The Qweak experiment

A Search for New Physics at the TeV Scale via a Measurement of the Weak Charge of the Proton

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UVA Department Seminar 2013/03/26

Outline

- Theoretical background,
  Motivation for the Qweak measurement
- The Qweak experiment
- First results:
  The 25% measurement
- Outlook, Conclusion

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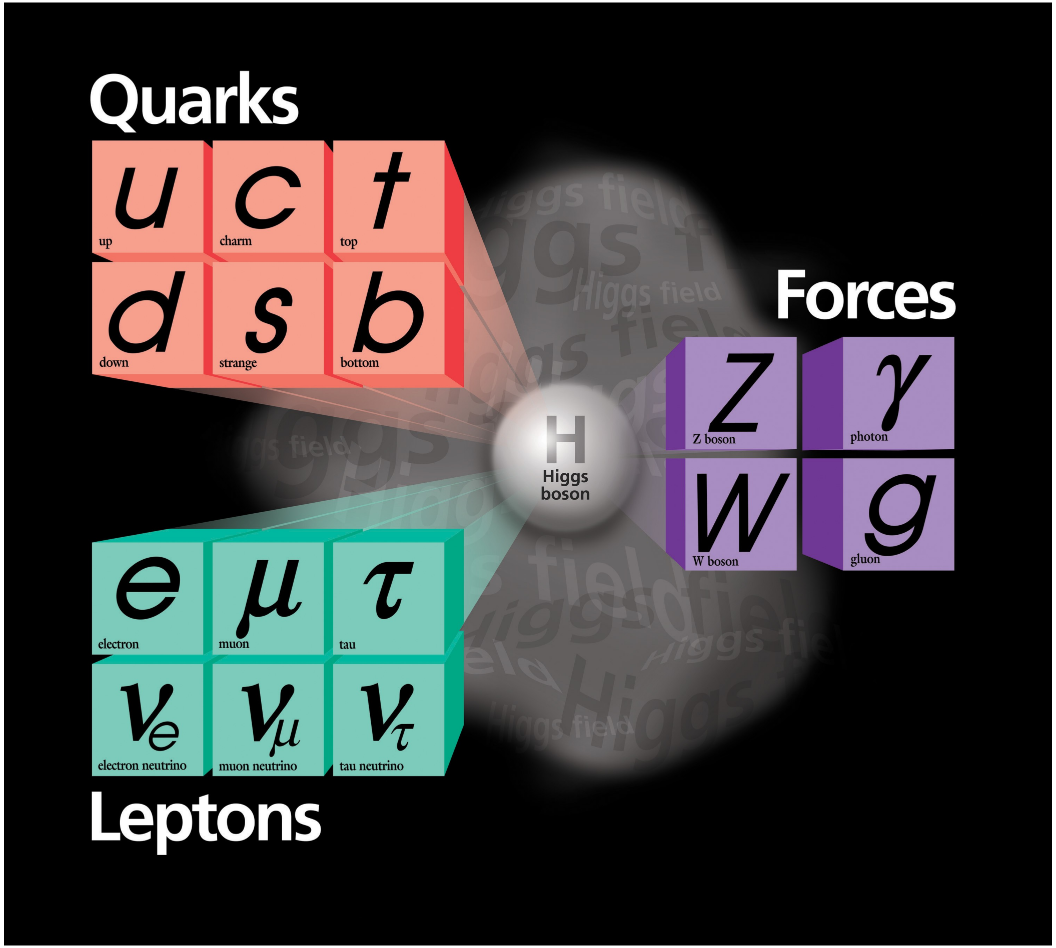
The Standard Model of Physics



strong electroweak

- SU(3)xSU(2)xU(1)
- 3 families of leptons and quarks, force carriers
- *"The theory of almost everything"*
- *Extremely successful* at predicting and describing experimental results

The Standard Model of Physics

… but, is that all there is?!

With all its amazing success, we have reasons to believe that there is Physics *beyond* the Standard Model

- *Major omissions*
  What about gravity? Dark matter?

- *Experimental evidence*
  Neutrino oscillations first evidence of a shortcoming

- *Hierarchy, fine-tuning, free parameters*
  Up to 25 free parameters in the SM: how fundamental is *that*?
  Underlying symmetry? Is the SM an effective theory at low energies?

The Standard Model: Electro-Weak Symmetry

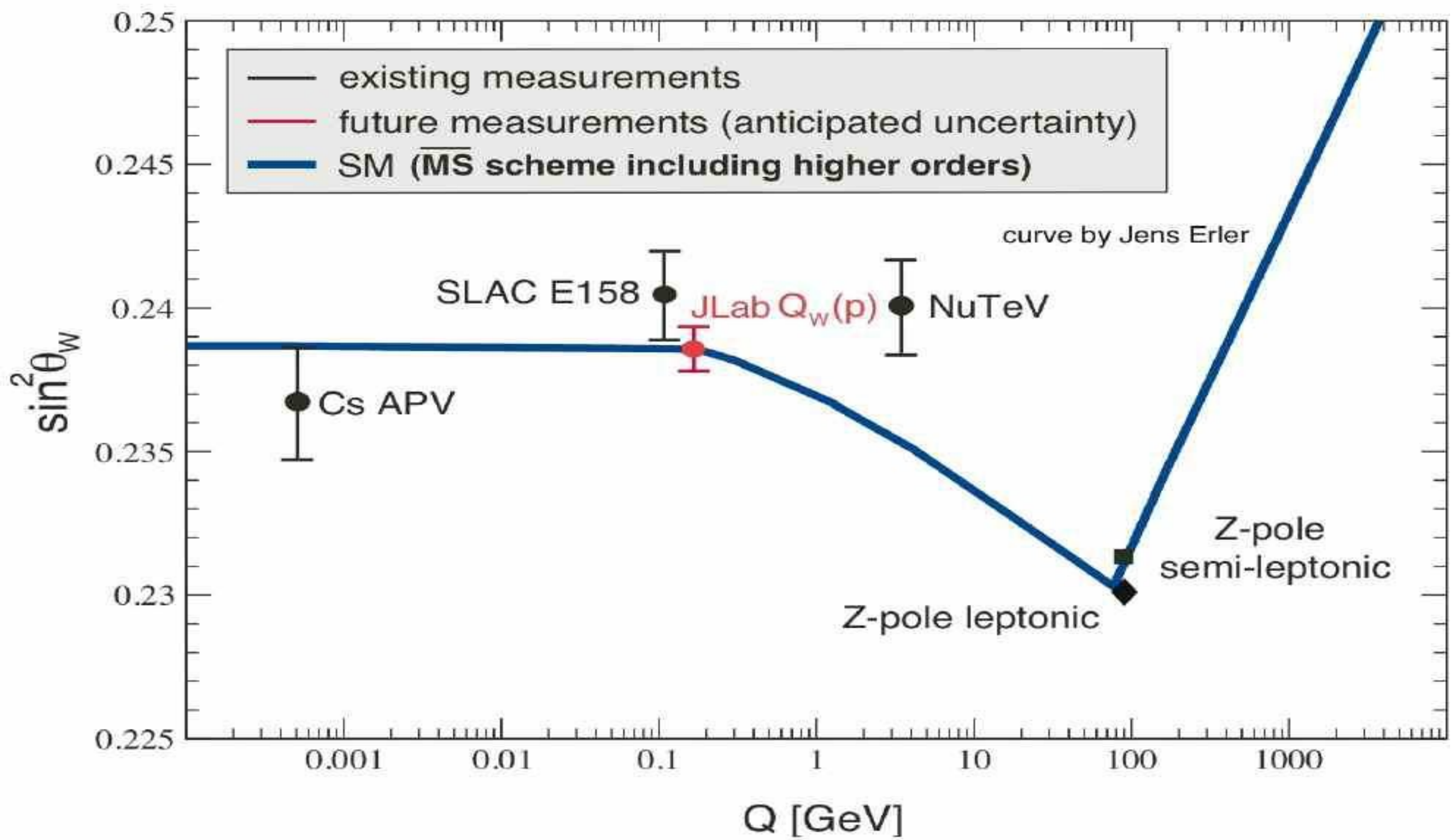
Electro-Weak unification: an example of an underlying symmetry

Interaction	*Carrier*	*Field*	*Mass*
EM	Photon	$A_\mu = B_\mu^0 \cos\theta_W + W_\mu^0 \sin\theta_W$	Massless!
(Neutral) Weak	Z boson	$Z_\mu = W_\mu^0 \cos\theta_W - B_\mu^0 \sin\theta_W$	91.2 GeV

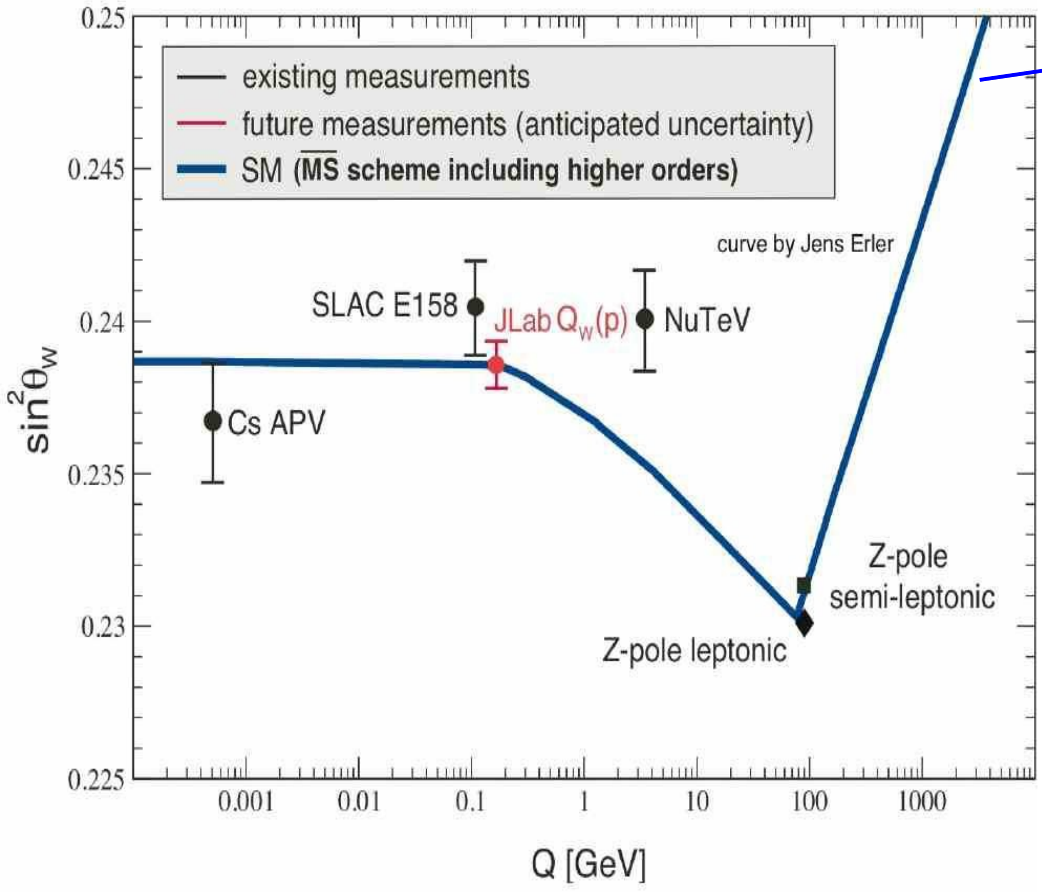
The weak mixing angle:
A fundamental parameter of the EW sector of the SM

$$\sin\theta_W = \frac{e}{g} \qquad \cos\theta_W = \frac{M_W}{M_Z}$$

The Weak Mixing Angle



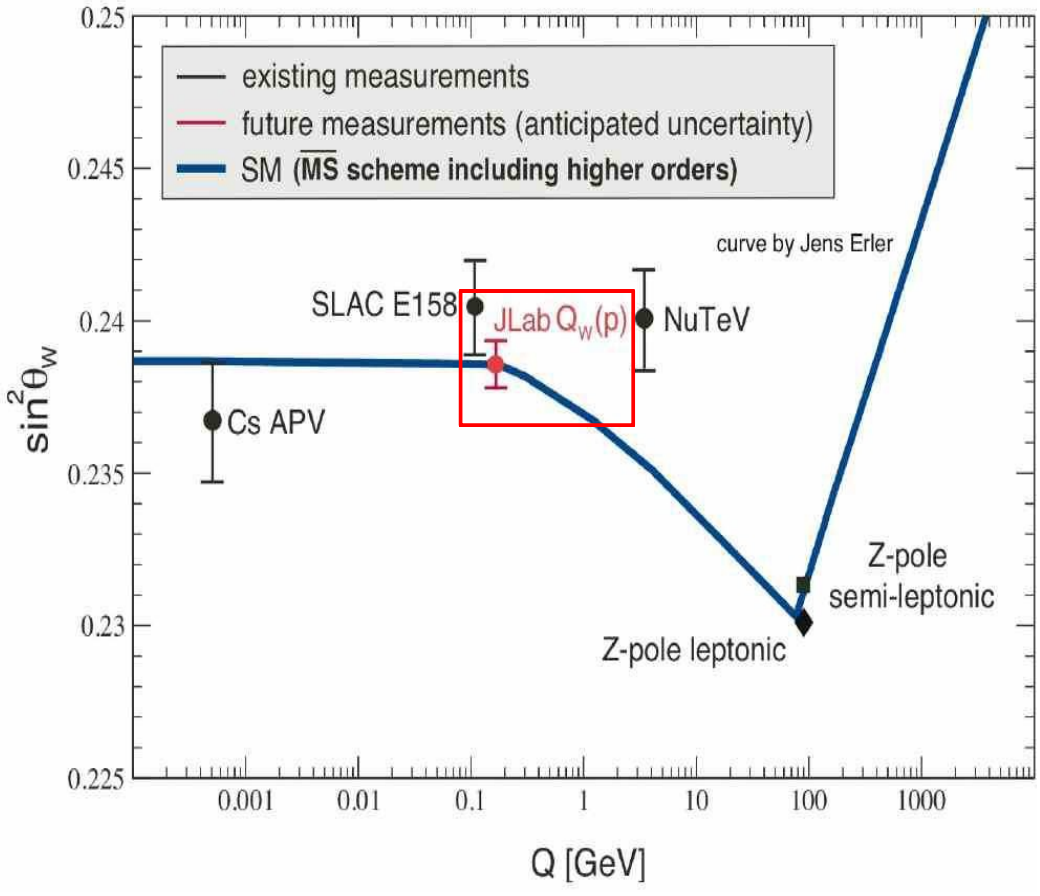
"Running" of $\sin^2\theta_w$ in the $\overline{MS}$ scheme



Firm SM theoretical prediction

Current world data from:
- Z-pole measurements from colliders (LEP, SLD)
- ν-N scattering
- Moller scatterning
- Atomic Cs transition

Future Q_W(p) measurement on SM prediction



The Qweak measurement

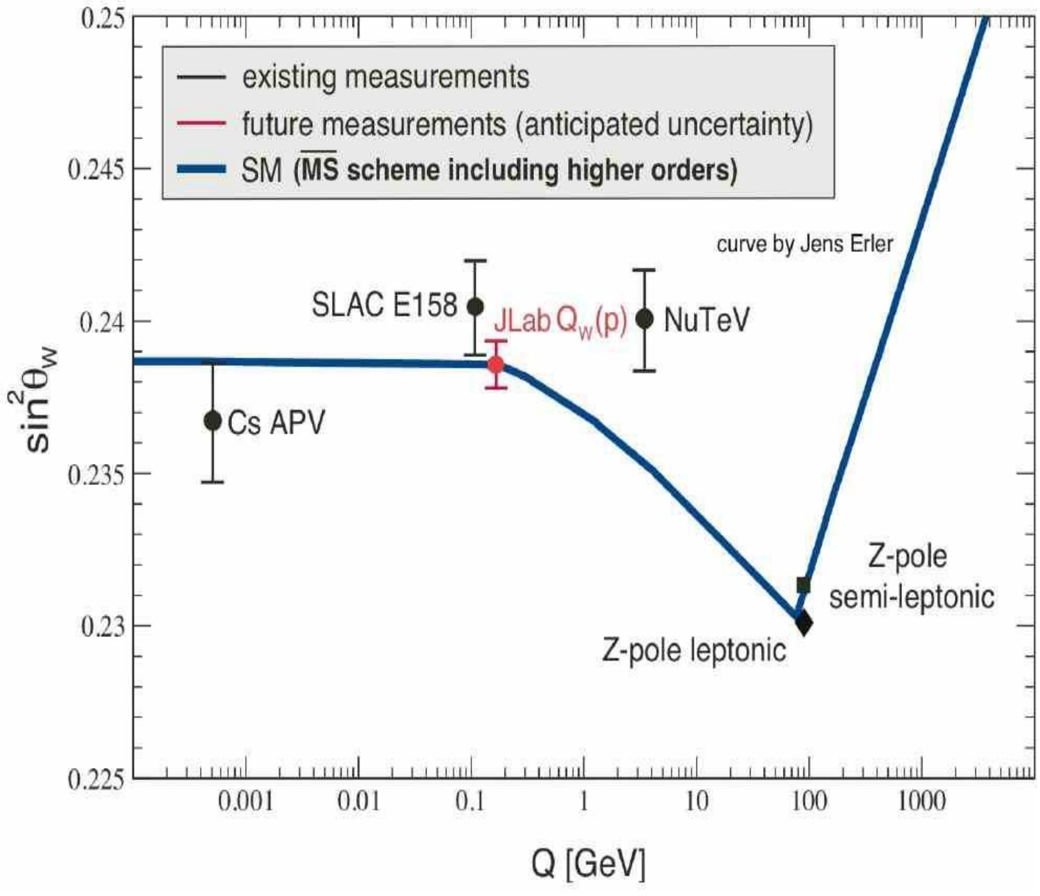
The weak charge of the proton is connected to $\sin^2\theta_w$:

$$Q_w^p = 1 - 4\sin^2\theta_w \approx 0.071$$

Tree level

$Q_w(p)$ is suppressed in the SM

4% measurement of $Q_w(p)$ will determine $\sin^2\theta_w$ to 0.3%



A 0.3% measurement at low Q^2:

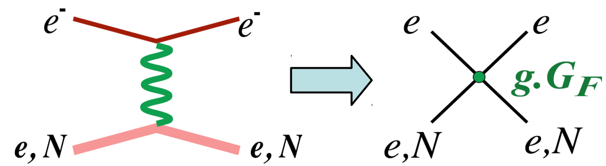
- Most precise determination off the Z-pole
- A 10-sigma confirmation of the predicted running
- A unique testing ground for the SM

Agreement with theory would impose significant constraints on possible SM extensions

On the other hand, a significant deviation could be a signal of new physics at the quantum loop level

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

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



$$\mathcal{L}^{PV}_{e-q} = \mathcal{L}^{PV}_{SM} + \boxed{\mathcal{L}^{PV}_{New}}$$
$$= -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2} \bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

$$\frac{\text{Mass}}{\text{Coupling}} \qquad \frac{\Lambda}{g} \approx \frac{1}{\sqrt{\sqrt{2}\, G_F \left|\Delta Q_W(p)\right|}} \approx 4.6\, TeV$$

Sensitivity to new physics up to the TeV scale
(thanks to suppression of $Q_W(p)$ in the SM)

Complementarity with searches at the intensity frontier:
In the event of a discovery at the LHC, precision experiments like Qweak will be very important to determine the characteristics of the new interaction.

Weak quark charges $C_{1u,d}$

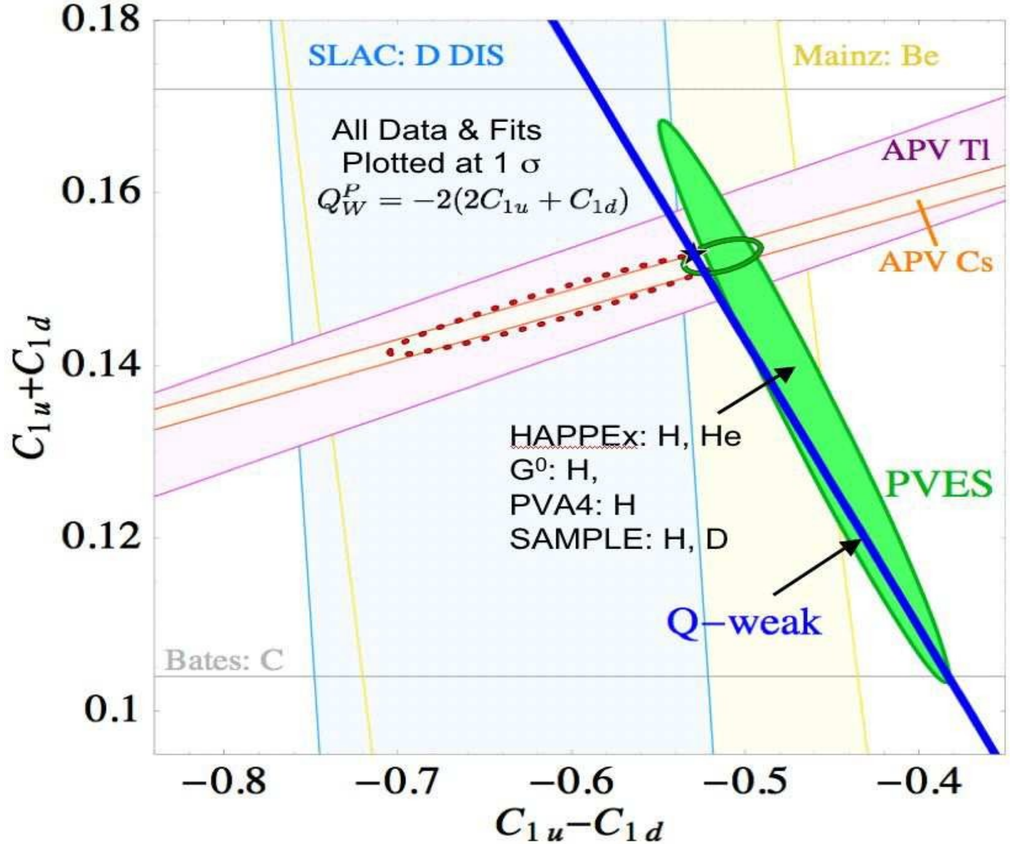
$C_{1u,d}$: Effective couplings to the vector quark current

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

PVES data access almost orthogonal combination to APV

Qweak will determine both $C_{1u,d}$ to very high precision, providing tight constraints to the flavor dependence of relevant new physics

Isoscalar weak charge



Isovector weak charge

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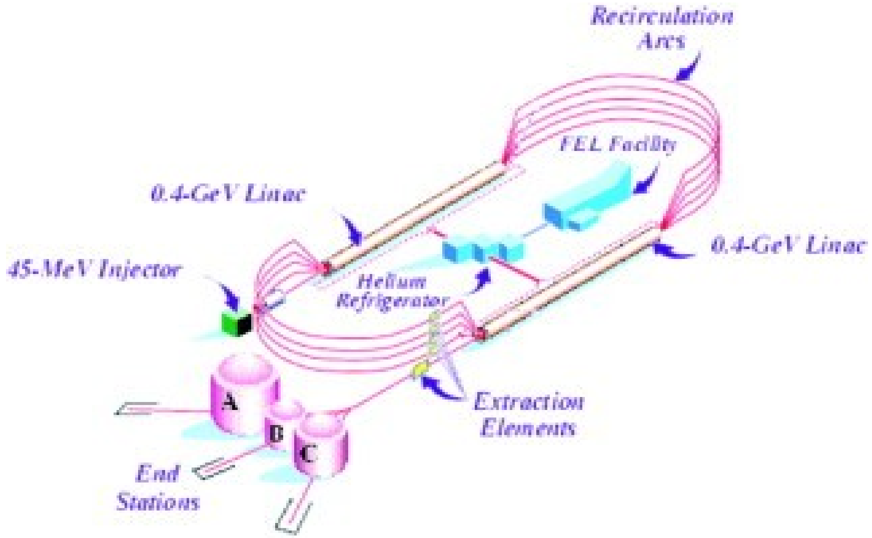
The Qweak experiment at Jefferson Lab

Qweak ran in experimental Hall C
of Jefferson Lab
in Newport News, Va

Completed May 2012
after 2 years of data taking



The Thomas Jefferson National Accelerator Facility

Parity Violating Asymmetry

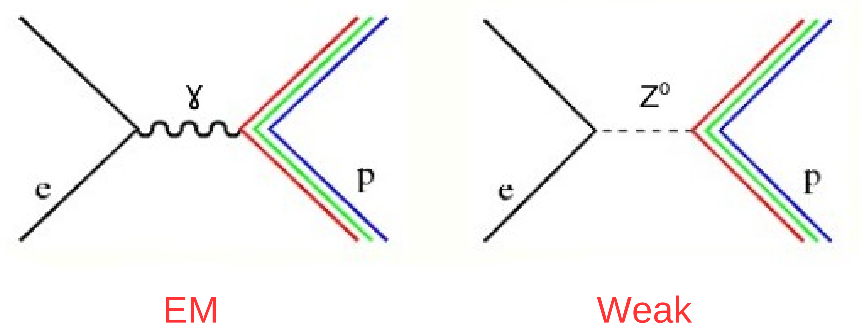
Experimental probe: e-p scattering
Proceeds through exchange of a photon or a Z boson

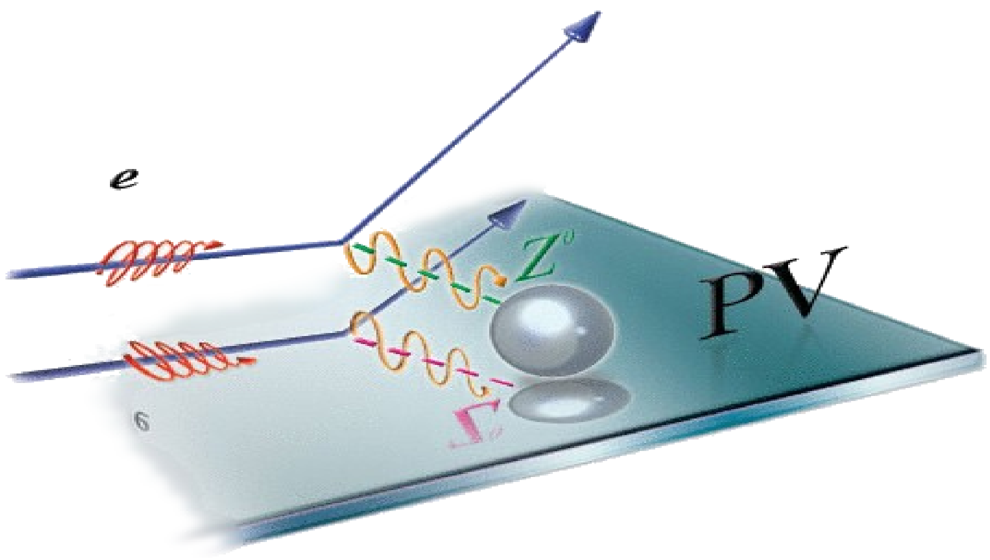
$$\sigma \propto \left| M_{EM} + M_{Weak} \right|^2 \approx M_{EM}^2 + 2 M_{EM} M_{Weak}$$

$$\left| M_{EM} \right| / \left| M_{weak} \right| \approx 10^4$$

EM amplitude *swamps* the weak.
Access the interference term through *parity violation*
Measure asymmetry between left and right helicity states:

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{2\left| M_{Weak} \right|}{\left| M_{EM} \right|}$$





Parity Violating Asymmetry

At forward angles and low Q^2:

$$A_{LR} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{-G_F}{4\sqrt{2}\pi\alpha}\left[\underline{\boldsymbol{Q_w^p}\, Q^2} + \boldsymbol{B}\left(\boldsymbol{Q}^2\right) Q^4 \right]$$

Extraction of $Q_w(p)$
from the PV asymmetry

Parity Violating Asymmetry

At forward angles and low Q2:

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

Nucleon structure enters here.
Hadronic form factors
constrained by the PVES
programs in Jlab, MIT-Bates,
Mainz.

Hadronic structure corrections suppressed at low Q^2,
but so is the asymmetry!

At Qweak kinematics: $Q^2 \sim 0.026 \text{ GeV}^2$

SM prediction:
$A_{LR} \sim -0.23$ ppm

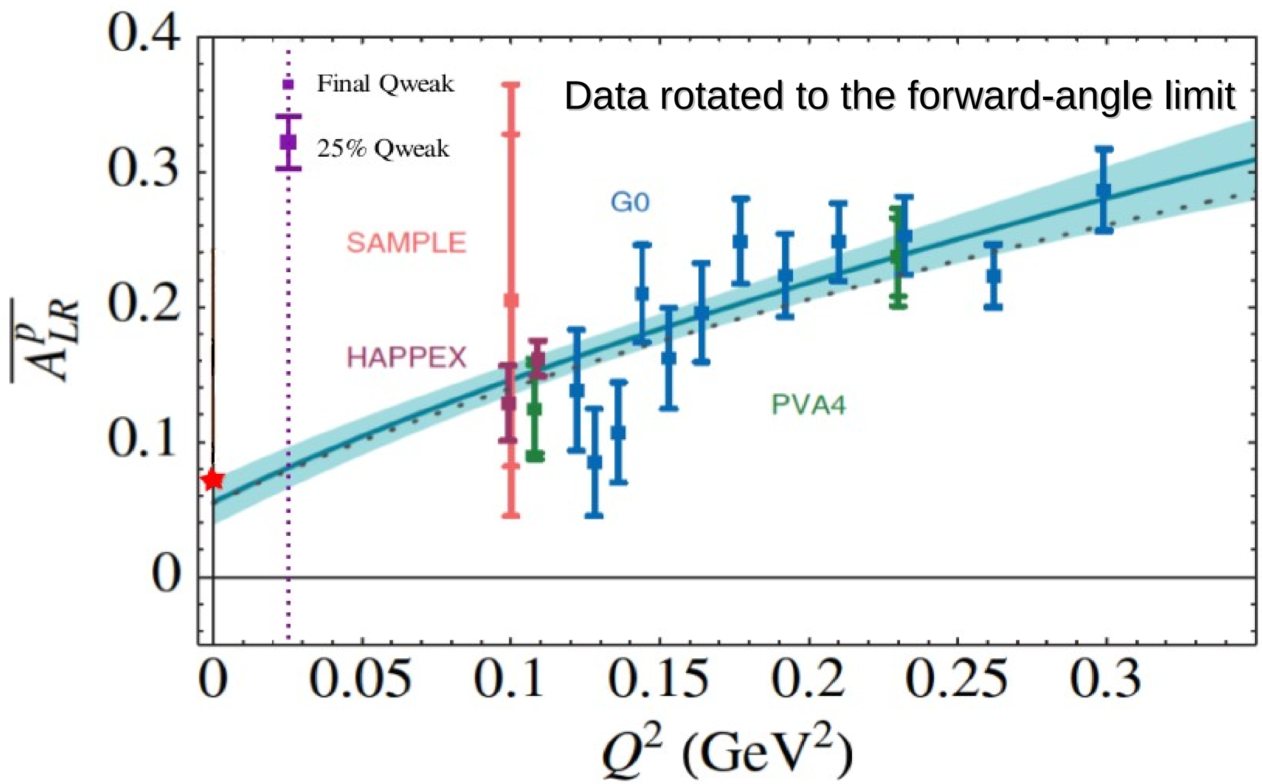
A very small asymmetry!
Qweak proposes a ~2% measurement, which requires:

→ High statistics (high current, high polarization, high power cryotarget)
→ Careful control of systematics (false asymmetries, backgrounds, polarization)

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

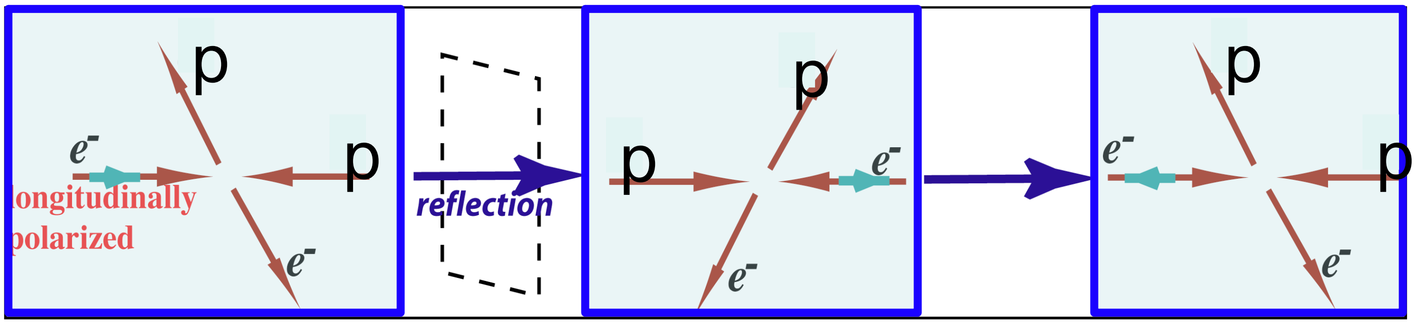
→ Reduced asymmetry $$\overline{A_{LR}} = -\frac{4\pi\alpha\sqrt{2}}{G_F Q^2} A_{RL} = \boldsymbol{Q_w^p} + \boldsymbol{B}\left(\boldsymbol{Q^2}\right) Q^2$$

Existing PVES data constrain the hadronic structure effects, allowing for a relatively clean extraction of Qw(p) (compare to APV, NuTeV)



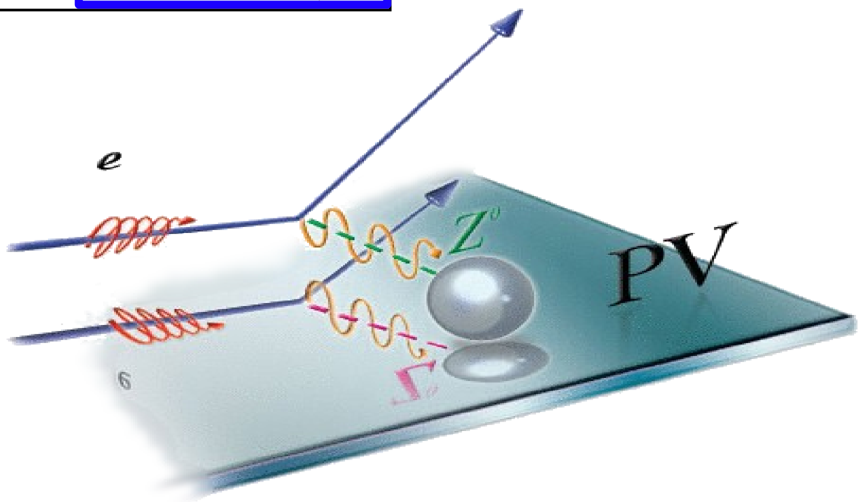
Experimental Technique

Electrons prepared in two opposite helicity states.
Equivalent to a parity inversion:

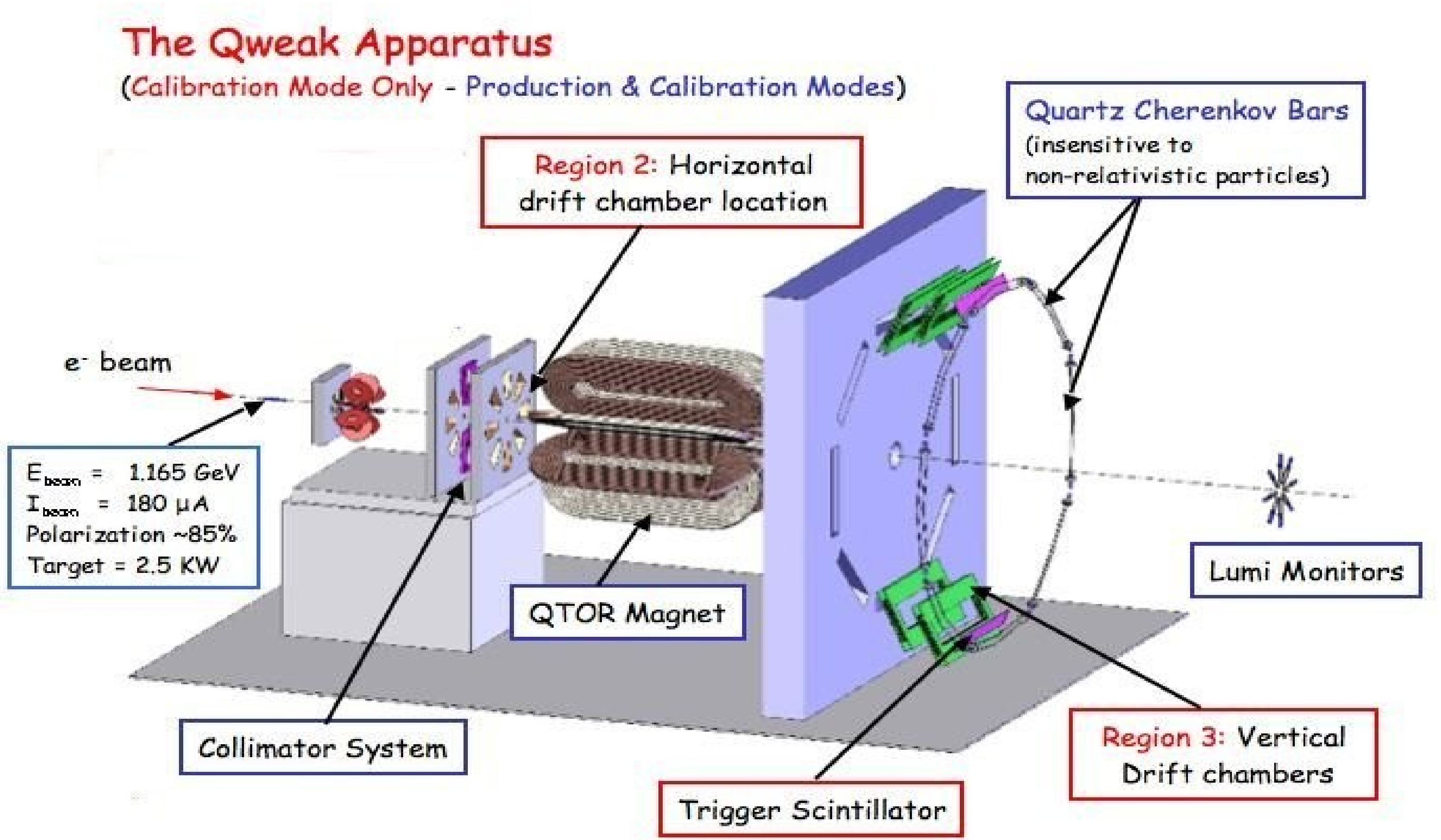


Measure the PV asymmetry in
detector rate between the two states:

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

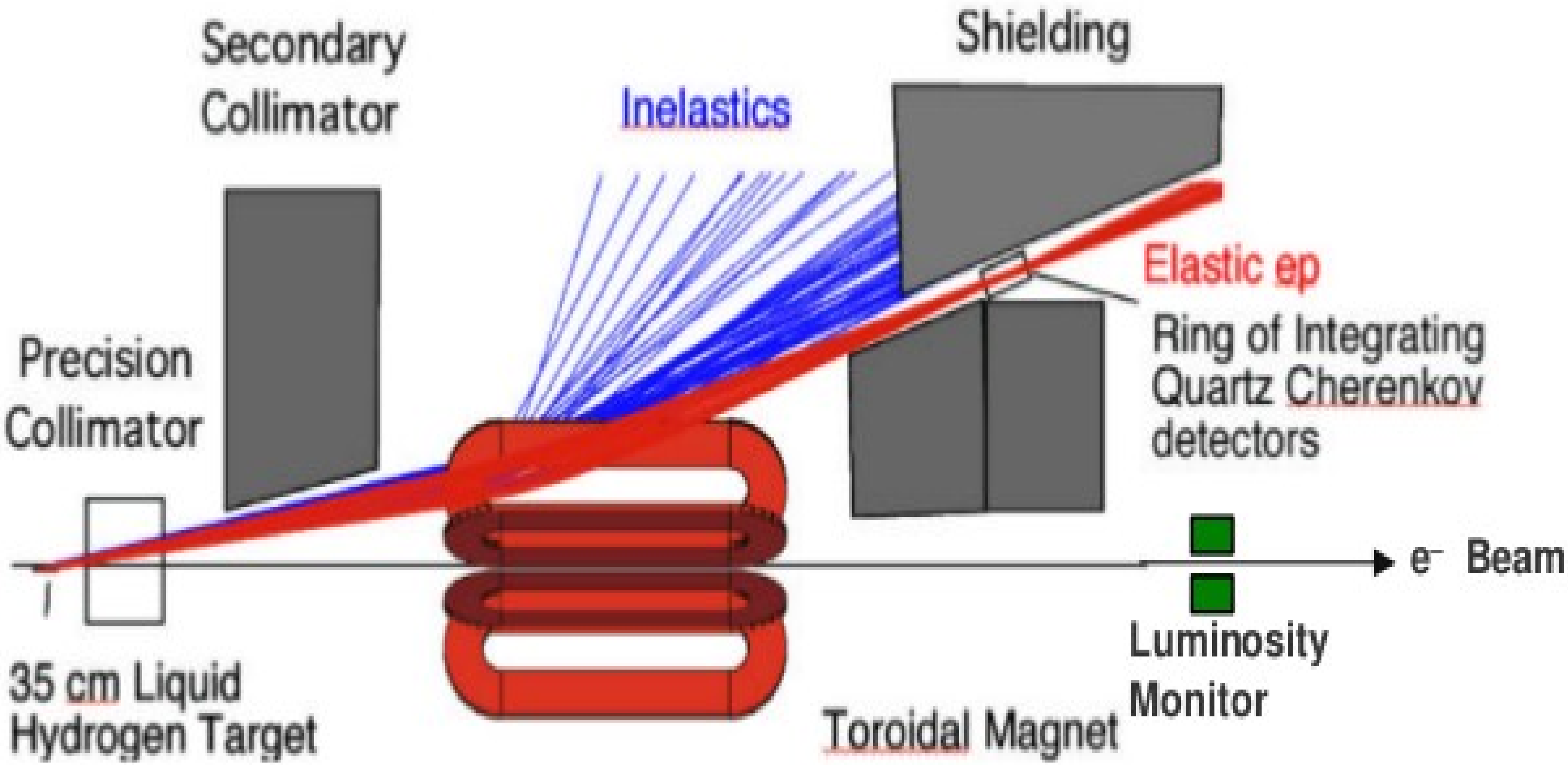


Then repeat for 2 years!

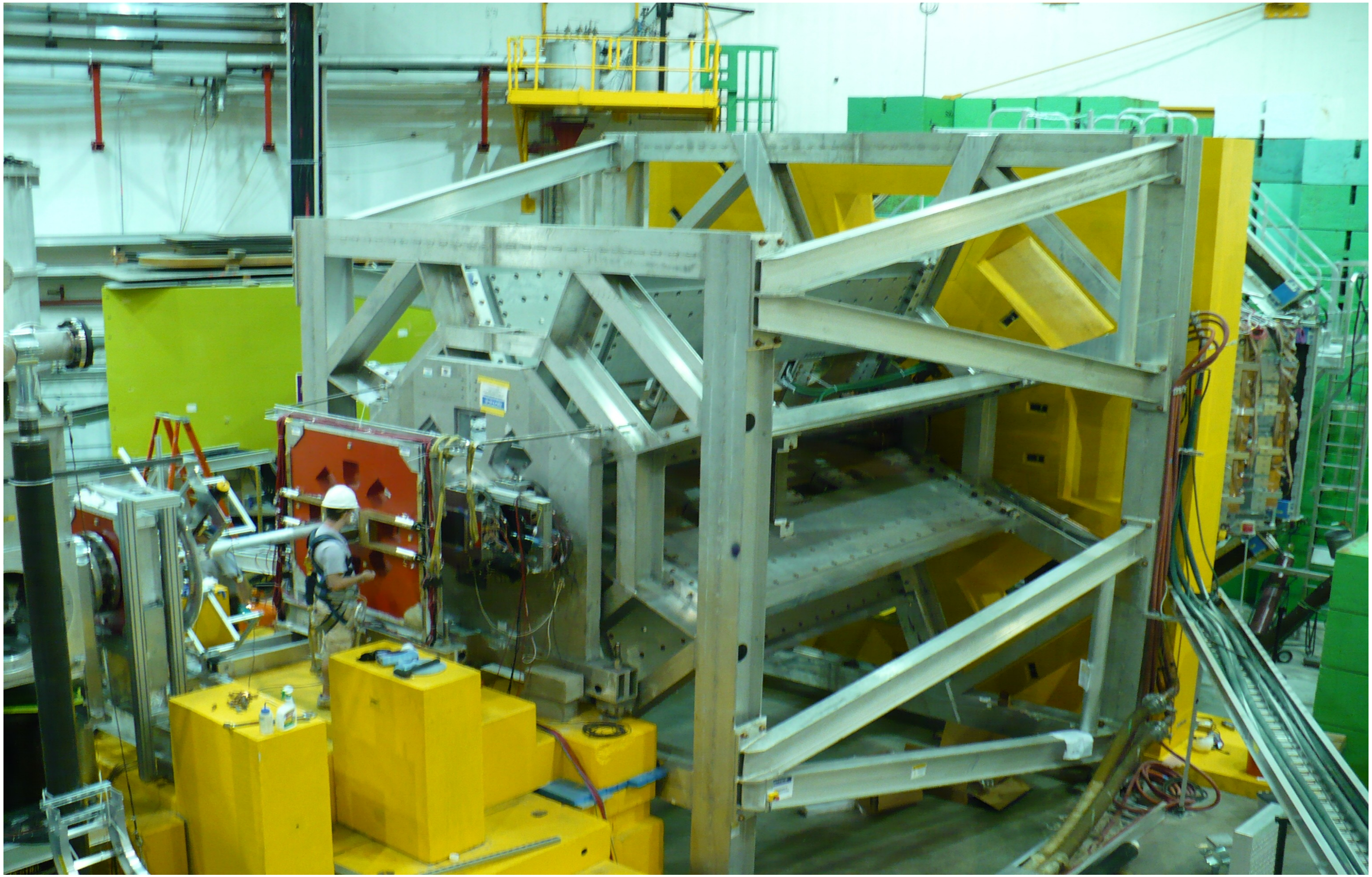


The Qweak Apparatus
(Calibration Mode Only - Production & Calibration Modes)
Quartz Cherenkov Bars
(insensitive to
non-relativistic particles)
Region 2: Horizontal
drift chamber location
e- beam
E beam = 1.165 GeV
I beam = 180 μA
Polarization ~85%
Target = 2.5 KW
Lumi Monitors
QTOR Magnet
Collimator System
Region 3: Vertical
Drift chambers
Trigger Scintillator

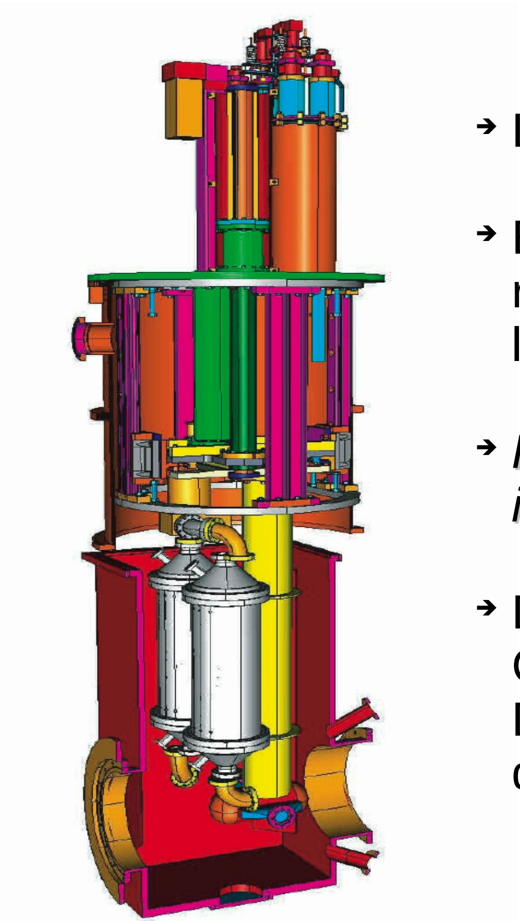
The Qweak Apparatus



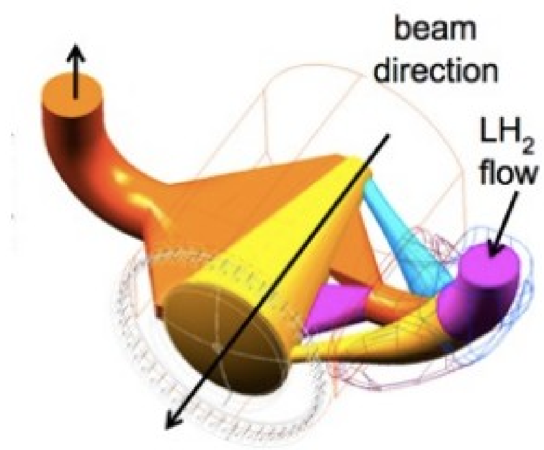
The Qweak Apparatus



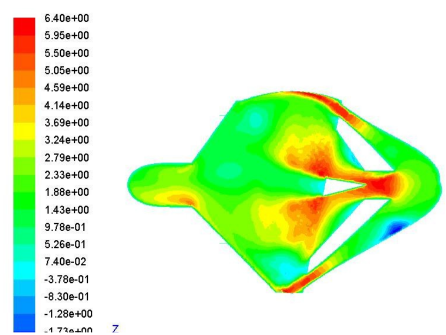
Liquid Hydrogen target



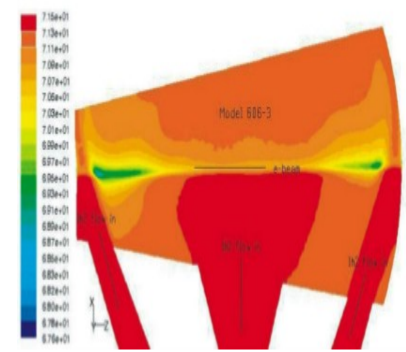
- Long (35cm) LH2 target
- Extreme cooling requirements due to large beam heat load
- *Highest power cryotarget in the world: 2.5kW*
- Design based on Computational Fluid Dynamics to reduce density fluctuations *(target boiling)*



Target Cell

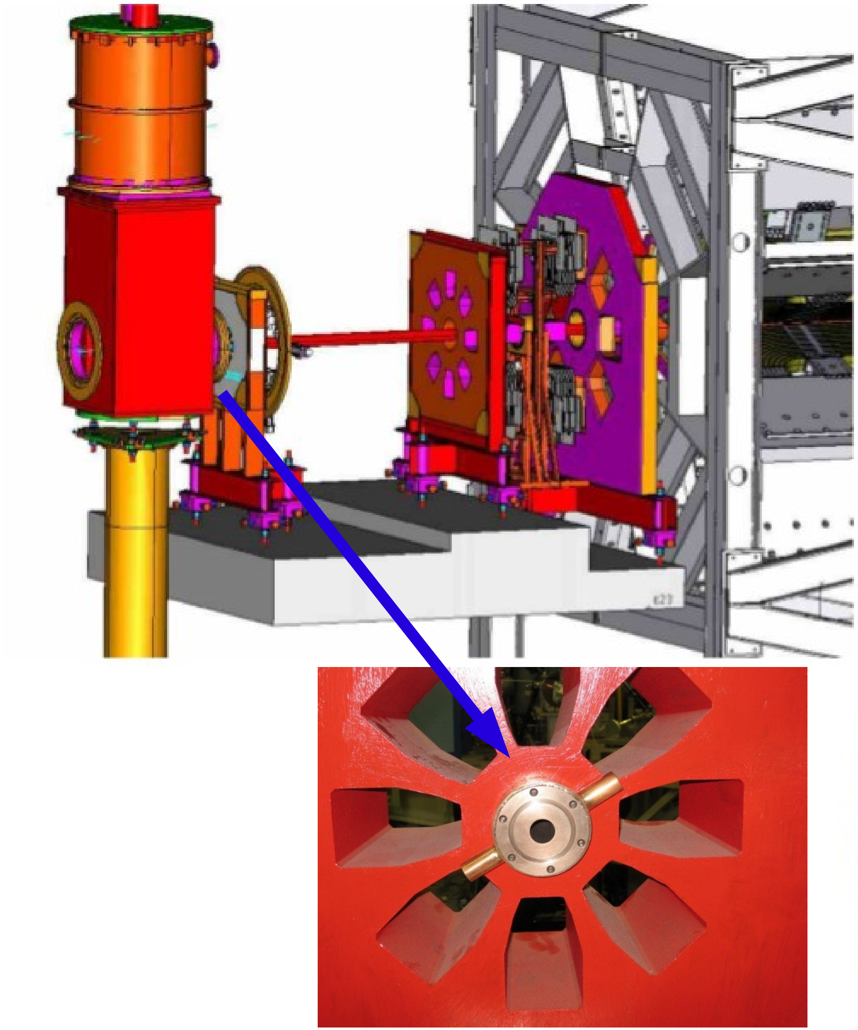


Fluid velocity



Fluid density

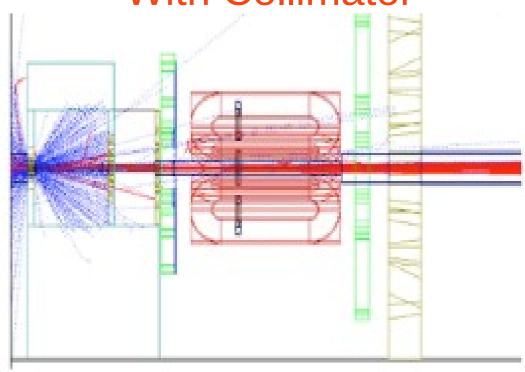
Collimator system



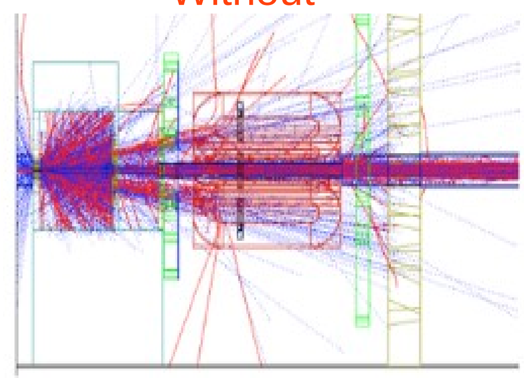
3-stage Pb collimator system defines the Q^2 acceptance of the apparatus and selects e^- scattered at ~8^o

Background reduction considerations:
Small-aperture Tungsten “plug” in collimator 1

With Collimator



Without

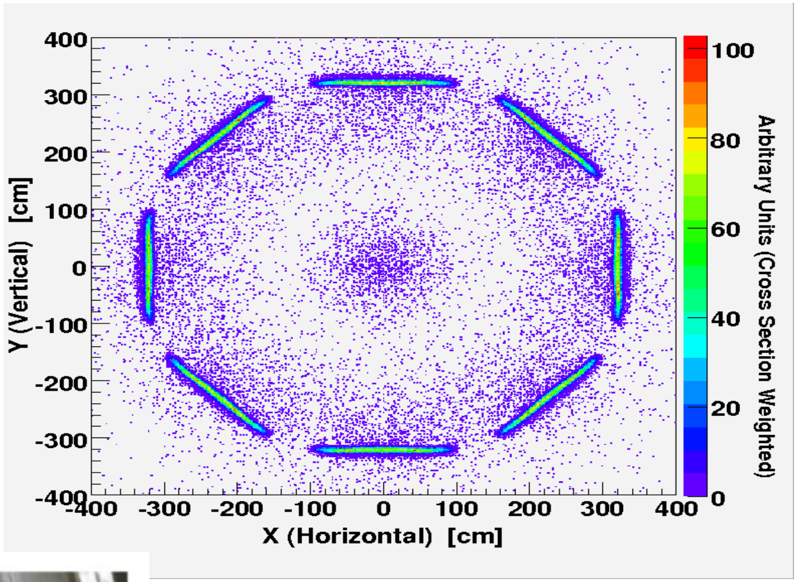


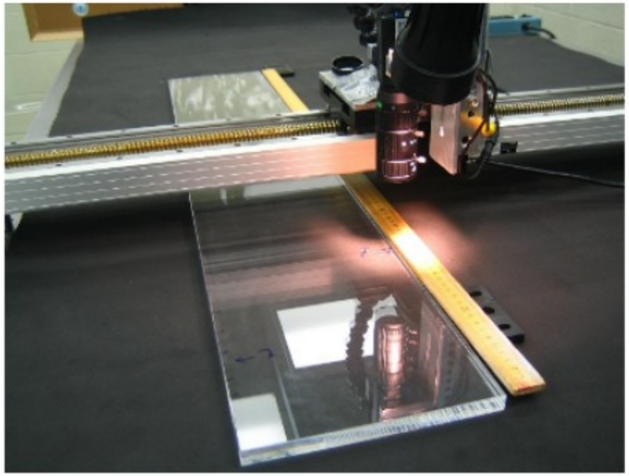
Main Detector

Azimuthally symmetric array
of 8 Čerenkov detectors

Synthetic quartz: Spectrosil 2000
Rad-hard, relatively insensitive to backgrounds,
uniform response, low intrinsic noise

Detectors sit in shielding house, protection
from radiation and backgrounds





Error Budget

Uncertainty	$\Delta A_{PV}/A_{PV}$	$\Delta Q_w/Q_w$
Statistical (~2,5k hours at 150 μA)	2.1%	3.2%
Systematic:		2.7%
Hadronic structure uncertainties	---	1.5%
Beam polarimetry	1.0%	1.5%
Absolute Q^2 determination	0.5%	1.0%
Backgrounds	0.5%	0.7%
Helicity correlated beam properties	0.5%	0.8%
Total:	2.5%	4.2%

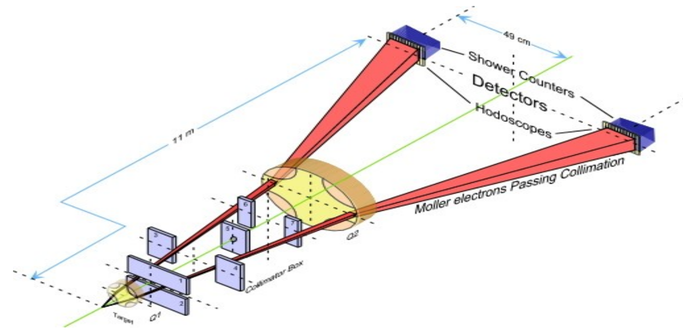
Error budget corresponds to a ~0.3% determination of $\sin^2\theta_W$, including uncertainties from higher order corrections:

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

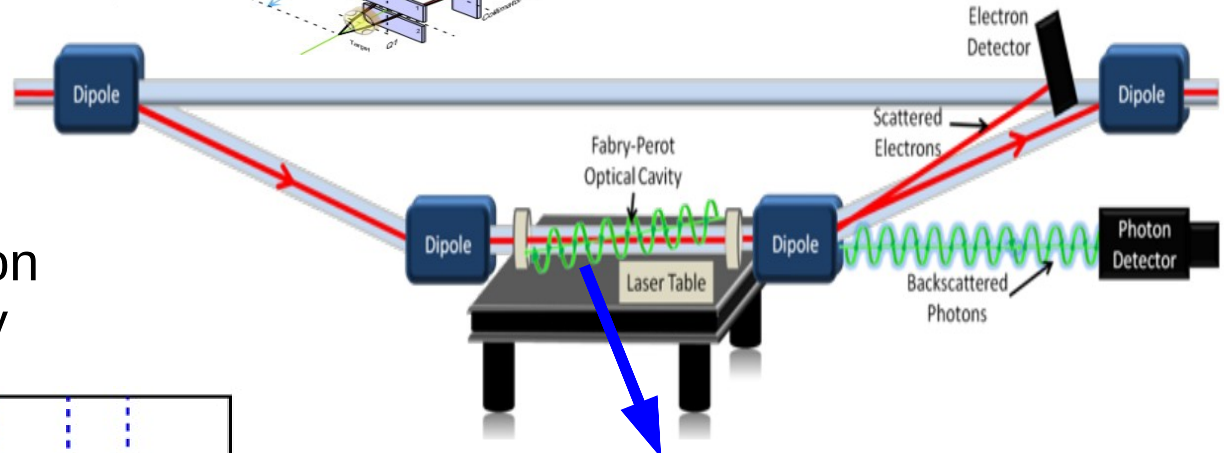
Polarimetry

Qweak requirement: dP/P = 1%

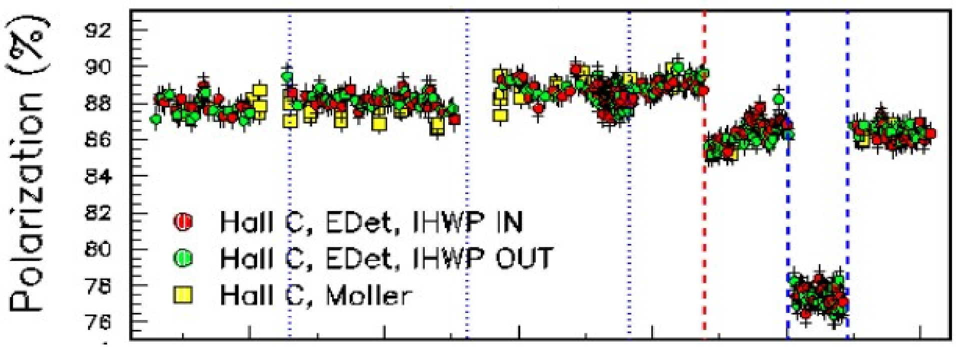
Two independent measurements:



Moller Polarimeter
Requires dedicated
low-current running



Compton Polarimeter
Installed by the collaboration
for continuous polarimetry



Consistency among independent measurements

Fabry-Perot cavity
fabricated by UVA
UVA Polarimetry group
maintained the laser and
the photon detector

Helicity Correlated False asymmetries

Qweak requirement: $dA_{PV}/A_{PV} = 0.5\%$

- Detector rate depends on beam parameters (position, angle, energy)
- Helicity correlated differences in these parameters can “immitate” parity violation and create false asymmetries:

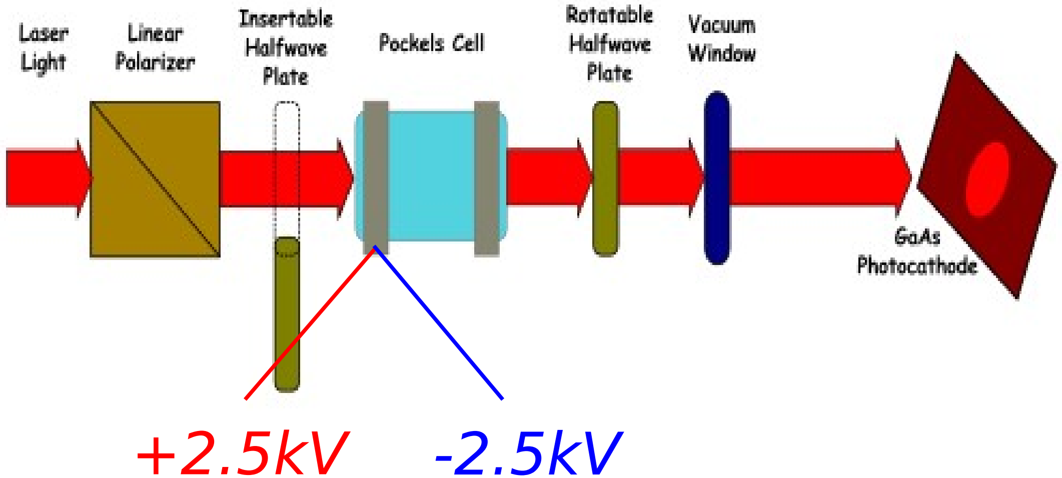
$$A_{meas} = A_{phys} + \boxed{\sum_i \frac{\partial A}{\partial P_i} \delta P_i}$$

false asymmetries

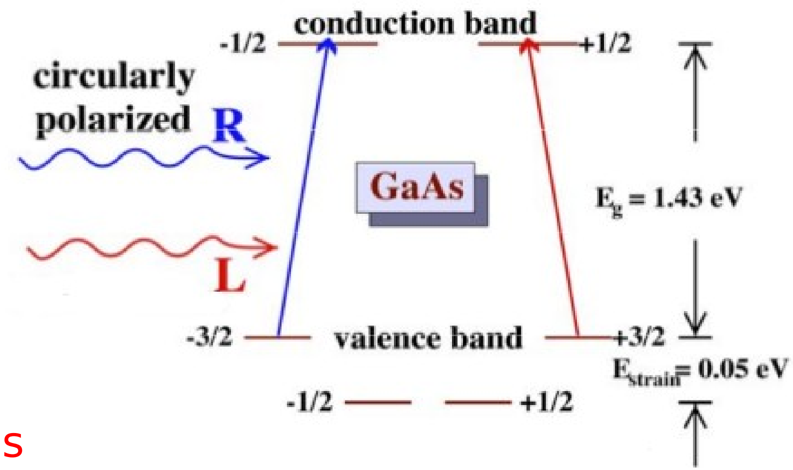
Strategy against false asymmetries:

- Design experiment to reduce sensitivity
- Set up the machine to minimize these differences
- Estimate sensitivity and subtract the false asymmetry
- Utilize cancellations to average out the residual effect

Polarized source at Jefferson Lab

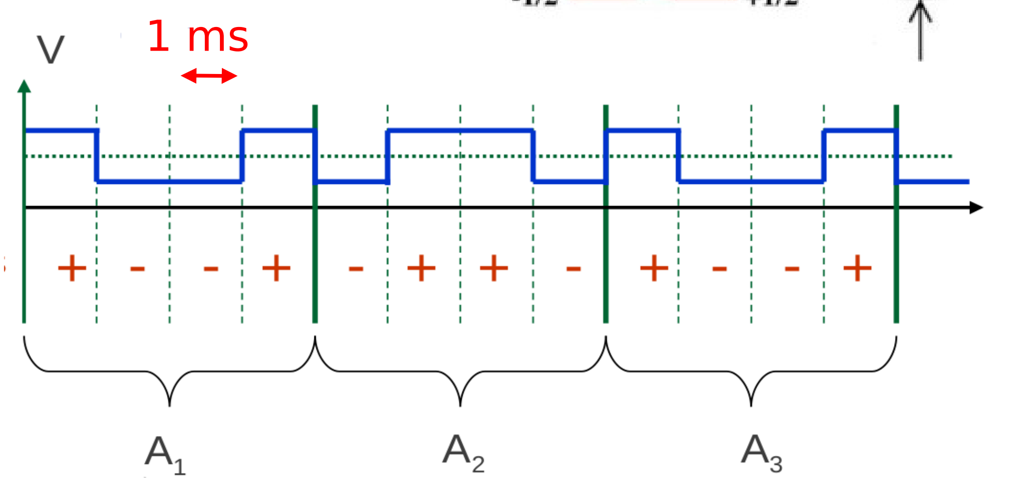


Polarized e⁻ produced from strained superlattice GaAs photocathode

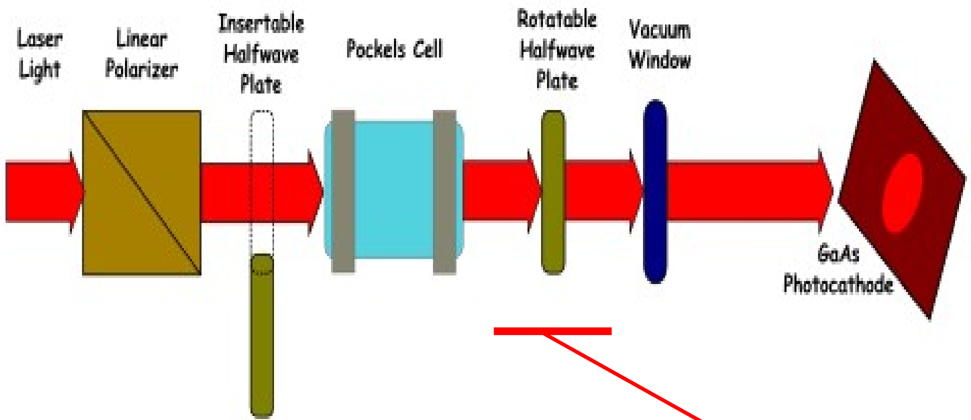


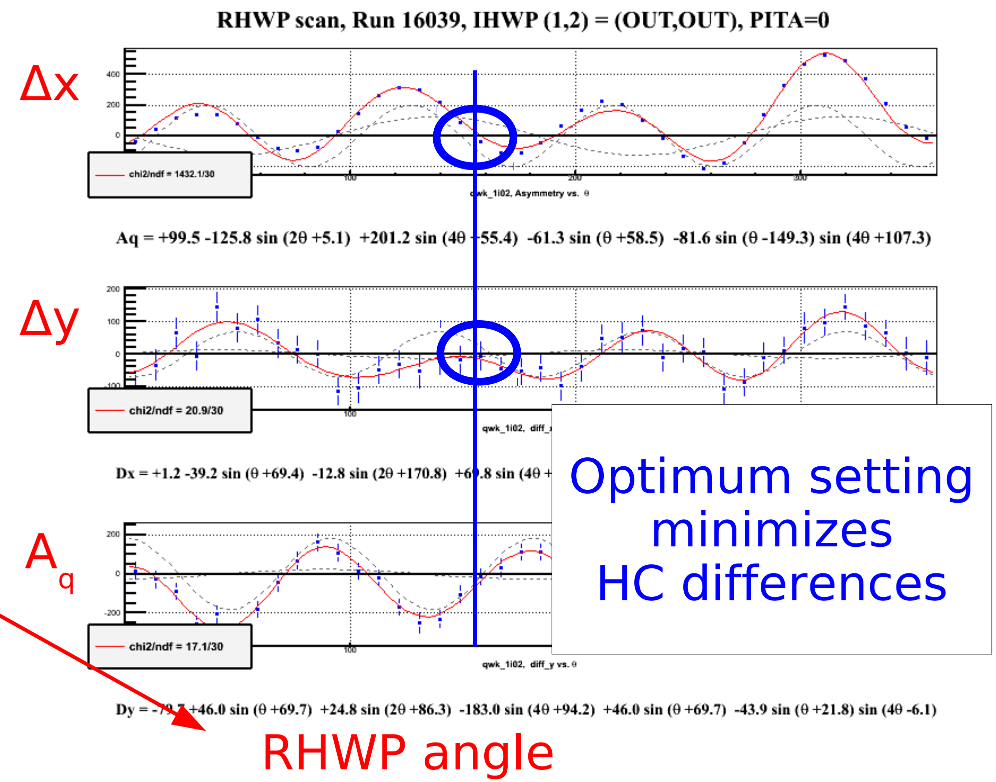
Pockels Cell acting as a λ/4 plate
(electro-optic effect)
creates circularly polarized light

Fast, 960Hz helicity flip
Pseudorandom quartet pattern



Polarized source at Jefferson Lab



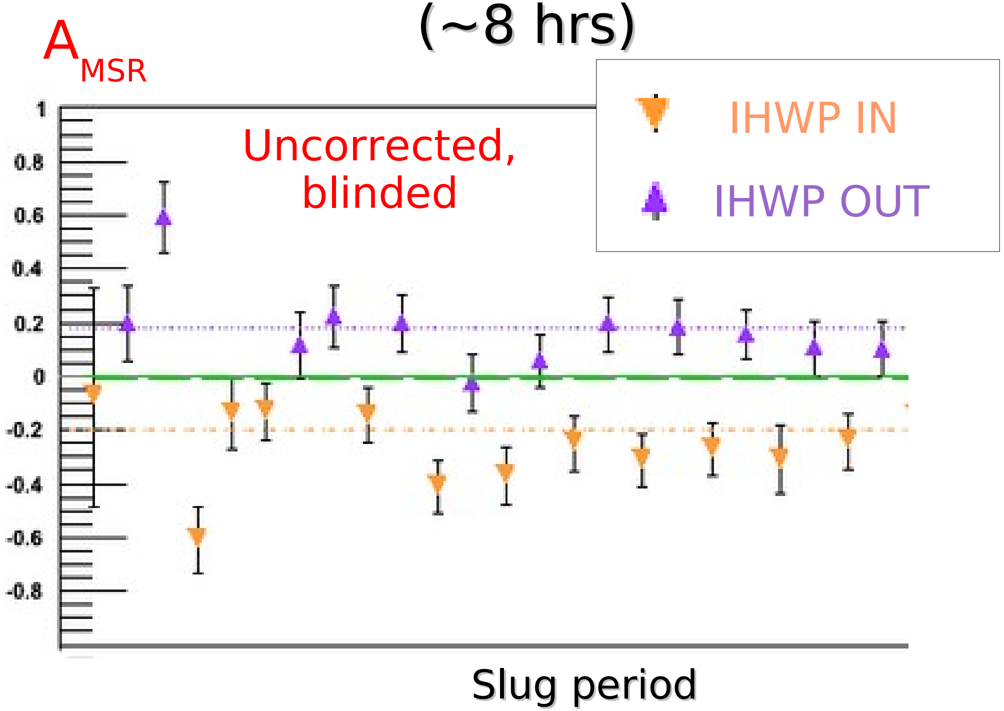


Main source of
helicity correlated differences:
relative residual linear light
coupled with an asymmetric transport.

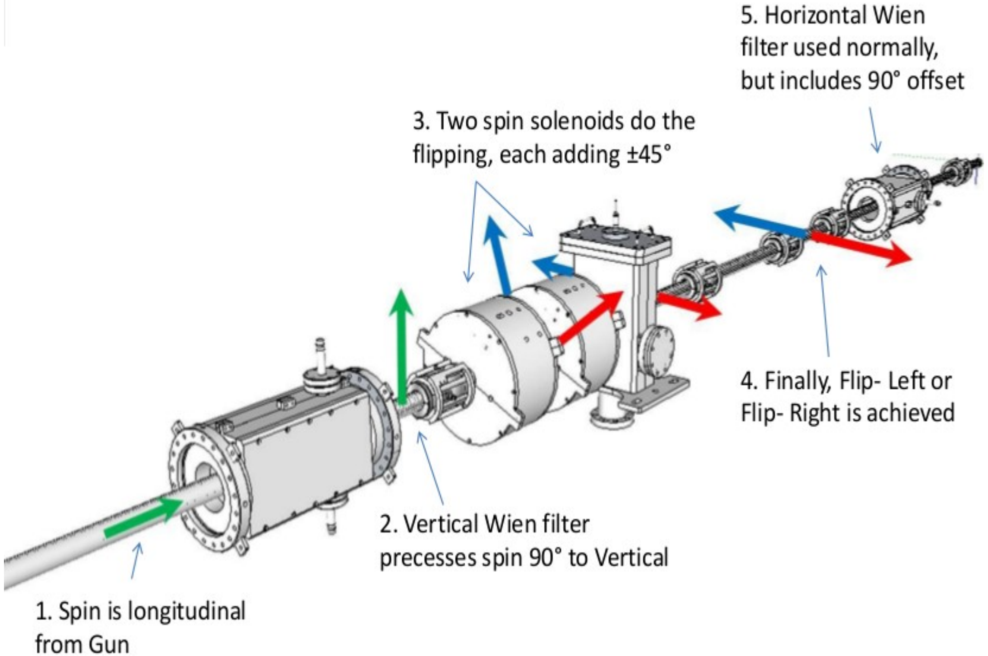
UVA Source group responsible for alignment and optimization,
achieved excellent suppression of HC differences in the injector
although optimum settings would drift.

Reversals, Cancellations

Laser table IHWP
(~8 hrs)



Injector spin manipulator
(~month)



Reversing the asymmetry with respect to helicity correlated differences cancels their residual effect

Reversing the spin of the e$^-$ beam should cancel all HC differences coming from the polarized source

Regression corrections

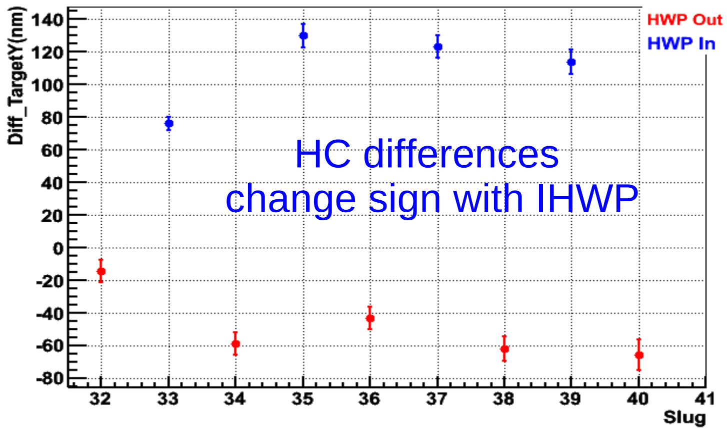
To correct the effect of remaining HC differences
the detector sensitivities are extracted from 5-parameter regression

$$A_{meas} = A_{phys} + \sum_i \frac{\partial A}{\partial P_i} \delta P_i$$

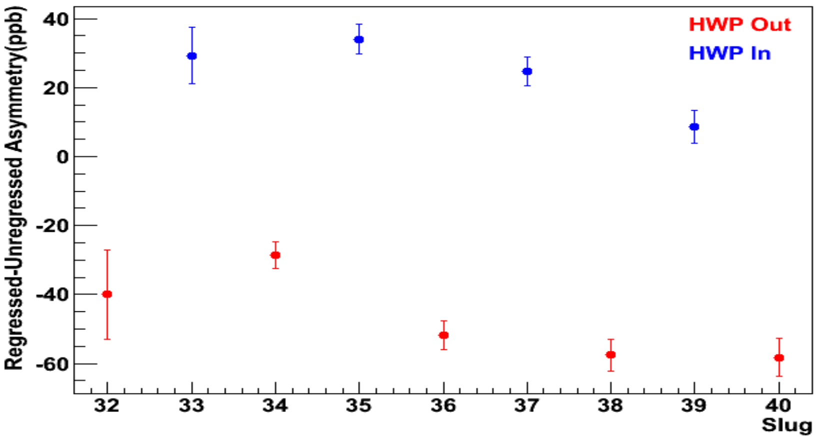
HC differences, monitored continuously

Detector sensitivities

ΔY Position Difference



Regression Correction



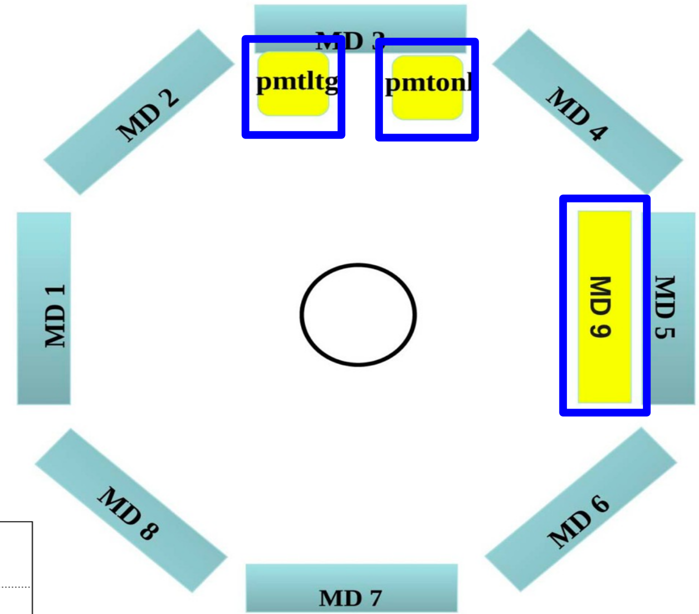
Sensitivities were also extracted indepentently from modulation (5% df),
but this subsystem was not available during the commissioning run

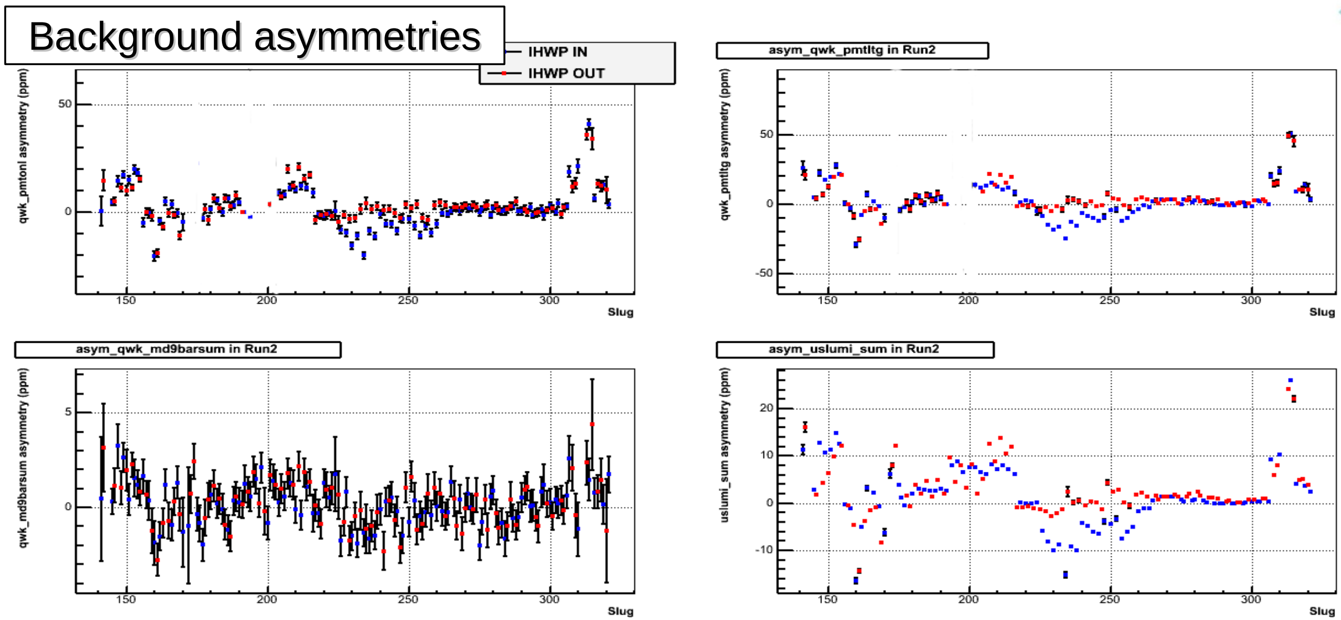
Beamline Background Asymmetry

Hypothesis: Asymmetric “beam halo” interacts
with the tungsten plug and the beamline

Different background detectors see asymmetries
proportional to the background fraction in their signal

Quite large background asymmetries
make this an important correction





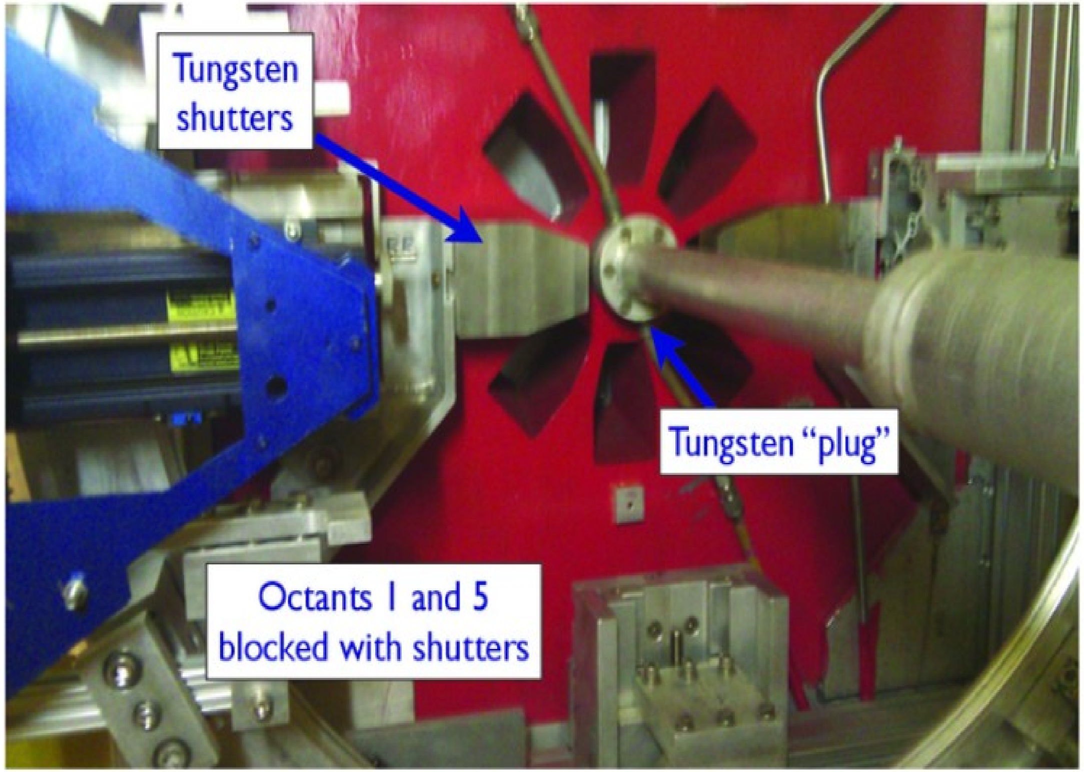
Continuous monitoring
from
background detectors

Beamline Background Asymmetry

Dedicated measurement with tungsten shutters directly measures the beamline background fraction in the Main Detector: ~0.19%

Consistency with estimations from continuous monitoring, appears to be well understood.

Still, very modest uncertainty in this correction for the 25% measurement.



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- An overview of the Qweak experiment
- First results:
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The 25% data set

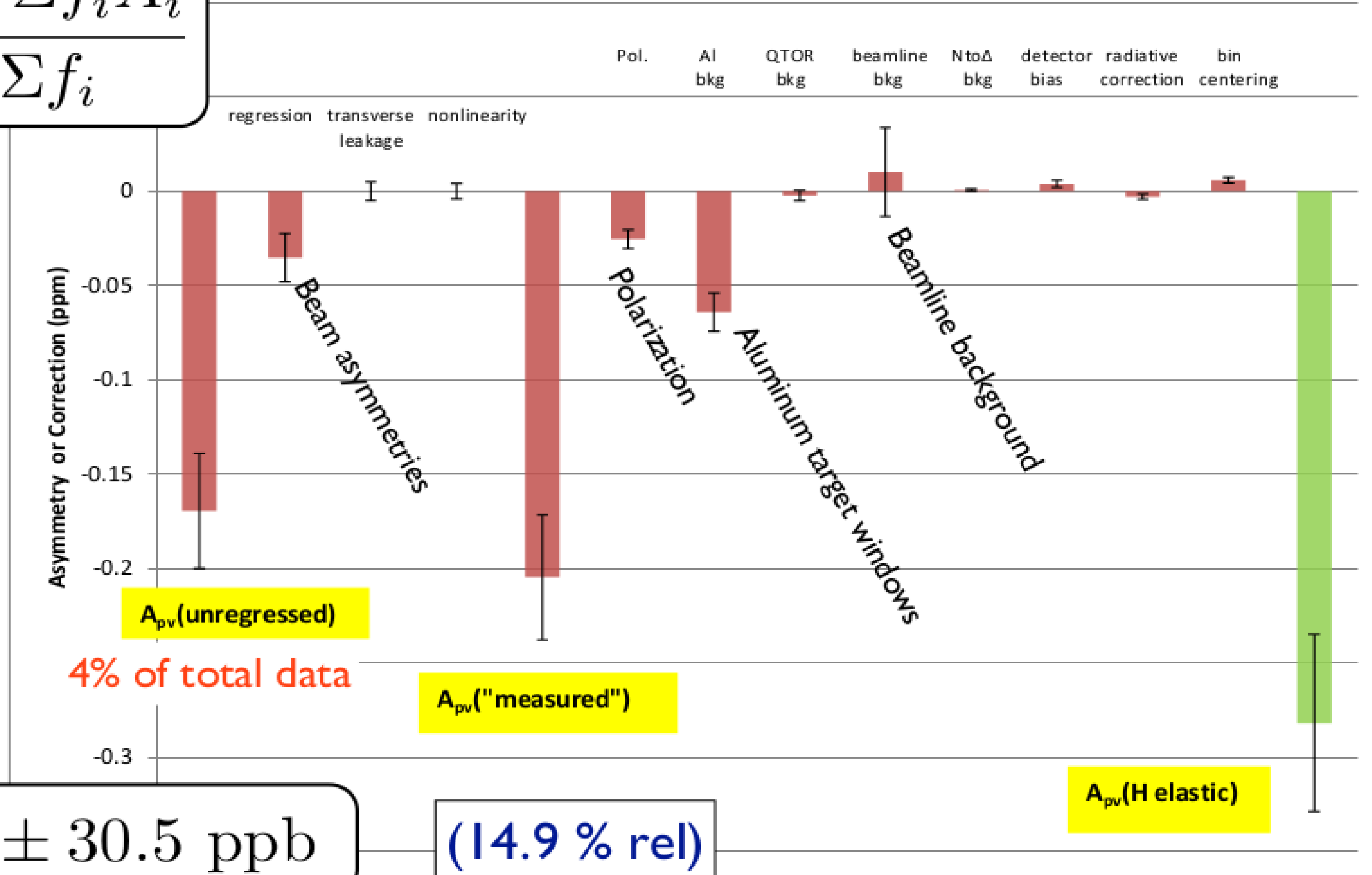
~4% of the full Qweak data
Taken at the end of the Commissioning Run,
Jan. 31 2011 – Feb. 8 2011

Some equipment was still being commissioned and
will be used only for the full measurement:
Modulation, Compton polarimeter,
Injector spin manipulator

Will provide a ~25% measurement of $Q_w(p)$

$$A_{\rm PV} = \frac{\frac{A_{\rm msr}}{P} - \Sigma f_i A_i}{1 - \Sigma f_i}$$

Hydrogen Elastic Asymmetry Effective Corrections

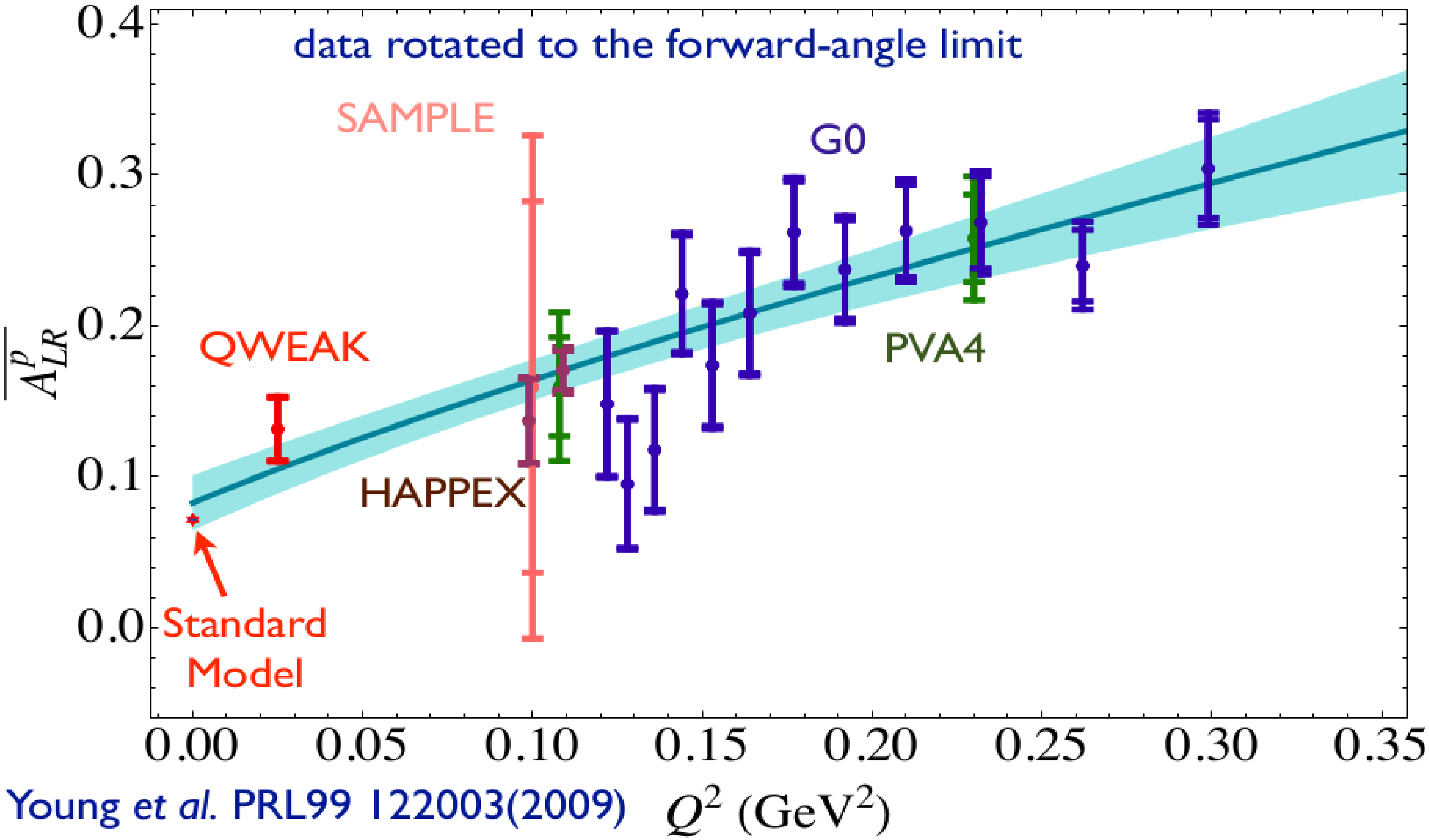


$$A_{\rm msr} = -204.6 \pm 30.5 \text{ ppb}$$

(14.9 % rel)

$$A_{\rm PV} = -281.2 \pm 35.1(\text{stat}) \pm 29.6(\text{syst}) \text{ ppb}$$

(16.3 % rel)

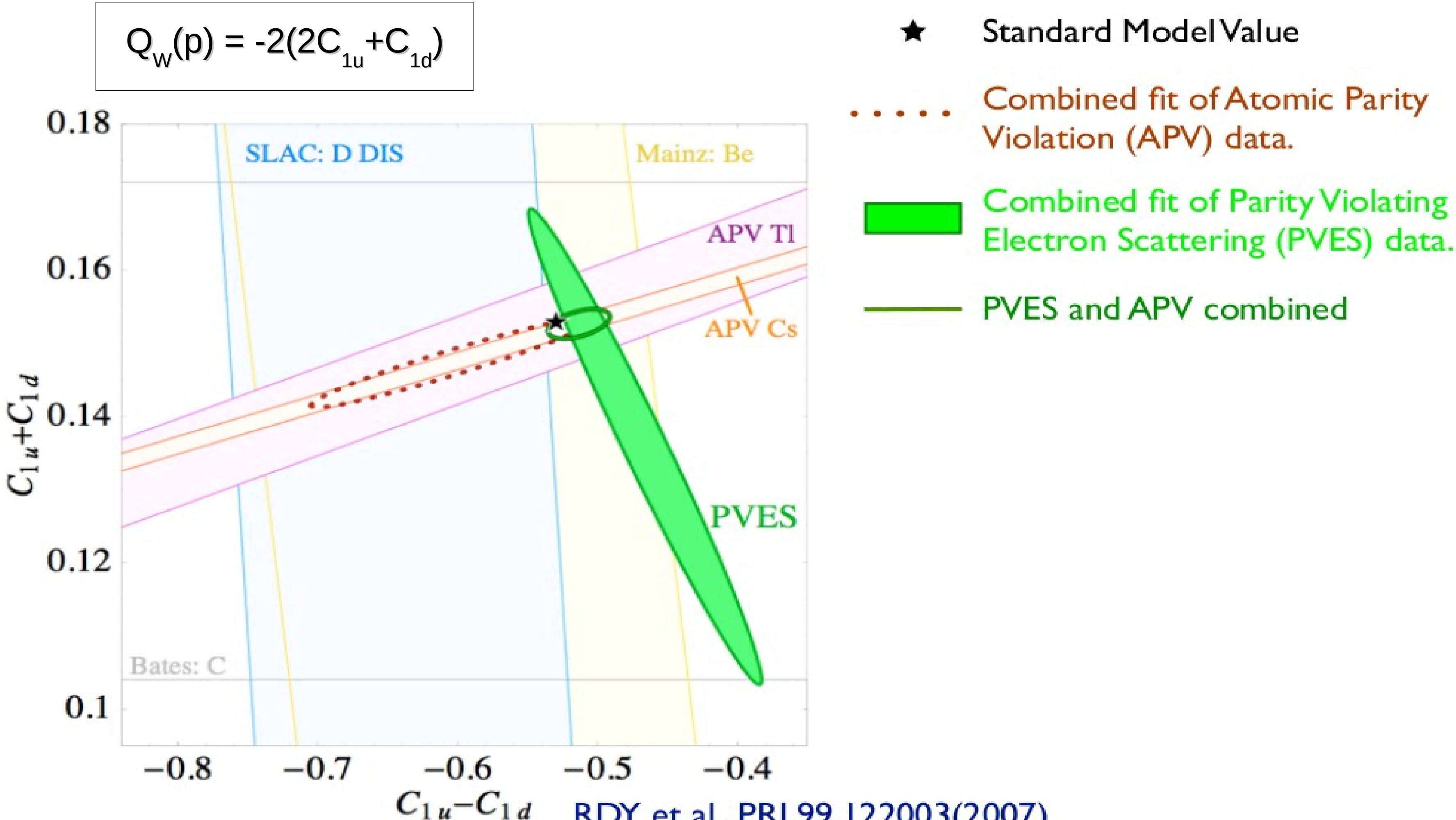


4% Qweak result: $Q_W^p = 0.0945 \pm 0.0156(\mathrm{stat}) \pm 0.0132(\mathrm{syst}) \pm 0.001(\mathrm{th})$

22% measurement, 1.1σ above SM prediction

Impact on quark weak charges

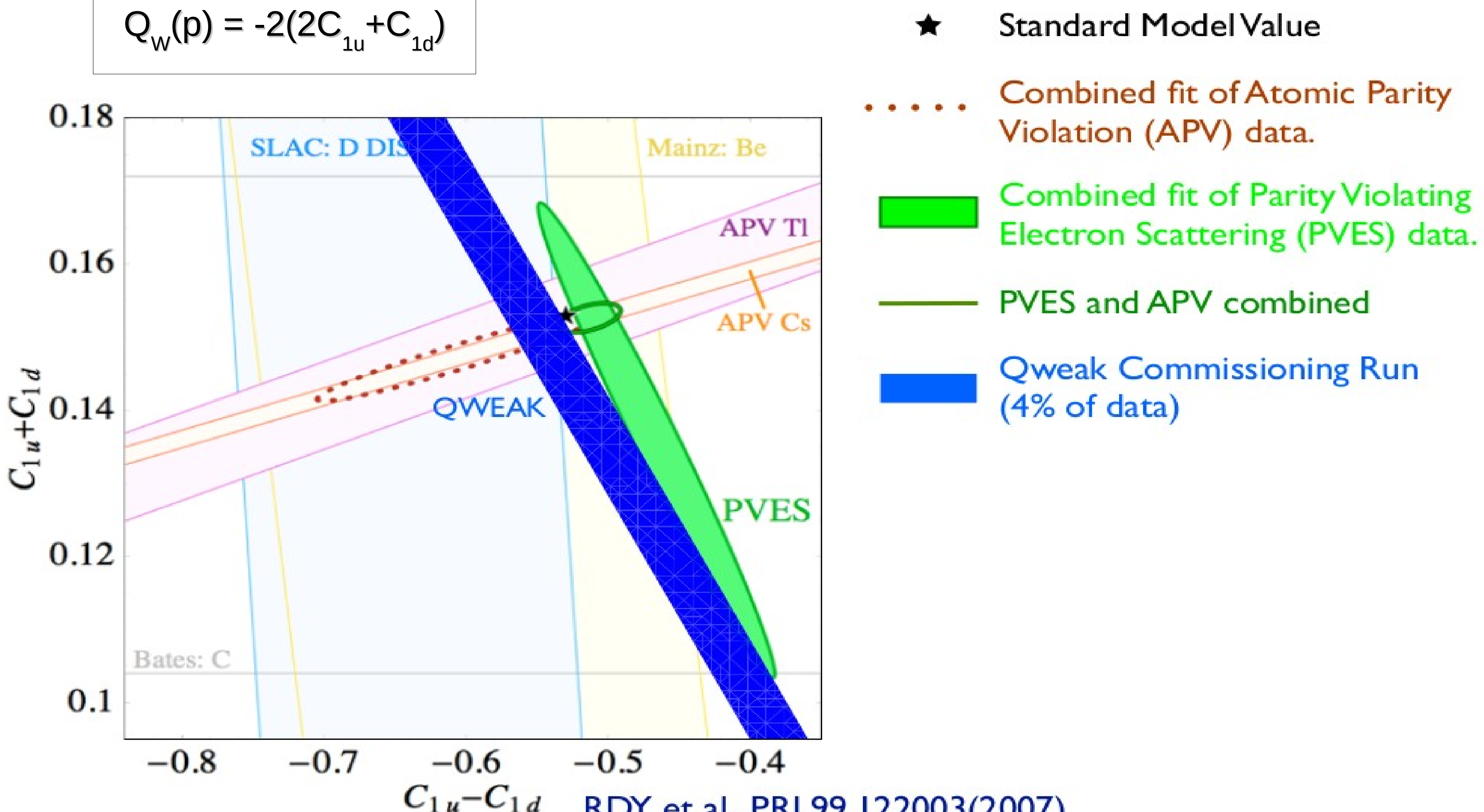
$Q_W(p) = -2(2C_{1u}+C_{1d})$



RDY et al., PRL99,122003(2007)

Impact on quark weak charges

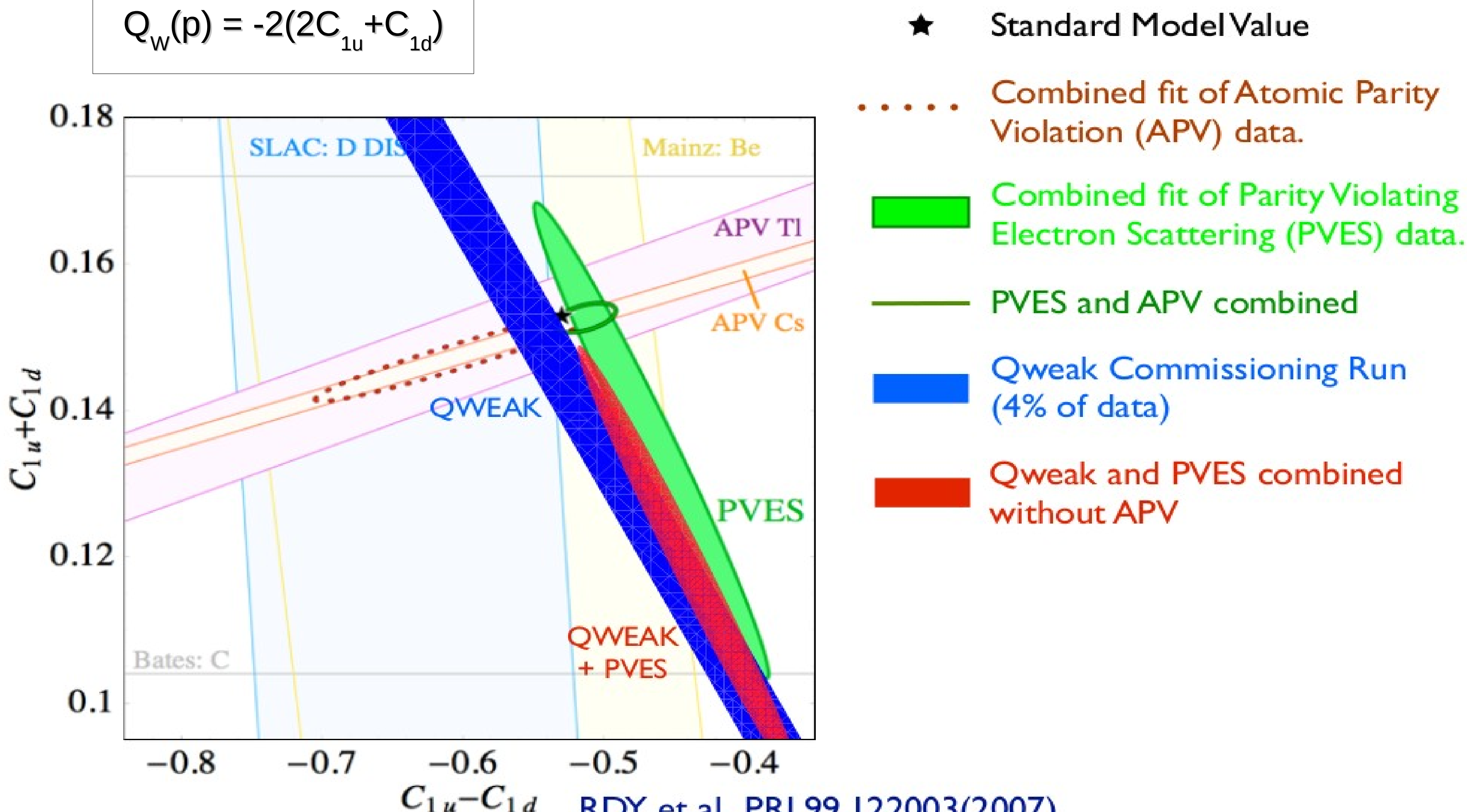
$Q_W(p) = -2(2C_{1u}+C_{1d})$



RDY et al., PRL99,122003(2007)

Impact on quark weak charges

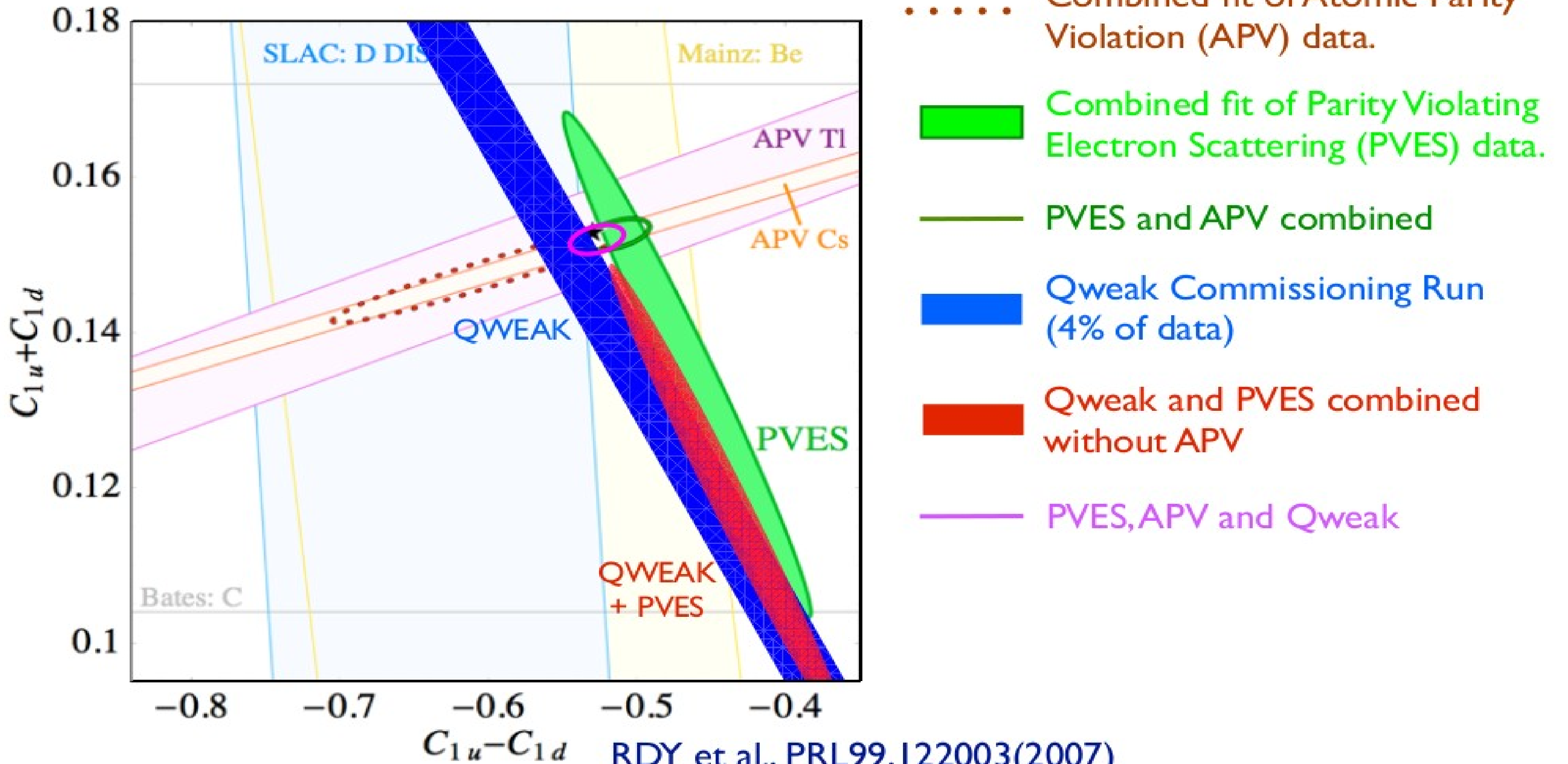
$Q_W(p) = -2(2C_{1u}+C_{1d})$



RDY et al., PRL99,122003(2007)

Impact on quark weak charges

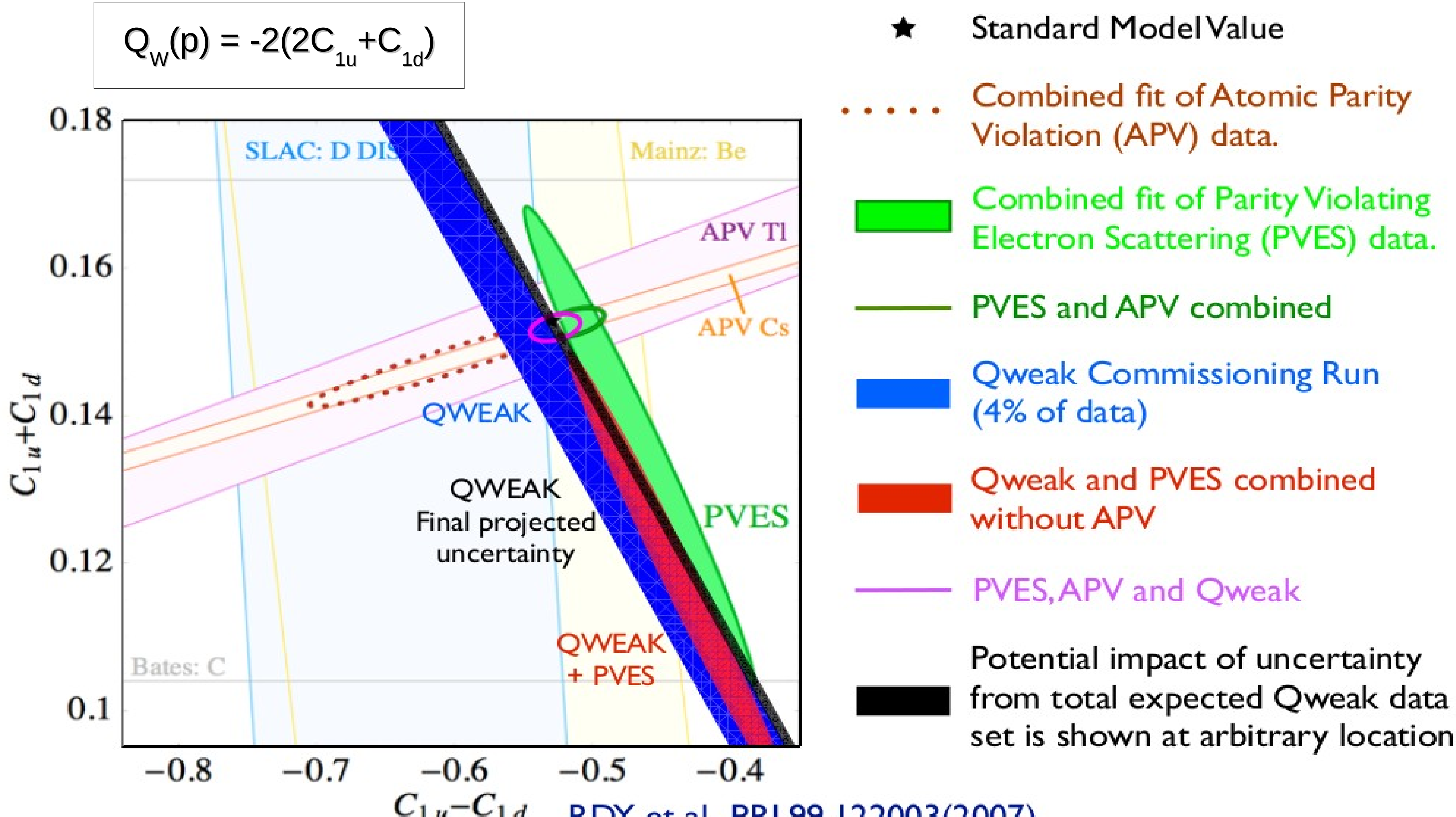
$Q_W(p) = -2(2C_{1u}+C_{1d})$



RDY et al., PRL99,122003(2007)

Impact on quark weak charges

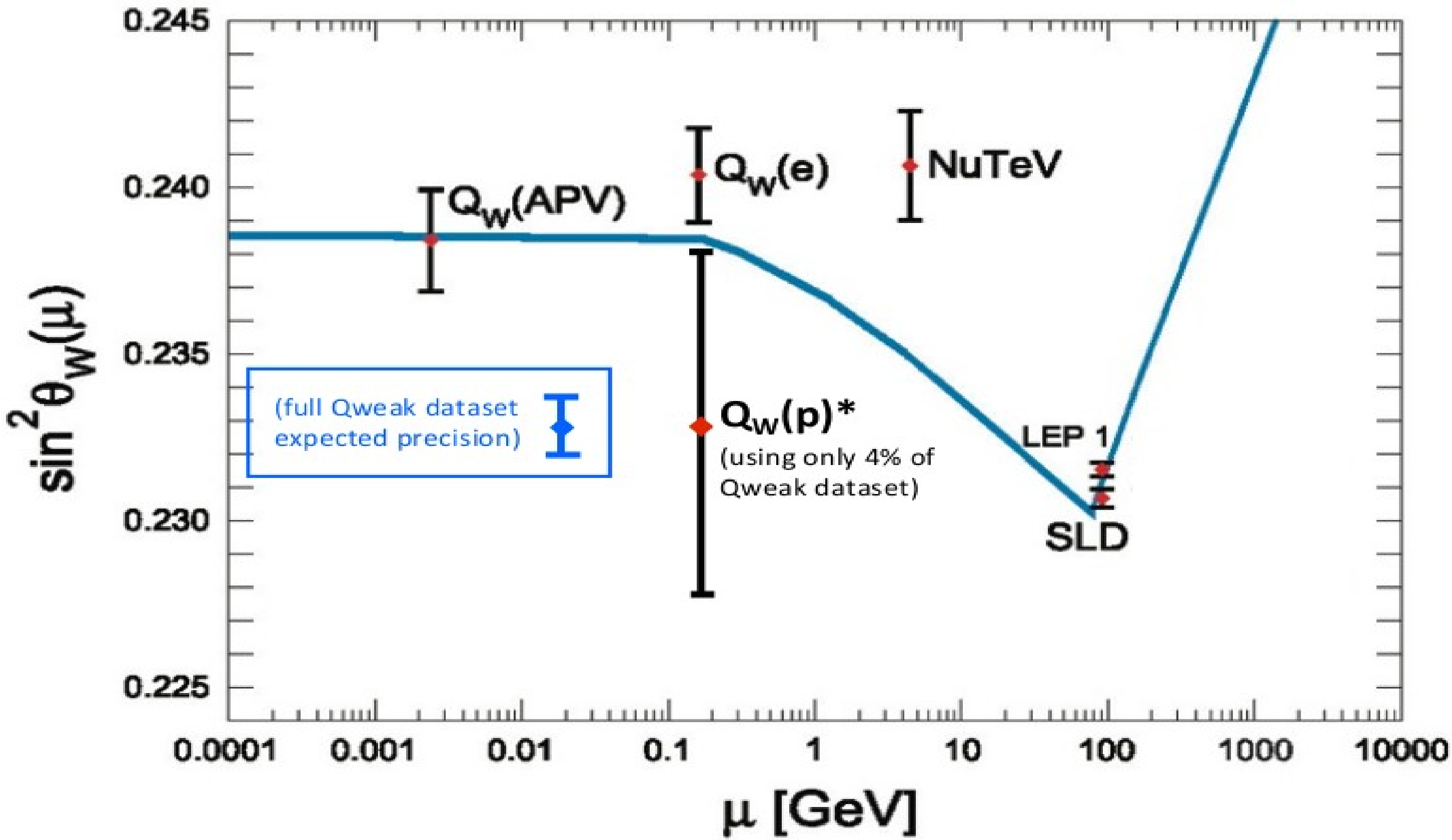
$Q_W(p) = -2(2C_{1u}+C_{1d})$



RDY et al., PRL99,122003(2007)

Weak mixing angle

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

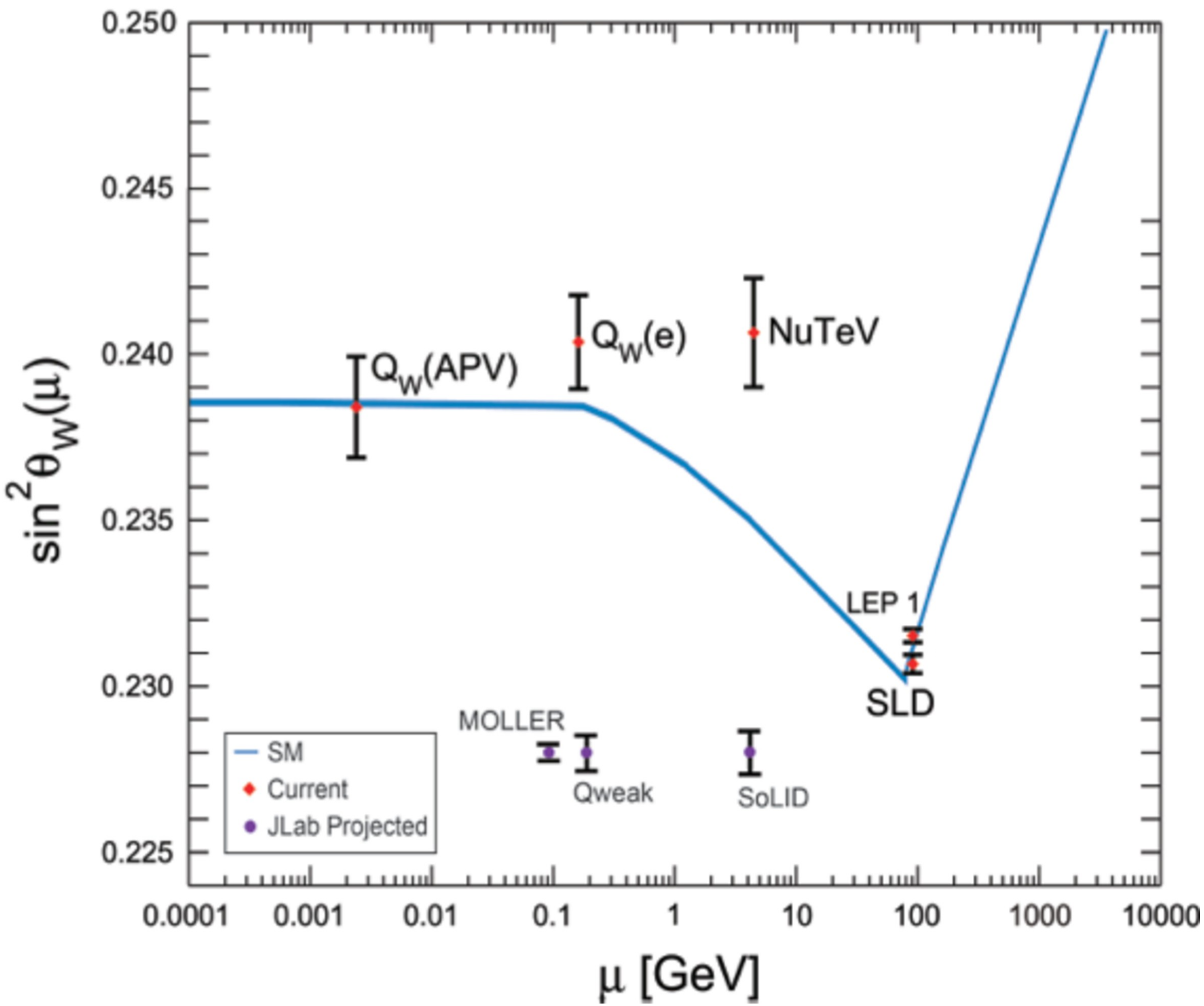


* Uses electroweak radiative corrections from Erler, Kurylov, Ramsey-Musolf, PRD **68**, 016006 (2003).

Outlook

Next generation of experiments to test the EW sector of the SM.

High precision measurements planned in the upgraded 12GeV Jefferson Lab, after Qweak demonstrated sufficient control of systematics.



Summary

Qweak has produced the first direct measurement
of the weak charge of the proton, with 4% of the data set

The result is:

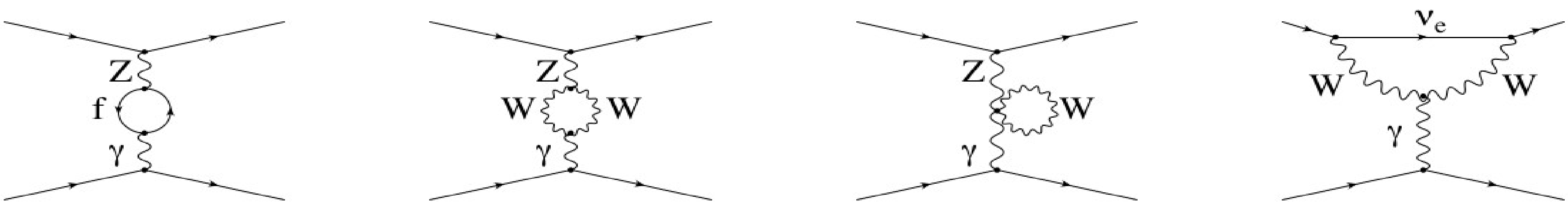
$$Q_W^p = 0.0945 \pm 0.0156(\mathrm{stat}) \pm 0.0132(\mathrm{syst}) \pm 0.001(\mathrm{th})$$

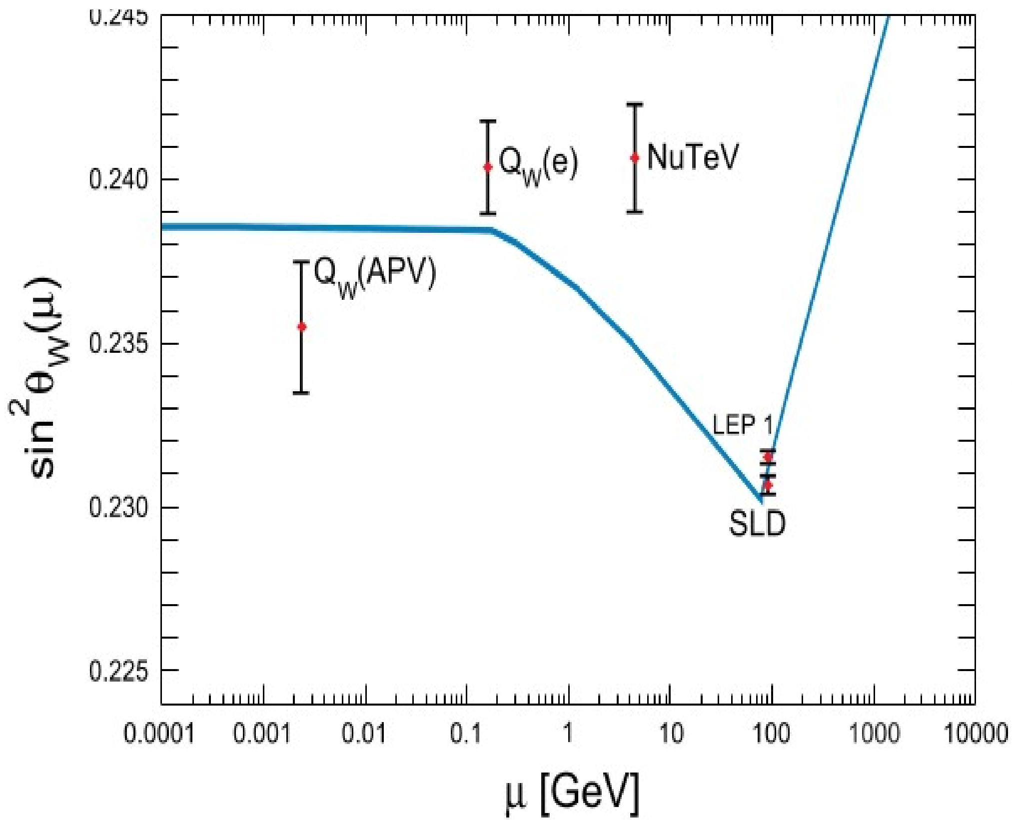
A 22% measurement, 1.1σ above the SM prediction

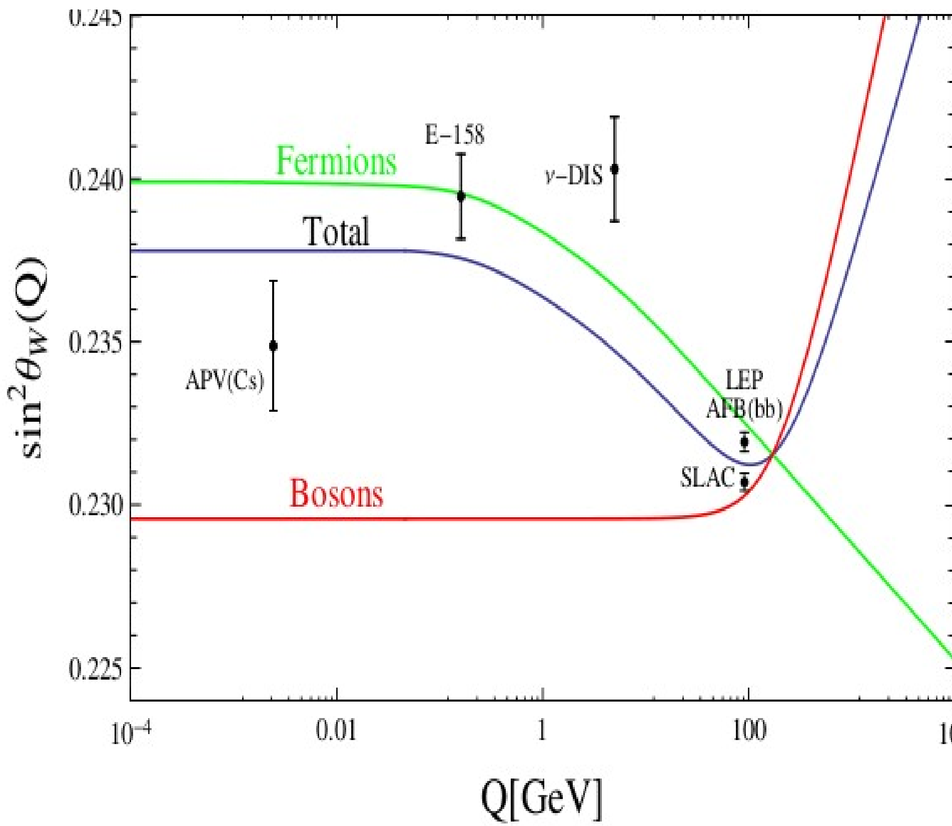
~25 times more statistics and additional calibration data are in hand
for the full Qweak measurement, which will extend reach to the TeV scale
and constrain new physics scenarios

The experiment achieved and demonstrated the technological base for future
ultra-precision tests of the SM at an upgraded 12GeV Jefferson Lab

Backup Slides



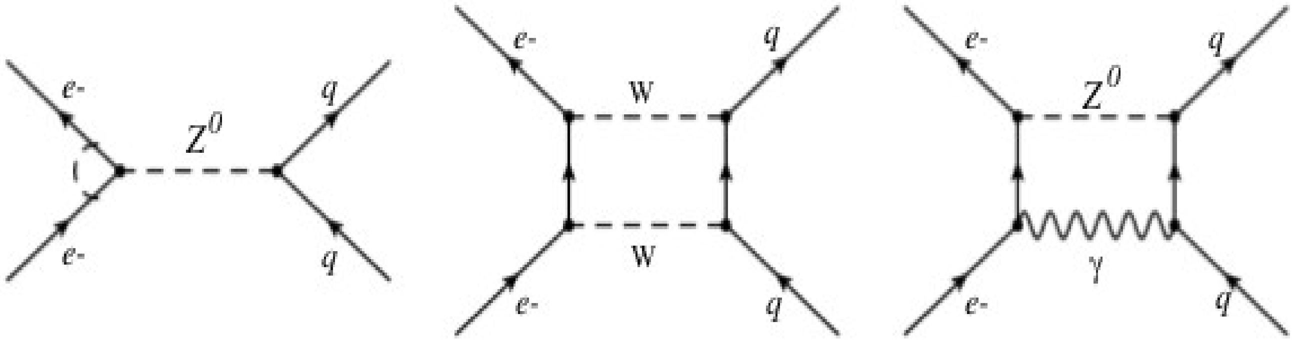


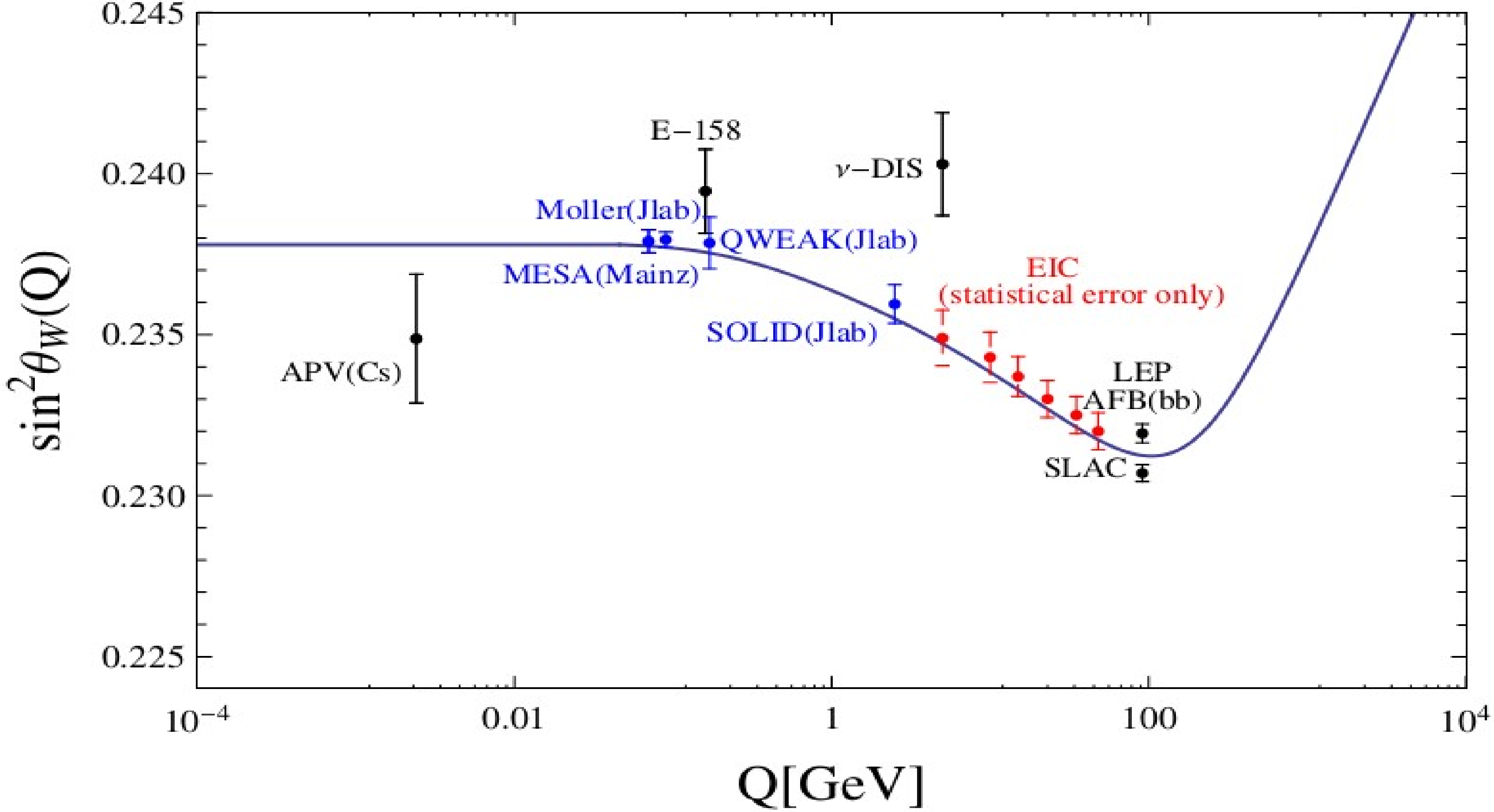


1302.6263v1 [hep-ex] (2013)

Qweak radiative corrections

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





0.245
0.240
0.235
0.230
0.225
$\sin^2\theta_W(Q)$
E−158
ν−DIS
Moller(Jlab)
QWEAK(Jlab)
MESA(Mainz)
EIC
(statistical error only)
SOLID(Jlab)
APV(Cs)
LEP
AFB(bb)
SLAC
10^{-4}
0.01
1
100
10^4
Q[GeV]