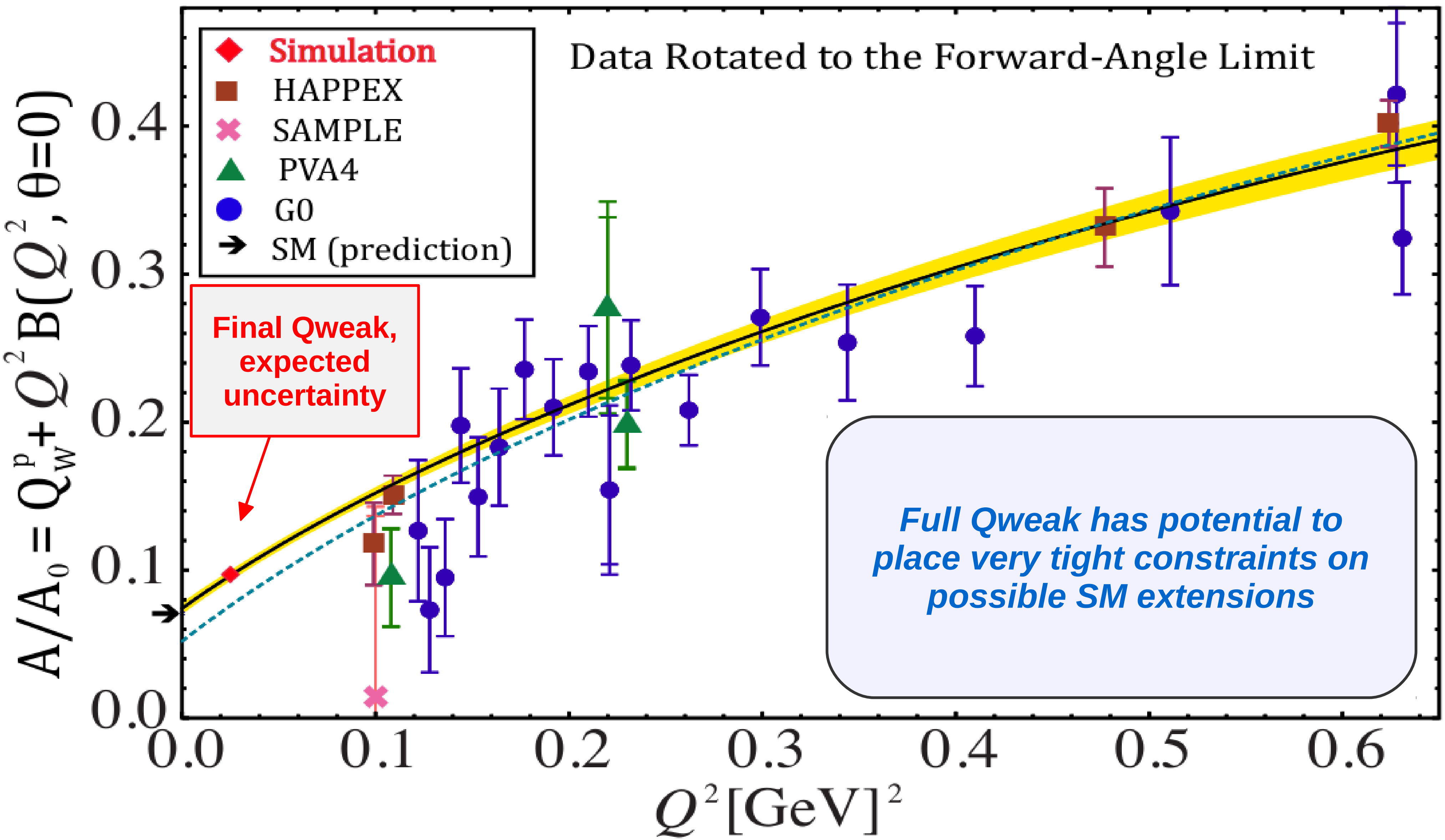
- 25x more data in hand for the full measurement.
- Systematic uncertainties very conservative for preliminary results. Analysis ongoing.
- Important subsystems became available after commissioning.
- *Full Q_{Weak} result expected in late 2014*

Outlook



This Experiment
HAPPEX
SAMPLE
PVA4
G0
SM (prediction)
Data Rotated to the Forward-Angle Limit
Preliminary Qweak result
$A/A_0 = Q^p_W + Q^2 B(Q^2, \theta=0)$
0.0
0.1
0.2
0.3
0.4
0.0
0.1
0.2
0.3
0.4
0.5
0.6
$Q^2 [\mathrm{GeV}]^2$

Outlook



Simulation
HAPPEX
SAMPLE
PVA4
G0
SM (prediction)
Data Rotated to the Forward-Angle Limit
Final Qweak, expected uncertainty
Full Qweak has potential to place very tight constraints on possible SM extensions
$A/A_0 = Q_W^p + Q^2 B(Q^2, \theta=0)$
Q^2 [GeV]^2
0.0
0.1
0.2
0.3
0.4
0.5
0.6

Summary

- The Qweak experiment measured the Parity-Violating asymmetry in elastic ep scattering
- Preliminary result released, from only 4% of full dataset
- First determination of the neutral-weak charge of the proton:

$$Q_w^p = 0.064 \pm 0.012 \quad (18.7\,\%\ relative)$$

Consistent with SM prediction: $Q_w^p(SM) = 0.0710 \pm 0.0007$

- 25x more data in hand, f*ull Qweak result expected in 2014*
- Demonstrated the technological base for the next generation of ultra-precise SM tests at an upgraded 12 GeV Jefferson Lab.

The Qweak Collaboration

97 collaborators 23 grad students
10 post docs 23 institutions

Institutions:

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[3] A. I. Alikhanyan National Science Laboratory
[4] Massachusetts Institute of Technology
[5] Thomas Jefferson National Accelerator Facility
[6] Ohio University
[7] Christopher Newport University
[8] University of Manitoba,
[9] University of Virginia
[10] TRIUMF
[11] Hampton University
[12] Mississippi State University
[13] Virginia Polytechnic Institute & State Univ
[14] Southern University at New Orleans
[15] Idaho State University
[16] Louisiana Tech University
[17] University of Connecticut
[18] University of Northern British Columbia
[19] University of Winnipeg
[20] George Washington University
[21] University of New Hampshire
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[23] University of Adelaide

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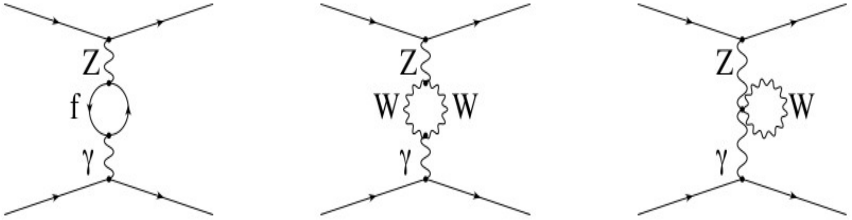
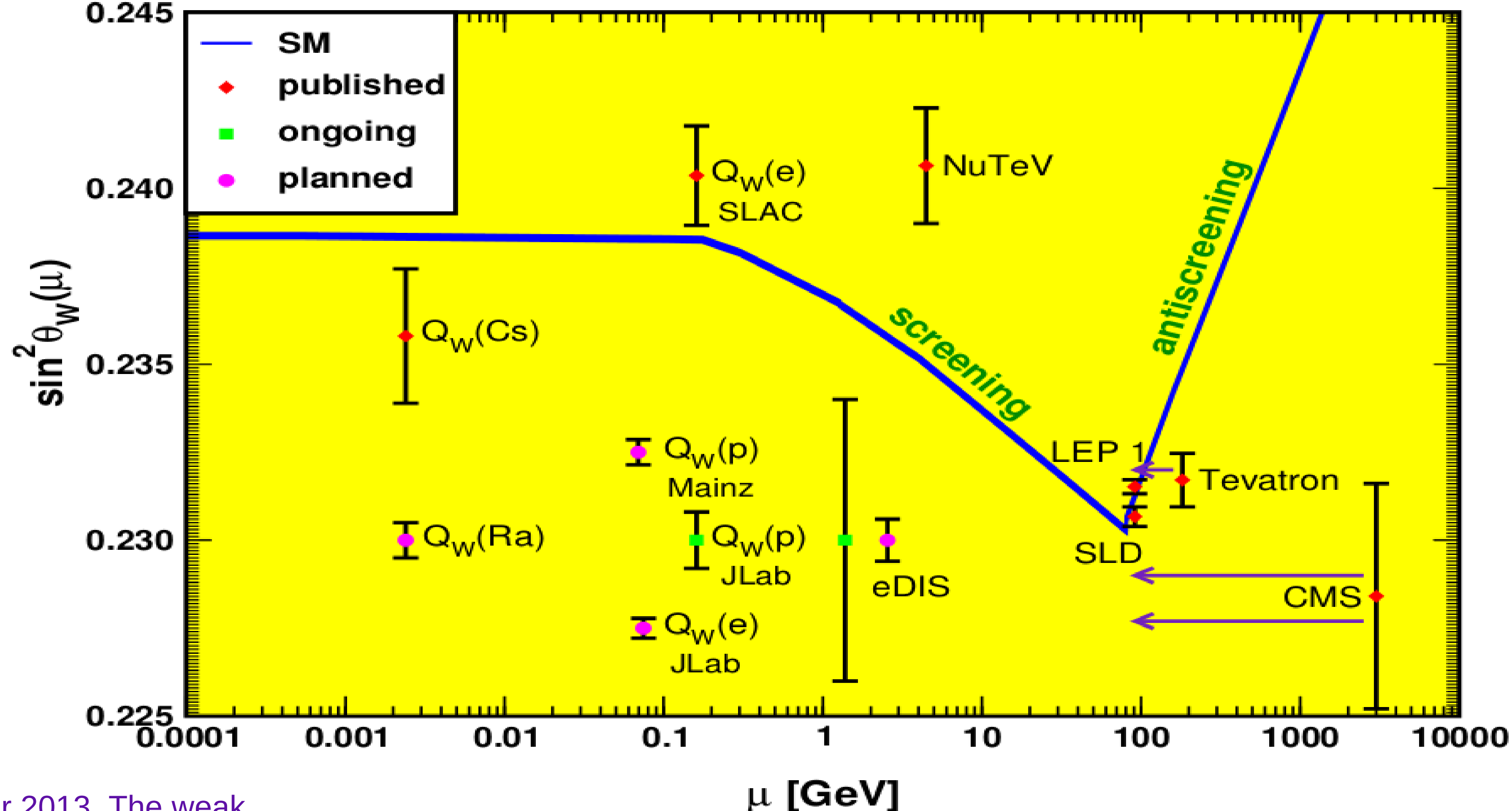
Spokespersons Project Manager Grad Students

Backup slides

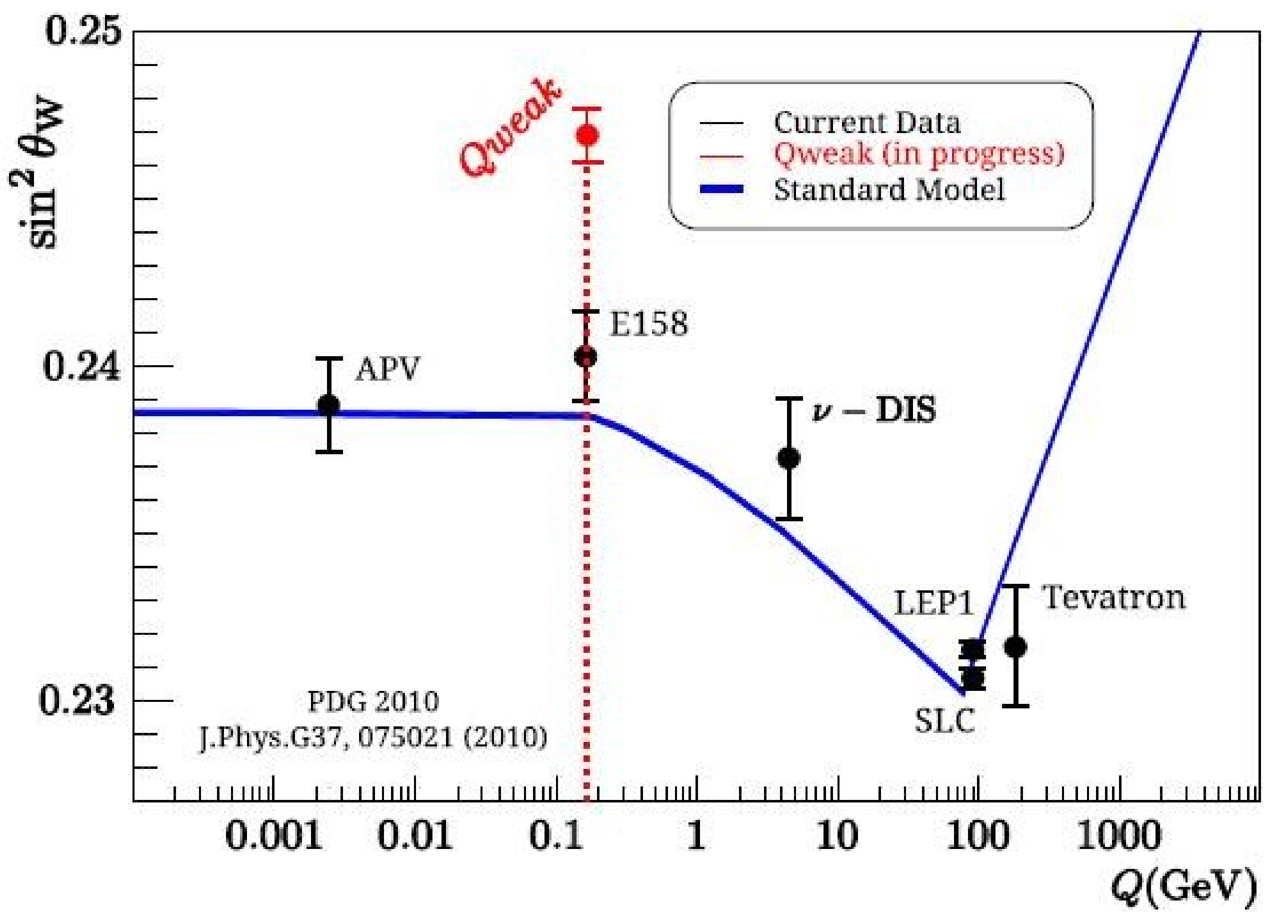
Running of the weak mixing angle





Erler 2013, The weak neutral current

Weak mixing angle, PDG 2010



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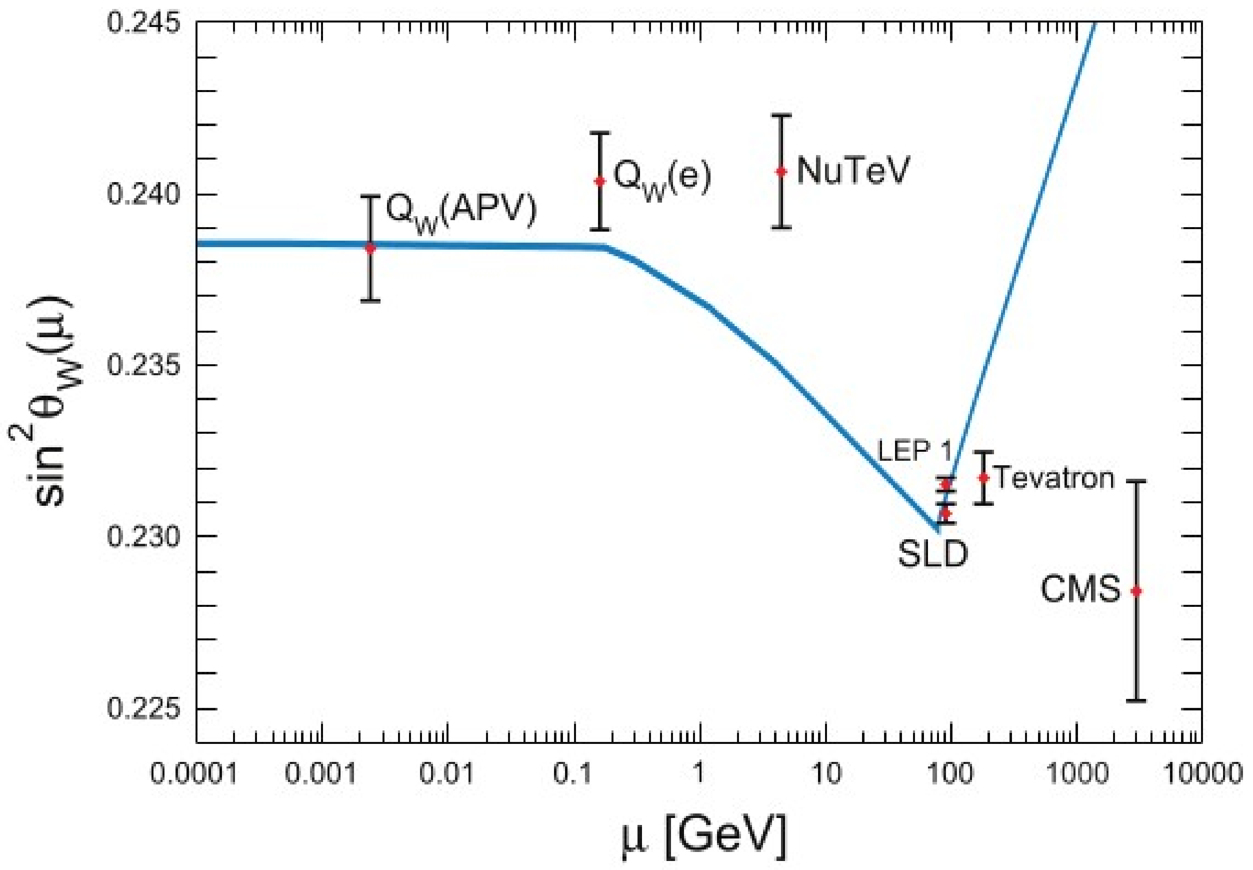

Erler 2013, The weak neutral current

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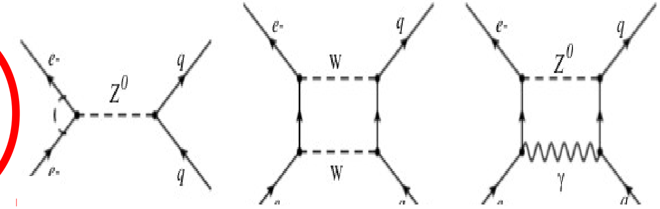
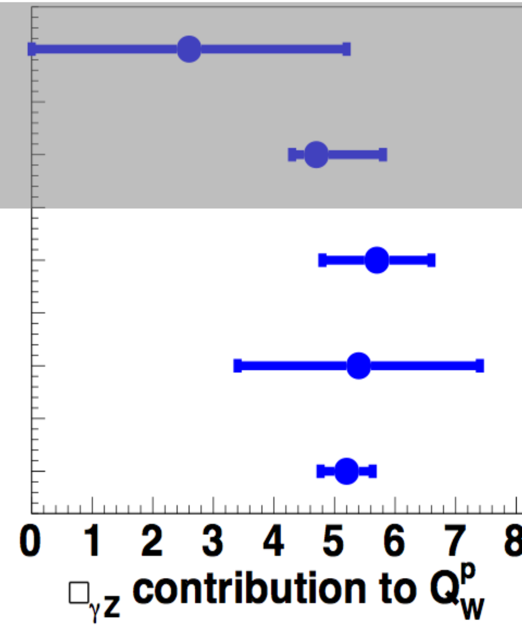
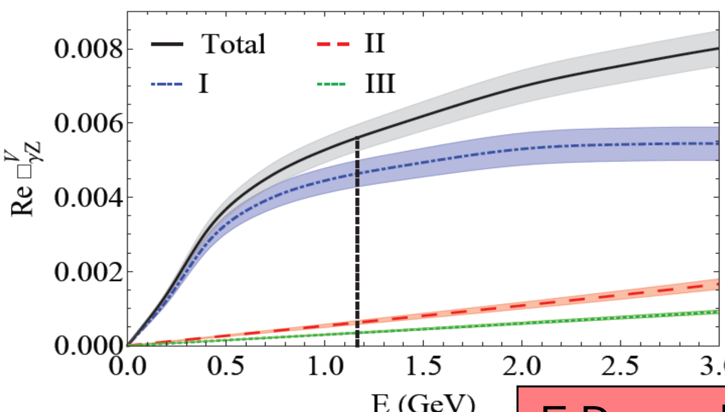


$\Box_{\gamma Z}$ contribution to Q_W^p (Qweak kinematics)

OLDER CALCULATIONS

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 *arXiv:1011.2397 (2010)*	0.0057 ± 0.0009
Gorchtein, Horowitz & Ramsey-Muslof PHYSICAL REVIEW C **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





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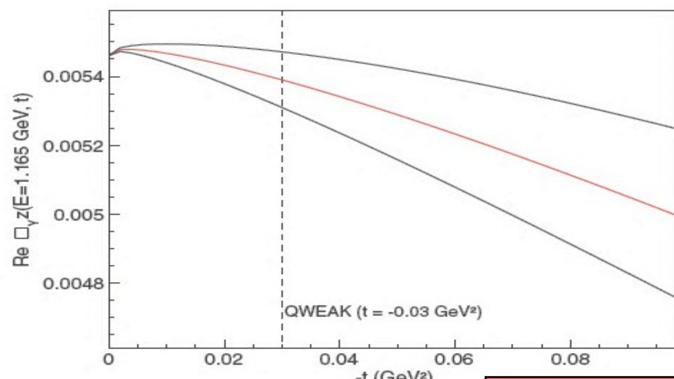
E Dependence



Q^2 Dependence

Pushing the envelope of Intensity and Precision

Very challenging precision goals of Q-weak require:

Statistics

- High current, high polarization
- High power cryotarget, long target cell
- Long running period
- Large acceptance detector, high rates

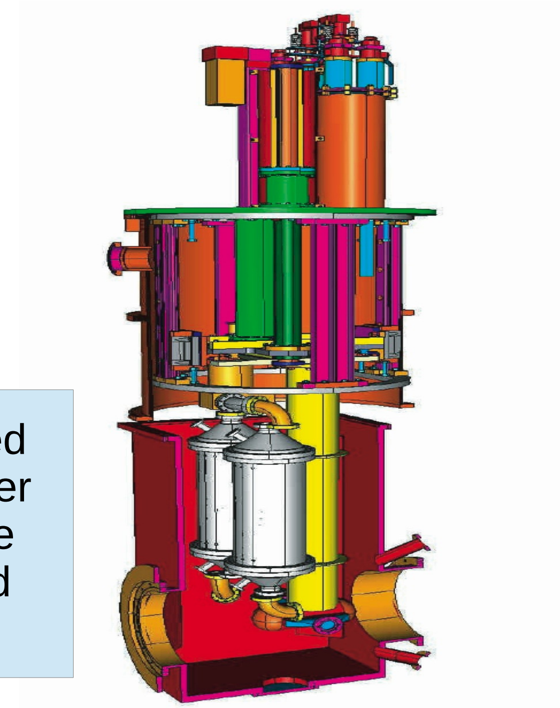
Noise

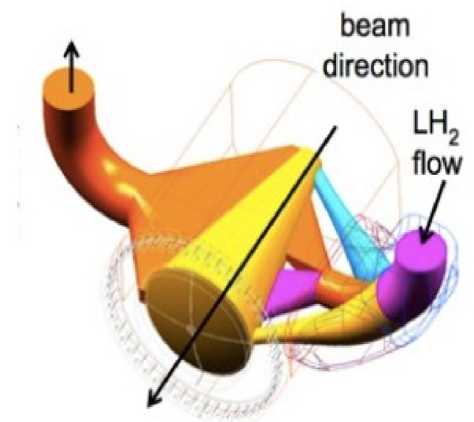
- Detector and monitor resolution
- Target density fluctuations
  → fast helicity flip

Systematics

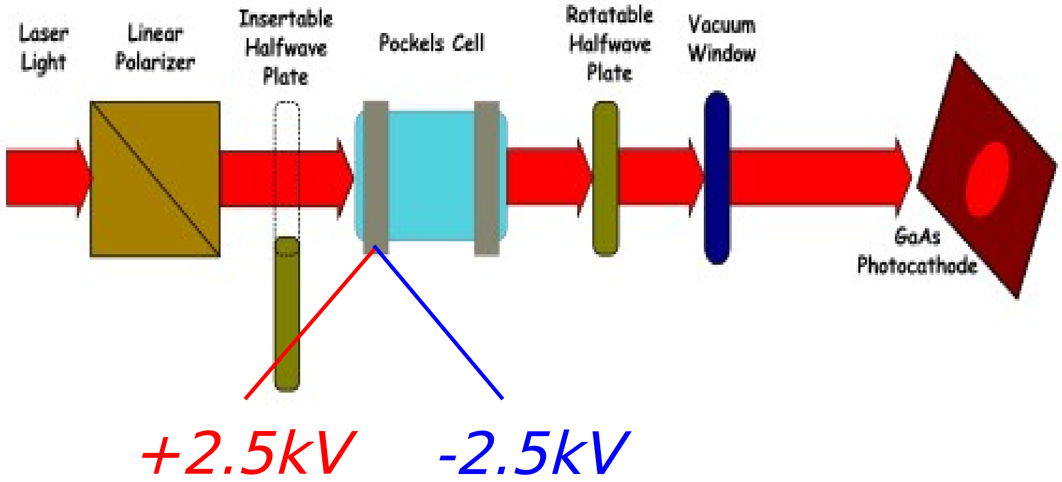
- Backgrounds
- Beam polarization, Q^2
- False asymmetries from helicity-correlated beam parameters

Qweak employed the highest-power cryotarget in the world, designed with CFD

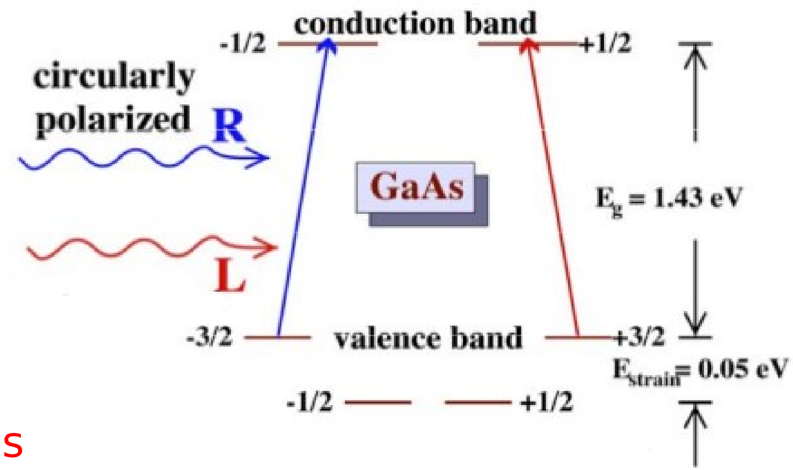




Polarized source at Jefferson Lab

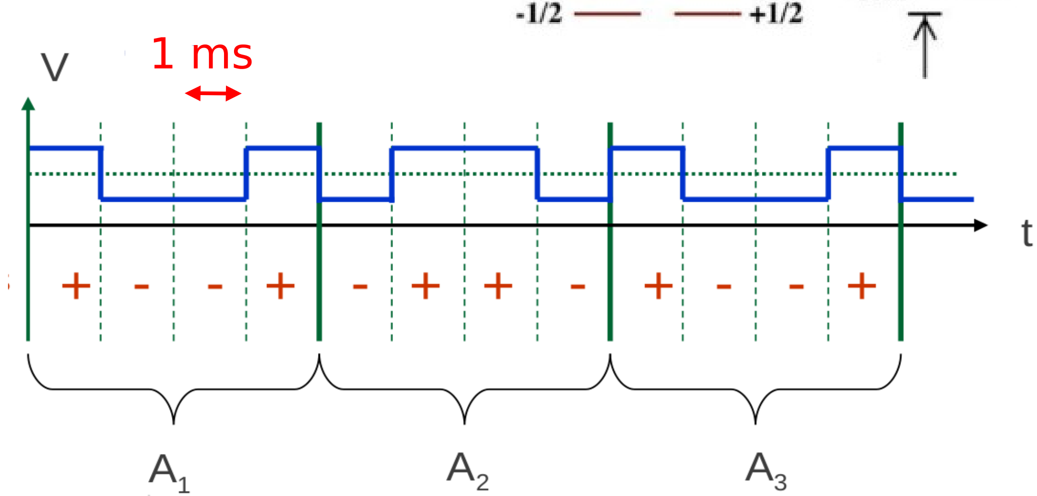


Polarized e⁻ produced from strained superlattice GaAs photocathode



Pockels Cell acting as a λ/4 plate
(electro-optic effect)
creates circularly polarized light

Fast, 960Hz helicity flip
Pseudorandom quartet pattern



Aluminum target window background correction

Largest correction to the measured asymmetry (~30%)

At Qweak kinematics:

$$A_{PV}(^{27}Al) \approx \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[Q_w^p + Q_w^n \left(\frac{N}{Z}\right) \right] \Longrightarrow$$

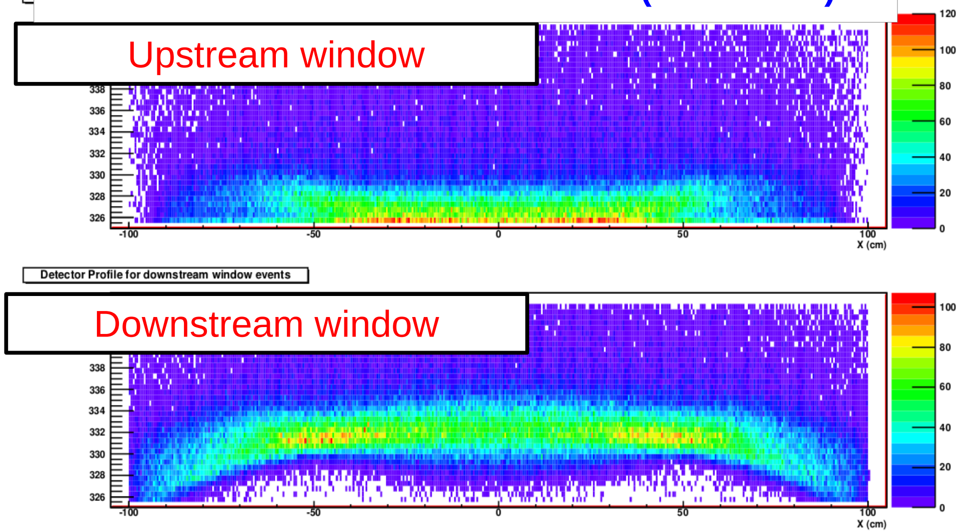
Order of magnitude higher asymmetry than H

Aluminum signal fraction (Run 0 value)

$$f_{Al} = 3.2 \pm 0.2\ \%$$

Goal: Reduce uncertainty of this fraction by factor of 4

Profile of US and DS Al windows (simulation)



Average Q^2 of e^- scattered from the US window is lower due to kinematic acceptance.

Signal fractions from the US and DS windows are different and radiative corrections applied separately.

Polarimetry

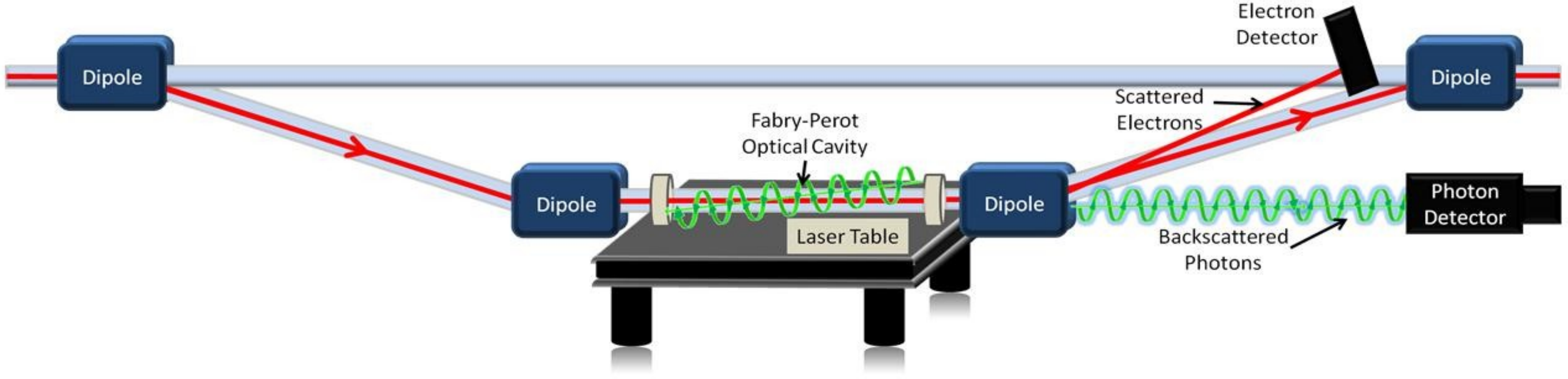
The Hall C Møller polarimeter provided the polarization for Run 0:

$$P = 89.0 \pm 1.8\ \%$$ (Run 0 value)

Main systematic uncertainties: High current extrapolation, beam position;

Goal: Reduce uncertainty down to ~1%

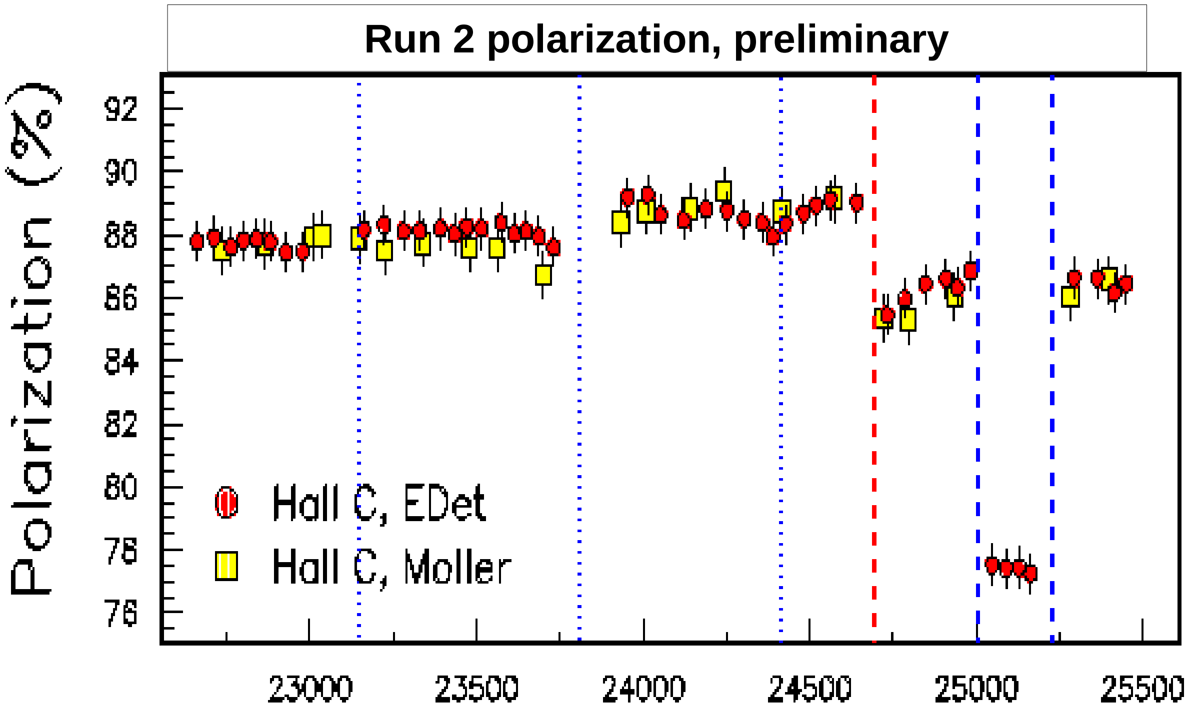
The Compton polarimeter was available after April 2011.
Non-invasive continuous monitoring of the polarization from two independent detectors: electron and photon



Polarimetry

The Compton e⁻ detector performed admirably!

Provided continuous polarization measurements in very good agreement with Møller.



Run 1:

Different combinations of Møller and Compton may be used. Møller Q3 issues, Compton unavailable before April.

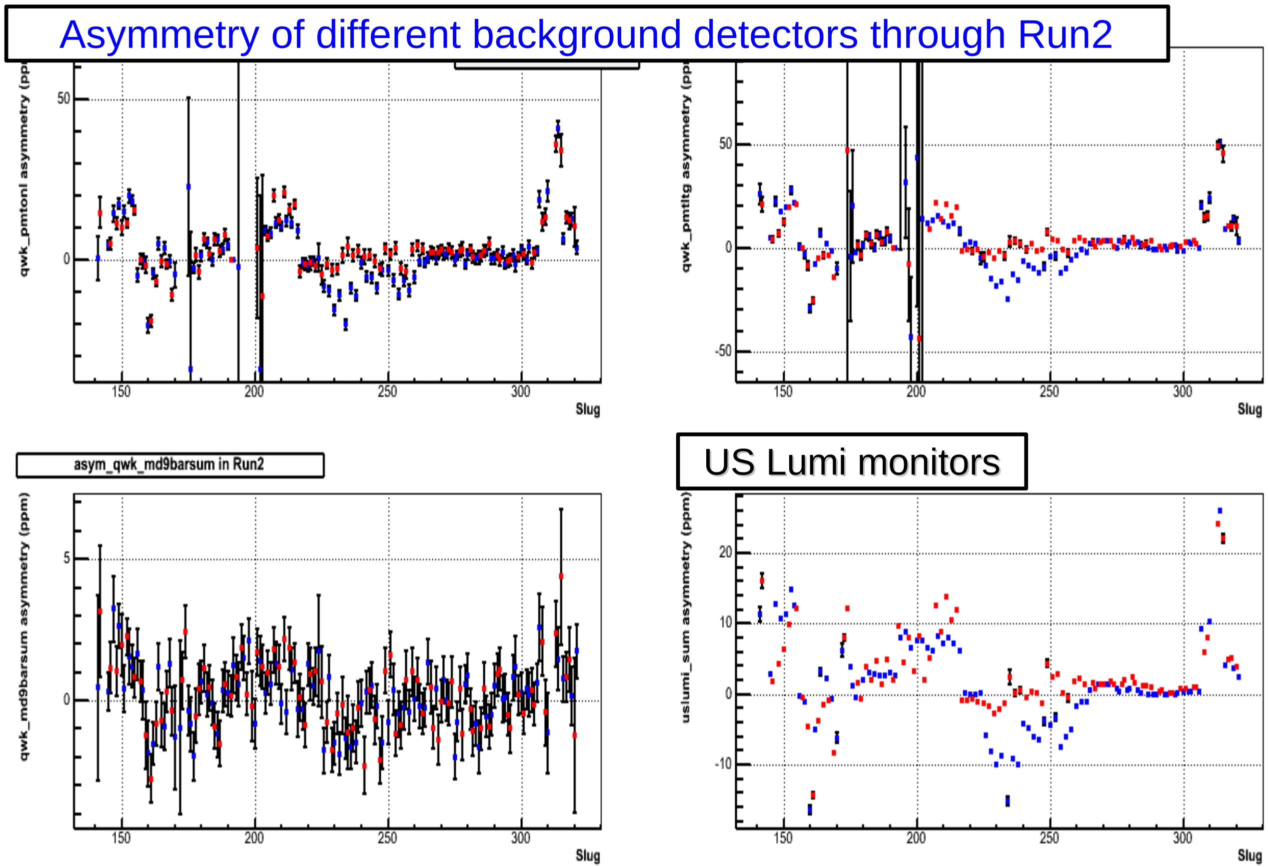
Run 2:

"Default" polarization value from Compton e⁻ detector with input from Møller and Compton γ.

The Polarimetry group will likely achieve **<1% precision**, better than our proposal.

Beamline Background asymmetry correction

Background detectors provide continuous monitoring. They see large and highly correlated asymmetries, roughly proportional to their background signal fraction.

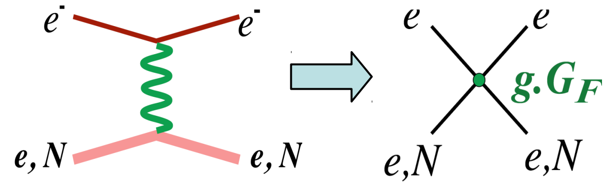


Contribution to the Main Detector signal constrained experimentally by dedicated measurement:

f_{BB} ~ 0.2%

Correction is significant relative to required precision but appears well understood.

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



A "new physics" term in the Lagrangian
(approximated by a 4-fermion contact interaction) :

$$\mathscr{L}^{PV}_{e\text{-}q} = \mathscr{L}^{PV}_{SM} + \mathscr{L}^{PV}_{New}$$

$$= -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu\gamma^5 e \sum_q C^{SM}_{1q} \bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2} \bar{e}\gamma_\mu\gamma^5 e \sum_q h^q_V \bar{q}\gamma^\mu q$$

Model-independent mass reach of full Qweak, 95% CL :

Mass scale over coupling of new physics

$$\frac{\Lambda}{g} \approx \frac{1}{\sqrt{2\sqrt{2}G_F\left|\Delta Q_W(p)\right|}} \approx 3.25\,TeV$$

Erler et al, PRD 68, 016006 (2003)

Benchmark $LL^{\pm}$ model often used, with $g^2=4\pi$.

Confronting Top A_{FB} with PV constraints

Gresham et.al.
arXiv:1203.1320 [hep-ph]

CDF and D0 observe a 3.4σ deviation from the SM of the $t\bar{t}$ A_{FB}.

t-channel models of extra mediators with flavour-violating coupling between u/d and t, could explain the excess while evading collider constraints.

The Cs APV measurement disfavours these models, and Qweak has the reach to place even stronger limits.