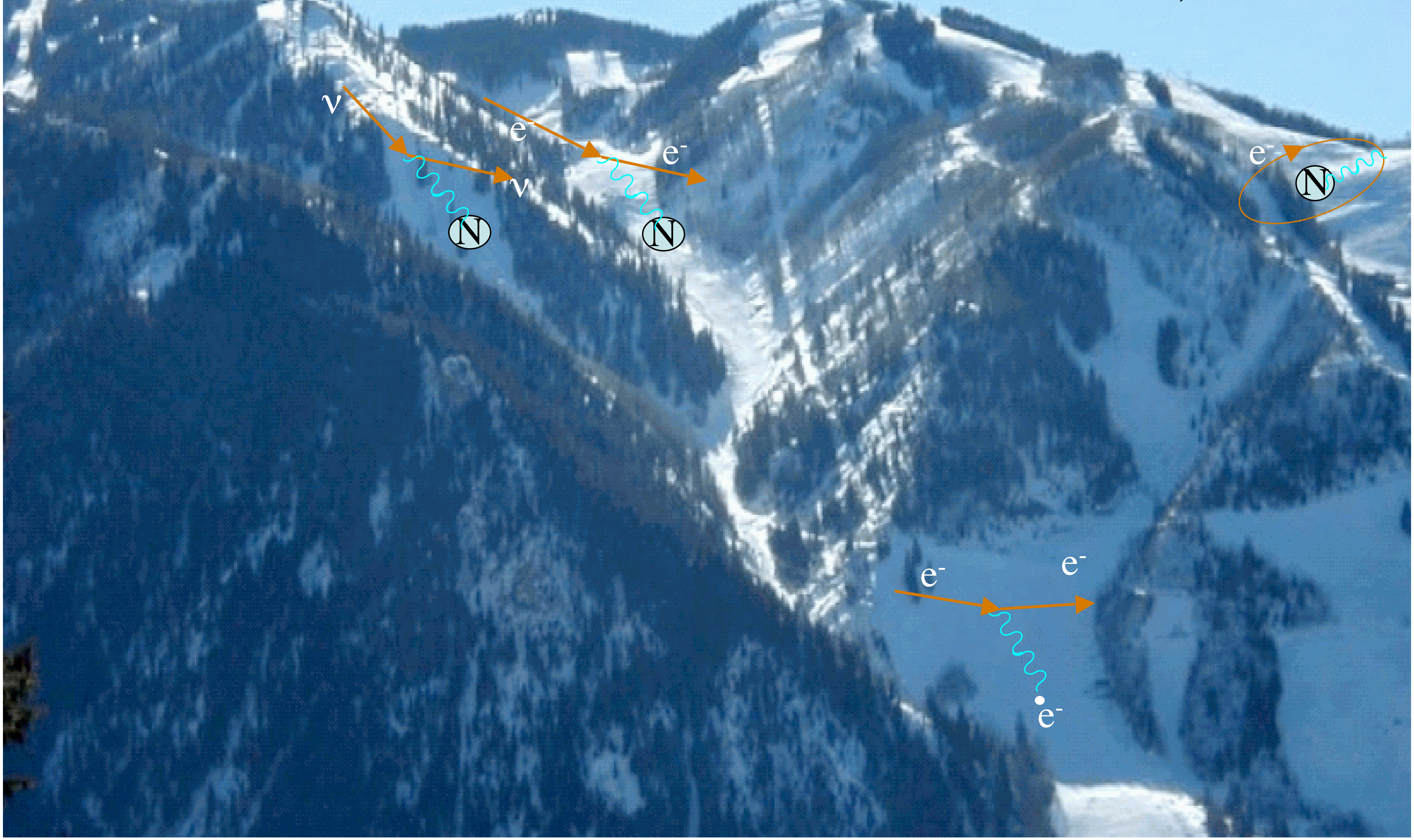
2005 Aspen Winter Conference, 13-19 February
The Highest Energy Physics

Low Energy
Precision Electroweak Measurements

Mike Woods, *SLAC*



Beyond the Standard Model

Energy Frontier

- Tevatron
- LHC
- (Linear Collider)

Symmetry Violations

Rare or Forbidden Processes

Precision Electroweak Measurements

Indirect access to TeV-scale physics

Can clarify gauge structure and nature of
New Physics discoveries at colliders
Can motivate parameters for new colliders
(ex. ILC, LHC upgrades, VLHC)

Current Low Energy experiments can probe New Physics at (1 – 10) TeV!

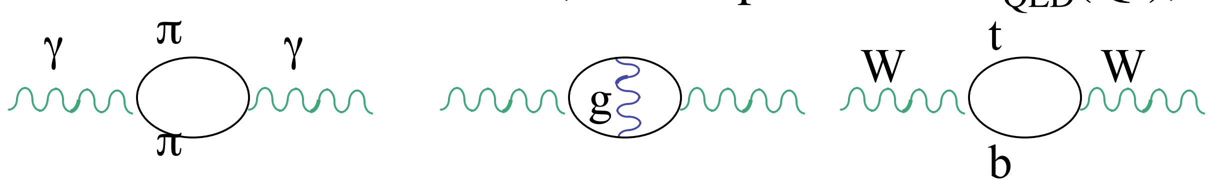
Precision Electroweak Measurements

3 SM gauge parameters g, g', v_0 || α, G_F, m_Z from experiment

α_{QED}, known to 3 ppb: electron (g-2)
G_F, known to 9 ppm: muon lifetime
m_Z, known to 23 ppm: *Z* boson mass

To compare precision measurements with SM predictions,

need accurate radiative corrections, with input from $\Delta\alpha_{QED}(Q^2)$, α_S, m_{top}



High energy measurements: Z lineshape, W mass, Z-pole asymmetries

Low energy measurements: muon (g-2), ν-N DIS,
atomic PV, e-e PV, e-N PV

This talk ⟶ $\mathbf{a_\mu}$ **R$^-$(νN)** **APV (Cs)** $\boldsymbol{A_{PV}}$ **(e-e)**

Level of Precision

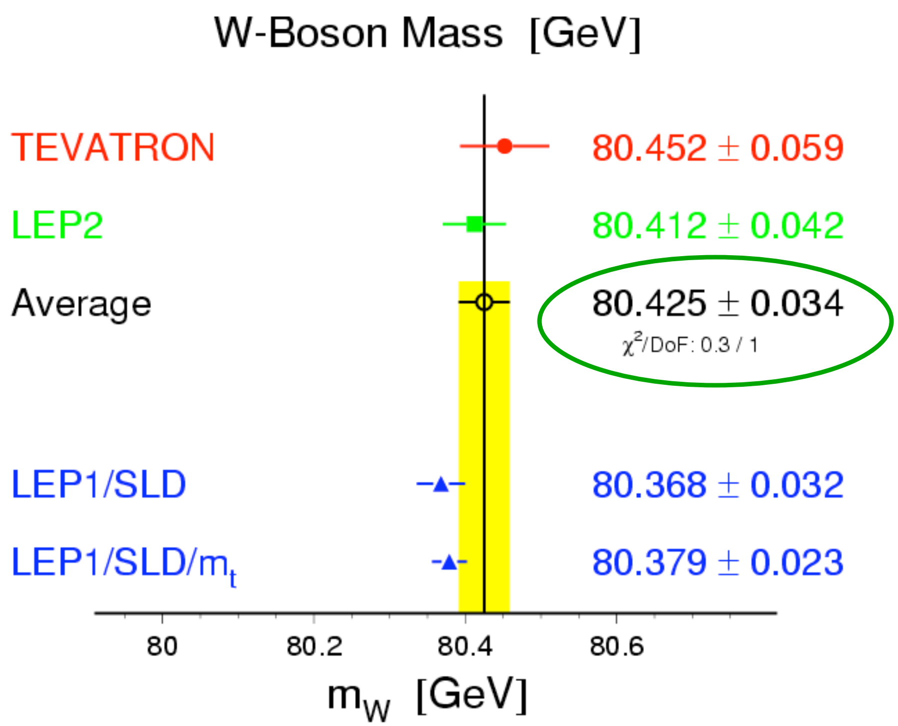
Experiment	Measured Quantity	Absolute Size	Relative Precision	Absolute Precision
BNL E869	$a_\mu = \_(g\text{-}2)_\mu$	$(\alpha/2\pi) \sim 0.1\%$	0.9 ppm	$9 \cdot 10^{-10}$
FNAL NuTeV	$R^- = \dfrac{\sigma^{NC}_{\nu N} - \sigma^{NC}_{\bar{\nu} N}}{\sigma^{CC}_{\nu N} - \sigma^{CC}_{\bar{\nu} N}}$	0.3	0.5%	1500 ppm
Boulder APV	Cs APV	6 ppm	0.7%	40 ppb
SLAC E-158	$A_{PV}(ee) = \dfrac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$	130 ppb	14%	18 ppb

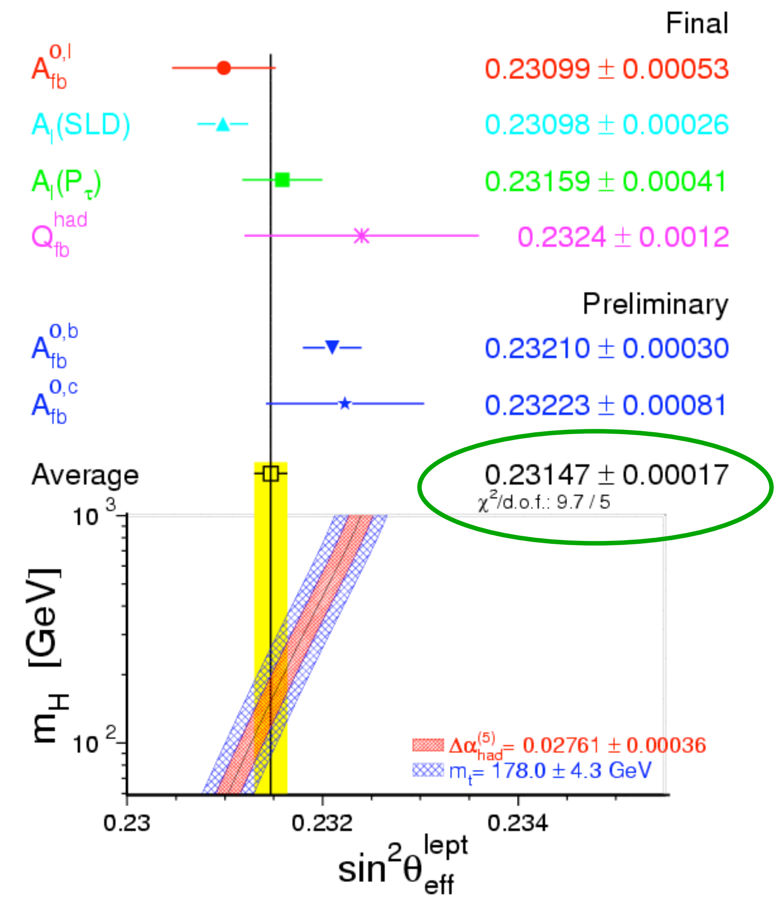
These experiments are precise <u>and</u> difficult

- degree of difficulty depends on different considerations for size, relative precision and absolute precision of measured quantities
- desire for redundant and complementary measurements

At high energy: precise M_W and $\sin^2\theta_W$

from LEP1, LEP2, SLC and Tevatron

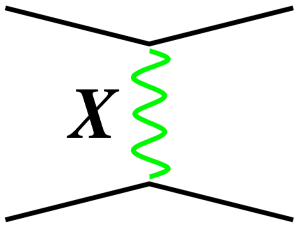




- Data consistency within context of SM is generally good
- Higgs mass constraints:
  - W mass and leptonic asymmetries predict light Higgs
  - Hadronic asymmetries predict heavy Higgs

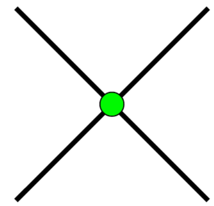
Electroweak Measurements away from the Z-pole *also* needed!

consider



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

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



Contact interaction

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

no interference!

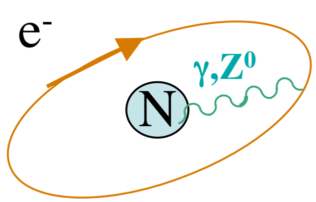
Better sensitivity to contact interactions, Z', other New Physics is possible with precision Low Energy measurements

- Running of α_{em} and α_S with Q^2 are well established

What about the Q^2 evolution of $\sin^2\theta_W$?

And does it agree with SM prediction?

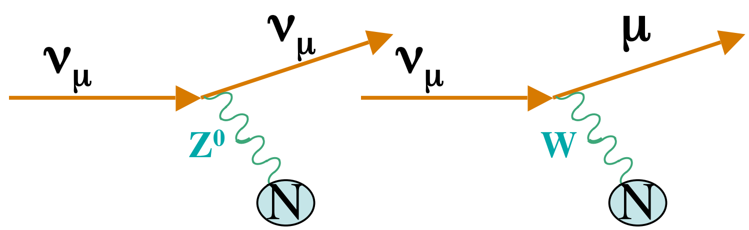
Low Q^2 Measurements of θ_W



Boulder Cs

$Q_W(Cs) = -N+Z(1-4\sin^2\theta_W)$

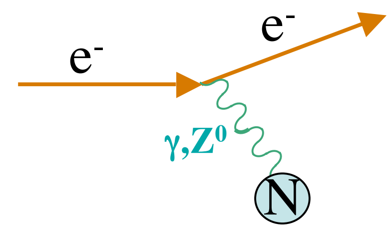
$$\delta \sin^2\theta_W\left(M_Z^2\right) = 0.0019$$



FNAL NuTeV

$$R^- = \frac{\sigma_{\nu N}^{NC} - \sigma_{\bar{\nu} N}^{NC}}{\sigma_{\nu N}^{CC} - \sigma_{\bar{\nu} N}^{CC}}$$

$$\delta \sin^2\theta_W\left(M_Z^2\right) = 0.0017$$



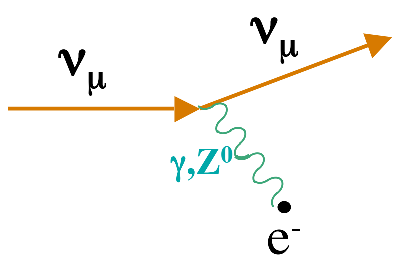
JLAB QWEAK (future)

$A_{PV} \propto 1 - 4\sin^2\theta_W$

$$\delta \sin^2\theta_W\left(M_Z^2\right) = 0.0007$$

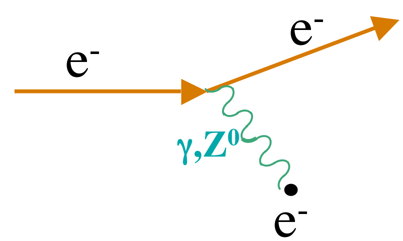
Goal

Purely leptonic



CERN CHARMII

$$\delta \sin^2\theta_W\left(M_Z^2\right) = 0.008$$



SLAC E158

$A_{PV} \propto 1 - 4\sin^2\theta_W$

$$\delta \sin^2\theta_W\left(M_Z^2\right) = 0.0015$$

References on *Low Energy* Electroweak Measurements:

- J. Erler and M.J. Ramsey-Musolf, hep-ph/0404291
  "Low Energy Tests of the Weak Interaction"

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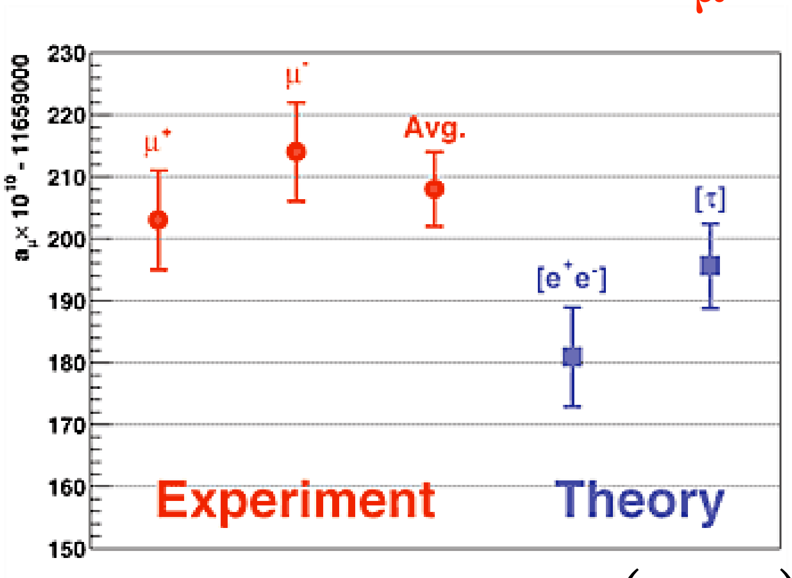
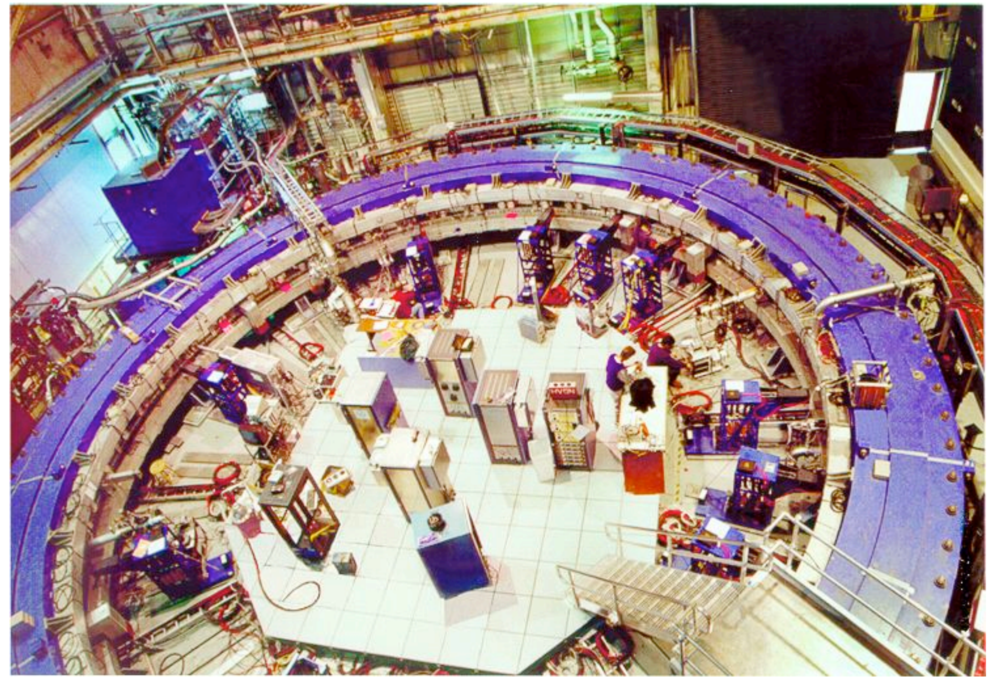
  http://www.krl.caltech.edu/~subZ/meet/

- **Workshop on Low Energy Precision Electroweak Measurements**
  (LEPEM2002)
  TRIUMF, April 4-6, 2002

  http://www.triumf.ca/lepem2002/

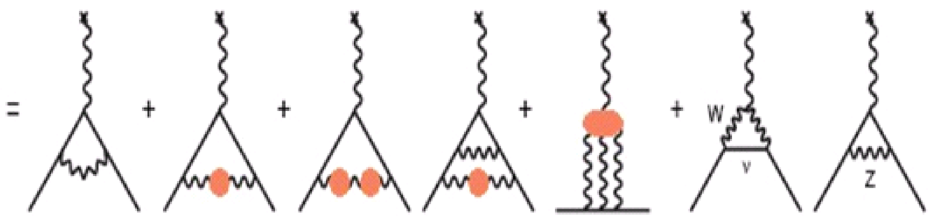
Brookhaven $(g\text{-}2)_\mu$





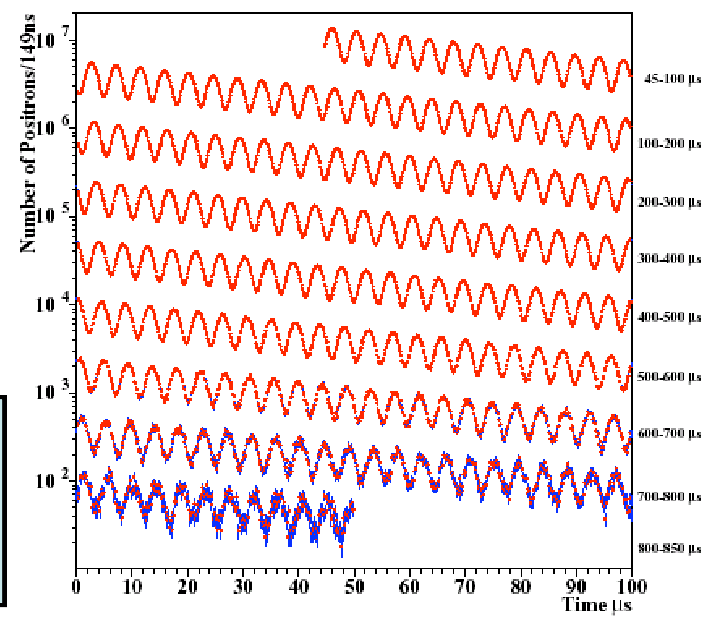
$$\vec{\mu}_s = g_s\left(\frac{e}{2m}\right)\vec{s} \qquad a_\mu = \frac{(g_s - 2)}{2}$$

$$a_\mu(SM) = a_\mu(QED) + a_\mu(Had) + a_\mu(Weak)$$



$$\frac{a_\mu(\mathrm{BNL\ E821}) - a_\mu(\mathrm{SM})}{a_\mu(\mathrm{SM})} = \begin{bmatrix} 2.2 \pm 0.5(\mathrm{expt}) \\ \pm 0.7(\mathrm{theory}) \end{bmatrix} \mathrm{ppm}$$

4 Billion Positrons with E> 2 GeV



$$\frac{a_\mu(\text{BNL E821}) - a_\mu(\text{SM}|_{e+e-})}{a_\mu(\text{SM})} = \begin{bmatrix} 2.2 \pm 0.5(\text{expt}) \\ \pm 0.7(\text{theory}) \end{bmatrix} \text{ppm}$$

2.7σ

Sensitive to weak corrections: $\frac{a_\mu(weak)}{a_\mu(SM)} = 1.3 \text{ ppm}$

Deviation from New Physics? Hints of SUSY??

Future experiments?

- BNL E969 proposal to reach 0.2 ppm total expt error (scientific approval by Lab in Fall '04; needs funding)
- LOI submitted to J-PARC to reach 0.1 ppm

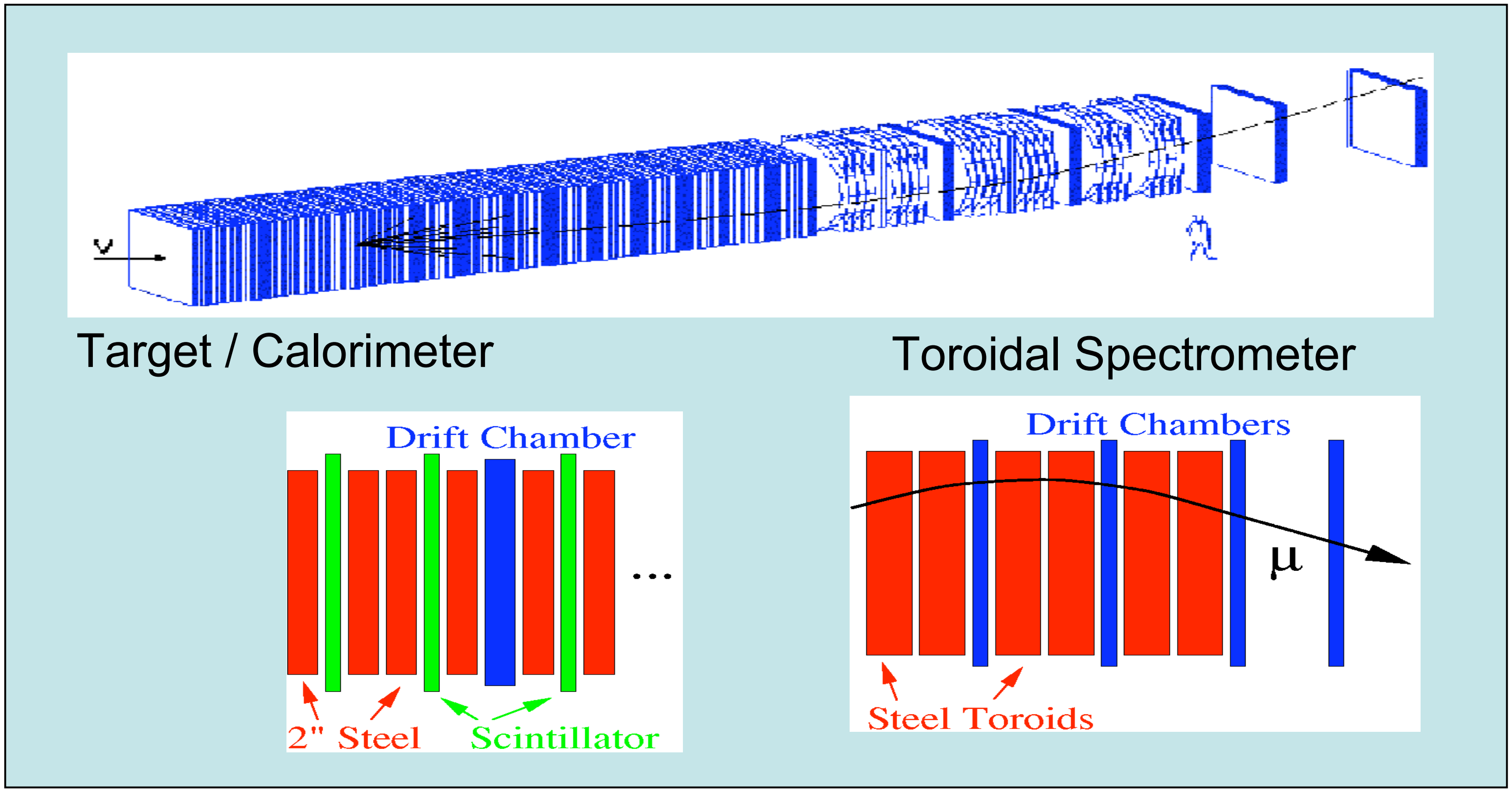
➢ Need reduced error in hadronic corrections:

currently, $\frac{\delta a_\mu(\text{had, LO})}{a_\mu} = 0.5 \text{ ppm}$

$\frac{\delta a_\mu(\text{had, LBL})}{a_\mu} = 0.3 \text{ ppm}$

Additional e^+e^- data needed: BaBar, Belle, KLOE

NuTeV Neutrino Experiment



$$R^- = \frac{\sigma_{\nu N}^{NC} - \sigma_{\bar{\nu} N}^{NC}}{\sigma_{\nu N}^{CC} - \sigma_{\bar{\nu} N}^{CC}} \approx \rho^2 \left(\frac{1}{2} - \sin^2 \theta_W \right)$$

$$\sin^2 \theta_W^{(on-shell)} = 0.2277 \pm 0.0013(stat.) \pm 0.0009(syst.)$$

Standard Model prediction is 0.2227
(3σ deviation)

NuTeV Result:

New Physics?

- not MSSM or RPV SUSY
- Z' possible

"Old" Physics?

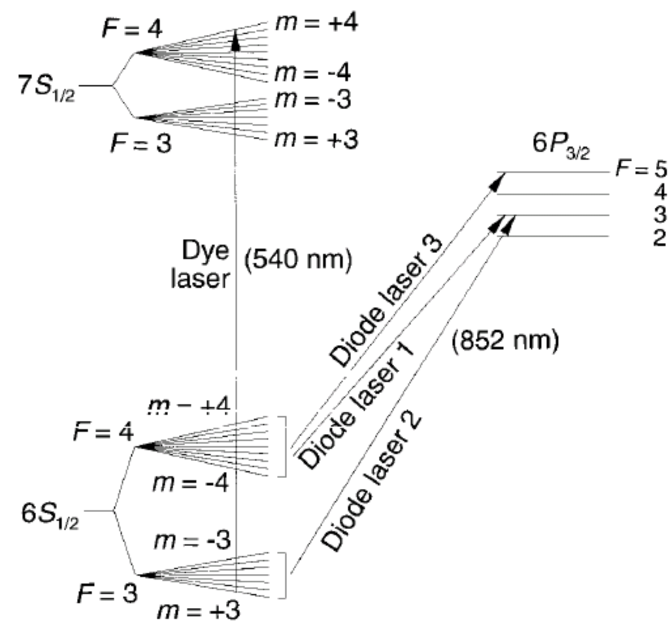
- Isospin symmetry violated? $u_p(x) \neq d_n(x)$?
  - 5% effect needed to move result to SM
  - Difficult to constrain
- Asymmetric strange sea? $s(x) \neq \bar{s}(x)$?
  - Unlikely from NuTeV direct measurement
- NLO QCD? Theoretically small, being checked by NuTeV
- Electroweak radiative corrections?
  - ISR, FSR and exp't acceptance
  - New calculations and RC codes being checked in NuTeV simulation

Jury is still out…

SOURCE OF UNCERTAINTY	$\delta \sin^2 \theta_W$
Data Statistics	0.00135
Monte Carlo Statistics	0.00010
TOTAL STATISTICS	0.00135
$\nu_e, \overline{\nu}_e$ Flux	0.00039
Energy Measurement	0.00018
Shower Length Model	0.00027
Counter Efficiency, Noise, Size	0.00023
Interaction Vertex	0.00030
TOTAL EXPERIMENTAL	0.00063
Charm Production, Strange Sea	0.00047
Charm Sea	0.00010
$\sigma^{\overline{\nu}}/\sigma^{\nu}$	0.00022
Radiative Corrections	0.00011
Non-Isoscalar Target	0.00005
Higher Twist	0.00014
R_L	0.00032
TOTAL MODEL	0.00064
TOTAL UNCERTAINTY	0.00162

$$\left(\frac{\delta R^-}{R^-} \approx 0.5\% \right)$$

APV: Boulder Cs Experiment



- measure APV component of $6s \rightarrow 7s$ transition in ^{133}Cs ;
  interferes with E1 (Stark) transition
- 5 reversals to isolate APV signal and suppress systematics
- APV signal is ~ 6 ppm of total rate, measured to 0.7% (40 ppb!)

$$Q_W = -N + Z\left(1 - 4\sin^2\theta_W\right)$$

$$Q_W\left({}^{133}\mathrm{Cs}\right) = -72.74 \pm 0.29\,(\mathrm{expt}) \pm 0.36\,(\mathrm{theory})$$
$$= -73.19 \pm 0.13 \quad (\mathrm{SM})$$

$$Q_W\left({}^{133}\mathrm{Cs}\right) = -72.74 \pm 0.46\,(\mathrm{expt})$$
$$= -73.19 \pm 0.13\,(\mathrm{SM})$$

Currently <1σ deviation

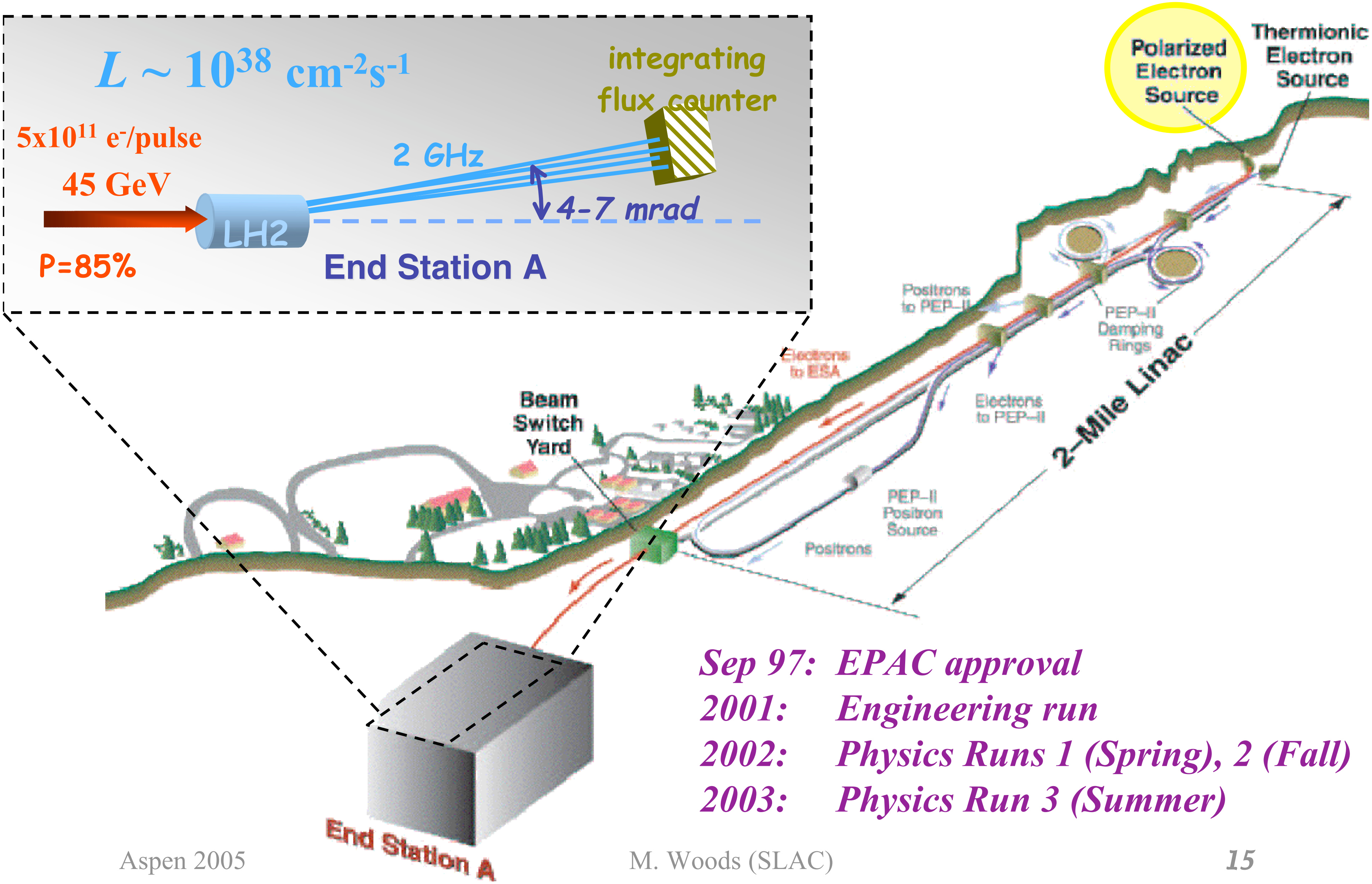
- Deviation between experiment and SM has been as large as 2.5σ.
- Atomic theory corrections since 2000, have resulted in current consistency:
  - Breit interaction, -0.6%
  - Vacuum Polarization, +0.4%
  - αZ Vertex Corrections, - 0.7%
  - Nuclear Skin Effect, - 0.2%

(Ginges and Flambaum, Phys.Rept.**397**:63-154,2004)

Future Atomic PV experiments

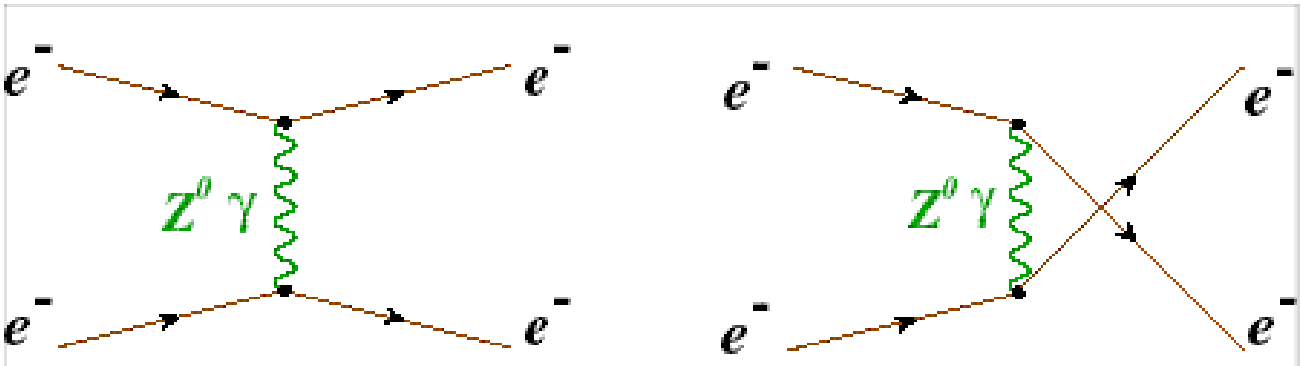
- **Paris group: Cs 6S _ 7S**, but with different systematics than Boulder expt; 2.7% current accuracy, 1% within reach and 0.1% (expt) may be possible (physics/0412017, 2004)
- **single Ba^+ ion (U. Washington), Ra^+ ion (KVI)** (talk by Fortson at subZ Workshop 2004; sub-1% possible)
- **Berkeley group: Yb isotopes** (talk by Budker at LEPEM2002 Workshop; sub-1% possible)

SLAC E-158



Sep 97: EPAC approval
2001: Engineering run
2002: Physics Runs 1 (Spring), 2 (Fall)
2003: Physics Run 3 (Summer)

Parity Violation in Moller Scattering



Polarized electron beam;
unpolarized electron target

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{M_Z^R - M_Z^L}{M_\gamma}$$

(γ-Z interference)

$$A_{PV} \approx \frac{Q^2}{M_Z^2}(1 - 4\sin^2\theta_W)$$

$$A_{PV}^{meas} = P_e \cdot A_{PV}$$

For E158, E=48 GeV, Q^2=0.03 GeV^2

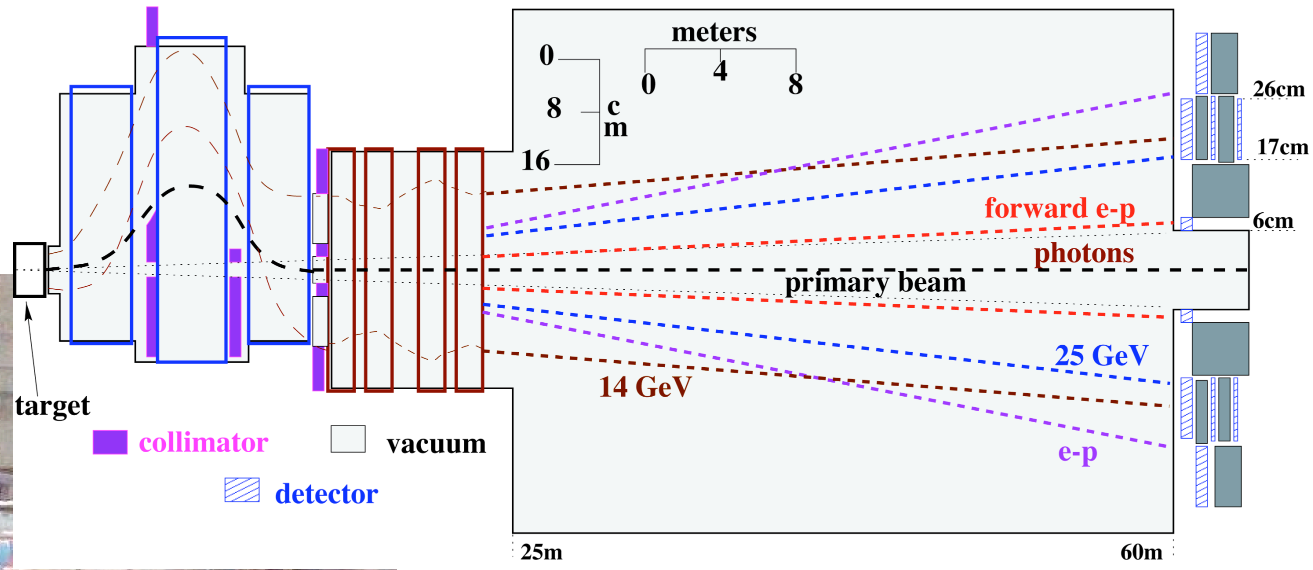
At tree level, A_{PV}= -3 x 10^{-7}

Weak Radiative Corrections reduce this by more than 50%

Key Ingredients

Beam

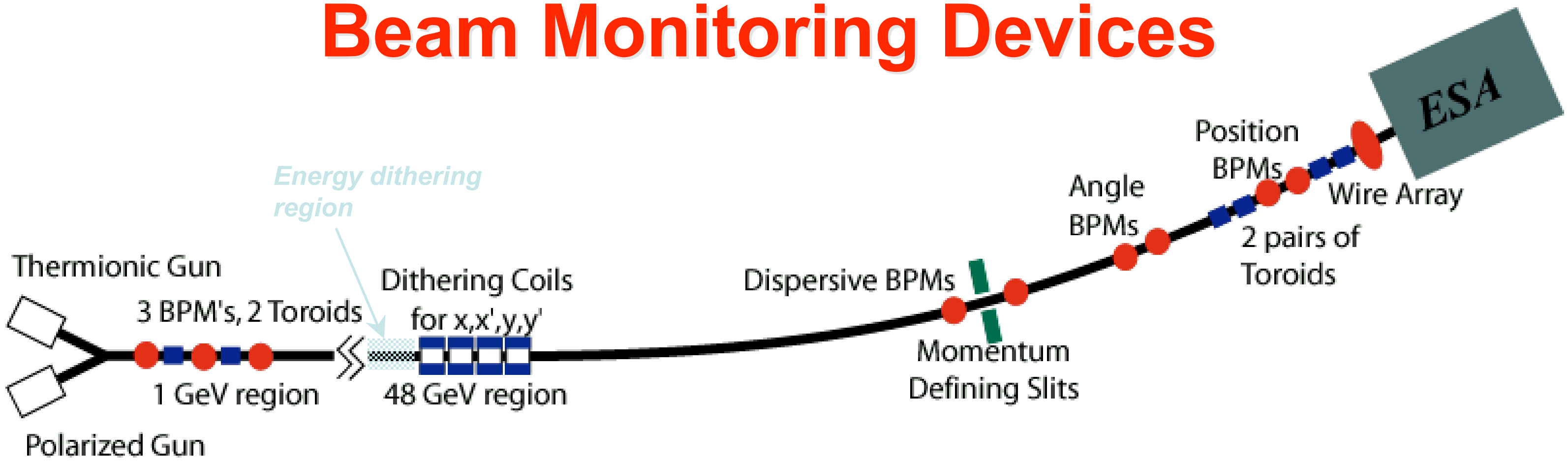
- High beam polarization (85-90%!) and beam current
- Strict control of helicity-dependent systematics
- Passive asymmetry reversals



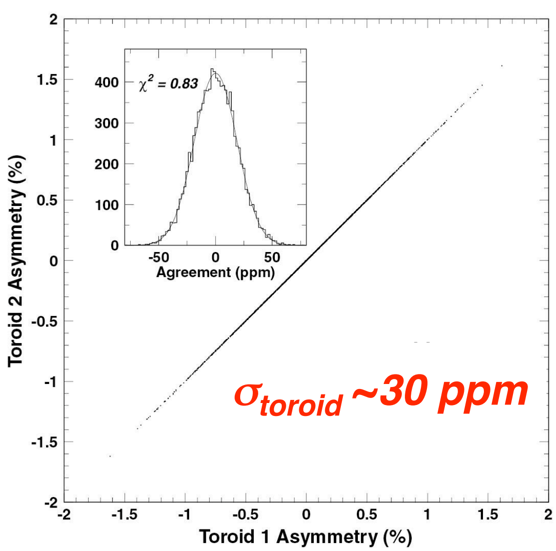
Target and Spectrometer

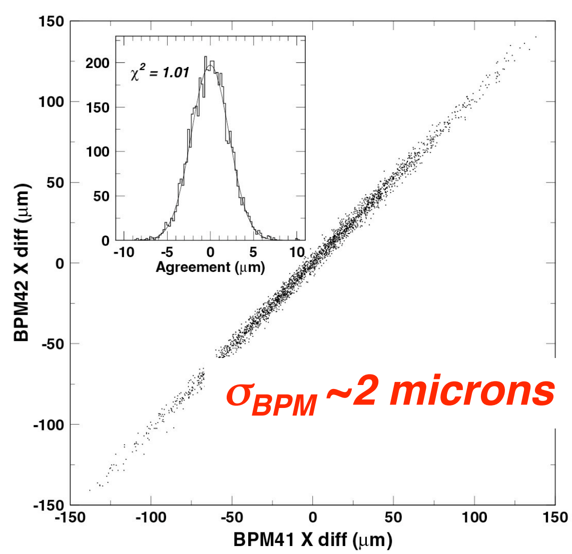
- High power LH_2 target
- Spectrometer optimized for Møller kinematics

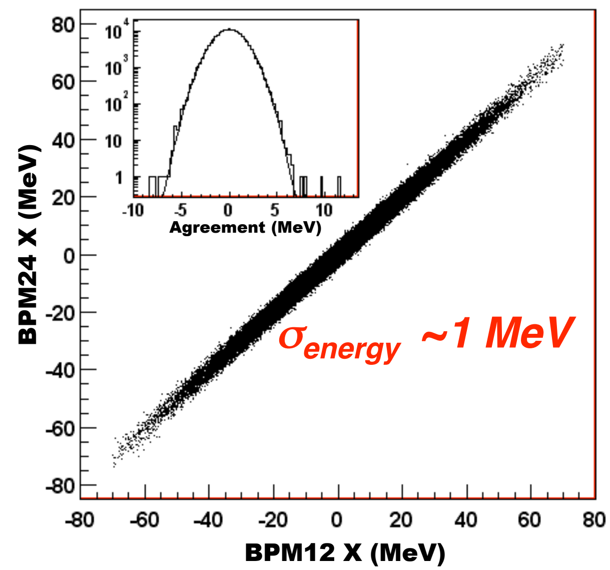
Beam Monitoring Devices



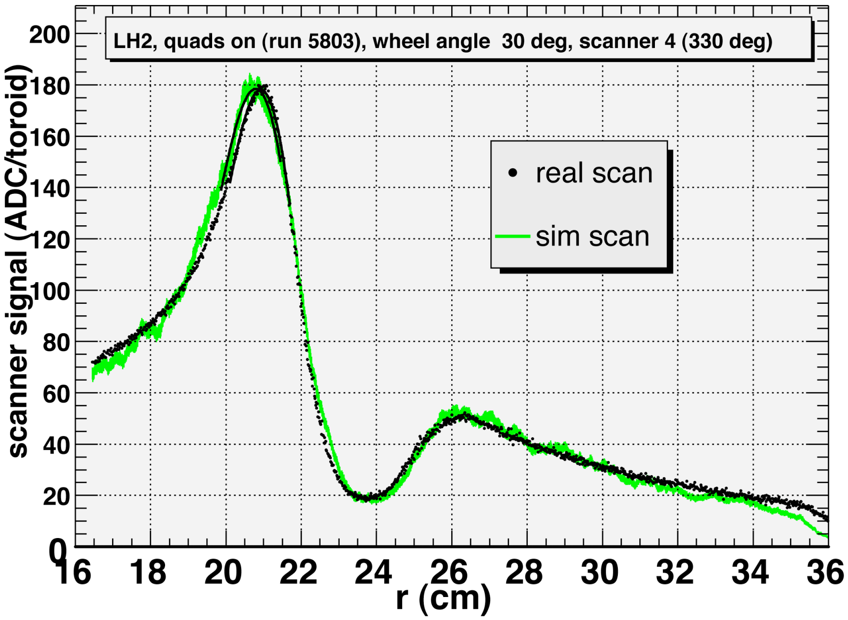
Can compare measurements of neighboring devices to determine the precision of the measurement.

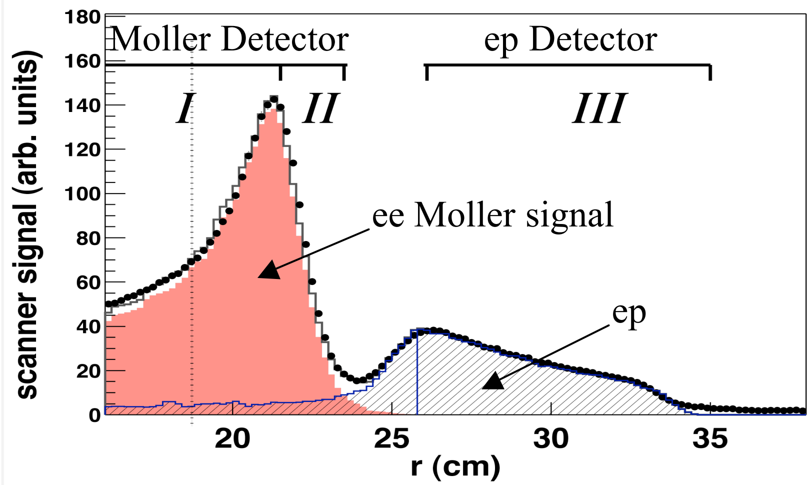




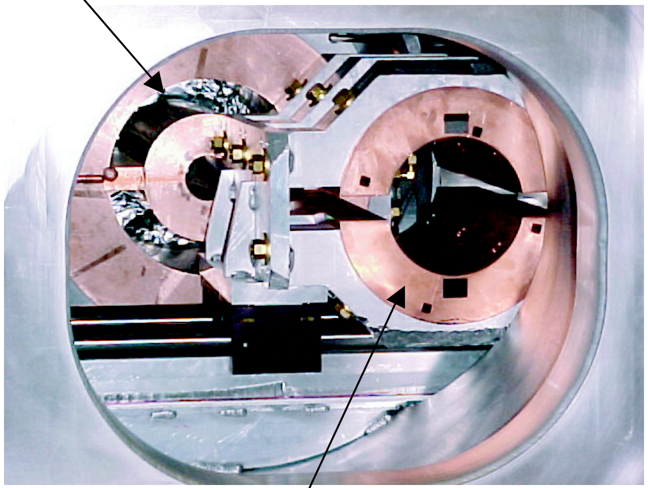


Scattered Flux Profile





QC1B (main acceptance) collimator

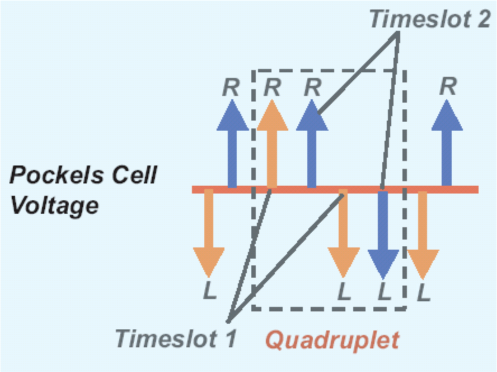


Insertable QC1A collimator
- used for polarimetry

ep Background to Moller sample:

- 6% from elastic scattering
- 1% from inelastic scattering
- (30±6) ppb correction

Experimental Features



Beam helicity is chosen pseudo-randomly at 120 Hz

- use electo-optical Pockels cell in Polarized Light Source
- sequence of pulse quadruplets; one quadruplet every 33 ms: $R_1 R_2 \overline{R_1}\,\overline{R_2} R_3 R_4 \overline{R_3}\,\overline{R_4} \ldots$

Physics Asymmetry Reversals:

- Insertable Halfwave Plate in Polarized Light Source
- (g-2) spin precession in A-line (45 GeV and 48 GeV data)

'Null Asymmetry' Cross-check is provided by a Luminosity Monitor

- measure very forward angle e-p (Mott) and Moller scattering

Also, False Asymmetry Reversals: (reverse false beam position and angle asymmetries; physics asymmetry unchanged)

- Insertable "-I/+I" Inverter in Polarized Light Source

A_{PV} Measurement

1. Measure asymmetry for each pair of pulses, p,

$$A^{p}_{exp} = \frac{ó_R - ó_L}{ó_R + ó_L}$$

2. Correct for difference in R/L beam properties,

$$A^{p}_{raw} = A^{p}_{exp} - \sum a_i Äx_i$$

← charge, position, angle, energy R-L differences

coefficients determined experimentally by regression or from dithering coefficients

3. Sum over all pulse pairs, $A_{raw} = \sum A^{p}_{raw}$

4. Obtain physics asymmetry:

$$A_{PV} = \frac{1}{P_b \cdot \varepsilon} \frac{A_{raw} - \sum \Delta A_{bkg}}{1 - \sum f_{bkg}}$$

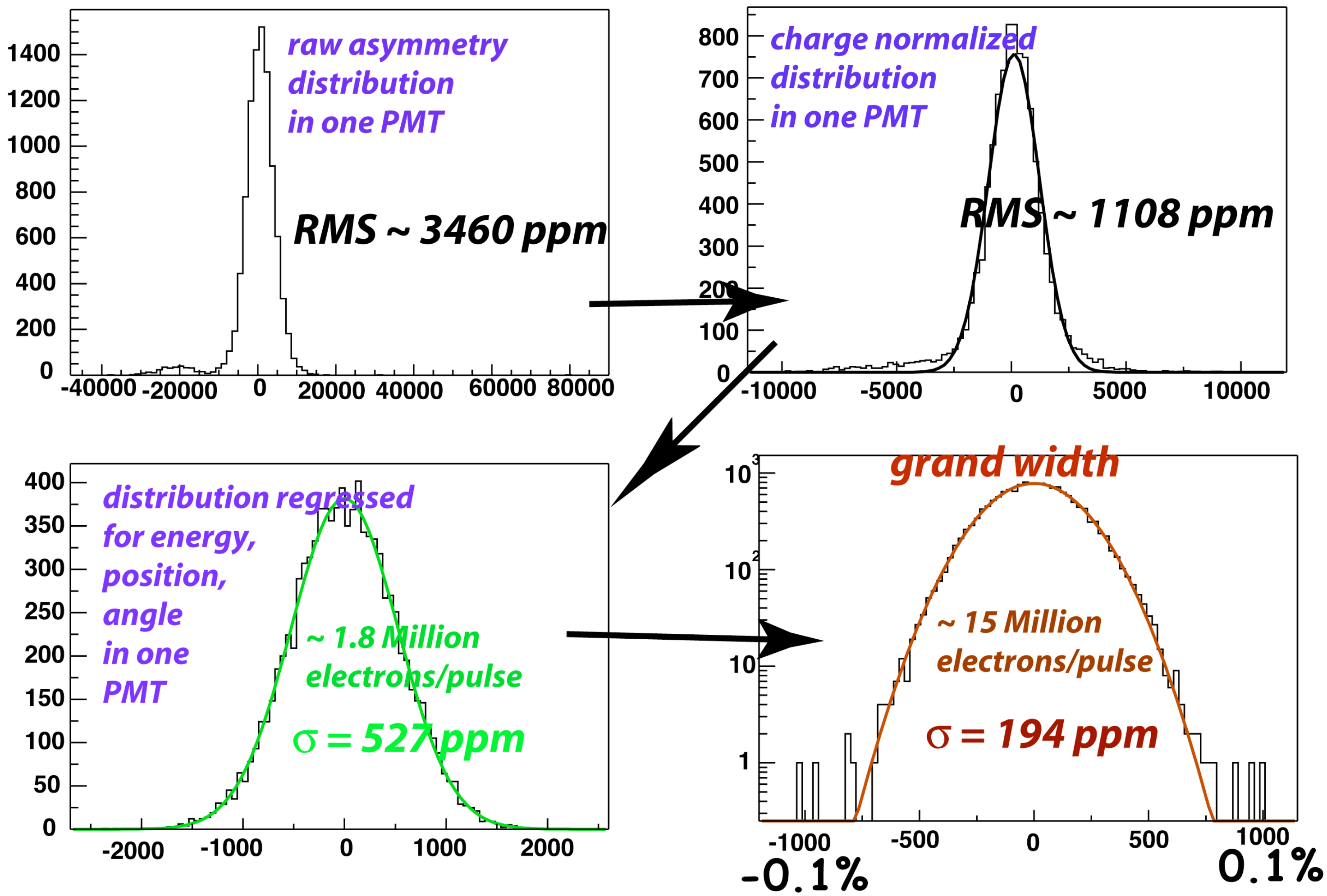
← backgrounds

← background dilutions

← beam polarization, linearity

Moller Detector
Regression Corrections

observed left-right asymmetry distribution



In addition, independent analysis based on beam dithering

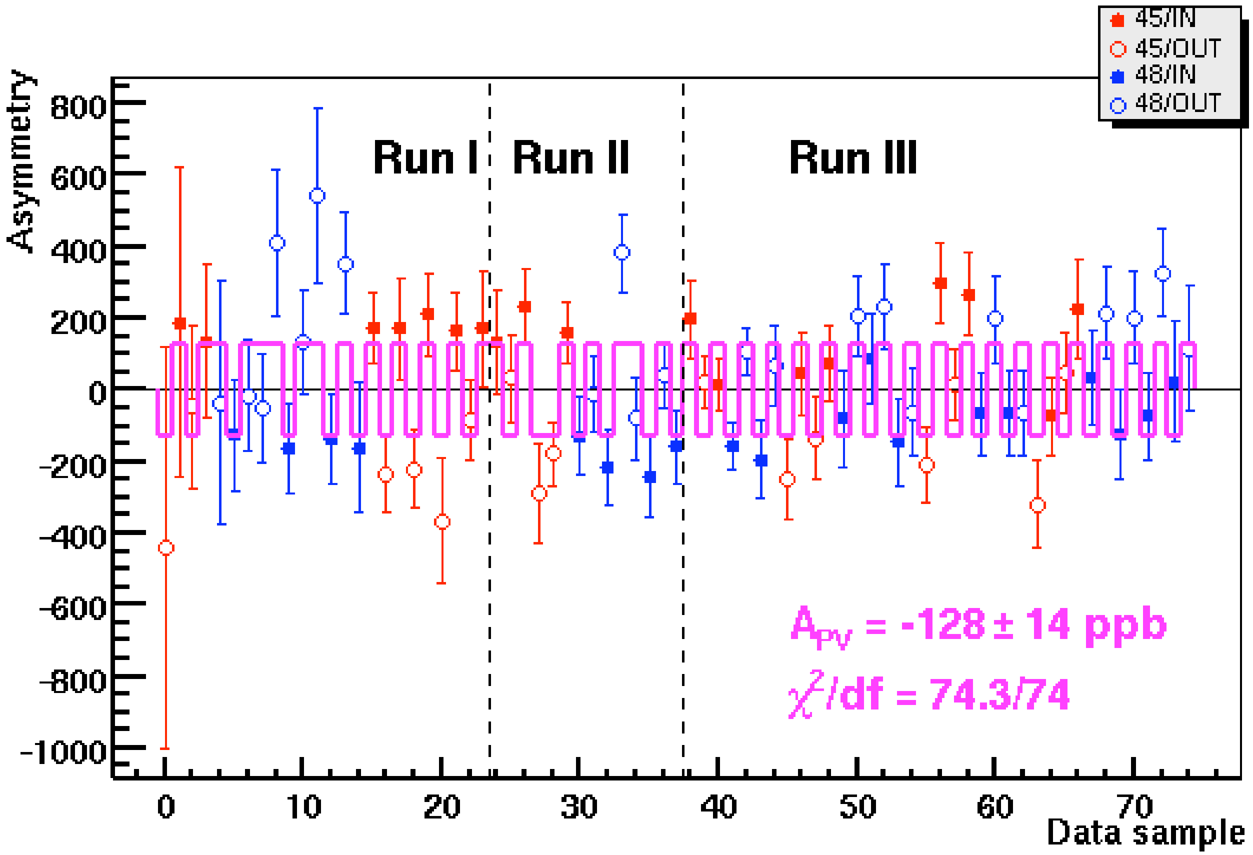
A_{PV} Corrections, ΔA, and dilution factors, f

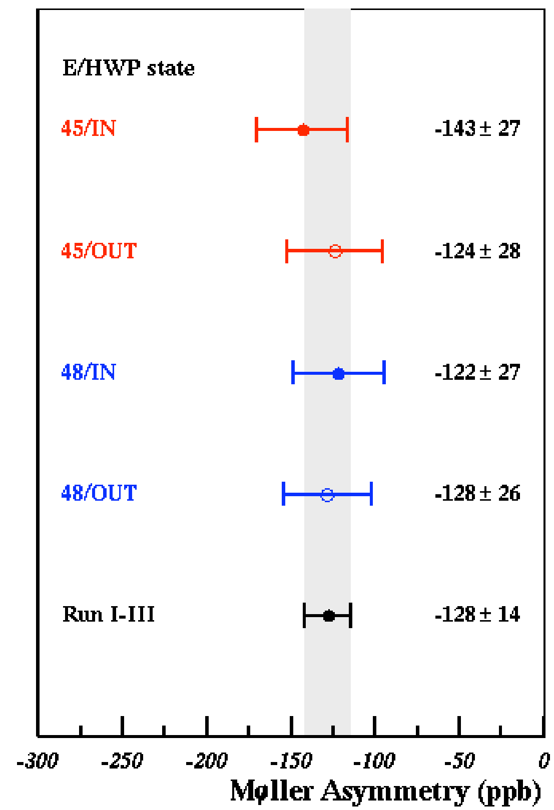
Source	ΔA (ppb)	*f*
Beam asymmetries	(-) ± 4	-
Beam spotsize	0 ± 1	-
Transverse polarization	-4 ± 2	-
ep elastic	-8 ± 2	0.058 ± 0.007
ep inelastic	-22 ± 6	0.009 ± 0.003
Brem and Compton electrons	0 ± 1	0.005 ± 0.002
Pions	1 ± 1	0.001 ± 0.001
High energy photons	3 ± 3	0.004 ± 0.002
Synchrotron photons	0 ± 2	0.0015 ± 0.0005
Neutrons	-1 ± 1	0.0006 ± 0.0002
TOTAL	**-31 ± 8**	**0.079 ± 0.009**

$$A_{PV} = \frac{1}{P_b \cdot \mathring{a}} \cdot \frac{A_{raw} - \sum \Delta A}{1 - \sum f}, \quad P_b = 0.88 \pm 0.05, \quad \varepsilon(\text{linearity}) = 0.99 \pm 0.01$$

**Beam polarization measured using polarized foil target; same spectrometer used with dedicated movable detector*

Moller Asymmetry, APV





$A_{PV}(e^-e^-$ at Q^2 = 0.026 $GeV^2)$:

-128± 14 (stat) ± 12 (syst) parts per billion *(preliminary)*

Significance of parity nonconservation in Møller scattering: 8σ

from A_{PV} to $\sin^2\theta_W^{eff}$

$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \cdot \frac{1-y}{1+y^4+(1-y)^4} \cdot F_{brem} \cdot \left(1 - 4\sin^2\theta_W^{eff}\right)$$

where:

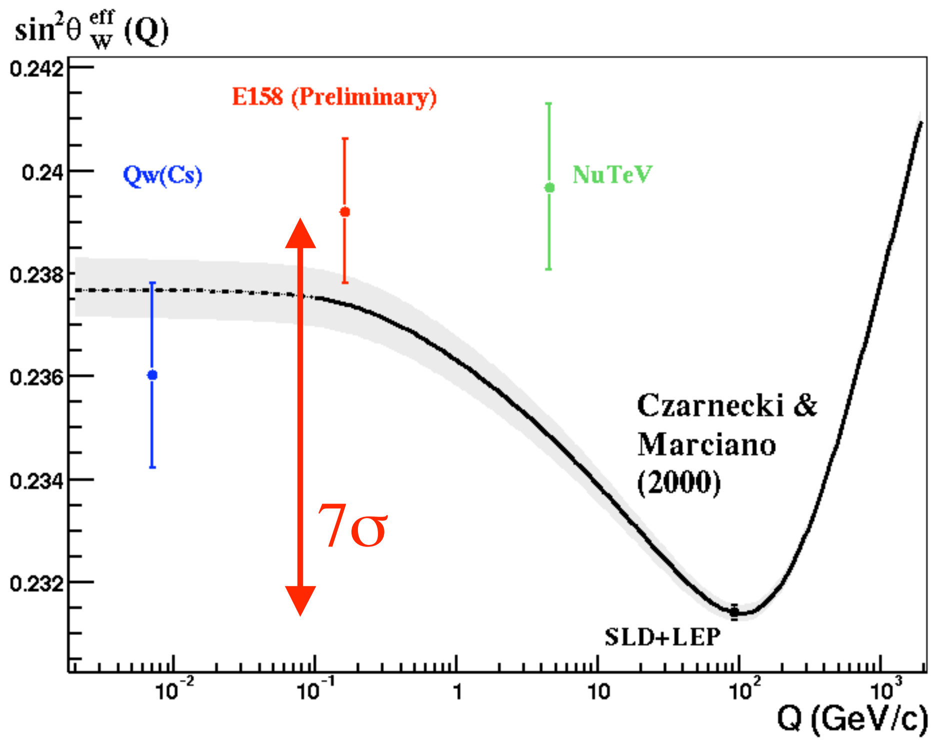
$$-\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \cdot \frac{1-y}{1+y^4+(1-y)^4}$$

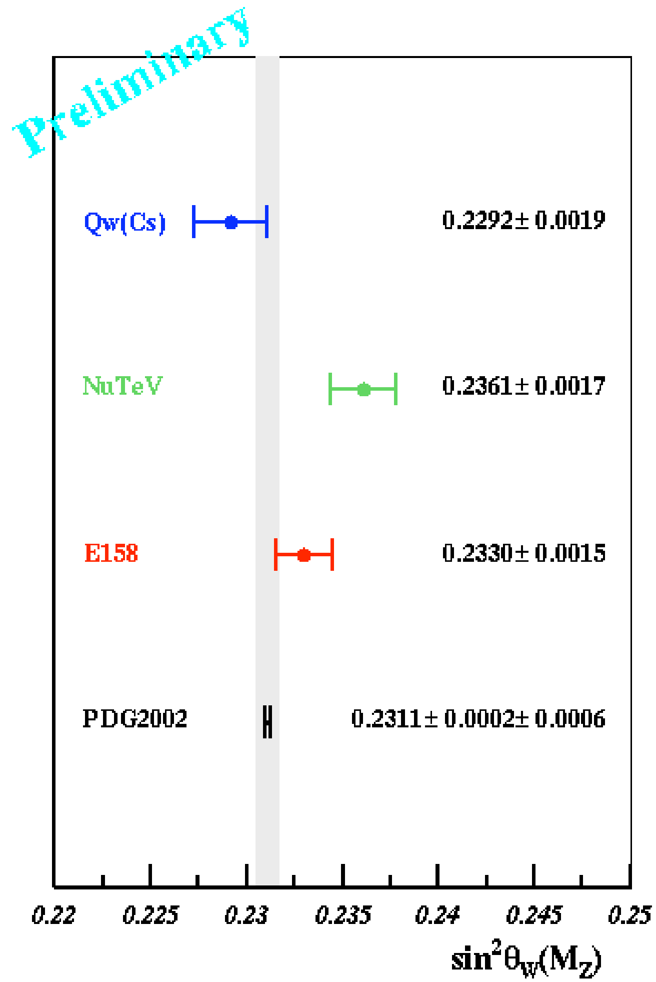
is an analyzing power factor; depends on kinematics and experimental geometry. Uncertainty is 1.7%. ($y = Q^2/s$)

$\boldsymbol{F_{brem}}$ = (1.016 ± 0.005) is a correction for ISR and FSR;
(but thick target ISR and FSR effects are included in the analyzing power calculation from a detailed MonteCarlo study)

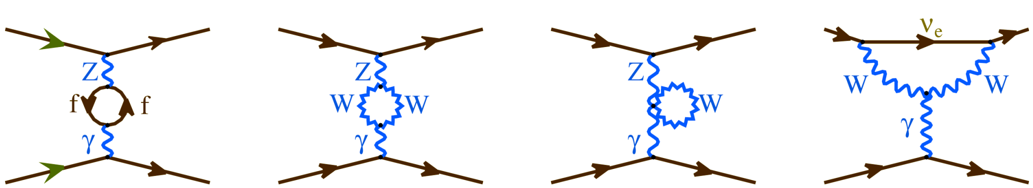
θ_W^{eff} is derived from an effective coupling constant, g_{ee}^{eff}, for the **Z**ee coupling, with loop and vertex electroweak corrections absorbed into g_{ee}^{eff}

Weak Mixing Angle Results





Q^2-dependence of θ_W



SUMMARY

Low Energy contributions to Precision Electroweak

SLAC E158 A_{PV} (e-e)

- Running of the weak mixing angle established (7σ)
- ***Probing TeV-scale physics***: 900 GeV limit on SO(10) Z' (95% CL)
  10 TeV limit on Λ_{LL}

Boulder APV (Cs)

- Previous 2.5σ discrepancy with SM prediction is reduced to below 1σ, with improved atomic wave function and nuclear structure calculations
- ***Probing TeV-scale physics***: 750 GeV limit on SO(10) Z' (1-sigma)

NuTeV R^- (νN)

- Currently 3σ discrepancy with SM prediction; investigations of "*Old Physics*" explanations continuing
- ***Probing TeV-scale physics***: "*designer*" Z'?
  (re. limits from Tevatron, E158, Cs APV)

BNL $(g-2)_\mu$

- **2.7σ discrepancy with SM prediction** – perhaps the biggest current challenge to SM! **SUSY could contribute at this level.**

OUTLOOK

Future Low Energy Experiments / Proposals

$(g\text{-}2)_\mu$ (0.5 ppm expt, 0.7 ppm theory is current precision)

BNL 969 proposal (0.2 ppm)
J-PARC LOI (0.1ppm)

Atomic Parity Violation (0.35% expt, 0.5% theory for Cs is current precision)

Paris Cs _ (0.1-1)%
U. Washington Ba^+, KVI Ra^+ _ sub-1%
Berkeley Yb isotopes _ sub-1%

ν-e scattering ($\delta\sin^2\theta_W$ = 0.008 is current precision)

Reactor experiment? $\delta\left(\sin^2\theta_W\right) \approx 0.0019$ (hep-ex/0403048)
Future ν Factory?? $\delta\left(\sin^2\theta_W\right) \approx 0.0003$ (Blondel talk at PAVI2004)

e scattering ($\delta\sin^2\theta_W$ = 0.0015 is current precision)

JLAB QWEAK A_{PV} (elastic e-p) $\delta\left(\sin^2\theta_W\right) \approx 0.0007$ (http://www.jlab.org/qweak/)
JLAB 12-GeV upgrade:
- **A_{PV} (DIS eD, ep) and test of isospin symmetry violation** $\delta\left(\sin^2\theta_W\right) \approx 0.0015$
- **A_{PV} (e-e)?** $\delta\left(\sin^2\theta_W\right) \approx 0.0005$

Fixed target at ILC?? A_{PV} (e-e) $\delta\left(\sin^2\theta_W\right) \approx 0.0001$ (Snowmass 2001 study)