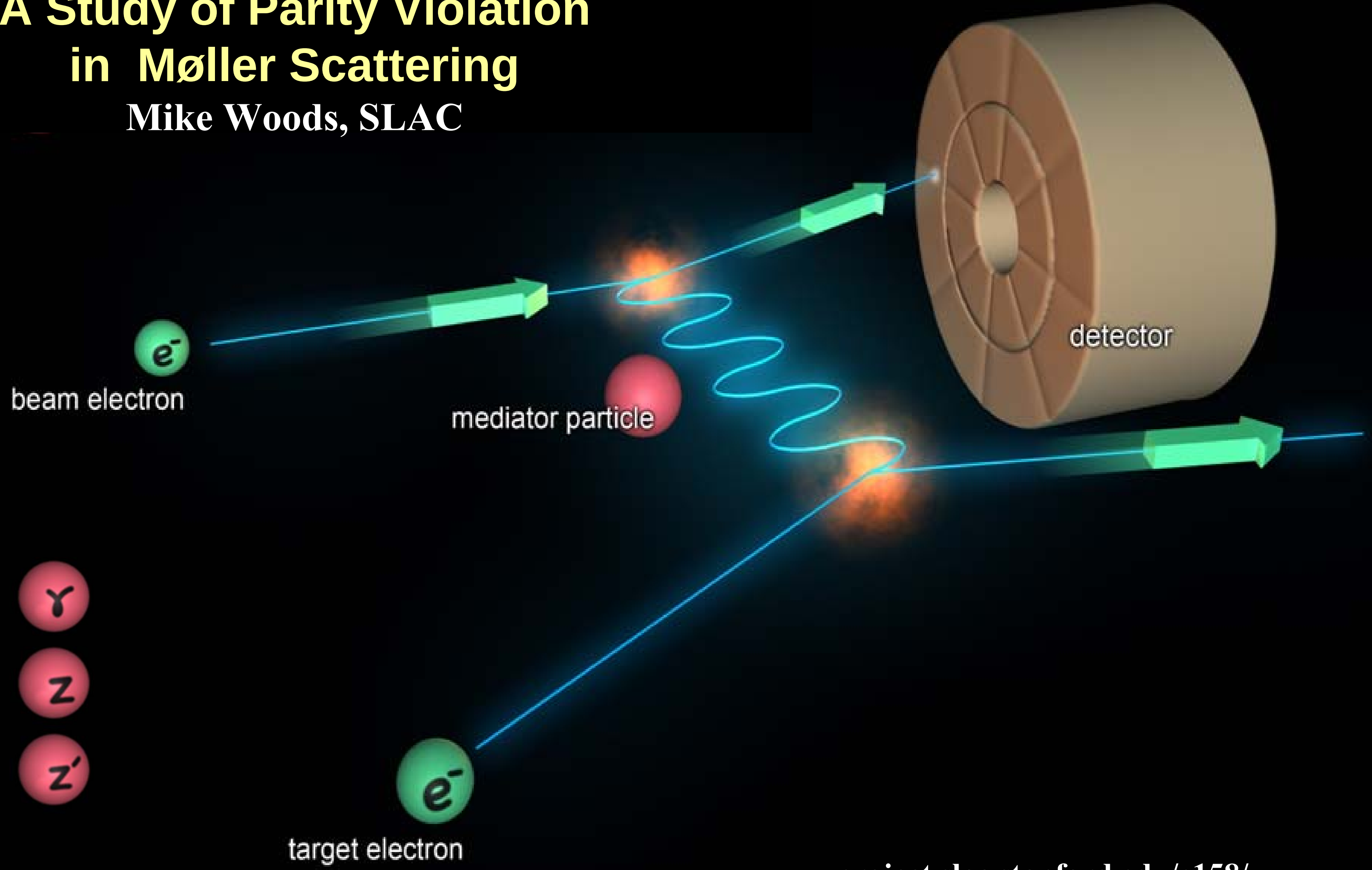
SLAC E-158

A Study of Parity Violation in Møller Scattering

Mike Woods, SLAC



www-project.slac.stanford.edu/e158/

Outline

- Physics Motivation
- E158 Beam and Beam Monitors
- LH_2Target and Spectrometer
- Detectors
- Analysis
- Results & Outlook

Beyond the Standard Model

Energy Frontier

- Tevatron
- LHC
- (Linear Collider)

Symmetry Violations

Rare or Forbidden Processes

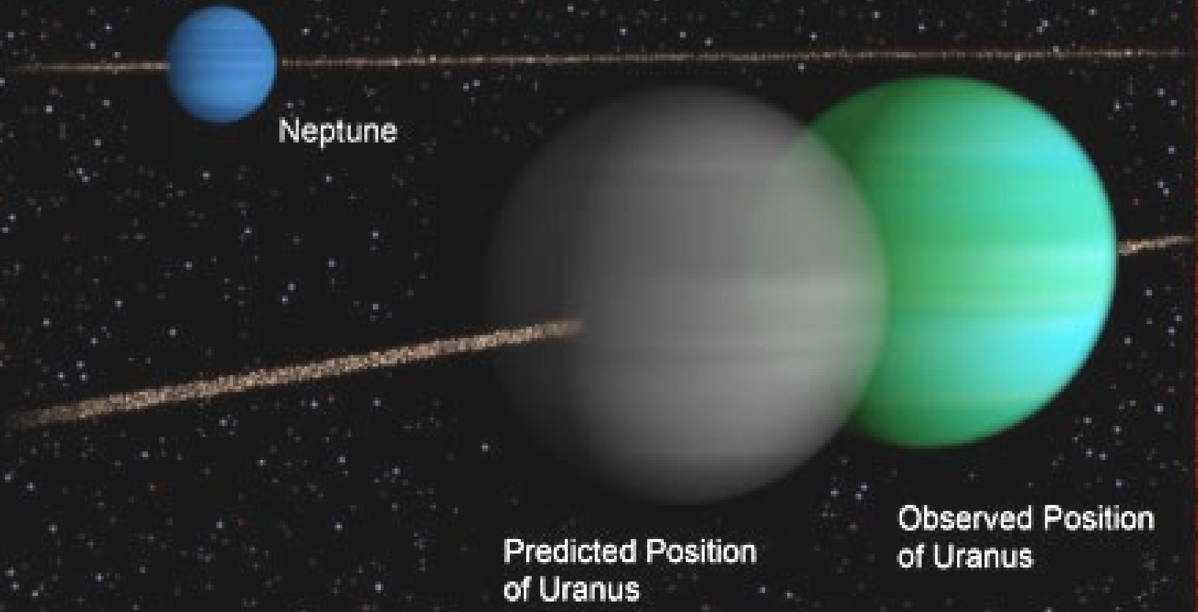
Precision Electroweak Measurements

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!

NEW DISCOVERIES FROM PRECISION MEASUREMENTS



The discovery of Neptune is an example of using precision measurements to find things that are otherwise difficult or impossible to directly detect. In the 1840s, astronomers theorized that the gravitational pull of an unseen planet accounted for the unpredictable positions of Uranus. Using the observational data gathered over decades, theorists calculated where the new planet should be located, limiting the search to a manageable region of the heavens. Astronomers found Neptune by telescope in 1846.

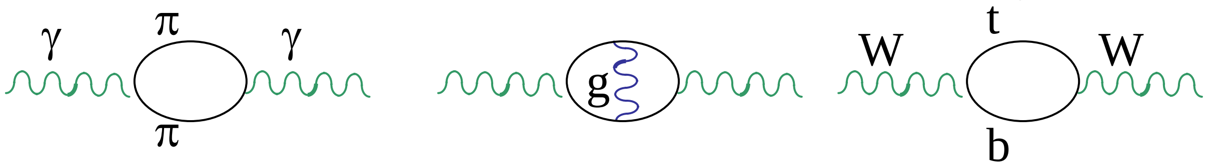
Precision Electroweak Measurements

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}

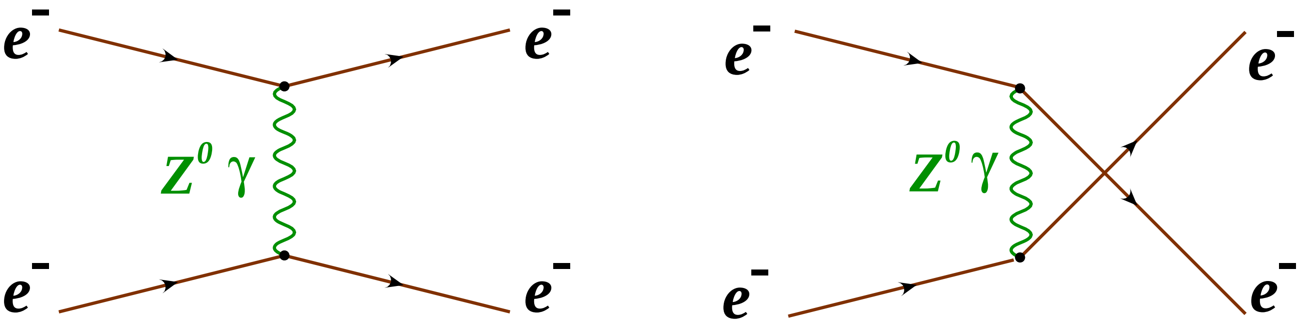


High energy measurements: Z lineshape, W mass, Z-pole asymmetries

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

This talk ⟶ $\boldsymbol{A_{PV}}$ **(e-e)**

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%

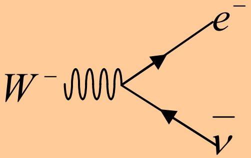
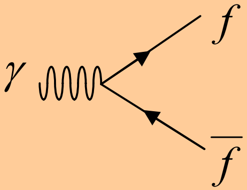
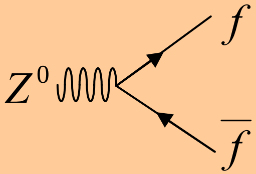
Parity Violation, Weak Mixing Angle

Electroweak Theory:

$SU(2)_L$ x $U(1)$, with isotriplet field A_i^μ and isosinglet field B^μ

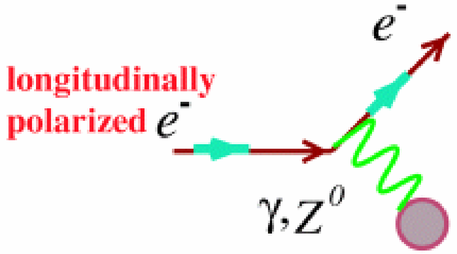
$SU(2)_L$ coupling constant is g
$U(1)$ coupling constant is g'

A_1^μ, A_2^μ are charged fields and correspond to W^+, W^- particles
A_3^μ, B^μ are neutral and can mix, giving the Z^0 and γ particles
Weak mixing angle: $g' = g \tan\theta_W$

	LH coupling	RH coupling
	$g/\sqrt{2}$	0
	$Q^f g \sin\theta_W$	$Q^f g \sin\theta_W$
	$(g^2+g'^2)^{1/2}(I_3^f - Q^f \sin^2\theta_W)$	$(g^2+g'^2)^{1/2}(-Q^f \sin^2\theta_W)$

Parity Violation at Low Q^2

(γ-Z interference)



$$-A_{LR} = A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{\gamma}} \sim \frac{G_F Q^2}{4 \pi \alpha}$$

$$\sigma \quad \alpha \; | A_{\gamma} + A_{weak} |^2$$

$$Q^2 \sim 0.01 - 1 \text{ GeV}^2 \longrightarrow A_{PV} \lesssim 10^{-7} - 10^{-4}$$

Studies pioneered by SLAC E-122 (semi-leptonic DIS):

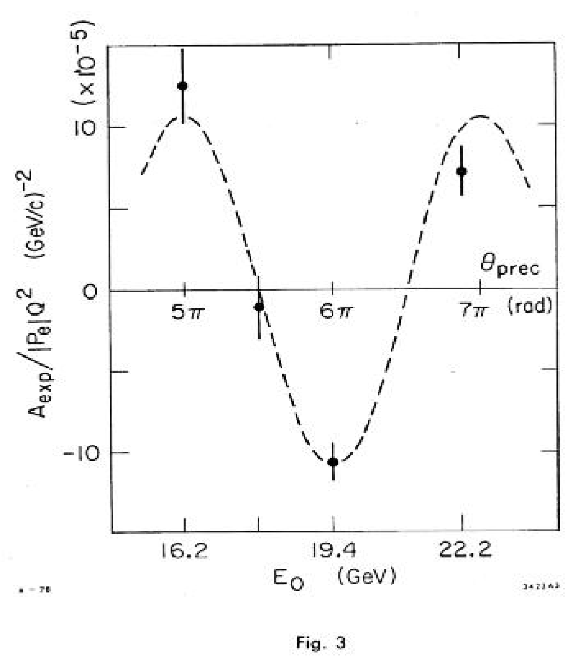


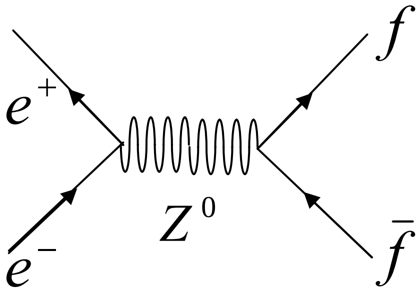
Fig. 3

- first observation of PV in weak neutral scattering
- cornerstone experiment that solidified the Standard Model developed by Glashow, Weinberg and Salam

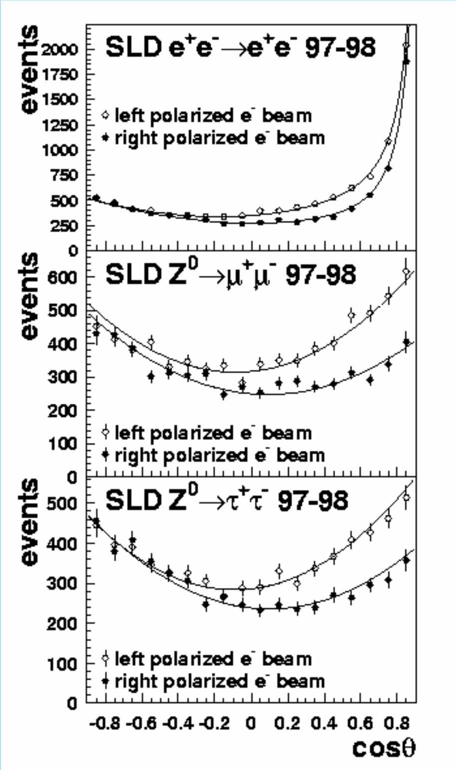
$$\sin^2 \theta_W = 0.224 \pm 0.020$$

($A_{PV} \sim 10^{-4}$)

Parity Violation at the Z-pole



$$-A_{PV} = A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{2\left[1 - 4\sin^2\theta_W^{eff}\right]}{1 + \left[1 - 4\sin^2\theta_W^{eff}\right]^2}$$



Very precise measurements by *SLD* at SLAC

- best measurement of weak mixing angle

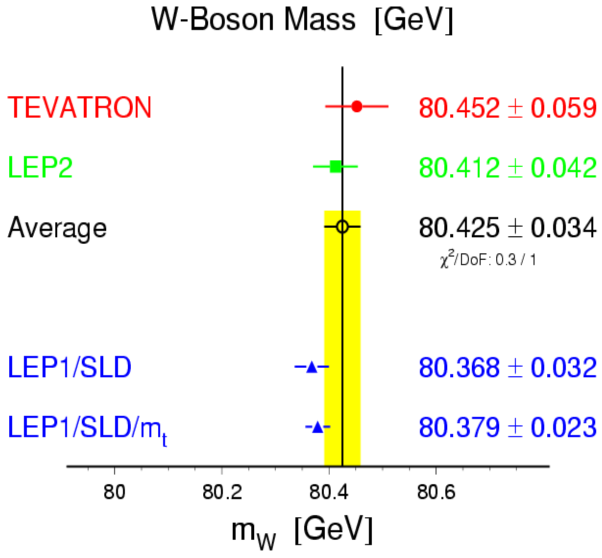
best indirect constraint on the Higgs mass

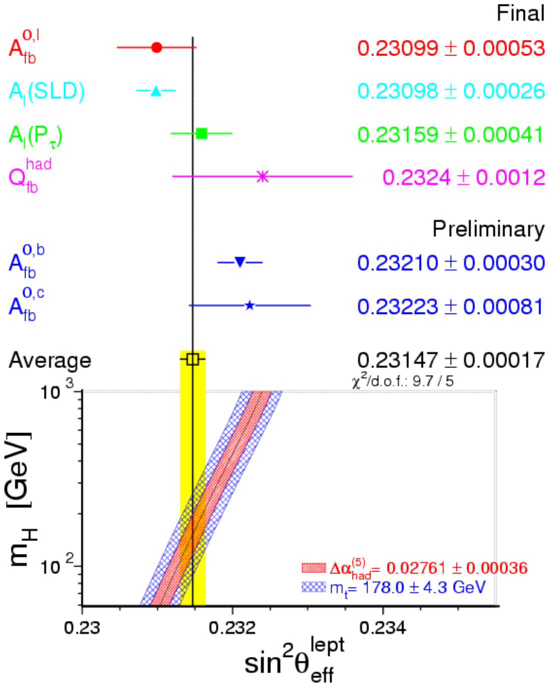
$$\sin^2\theta_W^{eff}\left(M_Z^2\right) = 0.23098 \pm 0.00026$$

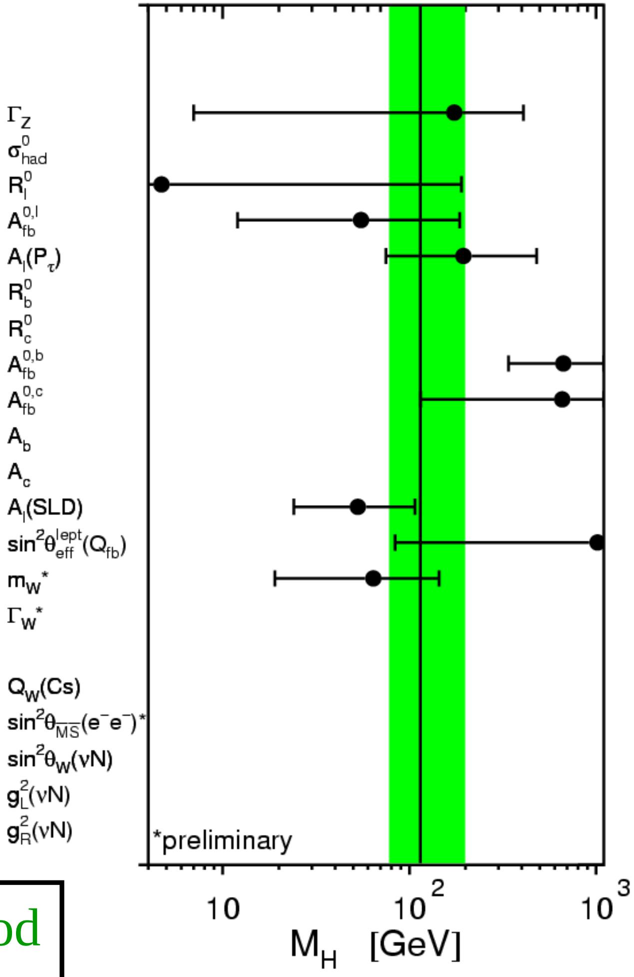
(A_{PV} ~ -0.15)

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

from LEP1, LEP2, SLC and Tevatron

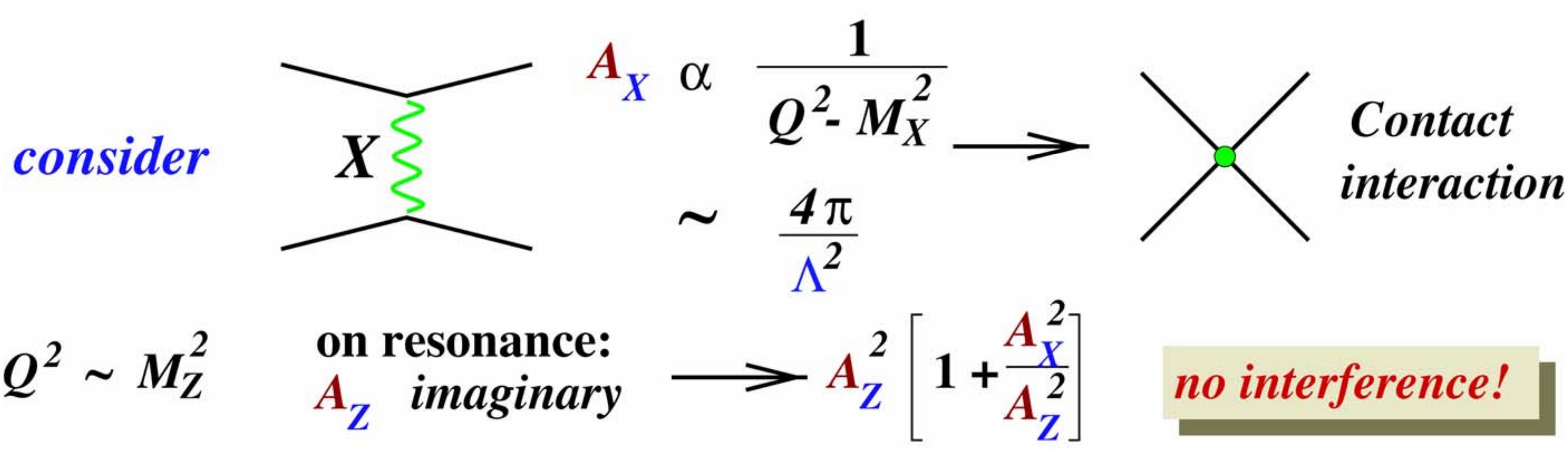






- ➢ Data consistency within context of SM is generally good
- ➢ Higgs mass constraints:
  - W mass and leptonic asymmetries predict light Higgs
  - Hadronic asymmetries predict heavy Higgs

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



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

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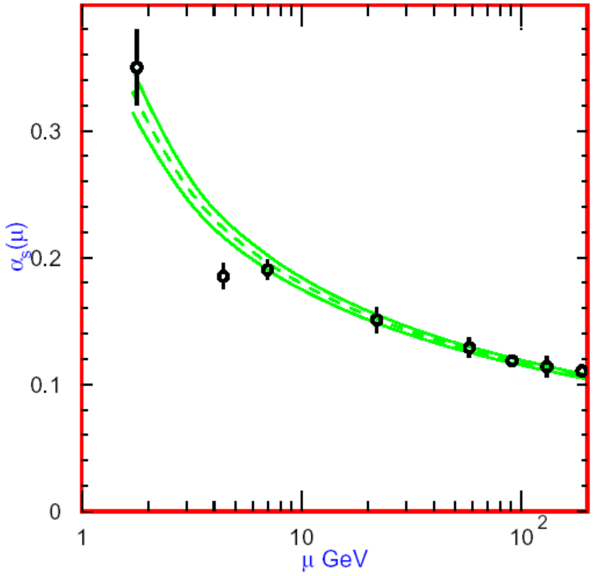
- Running of α_{em} and α_S with Q^2 are well established

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

And does it agree with SM prediction?

Running Coupling Constants, Unification



Running of α_S:

From PDG: data from μ, τ width;
ϒ decays; DIS; e^+e^- event rate at 25 GeV; event shapes at TRISTAN; Z width and e^+e^- event shapes at LEP-I, LEP-II.

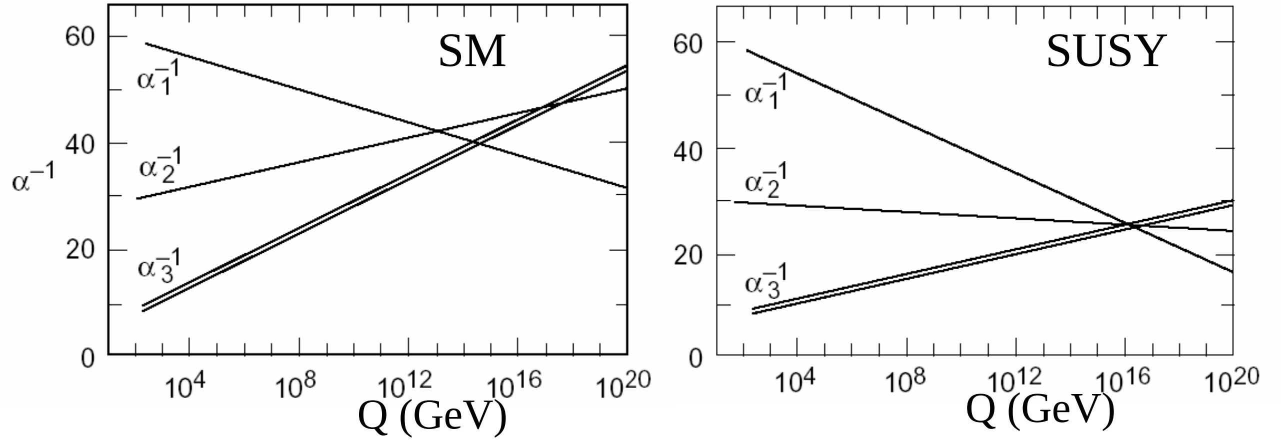
Running of α_{EM}:

established with data from Brookhaven $(g-2)_\mu$;
VENUS and TOPAZ at Tristan; L3 and OPAL at LEP

Gauge coupling unification?

g_1, g_2, g_3 are U(1), SU(2), and SU(3) coupling constants, and $\alpha_i = g_i^2 / 4\pi$

(from M. Peskin, hep-ph/9705479)

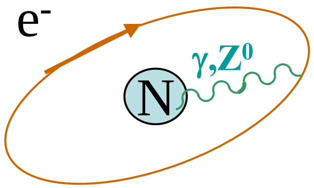


$$\alpha_1 = \frac{5}{3} \cdot \frac{\alpha_{EM}}{\cos^2 \theta_W}$$

$$\alpha_2 = \frac{\alpha_{EM}}{\sin^2 \theta_W}$$

$$\alpha_3 = \alpha_S$$

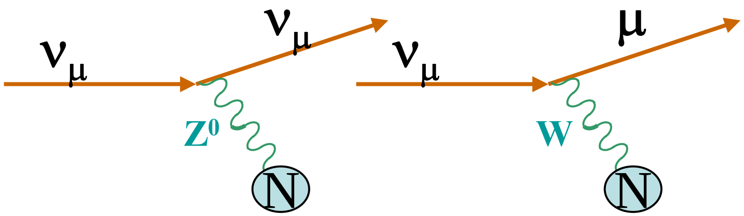
Low Q^2 Measurements of θ_W



Boulder Cs

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

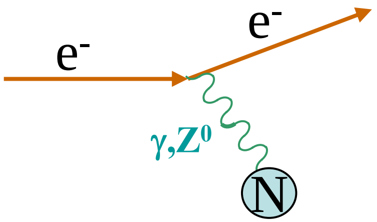
$$\boxed{\delta\sin^2\theta_W\left(M_Z^2\right) = 0.0019}$$



FNAL NuTeV

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

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

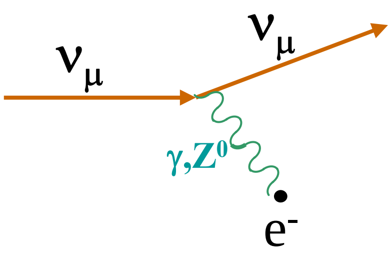


JLAB Qweak (~2007)

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

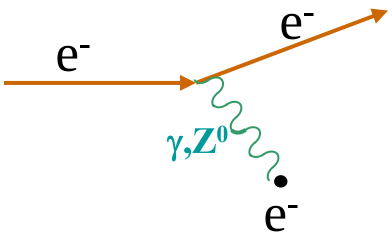
$$\boxed{\begin{array}{r}\delta\sin^2\theta_W\left(M_Z^2\right) = 0.0007\\ \underline{\text{Goal}}\end{array}}$$

Purely leptonic



CERN CHARMII

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



SLAC E158

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

$$\boxed{\delta\sin^2\theta_W\left(M_Z^2\right) = 0.0014}$$

References on *Low Energy* Electroweak Measurements:

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

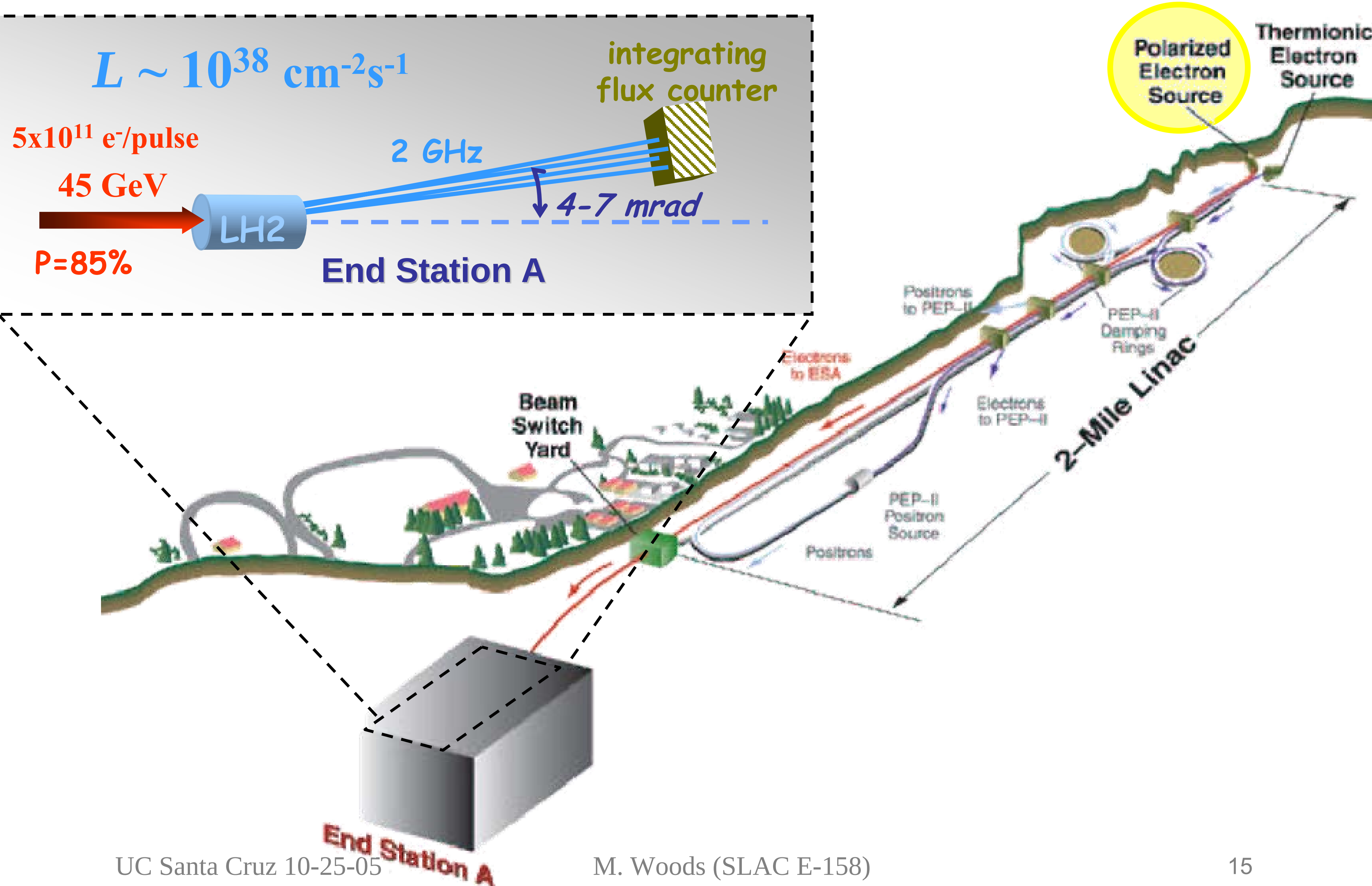
- 
  From Zero to Z^0
  A WORKSHOP ON PRECISION ELECTROWEAK PHYSICS
  Fermilab, May 12-14, 2004

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

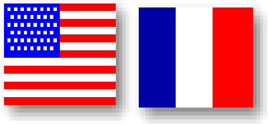
- 
  Workshop on Low Energy Precision Electroweak Measurements
  (LEPEM2002)
  TRIUMF, April 4-6, 2002

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

SLAC E-158


$L \sim 10^{38}$ cm^{-2}s^{-1}
integrating flux counter
$5\text{x}10^{11}$ e^{-}/pulse
2 GHz
45 GeV
4-7 mrad
LH2
P=85%
End Station A
Polarized Electron Source
Thermionic Electron Source
Positrons to PEP-II
PEP-II Damping Rings
Electrons to ESA
Beam Switch Yard
Electrons to PEP-II
2-Mile Linac
PEP-II Positron Source
Positrons
End Station A

E158 Collaboration



- **UC Berkeley**
- **Caltech**
- **Jefferson Lab**
- **Princeton**
- **Saclay**
- **SLAC**
- **Smith College**
- **Syracuse**
- **UMass**
- **Virginia**

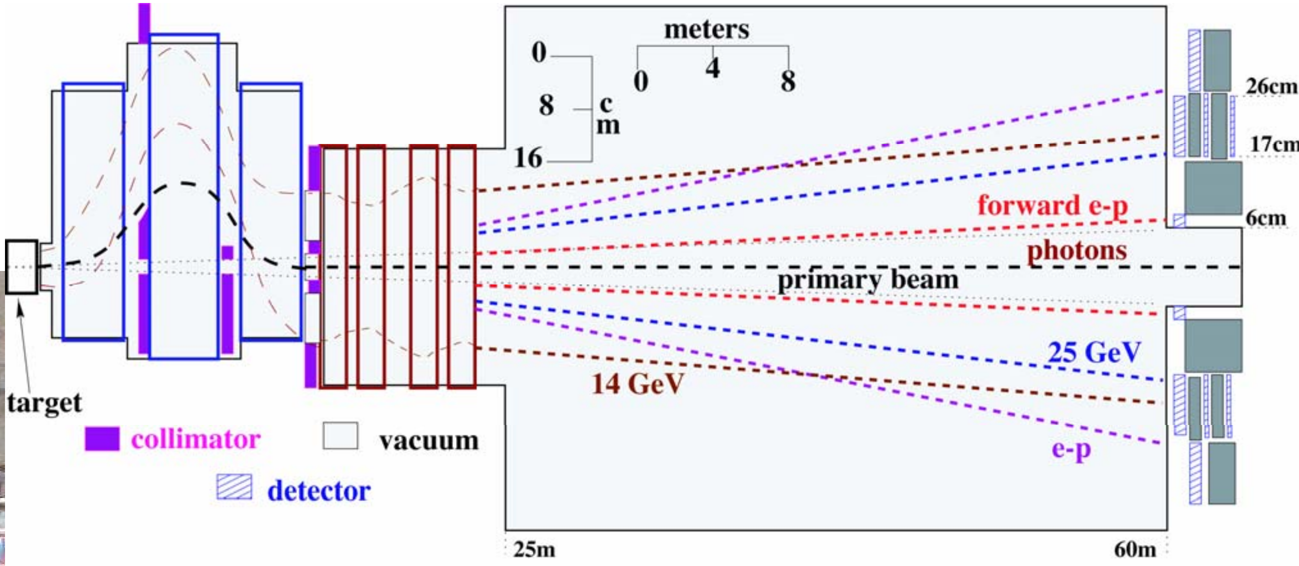
8 Ph.D. Students
60 physicists

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

Key Ingredients

Beam

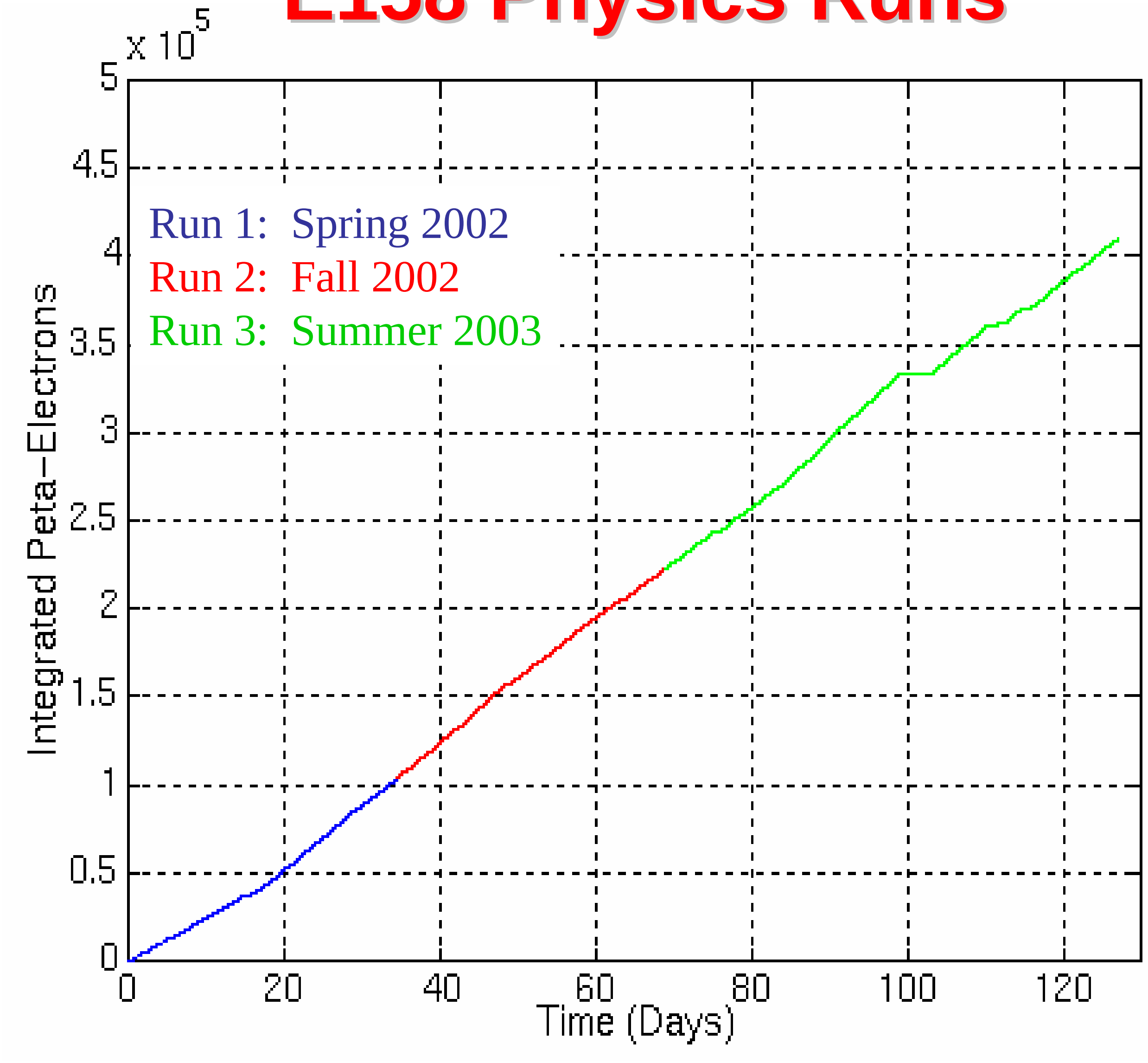
- High beam polarization (85-90%!) and beam current
- Strict control of helicity-dependent systematics
- Passive asymmetry reversals



Target and Spectrometer

- High power LH_2 target
- Spectrometer optimized for Møller kinematics

E158 Physics Runs



Run 1: Spring 2002

Run 2: Fall 2002

Run 3: Summer 2003

*1 Peta-Electron = 10^{15} electrons

E-158 Beam Parameters

Parameter	**Proposal**	**Achieved**
Intensity at 45 GeV	6 x 10^{11} / pulse	5.3 x 10^{11}
Intensity at 48 GeV	3.5 x 10^{11}	4.3 x 10^{11}
Polarization	80%	85-90%
Repetition Rate	120 Hz	120 Hz
Intensity jitter / pulse	2% rms	0.5% rms
Energy jitter / pulse	0.4% rms	0.03% rms
Energy spread	-	0.15% rms
Delivered Charge (Peta-E)	345K	410K

Polarized Source Laser System

IA Feedback Loop

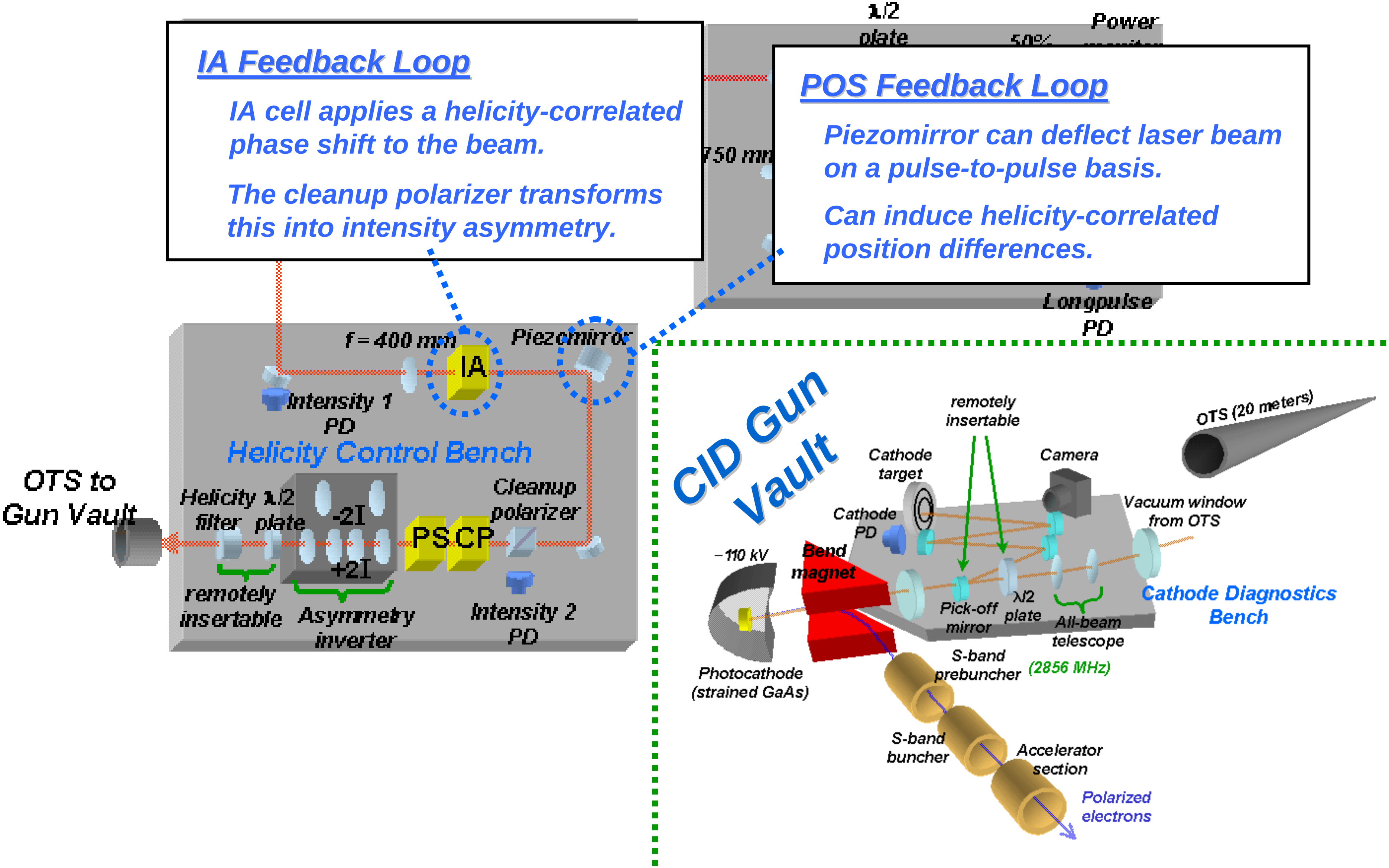
IA cell applies a helicity-correlated phase shift to the beam.

The cleanup polarizer transforms this into intensity asymmetry.

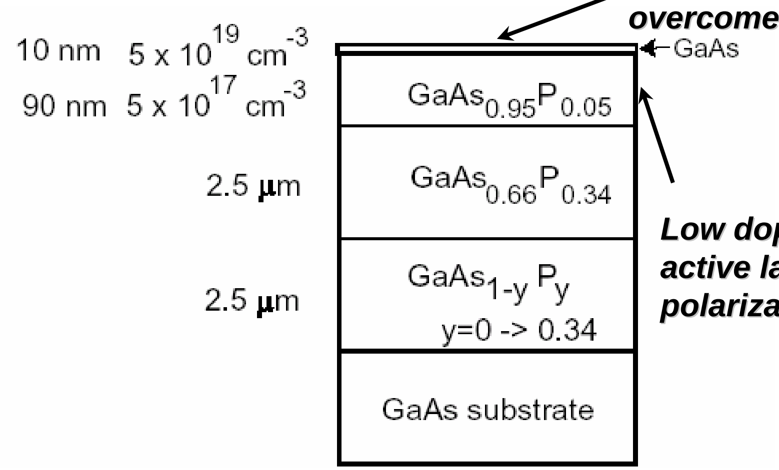
POS Feedback Loop

Piezomirror can deflect laser beam on a pulse-to-pulse basis.

Can induce helicity-correlated position differences.



Photocathode for Polarized Gun



10 nm 5×10^{19} cm^{-3}

90 nm 5×10^{17} cm^{-3}

2.5 µm

2.5 µm

GaAs

$GaAs_{0.95}P_{0.05}$

$GaAs_{0.66}P_{0.34}$

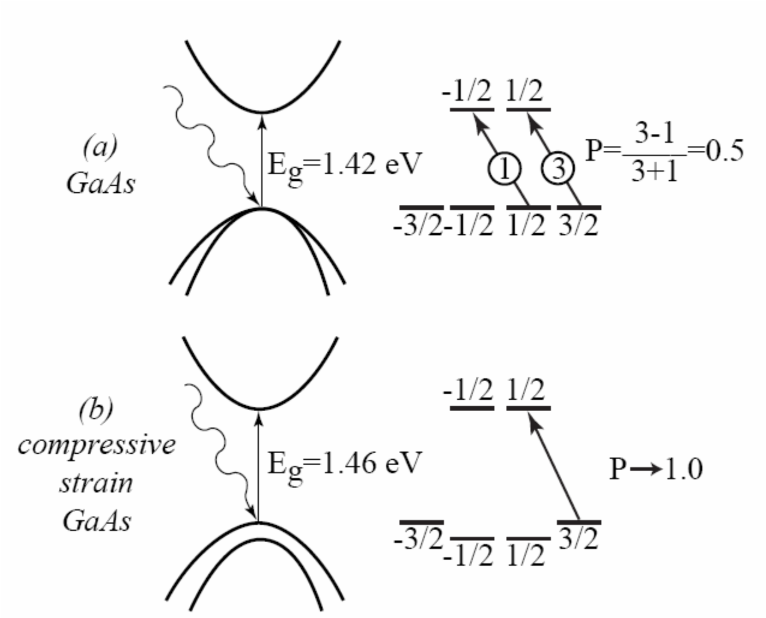
$GaAs_{1-y}P_y$

y=0 -> 0.34

GaAs substrate

High doping for 10-nm GaAs surface overcomes charge limit.

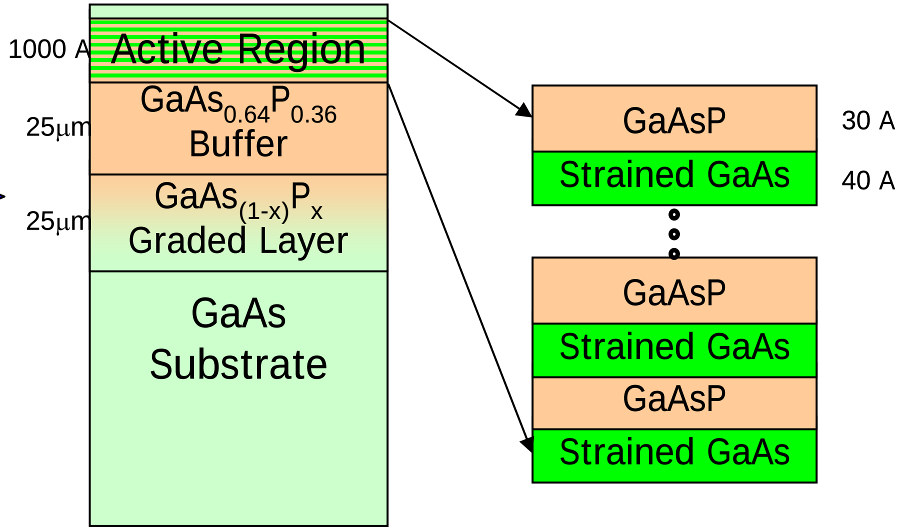
Low doping for most of active layer yields high polarization.



NEW

Cathode for Run 3

Gradient-doped strained superlattice; **5% higher polarization** than for Runs 1,2



1000 A

25µm

25µm

Active Region

$GaAs_{0.64}P_{0.36}$ Buffer

$GaAs_{(1-x)}P_x$ Graded Layer

GaAs Substrate

GaAsP 30 A

Strained GaAs 40 A

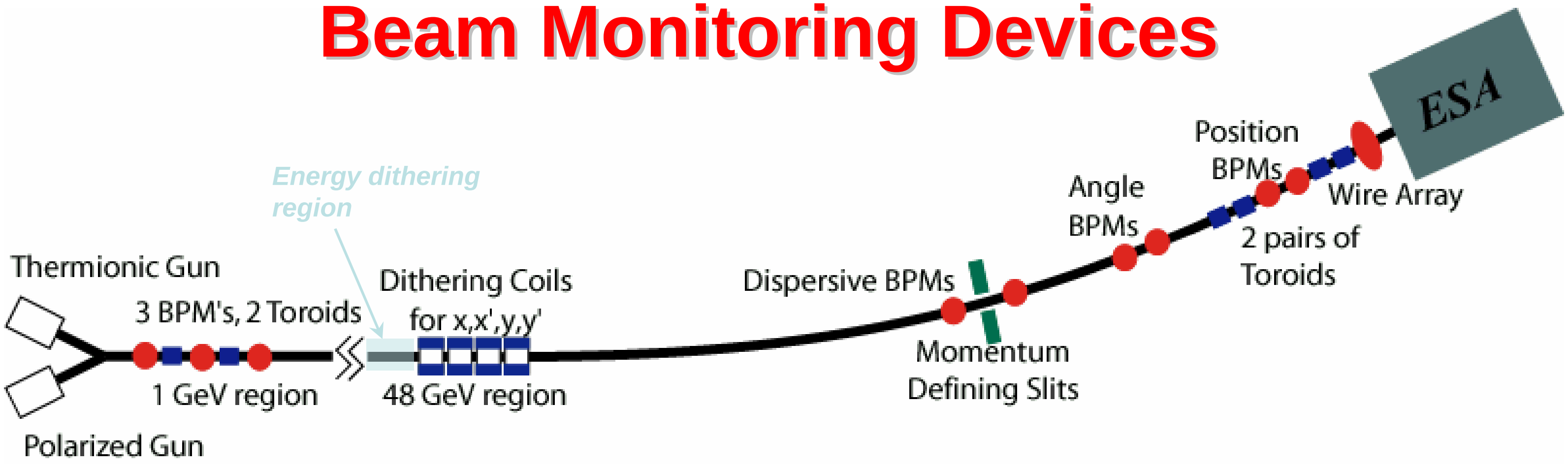
GaAsP

Strained GaAs

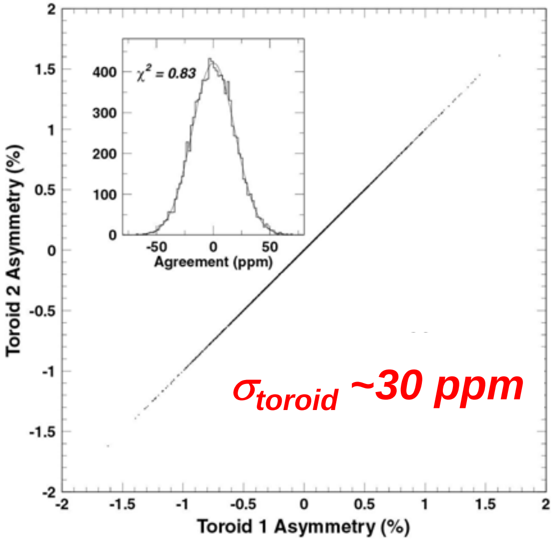
GaAsP

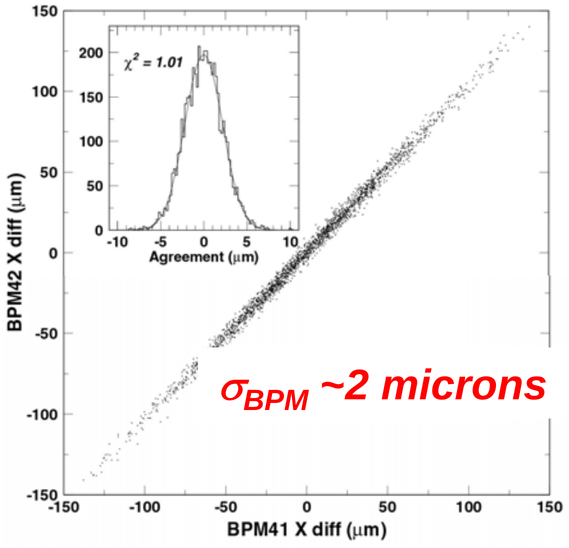
Strained GaAs

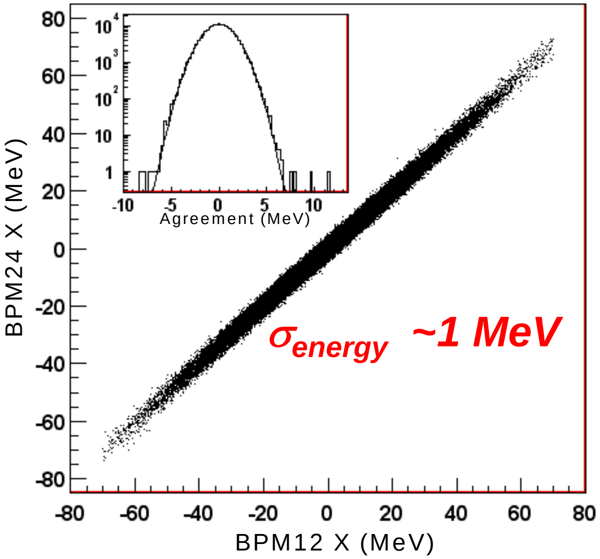
Beam Monitoring Devices

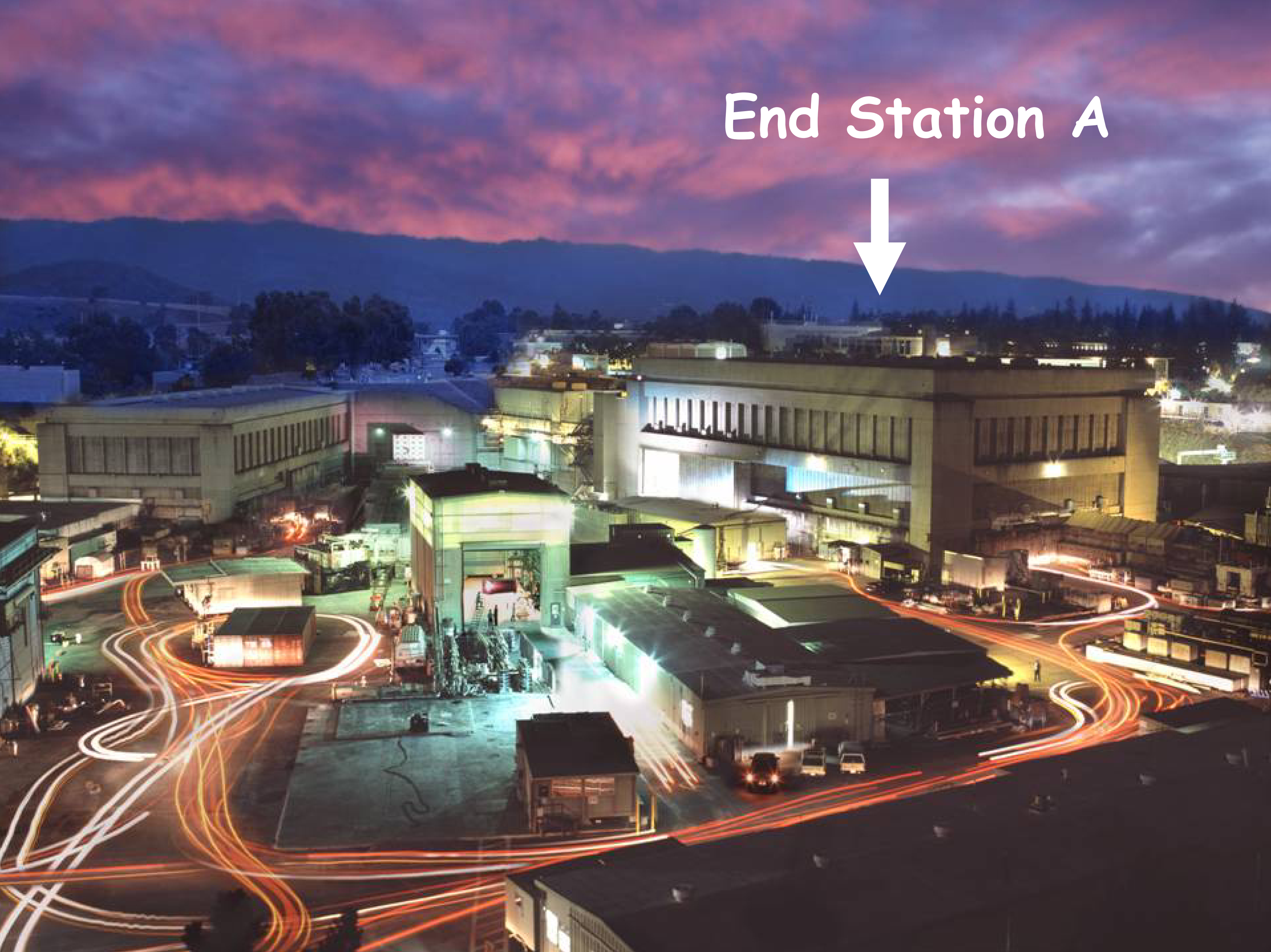


Can compare measurements of neighboring devices to determine the precision of the measurement.





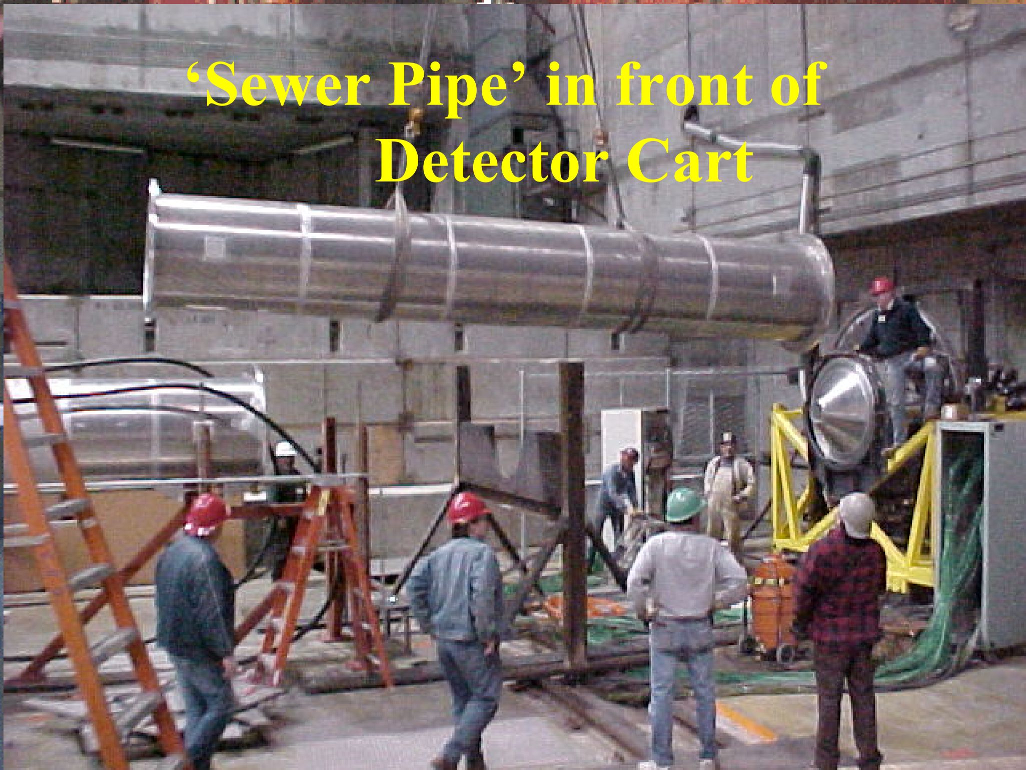




End Station A

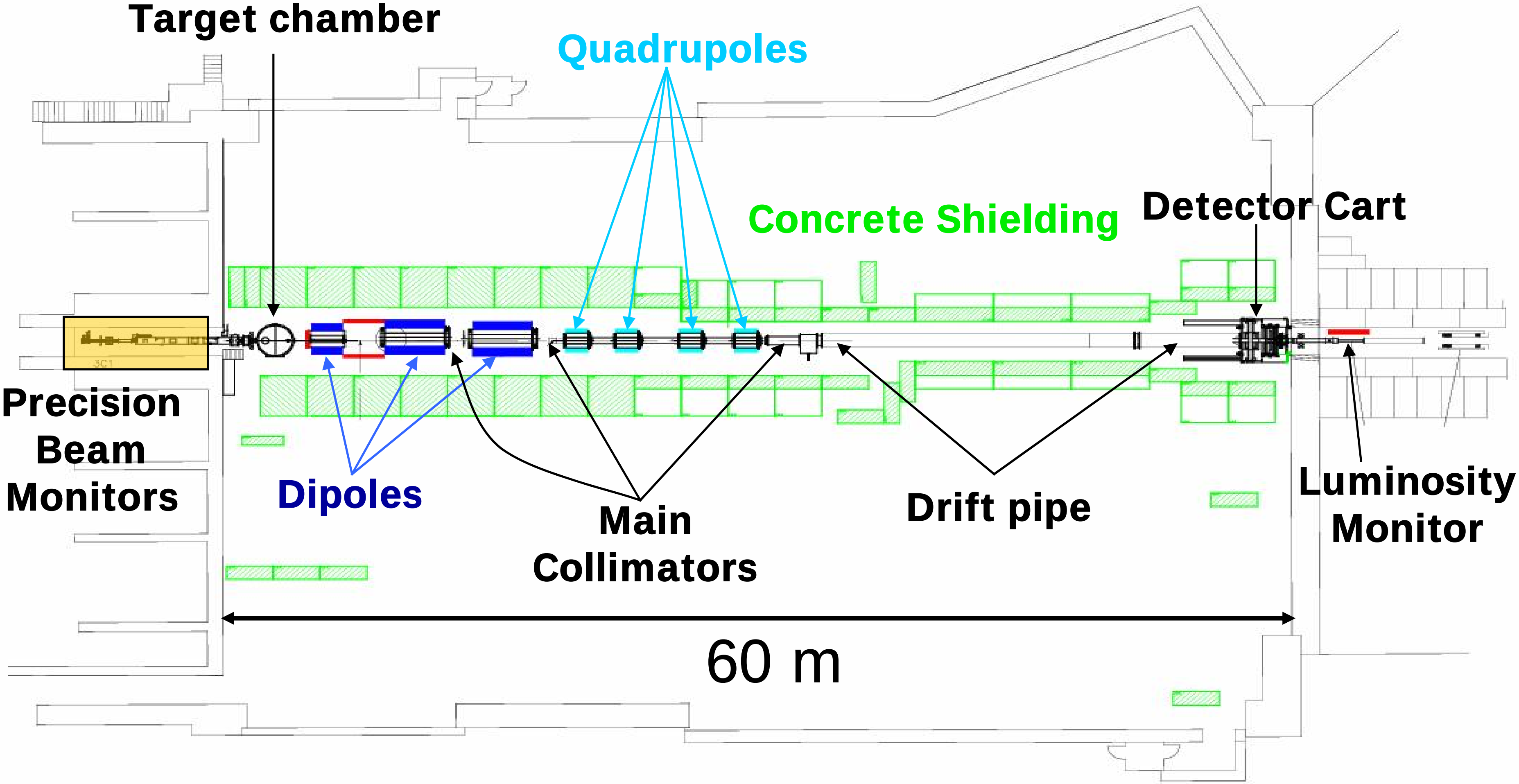
Scattering Chamber and Spectrometer Magnets

LH_2 Scattering Chamber

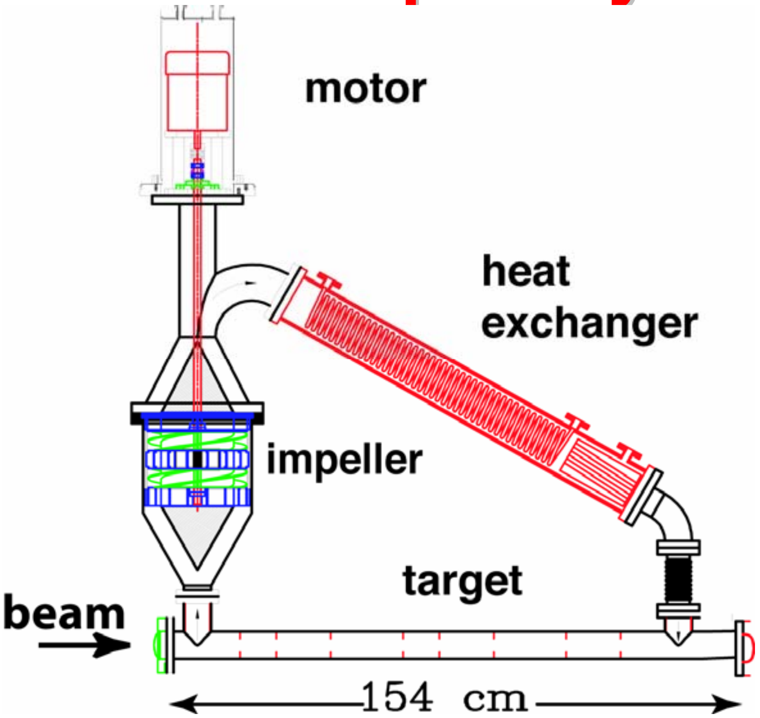


‘Sewer Pipe’ in front of Detector Cart

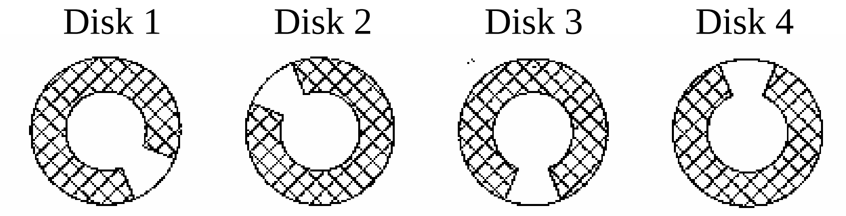
Experimental Layout in ESA



Liquid Hydrogen Target



Refrigeration Capacity	1000W
Max. Heat Load:	
- Beam	500W
- Heat Leaks	200W
- Pumping	100W
Length	1.5 m
Radiation Lengths	0.18
Volume	47 liters
Flow Rate	5 m/s

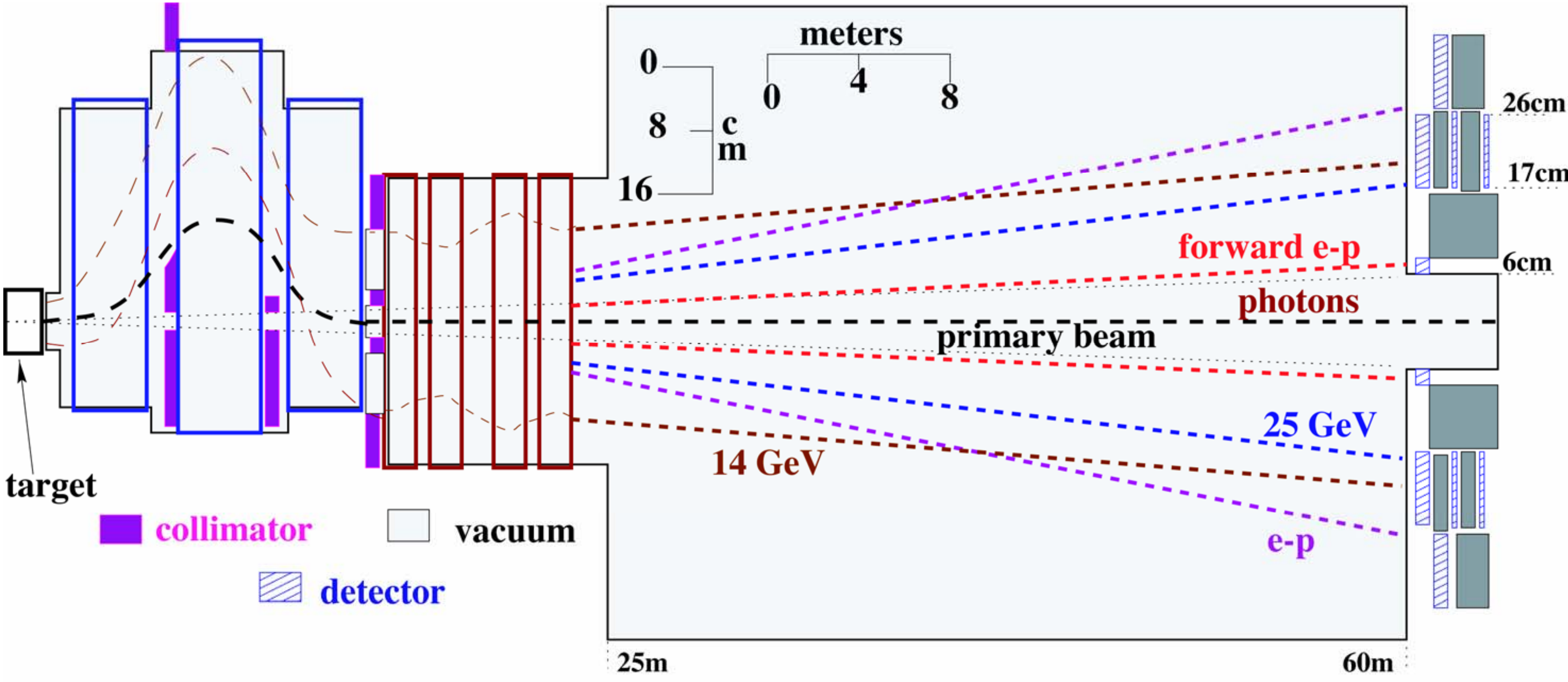


Wire mesh disks in target cell region to introduce turbulence at 2mm scale and a transverse velocity component. Total of 8 disks in target region.

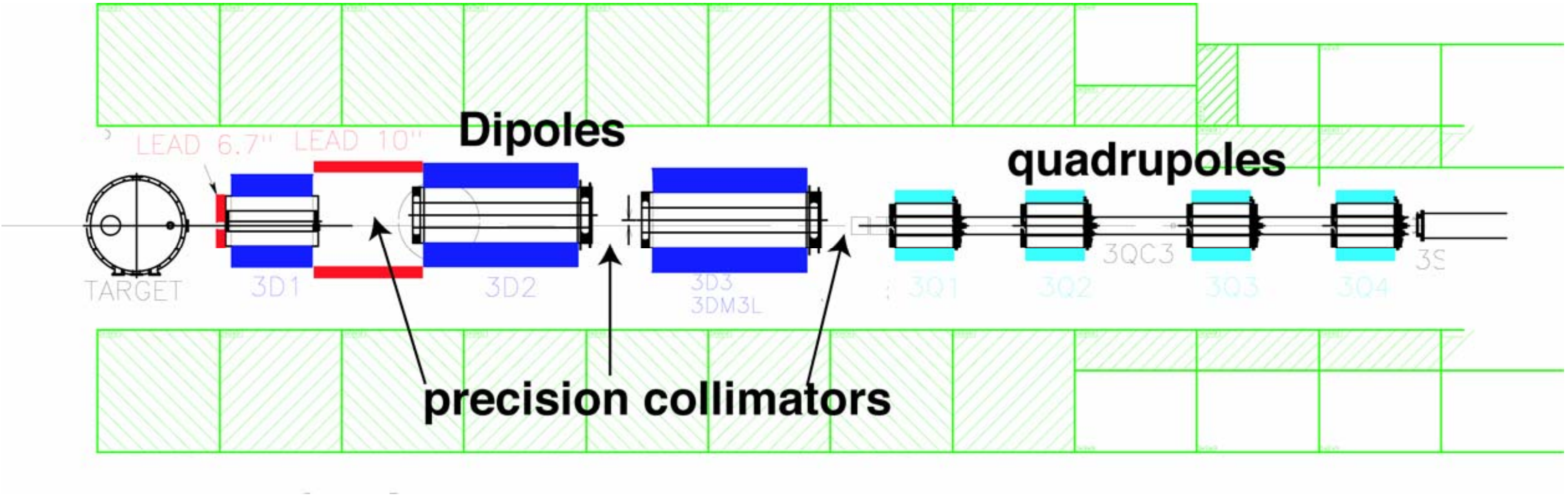
E158 Spectrometer

- *Target is an 18% radiator*
- *Moller ring is 20 cm from the beam*

Chicane for Line-of-sight shielding



Collimators

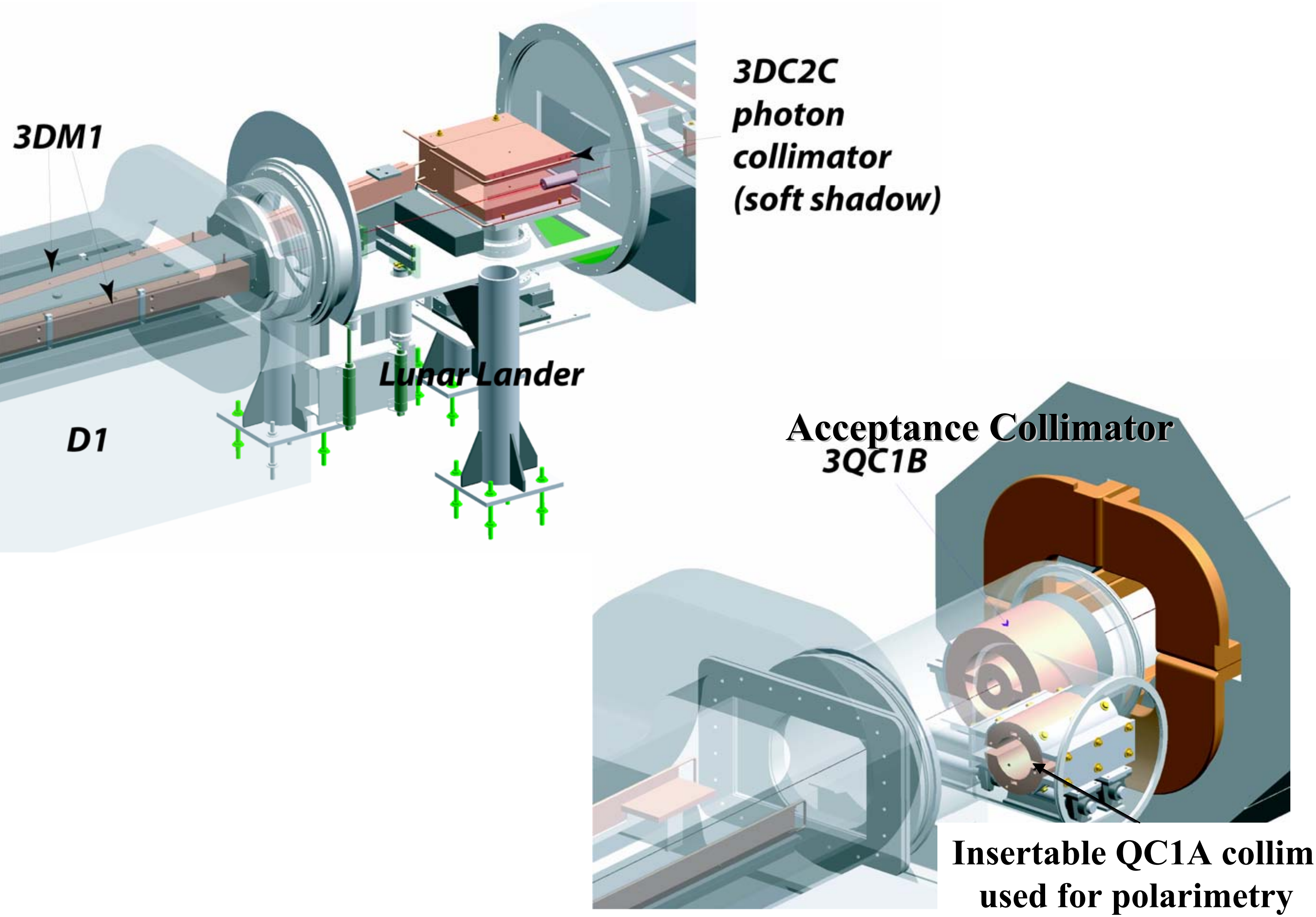


Dipoles

quadrupoles

precision collimators

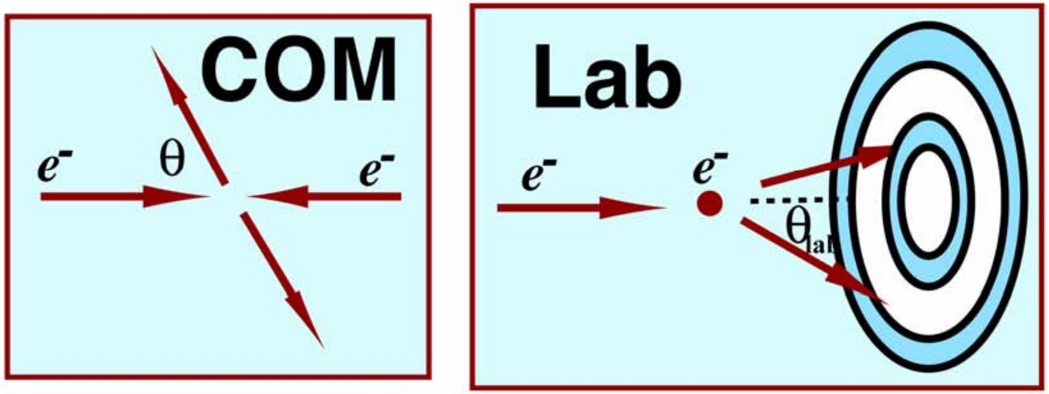
Collimators

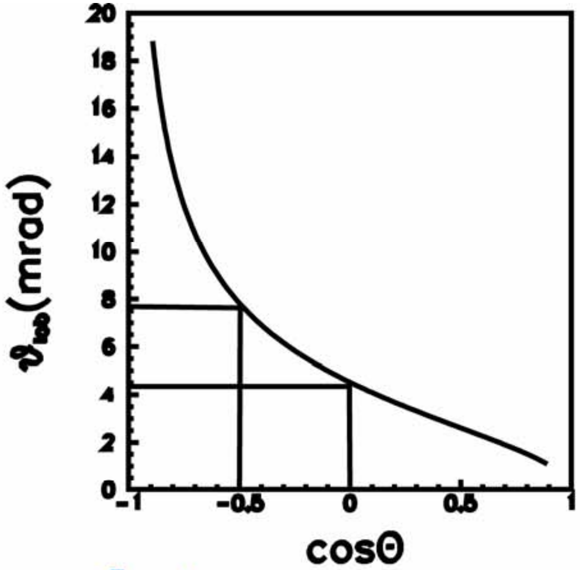


Acceptance Collimator

Insertable QC1A collimator, used for polarimetry

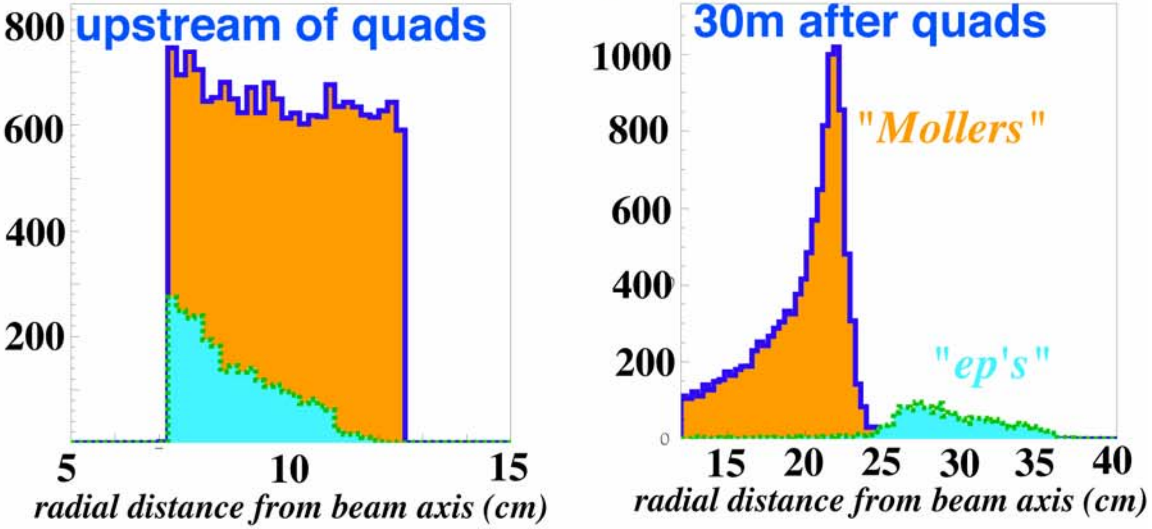
Kinematics



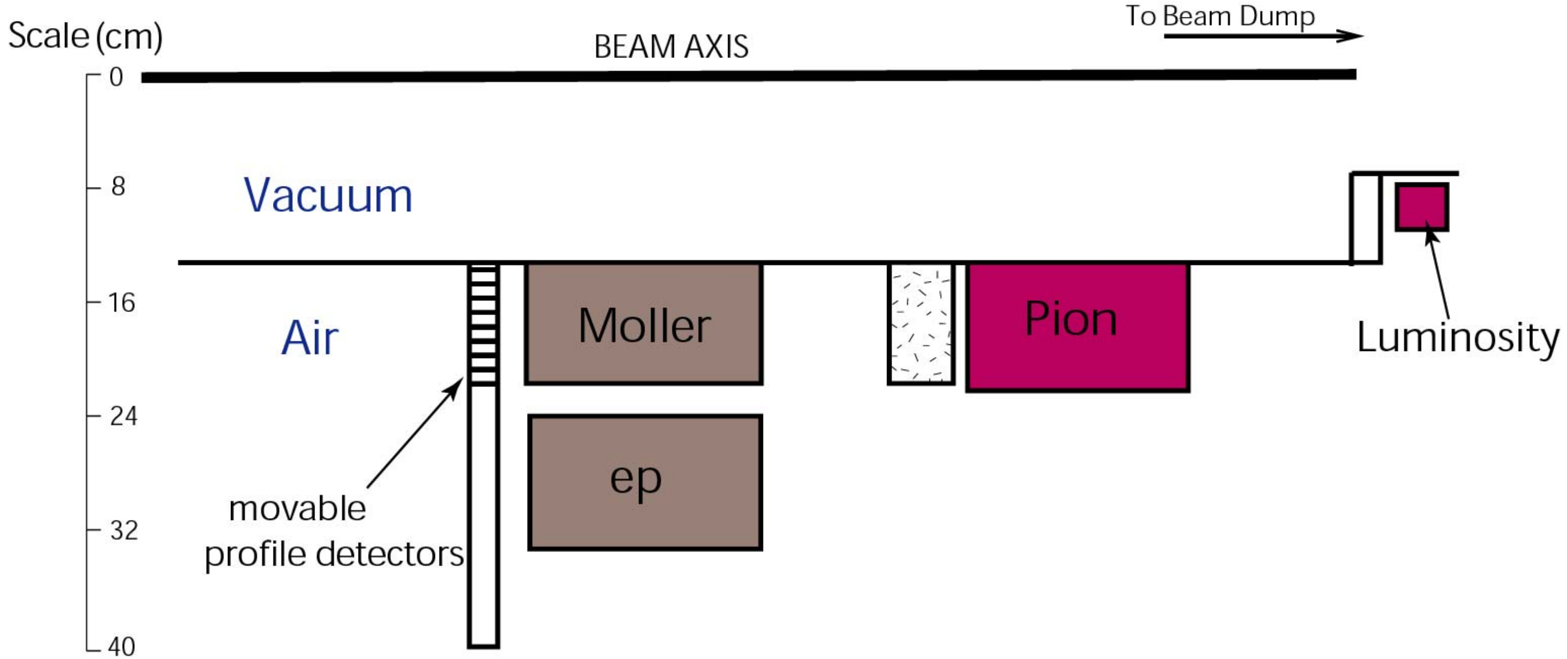


Quadrupole Quadruplet

- *primary & scattered electrons enclosed in quadrupoles*
- *Mollers (e-e) focused, Motts (e-p) defocused*
- *full range of azimuth*



Detectors



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

All detectors have azymuthal segmentation, and have PMT readout to 16-bit ADC

$$\sigma^{MOLLER} \propto \frac{1}{E\theta^4} \qquad \sigma^{MOTT} \propto \frac{1}{E^2\theta^4}$$

$$\left\langle \theta_{lab}^{LUMI} \right\rangle = 1.5mrad$$

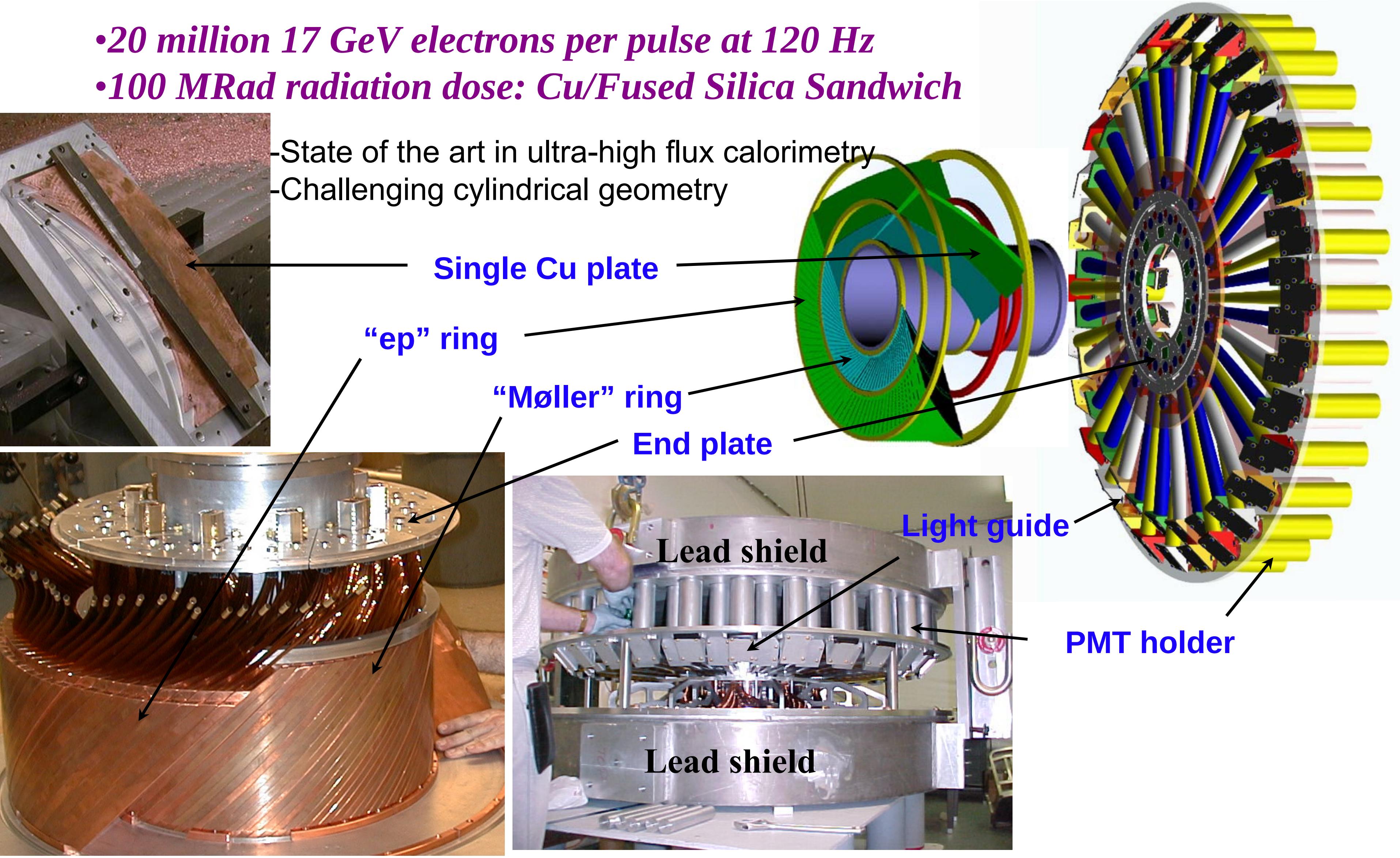
$$\left\langle \theta_{lab}^{MOLLER} \right\rangle = 6.0mrad$$

Moller, ep Detector

- *20 million 17 GeV electrons per pulse at 120 Hz*
- *100 MRad radiation dose: Cu/Fused Silica Sandwich*

-State of the art in ultra-high flux calorimetry

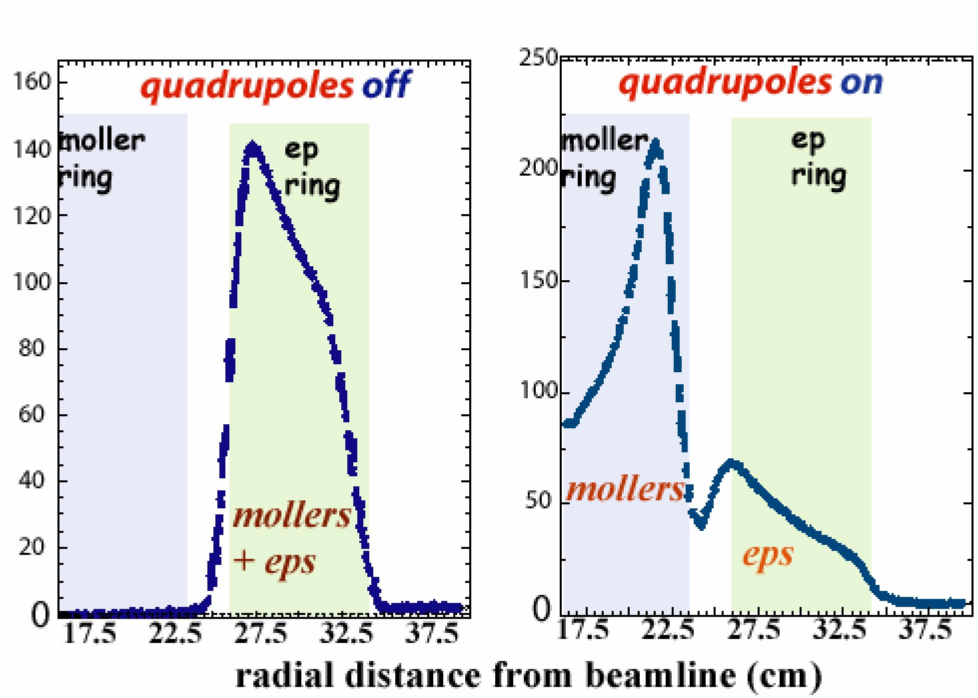
-Challenging cylindrical geometry

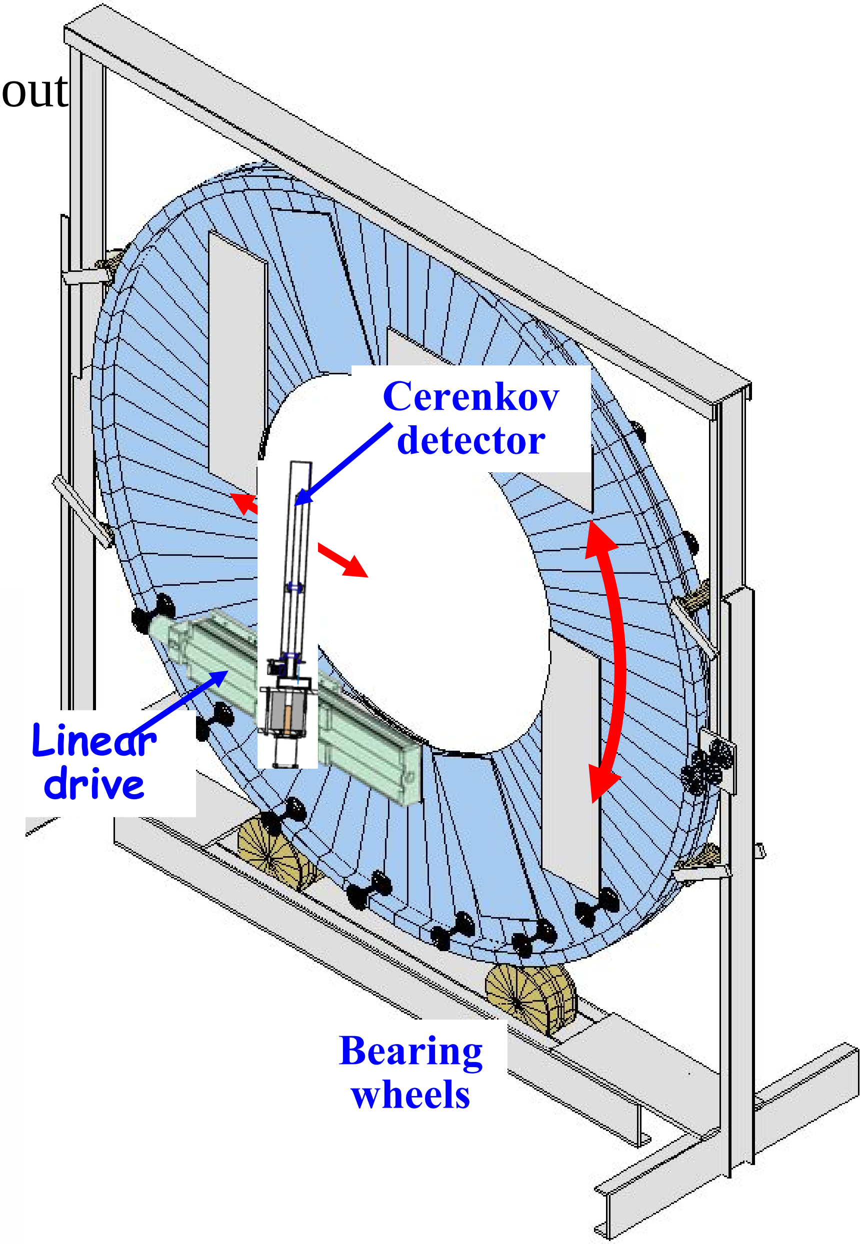


Profile Detector

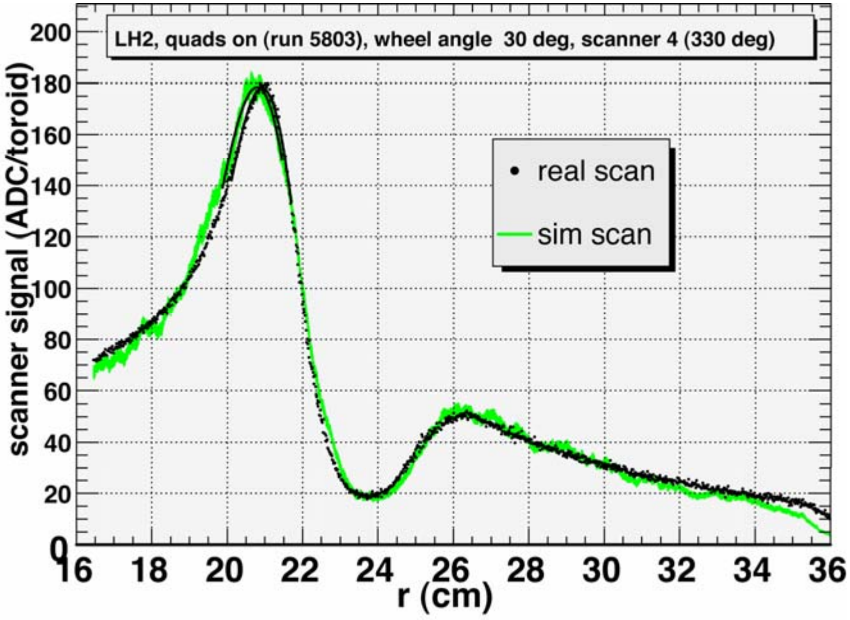
4 Quartz Cherenkov detectors with PMT readout
insertable pre-radiators
insertable shutter in front of PMTs
Radial and azymuthal scans

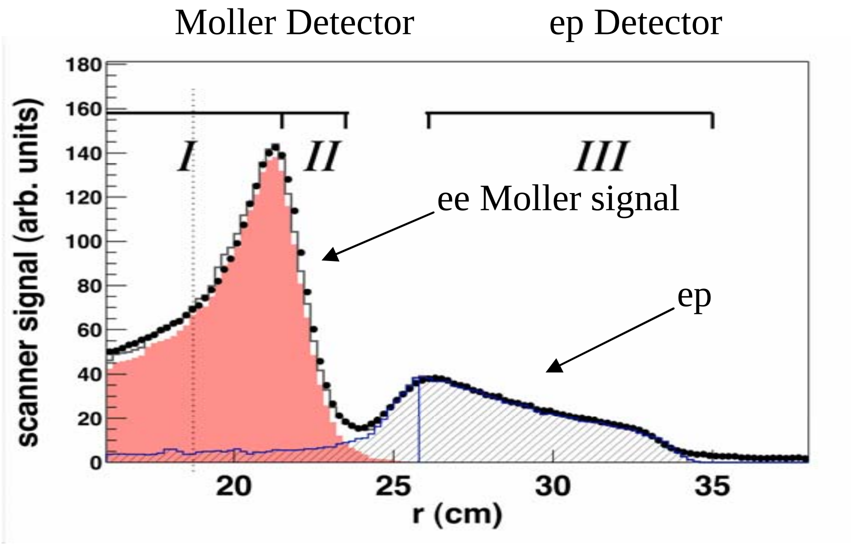
- **collimator alignment, spectrometer tuning**
- **background determination**
- **Q^2 measurement**





Scattered Flux Profile



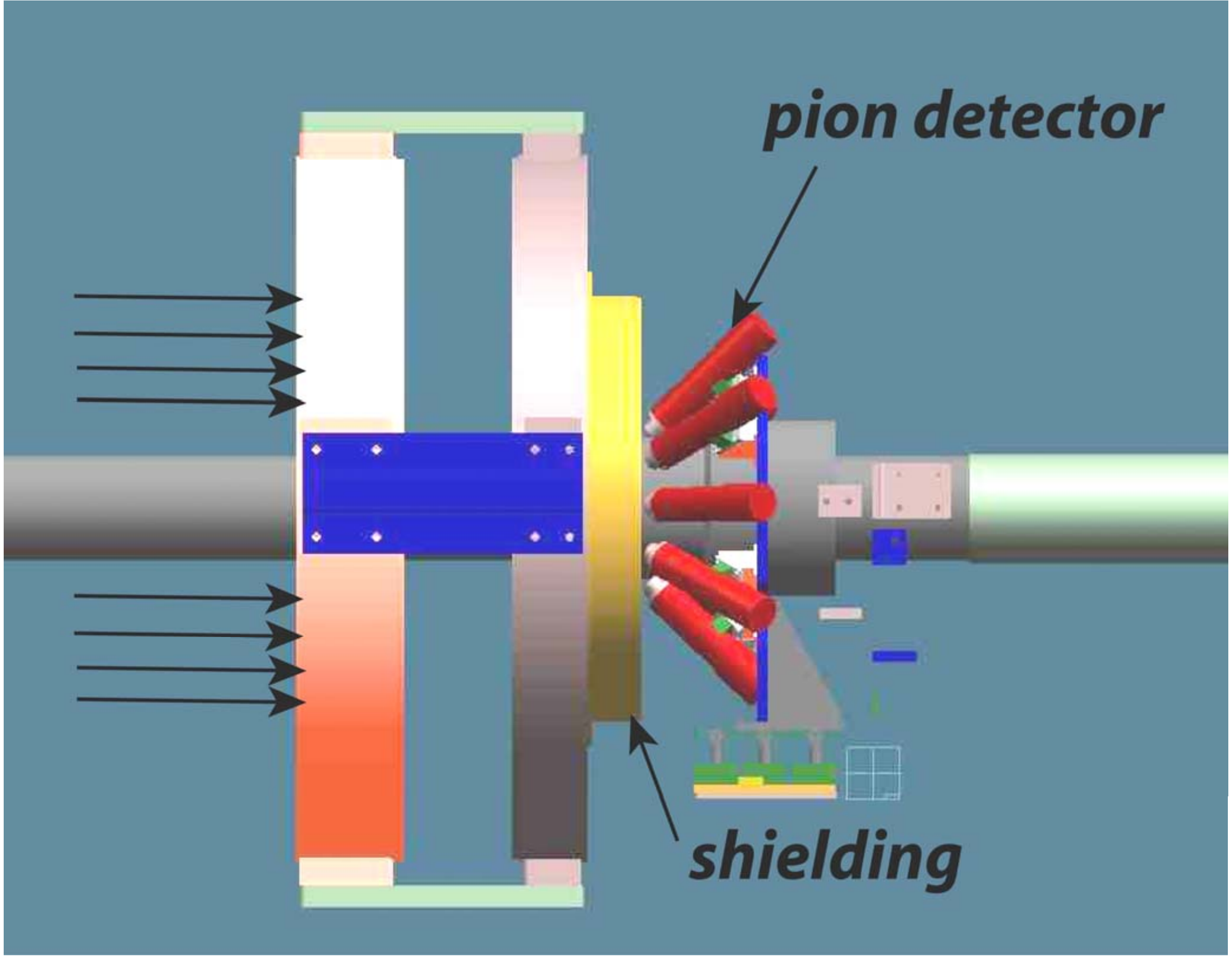


ep Background to Moller sample:

- 6% from elastic scattering
- 1% from inelastic scattering
- (29±4) ppb correction

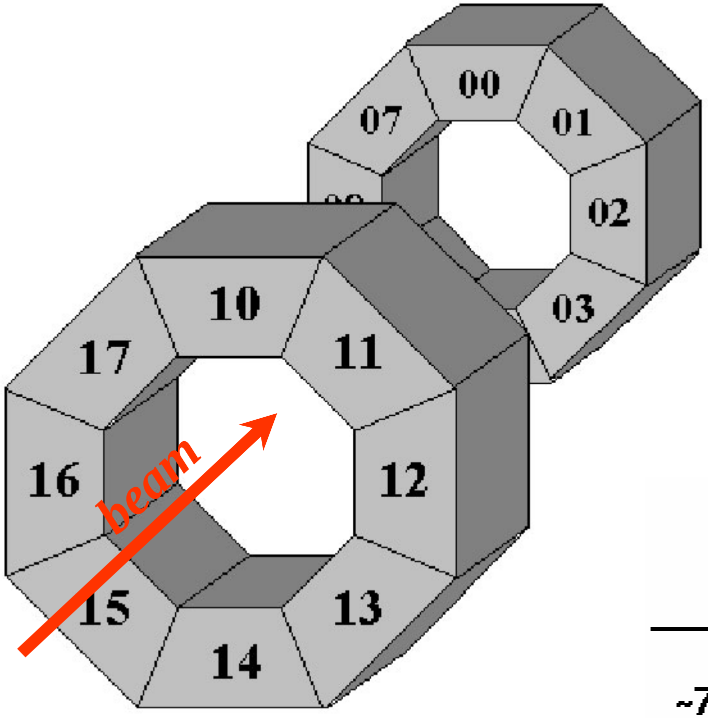
Pion Detector

Quartz Cherenkov Detector
with PMT readout



~ 0.2 % pion flux
~ 1 ppm asymmetry
~ (0 ± 2) ppb correction

LUMI Detector



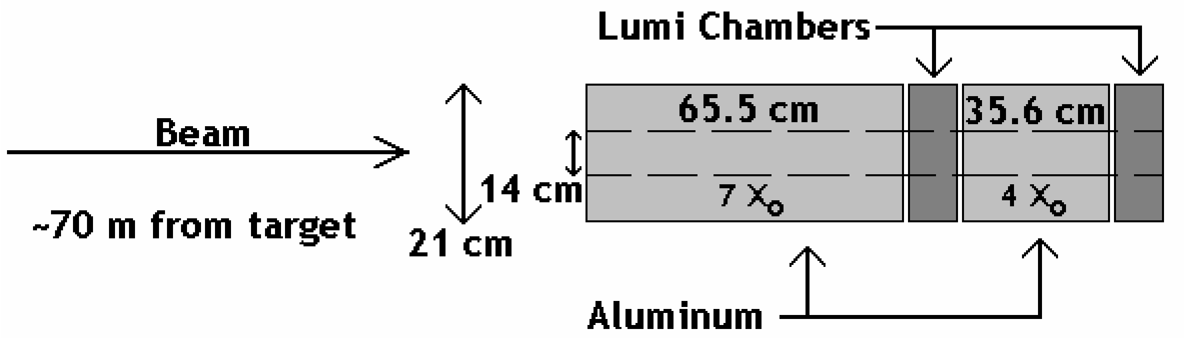
Segmented ion chamber detector with Aluminum preradiator.

500W incident power (50W from synchrotron radiation)

Signal: Motts and high energy Mollers

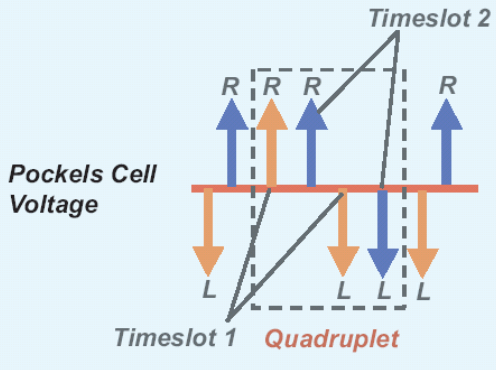
350M electrons per pulse; <E>~40 GeV

A_{PV} ~ -10ppb



- **Enhanced sensitivity to beam fluctuations**
- **Null asymmetry measurement**
- **Diagnostic for luminosity fluctations, including target density fluctuations.**

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: $R_1 R_2 \overline{R_1}\,\overline{R_2} R_3 R_4 \overline{R_3}\,\overline{R_4} \cdots$

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

$$\phi_{det} \propto \frac{I}{E\theta^4}$$

$$(\phi_{det} \sim \sigma_{phys} \cdot L \cdot acceptance)$$

where:

ϕ_{det} : detected flux (20 million Moller electrons/spill)

I : beam intensity

E: beam energy

θ: scattering angle

Assume dependence on beam parameters is linear over the jitter range:

$$A_{PV}^{meas} = P_e A_{PV}^{phys} + \boxed{A_Q + \sum_{\xi} \alpha_{\xi} \Delta\xi}$$

Contribution due to 'False' beam asymmetries

$$\xi \equiv \{E,\ x,\ y,\ x',\ y'\}$$

$$\alpha_{\xi} = \frac{\partial A_{PV}}{\partial \xi}$$

$\alpha_E \approx 1$ ppb/ppb

$\alpha_x \approx 1$ ppb/nm $\quad \alpha_{x'} \approx 2$ ppb/nm

$\alpha_y \approx 1$ ppb/nm $\quad \alpha_{y'} \approx 2$ ppb/nm

A_{PV} Measurement

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

$$A^p_{exp} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

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

$$A^p_{raw} = A^p_{exp} - \sum a_i \Delta x_i$$

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:

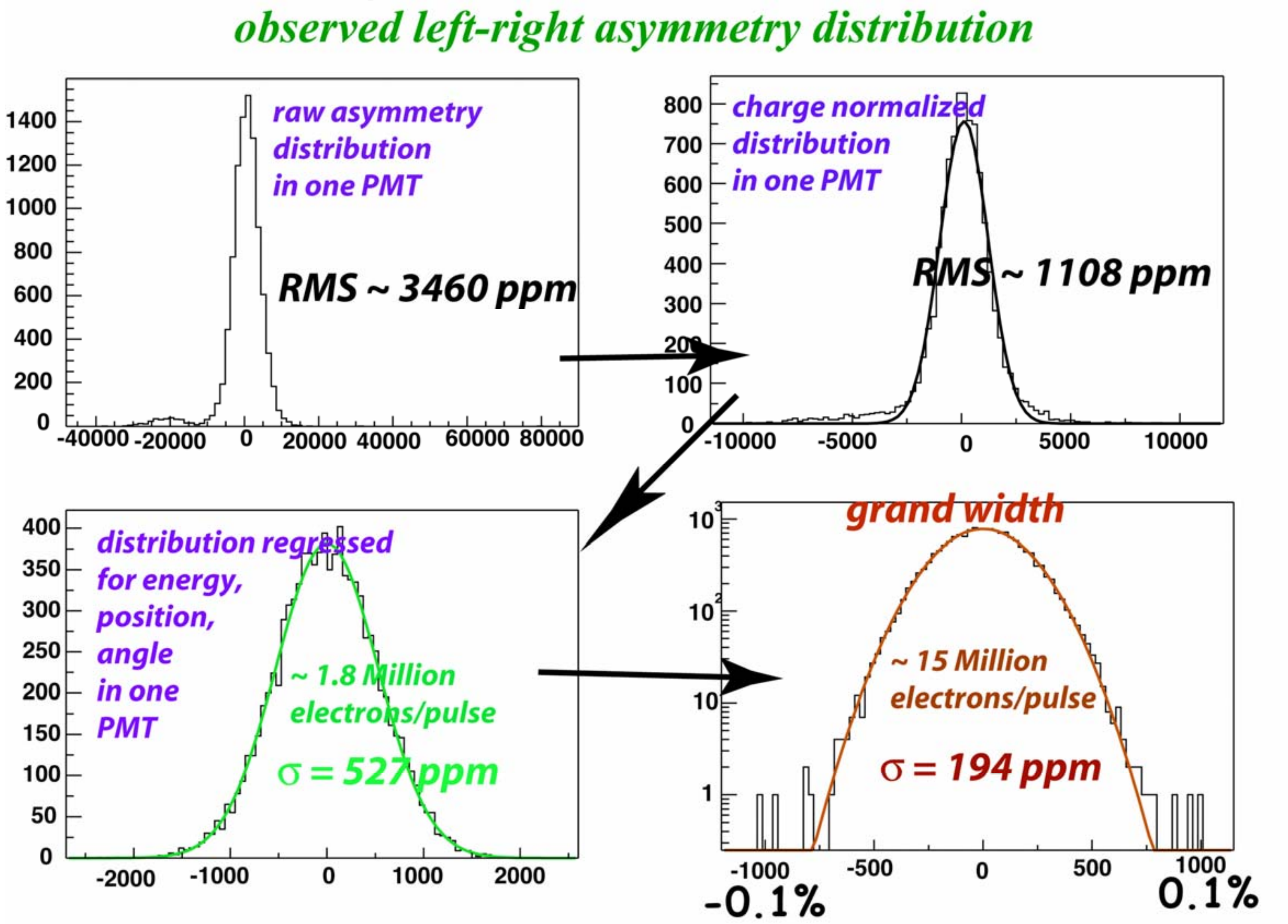
$$A_{PV} = \frac{1}{P_b \cdot \varepsilon} \, \frac{A_{raw} - \sum \Delta A_{bkg}}{1 - \sum f_{bkg}}$$

backgrounds

background dilutions

beam polarization, linearity

Moller Detector
Regression Corrections



In addition, independent analysis based on beam dithering

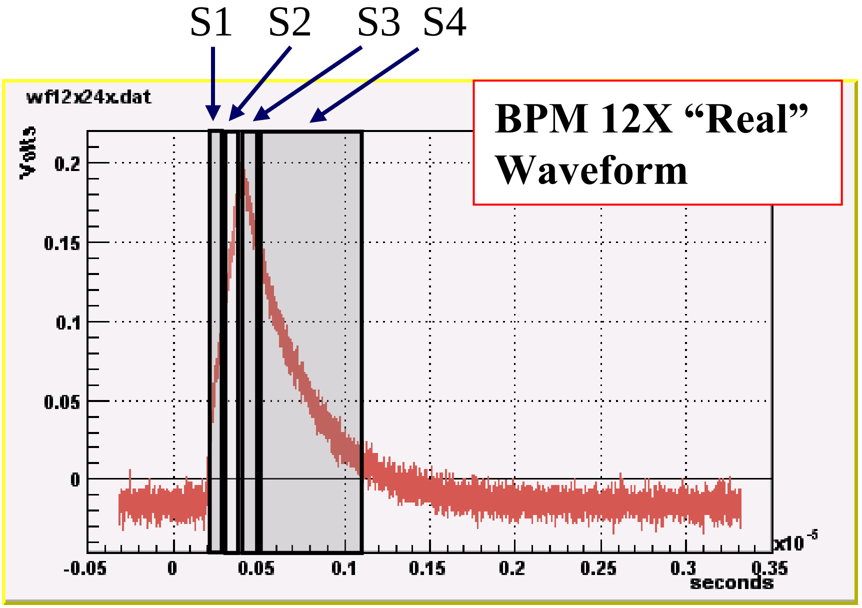
Raw Asymmetry Systematics

- First order systematic effects
  - False asymmetry in electronics
    - Measured to be smaller than 1 ppb
  - Errors in correction slopes
    - Measured by comparing two 60 Hz “timeslots”
    - Beam-induced asymmetries of ~1 ppm corrected to below stat errors of 50 ppb in multiple data samples
- Higher-order corrections
  - Beam size fluctuations
    - Measured by wire array
  - Correlation between beam asymmetry and pulse length (intra-spill asymmetries)
    - New electronics in Run III

SLICES: Temporal Beam Profile

- SLICES readout in 10 bit ADCs

  Q : bpm31Q (4)
  E : bpm12X (3)
  X : bpm41X (4)
  Y : bpm41Y (4)
  dX : bpm31X (4)
  dY : bpm31Y (4)

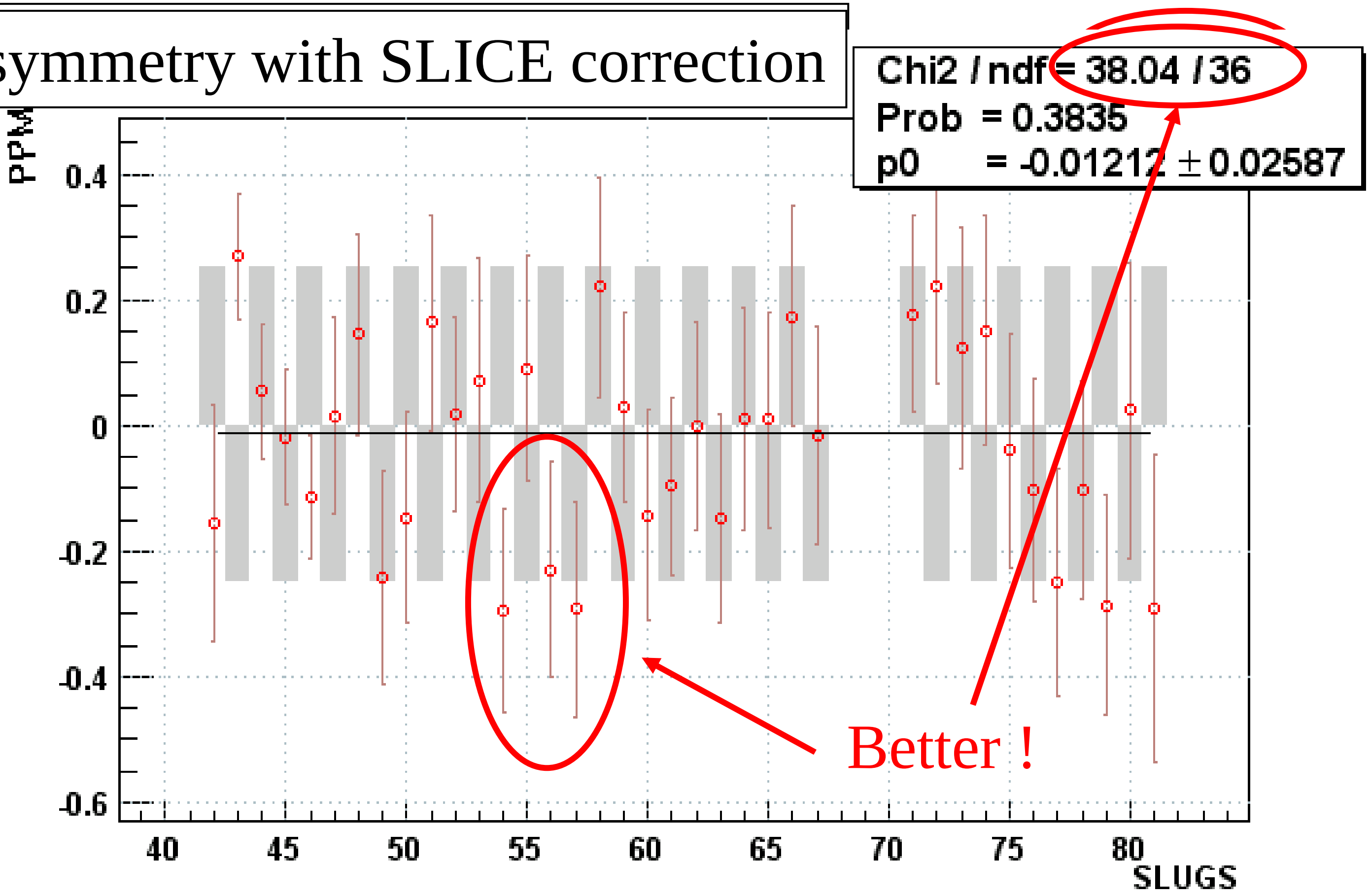


Integration time :
S1 : 0 -100 ns
S2 : 100-200 ns
S3 : 200-300 ns
S3 : 300-1000 ns

Additional Corrections

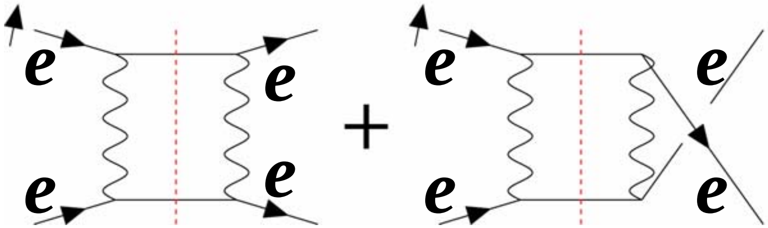
- OUT detector at edge of Møller acceptance most sensitive to beam systematics
- Use it to set limits on the grand asymmetry

OUT asymmetry with SLICE correction

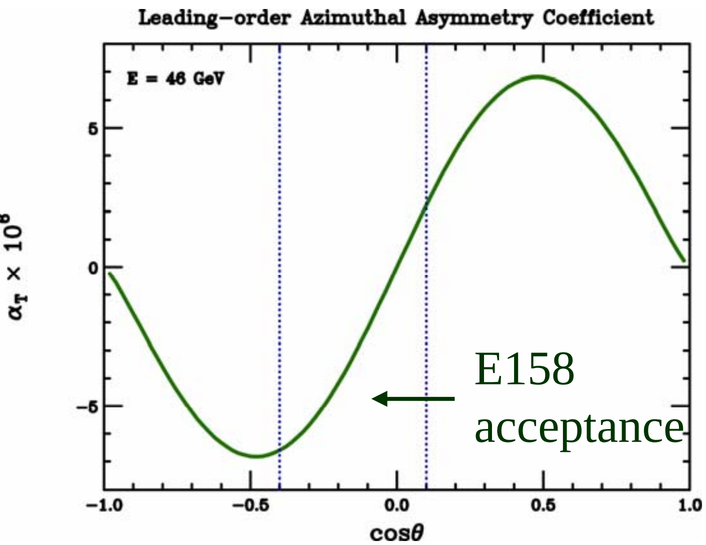


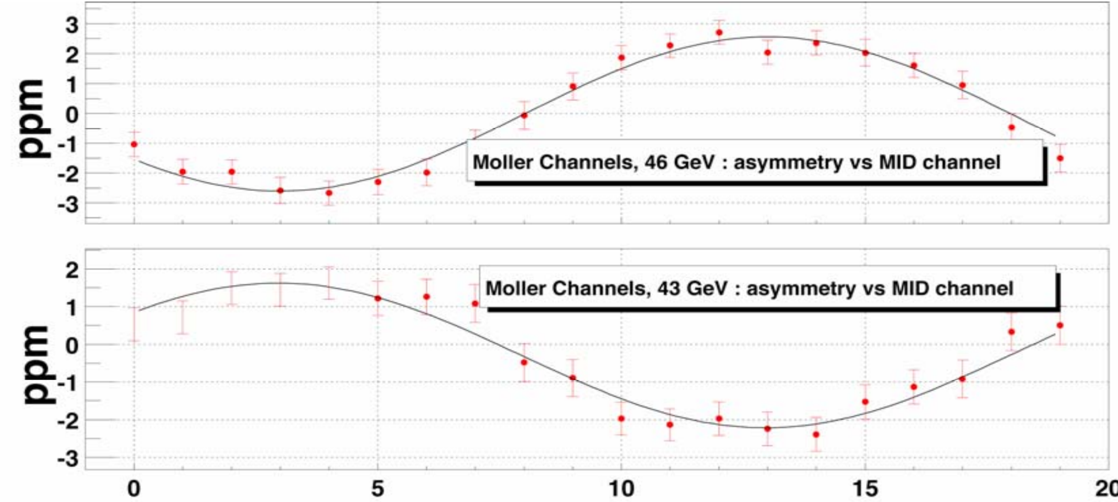
Better !

Transverse ee Asymmetry



$$A_T \propto \frac{\alpha m_e}{\sqrt{s}} \qquad \sqrt{s} \approx 200\, MeV$$





Prediction for 46 GeV: ~ -3.5 ppm

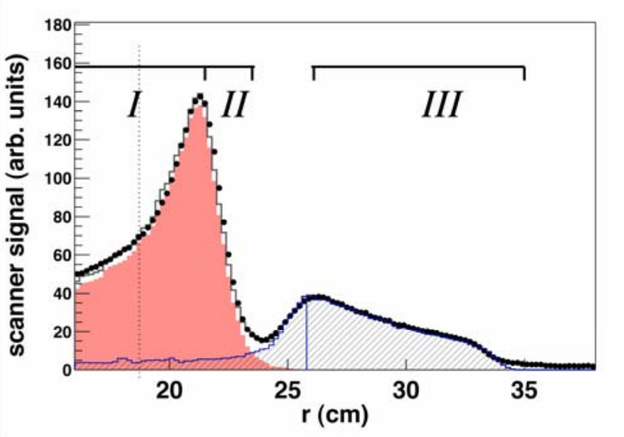
Observe ~ 2.5 ppm asymmetry
First measurement of single-spin transverse asymmetry in e-e scattering.

i) interesting ***signal***,
ii) potential ***background*** for A_{PV} measurement

Theory References:

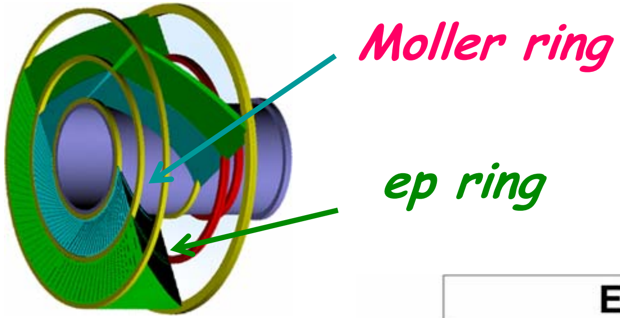
1. **A. O. Barut and C. Fronsdal, (1960)**
2. **L. L. DeRaad, Jr. and Y. J. Ng (1975)**
3. **Lance Dixon and Marc Schreiber:hep/ph-0402221**
   (Included bremsstrahlung corrections: few percent)

Transverse ep Asymmetry



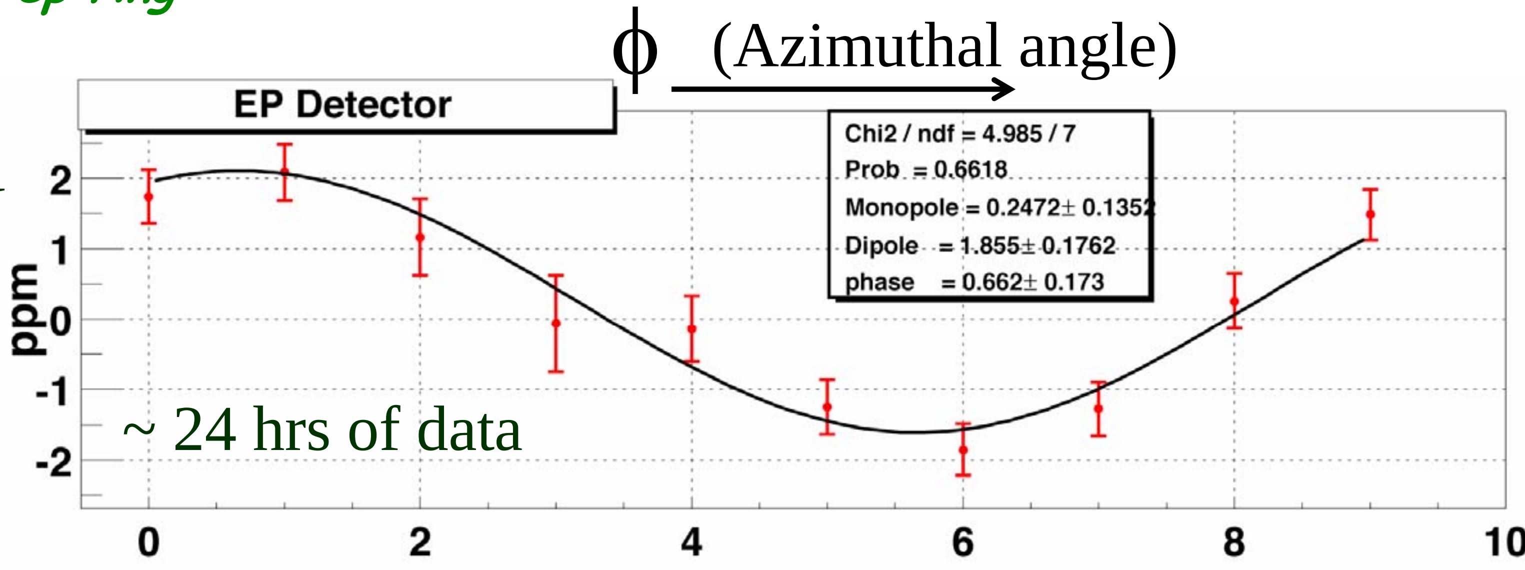
- Has the opposite sign! (preliminary!)
- ~ 25% inelastic ep
- Few percent pions (asymmetry small)

✓ Proton structure at E158 !



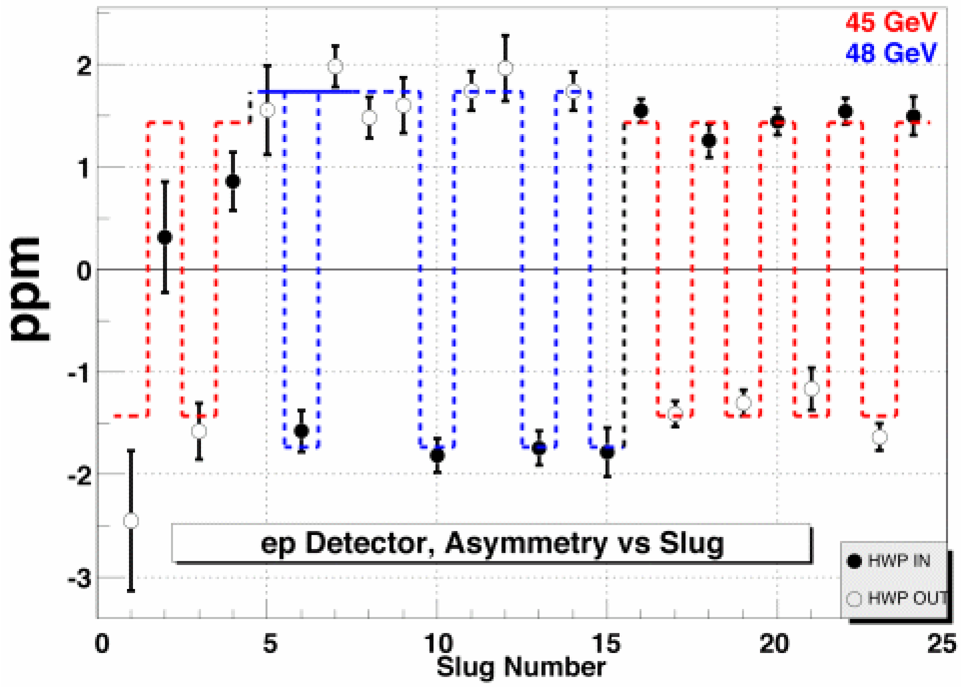
43 & 46 GeV

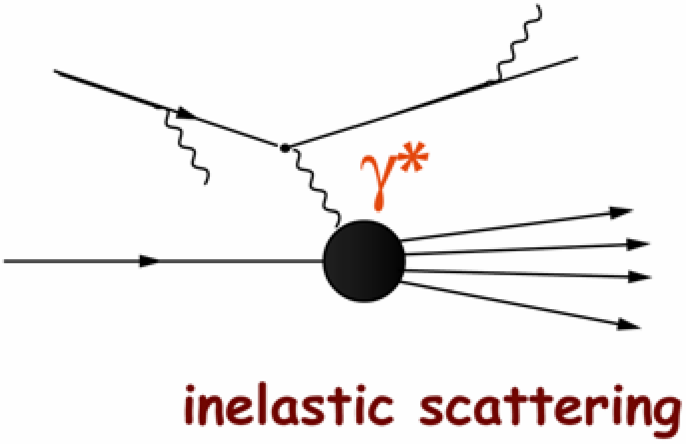
ep → ep



~ 24 hrs of data

Longitudinal ep Asymmetry





A_{RAW}(45 GeV) = -1.36 ± 0.05 ppm (stat. only)
A_{RAW}(48 GeV) = -1.70 ± 0.08 ppm (stat. only)

Ratio of asymmetries:

A_{PV}(48 GeV) /A_{PV}(45 GeV) = 1.25 ± 0.08 (stat) ± 0.03 (syst)

- **Consistent with expectations for inelastic ep asymmetry, but hard to interpret in terms of fundamental parameters**

Backgrounds for Møller Analysis

- Electron-proton elastic scattering
  - Well-understood at our kinematics
- Radiative electron-proton inelastic scattering
  - PV asymmetry unknown at our kinematics
  - Naïve quark model prediction O(1 ppm)
- Pion production
- Two-photon exchange events with transverse polarization
  - A bit of a surprise
- Other contributions at O(0.1%) level

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

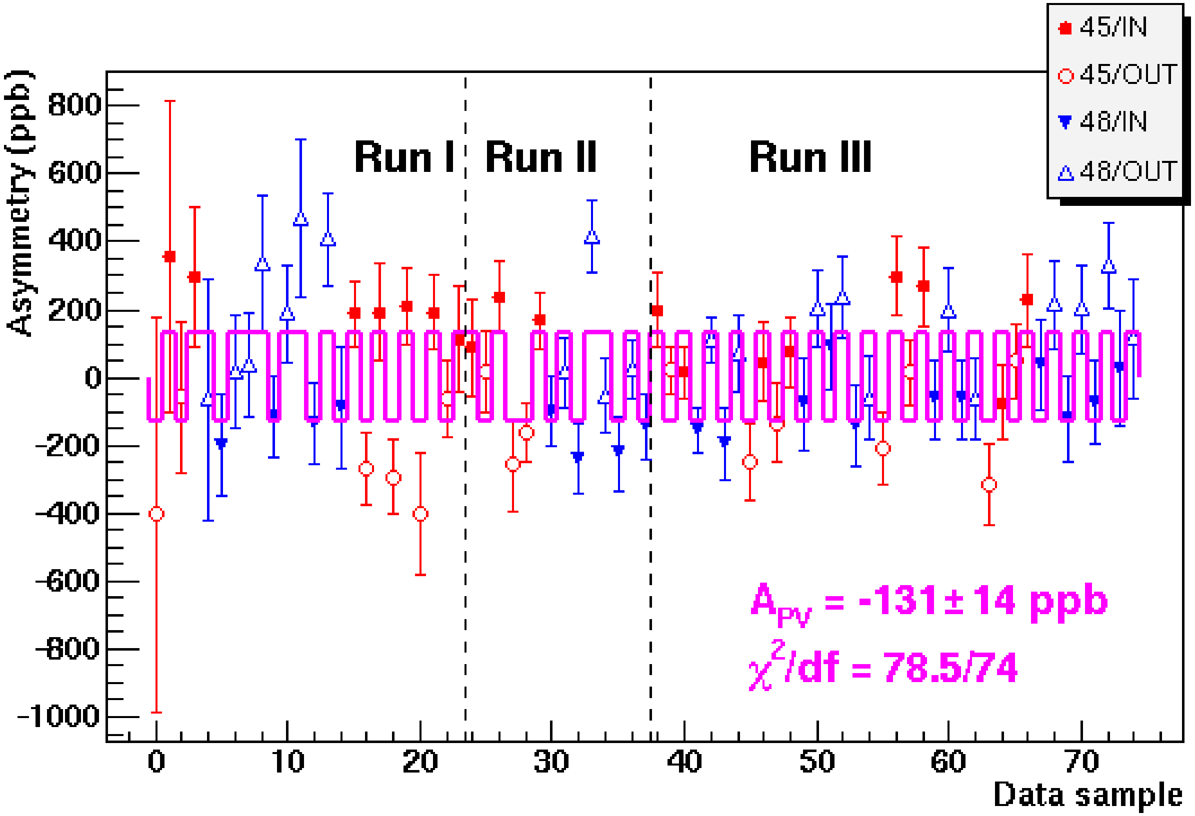
Source	ΔA (ppb)	f
Beam[1] (1st order)	(-) ± 1.4	-
Beam (higher order)	0 ± 3	-
Transverse polarization	-4 ± 2	-
$e^- + p \to e^- + p(\gamma)$	-7 ± 1	0.056 ± 0.007
$e^-(\gamma) + p \to e^- + X$	-22 ± 4	0.009 ± 0.001
Brem and Compton electrons	0 ± 1	0.005 ± 0.002
Pions	1 ± 1	0.001 ± 0.001
High energy photons	3 ± 3	0.004 ± 0.002
Synchrotron photons	0 ± 1	0.002 ± 0.0001
TOTAL	**-29 ± 7**	**0.077 ± 0.008**

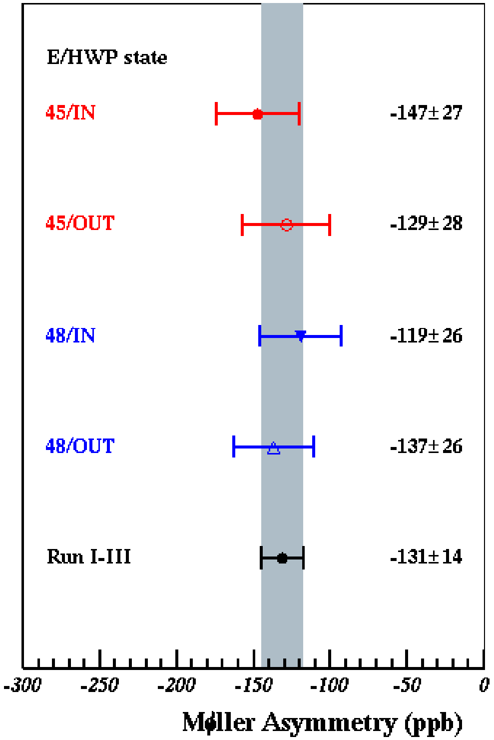
$$A_{PV} = \frac{1}{P_b \cdot \varepsilon} \cdot \frac{A_{raw} - \sum \Delta A}{1 - \sum f}, \quad P_b = 0.89 \pm 0.04,^{2} \quad \varepsilon(\text{linearity}) = 0.99 \pm 0.01$$

[1] Beam asymmetry correction to A_{exp} is (-9.7 ± 1.4) ppb

[2] Beam polarization measured using polarized foil target; same spectrometer used with dedicated movable detector

Moller Asymmetry, A_{PV}





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

-131± 14 (stat) ± 10 (syst) parts per billion *(preliminary)*

Significance of parity nonconservation in Møller scattering: 8.3σ

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

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

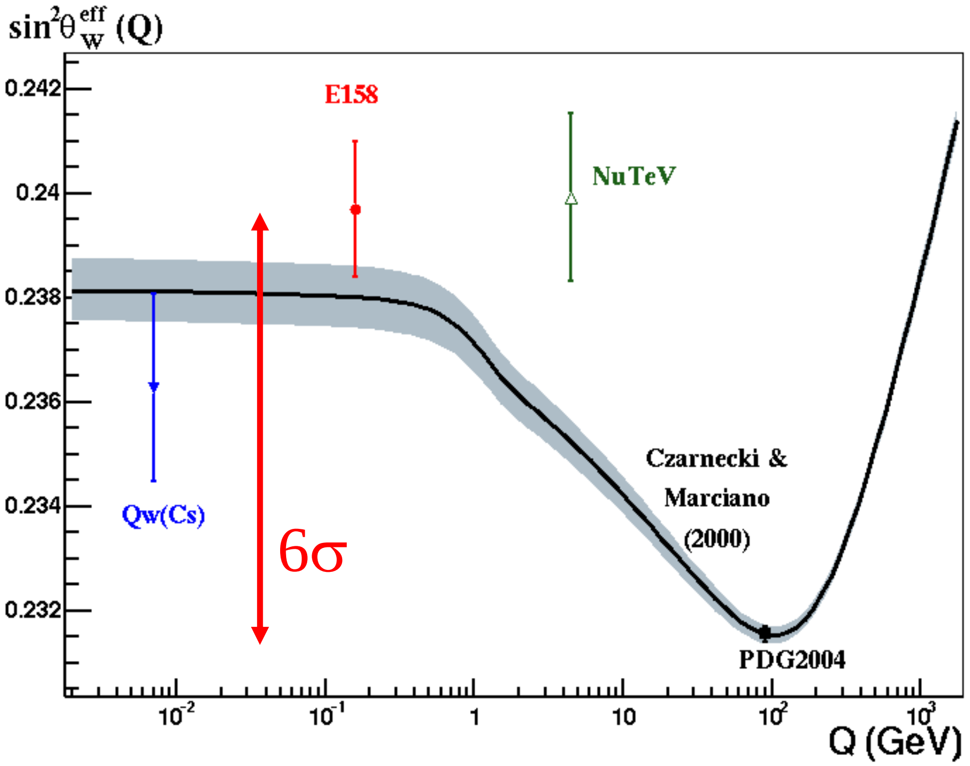
where:

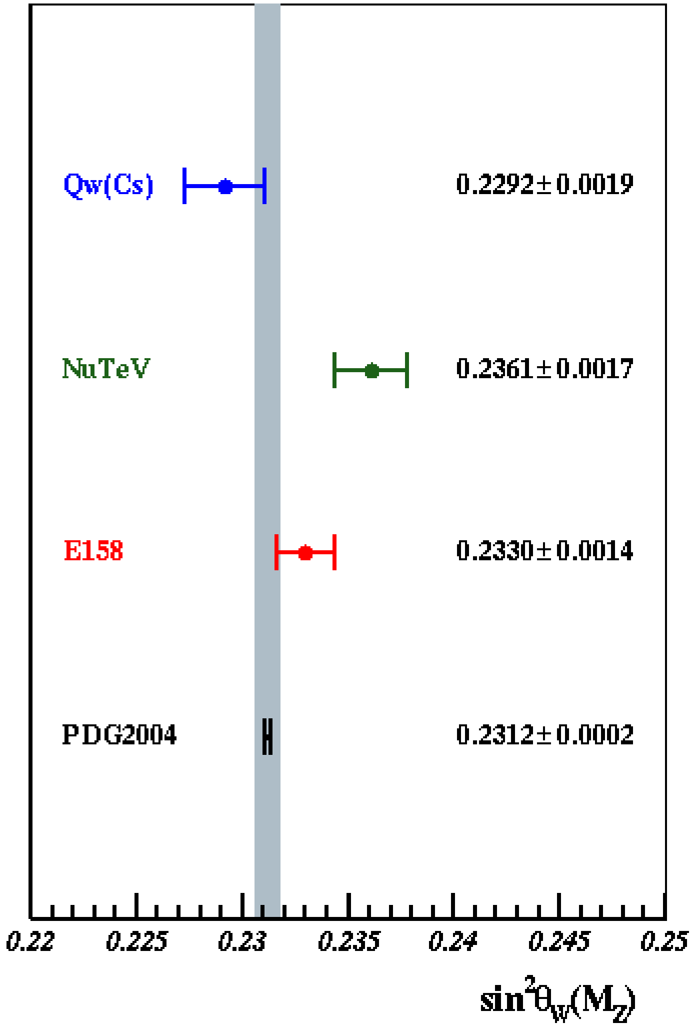
$-\frac{G_F Q^2}{\sqrt{2}\pi\alpha}\cdot\frac{1-y}{1+y^4+(1-y)^4}$ is an analyzing power factor; depends on kinematics and experimental geometry. Uncertainty is 1.5%. ($y = Q^2/s$)

$\boldsymbol{F_{QED}}$ = (1.01 ± 0.01) 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)

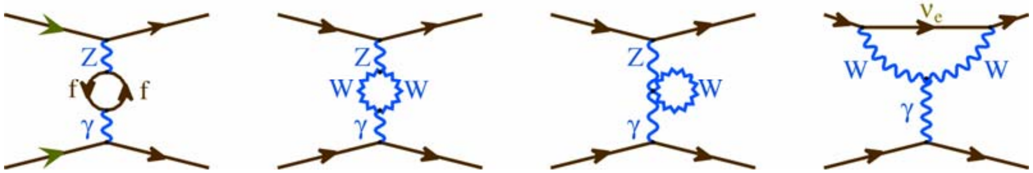
θ_W^{eff} is derived from an effective coupling constant, g_{ee}^{eff}, for the **Z**ee coupling, with loop and vertex electroweak corrections absorbed into g_{ee}^{eff}

Weak Mixing Angle Results





Q^2-dependence of θ_W



E158 final result: Phys.Rev.Lett.95:081601,2005

Future Low Energy Experiments / Proposals

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 ($\delta\sin^2\theta_W = 0.0014$ is current precision)

JLAB Q_{weak} A_{PV} (elastic e-p) $\delta\left(\sin^2\theta_W\right) \approx 0.0007$
JLAB 12-GeV upgrade:
  A_{PV} (DIS eD, ep) $\delta\left(\sin^2\theta_W\right) \approx 0.0009$
  A_{PV} (e-e)? $\delta\left(\sin^2\theta_W\right) \approx 0.0003$
Fixed target at ILC?? A_{PV} (e-e) $\delta\left(\sin^2\theta_W\right) \approx 0.0001$ (Snowmass 2001 study)

Elucidating the new Standard Model

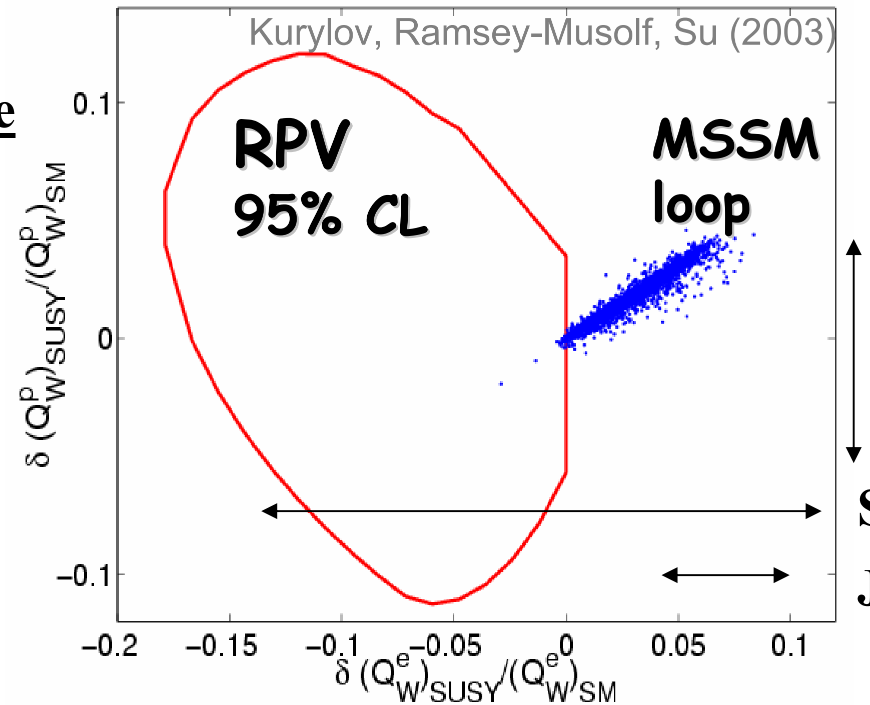
MSSM? RPV SUSY? Extra Z’

Leptoquarks? Extra dimensions?

Low energy +
High energy

Precision measurements important!

one example



JLAB Q_{weak} ±1σ

SLAC E158 ±1σ

JLAB ee(12 GeV) ±1σ

Summary: Physics results from E-158

Electro-weak parity violation

- *first observation of parity violation in Møller scattering (8.3σ)*
- *running of the weak mixing angle established (6.2σ)*
- *Probing TeV-scale physics: ~10 TeV limit on Λ_{LL},*
  ~1 TeV limit on SO(10) Z'
- *inelastic e-p asymmetry consistent with quark picture*

Transverse asymmetries

- *First measurement of e-e transverse asymmetry (QED)*
- *e-p transverse asymmetry measured (QCD)*

Weak Mixing Angle

Final Result using all data (Q^2 = 0.026 GeV^2)

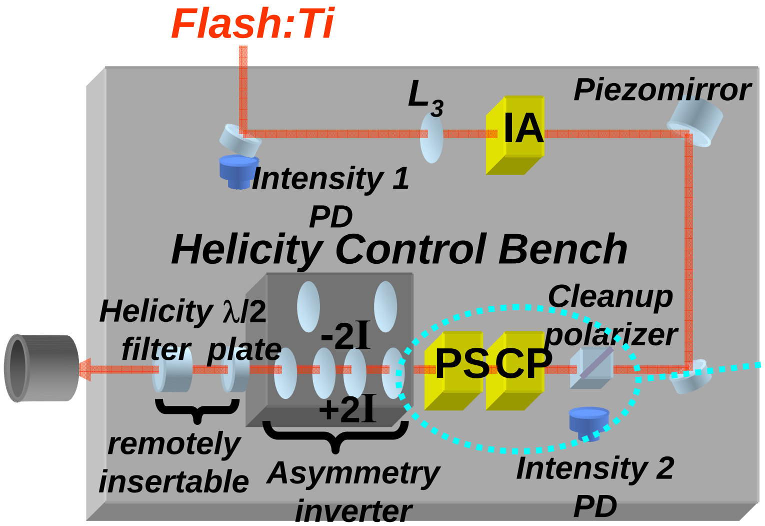
$$A_{PV}\text{(Moller)} = (-131 \pm 14 \pm 10) \text{ ppb}$$

$$\sin^2\theta_W^{eff} = 0.2397 \pm 0.0010 \text{ (stat)} \pm 0.0008 \text{ (syst)}$$

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

Backup Slides

Laser Polarization Control And Analysis



Stokes parameters for laser polarization:

$$s_1 = \cos(\delta_{CP}) = \frac{X-Y}{X+Y}$$

$$s_2 = \sin(\delta_{CP})\sin(\delta_{PS}) = \frac{U-V}{U+V}$$

$$s_3 = \sin(\delta_{CP})\cos(\delta_{PS}) = \frac{R-L}{R+L}$$

Electric Field Vector after PS Cell in Jones Matrix notation:

$$|E\rangle = \begin{bmatrix} \sin\left(\delta_{CP}/2\right) \\ e^{i\left(\pi/2+\delta_{PS}\right)}\cos\left(\delta_{CP}/2\right) \end{bmatrix}$$

$$\left(s_1^2 + s_2^2\right) + s_3^2 = L^2 + C^2 = 1$$

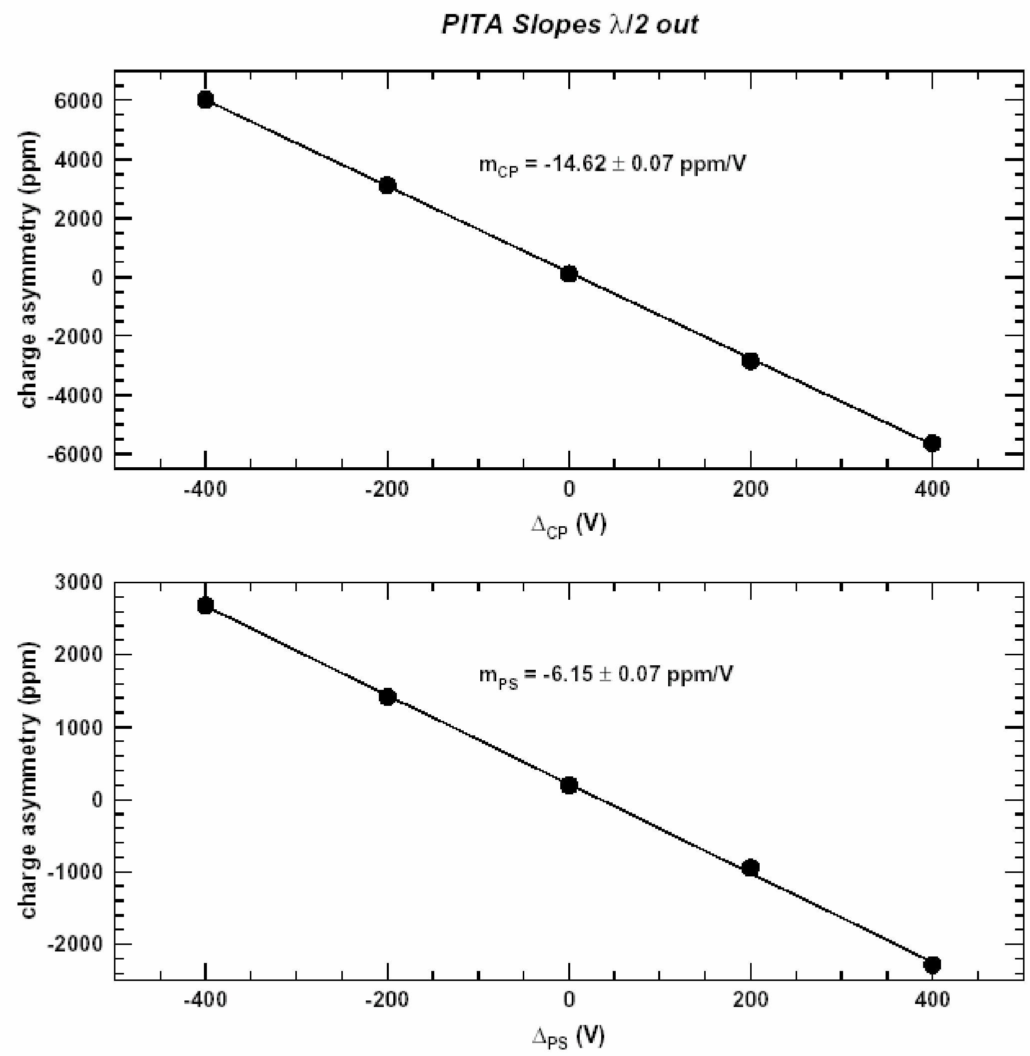
(ex. C=0.998, L=0.063)

Allow for imperfect Pockels cells and phase shifts in downstream optics:

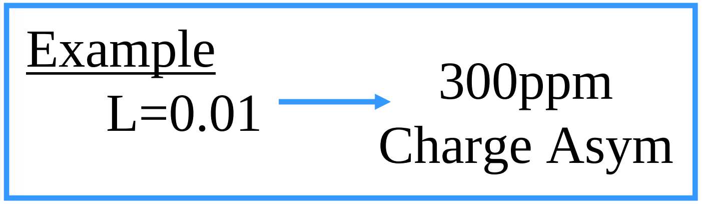
	Left Pulse	**Right Pulse**
δ_{CP}	$-\pi/2 - \alpha_{CP} + \Delta_{CP}$	$+\pi/2 + \alpha_{CP} + \Delta_{CP}$
δ_{PS}	$- \alpha_{PS} + \Delta_{PS}$	$- \alpha_{PS} + \Delta_{PS}$
s_1	$\sim - \alpha_{CP} + \Delta_{CP}$	$\sim - \alpha_{CP} - \Delta_{CP}$
s_2	$\sim - \alpha_{PS} + \Delta_{PS}$	$\sim - \alpha_{PS} - \Delta_{PS}$

Δ_{CP}, Δ_{PS} introduce significant linear polarization asymmetries

Charge Asymmetry due to anisotropic strain*



Sensitive to
linear polarization
In laser light



Recall, $A_{PV} \approx -0.1ppm$
and want ~ppb systematic errors!

V_{QW} = 2800V

*Reference: R.A. Mair et al., Phys. Lett. **A212**, 231 (1996)

Techniques for minimizing ${}^{beam}A_{LR}$'s

At the start:

→ ~1000 ppm, ~2 μm systematics

1) Passive setup:

- Helicity bits delayed by 1 pulse and RF modulated prior to broadcast.
- Collimation of laser beam and minimization of spot size at CP, PS cells.
- Image CP, PS cells onto the cathode.
- OTS brought to atmospheric pressure to avoid stress-induced birefringence in windows.
- Select Pockels cells and carefully align to minimize systematics.
- Null A_Q with Δ_{CP}, Δ_{PS}.

→ ~100 ppm, ~0.5 μm

2) Active suppression with feedbacks:

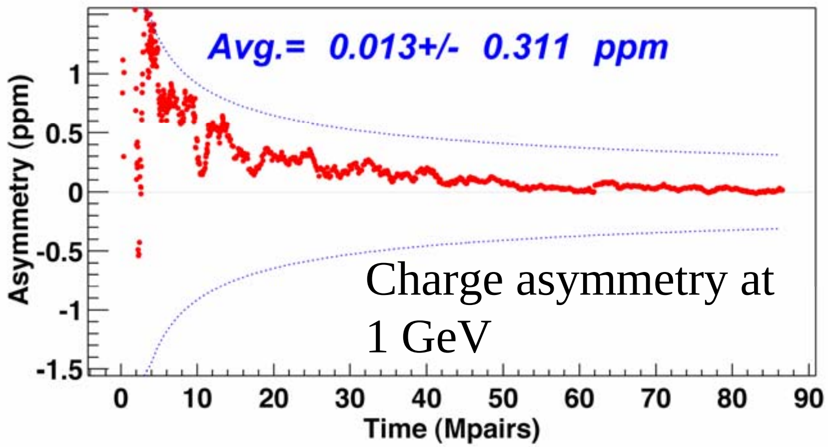
- IA loop & POS loop.
- Double-feedback loop.

→ <100 ppb, <100 nm

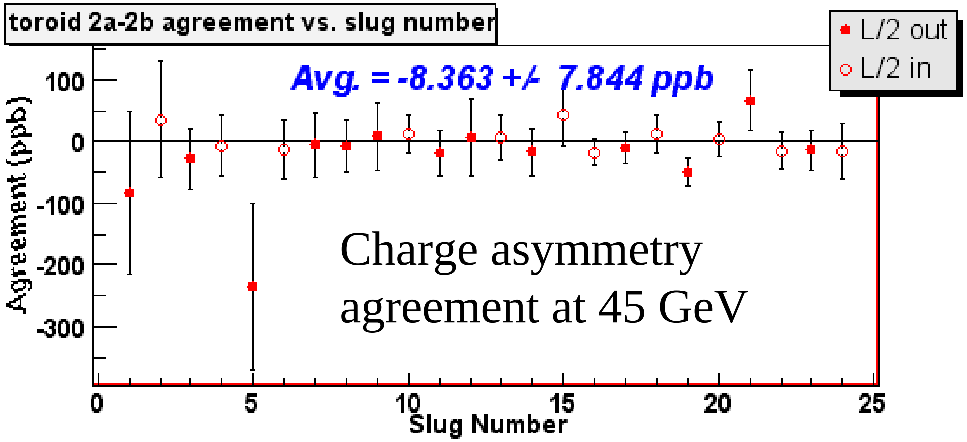
3) Slow reversals:

- Flip certain classes of asymmetries while leaving everything else unchanged.
  - λ/2 plates (2)
  - energy (g-2 precession)
  - asymmetry inverter
- These can provide cancellation of systematics, but they also serve as a cross-check that systematics are well-understood. Multiple reversals are essential!

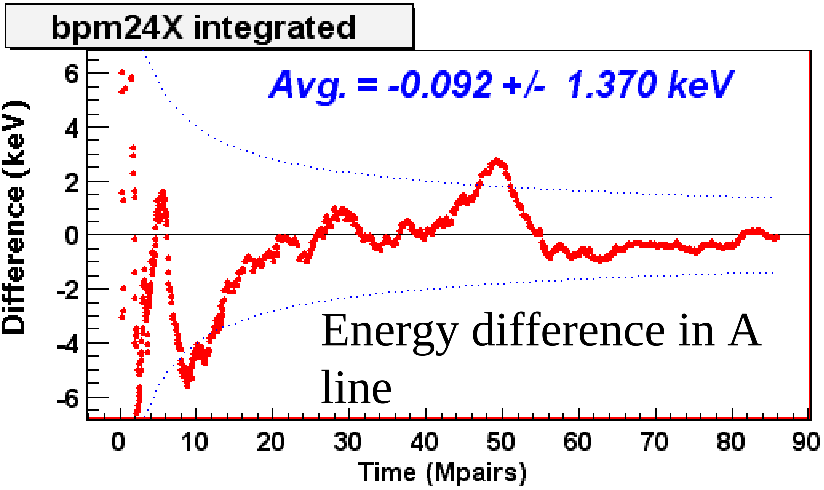
Beam Asymmetries



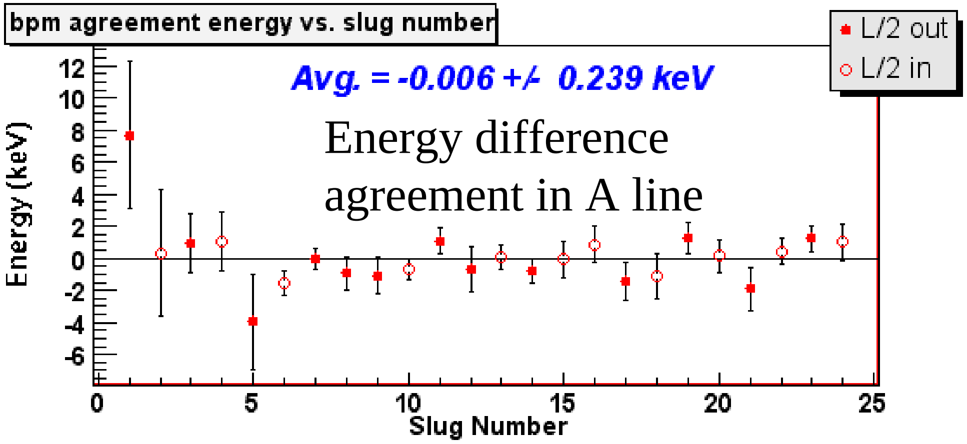
Charge asymmetry at 1 GeV



Charge asymmetry agreement at 45 GeV



Energy difference in A line



Energy difference agreement in A line

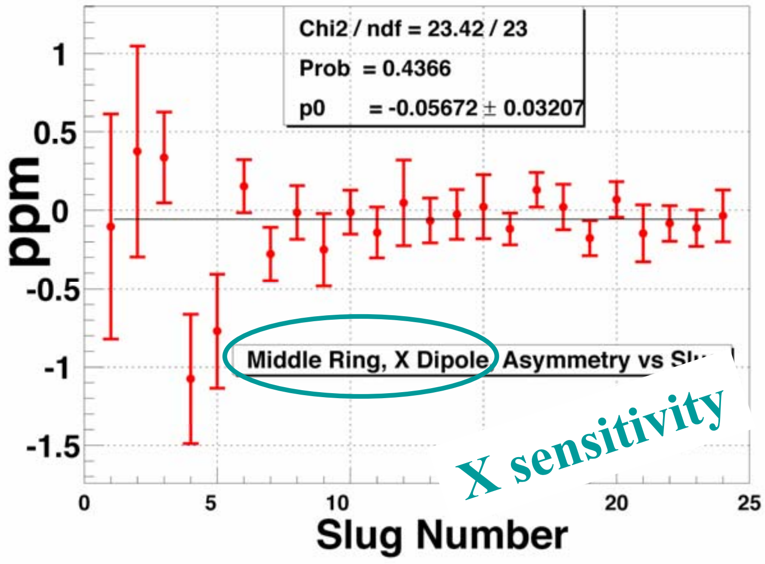
Position differences < 20 nm

Position agreement ~ 1 nm

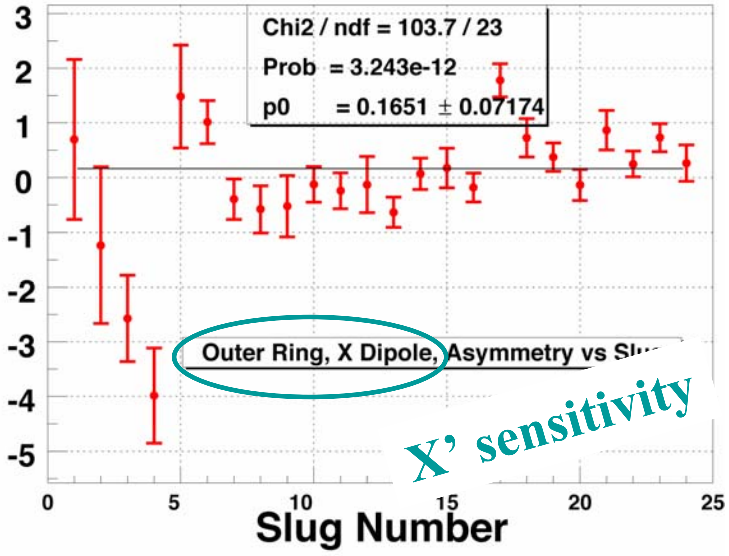
Beam Systematics in Run 1

Beam Parameter	Beam Monitors	Monitor Agreement	MOLLER correction Agreement
E	BPMs 12X, 24X	(0.09 ± 0.24) keV	(0.5 ± 1.3) ppb
X	BPMs 41X, 42X	(0.9 ± 0.6) nm	(0.8 ± 0.5) ppb
Y	BPMs 41Y, 42Y	(-1.0 ± 1.0) nm	(-0.2 ± 0.2) ppb
X’	BPMs 31X, 32X	(-2.3 ± 2.1) nm	(-2.0 ± 2.0) ppb
Y’	BPMs 31Y, 32Y	(0.9 ± 1.0) nm	(0.7 ± 0.8) ppb
Q	Toroids 2a, 3a	(-2.9 ± 5.3) ppb	(-2.9 ± 5.3) ppb

But, some detector ‘monitors’ show poor χ^2 and non-zero mean values.

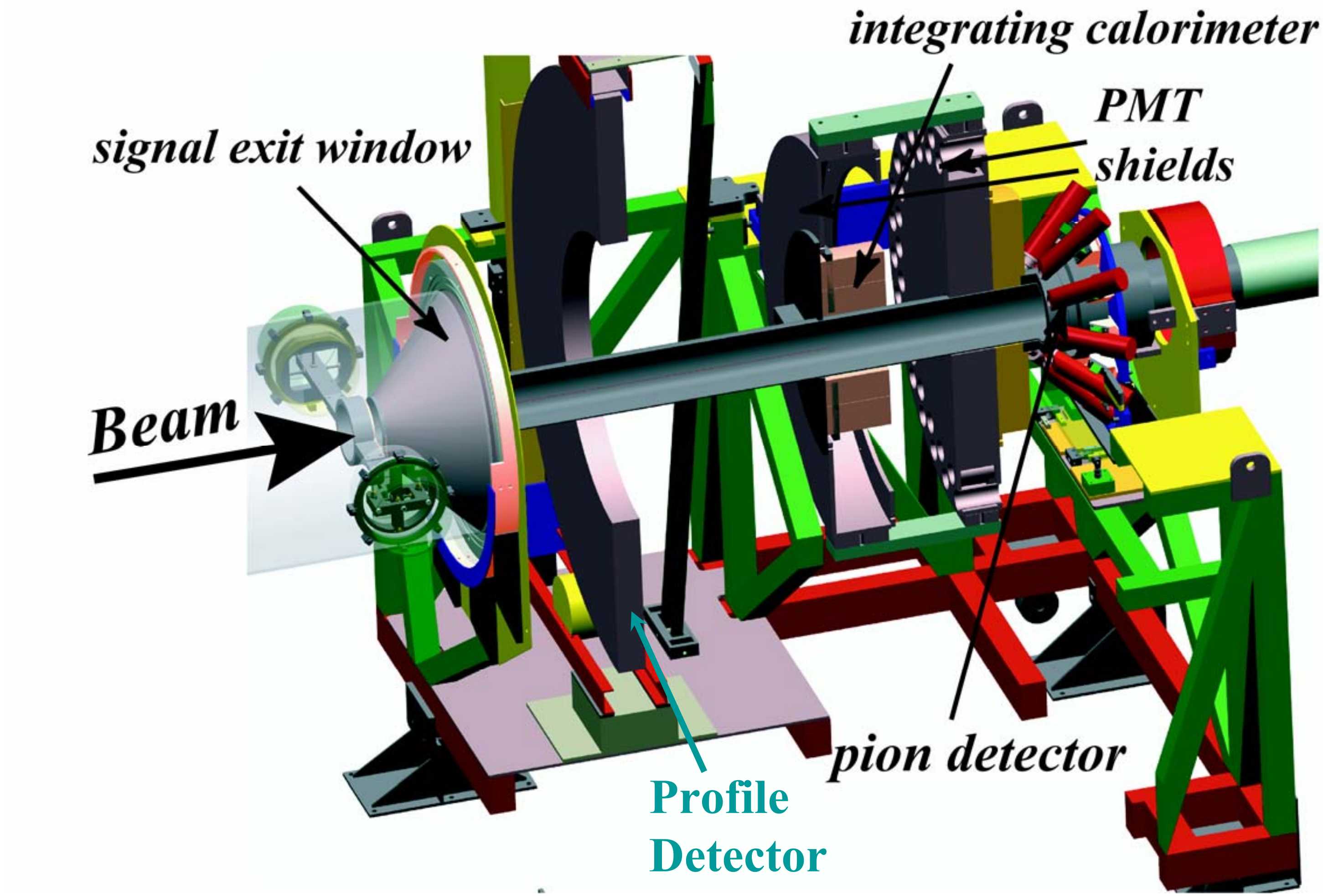


X sensitivity



X’ sensitivity

Detectors



Profile Detector wheel

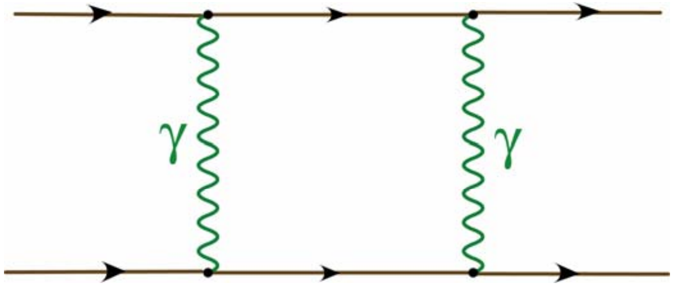
Luminosity Monitor region

Transverse Asymmetries

Beam-Normal Asymmetry in elastic electron scattering

- ☞ **Electron beam polarized transverse to beam direction**

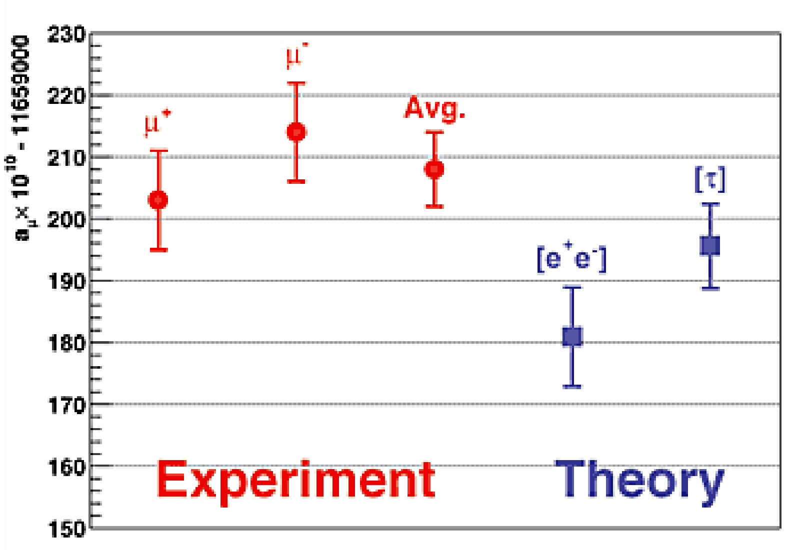
$$A_T \equiv \frac{2\pi}{\sigma^{\uparrow}+\sigma^{\downarrow}} \frac{d(\sigma^{\uparrow}-\sigma^{\downarrow})}{d\phi} \propto \vec{S}_e \bullet (\vec{k}_e \times \vec{k}'_e) \propto \sin\phi$$

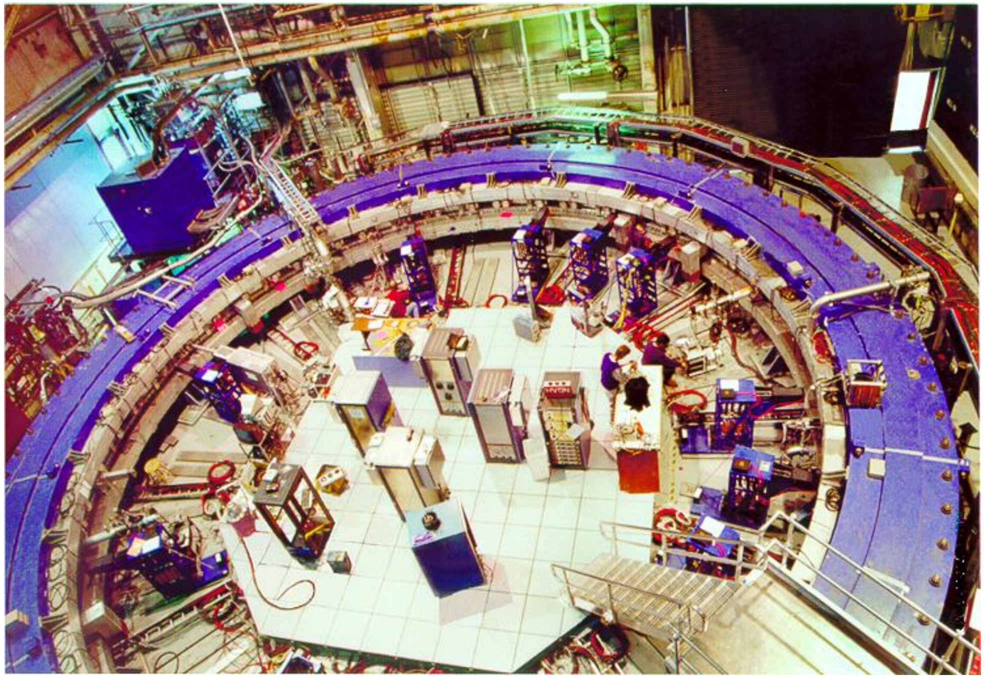


Interference between one- and two-photon exchange

$$A_T \propto \frac{\alpha m_e}{\sqrt{s}} = \frac{\alpha m_e}{\sqrt{2m_{\text{target}} E_{\text{beam}}}}$$

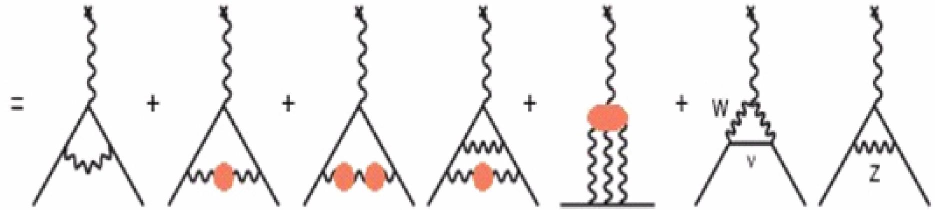
Brookhaven $(g\text{-}2)_\mu$



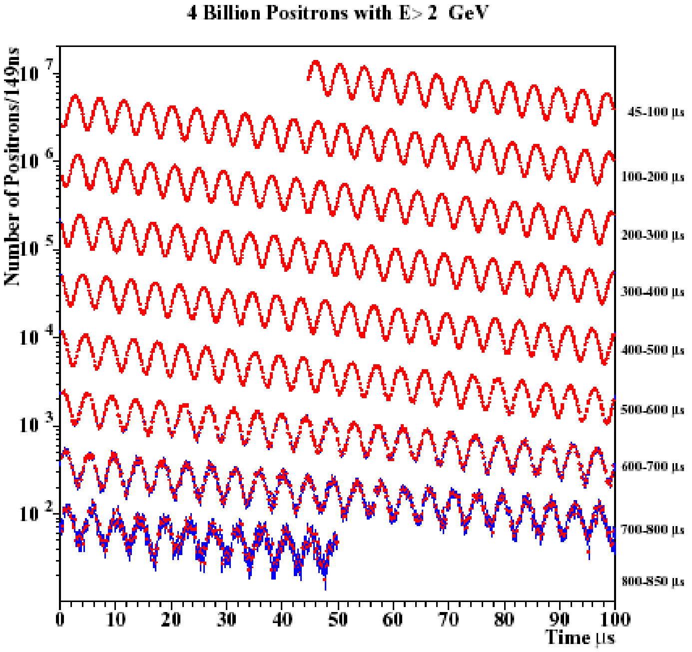


$$\vec{\mu}_s = g_s\left(\frac{e}{2m}\right)\vec{s} \qquad a_\mu = \frac{(g_s-2)}{2}$$

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



$$\boxed{\frac{a_\mu(\text{BNL E821})-a_\mu(\text{SM})}{a_\mu(\text{SM})} = \left[\begin{array}{l}2.2\pm0.5(\text{expt})\\ \qquad \pm0.7(\text{theory})\end{array}\right]\text{ppm}}$$



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

2.7σ

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

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

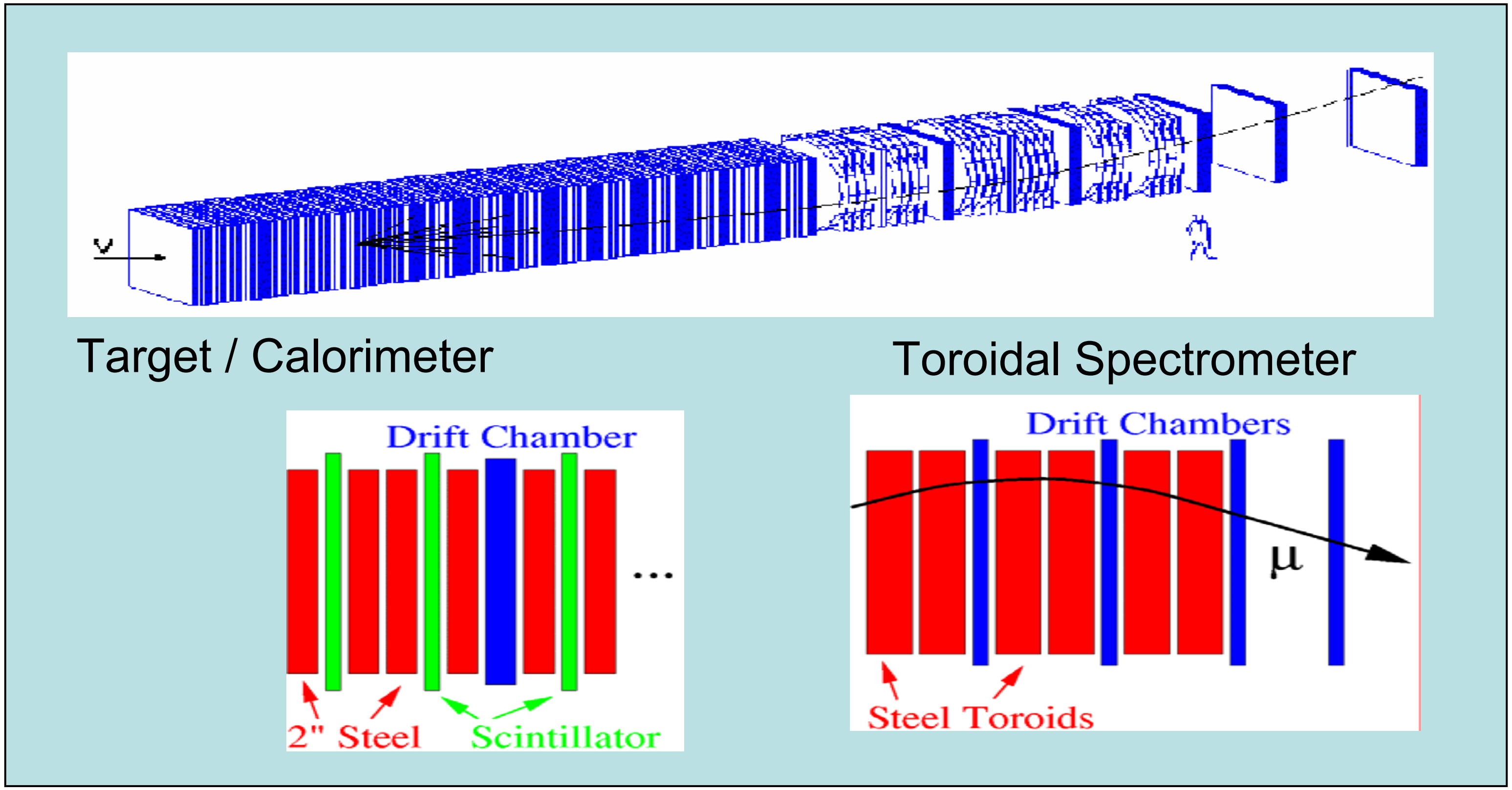
➢ Need reduced error in hadronic corrections:

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

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

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

NuTeV Neutrino Experiment



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

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

Standard Model prediction is 0.2227
(3σ deviation)

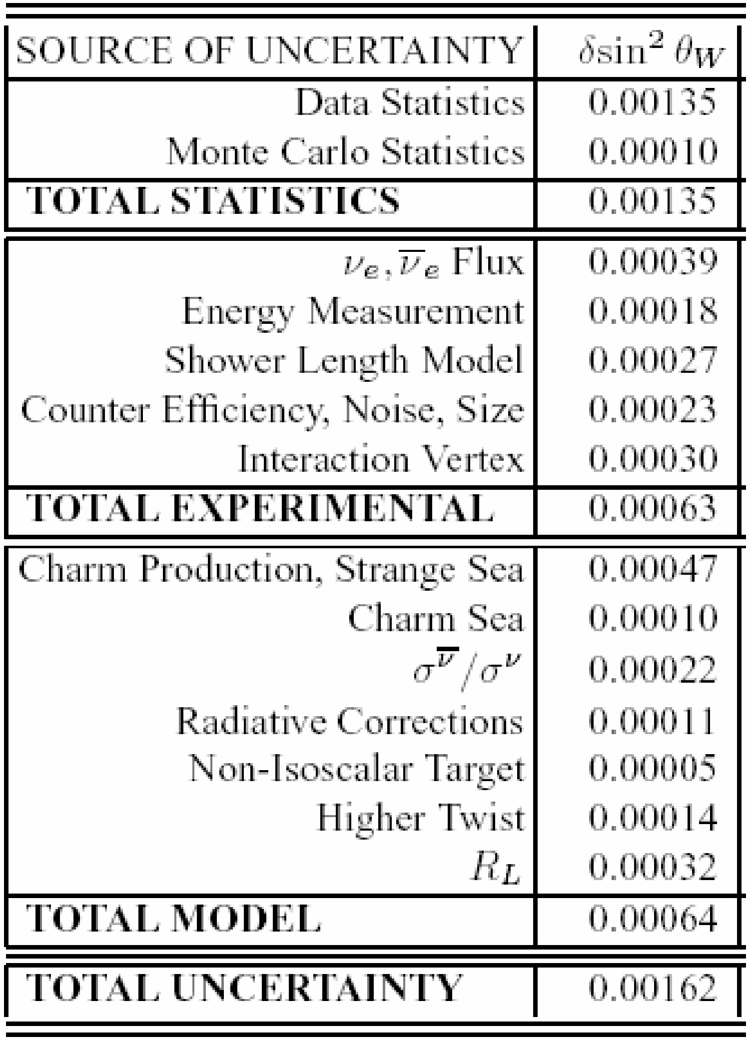
NuTeV Result:

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

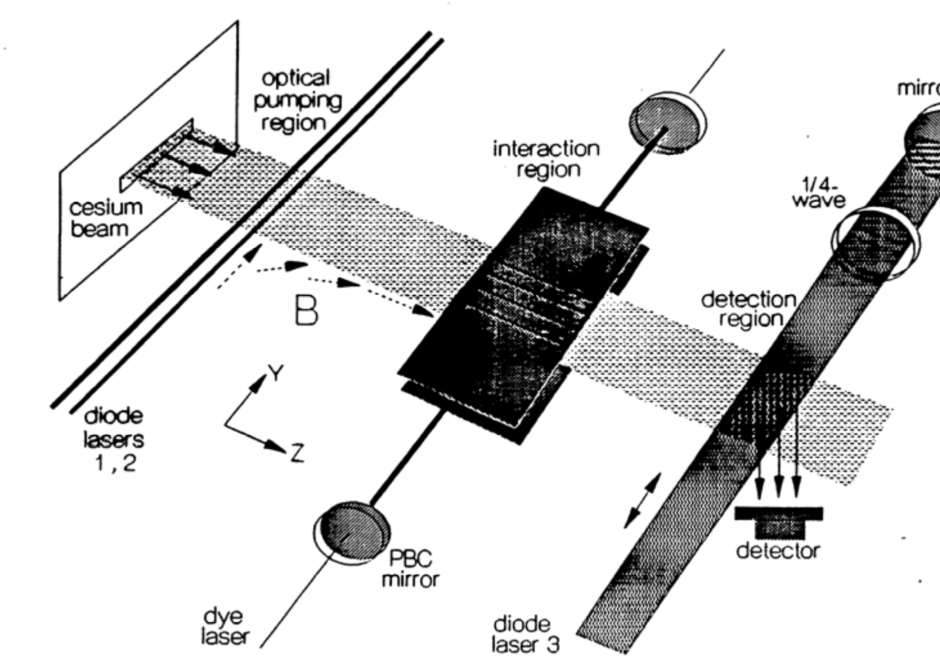


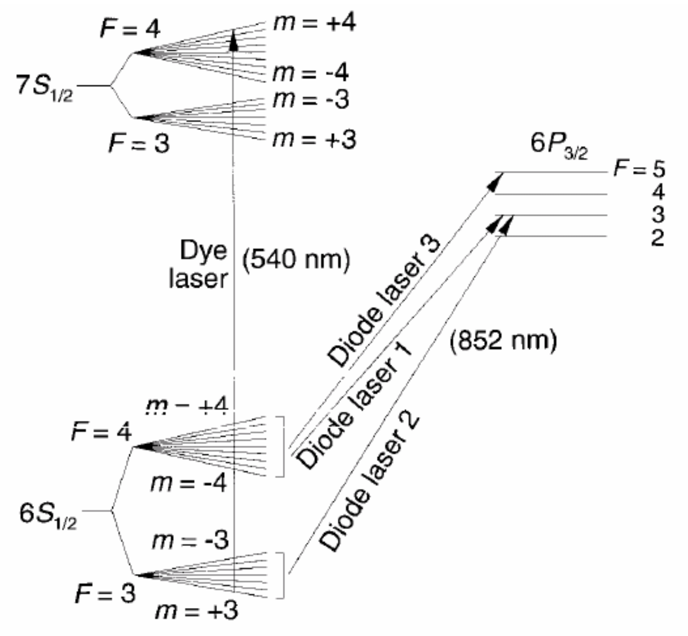
SOURCE OF UNCERTAINTY	$\delta\sin^2\theta_W$
Data Statistics	0.00135
Monte Carlo Statistics	0.00010
TOTAL STATISTICS	0.00135
$\nu_e, \overline{\nu}_e$ Flux	0.00039
Energy Measurement	0.00018
Shower Length Model	0.00027
Counter Efficiency, Noise, Size	0.00023
Interaction Vertex	0.00030
TOTAL EXPERIMENTAL	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

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

Jury is still out…

APV: Boulder Cs Experiment





- measure APV component of $6s \rightarrow 7s$ transition in $^{133}\mathrm{Cs}$;
  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!)

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

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

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

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)

A_{PV}(Møller) at JLAB 12 GeV-upgrade

(slide from K. Kumar, JLAB review April ‘05)

E’: 3-6 GeV

θ_{lab} = 0.53°-0.92°

A_{PV} = 40 ppb

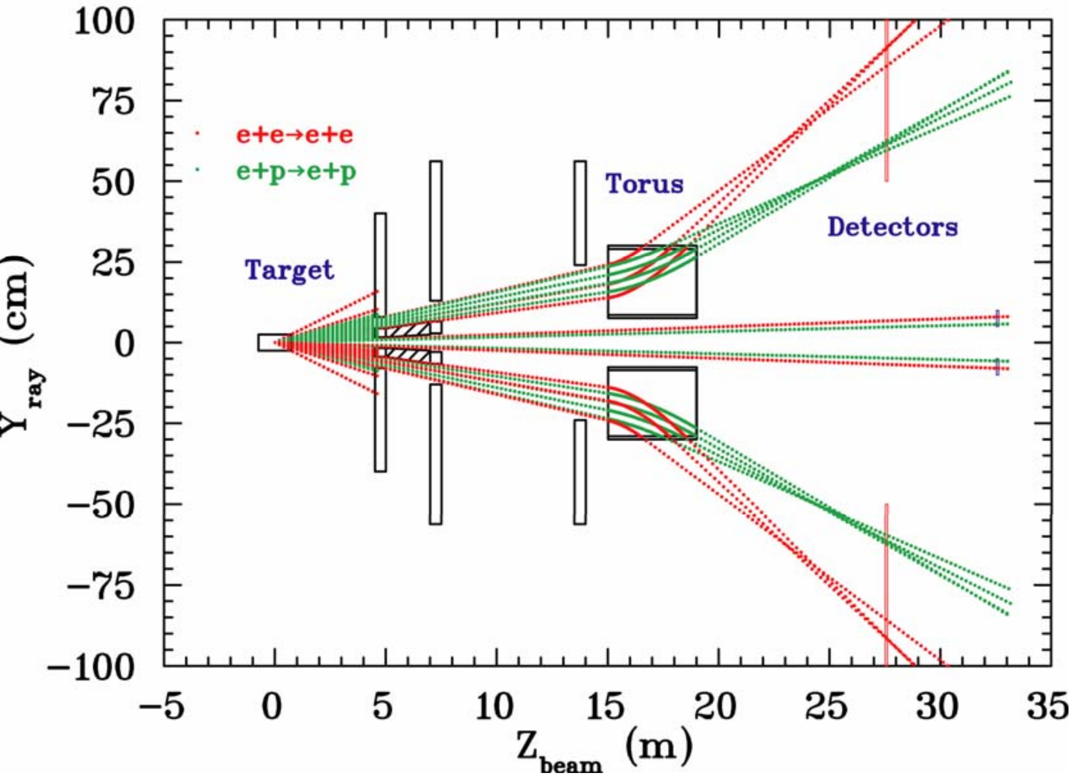
I_{beam} = 90 μA

150 cm LH_2 target

4000 hours

$\delta(A_{PV})$=0.58 ppb

Toroidal spectrometer → *ring focus*



- ***Beam systematics: steady progress (E158 Run III: 3 ppb)***
- ***Focus alleviates backgrounds:***
  $ep \rightarrow ep(\gamma)$, $ep \rightarrow eX(\gamma)$
- ***Radiation-hard integrating detector***
- ***Normalization requirements similar to other planned experiments***
- ***Cryogenics, density fluctuations and electronics will push the state-of-the-art***