Searches for Physics Beyond the Standard Model

Electroweak Tests of the Standard Model

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Outline

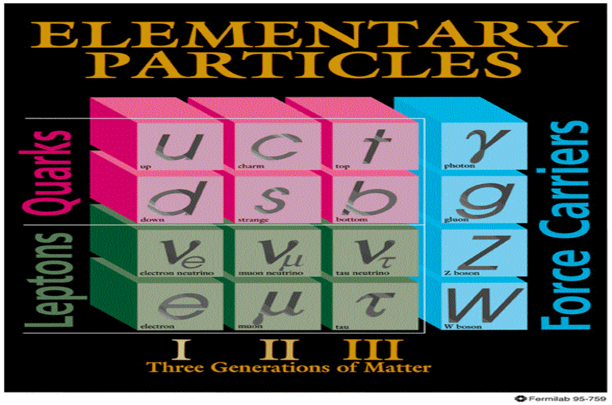
- Introduction
- The Qweak Experiment
- The MOLLER Experiment
- The PVDIS Experiment

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?

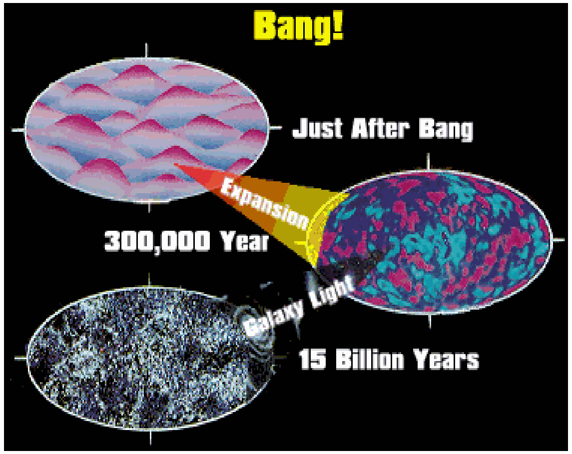
- Why 3 generations of leptons and quarks?
  Begs for an explanation!



- 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

Starting from a rational universe suggests that the SM is only a low order approximation of reality, as Newtonian gravity is a low order approximation of general relativity.



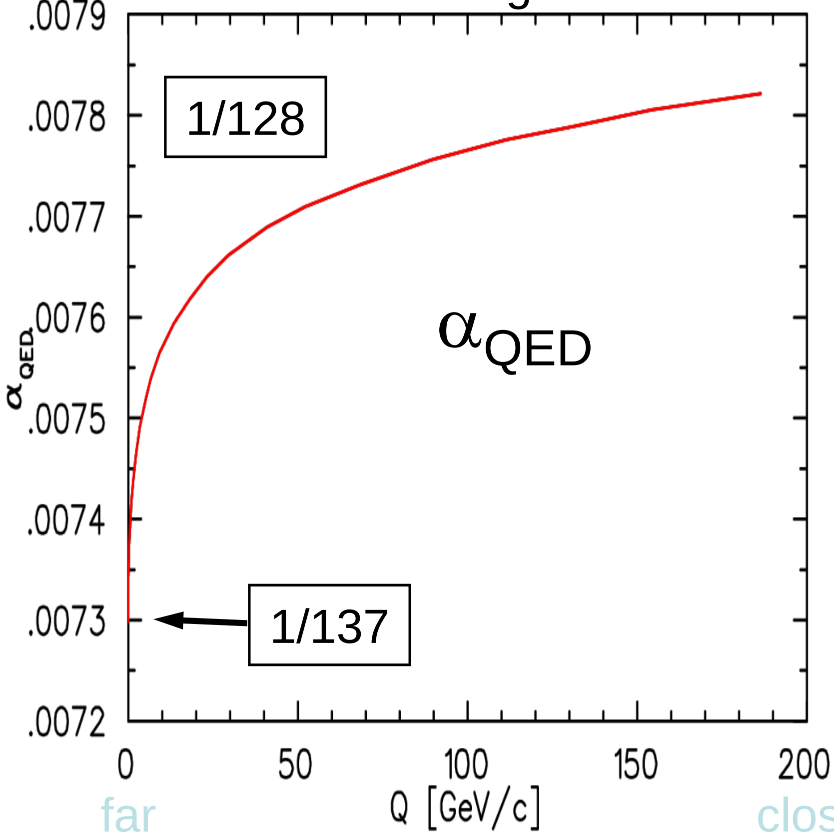
Measured Charges Depend on Distance

(running of the coupling constants)

Electromagnetic coupling is
stronger close to the bare charge

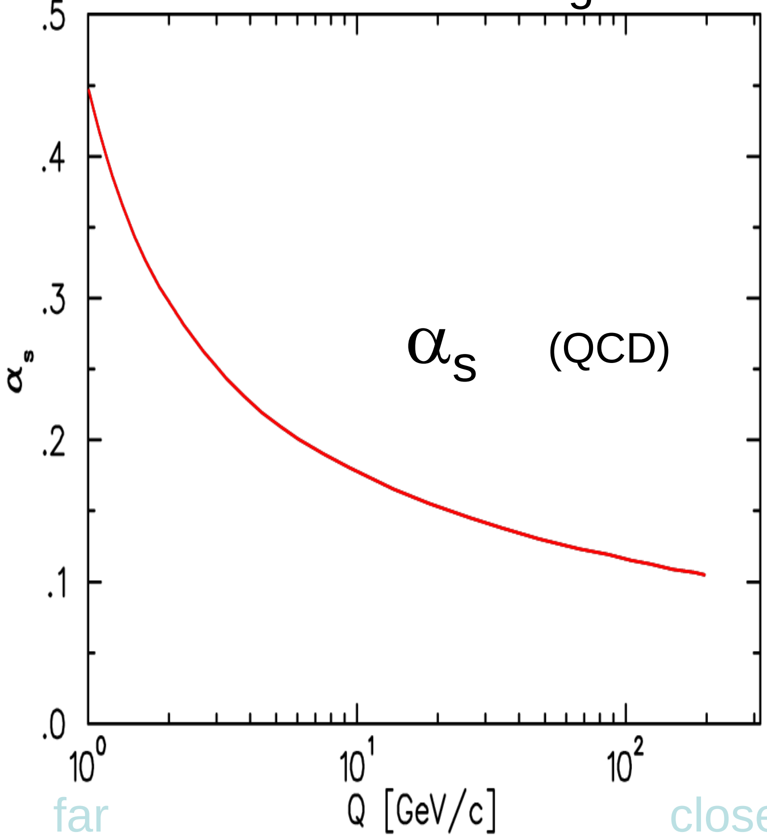
Strong coupling is
weaker close to the bare charge

“screening”



far close

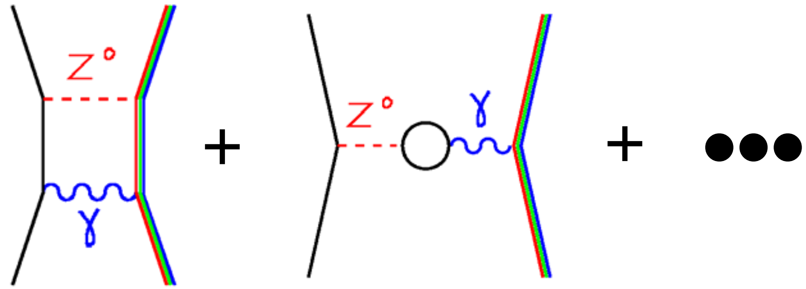
“anti-screening”

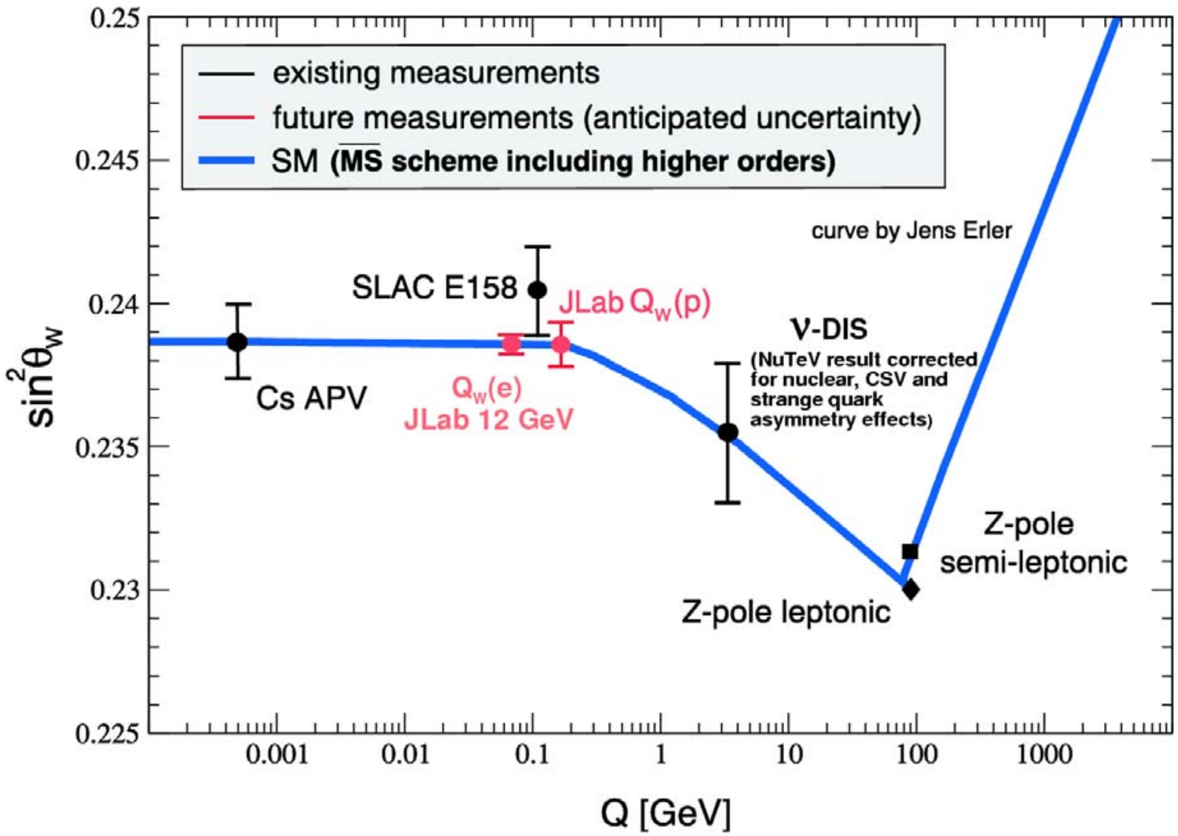


far close

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

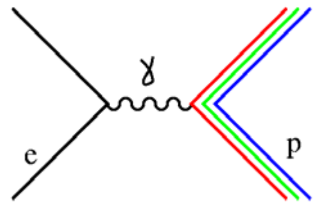
- Electroweak radiative corrections
  $\rightarrow \sin^2\theta_W$ varies with Q

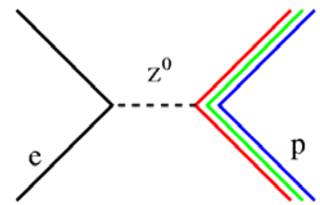




- All "extracted" values of $\sin^2\theta_W$ <u>must</u> agree with the Standard Model prediction or <u>new</u> physics is indicated.

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 have become almost reversed

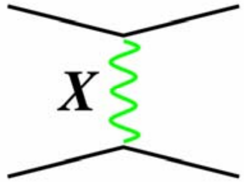
(ie, neutron weak charge is dominant, proton weak charge is almost zero!)

Q^e	**-1**	$-(1 - 4\sin^2\theta_W) = -.048$

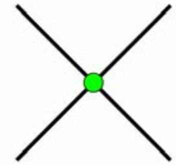
This accidental suppression of the proton weak charge in the SM makes it more sensitive to new physics (all other things being equal). Similarly for the electron weak charge.

Colliders vs Low Q^2

consider



$$A_X \;\alpha\; \frac{1}{Q^2 - M_X^2} \rightarrow$$



Contact interaction

$$\sim \frac{4\pi}{\Lambda^2}$$

$Q^2 \sim M_Z^2$ — **on resonance:** A_Z *imaginary* $\longrightarrow A_Z^2 \left[1 + \frac{A_X^2}{A_Z^2}\right]$

no interference!

Consider known weak neutral current interactions mediated by Z Bosons

$$\frac{\delta A_Z}{A_Z} \;\alpha\; \frac{\pi/\Lambda^2}{g\, G_F} \longrightarrow$$

$\delta(g)/g \sim 0.1$
$\Lambda \sim 10\ \mathrm{TeV}$

$$\frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \lesssim 0.01$$

Window of opportunity for weak neutral current measurements at $Q^2 \ll M_Z^2$

Processes with potential sensitivity:

- neutrino-nucleon deep inelastic scattering — ***NuTeV at Fermilab***
- atomic parity violation (APV) — ***^{133}Cs at Boulder***
- parity-violating electron scattering — ***E158@SLAC***
  Qweak, MOLLER, PVDIS

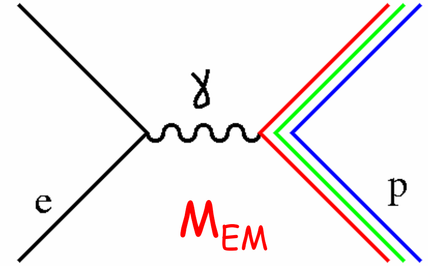
The Q^p_{weak} Experiment: A Search for New TeV Scale Physics via a Measurement of the Proton's Weak Charge

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

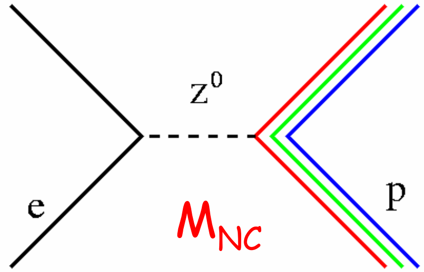
Extract: Proton's weak charge $Q^p_{weak} \sim 1 - 4 \sin^2\theta_W$
to get ~0.3% on $\sin^2\theta_W$ at $Q^2 \sim 0.03$ GeV^2

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

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



As $Q^2 \rightarrow 0$



measures Q^p – proton's electric charge

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

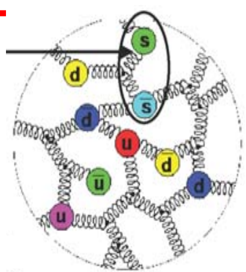
$$A = \frac{2M_{NC}}{M_{EM}} = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q^p_{weak} + F^p(Q^2,\theta)\right]$$

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

contains hadronic structure information – strange form factors

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

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



$G^s_E\,(Q^2)$

$G^s_M\,(Q^2)$

Strange electric and magnetic form factors
-measure contribution of strange quark sea
to nucleon structure

How Low a Value of Q^2 to be Used?

- low Q^2 reduces the hadronic correction, but also reduces A_z
- the experiment will use Q^2 = 0.03 $(Gev/c)^2$, $\theta = 8°$, where

$$A_Z = -194 \text{ ppb } - 74 \text{ ppb} = -268 \text{ ppb}$$

Qweak term

Hadronic correction constrained by G0, HAPPEX, PV-A4, SAMPLE

- The -300 ppb (-0.3 ppm) is technically manageable
- The hadronic corrections should introduce <2% error in Q_W

calculations Ross Young, JLab

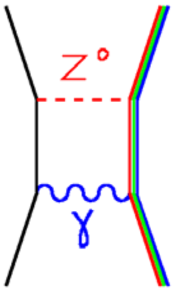
Electroweak Radiative Corrections

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

Q^p_{Weak}	Standard Model ($Q^2 = 0$)	0.0713 ± 0.0008
Q^p_{Weak}	experiment precision goal	± 0.003

Source	Q^p_{Weak} Uncertainty
$\Delta \sin \theta_W (M_Z)$	± 0.0006
$Z\gamma$ box	± 0.0005
$\Delta \sin \theta_W (Q)_{hadronic}$	± 0.0003
WW, ZZ box - pQCD	± 0.0001
Charge symmetry	0
Total	± 0.0008

Erler, Kurylov, Ramsey-Muslolf,, PRD 68(2003)016006.



Estimates of γ-Z box diagrams on A_{PV} at Qweak Kinematics

TBE (Tjon, Blunden, Melnitchouk) 0.13% (hadronic: N and Δ)
arXiv:0903.2759

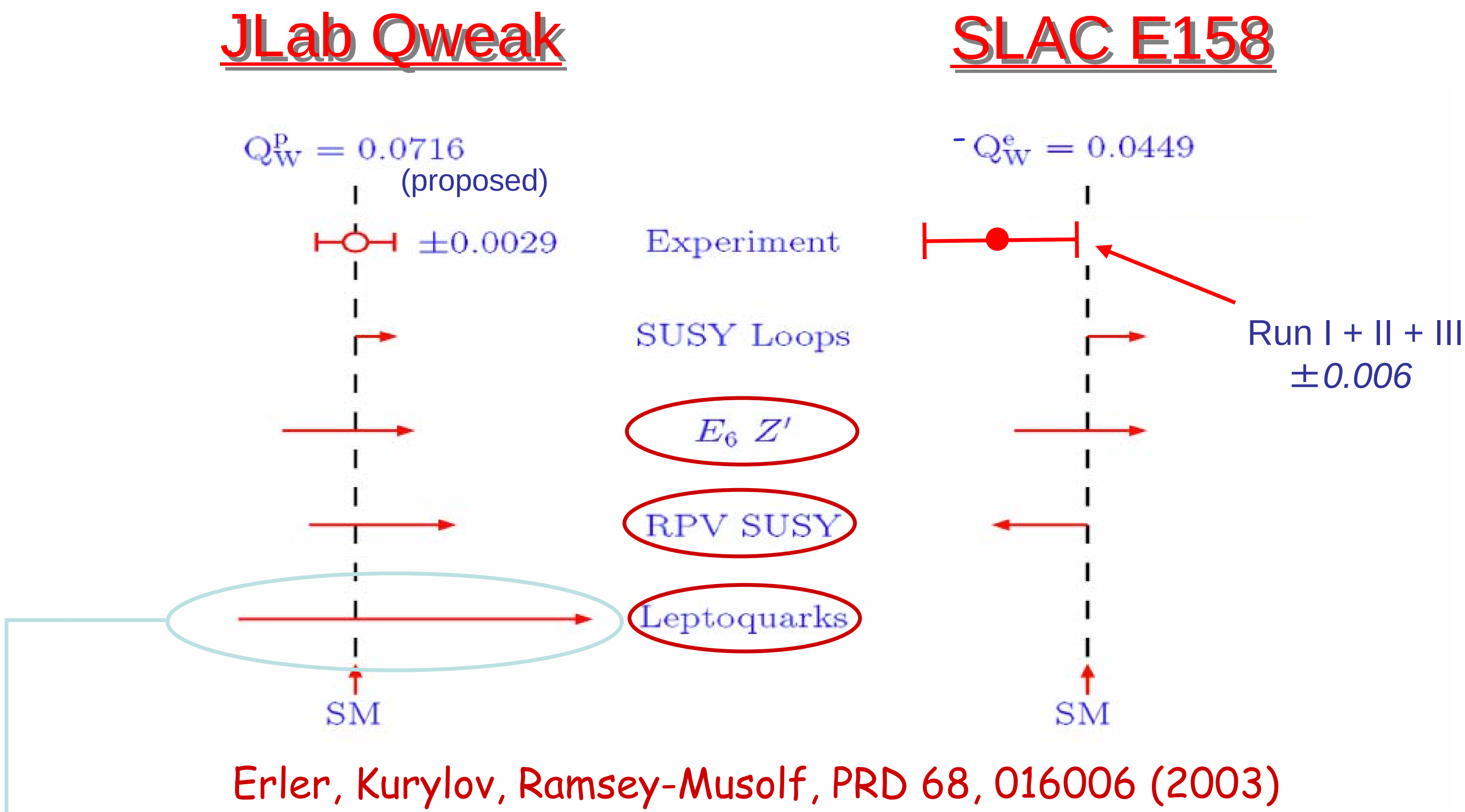
TBE (Gorchtein & Horowitz) 6 +/- 1.5% (dispersion relations; PVDIS FF)

Phys. Rev. Lett. 102, 091806 (2009)

However, see more recent calculations!

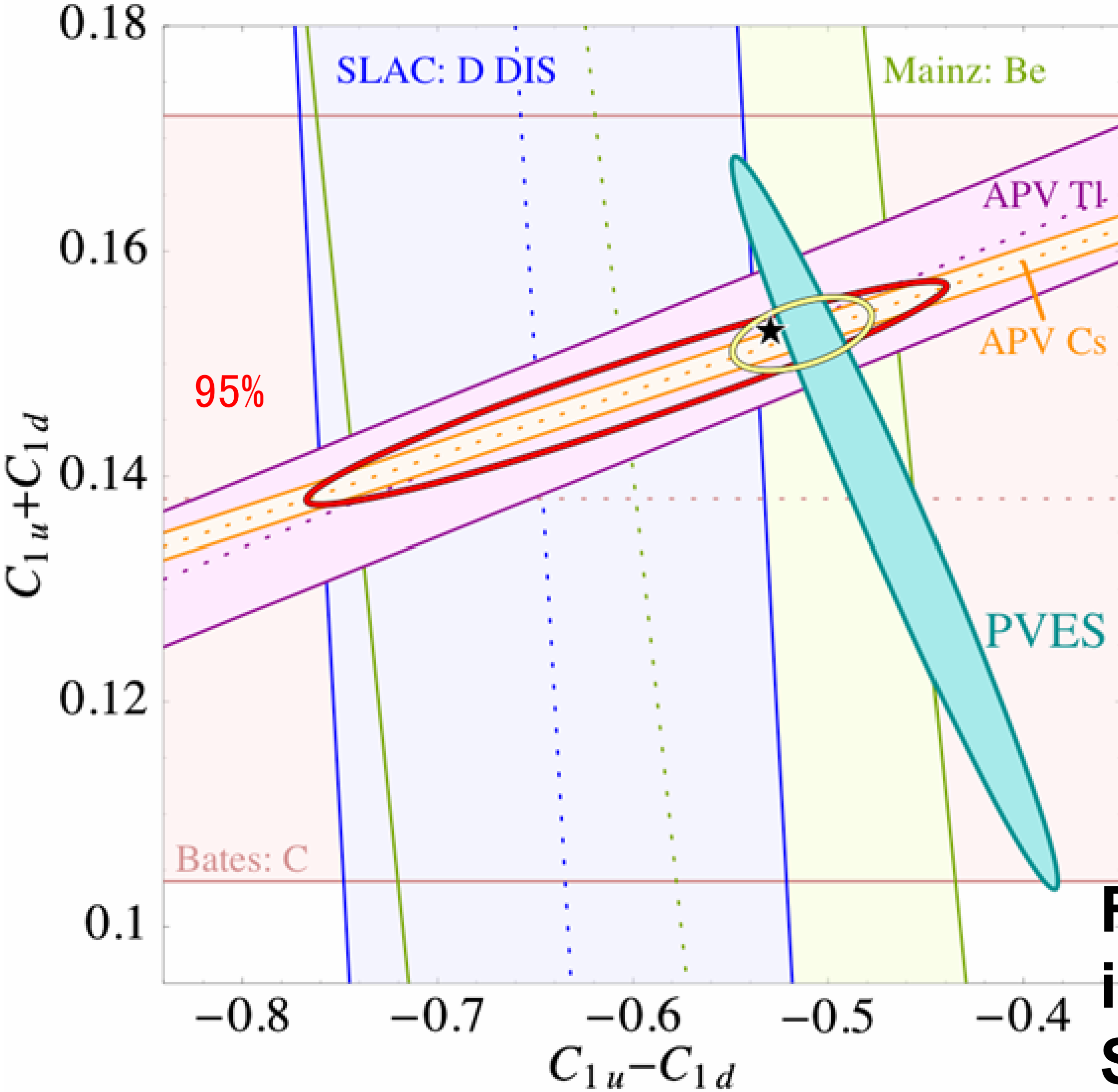
Note: Perhaps γ-W box diagrams involved in V_{ud} extraction in nuclear beta decay can provide insight? (Erler, et al.)

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



- 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.
- MOLLER (pure leptonic) is intended to do considerably better.

New update on C_{1q} couplings

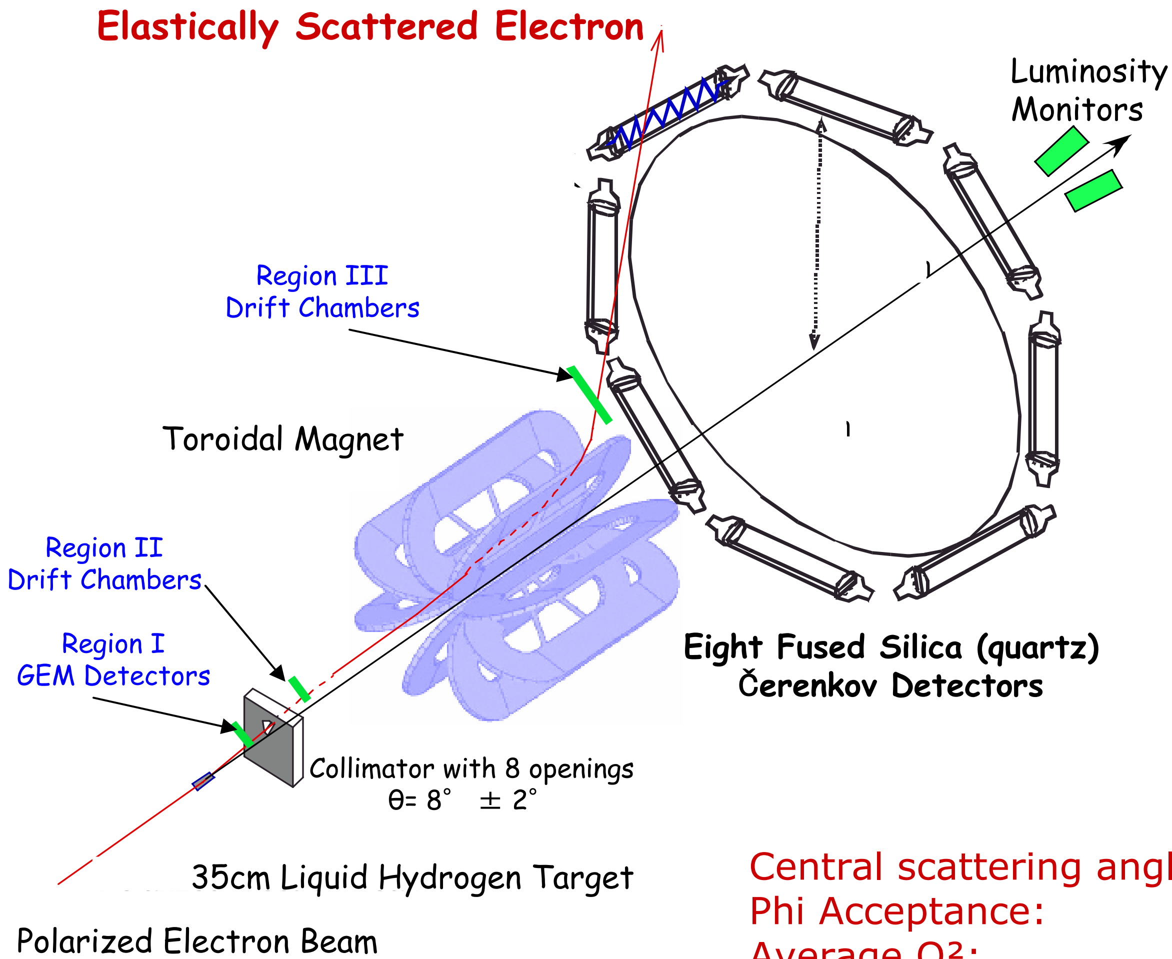


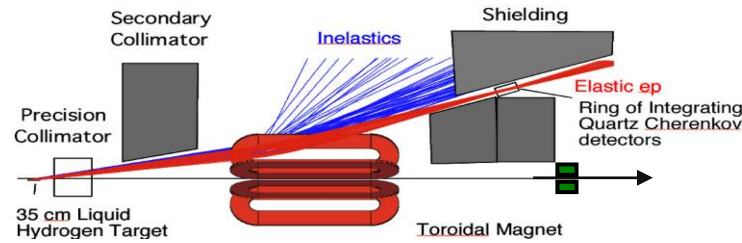
(R.D.Young et al.)

Dramatic improvement in knowledge of weak couplings!

Factor of 5 increase in precision of Standard Model values

Overview of the Q^p_{Weak} Experiment





Experiment Parameters (integration mode)

Incident beam energy:	1.165 GeV
Beam Current:	150 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:	0.026 $(GeV/c)^2$
Acceptance averaged asymmetry:	−0.27 ppm
Integrated Rate (all sectors):	6.4 GHz
Integrated Rate (per detector):	800 MHz

Anticipated Q^p_{Weak} Uncertainties

	$\Delta A_{phys} / A_{phys}$	$\Delta Q^p_{weak} / Q^p_{weak}$
Statistical (2500 hours production)	2.1%	3.2%
Systematic:		
Hadronic structure uncertainties	--	1.5%
Beam polarimetry	1.0%	1.5%
Absolute Q^2 determination	0.5%	1.0%
Backgrounds	0.5%	0.7%
Helicity-correlated Beam Properties	0.5%	0.7%
Total	**2.5%**	**4.1%**

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

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

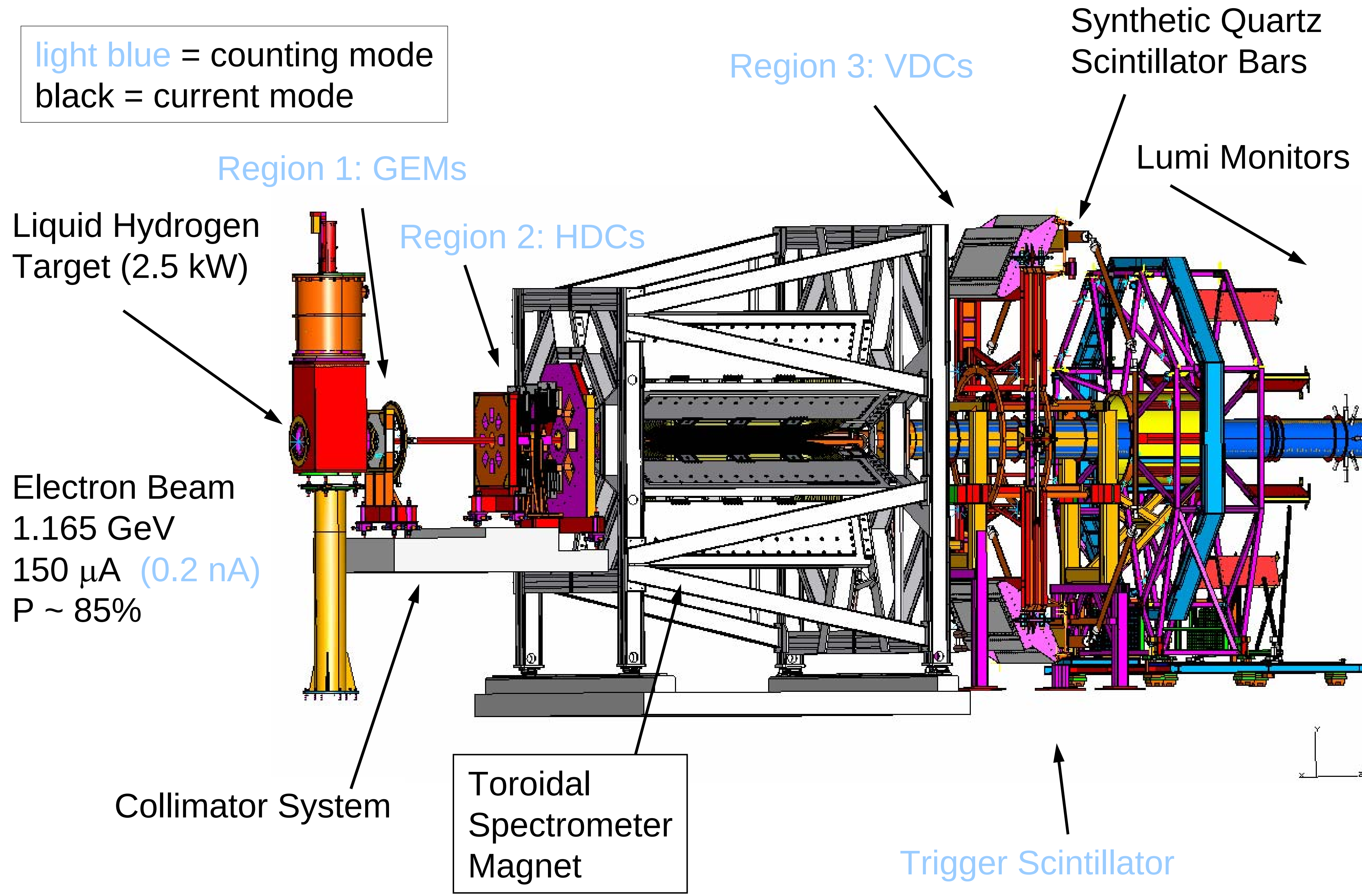
(Erler, Kurylov, Ramsey-Musolf, PRD **68**, 016006 (2003))

$Q^p_W = 0.0716 \pm 0.0006$ theoretically

1.1% error comes from QCD uncertainties in box graphs, etc.

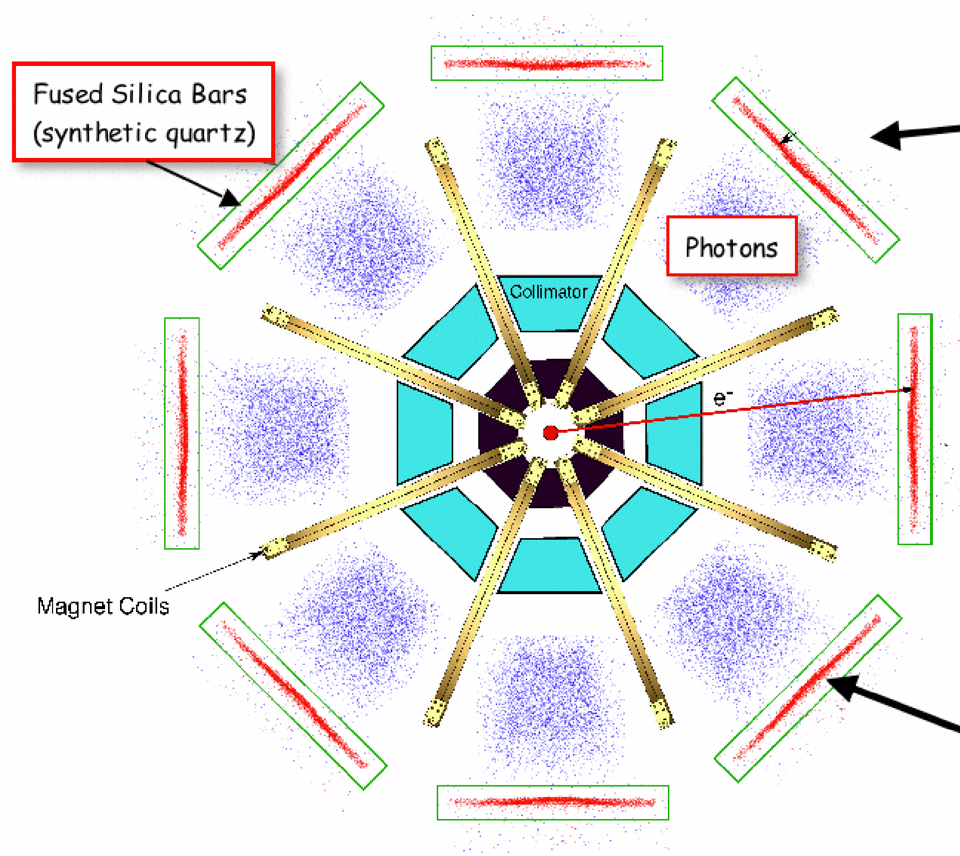
Principal Parts of the Q^p_{weak} Experiment

light blue = counting mode
black = current mode

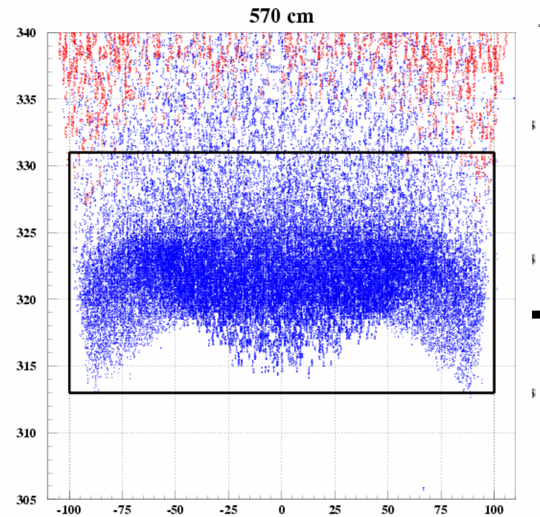


Inelastic/Elastic Separation in Q^p_{Weak}

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



In-elastic Events
(beyond detector)



rectangular quartz bar; 0.18 m wide X 2.0 meters long

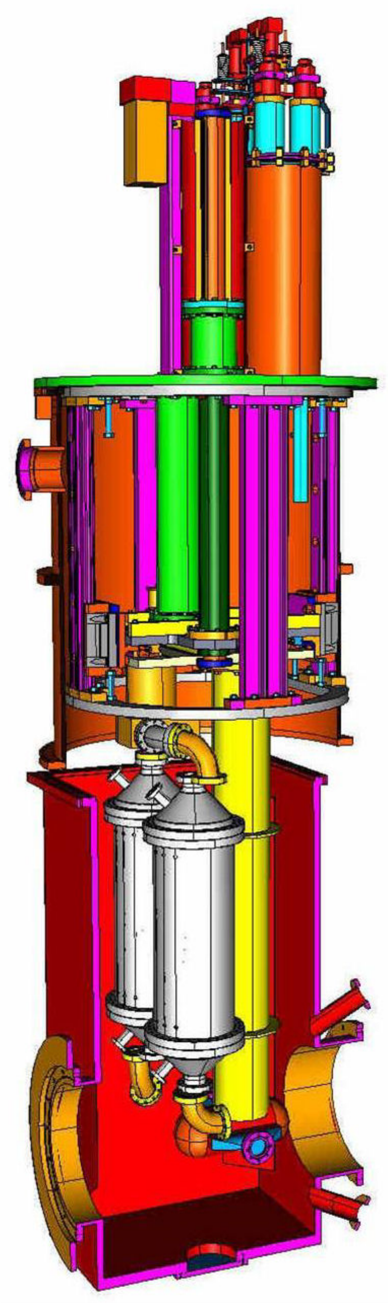
Elastic Events
(in focal plane)

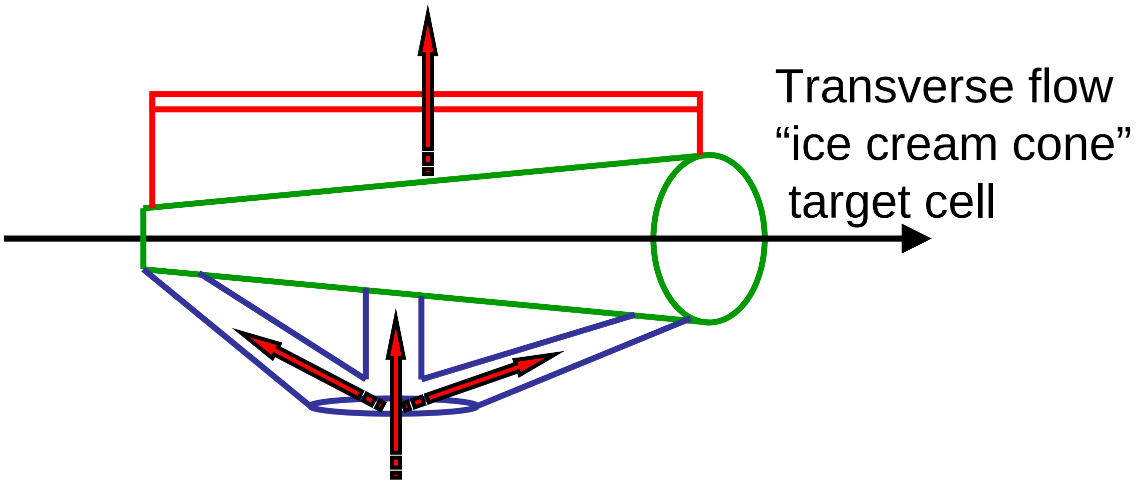
Black region in center is Pb shielding

Very clean elastic separation!

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

Cryotarget

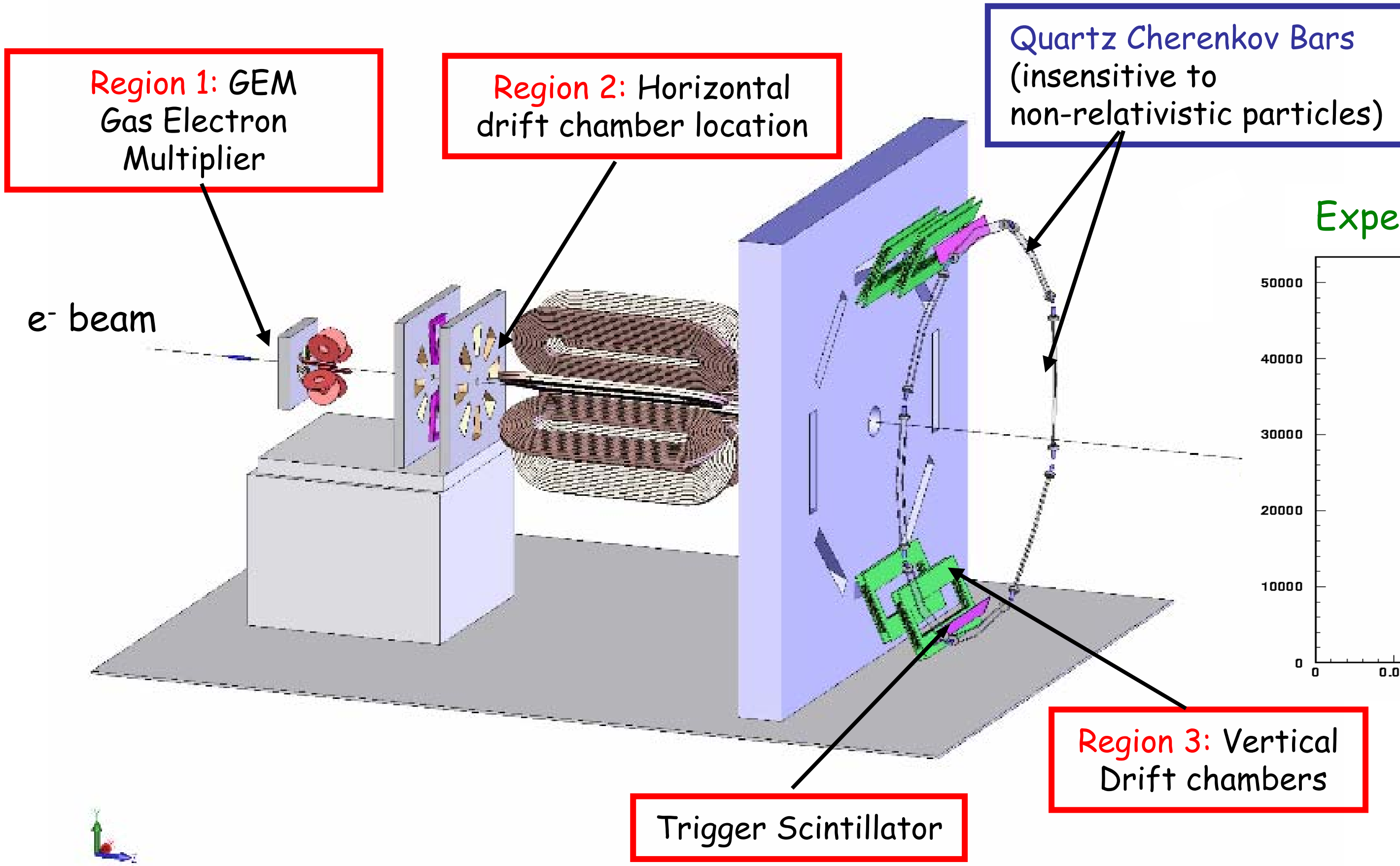




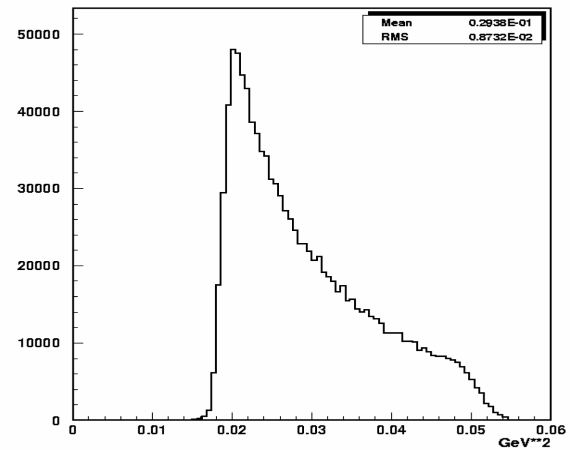
- Highest power (2500 watt) cryotarget ever
- ~50 litre liquid hydrogen inventory
- 35 cm long, 2200 watt beam load
- High capacity combined 4K and 15K heat exchanger
- LN2 pump tests ongoing

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.

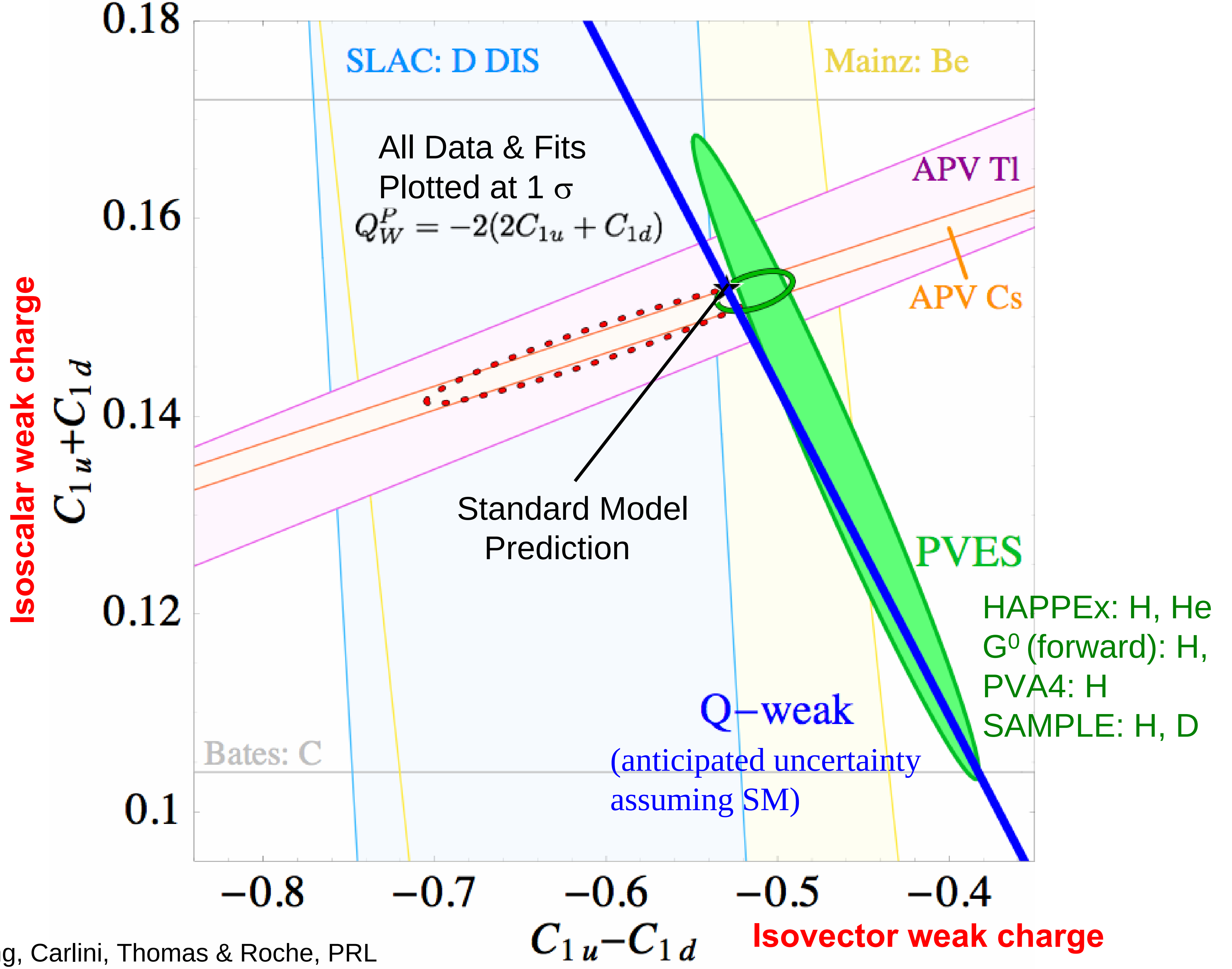


Expected Q^2 distribution



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

Region 3 chamber --> efficiency map of quartz detectors

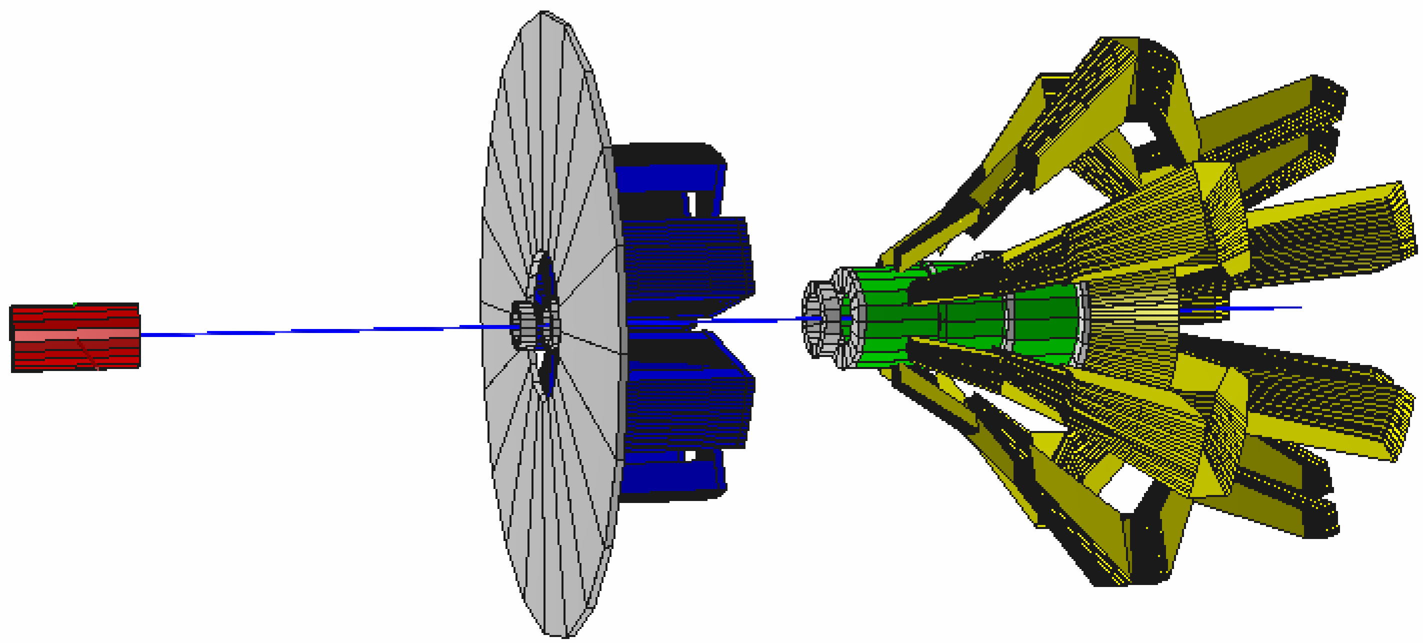


Young, Carlini, Thomas & Roche, PRL

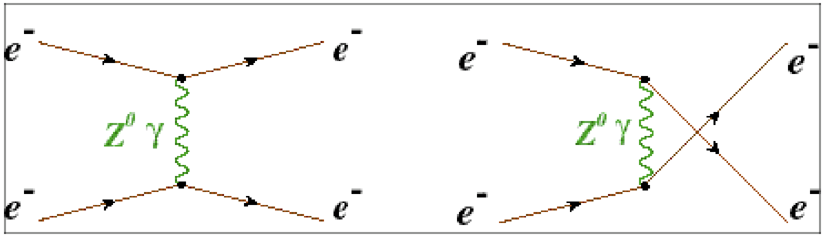
Progress of Qweak – Past to Future

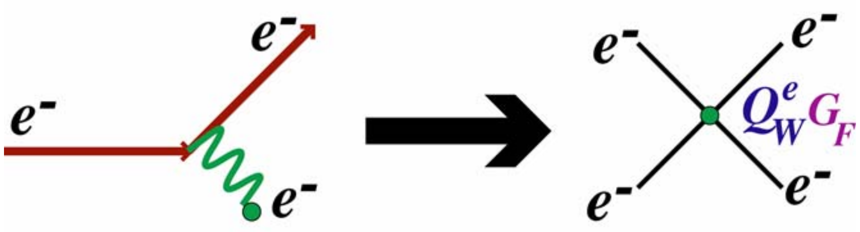
May 2000	Collaboration formed
July 2001	JLab Letter of Intent
December 2001	JLab Proposal submitted
January 2002	JLab Proposal approved with 'A' rating
January 2003	Technical design review completed,
2003 - 2004	Funding approved by to DOE, NSF & NSERC
January 2005	JLAB Jeopardy Proposal approved with 'A' rating
March 2007	Two day engineering run (at end of G zero) Beam noise and target boiling studies.
January 2008	PAC33 Jeopardy review. Qweak granted 198 PAC days as requested.
October 2009	Installation on the beam line starts
May 2010 – May 2011	Phase I commissioning and data taking
November 2011	Phase II data taking
May 2012	12 GeV conversion of CEBAF

11 GeV MOLLER Experiment double toroid configuration



Møller Scattering





Purely leptonic reaction

$$A_{PV} = -mE \frac{G_F}{\sqrt{2}\pi\alpha} \frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2} Q_W^e$$

Derman and Marciano (1978)

$$A_{PV} \propto m_e E_{lab} (1 - 4\sin^2\vartheta_W)$$

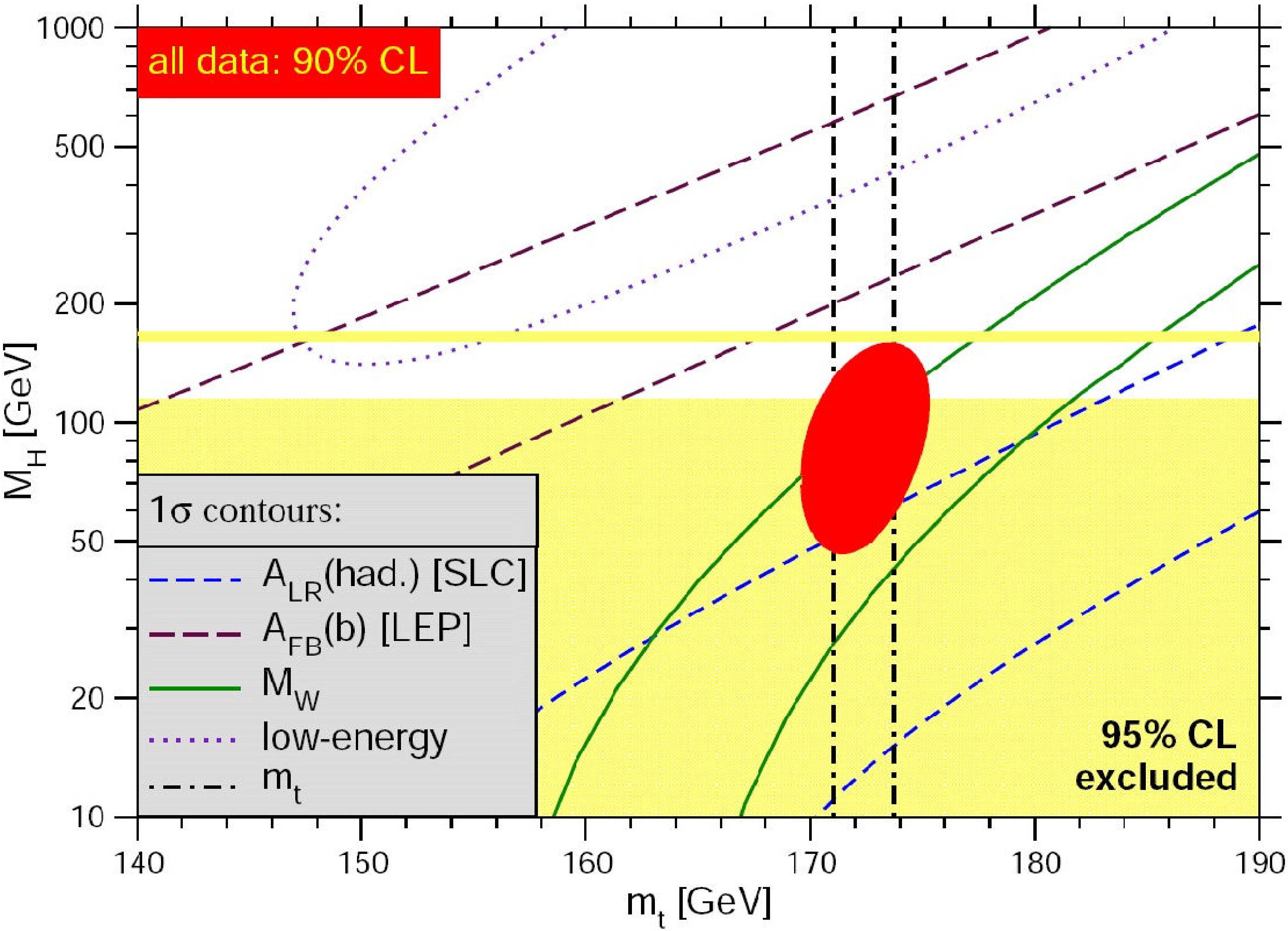
Small, well-understood dilution

$$\frac{\delta(\sin^2\vartheta_W)}{\sin^2\vartheta_W} \cong 0.05 \frac{\delta(A_{PV})}{A_{PV}}$$

$$\sigma \propto \frac{1}{E_{lab}}$$ ⇒ ***Figure of Merit rises linearly with E_{lab}***

SLAC: Highest beam energy with moderate polarized luminosity

JLab 11 GeV: Moderate beam energy with LARGE polarized luminosity



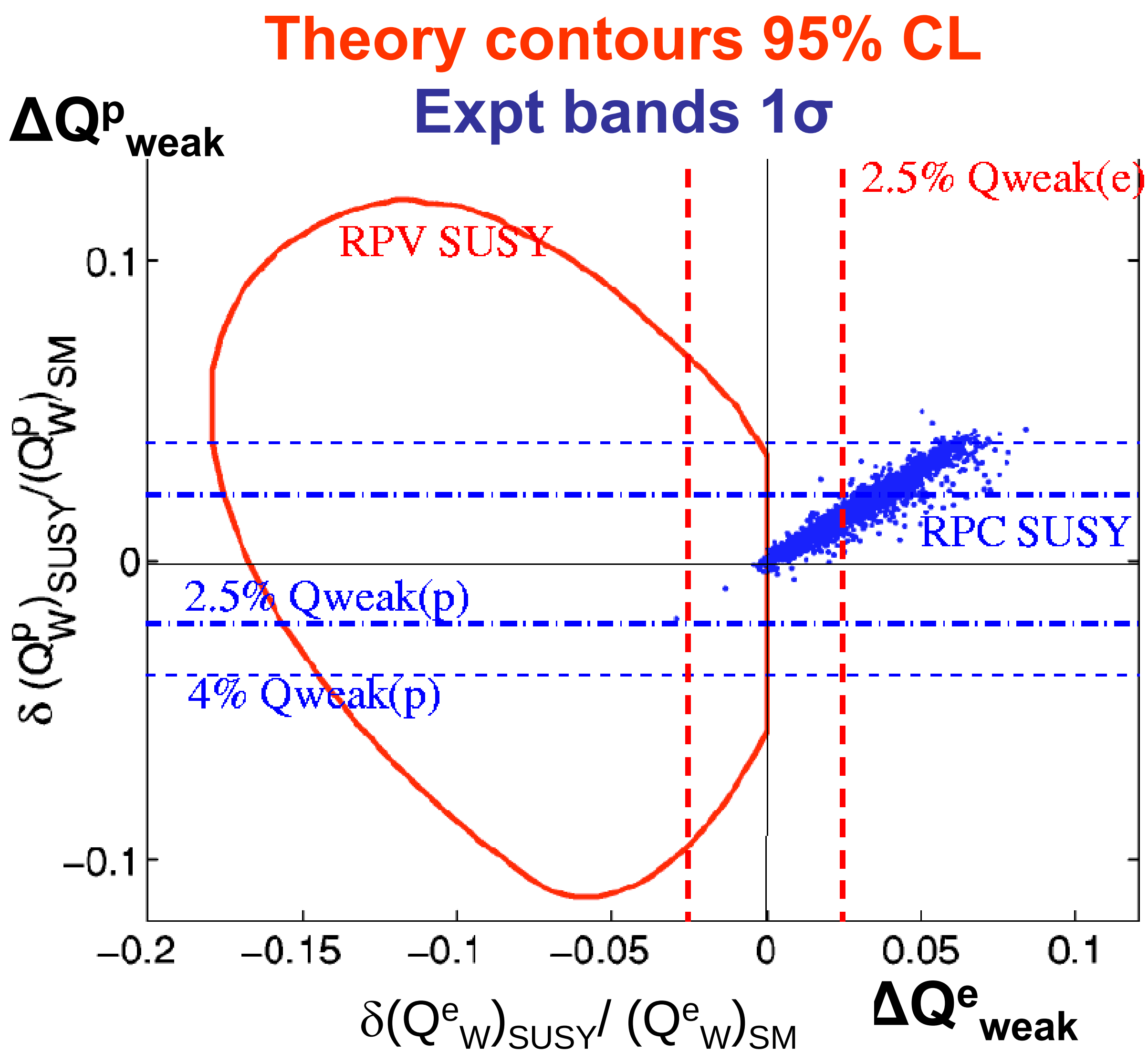
all data: 90% CL
1σ contours:
A_LR(had.) [SLC]
A_FB(b) [LEP]
M_W
low-energy
m_t
95% CL
excluded
M_H [GeV]
m_t [GeV]
1000
500
200
100
50
20
10
140
150
160
170
180
190

Parity-Violating Electron-Electron Scattering at 11 GeV

- **Q^e_{weak} would tightly constrain RPV SUSY (ie tree-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.



MOLLER Parameters

E_{beam} = 11 GeV   75 μA   80% polarized   ~ 38 weeks (~ 2 yrs) → $\delta(A_{PV})$ = 0.73 ppb

A_{PV} = 35.6 ppb → $\delta(Q^e_W) = \pm$ 2.1 (stat.) $\pm$ 1.0 (syst.) %

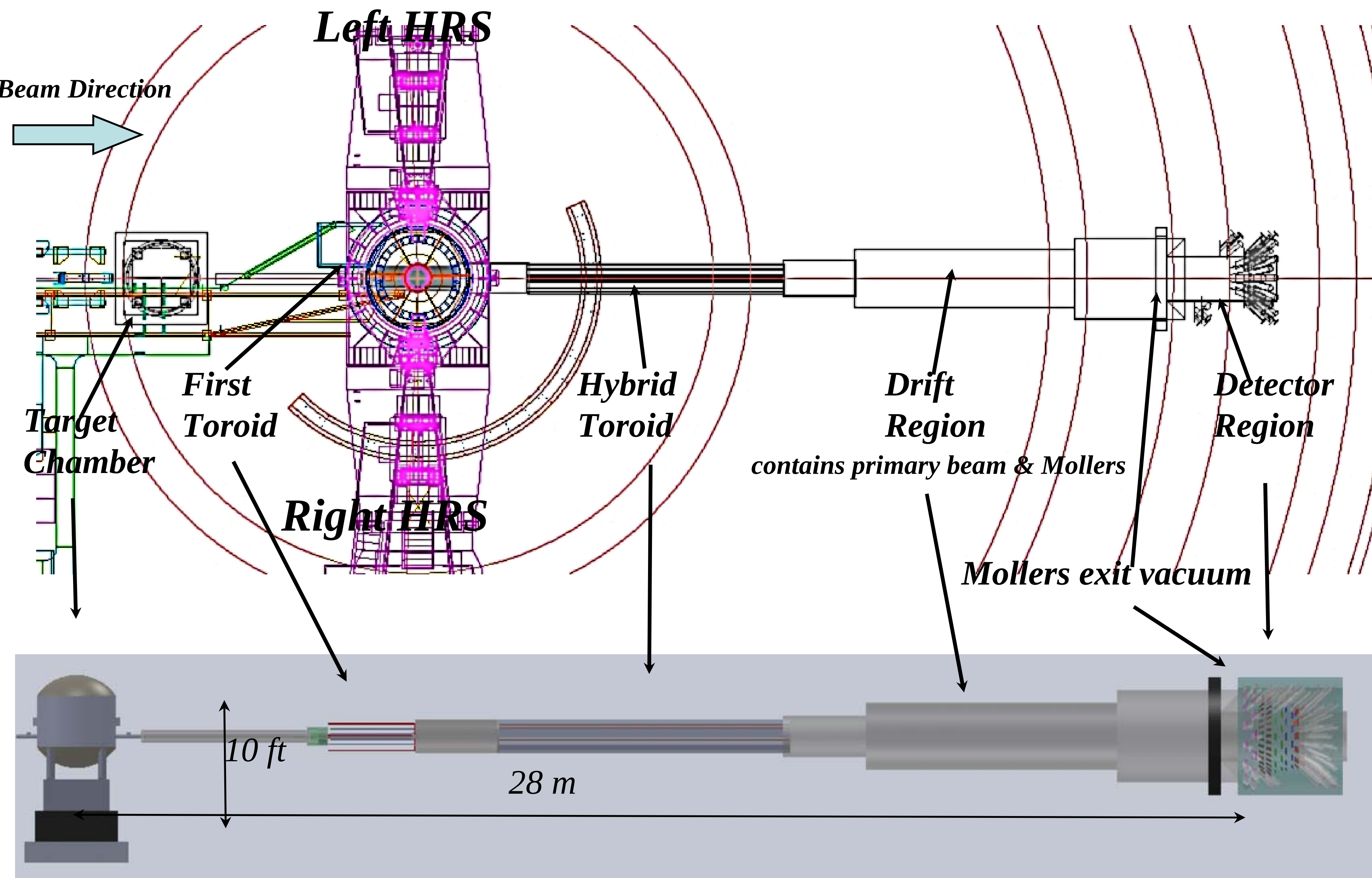
$\delta(\sin^2\theta_W) = \pm$ 0.00026 (stat.) $\pm$ 0.00012 (syst.) → ~ 0.1%

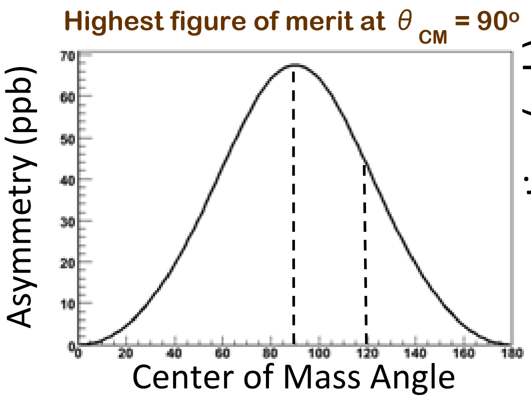
→ *not just "another measurement" of* $\sin^2\theta_W$

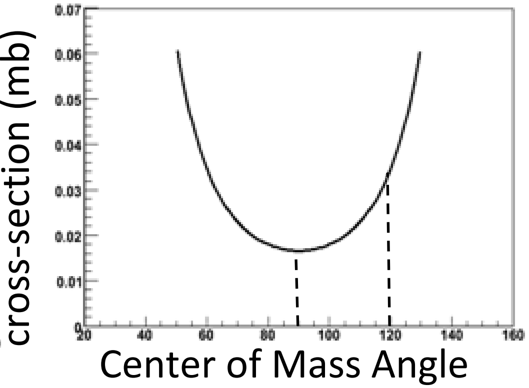
Compelling opportunity with the Jefferson Lab Energy Upgrade:

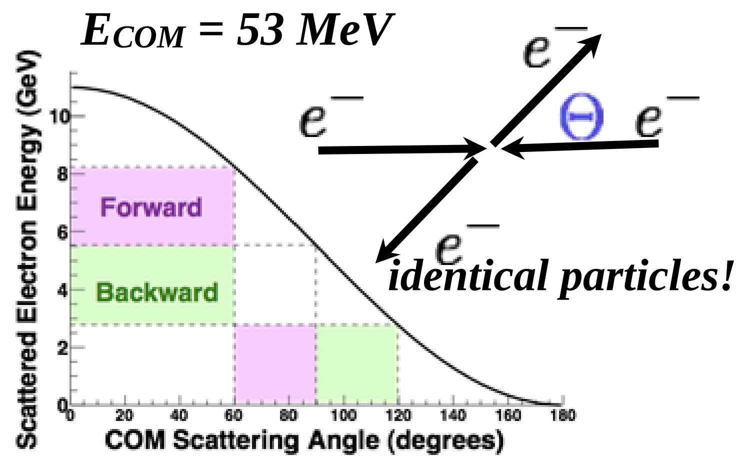
- Comparable to the two best measurements at colliders
- Unmatched by any other project in the foreseeable future
- At this level, one-loop effects from "heavy" physics

MOLLER Hall Layout



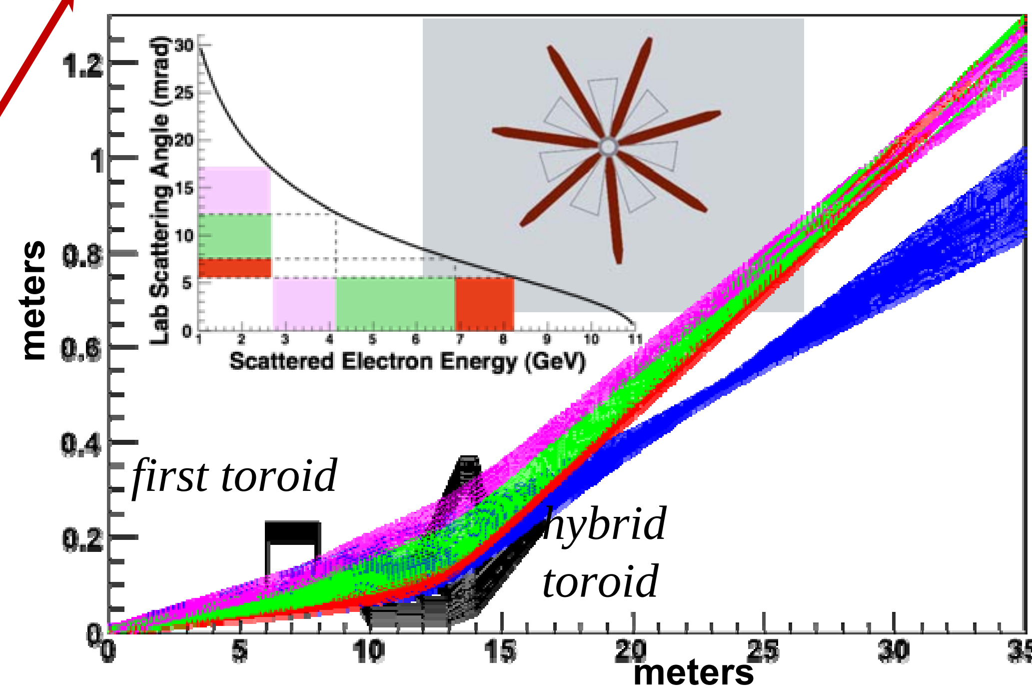






- Avoid superconductors
  - ~150 kW of photons from target
  - Collimation extremely challenging
- Quadrupoles a la E158
  - high field dipole chicane
  - poor separation from background
  - ~ 20-30% azimuthal acceptance loss
- Two Warm Toroids
  - 100% azimuthal acceptance
  - better separation from background

Odd number of coils: both forward & backward Mollers in same phi-bite

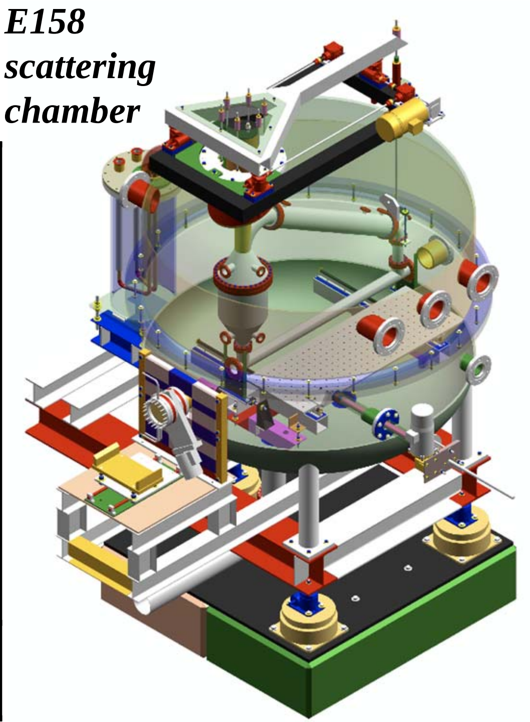


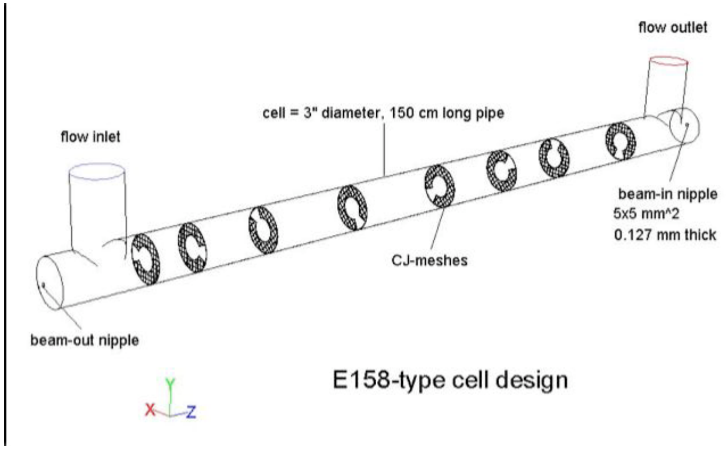
Target: Liquid Hydrogen

- Most thickness for least radiative losses
- No nuclear scattering background
- Not easy to polarize

- ***Need as much target thickness as technically feasible***
- ***Tradeoff between statistics and systematics***
- ***Default: Same geometry as E158***

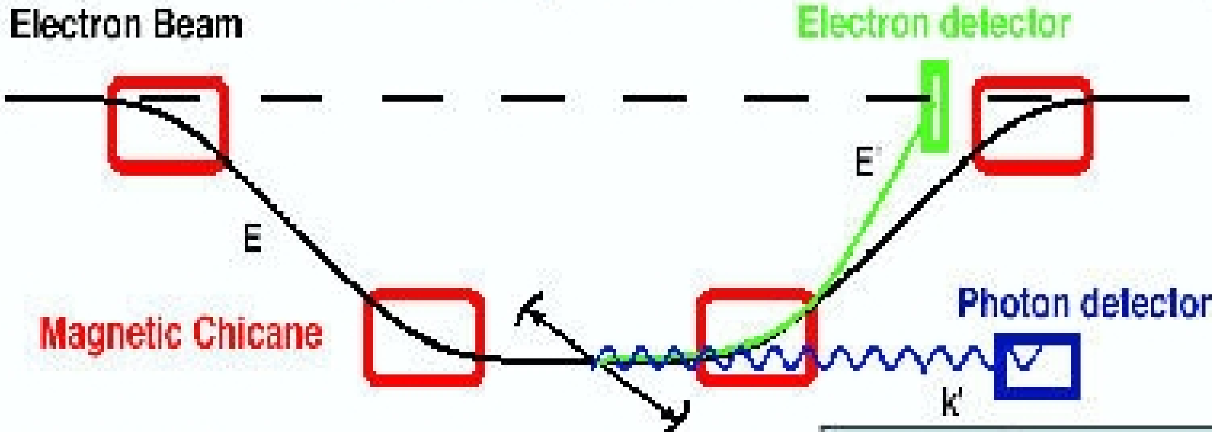
E158 scattering chamber





parameter	value
length	*150 cm*
thickness	*10.7 gm/cm^2*
X_0	*17.5%*
p,T	*35 psia, 20K*
power	*5000 W*

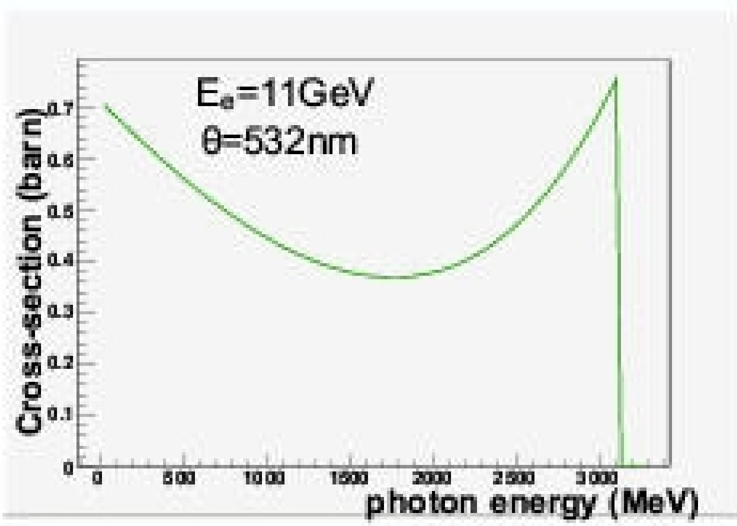
Compton Polarimetry

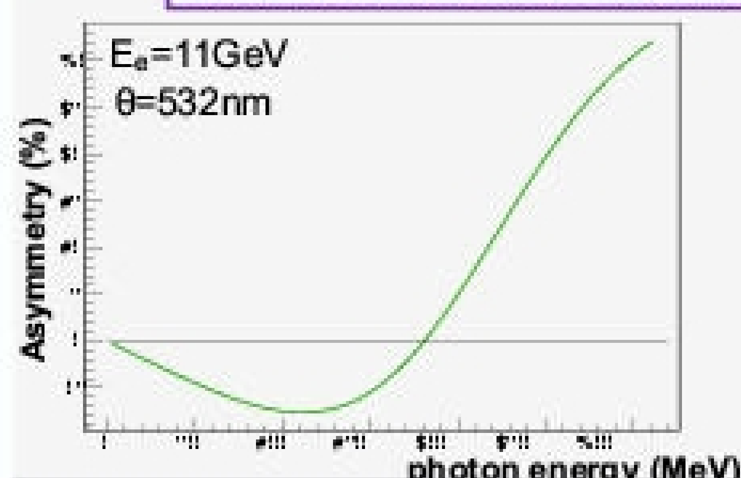


Two largely independent polarimetry measurements from asymmetries in detected electrons and photons

$$A_{exp} = \frac{n^+ - n^-}{n^+ + n^-} = P_\gamma \times P_e \times \langle A_{th} \rangle$$

Knowledge of analyzing power dominates systematic uncertainty





Near-Term Plans

- MOLLER proposal receives JLab PAC approval in January 2009
- With help of laboratory management, input to DoE planning retreat in Spring 2010 has been provided
- Director's Review January 14-15, 2010 has resulted in a strong endorsement of the MOLLER experiment
- Task is to prepare for a detailed engineering design for a first (CD0) DoE review later in 2010

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"
  NuTEV result in agreement with Standard Model after corrections have been applied

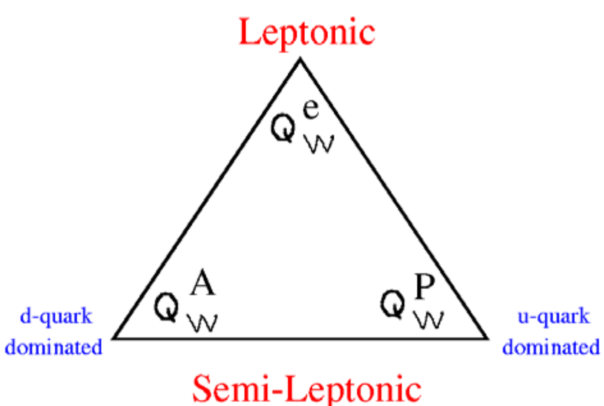
- Upcoming Q^p_{Weak} Experiment

  - 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 2010-2012 time frame

- Future 11 GeV Parity-Violating Moller Experiment Q^e_{weak} at JLAB

  - Conceptual design indicates reduction of E158 error by ~5 may be possible at 11 GeV JLAB. Experiment approved with A rating; JLab Directors review in early 2010.

weak charge triad → (Ramsey-Musolf)



PVDIS

- Measure the parity-violating analyzing power A_z to 0.6% in the scattering of longitudinally polarized electrons from deuterium

Objectives:

- search for higher twist effects in electron scattering from nucleons
- precision measurement of the electroweak mixing angle
- charge symmetry breaking of the nucleon quark distributions

Large solenoidal spectrometer SoLID