SLAC E158: Progress and First Results

E158: A Precision Measurement of the Weak Mixing Angle in Fixed Target Møller Scattering

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University of Massachusetts

Outline

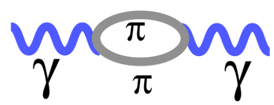
- *Physics Motivation*
- *Experimental Design*
- *Data Runs and Performance*
- *Physics Result*
- *Outlook*

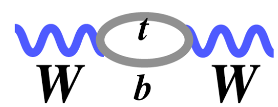
Beyond the Standard Model

- *High Energy Colliders*
- *Rare or Forbidden Processes*
- *Symmetry Violations*
- *Electroweak One-Loop Effects*

→ *Complementary Approaches*

α_{QED} G_F





M_Z

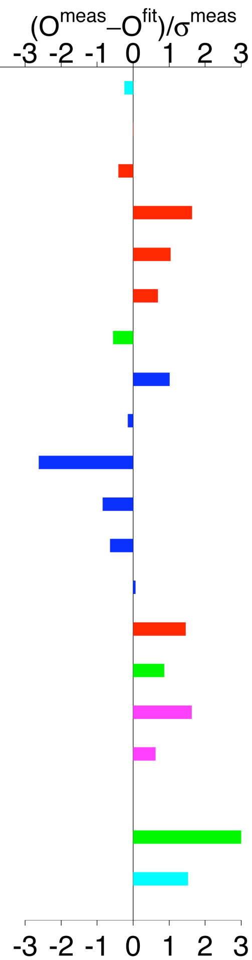
σ_Z M_W A_f

- *Precise predictions at level of 0.1%*
- *Indirect access to TeV scale physics*

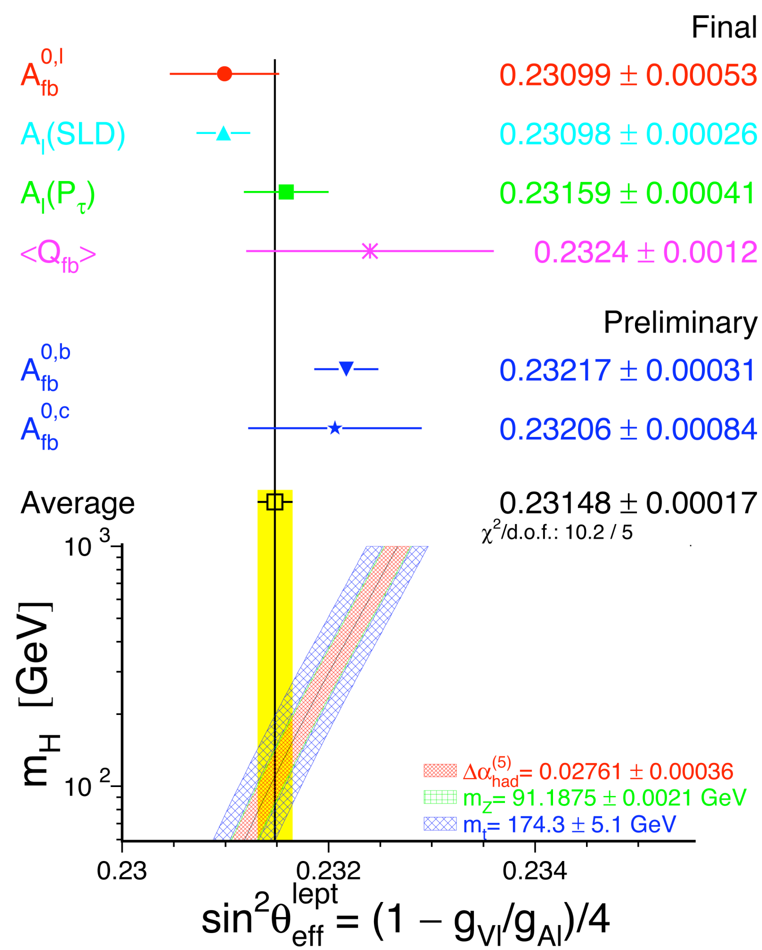
World Electroweak Data

Summer 2002

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.24
m_Z [GeV]	91.1875 ± 0.0021	0.00
Γ_Z [GeV]	2.4952 ± 0.0023	-0.41
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.04
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.68
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.55
R_b	0.21644 ± 0.00065	1.01
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.62
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.84
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.06
A_l(SLD)	0.1513 ± 0.0021	1.46
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.87
m_W [GeV]	80.449 ± 0.034	1.62
Γ_W [GeV]	2.136 ± 0.069	0.62
m_t [GeV]	174.3 ± 5.1	0.00
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
$Q_W(Cs)$	-72.18 ± 0.46	1.52



Winter 2003



World Electroweak Data

Perhaps the Standard Model is already broken

χ^2/dof ~ 30.4/15

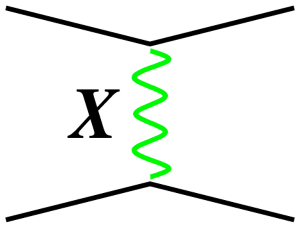
Leptonic and hadronic
Z couplings seem inconsistent

Probability ~ *1.5%*

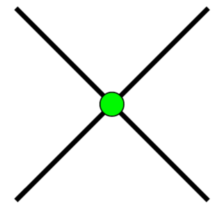
Perhaps there are bigger effects elsewhere

Electroweak Physics at Low Q^2

consider



$$A_X \;\alpha\; \frac{1}{Q^2 - M_X^2} \;\sim\; \frac{4\pi}{\Lambda^2} \longrightarrow$$



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!

Logical to push to higher energies, away from the Z resonance

LEPII and Tevatron access scales approaching □ ~ 10 TeV

Electroweak Physics at Low Q^2

Parity Violating Contact Interactions

$$\frac{\delta A_Z}{A_Z} \propto \frac{\pi/\Lambda^2}{g\, G_F} \longrightarrow \begin{array}{l} \delta(g)/g \sim 0.1 \\ \Lambda \sim 10\ TeV \end{array}$$

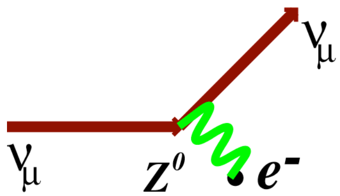
$$\frac{\delta(\sin\theta_W)}{\sin^2\theta_W} \lesssim 0.01$$

Logical to push to higher energies, away from the Z resonance

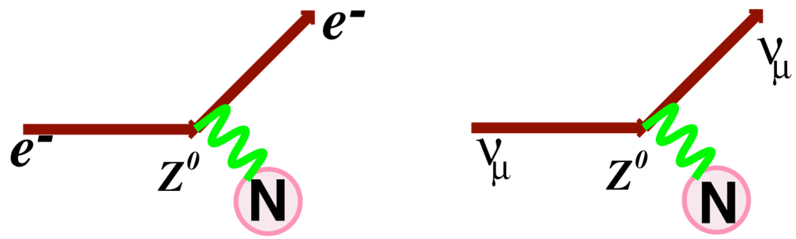
LEPII and Tevatron access scales approaching □ ~ 10 TeV

Parity Conserving Contact Interactions

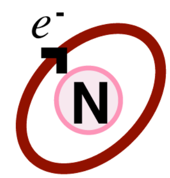
Fixed Target Møller Scattering



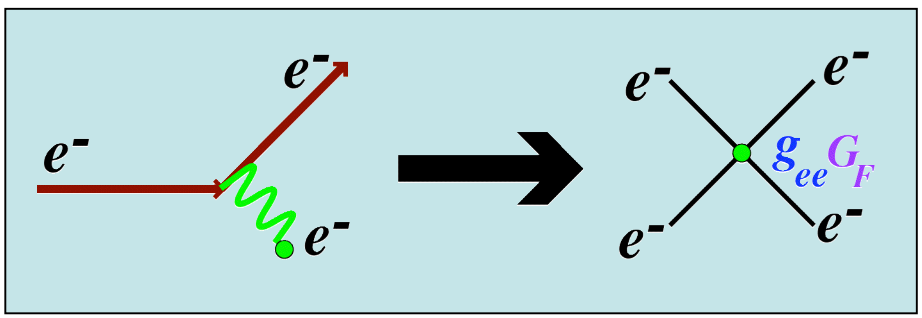
statistics



hadronic physics



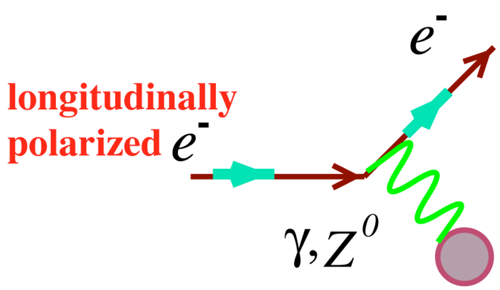
atomic wave function



Purely leptonic reaction

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

Weak-Electromagnetic Interference

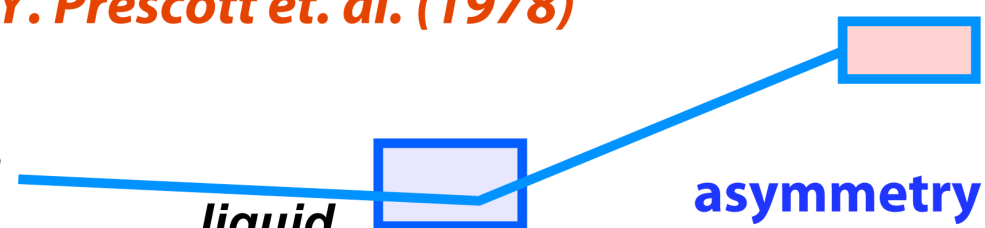


$$\sigma \;\; \alpha \; | A_\gamma + A_{weak} |^2$$

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

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

SLAC E122: C.Y. Prescott et. al. (1978)



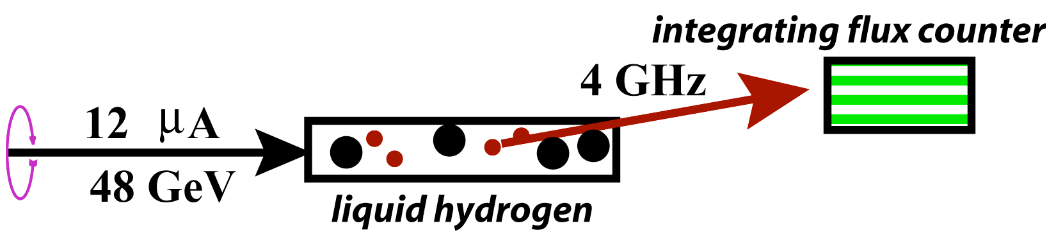
asymmetry ~ 10^{-4}

error ~ 10^{-5}

E158 at SLAC

A Precision Measurement of $\sin^2\theta_W$ at low Q^2

Parity-Violating Left-Right Asymmetry
In Fixed Target Møller Scattering



$Q^2 = mE = 0.025\ GeV^2$

$A_{raw} \sim 130$ ppb
$\delta(A_{raw}) \sim 10$ ppb
$\delta(\sin^2\theta_W) \sim 0.001$

- *Asymmetry rises linearly with beam energy*
- *Figure of merit rises linearly with beam energy*
- *High luminosity*
- *Precision monitoring at the micron level*
- *Systematic control at the nanometer level*

SLAC has unique capability

E158 Collaboration

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

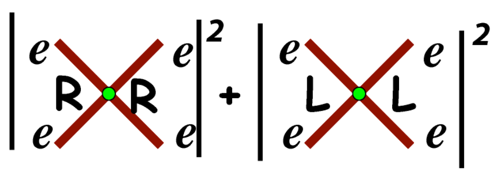
7 Ph.D. Students
60 physicists

E158 Chronology

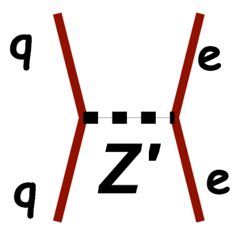
Sep 97: EPAC approval
Mar 98: First Laboratory Review
1999: Design and Beam tests
2000: Funding and construction
2001: Engineering run
2002: Physics

E158 New Physics Reach

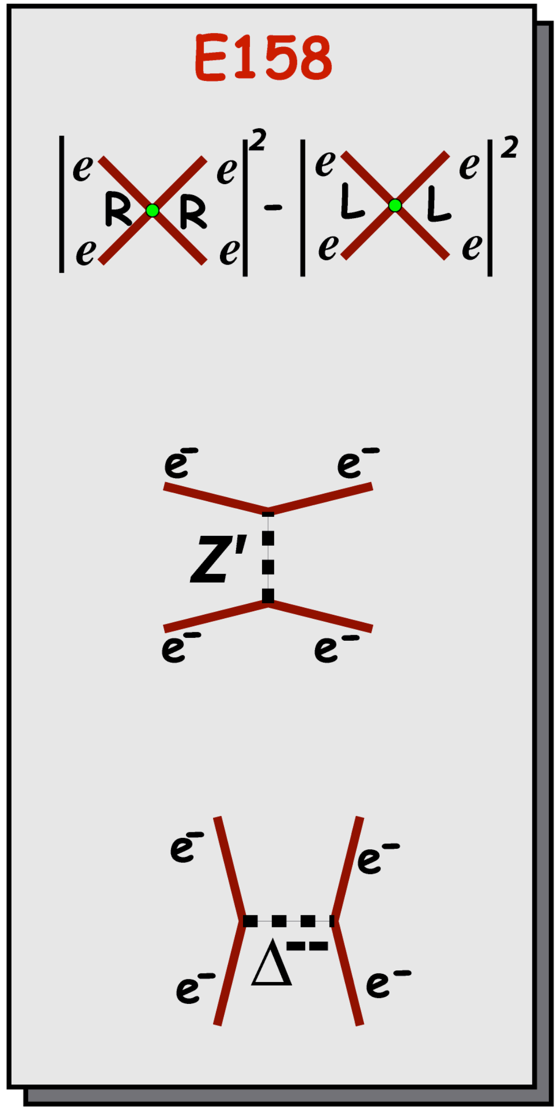
LEP II



Fermilab

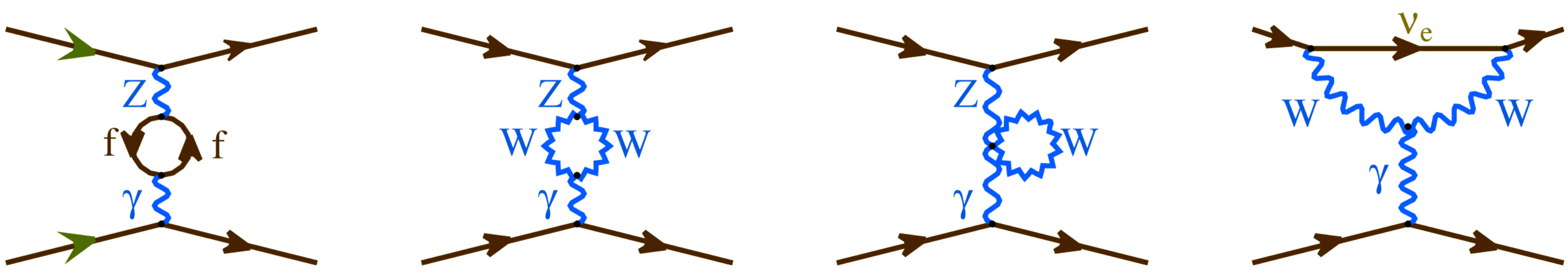


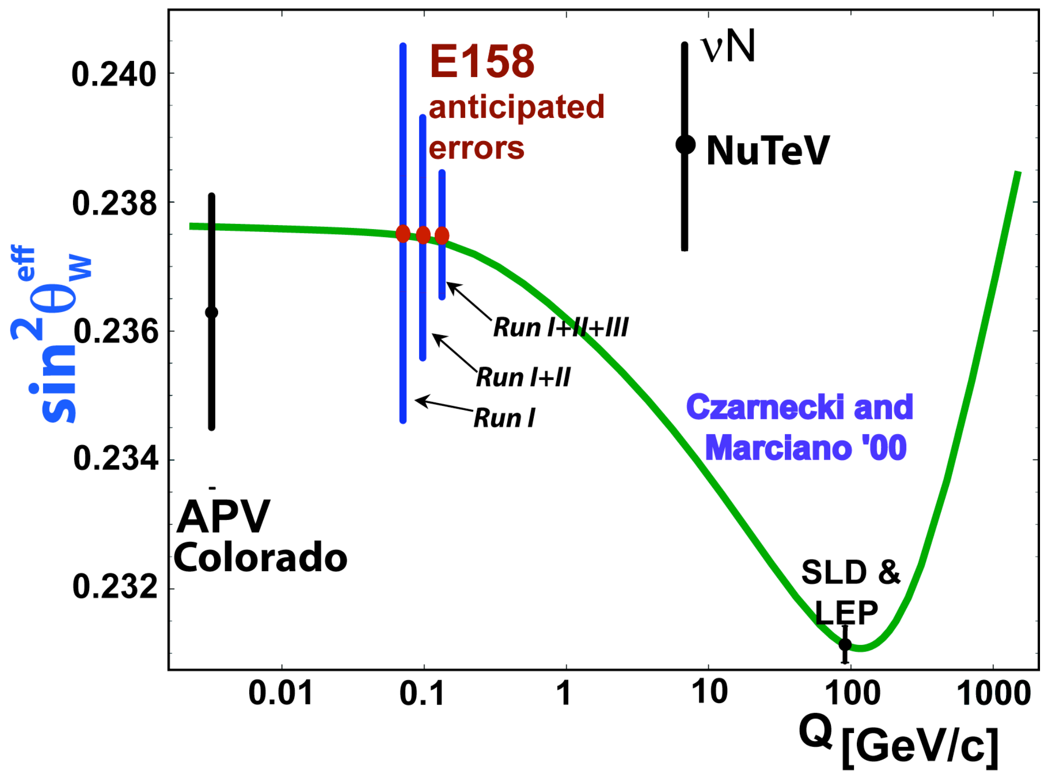
doubly charged scalar exchange



15 TeV	compositeness
0.5-1.0 TeV	GUTs
0.5-2.5 TeV	extra dimensions
$\frac{g^2}{2M_\Delta^2} < 0.01\ G_F$	lepton flavor violation

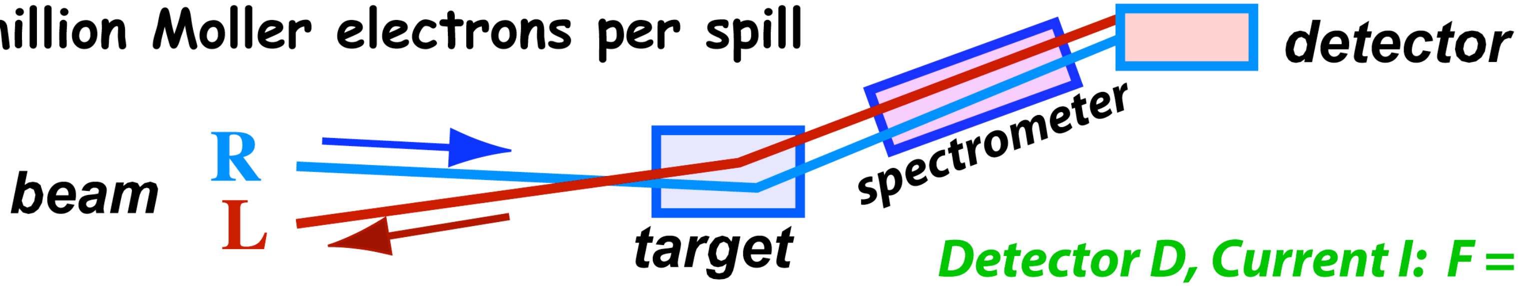
Electroweak Physics





Statistical Fluctuations

20 million Moller electrons per spill



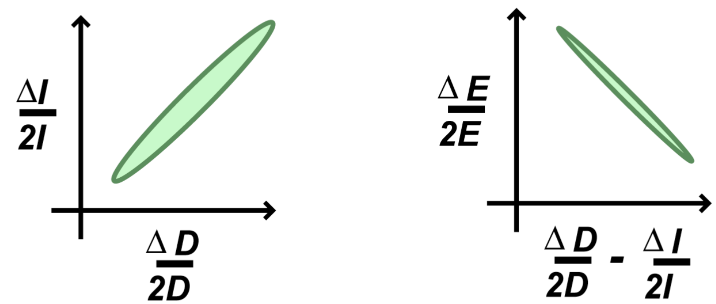
Detector D, Current I: $F = D/I$

$$A_{pair} = \frac{F_R - F_L}{F_R + F_L}$$

$$= \frac{\Delta F}{2F} + \text{fluctuations}$$

* Rapid helicity flips
* Spatially separate signal
* Integrate scattered flux
* control beam jitter

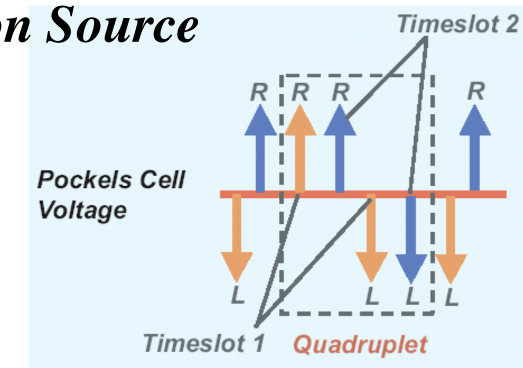
$$\frac{200\ ppm}{\sqrt{100\ M}} = 20\ ppb$$



→ precision monitoring and control of electron beam fluctuations

Systematic Fluctuations

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

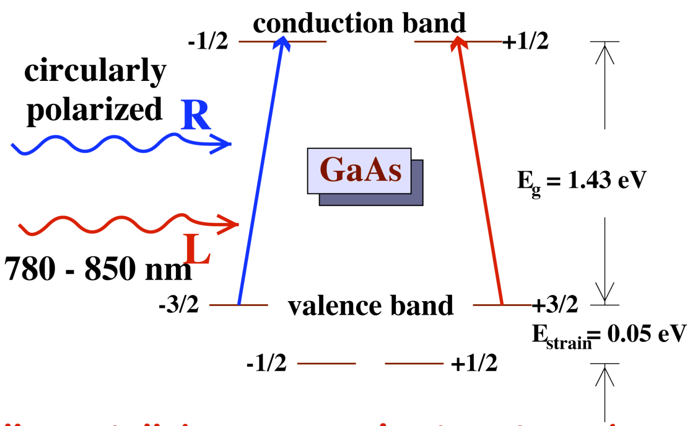


- ✧ ***Reduce beam asymmetries by feedback***
  - *Control beam charge and position asymmetries at Polarized Electron Source*

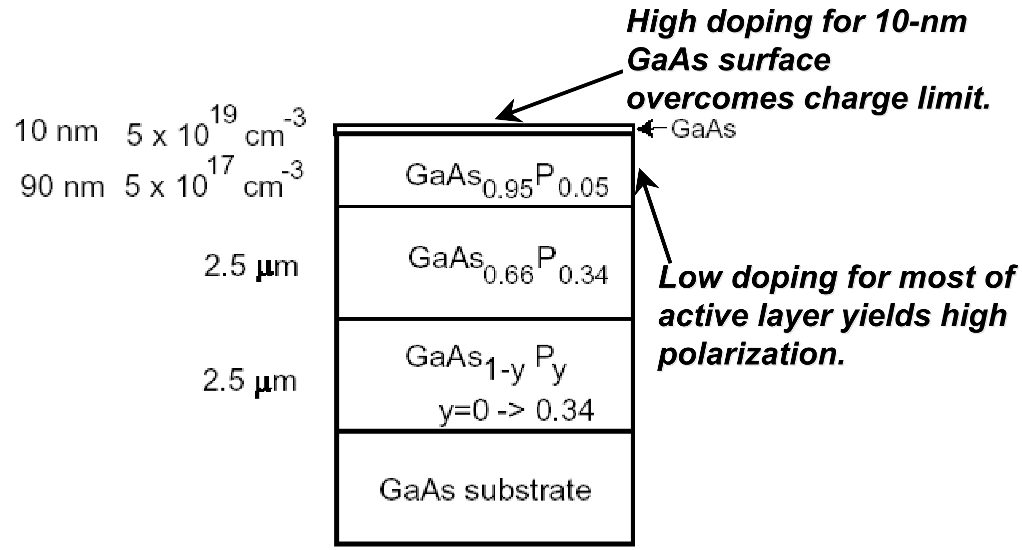
- ✧ ***Physics Asymmetry Reversals:***
  - *Insertable Half-Wave Plate at Polarized Electron Source*
  - *(g-2) spin precession in A-line (45 GeV and 48 GeV data)*

- ✧ ***"Null Asymmetry" Cross-check***
  - *Luminosity monitor measures very forward angle e-p and e-e scattering*

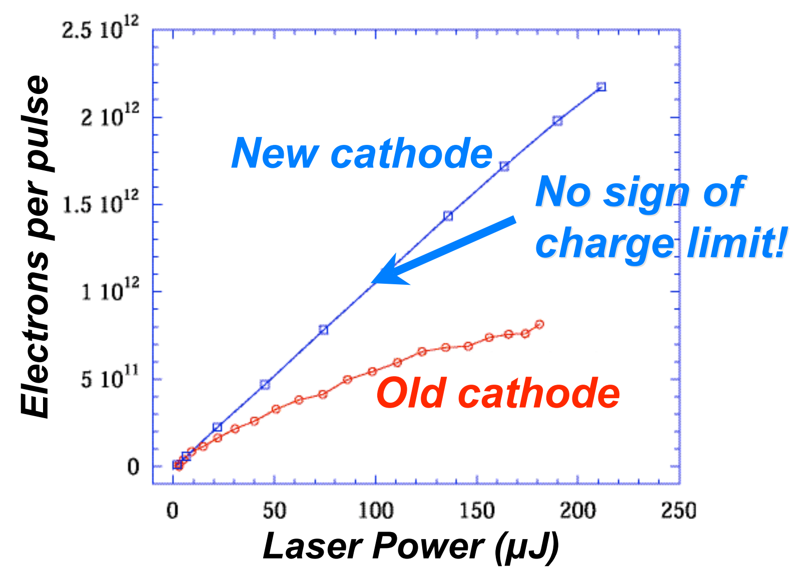
Polarized Beam



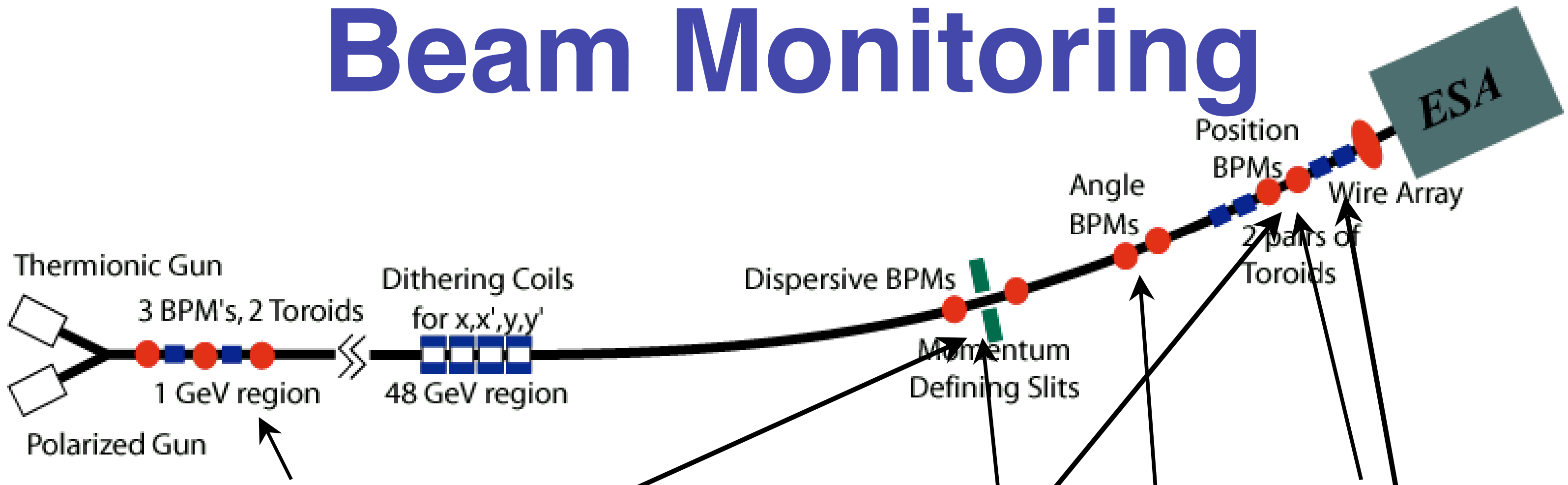
"strain" boosts polarization, but introduces anisotropy in response



Parameter	E158	NLC-500
Charge/Train	6×10^{11}	14.3×10^{11}
Train Length	270ns	260ns
Bunch spacing	0.3ns	1.4ns
Rep Rate	120Hz	120Hz
Beam Energy	45 GeV	250 GeV
e^- Polarization	80%	80%

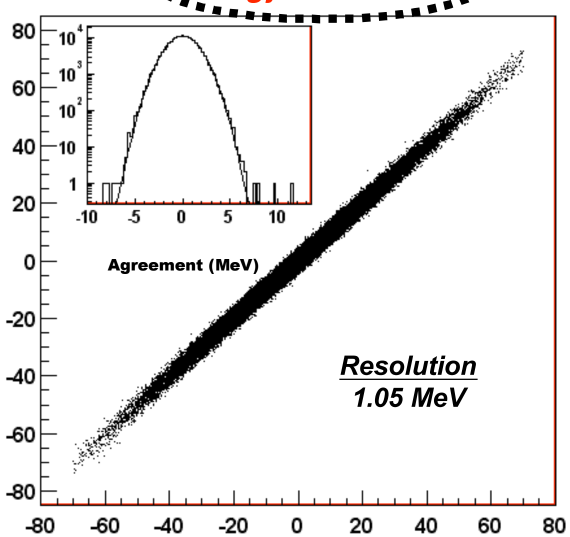


Beam Monitoring

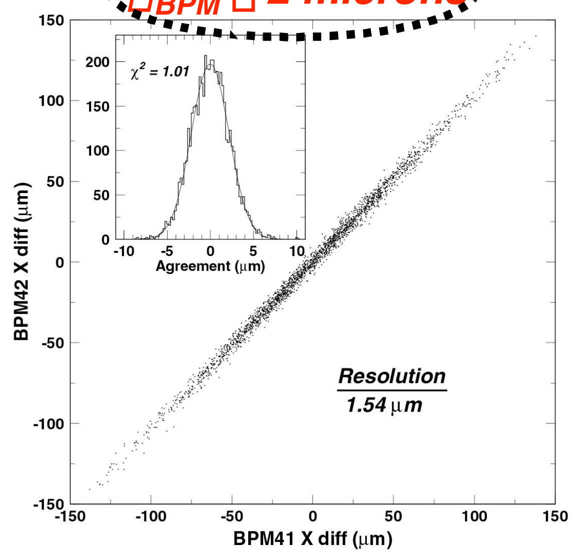


Event by event monitoring at 1 GeV and 45 GeV

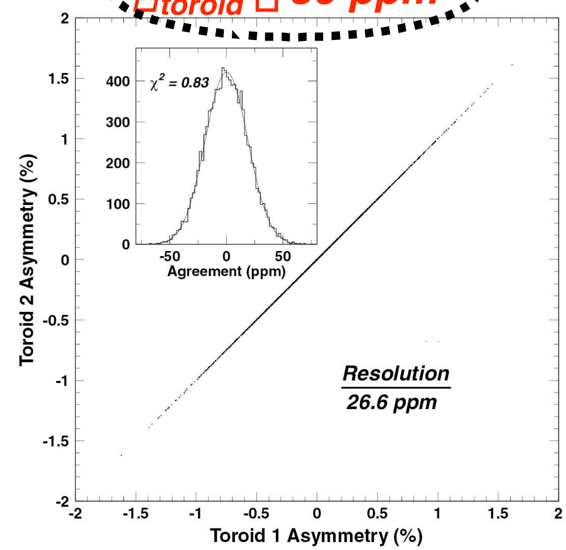
$\sigma_{energy} \approx$ 1 MeV



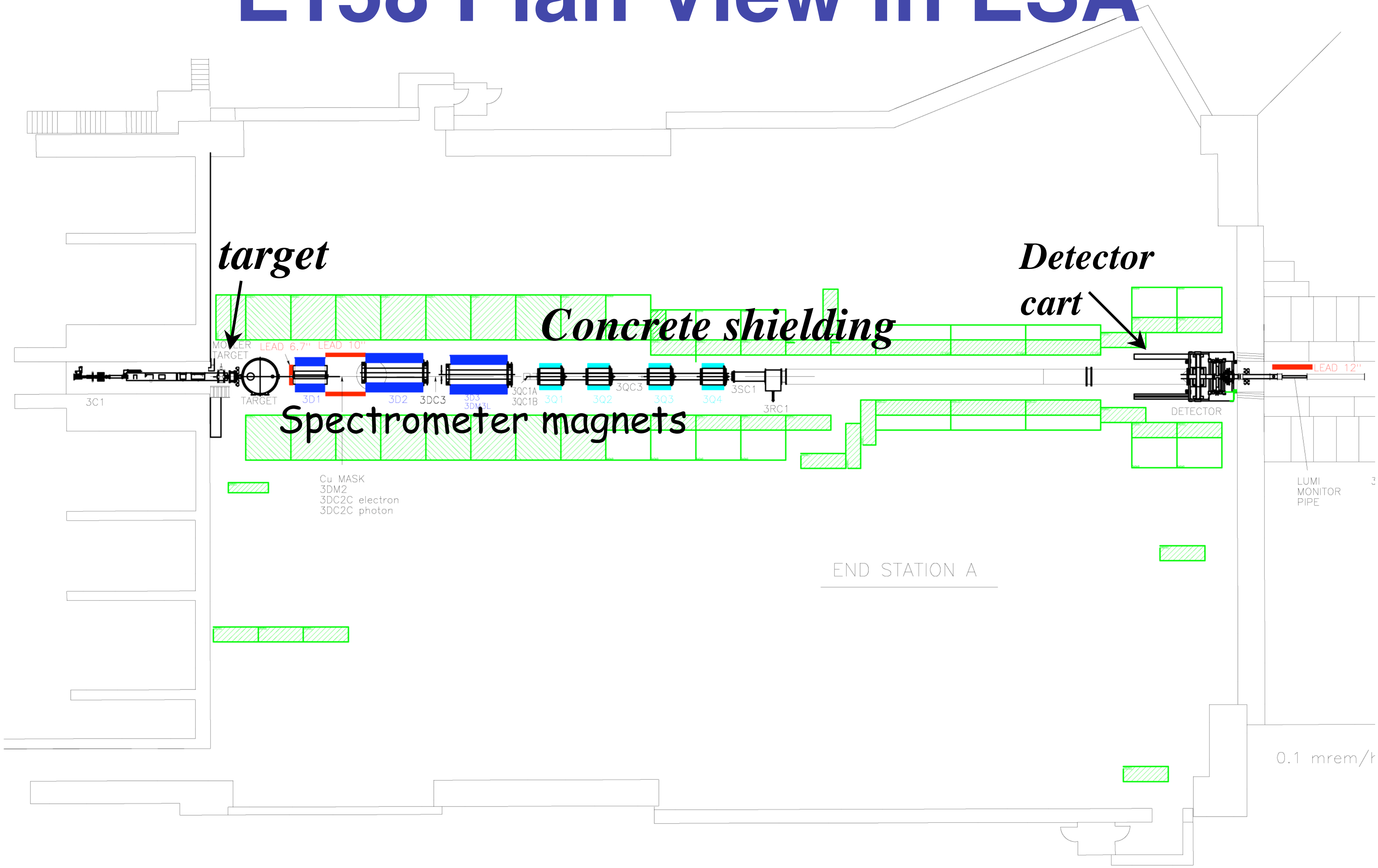
$\sigma_{BPM} \approx$ 2 microns



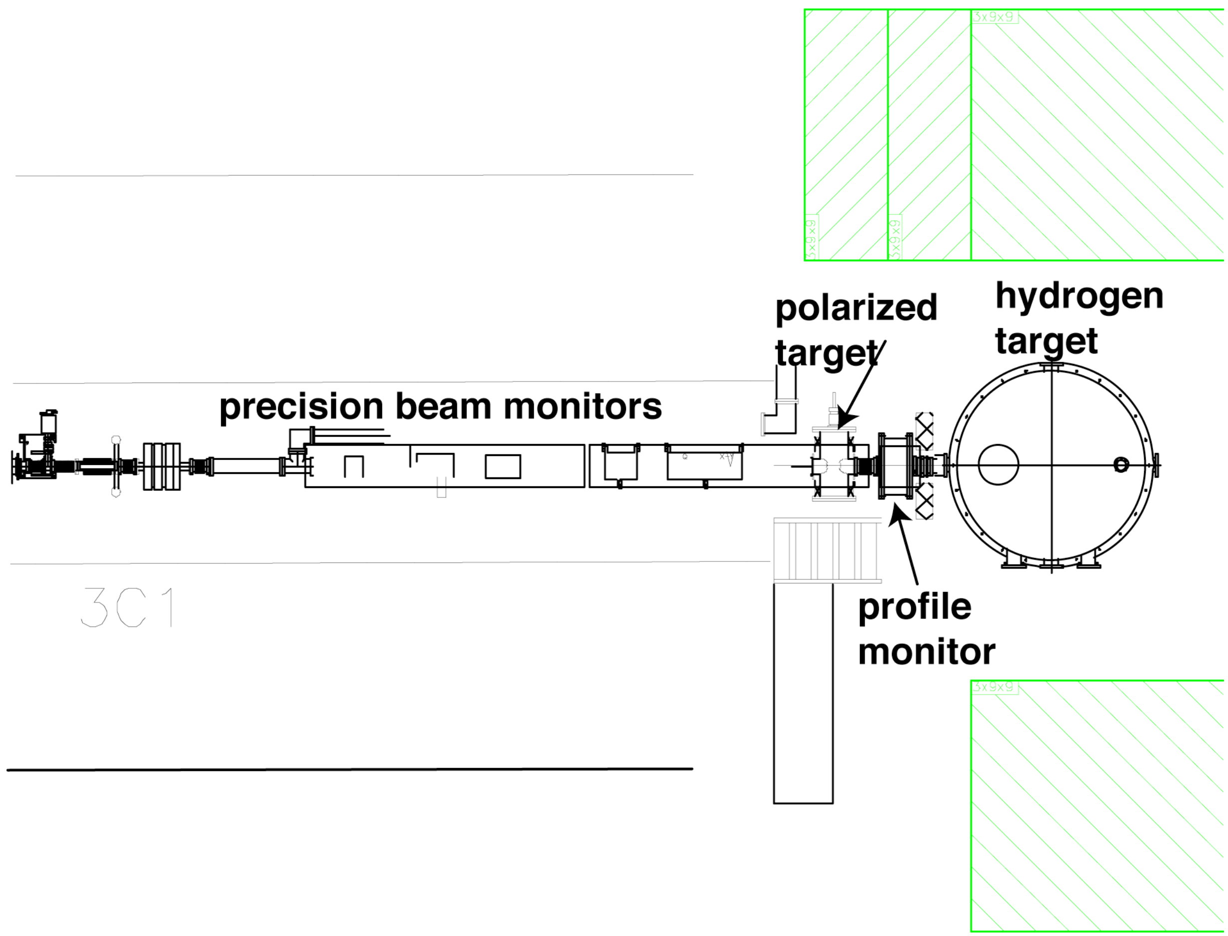
$\sigma_{toroid} \approx$ 30 ppm



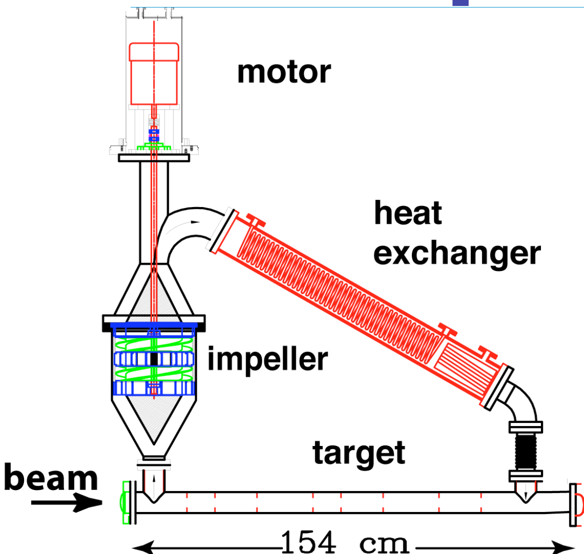
E158 Plan View in ESA

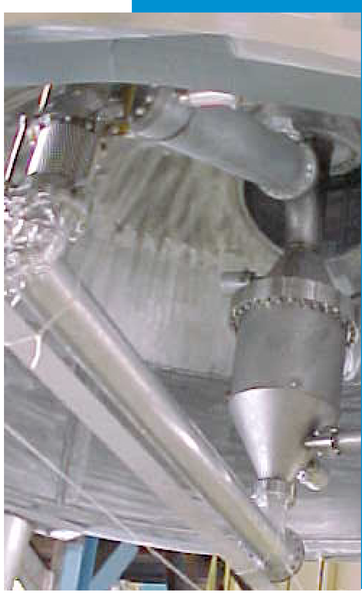


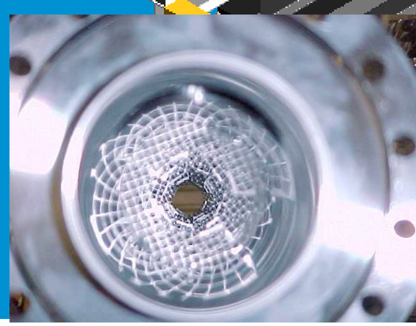
E158 Plan View in ESA



Liquid Hydrogen Target

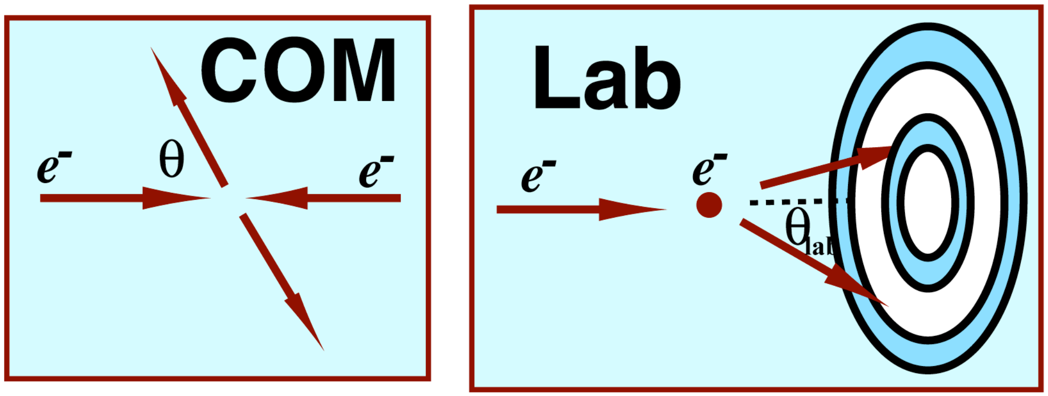


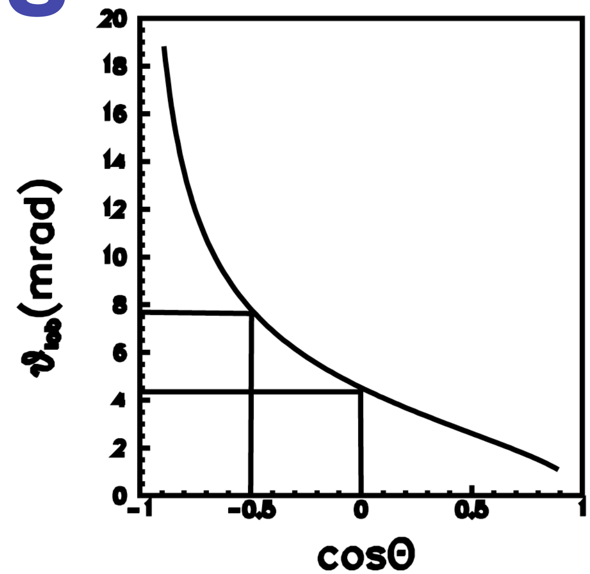




Refrigeration Capacity	1 kW
Operating Temperature	20 K
Length	1.5 m
Flow Rate	5 m/s
Vertical Motion	6 inches

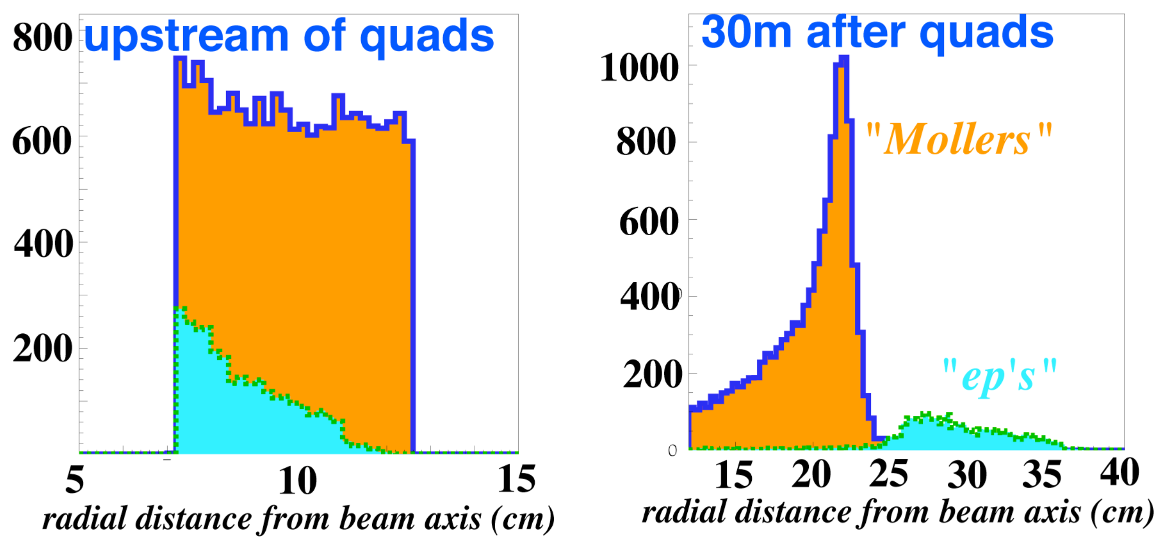
Kinematics





Quadrupole Quadruplet

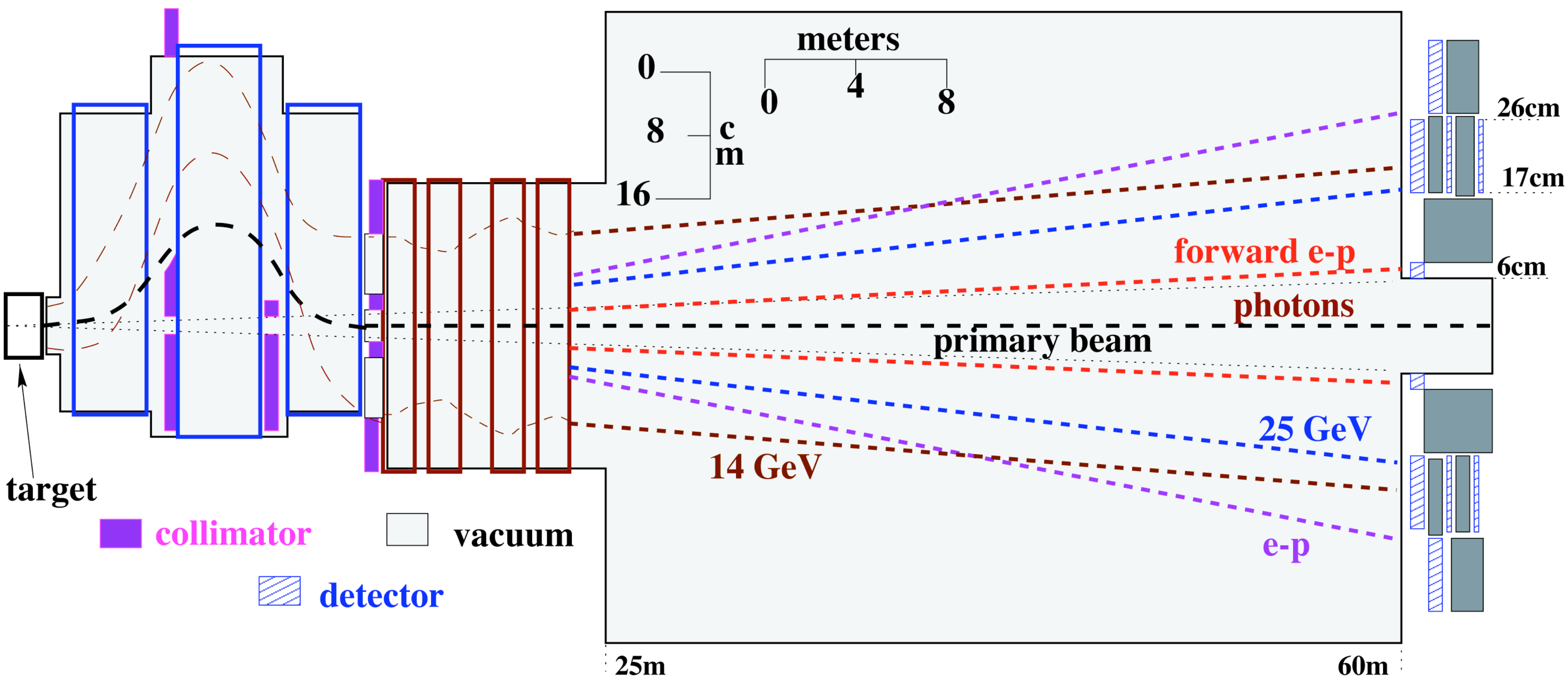
- *primary & scattered electrons enclosed in quadrupoles*
- *Mollers (e-e) focused, Motts (e-p) defocused*
- *full range of azimuth*



Dipole Chicane

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

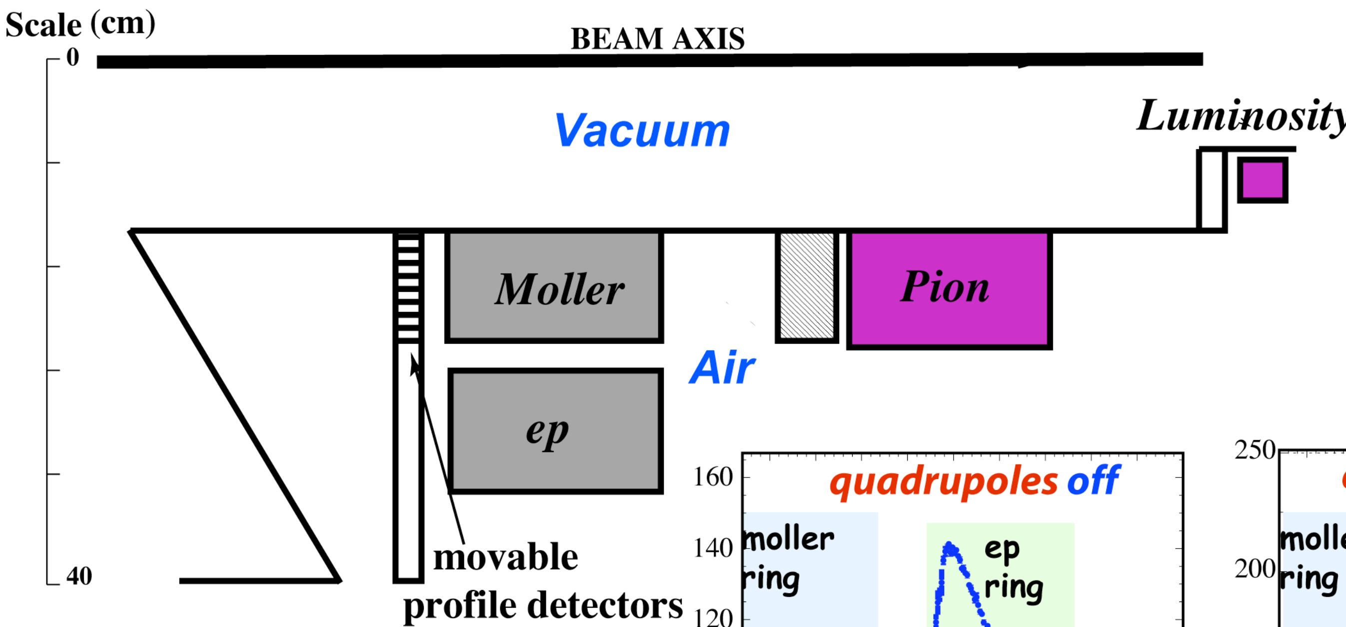
Line-of-sight shielding requires a "dogleg" or "chicane"

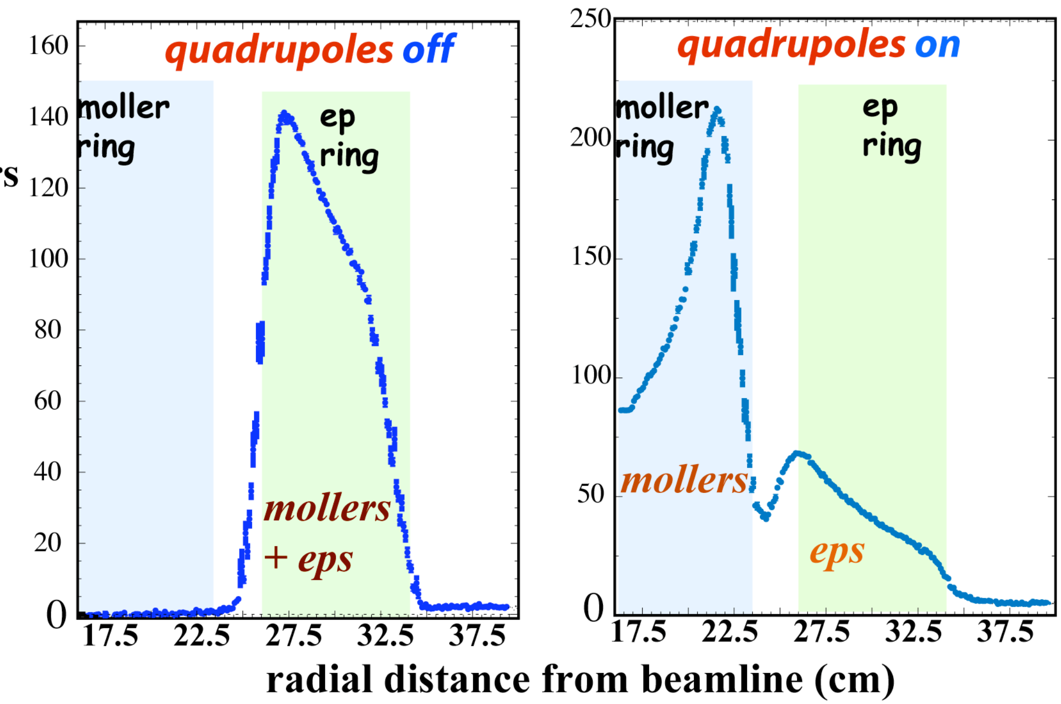


E158 Spectrometer

Downstream Configuration

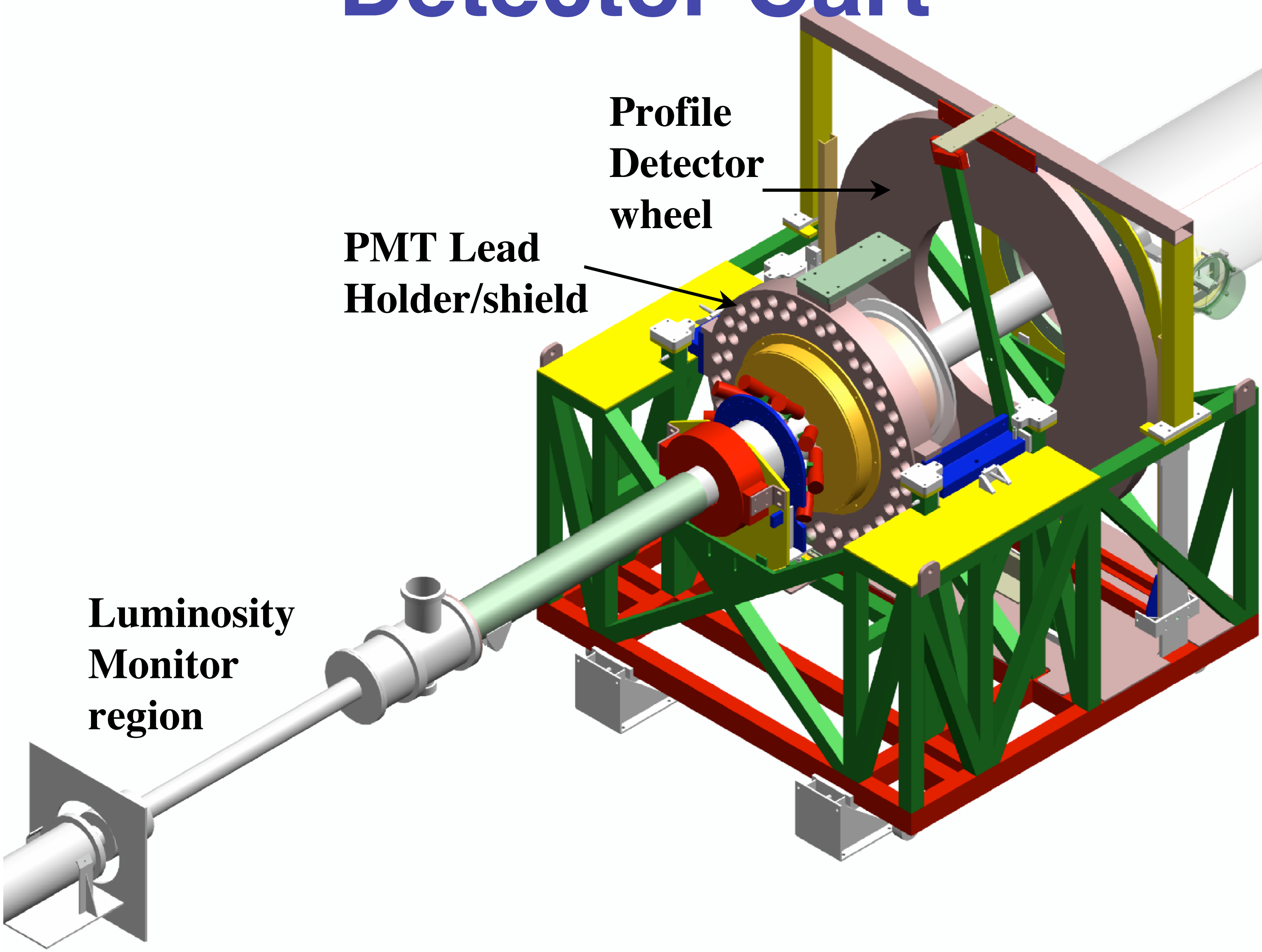
Detector Concept



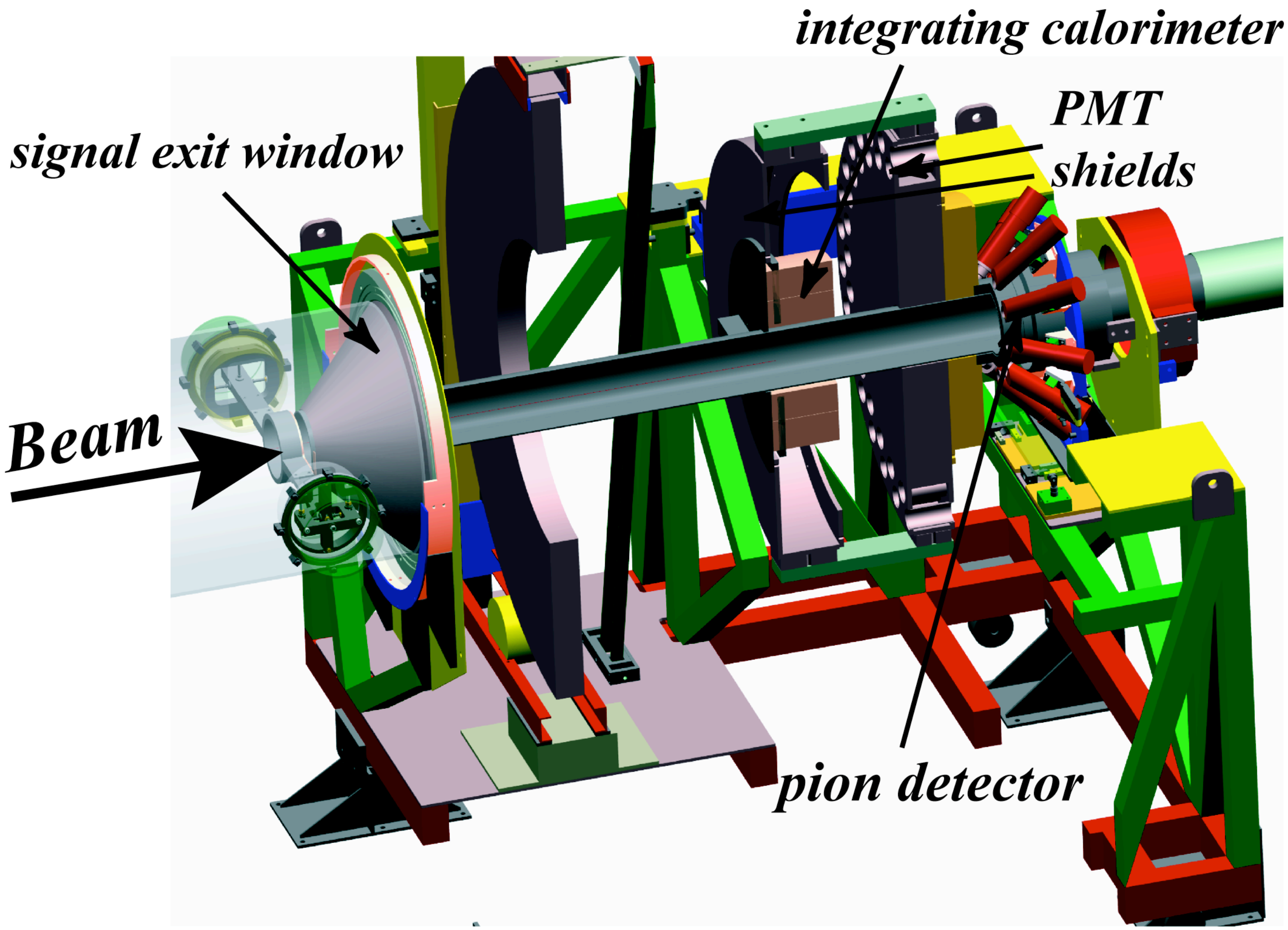


* 4 integrating detectors
* profile detectors for calibration

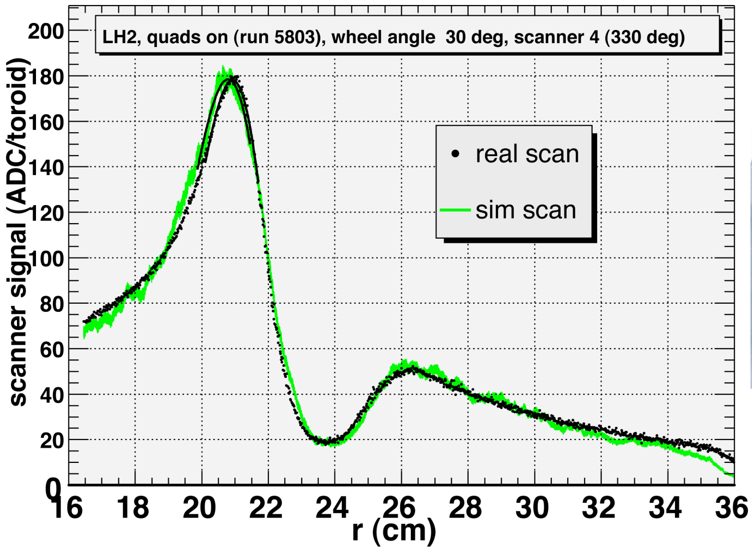
Detector Cart

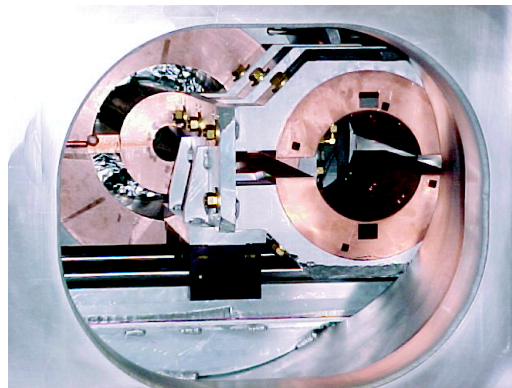


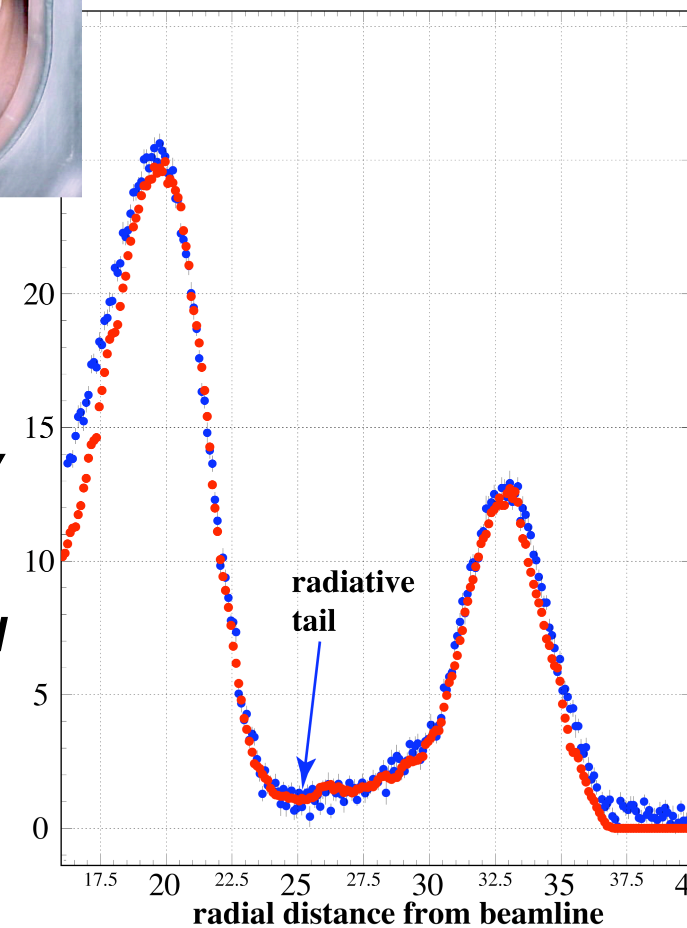
Detector Cart

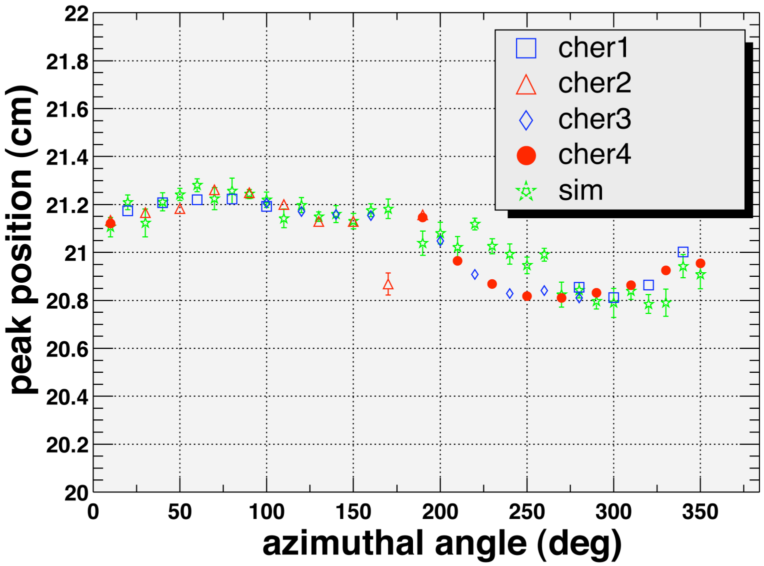


Scattered Flux Profile







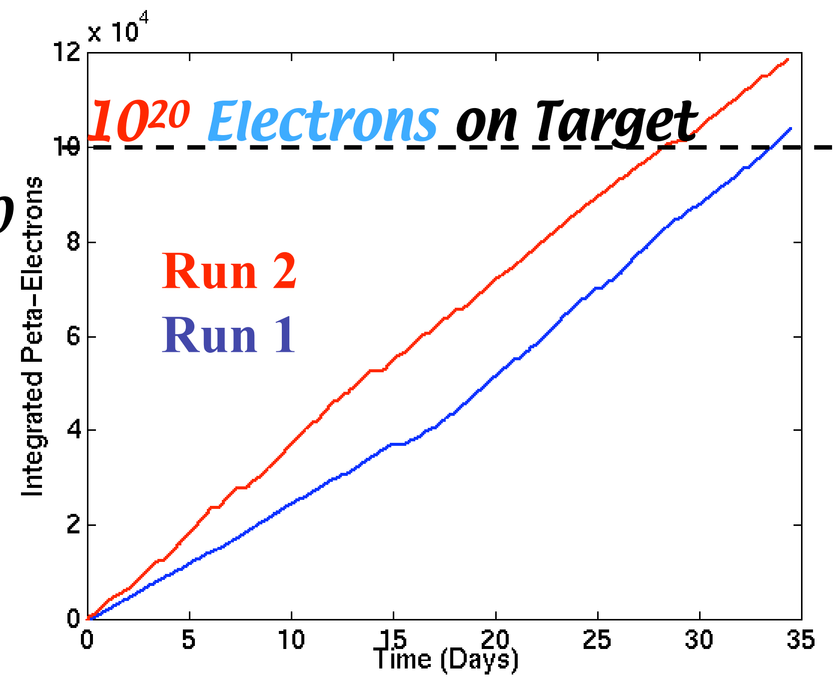


- ~ 2 mm geometry
- 1% energy scale
- Radiative tail
- < 1% background

Physics Runs

	Energy	#days @120Hz	# Peta-Electron	#spills	Average Charge	Production Efficiency*
Run 1	45.6 GeV	19.2	67K	125M	5.5×10^{11}	63%
Run 1	48.8 GeV	14.8	37K	105M	3.5×10^{11}	69%
Run 2	45.6 GeV	15.2	56K	113M	5.2×10^{11}	72%
Run 2	48.8 GeV	19.0	63K	153M	4.3×10^{11}	78%

*Efficiency is avg. delivered rate normalized to 119Hz

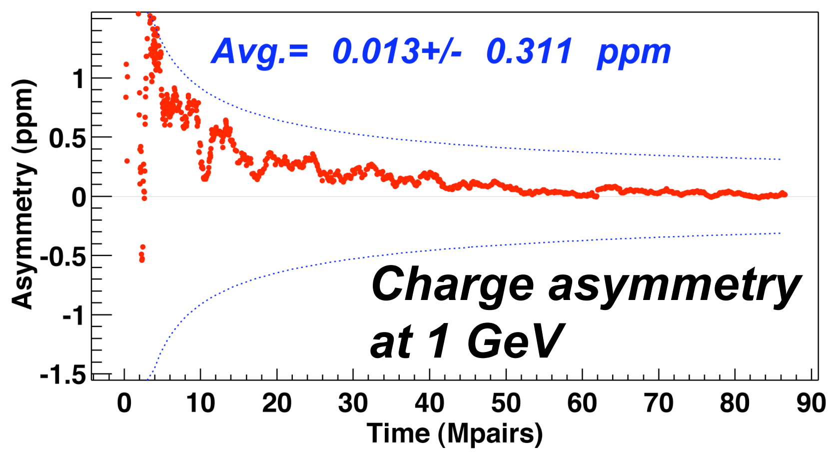


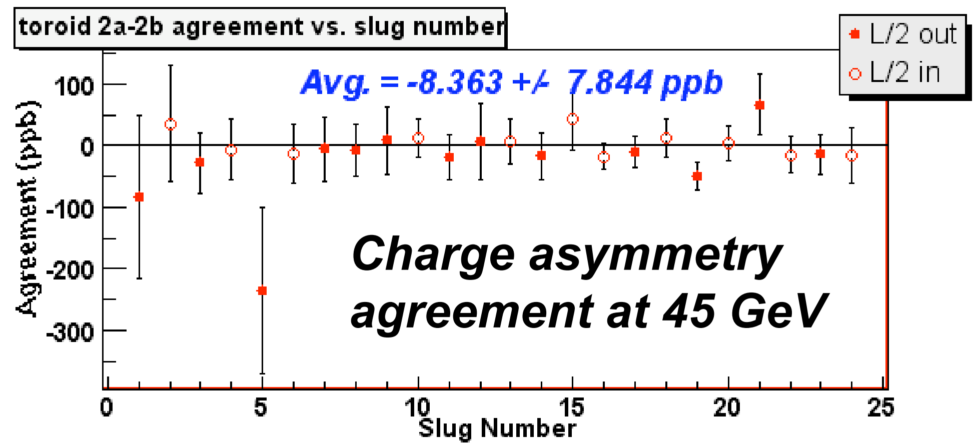
Run 1: April 23 12:00 - May 28 00:00

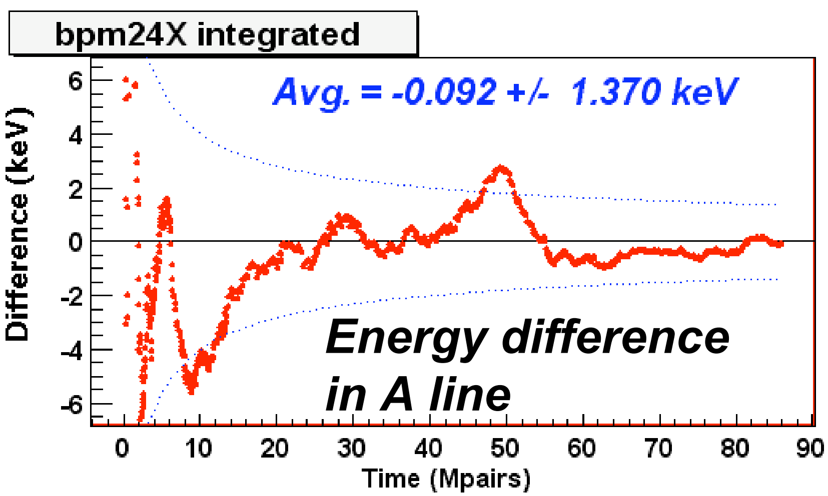
Run 2: October 10 08:00 - November 13 16:00

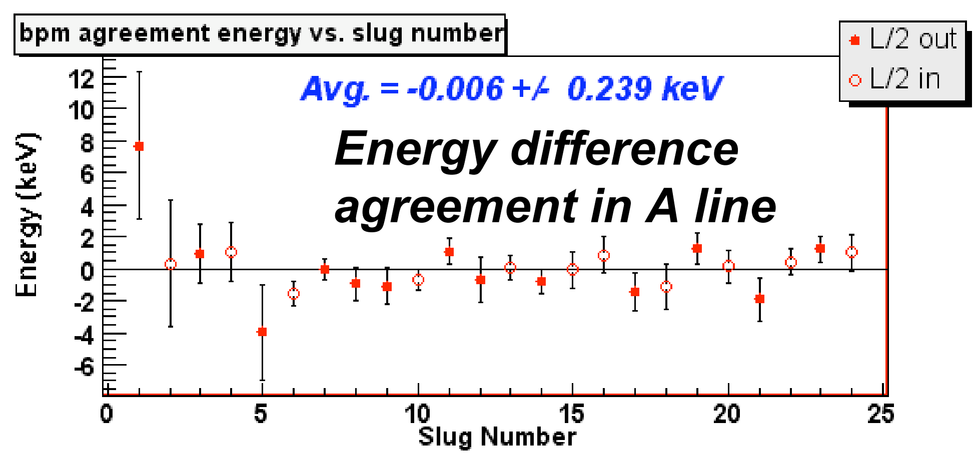
- *Run I with PEPII, Run II dedicated*
- *One g-2 flip in each run*
- *λ/2 flip roughly once in two days*
- *Asymmetry inverter flip once a week*
- *Run I data divided into 24 "slugs"*

Beam Asymmetries







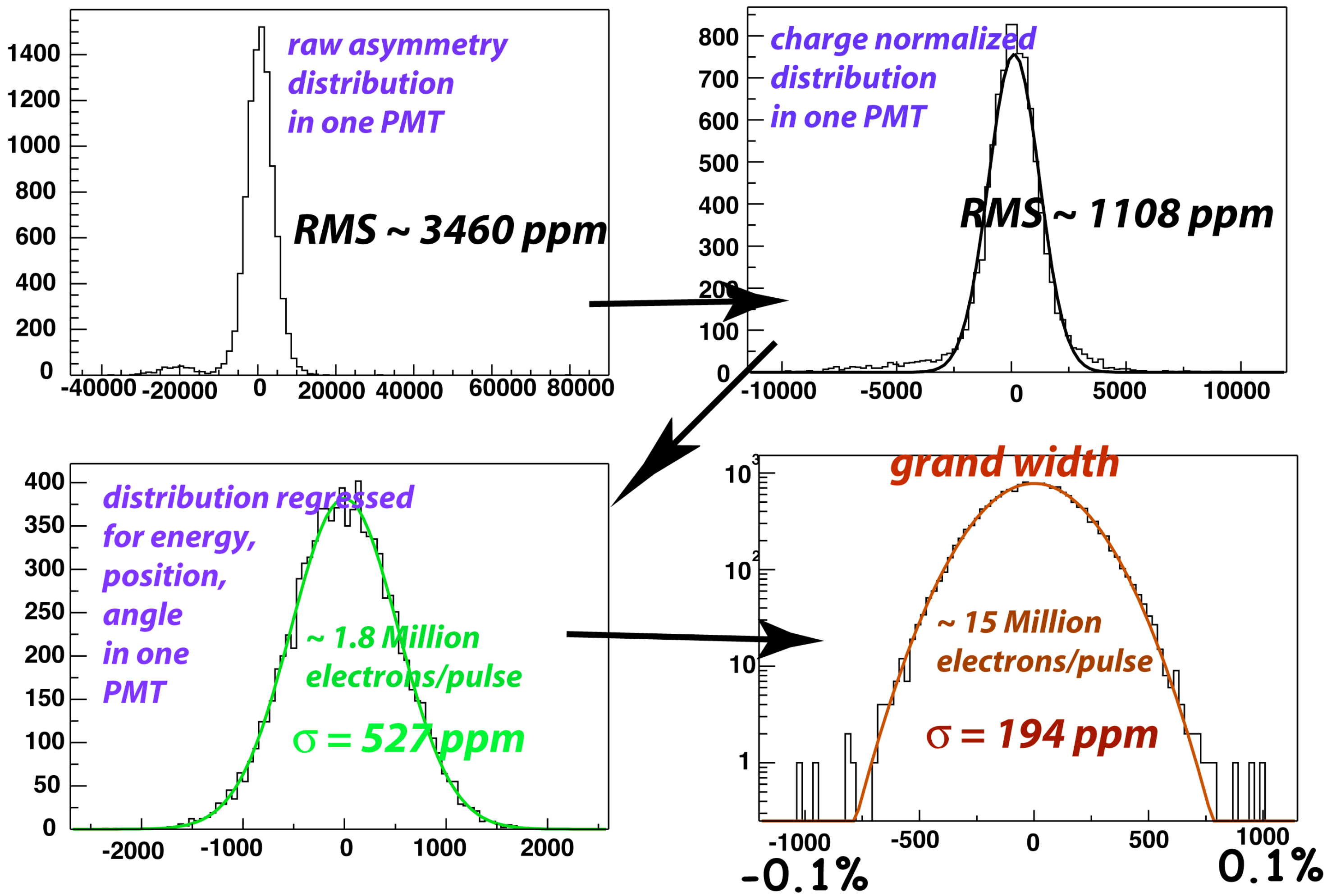


Position differences < 20 nm

Position agreement ~ 1 nm

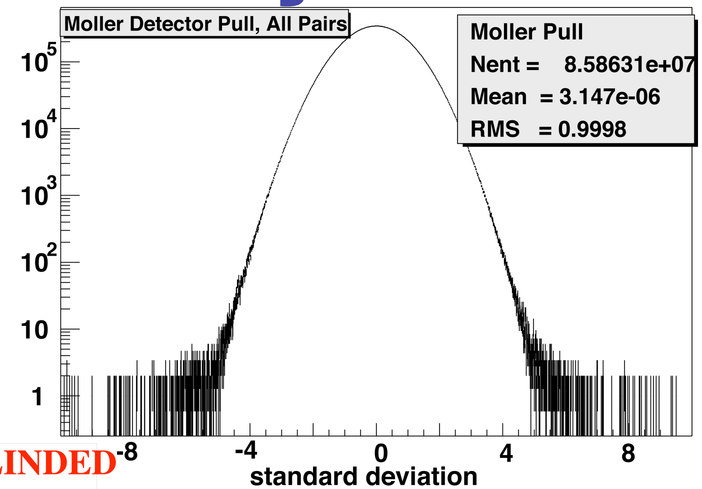
Regression Analysis

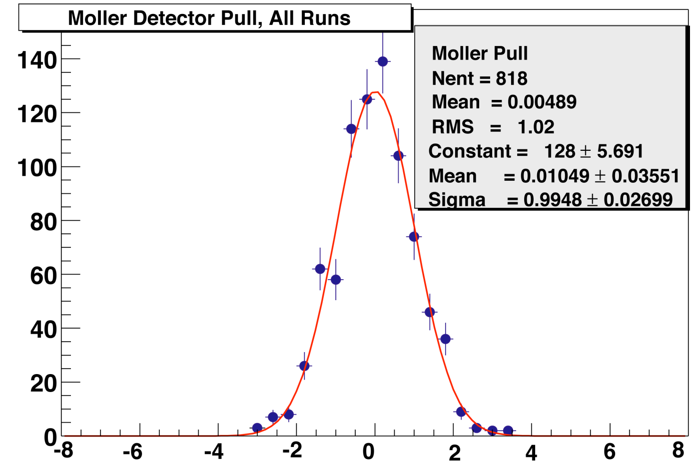
observed left-right asymmetry distribution

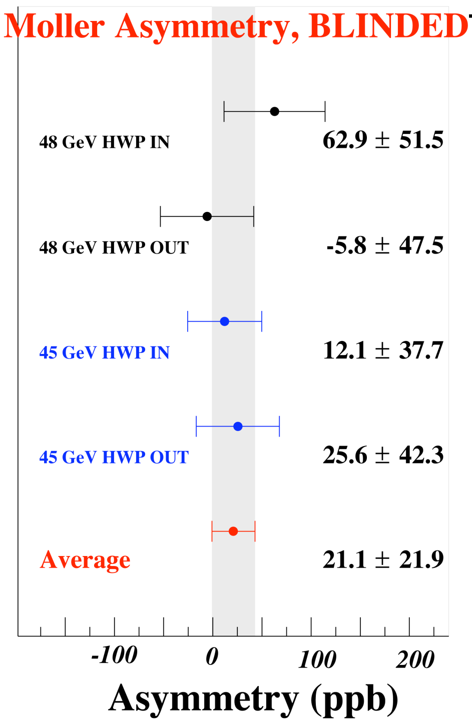


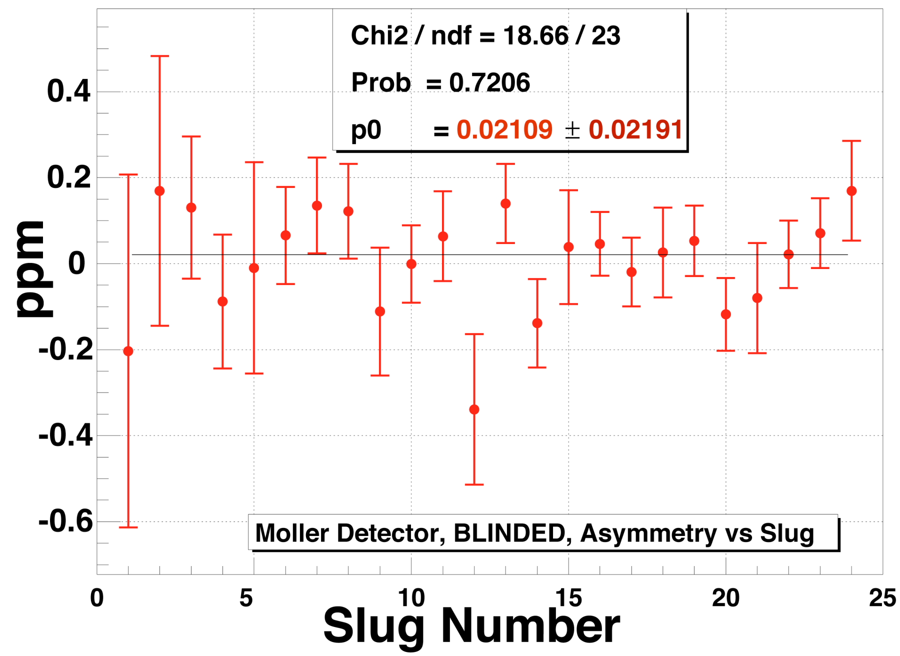
In addition, independent analysis based on beam dithering

Raw Asymmetry Statistics



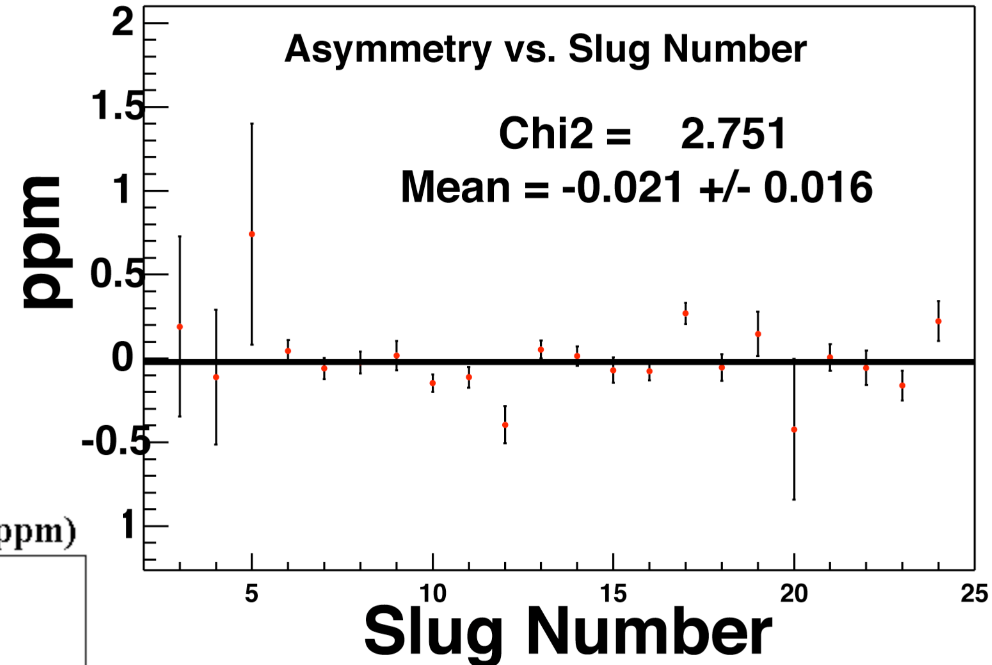


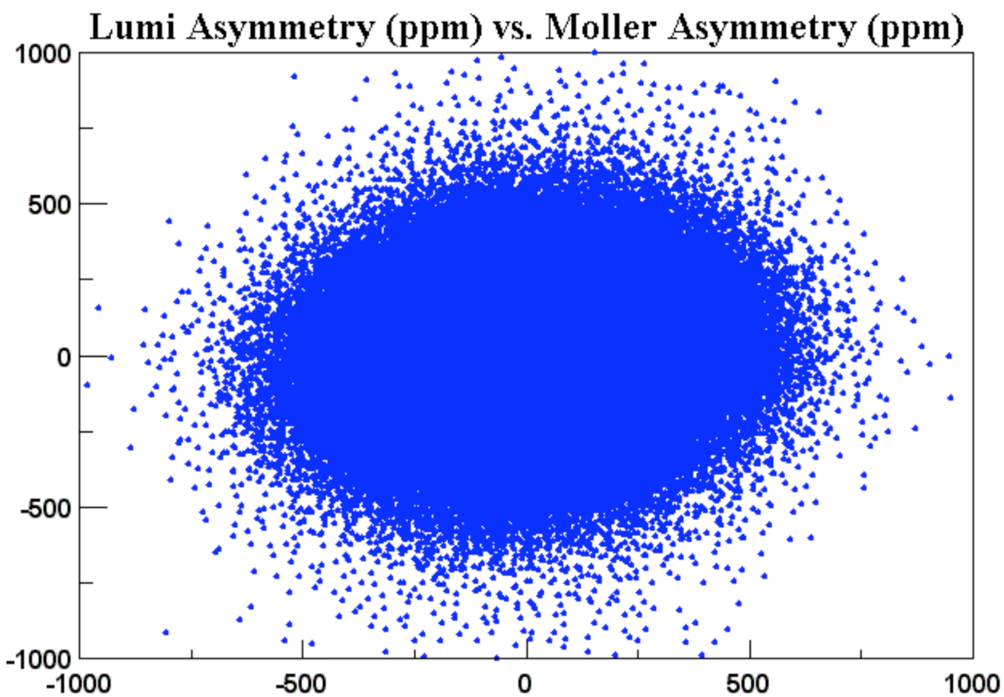




Luminosity Monitor Data

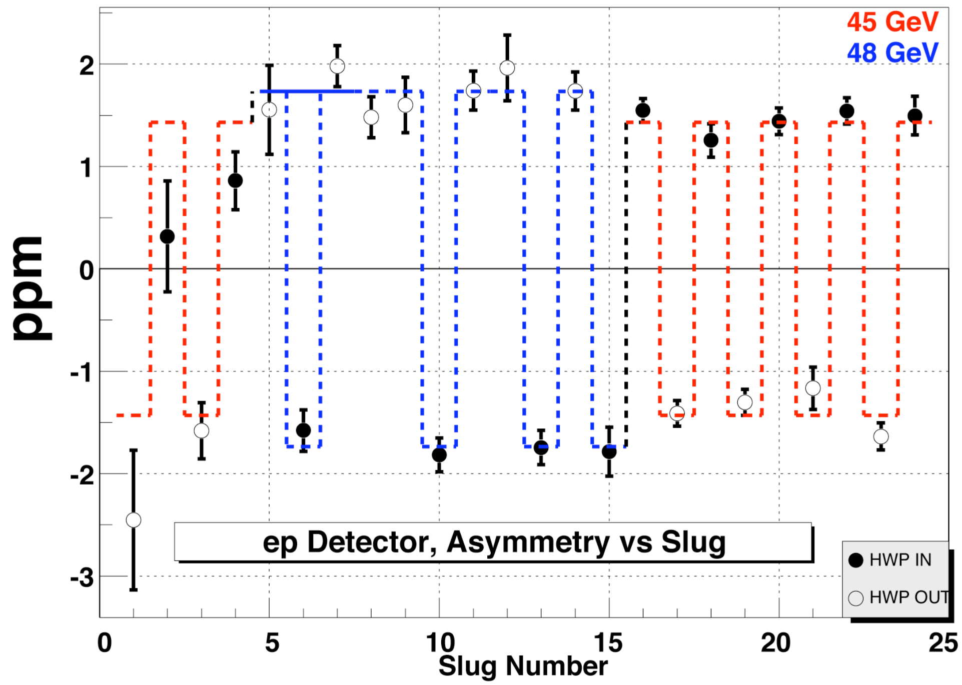
- *Null test at level of 20 ppb*

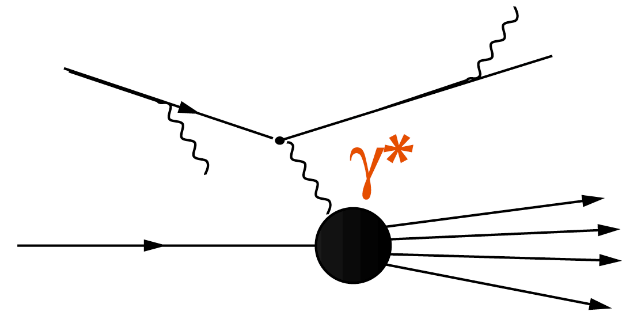




- *Density fluctuations small*
- *Limits on second order effects*

“ep” Detector Data





inelastic scattering

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

elastic scattering

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

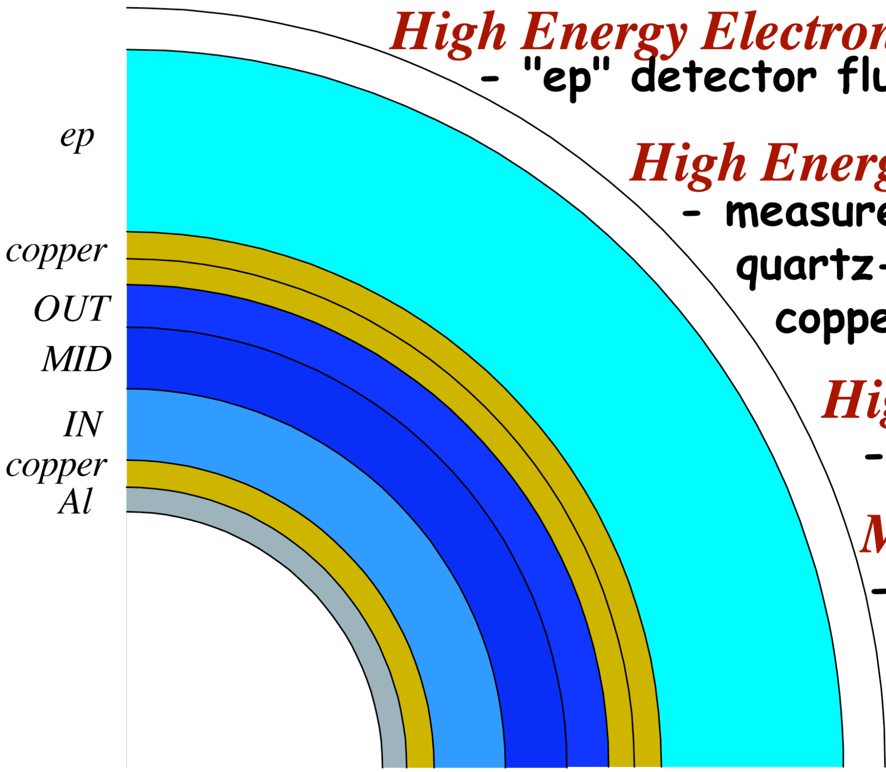
in the ep detector:

$Q^2 \sim 0.06$ GeV^2:

$A_{Raw} \sim 0.4$ +/- 0.2 ppm

- radiative tail dominated by elastic scattering: ~ 8% under Moller peak
- additional 1% contribution from inelastic scattering
- 35 ppb +/- 10 ppb
- reduced by 40% in run II

Backgrounds



High Energy Electrons:
- "ep" detector flux and asymmetry measurements

High Energy Pions:
- measure calibrated response to quartz-bar detectors behind 15 cm of copper + 20 cm of lead

High Energy Photons:
- Negligible due to collimation

Multibounce Photons:
- Quads off/on data with main detector & profile detector

Soft Photons and Neutrons:
- Quads off/on data with "blinded" PMTs

Synchrotron Photons:
- "target out" runs

integrating calorimeter:
All dilutions and asymmetries must be measured or bounded

Corrections Summary

Issue	f	df	A (ppb)	dA (ppb)
Beam first order	-	-	-	18
Beam spotsize	-	-	0	5
transverse asymmetry	-	-	5	0*
High Energy photons	0.004	0.002	0	0
Synchrotron	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
	0.109	0.021	42	24

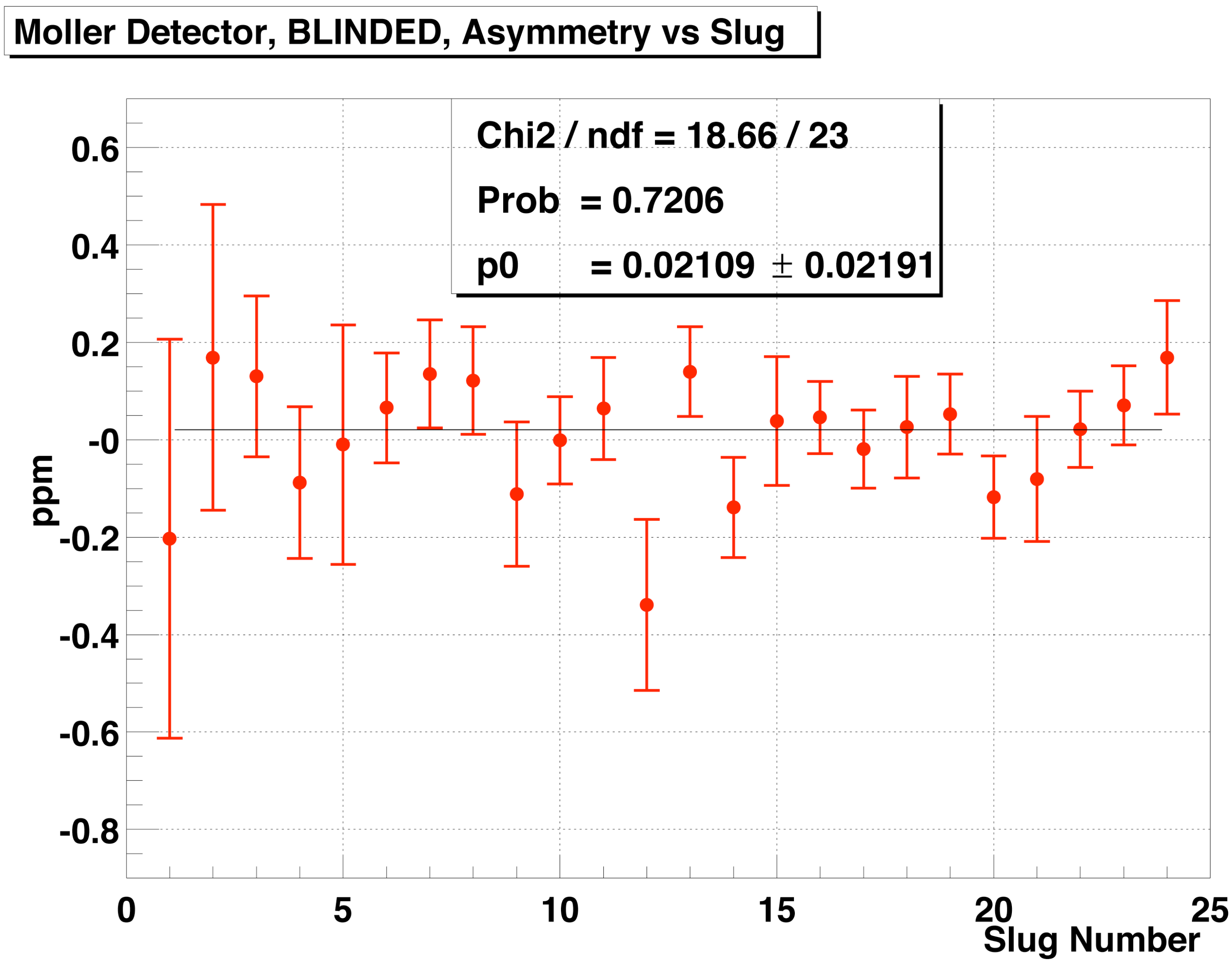
- ***Run I systematic error will reduce from 24 to less than 15 ppb***
- ***Run II corrections will be of order 25 ppb***

Normalization Errors

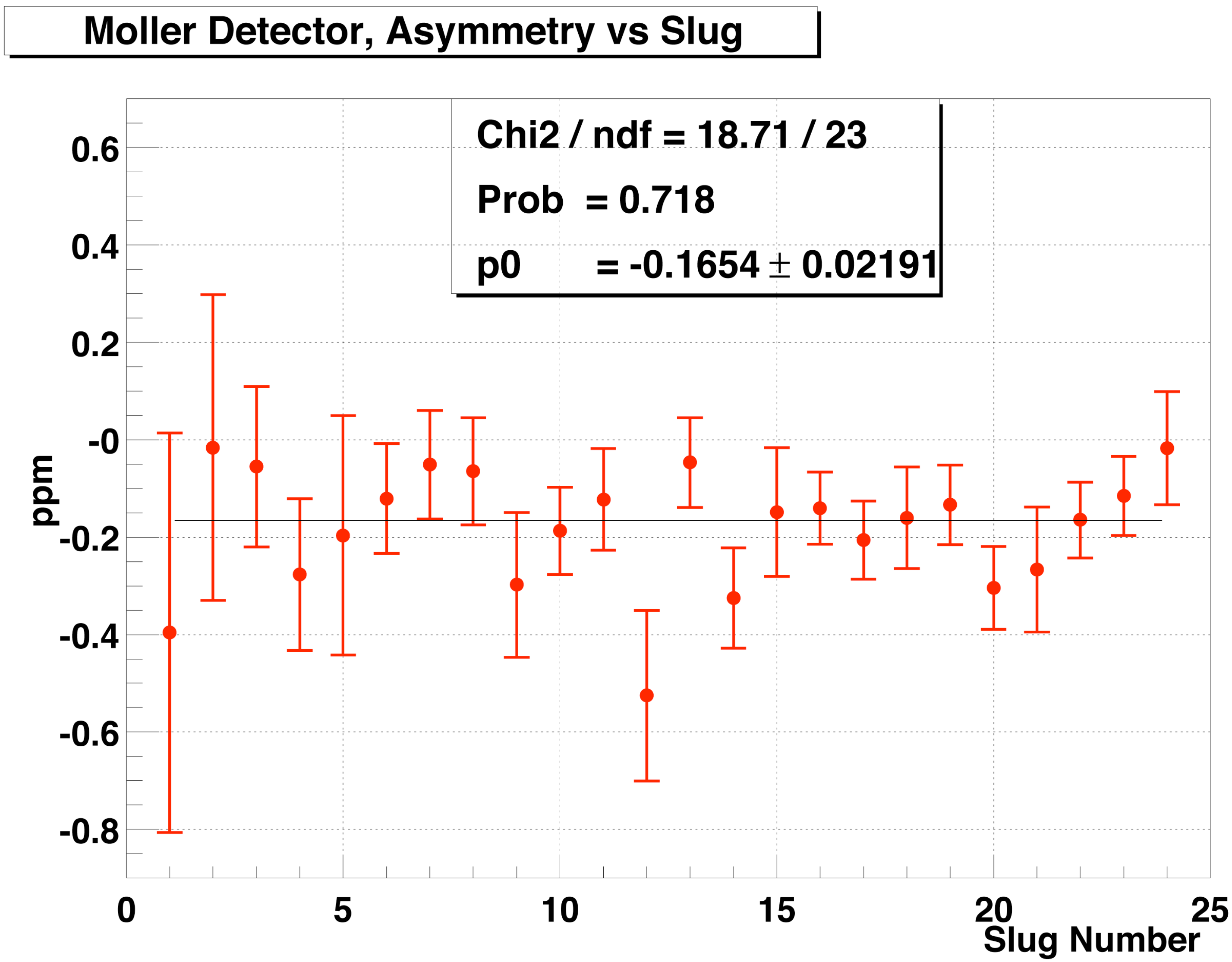
Issue	f	df
Polarimetry	0.85	0.05
Dilutions	0.89	0.02
Energy Scale	1.0	0.01
Geometry	1.0	0.01
Linearity	0.99	0.02

- *Beam polarization measured using polarized foil target*
- *Same spectrometer used with dedicated movable detector*

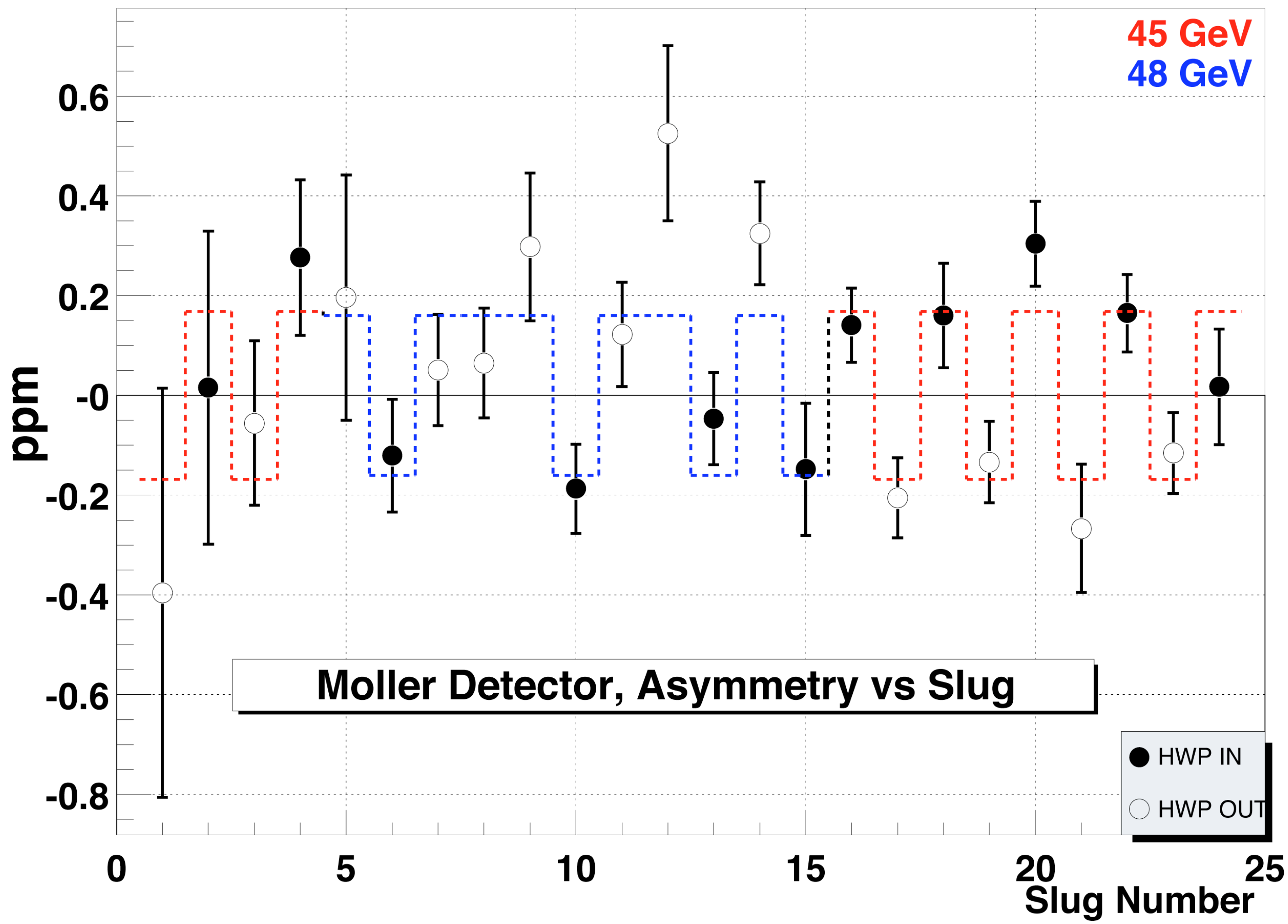
Raw Asymmetry Result



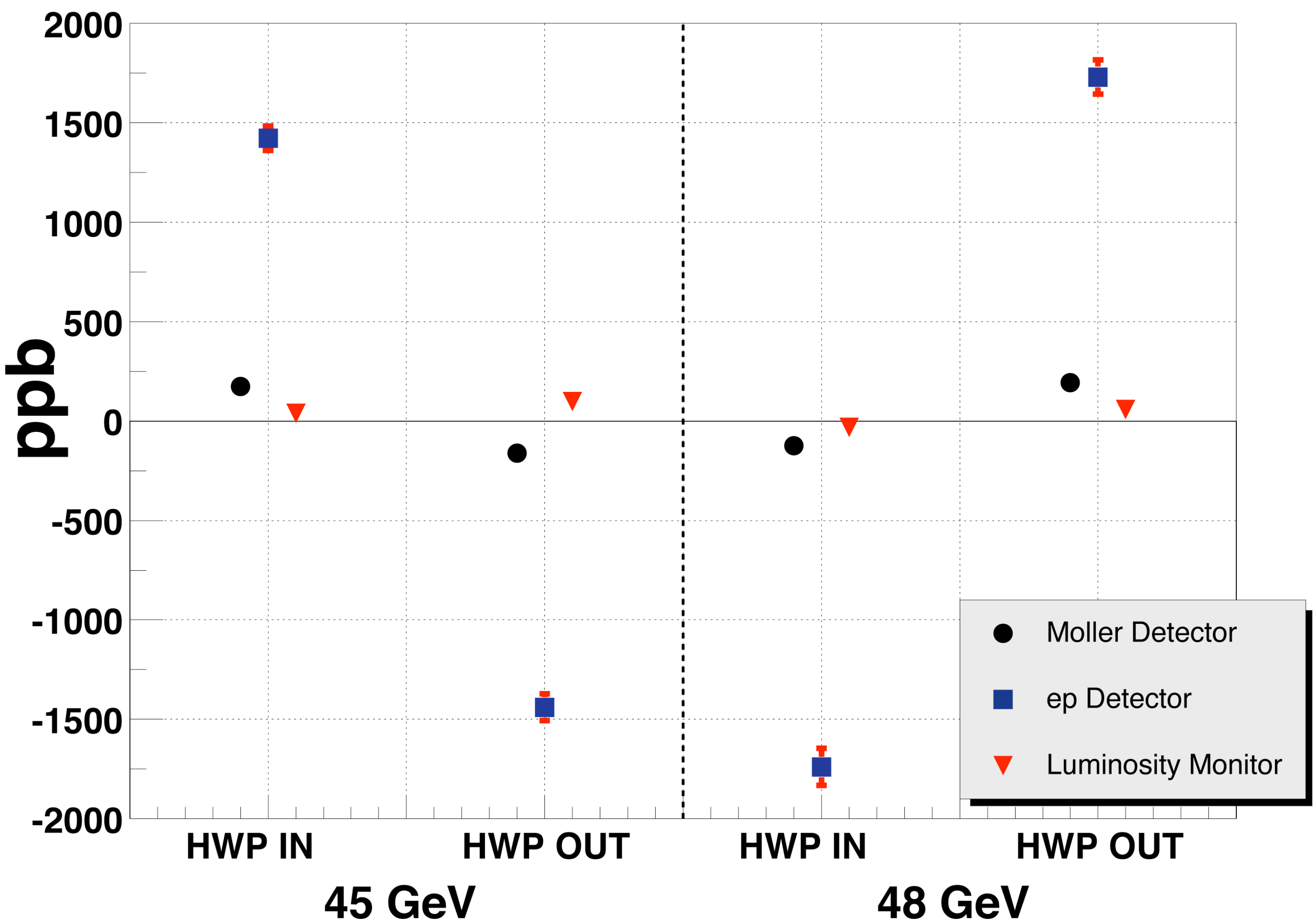
Raw Asymmetry Result



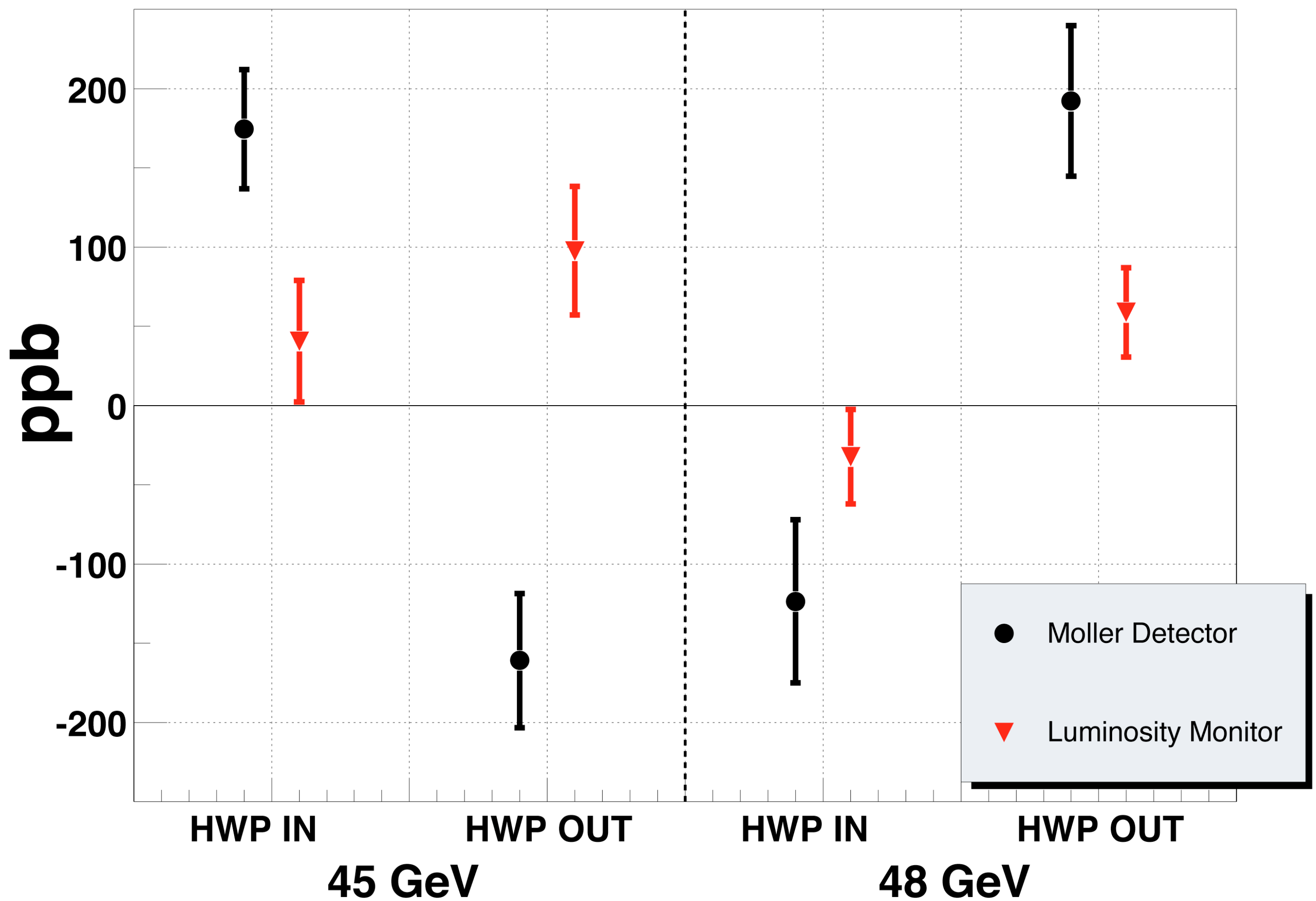
Asymmetry vs Slug



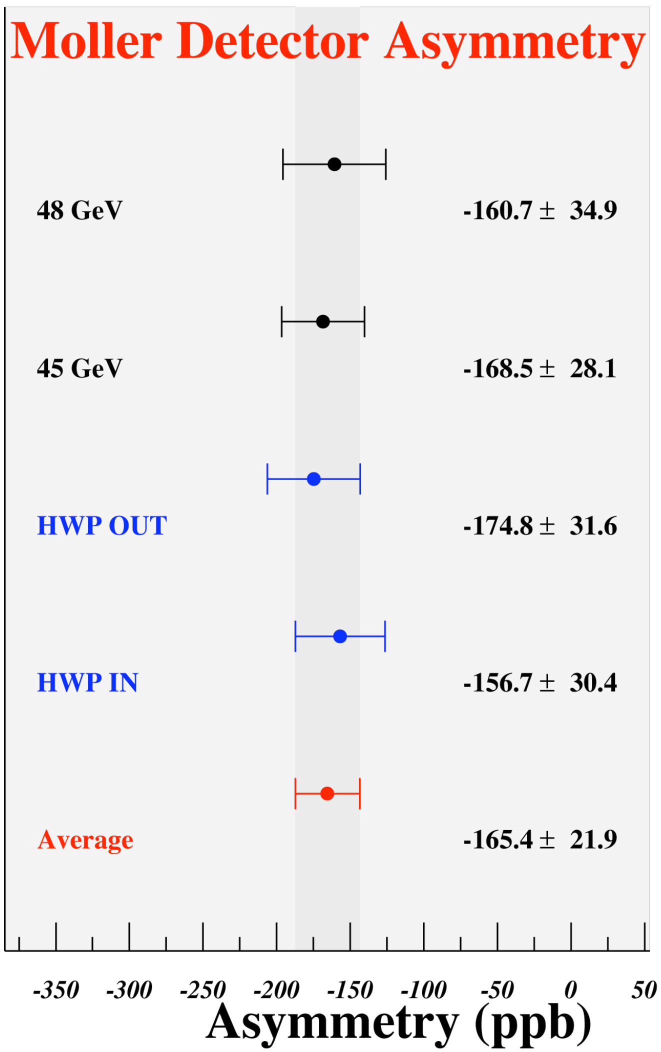
Grand Asymmetries

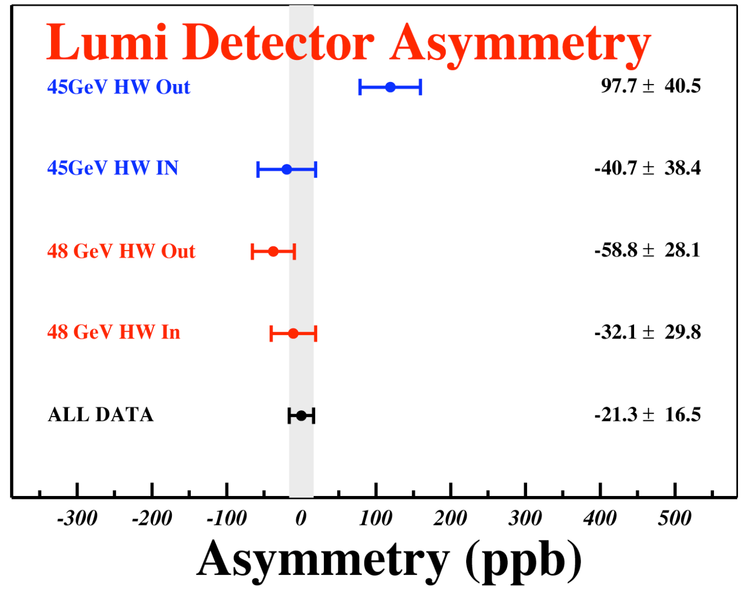


Grand Asymmetries



Grand Averages





A_{PV}(e^-e^- at Q^2 = 0.025 GeV^2):

-151.9 ± 29.0 (stat) ± 32.5 (syst)

parts per billion

(preliminary)

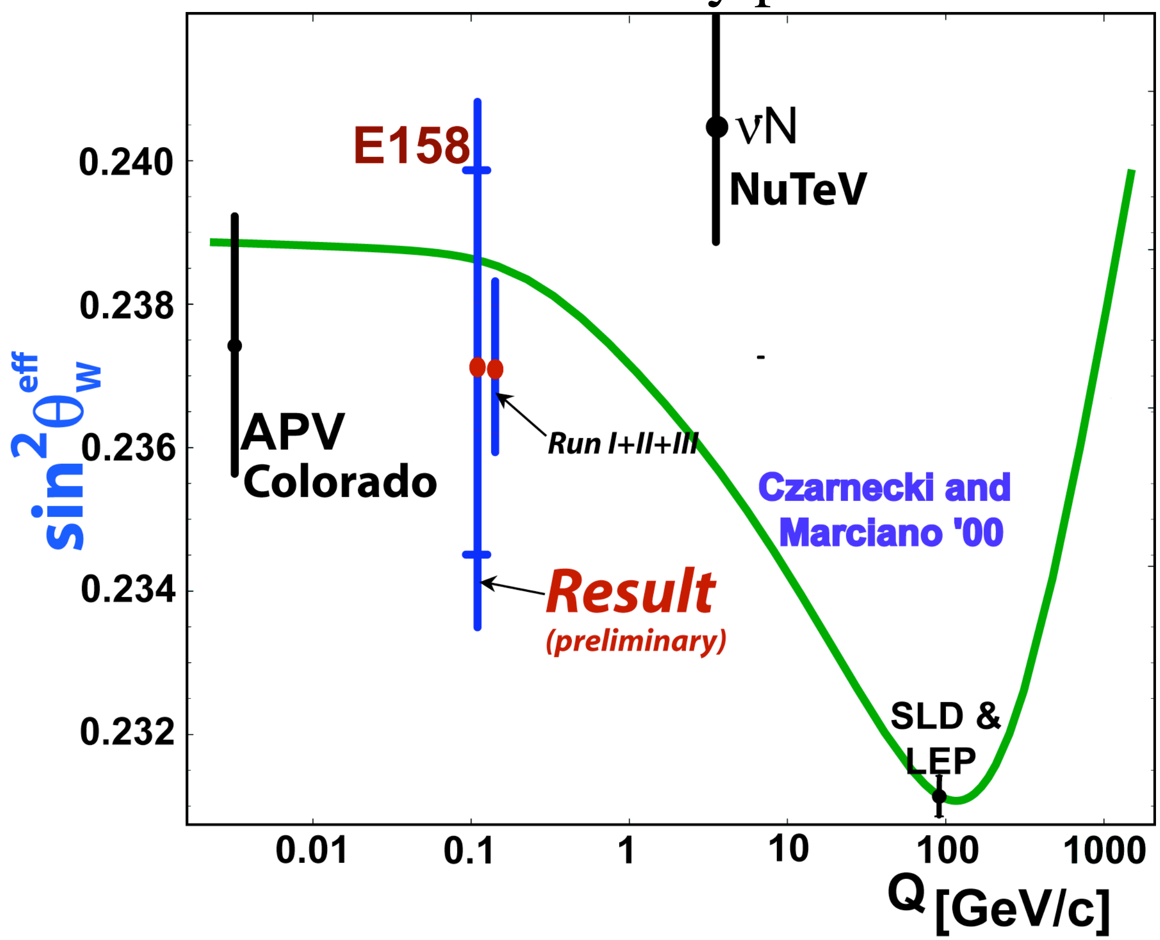
Significance of parity nonconservation in Møller scattering: 3.57 □

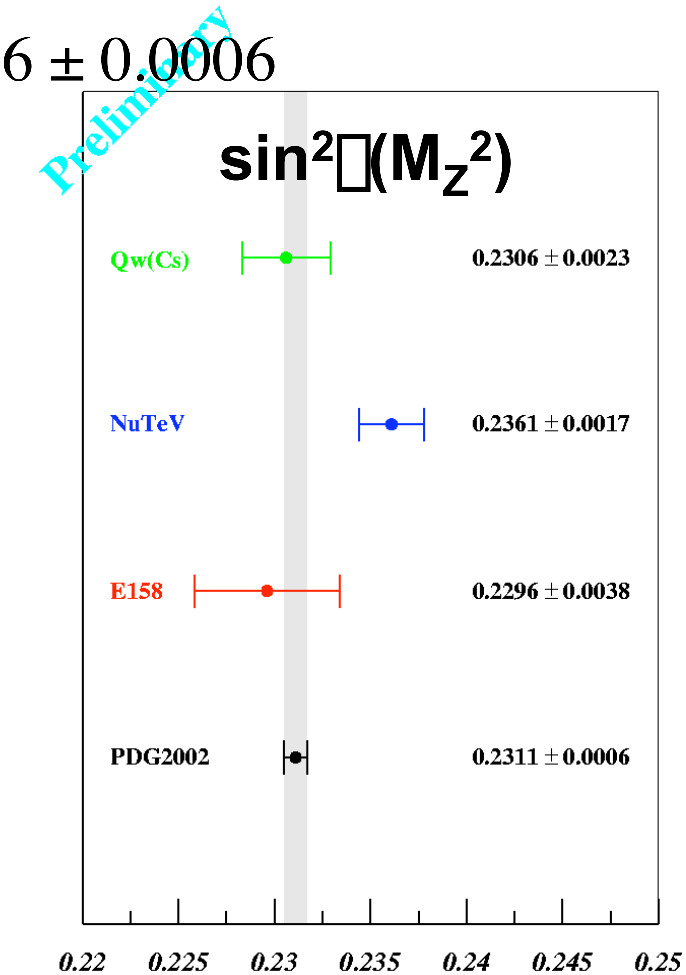
The Answer

$\sin^2\theta_{eff}(Q^2=0.025\ GeV^2)$ = 0.2371 ± 0.0025 (stat) ±0.0027 (syst)

(preliminary)

Theory prediction: 0.2386 ± 0.0006





Implications

- *Parity is violated in Møller scattering*
- *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 currently on par with collider limits

Clearly need to reduce statistical and systematic errors

A doubling of accumulated statistics essential to have major impact

Outlook

- *Analysis continues at an intense pace on Run I and Run II data*
- *Systematic errors will continue to reduce with statistics*
- *We hope to publish run I data by June*
- *Our goal is to unblind run II data just before the start of run III*

- ***An efficient run III is essential to have lasting impact***
- ***Currently, ~ 7 week run is scheduled***
- ***E158 represents a ~ $10M investment over 5 years***
- ***A 10 week run is required to guarantee world's most precise low Q^2 measurement and capitalize on investment***
- ***The collaboration cannot be sustained past 2003 for physics runs***

Conclusions

- *A very challenging experiment is producing physics results*
  - *Parity is violated in Møller scattering*
  - *Inelastic e-p asymmetry at low Q^2 consistent with quark picture*
  - *First measurement of e-e transverse asymmetry analyzing power*
  - *Preliminary result on A_{PV}: -151.9 ± 29.0 ±32.5 ppb*
  - *$\sin^2\theta_{eff}$ = 0.2371 ± 0.0025 ±0.0027 (preliminary)*
- *This experiment could not be done elsewhere in the world*
- *There were great benefits from SLAC technical experience*
- *We look forward to completing the final analysis of Run I + II*
- *We eagerly await a successful Run III*
- *Future of fixed target physics beyond E158 is in doubt*
  - *Loss of future unique precision measurements*
  - *Serious loss to diversity of SLAC physics capabilities*