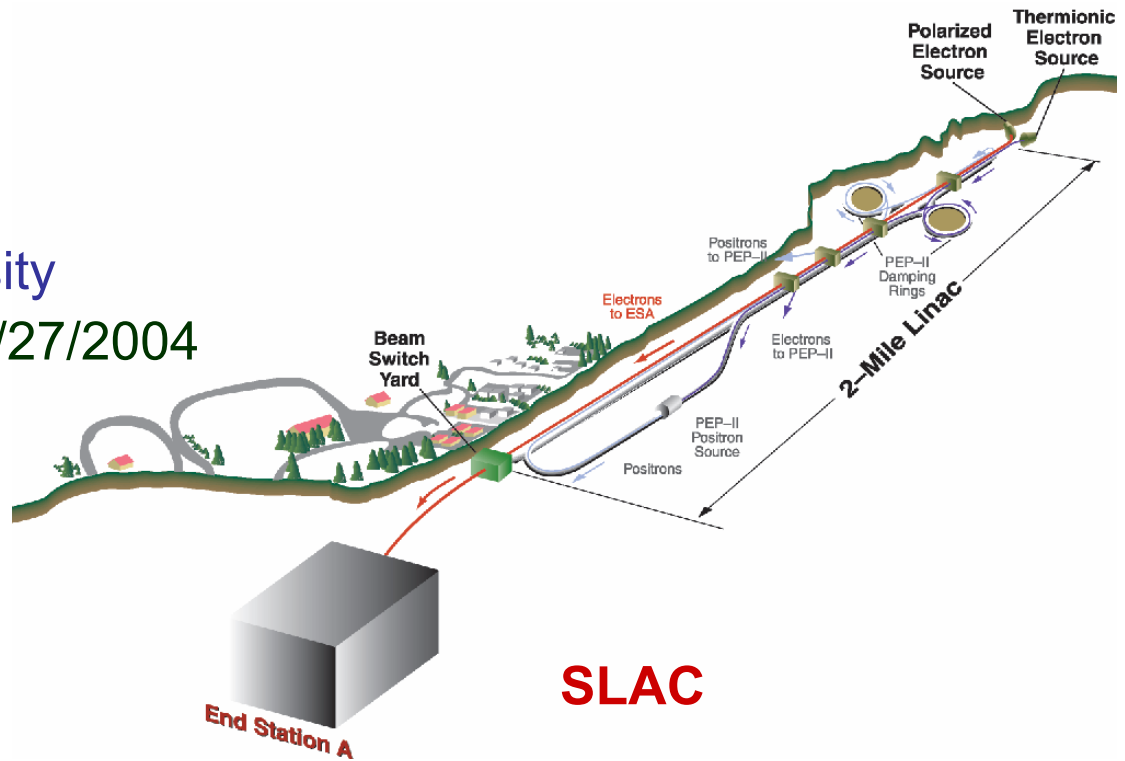


Precision Measurements of Parity Violation and the Weak Mixing Angle in Møller Scattering

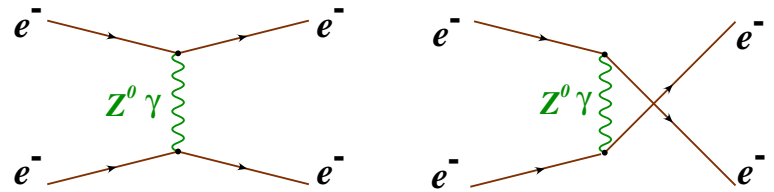
New results from SLAC E158

Waled Emam
Syracuse University
DFP Annual Meeting, 8/27/2004
UC Riverside



Parity Violation in Møller Scattering

- Scatter polarized 50 GeV electrons off unpolarized atomic electrons



- Measure

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -A_{LR} \sim \frac{A_{\text{weak}}}{A_{\gamma}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

- Small tree-level asymmetry

$$A_{PV}(e^-e^-) = -mE \frac{G_F}{\sqrt{2}\pi\alpha} \frac{16 \sin^2 \theta_{cm}}{(3 + \cos^2 \theta_{cm})^2} \left(\frac{1}{4} - \sin^2 \theta_W \right)$$

- At tree level,

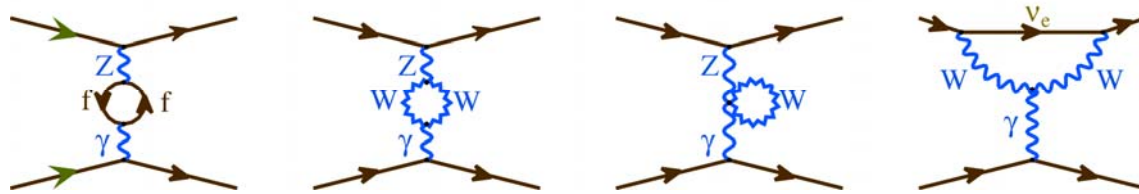
$$A_{PV}(Q^2 = 0.03) \approx 3.2 \times 10^{-7} \quad (320 \text{ ppb})$$

- Raw asymmetry about 130 ppb

- Measure it with precision of 10%
- Most precise measurement of $\text{Sin}^2\theta_W$ at low Q^2

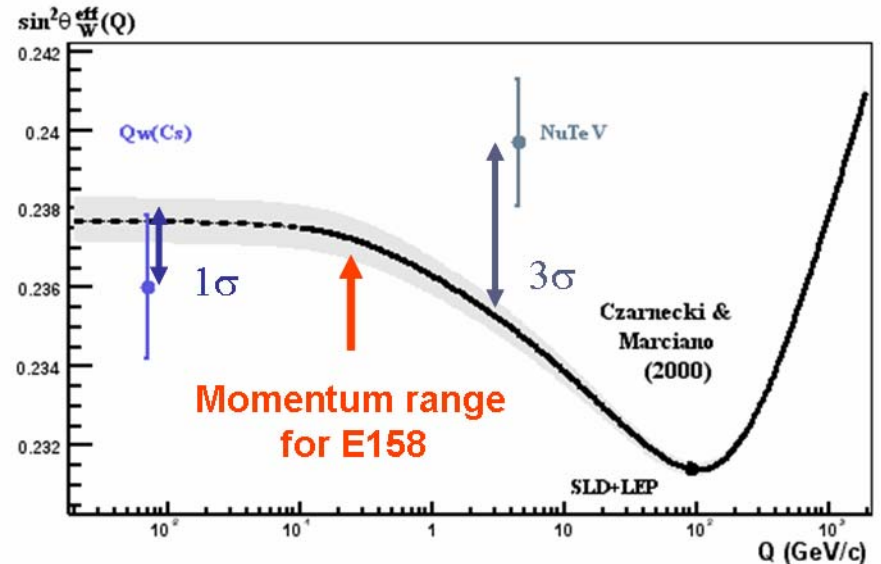
Running of $\sin^2 \theta_W$

- Largest effect comes from:
 - γ Z mixing & W-loop diagrams



- Other effects come from:
 - WW & ZZ box diagrams
 - Boxes with one γ & Z-loop diagrams

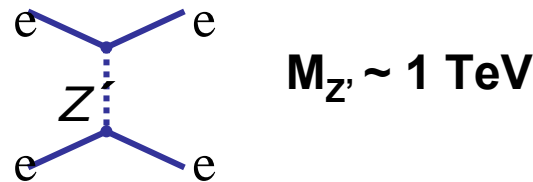
- A_{PV} at one-loop level goes down by $\Delta A_{PV} / A_{PV} \approx 40\%$



E158 and Physics Beyond SM

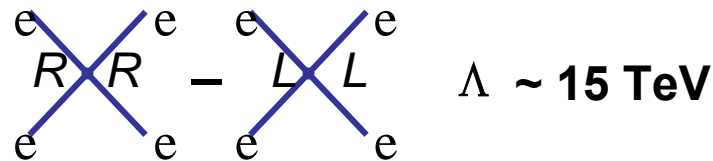
- Extra neutral gauge bosons:

- SO(10) model:



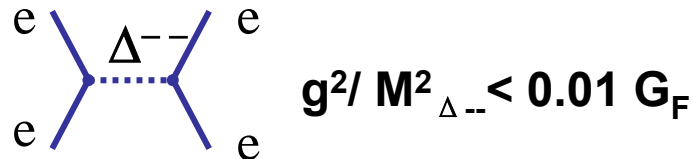
- Compositeness:

- four-electron contact interactions



- Doubly charged Higgs bosons:

- right-left-symmetric models



- Supersymmetry

- Together with a future measurement for $Q_W(p)$ from QWEAK experiment at the same energy could set limits on the MSSM model

E158 Collaboration

Institutions

Caltech

Princeton

SLAC

CEA Saclay

Smith College

Syracuse

Jefferson Lab

UC Berkeley

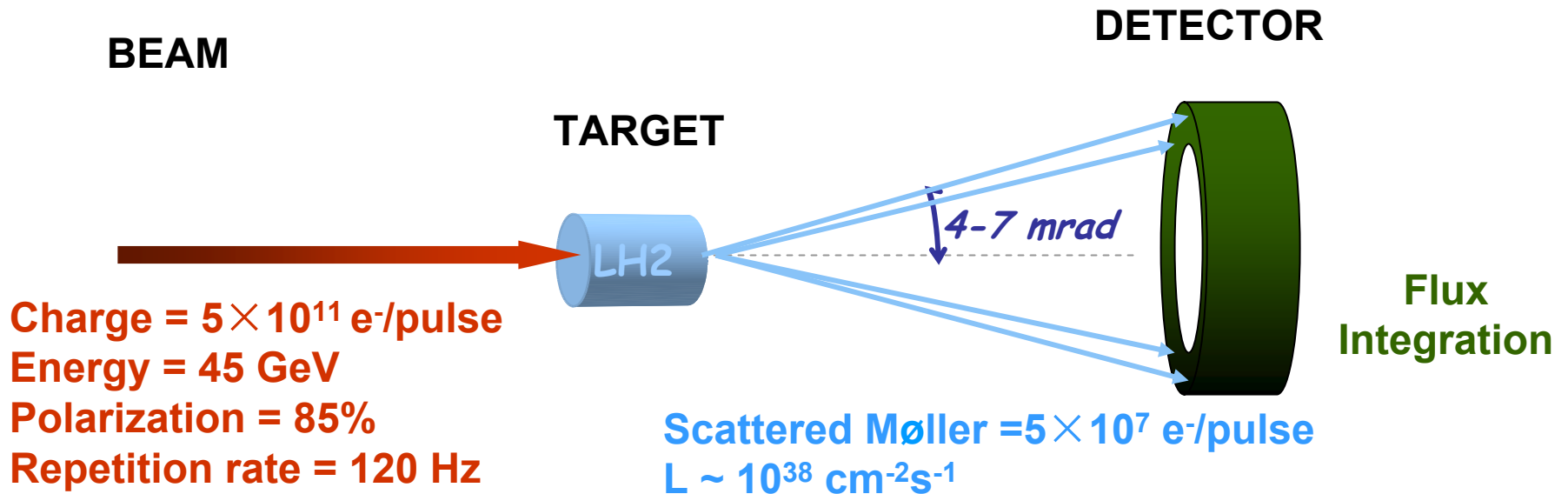
UMass Amherst

U. of Virginia

60 physicists, 7 Ph.D. students

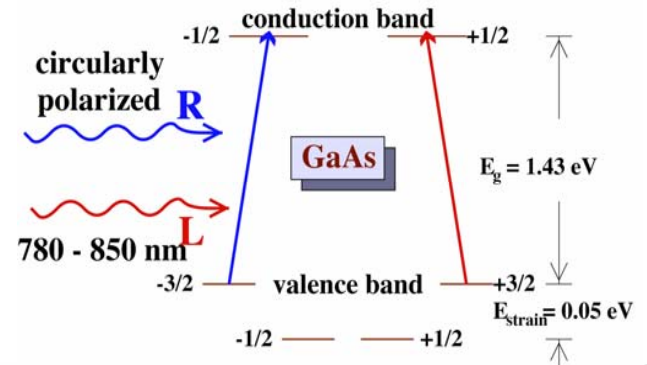
Sept 1997:	PAC approval
1998:	Polarized Beam Instrumentation R&D
1999:	Spectrometer and Detector Design
2000:	Construction Funds and Test Beams
2001:	Commissioning Run
Spring 2002:	Physics Run I
Fall 2002:	Physics Run II
Summer 2003:	Physics Run III (final statistics)

Experimental Technique

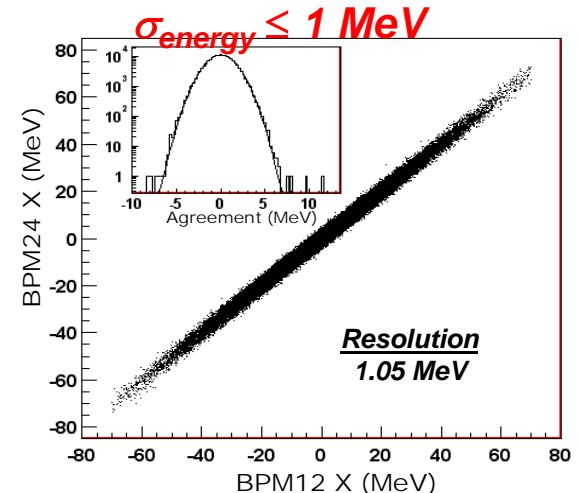
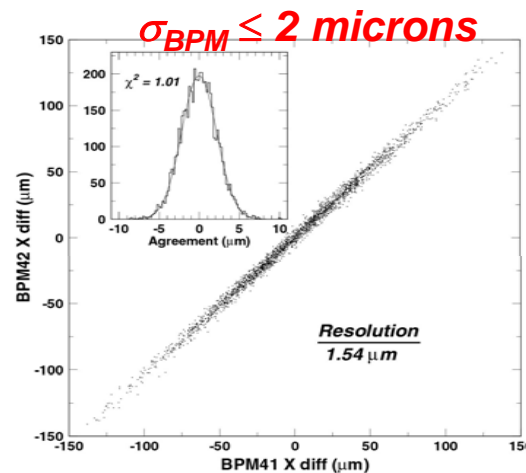
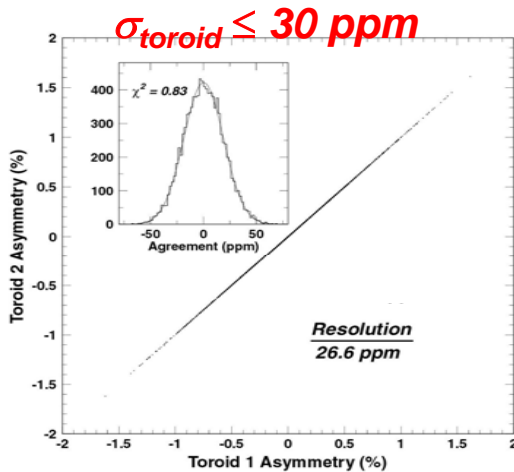
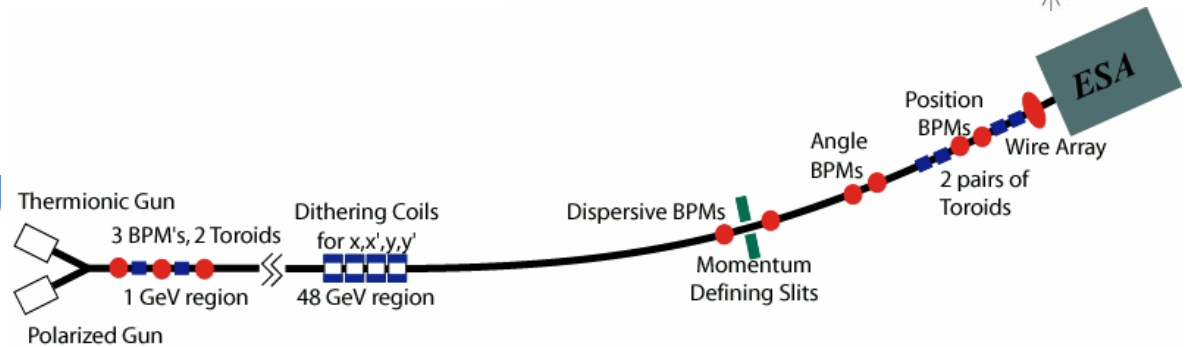


Polarized Electron Beam

- Photoemission from a Gallium Arsenide (GaAs) photocathode

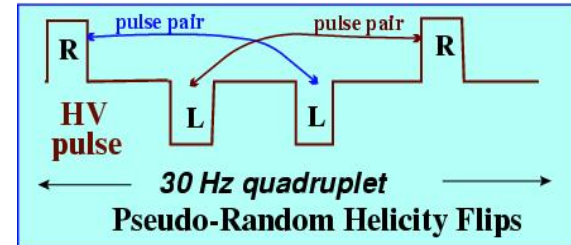


- Pulse to pulse Beam Monitoring



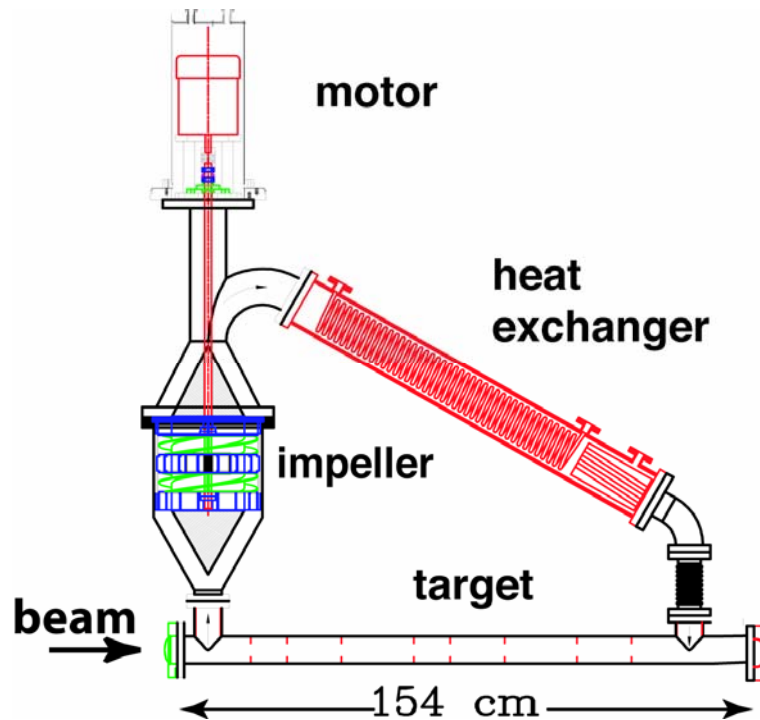
Beam Asymmetries Control

- **Beam helicity was chosen pseudo-randomly at 120 Hz**
 - use electro-optical Pockels cell in Polarized Light Source
 - sequence of pulse quadruplets



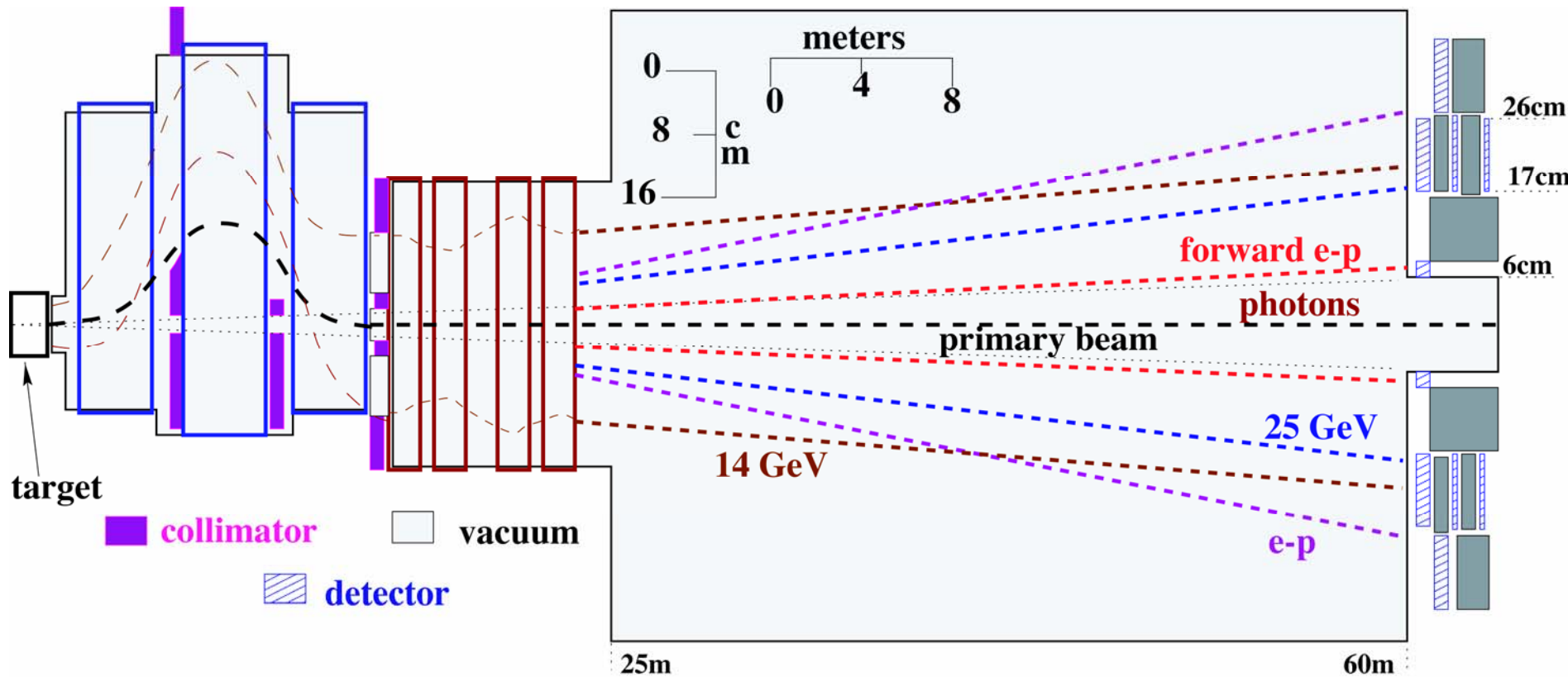
- **Reduce beam asymmetries by feedback at the Source**
 - Control charge asymmetry and position asymmetry
- **Physics Asymmetry Reversals:**
 - Insertable Half-Wave Plate in Polarized Light Source
 - (g-2) spin precession in A-line (45 GeV and 48 GeV)
- **“Null Asymmetry” Cross-check is provided by a Luminosity Monitor**
 - measure Møller and ep scatters at very forward angle

Liquid Hydrogen Target

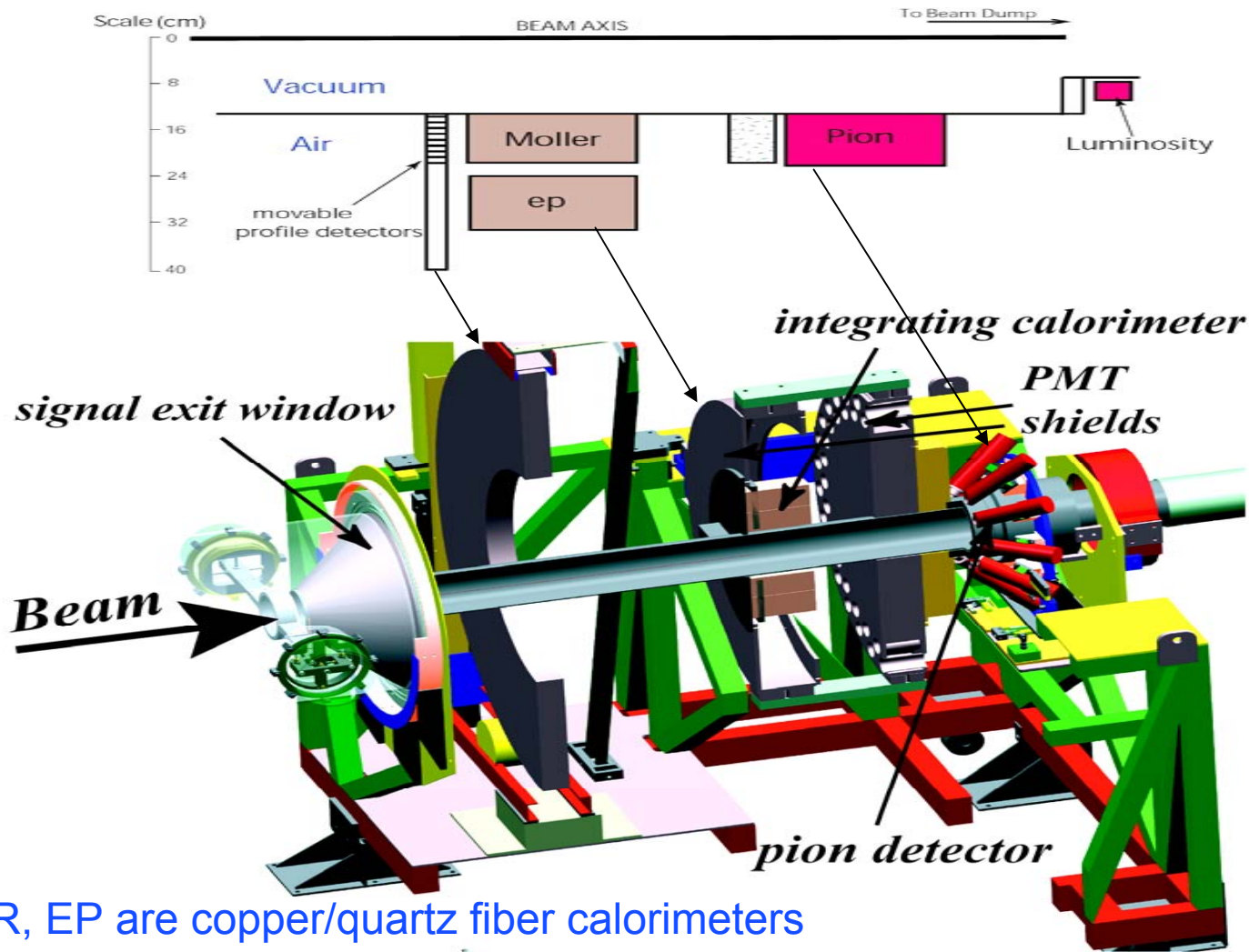


Refrigeration Capacity	1 kW
Operating Temperature	20 K
Length	1.5 m
Flow Rate	5 m/s
Vertical Motion	6 inches

Spectrometer

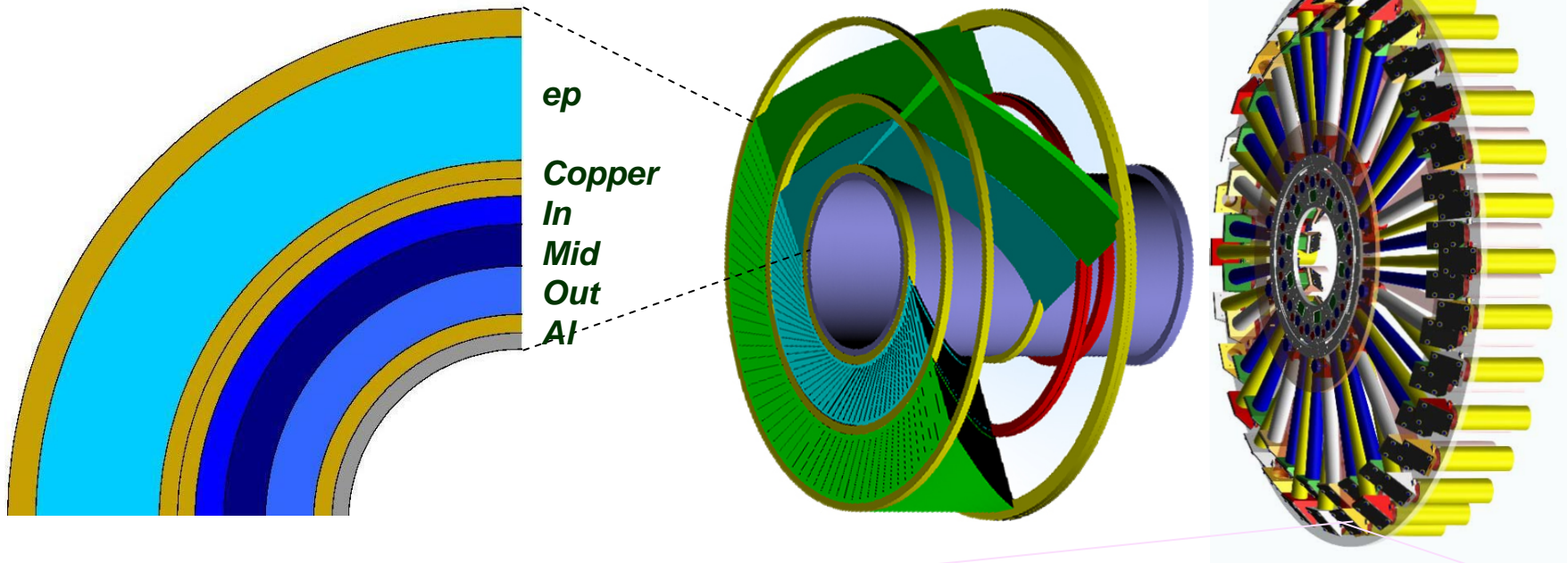


Detectors



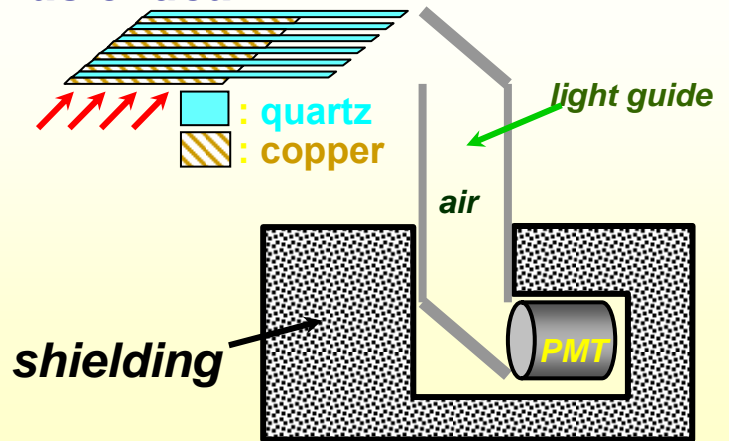
MOLLER, EP are copper/quartz fiber calorimeters
PION is a quartz bar Cherenkov
LUMI is an ion chamber with Al pre-radiator

MOLLER & EP Detectors

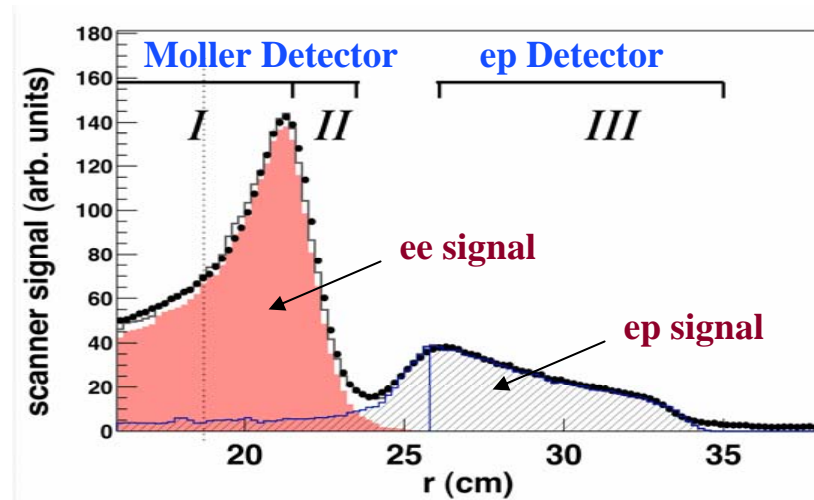
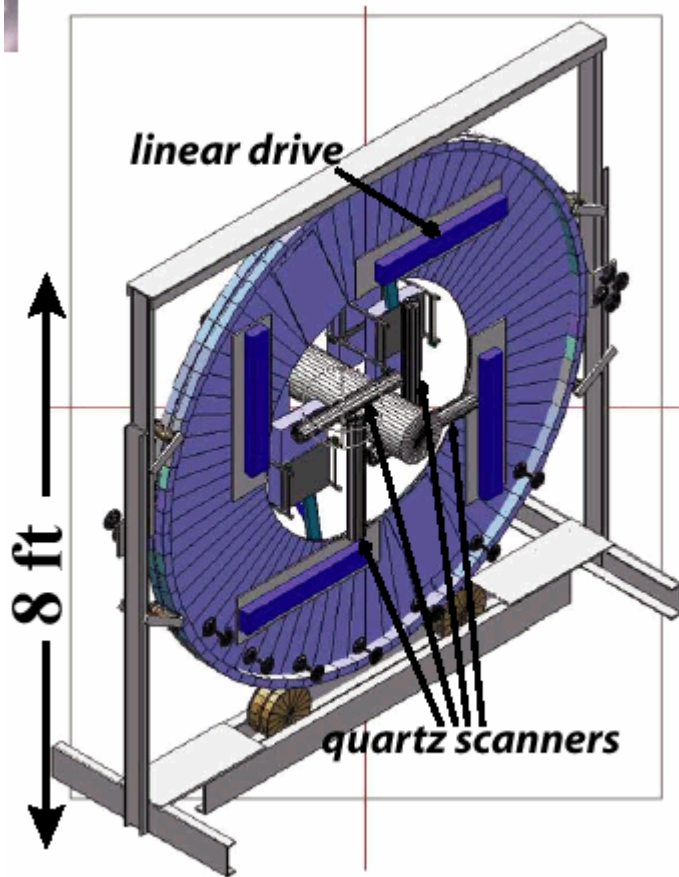


- Maximum response to ee & ep scatters
- Small response from pions & low-energy photons & hadrons
- No response from heavy ions.
- Excellent radiation resistance

Basic Idea:



Profile Detector



- 4 Quartz Cherenkov detectors with PMT readout
 - insertable pre-radiators
 - insertable shutter in front of PMTs
- Radial and azimuthal scans
 - collimator alignment, spectrometer tuning
 - background determination

Data Analysis

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

$$A_{\text{exp}}^p = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

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

$$A_{\text{raw}}^p = A_{\text{exp}}^p - \sum a_i \Delta x_i \quad \leftarrow \begin{array}{l} \text{charge, position, angle, energy} \\ \text{R-L differences} \end{array}$$

coefficients determined experimentally
by regression or from dithering coefficients

3. Sum over all pulse pairs,

$$A_{\text{raw}} = \sum A_{\text{raw}}^p$$

4. Obtain physics asymmetry:

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

← beam polarization, linearity

← background dilutions

← backgrounds

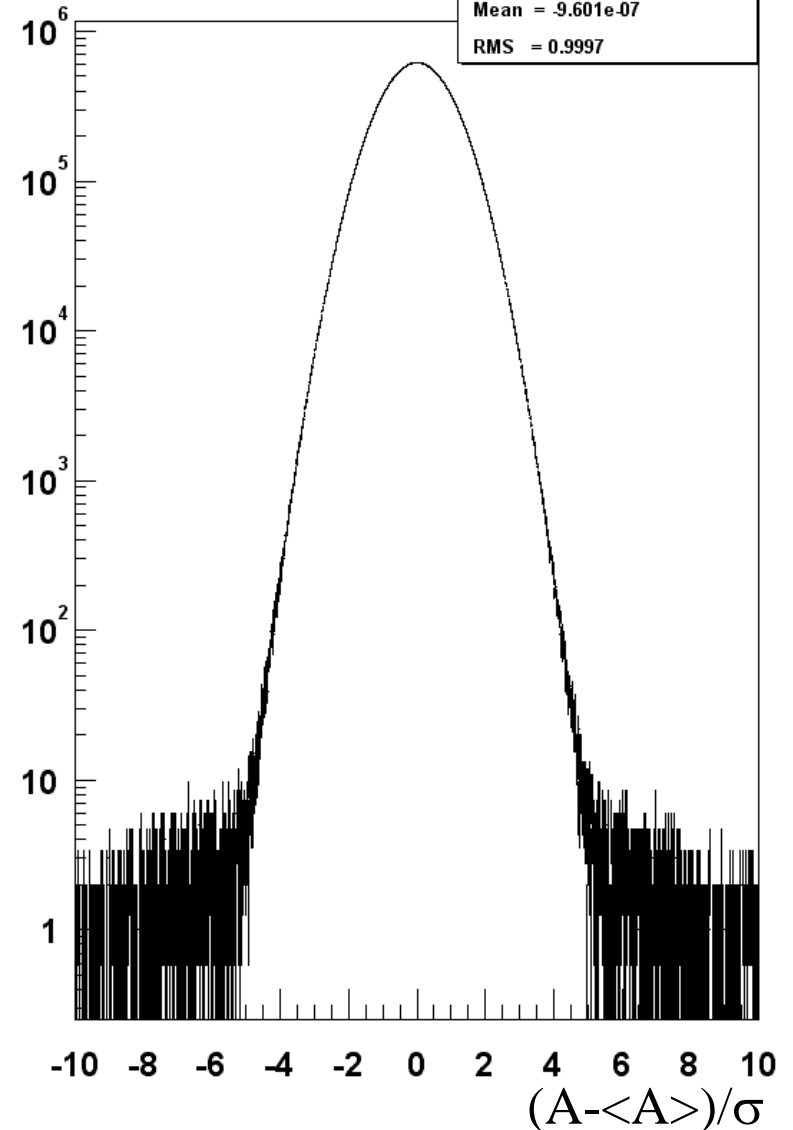
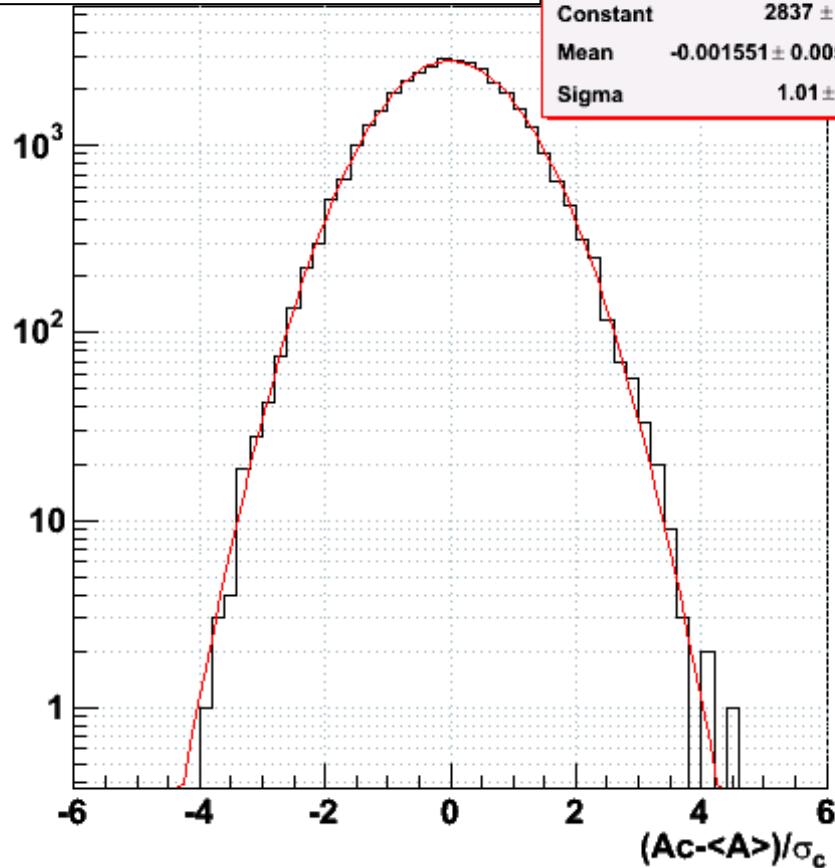
MOLLER Statistics and Fluctuations

Asymmetry pulls per pulse pair:

150M pairs

Asymmetry pulls
per 10k pair “chunks”

χ^2 / ndf	49.08 / 38
Prob	0.1074
Constant	2837 ± 18.4
Mean	-0.001551 ± 0.005334
Sigma	1.01 ± 0.00



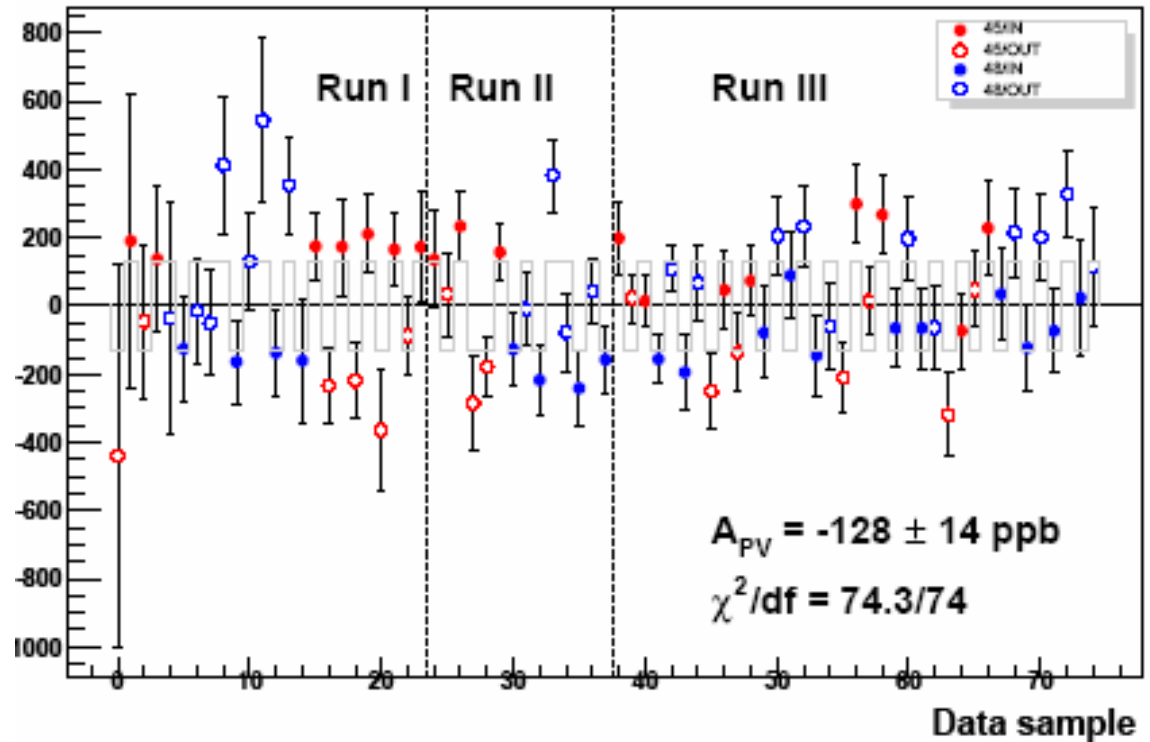
Asymmetry Corrections and Systematics

Corrections and Dilutions		
Source	f_{bkg}	A_{corr} (ppb)
Beam asymmetries	-	$- \pm 4$
Beam spotsize	-	0 ± 1
Transverse polarization	-	-4 ± 2
ep elastic	0.058 ± 0.007	-8 ± 2
ep inelastic	0.009 ± 0.003	-22 ± 6
High energy photons	0.004 ± 0.002	$+3 \pm 3$
Synchrotron photons	0.0015 ± 0.0005	0 ± 2
Neutrons	0.0006 ± 0.0002	-1 ± 1
Pions	0.001 ± 0.001	1 ± 1
TOTAL	0.082 ± 0.009	-27 ± 8
Normalizations		
Polarization	0.88 ± 0.05	
Linearity	0.99 ± 0.01	

A_{PV} Preliminary

Official Run I result :
PRL : *Phys. Rev. Lett.* **92**,
181602 (2004)

First observation of
parity violation in Møller
scattering



$$A_{PV}(e^-e^- \text{ at } Q^2=0.026 \text{ GeV}^2) = -128 \pm 14 \text{ (stat)} \pm 12 \text{ (syst)}$$

→ Significance of parity non-conservation in Møller scattering: 8σ

$\sin^2\theta_W$ Preliminary

$$\sin^2\theta_{\text{eff}}(Q^2=0.026 \text{ GeV}^2) = 0.2403 \pm 0.0010 \text{ (stat)} \pm 0.0009 \text{ (syst)}$$

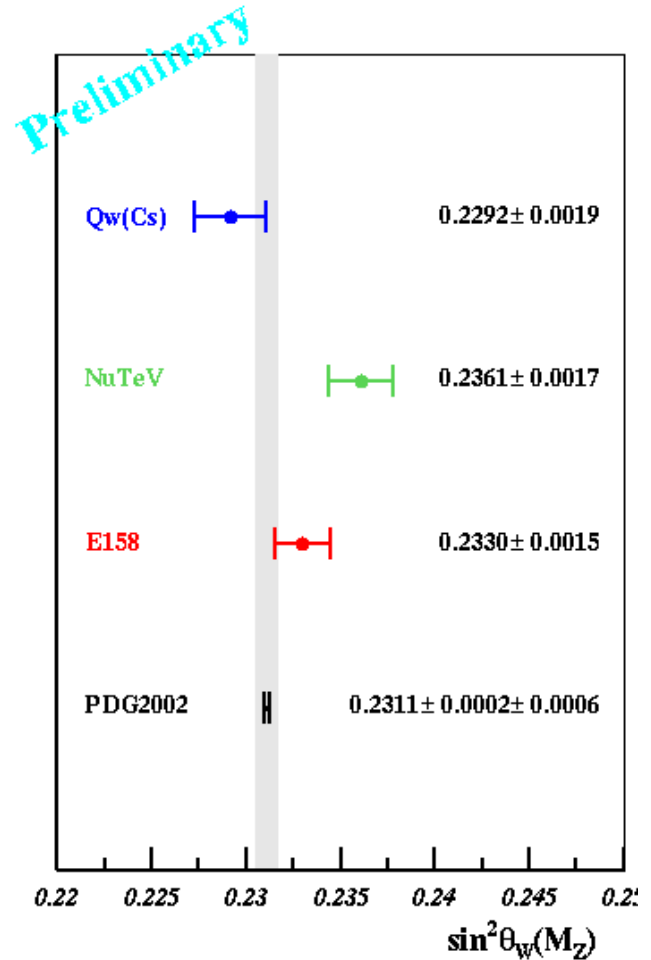
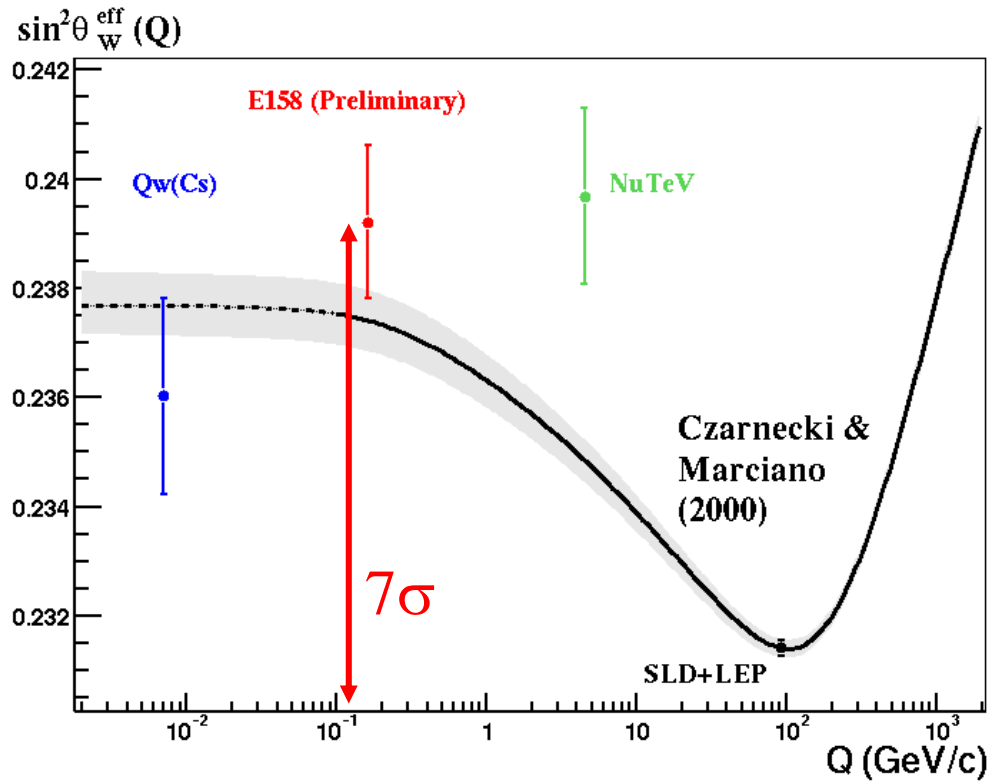
→ *Most precise measurement at low Q^2*

→ *Significance of running of $\sin^2\theta_W$: 7σ*

$$\sin^2\theta_W^{\text{MS}}(M_Z) = 0.2330 \pm 0.0011 \text{ (stat)} \pm 0.0010 \text{ (syst)}$$

→ *Standard Model pull: $+1.2 \sigma$*

World Measurements of $\sin^2\theta_W$



New Physics

- Parity is violated in Møller scattering
- Limit on 4-fermion contact term Λ_{LL} : 6-14 TeV at 95% C.L.
- Limits on extra Zs at the level of 900 GeV

Summary

- *first observation of parity violation in Møller scattering (8σ)*
- *running of the weak mixing angle established (7σ)*
- *Probing TeV-scale physics:*
 - *$\sim 6\text{-}14$ TeV limit on Λ_{LL}*
 - *~ 900 GeV limit on $SO(10)$ Z'*

Preliminary Results using all data

$$\mathbf{A_{PV}(Møller) = (-128 \pm 14 \pm 12) ppb}$$

$$\mathbf{\sin^2 \theta_W^{MS}(M_Z) = 0.2330 \pm 0.0011 (stat) \pm 0.0010 (syst)}$$

Best measurement of the weak mixing angle
away from the Z-pole!

SLD

- SLD Collaboration studied parity-violation in Z production and decay into charge lepton pairs:

$$e_{L,R}^- + e^+ \rightarrow Z^0 \rightarrow l^- + l^+$$
$$l = e, \mu, \tau$$

- They measured three asymmetries:

$$A_l = \frac{2(1-4\sin^2 \theta_W^{eff})}{1+(1-4\sin^2 \theta_W^{eff})^2}$$

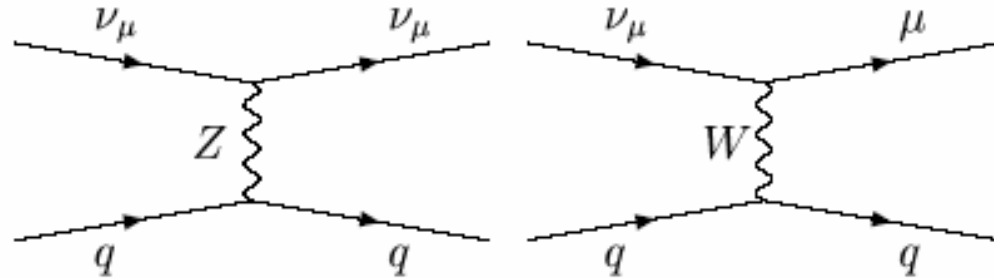
Asymmetries were expected to be Identical (Lepton Universality)

- Excellent agreement with the SM:

$$\sin^2 \theta_W^{eff} = 0.23098 \pm 0.00026$$

NuTeV

- NuTeV Collaboration studied Neutral Current & Charged Current neutrino-nucleon deep inelastic scattering:



NC coupling $\sim T_3 - Q \sin^2\theta_W$ CC coupling $\sim T_3$

- Extract $\sin^2\theta_W$ from the ratio NC/CC:

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

$$\text{or } \sin^2\theta_W^{(M_Z)_{\overline{MS}}} = 0.2361 \pm 0.0017 \text{ (+3}\sigma \text{ SM pull)}$$

APV

- APV measured $6S \rightarrow 7S$ in Cs
- $\text{Sin}^2\theta_W$ was extracted from the “weak charge” of the nucleus:

$$Q_W = \rho [Z(1-4\text{Sin}^2\theta_W)N]$$

- SM Prediction: $Q_W(^{133}\text{Cs}) = -73.19 \pm 0.03$
- Experiment: $Q_W(^{133}\text{Cs}) = -72.69 \pm 0.48$

- Excellent agreement with the SM:

$$\text{Sin}^2\theta_W^{(M_Z)_{\overline{MS}}} = 0.2292 \pm 0.0019 \text{ (-1}\sigma \text{ SM pull)}$$

Physics Runs

Run 1: Apr 23 12:00 – May 28 00:00, 2002

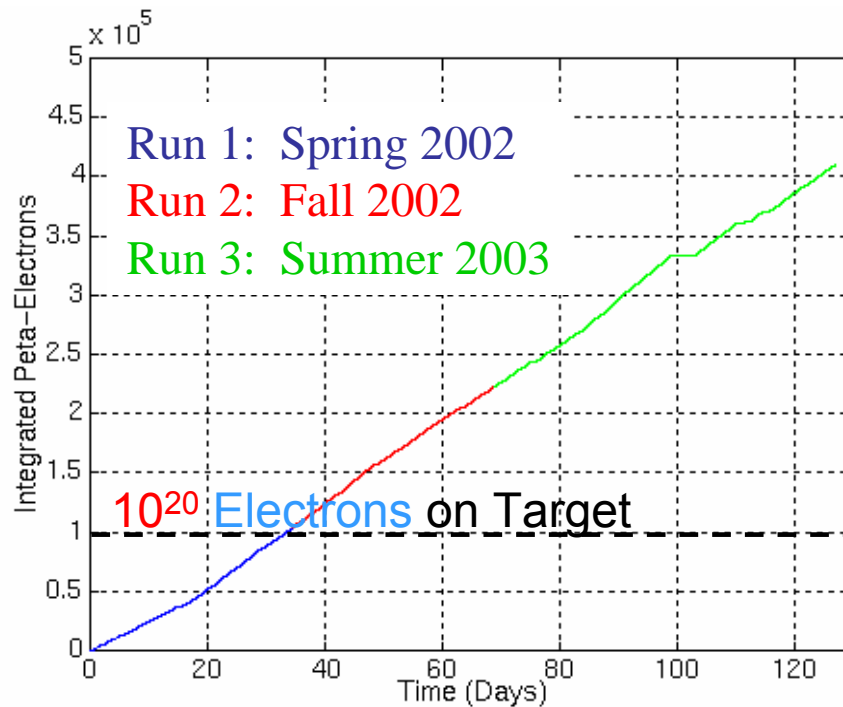
Run 2: Oct 10 08:00 – Nov 13 16:00, 2002

Run 3: July 10 08:00 - Sep 10 08:00, 2003

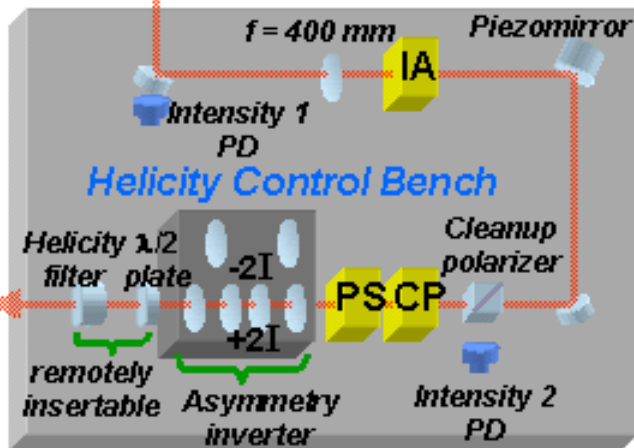
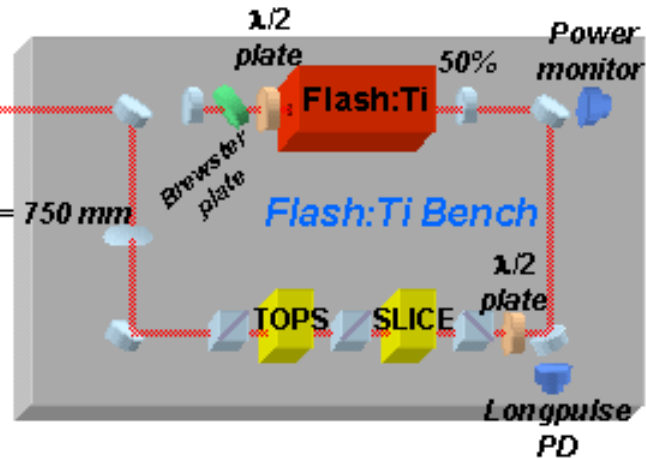
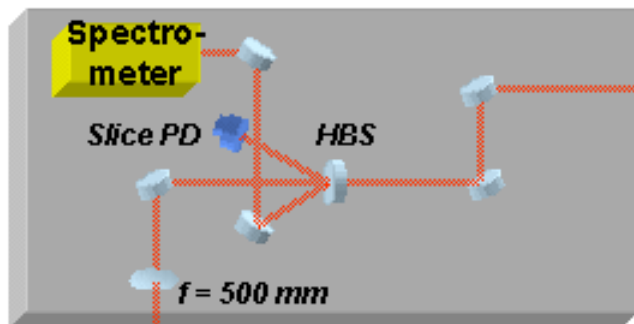
• *One g-2 flip in each run*

• *$\lambda/2$ flip roughly once in two days*

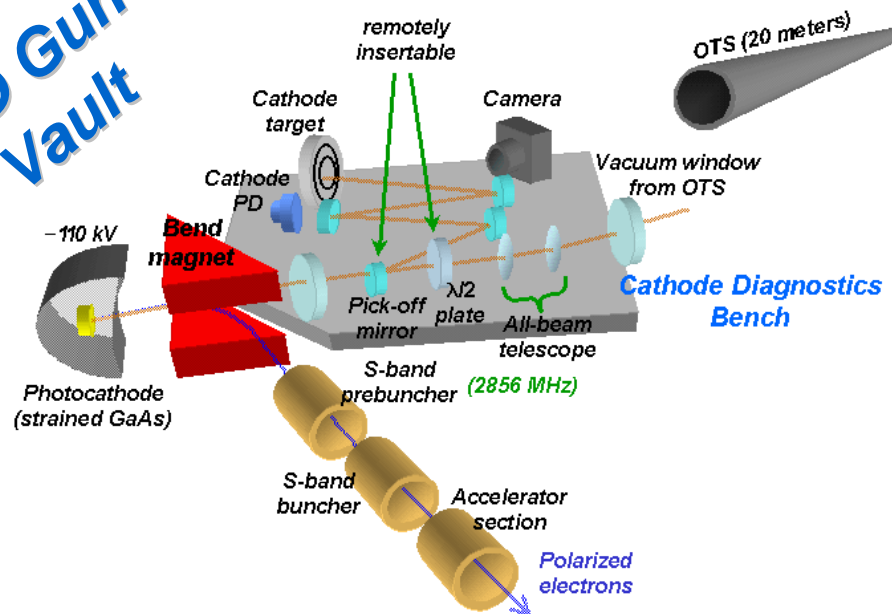
• *Data was divided into 73 “slugs”*



Polarized Electron Beam

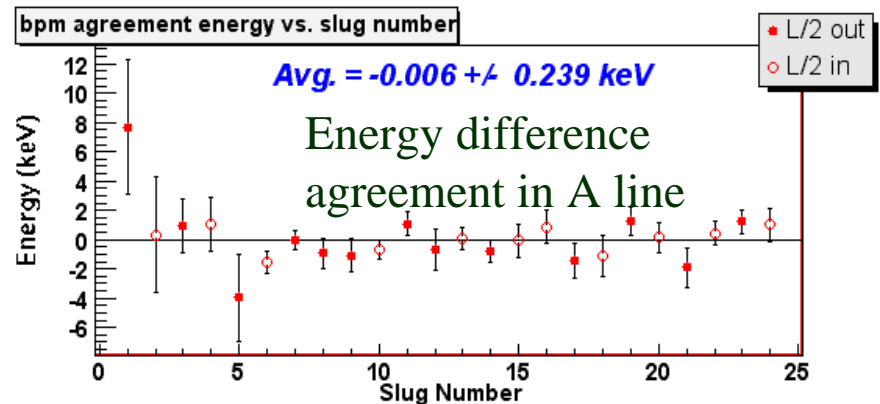
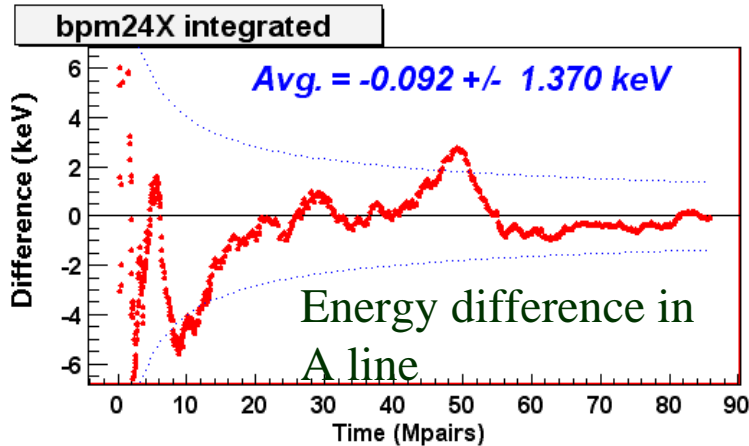
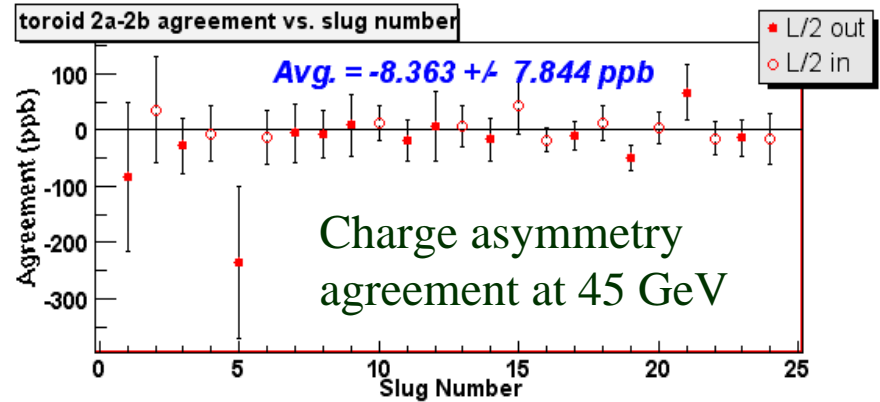
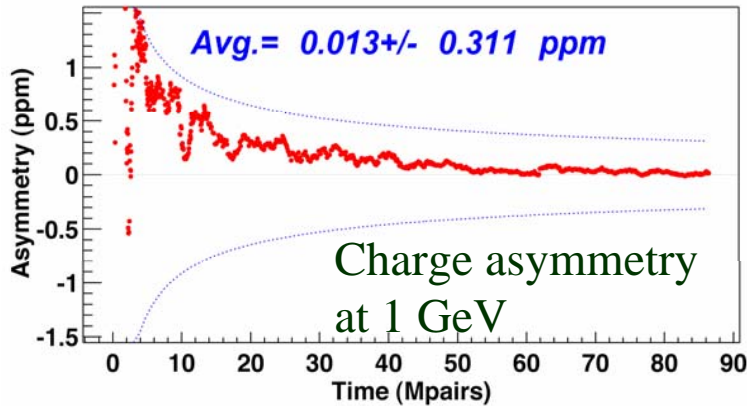


CID Gun Vault



OTS to Gun Vault

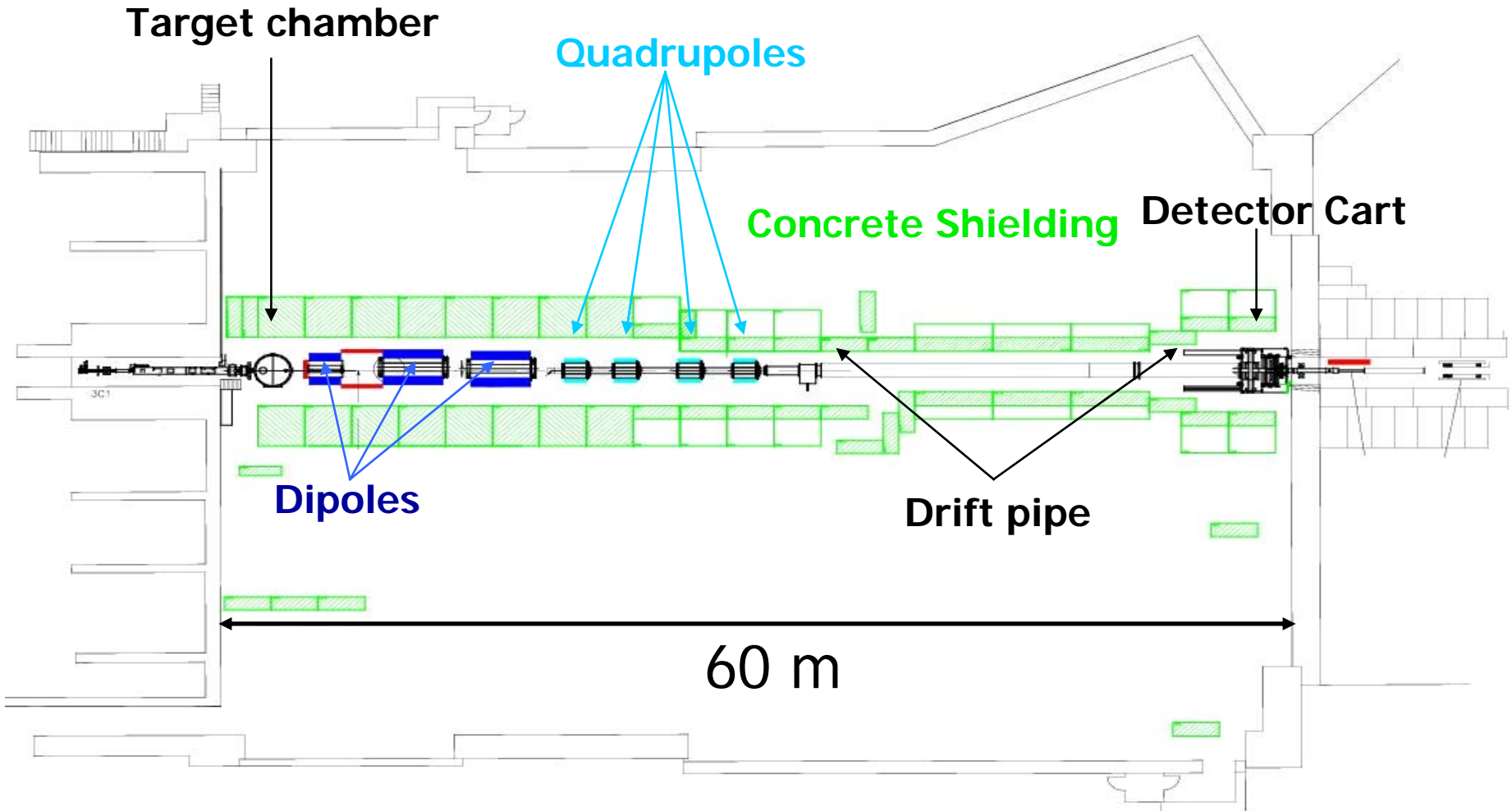
Feedback Performance



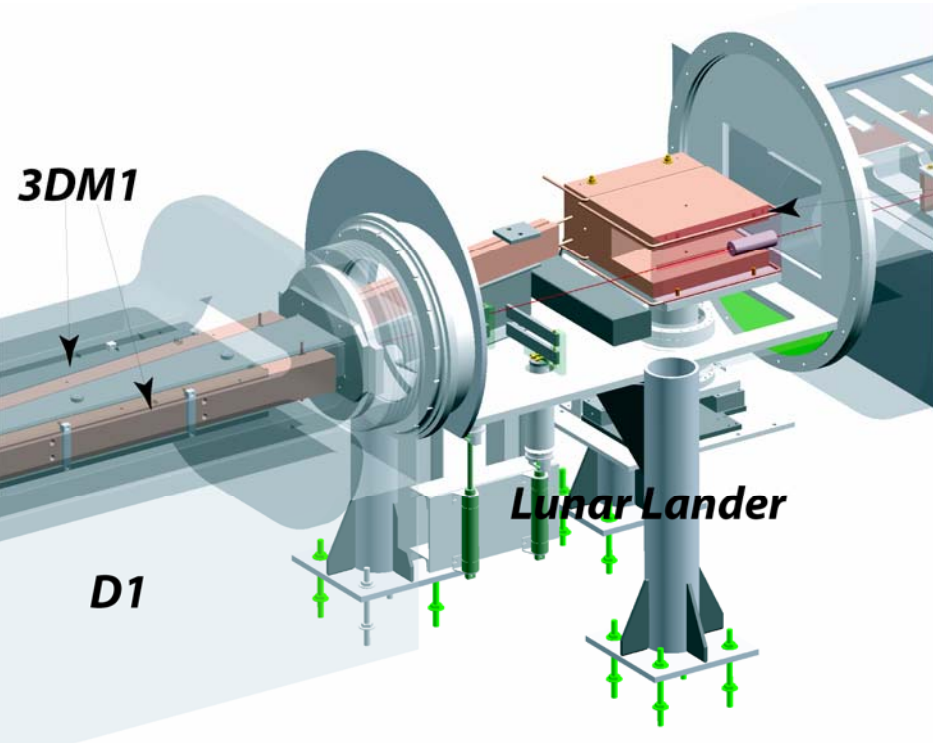
Position differences < 20 nm

Position agreement ~ 1 nm

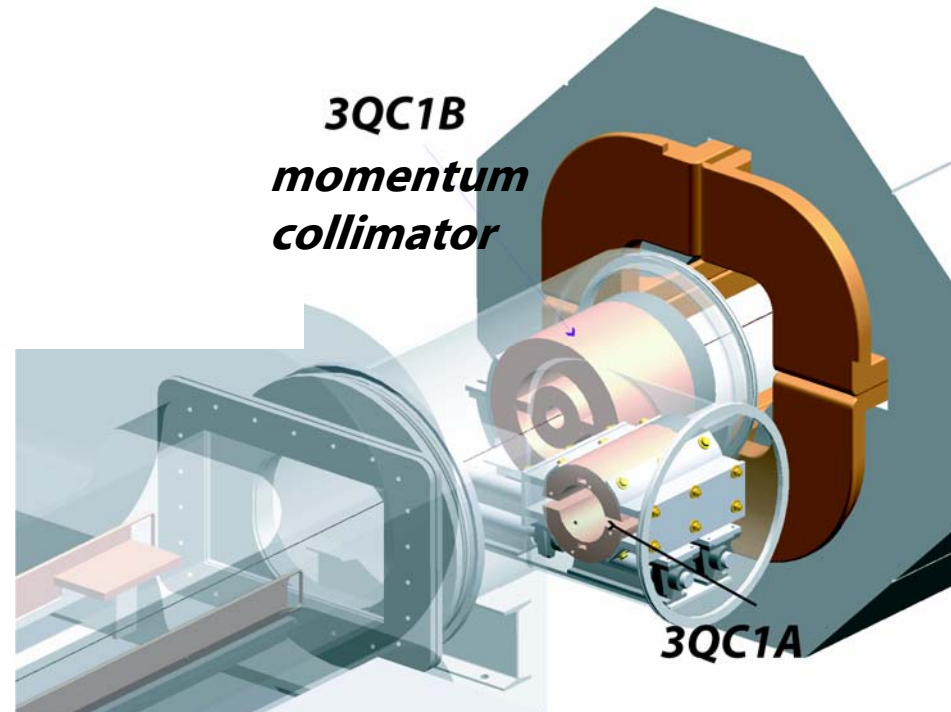
End Station A Setup



Collimators



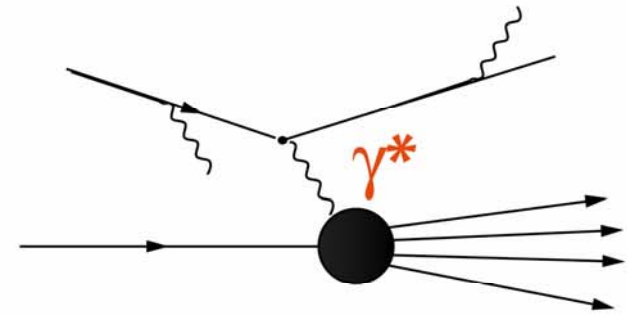
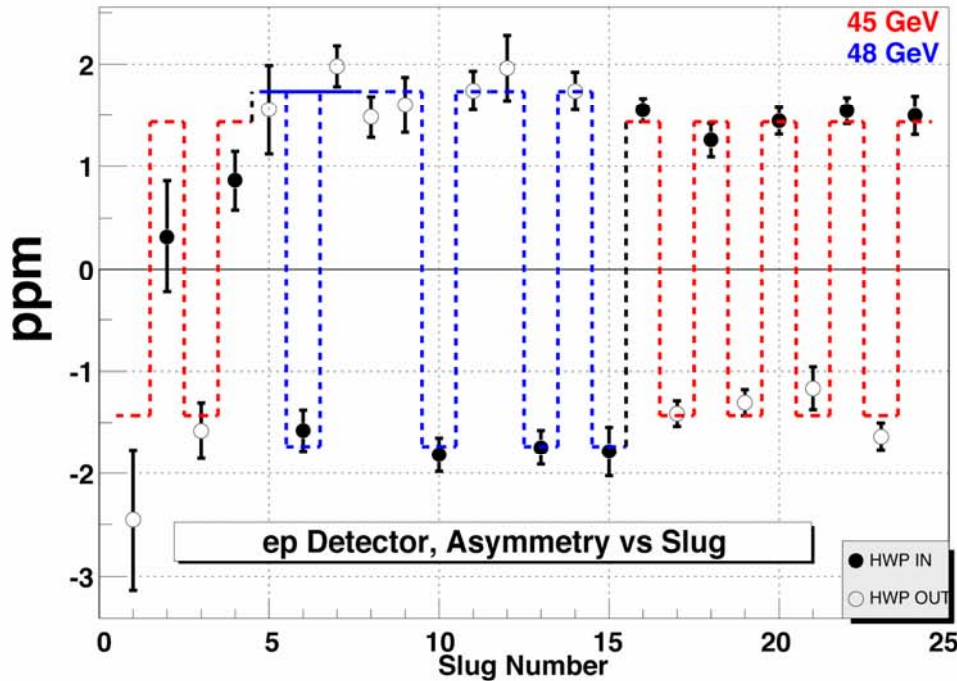
**3DC2C
photon
collimator
(soft shadow)**



**3QC1B
momentum
collimator**

3QC1A

"ep" Detector Data



inelastic scattering

At low Q^2 : $A_{LR} \sim 10^{-4} * Q^2$

elastic scattering

At low Q^2 : $A_{LR} \sim 10^{-5} * Q^2$

in the ep detector:

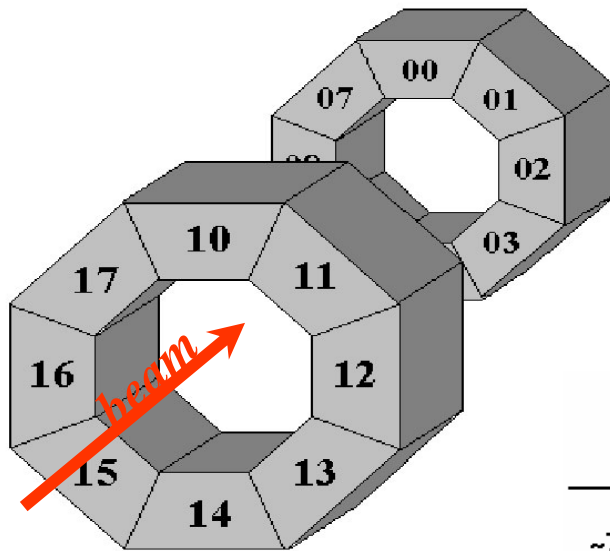
$Q^2 \sim 0.06 \text{ GeV}^2$:

$A_{\text{Raw}} \sim 0.4 \pm 0.2 \text{ ppm}$

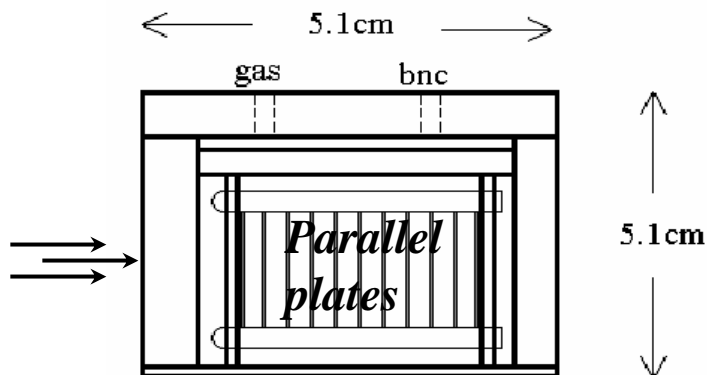
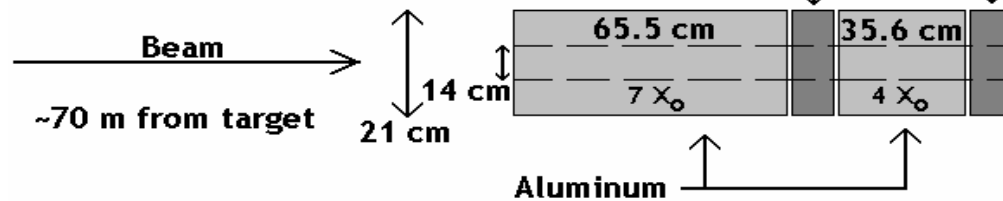
- radiative tail dominated by elastic scattering: $\sim 8\%$ under Moller peak
- additional 1% contribution from inelastic scattering
- 35 ppb \pm 10 ppb
- reduced by 40% in run II & III

Luminosity Monitor

more than 10^8 scattered electrons per spill at $\theta_{lab} \sim 1$ mrad

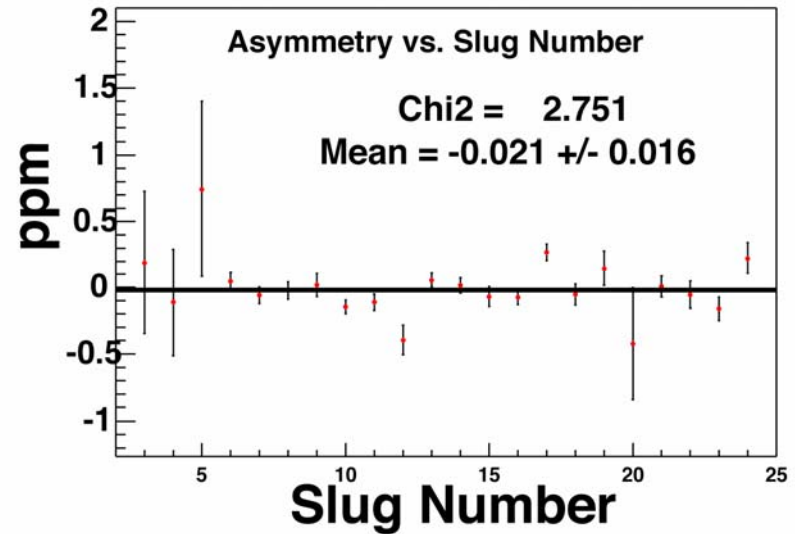


- Null asymmetry test
- Density fluctuations monitor
- Enhanced sensitivity to beam fluctuations

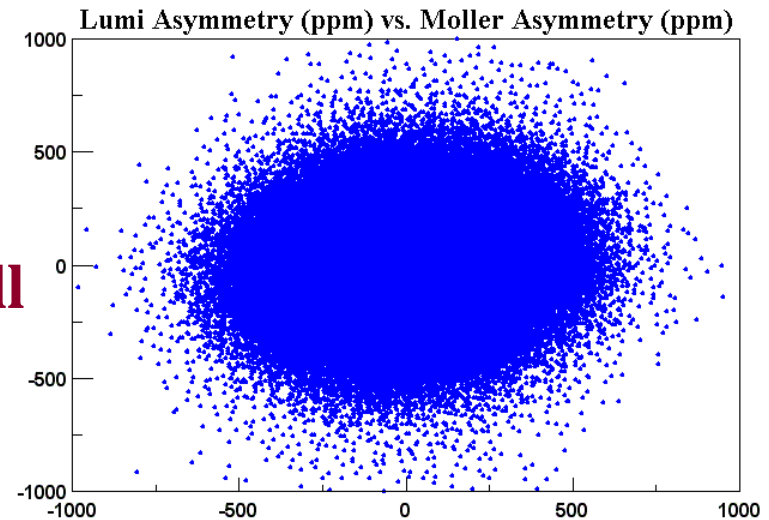


Luminosity Monitor Data

- Null test at level of 20 ppb

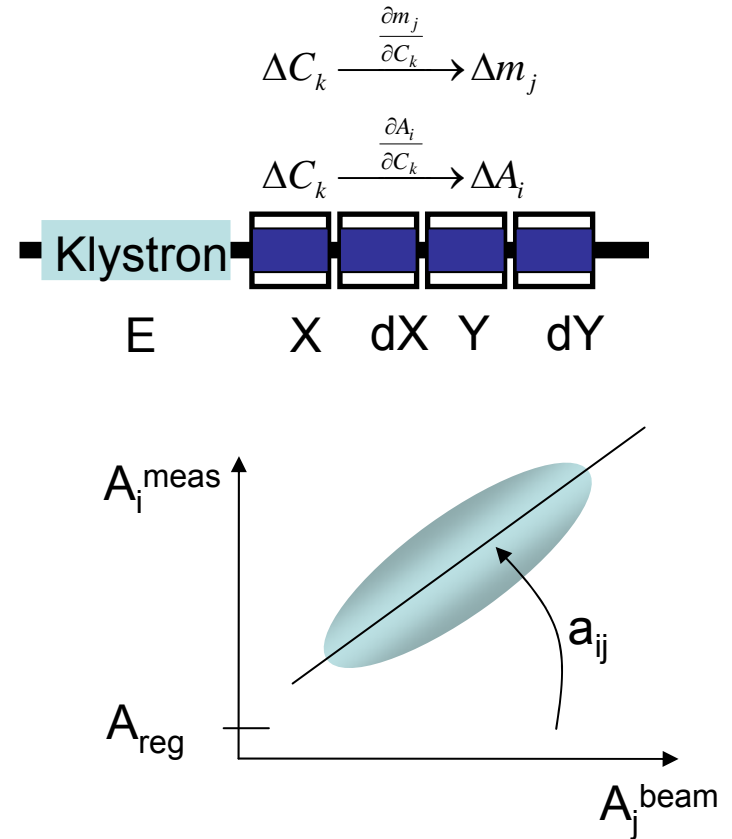


- Target density fluctuations small

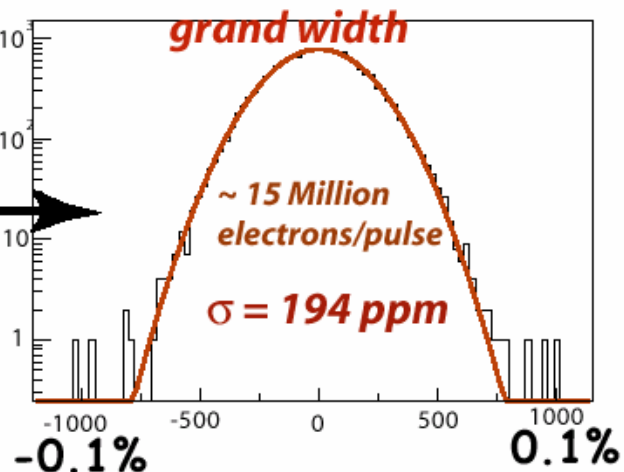
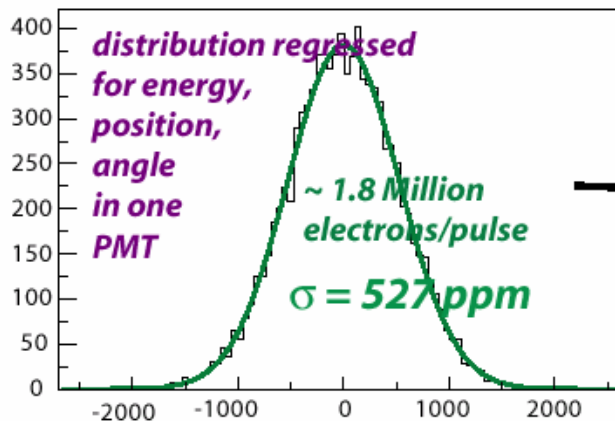
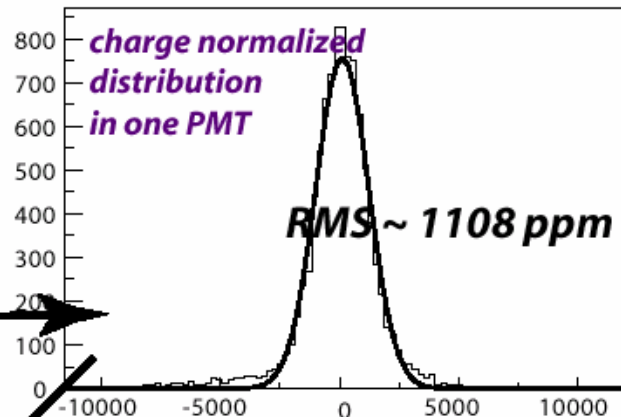
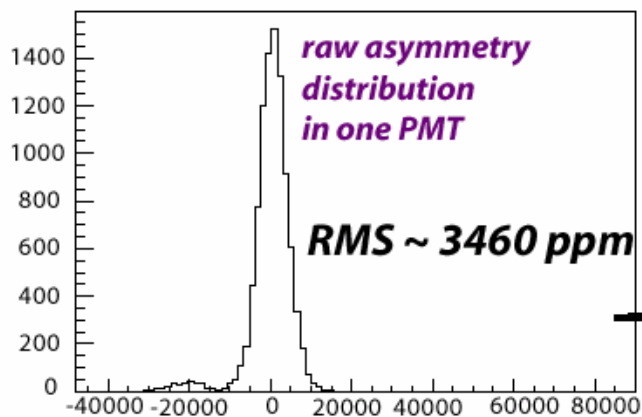


Beam Corrections

- Two Complementary methods to correct for the beam noise:
 - DITHERING
 - REGRESSION
- Two main steps:
 - Determine the dependence of the detector integrated flux to the beam parameters variables
 - Correct the detector asymmetry



MOLLER Statistics and Fluctuations



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

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

where:

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

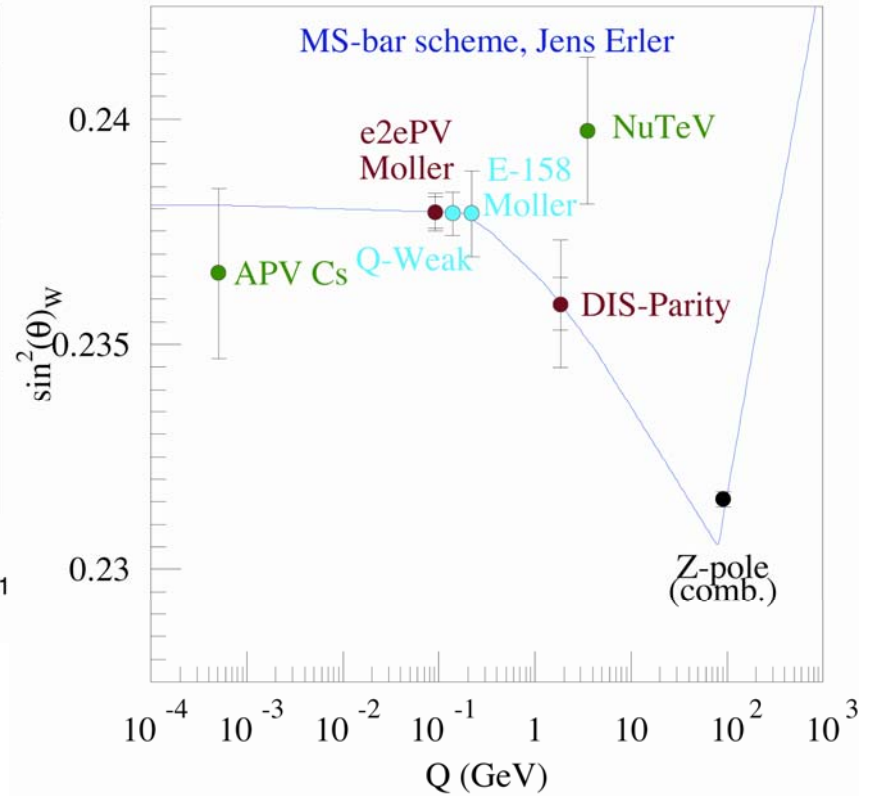
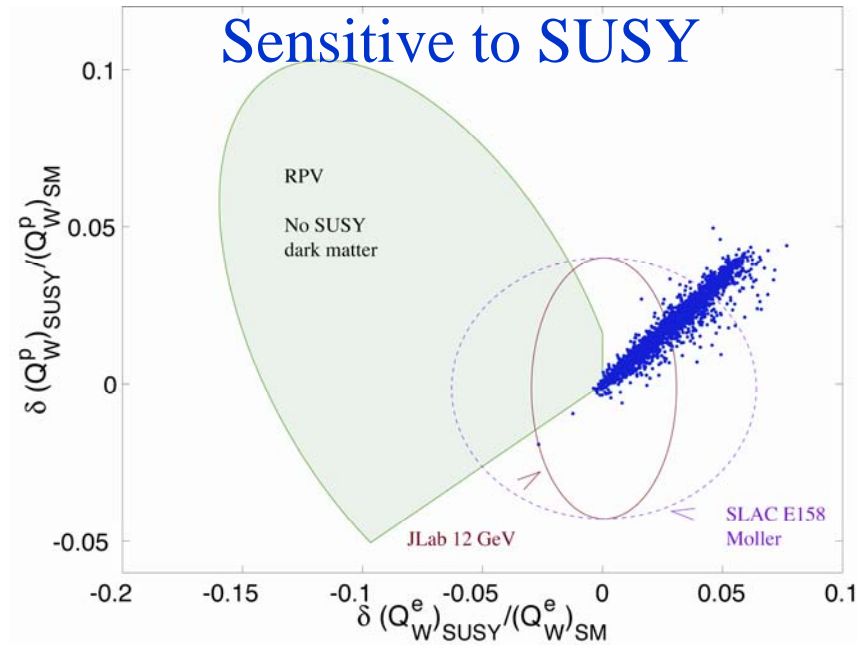
Analyzing Power factor; depends on kinematics and experimental geometry. Uncertainty is 1.7%. ($y = Q^2/s \sim 0.57$)

$F_{brem} = (1.016 \pm 0.005)$ 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}

E158 and Sensitivity to SUSY



New experiments at JLab:

- DIS-Parity
- e2ePV Moller
- Q-Weak