# A Measurement of the Weak Charge of the Proton through Parity Violating Electron Scattering using the Qweak Apparatus

By
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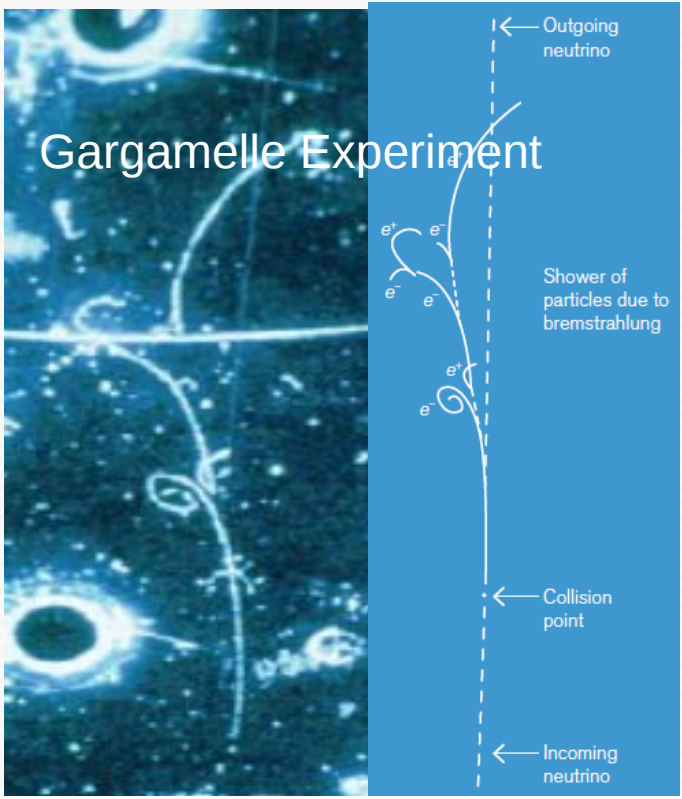
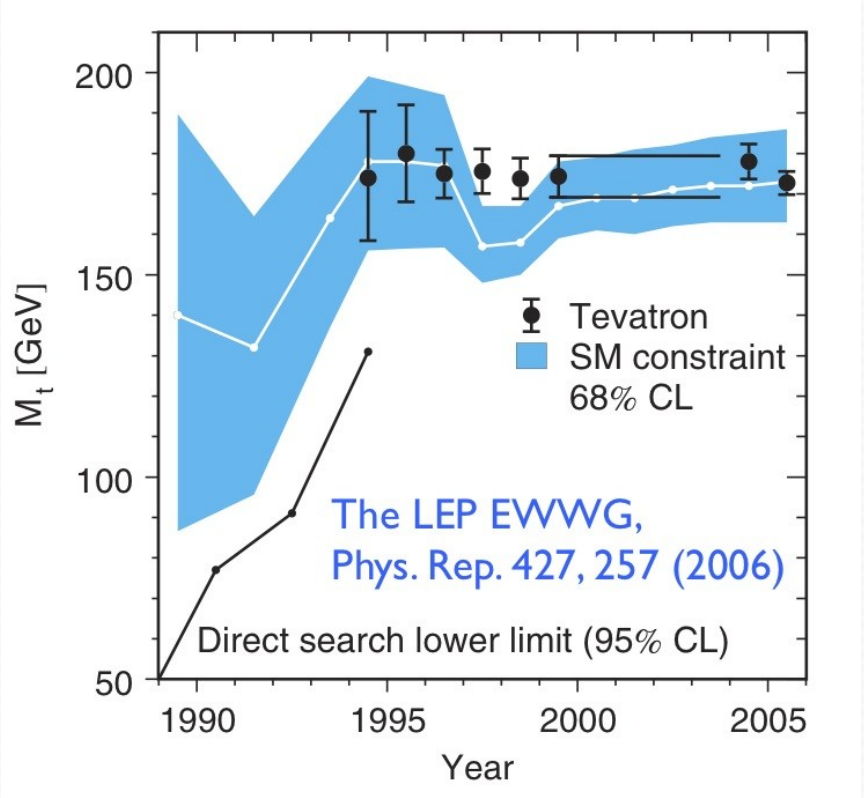
For
Qweak Collaboration

# Outline

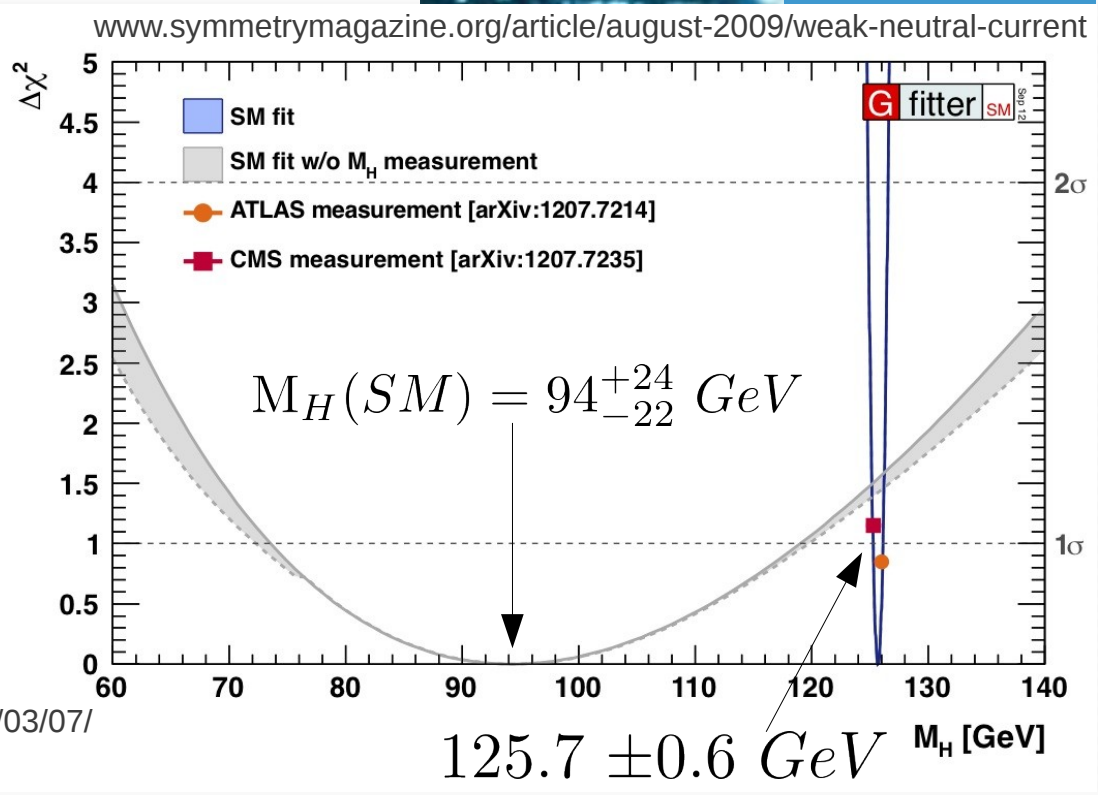
- Physics Motivation
- Qweak Apparatus
- Data Acquisition and Software
- Electron Beam Polarization
- Data Analysis
- Results and Discussion

The SM is the most successful elementary particle theory developed so far. But missing phenomena like gravity and dark matter suggest it is a “Low energy” effective theory



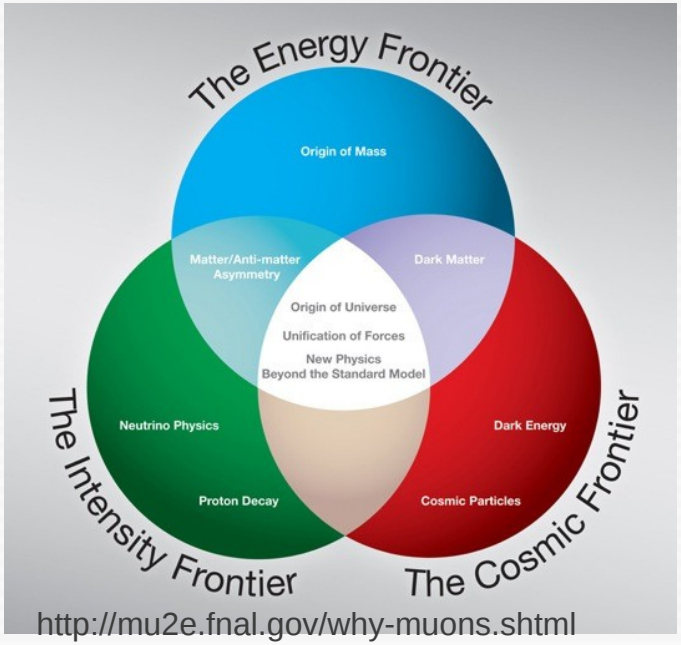




www.symmetrymagazine.org/article/august-2009/weak-neutral-current




http://www.quantumdiaries.org/2013/03/07/

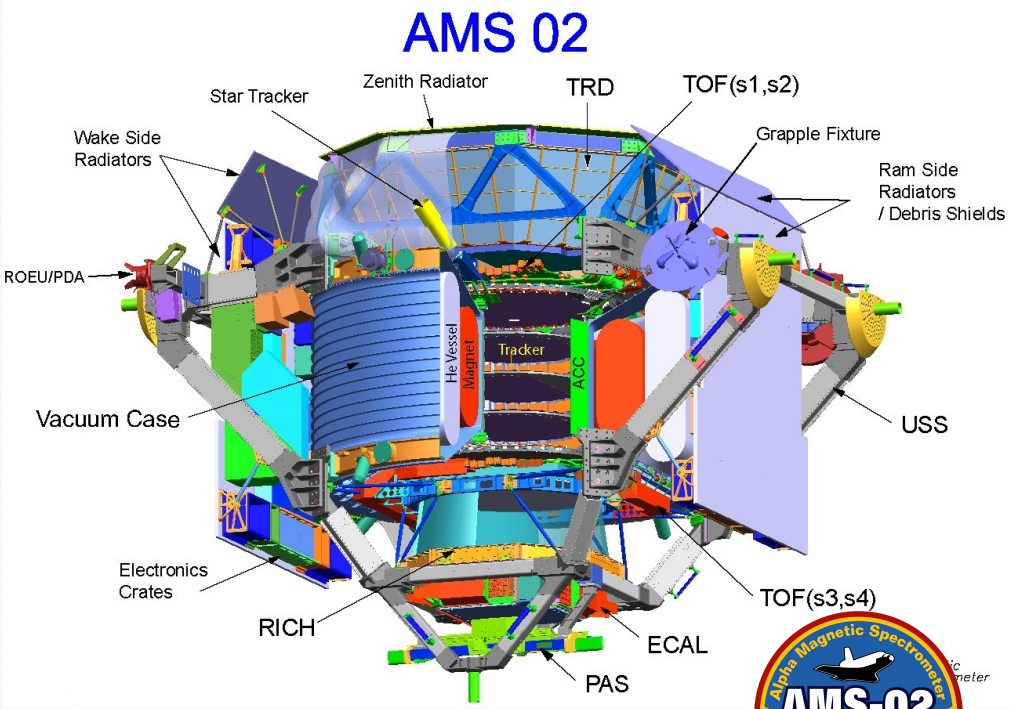
# Testing the Standard Model



http://mu2e.fnal.gov/why-muons.shtml

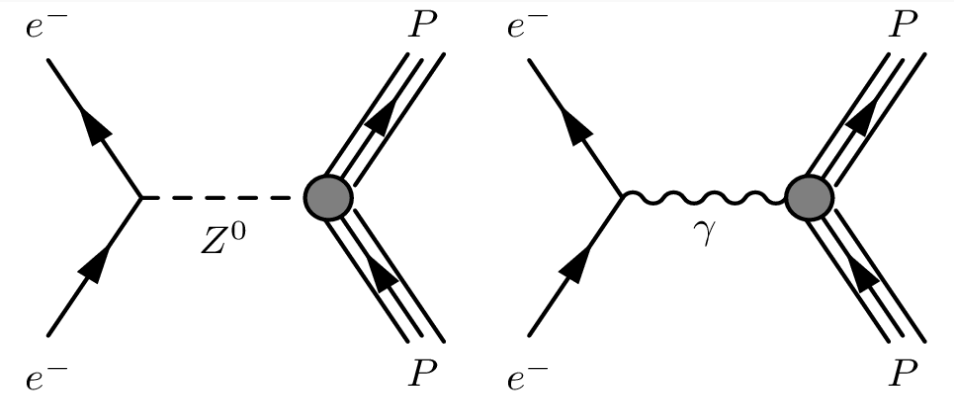
High energy frontier

Cosmological frontier




Precision (intensity) frontier

# Parity Violating Electron Scattering



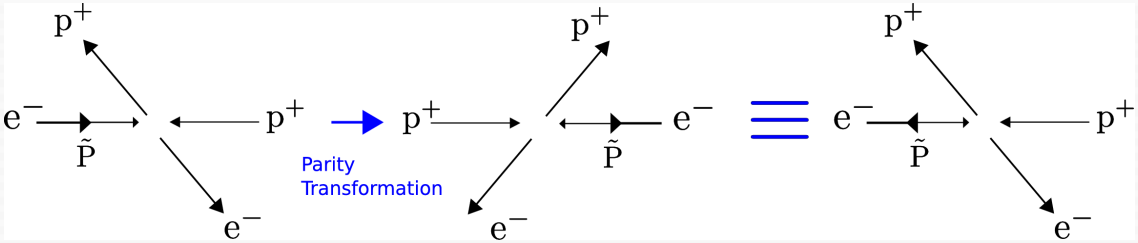

$$\mathrm{M}^{\mathrm{EM}} = \frac{4\pi\alpha}{\mathrm{Q}^2}\mathrm{Q}_\ell\, l^\mu \mathrm{J}^{\mathrm{EM}}_\mu$$

$$\mathrm{M}^{\mathrm{NC}} = \frac{-\mathrm{G_F}}{2\sqrt{2}}(\mathrm{g}^\ell_{\mathrm{V}} l^\mu + \mathrm{g}^\ell_{\mathrm{A}} l^{\mu 5})(\mathrm{J}^{\mathrm{NC}}_\mu + \mathrm{J}^{\mathrm{NC}}_{\mu 5})$$

Differential scattering cross section,

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \propto |\mathrm{M}^{\mathrm{Total}}|^2 \simeq |\mathrm{M}^{\mathrm{EM}}|^2$$

Due to PV nature of the neutral current, the total cross section is dependent on the helicity of the electron.




Right-helicity (R) Left-helicity (L)

The difference in helicity correlated scattering cross section is known as the PV asymmetry,

$$\mathrm{A_{LR}} = \frac{\frac{\mathrm{d}\sigma^{\mathrm{R}}}{\mathrm{d}\Omega} - \frac{\mathrm{d}\sigma^{\mathrm{L}}}{\mathrm{d}\Omega}}{\frac{\mathrm{d}\sigma^{\mathrm{R}}}{\mathrm{d}\Omega} + \frac{\mathrm{d}\sigma^{\mathrm{L}}}{\mathrm{d}\Omega}} \propto \frac{\mathrm{M}^{\mathrm{EM}} \cdot \mathrm{M}^{\mathrm{NC}}}{|\mathrm{M}^{\mathrm{EM}}|^2}$$

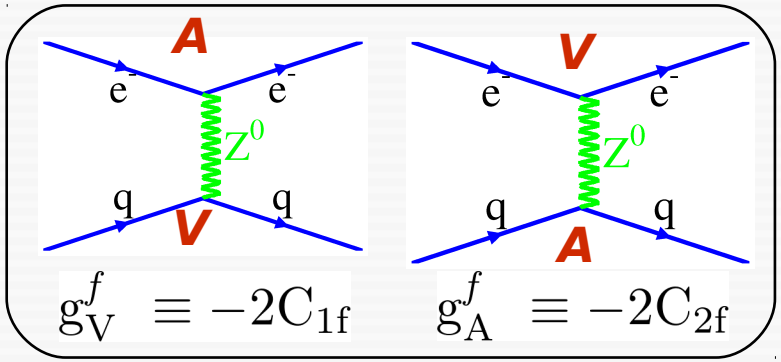
# Parity Violating Electron Scattering

Main contribution to the PV asymmetry is from weak charge of proton rest is related to hadronic structure of the proton and energy dependent electroweak corrections

$$A_{LR}(\vec{e}p) = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}[Q_W^P + F(Q^2,\theta)] = A_{Q_W^P} + A_{Had}$$

At $Q^2$ of 0.025 $GeV^2$ $F(Q^2,\theta)$ is about 25%

At tree level: $Q_W^p = 2g_V^u + g_V^d = 1 - 4\cdot\sin^2\theta_W$




$g_V^f \equiv -2C_{1f}$ $g_A^f \equiv -2C_{2f}$

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

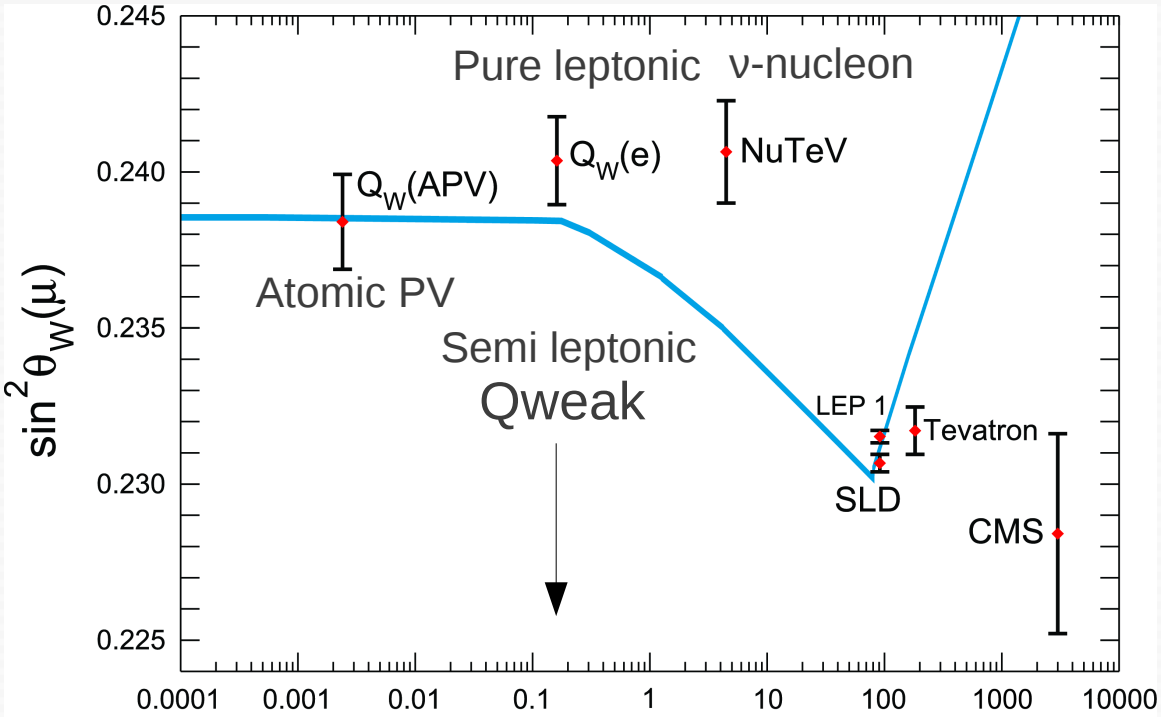
# Physics Motivation

**1. Extract the weak charge of the proton ($Q_W^P$) by measuring the PV asymmetry.**

At tree-level weak charges are given by,

| | EM Charge | Weak Charge $(g_V^l = -2C_{1f})$ |
|---|---|---|
| electron | -1 | $-1 + 4\sin^2\theta_W \approx -0.07$ |
| u quark | +2/3 | $1 - (8/3)\sin^2\theta_W \approx 1/3$ |
| d quark | -1/3 | $-1 + (4/3)\sin^2\theta_W \approx -2/3$ |
| Proton (2u+d) | +1 | $1 - 4\sin^2\theta_W \approx 0.07$ |
| Neutron (u+2d) | 0 | -1 |

$Q_W^P$ (and $Q_W^e$) are both suppressed in the SM, making percent level measurements sensitive to TeV-scale New PV Physics



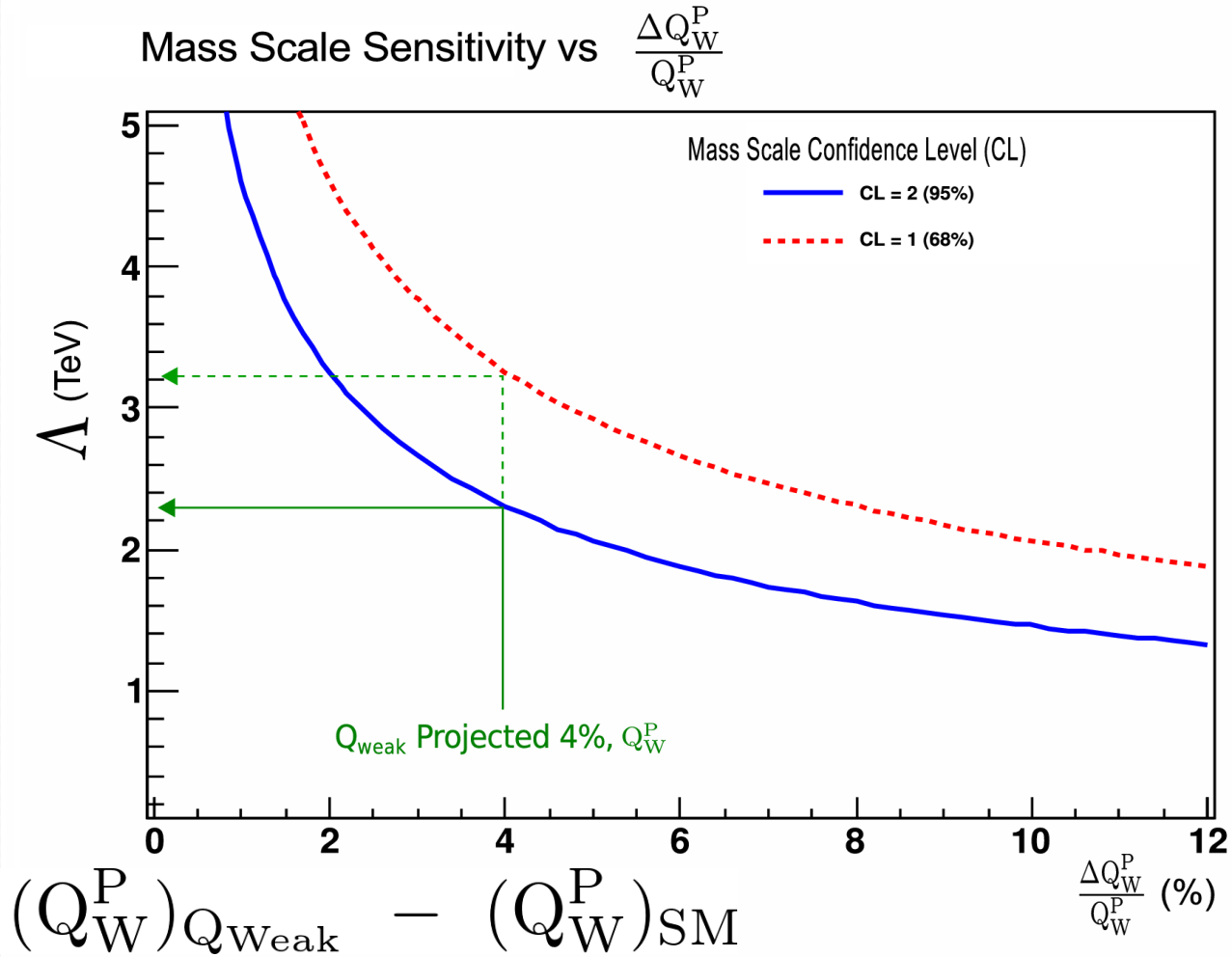

J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)

**2. From $Q_W^P$, the weak mixing angle ($\sin^2\theta_W$) is extracted.**

In SM weak mixing angle at low energies is predicted from the "running of weak mixing angle" using the Z-pole measurement

# New PV Physics:Model Independent Constraints

$$L_{eff}^{PV} = \underbrace{-\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \cdot \sum_q C_{1q}\bar{q}\gamma^\mu q}_{L_{SM}^{PV}} + \underbrace{\frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q}_{L_{new}^{PV}}$$

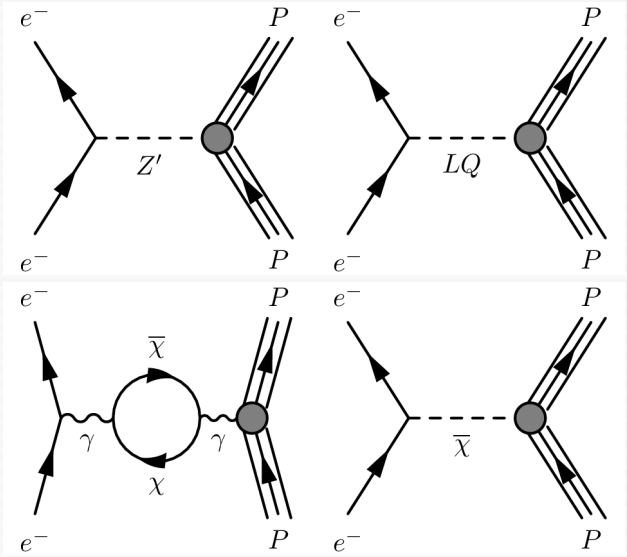


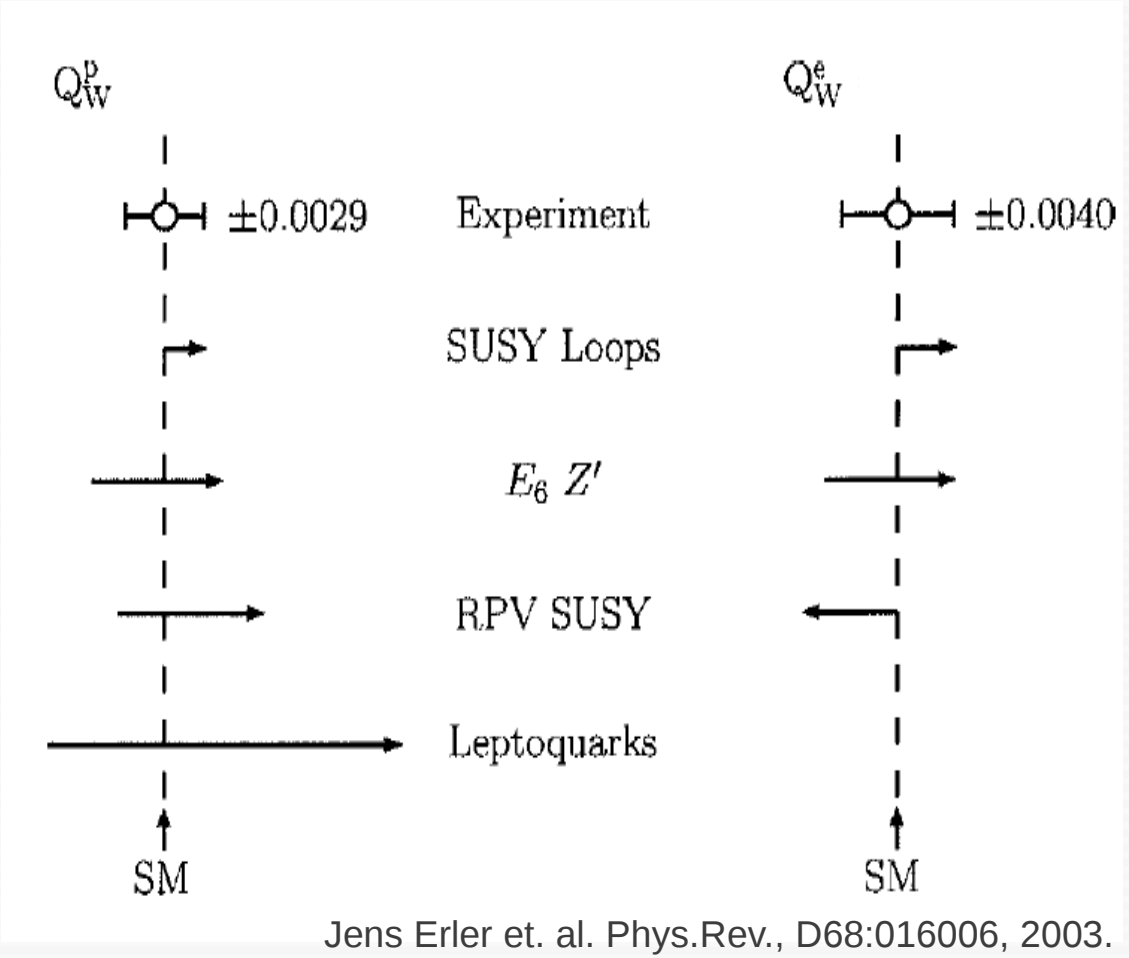

**g** is the new physics coupling while **Λ** is the new PV physics mass scale

$$\delta Q_W^P = (Q_W^P)_{Q_{Weak}} - (Q_W^P)_{SM}$$

# New PV Physics Beyond SM

- New neutral gauge bosons (Z')
- SUSY: MSSM
  - SUSY loop effects
  - R-Parity status
- Leptoquarks




Jens Erler et. al. Phys.Rev., D68:016006, 2003.

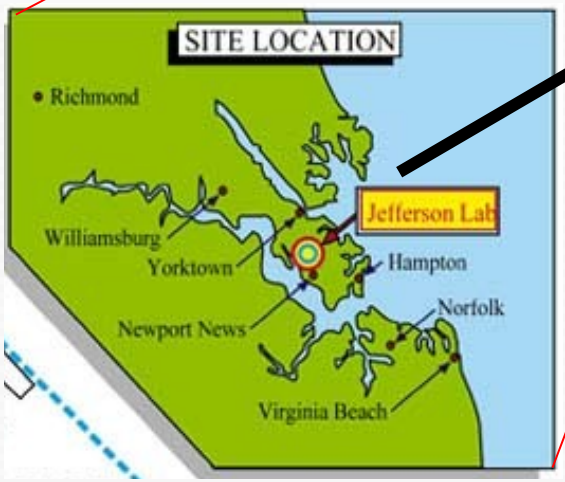
Weak charge of the proton and electron are complementary measurements for new physics. Effect of new physics at 95 % C.L.

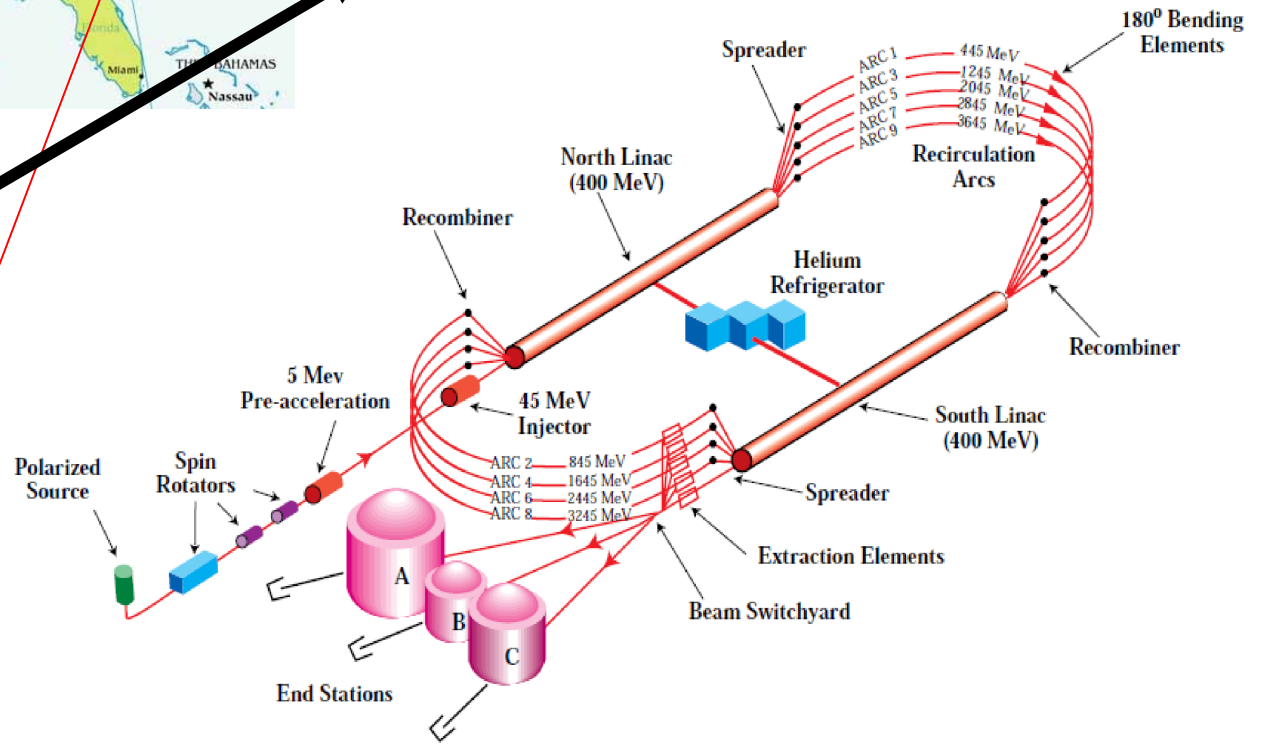
# Qweak Goals

- The Qweak experiment will provide a 4% direct measurement of the weak charge of the proton ($Q_W^P$) and a 0.3% measurement of the weak mixing angle ($\sin^2\theta_W$)
    - A test of Standard Model and new PV Physics beyond SM at TeV scale
- This talk is based on limited statistics data set: Run0
    - A proof of concept analysis which tested the analysis procedures and tools to be used for the final full data analysis
    - A 19% measurement of $Q_W^P$

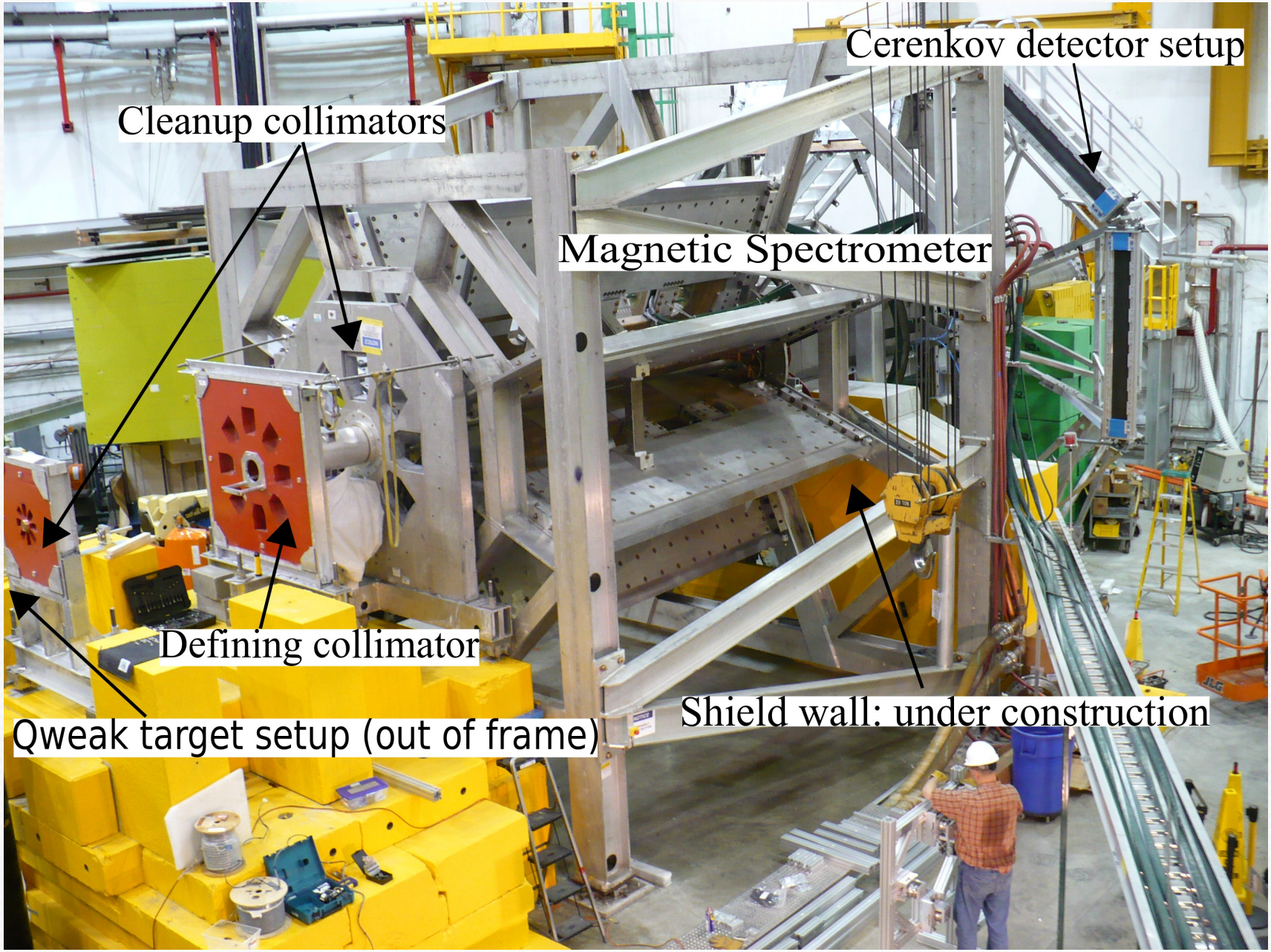
# Qweak Experiment

# CEBAF @ Jefferson Lab



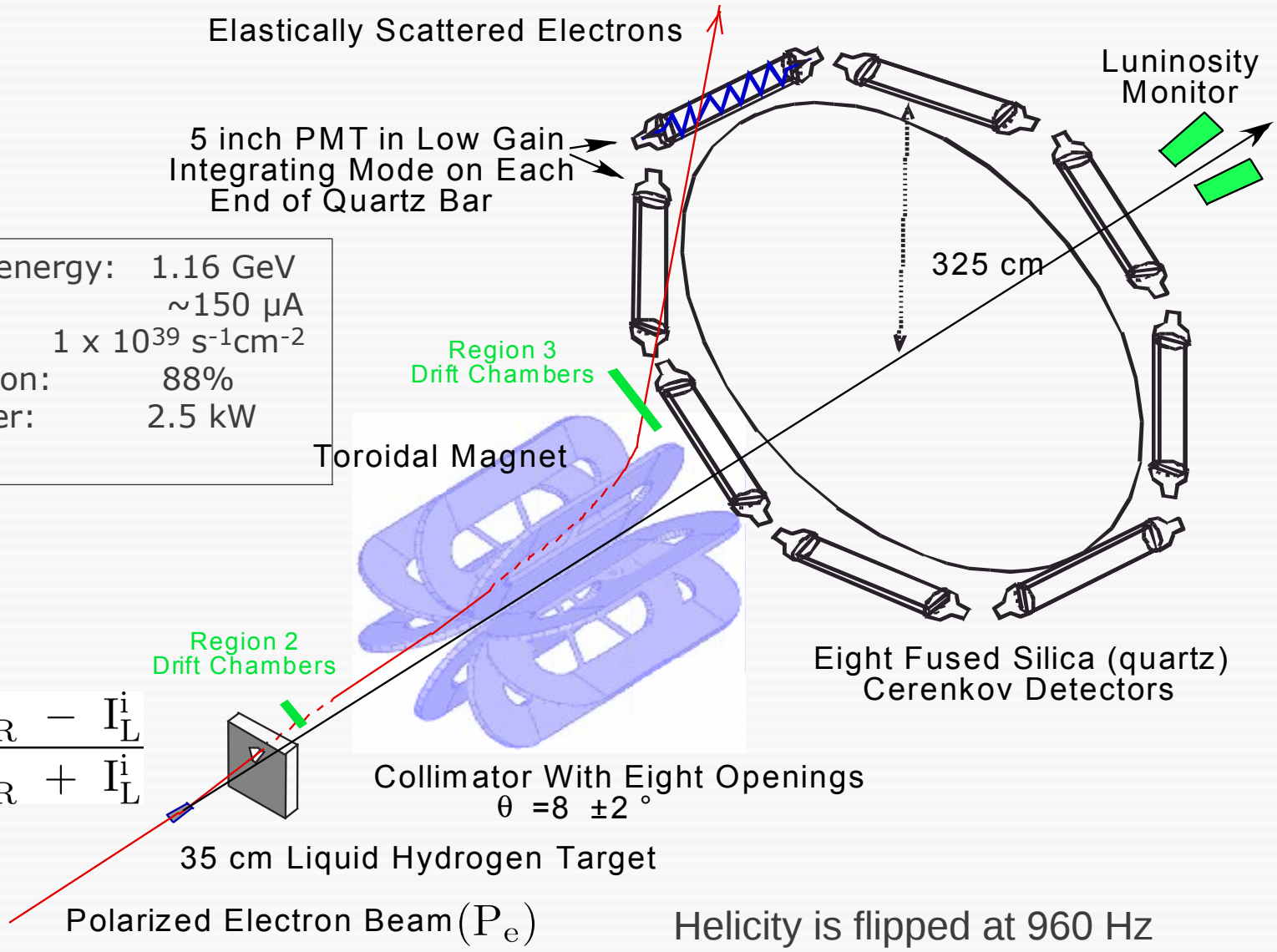



# The Experiment:Apparatus



# The Experiment:Apparatus

$$A_{pmt}^{raw} = \frac{N_R - N_L}{N_R + N_L}, \text{and } A^{raw} = \frac{\sum_{j=1}^{16} A_{pmt,j}^{raw}}{16}$$




| | |
|---|---|
| Incident beam energy: | 1.16 GeV |
| Beam Current: | ~150 μA |
| Luminosity: | 1 x $10^{39}$ $s^{-1}cm^{-2}$ |
| Beam Polarization: | 88% |
| $LH_2$ target power: | 2.5 kW |

$$A_{HCBA}^{i} = \frac{I_R^i - I_L^i}{I_R^i + I_L^i}$$

Helicity is flipped at 960 Hz

# The Experiment:Methodology

- Calculate the experimental asymmetry by measuring the yield from longitudinally polarized electrons scattering from unpolarized protons

$$A^{raw}_{pmt} = \frac{N_R - N_L}{N_R + N_L}, \text{and } A^{raw} = \frac{\sum_{j=1}^{16} A^{raw}_{pmt,j}}{16}$$

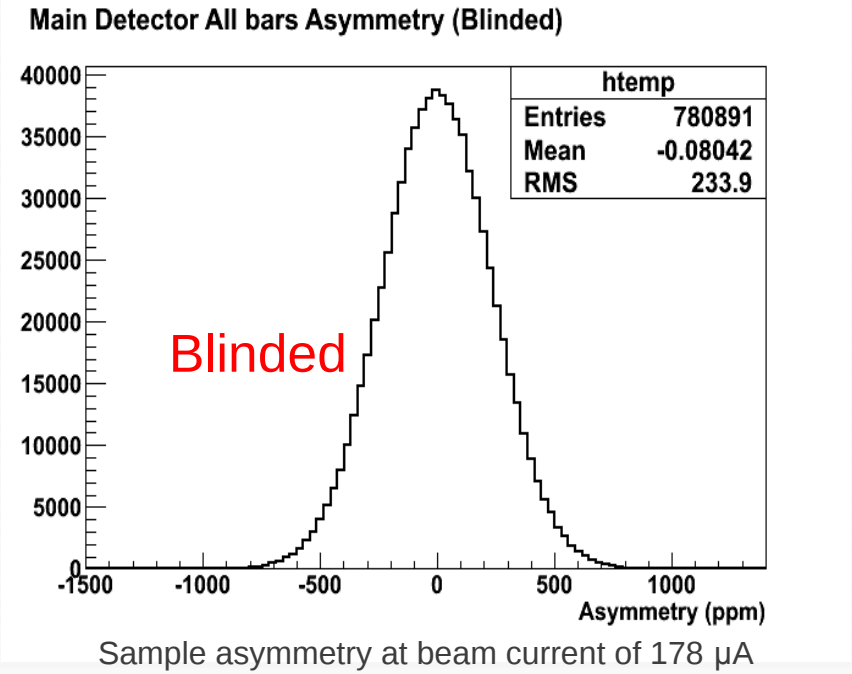
- Extract ep PV asymmetry by ,
  - Removing false asymmetries $(A^i_{False})$
  - Correcting for the beam polarization $(P_e)$
  - Removing background contaminations $(f_{bi},\ A_{bi})$

$$\frac{A^{raw} - \sum_i A^i_{False}}{P_e} = (1 - f_{Total}) \cdot A_{\vec{e}p} + \sum_{i=1}^{4} f_{bi} \cdot A_{bi}$$

# Qweak Performance

$$A^{raw} = \frac{N_R - N_L}{N_R + N_L}$$

$$\delta A = \frac{\sigma_A}{\sqrt{N_{Total}}}$$




Sample asymmetry at beam current of 178 μA

$\sigma_A$ = 230-260 ppm

$A_{Phys}$ = -0.200 ppm

**$\delta A_{Phys}$ = 0.006 ppm**

| Contribution | Expected width (ppm) |
|---|---|
| **Pure statistics** | **201** |
| Detector resolution | 92 |
| Current monitor resolution | 50 |
| Target boiling | 57 |
| **Total** | **233.7** |

# Outline

- Physics Motivation ✓
- Qweak Apparatus ✓
- **Data Acquisition and Software**
- **Electron Beam Polarization**
- Data Analysis
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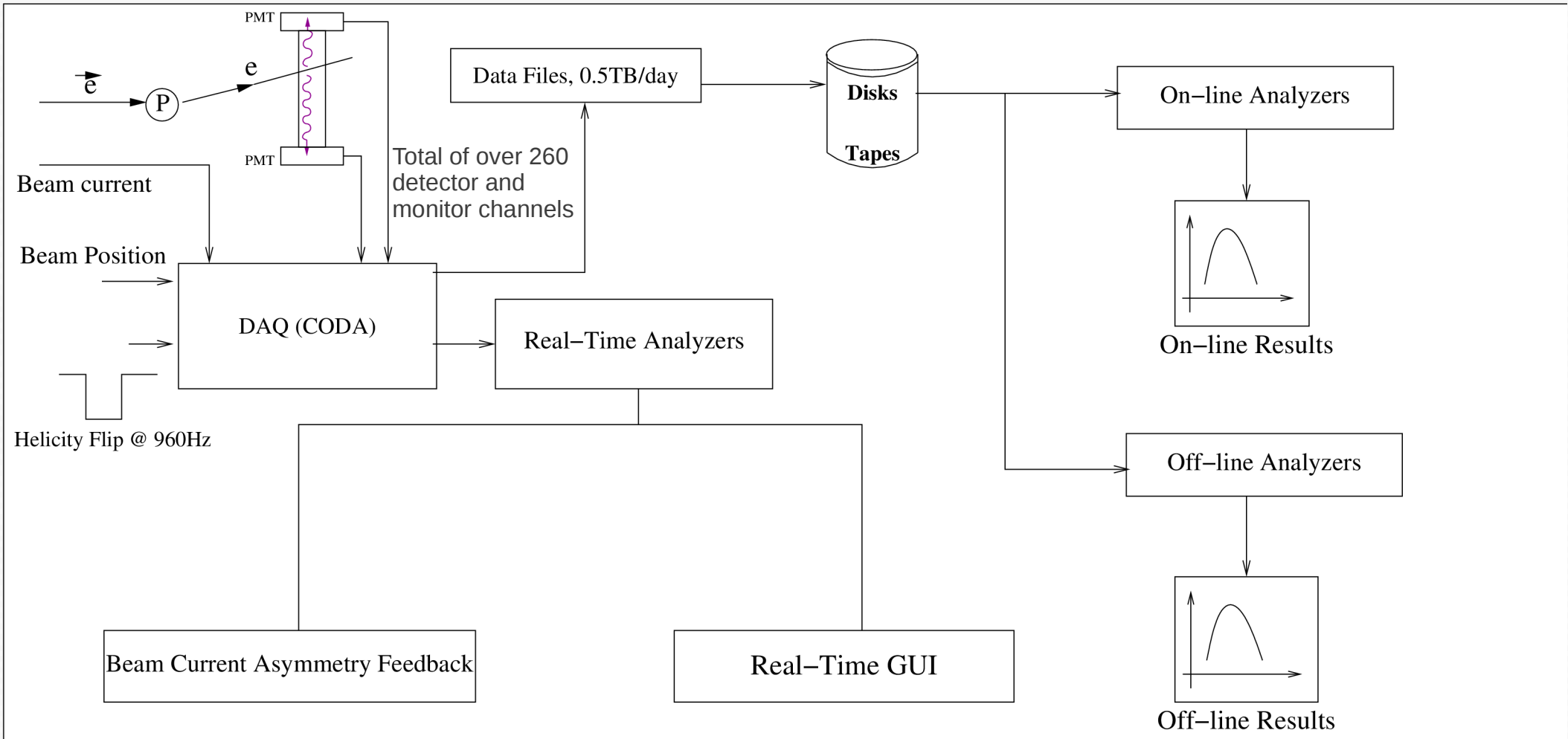
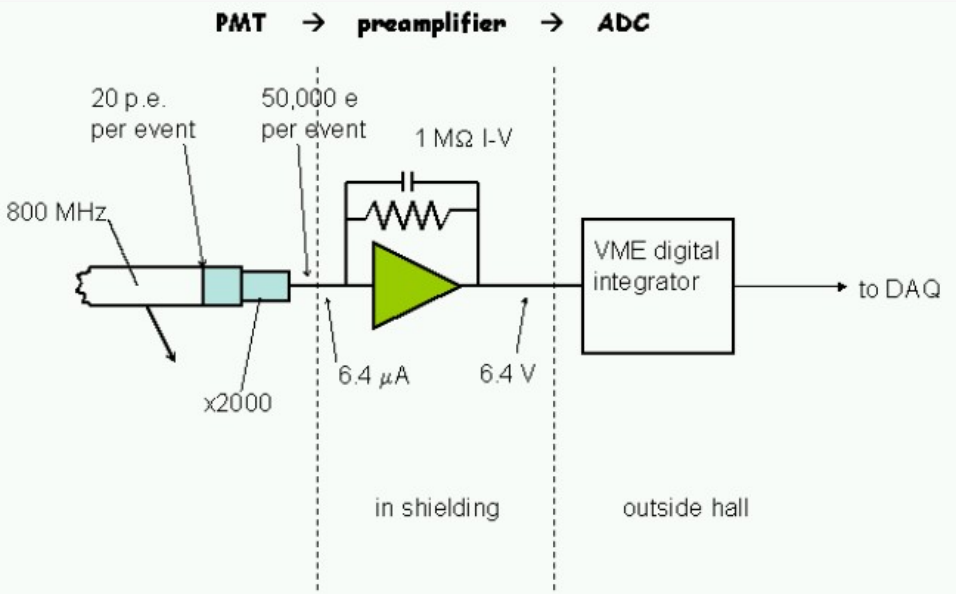
# Qweak Data Acquisition and Software System

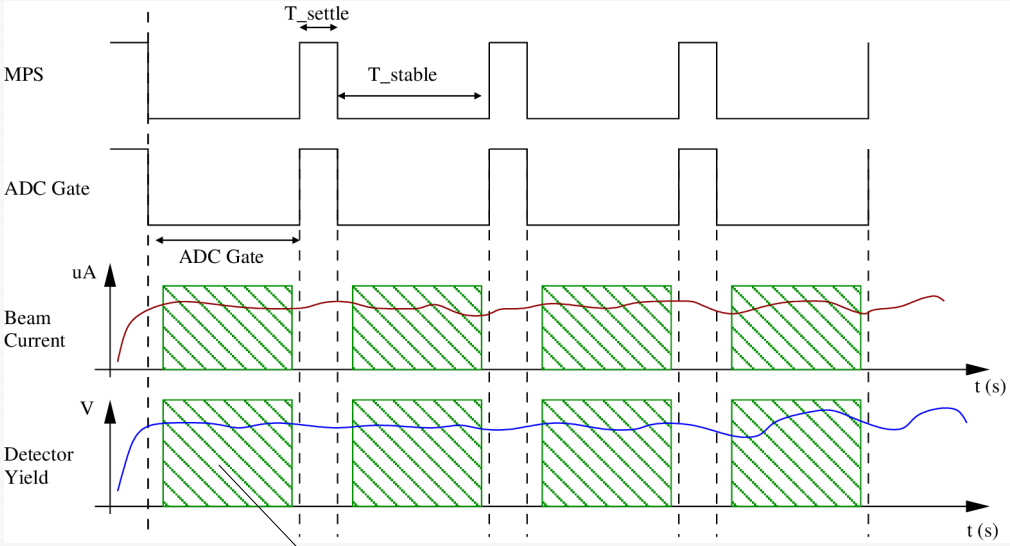



We also used an independent DAQ for low beam current auxiliary studies (backgrounds, kinematics and etc.)

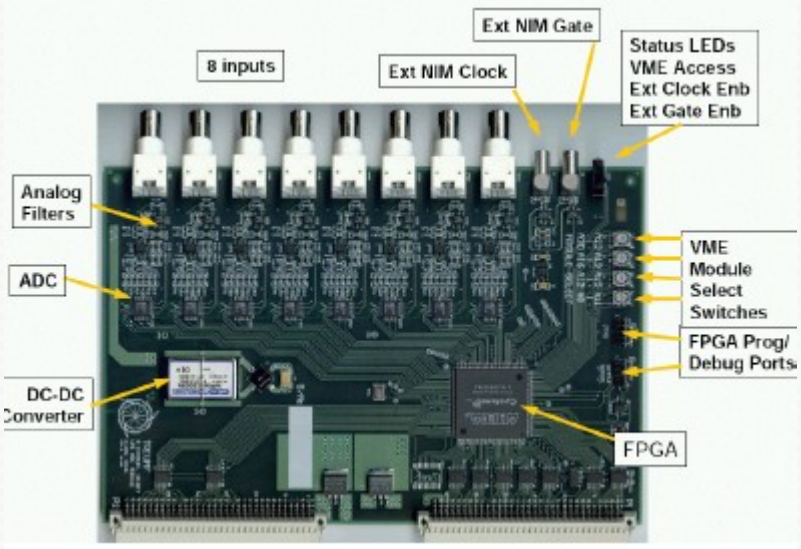
# Read-out Electronics

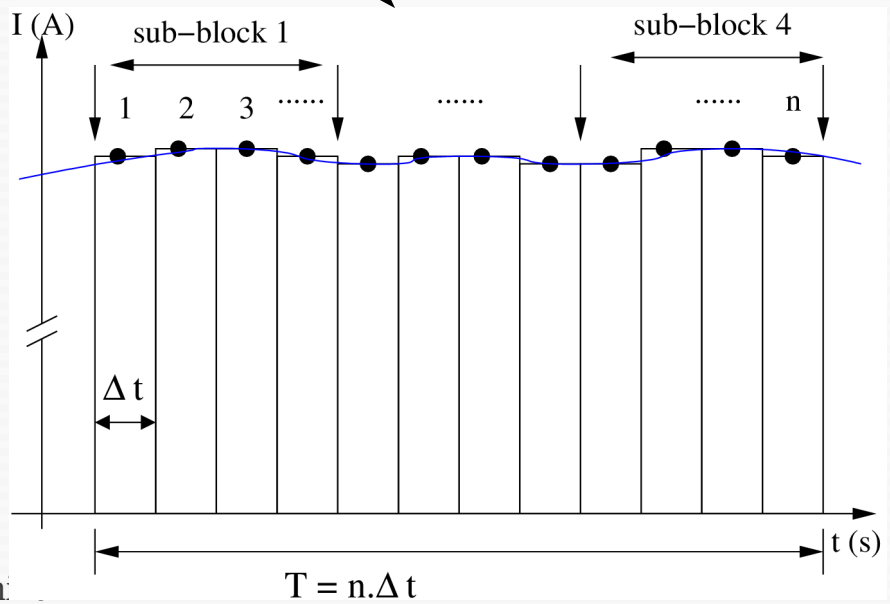
The scattered electron yield is integrated during each polarization (Helicity) state.The helicity is flipped pseudo-randomly at 960Hz




A 27 bit word is generated



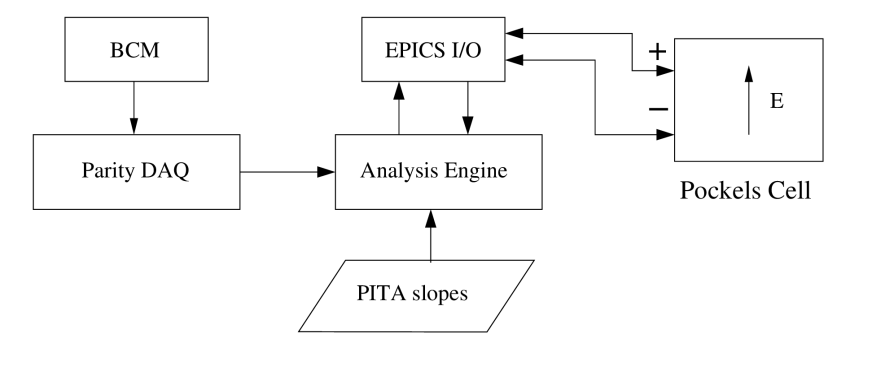



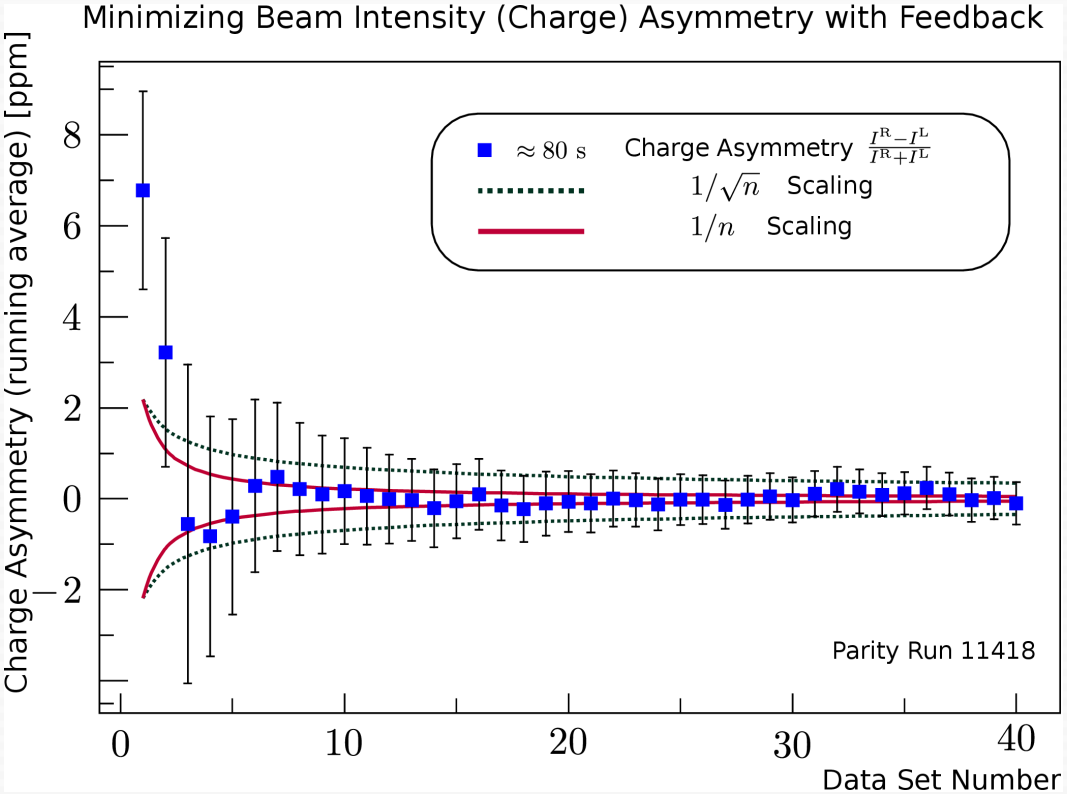
# Non-Linearity and Charge Asymmetry

- Required to minimize the false asymmetry from non-linearity
- Minimized the charge asymmetry by using an active feedback system

$$A_{Raw} = A_{Phys} + A_{False}$$

$$+ \text{Non-lin} \cdot A_{Charge} + \cdots$$

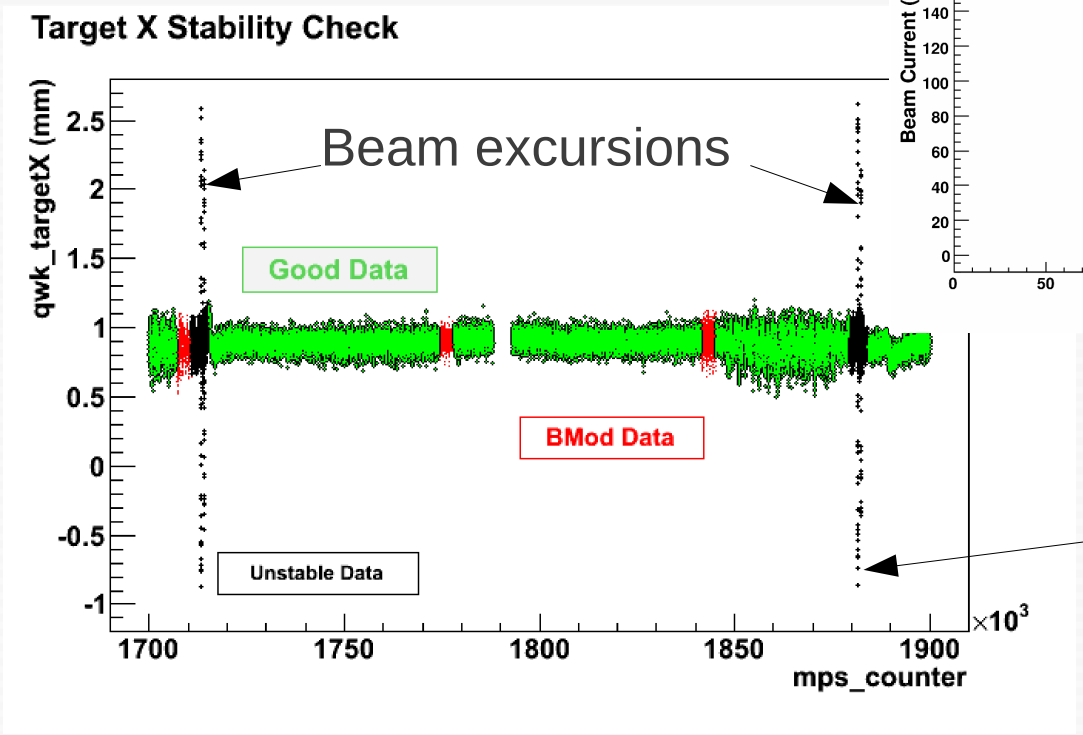


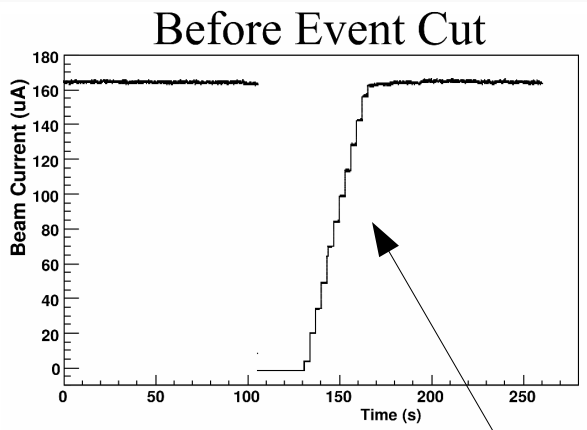



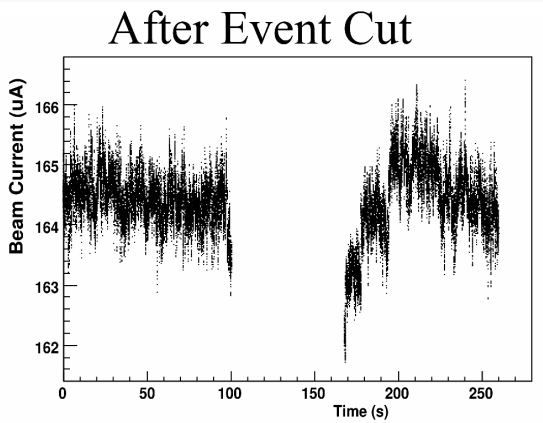
# Data Quality Checks

The data quality cuts framework is Integrated to the data analysis system which provides,

- Customizable quality checks for many different detector signals
- Diagnostic information on detectors during data taking and final data analysis



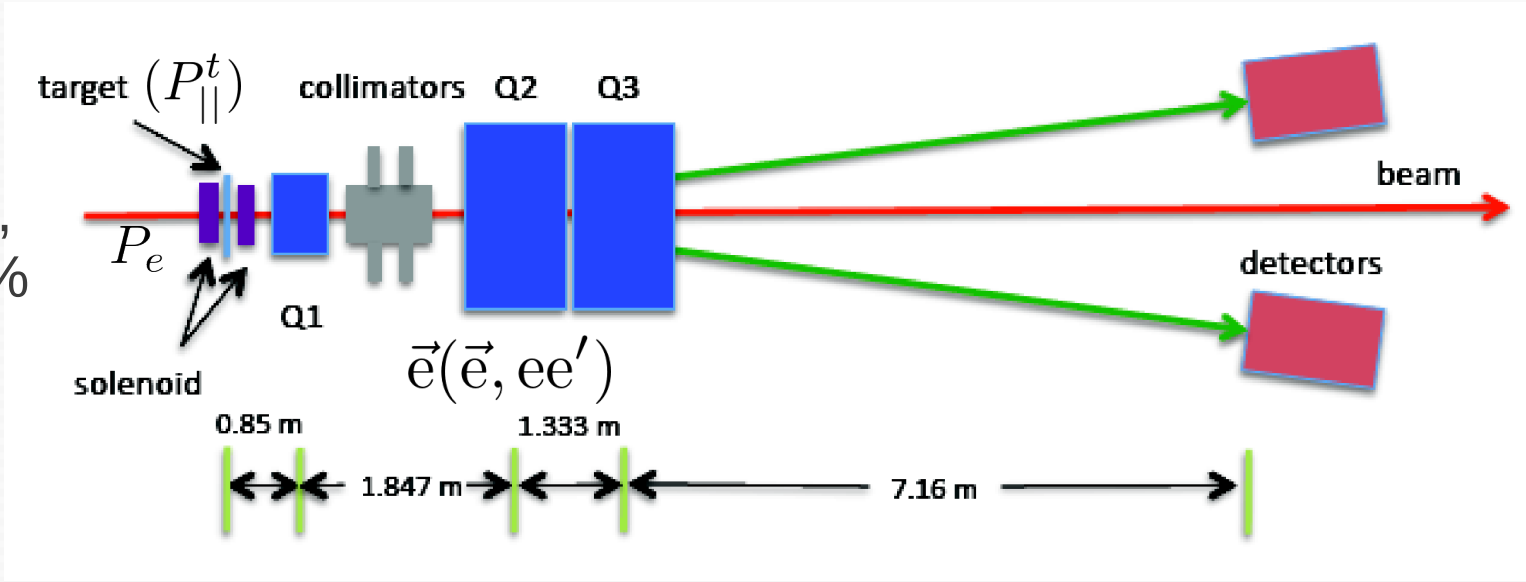



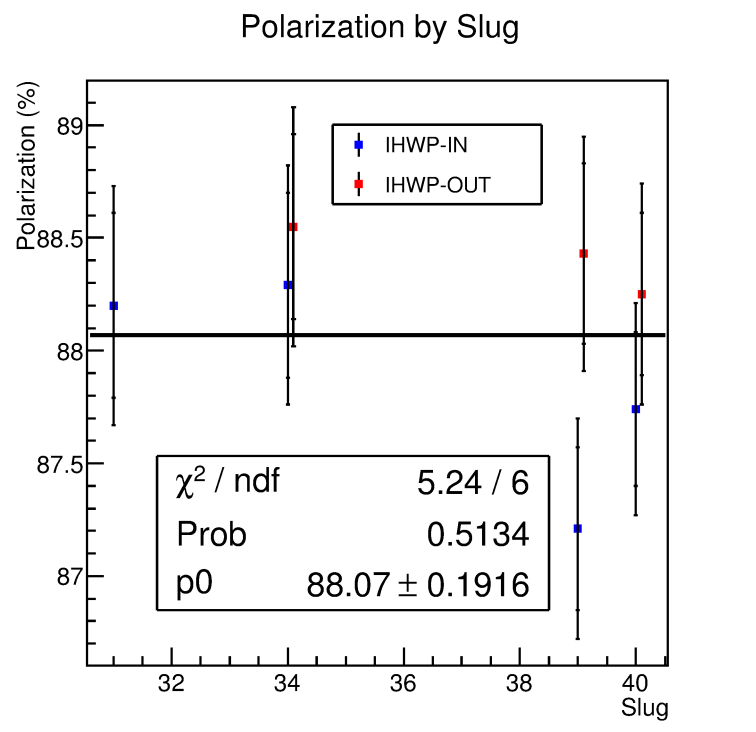




Data quality cuts are applied to remove unstable beam periods

# Møller Polarization Summary

Beam polarization,
$P_e = 88.95 \pm 1.83\%$




- Primary beam polarimetry during Run0
- Polarized Møller scattering to measure electron beam polarization
- Disruptive measurement done at every 2-3 days at about 1 μA

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# Background Corrections

- Measured yield consists of scattered elastic electrons (96.4%)
- Rest contains,
    - Scattered electrons from aluminum target window (3.2%), neutrals (0.4%), inelastic (0.02%)
- How backgrounds are corrected,

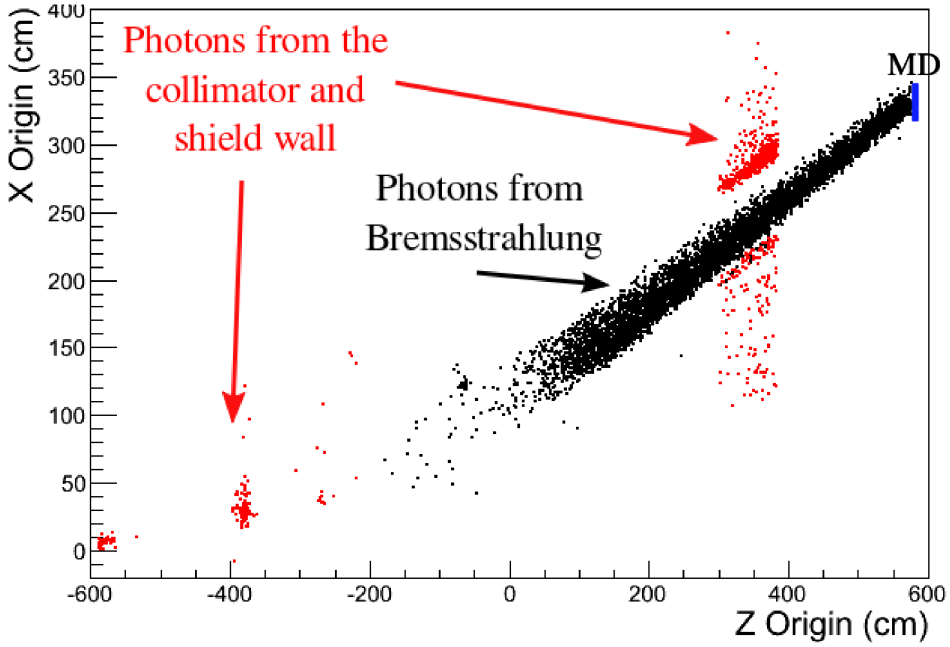
$$Y_{total} = Y_{\tilde{e}p} + \sum_{i=1}^{N} y_{bi}, \; f_{bi} = \frac{y_{bi}}{Y_{total}}$$

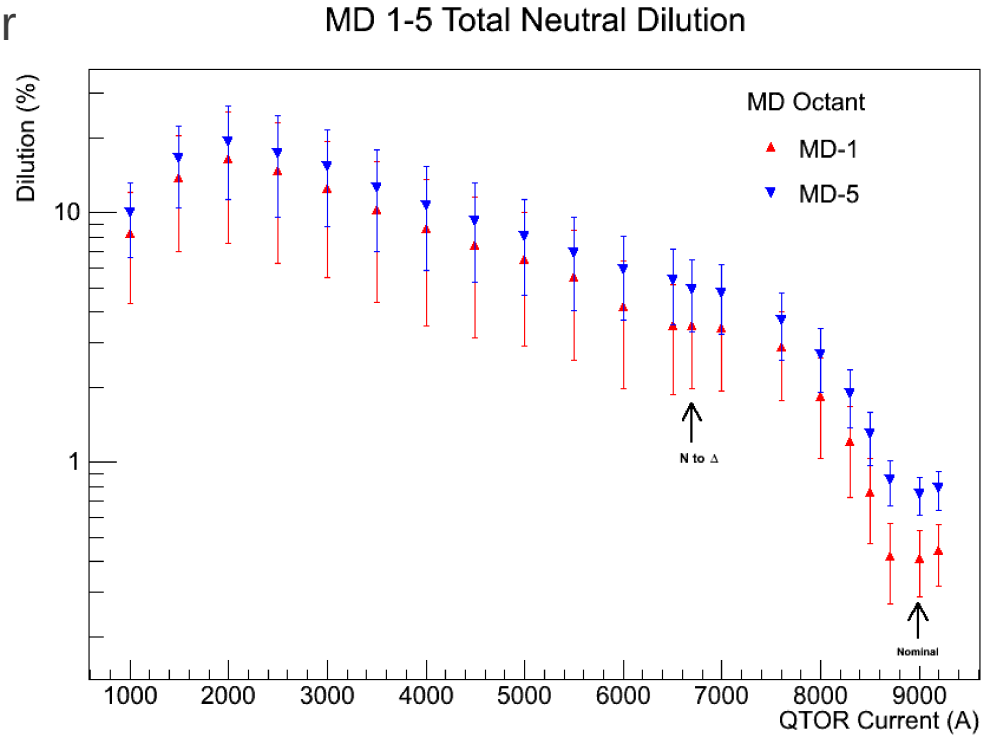
$$\frac{A_{msr}}{P_e} = (1 - f_{Total}) A_{\vec{e}p} + \sum_{i=1}^{N} f_{bi} \cdot A(y_{bi})$$

# Neutral Background Dilution

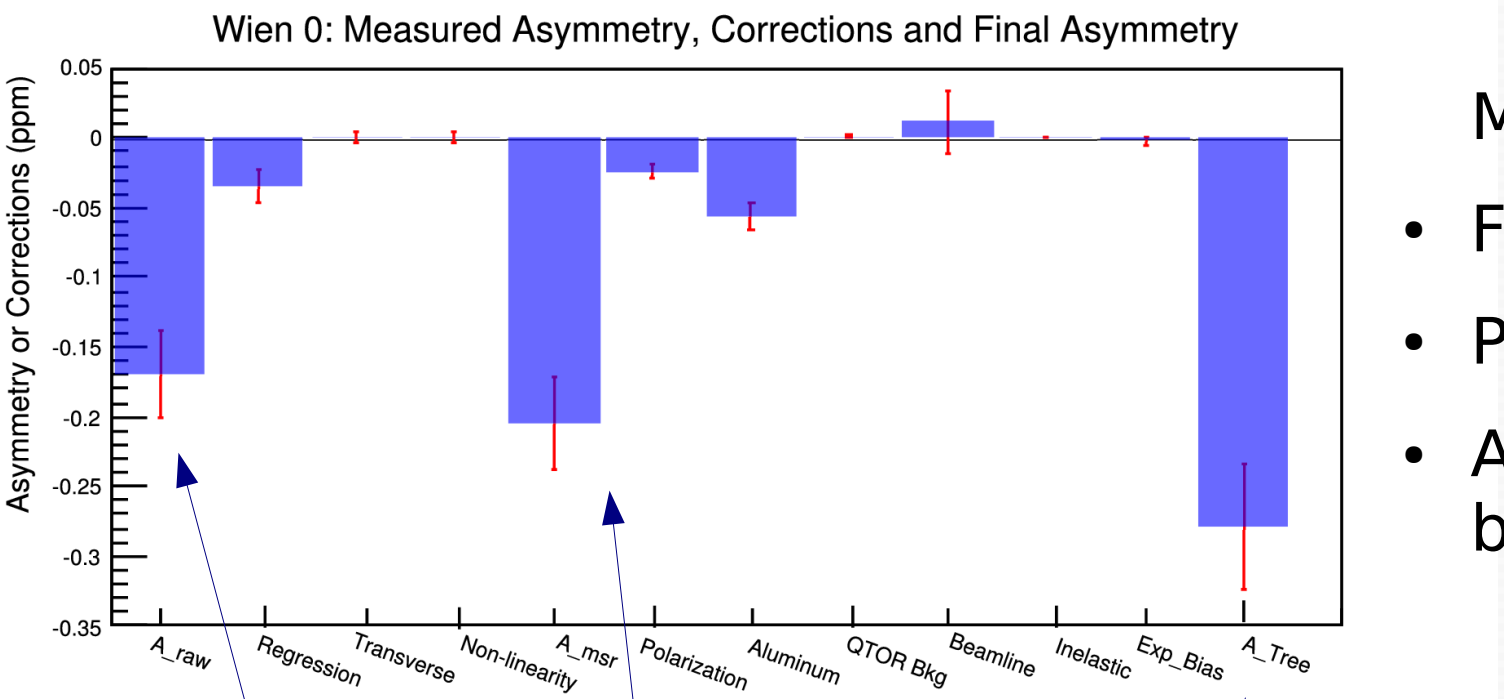
- Two sources of neutral backgrounds were not 100% contained by collimators and magnetic spectrometer
  - Scattered electron interactions with collimators and beam-line : *beam-line background*
  - Elastic electrons scraping in the collimators and shield wall : *QTOR transport channel background*
- Took auxiliary data to determine these neutral background dilutions

Origin of elastic photons that reach main detector



# Overview of Corrections




Raw asymmetry  measured asymmetry  Final ep asymmetry

- Major corrections
- False asymmetry
- Polarization
- Al window background ($b_1$)

$$A_{\vec{e}p} = R_{exp} \times$$

$$\frac{\{\frac{A_{msr}}{P_e} - f_{b1} \cdot A_{b1} - f_{b2} \cdot A_{b2} - f_{b3} \cdot A_{b3} - f_{b4} \cdot A_{b4}\}}{(1 - f_{Total})}$$

# Asymmetry Error Run0 Summary

The Breakdown of $A_{ep}$ errors.

| Source | Contribution to $dA_{\vec{e}p}$ (ppm) |
|---|---|
| $A_{msr}$ **statistical (Scaled)** | **0.0348** |
| $A_{msr}$ systematic (Scaled) | 0.0140 |
| Polarization | 0.0048 |
| Al window asymmetry (b1) | 0.0085 |
| Al window dilution (b1) | 0.0044 |
| QTOR transport neutral asymmetry (b2) | 0.0004 |
| QTOR transport neutral dilution (b2) | 0.0005 |
| Beamline neutral asymmetry (b3) | 0.0225 |
| Beamline neutral dilution (b3) | 0.0034 |
| $N \rightarrow \Delta$ asymmetry (b4) | 0.0002 |
| $N \rightarrow \Delta$ dilution (b4) | 0.0006 |
| Det. bias correction | 0.0018 |
| EM radiative correction | 0.0014 |
| Acceptance correction | 0.0028 |
| **Total Systematic error** | **0.0290** |
| **Total Error** | **0.0453 (16%)** |

# PV ep Asymmetry Results (Unblinded)

The measured ep elastic scattering asymmetry from Wien0 data set,

$$A_{\vec{e}p}(< Q^2 >_{eff}) = -0.2788 \pm 0.0348\ (\text{stat.})\ \pm 0.0290\ (\text{syst.})\ \text{ppm}$$

and Qweak kinematic at which this measurement was done,

| | |
|---|---|
| Beam energy at vertex , $< E_{eff} >$ | $1.155 \pm 0.003$ GeV |
| Momentum transfer $< Q^2_{eff} >$ | $0.0250 \pm 0.0006\ (\text{GeV})^2$ |
| Effective scattering angle, $< \theta_{eff} >$ | $7.90 \pm 0.30^{\circ}$ |

*Kinematics are acceptance averaged

The kinematics parameters and measured ep elastic asymmetry are corrected for EM radiative corrections.

# Results

# Weak Charge of the Proton

PV ep asymmetry in SM,

$$A_{\vec{e}p} = -\frac{1}{2} A^0_{LR} \left[ Q^p_W + F(Q^2, \theta) \right]$$

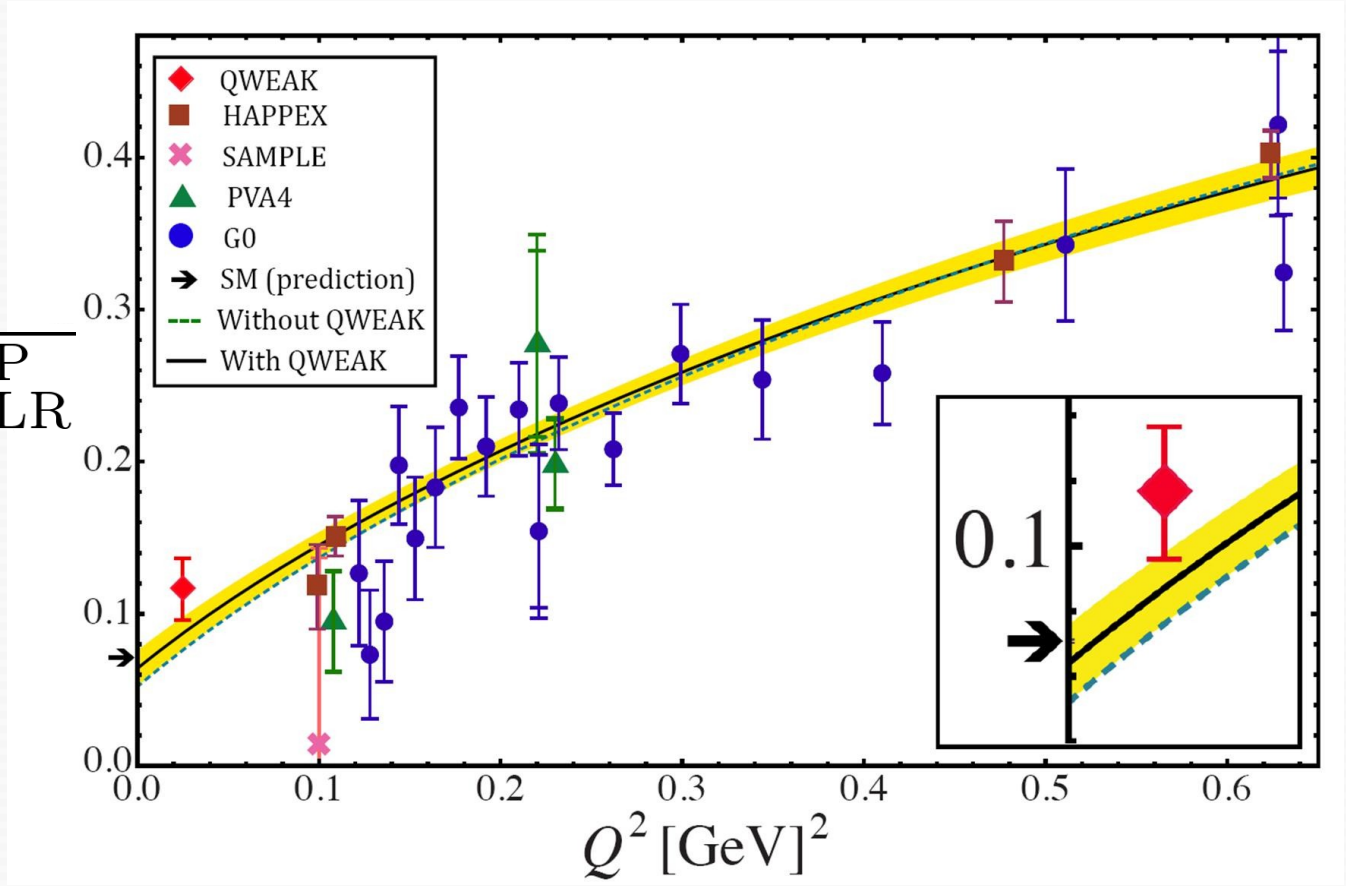
where $F(Q^2)$ contains hadronic contributions (form factors) and an energy dependent electroweak radiative correction.

Weak charge can be extracted using two methods,

1. Hadronic contribution is calculated using EM Sach's form factors and weak axial form factors
    - Strange form factors are assumed to be zero based on current Parity Violating Electron Scattering (PVES) global data analysis
2. For final results, the weak charge is extracted by PV electron scattering (PVES) global data analysis

# Weak Charge Extraction

The global analysis with PV asymmetry from Qweak experiment

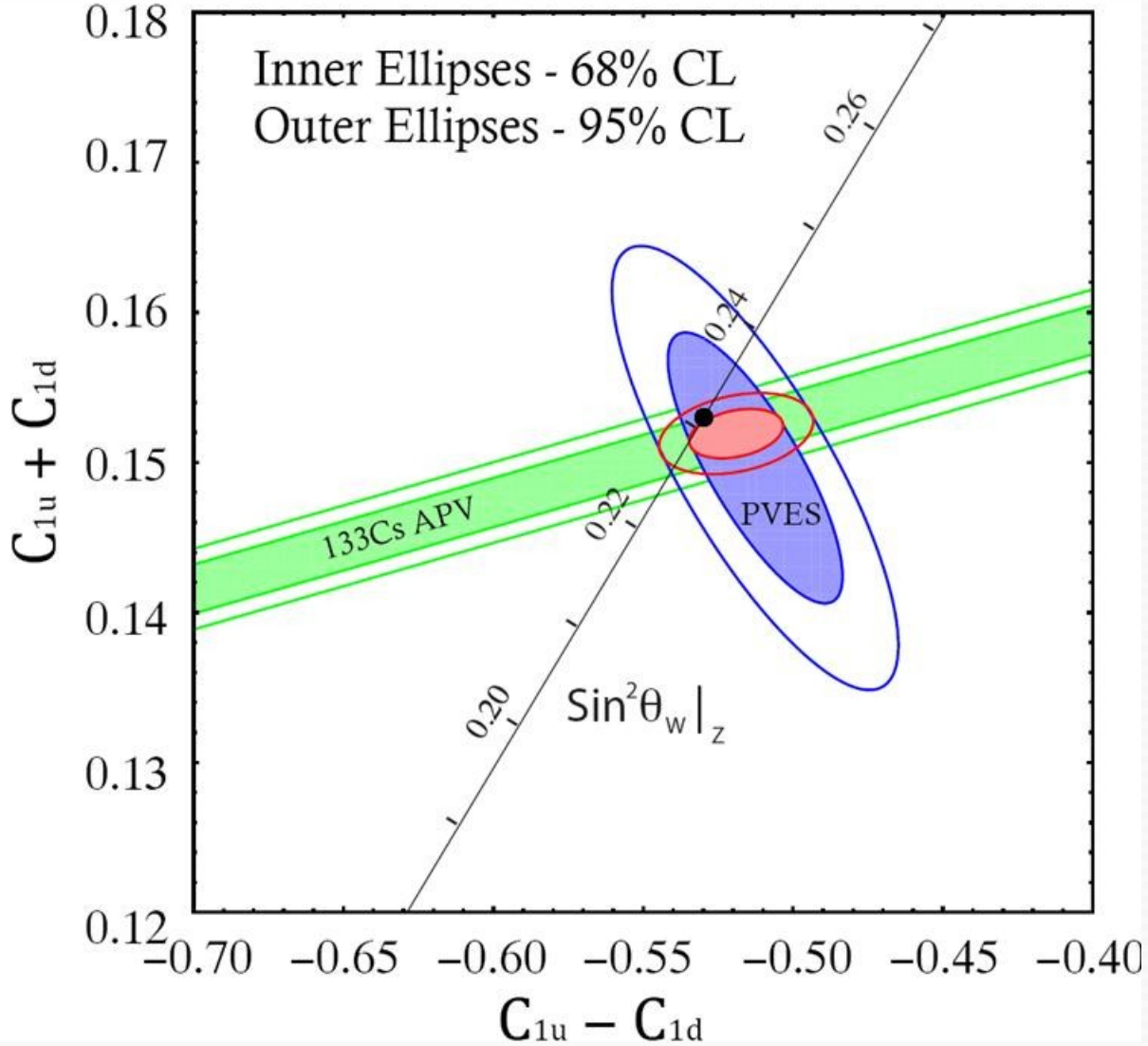



$$\overline{A_{LR}^{P}} \propto (Q_W^P + Q^2 B(Q^2))$$

Since Qweak asymmetry measured at about 0.025 GeV$^2$, It is less sensitive to hadronic structure.

# Constraints on $C_{1u}$ and $C_{1d}$

- Hadronic vector currents are build using only lightest quarks (u,d, and s)
- The weak charge of the proton is used to constrain the couplings for weak neutral hadronic vector currents in the SM
- Combination Atomic PV and PVES results are used to extract $C_{1u}$ and $C_{1d}$




From PVES and APV combined results,

$$C_{1u} = -0.1849 \pm 0.0053$$

$$C_{1d} = \ \ 0.3370 \pm 0.0050$$

# Final Results from Run0

| | | |
|---|---|---|
| $Q_w^p(\mathrm{msr})$ | $=$ | $+0.0640 \pm 0.0120$ |
| $Q_w^p(\mathrm{SM})$ | $=$ | $+0.0705 \pm 0.0008$ |
| $Q_w^n(\mathrm{msr})$ | $=$ | $-0.975 \pm 0.010$ |
| $Q_w^n(\mathrm{SM})$ | $=$ | $-0.989 \pm 0.001$ |

| | | |
|---|---|---|
| $C_{1u}(\mathrm{msr})$ | $=$ | $-0.1849 \pm 0.0053$ |
| $C_{1u}(\mathrm{SM})$ | $=$ | $-0.1885$ |
| $C_{1d}(\mathrm{msr})$ | $=$ | $+0.3370 \pm 0.0050$ |
| $C_{1d}(\mathrm{SM})$ | $=$ | $+0.3414$ |

Agreement of the weak charge of the proton result with the Standard Model sets the model independent new PV interaction mass scale to 1.1 TeV at 95% C.L.

# Future Work

- Main issues to resolve for final analysis,
  - False asymmetry correction
    - Improvements to HCBA correction techniques
  - Neutral background from beam-line
    - Estimation of the time varying beam-line background

Comparison of the precision on the measured Wien0 asymmetry to the precision goal of the full Qweak measurement.

| Source | Wien0 Results (ppm) | (%) | Proposed Goal (ppm) | (%) |
|---|---|---|---|---|
| Statistics | 0.035 | 12.5 | 0.006 | 2.1 |
| Systematics (HCBA+Transverse) | 0.015 | 5.3 | 0.001 | 0.5 |
| Backgrounds | 0.025 | 8.9 | 0.002 | 0.7 |
| $Q^2$ ( Exp. bias Corrections) | 0.004 | 1.3 | 0.001 | 0.5 |
| Polarization | 0.005 | 1.7 | 0.003 | 1.0 |
| **Total Error** | **0.046** | **16.3** | **0.007** | **2.5** |

# Summary: Run0 Results

- Run0 result is based on a statistically limited data set
    - Proof of concept analysis for final data set
    - Final results will be 5-6 times more accurate
    - First determination of weak charge of the proton
        - Publication is almost ready
        - One for the PDG
- Final results will be a test of the Standard Model and PV physics beyond SM at TeV scale

# Thank You!

Spokespersons:
R.D. Carlini (PI)
S. Kowalski
S.A. Page

Project Manager:
G. Smith

D.S. Armstrong, A. Asaturyan, T. Averett, J. Balewski, J. Beaufait, R.S. Beminiwattha, J. Benesch, F. Benmokhtar, J. Birchall, R.D. Carlini[1], J.C. Cornejo, S. Covrig, M.M. Dalton, C.A. Davis, W. Deconinck, J. Diefenbach, K. Dow, J.F. Dowd, J.A. Dunne, D. Dutta, W.S. Duvall, M. Elaasar, W.R. Falk, J.M. Finn[1], T. Forest, D. Gaskell, M.T.W. Gericke, J. Grames, V.M. Gray, K. Grimm, F. Guo, J.R. Hoskins, K. Johnston, D. Jones, M. Jones, R. Jones, M. Kargiantoulakis, P.M. King, E. Korkmaz, S. Kowalski[1], J. Leacock, J. Leckey, A.R. Lee, J.H. Lee, L. Lee, S. MacEwan, D. Mack, J.A. Magee, R. Mahurin, J. Mammei, J. Martin, M.J. McHugh, D. Meekins, J. Mei, R. Michaels, A. Micherdzinska, K.E. Myers, A. Mkrtchyan, H. Mkrtchyan, A. Narayan, L.Z. Ndukum, V. Nelyubin, Nuruzzaman, W.T.H van Oers, A.K. Opper, S.A. Page[1], J. Pan, K. Paschke, S.K. Phillips, M.L. Pitt, M. Poelker, J.F. Rajotte, W.D. Ramsay, J. Roche, B. Sawatzky,T. Seva, M.H. Shabestari, R. Silwal, N. Simicevic, G.R. Smith[2], P. Solvignon, D.T. Spayde, A. Subedi, R. Subedi, R. Suleiman, V. Tadevosyan, W.A. Tobias, V. Tvaskis, B. Waidyawansa, P. Wang, S.P. Wells, S.A. Wood, S. Yang, R.D. Young, S. Zhamkochyan

[1]Spokespersons; [2]Project Manager; Grad Students;

# Supplementary

# Summary of My Contributions

# My Contributions

- Qweak data analysis software development
    - Developed the framework to decode raw data
    - In event mode, developed multi-hit TDC decoder for drift chambers
    - Data quality cuts framework for parity data
- Qweak data acquisition development
    - Set-up multi-trigger inputs from different tracking detectors using NIM/VME modules
    - Programed VME read-out modules: VME CPU/Trigger interface/integrating ADC/QDC/TDC/Scalers
    - Developed an active feedback system
- Physics contribution,
    - Møller polarimetry
    - Determination of neutral background
    - **Weak charge of the proton measurement (DNP 2012 invited talk)**

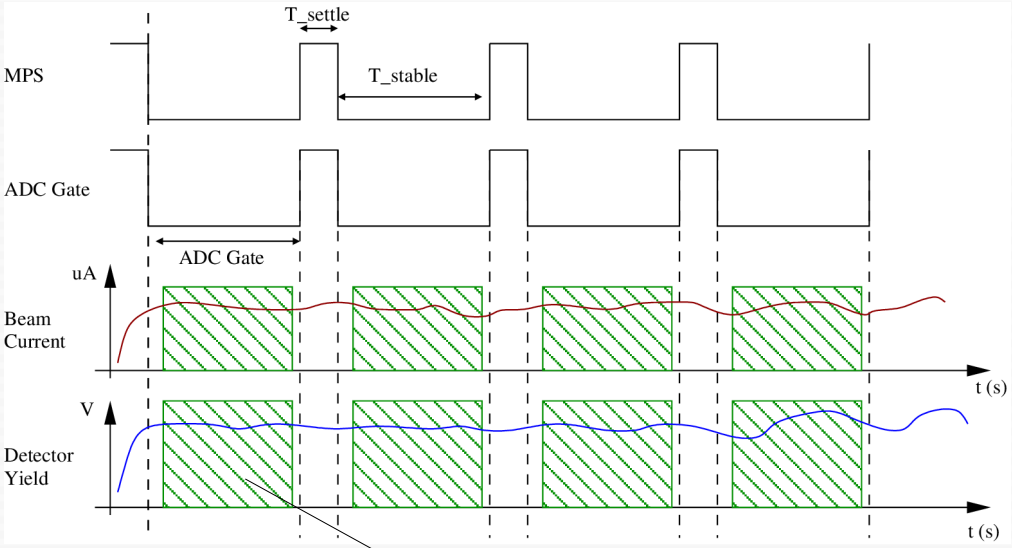
# Qweak Data Analysis System

- Developed the framework to decode data words from the electronic read-out channels in the raw CODA data files
    - Common framework for all the Qweak data
- In event mode, developed multi-hit TDC decoder for drift chambers
    - Drift chamber wire hits are accessible from ROOT
- Implemented Inter-detector communication system for charge normalization and etc.
- Data quality cuts framework for parity data
    - Single and extended event cuts for all detectors

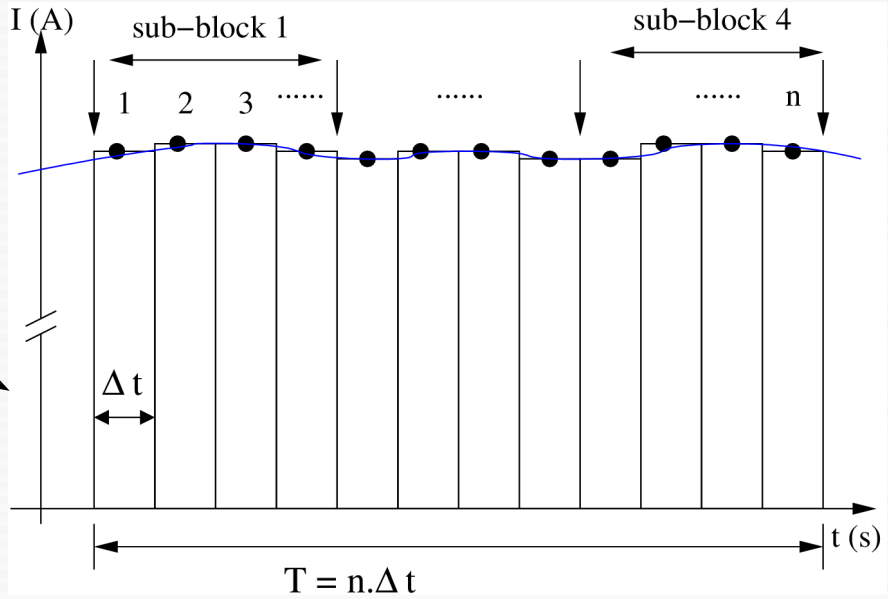
# Qweak DAQ

- Counting mode DAQ
    - Set-up multi-trigger inputs from different tracking detectors using NIM/VME modules
- Integrating mode DAQ
    - Implemented a system to add user flags to CODA data stream: GreenMonster
- Programed VME read-out modules: VME CPU/Trigger interface/integrating ADC/QDC/TDC/Scalers
- Experience working with the Trigger supervisor
- Set-up CODA to access read-out controllers

# Qweak Data Acquisition and Software System




The scattered electron yield is integrated during each polarization (Helicity) state. The helicity is flipped pseudo-randomly at 960Hz



# Qweak DAQ+Analysis

- Implemented the real-time data analysis system
    - Read CODA raw data stream to analysis data real-time
- Created the real-time monitor and an EPICS archiver
- Implemented the active charge feedback system for Qweak.
    - Maintained it during Qweak running
- **Software+DAQ on-call expert**

# Data Analysis Coordination

- Data replay in-charge
    - Replayed Qweak Run 1 data set using the Jlab computer farm
    - Lead three graduate students
- In-charge of organizing the first un-blinded release of e-p asymmetry
    - Computed the PV ep asymmetry and errors
    - Presented the endorsement talk

# Physics Results

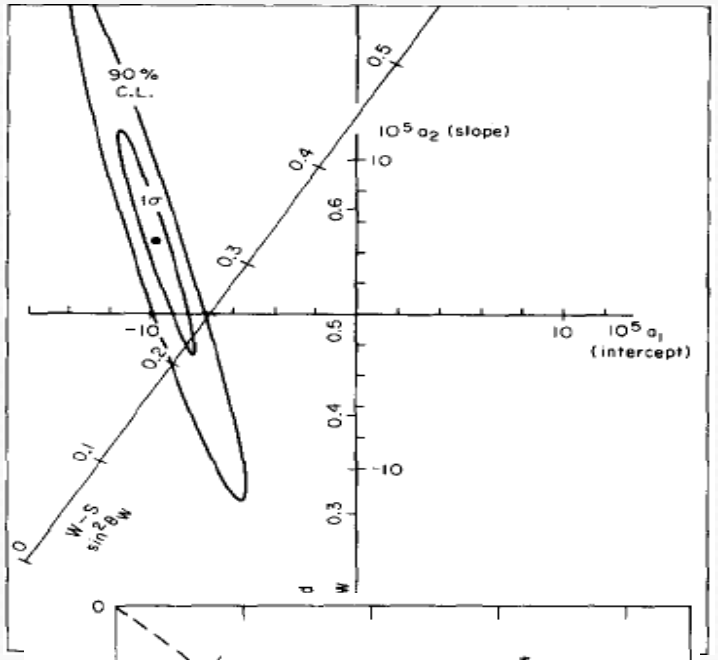
- Møller polarimetry
  - Commissioning and data taking
  - Systematic studies including simulations
  - Regular polarimetry measurements
- Measured total neutral background fraction
  - Developed run plans to take data and analyze
  - Working with GEANT3 simulation to compare the neutral yield and measure the neutral asymmetry
- 16% e-p parity violating asymmetry measurement
  - 21 % weak charge of the proton measurement

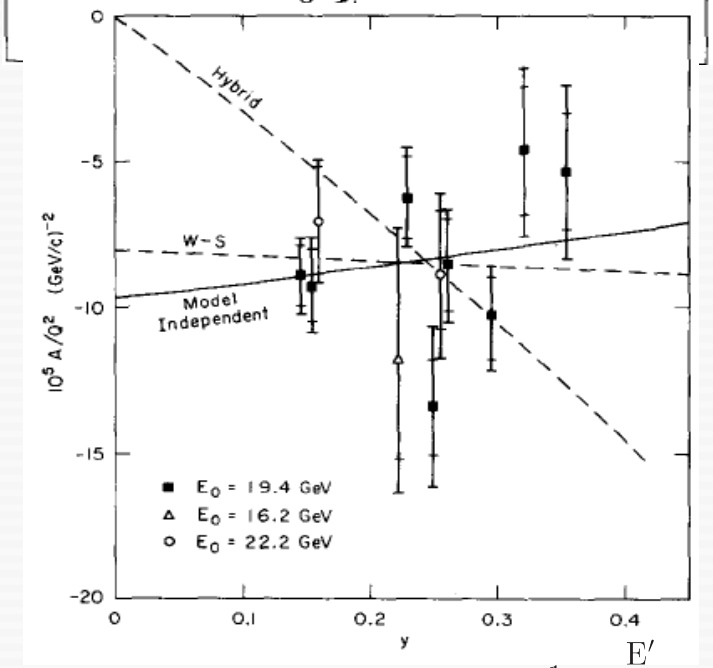
# Electroweak Theory of SM

- The neutral current interaction between the fermions and gauge bosons is given by,

$$\mathcal{L}_N = eJ^{em}_\mu A^\mu + \frac{g}{\cos\theta_W}(J^3_\mu - \sin^2\theta_W J^{em}_\mu)Z^\mu$$

- Parity Violation Electron Scattering (PVES) confirmed the electroweak structure
  - Confirmation of the model from the first PV electron scattering (PVES) experiment at SLAC
  - Found the weak mixing angle to be around 1/4
  - a small axial vector(e) **X** vector(f) weak neutral interaction.
  - Further demonstrated by low energy APV/PV and high energy Z-pole precision measurements.




$$y = 1 - \frac{E'}{E}$$

C. Prescott Phys. Lett. ,B84,524

# Electroweak Theory of SM

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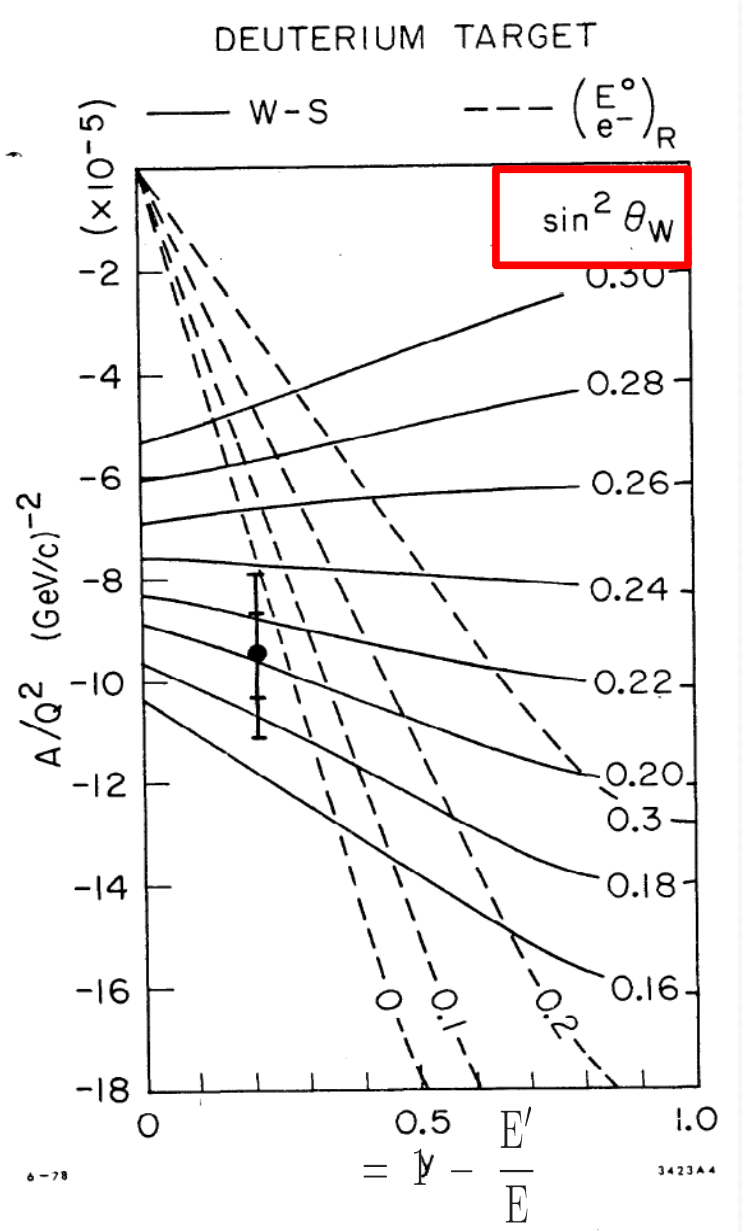
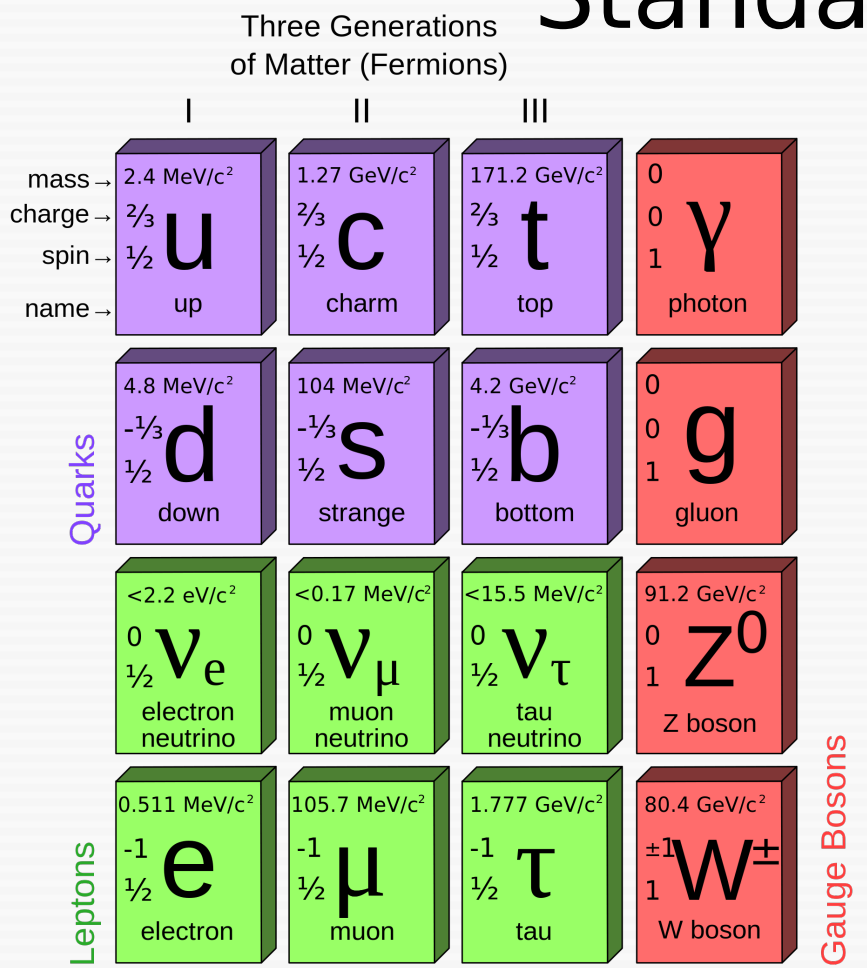



C. Prescott Phys. Lett. ,B77,347

# Standard Model




- The weak mixing (Weinberg) angle is a fundamental constant in electroweak interaction.
- The mixing angle is related to the $SU(2)_L$ and $U(1)_Y$ coupling constants, g and g', respectively

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ W^3_\mu \end{pmatrix}$$

$$\sin^2\theta_W = \frac{g'^2}{g'^2 + g^2} = 1 - \frac{M_W^2}{M_Z^2}$$

$$U(1)_Y \rightarrow B_\mu$$

$$SU(2)_L \rightarrow W^1_\mu,\ W^2_\mu,\ W^3_\mu$$

# Parity Violating Electron Scattering

PV asymmetry expressed in terms of Sachs form factors of the proton and neutron, strange quark form factors, and axial-vector weak form factor with the contributions from weak charges of proton, neutron, and electron separated,

$$\mathrm{A_{LR}}(\vec{\mathrm{e}}\mathrm{p}) = -\frac{1}{2}\mathrm{A^0_{LR}}\left[\mathrm{Q^p_W} + \right.$$

$$\mathrm{Q^n_W}\cdot\frac{[\varepsilon \mathrm{G^p_E}(\tau)\mathrm{G^n_E}(\tau)+\tau\mathrm{G^p_M}(\tau)\mathrm{G^n_M}(\tau)]}{\varepsilon\mathrm{G^p_E}(\tau)^2+\tau\mathrm{G^p_M}(\tau)^2} + \xi^{(0)}_{\mathrm{V}}\cdot\frac{[\varepsilon \mathrm{G^p_E}(\tau)\mathrm{G^{(s)}_E}(\tau)+\tau\mathrm{G^p_M}(\tau)\mathrm{G^{(s)}_M}(\tau)]}{\varepsilon\mathrm{G^p_E}(\tau)^2+\tau\mathrm{G^p_M}(\tau)^2} +$$

$$\left. \mathrm{Q^e_W}\cdot\frac{\sqrt{1-\varepsilon^2}\sqrt{\tau(1+\tau)}\mathrm{G^p_M}(\tau)\tilde{\mathrm{G}}^{\mathrm{p}}_{\mathrm{A}}(\tau)}{\varepsilon\mathrm{G^p_E}(\tau)^2+\tau\mathrm{G^p_M}(\tau)^2}\right]$$

$$= -\frac{1}{2}\mathrm{A^0_{LR}}\left[\mathrm{Q^p_W} + \mathrm{F}(\mathrm{Q}^2,\theta)\right]$$ At $Q^2$ of 0.025 $GeV^2$ $F(Q^2)$ is about 25%

where, $$\mathrm{A^0_{LR}} = \frac{\mathrm{G_F Q^2}}{2\pi\alpha\sqrt{2}},\ \varepsilon = \frac{1}{1+2(1+\tau)\tan^2\frac{\theta}{2}},\ \text{and}\ \tau = \mathrm{Q}^2/4\mathrm{M}^2$$

At tree level: $$\mathrm{Q^p_W} = 2\mathrm{g^u_V} + \mathrm{g^d_V},\quad \mathrm{Q^n_W} = 2\mathrm{g^d_V} + \mathrm{g^u_V},\quad \mathrm{Q^e_W} \equiv \mathrm{g^e_V}$$

# Weak Charge of the Proton

Weak charge of the proton in SM with electroweak radiative corrections,

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

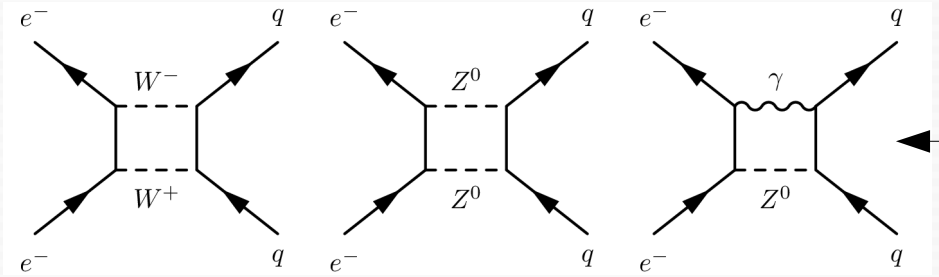
$$Q_W^p(SM) = 0.0705 \pm 0.0008$$

$$\sin^2\hat{\theta}_W(0) = 0.2387 \pm 0.0002$$

The values of electroweak radiative corrections

| Correction | Value |
|---|---|
| $\rho_{NC}$ | 1.047 |
| $\Delta_e$ | -0.001 |
| $\Delta'_e$ | -0.001 |
| $\Box_{WW}$ | 0.019 |
| $\Box_{ZZ}$ | 0.002 |
| $\Box_{\gamma Z}$ | 0.004 |

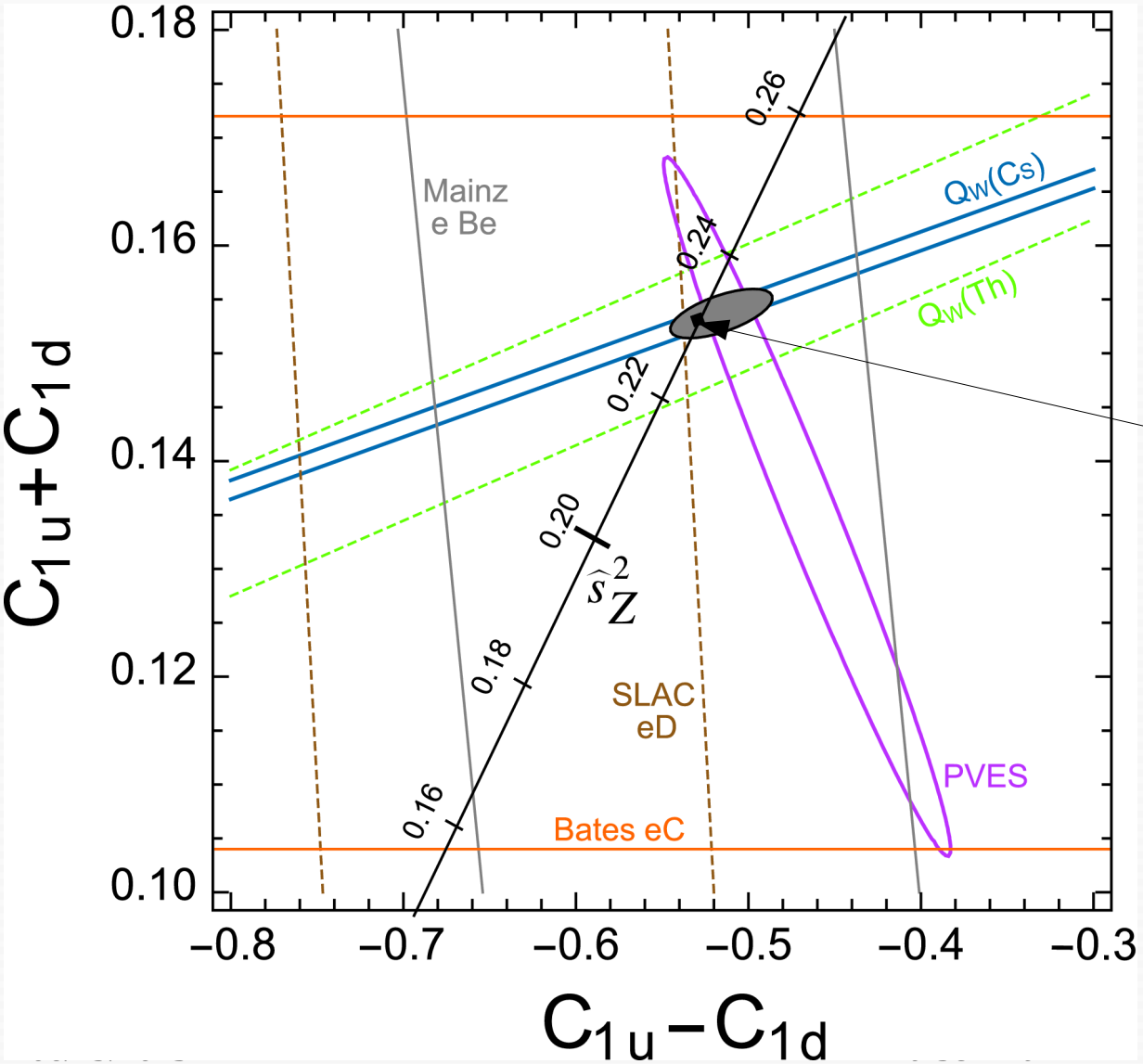
Corrections at e-vertex




These values will be compared with Qweak results

# Physics Motivation

**The $Q_W^P$ measurement will provide additional constraints on the SU(3) isovector ($C_{1u}$ - $C_{1d}$) and isoscalar ($C_{1u}$ + $C_{1d}$) hadronic currents effective couplings**




The constraints on $C_{1u}$ - $C_{1d}$ and $C_{1u}$ + $C_{1d}$ from parity violating electron scattering and APV experiments done so far.

The Standard Model prediction

$$C_{1u} \quad \rho'_e\left(-\tfrac{1}{2}+\tfrac{4}{3}\hat{\kappa}'_e\hat{s}^2_Z\right)+\lambda'$$

$$C_{1d} \quad \rho'_e\left(\tfrac{1}{2}-\tfrac{2}{3}\hat{\kappa}'_e\hat{s}^2_Z\right)-2\lambda'$$

# Coupling Constants

- The weak charge of the proton is used to constrain the couplings for weak neutral hadronic currents in the SM, which are build on the SU(3) octet and singlet currents using only lightest quarks (u,d, and s).

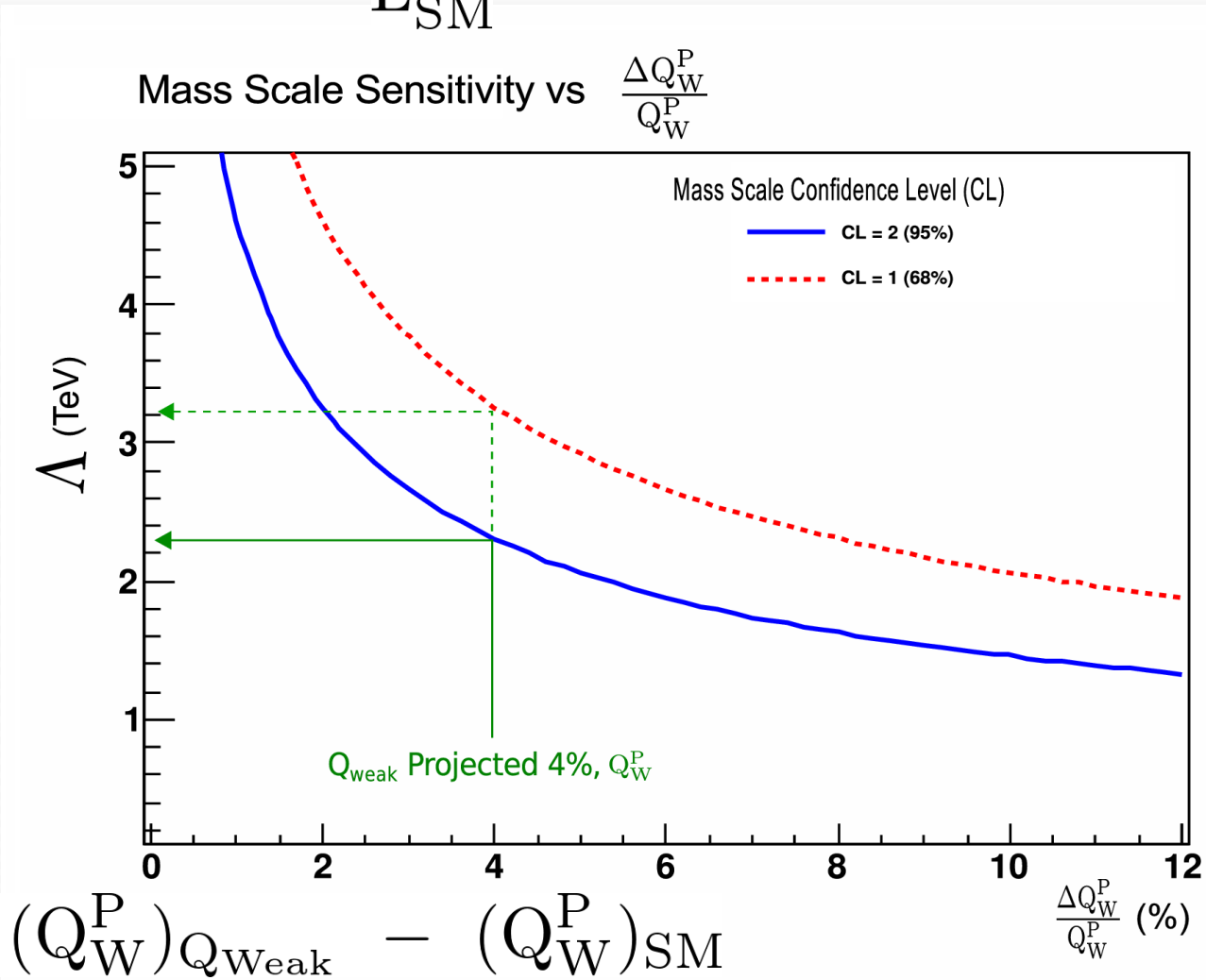
$$\xi_{\mathrm{V}}^{\mathrm{T}=0} = -2 \cdot \sqrt{3}(\mathrm{C}_{1\mathrm{u}} + \mathrm{C}_{1\mathrm{d}})$$
$$\xi_{\mathrm{V}}^{\mathrm{T}=1} = -2 \cdot (\mathrm{C}_{1\mathrm{u}} - \mathrm{C}_{1\mathrm{d}})$$
$$\mathrm{g}_{\mathrm{V}}^{f} = -2C_{1f} \; and \; g_{A}^{f} = -2C_{2f}$$

- Where couplings for leptons and quarks are defined below,

| Particle (f) | $\mathrm{g}_{\mathrm{V}}^{f}$ | $\mathrm{g}_{\mathrm{A}}^{f}$ |
|---|---|---|
| $\nu_{\mathrm{e}}$ | 1 | -1 |
| $\mathrm{e}^{-}$ | $-1 + 4\sin^2\theta_{\mathrm{W}}$ | 1 |
| u-quark | $1 - \frac{8}{3}\sin^2\theta_{\mathrm{W}}$ | -1 |
| d,s-quark | $-1 + \frac{4}{3}\sin^2\theta_{\mathrm{W}}$ | 1 |

# New PV Physics:Model Independent Constraints

$$L_{eff}^{PV} = \underbrace{-\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \cdot \sum_q C_{1q}\bar{q}\gamma^\mu q}_{L_{SM}^{PV}} + \underbrace{\frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q}_{L_{new}^{PV}}$$

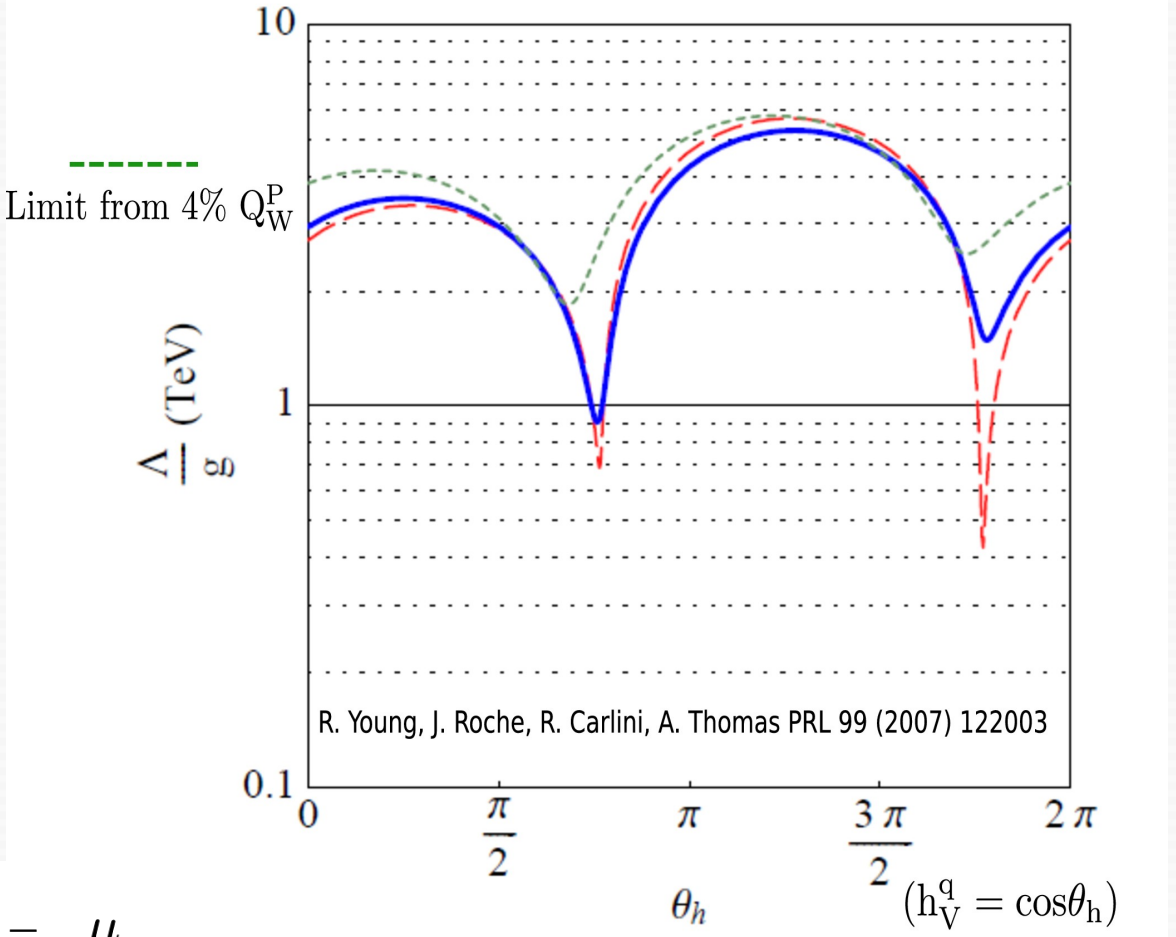



**g** is the new physics coupling while **Λ** is the new PV physics mass scale

$$\delta Q_W^P = (Q_W^P)_{Q_{Weak}} - (Q_W^P)_{SM}$$

# New Physics:Model Independent Constraints

- The bounds on new quark-lepton PV physics scale
- New physics is ruled out below the curve at 95% C.L.




$$L_{new}^{PV} = \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

$$h_V^u = \cos\theta_h$$

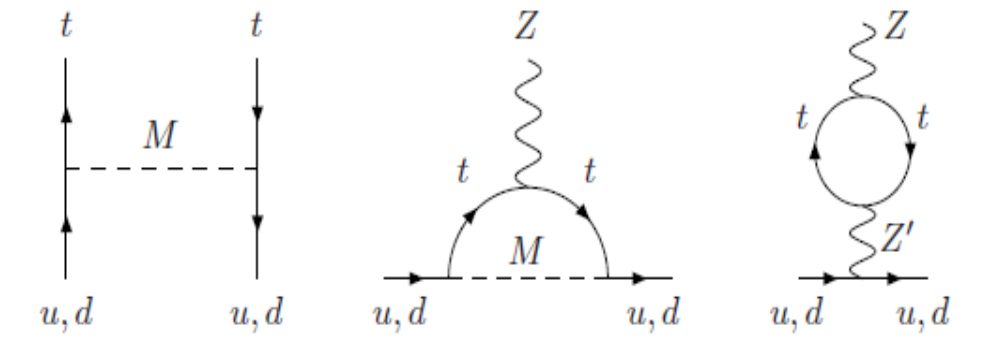
$$h_V^d = \sin\theta_h$$

# Model Dependent New Physics: Collider Example

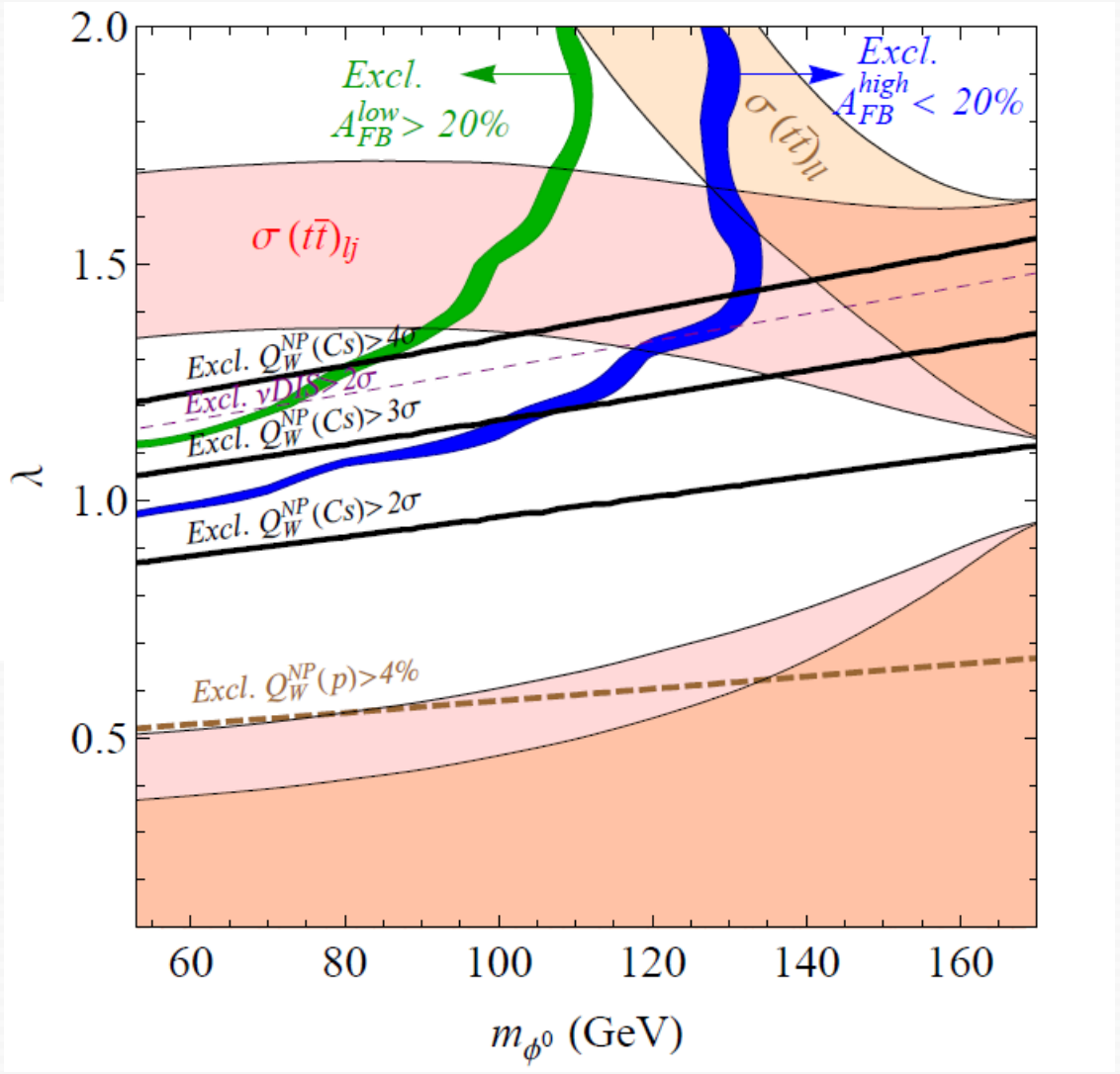
- CDF and D0 results of the $t\bar{t}$ forward backward asymmetry $A_{FB}$
  - Results favored t production in the incoming proton direction and $\bar{t}$ in the anti-proton direction
  - Observed $A_{FB}$ = 0.475 ± 0.114 a 3.4σ deviation from SM NLO prediction of 0.088 ± 0.013
- New physics models could account for the excess
  - **Gresham et.al. arXiv:1203.1320 [hep-ph]** discusses implications of Parity Violation constraints on these new models.

# $A_{FB}$ New PV Physics Constraints

Models discussed feature a scalar or vector mediator




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




Plot show how PV constraints could exclude certain models as the source of excess $A_{FB}$

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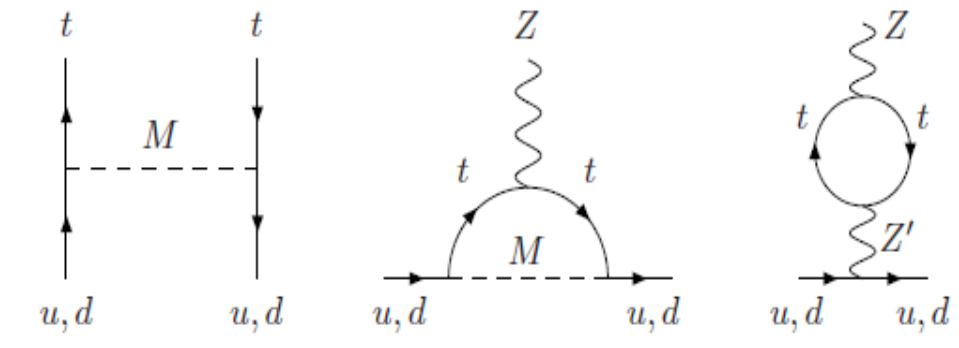
Models discussed feature a scalar or vector mediator

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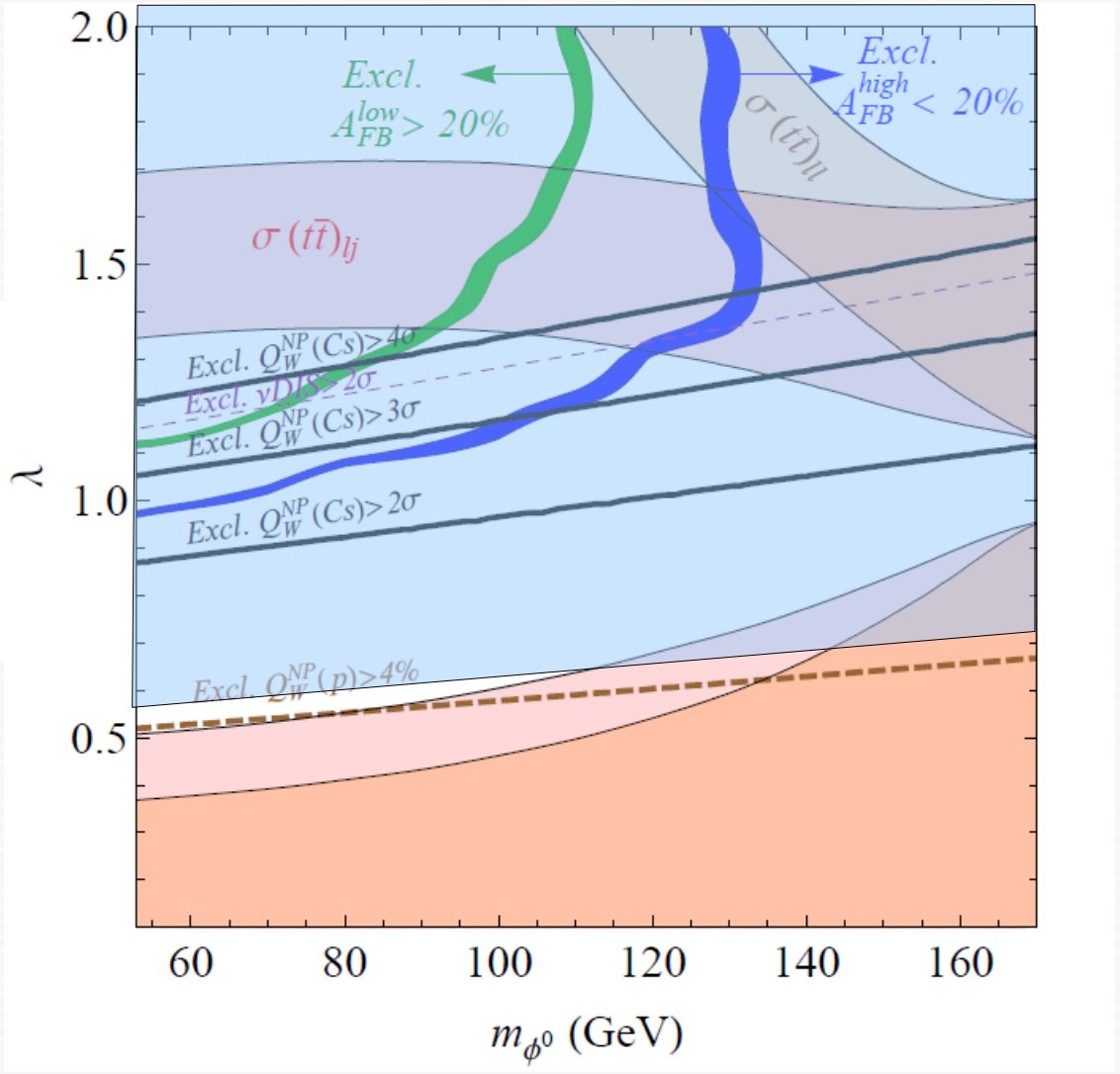



Plot show how PV constraints could exclude certain models as the source of excess $A_{FB}$

# From the Measured to PV ep Asymmetry

$$A_{\vec{e}p} = R_{exp} \times$$

$$\frac{\left\{ \frac{A_{msr}}{P_e} - f_{b1} \cdot A_{b1} - f_{b2} \cdot A_{b2} - f_{b3} \cdot A_{b3} - f_{b4} \cdot A_{b4} \right\}}{(1 - f_{Total})}$$

- $A_{msr}$ is the measured asymmetry
- Electron beam polarization: $P_e$
- Backgrounds (dilutions and asymmetries)
  - Al window background: $b_1$
  - QTOR transport channel: $b_2$ (neutral particles)
  - Beam-line: $b_3$ (neutral particles)
  - N → Δ electrons: $b_4$ (inelastic electrons)

# Tree level Asymmetry and Errors

$$A_{Tree} = R_{RC} \times R_{Det} \times \frac{\{\frac{A_{msr}}{P} - f_{b1} \cdot A_{b1} - f_{b2} \cdot A_{b2} - f_{b3} \cdot A_{b3} - f_{b4} \cdot A_{b4}\}}{(1 - f_{Total})}$$

$$dA_{Tree}|_{A_{msr}} = R_{RC} \times R_{Det} \times \frac{1}{P} \cdot \frac{1}{(1 - f_T)} \cdot dA_{msr}$$

$$dA_{Tree}|_{P} = R_{RC} \times R_{Det} \times -1 \cdot \frac{1}{(1 - f_T)} \cdot A_{msr} \cdot \frac{dP}{P^2}$$

$$dA_{Tree}|_{A_{b_i}} = R_{RC} \times R_{Det} \times -1 \cdot \frac{f_{b_i}}{(1 - f_T)} \cdot dA_{b_i}$$

$$dA_{Tree}|_{f_{b_1}} = R_{RC} \times R_{Det} \times \{\frac{A_{msr}}{P} + (-1 + f_{b_2} + f_{b_3} + f_{b_4})A_{b_1} - A_{b_2} f_{b_2} - A_{b_3} f_{b_3} - A_{b_4} f_{b_4}\} \cdot \frac{df_{b_1}}{(1 - f_T)^2}$$

Permutation of $1 \rightarrow 2$, $2 \rightarrow 3$, $3 \rightarrow 4$ and, $4 \rightarrow 1$ will give rest of the background errors

$$dA_{Tree}|_{R_{RC}} = dR_{RC} \times R_{Det} \times \frac{\{\frac{A_{msr}}{P} - f_{b1} \cdot A_{b1} - f_{b2} \cdot A_{b2} - f_{b3} \cdot A_{b3} - f_{b4} \cdot A_{b4}\}}{(1 - f_{Total})}$$

$$dA_{Tree}|_{R_{Det}} = dR_{Det} \times R_{RC} \times \frac{\{\frac{A_{msr}}{P} - f_{b1} \cdot A_{b1} - f_{b2} \cdot A_{b2} - f_{b3} \cdot A_{b3} - f_{b4} \cdot A_{b4}\}}{(1 - f_{Total})}$$

# Breakdown of Corrections

Let,

$$R_{Total} = R_{RC} \times R_{Det}$$

$$A_{Tree} = R_{Total} \times \frac{\{\frac{A_{msr}}{P} - f_{b1} \cdot A_{b1} - f_{b2} \cdot A_{b2} - f_{b3} \cdot A_{b3} - f_{b4} \cdot A_{b4}\}}{(1 - f_{Total})}$$

$$A_{Tree} = A_{msr} + \Delta A_P + \Delta A_{b1} + \Delta A_{b2} + \Delta A_{b3} + \Delta A_{b4} + \Delta A_{R_{Total}}$$

## Individual Corrections

$$\Delta A_P = \frac{R_{Total}}{(1 - f_{Total})}\{\frac{A_{msr}}{P} - A_{msr}\}$$

$$\Delta A_{b_1} = -1 \cdot \frac{R_{Total}}{(1 - f_{Total})}\{f_{b_1} \cdot A_{b_1}\}$$

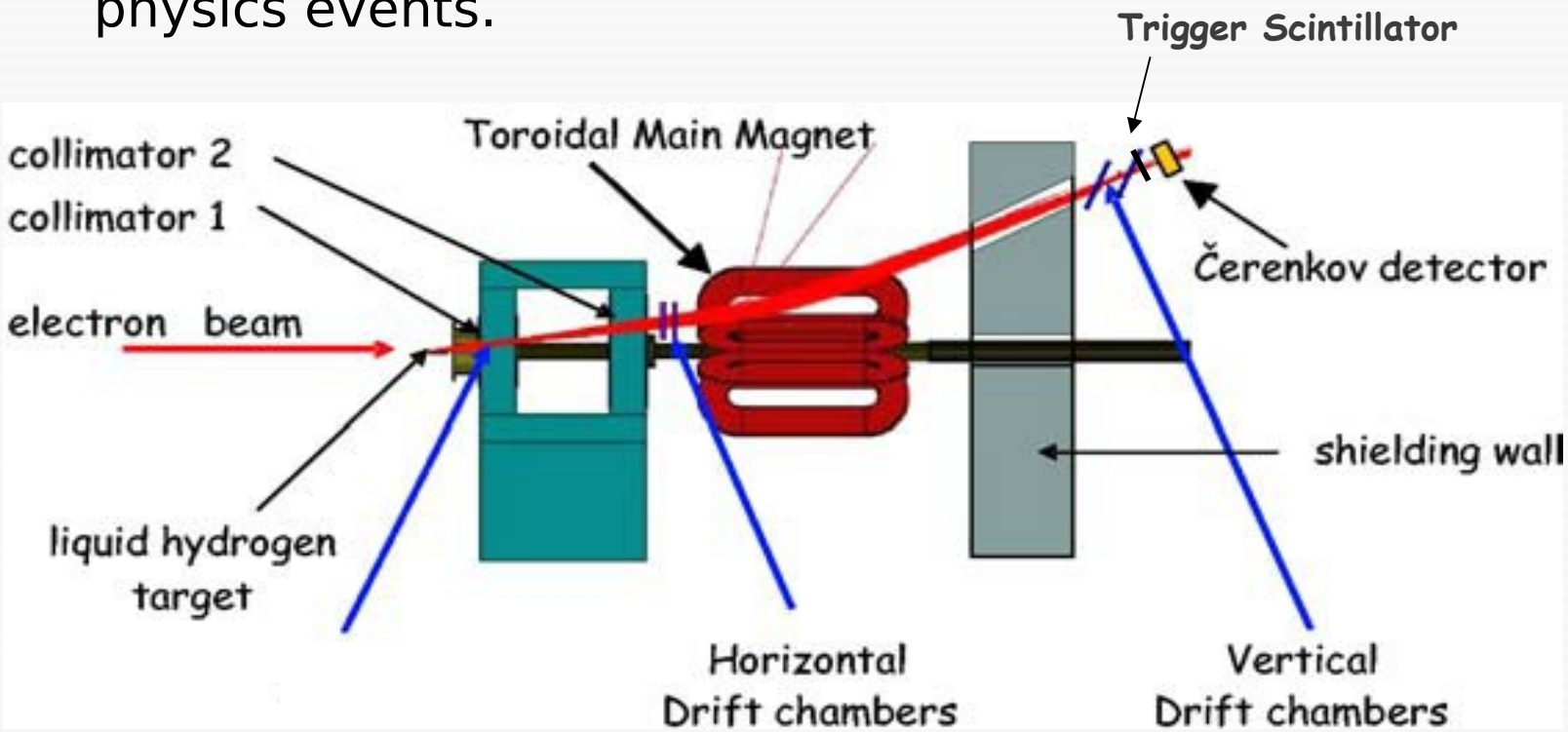
$$\Delta A_{R_{Total}} = \frac{R_{Total} \cdot A_{msr}}{(1 - f_{Total})} - A_{msr}$$

# Qweak Specifications (Wien0)

| Parameter | Value |
|---|---|
| Average beam energy at vertex | 1.155 GeV |
| Beam Polarization | 88% |
| Beam Current (integrating Mode) | 100-150 $\mu$A |
| Target | liquid hydrogen at 20 K |
| Target thickness | 35 cm |
| Beam Luminosity | $1.0 - 1.5 \times 10^{39}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ |
| Beam Luminosity (counting Mode) | less than 1 nA |
| Nominal electron scattering angle | $7.9^{o}$ |
| Angular acceptance | $\pm 3^{0}$ |
| Total azimuthal ($\phi$) acceptance | 49% of $2\pi$ |
| Solid angle, $\Delta\Omega$ | 37 msr |
| Integrated cross section | $4.0\mu$b |
| Integrated scattering rate | 5 GHz (0.6 GHz per detector) |
| Acceptance averaged $Q^2$ | 0.025 $\mathrm{GeV}^2$ |
| physics asymmetry | -0.200 ppm |

# Tracking Mode: What is It?

- Determine the $Q^2$ at low beam current using set of detectors located in three regions.
  - Using local track information of HDCs, and VDCs, it is possible to reconstruct the particle momentum.
  - A dedicated data analyzer is built to observe/analyze physics events.

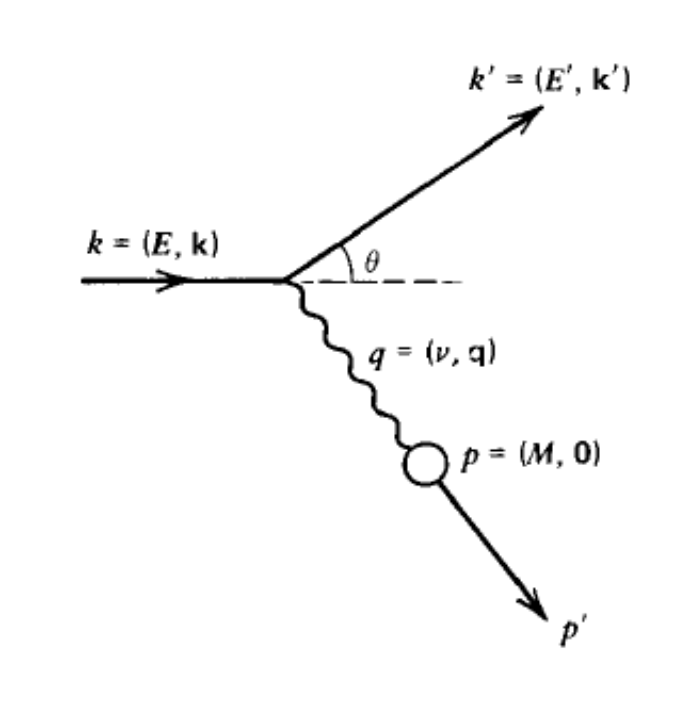


# Electron Kinematics

- For elastic scattering,

$$Q^2 = \frac{4E^2 \sin^2 \theta/2}{\left(1 + 2\frac{E}{M}\sin^2 \theta/2\right)}$$

  - E is the incident energy, θ is the scattering angle and M is the proton mass.




$$q = k - k'$$

$$k^2 = k'^2 \simeq 0 \text{ and } q^2 \simeq -2k \cdot k'$$

In the Lab frame, incident electron, k scattered off the proton with momentum k'. The momentum transferred into the proton is q.

$$q^2 \simeq -2k \cdot k' \simeq -2EE'(1 - \cos\theta) = -4EE' \sin^2\frac{\theta}{2} \qquad (1)$$

$$q = p' - p$$

$$q^2 + p^2 + 2pq = p'^2$$

$$q^2 = -2pq = -2\nu M$$

$$\nu \equiv E - E' = -\frac{q^2}{2M} \qquad (2)$$

# Data Analysis

# Qweak Data Overview

The main Čerenkov detector asymmetries are computed using the integrated signal measured from each of the 16-pmt channels (two per detector in each octant)

$$\mathrm{A}^{\mathrm{raw}}_{\mathrm{pmt}} = \frac{(\mathrm{Y}^{\mathrm{R1}} + \mathrm{Y}^{\mathrm{R2}}) - (\mathrm{Y}^{\mathrm{L1}} + \mathrm{Y}^{\mathrm{L2}})}{(\mathrm{Y}^{\mathrm{R1}} + \mathrm{Y}^{\mathrm{R2}}) + (\mathrm{Y}^{\mathrm{L1}} + \mathrm{Y}^{\mathrm{L2}})}, \text{and } \mathrm{A}^{\mathrm{raw}} = \frac{\sum_{\mathrm{j}=1}^{16} \mathrm{A}^{\mathrm{raw}}_{\mathrm{pmt,j}}}{16}$$

Helicity Correlated Beam Asymmetries (HCBA) refers to any difference in the beam parameters between the right and left (R and L) helicity states. We record,

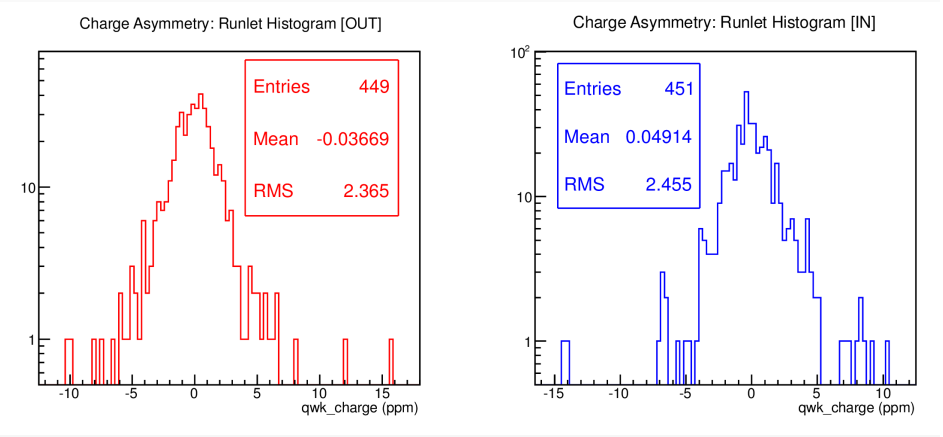
- Beam charge - $\mathrm{A}_{\mathrm{Q}}$
- Beam position/angle
- Relative momentum shift in the beam $\Big\}\ \mathrm{D}_{\mathrm{BPM}}$

during each helicity state and HCBA are computed to correct false asymmetries

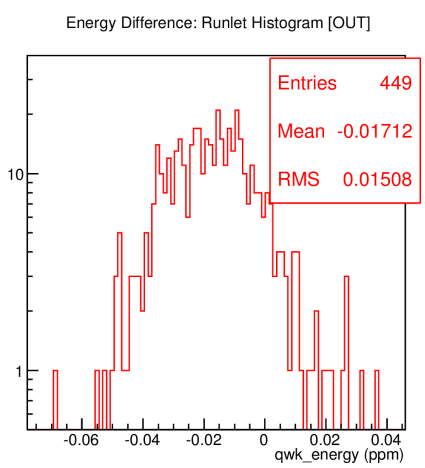
$$\mathrm{A}_{\mathrm{Q}} = \frac{(\mathrm{I}^{\mathrm{R1}}_{\mathrm{BCM}} + \mathrm{I}^{\mathrm{R2}}_{\mathrm{BCM}}) - (\mathrm{I}^{\mathrm{L1}}_{\mathrm{BCM}} + \mathrm{I}^{\mathrm{L2}}_{\mathrm{BCM}})}{(\mathrm{I}^{\mathrm{R1}}_{\mathrm{BCM}} + \mathrm{I}^{\mathrm{R2}}_{\mathrm{BCM}}) + (\mathrm{I}^{\mathrm{L1}}_{\mathrm{BCM}} + \mathrm{I}^{\mathrm{L2}}_{\mathrm{BCM}})}, \ \mathrm{D}_{\mathrm{BPM}} = \frac{(\mathrm{X}^{\mathrm{R1}}_{\mathrm{BPM}} + \mathrm{X}^{\mathrm{R2}}_{\mathrm{BPM}}) - (\mathrm{X}^{\mathrm{L1}}_{\mathrm{BPM}} + \mathrm{X}^{\mathrm{L2}}_{\mathrm{BPM}})}{4}$$

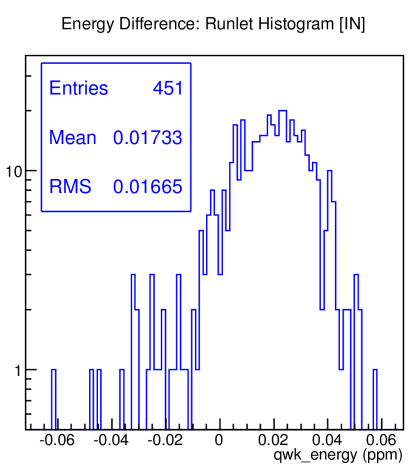
The Insertable Half-Wave Plate (IHWP) reversal flips the sign of the physics asymmetry due to reversal of the polarization vector, while if aligned properly, most HCBA do not reverse flip the sign.

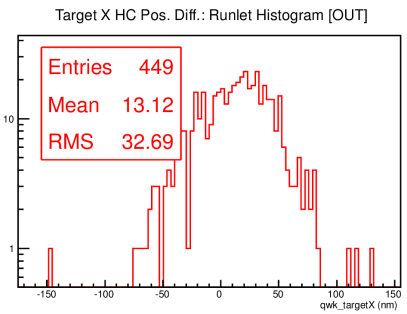
# Run0: HCBA

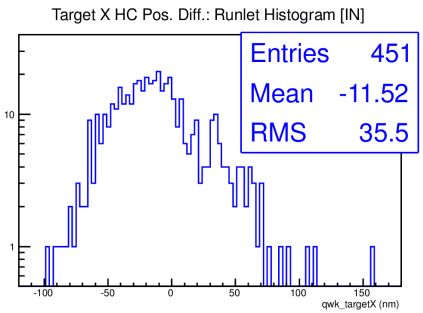

Charge Asymmetry: Runlet Histogram [OUT]
Entries 449
Mean -0.03669
RMS 2.365
qwk_charge (ppm)

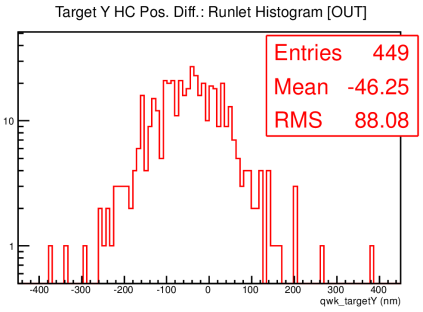

Charge Asymmetry: Runlet Histogram [IN]
Entries 451
Mean 0.04914
RMS 2.455
qwk_charge (ppm)

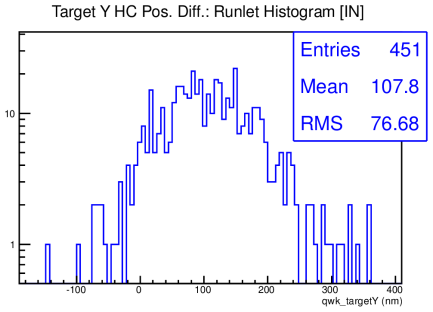

Energy Difference: Runlet Histogram [OUT]
Entries 449
Mean -0.01712
RMS 0.01508
qwk_energy (ppm)

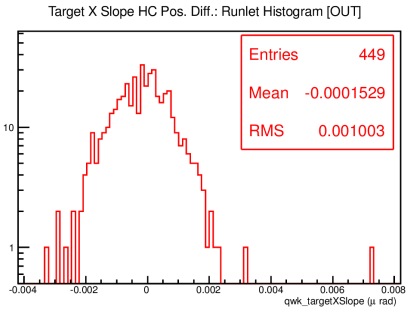

Energy Difference: Runlet Histogram [IN]
Entries 451
Mean 0.01733
RMS 0.01665
qwk_energy (ppm)

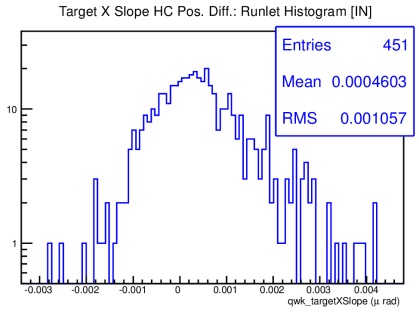

Target X HC Pos. Diff.: Runlet Histogram [OUT]
Entries 449
Mean 13.12
RMS 32.69
qwk_targetX (nm)

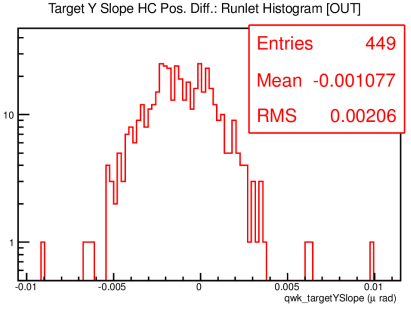

Target X HC Pos. Diff.: Runlet Histogram [IN]
Entries 451
Mean -11.52
RMS 35.5
qwk_targetX (nm)

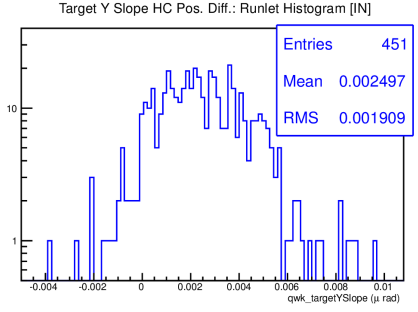

Target Y HC Pos. Diff.: Runlet Histogram [OUT]
Entries 449
Mean -46.25
RMS 88.08
qwk_targetY (nm)


Target Y HC Pos. Diff.: Runlet Histogram [IN]
Entries 451
Mean 107.8
RMS 76.68
qwk_targetY (nm)


Target X Slope HC Pos. Diff.: Runlet Histogram [OUT]
Entries 449
Mean -0.0001529
RMS 0.001003
qwk_targetXSlope (μ rad)


Target X Slope HC Pos. Diff.: Runlet Histogram [IN]
Entries 451
Mean 0.0004603
RMS 0.001057
qwk_targetXSlope (μ rad)


Target Y Slope HC Pos. Diff.: Runlet Histogram [OUT]
Entries 449
Mean -0.001077
RMS 0.00206
qwk_targetYSlope (μ rad)


Target Y Slope HC Pos. Diff.: Runlet Histogram [IN]
Entries 451
Mean 0.002497
RMS 0.001909
qwk_targetYSlope (μ rad)

# Run0: Raw Asymmetry

- During Run0, The IHWP state is changed roughly every 8 hours to help cancel HCBA.
    - A “Slug” has data in on IHWP state
- The IHWP IN and OUT data sets are averaged after correcting the sign of the asymmetry AVG(OUT,-IN), helping to cancel any false asymmetries which are independent of the IHWP state.
    - (OUT+IN)/2 is a measure of false asymmetry

| Slug OUT | Asymmetry (ppm) | Slug IN | Asymmetry (ppm) | $(\mathrm{OUT}+\mathrm{IN})/2$ (ppm) | $\mathrm{AVG}(\mathrm{OUT},-\mathrm{IN})$ (ppm) |
|---|---|---|---|---|---|
| 32 | $-0.029 \pm 0.117$ | | | | |
| 34 | $-0.174 \pm 0.084$ | 33 | $0.110 \pm 0.078$ | $-0.032 \pm 0.057$ | $-0.139 \pm 0.057$ |
| 36 | $-0.045 \pm 0.089$ | 35 | $0.215 \pm 0.088$ | $0.085 \pm 0.062$ | $-0.131 \pm 0.062$ |
| 38 | $-0.082 \pm 0.096$ | 37 | $0.259 \pm 0.087$ | $0.089 \pm 0.065$ | $-0.179 \pm 0.064$ |
| 40 | $-0.072 \pm 0.118$ | 39 | $0.476 \pm 0.094$ | $0.202 \pm 0.075$ | $-0.319 \pm 0.073$ |
| AVG | $-0.089 \pm 0.044$ | AVG | $0.248 \pm 0.043$ | $0.079 \pm 0.031$ | $-0.170 \pm 0.031$ |

# Linear Regression

The linear regression is applied to the measured raw Čerenkov detector asymmetry ($A^{raw}$) to remove false asymmetries generated from HCBA.

$$A_{msr} = A^{raw} - \sum_{i=1}^{5} \frac{\partial A^{raw}}{\partial x_i} \cdot \Delta x_i$$

$$= A^{raw} - \sum_{i=1}^{5} A_{false_i}$$

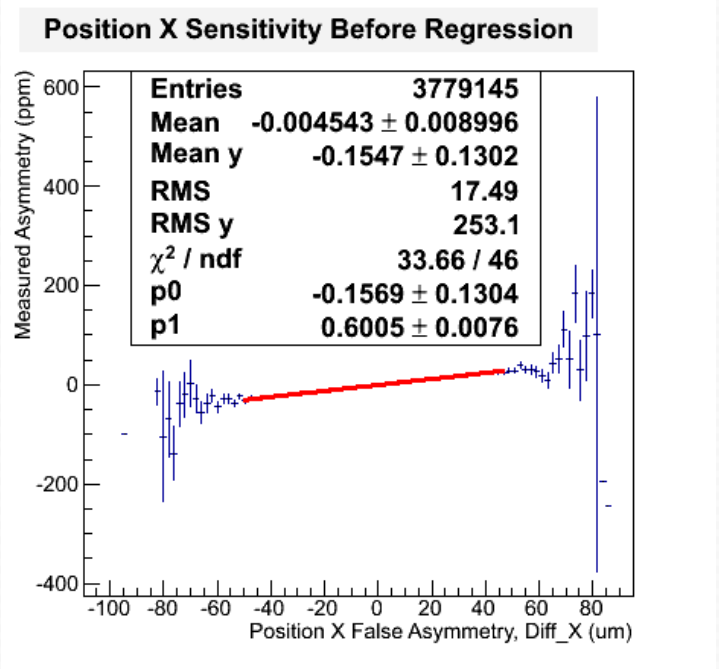
HCBA

Sensitivity/Slope

False asymmetries

The HCBA used for the linear regression,

| Beam Qty | Description |
|---|---|
| Dx (nm) | X position differences at target |
| Dy (nm) | Y position differences at target |
| Dxp (nrad) | X angle differences at target |
| Dyp (nrad) | Y angle differences at target |
| DE (ppm) | Relative energy differences at target |



# Linear Regression Corrections

| Qty | acro-ihwp-OUT | acro-ihwp-IN | AVG(OUT,-IN) |
|---|---|---|---|
| Dx (nm) | $14.43 \pm 0.25$ | $-13.60 \pm 0.25$ | $14.02 \pm 0.18$ |
| Dy (nm) | $-50.41 \pm 0.25$ | $108.44 \pm 0.25$ | $-79.03 \pm 0.18$ |
| Dxp (nrad) | $-0.13 \pm 0.05$ | $0.43 \pm 0.05$ | $-0.28 \pm 0.04$ |
| Dyp (nrad) | $-1.16 \pm 0.05$ | $2.51 \pm 0.05$ | $-1.84 \pm 0.04$ |
| $A_E$ (ppm) | $-0.02 \pm 0.0001$ | $0.02 \pm 0.0001$ | $-0.02 \pm 0.00004$ |
| $A_Q$ (ppm) | $-0.039 \pm 0.007$ | $-0.036 \pm 0.007$ | $-0.002 \pm 0.005$ |

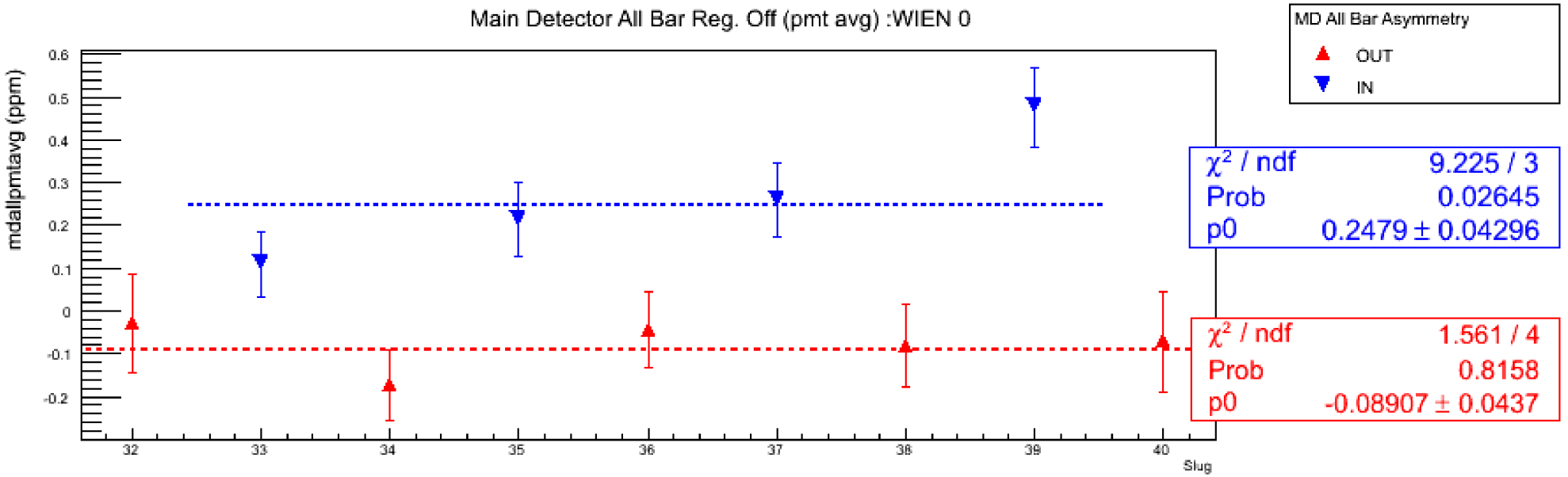
Linear regression average sensitivities

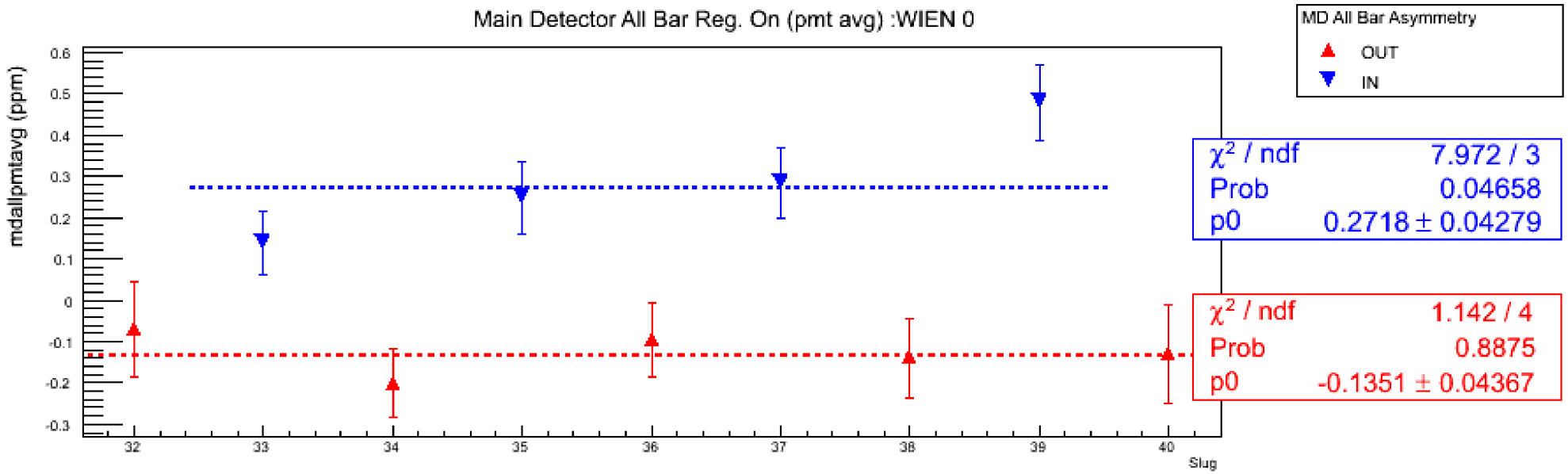
| Sensitivity | | Average value |
|---|---|---|
| $\frac{\partial A^{raw}}{\partial x}$ | (ppm/mm) | $-1000 \pm 10$ |
| $\frac{\partial A^{raw}}{\partial y}$ | (ppm/mm) | $300 \pm 10$ |
| $\frac{\partial A^{raw}}{\partial xp}$ | (ppm/$\mu$rad) | $38.0 \pm 0.3$ |
| $\frac{\partial A^{raw}}{\partial yp}$ | (ppm/$\mu$rad) | $-3.0 \pm 0.3$ |
| $\frac{\partial A^{raw}}{\partial A_E}$ | (ppm/ppm) | $-6.0 \pm 0.2$ |

Average False Asymmetries

| IV | IHWP-OUT Correction (ppm) | IHWP-IN Correction (ppm) |
|---|---|---|
| Dx | $-0.012 \pm 0.0003$ | $0.013 \pm 0.0003$ |
| Dy | $-0.019 \pm 0.0003$ | $0.037 \pm 0.001$ |
| Dxp | $-0.005 \pm 0.002$ | $0.018 \pm 0.002$ |
| Dyp | $0.004 \pm 0.0003$ | $-0.006 \pm 0.001$ |
| $A_E$ | $0.096 \pm 0.0005$ | $-0.107 \pm 0.0005$ |

# Linear Regression Results



# Linear Regression Results

- The reduced $X^2$ consistent with 1 for IHWP OUT state.
- The reduced $X^2$ is not consistent with 1 for IHWP IN state.
    - Related to outlier slug-39
- Overall, the $X^2$ has improved after the linear regression
- Residual false asymmetry has also reduced slightly after linear regression but still large
    - Reduced from 2.5 σ to 2.2 σ

The Standard regressed main detector asymmetry ($A_{msr}$) at slug-scale for Wien0.

| Slug OUT | Asymmetry (ppm) | Slug IN | Asymmetry (ppm) | (OUT + IN)/2 (ppm) | AVG(OUT, −IN) (ppm) |
|---|---|---|---|---|---|
| 32 | $-0.070 \pm 0.117$ | | | | |
| 34 | $-0.202 \pm 0.084$ | 33 | $0.139 \pm 0.077$ | $-0.032 \pm 0.057$ | $-0.168 \pm 0.057$ |
| 36 | $-0.097 \pm 0.089$ | 35 | $0.249 \pm 0.088$ | $0.076 \pm 0.062$ | $-0.174 \pm 0.062$ |
| 38 | $-0.139 \pm 0.096$ | 37 | $0.283 \pm 0.087$ | $0.072 \pm 0.065$ | $-0.219 \pm 0.064$ |
| 40 | $-0.130 \pm 0.118$ | 39 | $0.479 \pm 0.093$ | $0.174 \pm 0.075$ | $-0.344 \pm 0.073$ |
| AVG | $-0.135 \pm 0.044$ | AVG | $0.272 \pm 0.043$ | $0.068 \pm 0.031$ | $-0.205 \pm 0.031$ |

# Linear Regression Results

Wien0 measured asymmetry after linear regression,

$$A_{msr} = -0.205 \pm 0.031(stat) \pm 0.012(syst.)\ ppm$$

- The results from the two IHWP are combined by computing the weighted average of OUT and the opposite of the IN results, Avg(IN,-OUT)
- Ideally, the residual false asymmetry should to be zero after applying the linear regression
    - Worst HCBA during Wien0
    - Background contamination
    - Underlying issues related to the linear regression

# Systematic Error Summary

The systematic errors on $A_{msr}$

| Source | Error | Estimate (ppm) |
|---|---|---|
| Regression | Scheme dependence | ±0.007 |
| | Double peaking | ±0.008 |
| | Cut dependence | ±0.001 |
| | Non-linearity | ±0.004 |
| Regression | Total | ±0.011 |
| Transverse leakage | | ±0.004 |
| Total Systematic | | ±0.012 |

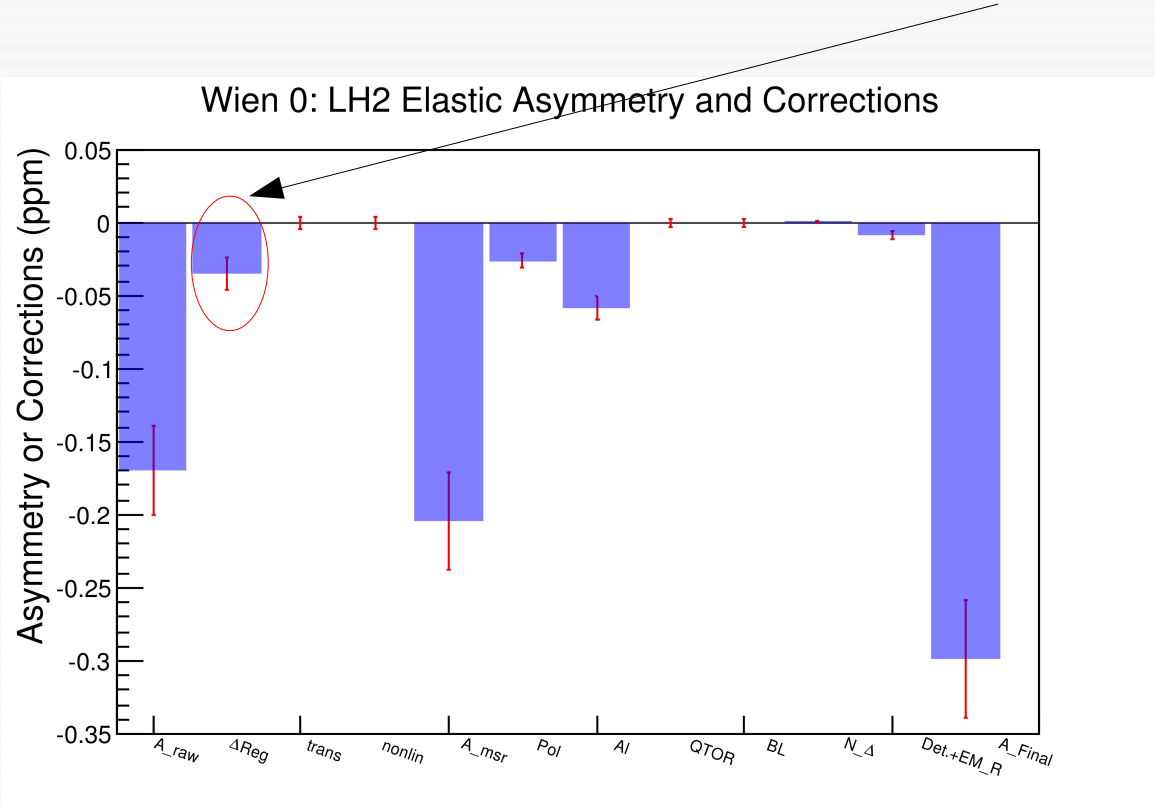
- Regression errors are related to underlying issues related to linear regression
- Transverse leakage: Electron beam has a non-zero transverse polarized component that generates a parity conserving asymmetry
    - During Wien0, the estimated residual transverse polarization in the electron beam is,
        - -3.8 ± 0.9% from horizontal and 4.2 ± 0.9% from vertical transverse polarizations

# Regression Errors

- The regression correction depends on which independent parameters used,
    - Charge-to-no-charge
    - Target-BPM-to-individual-BPMs
    - Error associated with this is difference in regressed asymmetry between schemes
        - Resultant error = 0.007 ppm (doc-db 1610, Katherine )
- Double peaking on beam properties induces an error on the regression slopes – e-log 772 Kent Paschke
    - Resultant error = 0.008 ppm
- Cut dependence error  (doc-db 1610, Katherine )
    - Resultant error = 0.004 ppm

# Regression Summary

- Total correction to the raw asymmetry,
  - Regression correction = 0.0351 ± 0.0114 ppm



# Background Corrections

- Measured yield consists of scattered elastic electrons (96.4%)
- Rest contains,
  - Aluminum target window (3.2%), neutrals (0.4%), inelastic (0.02%)

The list of Qweak backgrounds

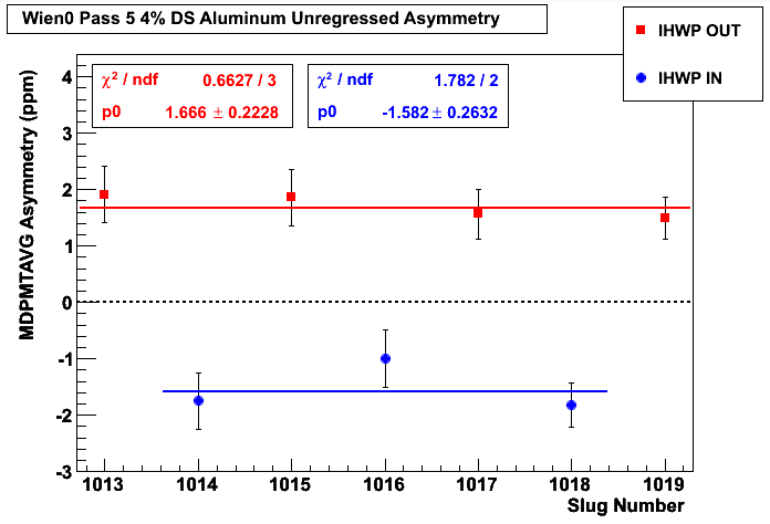
| Background | Dilution, $f_{bi}$ | Asymmetry, $A_{bi}$ (ppm) |
|---|---|---|
| Al window background, b1 | $0.0323 \pm 0.0021$ | $1.7581 \pm 0.2582$ |
| QTOR transport channel, b2 | $0.0019 \pm 0.0019$ | $0.0000 \pm 0.2000$ |
| Beam-line background, b3 | $0.0019 \pm 0.0006$ | $-5.5000 \pm 11.5000$ |
| $N \rightarrow \Delta$ inelastic, b4 | $0.0002 \pm 0.0002$ | $-3.0200 \pm 0.9700$ |

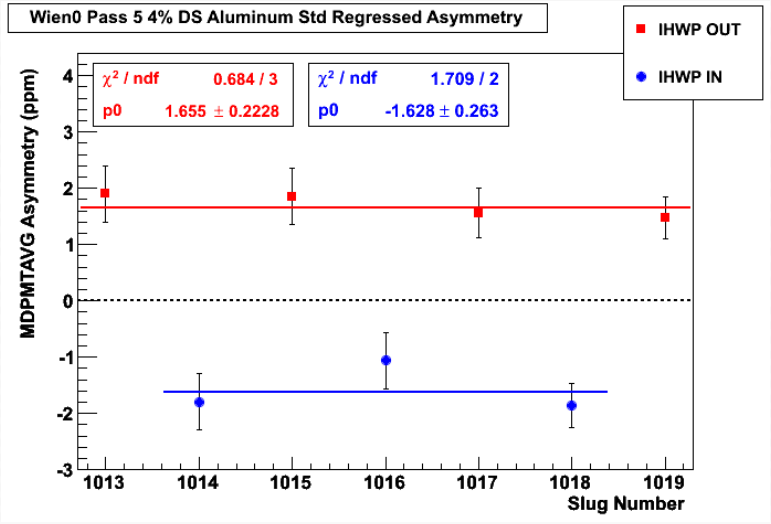
How backgrounds are corrected,

$$Y_{total} = Y_{\tilde{e}p} + \sum_{i=1}^{N} y_{bi}, \; f_{bi} = \frac{y_{bi}}{Y_{total}}$$

$$\frac{A_{msr}}{P_e} = (1 - f_{Total})A_{\vec{e}p} + \sum_{i=1}^{N} \frac{y_{bi}}{Y_{total}} \cdot A(y_{bi})$$

# Al Window Background Asymmetry



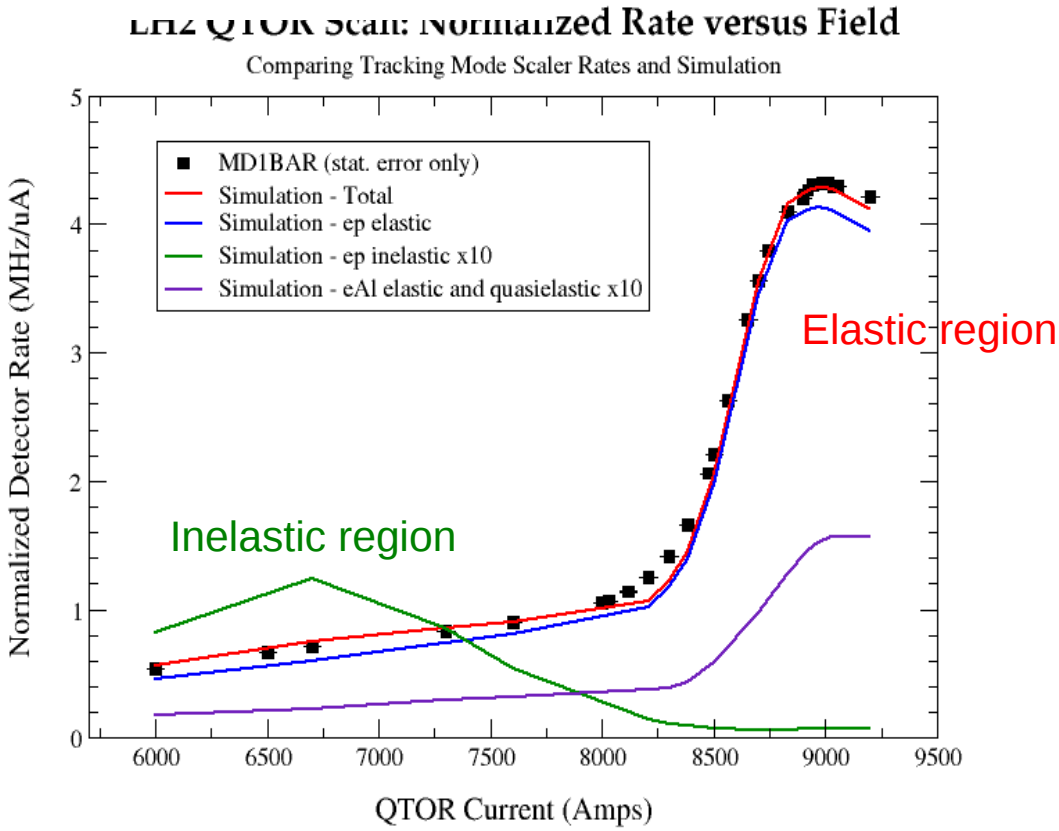

- Std. regressed Al asymmetry (e-log 743),
  - $A_{msr}$ = 1.645 ± 0.170 ppm (stat. Error)
- Correct the asymmetry for QTOR transport and beamline backgrounds to get final asymmetry (e-log 753),
  - $A_{final}$ = 1.8630 ± 0.1948 (stat.) ± 0.0492 (syst.) ppm
- The radiatively corrected asymmetry (e-log 748),
  - $A_{rad.cor}$ = 1.7385 ± 0.1918 ppm
- The dilution (elog 744)
  - f1 = 0.03226 +- .0001 (stat) +- 0.0004 (sys) +- 0.0021 (radiative model-uncertainty).

# Ancillary:N →Δ PV Inelastic Asymmetry

- N →Δ PV Inelastic Asymmetry dilutes the elastic PV asymmetry
  - 0.1 % dilution and 1% correction

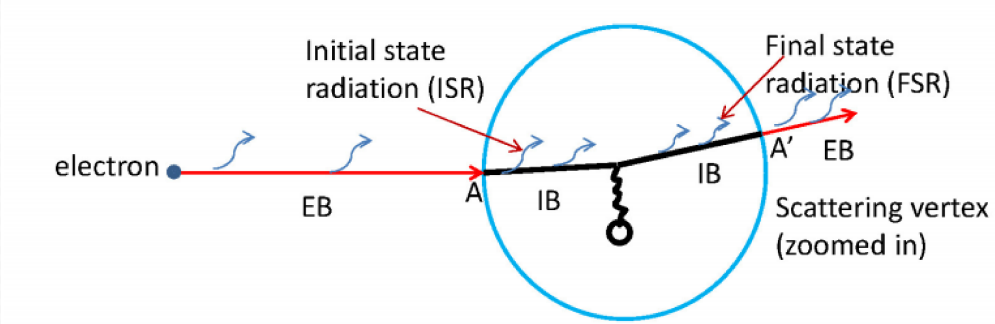
$$A_{\text{IN-PV}} = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\left[\Delta^{\pi}_{(1)} + \Delta^{\pi}_{(2)} + \Delta^{\pi}_{(3)}\right]$$

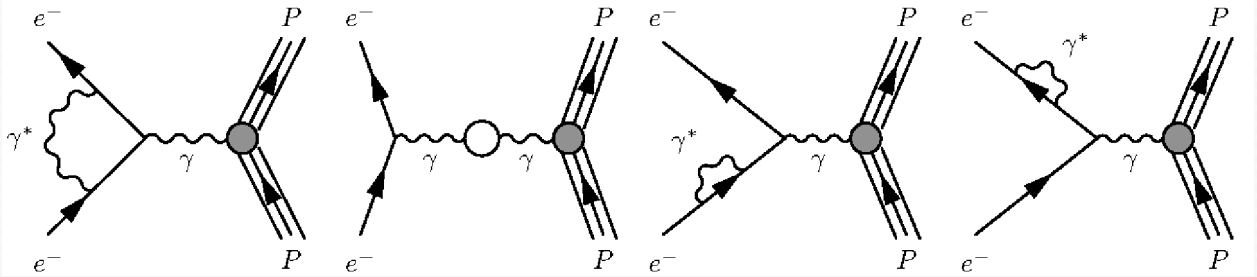
Important standalone physics measurement



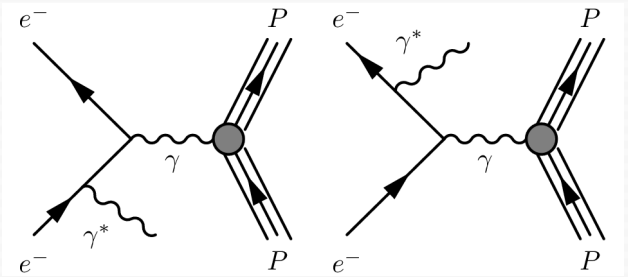
# Experimental Bias Corrections

- EM radiative effects result in modification of the measured asymmetry and momentum transfer ($R_{RC}$)
  - depolarization of the incident electron
  - energy loss and angle change



virtual photons and loop effects



Bremsstrahlung photon emission

# Experimental Bias Corrections

- Remove Čerenkov detector bias ($R_{Det}$)
- Transform acceptance averaged asymmetry to asymmetry quoted at Qweak effective kinematics
  - $A_{\tilde{e}p}(< Q^2 >) = R_{eff_acc} < A_{\tilde{e}p}(Q^2) >$

$$A_{\vec{e}p} = R_{exp} \times \cdots$$

Where,

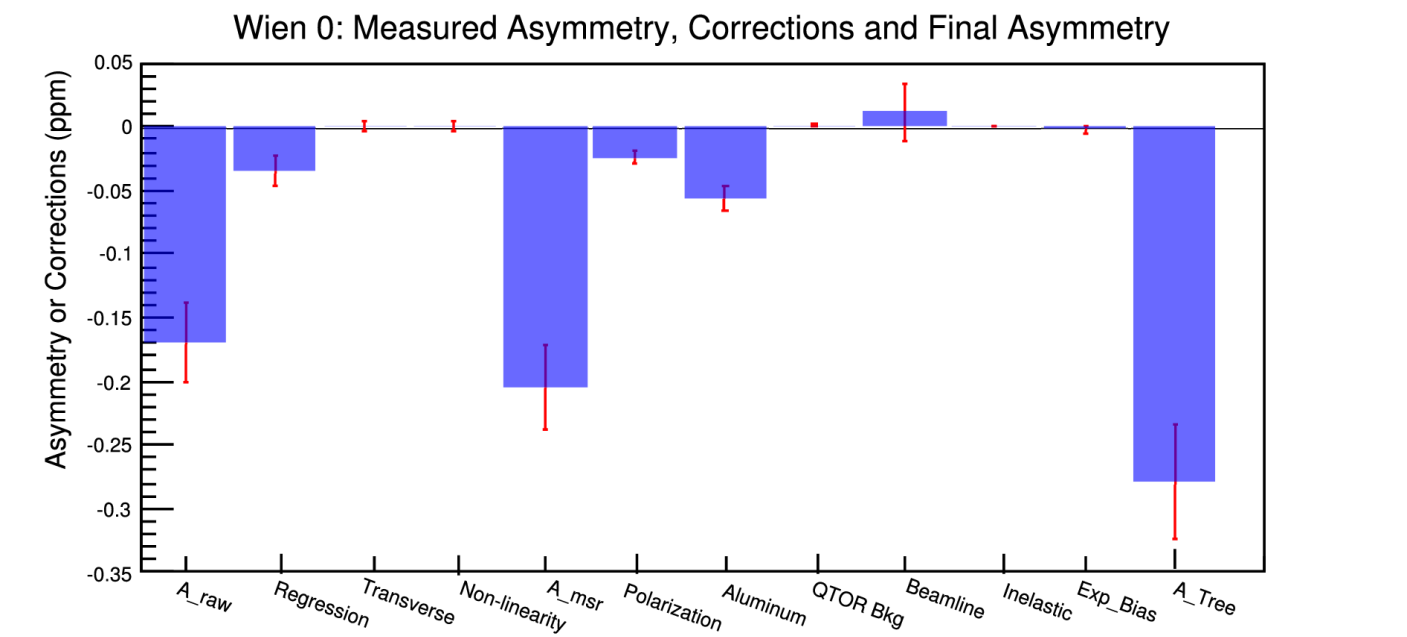
$$R_{exp} = R_{RC} \times R_{Det} \times R_{eff_acc} = 0.9769 \pm 0.0082$$

# Correction Summary

$$A_{msr} = -0.205 \pm 0.031(stat) \pm 0.012(syst.)\ ppm$$

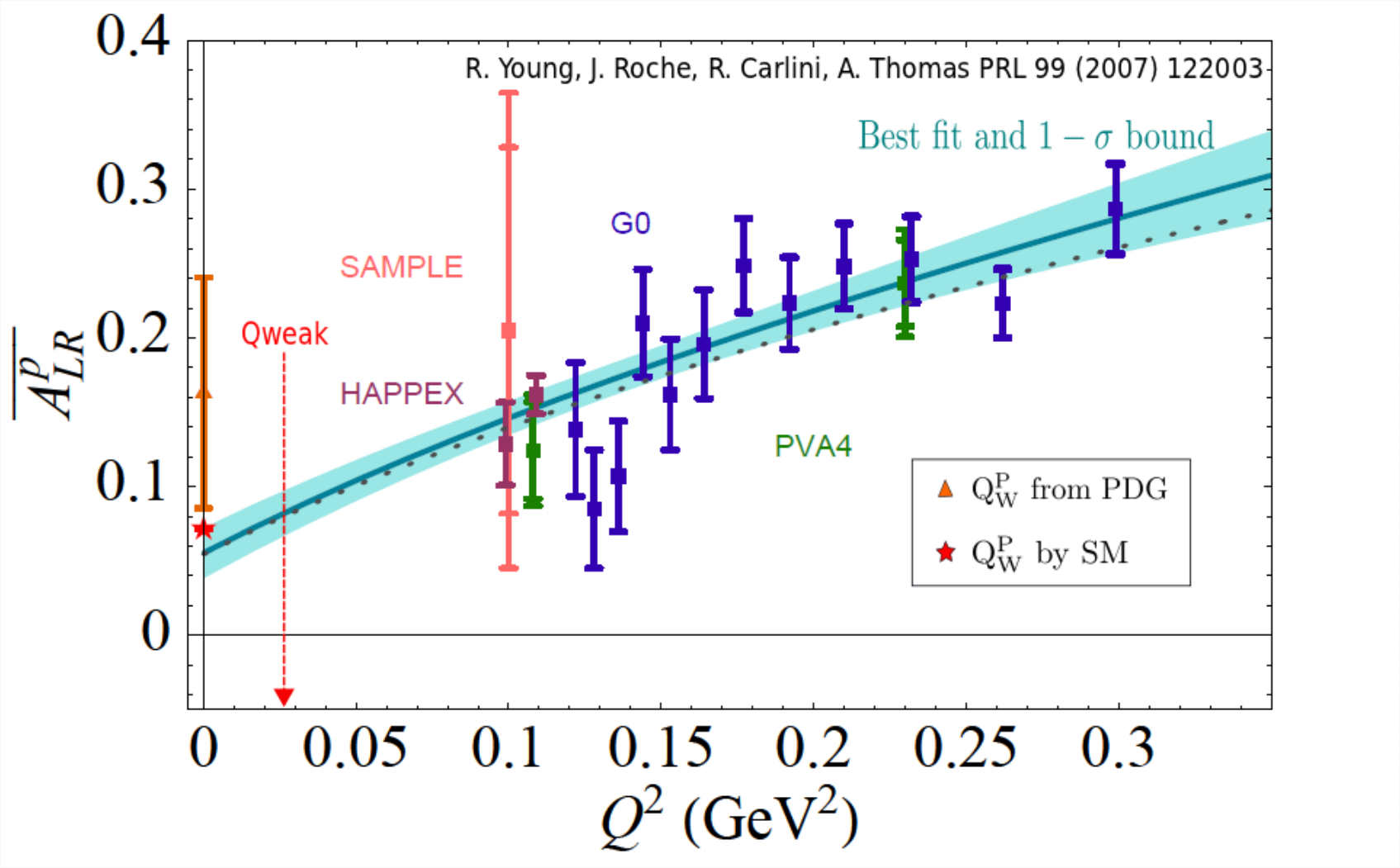
The breakdown of Corrections to $A_{msr}$ for Wien0 data

| Source | Correction to $A_{msr}$ (ppm) |
|---|---|
| Polarization, $\Delta A_P$ | -0.0257 |
| Aluminum windows, $\Delta A_{b1}$ | -0.0576 |
| QTOR transport channel, $\Delta A_{b2}$ | 0.0000 |
| Beam-line, $\Delta A_{b3}$ | +0.0108 |
| $N \rightarrow \Delta$, $\Delta A_{b4}$ | +0.0006 |
| $R_{exp}$ | -0.0028 |
| Total | $-0.0747$ |



# Results

# Qweak:PVES Global Fit




$$\overline{A_{LR}^P} \propto (Q_W^P + Q^2 B(Q^2))$$

# Weak Mixing Angle

- Weak mixing angle can now be extracted using the measured weak charge of the proton
    - Tree-level weak charge is computed by removing electroweak radiative corrections and then weak mixing angle is extracted

$$\mathrm{Q}_{\mathrm{W}}^{\mathrm{p}}(\mathrm{msr}) = [1.045][1 - 4 \cdot \sin^2\hat{\theta}_{\mathrm{W}}(\mathrm{msr}) - 0.001] + 0.025$$

# Qweak Effective Kinematics

These are the acceptance averaged values that we will quote associated with our result

- Incident beam energy, $E_s = 1155$ MeV
- Momentum transfer $Q^2 = 0.0250 \pm 0.0006$ (GeV/c)$^2$
- Scattering angle, $\theta = 7.90°$
  - Using Eq. 52 of HAPPEX paper
- See detailed e-log 769 by A. Subedi and 794 by M. Pitt

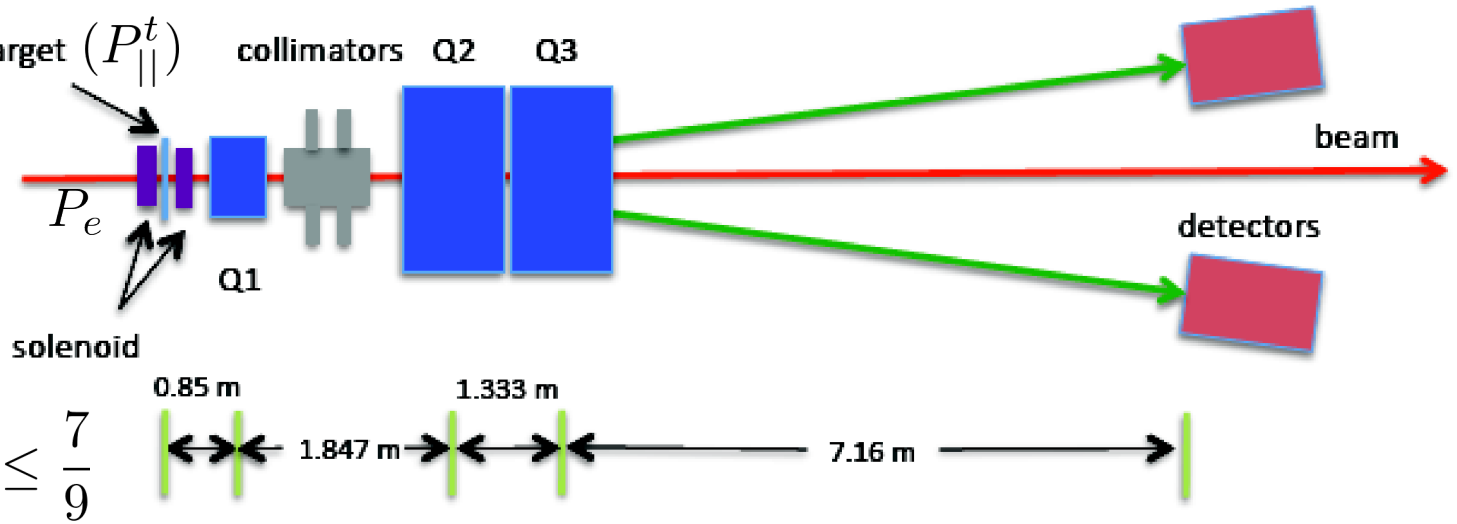
HAPPEX paper: Phys.Rev. C69 (2004) 065501

$$E_s = \left\langle E_{\text{beam}} - \frac{dE}{dx} t \right\rangle. \qquad (51)$$

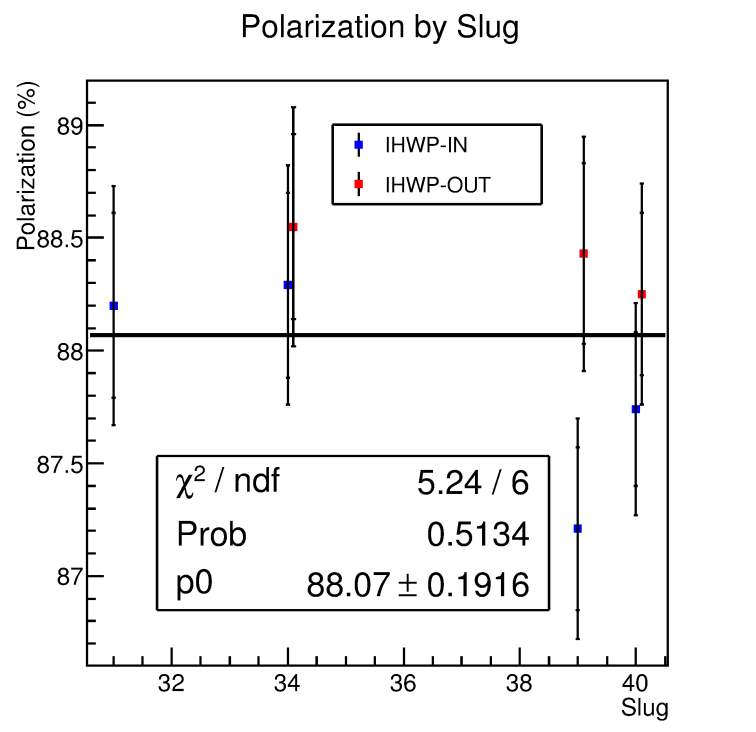
$$\cos(\theta_{\text{eff}}) = \frac{1 - (Q^2/(2E_s^2))(1 + E_s/M)}{1 - (Q^2/(2E_s^2))(E_s/M)}. \qquad (52)$$

# Møller Polarization Summary

$$\frac{d\sigma}{d\Omega} = \sigma_0[1 - P_e P_{||}^t A_{||}(\theta)]$$



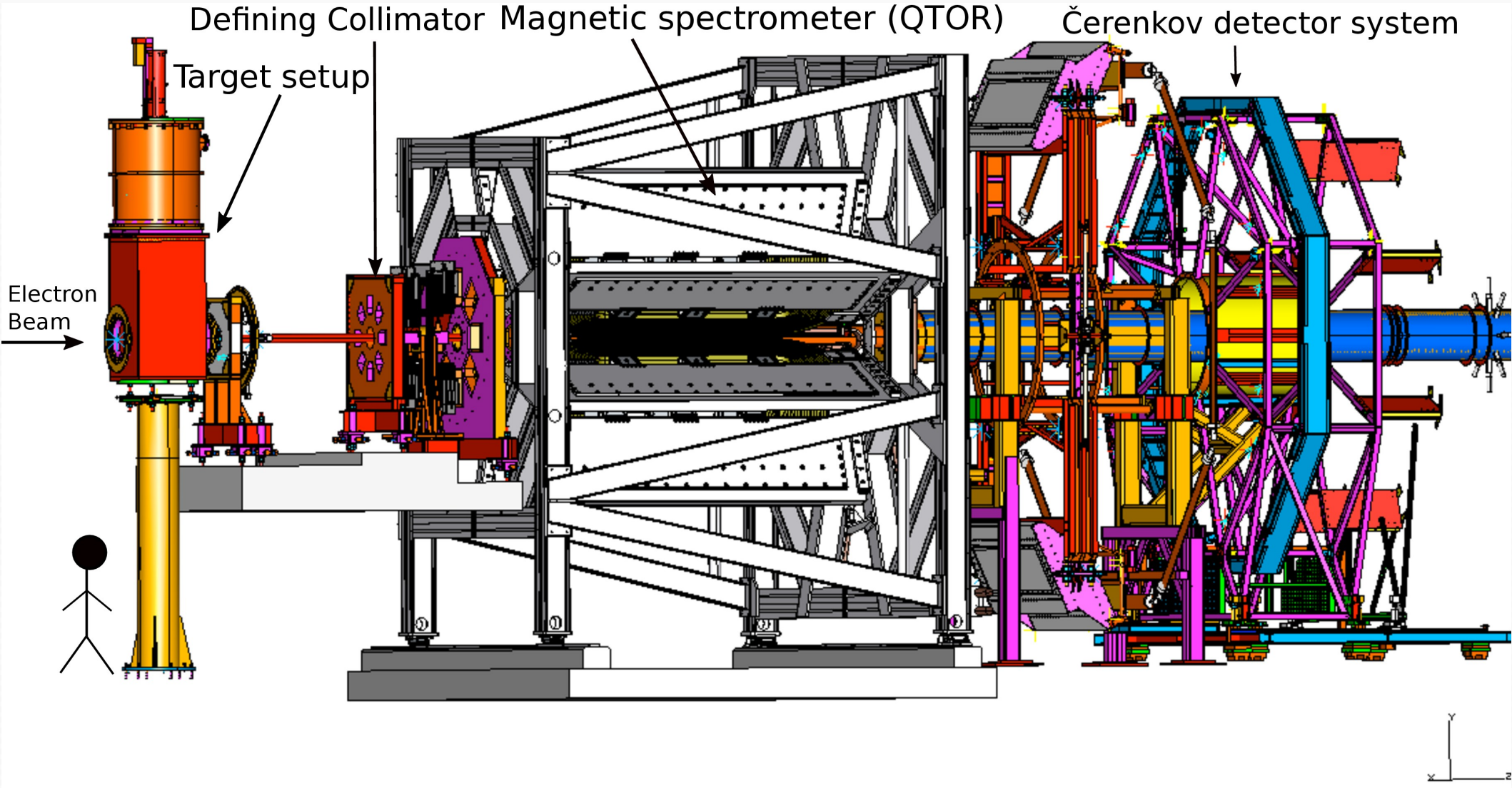

$$A_{||}(\theta) = \frac{(7 + cos^2\theta)sin^2\theta}{(3 + cos^2\theta)^2} \leq \frac{7}{9}$$




- Primary beam polarimetry during Wien0
- Polarized Møller scattering to measure electron beam polarization
- Disruptive measurement done at every 2-3 days at about 1 μA
- Beam polarization, $P_e$ = 88.95 ± 1.83%

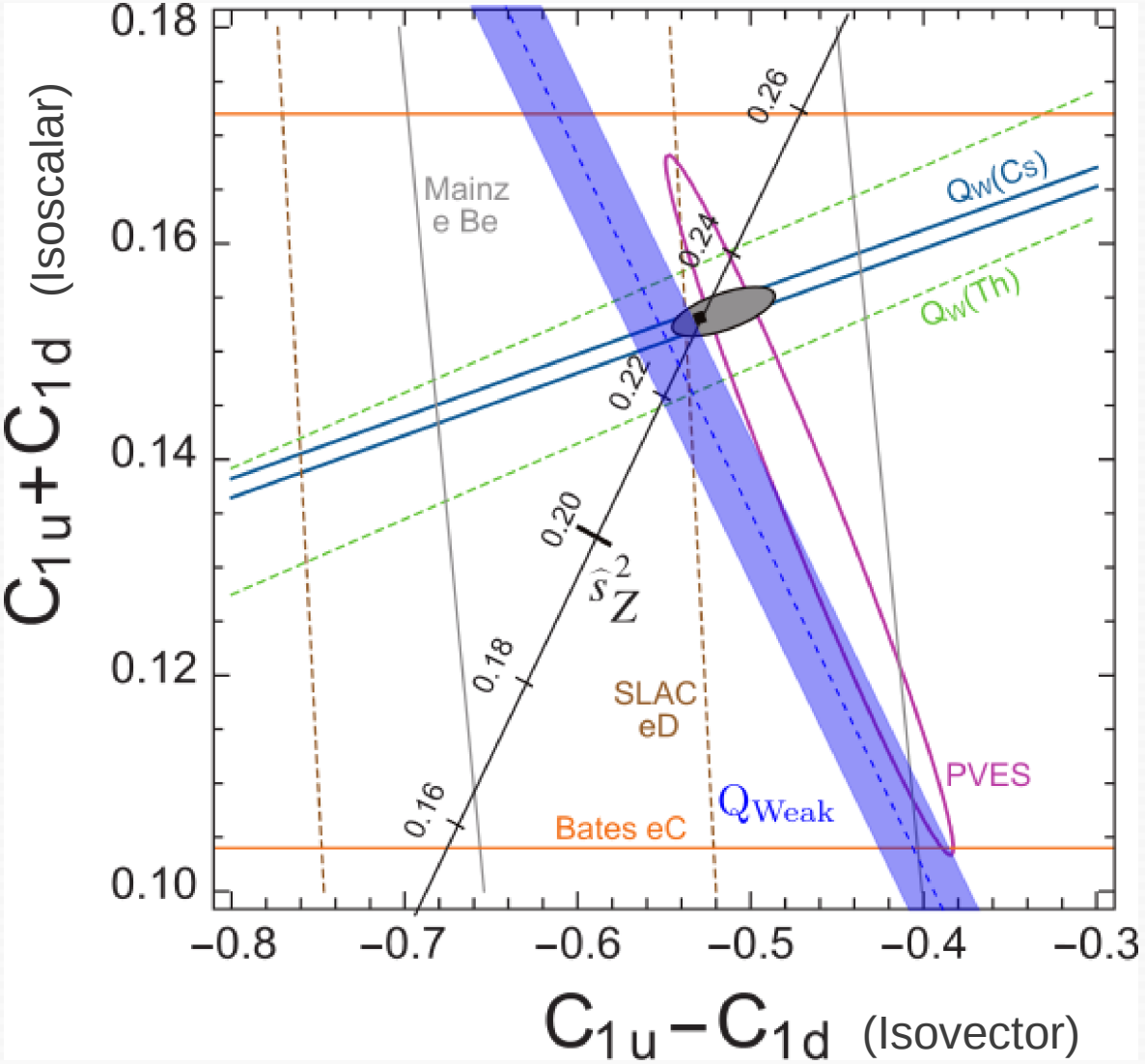
http://sro0.wordpress.com/2006/11/01/o-zoologico-das-particulas-elementares/

# The Experiment:Apparatus CAD View



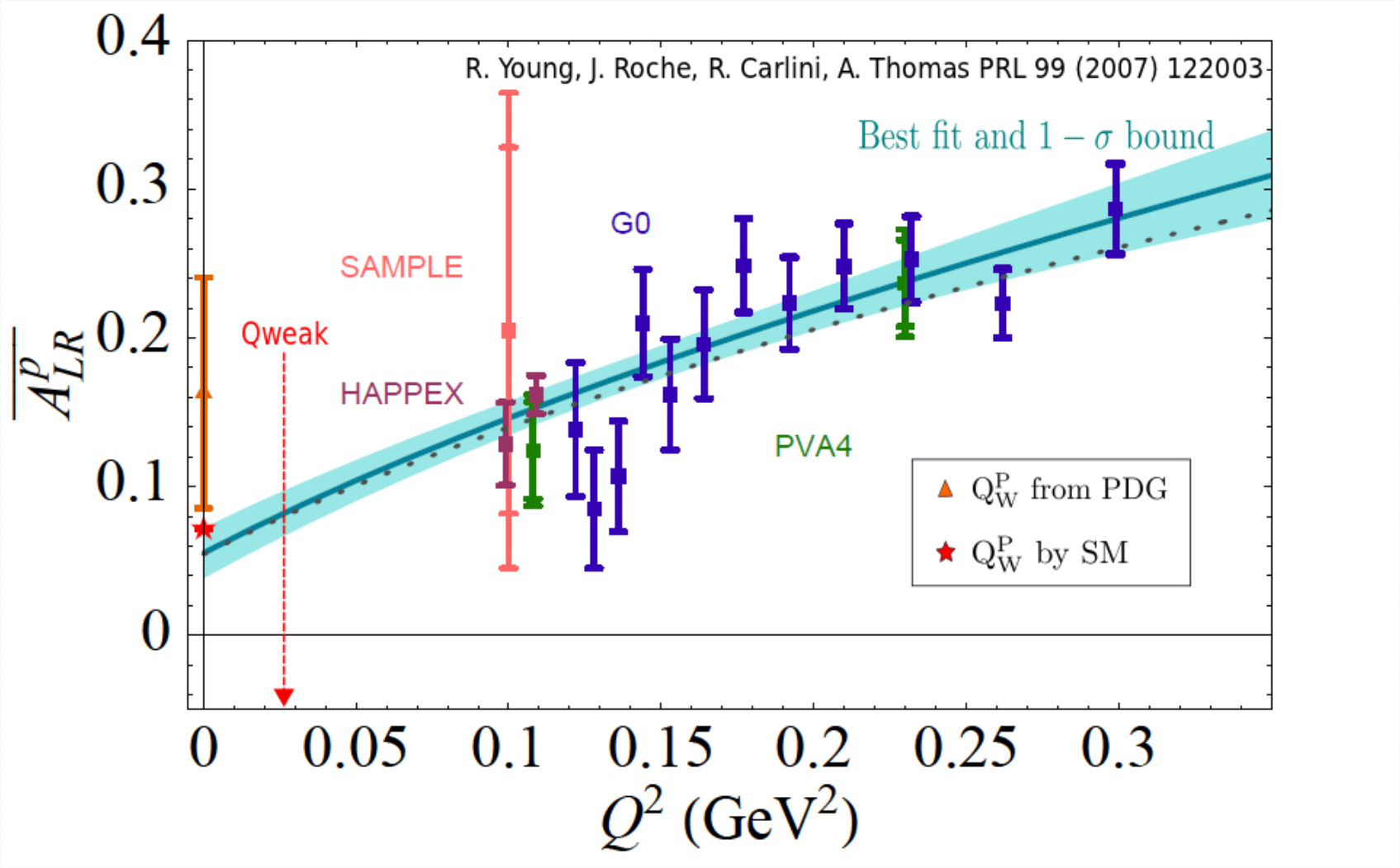
# Final Results

- Hadronic vector currents are build using only lightest quarks (u,d, and s)
- The weak charge of the proton is used to constrain the couplings for weak neutral hadronic vector currents in the SM
- Combination Atomic PV and Qweak results can be used to extract $C_{1u}$ and $C_{1d}$




J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)

# PV Asymmetry Global Analysis




$$\overline{A_{LR}^P} \propto (Q_W^P + Q^2 B(Q^2))$$