The Q^p_{weak} Experiment: A Search for New TeV Scale Physics via a Measurement of the Proton's Weak Charge

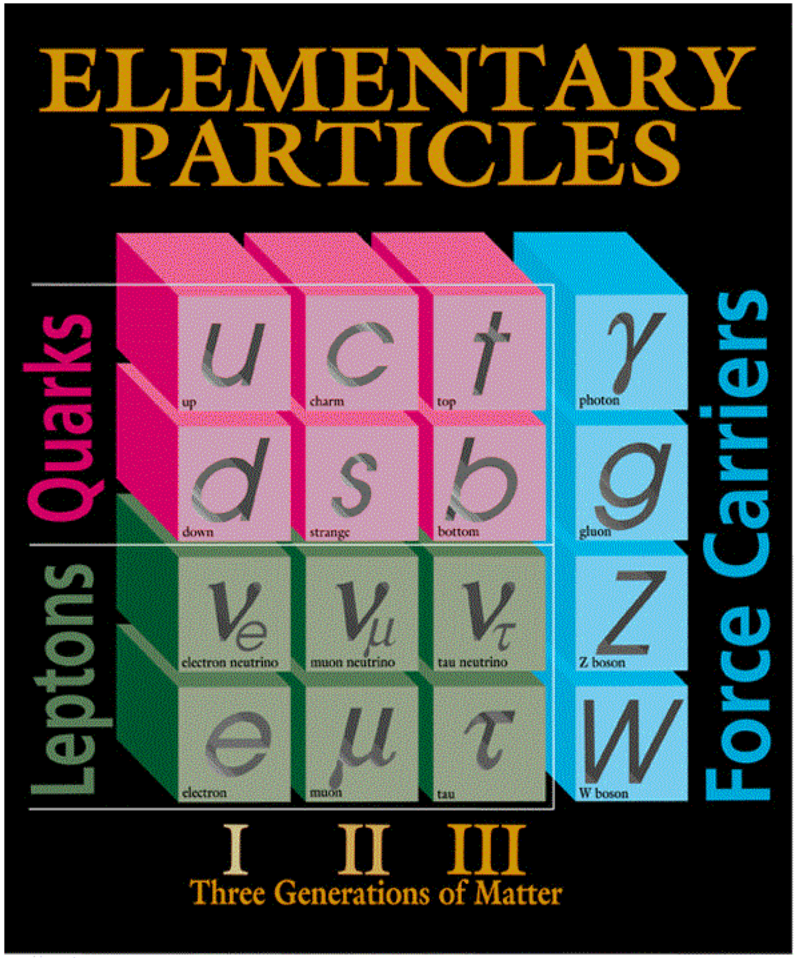
Measure: Parity-violating asymmetry in
$\vec{e}$ + p elastic scattering at $Q^2 \sim 0.03$ GeV^2
to ~4% relative accuracy at JLab

Extract: Proton's weak charge $Q^p_{weak} \sim 1 - 4 \sin^2\theta_W$
to get ~0.3% on $\sin^2\theta_W$ at $Q^2 \sim 0.03$ GeV^2

➡ tests "running of $\sin^2\theta_W$" from M^2_Z to low Q^2
➡ sensitive to new TeV scale physics

W.T.H. van Oers

The Standard Model



Fermilab 95-759

- Building blocks are quarks and leptons

  point-like, spin ½ particles
- Forces mediated by exchange of spin 1 particles:
  - Mostly neutral currents (gamma,Z,gluon)
  - One charged current (W+-)
  - One colored current (gluon)
- The different strengths and characters of these forces

  yield a rich phenomenology:

  most of the nucleon mass,
  the elements and their isotopes,
  fusion in stars,
  chemistry and life.

Courtesy of D.J. Mack

The Standard Model: Issues

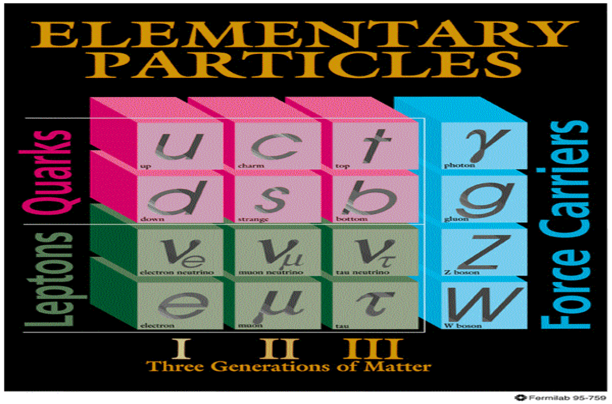
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- **Lots of free parameters (masses, mixing angles, and couplings)**

  How fundamental is that?

- **Why 3 generations of leptons and quarks?**

  Begs for an explanation (smells like a periodic table)

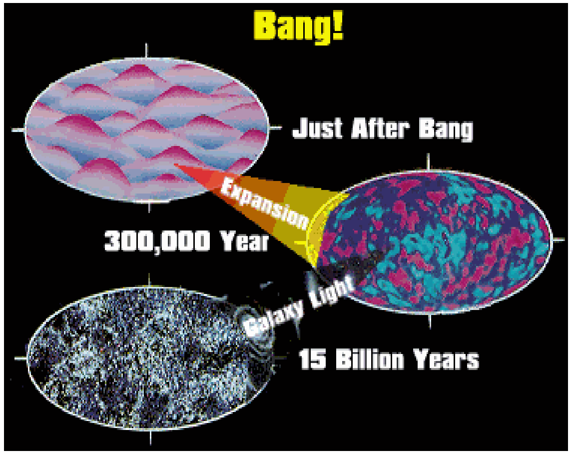


- **Insufficient CP violation to explain all the matter left over from Big Bang**

  Or we wouldn't be here.

- **Doesn't include gravity**

  Big omission … gravity determines the structure of our solar system and galaxy

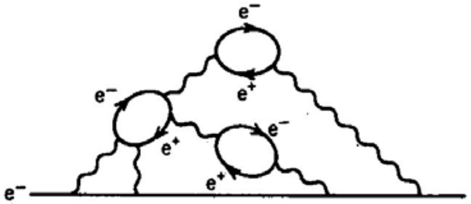


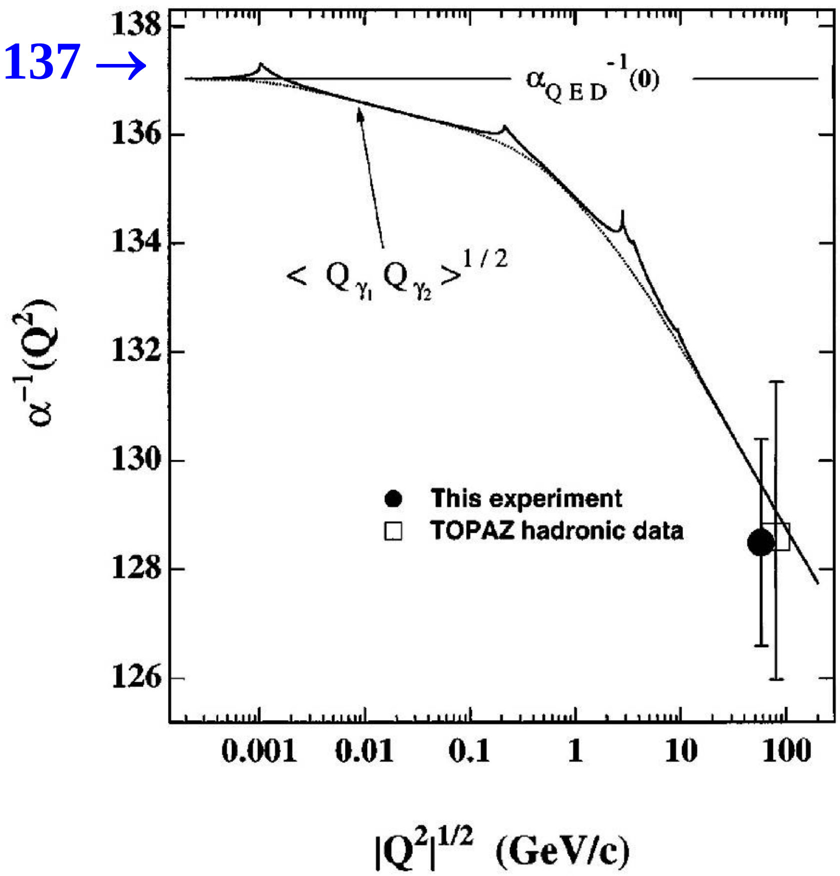
Belief in a rational universe (that something "ordered the muon") suggests that our SM is only a low order approximation of reality, as Newtonian gravity is a low order approximation of General Relativity.

Courtesy of D.J. Mack

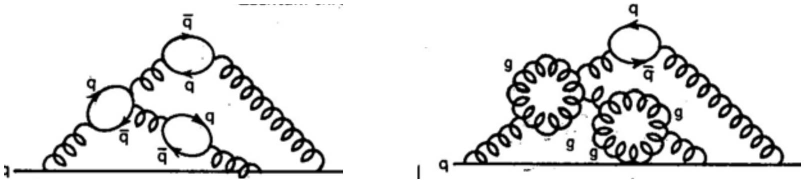
Running coupling constants in QED and QCD

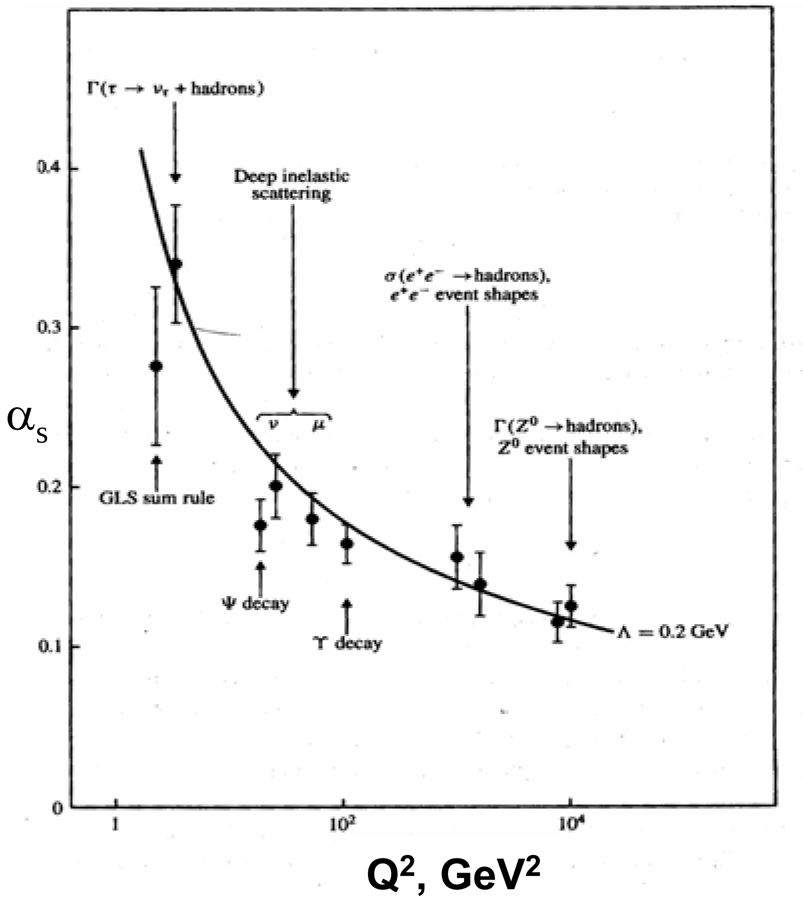
QED (running of α)





QCD(running of α_s)

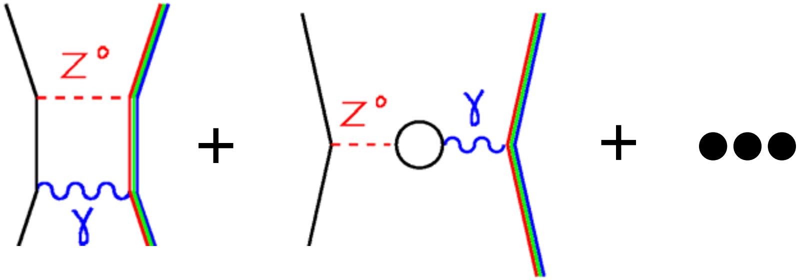


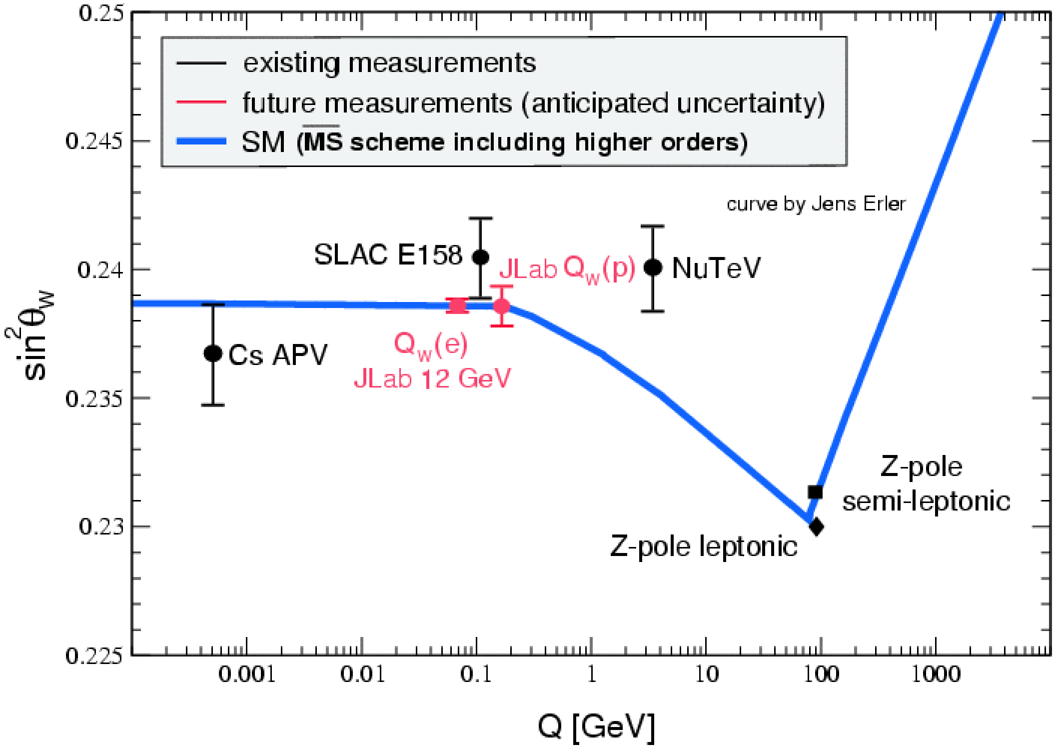


What about the running of $\sin^2\theta_W$?

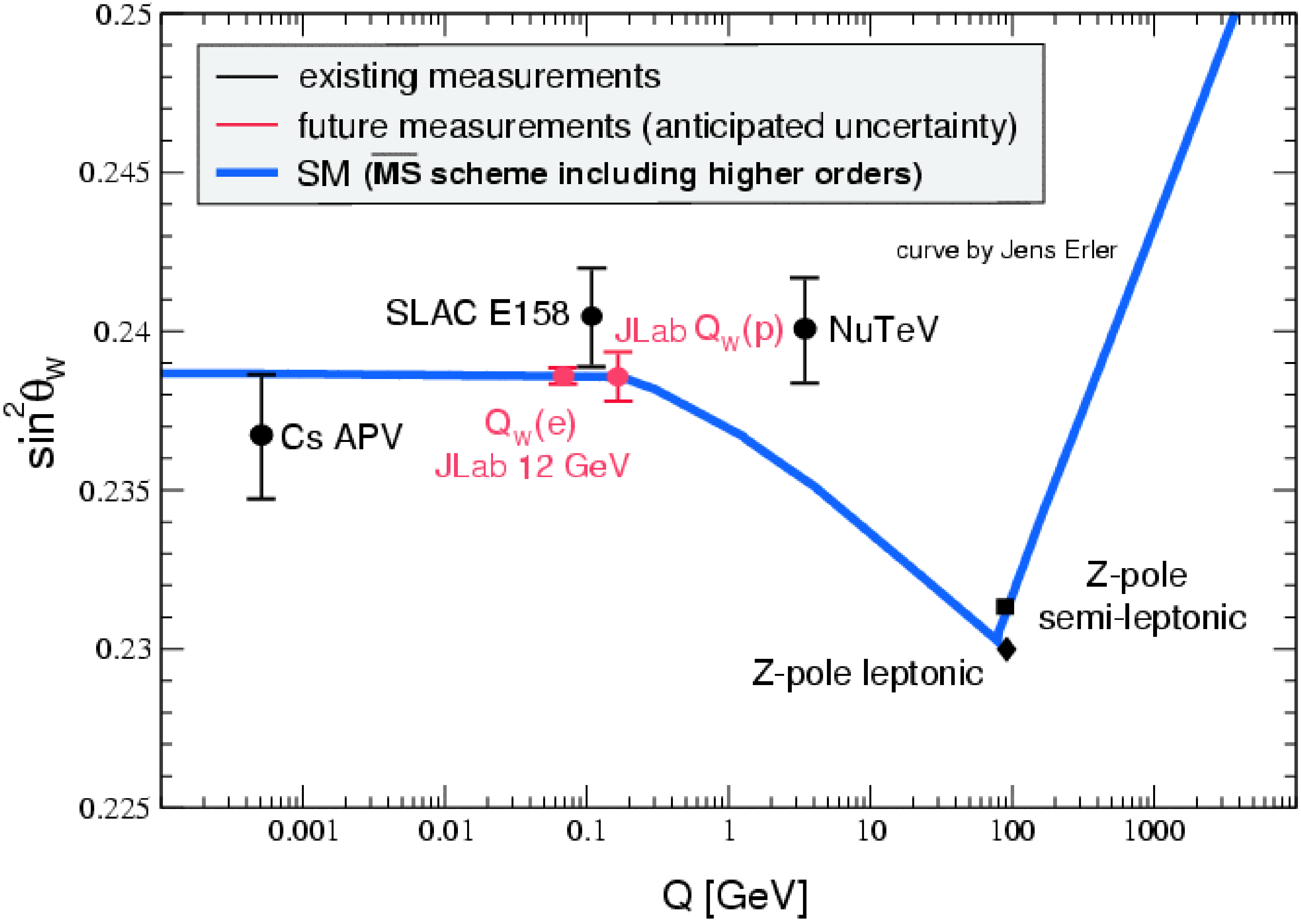
"Running of $\sin^2\theta_W$" in the Electroweak Standard Model

- Electroweak radiative corrections
  → $\sin^2\theta_W$ varies with Q





- All "extracted" values of $\sin^2\theta_W$ must agree with the Standard Model prediction or new physics is indicated.



existing measurements
future measurements (anticipated uncertainty)
SM (MS scheme including higher orders)
curve by Jens Erler
SLAC E158
JLab $Q_W(p)$
NuTeV
Cs APV
$Q_W(e)$
JLab 12 GeV
Z-pole
semi-leptonic
Z-pole leptonic
$\sin^2\theta_W$
0.25
0.245
0.24
0.235
0.23
0.225
0.001
0.01
0.1
1
10
100
1000
Q [GeV]

LE Experiments: Good News/Bad News

A 1% measurement of a weak-scale quantity, suppressed by an order of magnitude, is sensitive to physics at the scale 3 TeV.

This is well above present colliders and complementary to LHC.

Fine print:

- Low energy experiments can't measure Λ or g separately, only Λ /g.
- With no bump to display, enormous burden of proof on experiment and theory.
- If limited by systematic errors, a factor of 2 increase in mass scale requires $2^2 = 4$ reduction in the systematic error. (eg, atomic experiments)
- If limited by statistical errors, a factor of 2 increase in mass scale requires $(2^2)^2 = 16$ improvement in statistical figure of merit. (eg, scattering experiments)

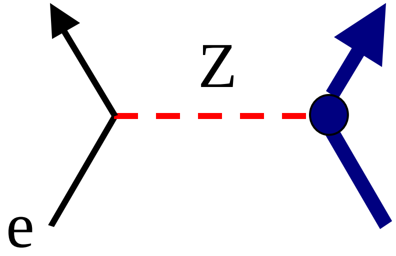
A factor of 2 increase in Λ /g in the scattering sector may happen only once per generation!

Nevertheless, JLab can do that and a bit more.

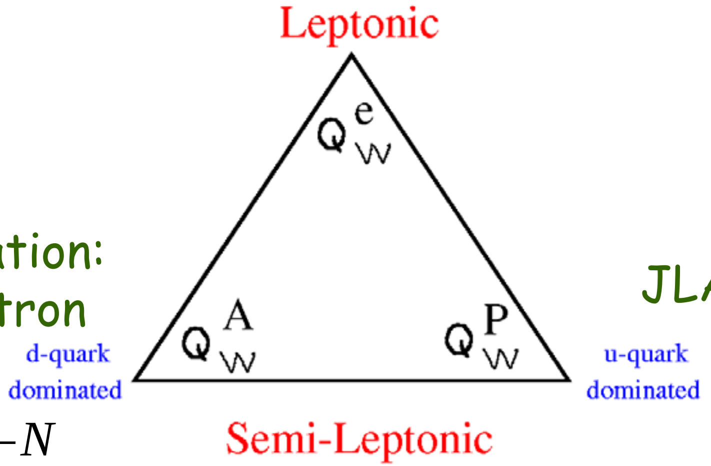
Courtesy of D.J. Mack

Low Energy Weak Neutral Current Standard Model Tests

Low energy
weak charge "triad" (M. Ramsey-Musolf)
probed in weak neutral current experiments



SLAC E158: parity-violating
Moller scattering
$\vec{e} + e \to e + e$ $\quad Q_W^e \approx -(1-4\sin^2\theta_W)$



Cesium Atomic Parity Violation:
primarily sensitive to neutron
weak charge

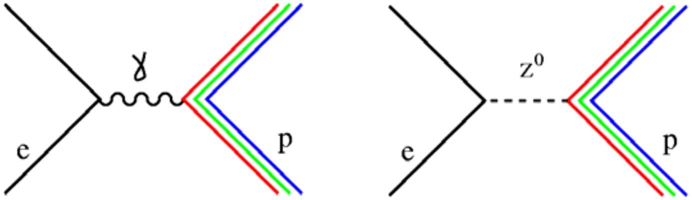
$$Q_W^A \approx -N + Z(1-4\sin^2\theta_W) \approx -N$$

JLAB Q^p_{weak}: parity-violating
$\vec{e}$-p elastic scattering
$\vec{e} + p \to e + p$

$$Q_W^p \approx 1-4\sin^2\theta_W$$

These three types of experiments are a complementary set for exploring new physics possibilities well below the Z pole.

Weak Charge Phenomenology



	EM Charge	Weak Charge
q^{up}	$+2/3$	$1 - \frac{8}{3}\sin^2\theta_W \approx 1/3$
q^{down}	$-1/3$	$-1 + \frac{4}{3}\sin^2\theta_W \approx -2/3$
$Q^p = 2q^{up} + 1q^{down}$	$+1$	$1 - 4\sin^2\theta_W = -.048$
$Q^n = 1q^{up} + 2q^{down}$	0	-1

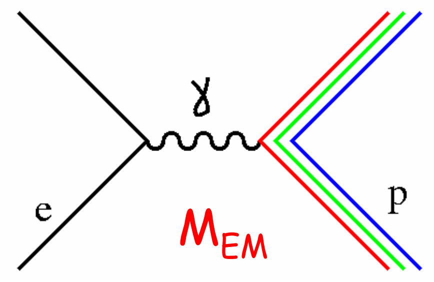
Note how the roles of the proton and neutron are become almost reversed

(ie, neutron weak charge is dominant, proton weak charge is almost zero!)

This accidental suppression of the proton weak charge in the SM makes it more sensitive to new physics (all other things being equal).

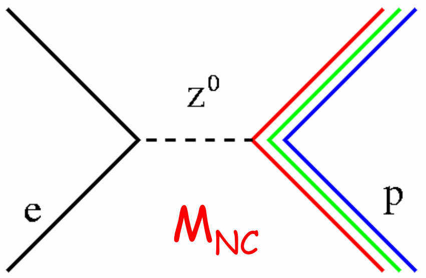
Courtesy of D.J. Mack

Q^p_{weak}: Extract from Parity-Violating Electron Scattering



measures Q^p – proton's electric charge

As $Q^2 \rightarrow 0$



measures Q^p_{weak} – proton's weak charge

$$A = \frac{2M_{NC}}{M_{EM}} = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, Q^p_{weak} + F^p\left(Q^2,\theta\right)\right]$$

$$\xrightarrow{\substack{Q^2\rightarrow 0\\ \theta\rightarrow 0}} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, Q^p_{weak} + Q^4 B\left(Q^2\right)\right]$$

contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$

$Q^p_{weak} = 1 - 4\sin^2\theta_W \sim 0.072$ (at tree level)

- Q^p_{weak} is a well-defined experimental observable
- Q^p_{weak} has a definite prediction in the electroweak Standard Model

Energy Scale of an “Indirect” Search for New Physics

- Parameterize New Physics contributions in electron-quark Lagrangian

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

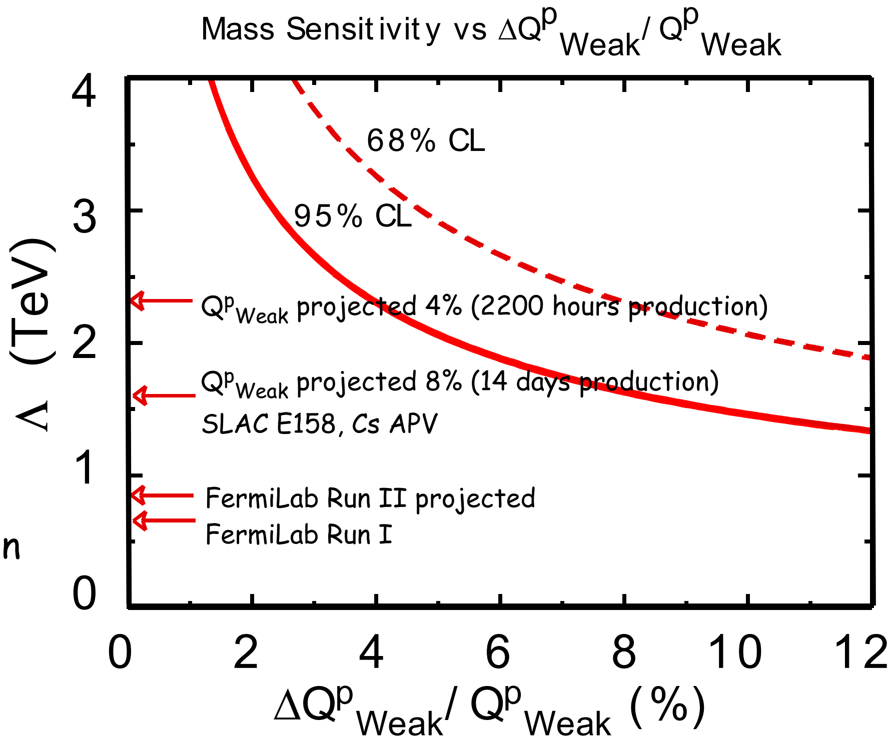
g: coupling constant, Λ: mass scale

- A 4% Q^p_{Weak} measurement probes with 95% confidence level for new physics at energy scales to:

$$\frac{\Lambda}{g} \sim \frac{1}{2\sqrt{\sqrt{2}G_F\left|\Delta Q_W^p\right|}} \approx \boxed{2.3\ \mathrm{TeV}}$$

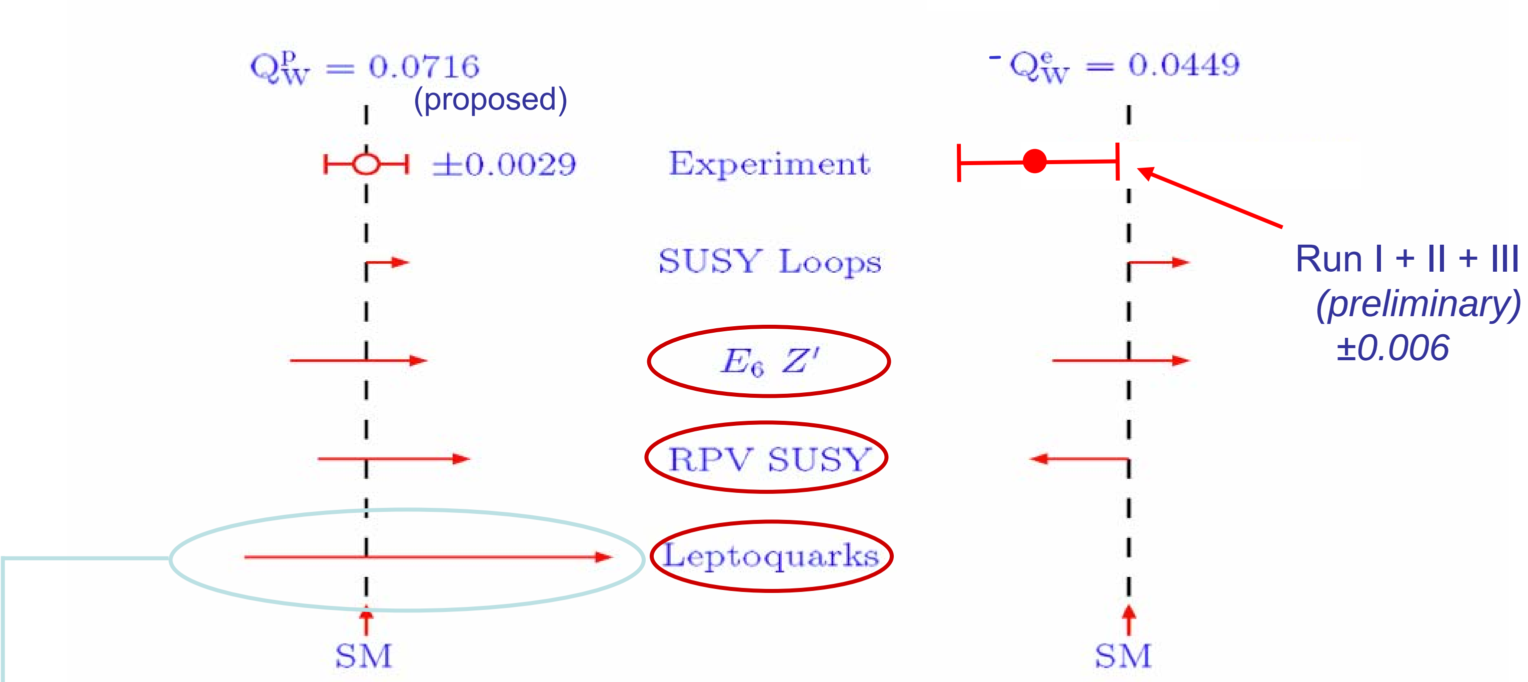
- The TeV discovery potential of weak charge measurements will be unmatched until LHC turns on.

- If LHC uncovers new physics, then precision low Q^2 measurements will be needed to determine charges, coupling constants, etc.



Q^p_{weak} & Q^e_{weak} – Complementary Diagnostics for New Physics

JLab Qweak **SLAC E158**



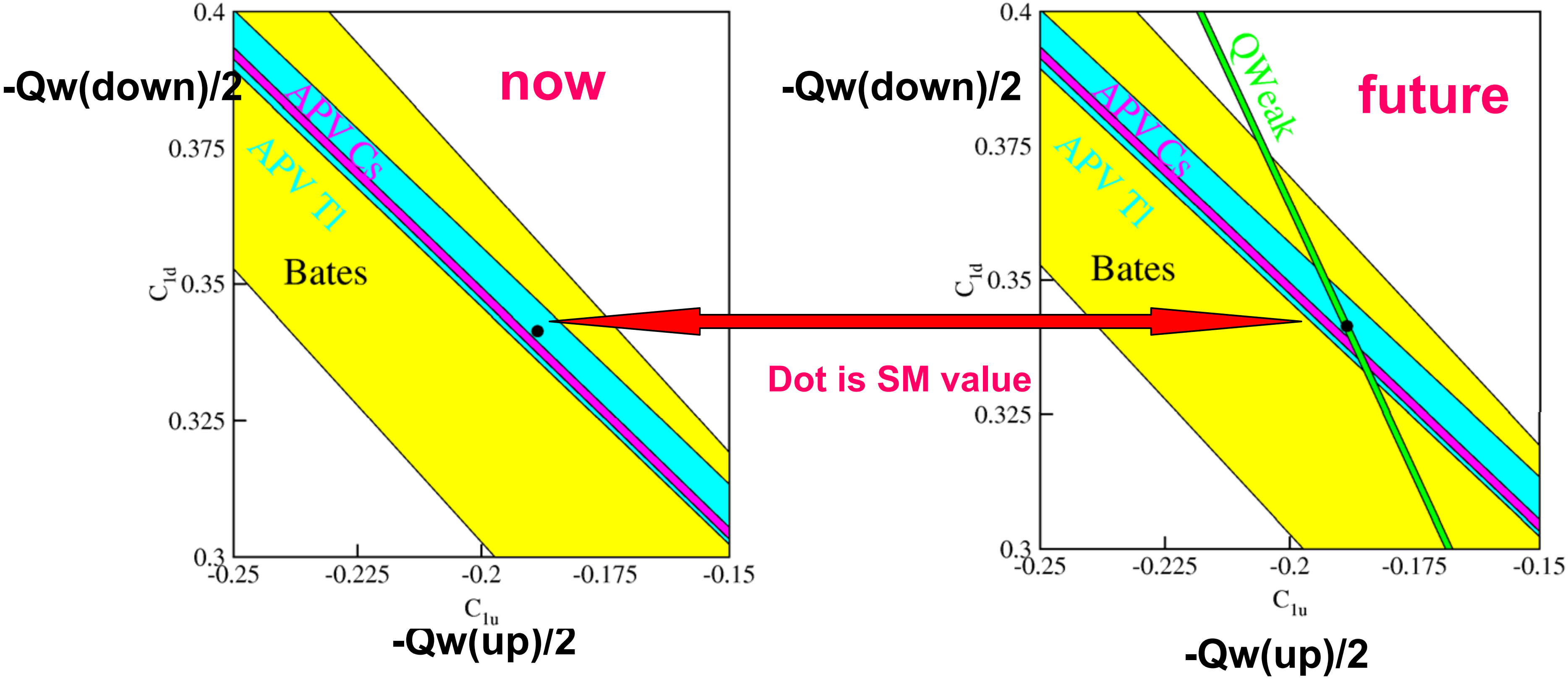
Erler, Kurylov, Ramsey-Musolf, PRD 68, 016006 (2003)

- Qweak measurement will provide a stringent stand alone constraint on Lepto-quark based extensions to the SM.
- Q^p_{weak} (semi-leptonic) and E158 (pure leptonic) together make a powerful program to search for and identify new physics.

Model-Independent Constraints

Forget about the predictions of any specific new physics model!

Do the up- and down-quarks have their expected SM weak charges?



-Qw(down)/2

now

-Qw(up)/2

-Qw(down)/2

future

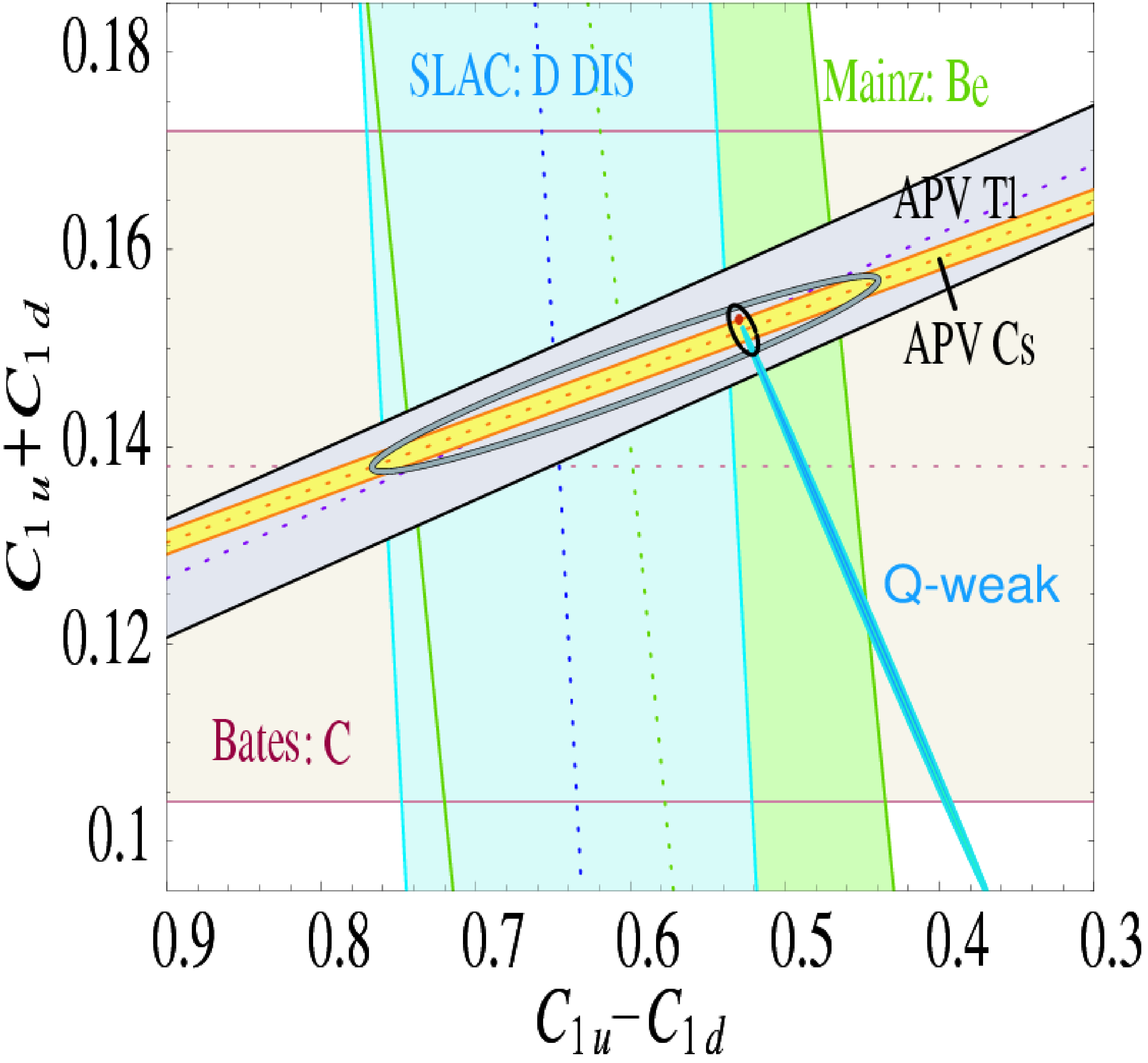
Dot is SM value

-Qw(up)/2

Constraints by 12C and APV are nearly parallel (N ~ Z). Proton measurement is needed so weak charges can be separated with interesting errors.

Qw(He) where N = Z could provide an important cross-check on Cs APV.

Figures courtesy of Paul Reimer (ANL)


SLAC: D DIS
Mainz: Be
APV Tl
APV Cs
Q-weak
Bates: C
0.18
0.16
0.14
0.12
0.1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
$C_{1u}+C_{1d}$
$C_{1u}-C_{1d}$

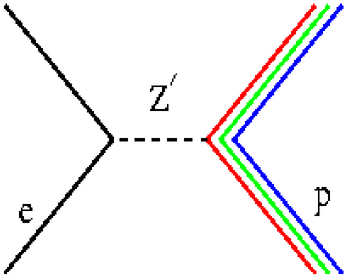
New Physics Sensitivity of Qw(p)

Qw(p) is sensitive to new electron-quark interactions such as

- Leptoquarks
- A new heavy vector (Z')
- R-parity violating SUSY
- Compositeness

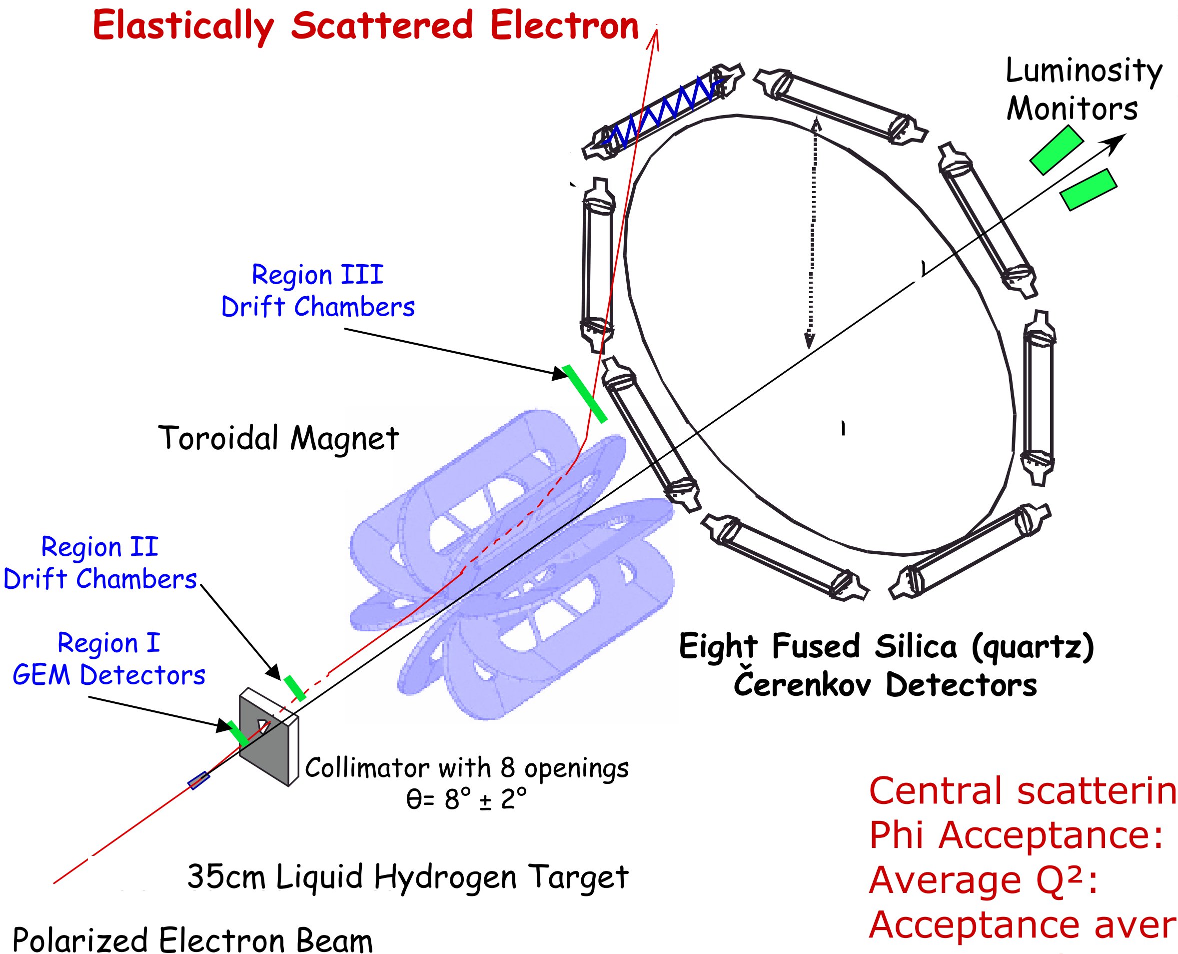
but not the usual R parity-conserving SUSY (she's very shy and hides in loops).

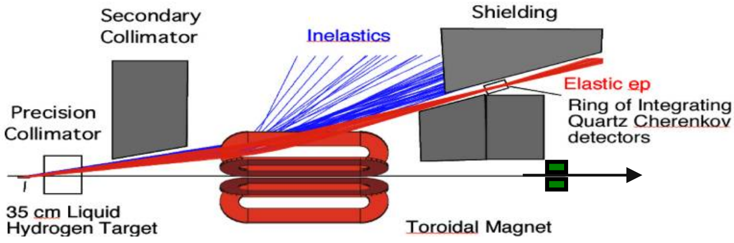
New Physics Type	CDF or LEP2 (TeV)	SLAC E158 14.5% (TeV)	JLab Q_w^p 4% (TeV)
Compositeness:			
e-e		11.9	—
e-q		—	27.5
Leptoquarks:			
γ_{up}	"1.5"	—	3.1
γ_{down}	"1.5"	—	4.3
(for $\lambda = 1$)			
Z-primes:			
$E_6\ Z_\chi$	.67 (LEP2)	.63	.95
Z_{LR}	.80 (LEP2)	.32	.45
$E_6\ Z_\psi$	.59 (CDF)	—	—



Courtesy of D.J. Mack

Overview of the Q^p_{Weak} Experiment





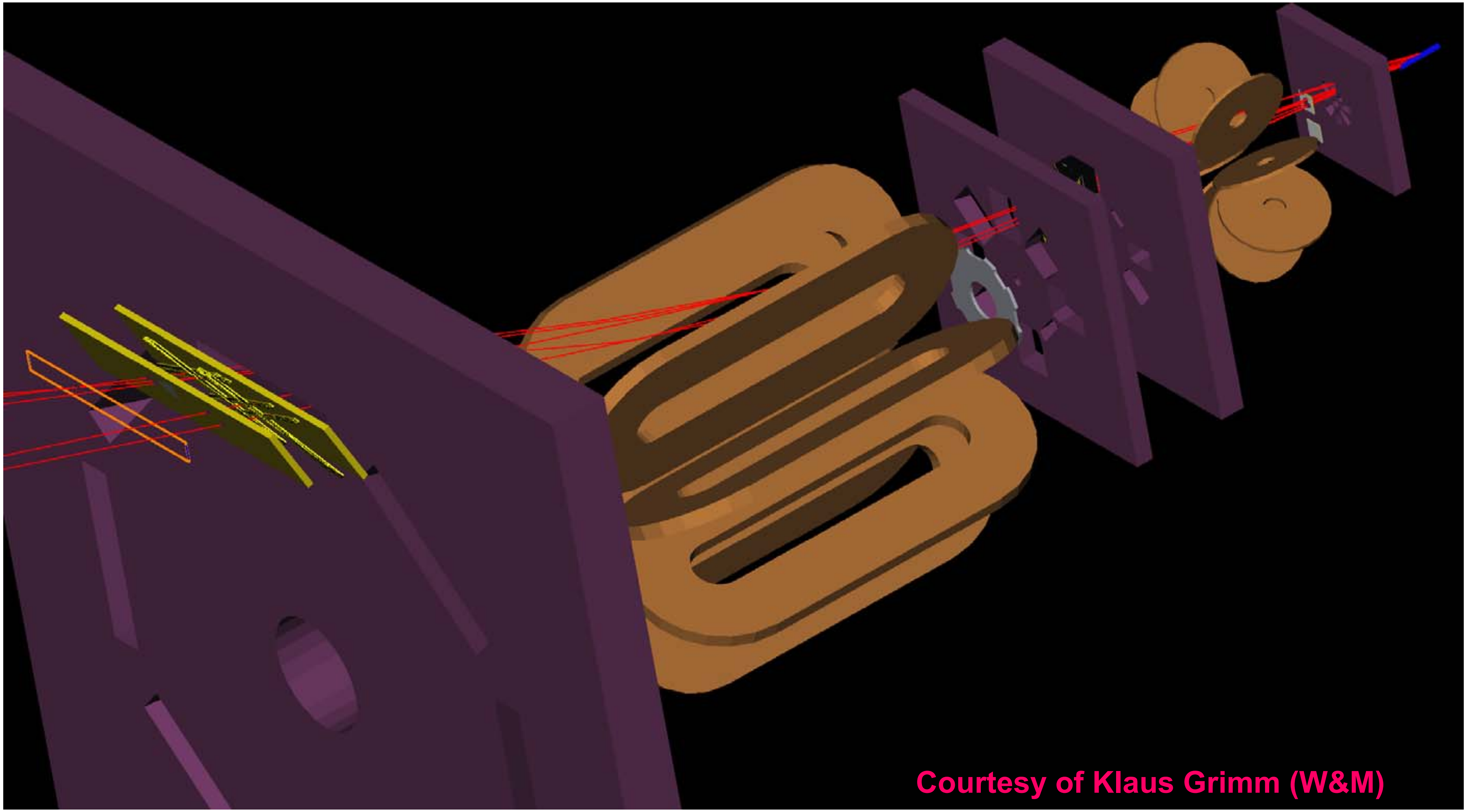
Experiment Parameters (integration mode)

Incident beam energy: 1.165 GeV
Beam Current: 180 μA
Beam Polarization: 85%
LH$_2$ target power: 2.5 KW

Central scattering angle: 8.4° ± 3°
Phi Acceptance: 53% of 2π
Average Q^2: 0.030 GeV^2
Acceptance averaged asymmetry: −0.29 ppm
Integrated Rate (all sectors): 6.4 GHz
Integrated Rate (per detector): 800 MHz

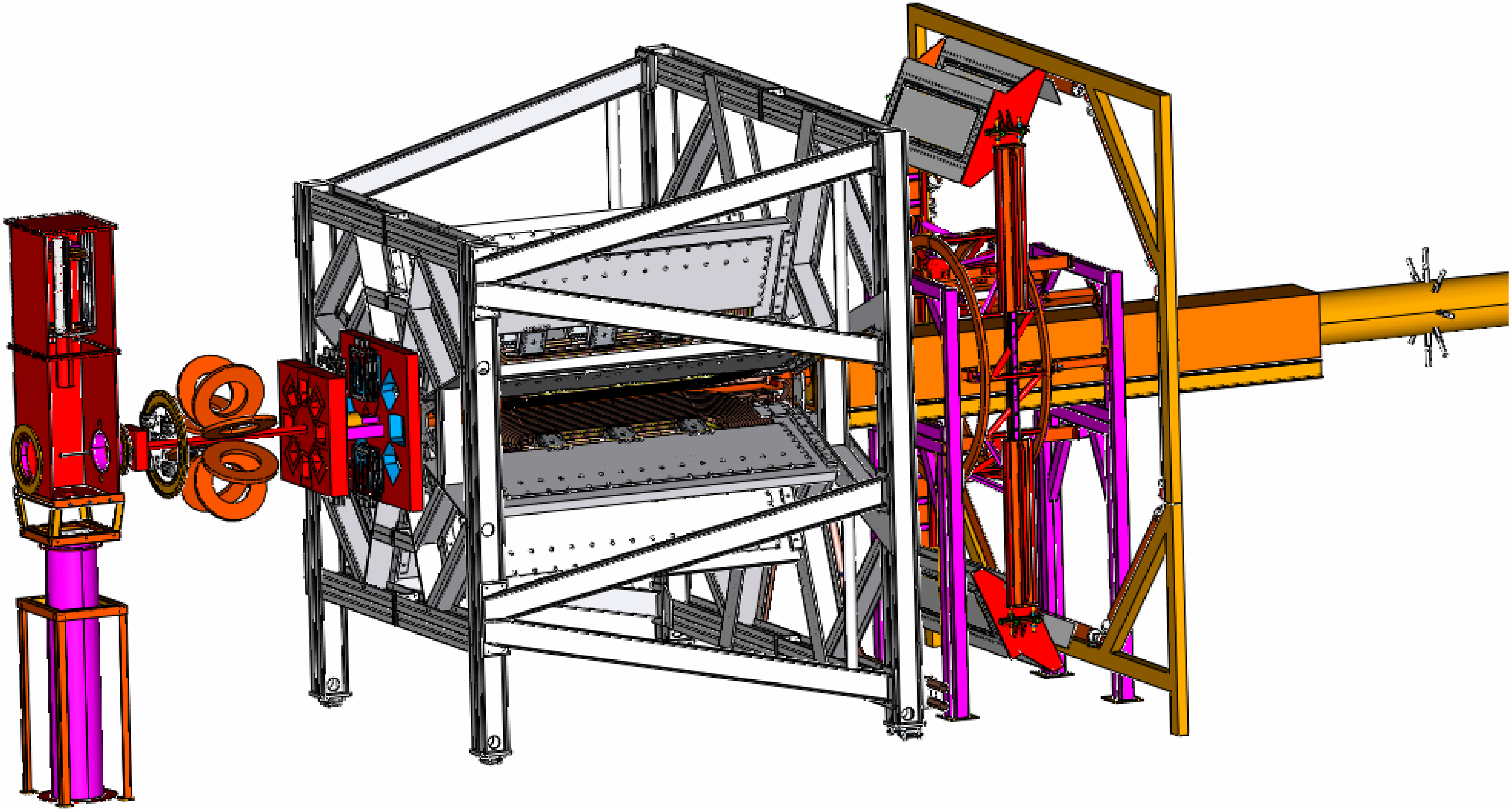
How it Works:

Qweak Apparatus in GEANT4



Courtesy of Klaus Grimm (W&M)

Courtesy of D.J. Mack



Anticipated Q^p_{Weak} Uncertainties

	$\Delta A_{phys} / A_{phys}$	$\Delta Q^p_{weak} / Q^p_{weak}$
Statistical (2200 hours production)	1.8%	2.9%
Systematic:		
Hadronic structure uncertainties	--	1.9%
Beam polarimetry	1.0%	1.6%
Absolute Q^2 determination	0.5%	1.1%
Backgrounds	0.5%	0.8%
Helicity-correlated Beam Properties	0.5%	0.8%
Total	**2.2%**	**4.1%**

4% error on Q^p_W corresponds to ~0.3% precision on $\sin^2\theta_W$ at $Q^2 \sim 0.03\ \mathrm{GeV}^2$

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

(Erler, Kurylov, Ramsey-Musolf, PRD **68**, 016006 (2003))

$Q^p_W = 0.0716 \pm 0.0006$ theoretically

0.8% error comes from QCD uncertainties in box graphs, etc.

Nucleon Structure Contributions to the Asymmetry

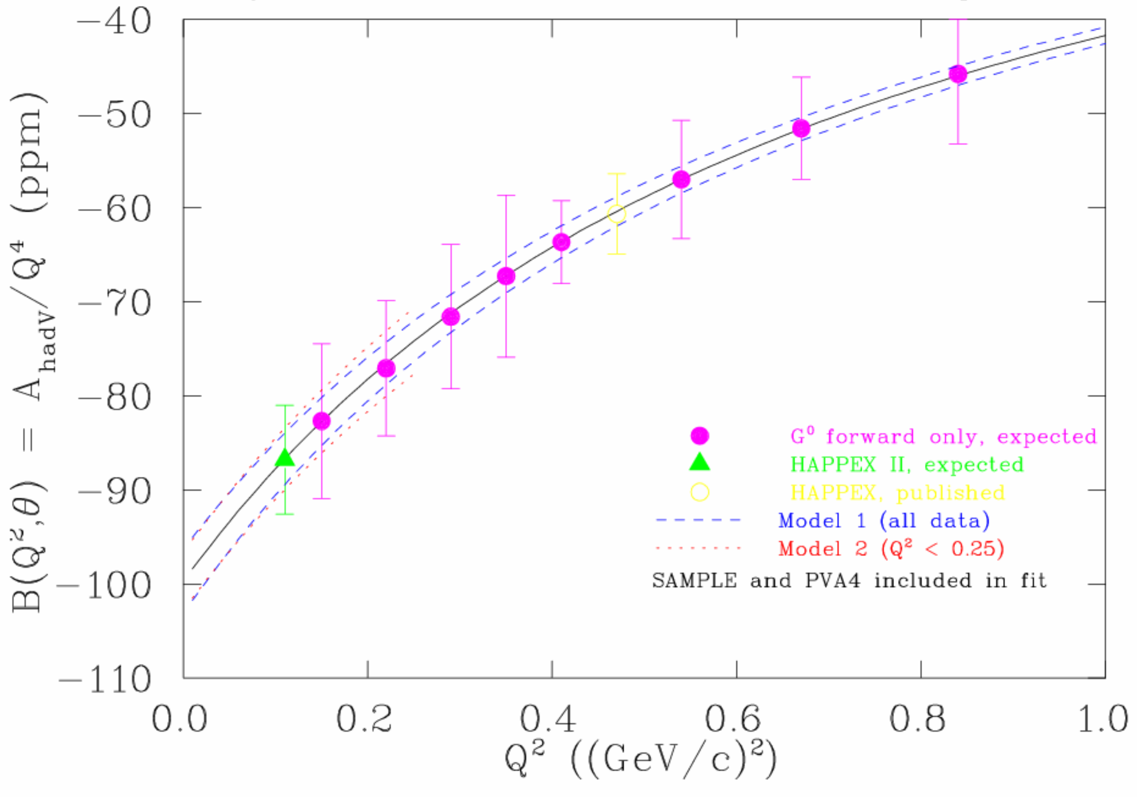
$$A = A_{Q_W^p} + A_{hadronic} + A_{axial}$$
$$= -.19 \text{ ppm} \quad -.09 \text{ ppm} \quad -.01 \text{ ppm}$$

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,
has large electroweak radiative corrections.
Constrained by
G^0 and SAMPLE

Constraints on $A_{hadronic}$ from other Measurements

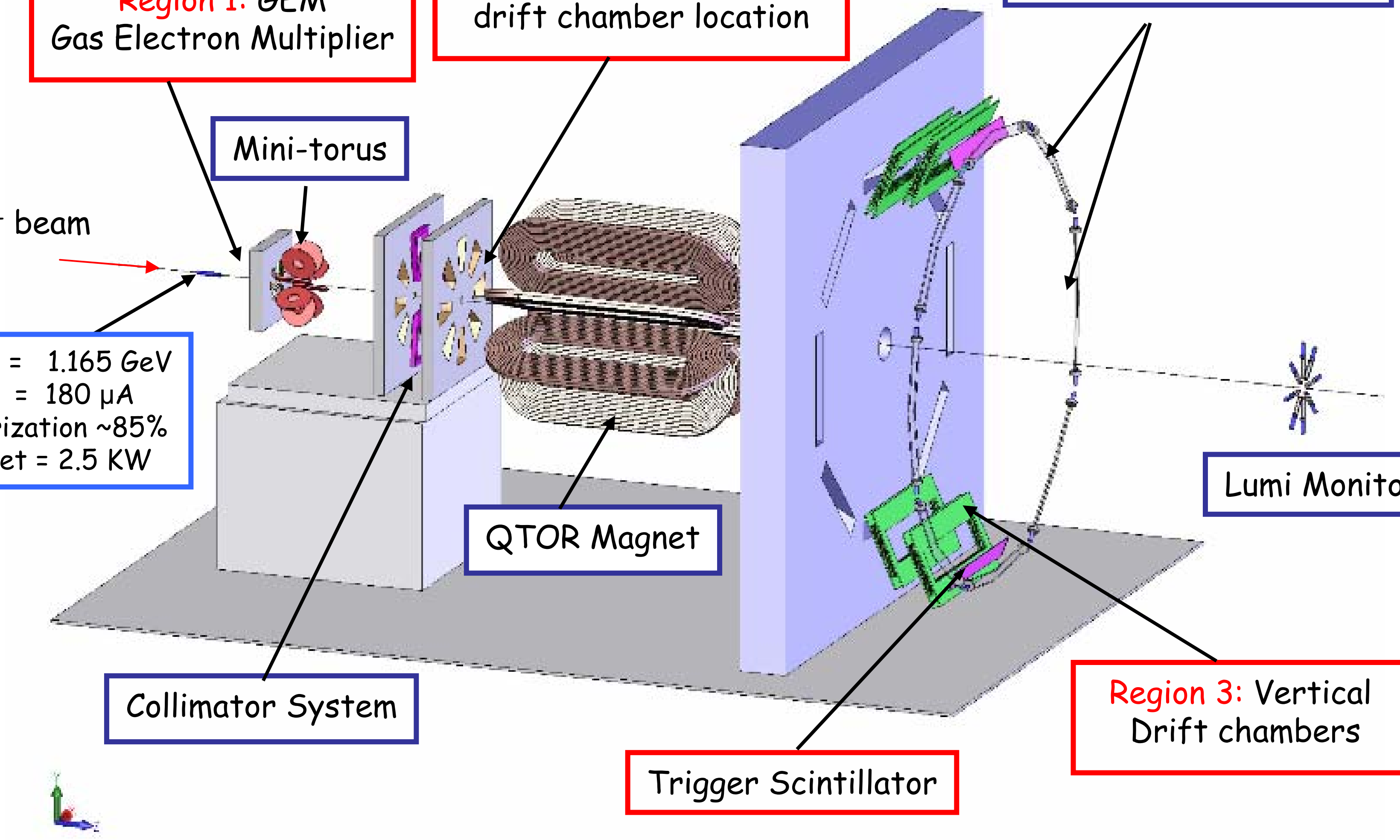
$$A_{hadronic} = Q^4 B(Q^2)$$



Quadrature sum of expected $\Delta A_{hadronic}$ = 1.5% and ΔA_{axial} = 1.2% errors contribute ~1.9% to error on Q^p_W

The Qweak Apparatus

(Calibration Mode Only - Production & Calibration Modes)



Quartz Cherenkov Bars
(insensitive to
non-relativistic particles)

Region 1: GEM
Gas Electron Multiplier

Region 2: Horizontal
drift chamber location

Mini-torus

e

e^- beam

E_{beam} = 1.165 GeV
I_{beam} = 180 μA
Polarization ~85%
Target = 2.5 KW

Lumi Monitors

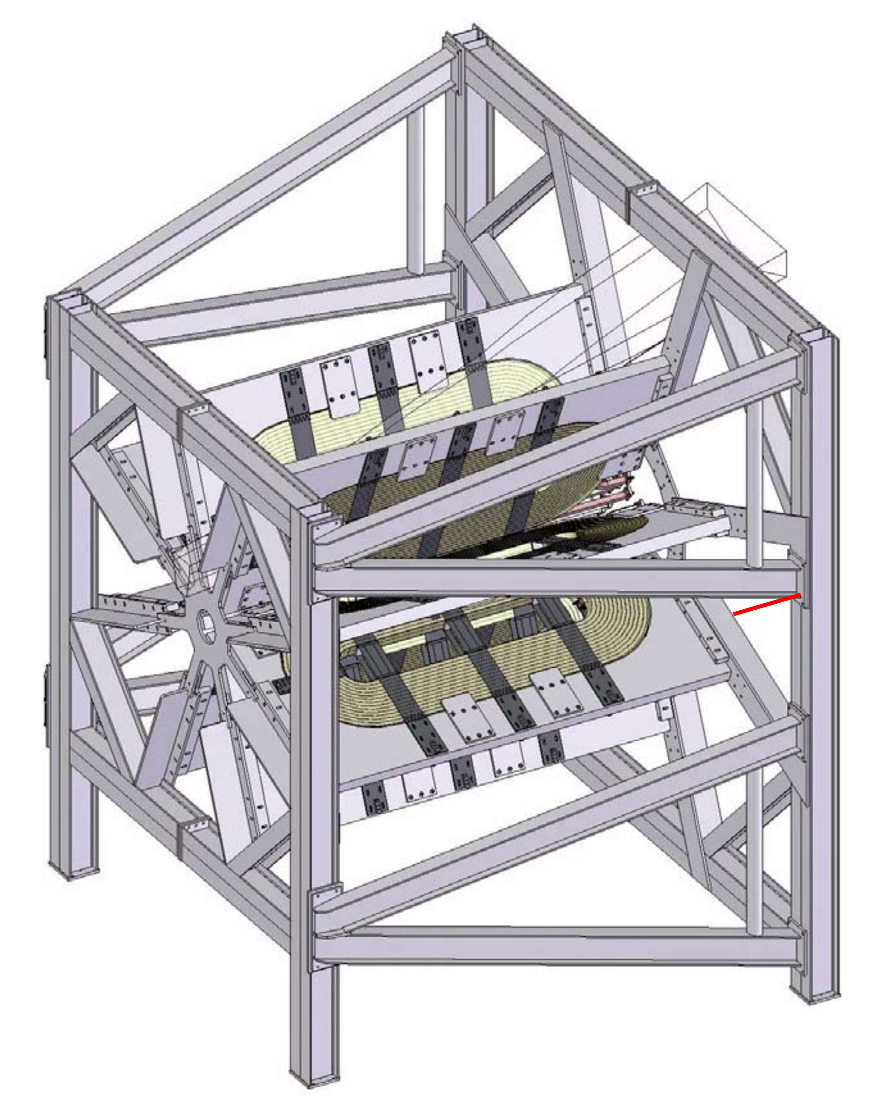
QTOR Magnet

Collimator System

Trigger Scintillator

Region 3: Vertical
Drift chambers

Q^p_{Weak} Toroidal Magnet - QTOR

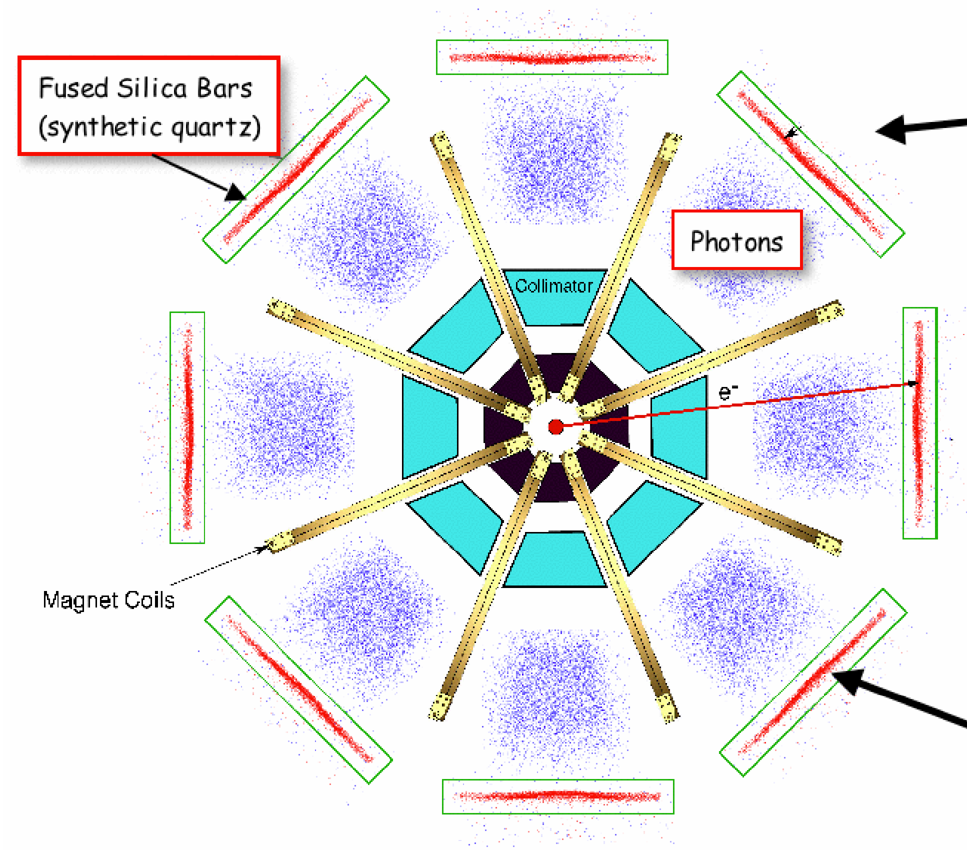


- 8 toroidal coils, 4.5m long along beam
- Resistive, similar to BLAST magnet
- Pb shielding between coils
- Coil holders & frame all Al
- $\int B \cdot dl \sim 0.7$ T-m
- bends elastic electrons ~ 10°
- current ~ 9500 A

Status:
- coils wound in France
- support stand under construction

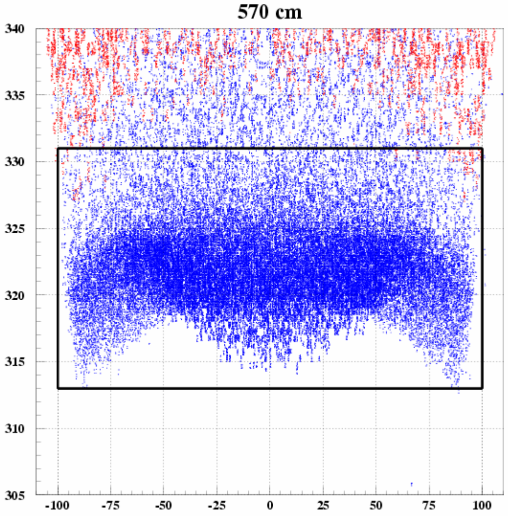
Inelastic/Elastic Separation in Q^p_{Weak}

View Along Beamline of Q^p_{Weak} Apparatus - Simulated Events



Fused Silica Bars
(synthetic quartz)

In-elastic Events
(beyond detector)



rectangular
quartz bar;
18 cm wide
X 2 meters
long

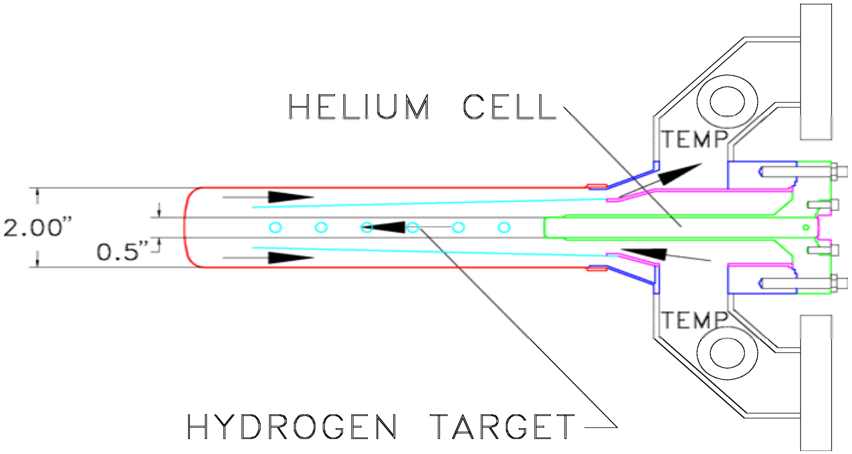
Elastic Events
(in focal plane)

Black region in center
is Pb shielding

Very clean elastic separation!

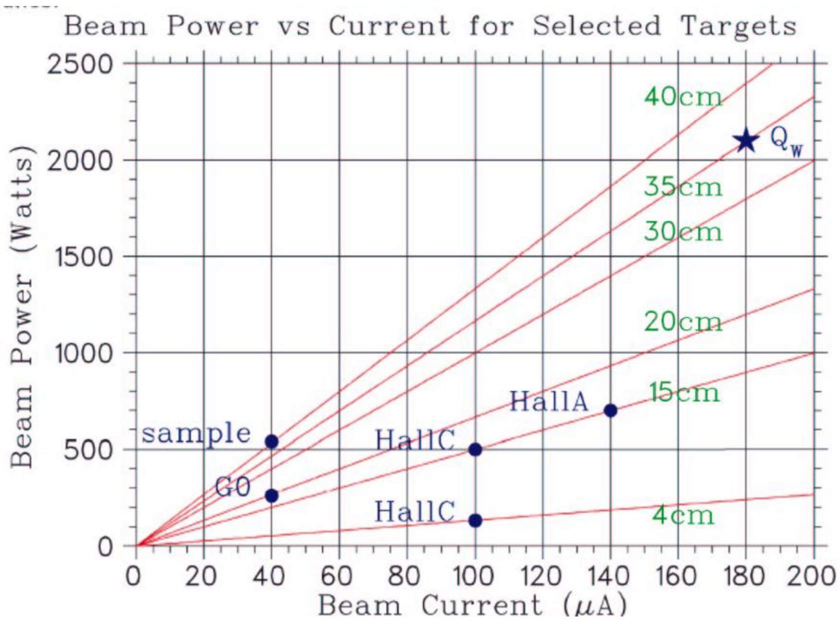
Central scattering angle:	~8.4° ± 3°
Phi Acceptance:	> 50% of 2π
Average Q^2:	0.030 GeV^2
Acceptance averaged asymmetry:	–0.29 ppm
Integrated Rate (per detector):	~801 MHz
Inelastic/Elastic ratio:	~0.026%

The Q^p_{Weak} Liquid Hydrogen Target



Target Concept:

- Similar in design to SAMPLE and G^0 targets
  → longitudinal liquid flow
  → high stream velocity achieved with perforated, tapered "windsock"



Q^p_{Weak} Target parameters/requirements:

- Length = 35 cm
- Beam current = 180 μA
- Power = 2200 W beam + 300 W heater
- Raster size ~4 mm x ~4 mm square
- Flow velocity > 700 cm/s
- Density fluctuations (at 15 Hz) < 5×10^{-5}
- Use reversal rate of 270 Hz

Helicity Correlated Beam Properties: False Asymmetry Corrections

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

$\Delta P = P_+ - P_-$

Y = Detector yield

(P = beam parameter
~energy, position, angle, intensity)

Example: $\frac{1}{2Y}\left(\frac{\partial Y}{\partial x}\right) \sim 1.0\ \%/\mathrm{mm}\,,\ \Delta x = 100\ \mathrm{nm}$

$$A_{\mathrm{false}} = \frac{1}{2Y}\left(\frac{\partial Y}{\partial x}\right)\Delta x \sim 10^{-6} = 1\,\mathrm{ppm}$$

Typical goals for run-averaged beam properties

Intensity: $A_{\mathrm{I}} = \frac{\mathrm{I}_+ - \mathrm{I}_-}{\mathrm{I}_+ + \mathrm{I}_-} < 1\,\mathrm{ppm}$

Position: $\Delta\mathrm{x}, \Delta\mathrm{y} < 2 - 20\ \mathrm{nm}$

$\Delta P = P_+ - P_-$ → keep small with feedback and careful setup

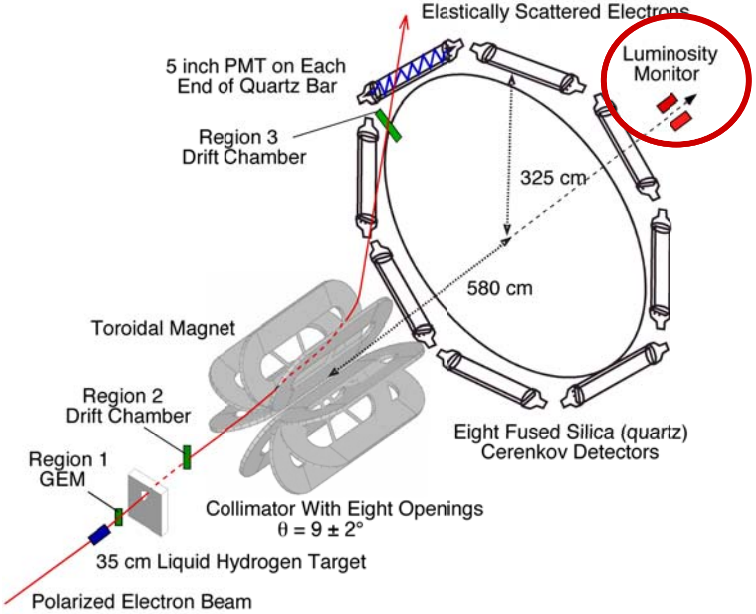
$\frac{1}{2Y}\left(\frac{\partial Y}{\partial \mathrm{P}}\right)$ → keep small with symmetrical detector setup

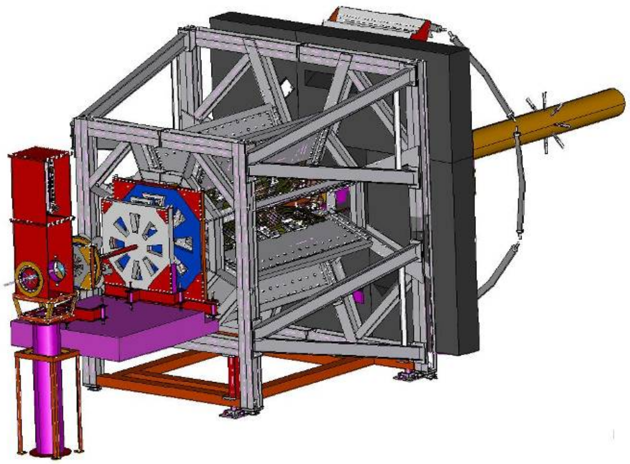
The Q^p_{Weak} Luminosity Monitor

- Luminosity monitor → Symmetric array of 8 quartz Cerenkov detectors instrumented with rad hard PMTs operated in "vacuum photodiode mode"
  & integrating readout at small θ (~ 0.8°).
  Low Q^2, high rates ~29 GHz/octant.

- Expected signal components: 12 GHz e-e Moeller, 11 GHz e-p elastic, EM showers 6 GHz.
- Expected lumi monitor asymmetry « main detector asymmetry.
- Expected lumi monitor statistical error ~ (1/6) main detector statistical error.

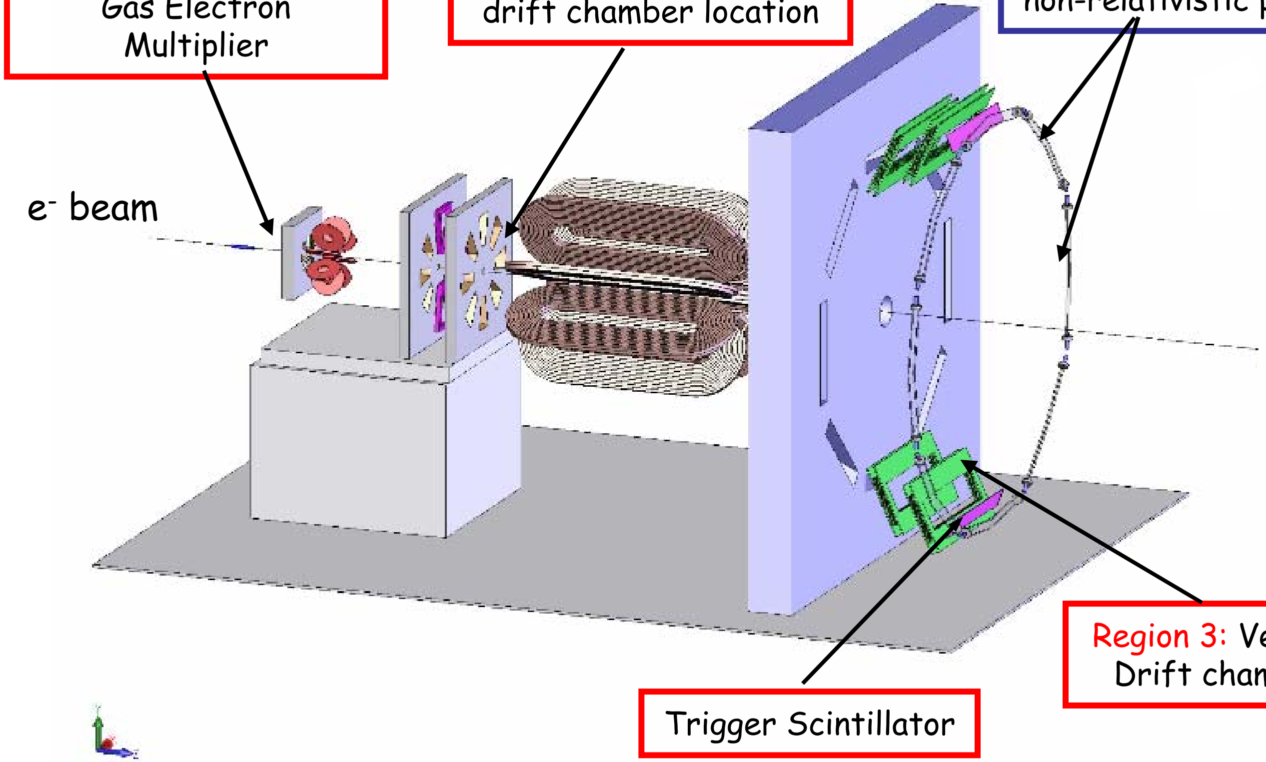
- Useful for:
  - Sensitive check on helicity-correlated beam parameter corrections procedure.
  - Regress out target density fluctuations.





Q^2 Determination

Use low beam current (~ few nA) to run in "pulse counting" mode with a tracking system to determine the "light-weighted" Q^2 distribution.



Region 1: GEM Gas Electron Multiplier

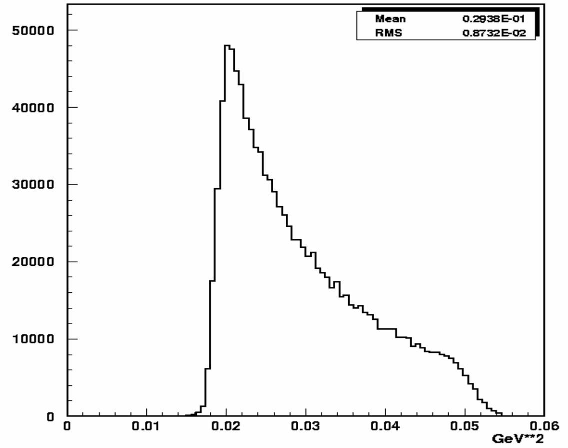
Region 2: Horizontal drift chamber location

Quartz Cherenkov Bars (insensitive to non-relativistic particles)

Region 3: Vertical Drift chambers

Trigger Scintillator

Expected Q^2 distribution



Region 1 + 2 chambers --> determine value of Q^2

Region 3 chamber --> efficiency map of quartz detectors

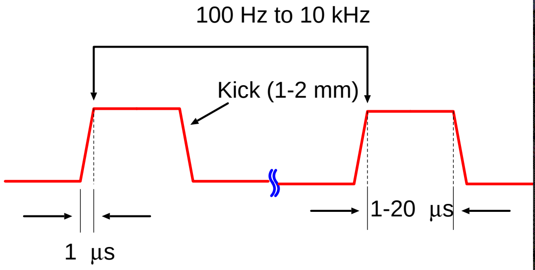
Precision Polarimetry

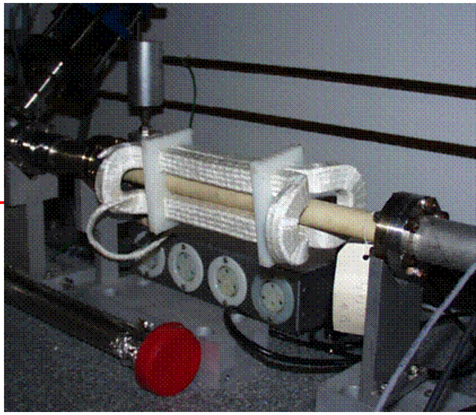
Hall C has existing ~1% precision Moller polarimeter

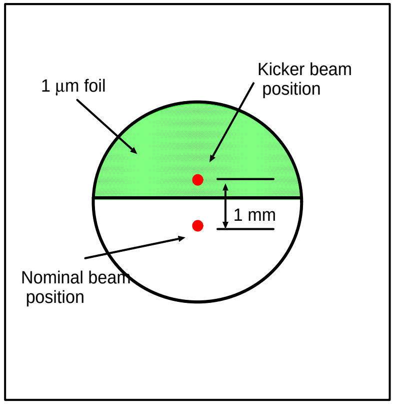
- Present limitations:
  - I_{Max} ~ 10 μA.
  - At higher currents the Fe target depolarizes.
  - Measurement is destructive

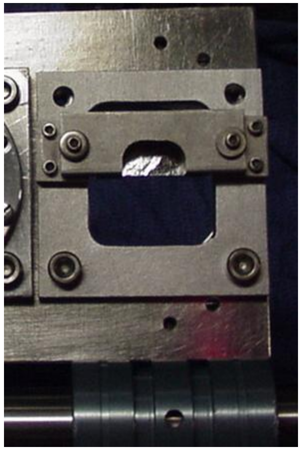
- Plan to upgrading Møller:
  - Measure P_{beam} at 100 μA or higher, quasi-continuously
  - Trick: kicker + strip or wire target (early tests look promising – tested up to 40 μA so far)

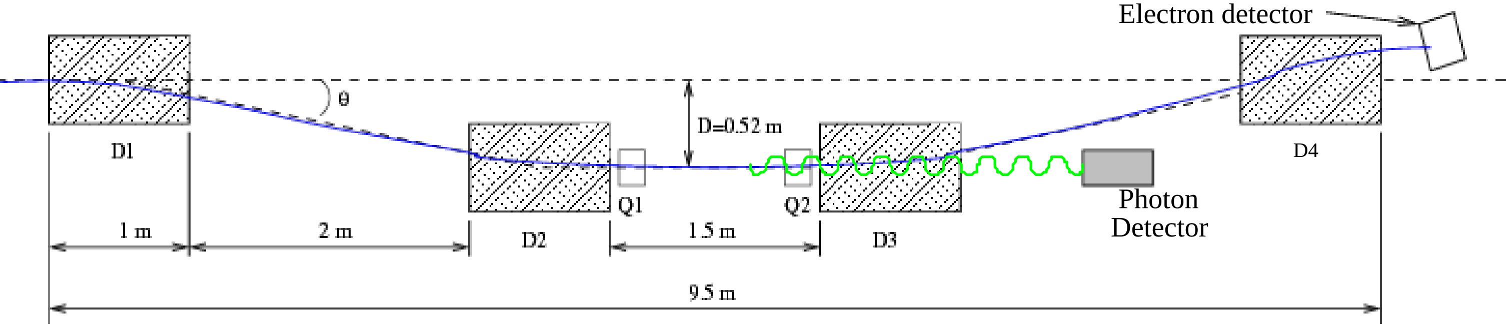
- Schematic of planned new Hall C Compton polarimeter.







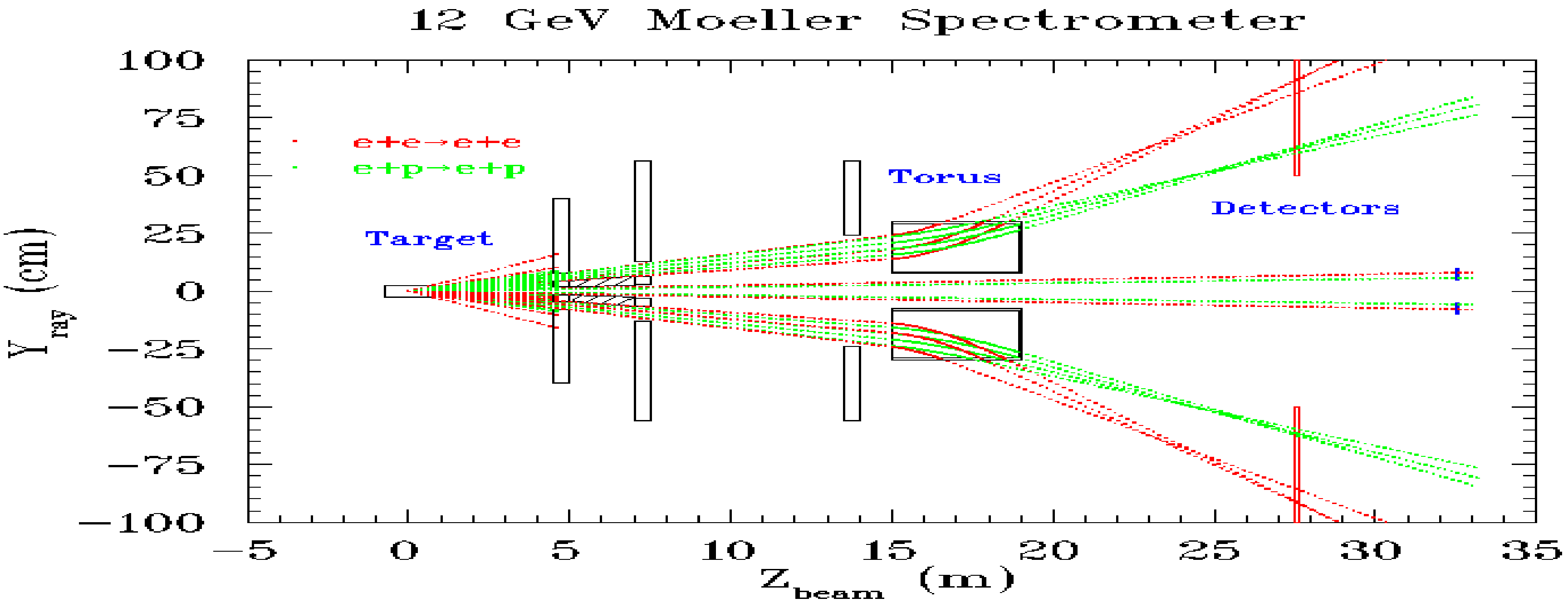




e2ePV at 12 GeV

JLab could determine Qw(e) to 2.5% as a search for new physics or the best low energy determination of the weak mixing angle.

- E = 12 GeV
- 4000 hours
- L = 150 cm
- A_{PV} = -40 ppb



Courtesy of D.J. Mack

e2ePV at 12 GeV

- Qw(e) would tightly constrain RPV SUSY (ie tree-level)
- Killer application of improved Qw(e) is to RPC SUSY

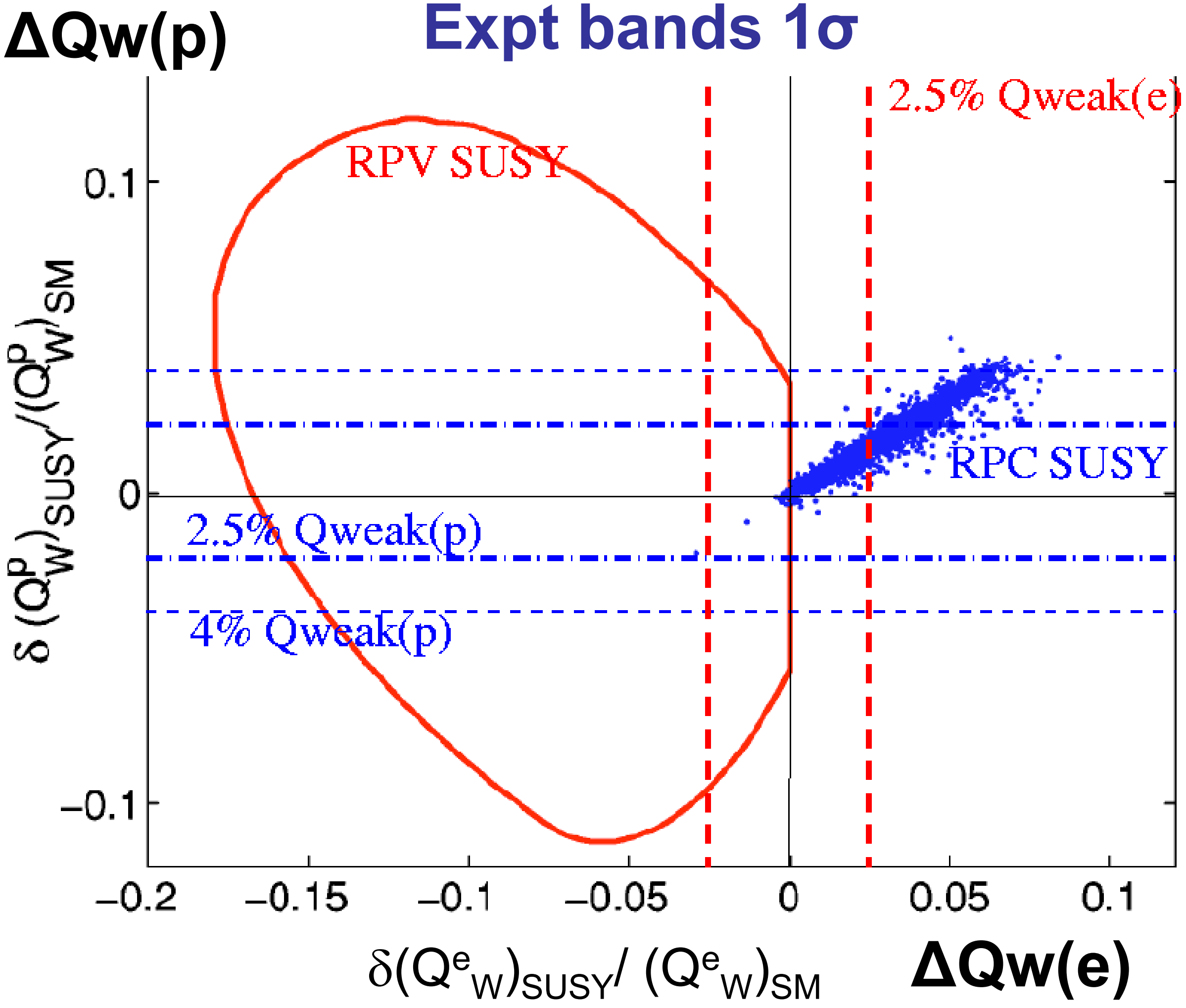
  (ie, loop-level)

  One of few ways to constrain RPC SUSY if it happens to conserve CP (hence SUSY EDM = 0).

  Direct associated-production of a pair of RPC SUSY particles might not be possible even at LHC.

Theory contours 95% CL

Expt bands 1σ

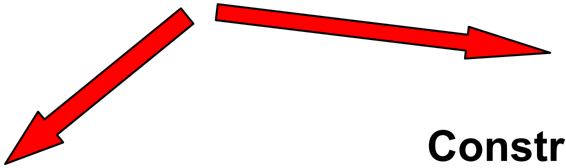


Contours courtesy of Shufang Su (U. Arizona)

Future of the JLab Weak Charge Program

- Qw(p) finish construction (mid 2007)
  Run I (8%) (2008?)
  (lick wounds following embarrassing confrontation with Mother Nature)
  Run II (4%)
  (Potential 1% Qw(He) as cross-check on Cs APV?)

What do we do when the LHC (or Atomic Physics) turns our world upside down?
Will Run II be finished so JLab can respond?
What do we do if we see a significant deviation in Run II?



2.5% Qw(p)/Qw(He)

Constrain e-up and e-down quark couplings of ~TeV mass particles discovered by LHC.

2.5% Qw(e) at 12 GeV

Constrain e-e couplings of ~TeV mass particles discovered by LHC.

or

If LHC finds the TeV-scale region is a desert, make world's best measurement of the weak mixing angle at low energy.

Courtesy of D.J. Mack

Summary

- Completed low energy Standard Model tests are consistent with Standard Model “running of $\sin^2\theta_W$”

  SLAC E158 (running verified at ~ 6σ level) - leptonic
  Cs APV (running verified at ~ 4σ level) – semi-leptonic, “d-quark dominated”

- Upcoming Q^p_W Experiment
  - Precision measurement of the proton’s weak charge in the simplest system.
  - Sensitive search for new physics with CL of 95% at the ~ 2.3 TeV scale.
  - Fundamental 10 σ measurement of the running of $\sin^2\theta_W$ at low energy.
  - Currently in process of 3 year construction cycle; goal is to have multiple runs in 2008 – 2009 timeframe

- Possible 12 GeV Parity-Violating Moller Experiment at JLAB
  - Conceptual design indicates reduction of E158 error by ~5 may be possible at 12 GeV JLAB.

weak charge triad →
(Ramsey-Musolf)