The Q-Weak Experiment: Measurement of the Weak Charge of the Proton

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on behalf of the Q-Weak Collaboration

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Outline

1. Motivation and PVES
2. The Q-Weak Experiment
3. Results from Commissioning run
4. Recent developments

Parity Violating Electron Scattering and Q_W of the Proton

PV ep asymmetry in terms of EM and Neutral-weak form factors

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

At low Q^2 and forward angles, can be expressed:

$$\frac{A_{ep}^{PV}}{A_0} = Q_W^p + Q^2 B(Q^2,\theta) \qquad A_0 = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]$$

Suppression of Q_W (proton) provides enhanced sensitivity to $sin^2\theta_W$

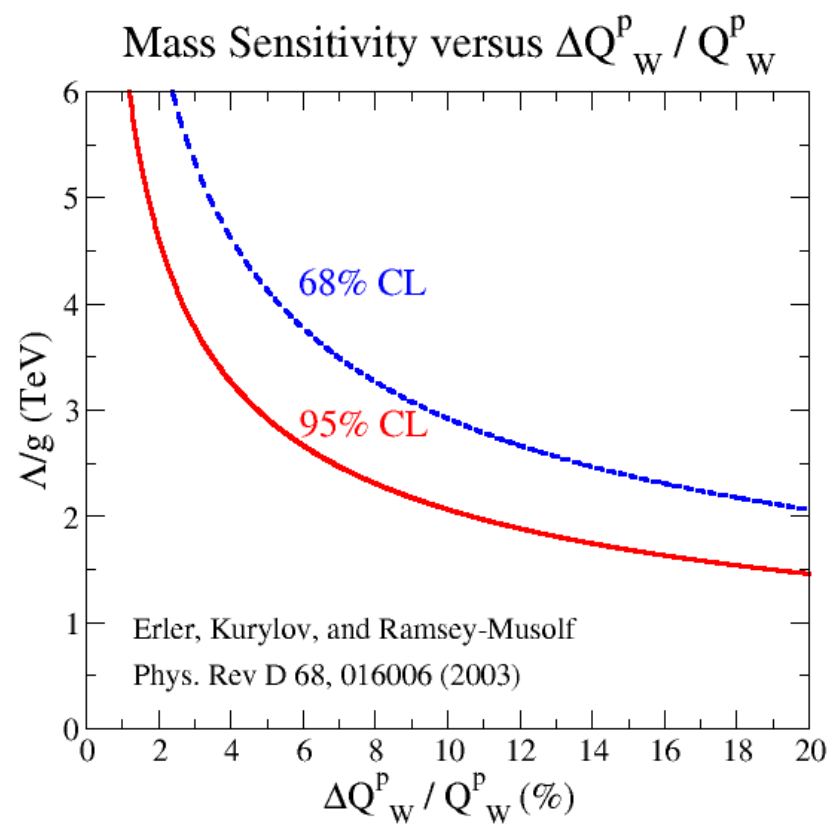
Particle	Electric charge	Weak vector charge ($\sin^2\theta_W \approx \frac{1}{4}$)
e	-1	$Q_W^e = -1 + 4\sin^2\theta_W \approx 0$
u	$+\frac{2}{3}$	$-2C_{1u} = +1 - \frac{8}{3}\sin^2\theta_W \approx +\frac{1}{3}$
d	$-\frac{1}{3}$	$-2C_{1d} = -1 + \frac{4}{3}\sin^2\theta_W \approx -\frac{2}{3}$
p(uud)	$+1$	$Q_W^p = 1 - 4\sin^2\theta_W \approx 0.07$
n(udd)	0	$Q_W^n = -1$

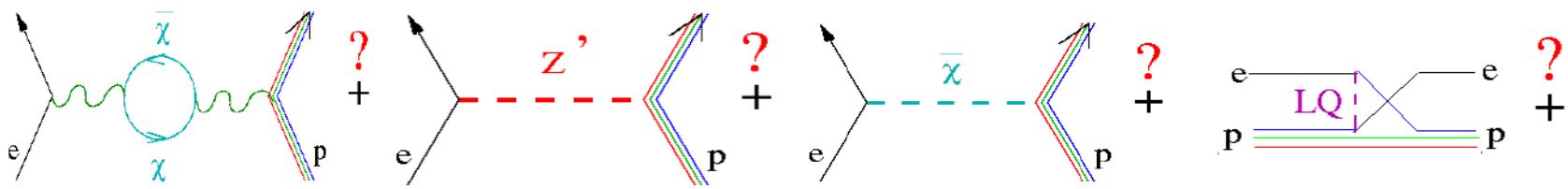
Q_W(proton) and New Physics

Weak mixing angle precisely measured at *Z*-pole
→ Running of $sin^2\theta_W$ to lower mass scales (momentum transfers) precisely predicted in context of Standard Model

Sensitivity to "New Physics" can be described in terms of mass scale Λ and model dependent coupling, *g*

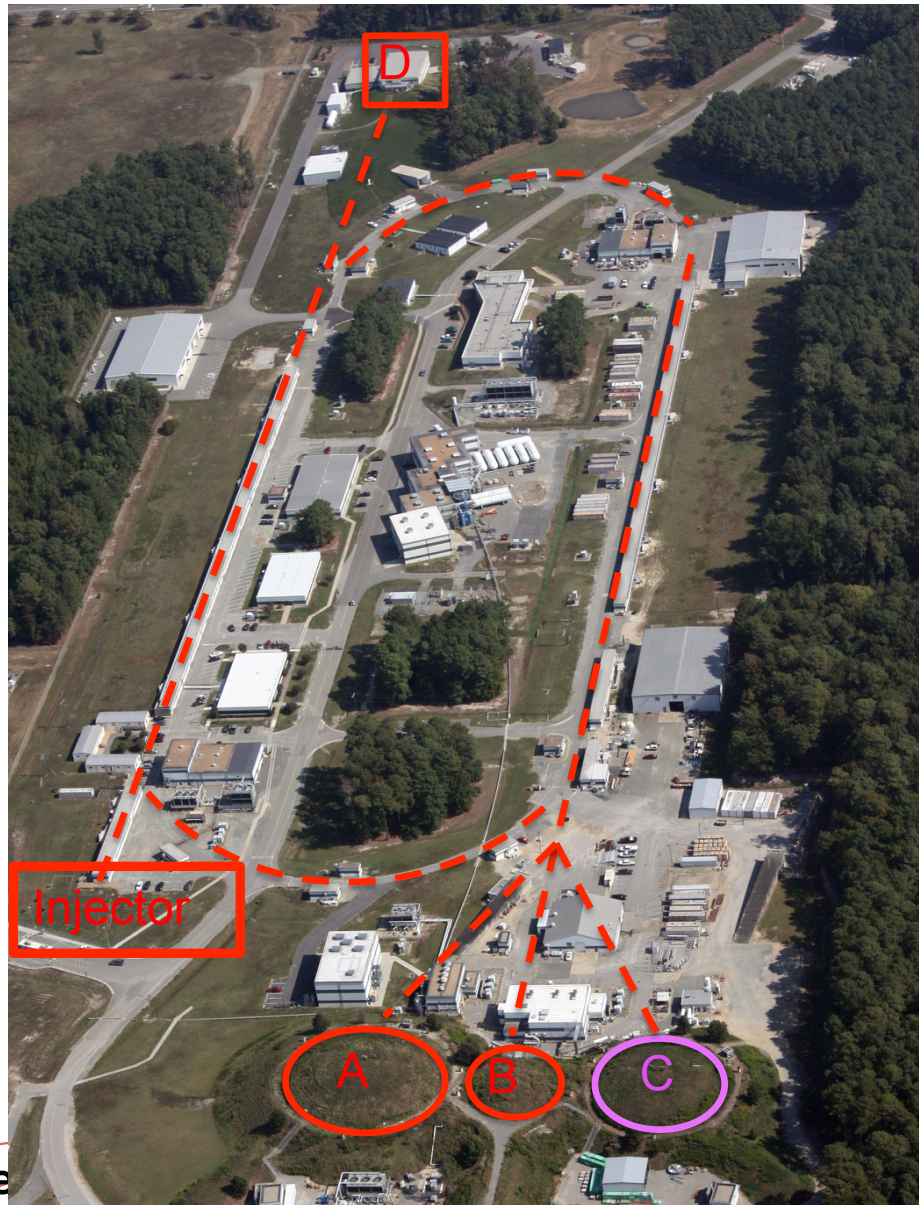
Absolute mass scale depends on both *g* and assumed Lagrangian





RPC SUSY | Generic Z' | RPV SUSY | Leptoquarks

Q-Weak Experiment at Jefferson Lab



Installed and run in experimental Hall C at Jefferson Lab: 2010-2012

Aim: Measure PV asymmetry in elastic ep scattering at $Q^2 \sim 0.025$ GeV^2

Nominal asymmetry ~ -230 ppb

<u>Three distinct run periods:</u>

1. Fall 2010-January 2011: Commissioning + “early run” data sample
2. January-Spring 2011: Run 1
3. Fall 2011-Spring 2012: Run 2

Q-Weak Apparatus

Parameters:

E_{beam} = 1.165 GeV

$\langle Q^2 \rangle$ = 0.025 GeV^2

$\langle \theta \rangle$ = 7.9° ± 3°

φ coverage = 50% of 2π

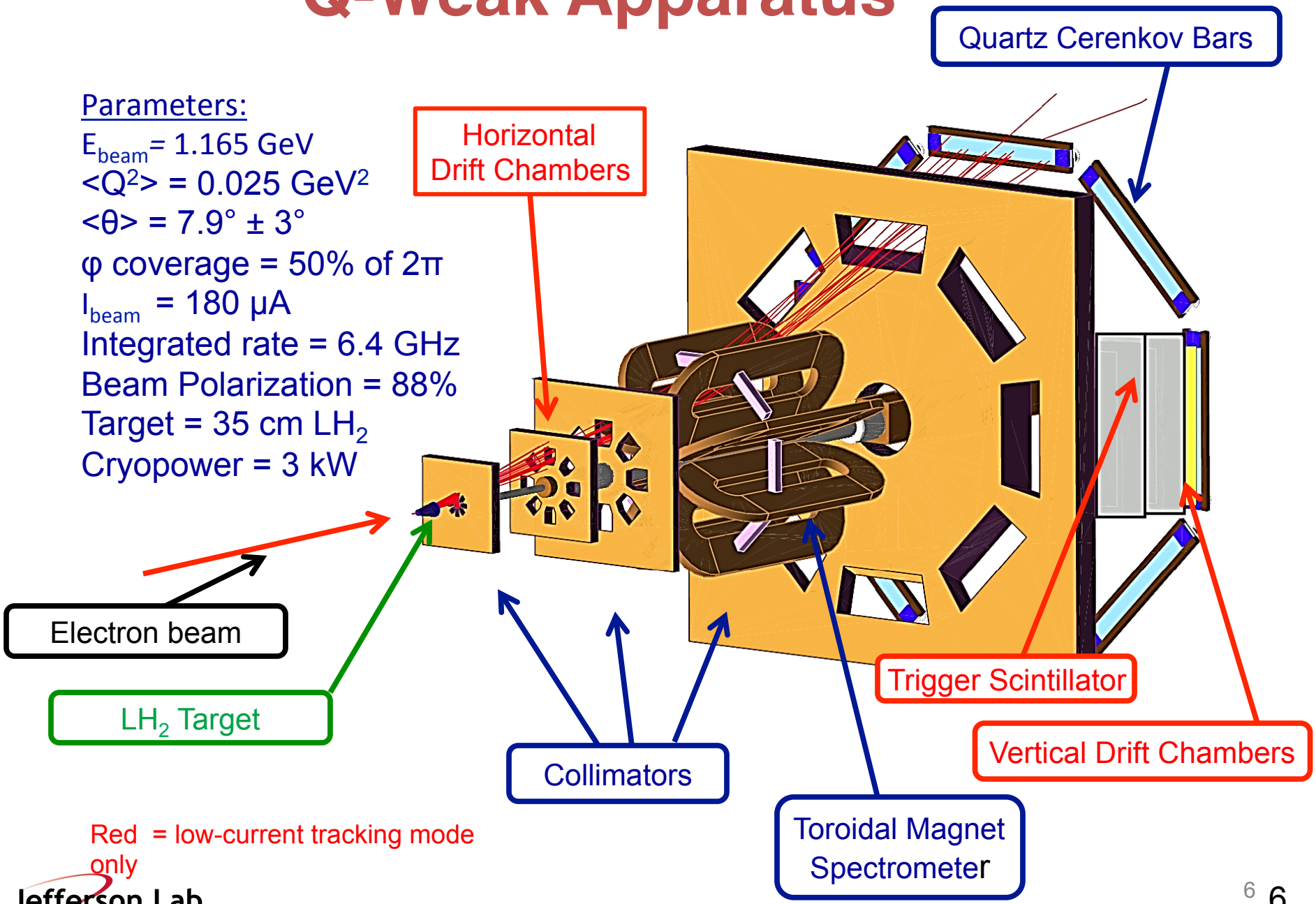
I_{beam} = 180 μA

Integrated rate = 6.4 GHz

Beam Polarization = 88%

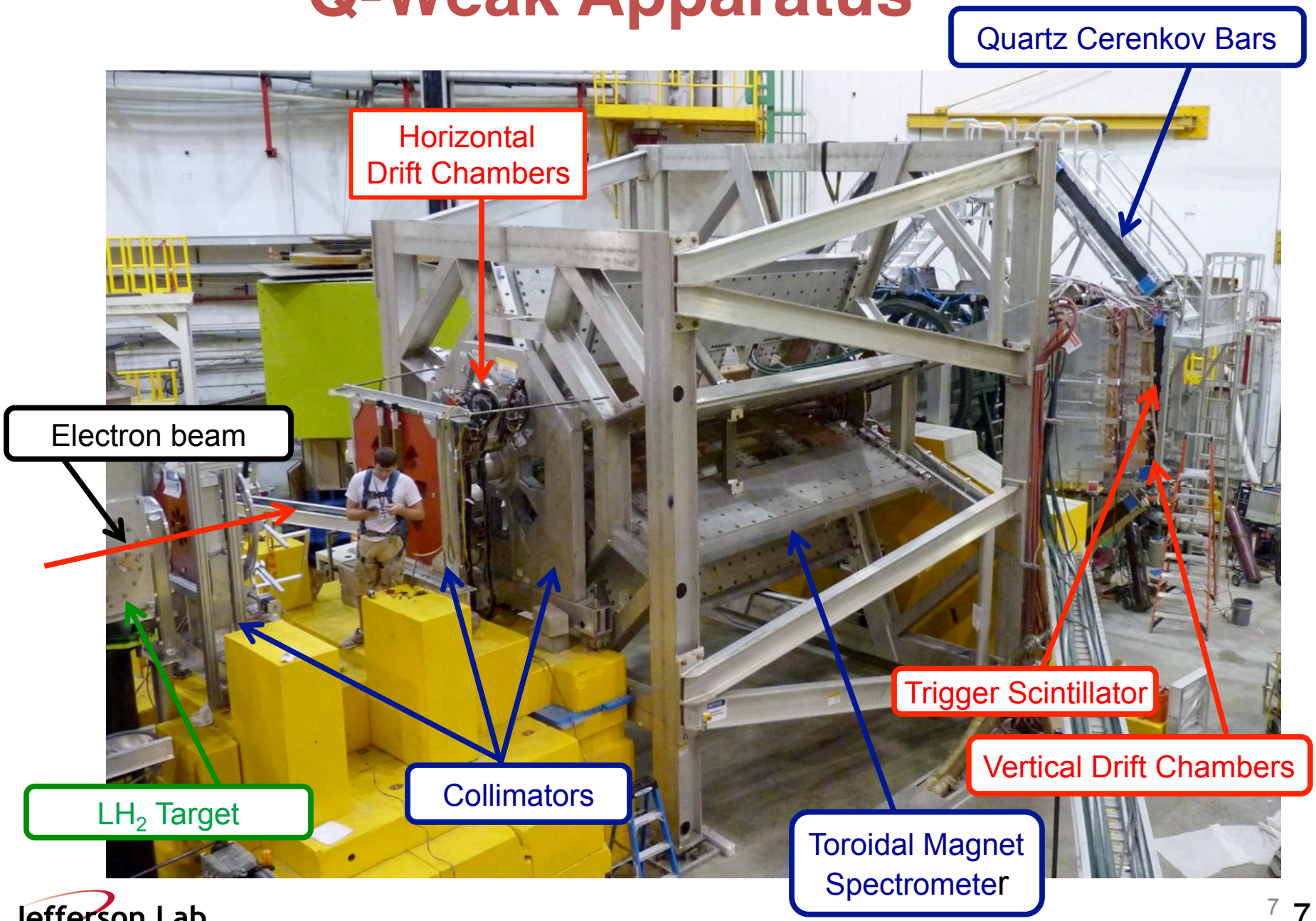
Target = 35 cm LH_2

Cryopower = 3 kW



Red = low-current tracking mode only

Q-Weak Apparatus

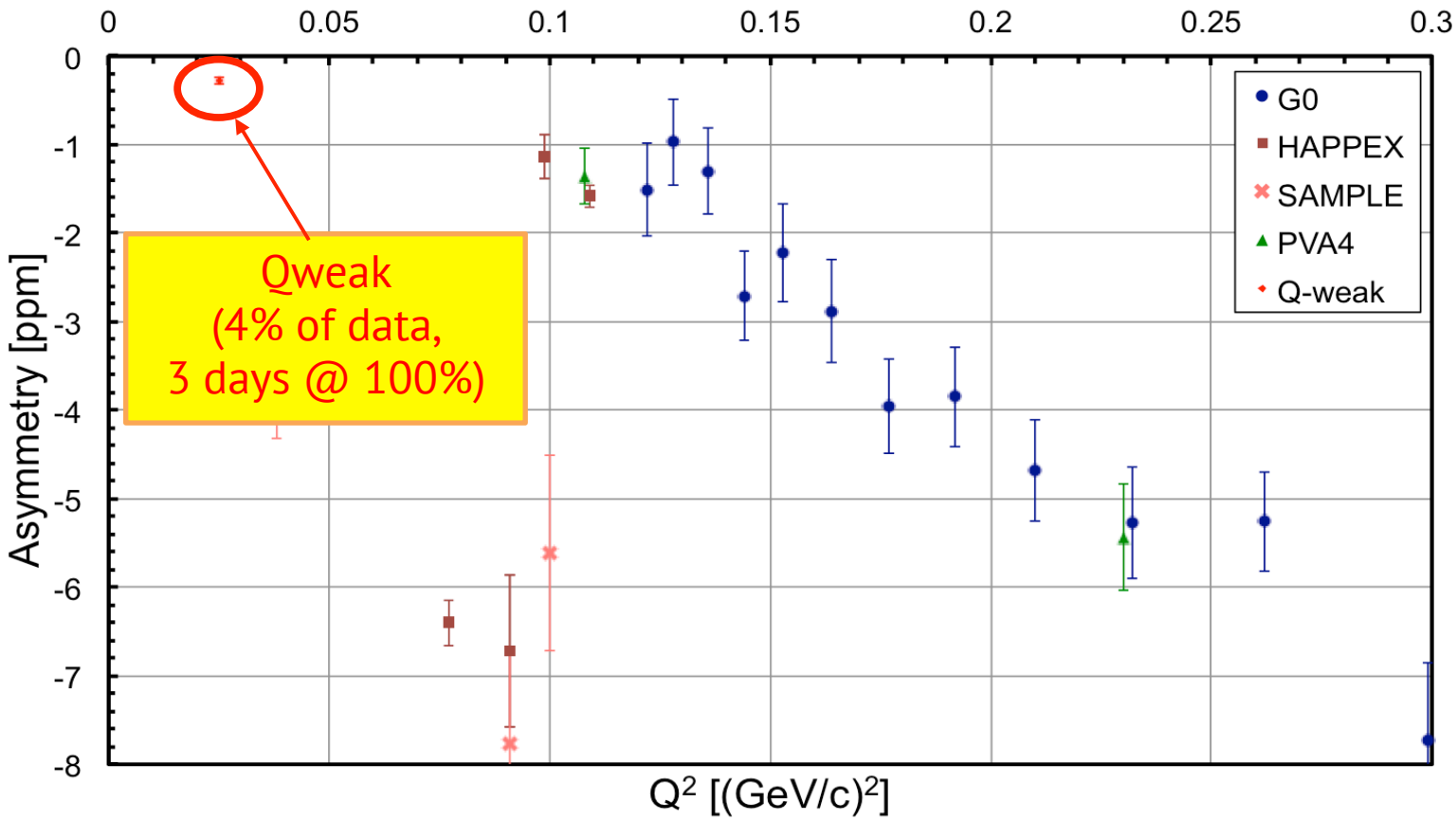


First Results: Asymmetry

Run 0 Results
→ 1/25th of total data set

$$\langle Q^2 \rangle = 0.0250 \pm 0.0006 \text{ GeV}^2$$
$$\langle E_{beam} \rangle = 1.155 \pm 0.003 \text{ GeV}$$

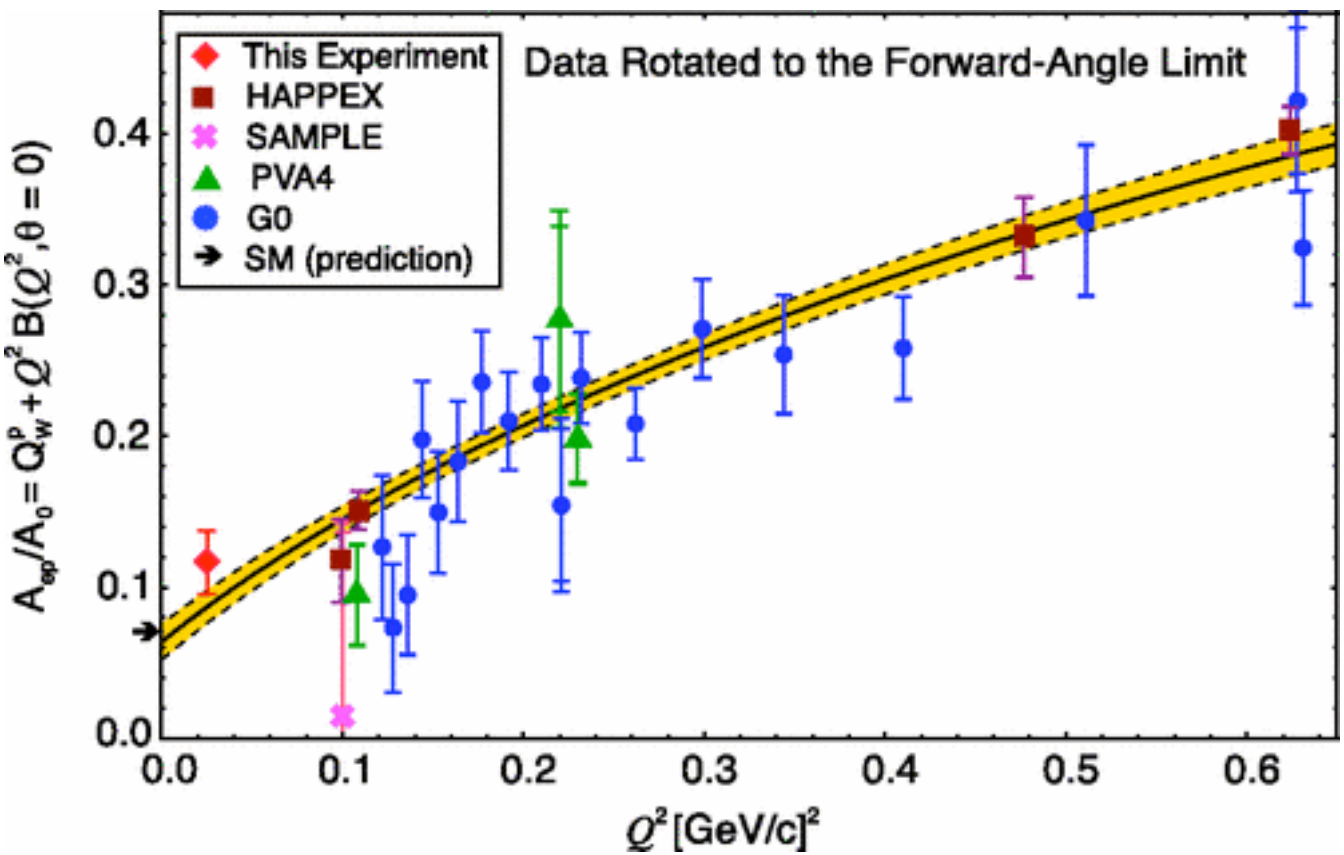
$$A_{ep} = -279 \pm 35 \text{ (stat)} \pm 31 \text{ (syst) ppb}$$



Published 10/2/2013: PRL **111**,141803 (2013)

Global Fit to A_{ep} Data

$$\frac{A_{ep}}{A_0} = Q_W^p + Q^2 B(Q^2, \theta = 0) \qquad A_0 = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]$$



Free parameters:
1. C_{1u}
2. C_{1d}
3. ρ_s – strange charge radius
4. μ_s – strange magnetic moment
5. $G_A^{Z(T=1)}$ – isovector axial form factor

*PRL **111**,141803 (2013)*

Neutral-weak Quark Coupling Constants

Combined analysis of PVES data and atomic PV

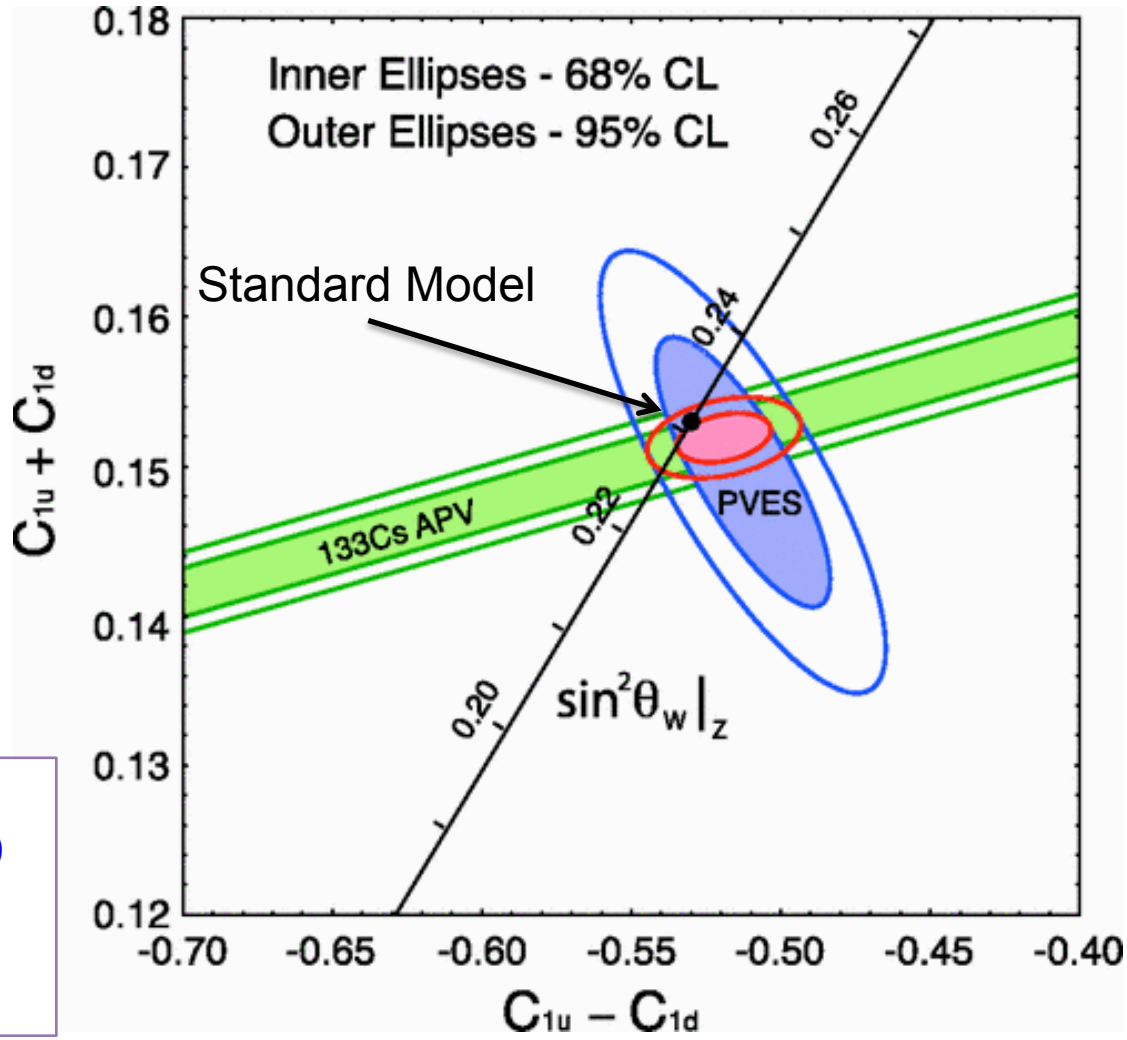
C_{1u} =-0.1835+/- 0.0054
C_{1d} = 0.3355 +/- 0.0050

Can use C_{1u} and C_{1d} to extract Q_W^n and Q_W^p

$Q^n_W = -2\,(C_{1u} + 2\,C_{1d})$
$= -0.975 \pm 0.010$

$Q^p_W = -2\,(2\,C_{1u} + C_{1d})$
$= 0.063 \pm 0.012$ (PVES+APV)
$= 0.064 \pm 0.012$ (PVES only)

SM prediction = 0.0710(7)



PRL ***111****,141803 (2013)*

A_{ep} Extraction and Uncertainties

$$A_{ep} = R_{tot} \frac{\frac{A_{msr}}{P} - \sum_i^4 f_i A_i}{1 - \sum f_i}$$

$$R_{tot} = R_{RC} R_{Det} R_{Bin} R_{Q^2}$$

- R_{Q^2}: Central Q^2 calibration
- R_{Bin}: Corrects avg. A to $A(\langle Q^2 \rangle)$
- R_{Det}: Light variation across detector
- R_{RC}: Radiative correction

f_1 (A_1) = aluminum target cell wall background
f_2 (A_2) = background from beamline
f_3 (A_3) = soft, neutral backgrounds
f_4 (A_4) = inelastic processes (N→Δ)

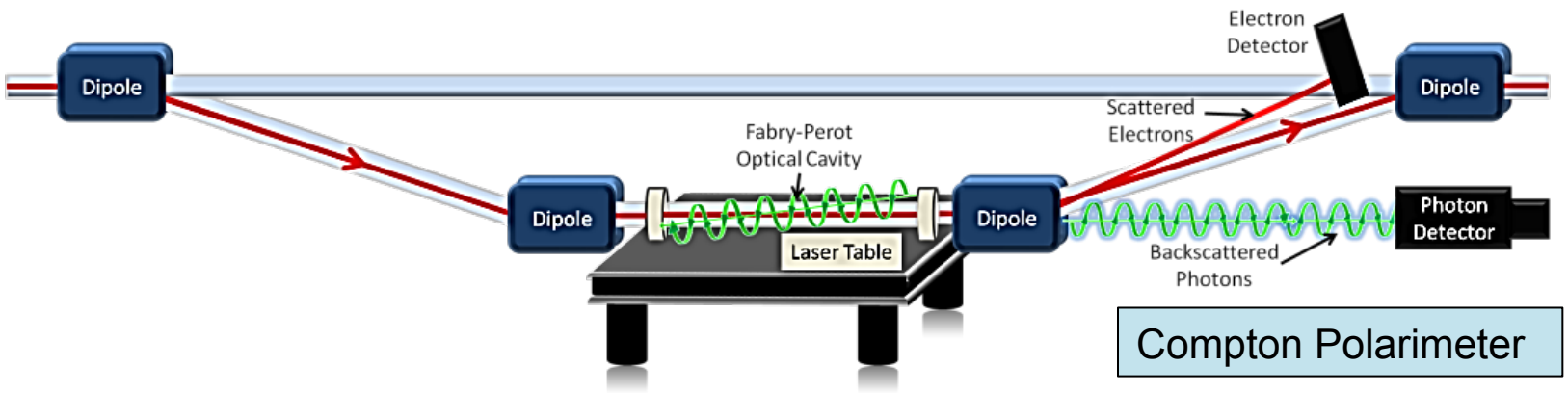
f_{tot}=3.6%

A_{ep} Extraction and Uncertainties

	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

2013 PRL Systematic Uncertainties

Polarimetry



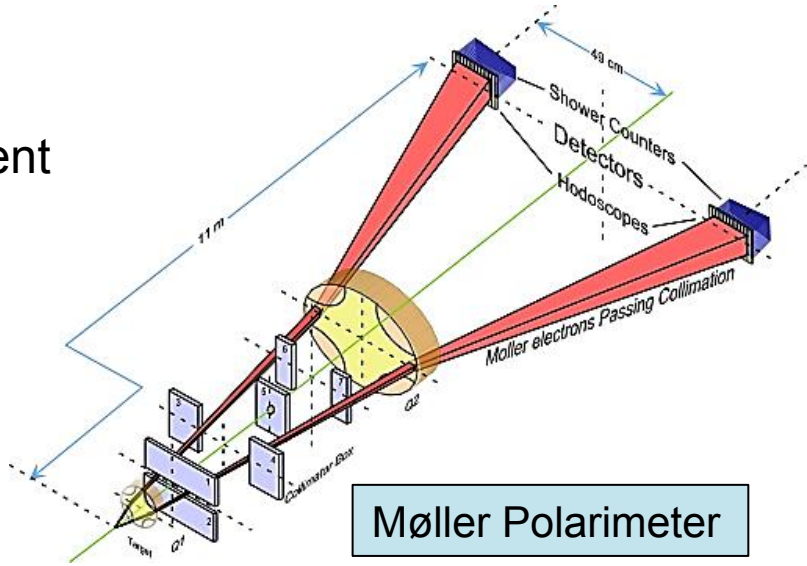
Compton Polarimeter

Q-Weak polarimetry precision goal: dP/P = 1%

<u>Strategy:</u>

1. Use existing Møller polarimeter to make precision, periodic measurements at low current
2. Build new Compton polarimeter to make continuous, non-invasive measurements

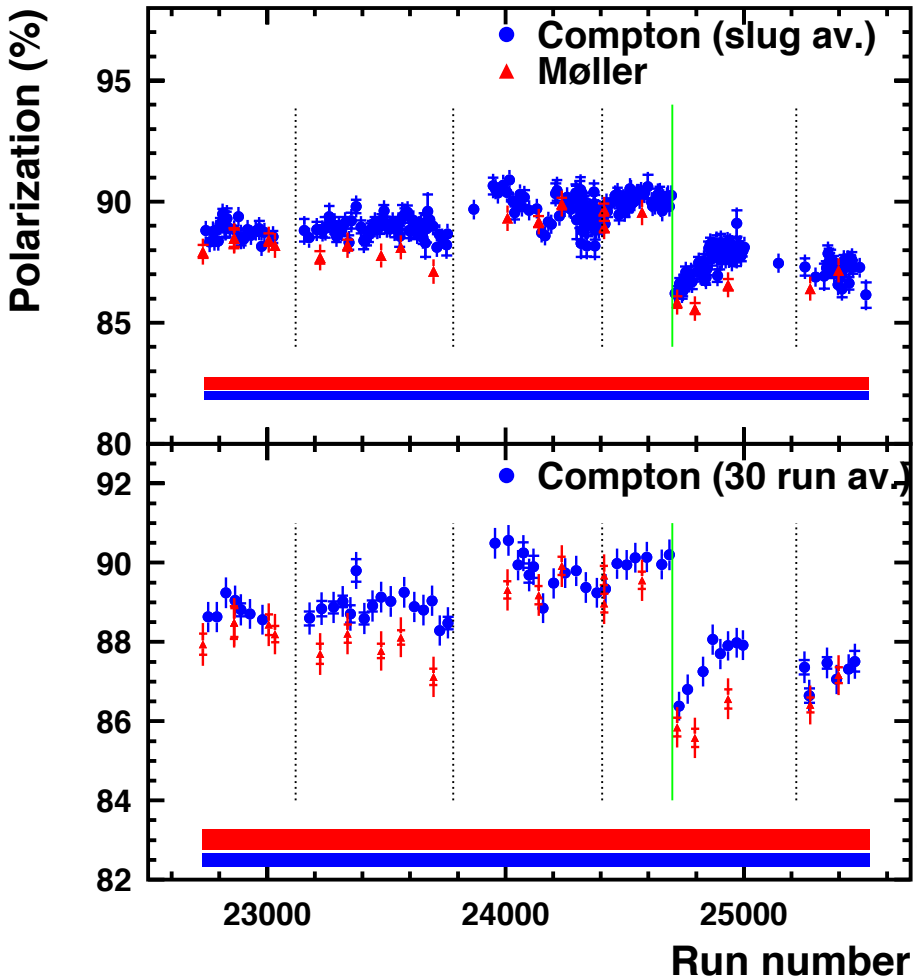
→ 2 independent techniques!



Møller Polarimeter

Q-Weak early result relied on Møller only.
Quoted uncertainty for 2013 PRL: *dP/P =2%*

Polarimetry (Preliminary) – Run 2



Systematic uncertainties

→ Compton: dP/P = 0.59%

→ Møller: dP/P = 0.84%

Both techniques agree to < 0.8%

Final polarization for experiment extracted using Compton polarimeter with comparison with Møller to improve the normalization uncertainty

Normalization uncertainties

▲ P_{Moller} +/- stat (inner) +/- point-to-point systematic (0.53%)

● $P_{Compton}$ +/- stat +/- point-to-point syst. (0.41%)

Beam parameter corrections

Beam parameters that change with helicity can give rise to false asymmetry

$$A_{beam} = \sum_{i}^{5} \left(\frac{\partial A}{\partial x_i} \right) \Delta x_i$$

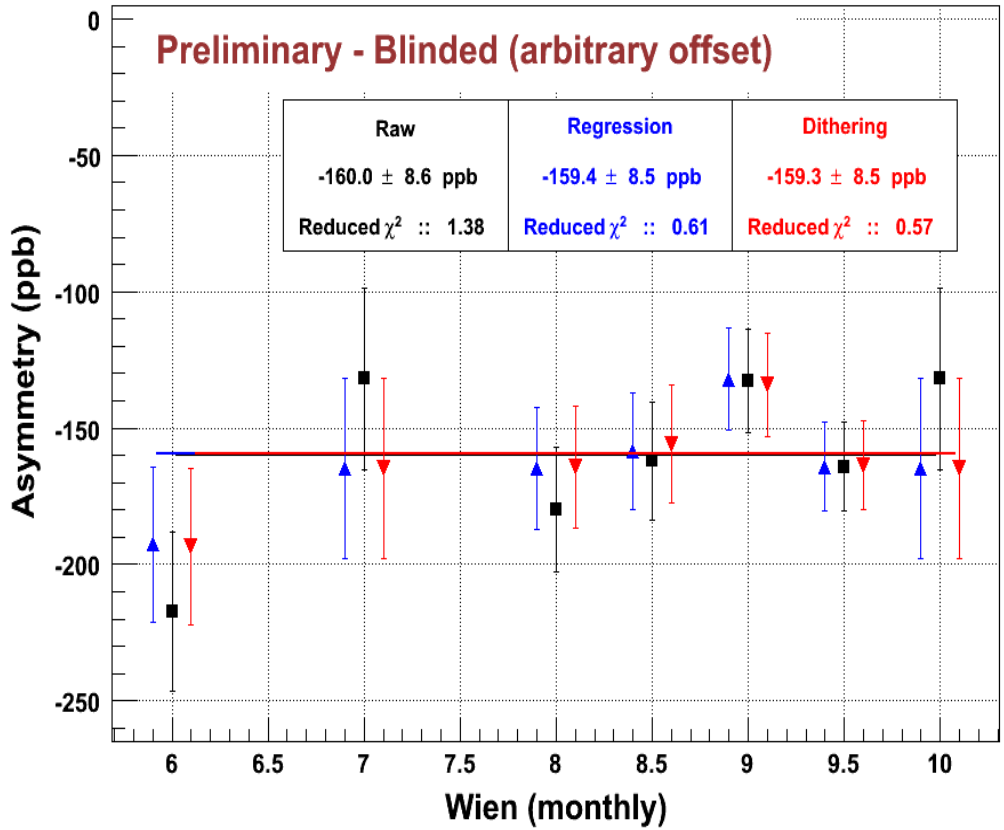
Sensitivity

Helicity correlated position, angle, or E

Can measure sensitivity 2 ways:

1. Regression – use "natural" motion of beam to determine response
2. Dithering – drive the beam (w/large amplitude)

Run2 measured asymmetry



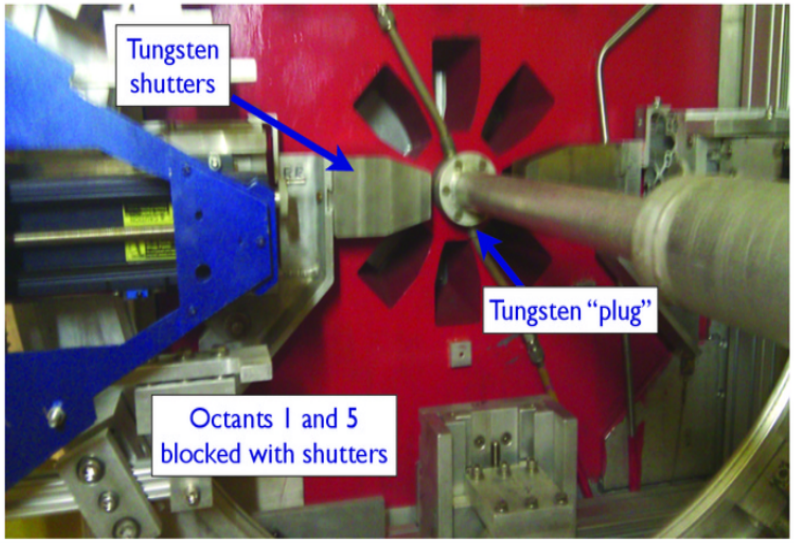
Excellent consistency between regression and dithering, for subset of data where both are available

→ 77% of Run 2 data set
→ Beam parameter correction only
→ No polarization, Al subtraction
→ Statistical errors

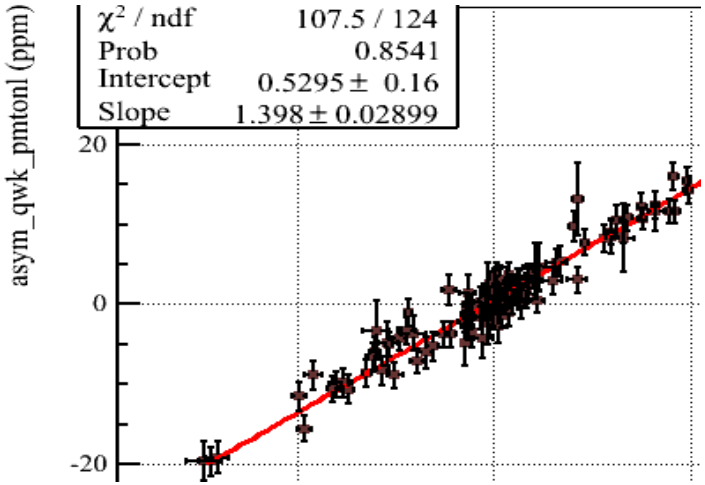
Beamline backgrounds

Contribution from beamline backgrounds largest uncertainty in 2013 result

→ Thought to be interactions of beam halo with narrow aperture of collimating "plug"
→ Dedicated measurements were performed ("blocked octant") to constrain size and asymmetry of these backgrounds : *f=0.19%*
→ Size and asymmetry of these backgrounds can be measured using ancillary detectors that have smaller (fractional) contribution from elastic signal



Correlation between asymmetries in background detectors



Kinematics and Aluminum Background

<u>Q^2 Determination</u>

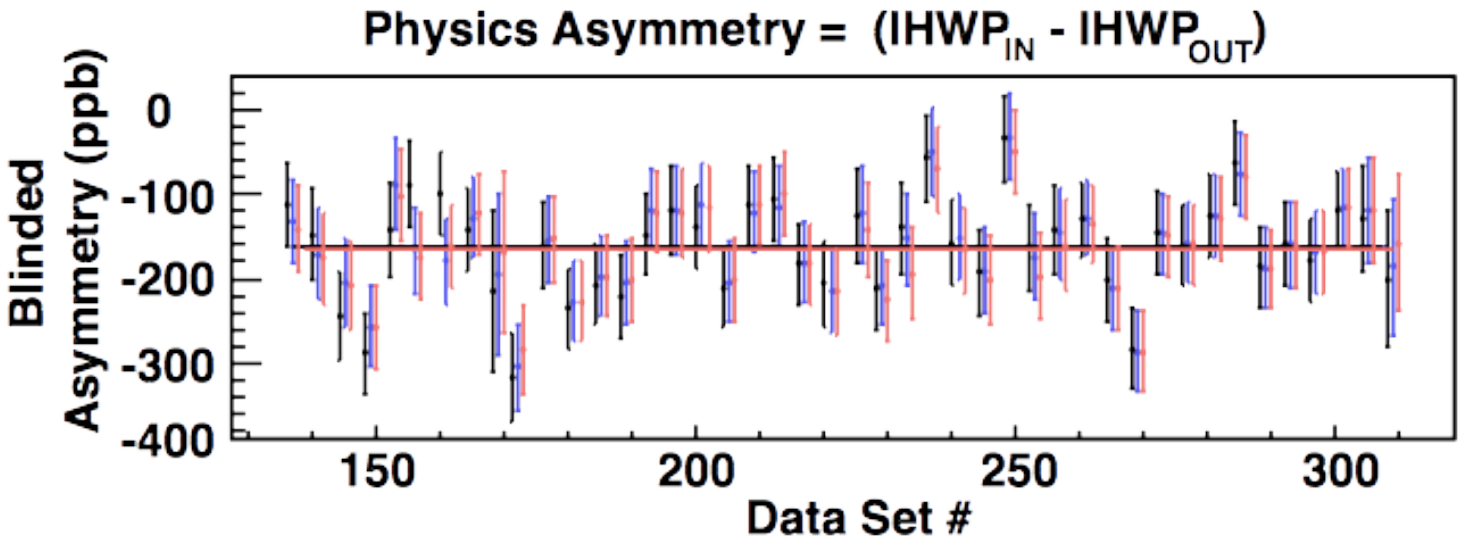
- Significant effort underway in analysis of low current tracking data for determination of nominal Q^2
- Uncertainty dominated by determination of scattering angle
- Excellent agreement between data and simulation

<u>Aluminum Background</u>

- Need both asymmetry and dilution with good precision
- Increased data set over 2013 result – smaller statistical uncertainties
- Systematic uncertainties in both A and f will be improved

Qweak Run 2 - Blinded Asymmetries

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



Raw = -161.8 ± 7.6

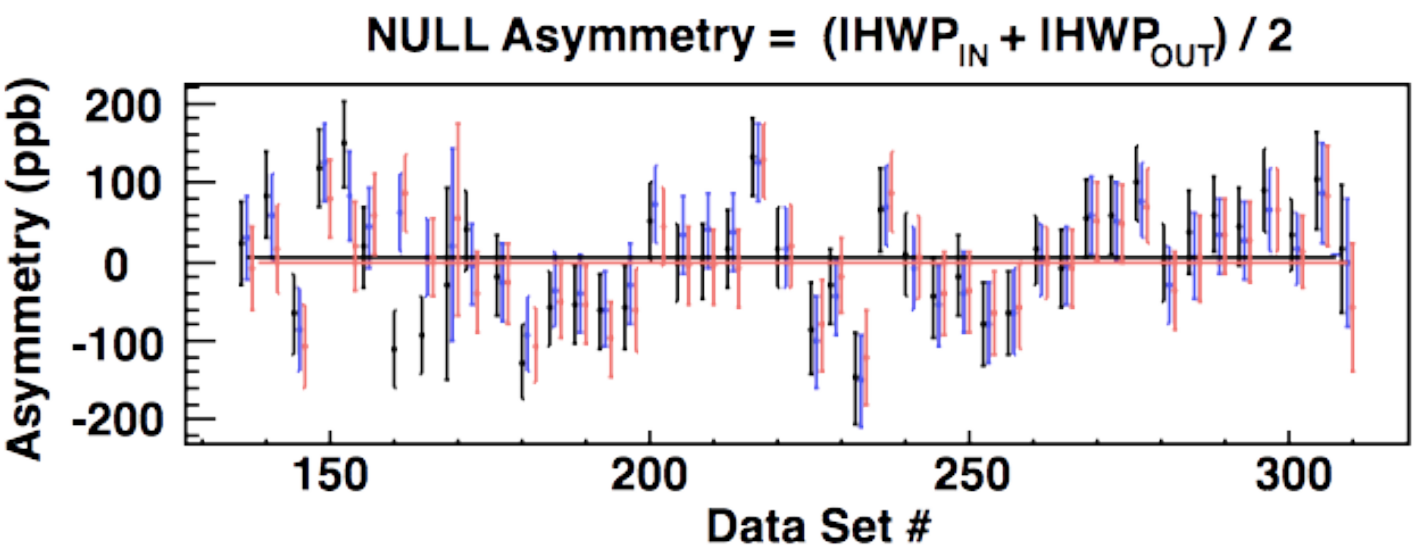
(χ^2/ NDF = 1.40, Prob = 0.043)

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)

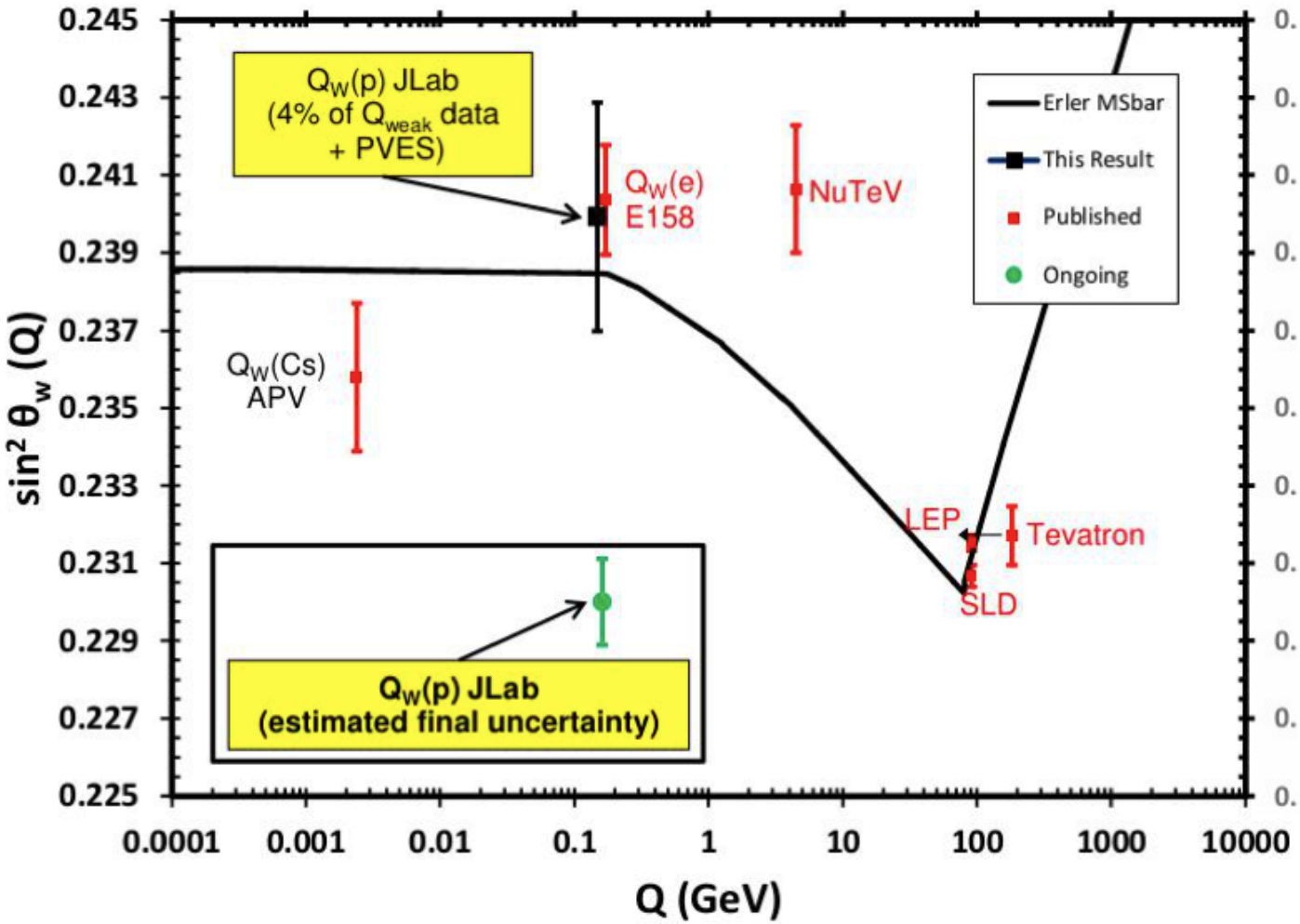
Regressed = 7.9 ± 7.7

(χ^2/ NDF = 1.38, Prob = 0.048)

Beamline Bkgd Corrected = -1.4 ± 7.7

(χ^2/ NDF = 1.29, Prob = 0.097)

$sin^2(\theta_W)$


0.245
0.243
0.241
0.239
0.237
0.235
0.233
0.231
0.229
0.227
0.225
sin² θw (Q)
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
Q (GeV)
Qw(p) JLab
(4% of Qweak data
+ PVES)
Qw(e)
E158
NuTeV
Qw(Cs)
APV
LEP
Tevatron
SLD
Qw(p) JLab
(estimated final uncertainty)
Erler MSbar
This Result
Published
Ongoing

Summary

- First results from Q-Weak (4% of total data set)
  - *PRL **111**,141803 (2013)*

$$A_{ep} = -279 \pm 35 \text{ (stat) } \pm 31 \text{ (syst) ppb}$$

- Significant progress has been made in analyzing full data set – both statistical and systematic uncertainties will be much improved
- Final results expected soon
- In addition to main ep results several results coming from ancillary/background measurements are expected

Additional Measurements

- PV asymmetries
  - Longitudinal asymmetry from aluminum (neutron radius a la PREX?)
  - Longitudinal asymmetry in resonance region
  - Longitudinal asymmetry (Delta) → 2 beam energies
- Parity conserving (2-boson exchange) azimuthal asymmetries
  - Hydrogen elastic → constrains backgrounds in main measurement, but also provides information on 2-photon exchange effects in form factor extraction
  - Hydrogen resonance (Delta)
  - Aluminum, carbon

The Qweak Collaboration

97 collaborators 23 grad students
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