The Q^p_{Weak} Experiment:

"A Search for New Physics at the TeV Scale Via a Measurement of the Proton's Weak Charge"

- 1st measurement of Q^p_w
- 10 σ measurement of $\sin^2\theta_W$ running

May 2000	Collaboration formed
January 2002	JLab Proposal Approved with 'A' rating
January 2003	Technical design review complete
2003	All needed funding secured DOE/JLab, NSF & NSERC
2004	Design work and prototyping
2007	Goal for initial experiment installation.

63 People at:

JLab, LANL, MIT, BATES, TRIUMF, William & Mary, Univ. of Manitoba, Virginia Tech, Louisiana Tech, Caltech, Univ. of Connecticut, Univ. Nacional Autonoma de Mexico, UNBC, Univ. of New Hampshire, Ohio Univ., Mississippi State, Hampton Univ., Yerevan Physics Institute

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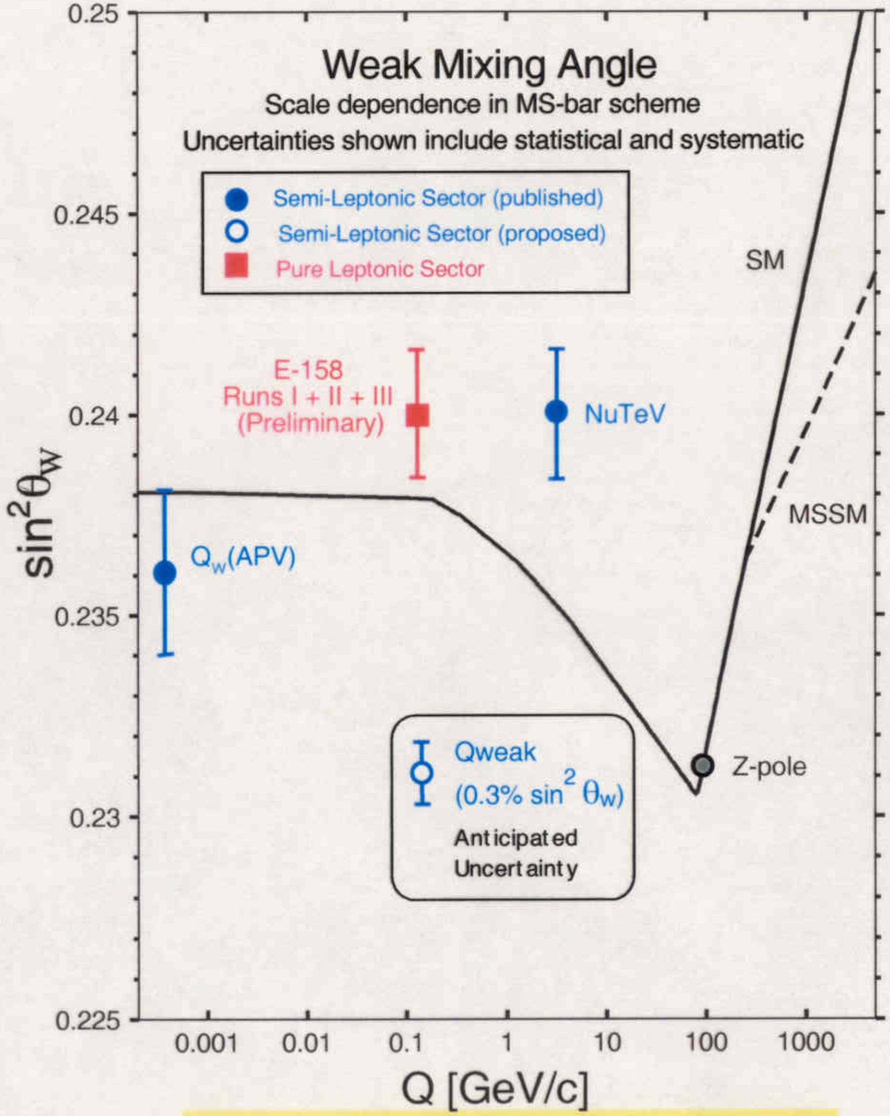
A.K. Opper July 2004

Jefferson Lab

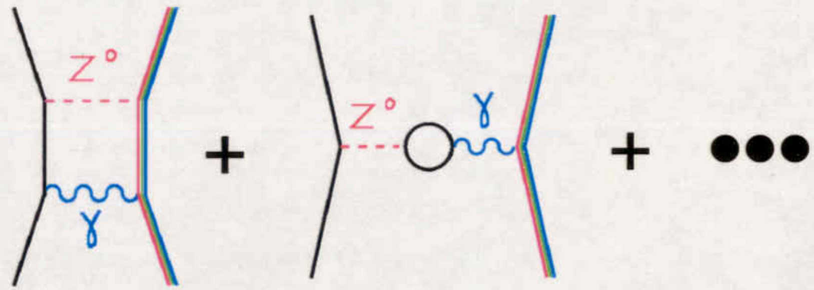
"Running of $\sin^2\theta_W$" in the Standard Model



Erler et al., Phys. Rev D 68, 016006

Electroweak radiative corrections

$\rightarrow \sin^2\theta_W$ varies with Q



At Q = 0.03 GeV/c:

* Q^p_{weak} (semi-leptonic) and

* SLAC E158 (pure leptonic)

* different sensitivities to SM extensions

$\Delta(Q^p_{weak})$ = 4% $\Delta(\sin^2\theta_W)$ = 0.3%

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Georgi, Quinn and Weinberg - PRL 33, p451 (1974)

The Parameter $\sin^2\theta_w$ is Not Arbitrary

- In unified theories the various electro-weak and strong charges of the particles need to add to zero so that $SU(2) \times U(1) \times SU(3)$ can be a subgroup of a larger group. This imposes relations between the coupling constants.

- For example fitting the groups into the smallest possible group $SU(5)$ puts a constraint on 3 couplings g_1, g_2 and g_3 which must all equal for unification to work.

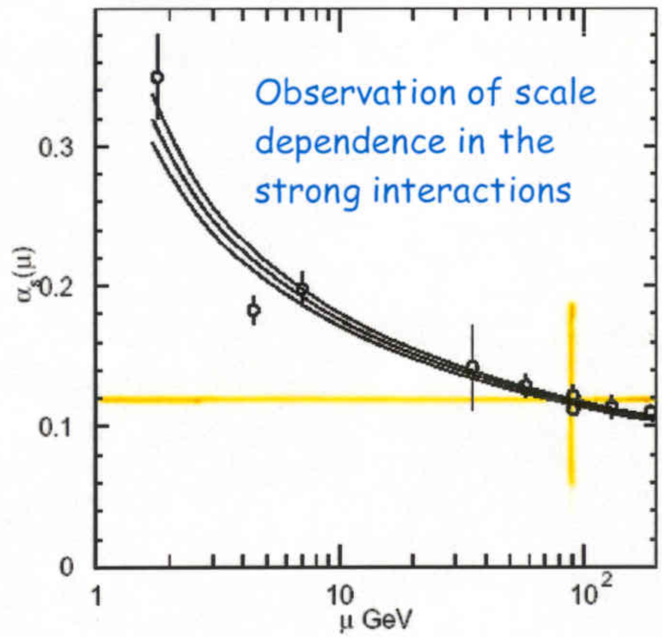
  - The electro-weak couplings we observe are $g = g_2$ and $g' = g_1/C_5$ where C_5 is a constant that depends on the unification group $SU(5)$

  - In $SU(5)$, $C_5^2 = 5/3$ predicts that $\sin^2\theta_w = 3/8$

Not Even the Fine Structure Constant is Constant

- The fine structure constant $a = \alpha^2/hc \sim 1/137$ at zero energy (large distance)
- But even it changes to around 1/128 by the time one gets to the Z mass (10^{-18} m)
- All of the couplings and masses are affected by loop diagrams, masses of extraneous particles change them.
- Scale dependence is an important thing to measure.

$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha_l(s) - \Delta\alpha^{(5)}_{\text{had}}(s) - \Delta\alpha_{top}(s)}$$

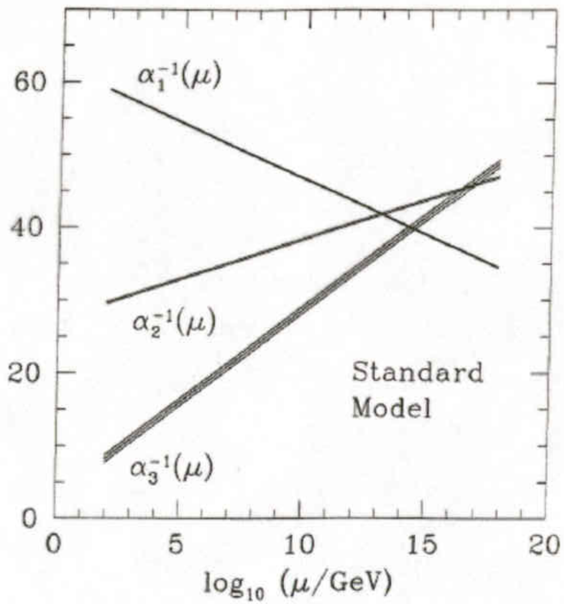


α(s) at the Z-pole is 0.1200 ± 0.0028

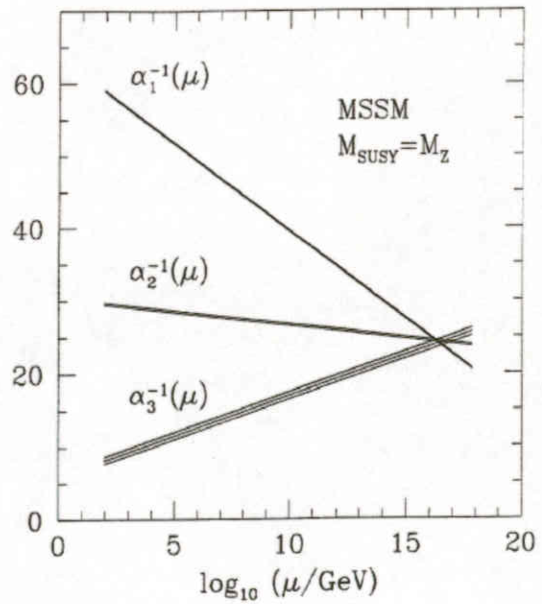
Wilczek hep-ph/9809509

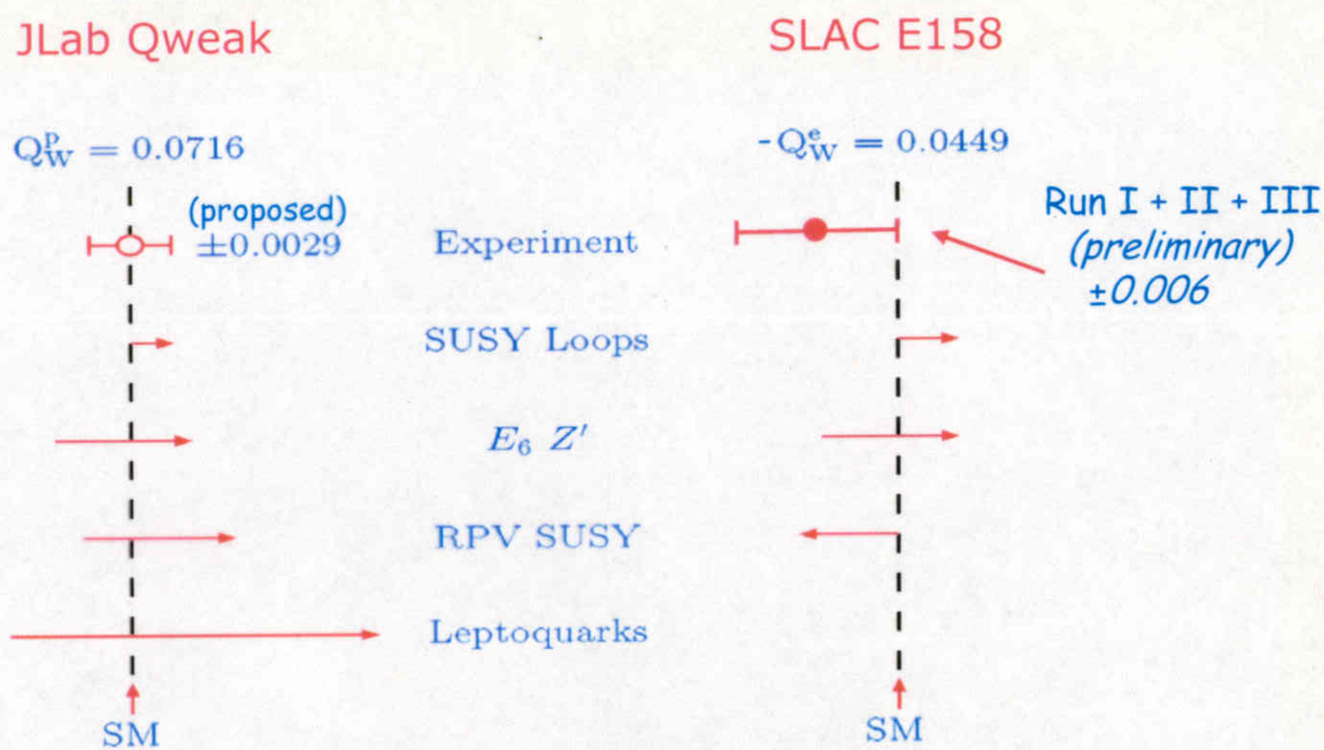
Predictions for the Running of Coupling Constants

Standard Model with no additional particles.



Standard Model with super-symmetric partners added.





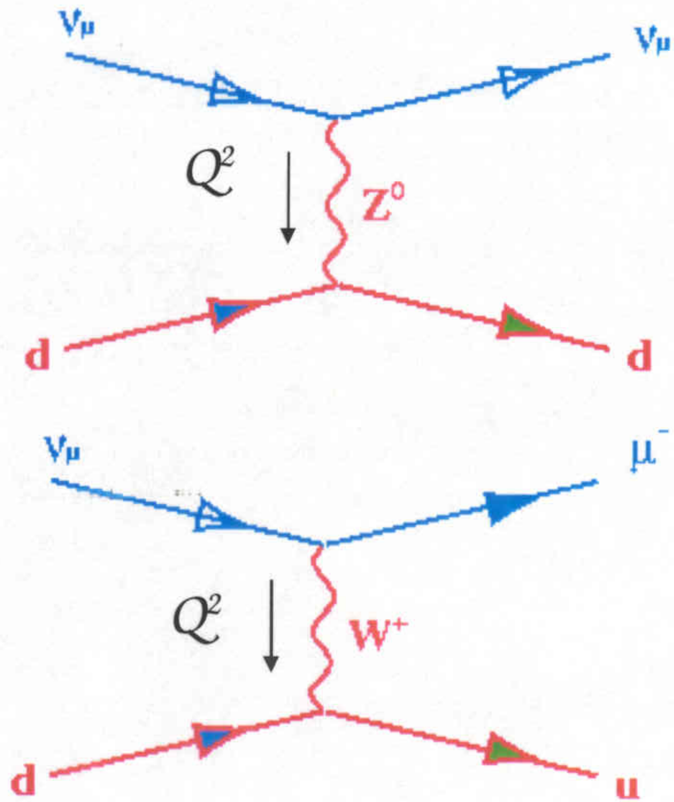
- Q^p_{weak} (semi-leptonic) and E158 (pure leptonic) together make a powerful program to search for and identify new physics.

- Qweak measurement will provide a stringent stand alone constraint on Lepto-quark based extensions to the SM.

The NuTeV Experiment: Q~ 5 GeV
Study the weak interactions in neutrino scattering

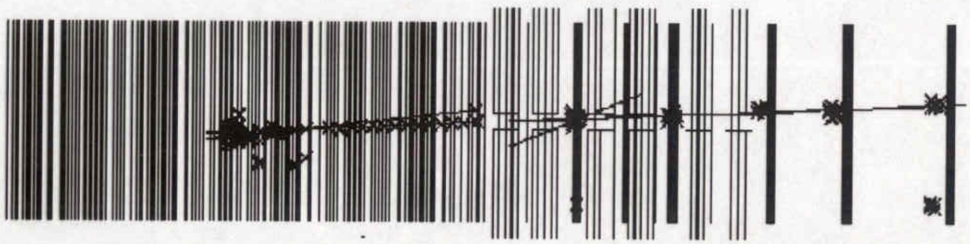
- *Here point-like particles interact via the exchange of the heavy vector bosons, W and Z.*
- *These are simple processes and we'd like to understand the couplings and propagators.*
- *3 mass scales,*

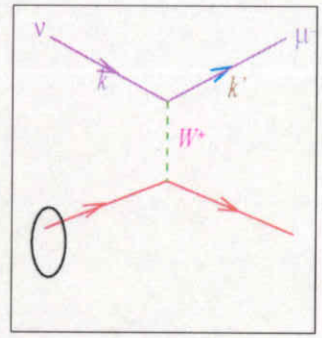
Q^2, $s \sim Q^2$, $M^2(W/Z)$



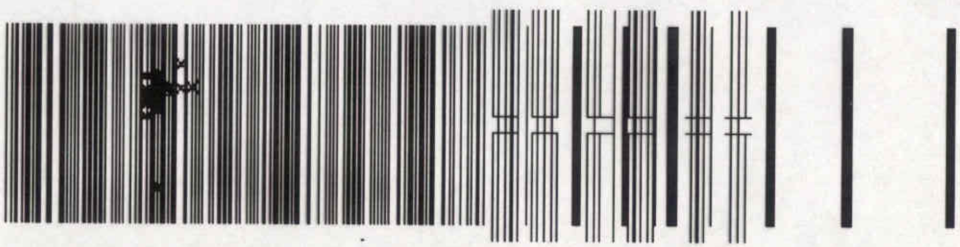
The NuTeV Technique

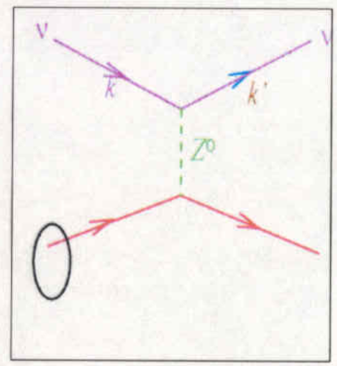
Two types of neutrino interactions,
One transforms neutrino to lepton
Other doesn't





charged current (W exchange)



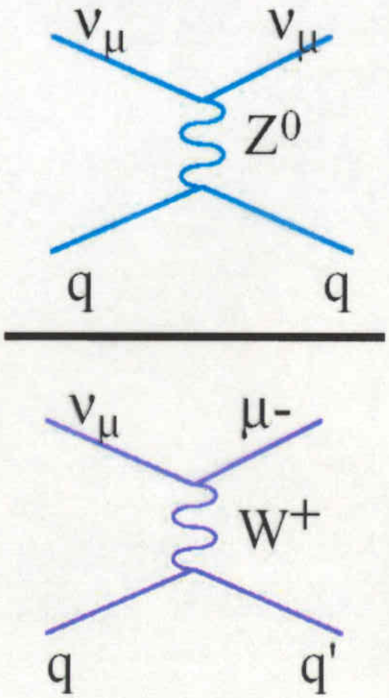


neutral current (Z^0 exchange)

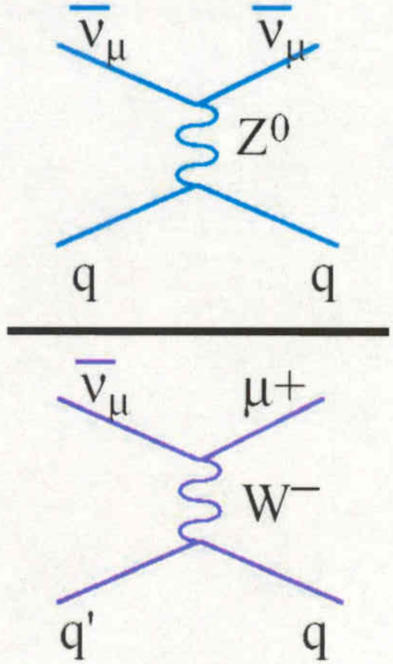
Use Llewellyn Smith Relation:

$$R^{\nu(\overline{\nu})} = \frac{\sigma_{NC}^{\nu(\overline{\nu})}}{\sigma_{CC}^{\nu(\overline{\nu})}} = \rho^2 \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W \left(1 + \frac{\sigma_{CC}^{\overline{\nu}(\nu)}}{\sigma_{CC}^{\nu(\overline{\nu})}} \right) \right)$$

$R^{\nu} =$



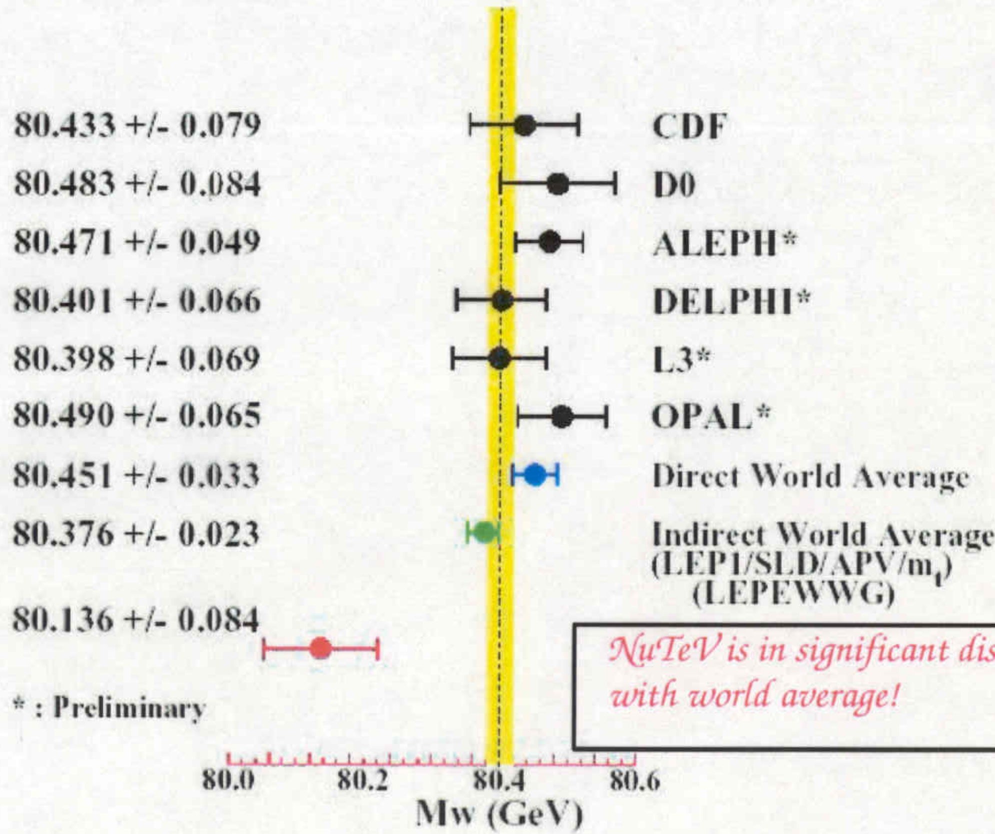
$R^{\overline{\nu}} =$



Given the precise measurement of the Z mass from LEP...

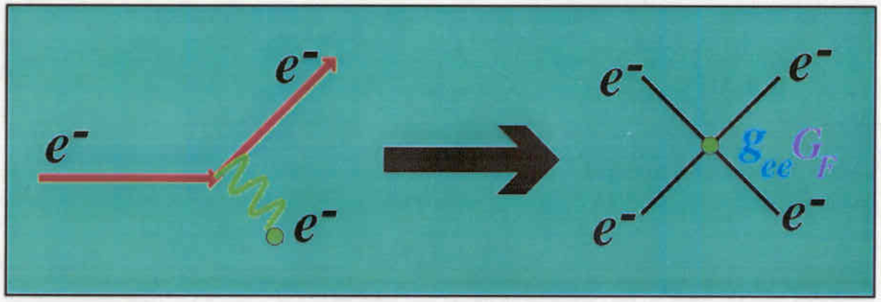
$$\sin^2\theta_W^{(\text{on-shell})} \equiv 1 - \frac{{M_W}^2}{{M_Z}^2}$$

... can express NuTeV $\sin^2\theta_W$ as an equivalent M_W



NuTeV is in significant disagreement with world average!

Fixed Target Møller Scattering

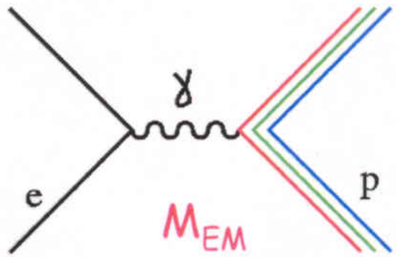


A purely leptonic reaction

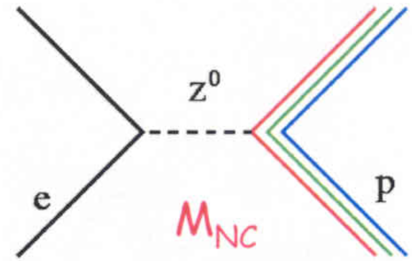
$g_{ee} \sim 1 - 4sin^2\theta_W$

In principle has a clean physics intrepretation, but in practice is systematics limited by instrumental related hadronic backgrounds.

Q^p_{weak}: Extract from Parity-Violating Electron 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 $G^{\gamma}_{E,M}$ 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

Q^e_{weak}: electron's weak charge is measured in PV Moller scattering (E158)

Energy Scale of an "Indirect" Search for New Physics

- Parameterize New Physics contributions in electron-quark Lagrangian

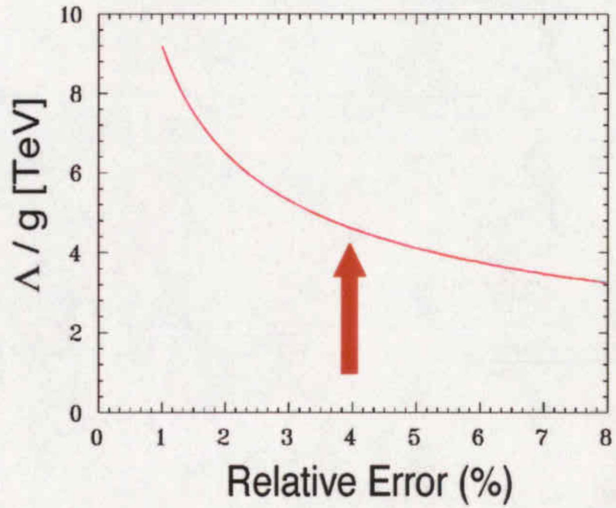
$$\mathbf{L}^{PV}_{e\text{-}q} = \mathbf{L}^{PV}_{SM} + \mathbf{L}^{PV}_{NEW} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e\sum_q C_{1q}\bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e\sum_q h_V^q\bar{q}\gamma^\mu q$$

g : coupling constant

Λ : mass scale

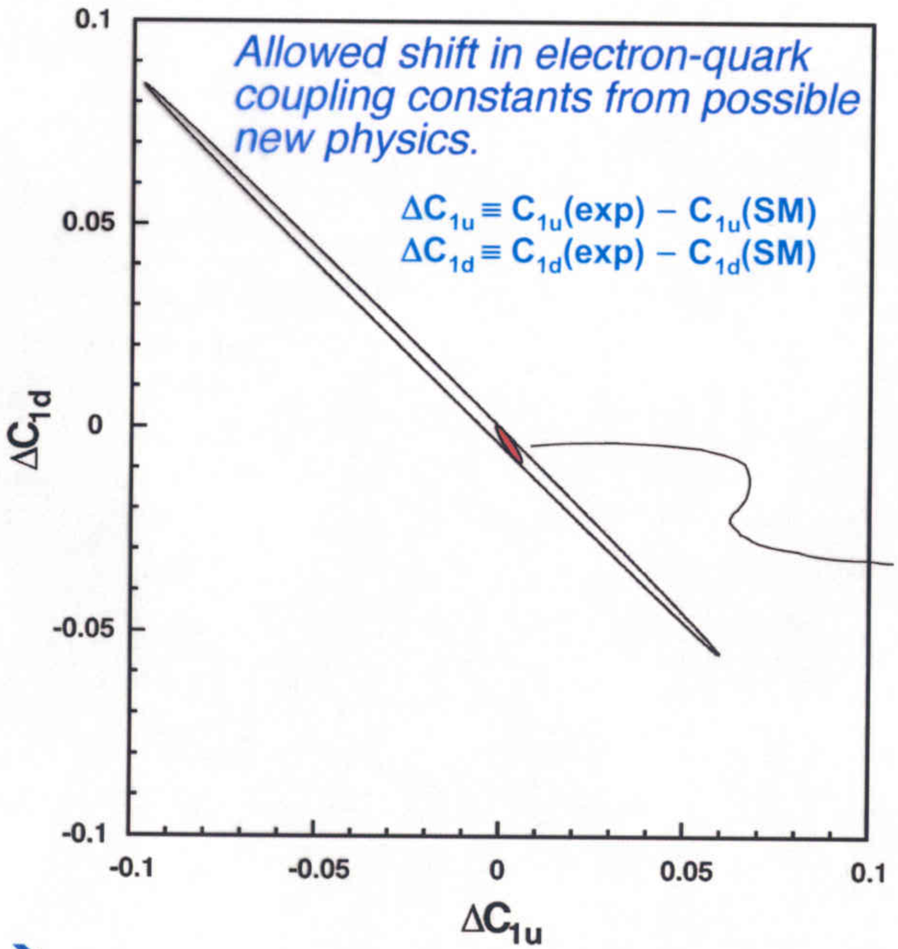
- 4% Q^p_{weak} measurement probes for new physics at energy scales to:

$$\frac{\Lambda}{g} \sim \frac{1}{\sqrt{\sqrt{2}G_F\left|\Delta Q^p_W\right|}} \approx 4.6 \text{ TeV}$$



- The TeV discovery potential of weak charge measurements will be unmatched until LHC turn on.
- If LHC uncovers new physics, the precision low Q^2 measurements will be needed to determine charges, coupling constants, etc.

Impact of Q^{p}_{weak} "Model-independent Semi-Leptonic Analysis"



Effective electron-quark neutral current Lagrangian:

$$\mathbf{L}^{PV}_{e\text{-}q} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e\sum_q C_{1q}\bar{q}\gamma^\mu q$$

$$\rightarrow A(e) \quad x \quad V(q)$$

Large ellipse (existing data):
SLAC e-D (DIS)
MIT-Bates ^{12}C (elastic)
Cesium atomic parity violation

Red ellipse:
Impact of Q^{p}_{weak} measurement (centroid assumes agreement with standard model)

$-2C_{1u} = \hat{g}_L(u) + \hat{g}_R(u)$

$-2C_{1d} = \hat{g}_L(d) + \hat{g}_R(d)$

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 $G^{\gamma}_{E,M}$ $G^{Z}_{E,M}$
Will be constrained
by HAPPEX, G^0, MAMI A4

axial: (4% of asymmetry)
Contains G^e_A, has large
electroweak radiative corrections
Will be constrained by G^0 and SAMPLE

Quadrature sum of expected $A_{hadronic}$ and A_{axial} errors contributes ~2% to error on Q^p_W

Expected constraints
on $A_{hadronic}$ from
upcoming experiments

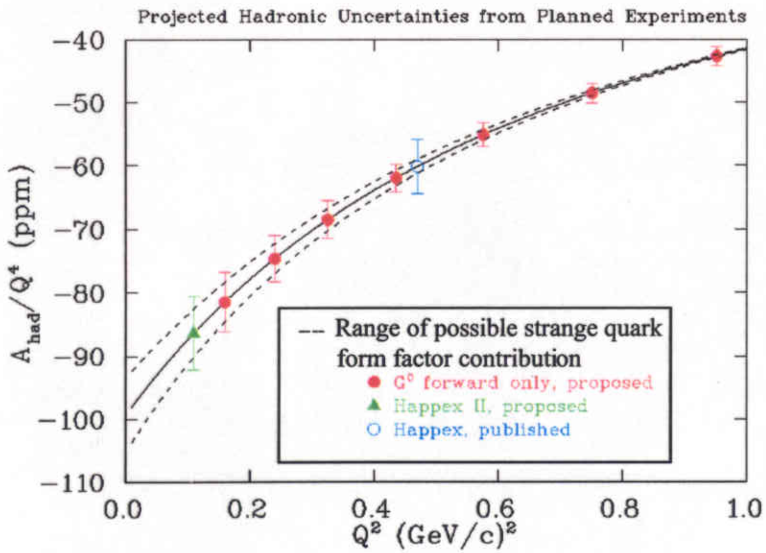
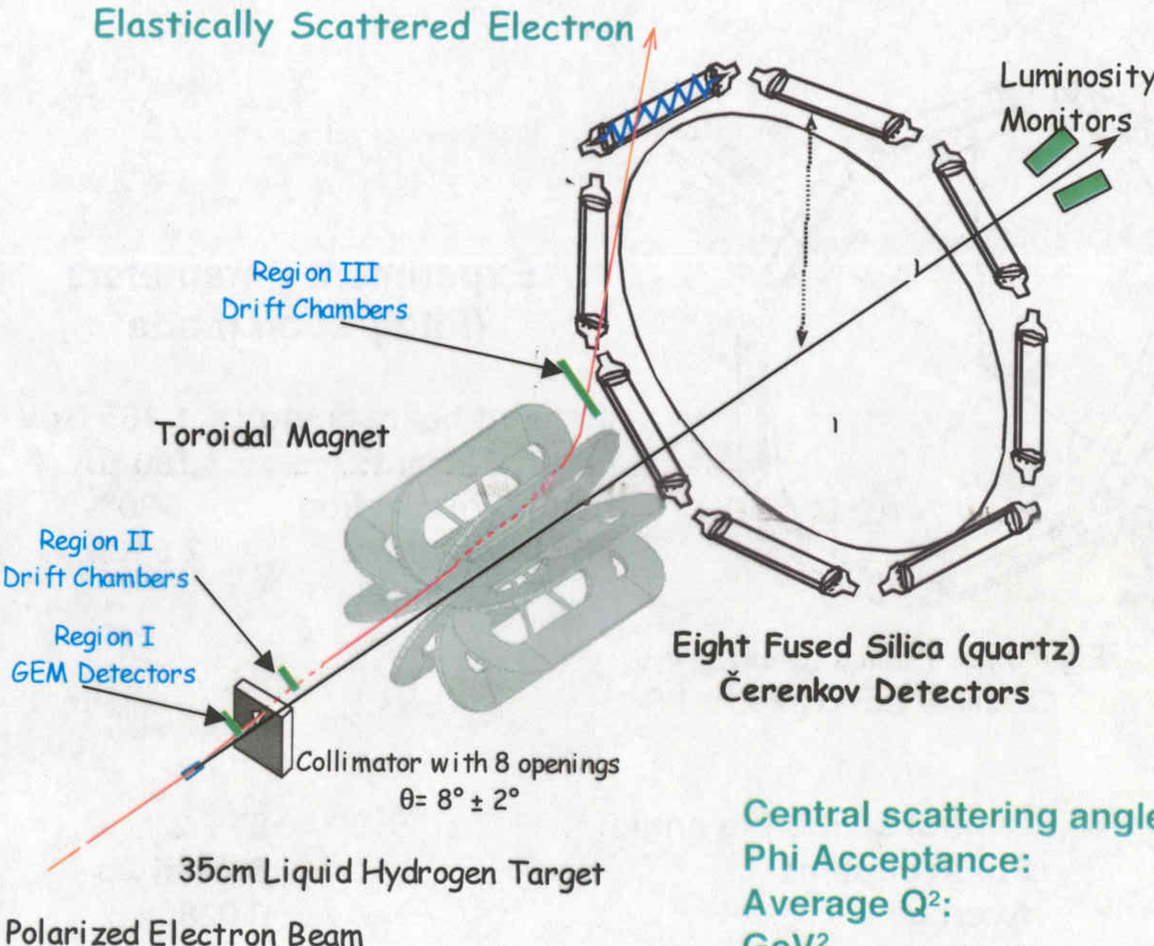


Illustration of the Q^{p}_{Weak} Experiment



Experiment Parameters
(integration mode)

Incident beam energy:	1.165 GeV
Beam Current:	180 μA
Beam Polarization:	~80%
LH_2 target power:	2.5 KW

Central scattering angle:	8° ± 2
Phi Acceptance:	50% of 2p
Average Q^2:	0.028
GeV^2	
Acceptance averaged asymmetry:	–0.28 ppm
Integrated Rate (all sectors):	5.2 GHz
Integrated Rate (per detector):	650 MHz

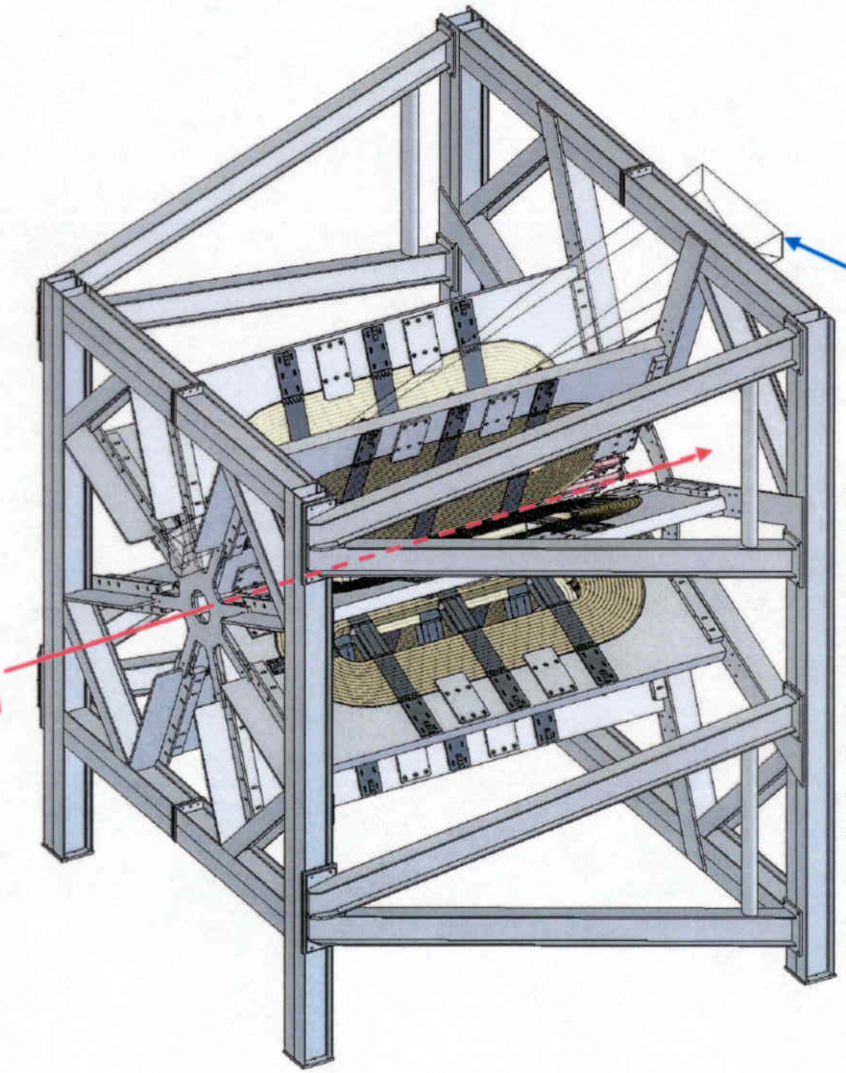
The Q^p_{Weak} Instrumentation

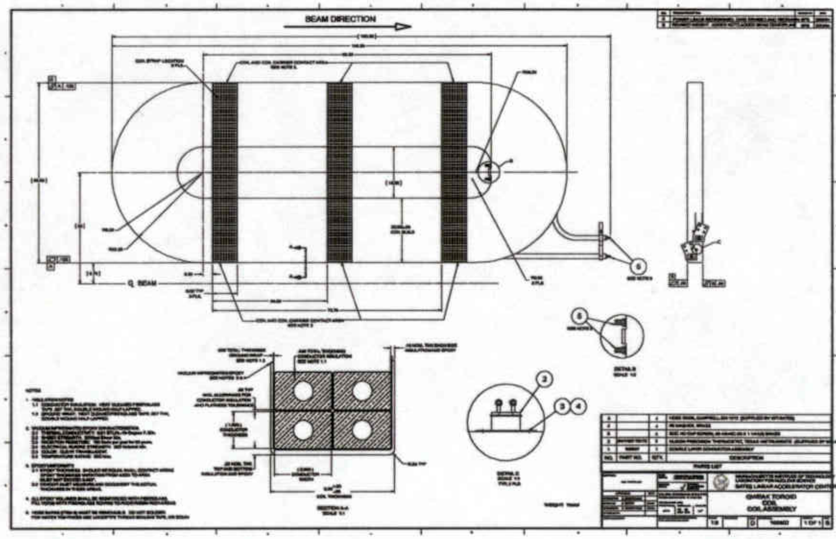
- Polarized source (~80%) + accelerator delivering 180μA at 1.175 GeV/c.
- Beamline instrumentation to measure helicity correlated beam properties.
- High power LH_2 target & luminosity monitor.
- Precision collimator system to define $\langle Q^2 \rangle$ acceptance.
- 8 octant toroidal Fe free magnet to focus elastics.
- 8 fused silica (synthetic quartz) Cerenkov detectors with integrating readout.
- Tracking system to verify $\langle Q^2 \rangle$ acceptance, map detector efficiency, check background estimates & perform dilution factor measurement.
- Precision beam polarimetry (Moller & Compton).

Existing Hardware
New Hardware

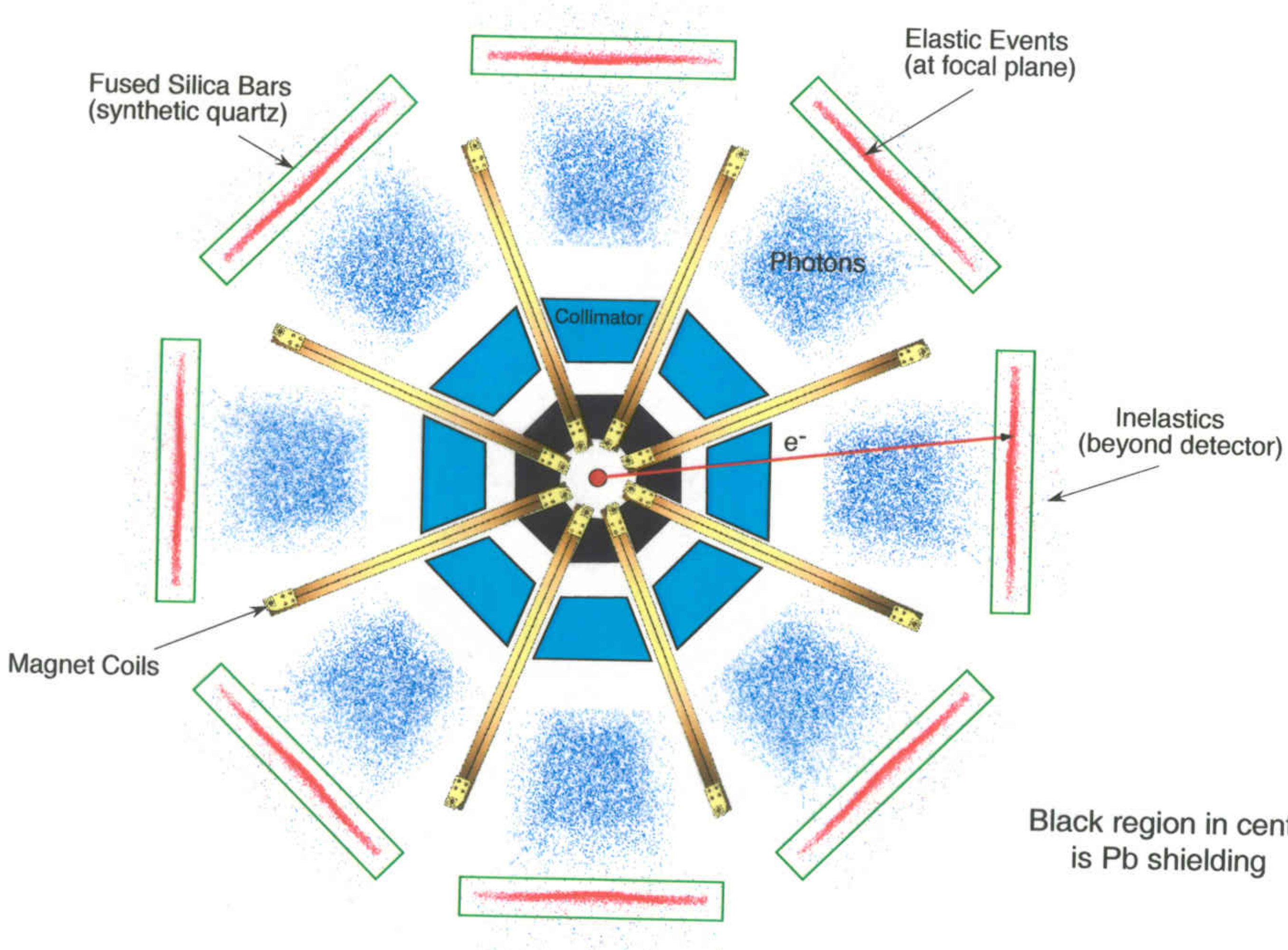
Q_{weak} Toroidal Magnet

- 8 toroidal coils, 4.5m long along beam
- Resistive, based on BLAST design
- Pb shielding between coils
- Coil holders & frame all Al
- $\int B \cdot dl \sim 0.7$ T-m
- ~9500 A





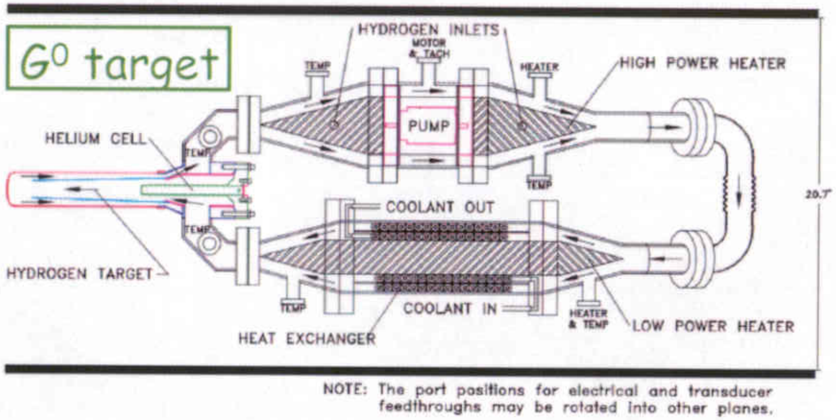
End View of Q^{p}_{Weak} Apparatus with GEANT Simulated Events



Black region in center is Pb shielding

R. Carlini - 1/27/03

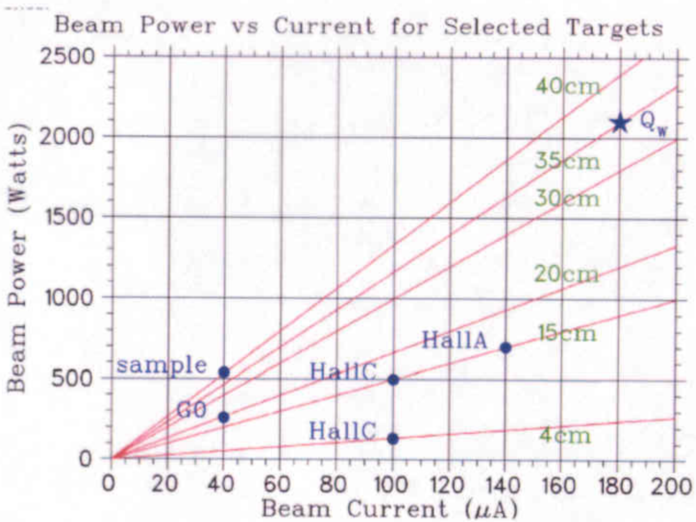
The Q^p_{weak} Liquid Hydrogen Target



Target: Similar in design to SAMPLE and G^0 targets

→ longitudinal liquid flow

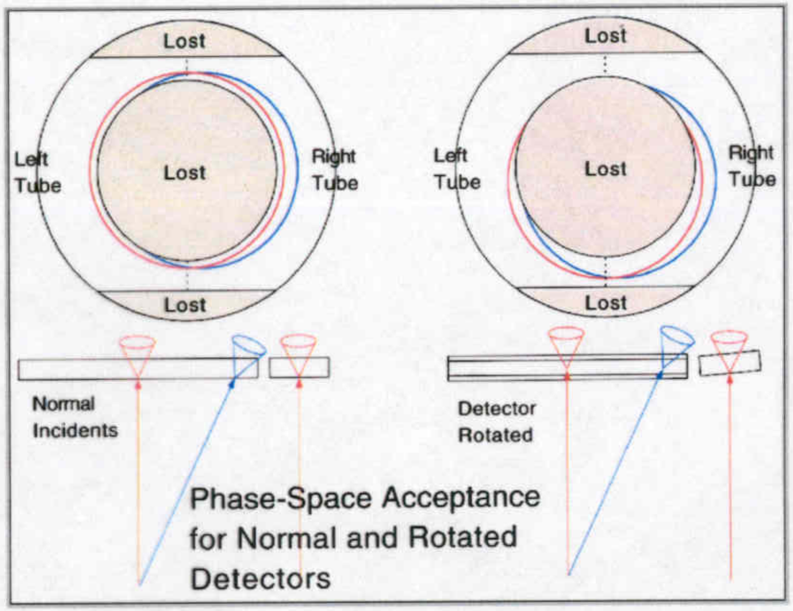
→ high stream velocity achieved with perforated, tapered "windsock"

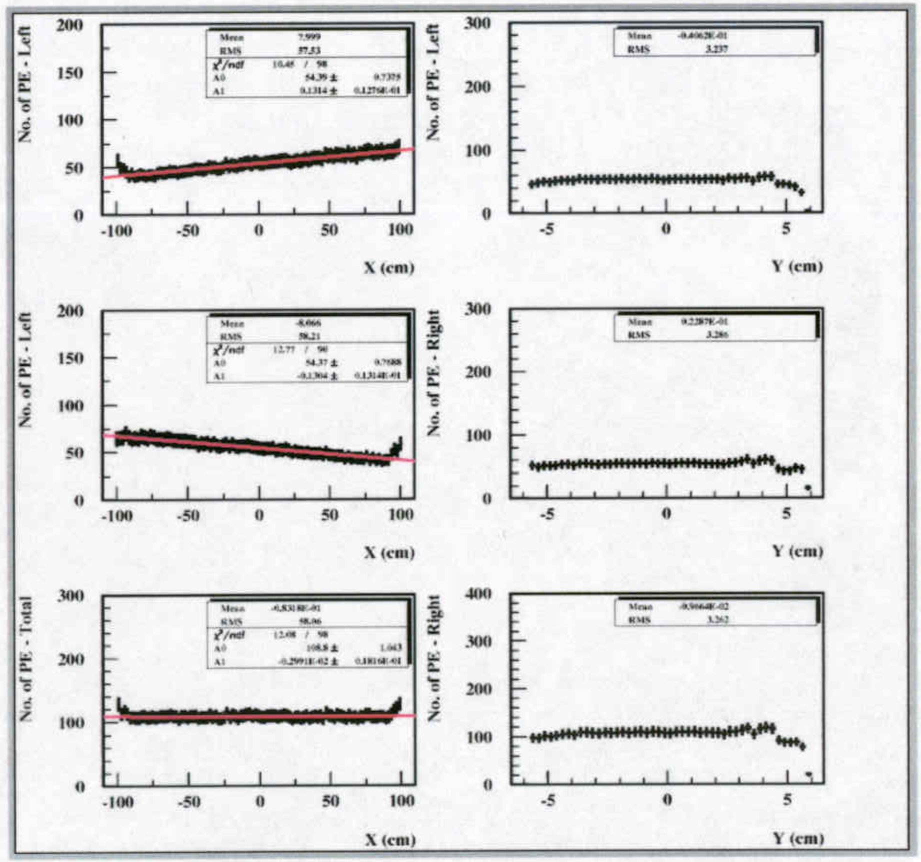


Q^p_{weak} Target parameters/requirements:

- length = 35 cm
- beam current = 180 μA
- beam power = 2200 W
- raster size ~2 mm x ~2 mm square
- flow velocity > 700 cm/s
- density fluctuations (at 15 Hz) < 5×10^{-5}

Light Collection in 12 cm x 2.54 cm x 2 m Quartz Cerenkov Detectors





Length

Width

Position dependence of the # of pe's on each of the PMTs.

Simulation includes the full weighted cross-section & spectrometer optics.

Rotate Detector 12.5°

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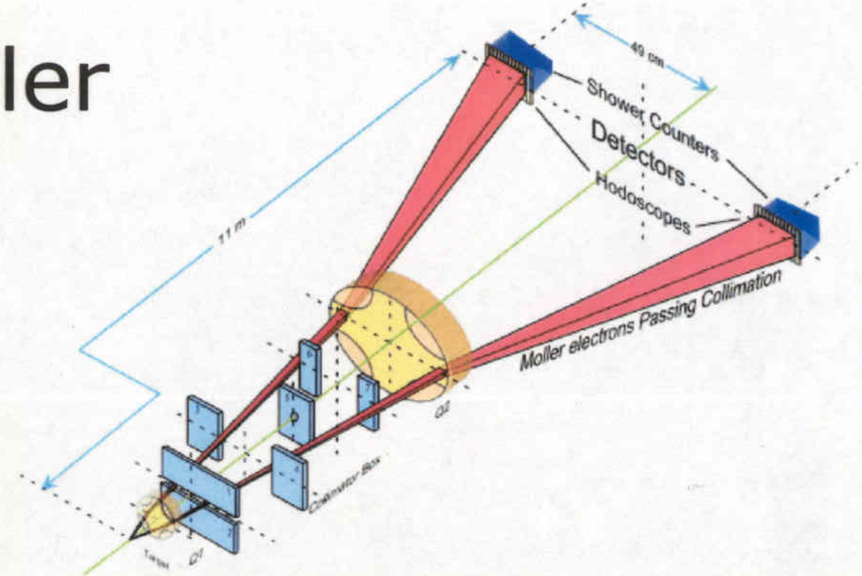
Basel/Hall C Møller



- Existing Hall C Møller can do 1% (stat) in a few minutes
- With care, absolute accuracy <1%

- Limitations
  - $I_{Max} \sim 10\ \mu A$
    At higher currents the Fe target depolarizes.
  - Measurement is destructive

- Goals for an upgraded Møller
  -Measure P_{beam} at 100 μA or higher, quasi-continuously
  -Trick: kicker + strip or wire target (looks promising)

- Plus new HallC Compton polarimeter
  -Measure P_{beam} at 100 μA or higher, quasi-continuously

Preliminary Beam Parameter Specifications for the Qweak Experiment

Beam Property	Nominal value	Maximum deviation from nominal (DC)	Maximum noise at the helicity reversal frequency	Maximum noise at all other frequencies	Maximum allowed run-averaged helicity-correlation
Energy (average)	1.165 GeV	1×10^{-4}	1×10^{-5}	1×10^{-4}	1×10^{-8}
Energy Spread (1 σ)	$\sigma_E/E < 5 \times 10^{-5}$	$\sigma_E/E < 5 \times 10^{-5}$			
CW average current	180 μA	± 5%	< 70 ppm	< 0.1%	< 0.1 ppm
Position at Qweak target	"0"	± 0.1 mm	± 28 μm	< 100 μm	< 20 nm
Angle at Qweak target	"0"	60 microrad	< 0.3 millirad	< .02 millirad	< 100 nrad
Angular divergence at target	$\sigma_{X'}, \sigma_{Y'} < 100\mu r$	+- 10%			
rms size (unrastered) at target	< 150 μm	± 25%	< 10 μm	< 0.1 mm	< 2.6 μm
Polarization	> 80%				
Beam halo at Qweak target	$< 1 \times 10^{-6}$ outside of 3 mm radius				

Anticipated Uncertainties on Q^p_{Weak}

	$\Delta Q^p_{weak}/Q^p_{weak}$		Possible Improvements
Statistical (2200 hours)	2.8%	→	2.5%
Systematic:			
Hadronic structure corrections	2.0%	→	1.5%
Beam polarization	1.4%	→	1.0%
Average Q^2 determination	1.0%		
Helicity-correlated Beam Properties	0.6%		
Uncertainty in Inelastic contamination	0.2%		
Al Target window Background	<1.0%	→	0.3% (Be)
Total systematic	2.9%		2.2%
Total	4.0%		3.3%

Additional uncertainty associated with QCD corrections (from extraction of $\sin^2\theta_W$):
raises $\Delta \sin 2\theta W$ / $\sin 2\theta W$ from 0.2% to 0.3%.

Bottom line:

Precision measurement of the running of $\sin^2\theta_W$ requires effort but no new technology!

Status Qweak: Summary

- Broad community performing precision measurements to test SM – including Qweak.
- Capital funding (NSF + university matching, JLAB, NSERC) secured
  JLab → "infrastructure" - AC, DC, cooling water, installation manpower, recycle G^0 beamline systems....
- Magnet procurements during FY-04. Detector prototyping begun.
- On track for a ~3.5 year construction effort with possible installation in 2007.
- Strong scientific support for the measurement.
  Nuclear theory (Ramsey-Musolf, Erler, Haxton, Donnelly, Friar,...) and high energy theory (W. Marciano & P. Lanacker).
- Collaboration healthy and growing -- addition of MIT/Bates Staff and the hiring of postdocs by a number of groups.
- Investigating possibility of better than a 4% measurement of Qweak.