SLAC E158:
Measuring Parity Violation in Fixed-Target Møller Scattering

E158 Goal:
$\delta\sin^2\theta_W$ = +/- 0.0008
Best measurement of $\sin^2\theta_W$ away from the Z-pole

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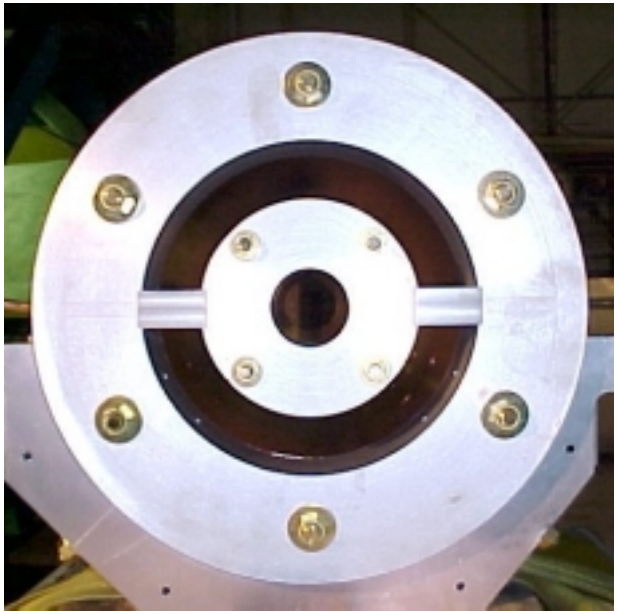
Princeton University

SPIN 2002
13 September, 2002



QC1B
Main acceptance collimator

E158 Collaboration

Institutions

Caltech	Syracuse
Princeton	Jefferson Lab
SLAC	UC Berkeley
Saclay	UMass Amherst
Smith College	U. of Virginia

65 physicists

5 grad students

Sept 1997:	PAC approval
1998:	Polarized Beam Instrumentation R&D
1999:	Spectrometer and Detector Design
2000:	Construction Funds and Test Beams
2001:	Commissioning Run
2002:	Physics Run I

Precision Electroweak Measurements

(LEP Electroweak Working Group)

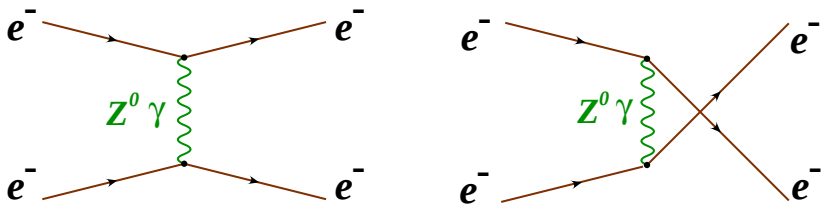
	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.27
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.05
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.70
$A_l(P_\tau)$	0.1465 ± 0.0033	-.53
R_b	0.21646 ± 0.00065	1.06
R_c	0.1719 ± 0.0031	-.11
$A^{0,b}_{fb}$	0.0994 ± 0.0017	-2.64
$A^{0,c}_{fb}$	0.0707 ± 0.0034	-1.05
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.50
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
m_W [GeV]	80.451 ± 0.033	1.73
Γ_W [GeV]	2.134 ± 0.069	.59
m_t [GeV]	174.3 ± 5.1	-.08
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
$Q_W(Cs)$	-72.39 ± 0.59	.84

$$\chi^2/dof = 30.4/15$$

Probability ~ 1.5%

Few smoking guns, no definitive clue for New Physics yet

Parity Violation in Møller Scattering

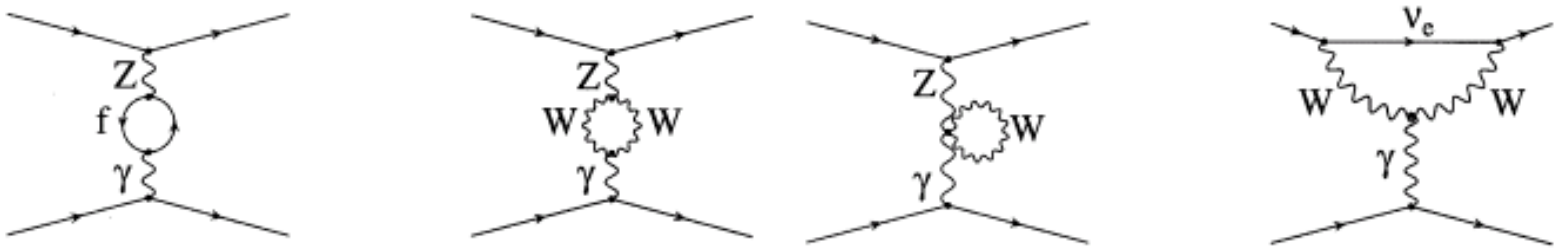


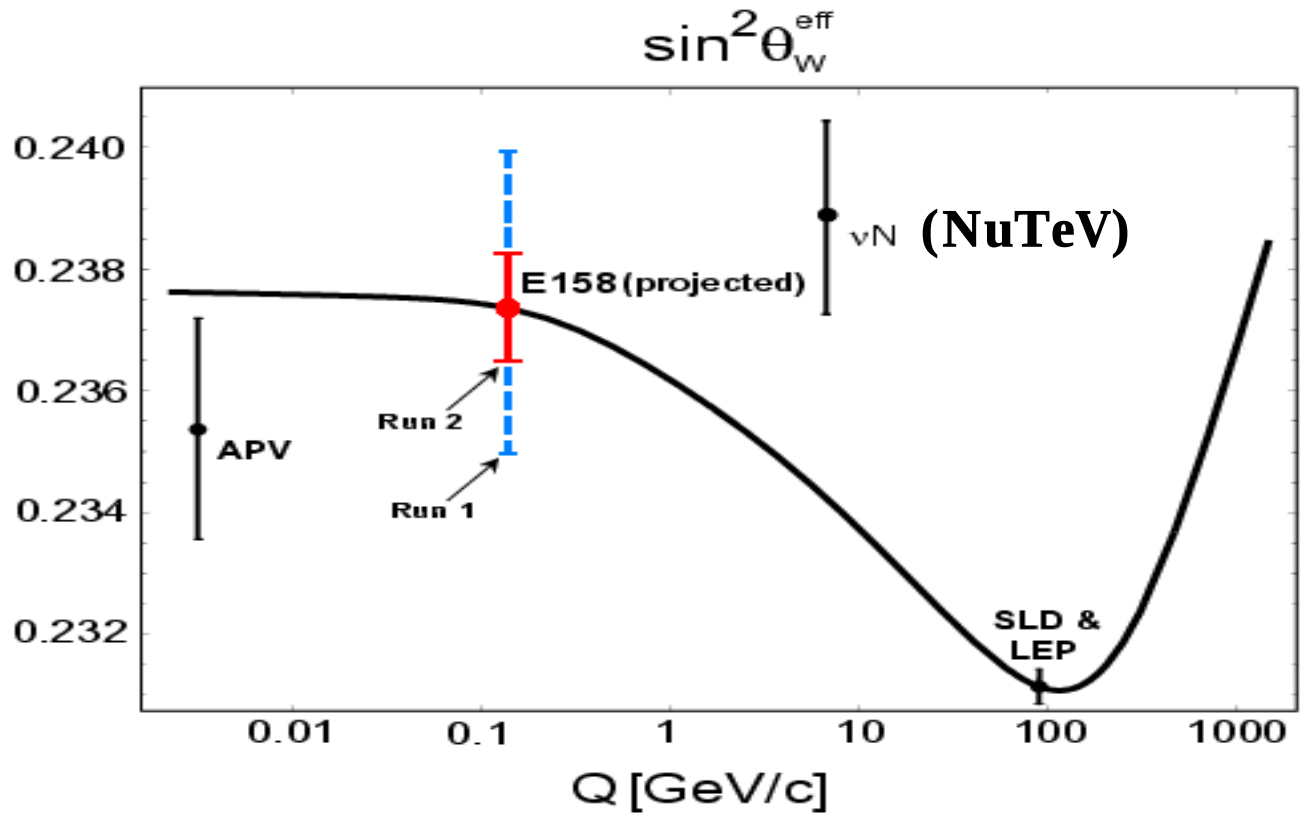
- Scatter polarized 50 GeV electrons off *unpolarized* atomic electrons
- Measure $$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$
- Small tree-level asymmetry

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

- At tree level, $A_{PV} \approx 320 \cdot 10^{-9}$ (at 90 degrees in CM frame)
- Raw expected asymmetry about 140 ppb
  - Goal is to measure it with precision of 8%
  - Most precise to date measurement of $\sin^2\theta_W$ at low Q^2 with $\sigma(\sin^2\theta_W)=0.0008$

Radiative Corrections: Running of $\sin^2\theta_W$

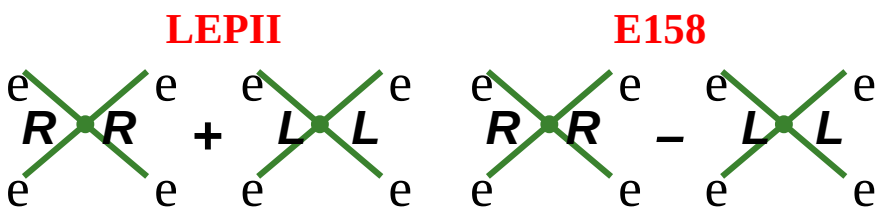




E158: Physics Impact

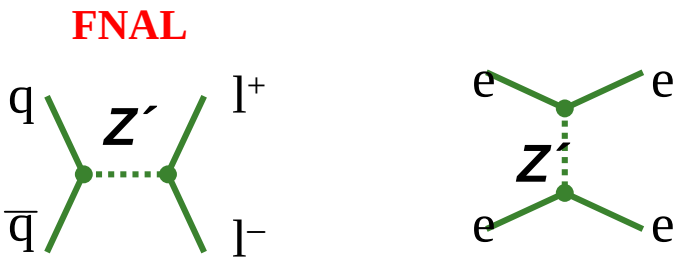
- Establish running of $\sin\theta_W$ to 8σ level
- Sensitivity to new physics: compositeness up to 15 TeV, Z' (GUTs) to ~1TeV
  - Complementary to collider limits, different couplings

Compositeness



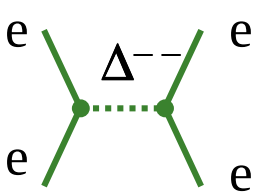
$$\Lambda \approx 15\,\text{TeV}$$

Neutral currents (GUTs)



$$M_{Z'} \approx 1\,\text{TeV}$$

Scalar interactions (LFV)

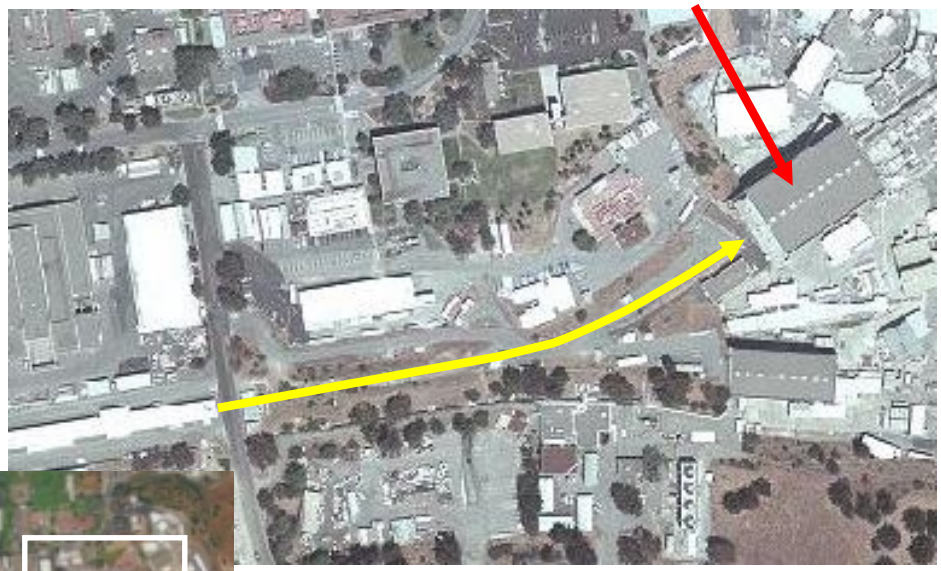


$$\frac{g^2}{2M_\Delta^2} < 0.01 G_f$$

Experimental Technique

- Scatter polarized electrons off atomic electrons
  - High cross section (14 μBarn)
  - High intensity electron beam, ~84% polarization
  - 0.18 r.l. LH2 target (1.5 m)
    - Luminosity $4*10^{38}$ $cm^{-2}s^{-1}$
  - High counting rates ⇨ flux-integrating calorimeter
- Principal backgrounds:

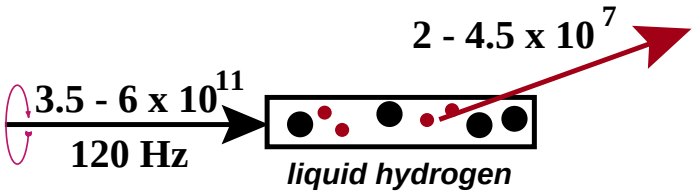
  elastic and inelastic **ep**
- Main systematics:
  - Beam polarization
  - Helicity-correlated beam effects
  - Backgrounds



Parity-Violating Asymmetry

1. Measure pulse-pair asymmetry:

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



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

$$A_{raw} = A_{exp} - \sum a_i \Delta x_i$$

charge, position, angle, energy R-L differences

coefficients determined experimentally

3. Obtain physics asymmetry:

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

backgrounds

beam polarization

Experimental Challenges

1. Electron Beam

i) high intensity
- 500 kWatt beam power

ii) stability
- intensity jitter <1%
- spotsize jitter <10%
- position jitter <10%

iii) small left-right asymmetries
- intensity
- position/angle
- energy

iv) compatibility with PEPII operation

2. Electron Beam monitoring

i) toroid resolution: < 30 ppm per pulse
ii) BPM resolution: < 1 μm per pulse
iii) energy resolution: < 50 ppm per pulse

$$A_I = \frac{\langle I \rangle_R - \langle I \rangle_L}{\langle I \rangle_R + \langle I \rangle_L} < 2 \cdot 10^{-7}$$

$$A_x = \langle x \rangle_R - \langle x \rangle_L < 10 \text{ nm}$$

$$A_E = \frac{\langle E \rangle_R - \langle E \rangle_L}{\langle E \rangle_R + \langle E \rangle_L} < 2 \cdot 10^{-8}$$

3. Liquid Hydrogen Target

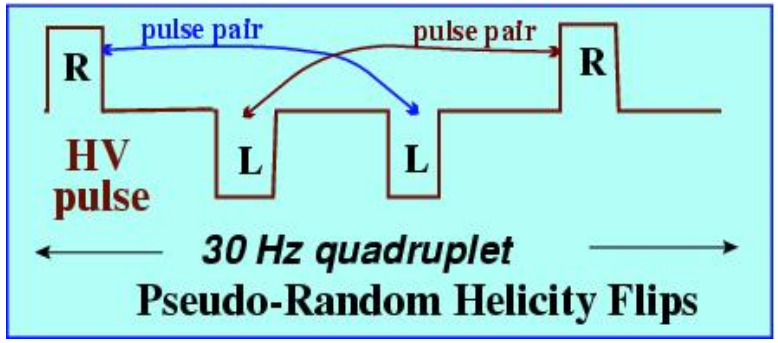
i) target density fluctuations: $<10^{-4}$ per pulse
ii) 18% radiation length
- absorbs 500W beam power

iii) safety

4. Detectors

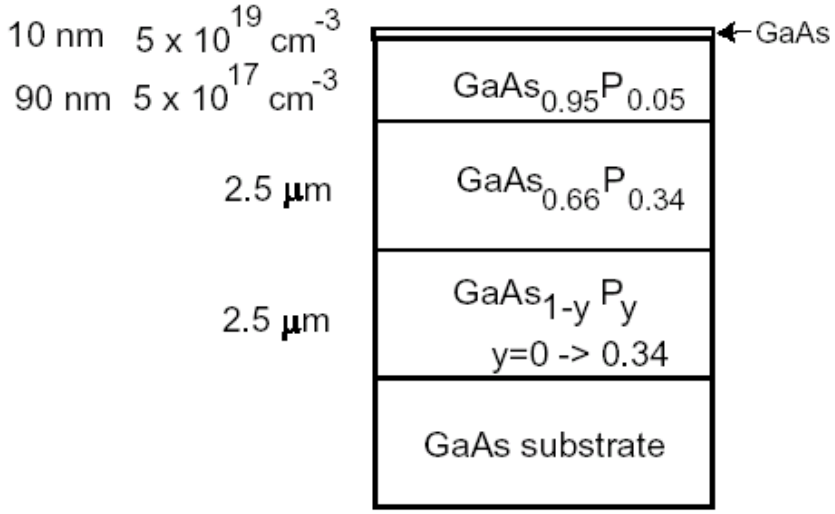
i) detector resolution: <100 ppm per pulse
ii) multiple backgrounds
iii) radiation damage
iv) linearity < 1%

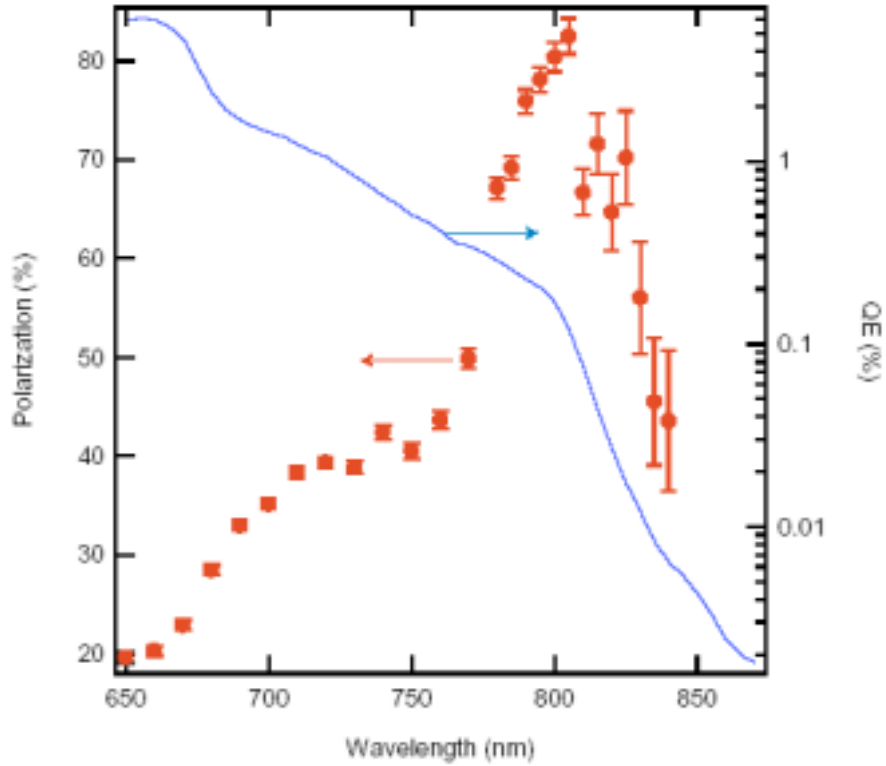
Electron Beam: Systematics



- **Beam helicity is chosen pseudo-randomly by using electro-optical Pockels cells in the Polarized Light Source**
  - **Create pulse quadruplets at 30 Hz**
- **Beam asymmetries reduced by using feedback at the Source**
  - **Control charge asymmetry and position asymmetry**
- **Physics Asymmetries can be reversed**
  - **Insert a half-wave plate in the Source**
  - **Change the (g-2) spin precession in the A-Line (take 45 GeV and 48 GeV data)**
- **False Asymmetries can also be reversed**
  - **Insert the "-I/+I" Inverter in Polarized Light Source**
  - **Reverses both false beam position and angle asymmetries**
  - **Leaves physics asymmetry unchanged**
- **"Null Asymmetry" cross-check is provided by a Luminosity Monitor**
  - **Measures very forward angle e-p (Mott) and Møller scattering**

Electron Beam: Polarized Source Photocathode





Reference: T. Maruyama et al., SLAC-PUB-9133, March 2002; (submitted to Nucl. Inst. Meth. A).

NOTES:

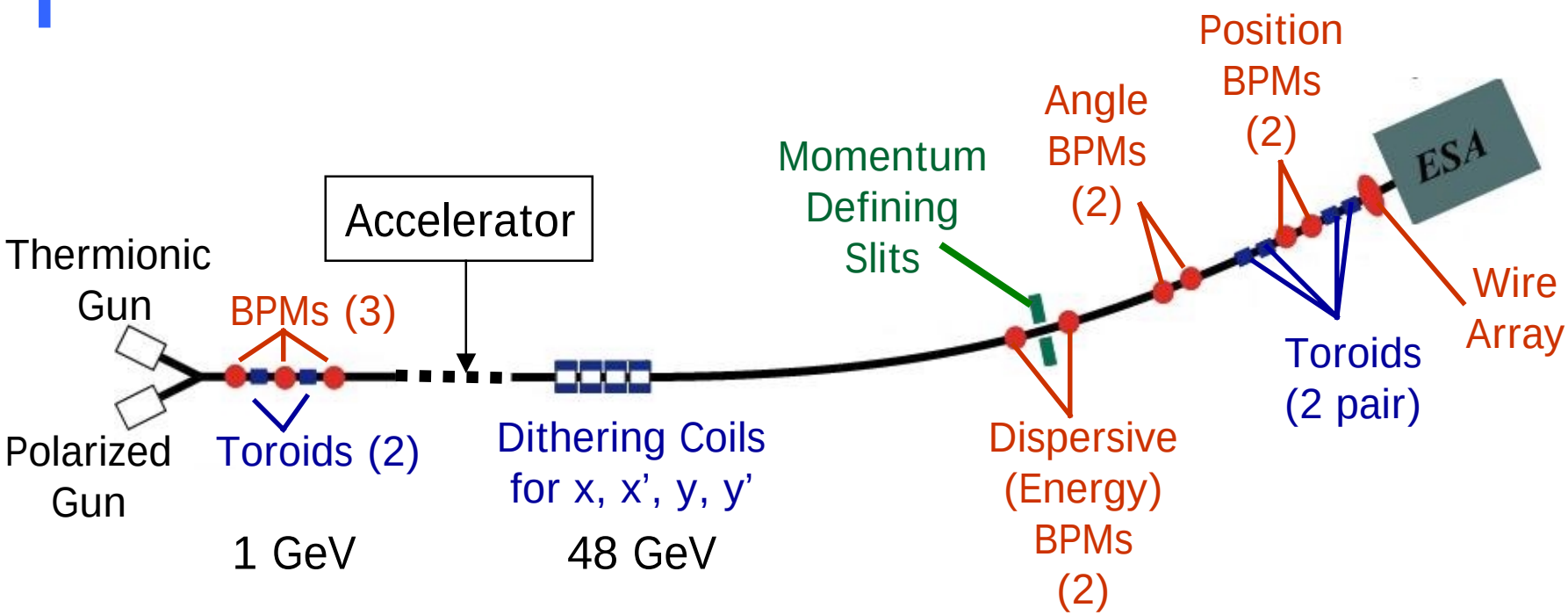
1. Gradient-doped cathode structure
   - high doping for surface 10nm overcomes charge limit
   - low doping for most of the active layer gives high polarization
2. Previous "standard" cathode was active layer of 100nm GaAs w/ $5 \cdot 10^{18}$ cm^{-3} doping
3. Small anisotropy in strain: ~3% analyzing power for residual linear polarization

Electron Beam: Delivery Summary

ITEM	Goal	Run I (2002)
Beam Charge	6×10^{11}	6×10^{11}
Intensity Jitter	2% rms[a]	0.5% rms
Position Jitter	<10% of spotsize	5% of spotsize
Spotsize Jitter	<10% of spotsize	5% of spotsize
Energy Spread	0.3% rms	0.1% rms
Energy Jitter	0.2% rms	0.03% rms
Polarization	75%	~85%

[a]2% required for physics measurement; 1% for accelerator operation

Electron Beam: Diagnostics



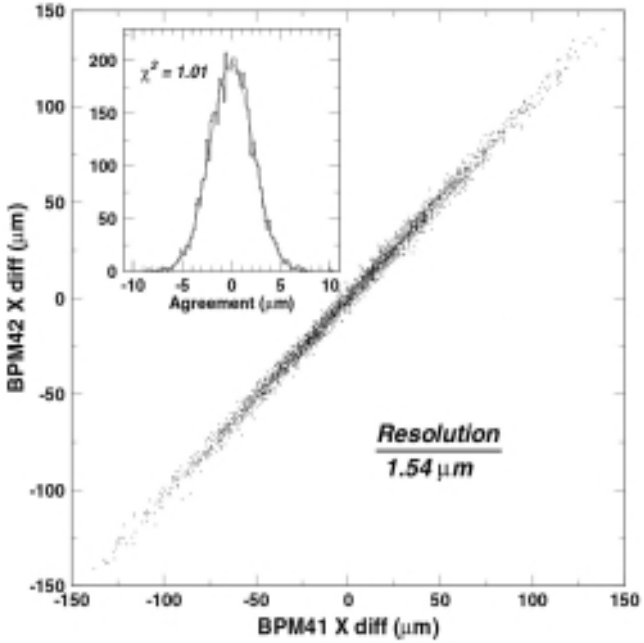
Not shown:

- Møller Polarimeter in ESA
- Synchrotron Light Monitor before momentum slits
- Energy dithered by using sub-booster phases for Sectors 27, 28

Electron Beam: Monitor Resolutions

Device	Goal	Tests	Run I results[a]
Target BPM x,y	1 μm	0.5 μm	2 μm
Target BPM x',y'	0.4 μrad	0.03 μrad	0.1 μrad
Energy BPM[b]	30 ppm		40 ppm
Target Toroid	30 ppm	30 ppm	60 ppm

Resolution goals are to achieve 1ppb error after 600M pulses for each of x, x', y, y', E, I



Resolution of target position BPMs

[a]Relaxed goals for Run I (due to statistics)

[b]Energy goal ignores detector calorimetric compensation for 1/E – dependence of Møller cross section

Electron Beam: Asymmetries

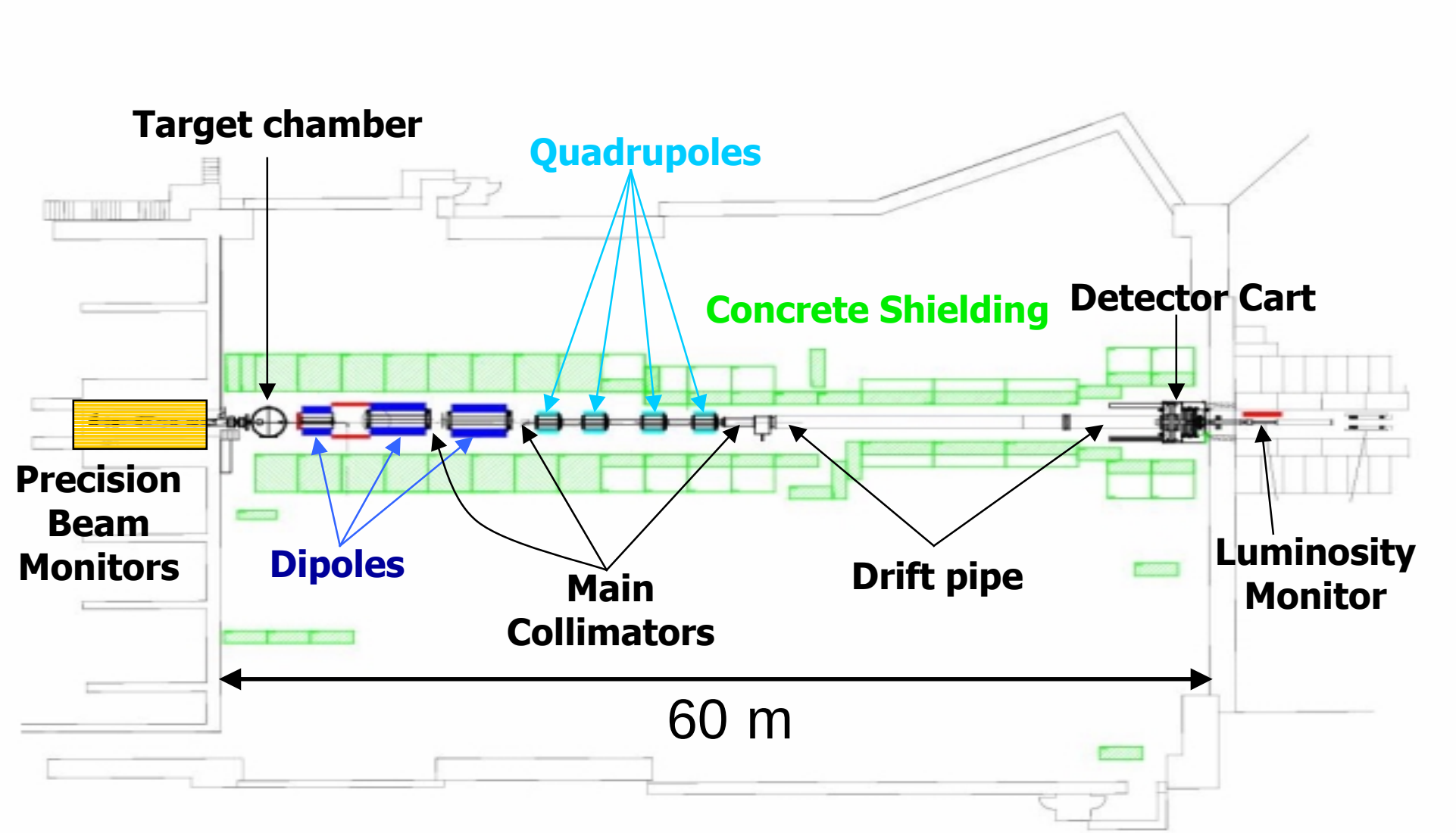
Beam property	$^{beam}A_{LR}$	Contribution to A_{LR} (stat)	Contribution to A_{LR} (sys)
Intensity	340 ppb	5.7 ppb	3.4 ppb
Energy	5 ppb	2.6 ppb	<1 ppb
Position	15 nm	1.0 nm	~1 ppb
Angle	0.25 nrad	1.0 nm	~1 ppb
Spotsize	0.7 nm	1.5 nm	~1 ppb

PRELIMINARY!!

Total Contributions to $\delta(A_{LR})$: ~7 ppb (stat) and ~4 ppb (sys)

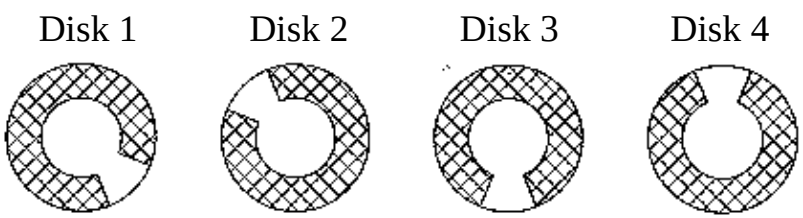
Expected $\delta(A_{LR})^{stat} \approx (20 - 25)$ ppb

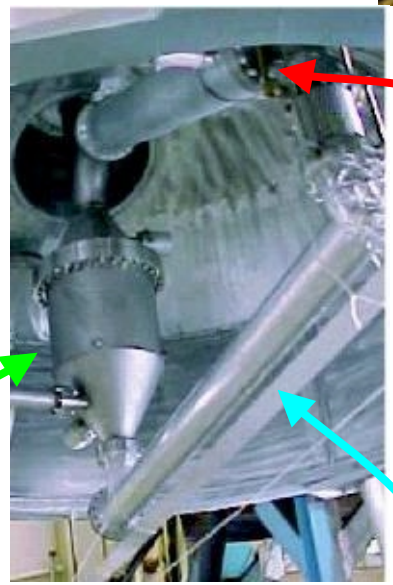
Experimental Layout: ESA

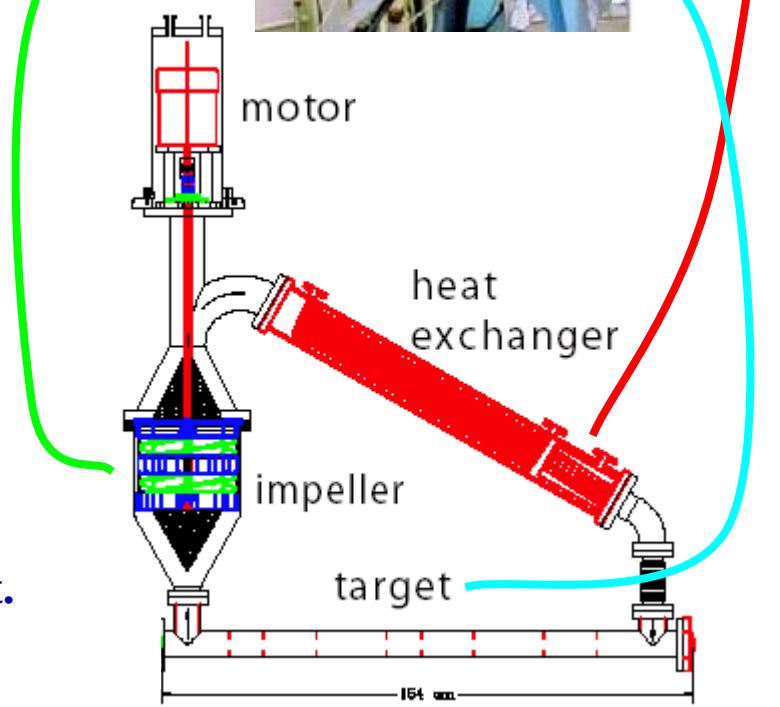


Experimental Layout: Liquid Hydrogen Target

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		**10 m/s**
Reynolds number in target cell		**10^6**

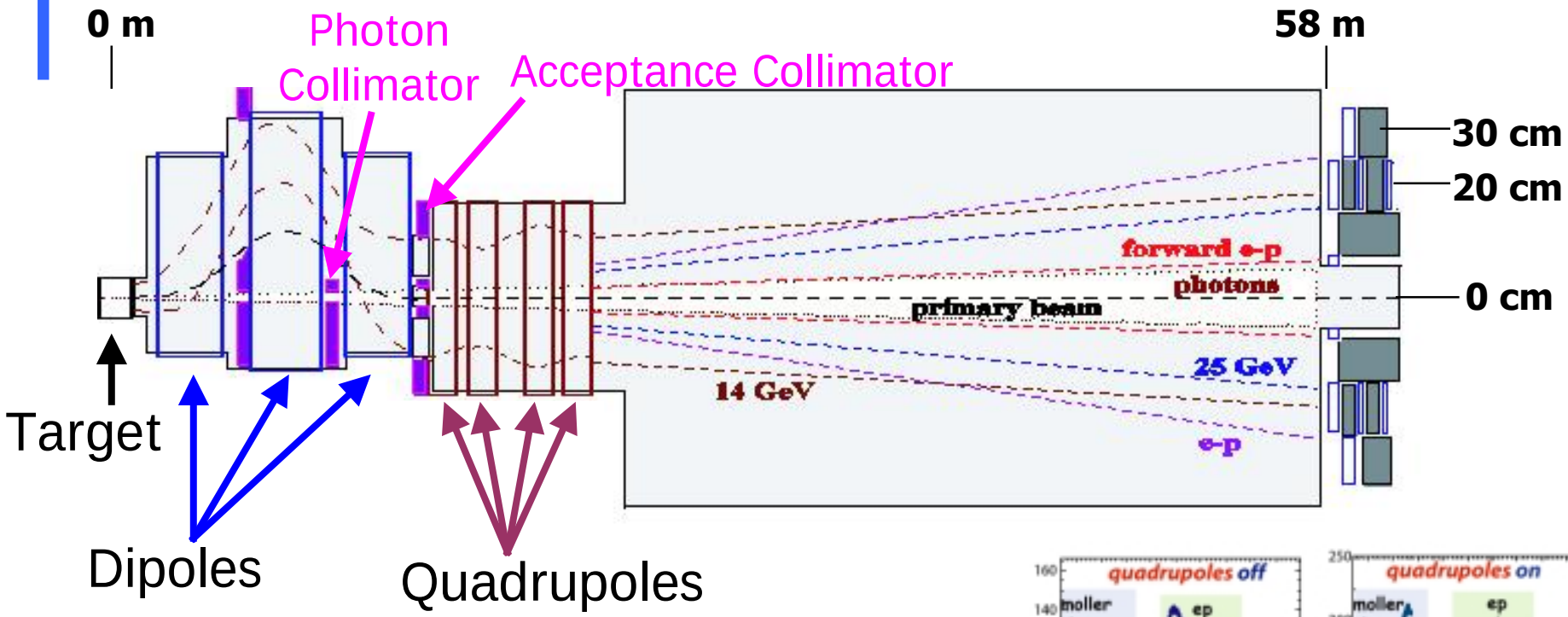


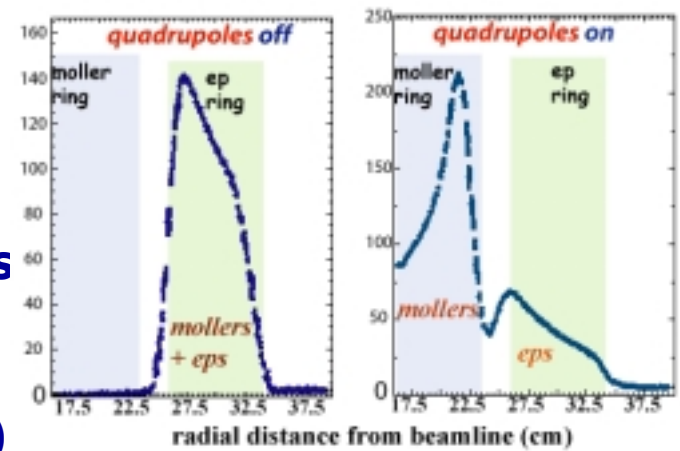




Wire mesh disks in the target introduce turbulence at the 2mm scale and a transverse velocity component. Total of 8 disks in the target.

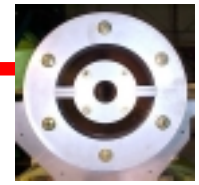
Experimental Layout: Spectrometer

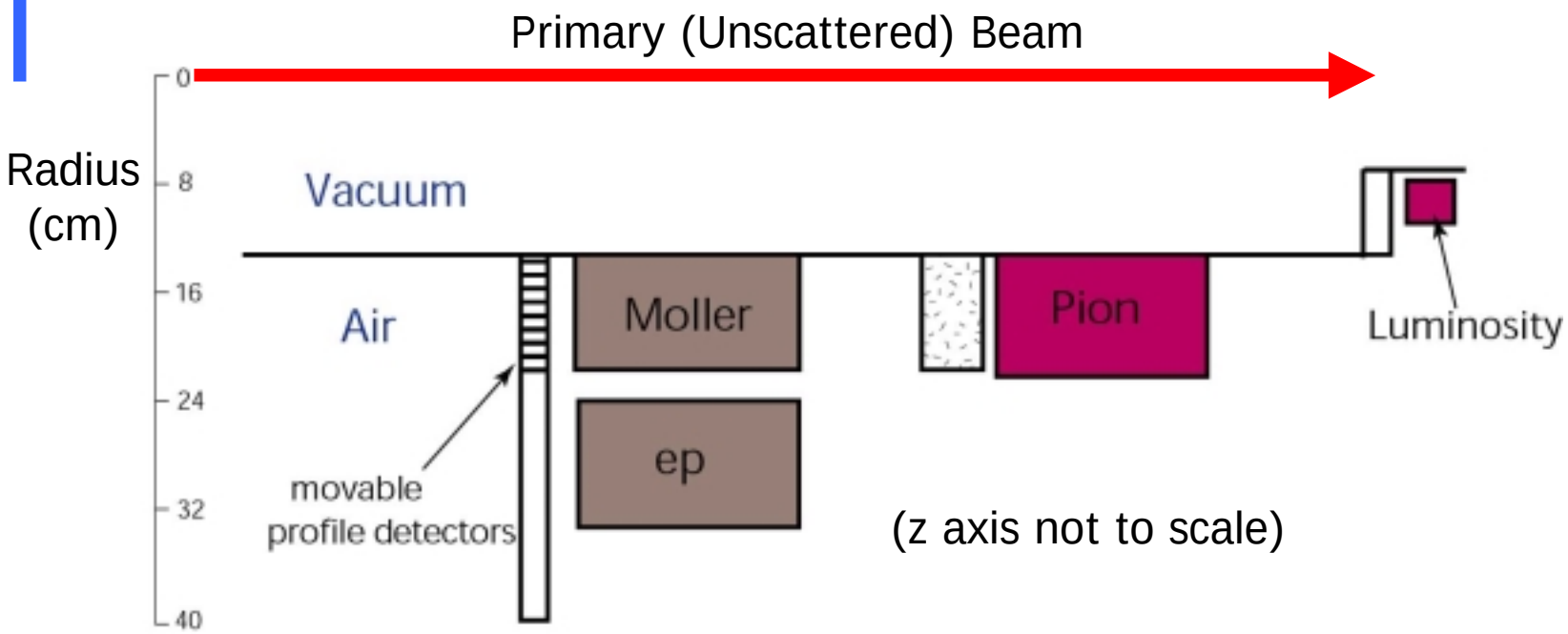




- **Dipole chicane allows clean collimation of photons and positrons from target interactions**
- **Quadrupoles separate moller and ep flux at detector face (see inset)**
- **Main acceptance collimator (upper right corner) accepts mollers in desired momentum/radial range**
- **Synchrotron collimators (not shown) block synchrotron radiation**

Experimental Layout: Detectors





MOLLER, EP are copper/quartz fiber calorimeters $\left\langle \theta_{lab}^{MOLLER} \right\rangle = 6.0 mrad$

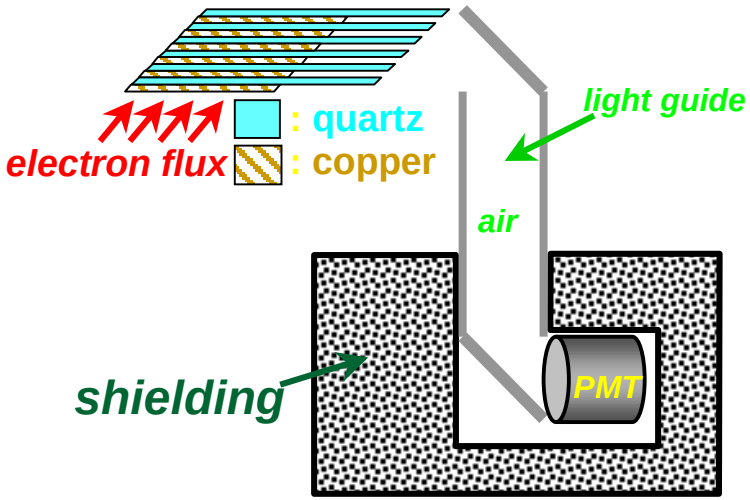
PION is a quartz bar Cherenkov

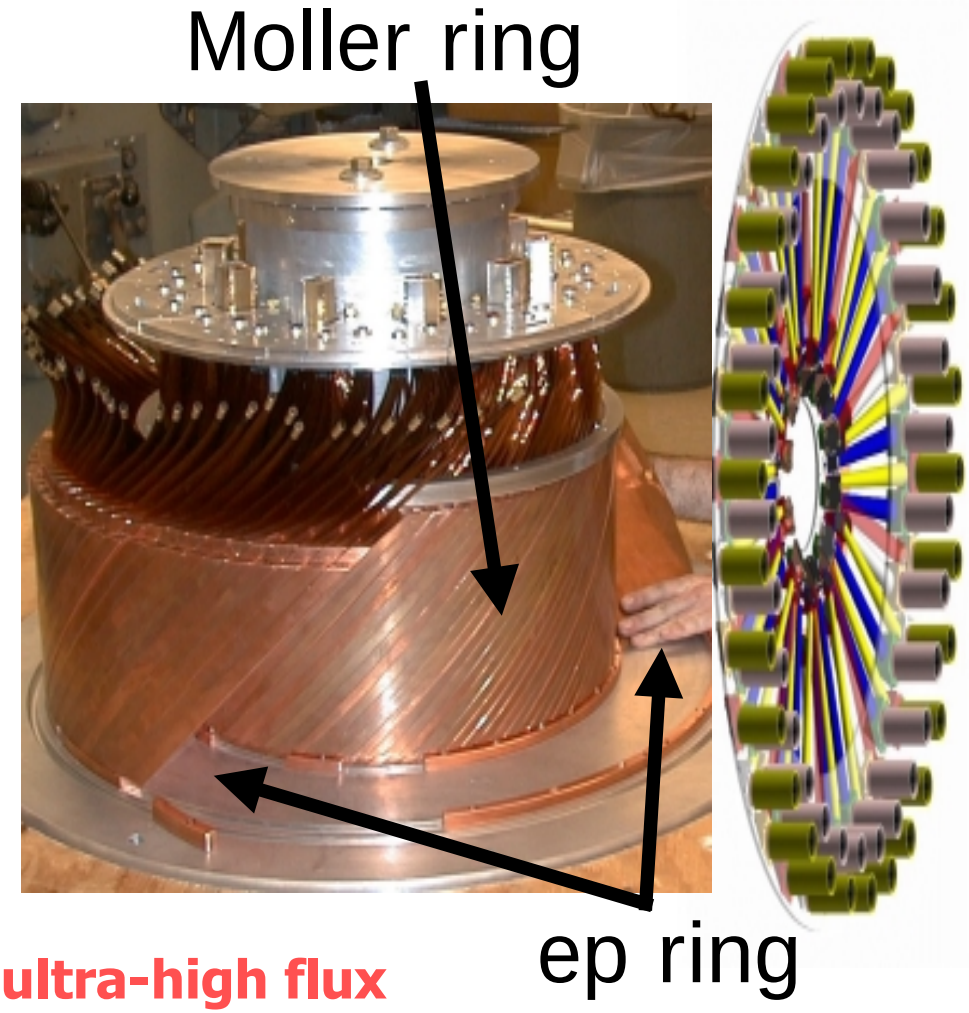
LUMINOSITY is an ion chamber with Al pre-radiator $\left\langle \theta_{lab}^{LUMI} \right\rangle = 1.5 mrad$

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

Experimental Layout: Moller Detector

Basic Idea:

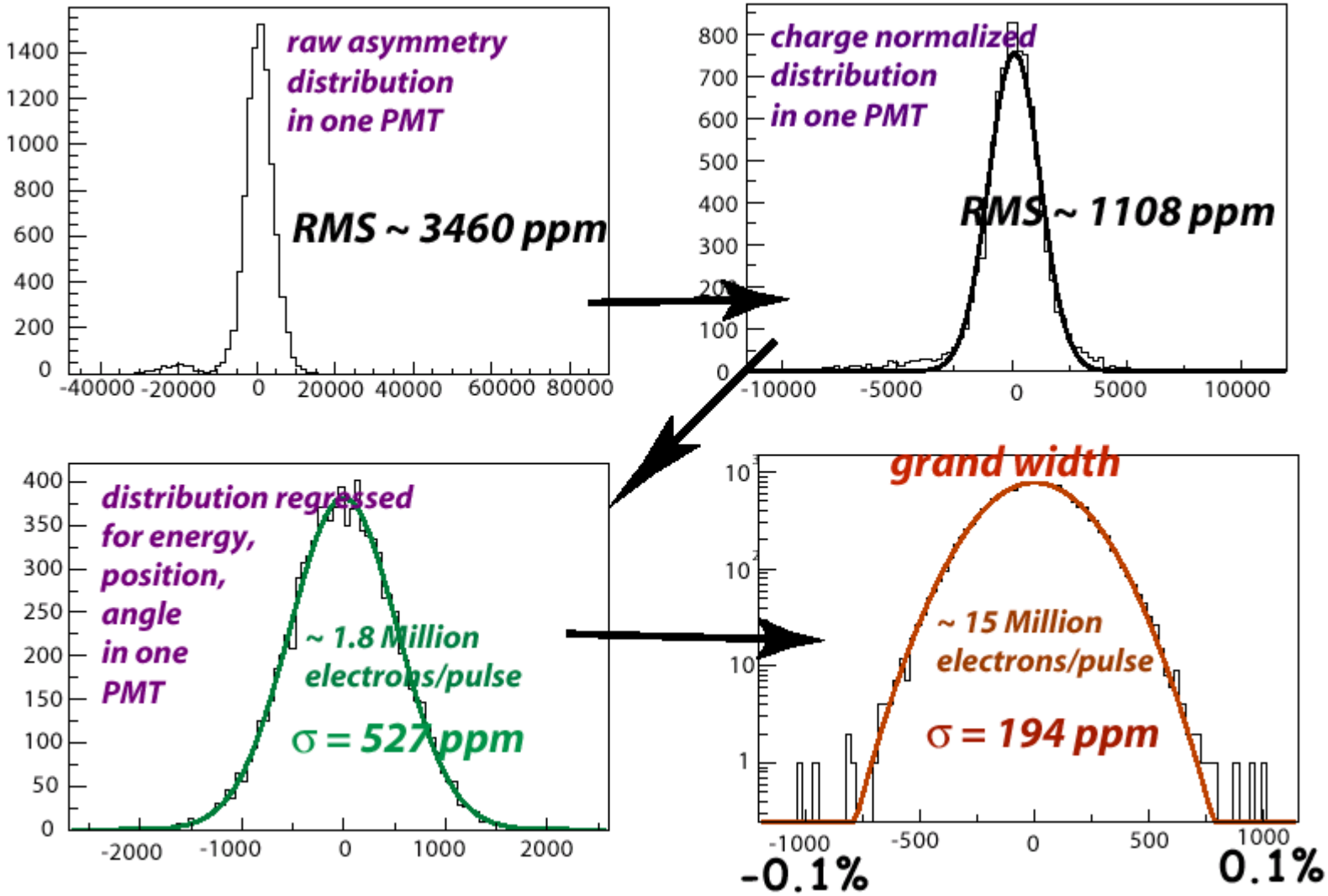




- 20 million electrons/pulse at 120 Hz
- 100 Mrad radiation dose
- Copper/fused silica fiber sandwich

- **State of the art in calorimetry at ultra-high flux**

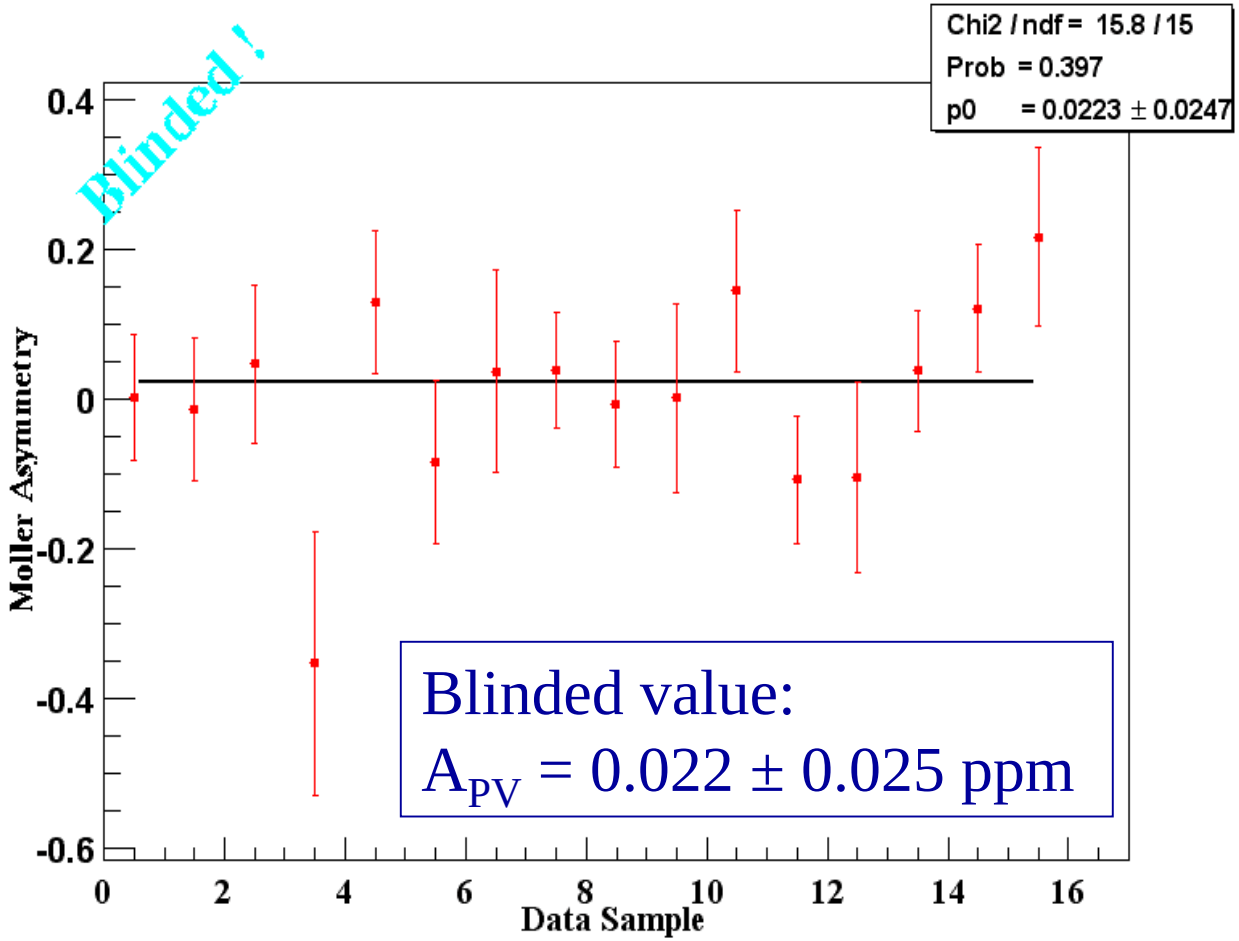
Results:
Moller Asymmetry Resolution



Results: Moller Asymmetry (Blind)

Based on analysis of 146M spills collected in April-May 2002

Asymmetry blinded to avoid bias (expect ~ –0.14 ppm)

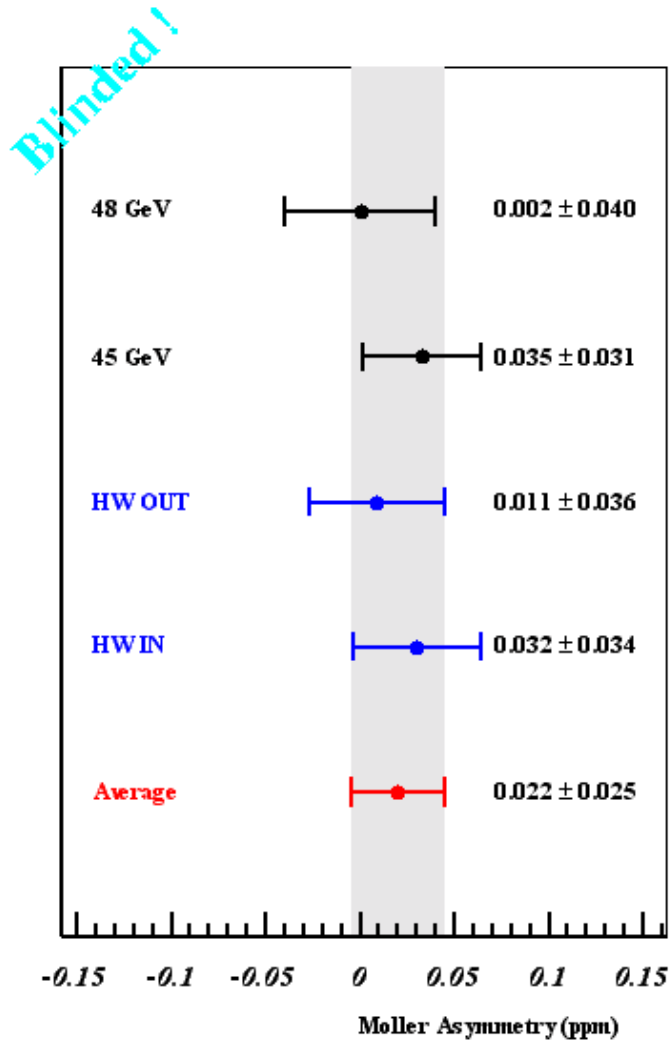


Blinded value:

$A_{PV} = 0.022 \pm 0.025$ ppm

Results: Systematic Check

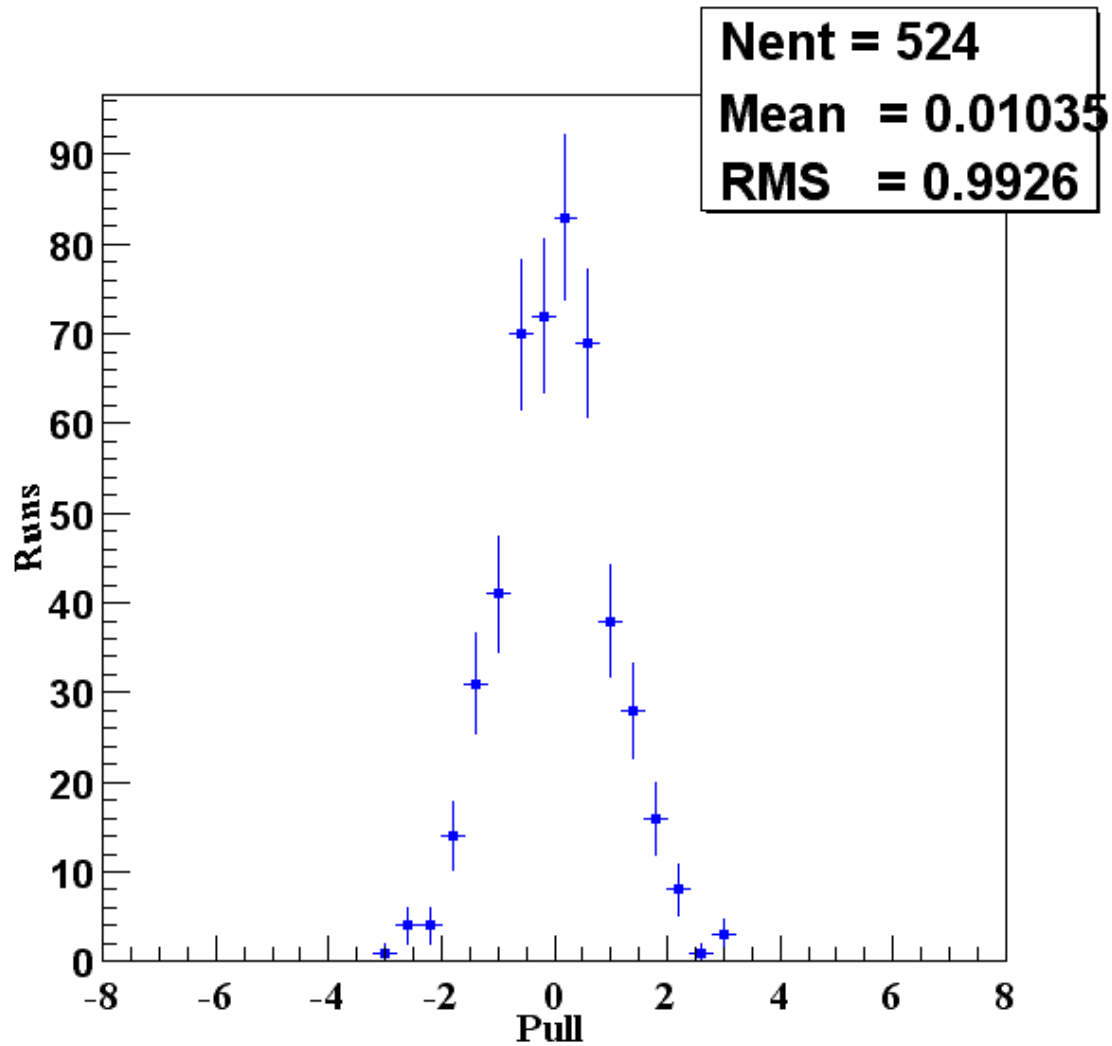
Experiment run at 2 energies (for g-2 asymmetry flip)
Equal data samples taken at both half-wave plate settings



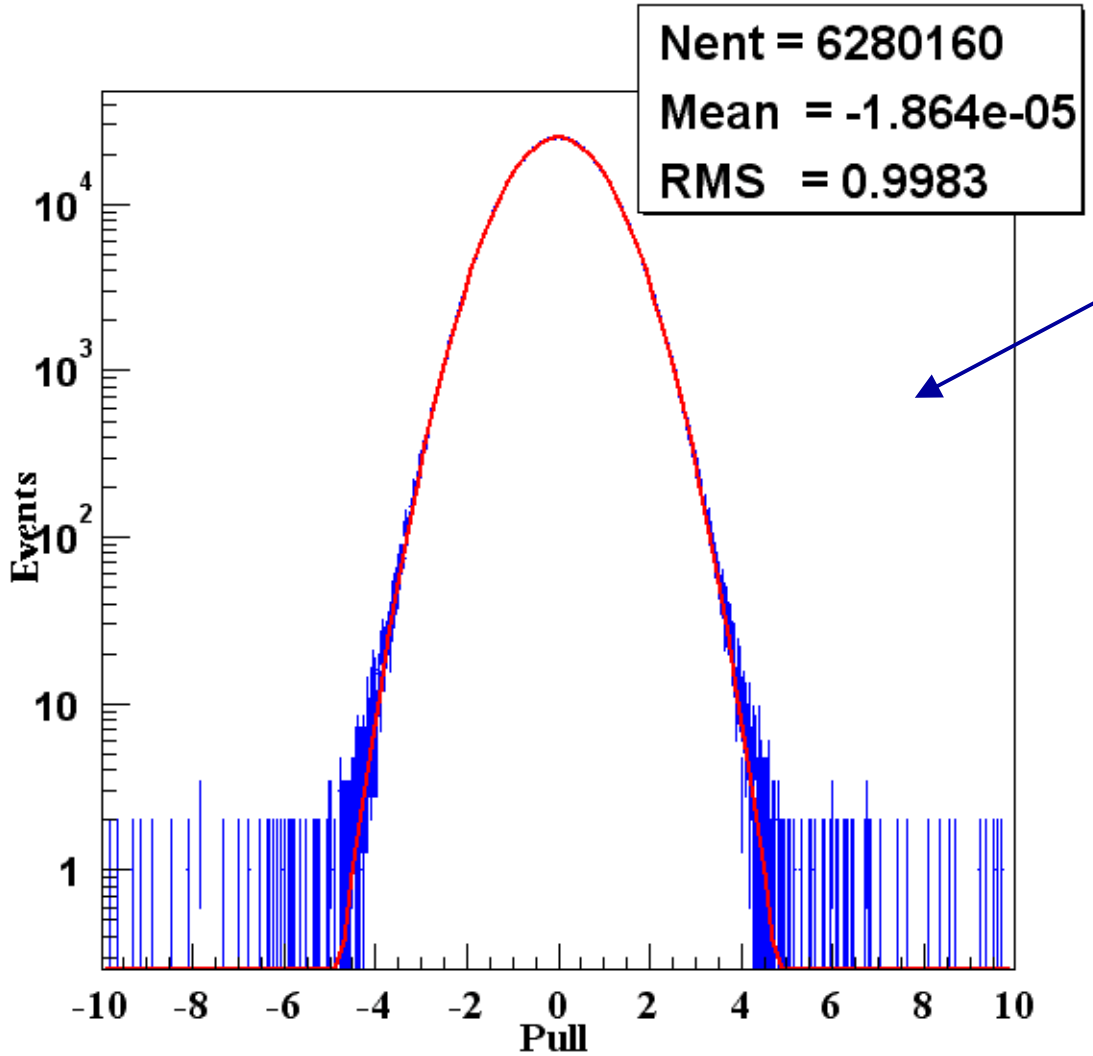
Results: Asymmetry Pulls Per Run

$$\text{Pull} = \frac{A_{run} - \langle A_{run} \rangle}{\sigma_{run}}$$

Expect a mean of 0 and an RMS of 1



Results: Statistics and Systematics



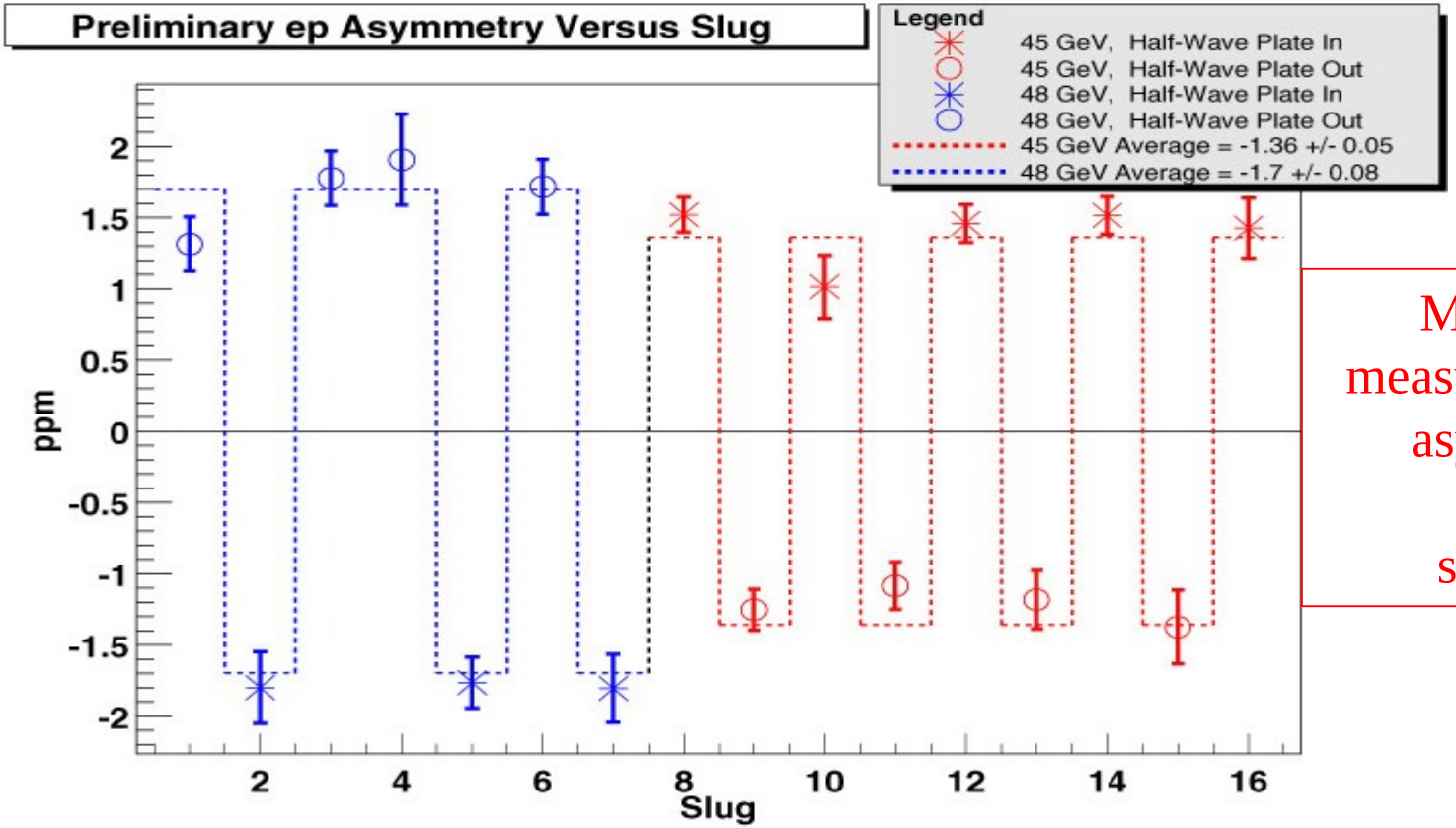
Asymmetry pulls
per event pair: 12M spills
(about 2 days of data)

Average asymmetry
width: 195 ppm

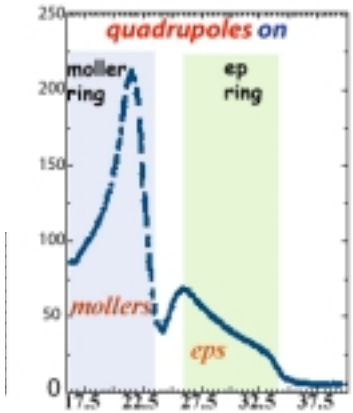
Expected systematic error
in Run I ~ 10-15 ppb

☞ Dominated by background subtraction (inelastic ep) and polarization measurement

Results: EP Asymmetry



Most precise measurement of PV asymmetry in electron scattering !



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

20-30 ppb correction to Møller asymmetry in Run I
<20 ppb correction for Run II

E158: Summary

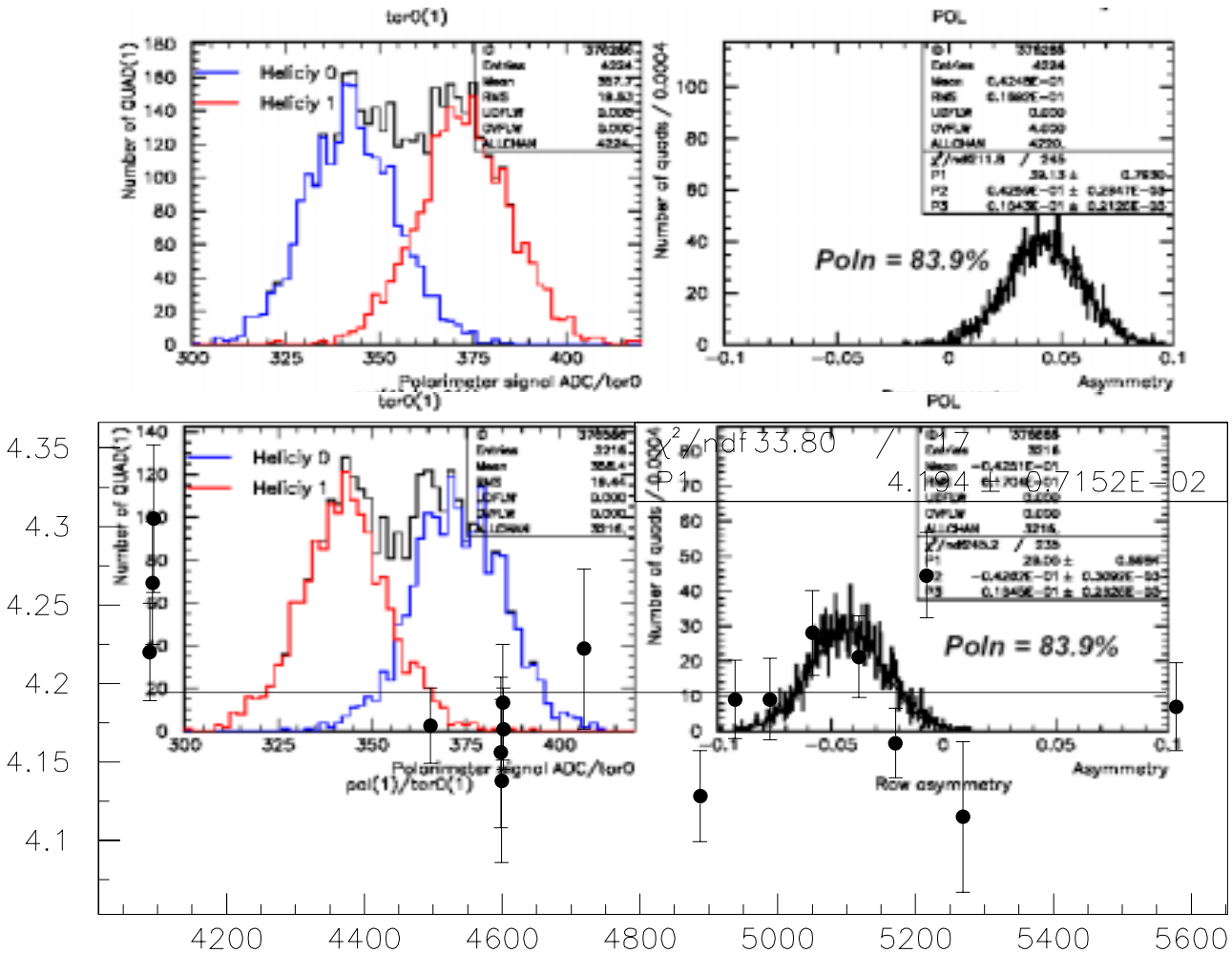
- High quality physics data collected in Run I
  - Approx. 250 million spills logged
    - 200 million spills for A_{LR}
  - δA_{LR} = 0.025 ppm (150 million spills analyzed)
  - Excellent beam quality (SLAC is amazing)
  - All experimental systems working reliably
- Expected physics result in 2002
  - Goal: first observation of Parity Violation in Møller scattering $\delta \sin^2\theta_W < 0.003$ (stat and syst)

Future

☞ Experiment poised to achieve proposal goals

- Nontrivial constraints on New Physics with $\delta\sin^2\theta_W < 0.0008$
  - Unique window of opportunity, complementary to FNAL Run II
  - Need 4 months of data taking at 120 Hz
- Current plan at SLAC:
  - 1.5 months October-November 2002
  - We hope to complete the experiment by the end of calendar 2003

Electron Beam: Møller Polarimetry



~ 84 % polarization throughout Run I

Beam Delivery for E158

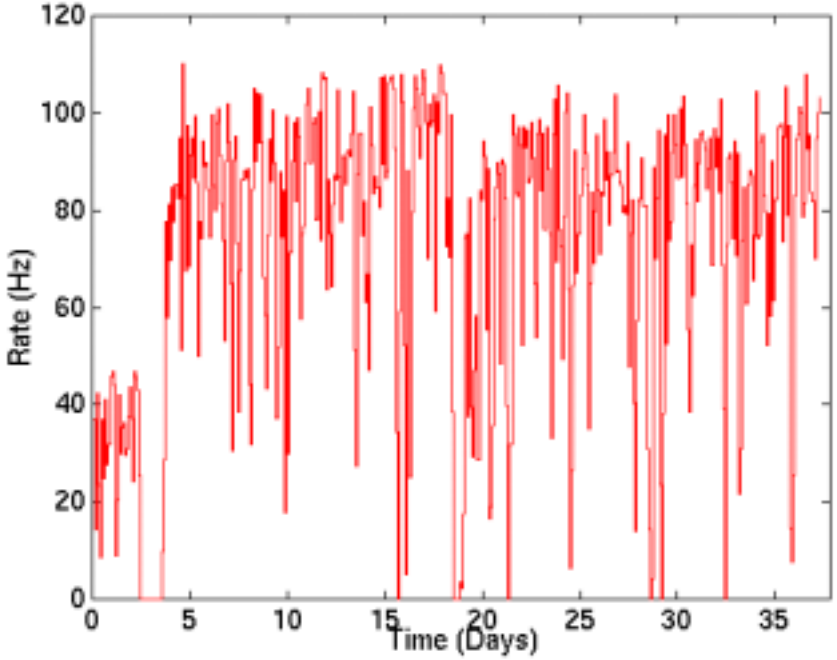
(April 20 - May 27)

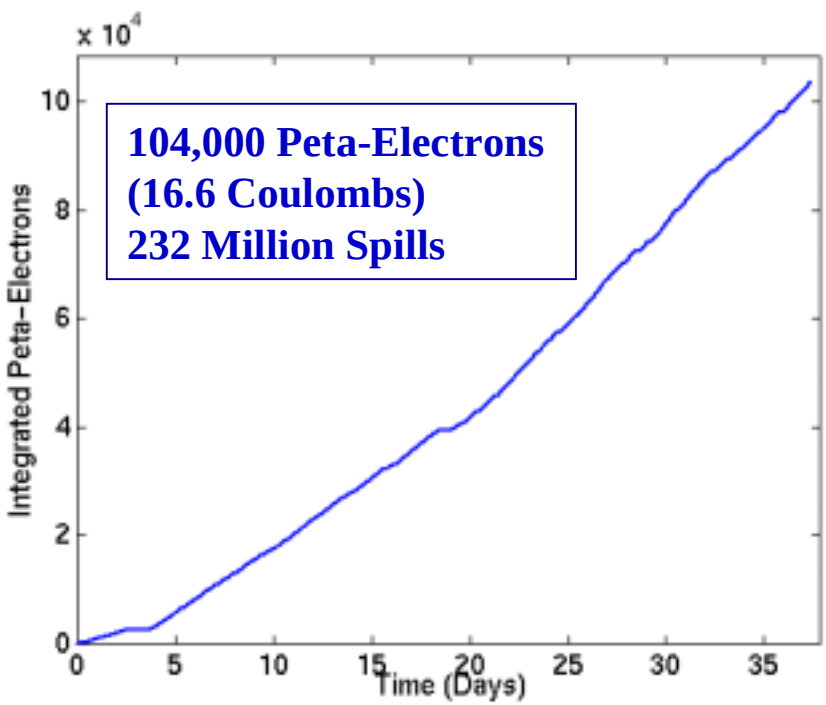
~84% Electron Polarization

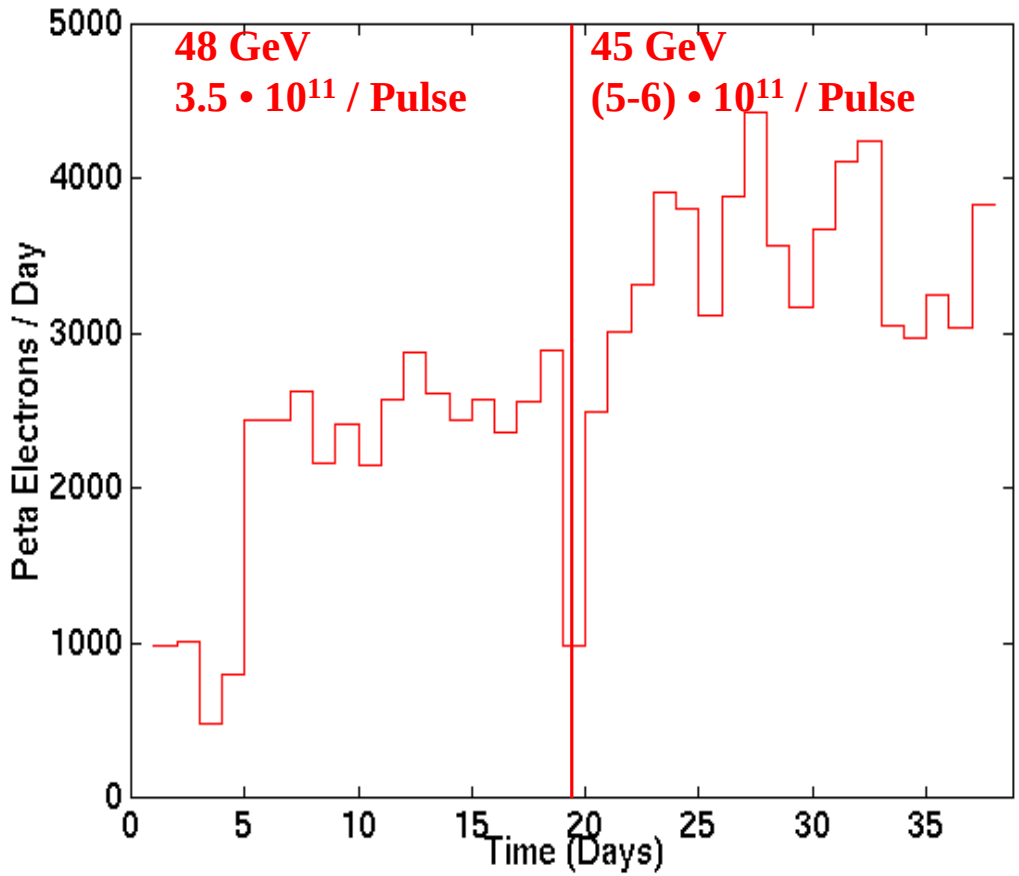
Beam Delivery Efficiency (120Hz running)

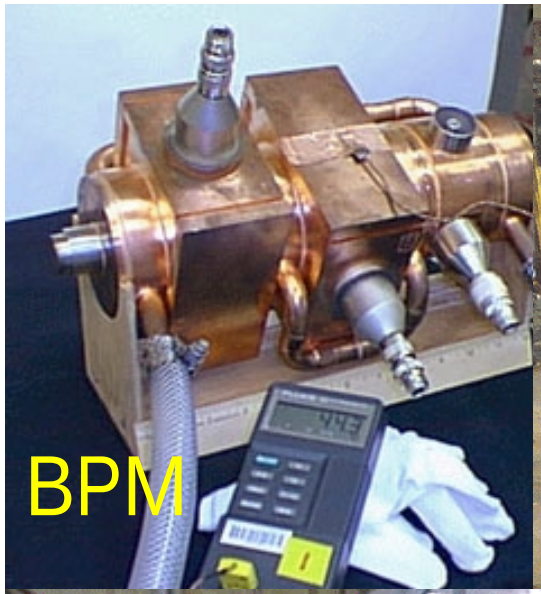
72% for 48 GeV, 3.5 x 10^{11}

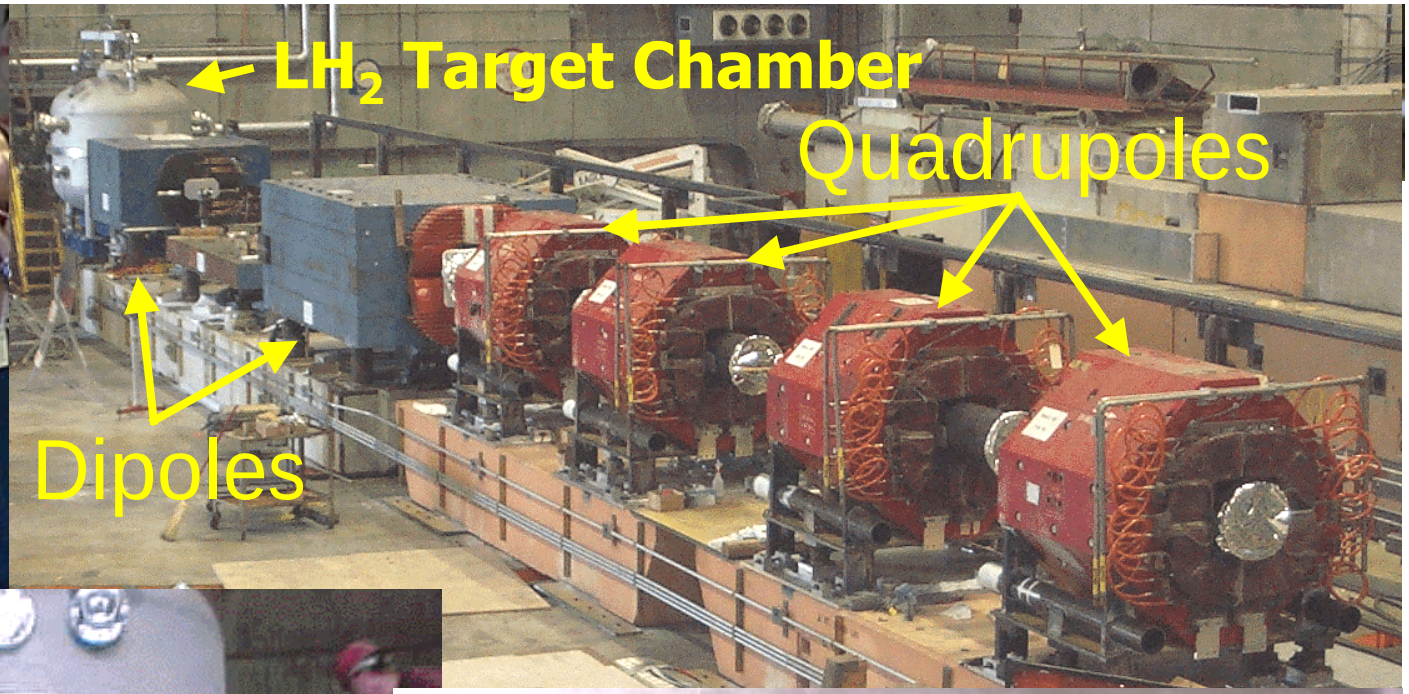
65% for 45 GeV, (5-6) x 10^{11}



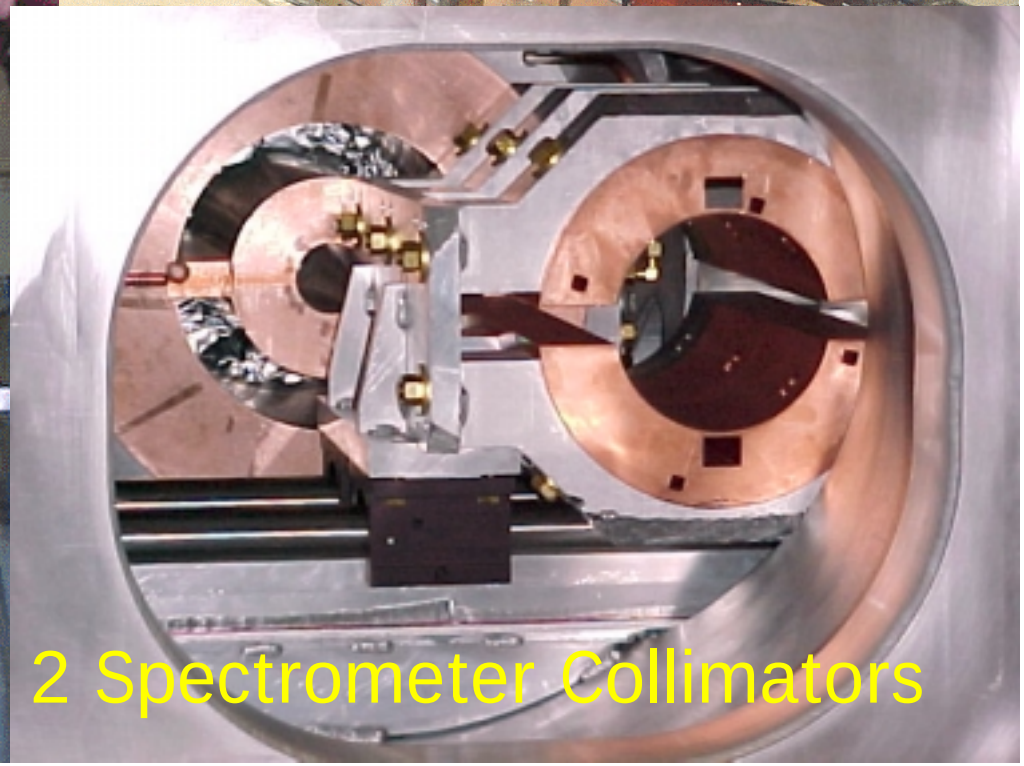




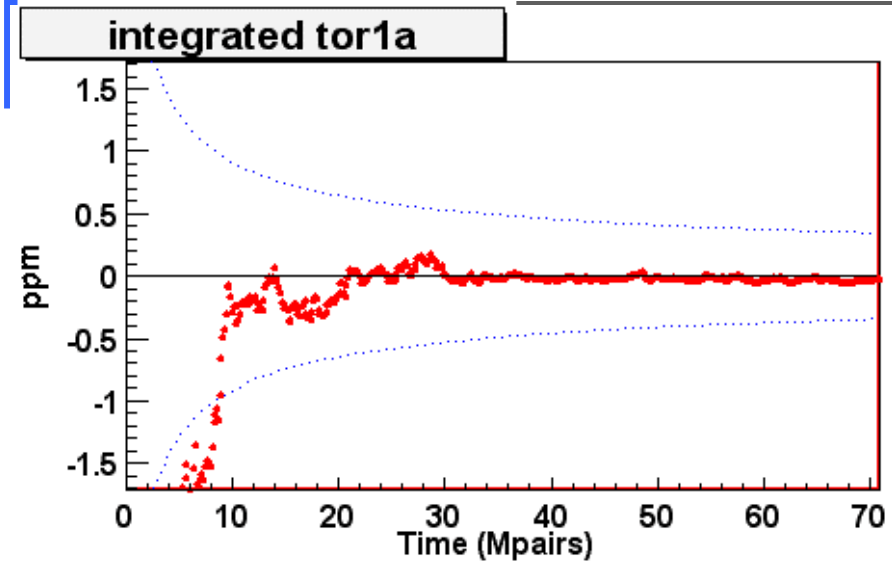

BPM

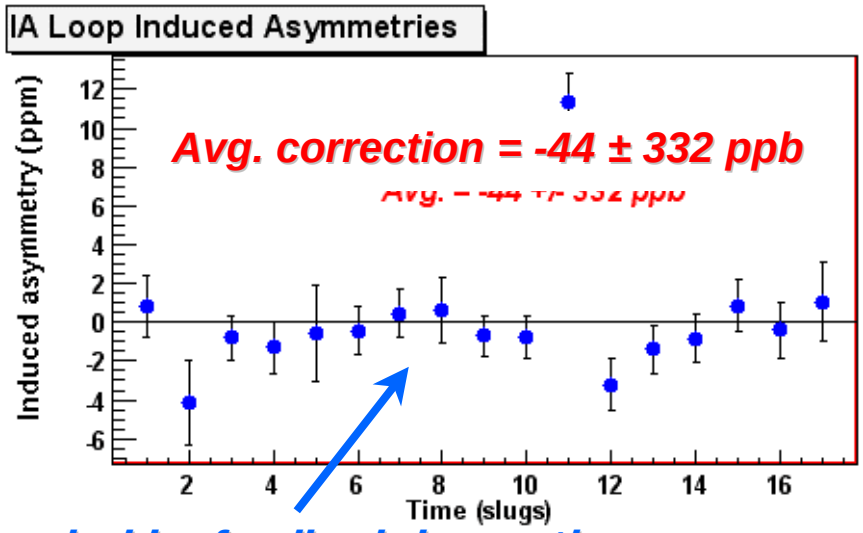

LH_2 Target Chamber
Quadrupoles
Dipoles

LH_2
Scattering Chamber

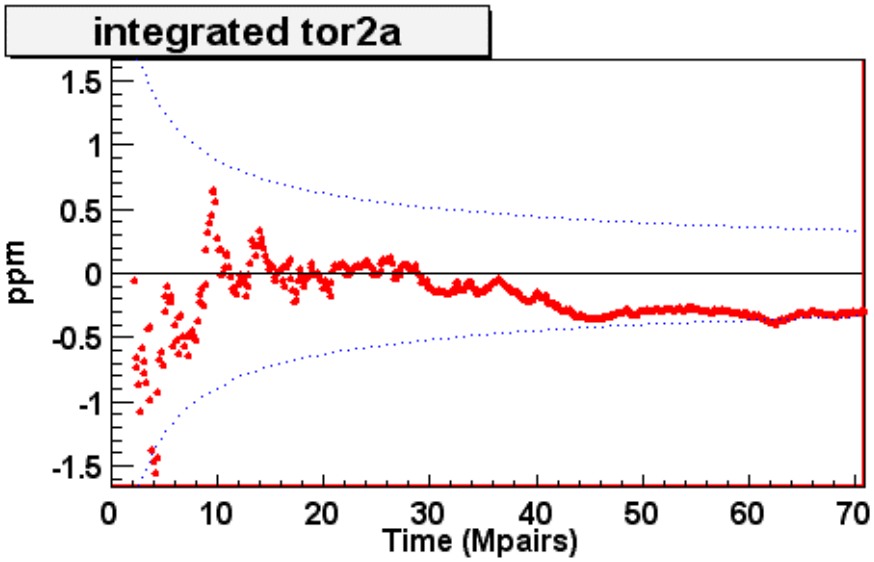

2 Spectrometer Collimators

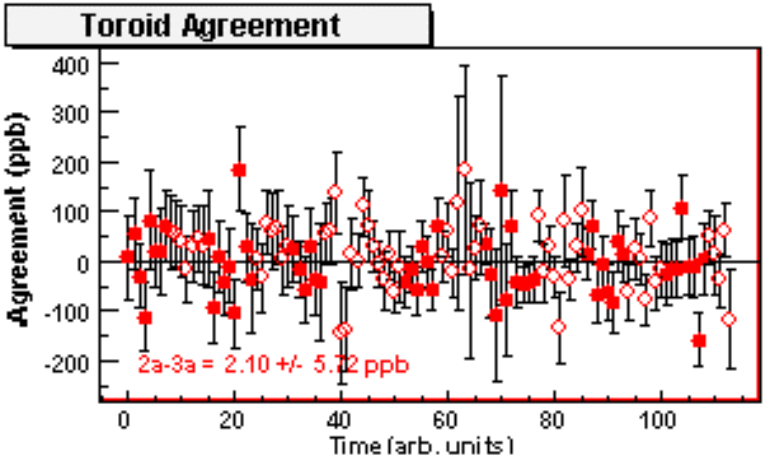
Charge Asymmetry





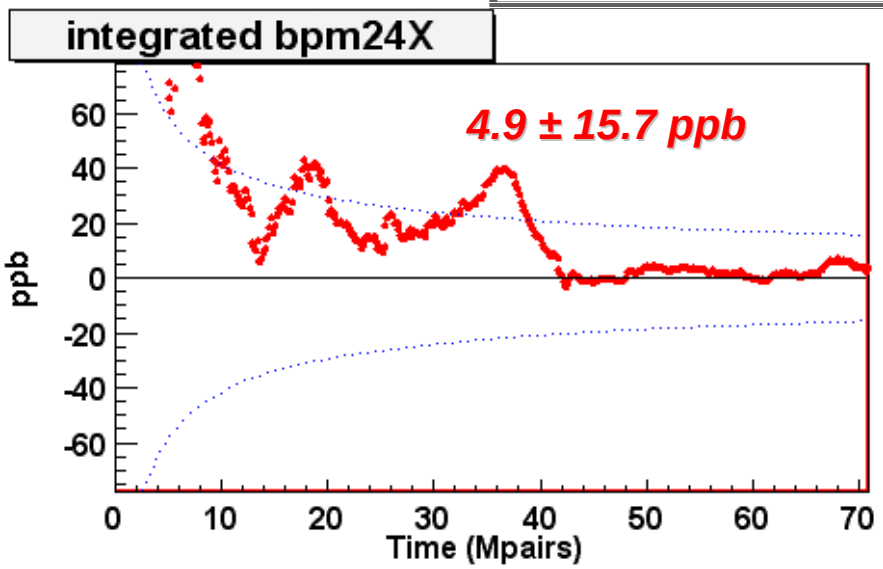
The double-feedback keeps the average charge asymmetry corrections tiny!



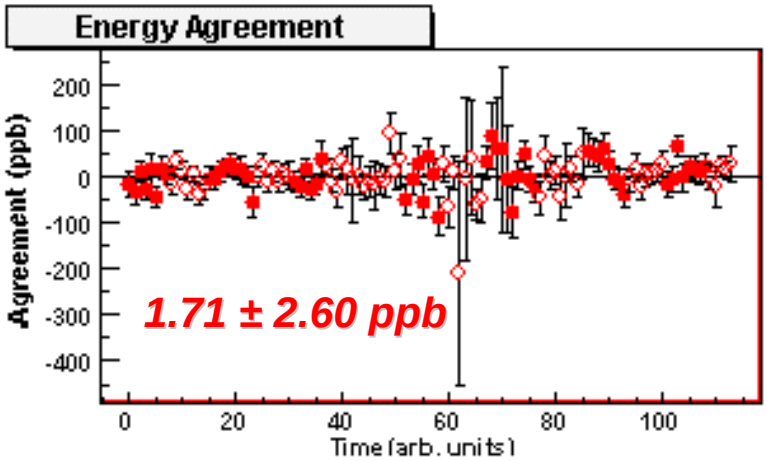


2a-3a = 2.10 ± 5.72 ppb

Energy Asymmetry



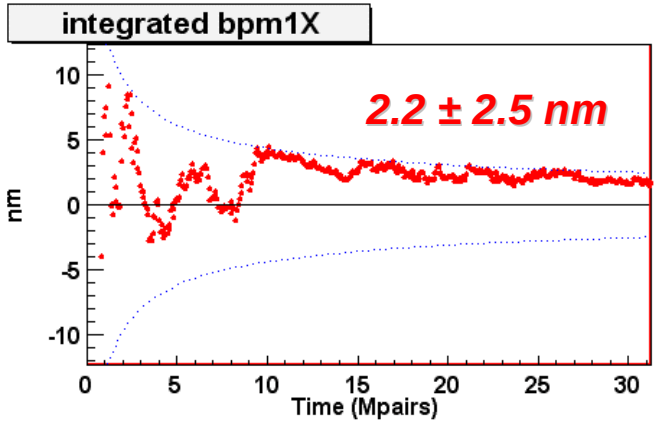
Nulling the charge asymmetry at 1.2 GeV region does indeed seem to help zero the energy asymmetry.

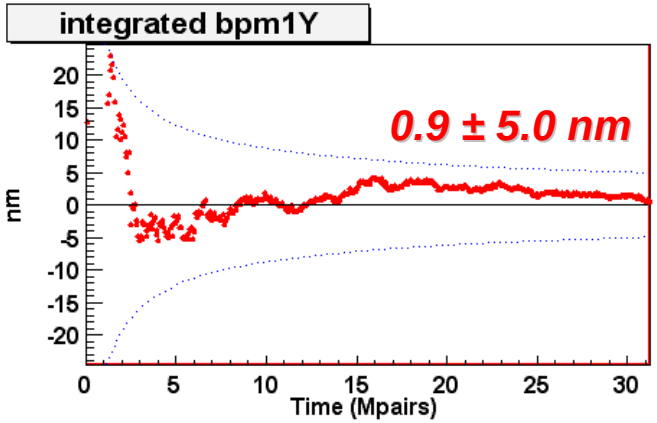


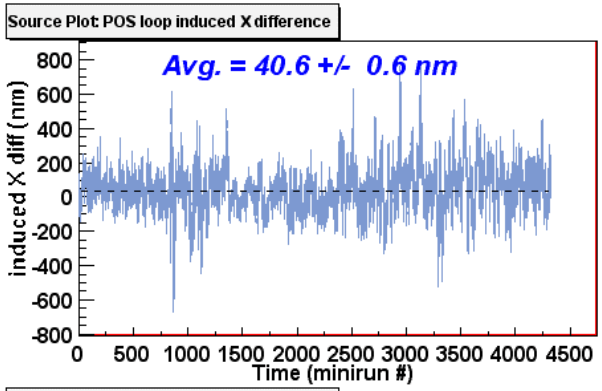
The two energy BPM's agree to very high precision!

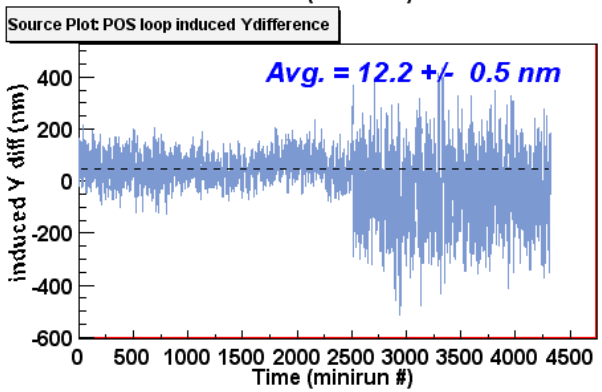
POS Loop Performance

Feeding back on ASSET BPM's, after ~30M pairs:

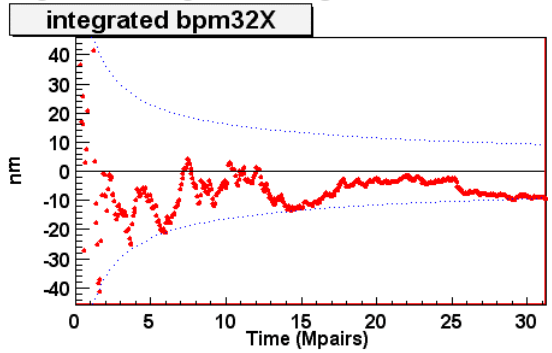


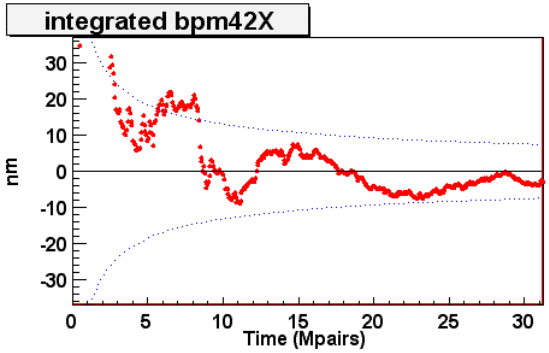


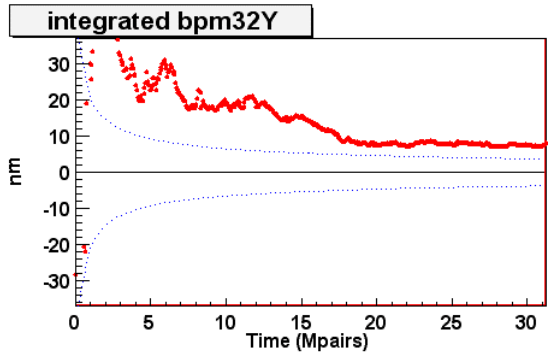


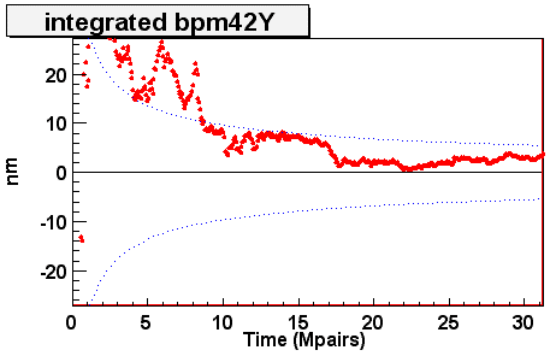


Some A-line BPM's:







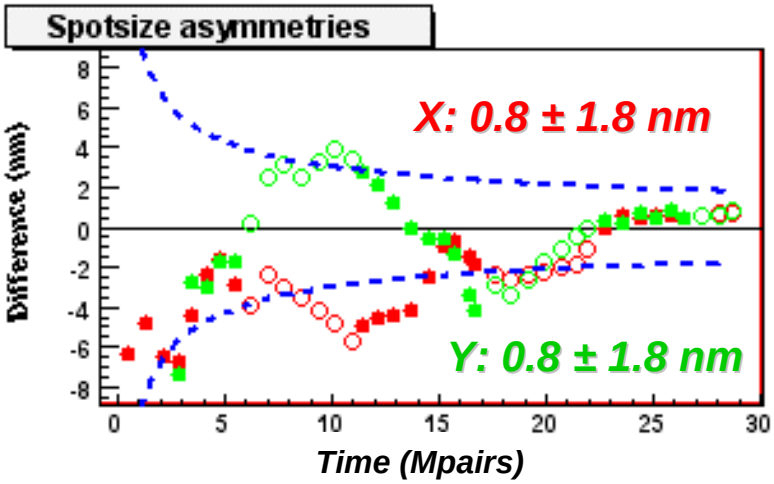


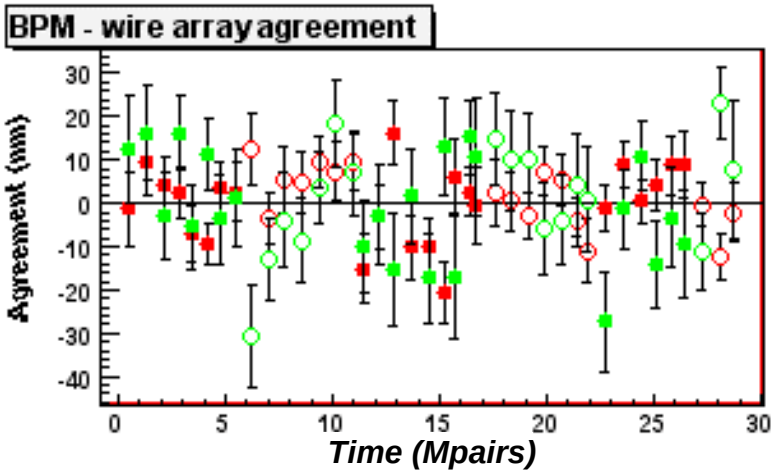
POS Loop On vs. Off

Quantity	38.6M pairs POS "On"	29.7M pairs POS "Off"
Δx_{ASSET}	X: 0.6 ± 2.1 nm Y: -2.7 ± 4.4 nm	X: 12.6 ± 2.4 nm Y: -49.8 ± 5.7 nm
Δx_{Target}	X: -23.3 ± 7.0 nm Y: 4.4 ± 5.0 nm	X: -5.1 ± 5.9 nm Y: -7.6 ± 5.7 nm
$\delta(\Delta x)_{Target}$	X: 2.1 ± 0.8 nm Y: -0.2 ± 1.4 nm	X: 0.9 ± 1.0 nm Y: 1.1 ± 1.6 nm
Δx_{Angle}	X: -19.2 ± 8.4 nm Y: 6.0 ± 3.4 nm	X: 13.2 ± 8.5 nm Y: 2.6 ± 4.3 nm
$\delta(\Delta x)_{Angle}$	X: 0.1 ± 1.3 nm Y: 0.4 ± 0.8 nm	X: -0.3 ± 1.8 nm Y: 0.6 ± 1.1 nm

POS loop definitely nulls position differences at ASSET, but it doesn't look to be doing any good in the A-line. The feedback may be steering the pulse funny in order to null position differences at ASSET. Overall, though, things look very good.

Wire Array Results





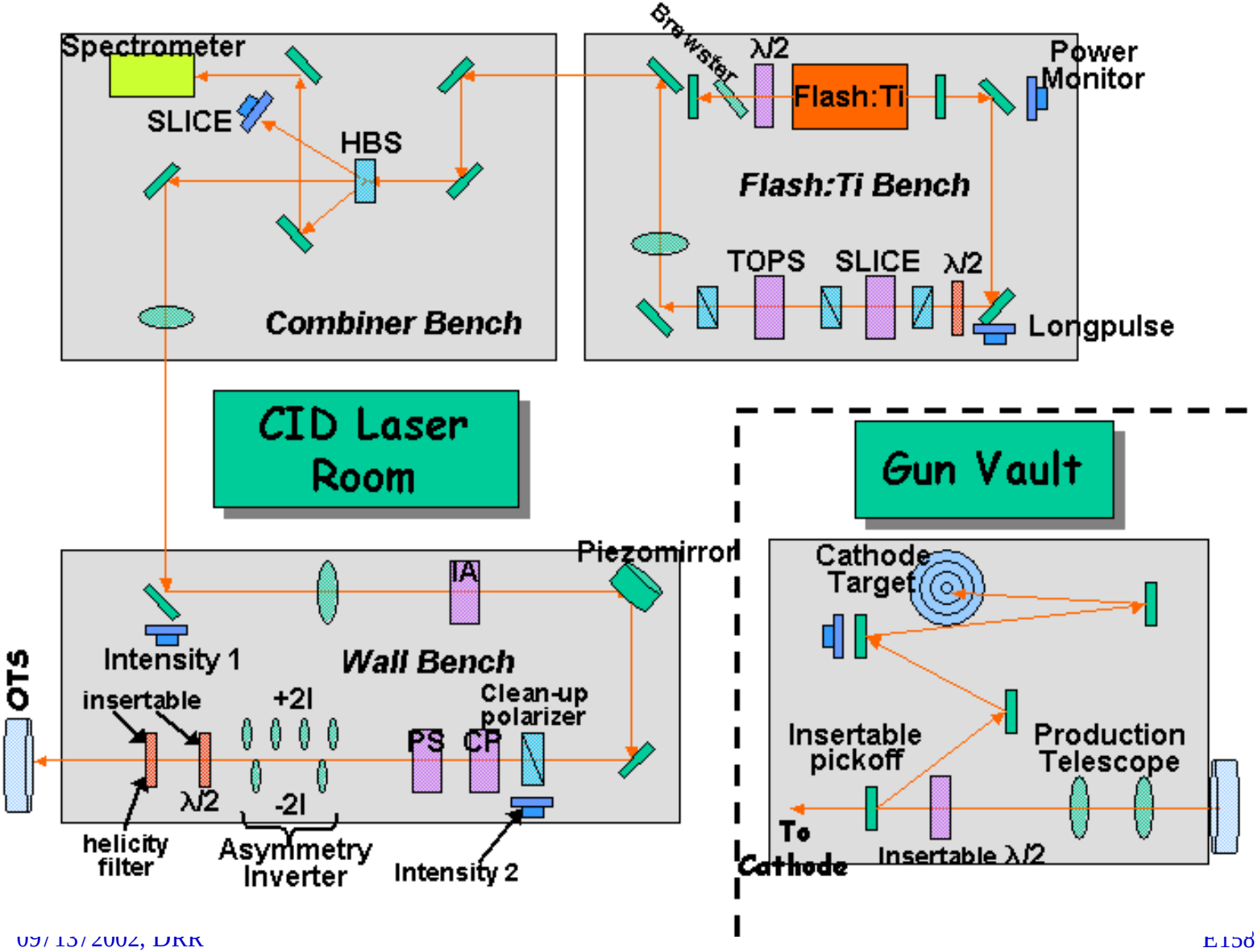
X agree: 1.0 ± 1.1 nm

Y agree: 0.3 ± 1.7 nm

Wire array broke in the middle of the run, so only 30M pairs represented here.

(2nm spotsize difference is ~2ppm spotsize asymmetry
and this size effect could give ~ppb false asymmetry due to
induced target density changes;
need to quantify better from data analysis)

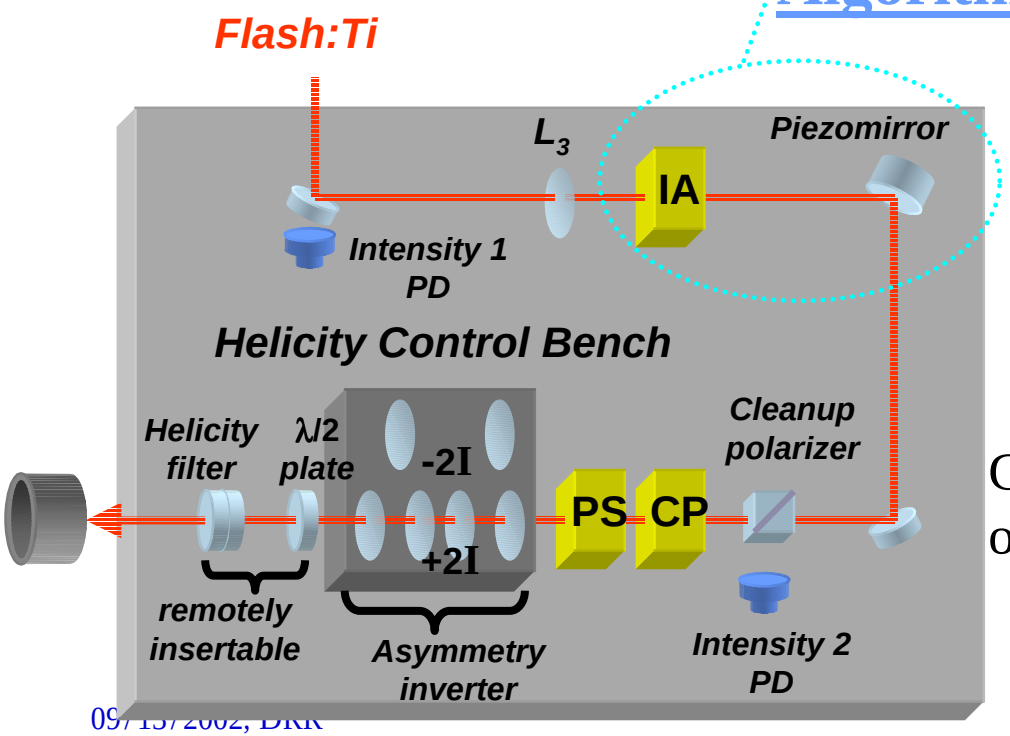
Polarized Source Laser System



Beam Asymmetry Feedbacks

Item	Control	Diagnostic
Intensity	IA Pockels Cell	Toroid (@ 1 GeV)
Position	Piezo Mirror	BPM (@ 1 GeV)

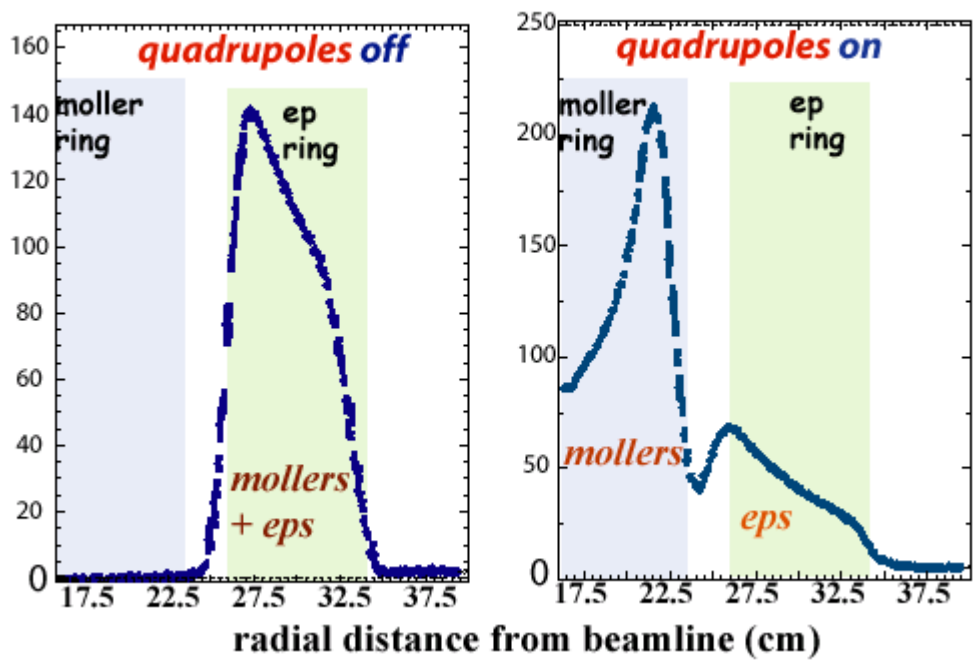
Algorithm: - measure asymmetry on a run with N pulses (typically 1-30K pulses)
- induce asymmetry on next run to cancel measured asymmetry on current run

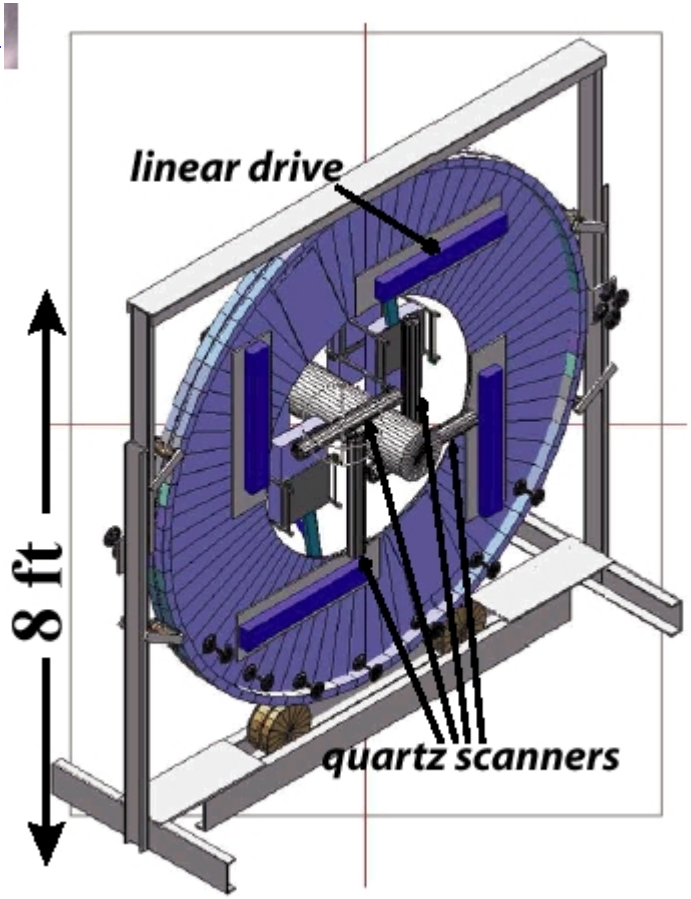


Gives better than 1/sqrt(N) scaling of charge asymmetry, position difference

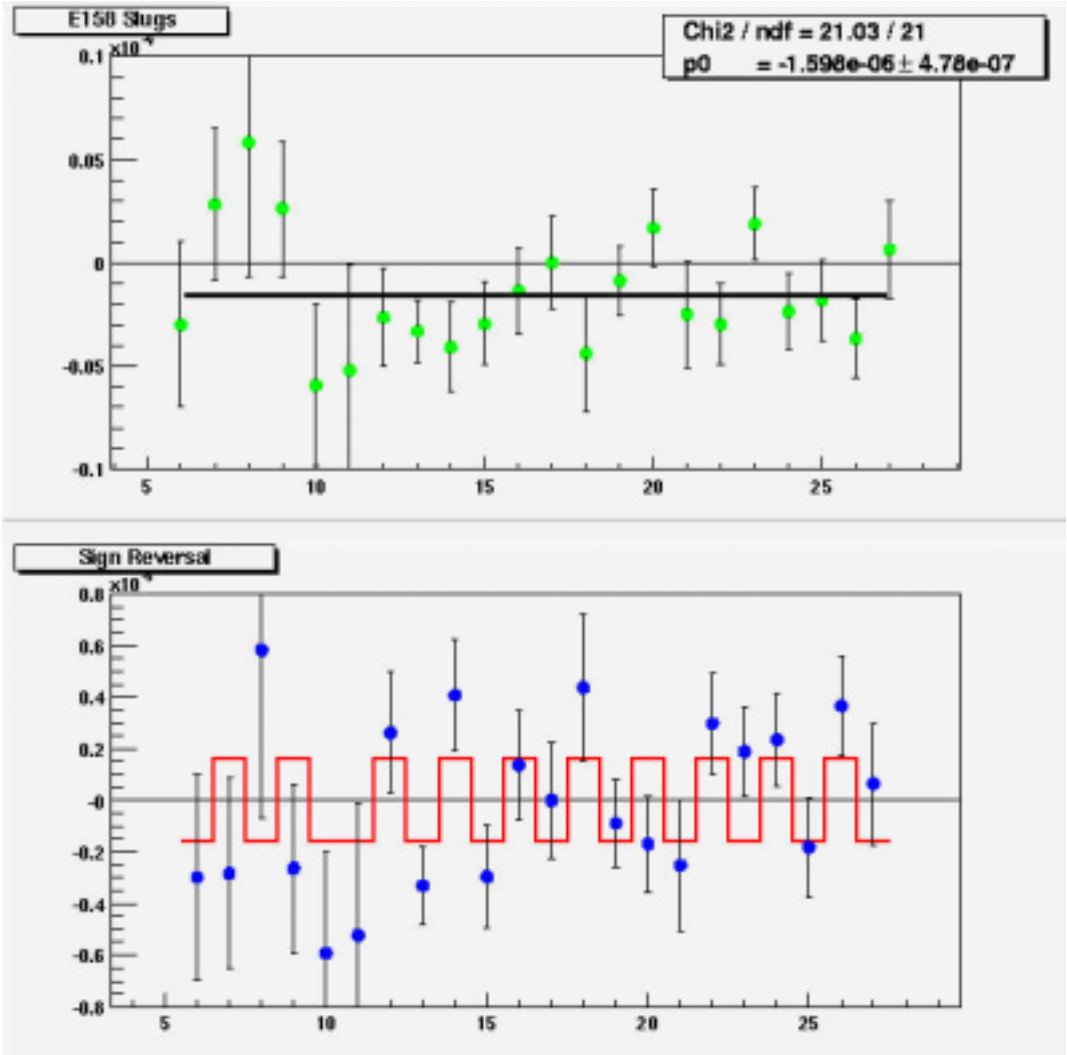
Profile Detector

- ✓ 4 Quartz Cherenkov detectors with PMT readout
  - ☞ insertable pre-radiators
  - ☞ insertable shutter in front of PMTs
- ✓ Radial and azimuthal scans
  - ➢ collimator alignment, spectrometer tuning
  - ➢ background determination
  - ➢ Q^2 measurement





Results: Pion Asymmetry



$A_{LR}(\pi)$ = 1.6 ppm

Estimated correction to A_{LR} ~2 ppb