Qweak: A Precision Standard Model Test at Jefferson Lab

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Qweak uses parity-violating elastic electron-proton scattering to measure the proton's weak charge at Jefferson Lab

- Precision Standard Model test
- tests "running of $\sin^2\theta_W$" from M^2_Z to low Q^2
- sensitive to new TeV scale physics

- Background: What and Why?
- The Science
- The Experiment
- Status and Outlook

* Work partially supported by the National Science Foundation

The Collaboration

Funded by DOE, NSF, NSERC

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[1]Spokespersons *deceased [2]Project Manager

The Q_{weak} Experiment:
A Search for New Physics at the TeV Scale Via a
Measurement of the Proton's Weak Charge

December 3, 2001

D. Armstrong[1], T. Averett[1], J.D. Bowman[5], R. Carlini[9] (contact person), C.A. Davis[11] J. Erler[3], R. Ent[9], M. Finn[1], T.A. Forest[6], K. Johnston[6], R. Jones[2], S. Kowalski[8], L. Lee[7], A. Lung[9], D. Mack[9], S.A. Page[7], S. Penttila[5], M. Pitt[10], M. Poelker[9], W.D. Ramsay[7], M. Ramsey-Musolf[2,4], J. Roche[1,9], N. Simicevic[6], G. Smith[9], R. Suleiman[8], S. Taylor[8], W.T.H. van Oers[7], S. Wells[6], S. Wilburn[5], S.A. Wood[9]

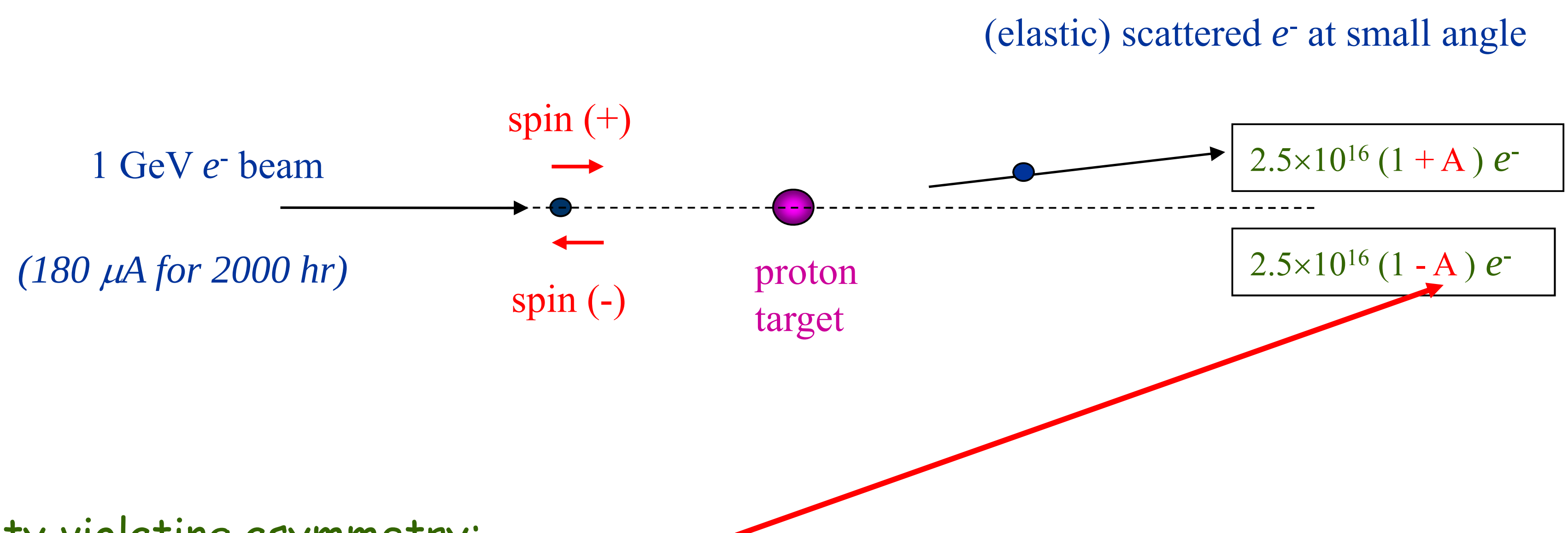
Timeline

- *Proposal 2001*
- *Design/Construction 2003 – 2010*
- *Data-taking 2010 - 2012*
- *Now ~ 100 collaborators!*

The Qweak Experiment: Essentials

Elastic scattering of longitudinally polarized electrons on protons

$$\vec{e}^{\,-} + p \rightarrow e^- + p$$

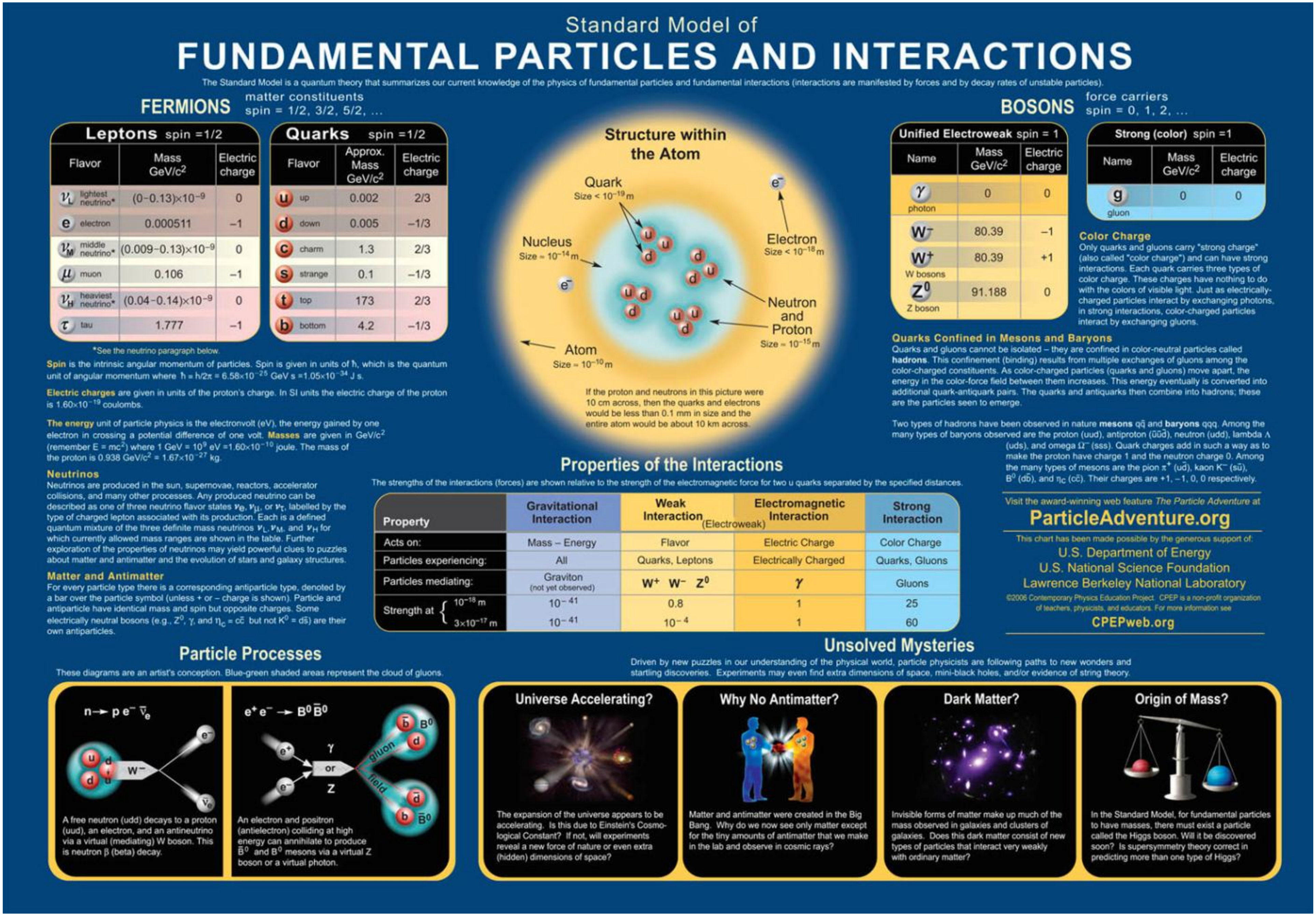


Parity violating asymmetry:
$A \sim -2.3 \times 10^{-7}$ or - 0.23 ppm (parts per million)
or -230 ppb (parts per billion)

proportional to the proton's weak charge ("Qweak")

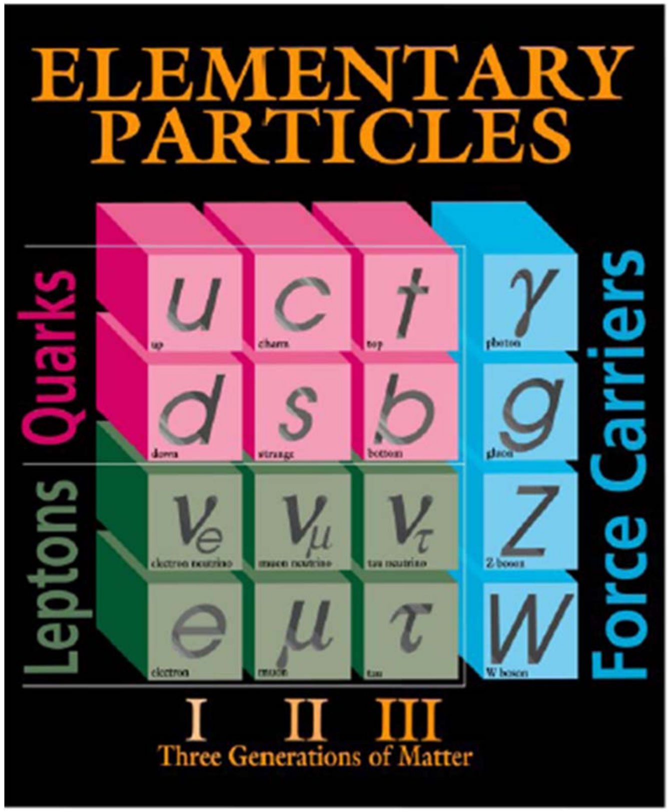
Asymmetry measured with precision of 2% $\rightarrow$ sensitive Standard Model test

The Standard Model



Elastic electron-proton scattering – Standard Model "Players"

In the Standard Model, the electron and proton interact through two of the four fundamental forces – weak and electromagnetic – the unified "electroweak" force



$$\vec{e}^{\,-} + p \rightarrow e^- + p$$

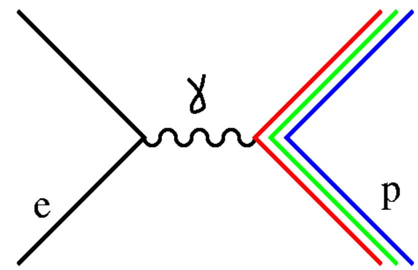
Participants:

proton – 2 up quarks, 1 down quark (u u d)
mass = 0.938 GeV/c^2

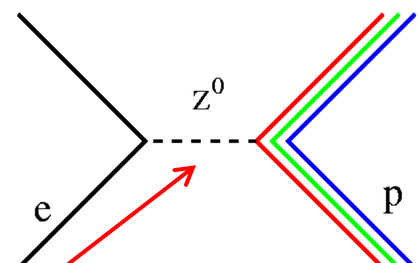
electron – mass = 0.000511 GeV/c^2

Force carriers:

Electromagnetic:
γ - photon – mass = 0 GeV/c^2



Weak:
Z^0 boson – mass = 91 GeV/c^2



Z^0 produced virtually;
Heisenberg ($\Delta E\ \Delta t$ > h) says its okay!

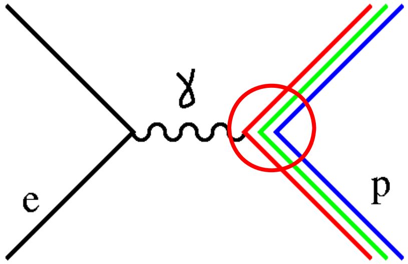
Elastic electron-proton scattering - Standard Model Couplings

The Standard Model prescribes the couplings of the fundamental particles to each other →

	Q^γ	Q^Z
u	+2/3	$1 - 8/3 \sin^2\theta_W$
d	−1/3	$-1 + 4/3 \sin^2\theta_W$

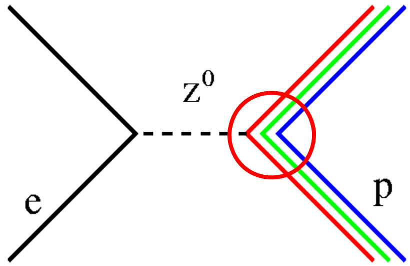
Electromagnetic force → proton's electric charge

$$Q^p = 2\left(+\frac{2}{3}\right) + 1\left(-\frac{2}{3}\right) = +1$$



Weak force → proton's neutral weak charge - Q_{weak}

$$Q^p_{weak} = 2\left(1 - 8/3\sin^2\theta_W\right) + 1\left(-1 + 4/3\sin^2\theta_W\right)$$
$$= 1 - 4\sin^2\theta_W$$

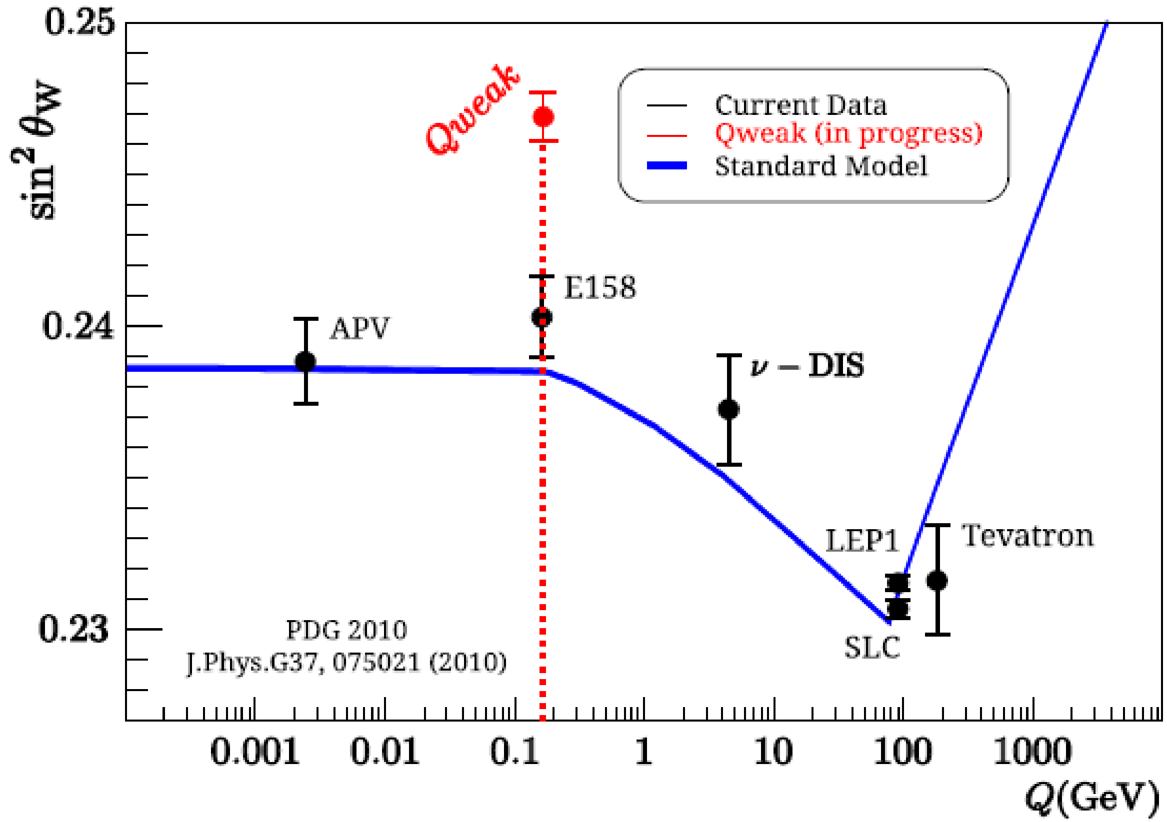


What is $\sin^2\theta_W$ – "weak mixing angle"? → key parameter of the Standard Model

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

$\sin^2\theta_W$ – "weak mixing angle", parameterizes the mixing between the two neutral currents in the model → needs to be determined from experiment

"Running" of the Weak Mixing Angle - $\sin^2\theta_W$



"Running" of the weak mixing angle → key prediction of the Standard Model
(Q = 4-momentum transfer between scattering particles)

- Experimental Standard Model measurements (cross sections, asymmetries, decay rates, etc. in electroweak processes) extract values of $\sin^2\theta_W$
  → success of SM is due to internal consistency of these values

- If an experiment disagrees with the SM prediction then it could be a signature of "New Physics"

The Hunt for New Physics

Isn't new physics supposed to come from energies > 1000 GeV = 1 TeV?

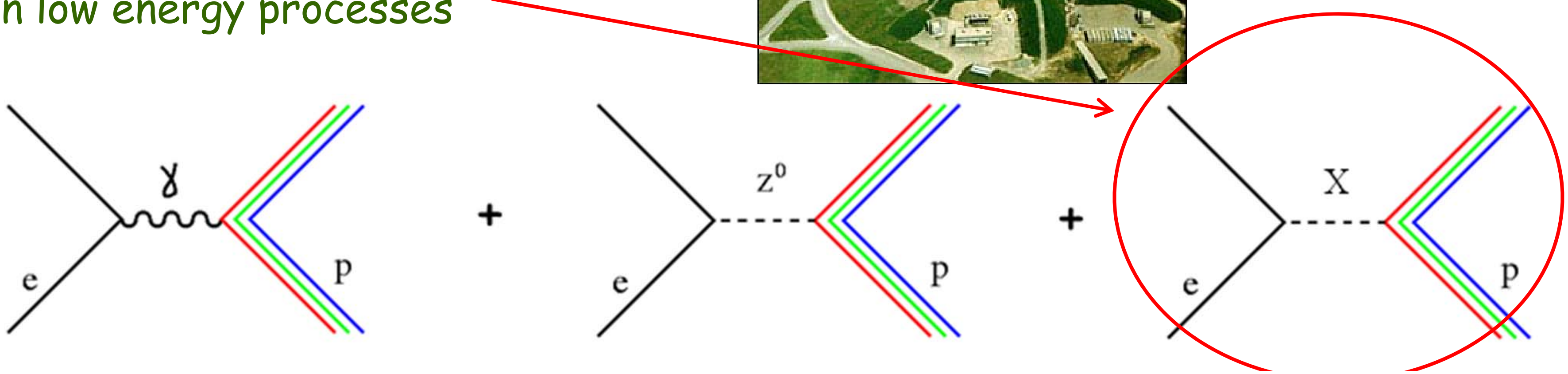
How can Q_{weak} (scattering experiment with beam energy 1 GeV) hunt for New Physics?

"Energy frontier"
- like LHC – Large Hadron Collider

→ Make new particles ("X") directly in high energy collisions

"Precision frontier"
- like Jefferson Lab

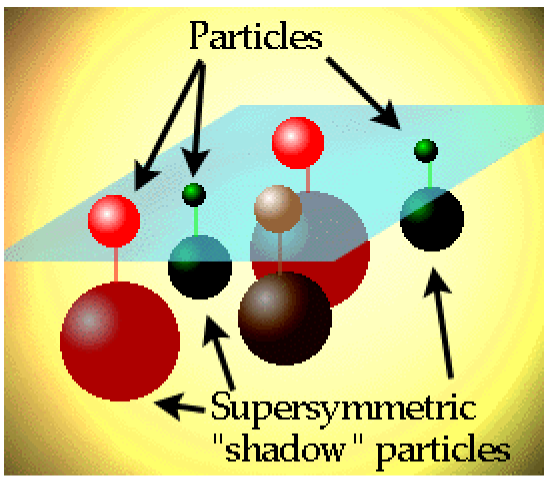
→ Look for indirect effect of new particles ("X") made virtually in low energy processes

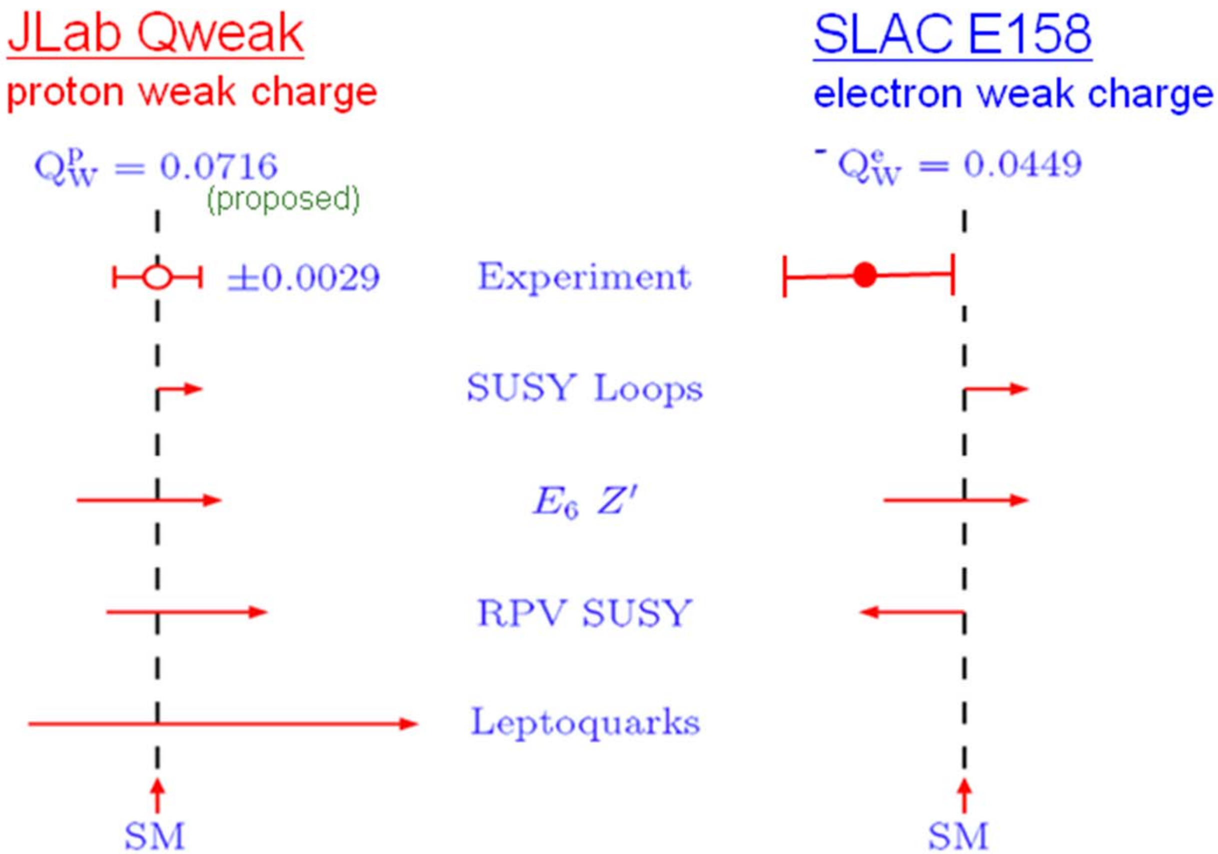


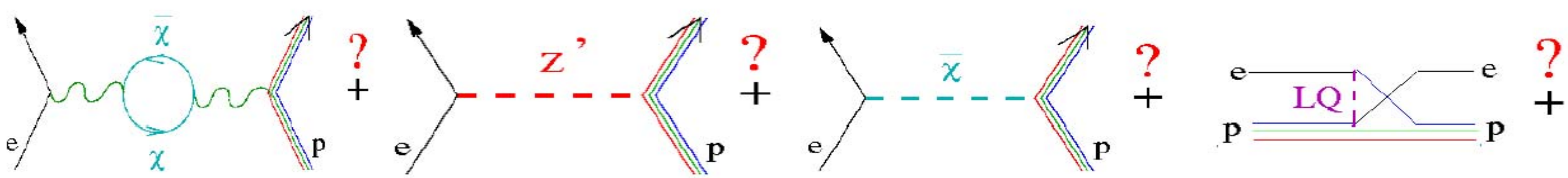
Q_{weak} "New Physics" Sensitivity

What kinds of New Physics is Qweak sensitive to?

→ supersymmetry, heavy Z', leptoquarks, …







RPC SUSY   Generic Z'   RPV SUSY   Leptoquarks

New Physics Energy Reach of Q_{weak}

What energy scales can a precision 4% measurement of Q_{weak} reach?

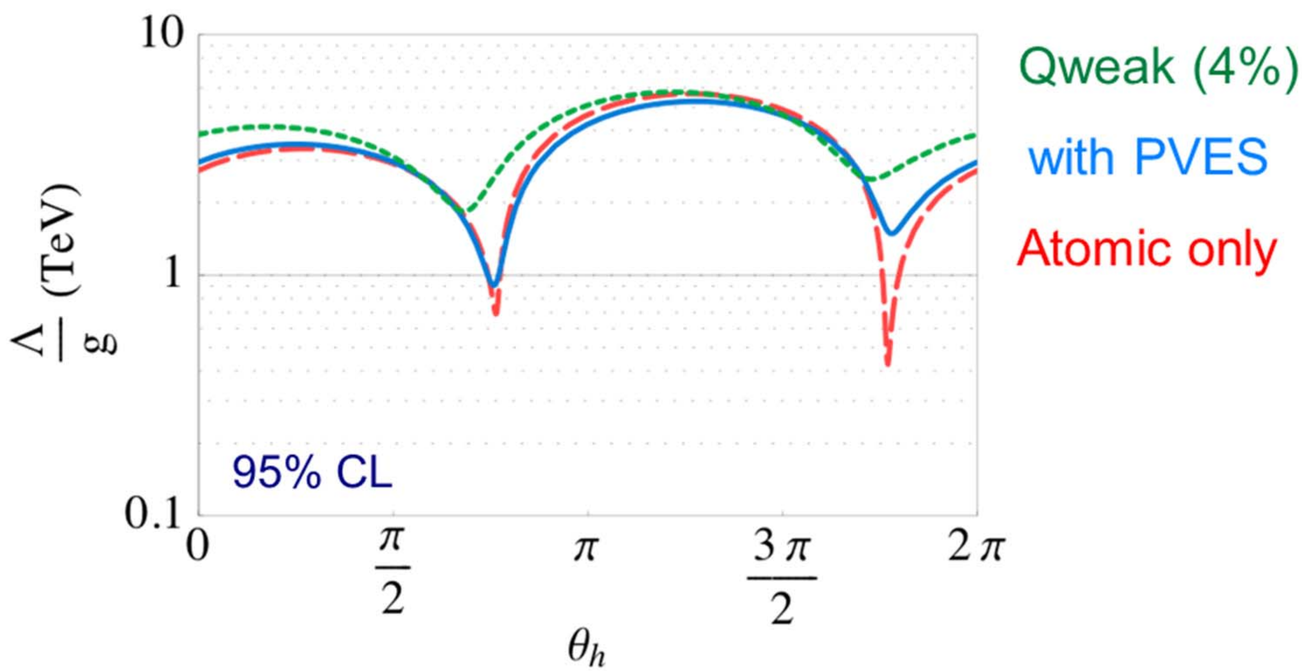
Parameterize new physics with a new contact interaction in the Lagrangian:

$$\mathcal{L}_{\mathrm{NP}}^{\mathrm{PV}} = -\frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

g=coupling
Λ=mass scale

Arbitrary quark flavor dependence of new physics:

$$h_V^u = \cos\theta_h \qquad h_V^d = \sin\theta_h$$



Qweak constrains new PV physics to beyond 2 TeV

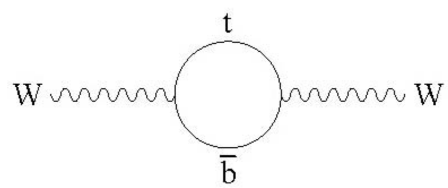
Young, Carlini, Thomas & Roche, PRL 99, 122003 (2007)

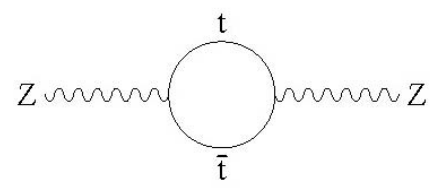
Historical Example: Top Quark

Past example of interplay between energy frontier and precision frontier

"Precision frontier"
Precision electroweak measurements (LEP at CERN and SLD at SLAC) were sensitive to "virtual top quarks" in loops

Prior to the direct top quark discovery, theorists predicted it would fall in a range from 145 GeV/c^2 - 185 GeV/c^2





"Energy frontier"
Top quark was produced directly at Tevatron at Fermilab in 1995

Direct production at energy frontier →

Indirect evidence at precision frontier →

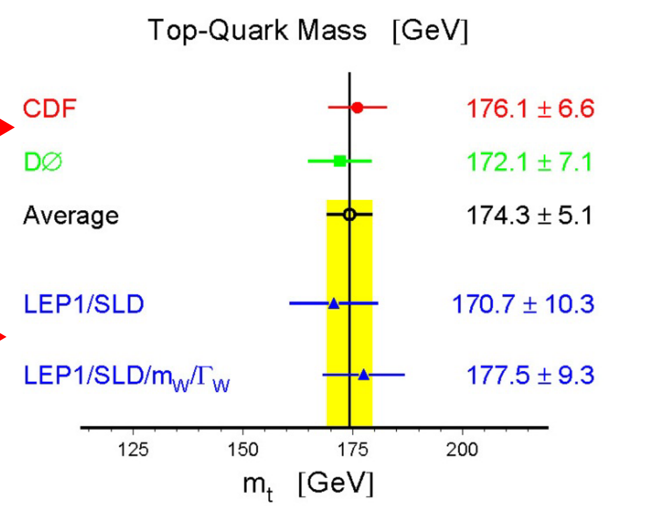
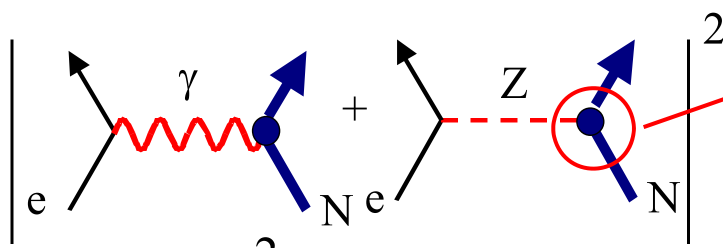


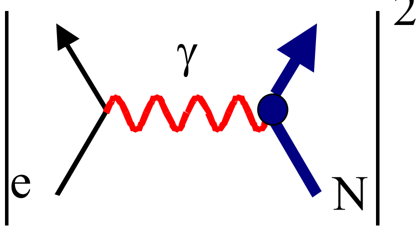
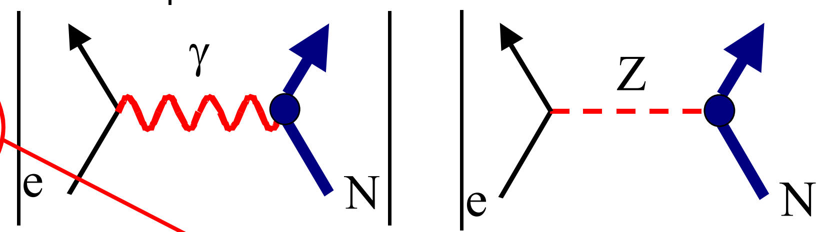
Figure 4. Measurements of the top quark mass at Fermilab (CDF and D0) and indirect predictions from precision measurements (LEP1, SLD and M_W).[3]

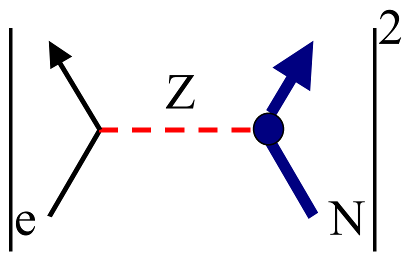
Parity-Violating Asymmetry

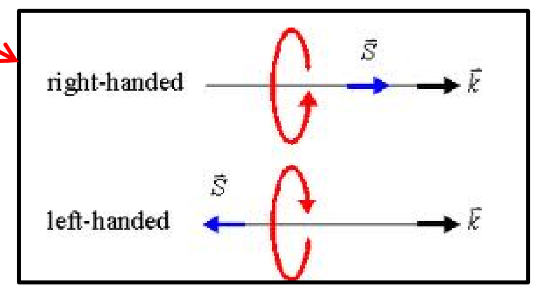
Qweak experiment – exploit the interference between EM and weak interactions

$\sigma \propto$ 

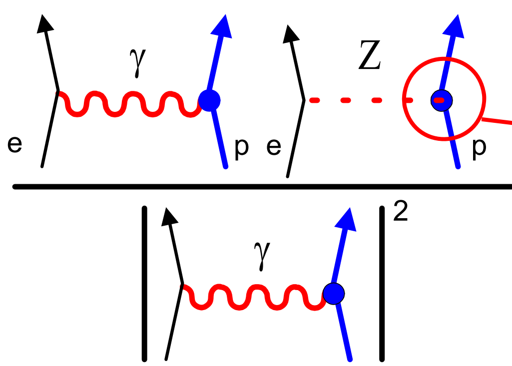
$Q^p_W = 1 - 4\sin^2\theta_W$

$=$  $+\, h_e$ 

$+$ 



$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto$$

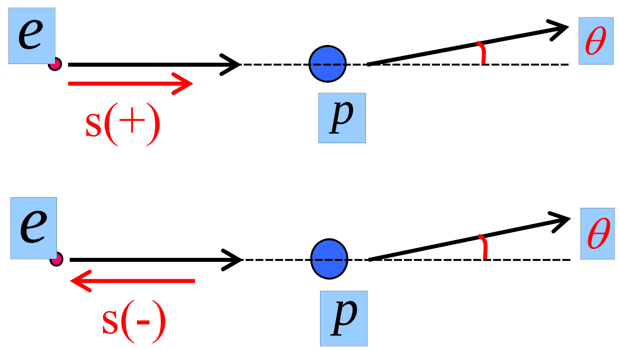


~ -230 ppb

$Q^p_W = 1 - 4\sin^2\theta_W$

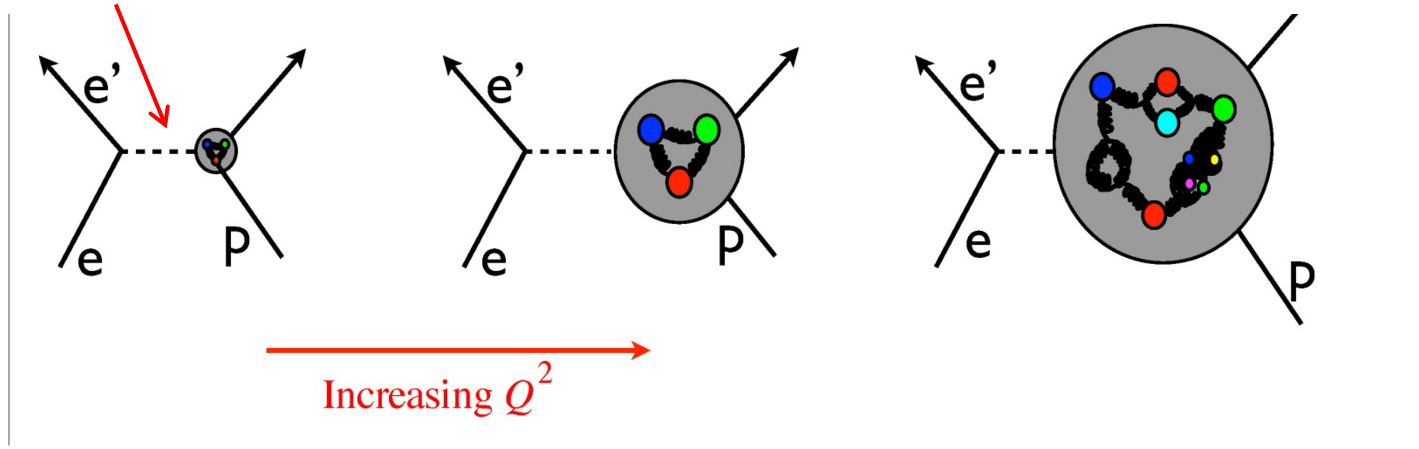
Parity-Violating Asymmetry for the Q_{weak} Experiment

$$A \equiv \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} \xrightarrow[\theta \to 0]{Q^2 \to 0} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 \boxed{Q^p_{weak}} + Q^4 B\left(Q^2\right)\right]$$



"Form factor" correction due to finite proton size – not a pointlike particle

Q^2 = 4-momentum transfer



By running at a small value of Q^2 (small beam energy, small scattering angle) we minimize our sensitivity to the effects of the proton's detailed spatial structure.

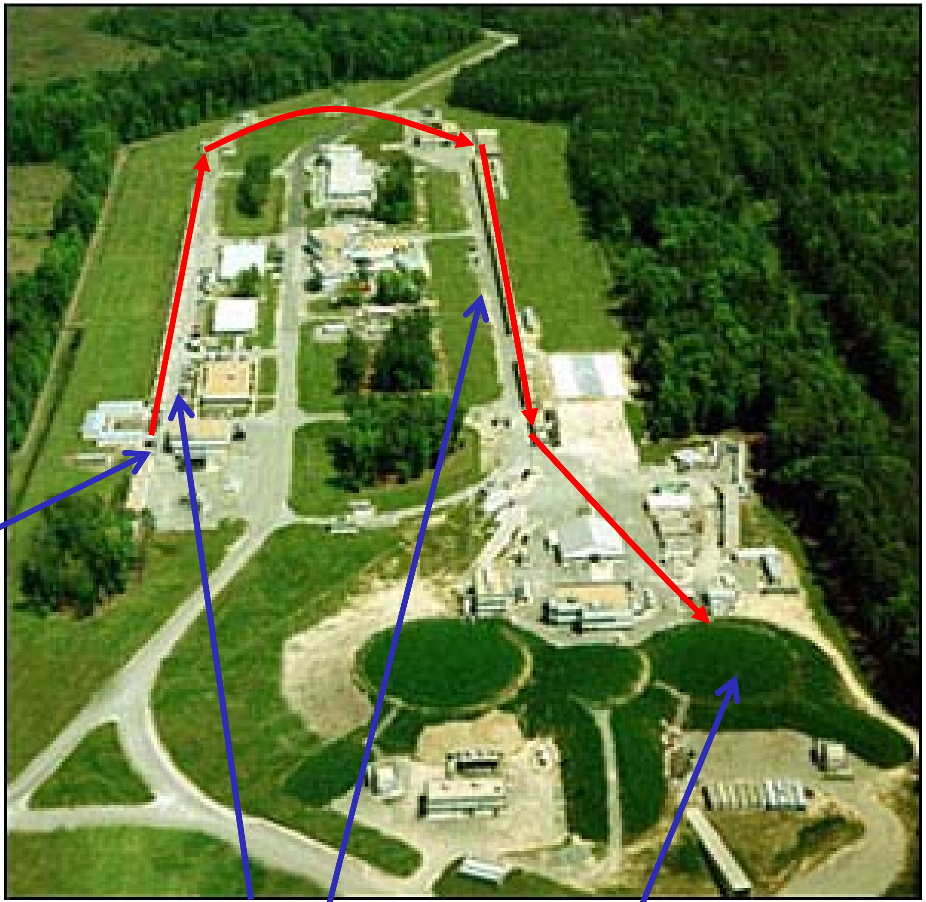
Overview of Jefferson Lab – The Parts Critical to Qweak

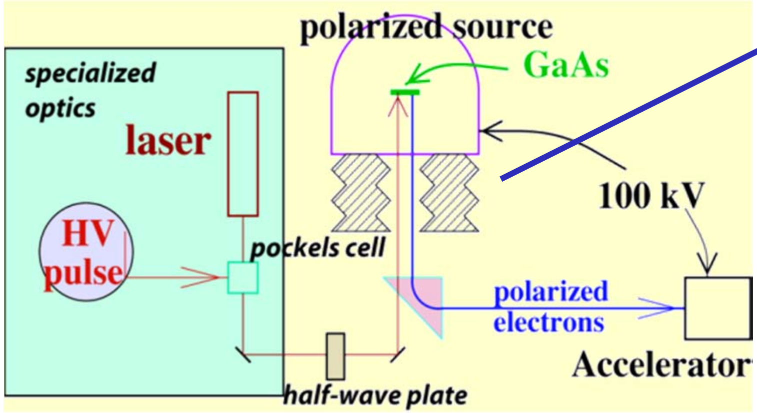
CEBAF Polarized Injector:

→ Polarized electrons photoemitted from GaAs wafer

→ Laser light is polarized; reversed rapidly with high voltage pulses to "Pockels cell"

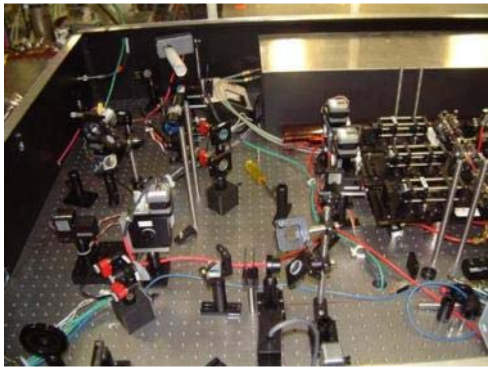
→ Much effort goes into insuring that position, angle, intensity, of laser beam doesn't change with "flip" – only circular polarization

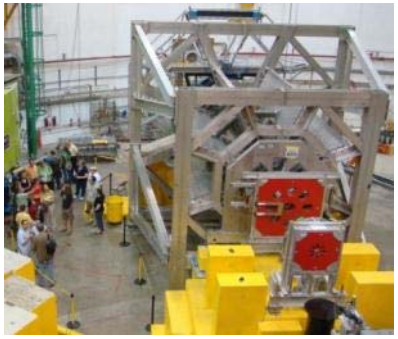




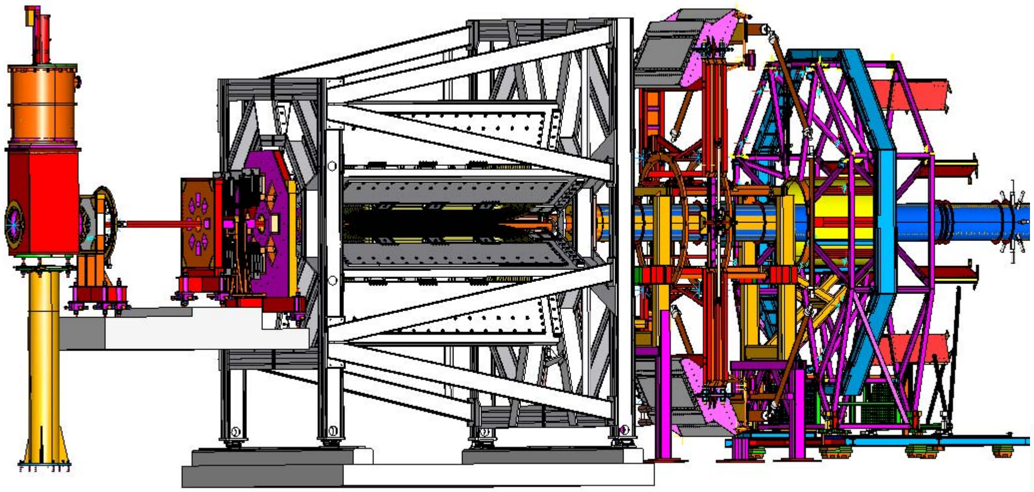
Linear Accelerators

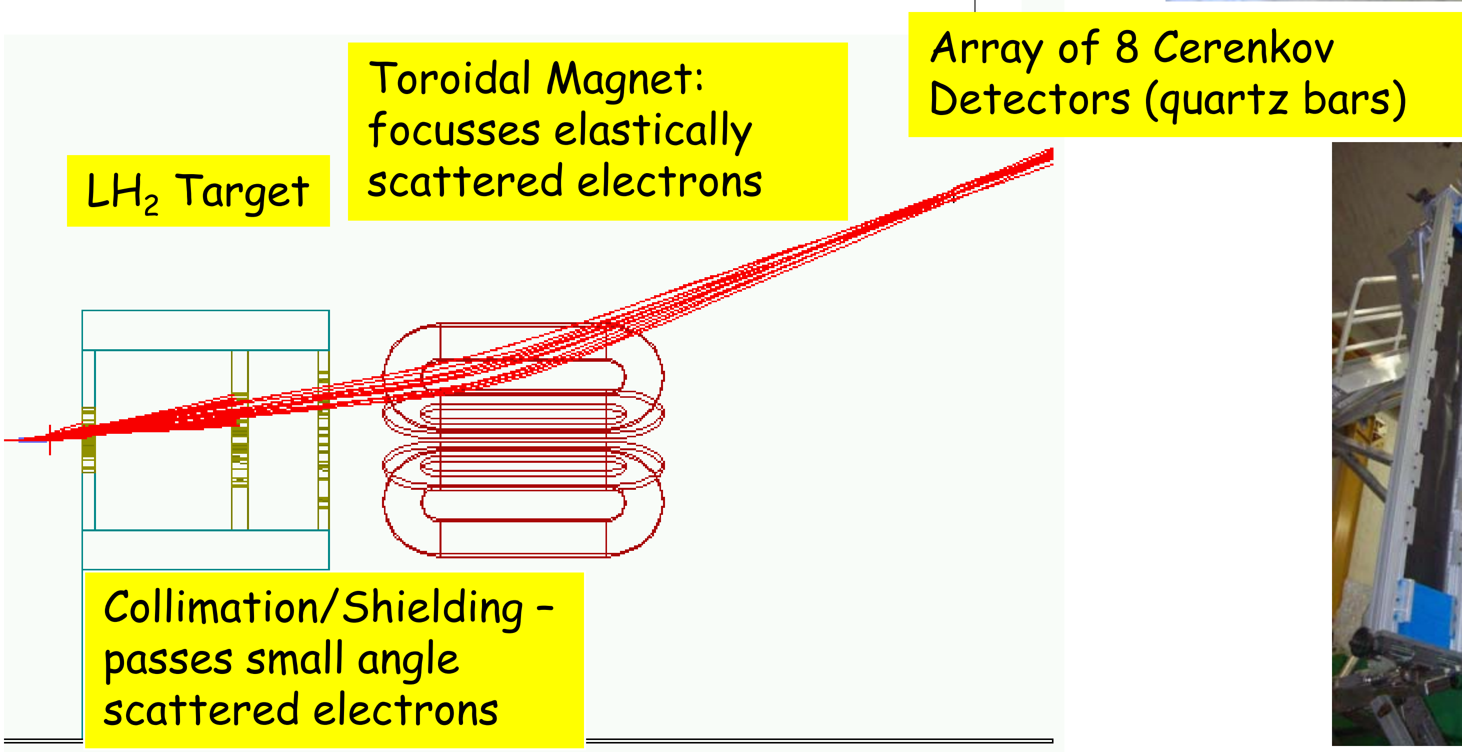
Qweak in Hall C

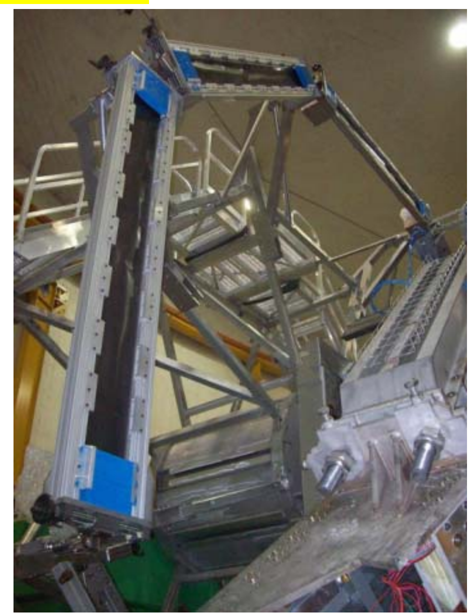




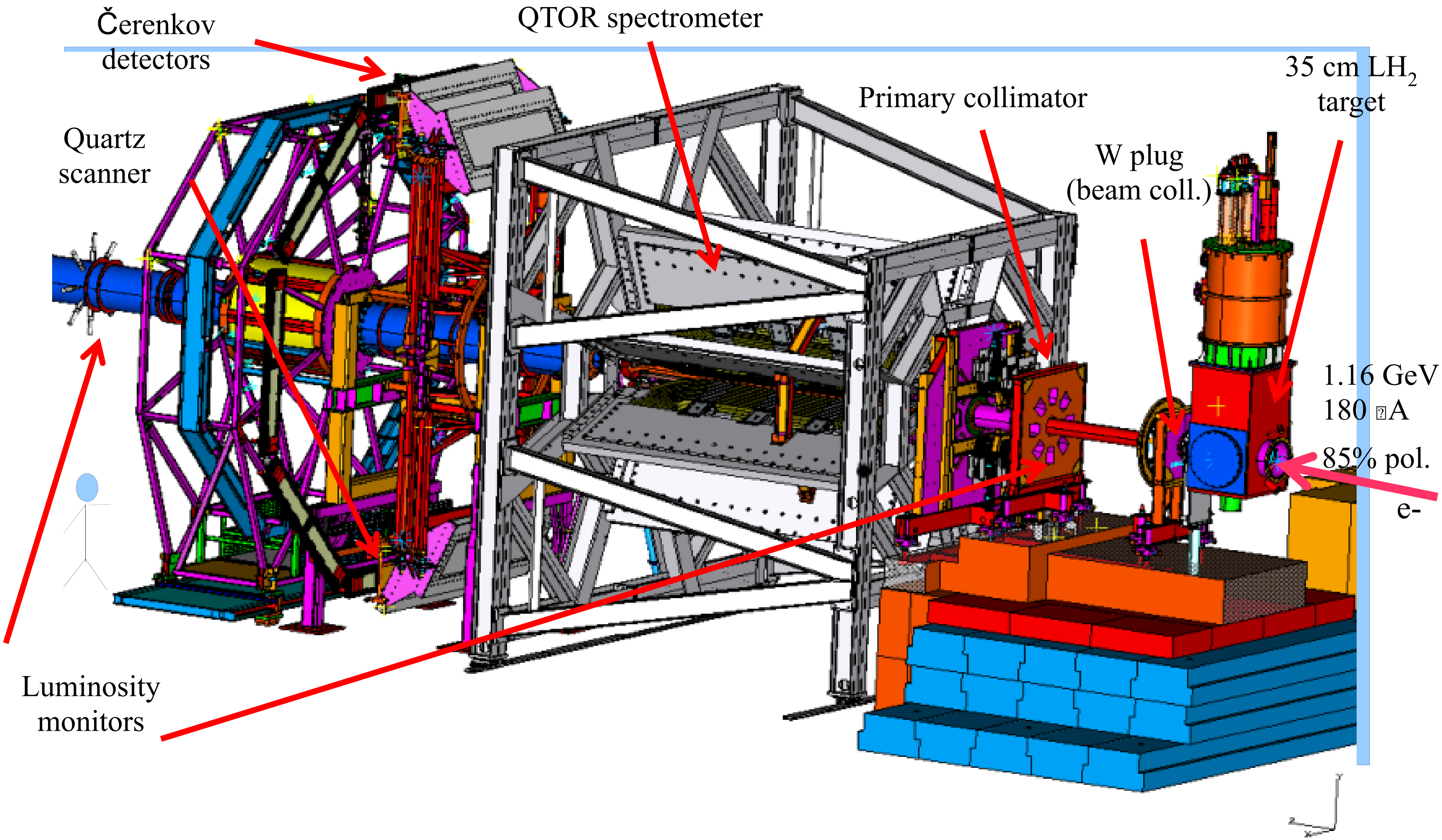
Overview of Q_{weak} Apparatus



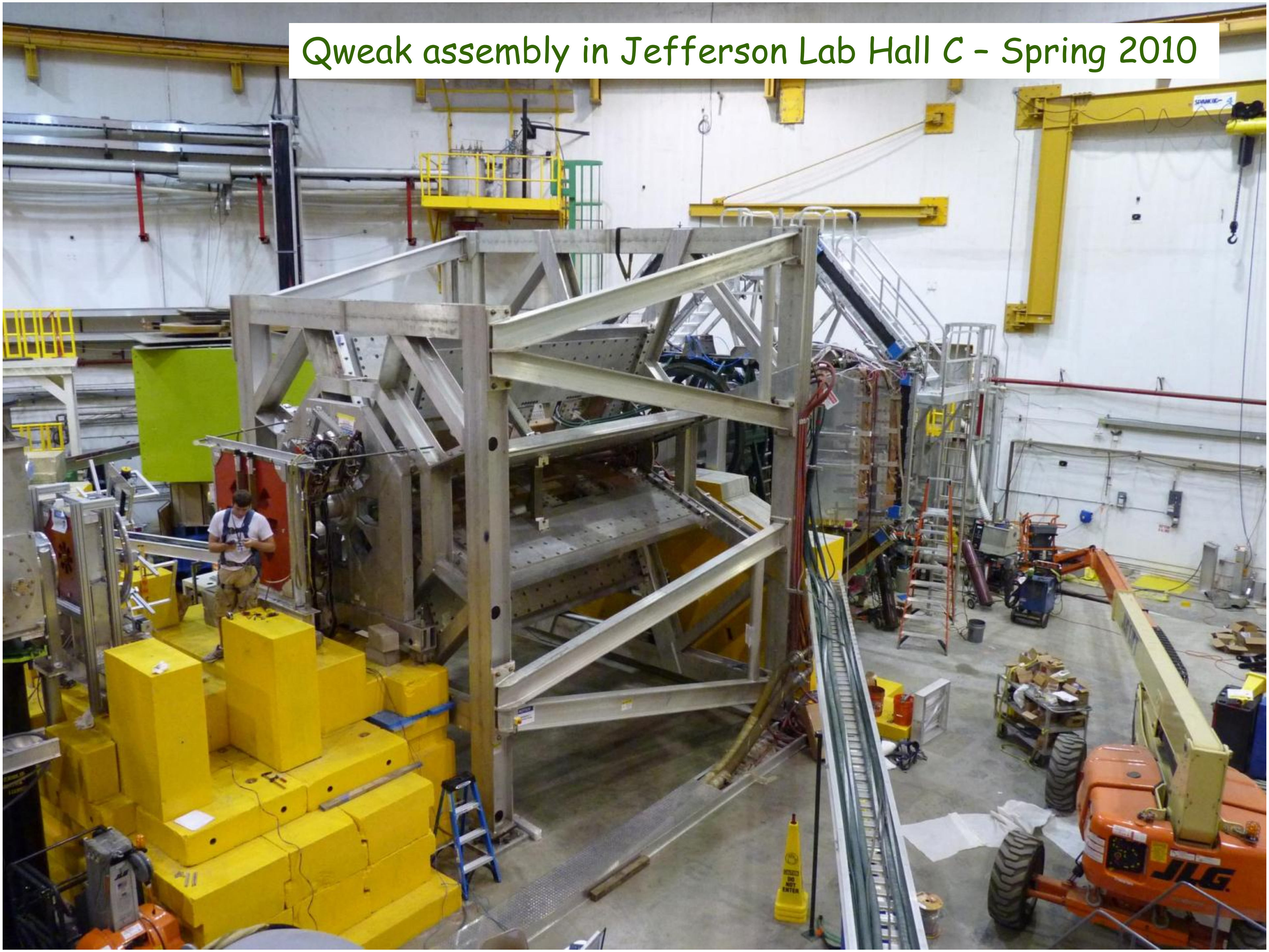




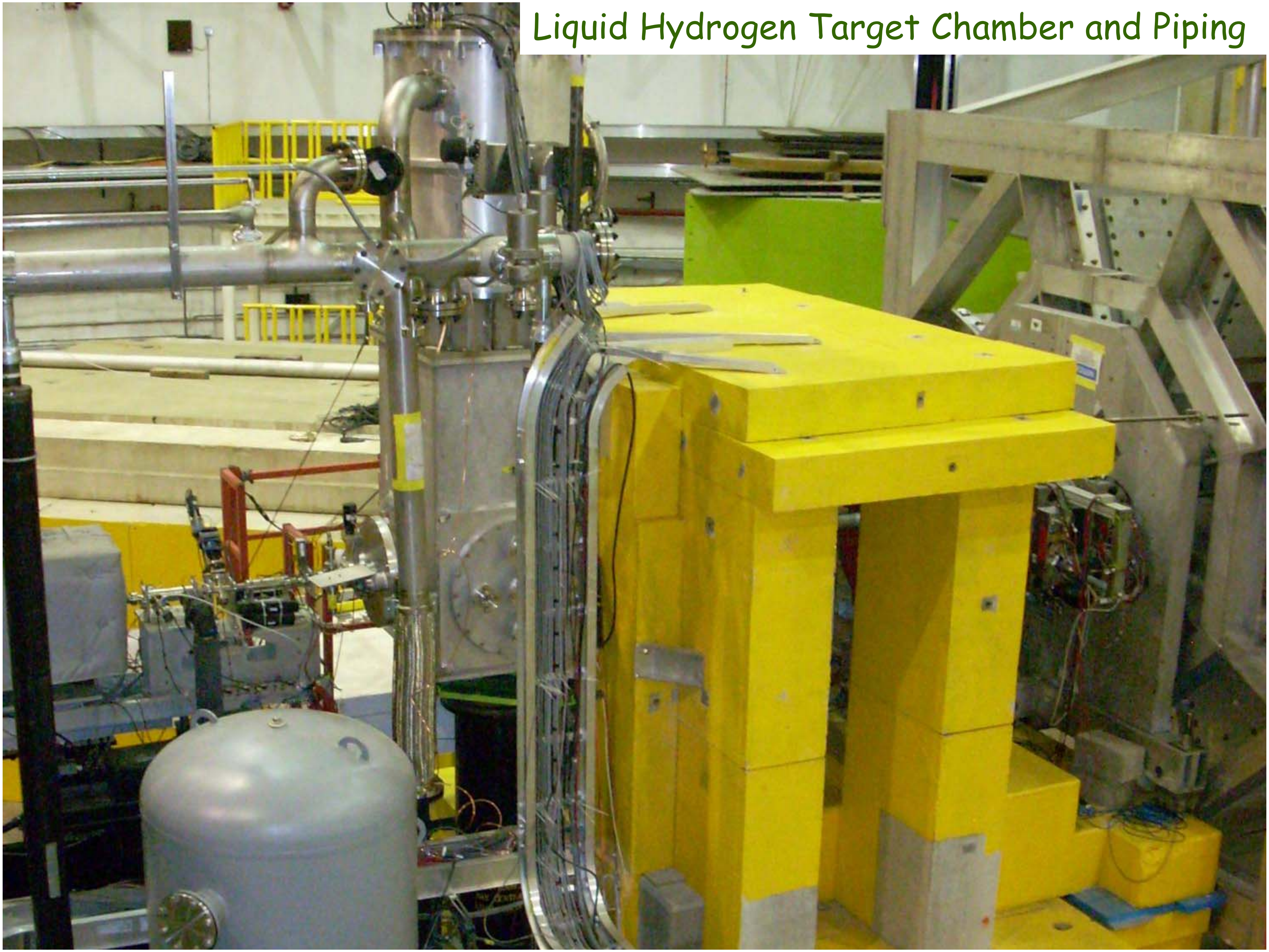
Qweak Apparatus Overview



Qweak assembly in Jefferson Lab Hall C – Spring 2010



Liquid Hydrogen Target Chamber and Piping



Quartz Detectors on their "Ferris Wheel"


Main Detector Shield House

Experimental Technique

How do we take the bulk of our data? Pretty simple actually…

- Integrate the light signal in the Cerenkov detectors, sum them, and record the value every 1 msec

- "Normalize" the integrated signal (S) to the amount of charge (Q) in the beam

$$Y = \frac{S}{Q}$$

- Flip the electron beam helicity and form the asymmetry

$$A_{PV} = \frac{Y^{+} - Y^{-}}{Y^{+} + Y^{-}}$$

- Repeat 4 billion times! (2200 hours of data-taking)

Anticipated Q^p_{weak} Uncertainties

	$\Delta A_{phys} / A_{phys}$	$\Delta Q^p_{weak} / Q^p_{weak}$
Statistical (2200 hours production)	2.1%	3.2%
Systematic:		
Helicity-correlated Beam Properties	0.5%	0.7%
Beam polarimetry	1.0%	1.5%
Backgrounds	0.5%	0.7%
Absolute Q^2 determination	0.5%	1.0%
Hadronic structure uncertainties	--	1.5%
Total	**2.5%**	**4.1%**

Due to hadronic dilutions, a 2.5% measurement of the asymmetry is required to determine the weak charge of the proton to ~4%.

$$A_{ep} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, Q^p_{weak} + Q^4 B\left(Q^2\right)\right]$$

First – statistics on the raw measured asymmetry A $\rightarrow\rightarrow\rightarrow\rightarrow$

Statistical Error

To achieve our desired final statistical error the error on each 4 msec measurement of the asymmetry ("quartet") needs to be small

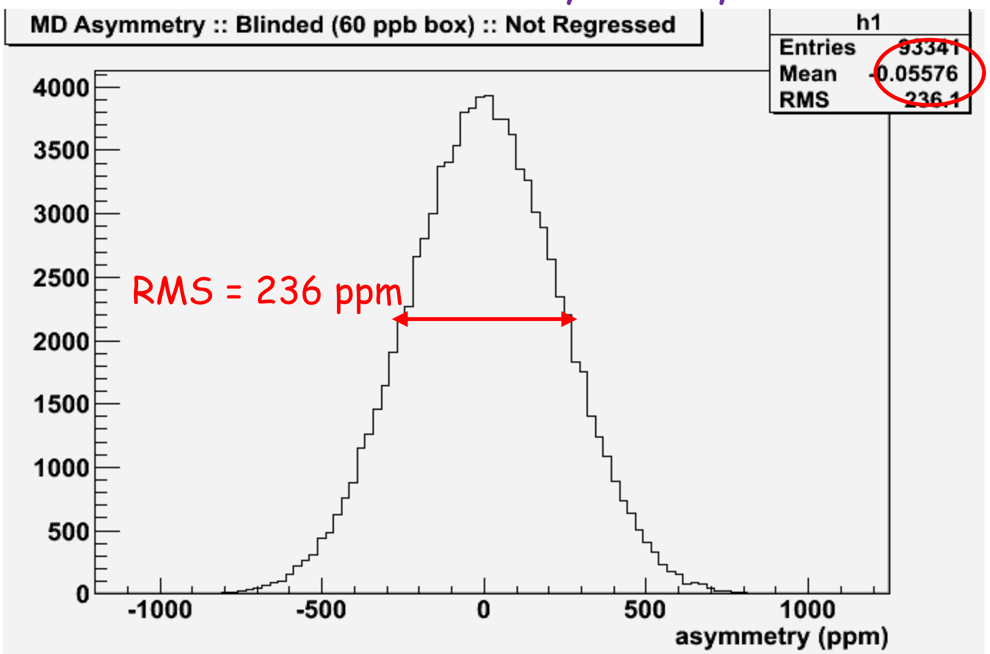
At 165 μA, total detected rate is 5.83 GHz $\rightarrow$ expect ~ 23 million primary events

$\rightarrow$ Expect 207 ppm error from "counting statistics" per quartet

$\rightarrow$ Observe slightly higher value (236 ppm) for understood reasons

$\rightarrow$ Doing this 4 billion times gives final error of ~ 5 ppb

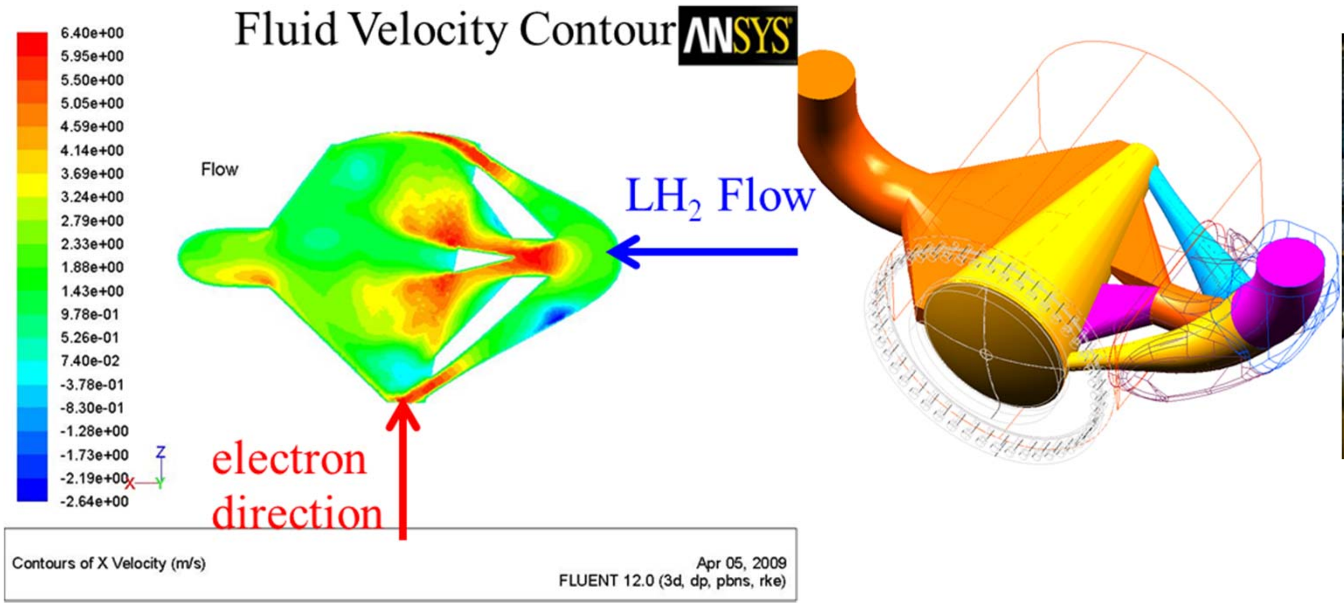
Full Detector Asymmetry

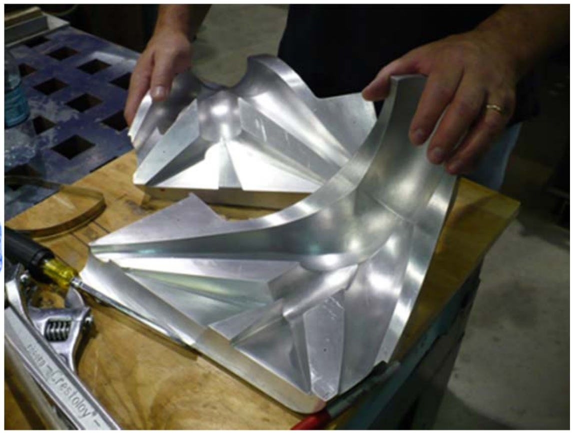


Need to keep all other sources of random noise small compared to this. Potentially most problematic contribution **was** target density fluctuations **BUT…**

$$\Gamma_{stat} = \sqrt{\Gamma^2_{\text{count}} + \Gamma^2_{\text{electronics}} + \Gamma^2_{\text{target}}}$$

Qweak Target – World's Highest Power Liquid Hydrogen Target





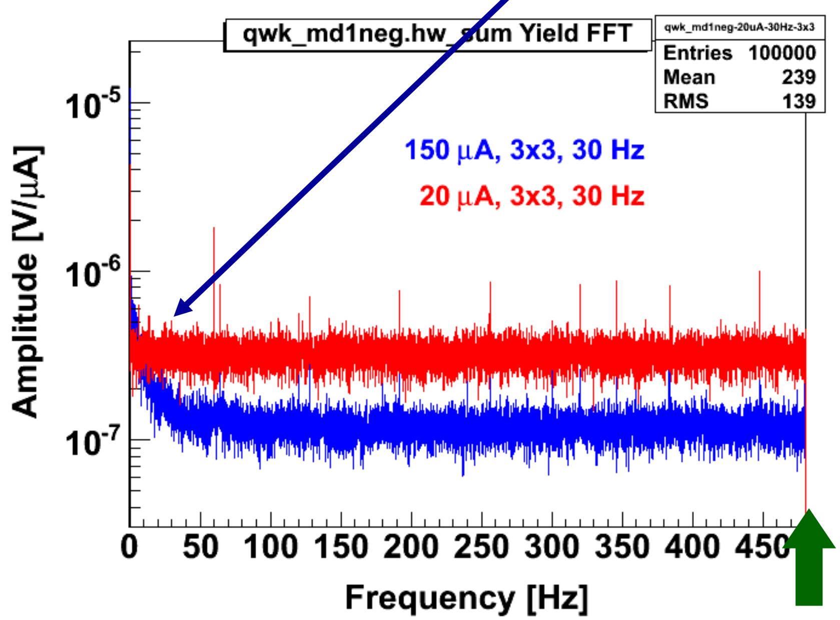
- Target has power capacity of 2500 W – adequate for 180 μA electron beam on 35 cm target
- First target of this type to use computational fluid dynamics (CFD) in its design
- Designed to minimize contribution to random noise from target density fluctuations – "boiling"

Target Density Fluctuations

Critical that target density fluctuations at our flip rate be kept less than counting statistics fluctuations ~ 236 ppm (achieved! contribution < 46 ppm)

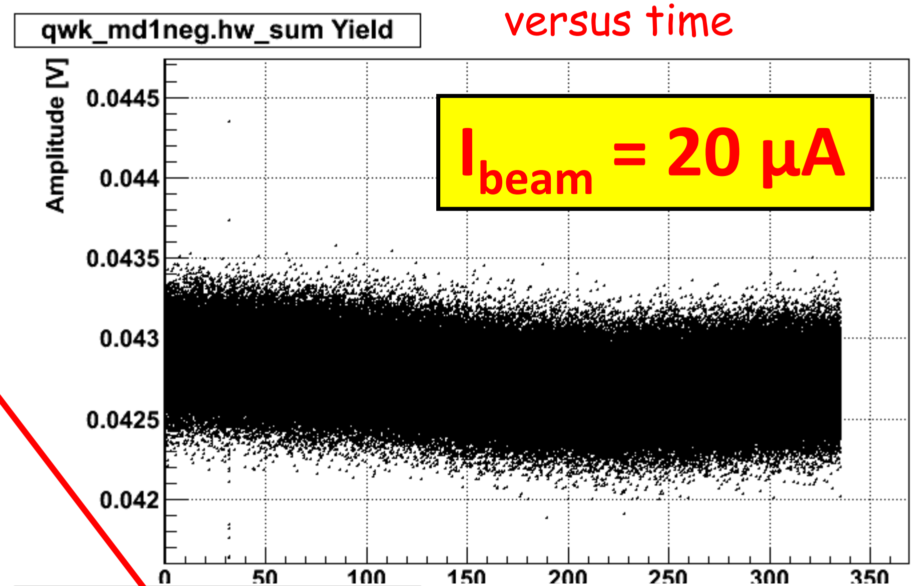
1. Versus time, two beam currents … target bubble formation ?

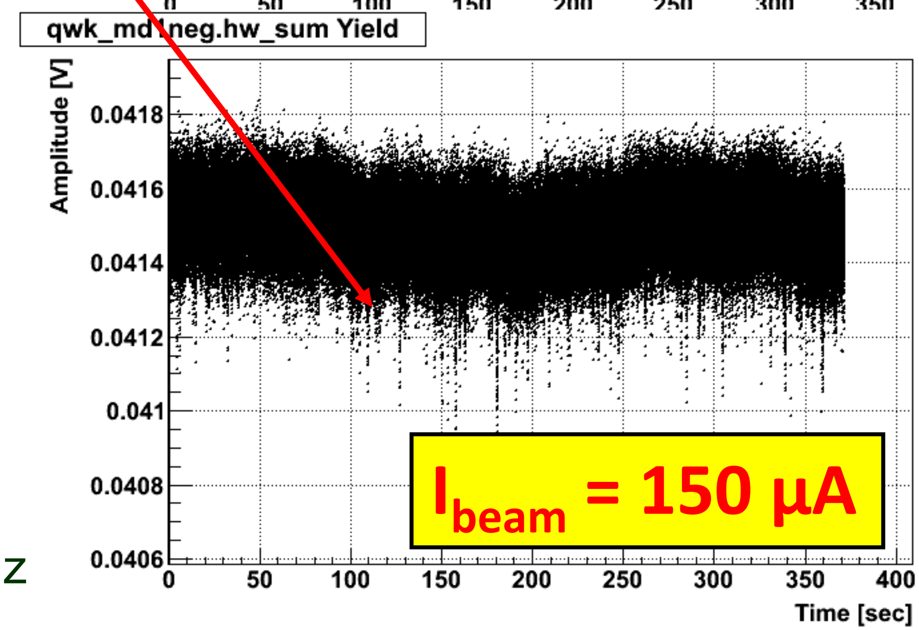
2. Fast Fourier transform – rapid spin flip immunizes the experiment to low freq. noise!



1 spin cycle = 480 Hz

Main detector yield versus time





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Helicity-correlated Beam Properties (like beam position, angle, energy):

$$A_{corrected} = A_{measured} - A_{false}$$

Two correction procedures applied:

- Linear regression using "natural beam motion"
- Beam modulation (Josh Hoskins, BC.00005)

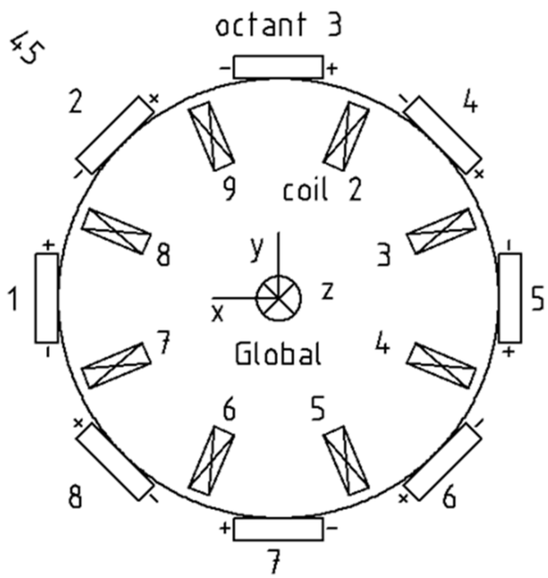
Helicity-Correlated Beam Properties – "Natural Beam Motion"

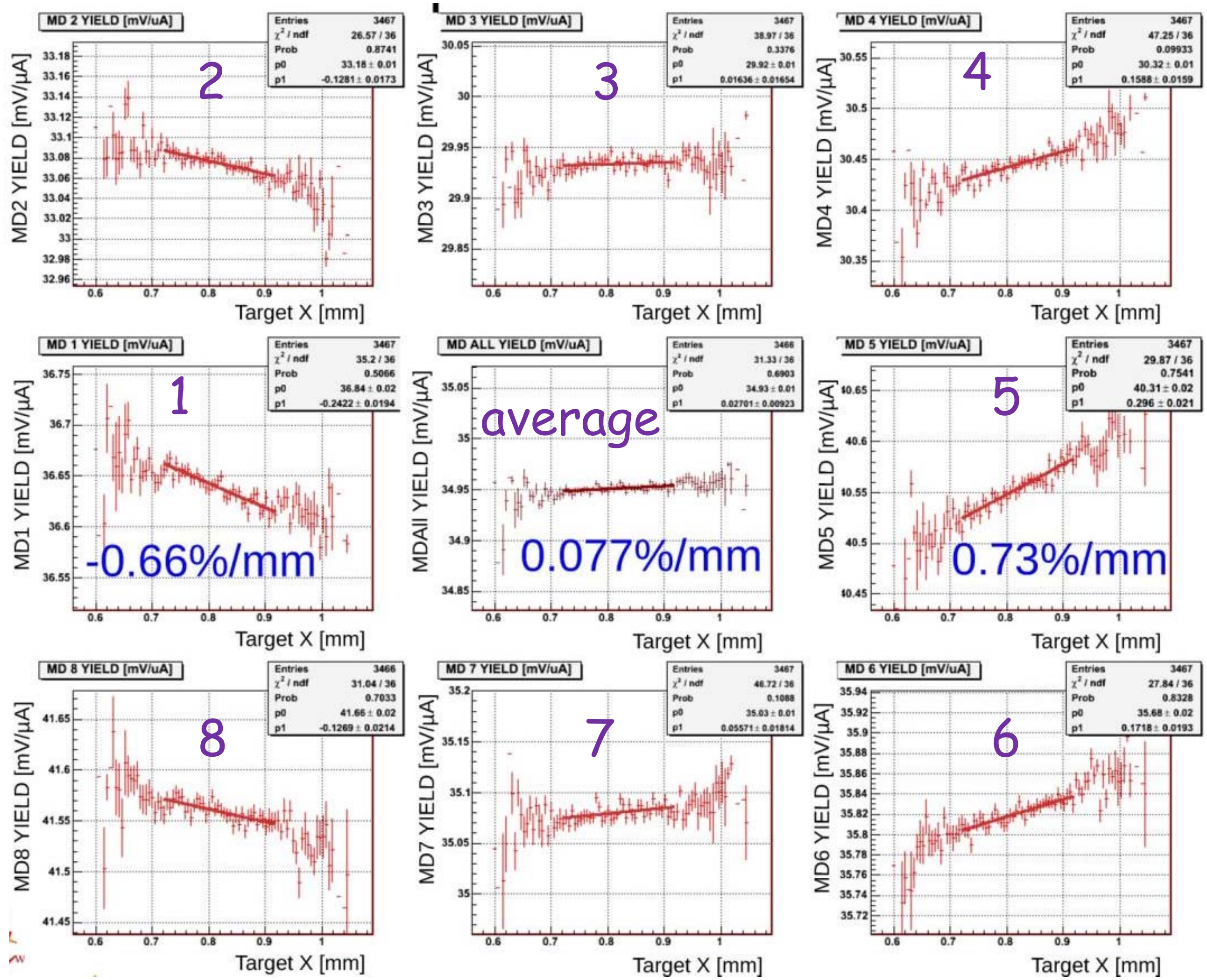
The beam parameters (like X beam position) can be different for + and – helicity

$\Delta P = P_+ - P_-$ we continually measure this and correct for it

$$A_{false} = \sum_{i=1}^{N} \frac{1}{2Y} \left(\frac{\partial Y}{\partial P_i} \right) \Delta P_i$$

Response of detector to natural beam motion fluctuations in the X direction; Symmetry of the detector reduces sensitivity to position and angle motion





Anticipated Q^p_{weak} Uncertainties

	$\Delta A_{phys} / A_{phys}$	$\Delta Q^p_{weak} / Q^p_{weak}$
Statistical (2200 hours production)	2.1%	3.2%
Systematic:		
Helicity-correlated Beam Properties	0.5%	0.7%
Beam polarimetry	1.0%	1.5%
Backgrounds	0.5%	0.7%
Absolute Q^2 determination	0.5%	1.0%
Hadronic structure uncertainties	--	1.5%
Total	**2.5%**	**4.1%**

Beam Polarimetry:

$$A_{phys} = \frac{A_{corrected}}{P_{beam}}$$

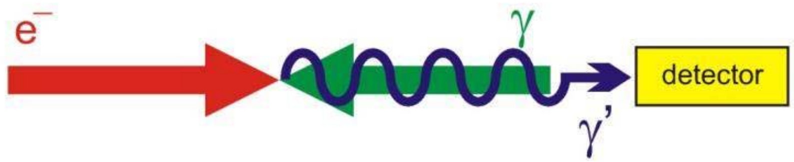
Typical electron beam polarization is ~ 88%; accurately measured with two techniques:

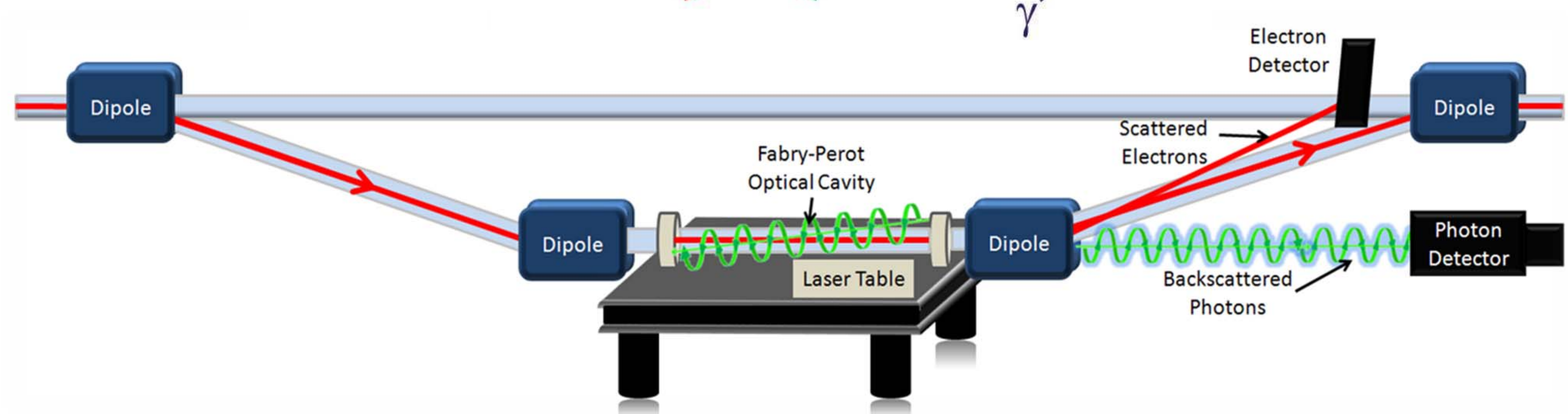
- Moller polarimetry $\vec{e} + \vec{e} \rightarrow e' + e'$ (Josh Magee, BC.00006)
- Compton polarimetry (Amrendra Narayan, BC.00007)

Compton Polarimetry

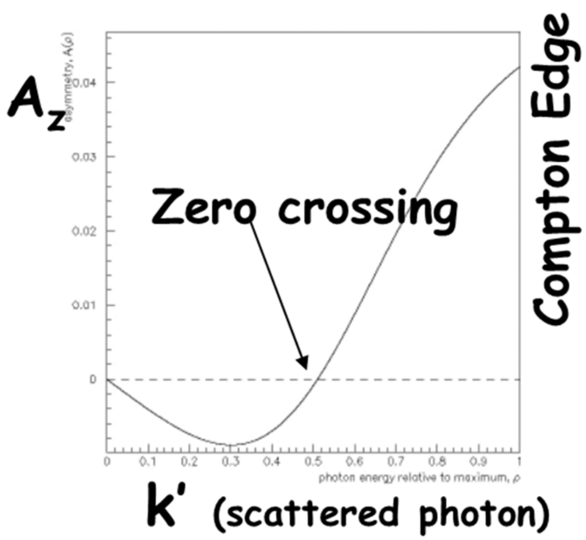
Compton backscattering: boost laser photon energy; can be done non-invasively

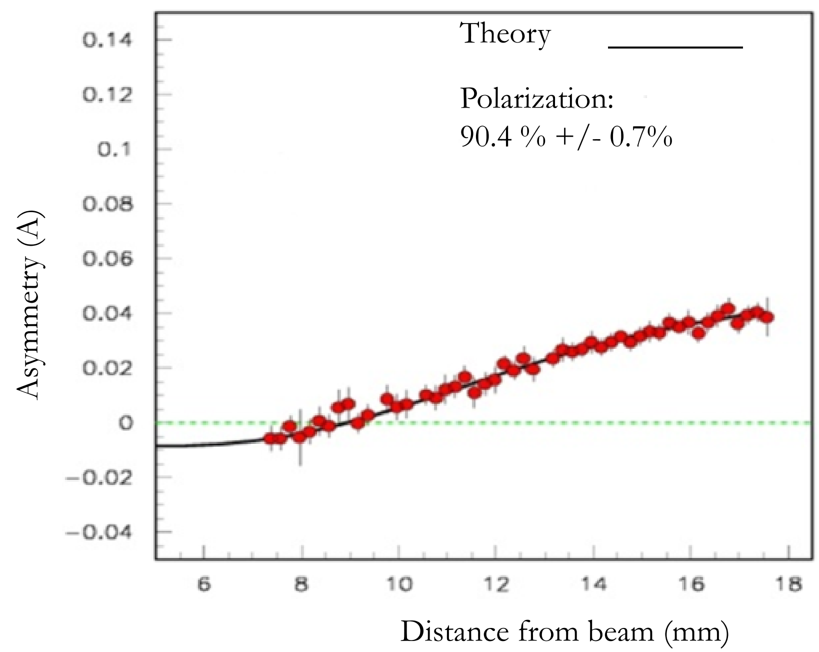
$$\vec{e} + \vec{\gamma} \rightarrow e' + \gamma'$$





$$A_{exp} = \frac{N^+ - N^-}{N^+ + N^-} = P_e P_\gamma A_{th} \quad \text{where } P_e = \frac{A_{exp}}{P_\gamma A_{th}}$$





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Backgrounds:

$$A_{ep} = \frac{1}{1-f}\left[A_{phys} - f\ A_{back}\right]$$

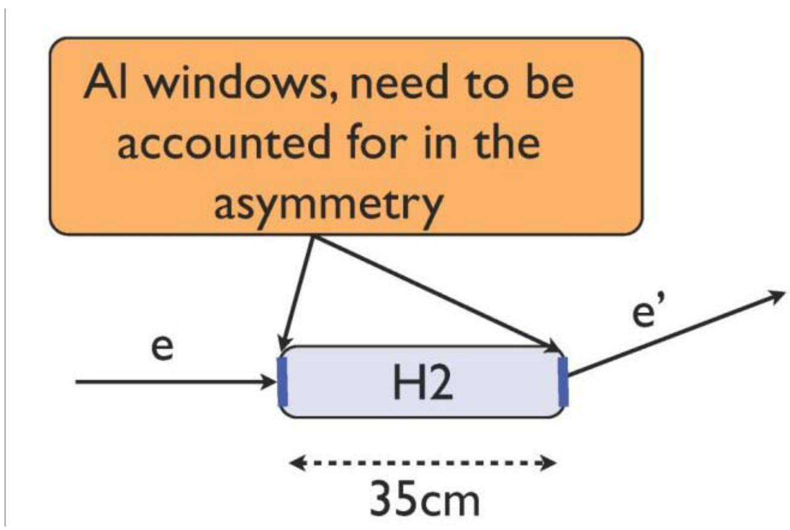
Physics asymmetry is corrected for asymmetries from background processes ("dilution factor" = f):

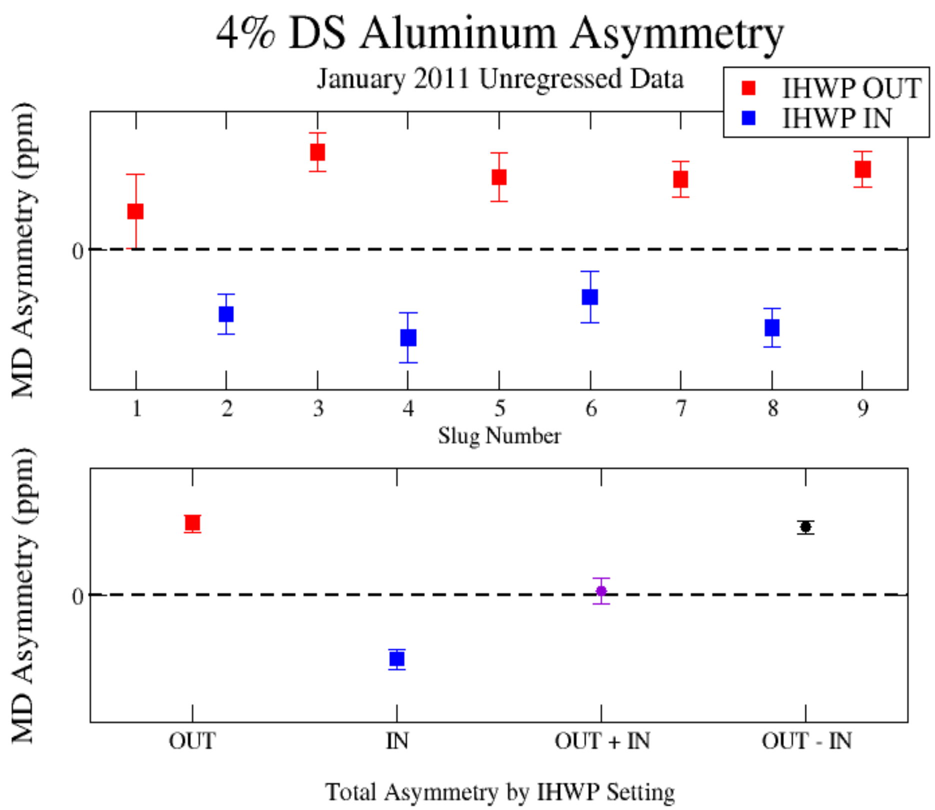
- *Aluminum target windows*
- Inelastic e-p scattering (John Leacock, BC.00003)
- Beamline backgrounds

Aluminum Background Asymmetry

The target cell has aluminum end windows

- Aluminum asymmetry is larger than e-p asymmetry; we must measure it in separate runs
- "dilution" f ~ 3%; anticipated asymmetry correction ~ 20%





Anticipated Q^p_{weak} Uncertainties

$\Delta Q^p_{weak}/Q^p_{weak}$	$\Delta A_{phys}/A_{phys}$	
Statistical (2200 hours production)	2.1%	3.2%
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Total	**2.5%**	**4.1%**

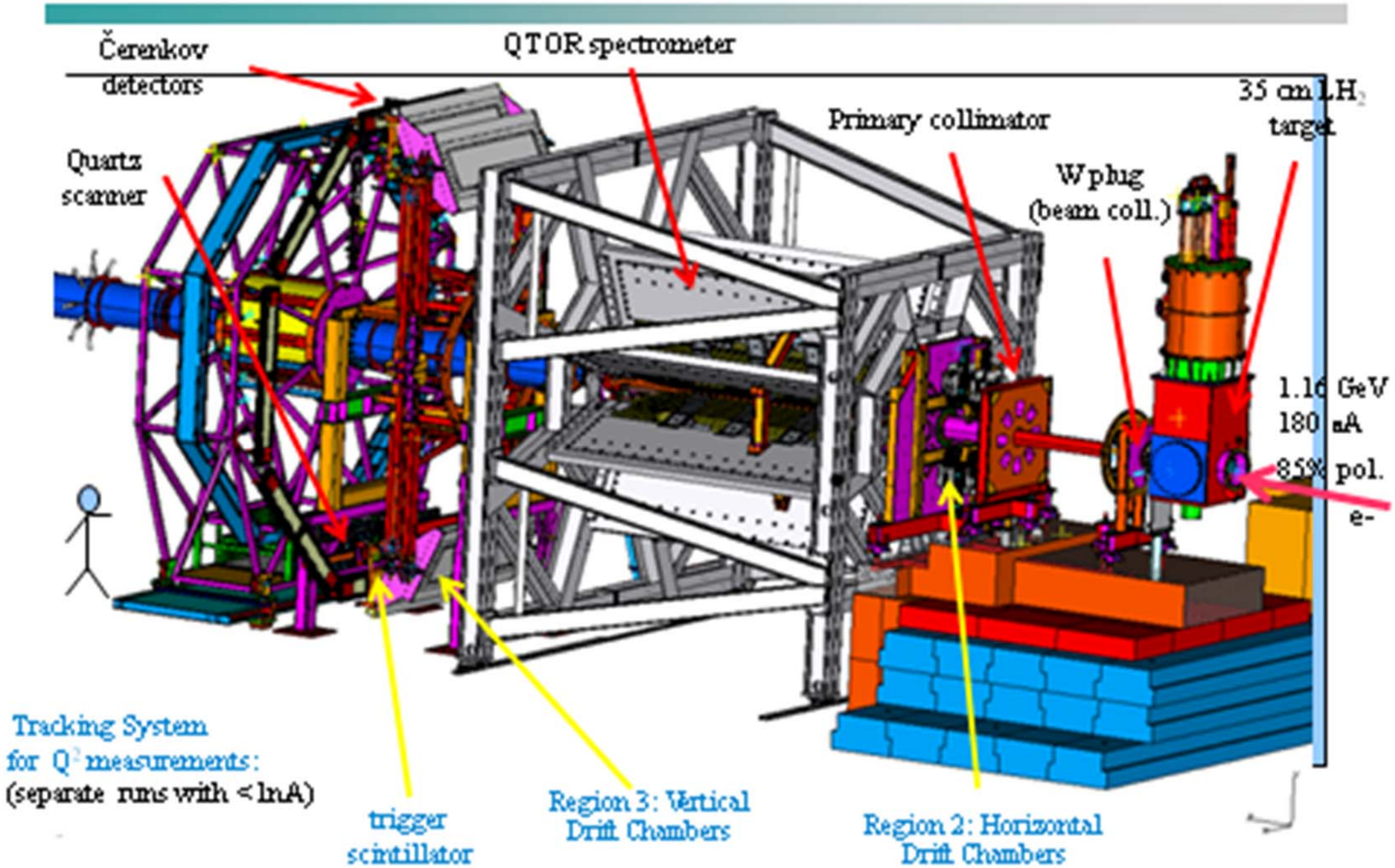
$$A_{ep} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q^p_{weak} + Q^4 B(Q^2)\right]$$

Absolute Q^2 determination:

Must measure Q^2 accurately in order to extract Q^2 from A_{ep}

Dedicated tracking system was built; tracks individual events at low beam current

Qweak Tracking System



Vertical drift chambers
after magnet

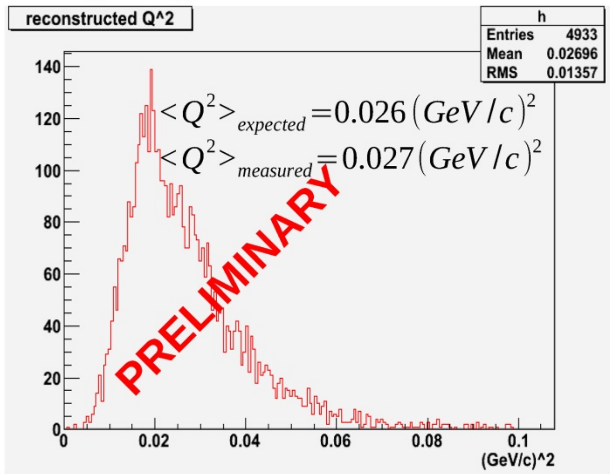
Horizontal drift chambers
after magnet

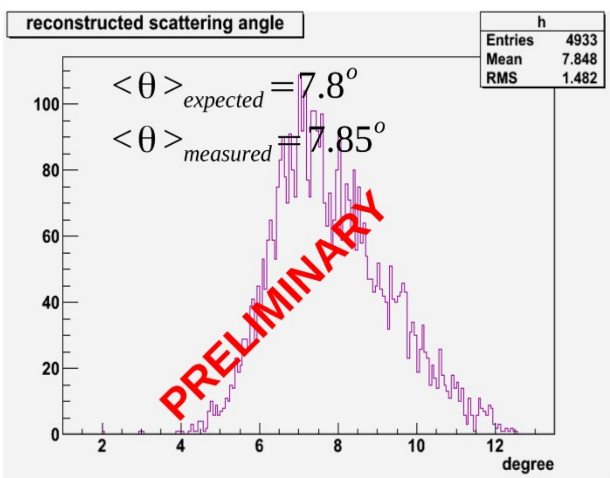
Q^2 Measurement with Qweak Tracking System

Measurement of Q^2 requires

$$Q^2 = 4EE'\sin^2\left(\frac{\theta}{2}\right)$$

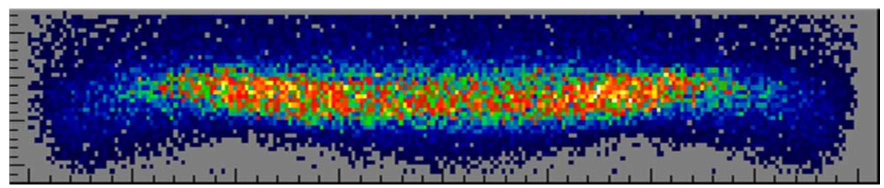
- Measurement of scattering angle θ before the magnet
- Verification of elastic scattering event after the magnet (correct E')
- Detailed measurements of spatial light distribution from detectors ("light-weighted" Q^2 distribution)



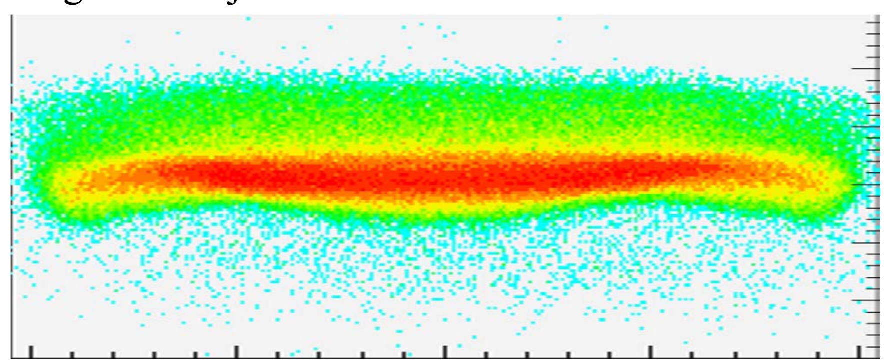


Electron Profile at Detector

Simulation

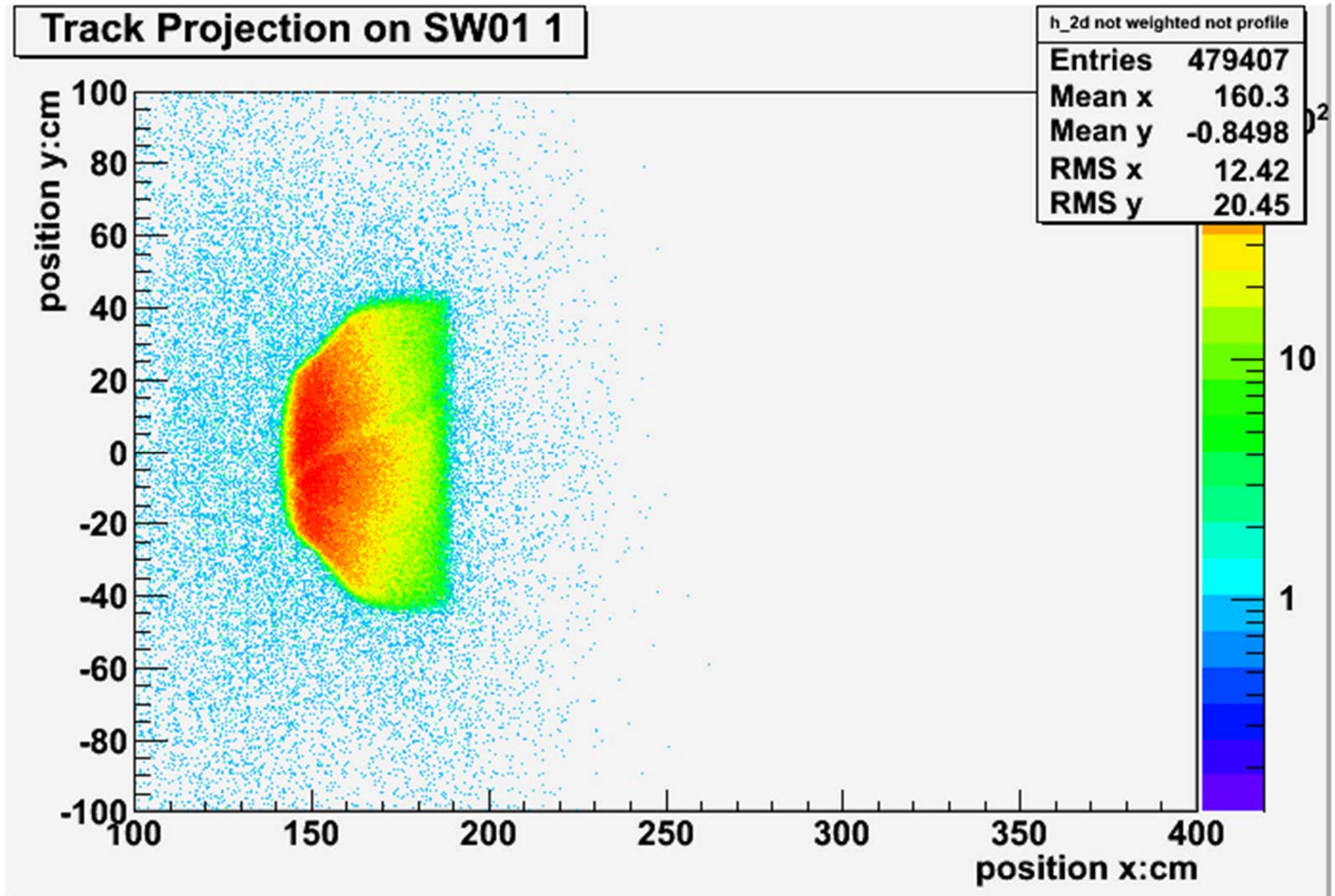


Region 3 Projection:



Scattered Electron Beam Envelope After Magnet

Animation from track reconstructed profiles from vertical drift chambers after the QTOR magnet



(yes, there is one dead wire…)

Anticipated Q^p_{weak} Uncertainties

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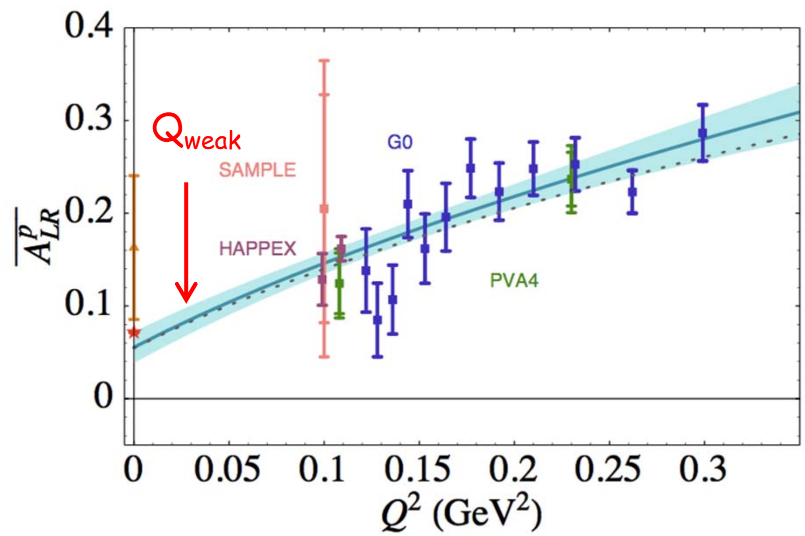
$$A_{ep} = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, Q^p_{weak} + Q^4 B(Q^2)\right]$$

Hadronic struture uncertainties:

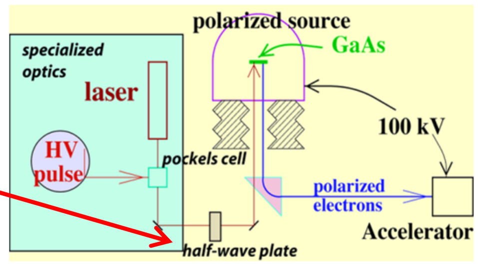
The "form factor" $B(Q^2)$ term – due to proton structure
$\rightarrow$ Determined by extrapolation from previous PV electron scattering at higher Q^2 to Qweak Q^2 of ~ .026 $(GeV/c)^2$



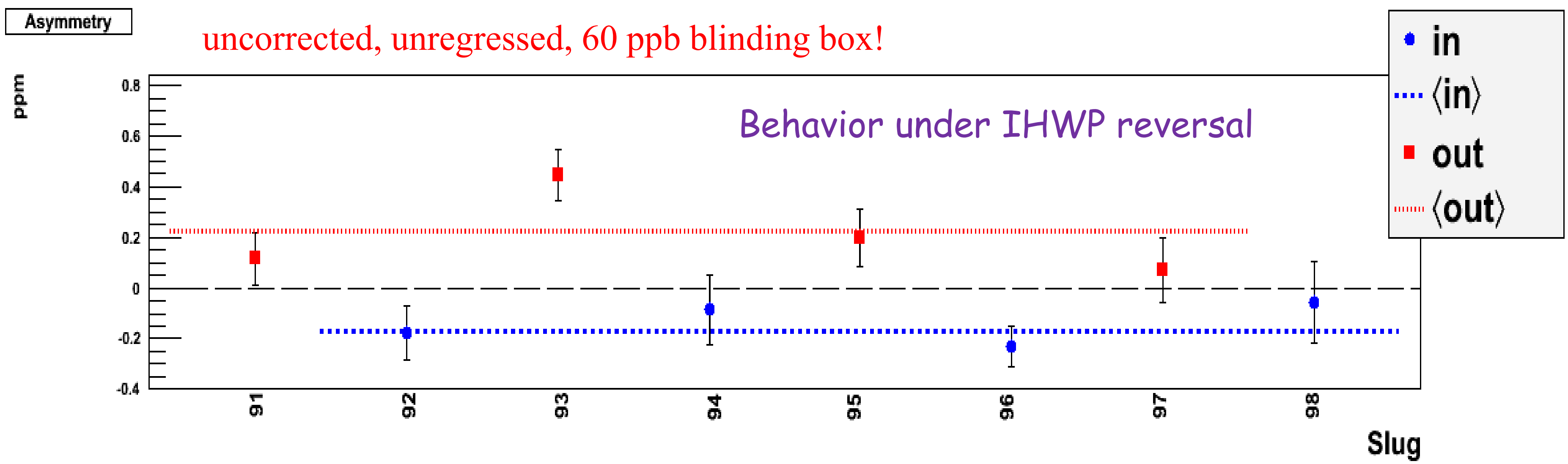
Data Quality – Slow Reversals

We are measuring a small quantity for a long time; what diagnostics do we have to know that everything is "OK"? → "slow" reversals are one example

- IHWP: "Insertable Half Wave Plate" at the polarized injector
  → reverses electron beam helicity, but nothing else; real physics asymmetries should reverse sign under this reversal (timescale ~ 8 hours)



- "Double wien": Accelerator system that manipulates electron beam helicity to reverse it and nothing else; real physics asymmetries should also reverse sign under this reversal (timescale ~ 1 week)



Future Prospects at Jefferson Lab

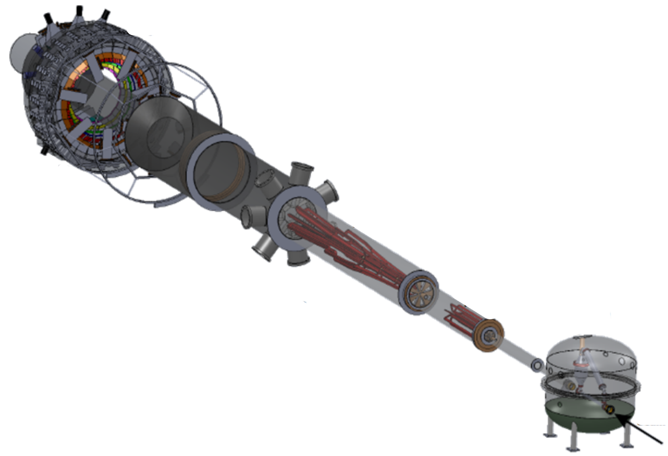
Jefferson Lab will double its beam energy ("12 GeV Upgrade" project); with running anticipated at the new energy by ~ late 2014.

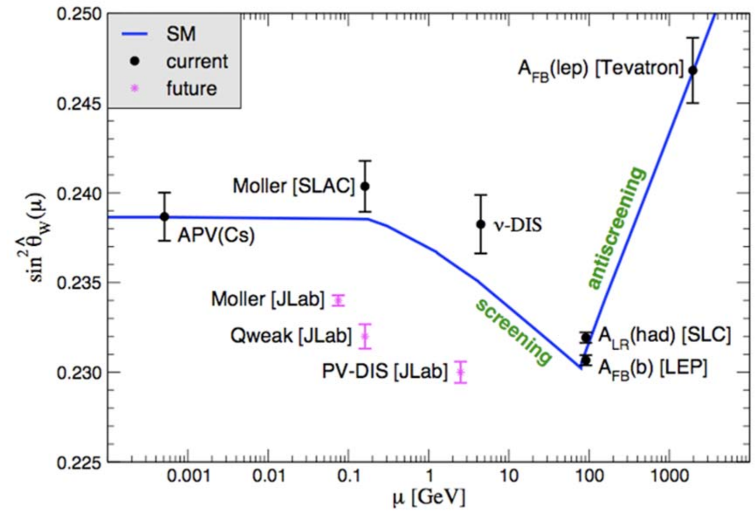
$\rightarrow$ There are two major approved projects involving PV electron scattering

MOLLER Experiment (Measurement of a Lepton Lepton Electroweak Reaction)

$$\vec{e} + e \rightarrow e' + e'$$

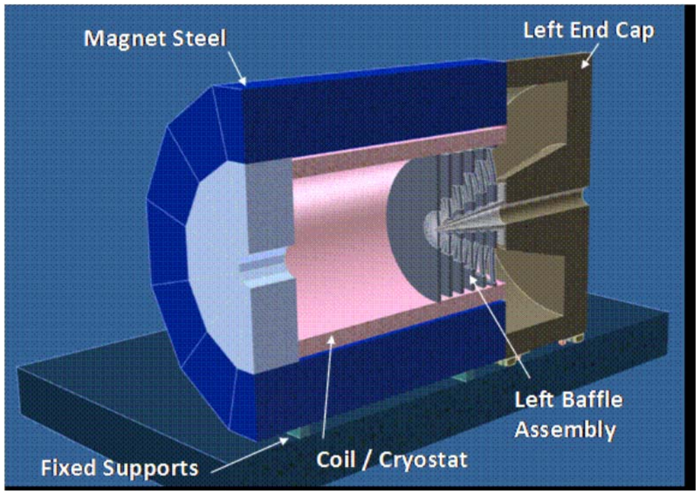
- Parity violating Moller scattering at 11 GeV
- Will improve E158 error by factor of 5
- Competitive $\sin^2\theta_W$ with Z pole measurements





SOLID (Parity Violation in Deep Inelastic Scattering)

- Broad program built around retasked solenoidal magnet
- Electroweak couplings
- Charge symmetry
- Higher twist
- SIDIS

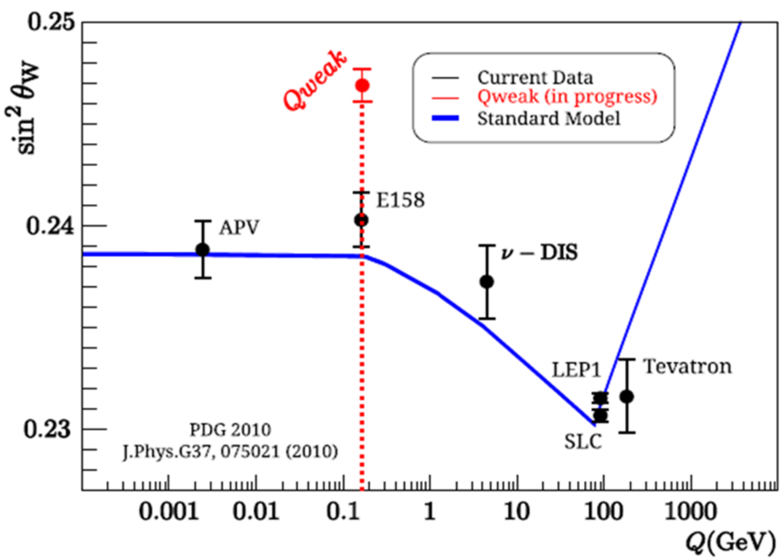


Summary and Outlook

- The Qweak experiment at Jefferson Lab is well underway, with ~25% of its data collected in "Run I" with the remainder expected in "Run II" from November 2011 to May 2012

- The Qweak experiment will make the first direct measurement of the weak charge of the proton, with an anticipated precision of ~ 4%.

- The expected precision on Q^p_{weak} will result in the most precise measurement of the weak mixing angle at low energies



- Building on techniques developed by Qweak, further parity-violating electron scattering experiments are planned at Jefferson Lab for the "12 GeV Era"

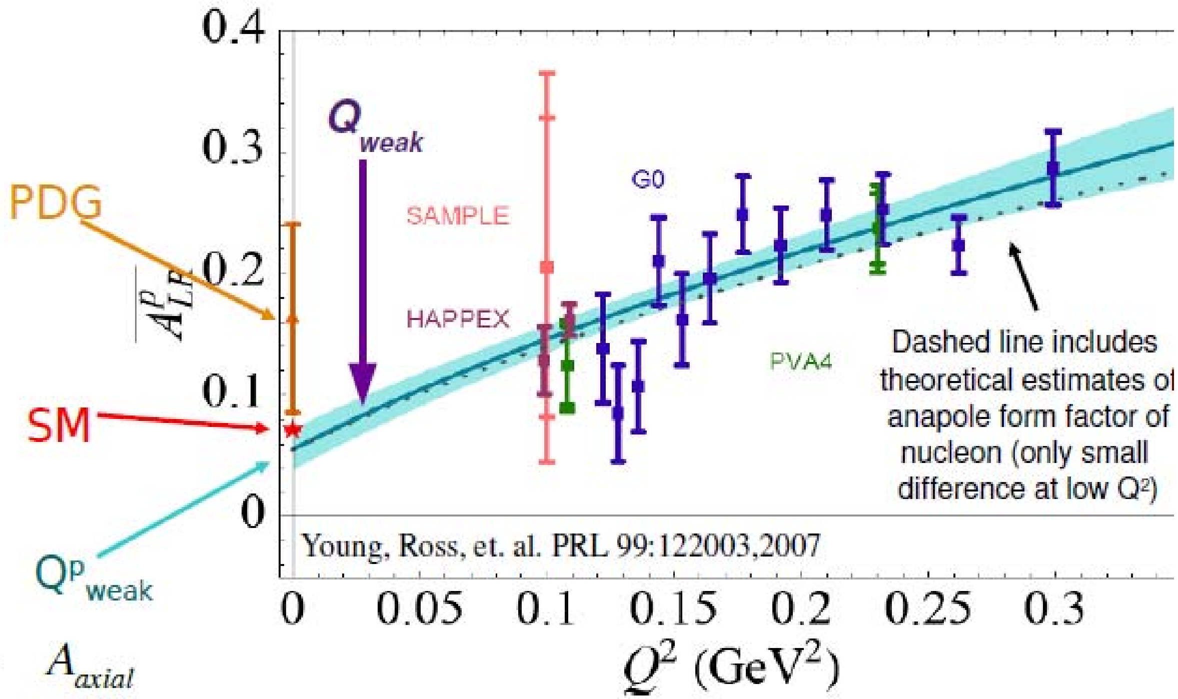
Backups

Parity-Violating Asymmetry Extrapolated to $Q^2 = 0$

(Young, Carlini, Thomas & Roche, PRL 99, 122003 (2007))

Divide out leading Q^2 dependence:

$$\overline{A^p_{LR}} \simeq Q^p_{weak} + B(Q^2)Q^2 + \ldots$$



$$A = A_{Q^p_W} + A_{hadronic} + A_{axial}$$

$$= -0.17 \text{ ppm} - 0.07 \text{ ppm} - 0.01 \text{ ppm}$$

hadronic:
(31% of asymmetry)
contains $G^{\gamma}_{E,M}$ $G^{Z}_{E,M}$
Constrained by
HAPPEX, G^0, MAMI PVA4

axial:
(4% of asymmetry)
contains G^e_A
large electroweak radiative corrections
Constrained by G^0 and SAMPLE

Quark Couplings

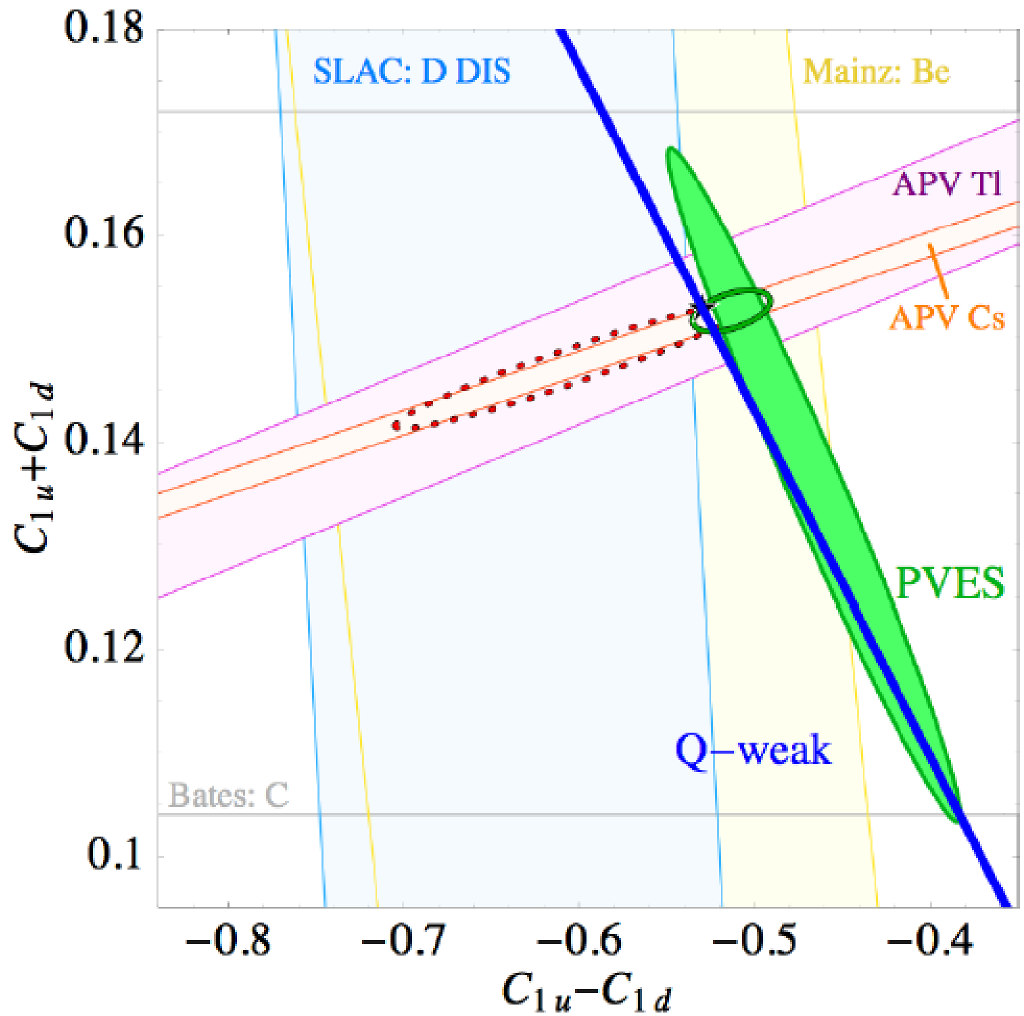
- Qweak will fully constrain the vector quark couplings:

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

PVES ellipse:
HAPPEx,G0,PVA4,SAMPLE

Q_{weak} : Anticipated error band assuming SM

$\star$ = SM prediction



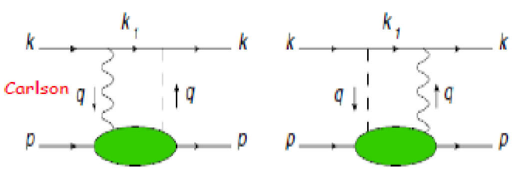
Plot from Young, Carlini, Thomas & Roche, PRL **99**, 122003 (2007)

Radiative Corrections

Several corrections: $\Delta sin^2\theta_W(M_Z)$, WW and ZZ box – but these have small uncertainties

Focus on: **γZ Box Corrections near 1.16 GeV**

Rislow and Carlson



* In 2009, Gorchtein and Horowitz showed the vector hadronic contribution to be significant and energy dependent.

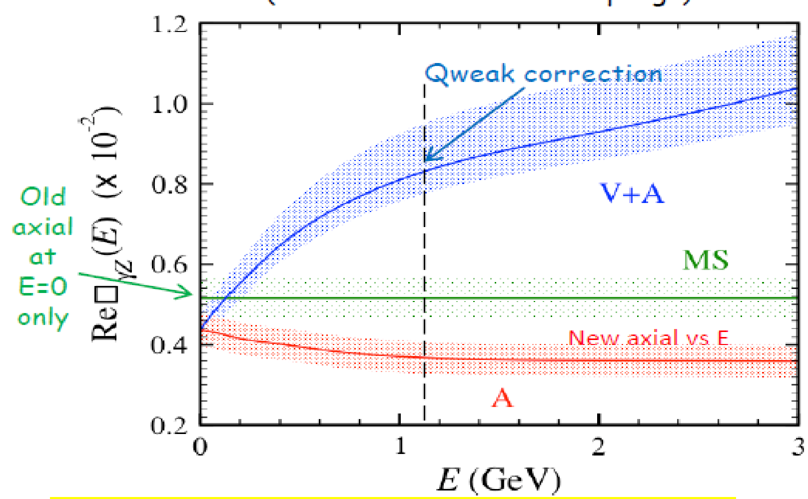
* This soon led to more refined calculations with corrections of ~8% and error bars ranging from ±1.1% to ±2.8%.

* It will probably also spark a refit of the global PVES database used to constrain G_E^s, G_M^s, G_A.

PV Amplitude	Authors	Correction* @ E=1.165 (GeV)
$A^e \times V^p$ (vanishes as E→0)	GH	0.0026+-0.0026**
	SBMT	0.0047 $^{+0.0011}_{-0.0004}$
	RC	0.0057±0.0009
	GHR-M	0.0054±0.0020
$V^e \times A^p$ (finite as E→0)	MS (as updated by EKR-M)	0.0052±0.0005***
	BMT	0.0037±0.0004

*Does not include a small contribution from the elastic.
** 5.7%×Q_w^p(LO) = 0.0026. Q_w^p(LO) = 0.04532.
***Included in Q_w^p. For reference, Q_w^p =0.0713(8).

Blunden, Melnitchouk, Thomas (2011)
(V and A are hadronic couplings)



Forthcoming axial results for Q_w^n have the potential to impact the interpretation of Cs APV.

1