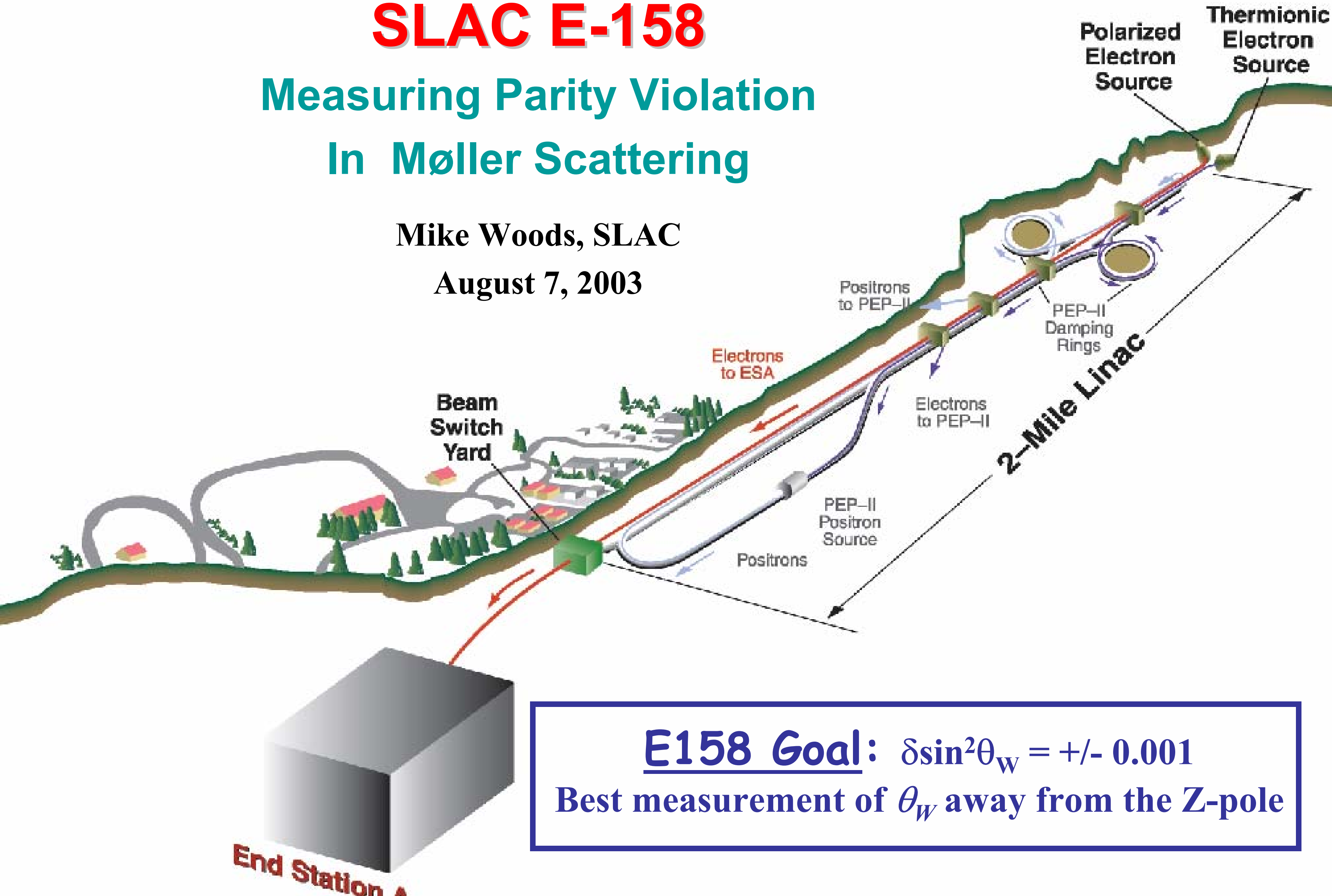
First Results from SLAC E-158

Measuring Parity Violation In Møller Scattering

Mike Woods, SLAC

August 7, 2003



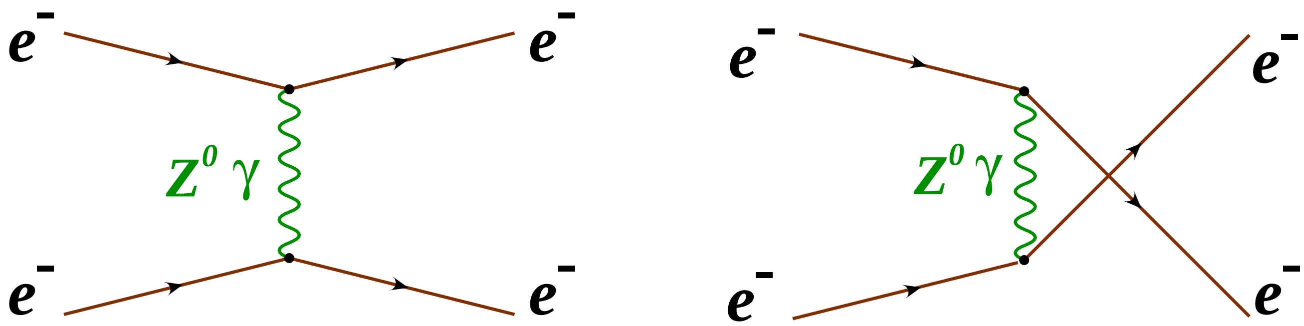
E158 Goal: $\delta\sin^2\theta_W = +/- 0.001$

Best measurement of θ_W away from the Z-pole

Outline

- Physics Motivation
- E158 Beam and Beam Monitors
- LH_2 Target and Spectrometer
- Detectors
- Analysis
- Preliminary Results for Run 1
- Outlook

Parity Violation in Moller Scattering



$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

For a polarized electron beam and an unpolarized electron target,

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

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

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

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

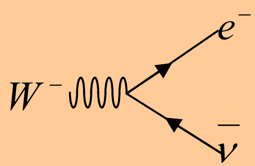
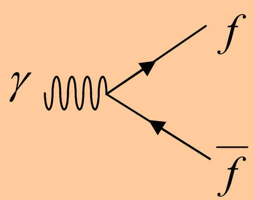
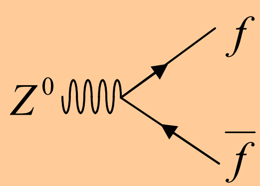
Parity Violation, Weak Mixing Angle

Electroweak Theory:

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

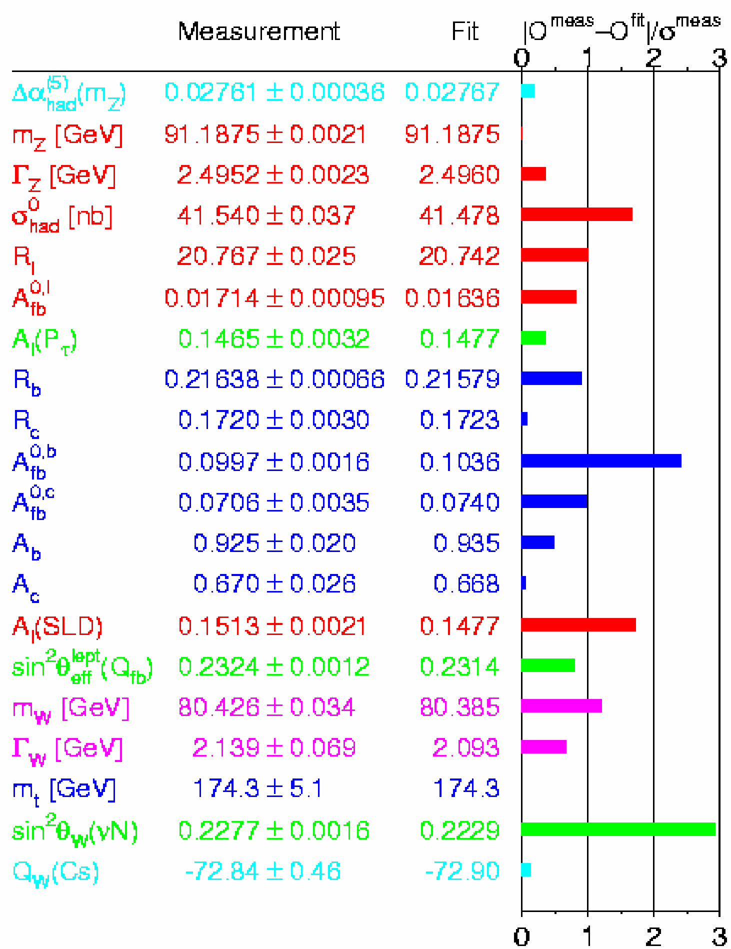
$SU(2)_L$ coupling constant is g
U(1) coupling constant is g'

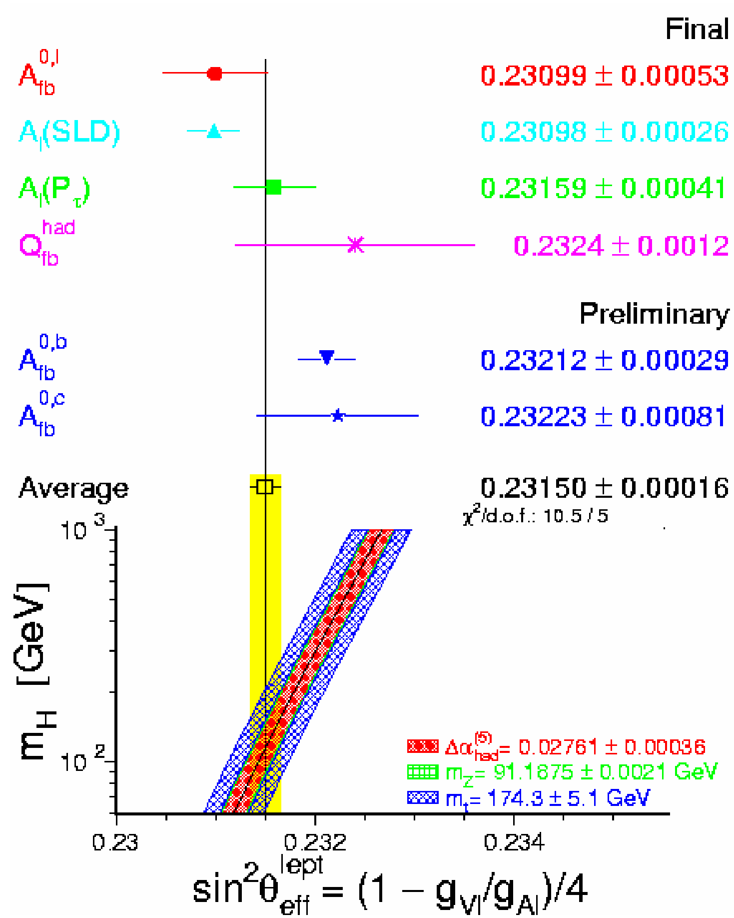
A_1^μ, A_2^μ are charged fields and correspond to W^+, W^- particles
A_3^μ, B^μ are neutral and can mix, giving the Z^0 and γ particles
Weak mixing angle: $g' = g \tan\theta_W$

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

World Electroweak Data

LEPEWWG Summary: Summer 2003





World Electroweak Data

LEPEWWG Summary: Summer 2003

$\chi^2/\mathrm{dof} \sim 27.3/15$

Leptonic and hadronic Z couplings seem inconsistent

Probability ~ 3%

World Electroweak Data

Perhaps the Standard Model is breaking

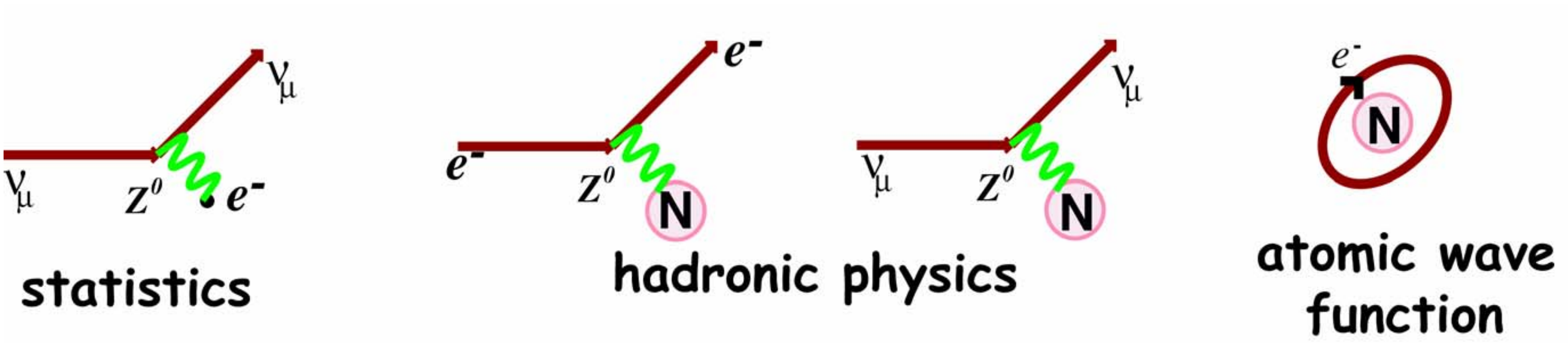
$$\chi^2/\mathrm{dof} \sim 27.3/15$$

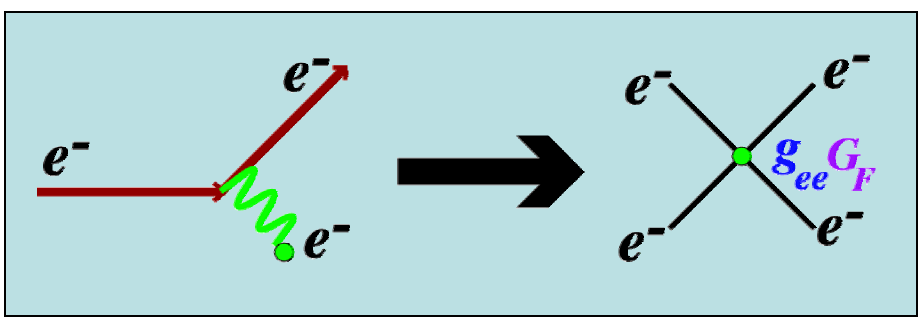
Leptonic and hadronic
Z couplings seem inconsistent

Probability ~ 3%

Perhaps there are bigger effects elsewhere

Low Q^2 Measurements of θ_W

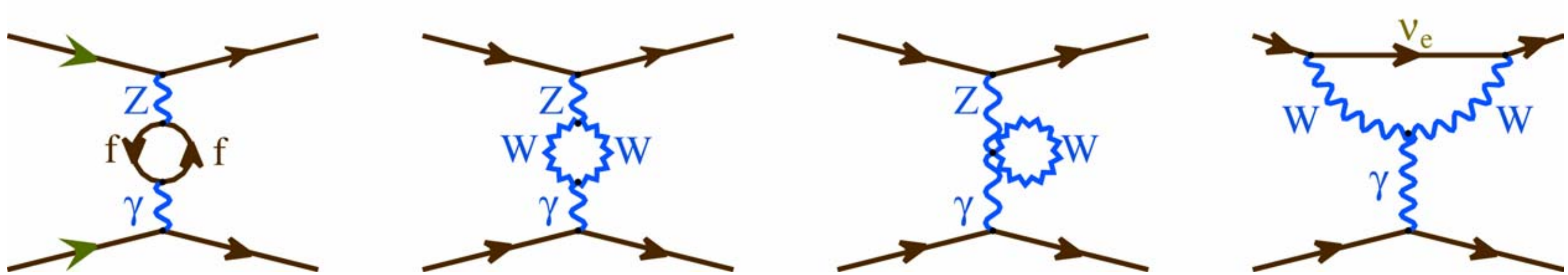


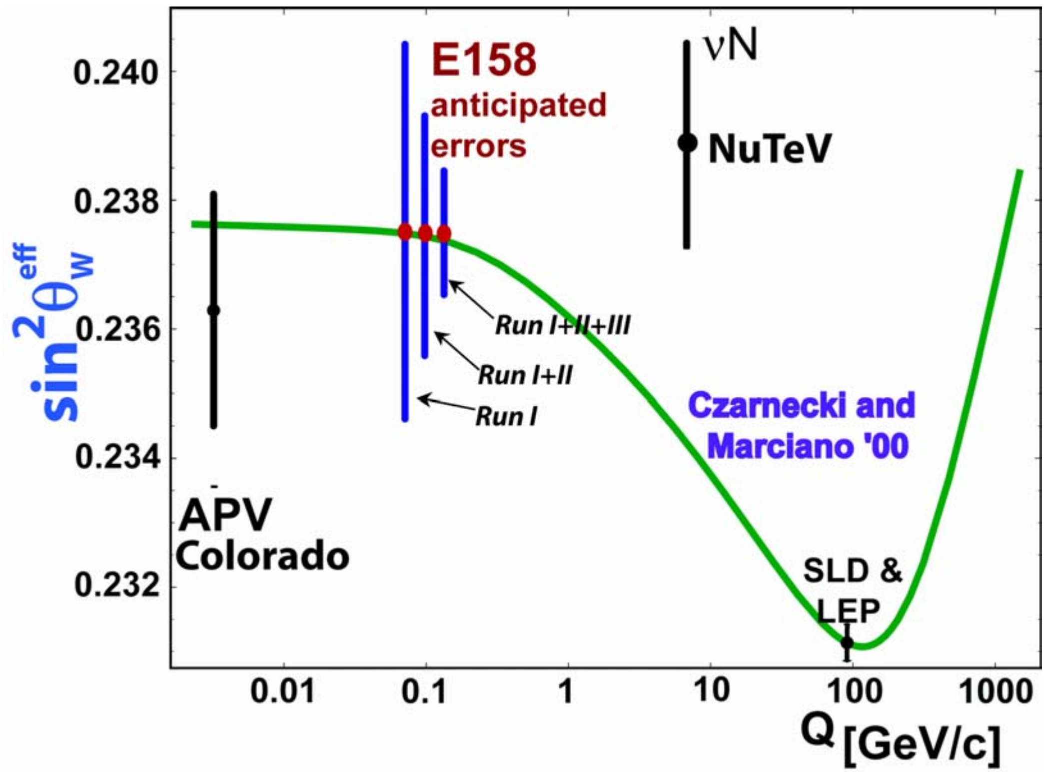


Purely leptonic reaction

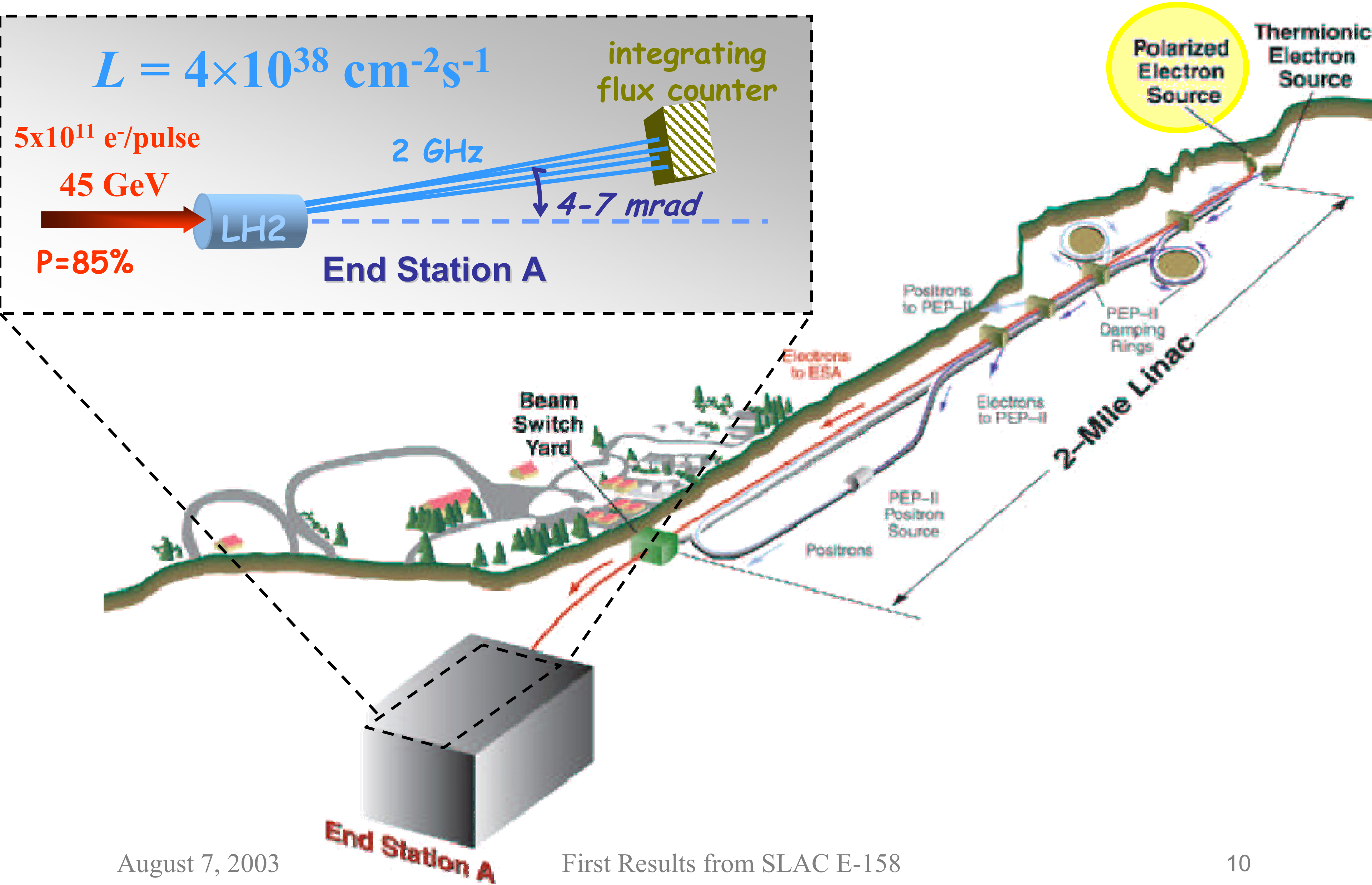
$$g_{ee} \sim 1 - 4\sin^2\theta_W$$

Q^2-dependence of θ_W

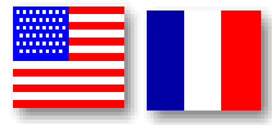




SLAC E-158


$L = 4\times10^{38}$ cm^{-2}s^{-1}
integrating flux counter
5×10^{11} e^-/pulse
45 GeV
2 GHz
LH2
4-7 mrad
P=85%
End Station A
Polarized Electron Source
Thermionic Electron Source
Positrons to PEP-II
PEP-II Damping Rings
Electrons to ESA
Electrons to PEP-II
Beam Switch Yard
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

7 Ph.D. Students
60 physicists

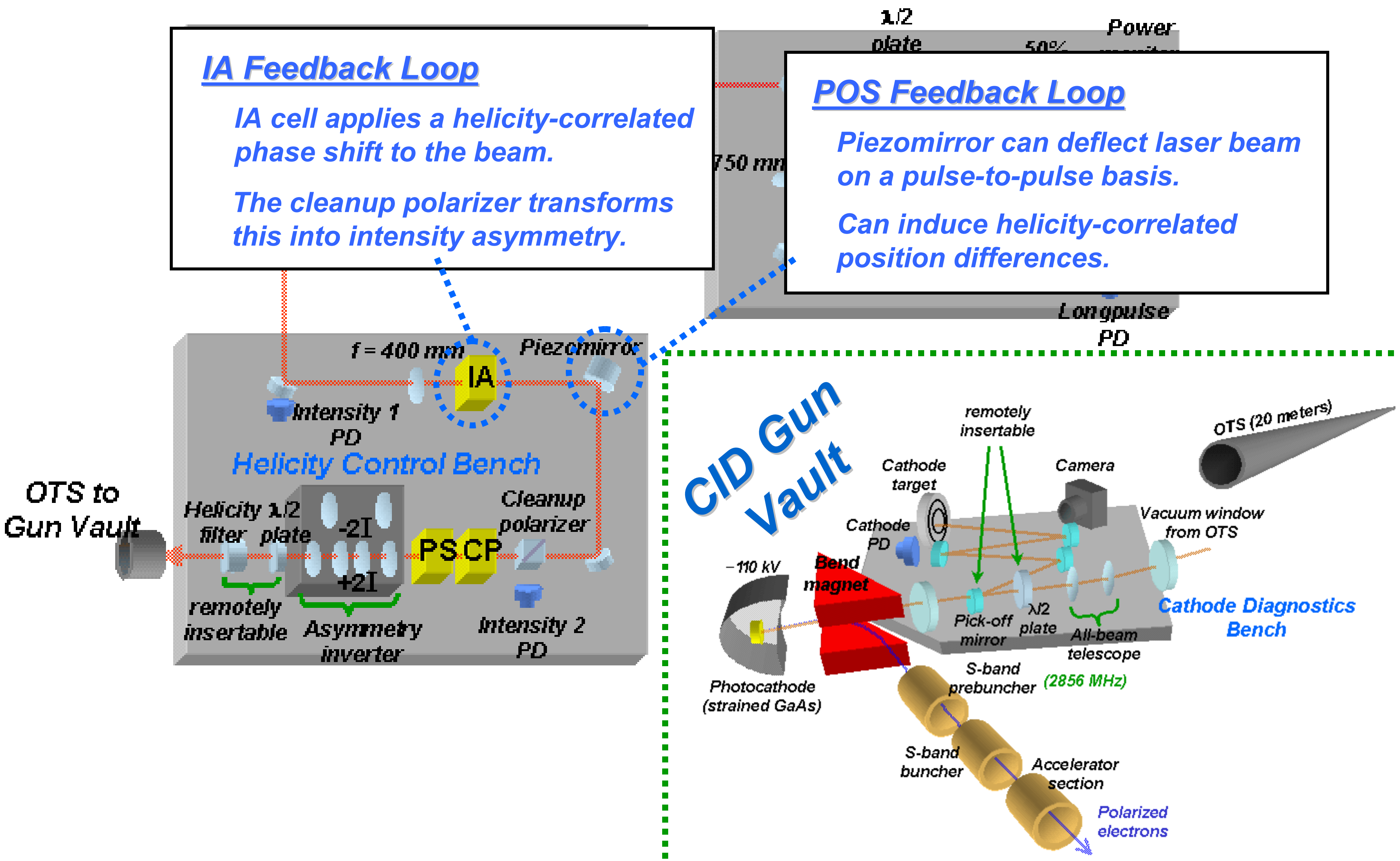
Sep 97: EPAC approval
1998-99: Design and Beam Tests
2000: Funding and construction
2001: Engineering run
2002: Physics Runs 1 (Spring), 2 (Fall)
2003: Physics Run 3 (Summer)

E-158 Beam

(and comparison with 500 GeV Linear Collider Design)

Parameter	E-158	NLC-500
Charge/Train	5×10^{11}	14.4×10^{11}
Repetition Rate	120 Hz	120 Hz
Energy	45 GeV	250 GeV
e^- Polarization	85%	80%
Train Length	270ns	267ns
Microbunch spacing	0.3ns	1.4ns
Beam Loading	13%	22%
Energy Spread	0.15%	0.16%

Polarized Source Laser System



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}.

→ $\lesssim$ 100 ppm, ~0.5 μm

2) Active suppression with feedbacks:

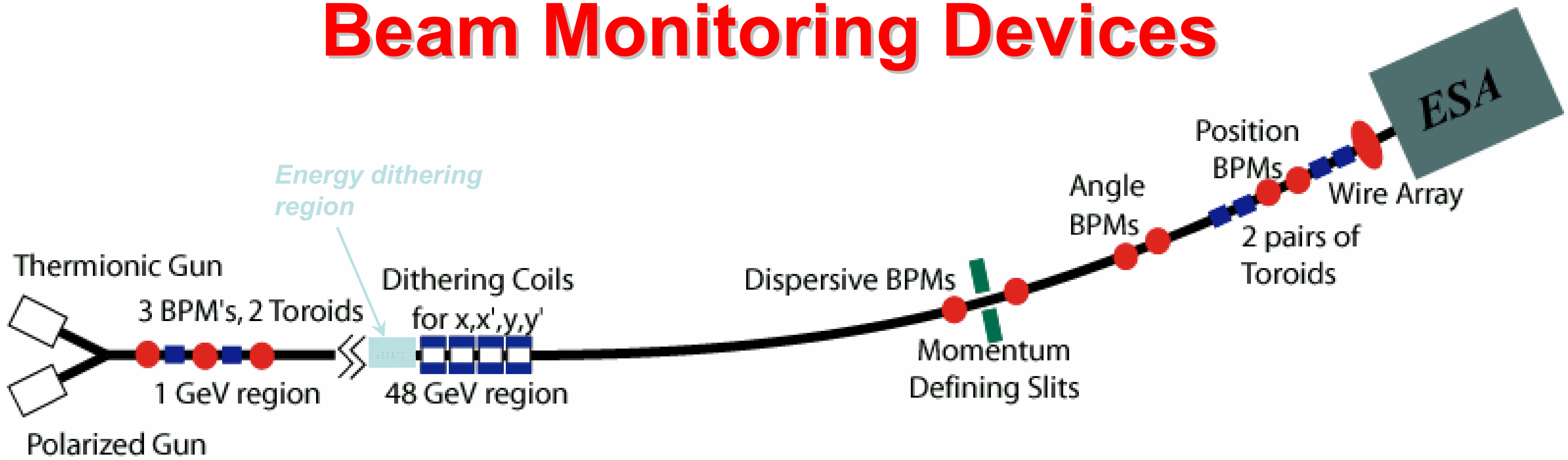
- IA loop & POS loop.
- Double-feedback loop.

→ ~few ppb, nm level

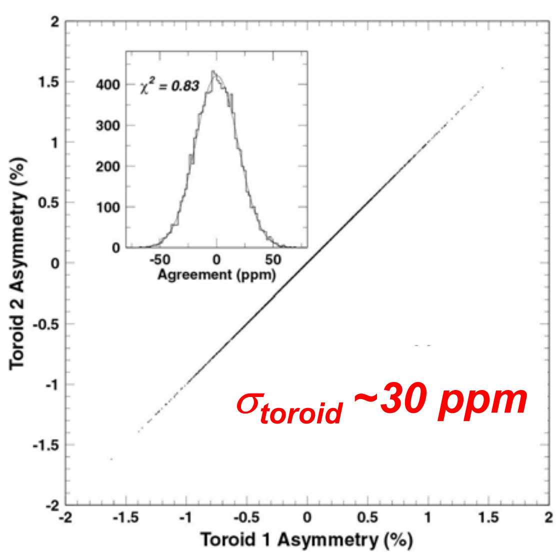
3) Slow reversals:

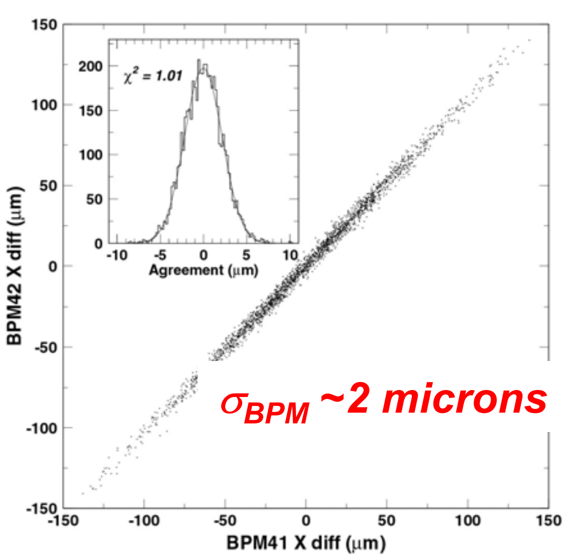
- Flip certain classes of asymmetries while leaving everything else unchanged.
  - $\lambda/2$ plates (2)
  - energy (g-2 precession)
  - asymmetry inverter
- These can provide cancellation of systematics, but they also serve as a cross-check that systematics are well-understood. Multiple reversals are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

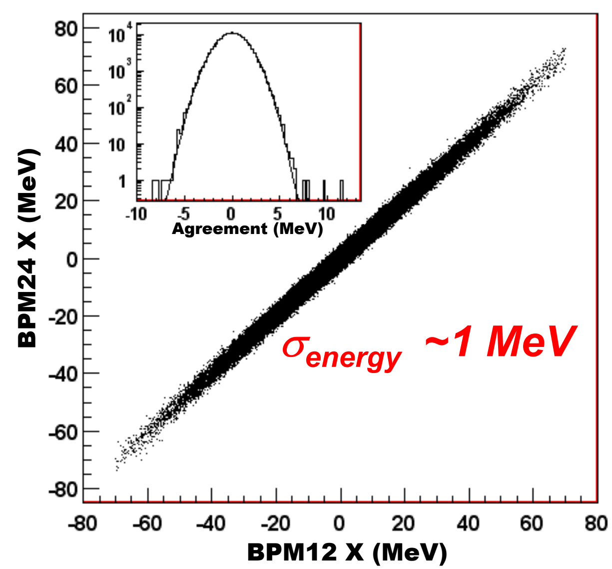
Beam Monitoring Devices



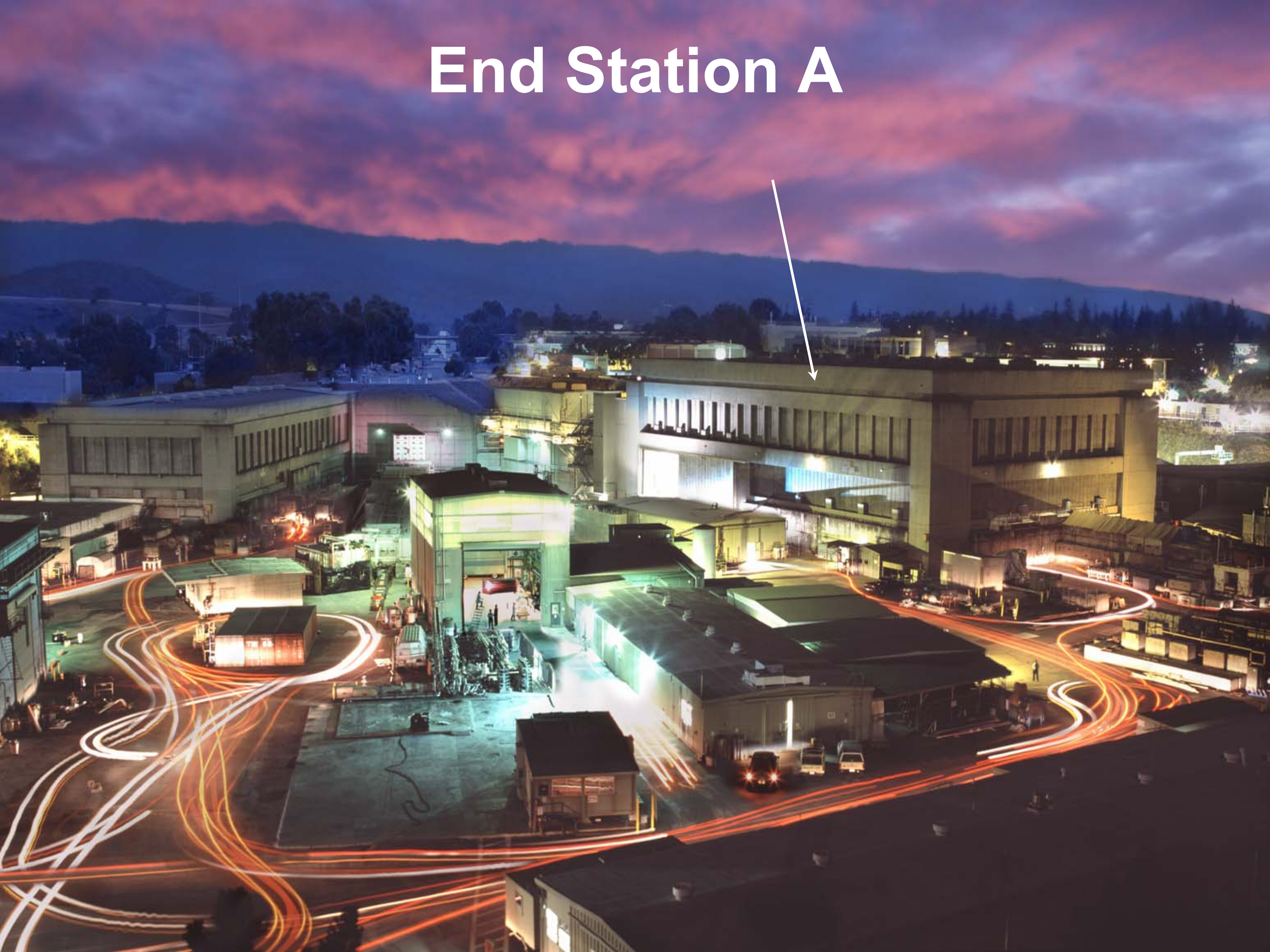
Can compare measurements of neighboring devices to determine the precision of the measurement.





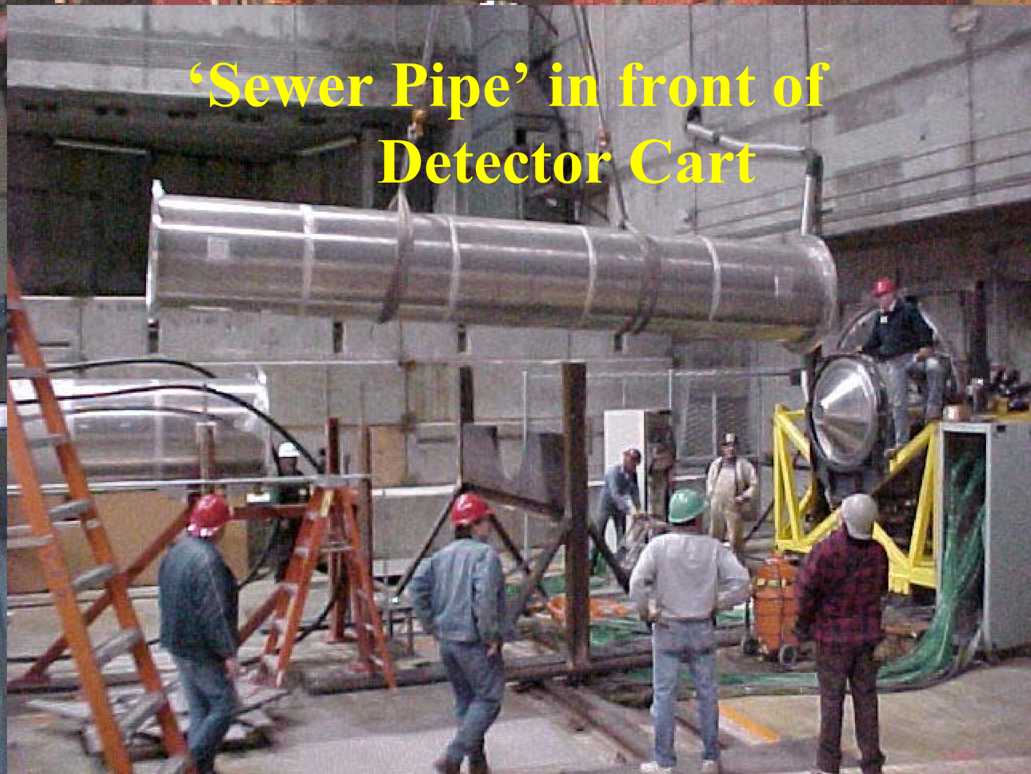


End Station A

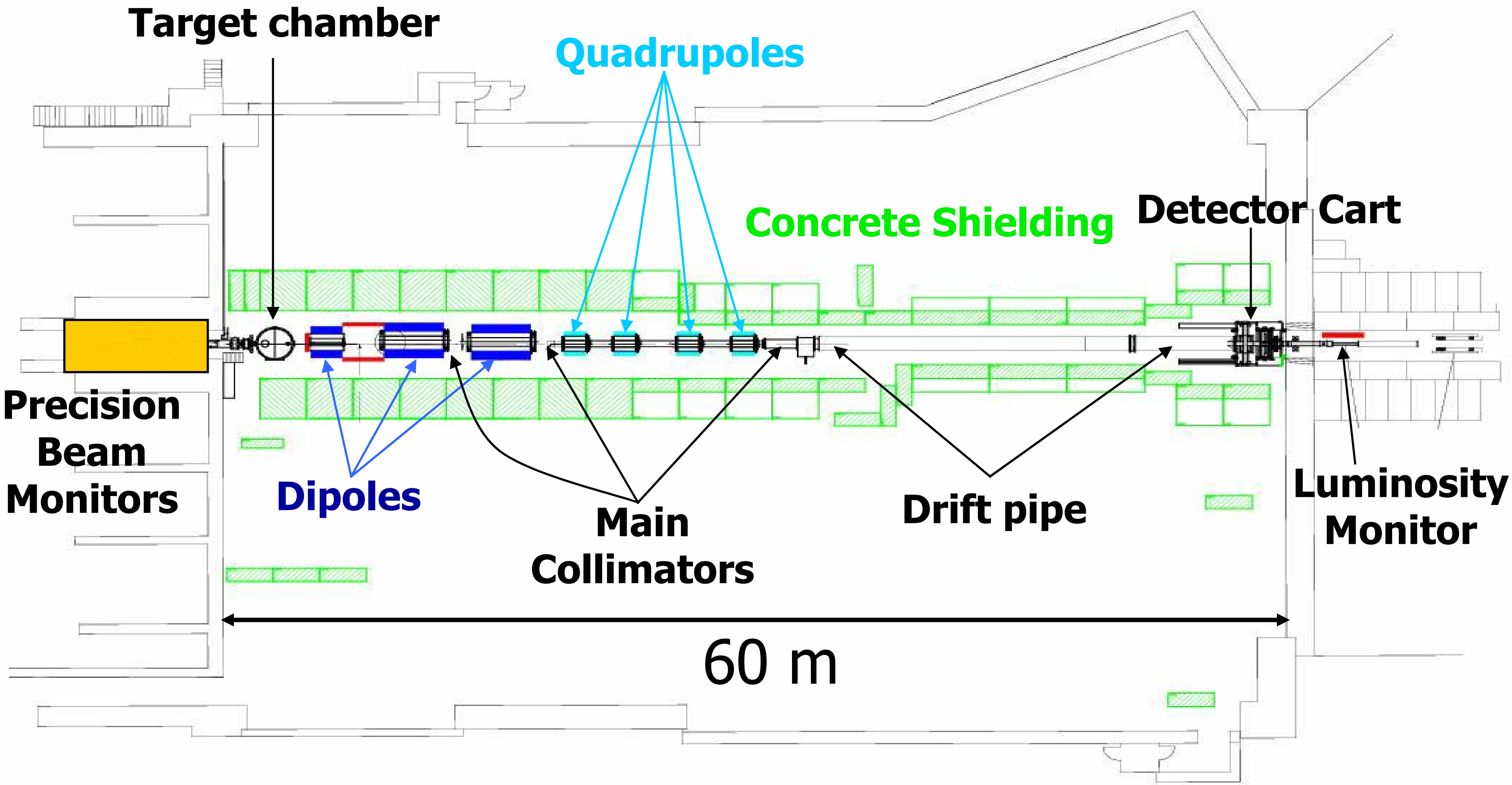



Scattering Chamber and
Spectrometer Magnets

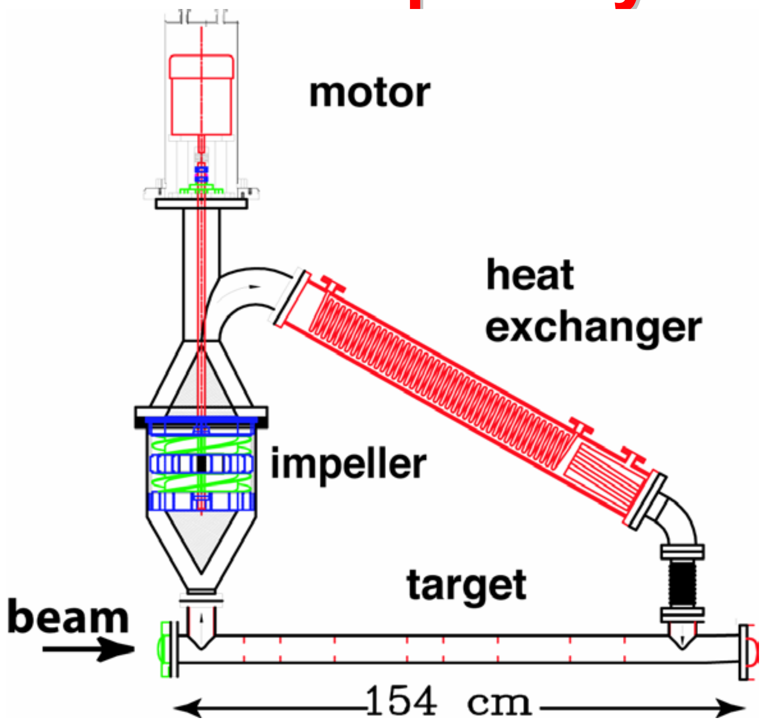

LH_2
Scattering Chamber


'Sewer Pipe' in front of
Detector Cart

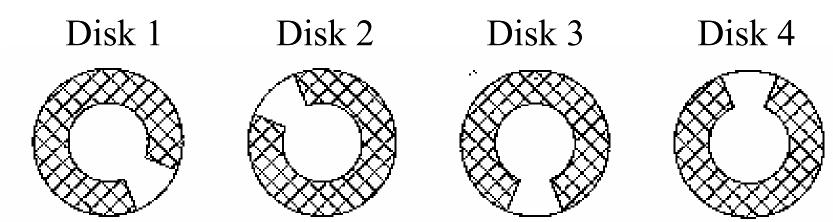
Experimental Layout in ESA



Liquid Hydrogen Target

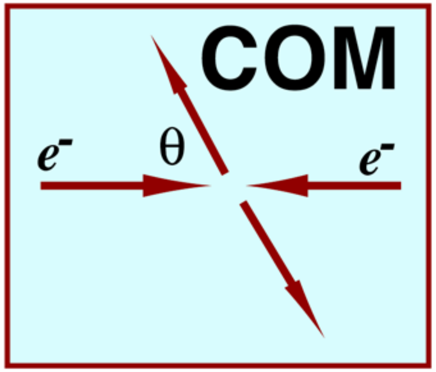


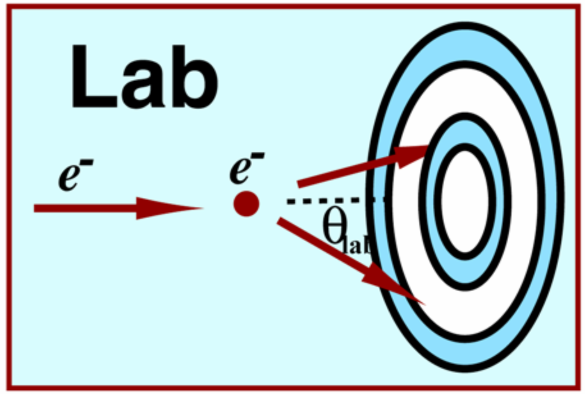
Refrigeration Capacity	1000W
Max. Heat Load:	
- Beam	500W
- Heat Leaks	200W
- Pumping	100W
Length	1.5 m
Radiation Lengths	0.18
Volume	47 liters
Flow Rate	5 m/s

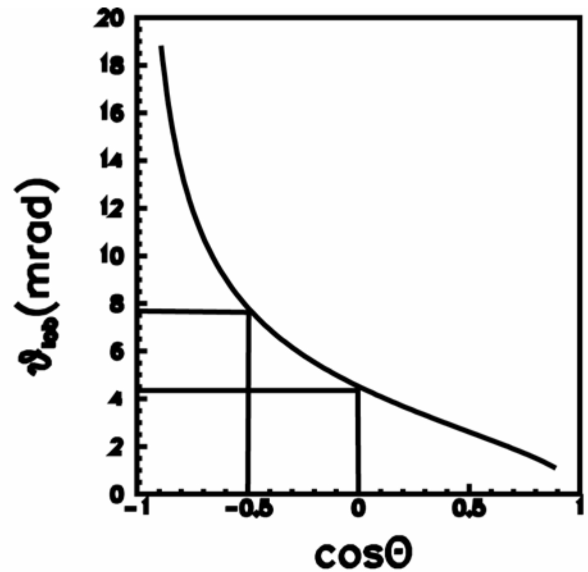


Wire mesh disks in target cell region to introduce turbulence at 2mm scale and a transverse velocity component. Total of 8 disks in target region.

Kinematics

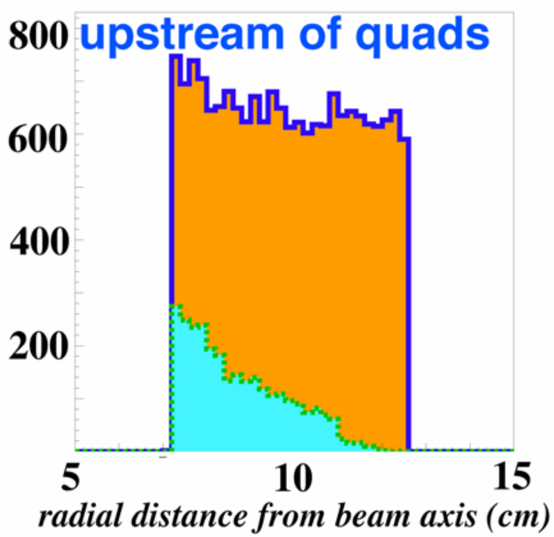


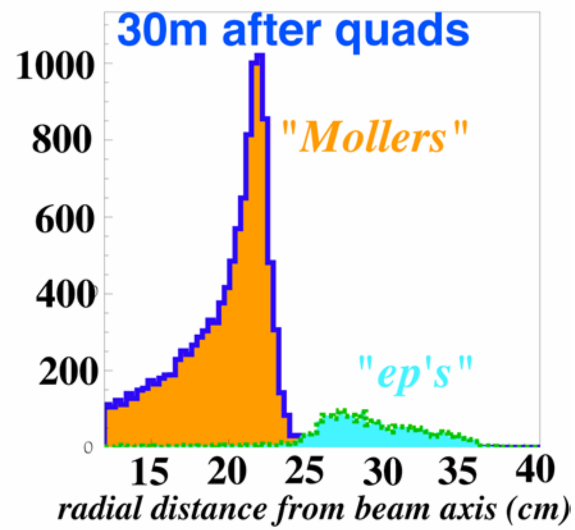




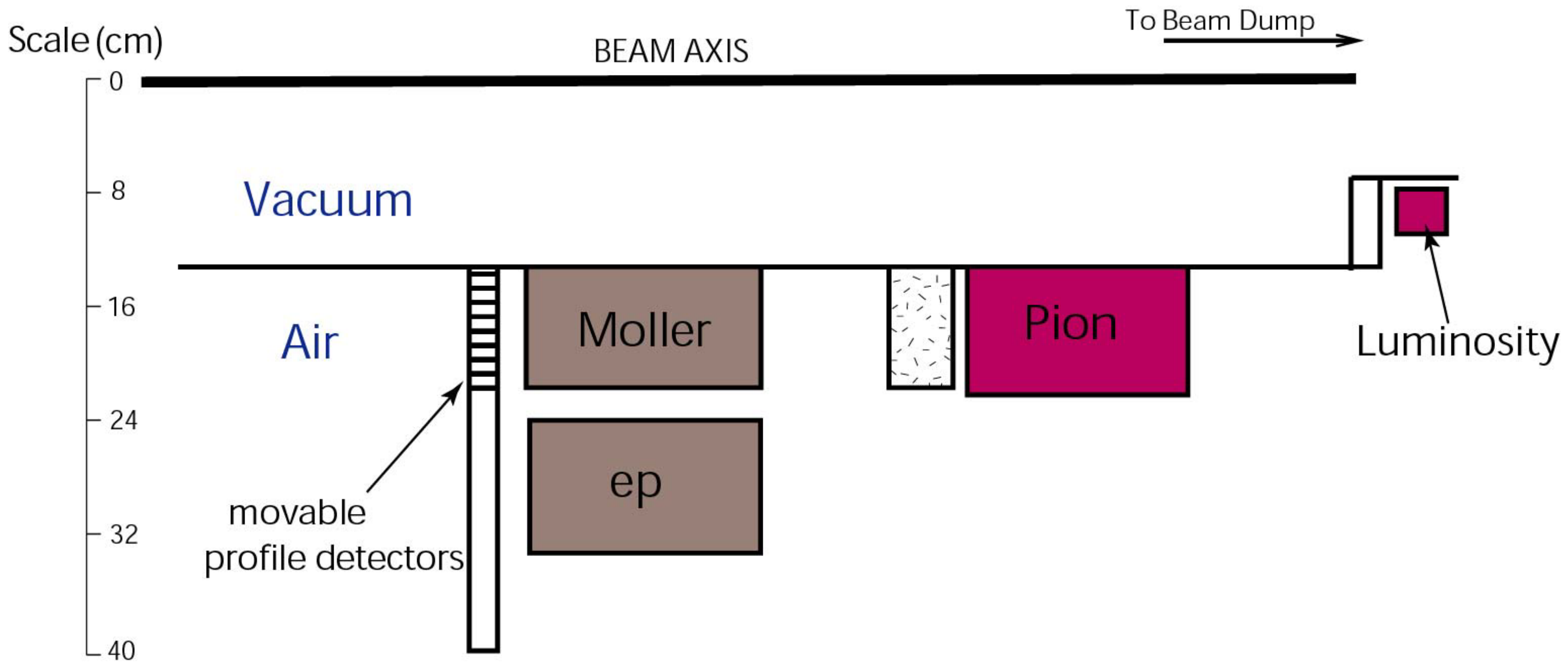
Quadrupole Quadruplet

- 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

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

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

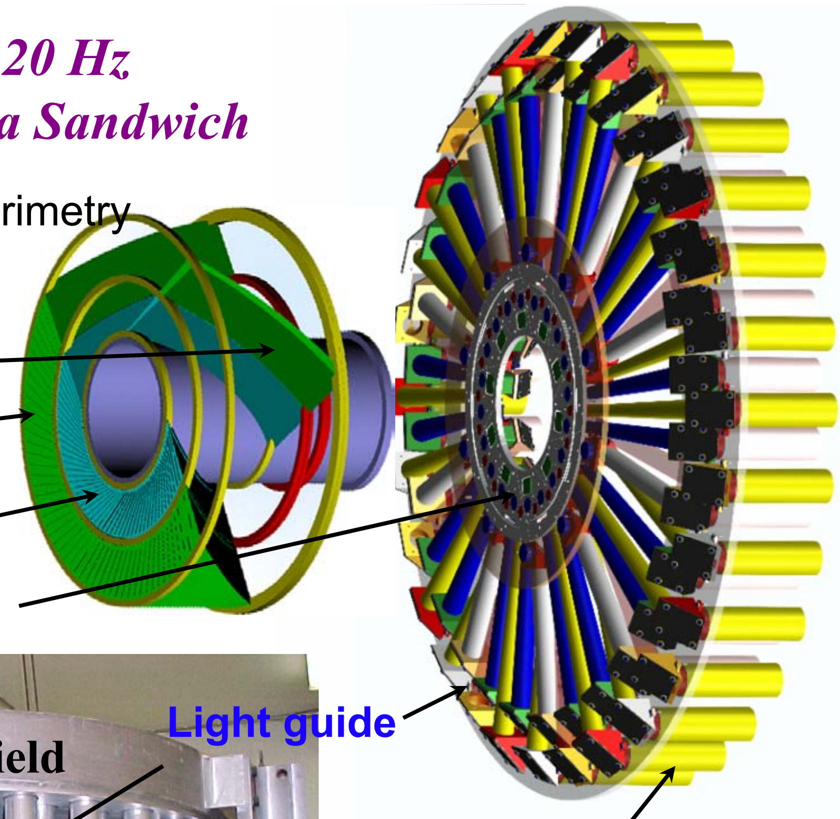
$$\left\langle \theta_{lab}^{MOLLER} \right\rangle = 6.0 mrad$$

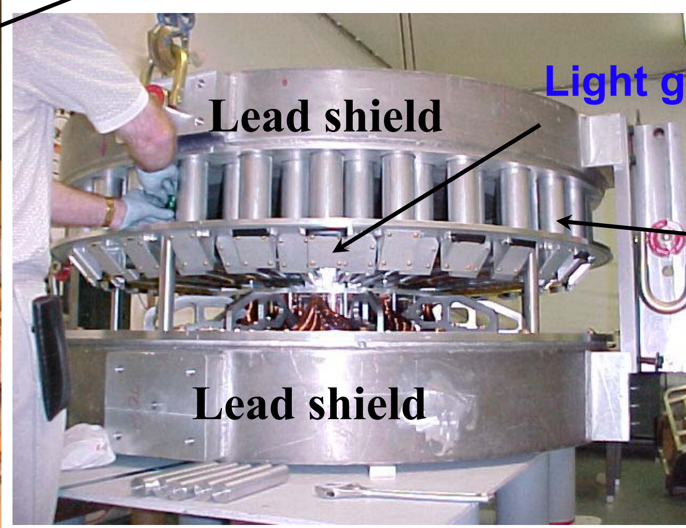
All detectors have azymuthal segmentation,
and have PMT readout to 16-bit ADC

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



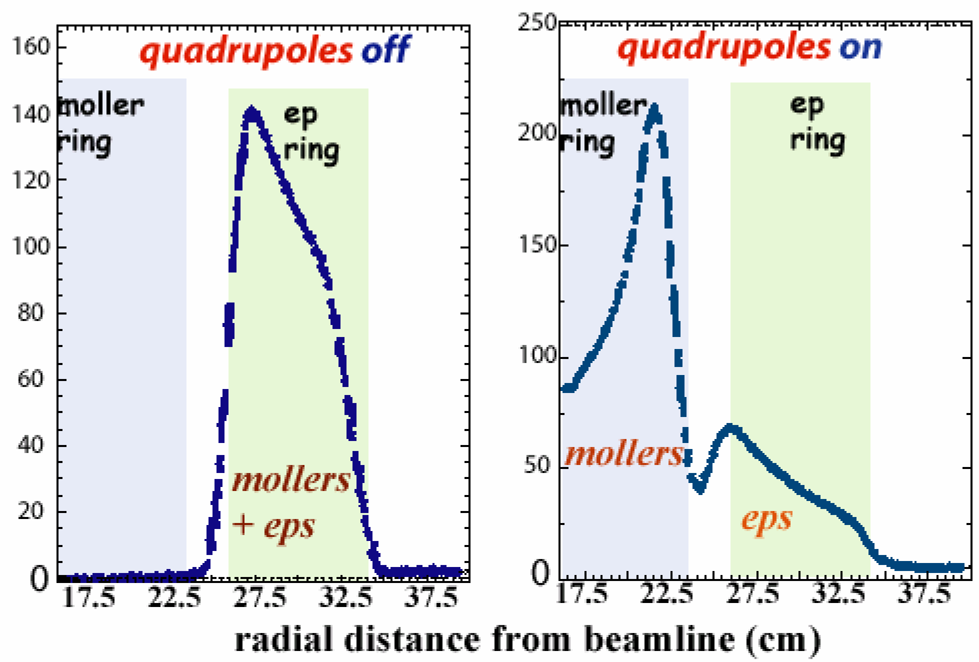


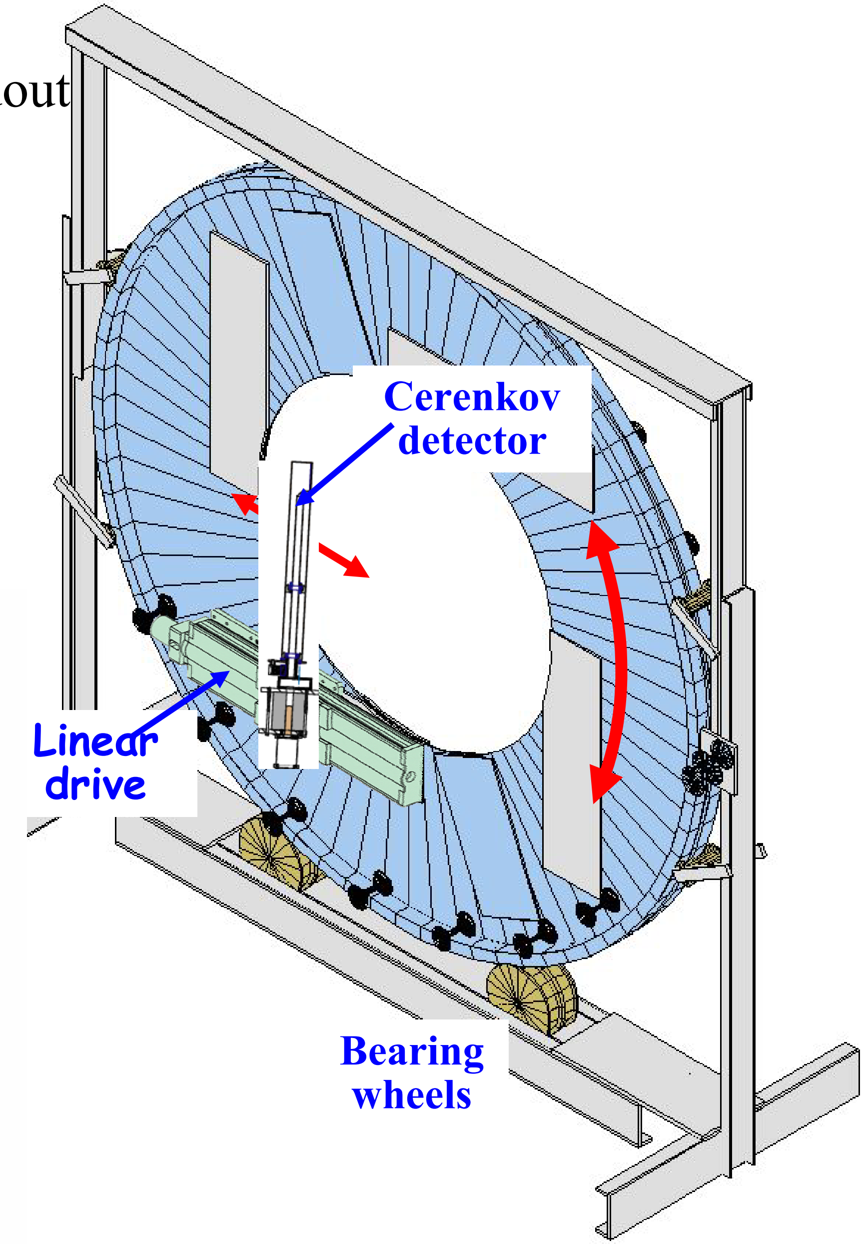
Profile Detector

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

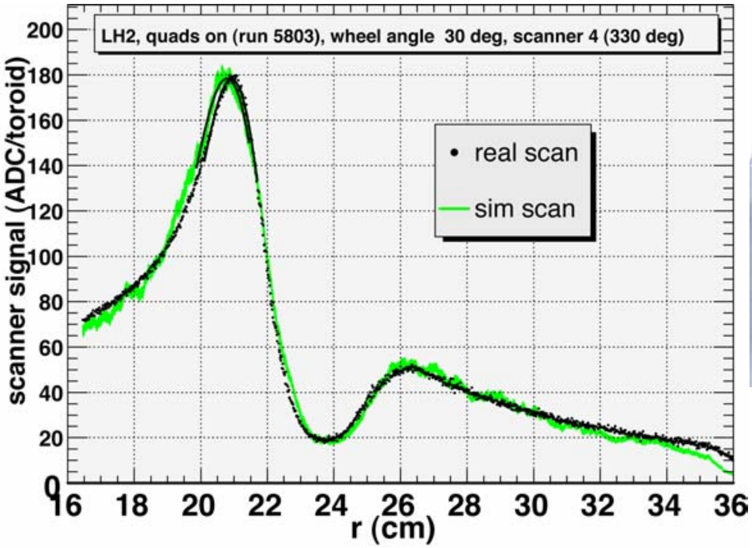
Radial and azymuthal scans

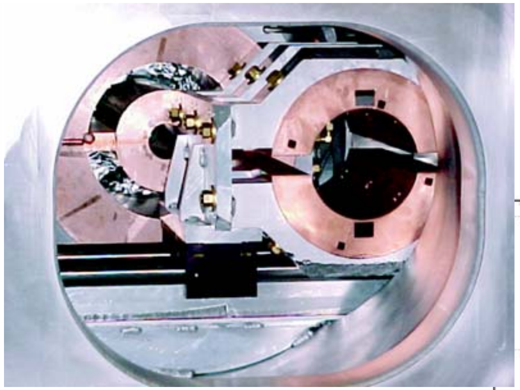
- **collimator alignment, spectrometer tuning**
- **background determination**
- **Q^2 measurement**

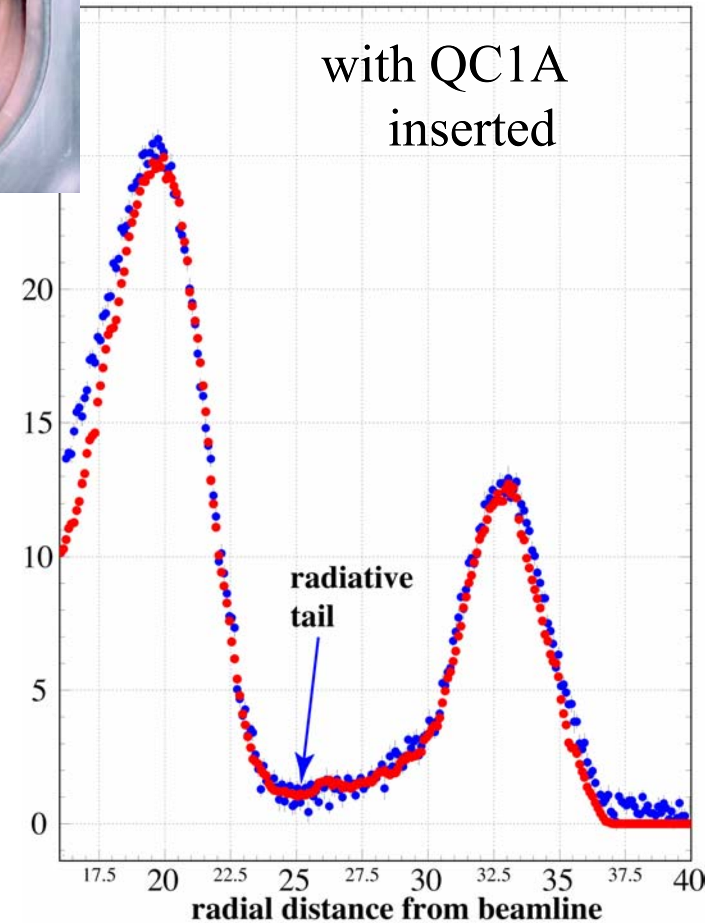




Scattered Flux Profile



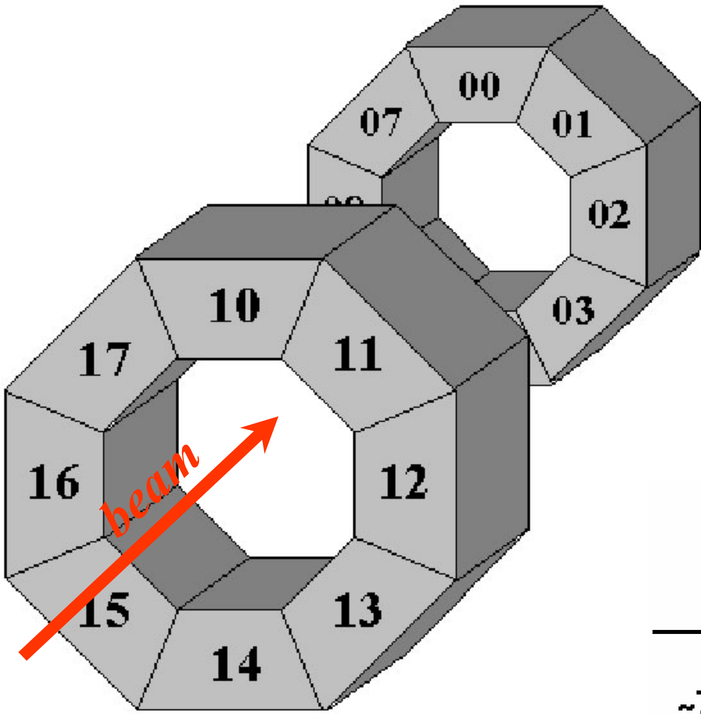




ep Background to Moller sample:

- 8% from elastic scattering
- 1% from inelastic scattering
- (42±11) ppb correction for Run 1;
  reduced for Runs 2, 3

LUMI Detector



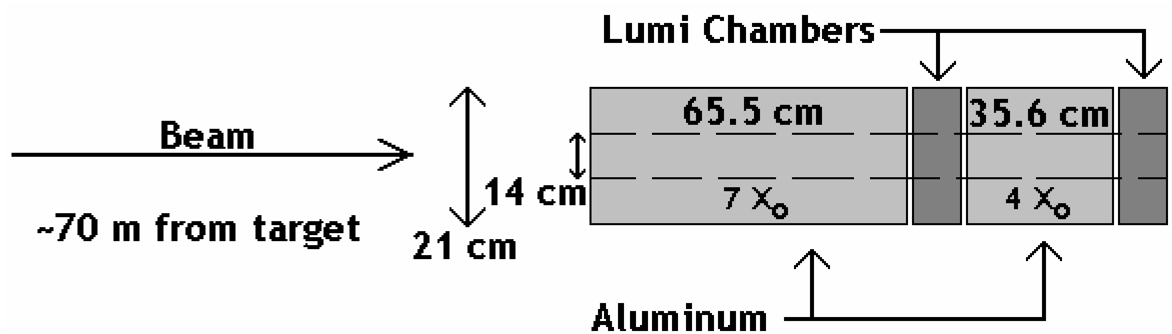
Segmented ion chamber detector with Aluminum preradiator.

500W incident power (50W from synchrotron radiation)

Signal: Motts and high energy Mollers

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

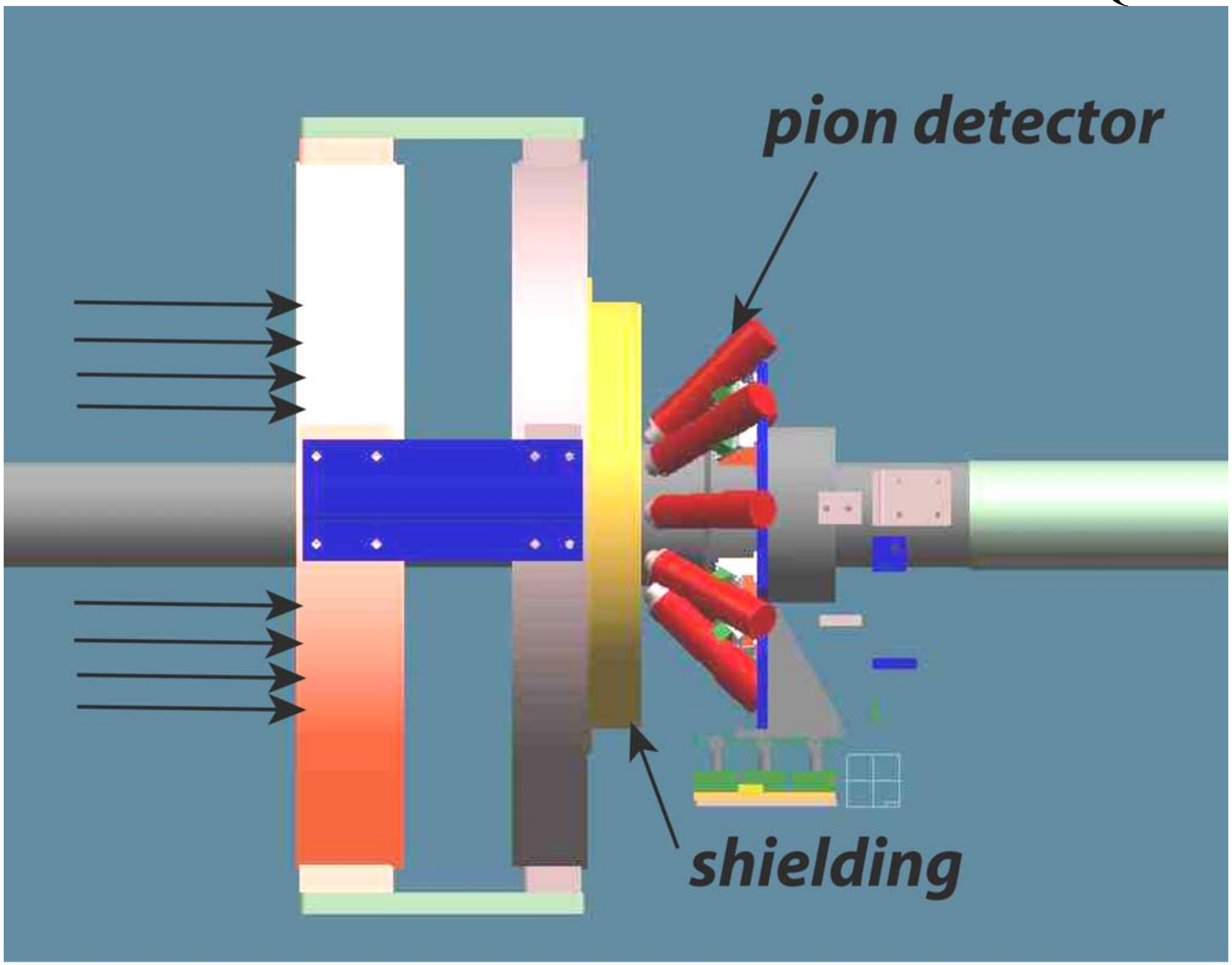
A_{PV} ~ -10ppb



- Null asymmetry measurement
- Diagnostic for luminosity fluctations, including target density fluctuations.

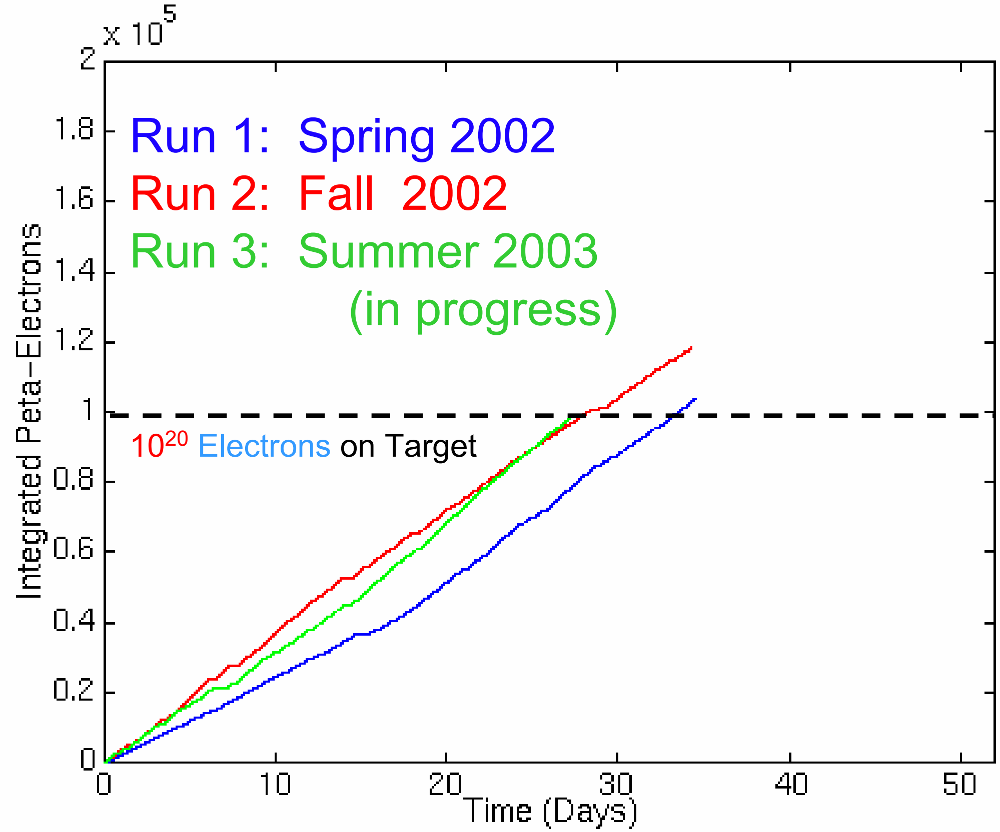
Pion Detector

Quartz Cherenkov Detector
with PMT readout



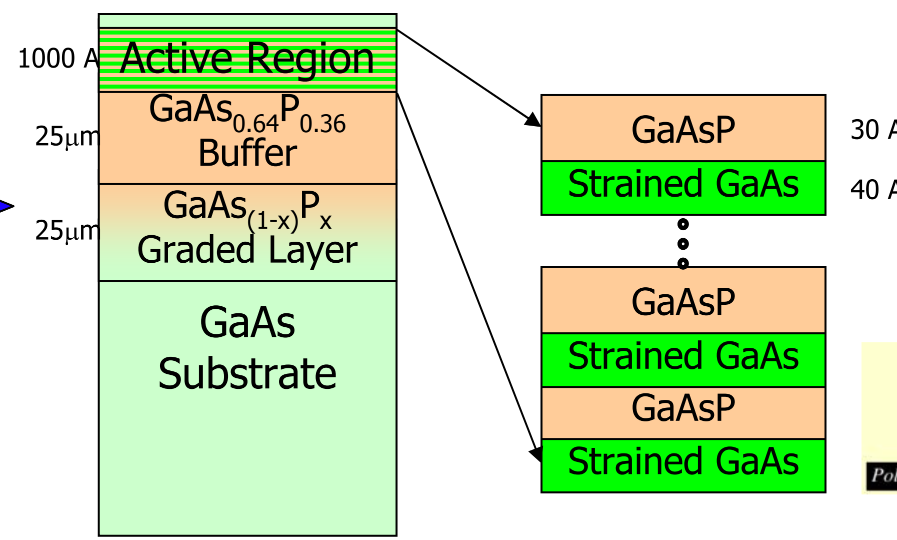
~ 0.2 % pion flux
~ 1 ppm asymmetry
~ (0 ± 2) ppb correction

E-158 Physics Runs



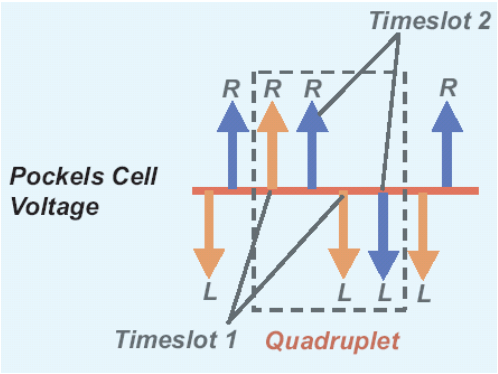
NEW Cathode for Run 3

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



Polarized Electron Source Group

Experimental Features



Beam helicity is chosen pseudo-randomly at 120 Hz

- use electo-optical Pockels cell in Polarized Light Source
- sequence of pulse quadruplets:

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

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

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:

$$A_{PV} = \frac{1}{P_b} \frac{A_{raw} - f_{bkg} A_{bkg}}{f_{norm}}$$

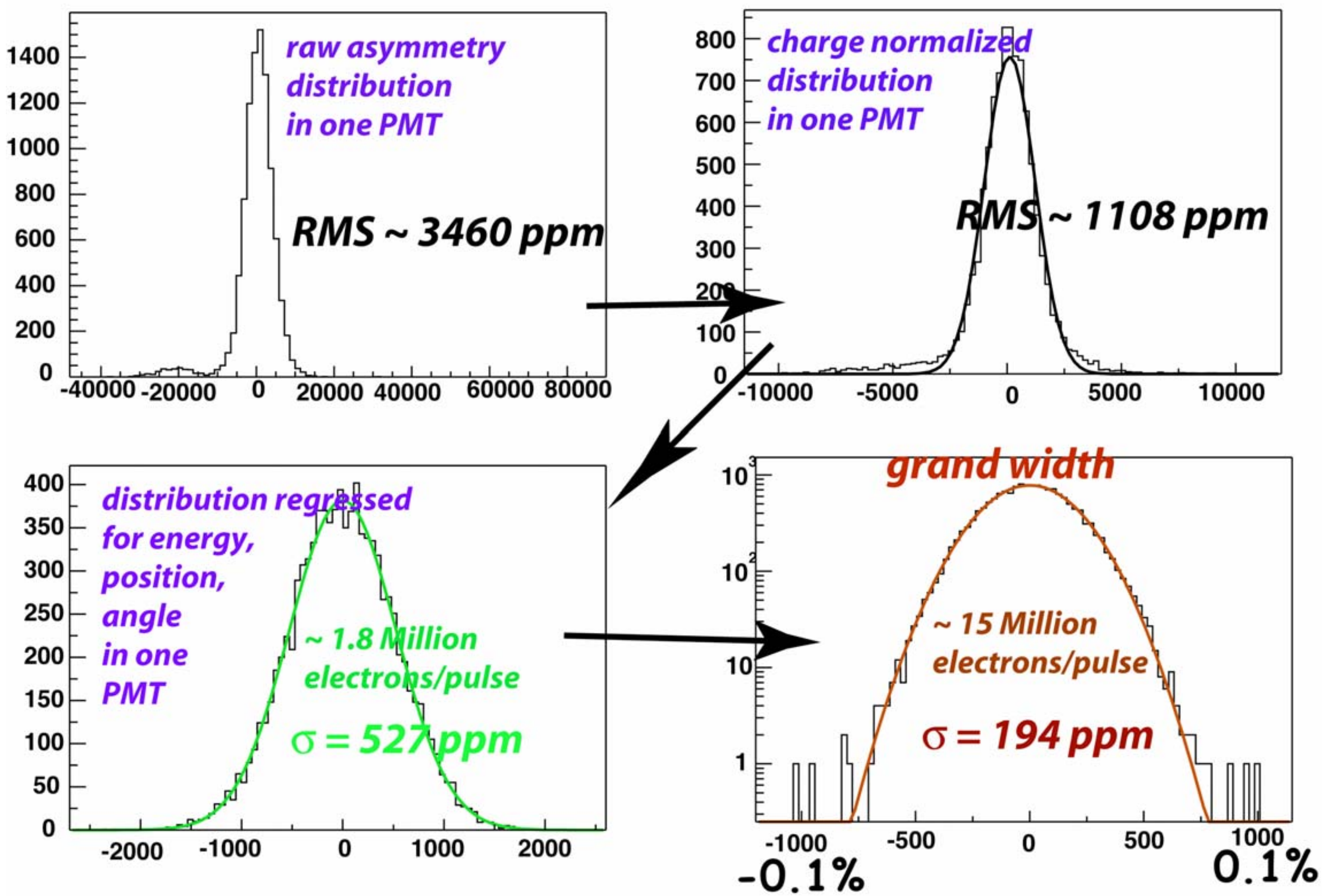
backgrounds

dilutions

beam polarization

Moller Detector
Regression Corrections

observed left-right asymmetry distribution

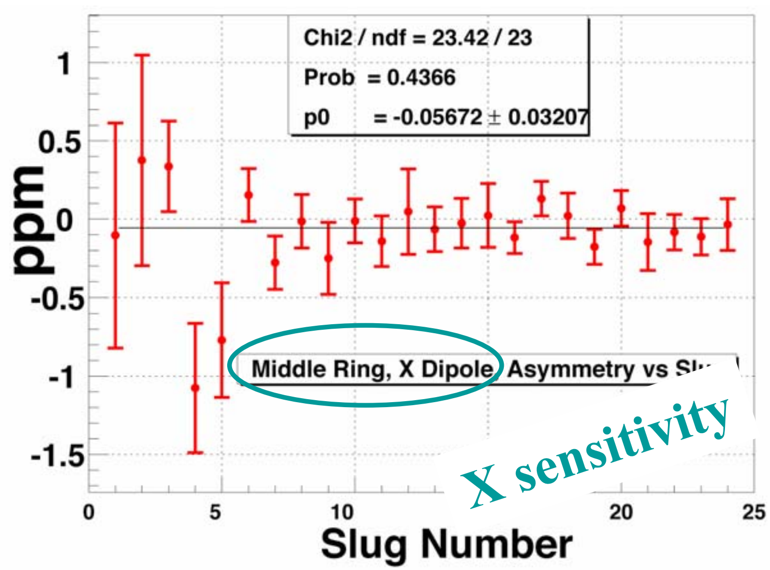


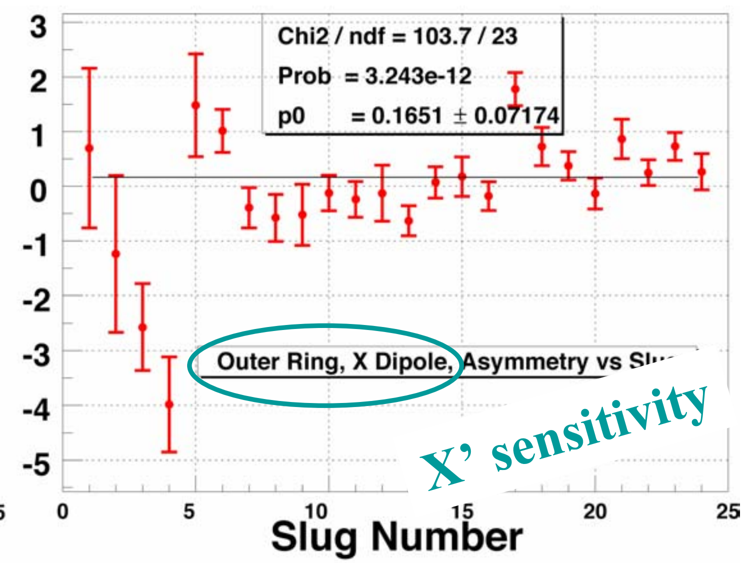
In addition, independent analysis based on beam dithering

Beam Systematics

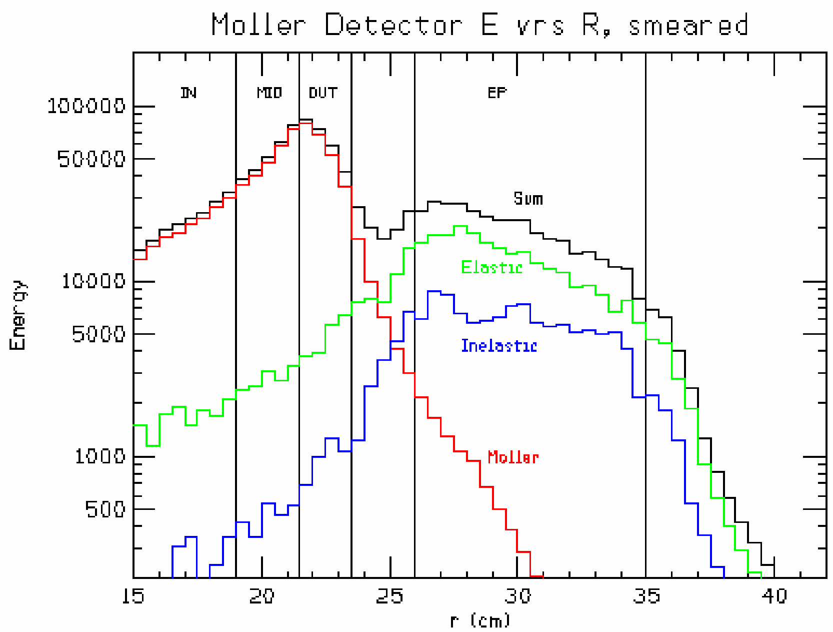
Beam Parameter	Beam Monitors	Monitor Agreement	MOLLER correction Agreement
E	BPMs 12X, 24X	(0.09 ± 0.24) keV	(0.5 ± 1.3) ppb
X	BPMs 41X, 42X	(0.9 ± 0.6) nm	(0.8 ± 0.5) ppb
Y	BPMs 41Y, 42Y	(-1.0 ± 1.0) nm	(-0.2 ± 0.2) ppb
X’	BPMs 31X, 32X	(-2.3 ± 2.1) nm	(-2.0 ± 2.0) ppb
Y’	BPMs 31Y, 32Y	(0.9 ± 1.0) nm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





Beam Systematics

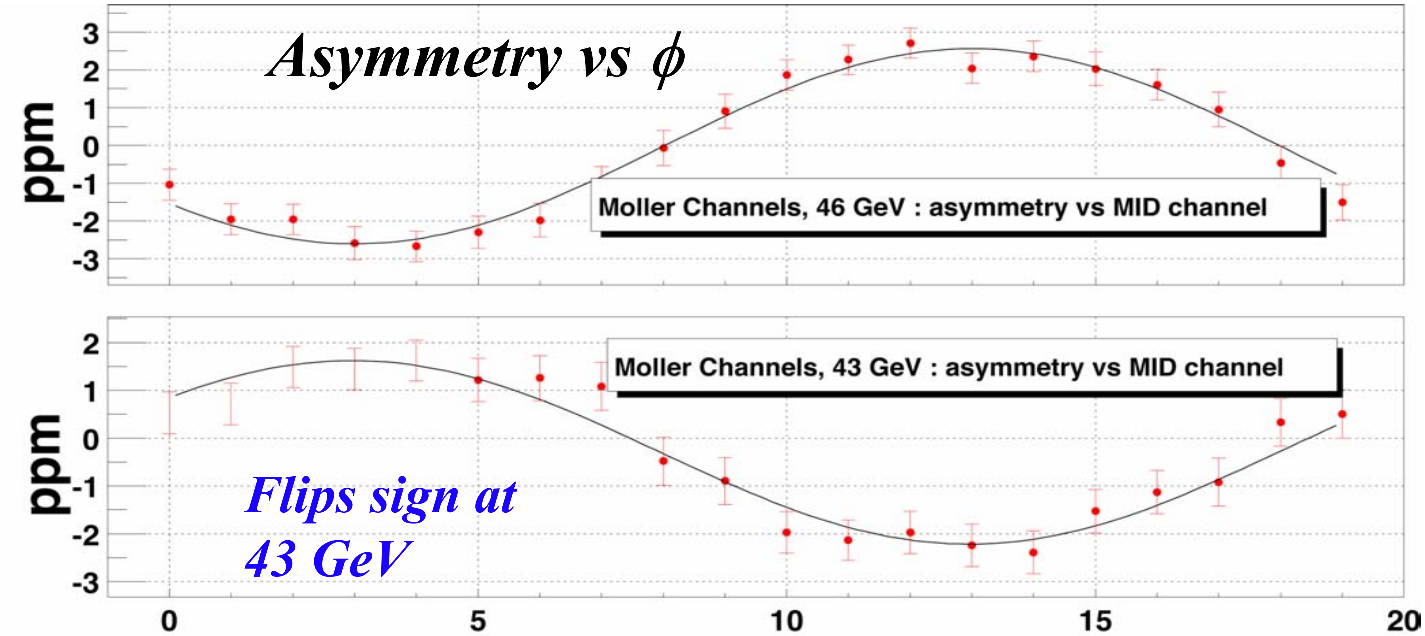


Use radial and azymuthal segmentation of Moller detector to construct 'monitors' that have much larger sensitivity to beam parameters than the Moller 'monopole'

Beam Parameter	Detector Monitor	Monitor slope / Moller monopole slope
E	(OUT-MID) monopole	11
X	MID xdipole	20
Y	MID ydipole	35
X'	OUT xdipole	37
Y'	(OUT-MID) ydipole	52

Current systematic error: 18 ppb → Should reduce to 10 ppb or less

Transverse Asymmetry



Observe ~ 2.5 ppm up-down asymmetry
w/ horizontal polarization
First measurement of single-spin
transverse asymmetry in e-e scattering.

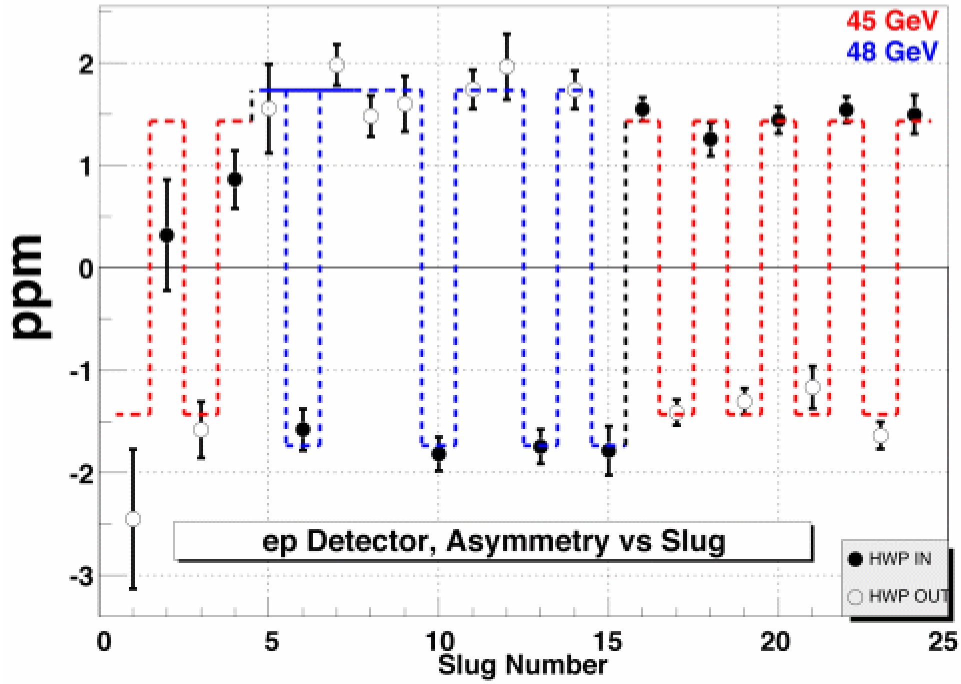
Two-photon exchange
QED effect

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; (higher order calc. in progress)**

⇨ *May also be useful for checking normalization factors (polarization, dilutions)*

ep Detector Data



$A_{RAW}(45\ \mathrm{GeV}) = -1.36 \pm 0.05$ ppm (stat. only)
$A_{RAW}(48\ \mathrm{GeV}) = -1.70 \pm 0.08$ ppm (stat. only)

Ratio of asymmetries:

$$A_{PV}(48\ \mathrm{GeV}) / A_{PV}(45\ \mathrm{GeV}) = 1.25 \pm 0.08\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst})$$

- **Consistent with expectations for inelastic ep asymmetry**

A_{PV} Corrections and Backgrounds

Correction	f_{bkg}	$\delta(f_{bkg})$	A_{corr} (ppb)	$\delta(A_{corr})$ (ppb)
Beam first order	-	-	-	18
Beam spotsize	-	-	0	5
Transverse asymmetry	-	-	0	0*
High energy photons	0.004	0.002	0	0
Synchrotron photons	0.0015	0.0015	0	5
Neutrons/	0.003	0.001	-5	3
ep elastic	0.080	0.020	-11	4
ep inelastic	0.017	0.005	-31	10
Soft photons	0.001	0.001	0	9
Pions	0.002	0.002	0	5
TOTAL	0.109	0.021	-47	24

$$A_{PV} = \frac{1}{P_b} \cdot \frac{A_{raw} - f_{bkg} A_{bkg}}{f_{norm}}, \quad A_{corr} = f_{bkg} A_{bkg}$$

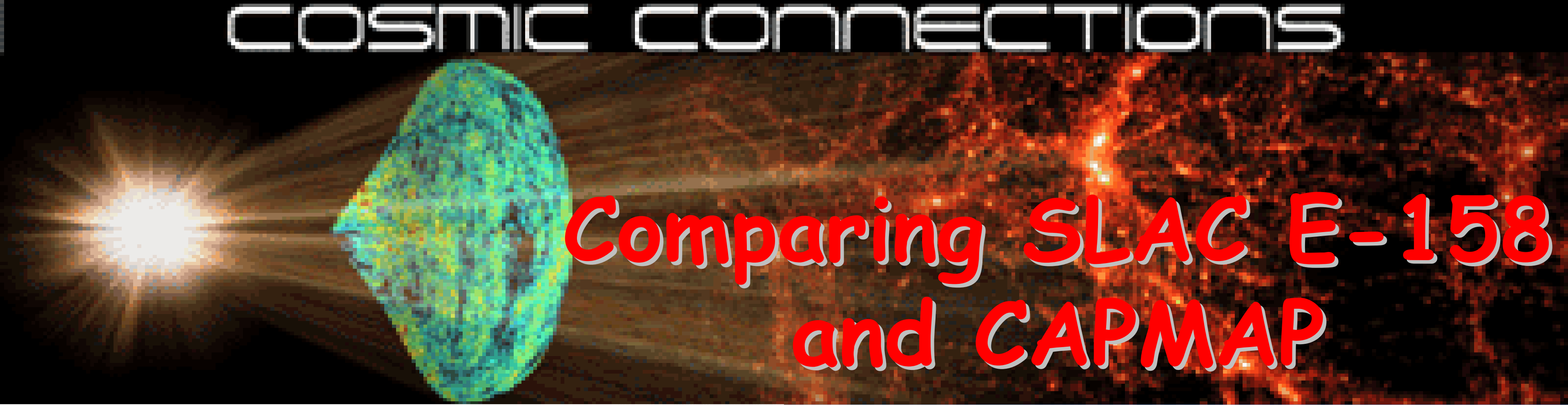
- *Run I systematic error will reduce from 24 to less than 15 ppb*

Normalization Factors

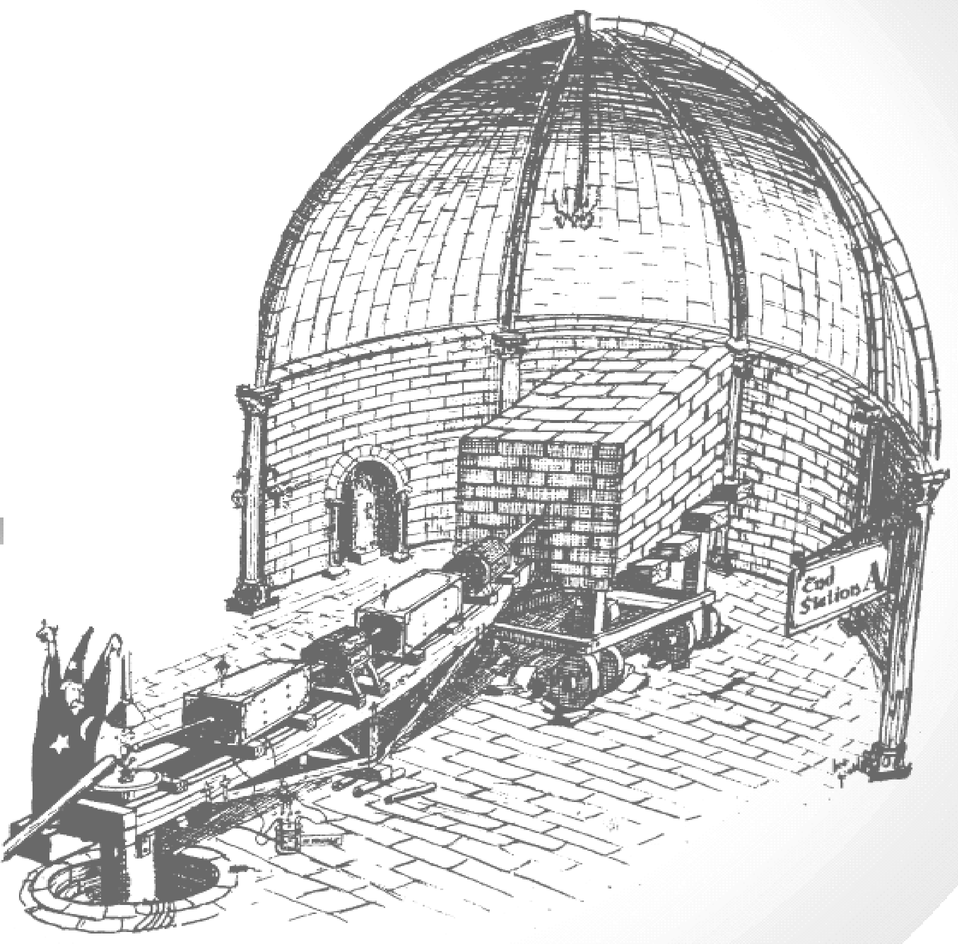
Normalization Factor	f	δ(f)
Dilutions	0.89	0.02
Polarization*	0.85	0.05
Energy Scale	1.0	0.01
Geometry	1.0	0.01
Linearity	0.99	0.02

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

$$A_{PV} = \frac{1}{P_b} \cdot \frac{A_{raw} - f_{bkg} A_{bkg}}{f_{norm}}$$

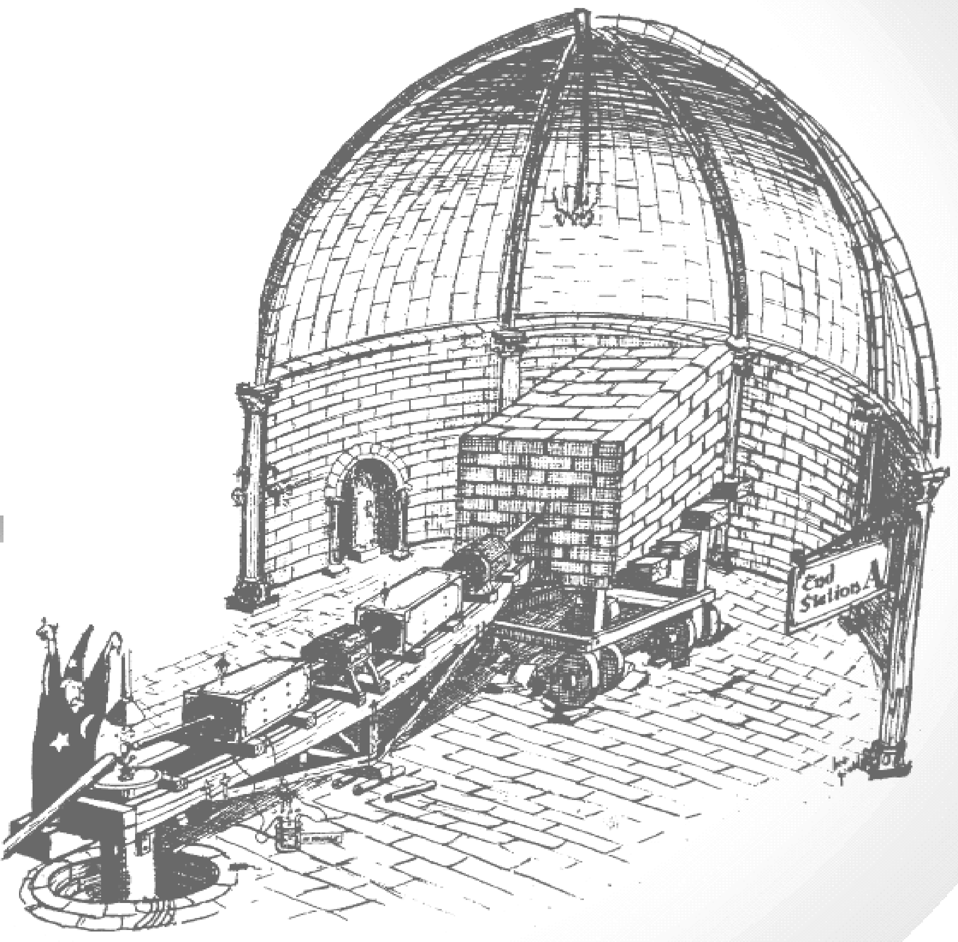


Comparing SLAC E-158 and CAPMAP



SLAC -
Moller Asymmetry Probe

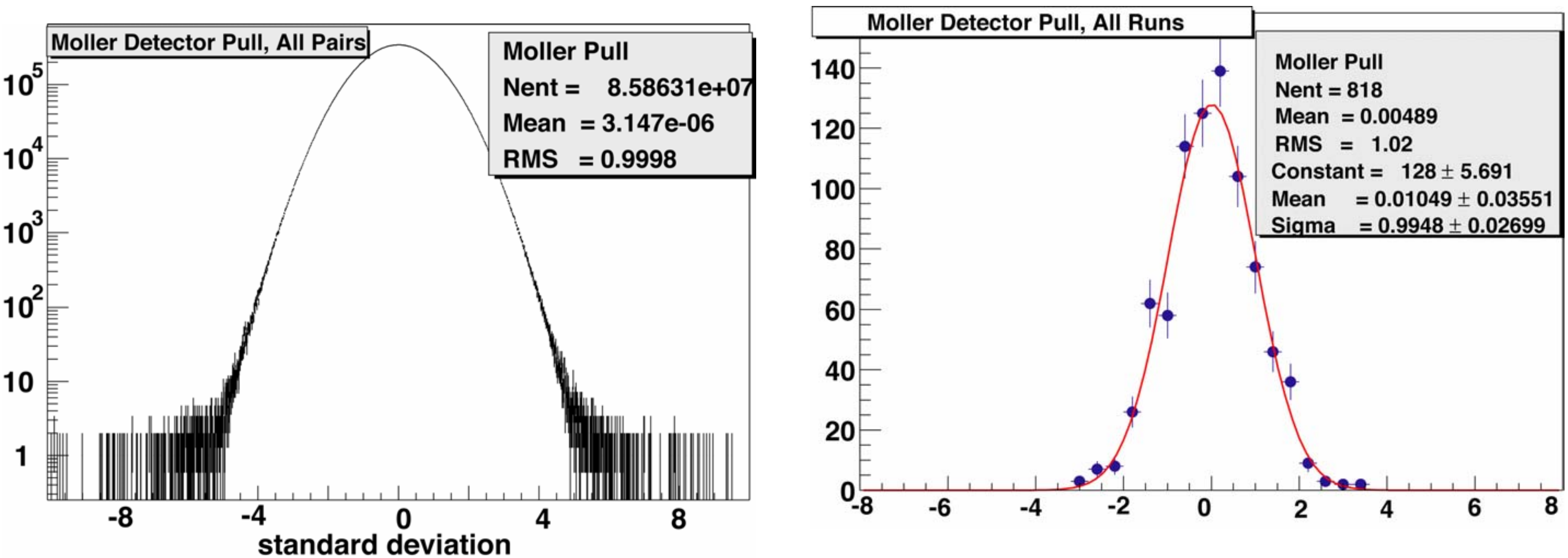
Comparing S-MAP and CAPMAP



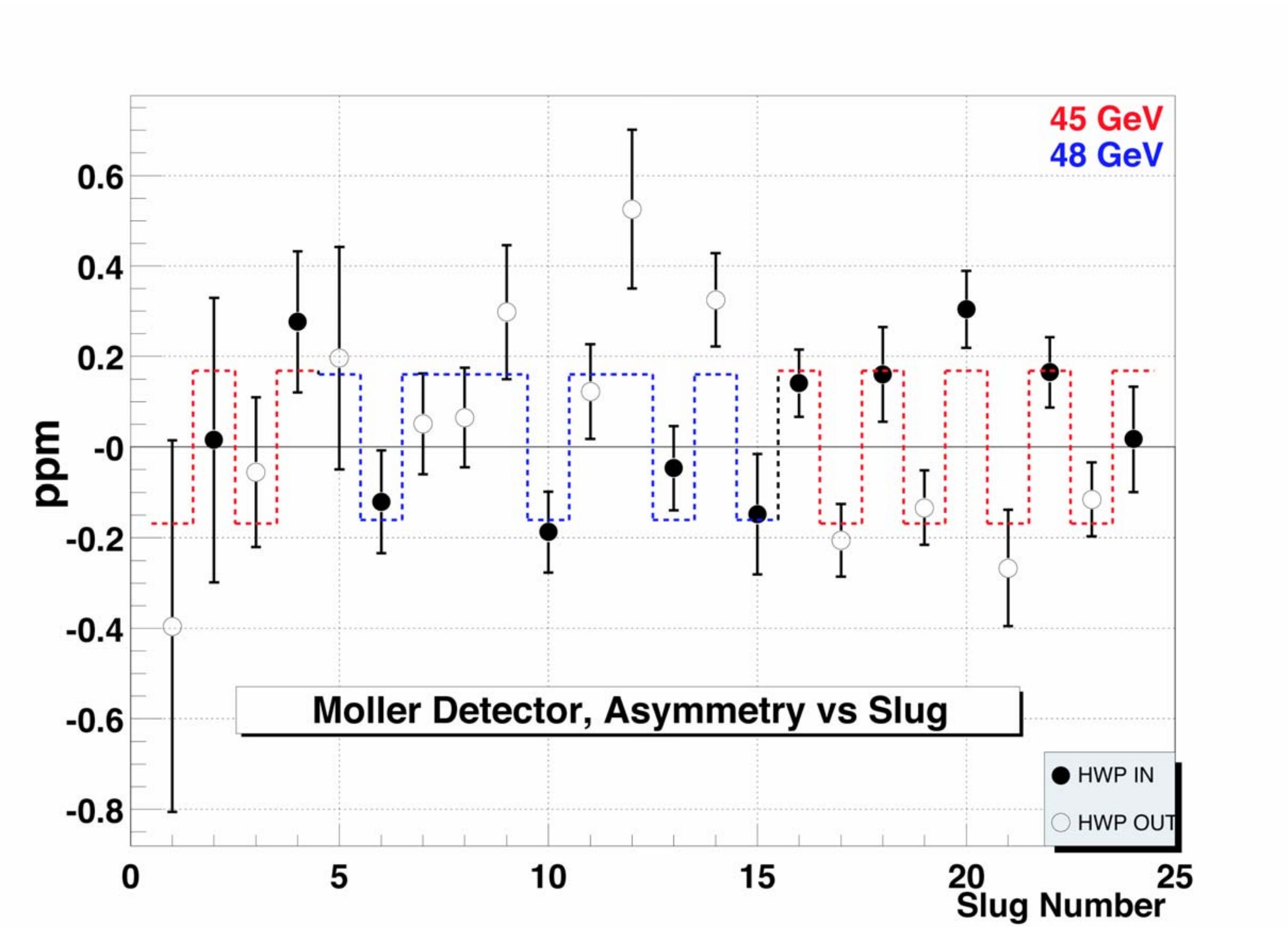
	E-158	CAPMAP
Beam	left- and right- longitudinally polarized electron beams	2 linear-polarized CMB photon beams
Dicke Switching	every 16 milli-seconds, observe one (L,R) pair	4kHz fast switch from LO mixing; slow 8-second sweep over 20 3-minute pixels
Signal	Moller asymmetry for 2 beam polarization states; ~ 0.1 ppm	CMB Temperature asymmetry for 2 beam polarization states; ~ 1 ppm (3 μK)
Sensitivity	25 ppm / √time(sec)	300 ppm / √time(sec) (1 mK / √sec)

Raw Moller Asymmetry

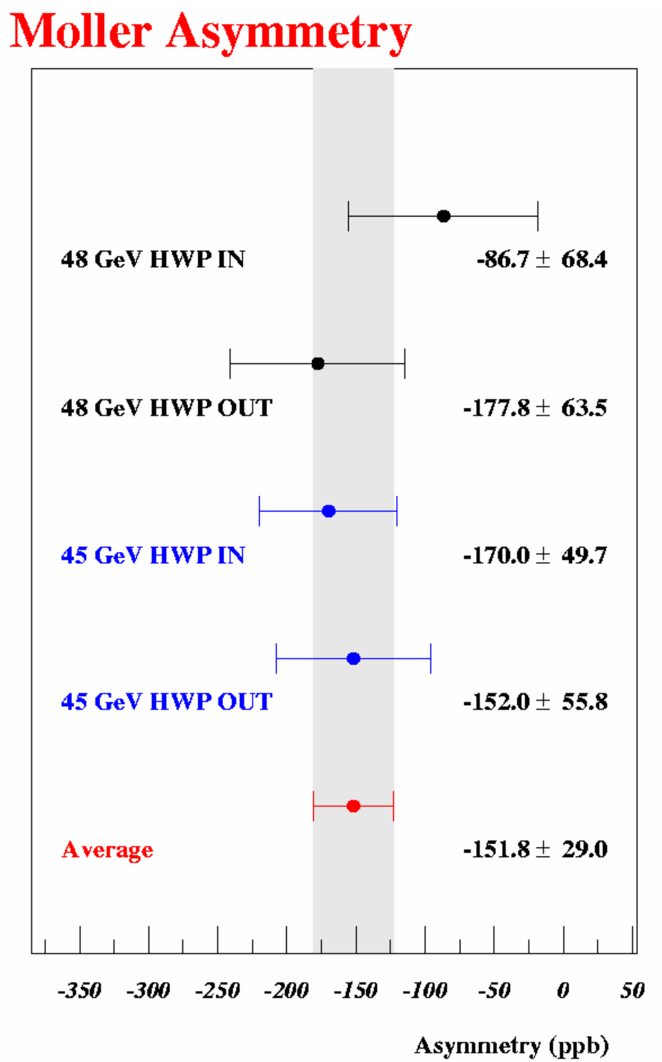
(pull plots)

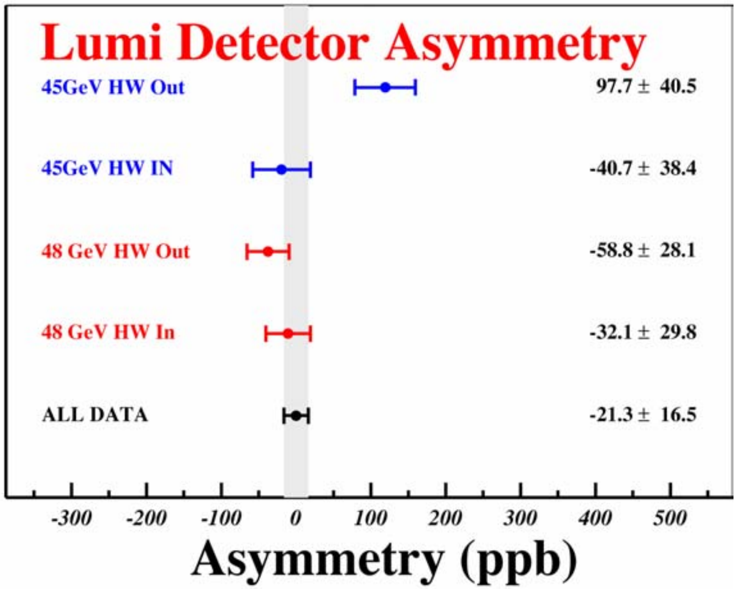


Moller Asymmetry vs Slug



Moller PV Asymmetry





A_{PV}(e^-e^- at Q^2 = 0.027 GeV^2):

-151.9 ± 29.0 (stat) ± 32.5 (syst)

parts per billion

(preliminary)

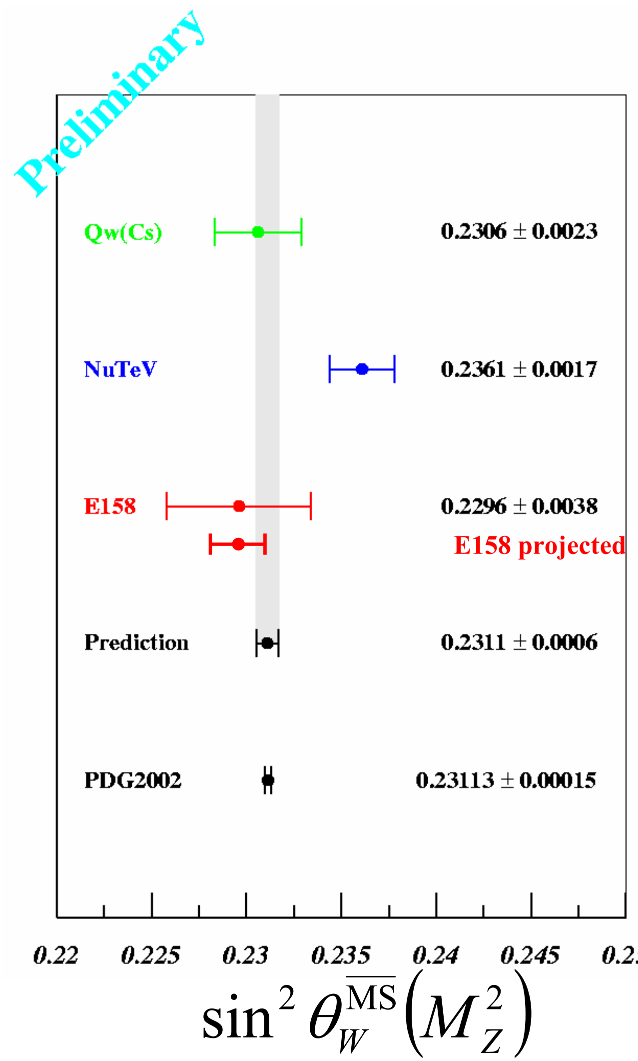
Significance of parity nonconservation in Møller scattering: 3.6σ

Weak Mixing Angle

$\sin^2\theta_W(Q^2=0.027\ \text{GeV}^2)$ = 0.2371 ± 0.0025 (stat) ±0.0027 (syst)

(preliminary)

Convert to $\sin^2\theta_W^{\overline{\rm MS}}(M_Z^2)$ for comparison with other experiments:



Implications

- **Limit on Λ_{LL} at the level of 3-4 TeV (90% C.L.)**
- **Limits on extra Zs at the level of 400-500 GeV**
- **Limit on lepton-flavor violating coupling ~ 0.02 G_F**

These numbers are competitive with collider limits

Conclusions

A very challenging experiment is producing physics results

- ***Parity is violated in Møller scattering***
- ***Inelastic e-p asymmetry at low Q^2 measured; consistent with quark picture***
- ***First measurement of e-e transverse asymmetry***

- **Run II data are being analyzed**

- **Final Run III in progress** (Summer 2003)

Preliminary Run 1 results

A_{PV} ***(Moller) = -151.9 ± 29.0 ±32.5 ppb***

$\sin^2\theta_W^{\overline{MS}}(M_Z^2) = 0.2296 \pm 0.0038$