Parity Nonconservation in Møller Scattering

E158: A Precision Measurement of the Weak Mixing Angle in Fixed Target electron-electron (Møller) Scattering

(The structure of the virtual Z in dense electronic matter)

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DIS05, April 29, 2005

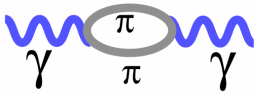
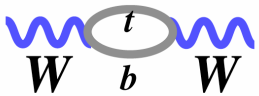
Outline

- *Physics Motivation*
- *Experimental Overview*
- *Final Results*
- *Physics Implications*
- *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

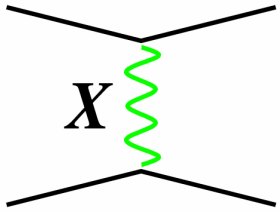
- **Precise predictions at level of 0.1%**
- **Indirect access to TeV scale physics**

- ***World electroweak data has marginal χ^2***
- ***Leptonic and hadronic Z couplings barely consistent***
- ***Perhaps there are deviations lurking elsewhere?***

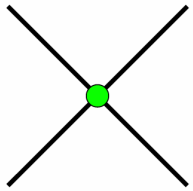
Electroweak Physics at Low Q^2

Q^2 << scale of EW symmetry breaking

consider



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



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

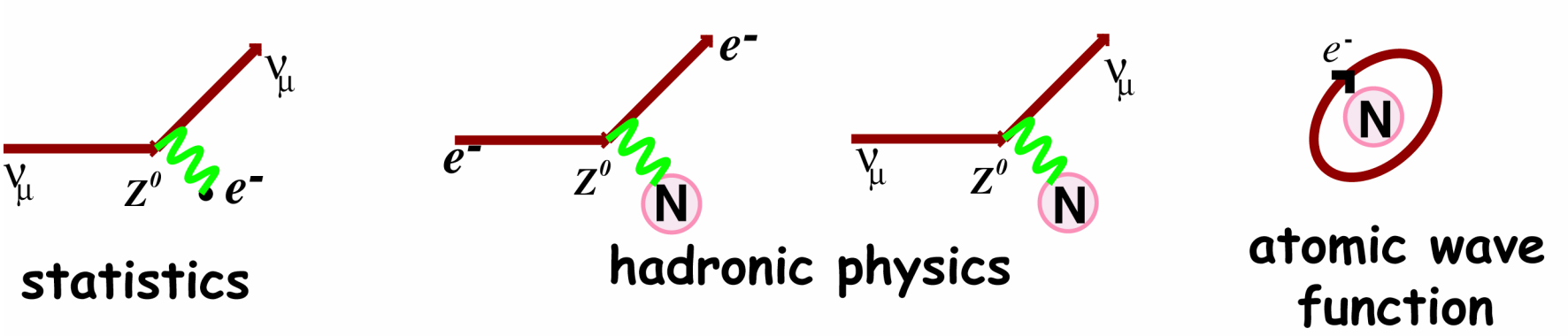
LEPII, Tevatron, LHC access scales greater than $\Lambda \sim 10$ TeV

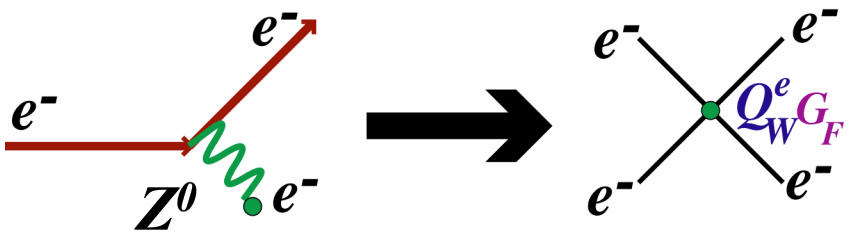
$$\frac{\delta A_Z}{A_Z} \propto \frac{\pi/\Lambda^2}{g\,G_F} \longrightarrow \delta(g)/g \sim 0.1 \quad \Lambda \sim 10\ \text{TeV}$$

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

Complementary:* Parity *Violating* vs Parity *Conserving

Weak Neutral Current at low Q^2

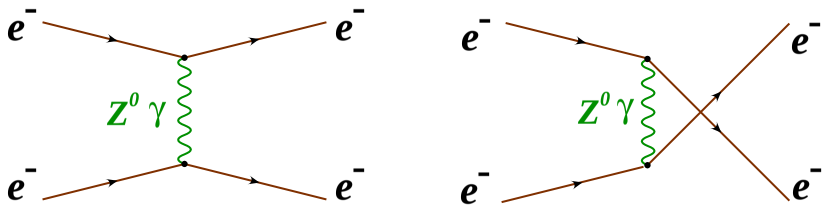




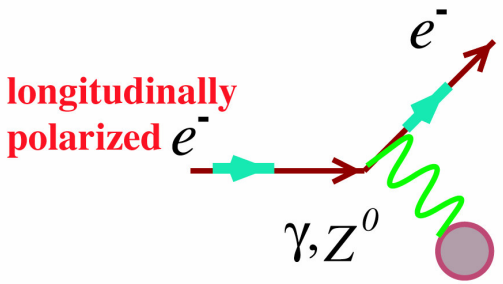
Purely leptonic reaction

$$Q^e_W \sim 1 - 4\sin^2\theta_W$$

Fixed Target Møller Scattering



Weak-Electromagnetic Interference



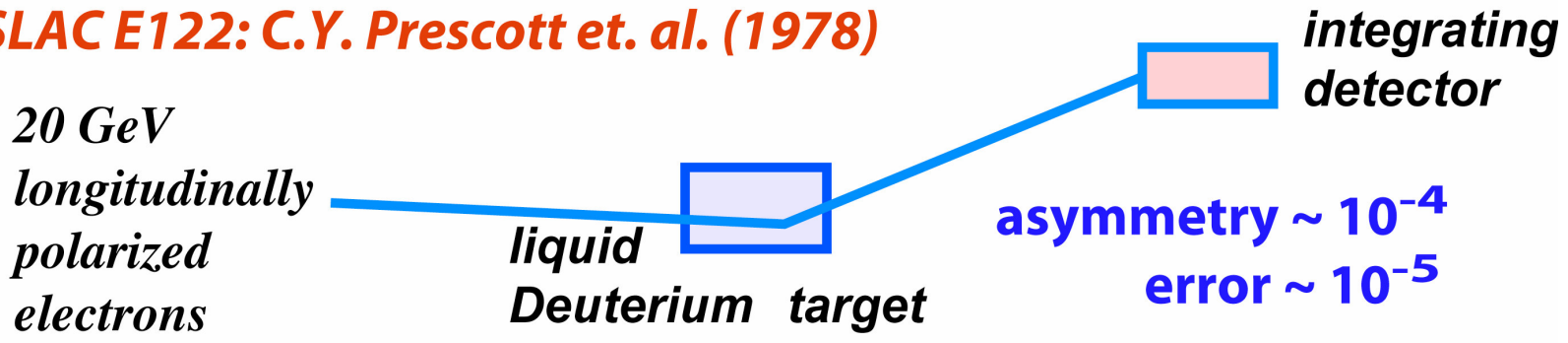
$$\sigma \quad \alpha \, | A_\gamma + A_{weak} |^2$$

Zel'dovich '59

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

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

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



E158 at SLAC

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

$$A_{PV} \approx -1\times10^{-7}\times E_{beam}\times P_{beam}\times(1-4\sin^2\vartheta_W)$$

Highest electron beam energy with longitudinal beam polarization: SLAC

$Q^2 = mE = 0.025\ GeV^2$ ⇨ **Raw asymmetry ~ *130 ppb***

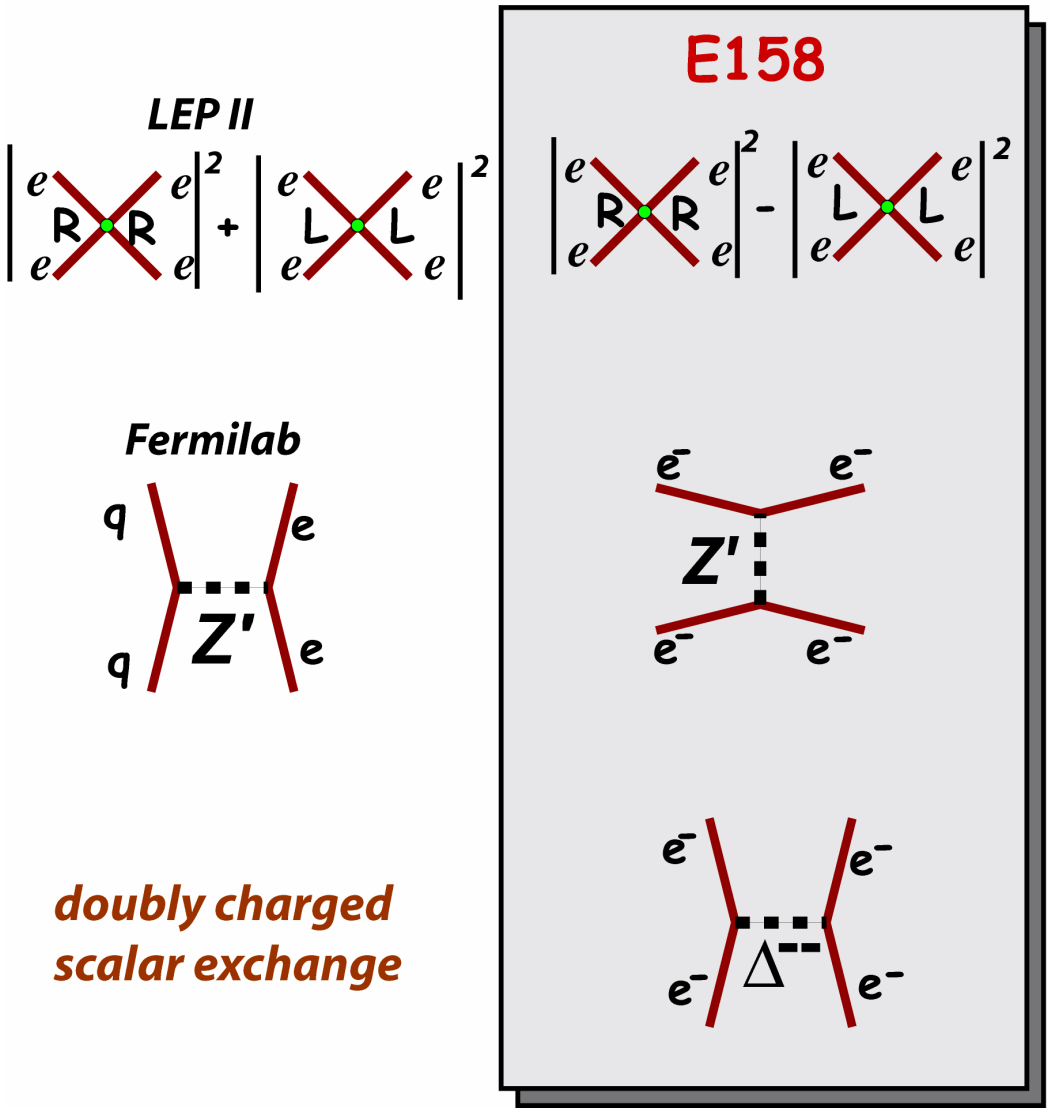
Need *10^{16}* events ⇨ **Count at ~ *1 GHz*** ⇨ $\delta(A_{PV})$ **~ *10 ppb***

- *1997: EPAC approval*
- *2000: Construction*
- *2002-2003: Data collection*
- *2004: First publication*

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

7 Ph.D. Students
60 physicists

E158 New Physics Reach



15 TeV compositeness

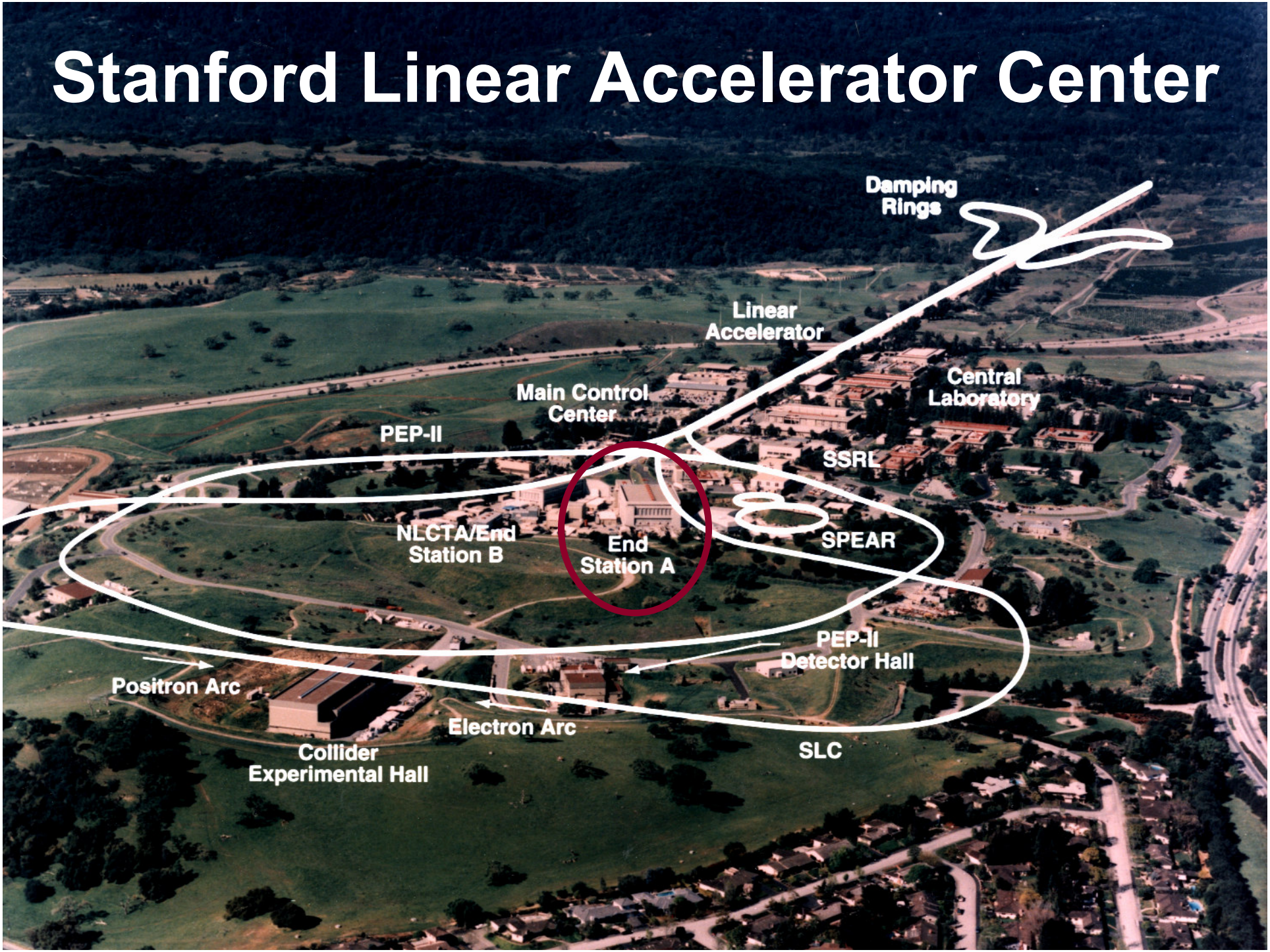
0.5-1.0 TeV GUTs

0.5-2.5 TeV extra dimensions

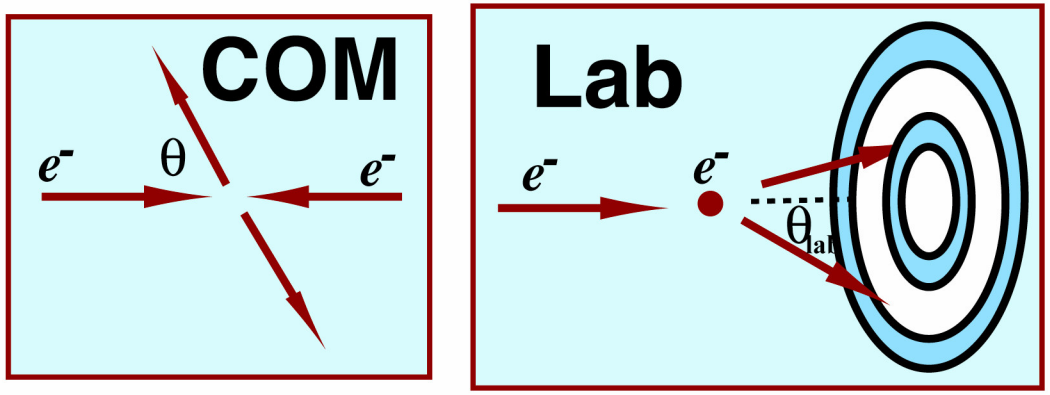
$\frac{g^2}{2M_\Delta^2}$ lepton flavor violation

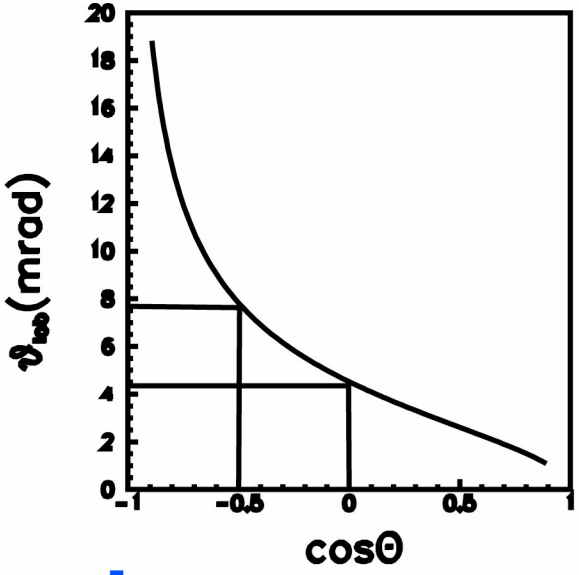
$< 0.01\ G_F$

Stanford Linear Accelerator Center



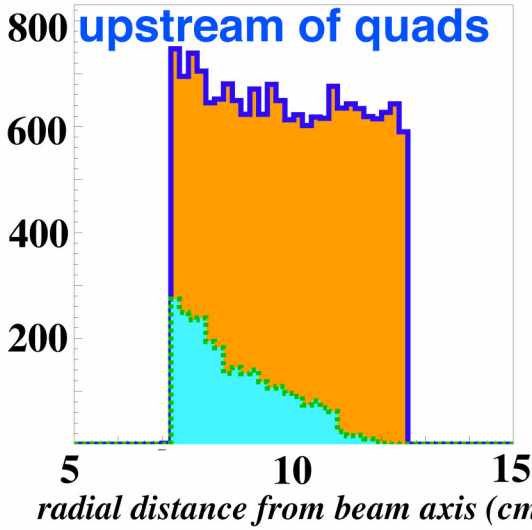
Kinematics

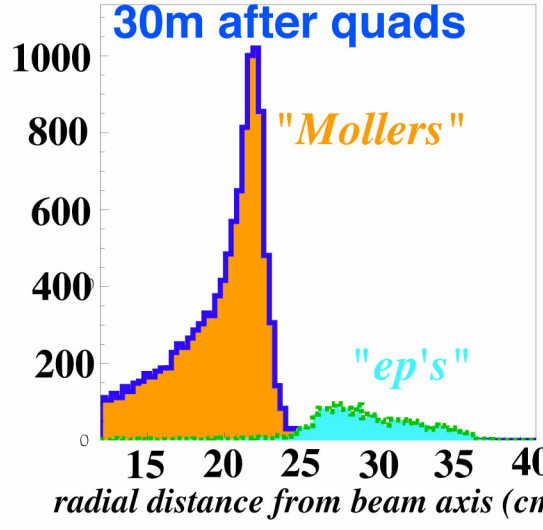




Quadrupole Quadruplet

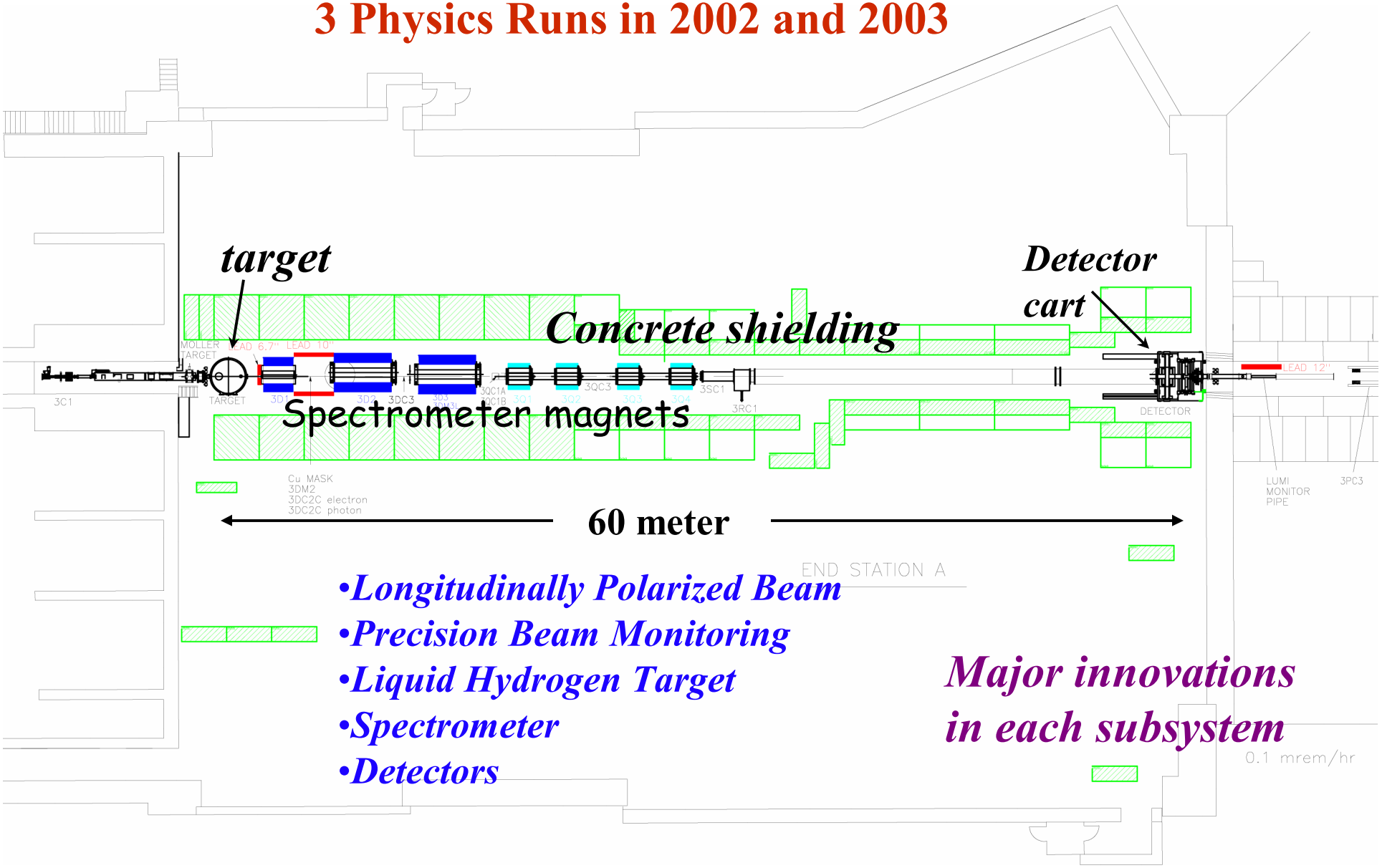
- *primary & scattered electrons enclosed in quadrupoles*
- *Mollers (e-e) focused, Motts (e-p) defocused*
- *full range of azimuth*





Experimental Apparatus

3 Physics Runs in 2002 and 2003



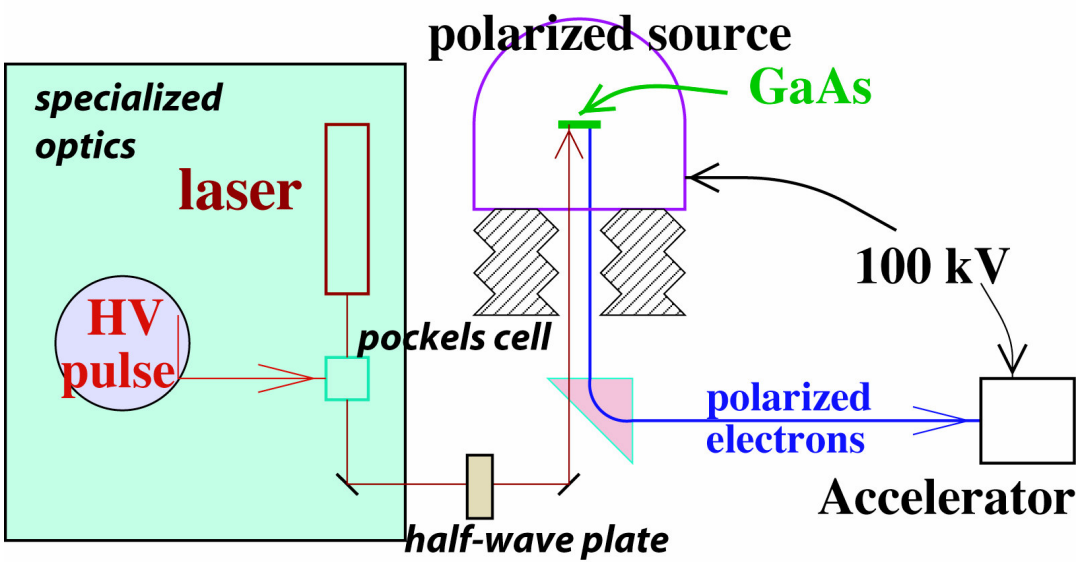
E158 Spectrometer

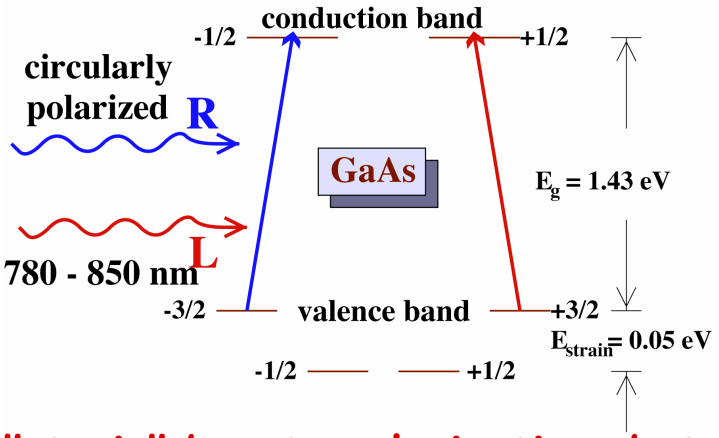
Optical Pumping

Modulate longitudinal polarization of the electron beam

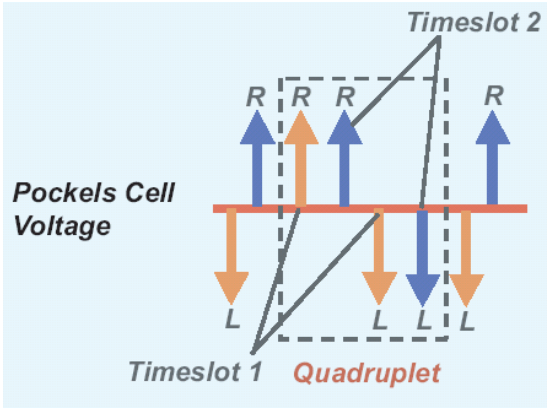
✧ Beam helicity is chosen pseudo-randomly at 120 Hz

- *sequence of pulse quadruplets*
- *Data analyzed as "pulse-pairs"*



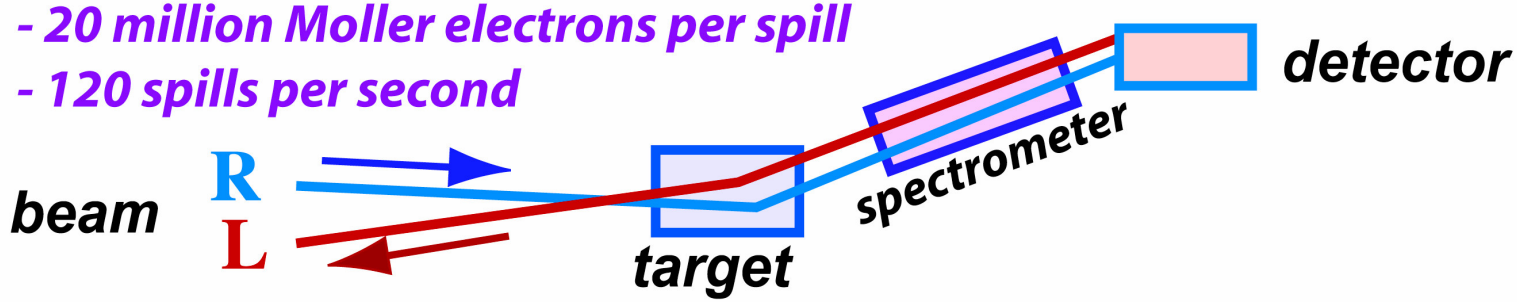


"strain" boosts polarization, but introduces anisotropy in response



Experimental Technique

- 20 million Moller electrons per spill
- 120 spills per second

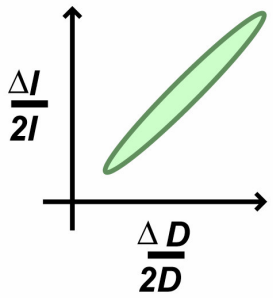


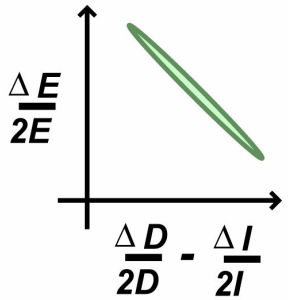
Detector D, Current I: $F = D/I$

* Rapid helicity flips at 120 Hz
* Spatially separate signal
* Integrate scattered flux
* control beam jitter

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

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



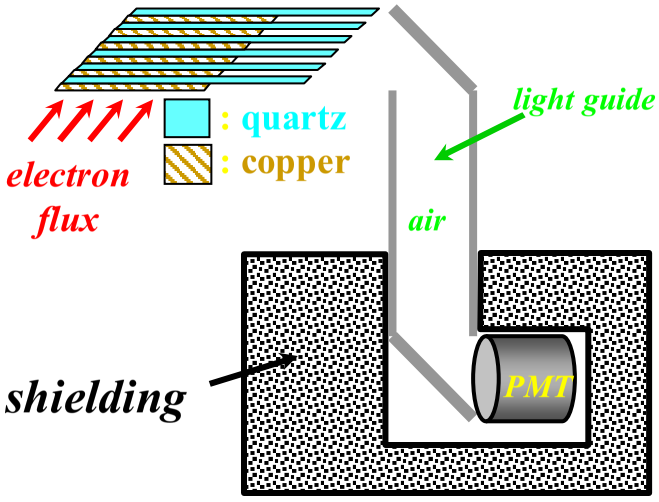


each 60 Hz pair measures A_{pair} with variance of 200 ppm

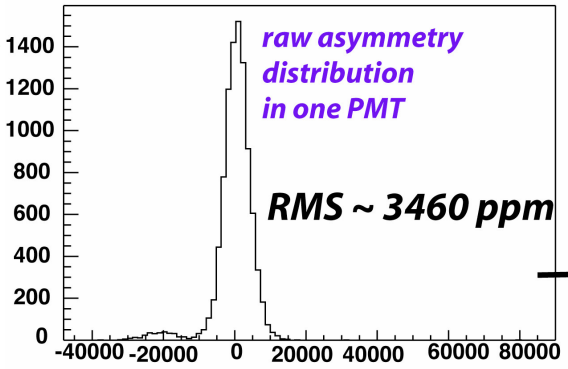
$$\frac{200\ \text{ppm}}{\sqrt{100\ M}} = 20\ \text{ppb}$$

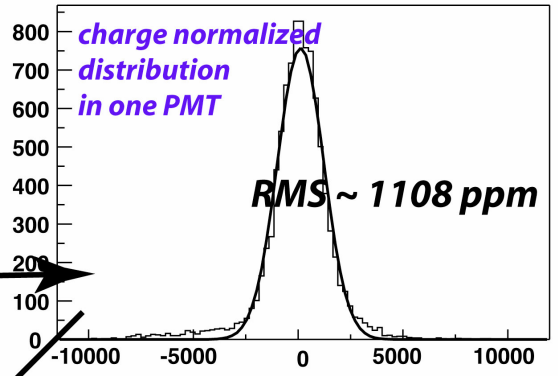
E158 Analysis

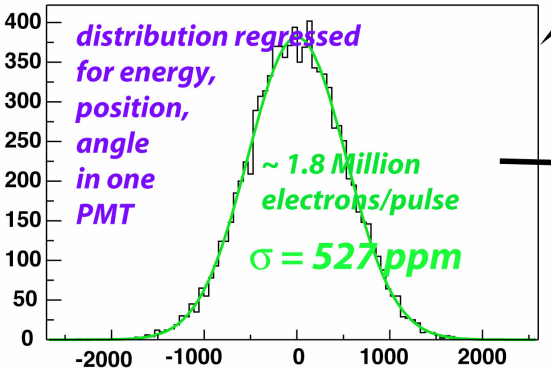
Basic Idea:

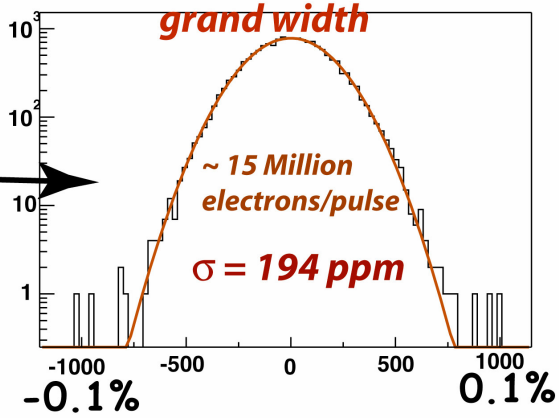


observed left-right asymmetry distribution

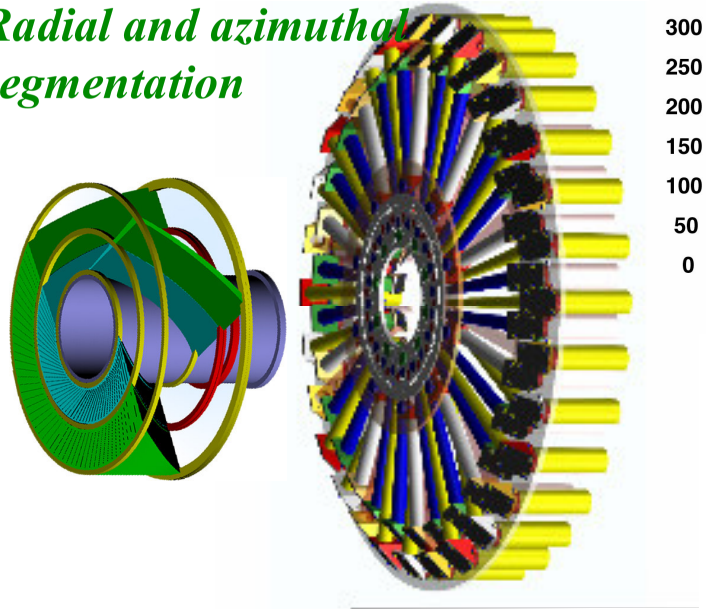






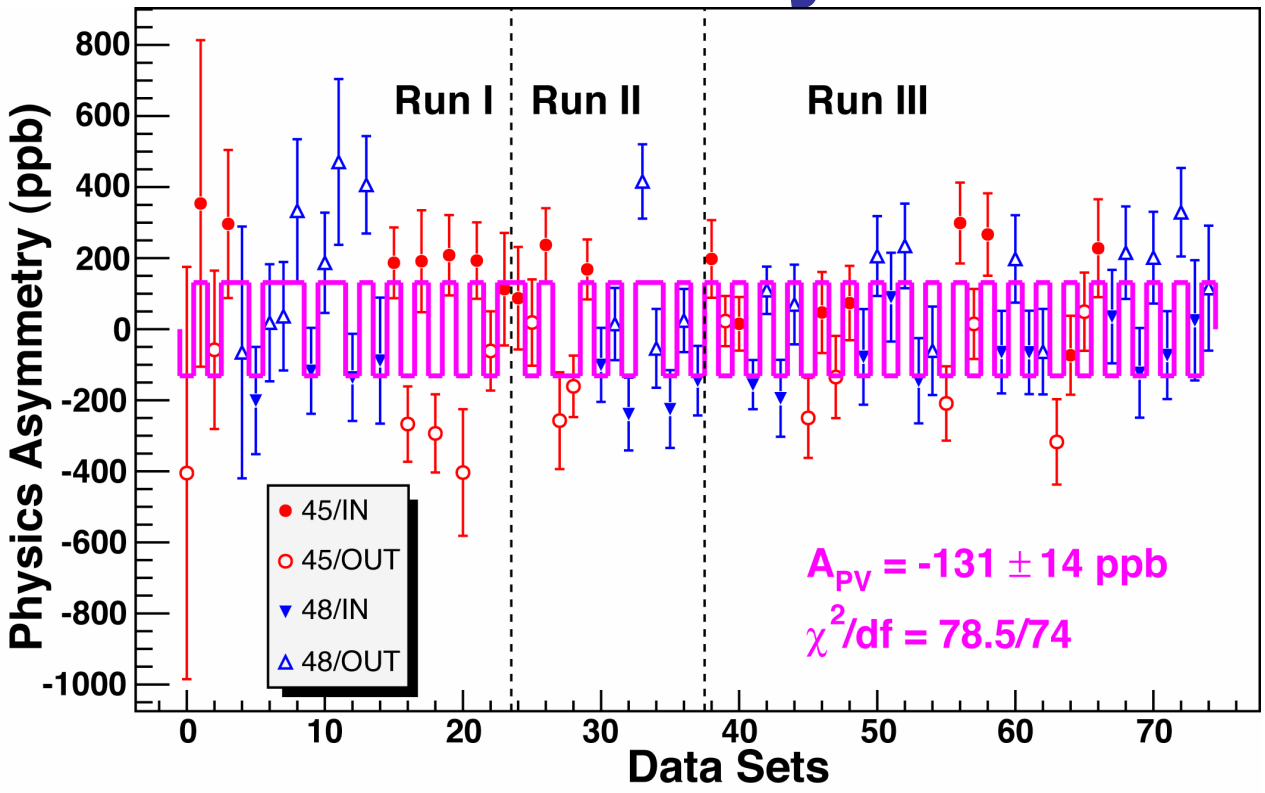


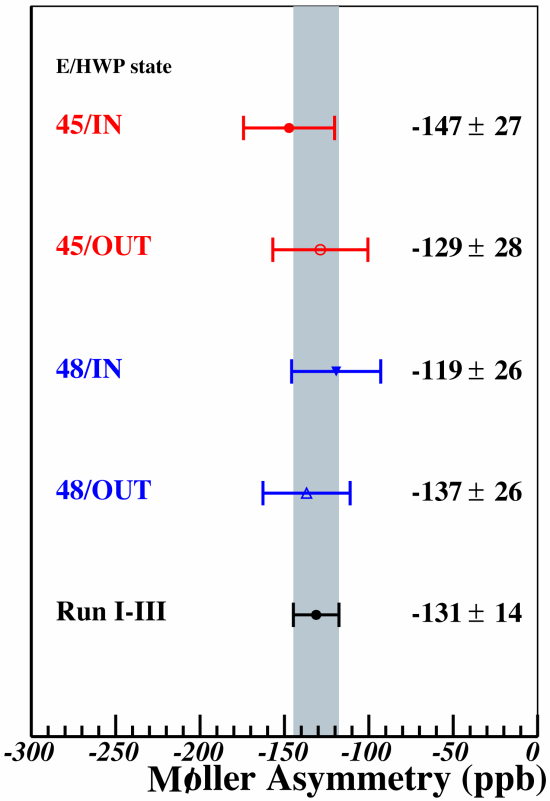
Radial and azimuthal segmentation

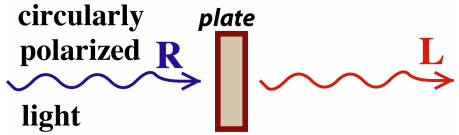


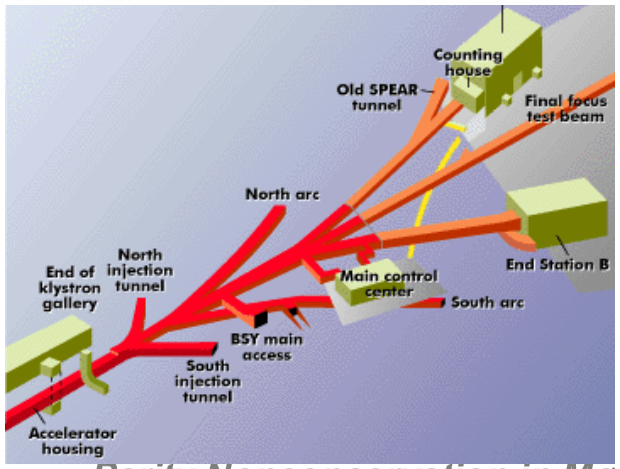
- Corrections for beam fluctuations
- Average over runs
- Statistical tests
- Beam polarization and other normalization

Final Analysis of All 3 Runs









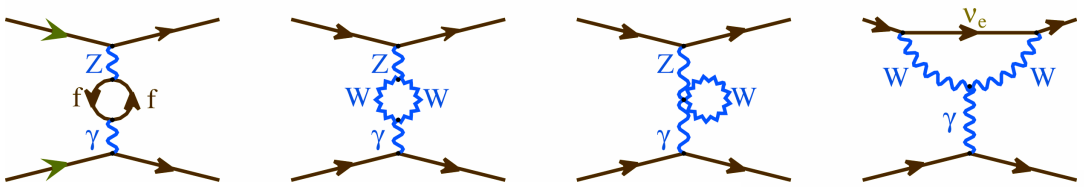
g-2 spin precession

45 GeV: 14.0 revs

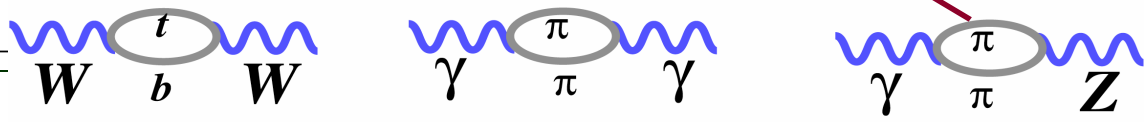
48 GeV: 14.5 revs

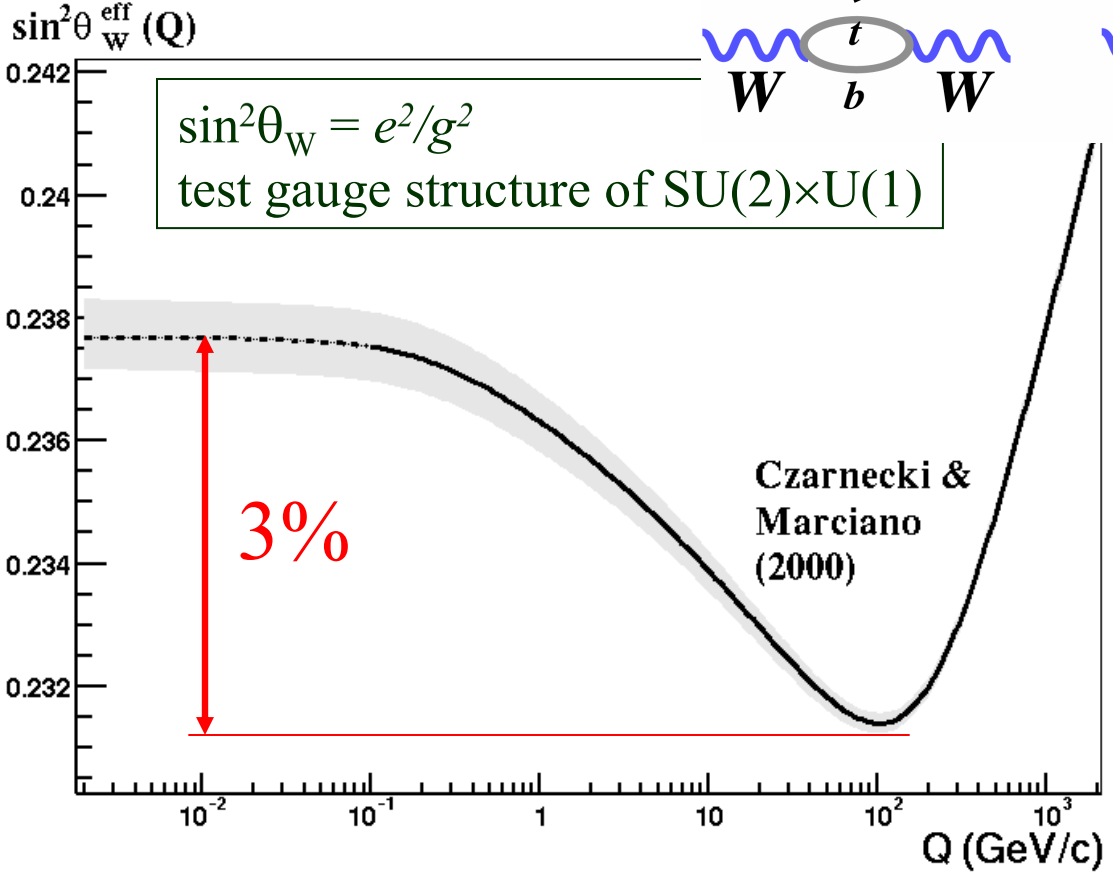
$$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$$

Electroweak Physics



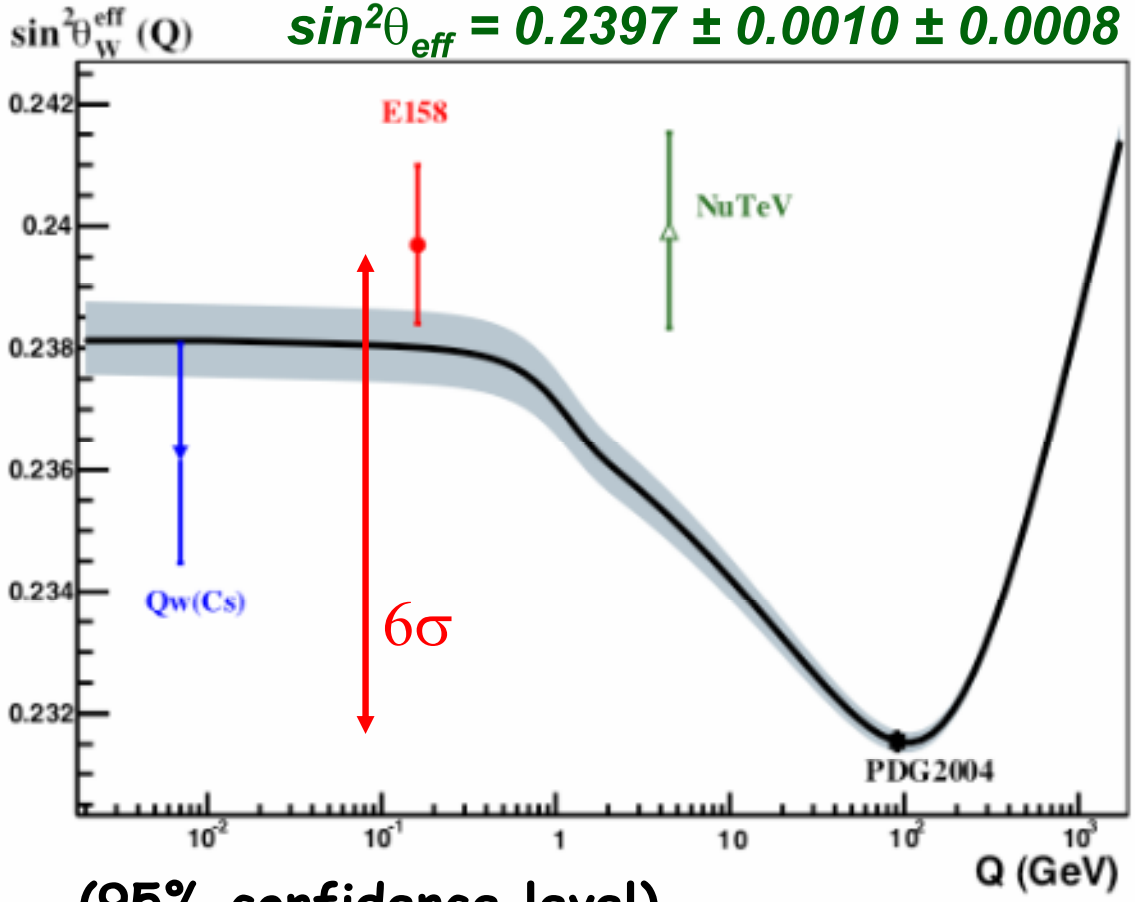
$$\frac{1}{2} - q \sin^2 \theta_W$$



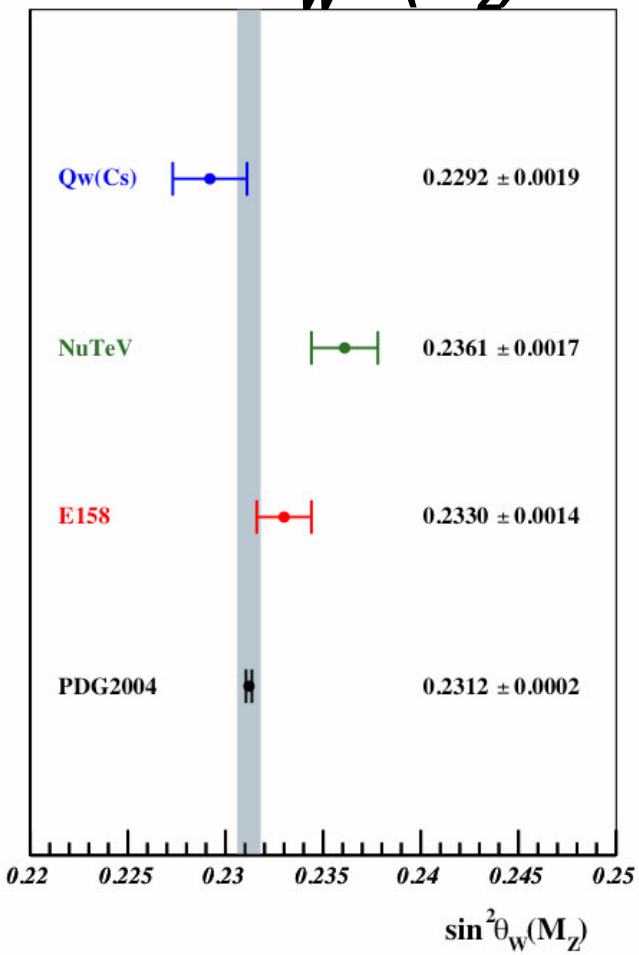


Final Physics Results

$\sin^2\theta_{eff} = 0.2397 \pm 0.0010 \pm 0.0008$



$\sin^2\theta_W^{MS}(M_Z)$



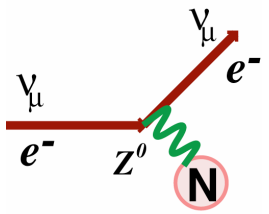
(95% confidence level)

* Limit on Λ_{LL} ~ 7 or 16 TeV
* Limit on SO(10) Z' ~ 1.0 TeV
* Limit on lepton flavor violating coupling ~ $0.01G_F$

hep-ex/0504049
submitted Tuesday!

Future Measurements

Semi-Leptonic: Is NuTeV new EW or QCD physics?



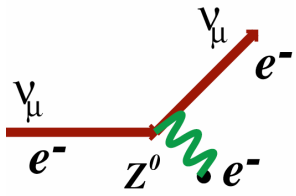
PV Elastic electron-proton scattering at JLab: $\delta(\sin^2\theta_w)=0.0007$

PV Deep Inelastic Scattering at upgraded JLab

- *Unique, complementary probes of New Physics*
- *Theoretical issues are interesting in themselves:*

Unique, outstanding opportunity for a dedicated apparatus with JLab upgrade

Leptonic: Ultimately the "best" EW precision measurements



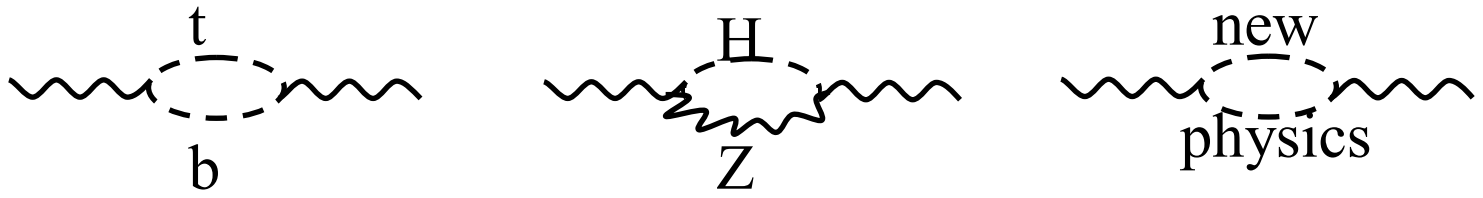
ν-e scattering in reactor: at best can do $\delta(\sin^2\theta_w)=0.002$

Møller scattering at upgraded JLab: $\delta(\sin^2\theta_w)=0.0003$!

- *Comparable to single LEP measurements: shed light on disagreement*
- *Best low energy measurement until ILC or ν-Factory*
- *Could be done ~ 2012*

Ultrahigh Precision

Measure contribution from scalars to oblique corrections



$\frac{\delta m_H}{m_H} \approx 10\%$ for $\delta \sin^2\theta_W \approx 0.00004$ (world average ~0.00016)

Compare with masses of "bumps" at new colliders: Critical crosscheck

A_{LR} and M_W at future colliders:

Systematics extremely challenging!

Energy scale to 10^{-4}, polarimetry to 0.15%

Møller scattering at the ILC

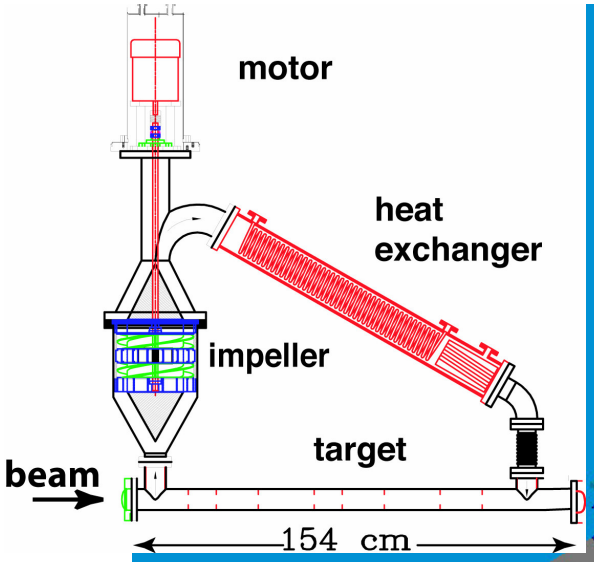
- ***Fixed target has advantages for systematics***
- ***Could work with ILC "exhaust"beam***

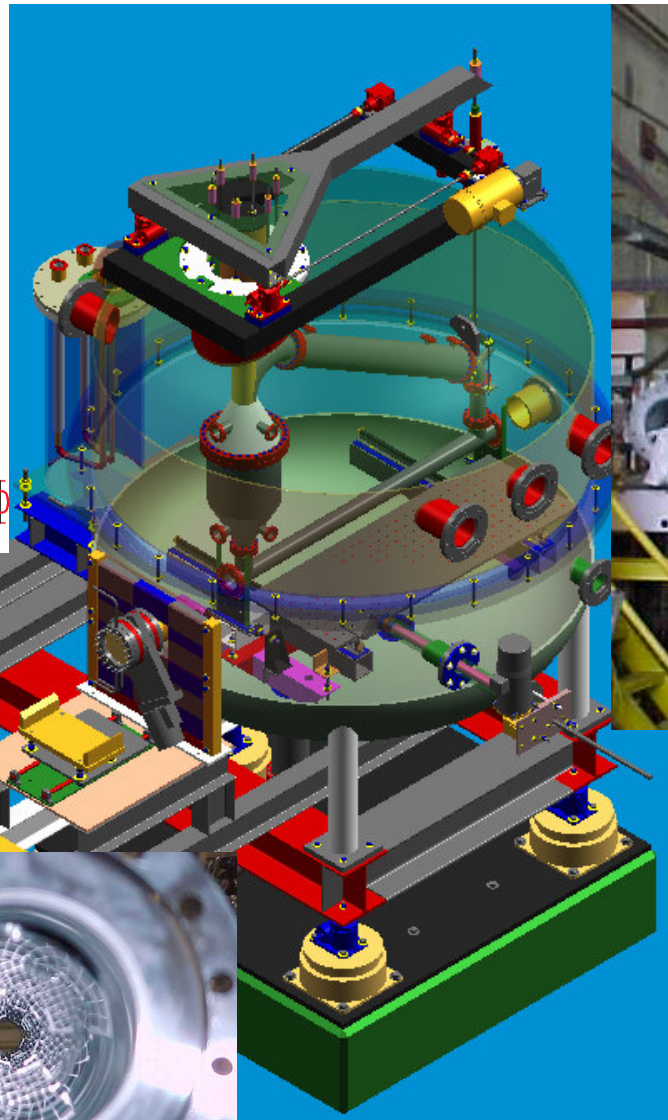
K.K, Snowmass 96	E158	LC
Energy (GeV)	48	250-500
Intensity/pulse	4.5×10^{11}	14×10^{11}
Pulse Rate (Hz)	120	120
P_e	85%	90%
Time (s)	5×10^6	2×10^7
A_{LR} (ppm)	0.15	1-2
δA_{LR} (ppm)	0.015	0.008
$\delta \sin^2(\theta_W)$	0.001	0.00008

Conclusions

- *SLAC E158 data taking phase has been completed*
- *Physics results:*
  - *Parity is violated in Møller scattering*
  - *Final result with all data: A_{PV}: -131 ± 14 ± 10 ppb*
  - *Running of weak mixing angle established at 6σ*
  - *$\sin^2\theta_{eff}$ = 0.2397 ± 0.0010 ± 0.0008*
  - *New constraints on TeV scale physics*
  - *Inelastic e-p asymmetry at low Q^2 consistent with quark picture*
  - *First measurement of e-e transverse asymmetry analyzing power*
- *This experiment could not be done elsewhere in the world*
  - *Last Fixed Target Experiment at Historic SLAC End Station A!*
- *Final publication just submitted: hep-ex/0504049*
- *Future experiments could improve sensitivity by ~ 2 to 6*
- *An "ultimate" measurement could be done at an LC or neutrino factory*

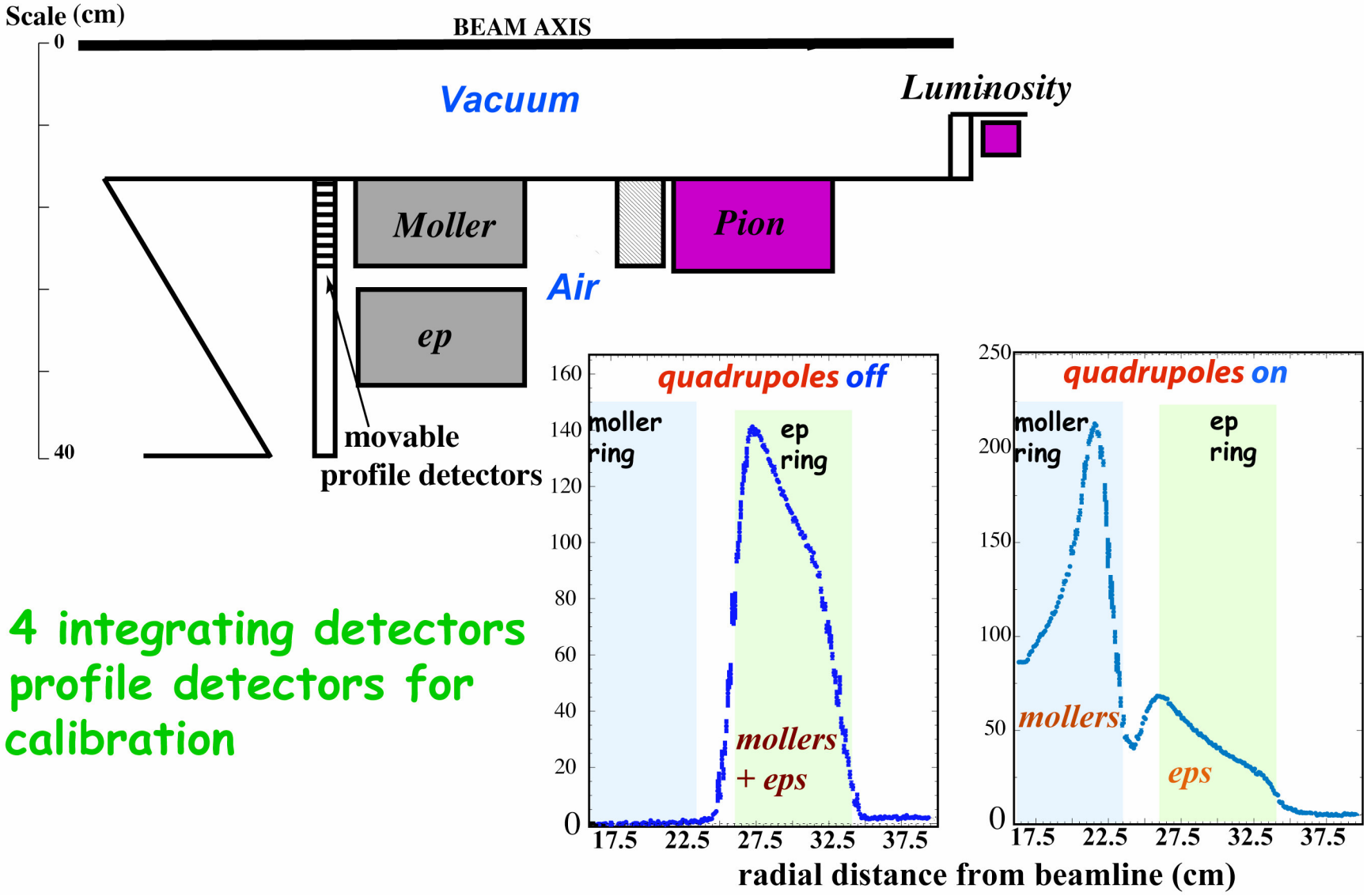
Liquid Hydrogen Target





Refrigeration Capacity	*1 k*
Operating Temperature	*20*
Length	*1.5*
Flow Rate	*5 n*
Vertical Motion	*6 inch*

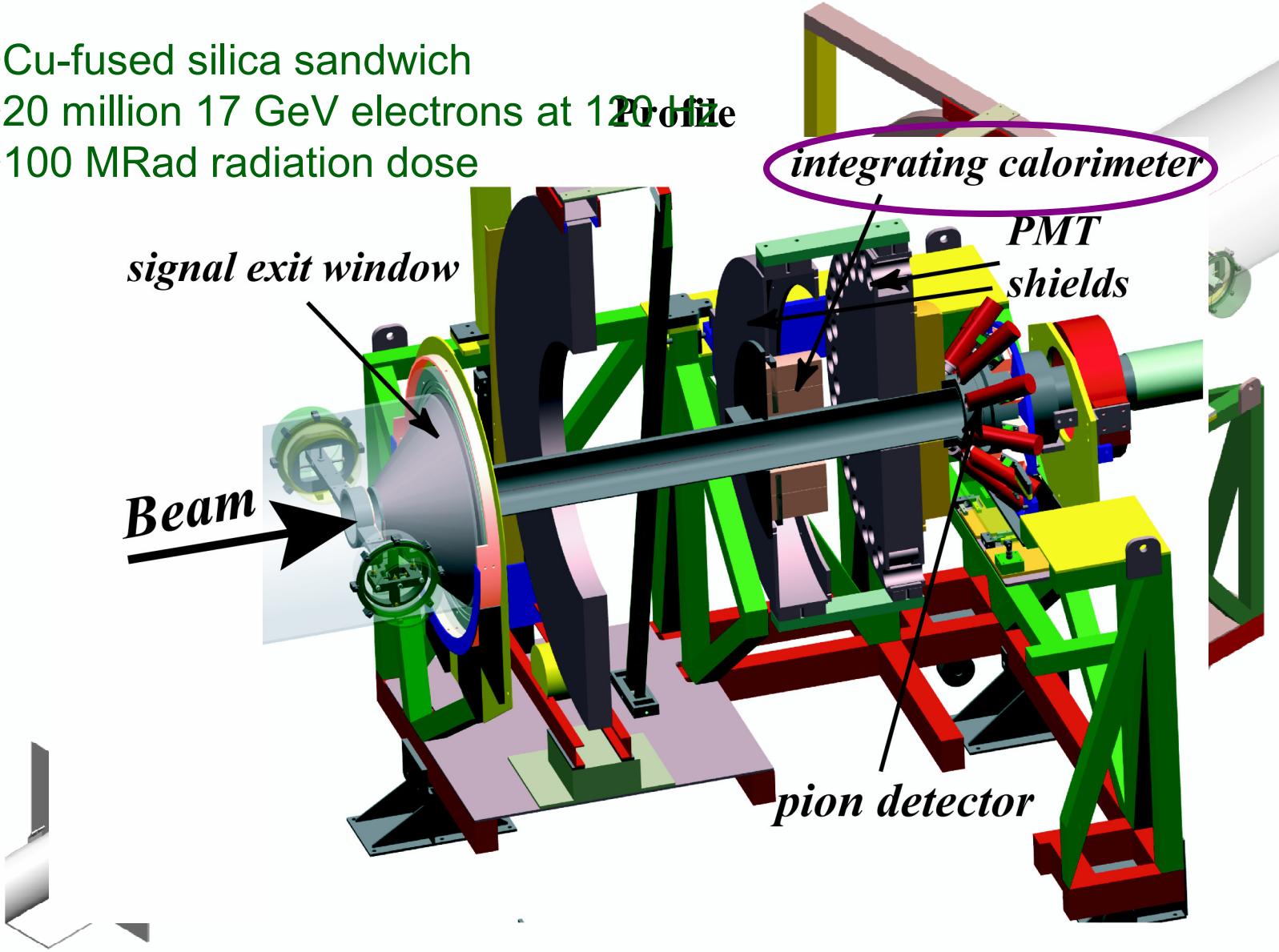
Detector Concept

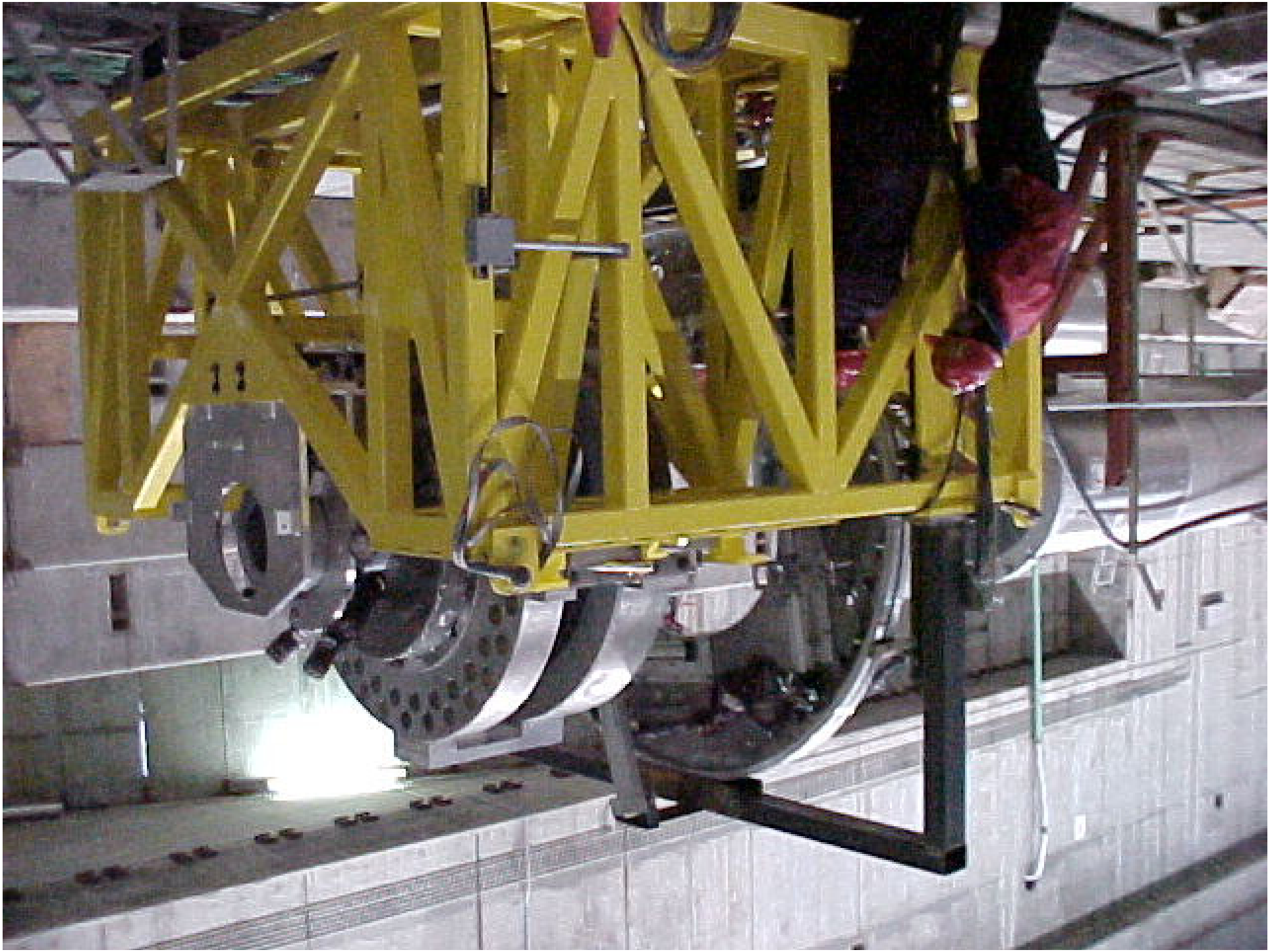


* 4 integrating detectors
* profile detectors for calibration

Detector Cart

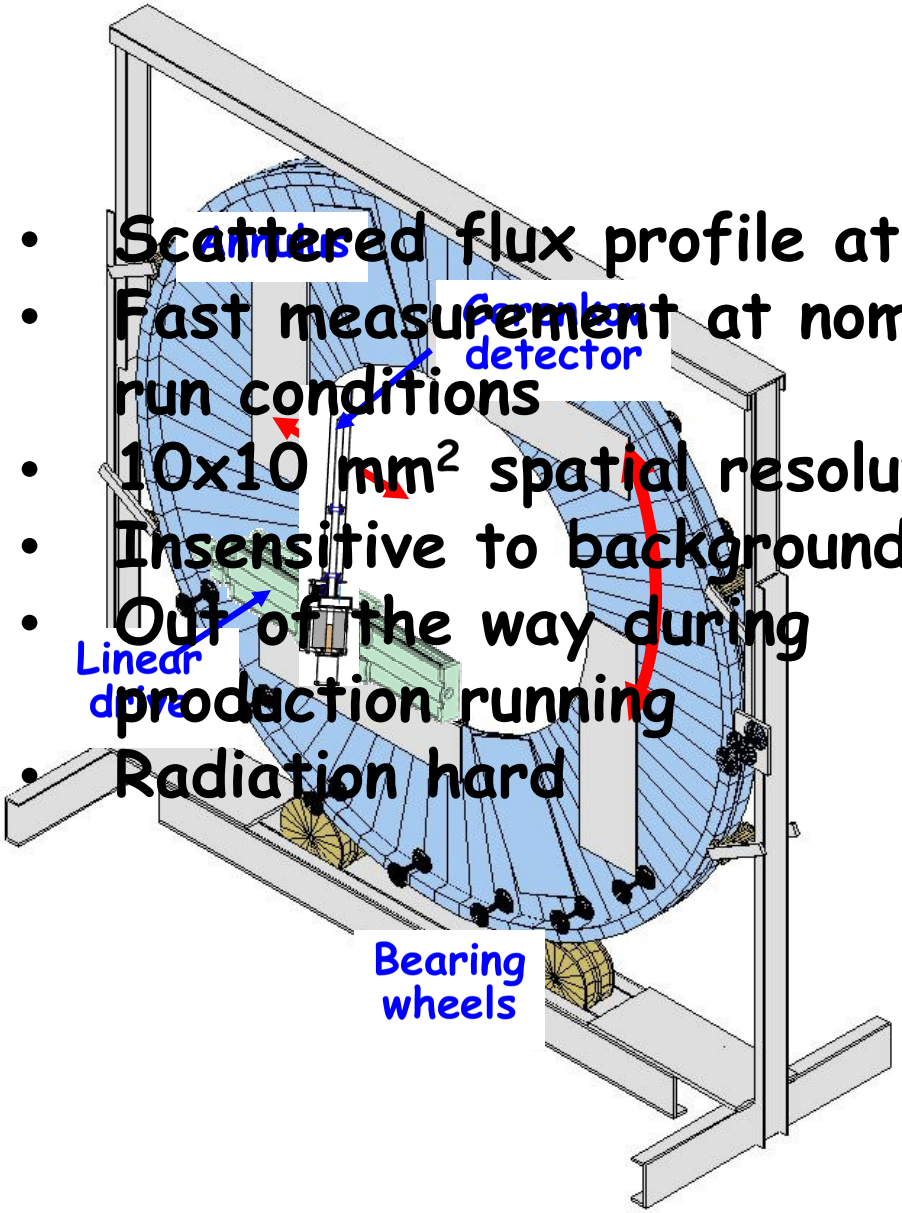
- Cu-fused silica sandwich
- 20 million 17 GeV electrons at 120 Hz
- 100 MRad radiation dose

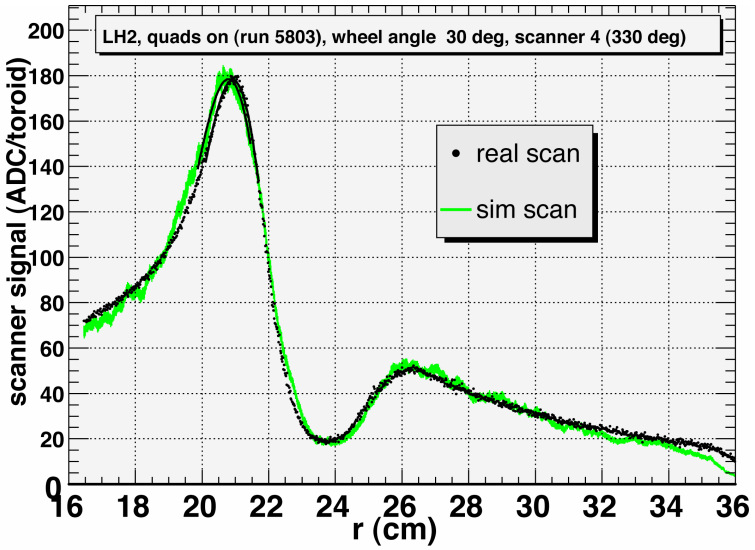


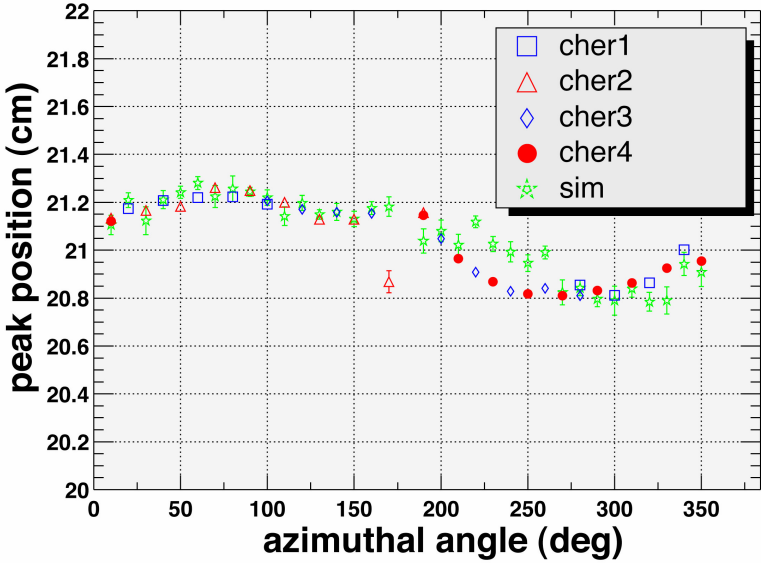


Scattered Flux Profile

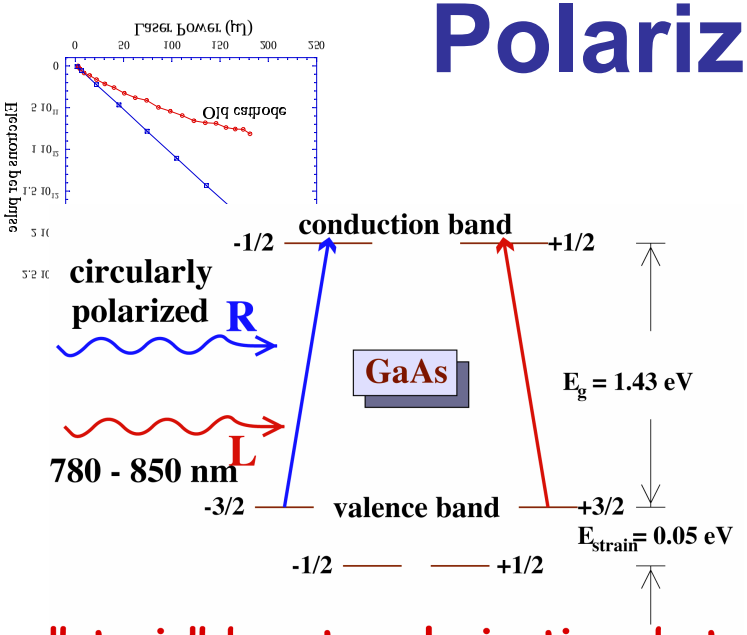
- Scattered flux profile at all Ø
- Fast measurement at nominal run conditions
- 10x10 mm^2 spatial resolution
- Insensitive to backgrounds
- Out of the way during production running
- Radiation hard



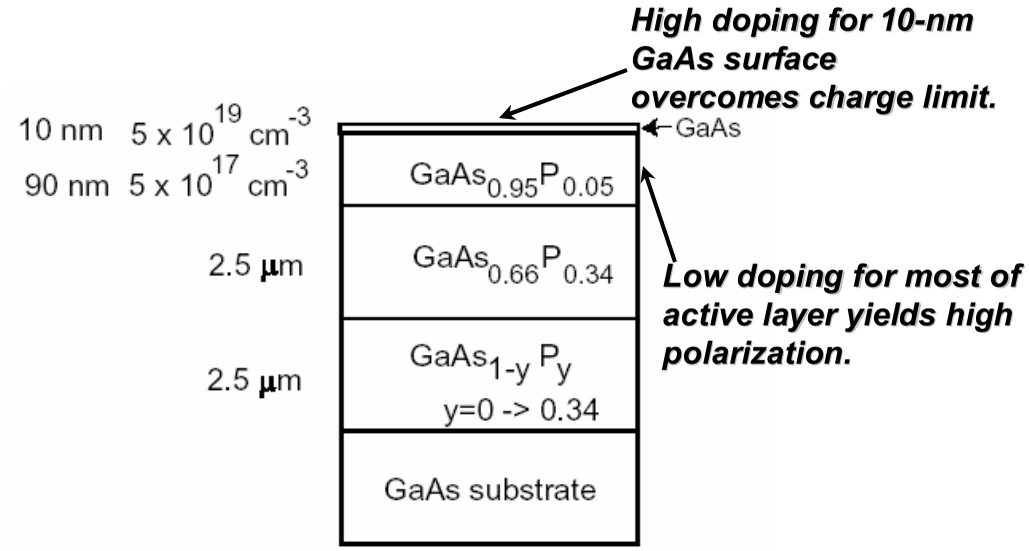




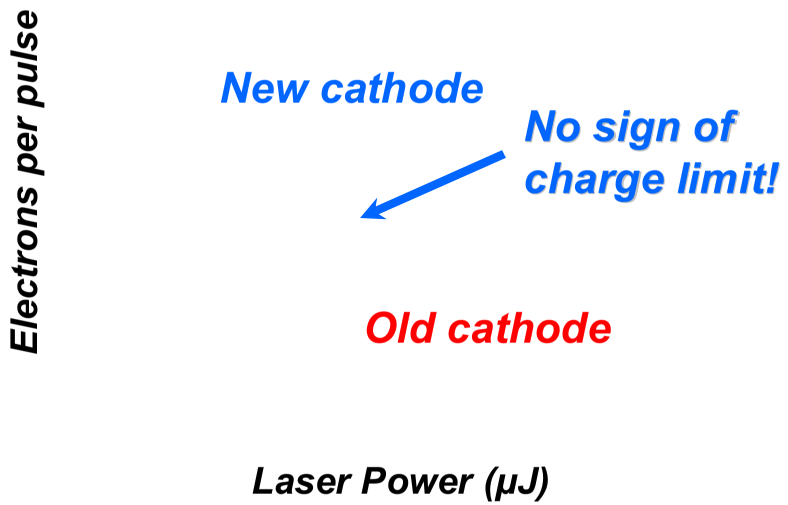
Polarized Photocathode



"strain" boosts polarization, but introduces anisotropy in response



Parameter	E158	NLC-500
Charge/Train	6 x 10^{11}	14.3 x 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%

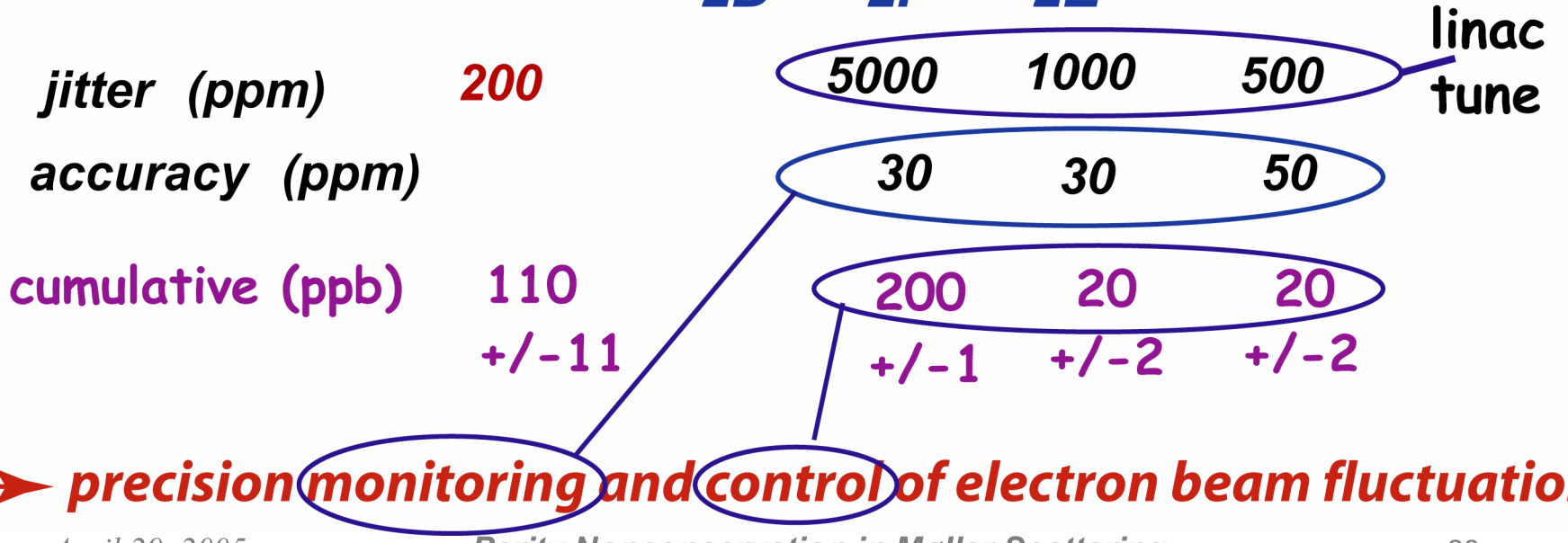


Systematic Control (II)

Detector D, Current I: F = D/I

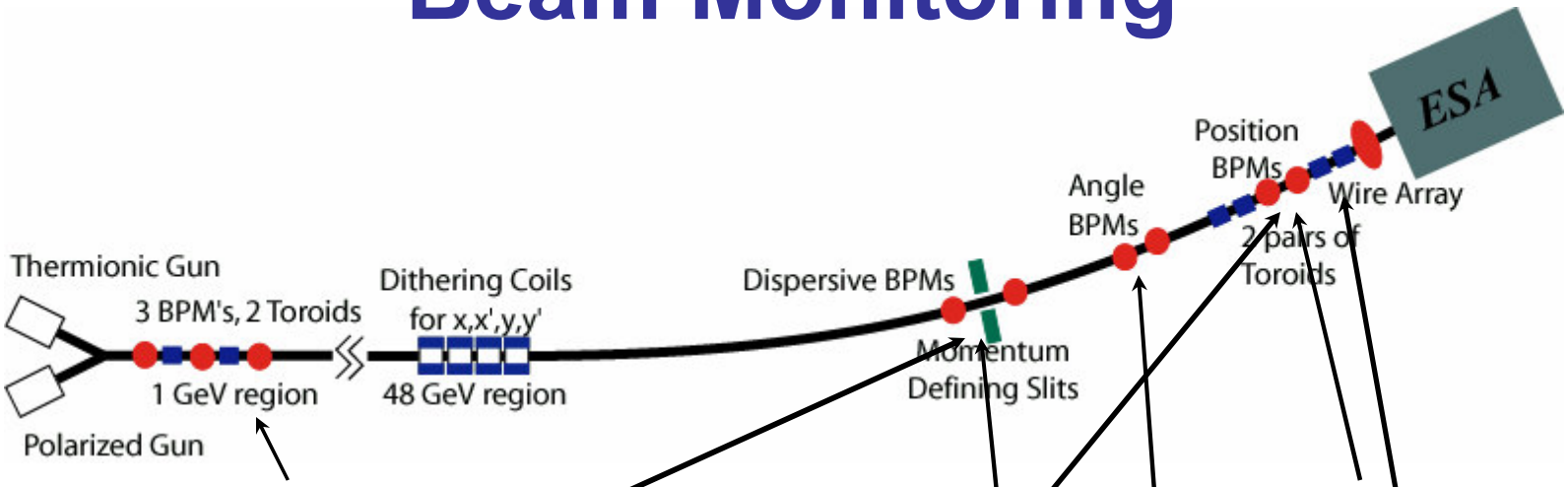
$$A_{pair} = \frac{F_R - F_L}{F_R + F_L} = \frac{\Delta F}{2F} + \textit{fluctuations}$$

$$A_{pair} \cong \frac{\Delta D}{2D} - \frac{\Delta I}{2I} + \frac{\Delta E}{2E} + \alpha_i \Delta X_i$$



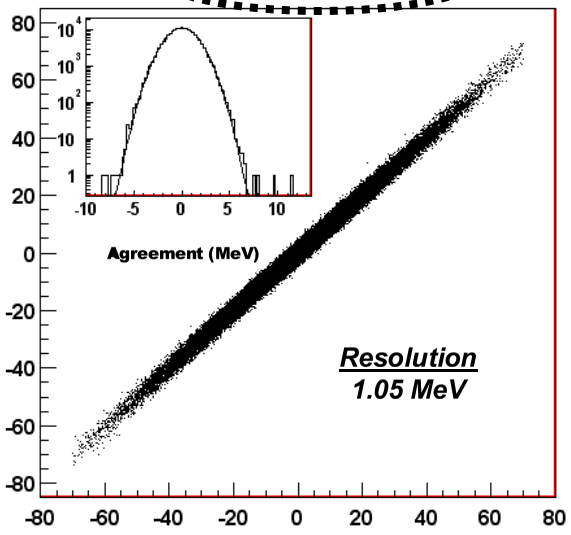
precision monitoring and control of electron beam fluctuations

Beam Monitoring

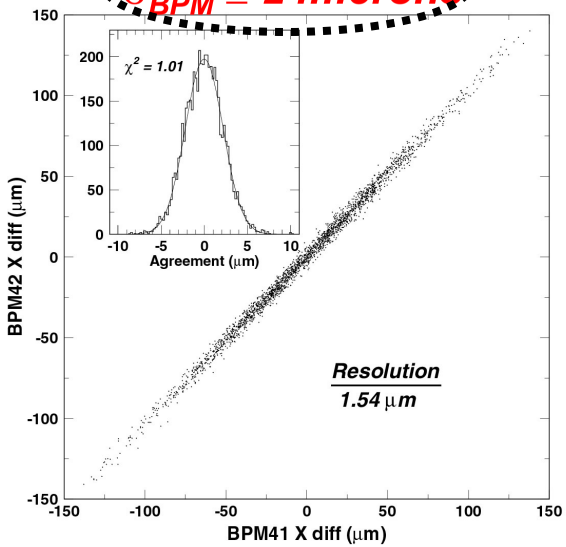


Pulse by pulse monitoring at 1 GeV and 45 GeV

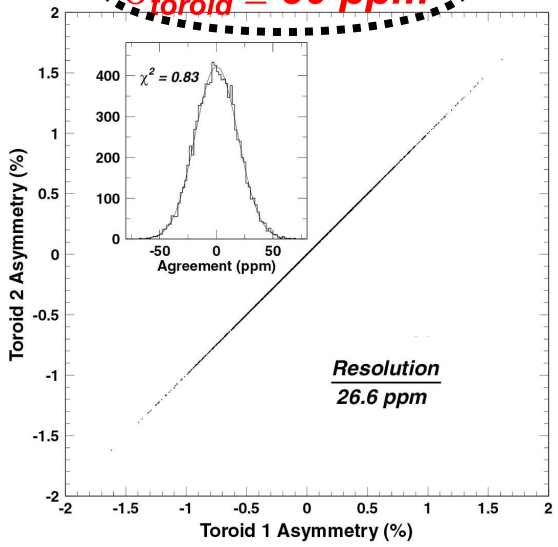
$\sigma_{energy} \leq 1$ MeV



$\sigma_{BPM} \leq 2$ microns

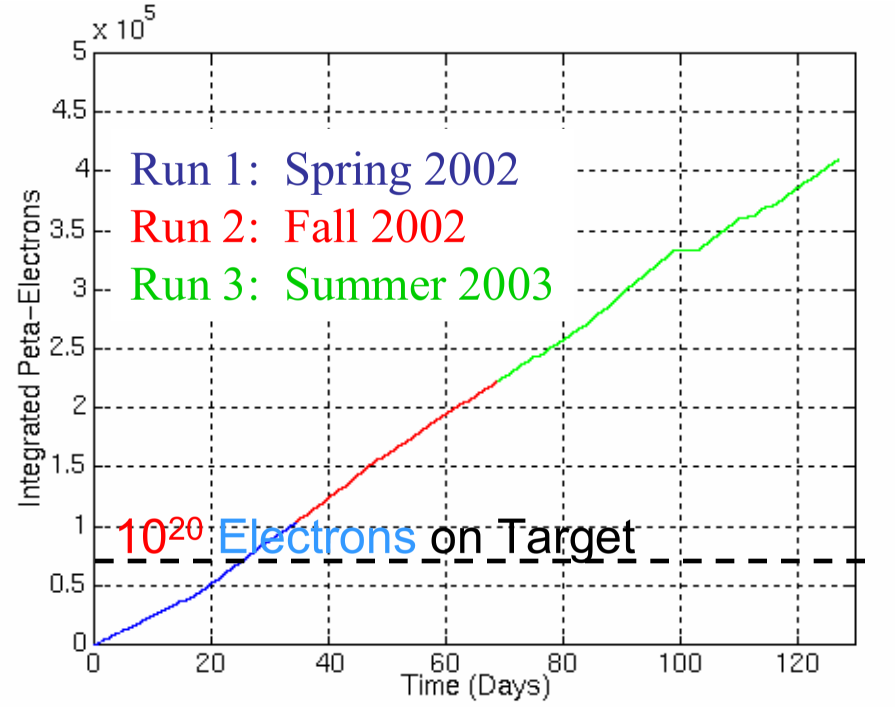


$\sigma_{toroid} \leq 30$ ppm

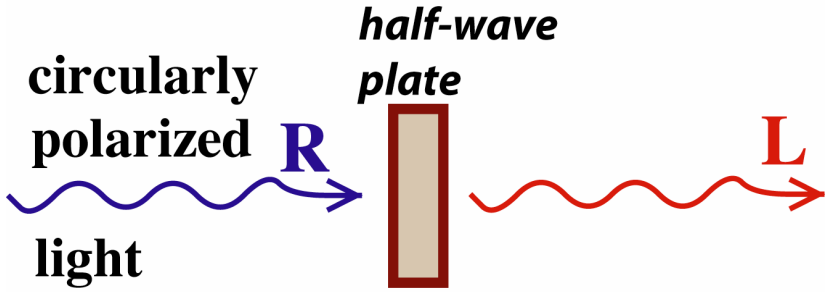


Physics Runs

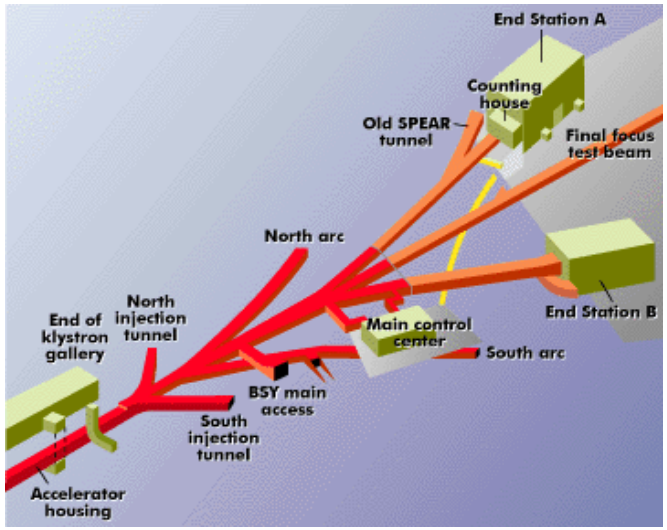
Run 1: Apr 23 12:00 – May 28 00:00, 2002
Run 2: Oct 10 08:00 – Nov 13 16:00, 2002
Run 3: July 10 08:00 - Sep 10 08:00, 2003



A_{PV} Sign Flips

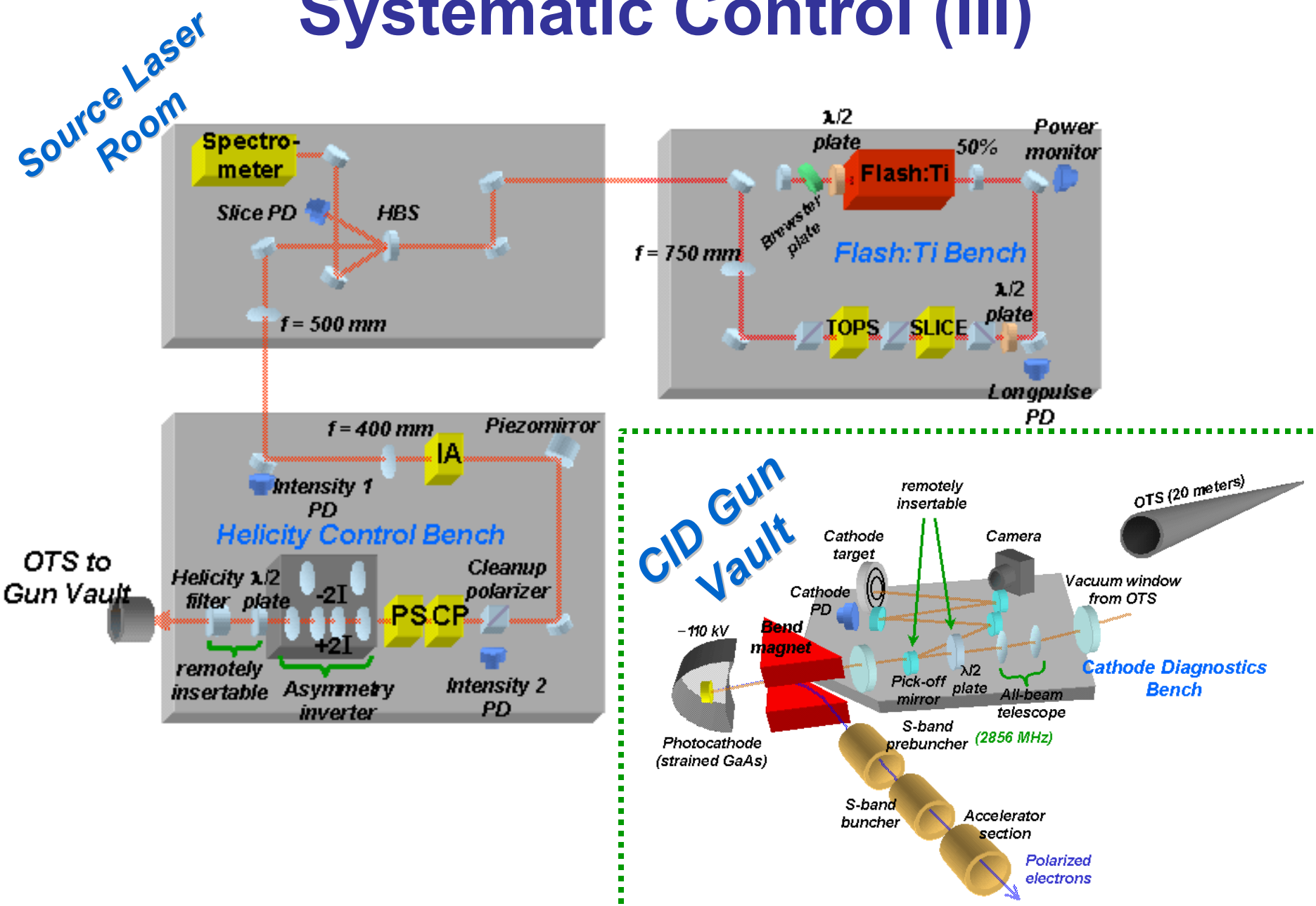


g-2 spin precession
45 GeV: 14.0 revs
48 GeV: 14.5 revs

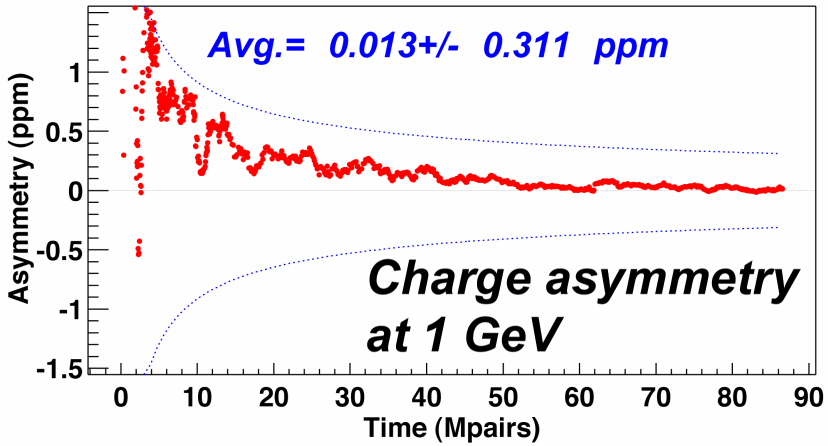


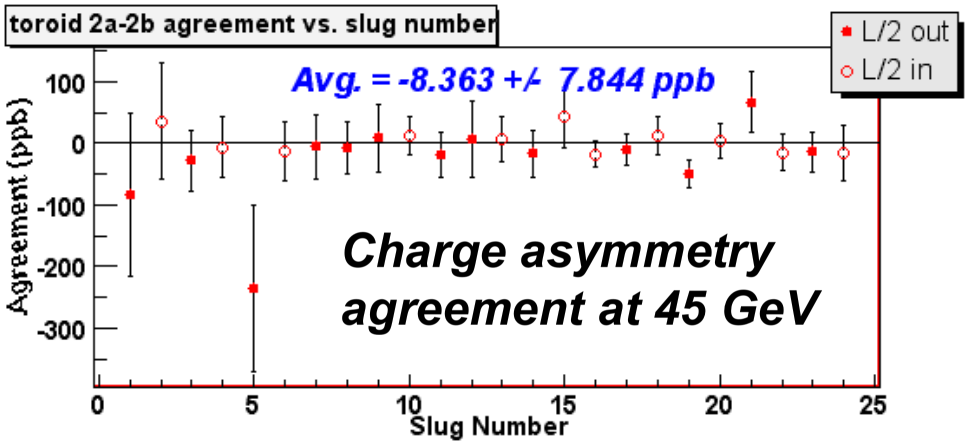
Data divided into 75 "slugs":
- Wave plate flipped ~ few hours
- Beam energy changed ~ few days

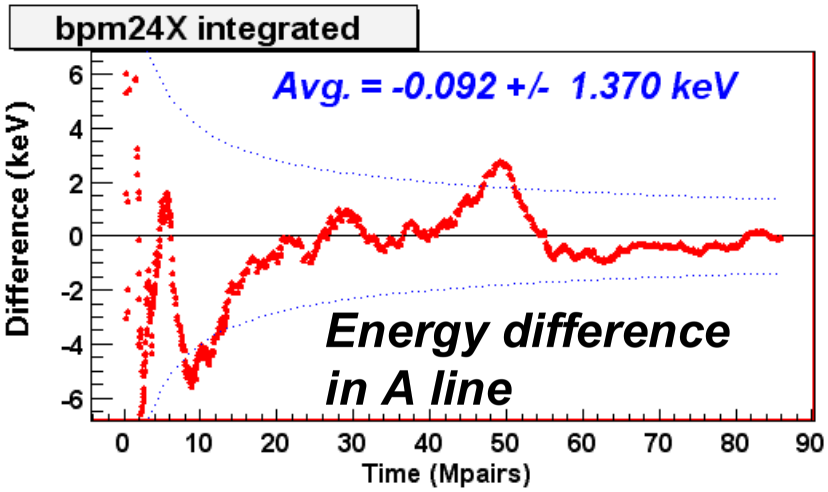
Systematic Control (III)

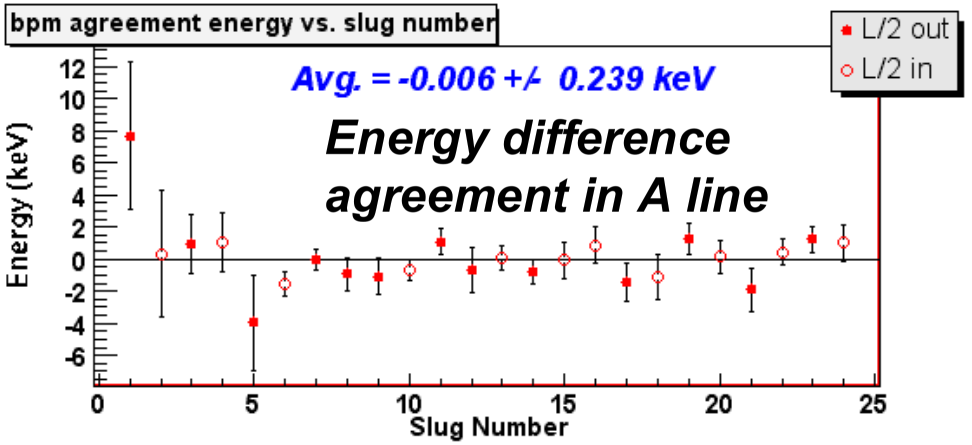


Beam Asymmetries





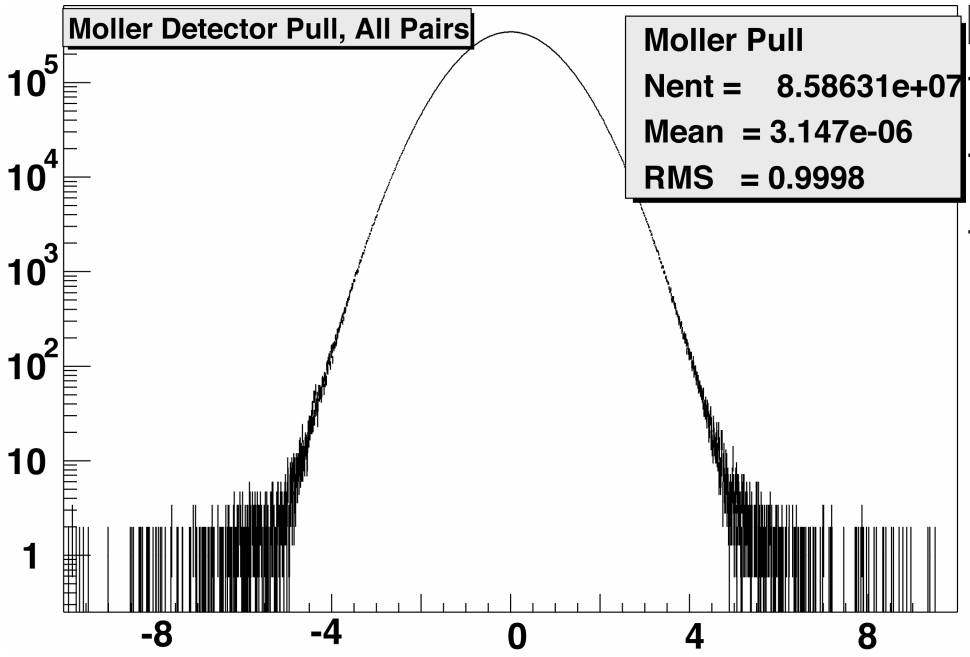


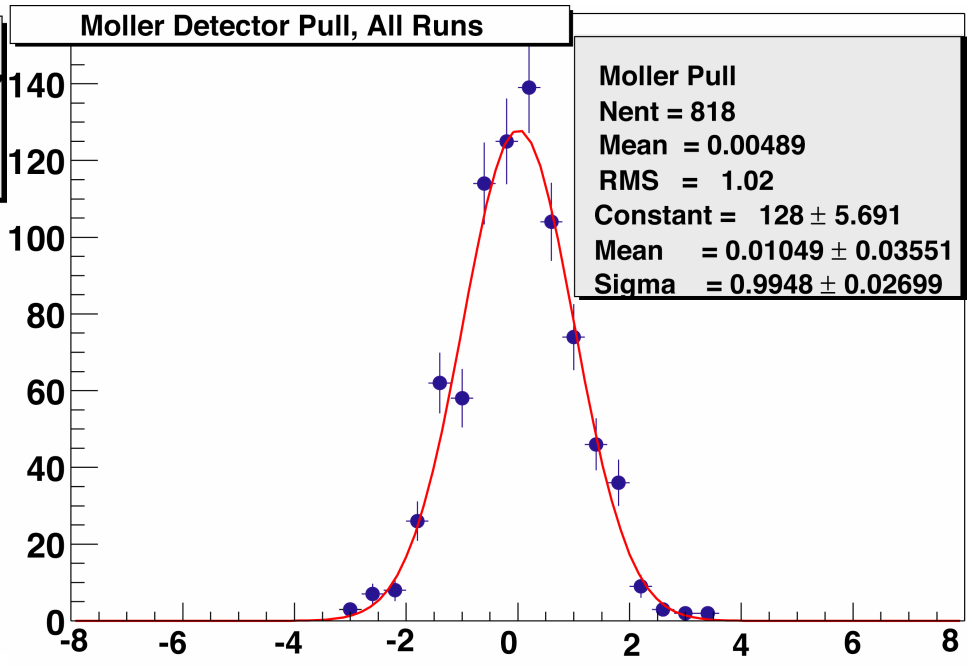


Position differences < 20 nm

Position agreement ~ 1 nm

Raw Asymmetry Statistics





$$\frac{A_i - \langle \overline{A} \rangle}{\sigma_i}$$

$\sigma_i \approx 200$ ppm

$N = 85$ Million

$$\frac{A_i - \langle \overline{A} \rangle}{\sigma_i}$$

$\sigma_i \approx 600$ ppb

$N = 818$

Backgrounds & Normalization

Integrating calorimeter:

background dilutions and asymmetries must be separately measured or bounded.

- Elastic and inelastic e-p scattering and radiative tail
- High energy pions
- High and low energy photons
- Neutrons
- Synchrotron radiation

Total dilution: 9.3% in Run I, 7.6% in Run II & III

- Beam polarization measured using polarized foil target
  - Same spectrometer used with dedicated movable detector
- Energy scale and spectrometer alignment to determine $\langle Q^2 \rangle$
- Linearity of PMTs

Largest systematic errors:

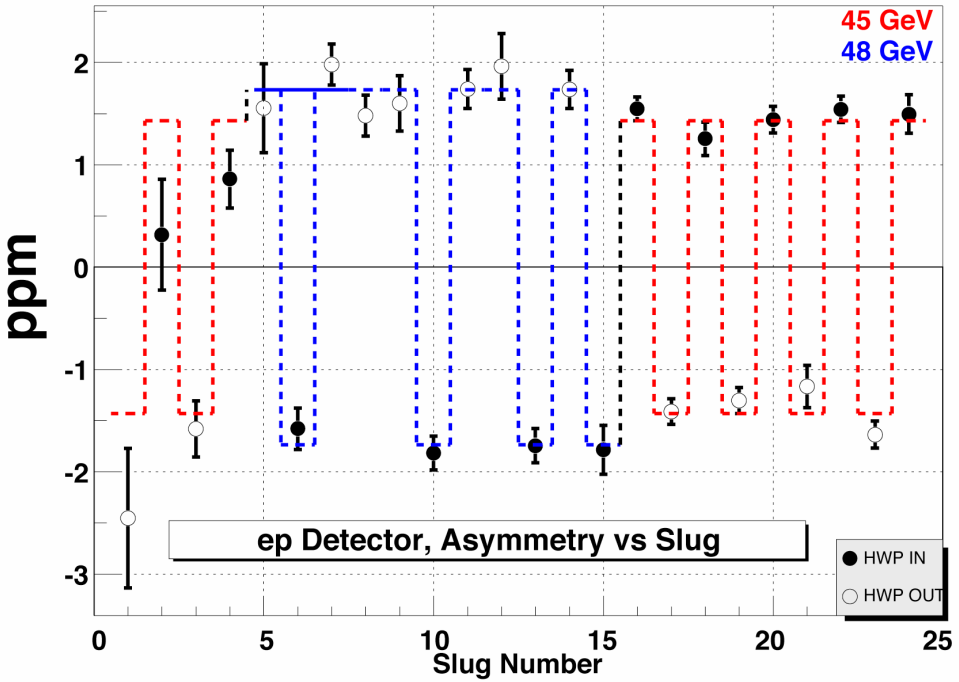
- Inelastic ep: -22 ± 4 ppb
- Beam polarization: 0.89 ± 0.04

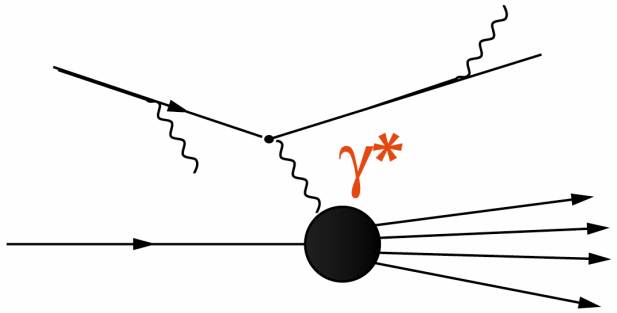
Summary of Corrections

Correction	f_{bkg}	$\sigma(f_{bkg})$	A_{corr} (ppb)	$\sigma(A_{corr})$ (ppb)
Beam first order	-	-	-10	1
Beam higher orders	-	-	0	3
Beam spotsize	-	-	0	1
Transverse asymmetry	-	-	-4	2
High energy photons	0.004	0.002	3	3
Synchrotron photons	0.002	0.001	0	1
Neutrons	0.003	0.001	-1	1
ep elastic	0.056	0.007	-7	1
ep inelastic	0.009	0.001	-22	4
Pions	0.001	0.001	1	1
TOTAL	0.075	0.008	-40	6

- Scale factors:
  - Average Polarization 89 ± 4% ⇦ New "NLC" cathode !
  - Linearity 99 ± 1%
  - Radiative corrections: 1.01 ± 0.01

“ep” Detector Data



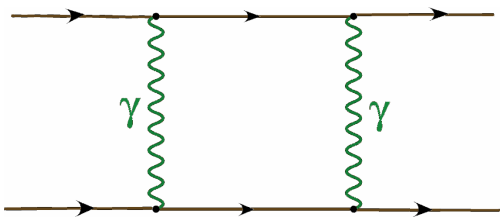


inelastic scattering

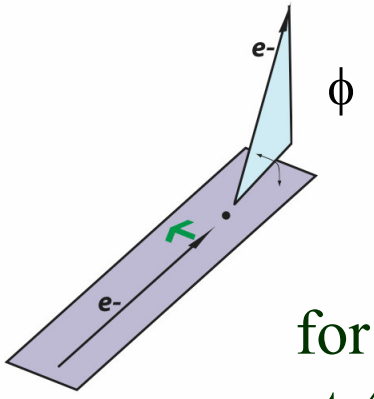
At low Q^2 : $A_{LR} \sim 10^{-4} * Q^2$

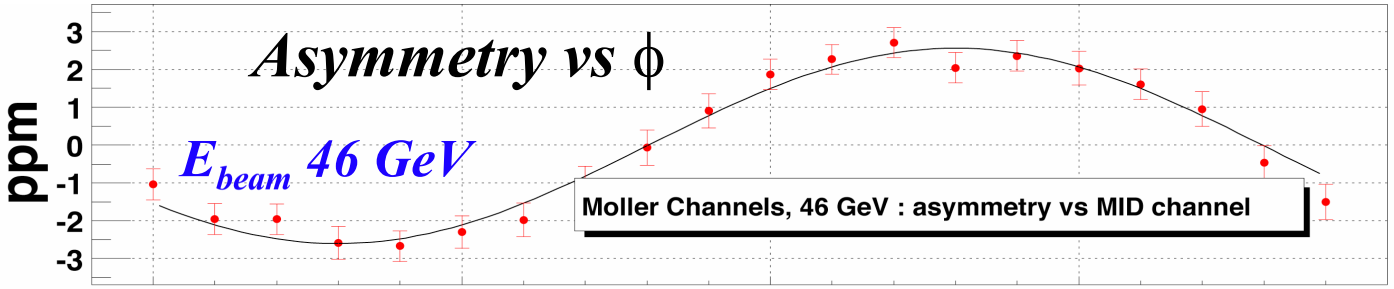
- *Radiative tail of elastic ep scattering is dominant background*
- *8% under Moller peak*
- *Additional 1% from inelastic e-p scattering*
- *Coupling is large: similar to 3 incoherent quarks: $0.8 \times 10^{-4} \times Q^2$*
- *Background reduced in Run II & III with additional collimation*

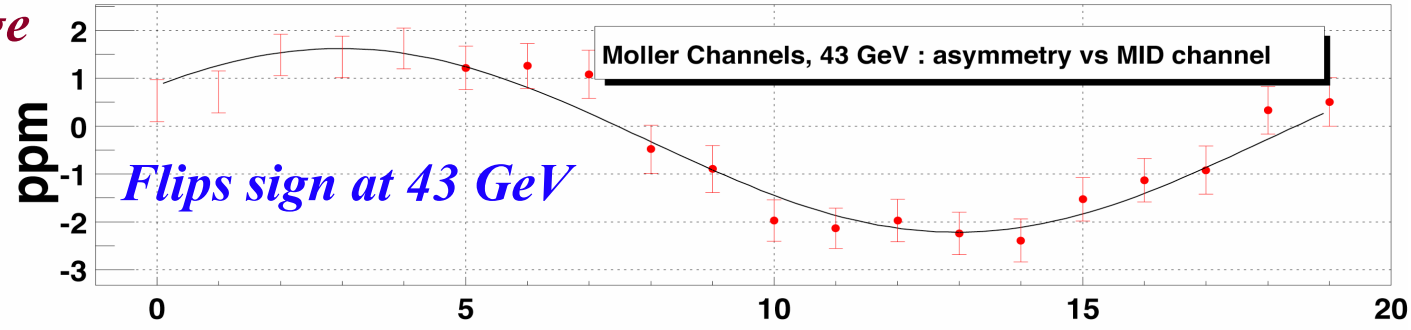
Transverse Asymmetry



Two-photon exchange
QED effect







for Møller scattering at 46 GeV

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

$$A_T \propto \frac{\alpha m_e}{\sqrt{s}} = -3.5 \text{ ppm} \bullet \sin\phi$$

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 (2004)**

SUSY and Q^e_W, Q^p_W

SUSY effects in "oblique" corrections highly suppressed:

No "electroweak nondecoupling"

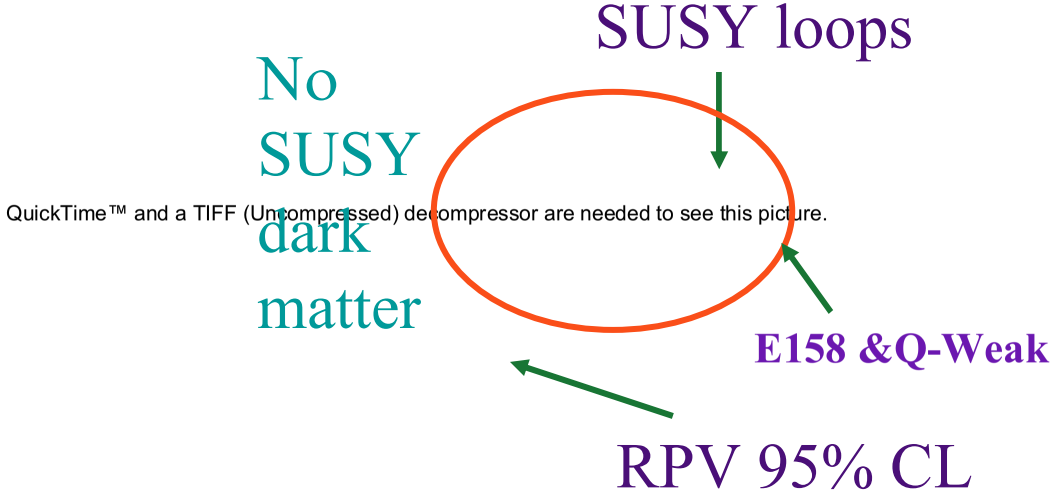
SUSY provides a potential dark matter candidate

$\tilde{\chi}^0$

- Stable, lightest SUSY particle if baryon (B) and lepton (L) numbers are conserved
- However, B and L need not be conserved in SUSY, leading to neutralino decay (RPV)

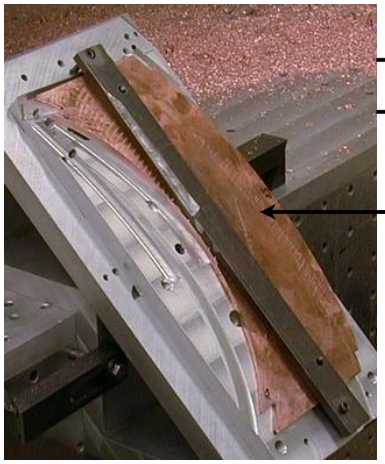
Q^e_W and Q^p_W would have new contributions from RPV

Kurylov, Ramsey-Musolf, Su

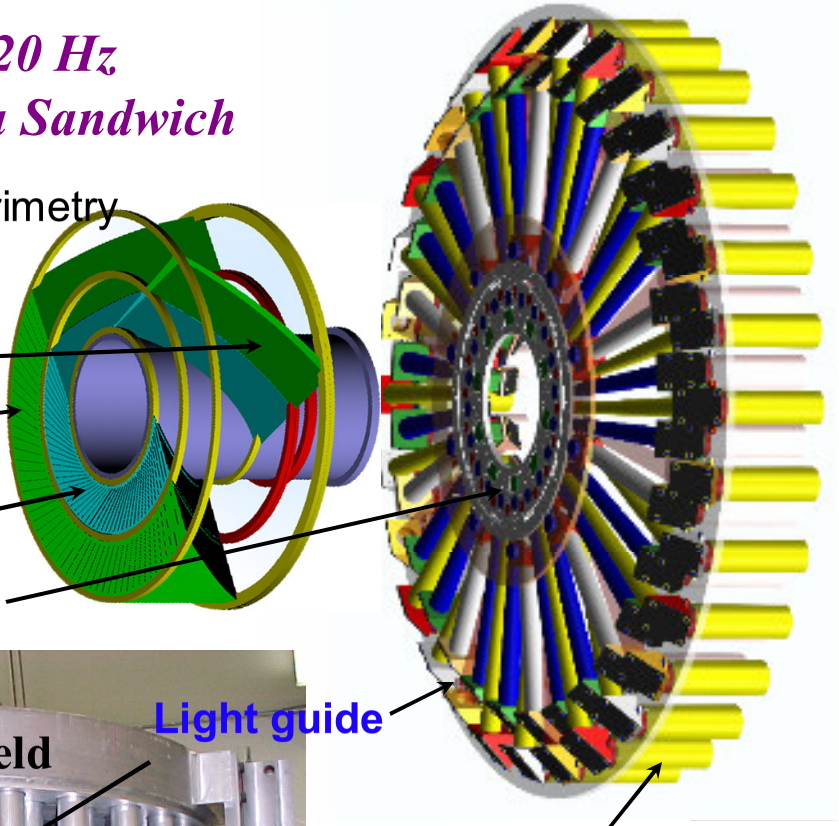


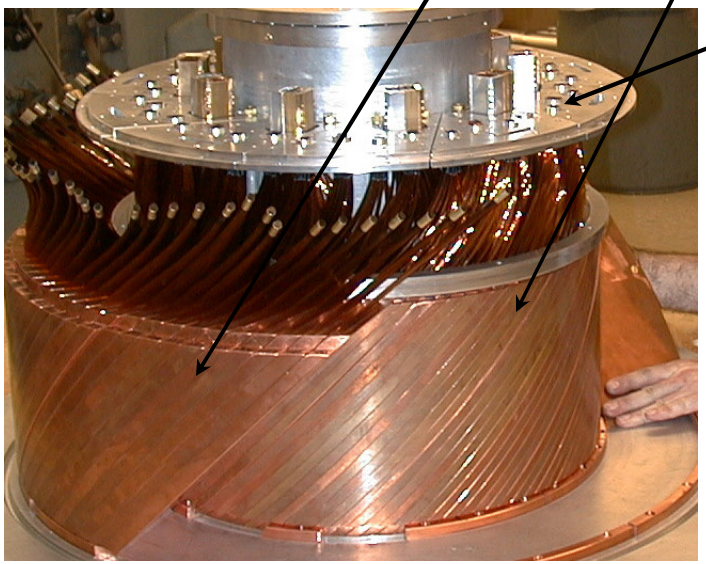
Integrating Calorimeter

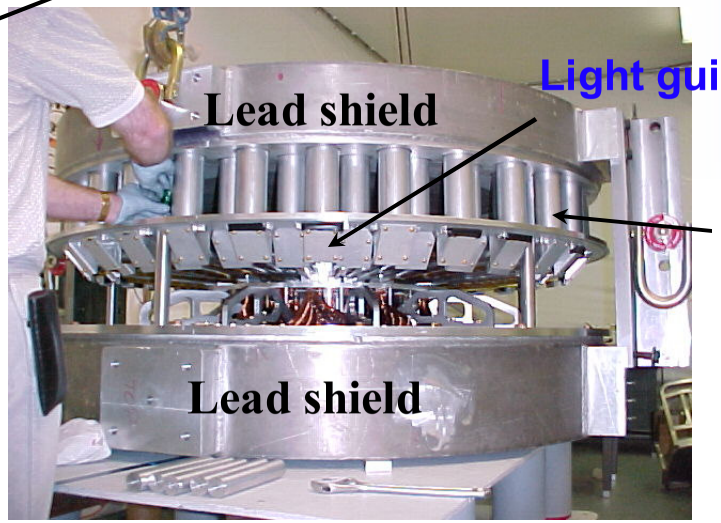
- *20 million 17 GeV electrons per pulse at 120 Hz*
- *100 MRad radiation dose: Cu/Fused Silica Sandwich*



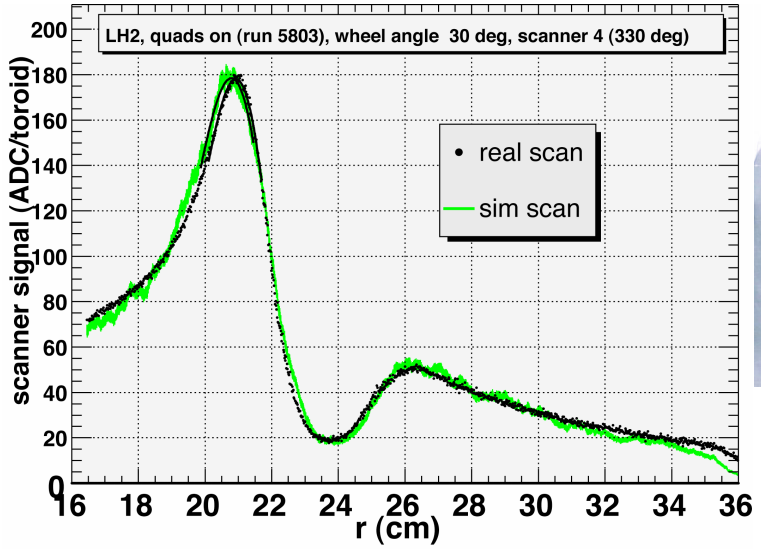
-State of the art in ultra-high flux calorimetry
-Challenging cylindrical geometry

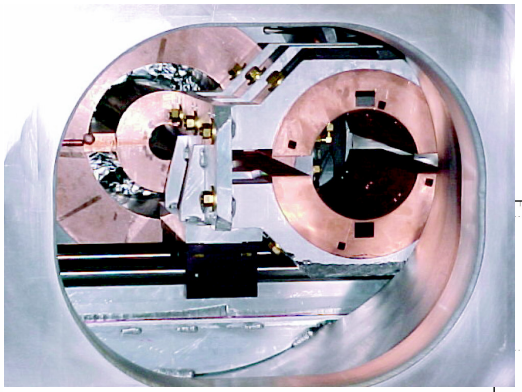


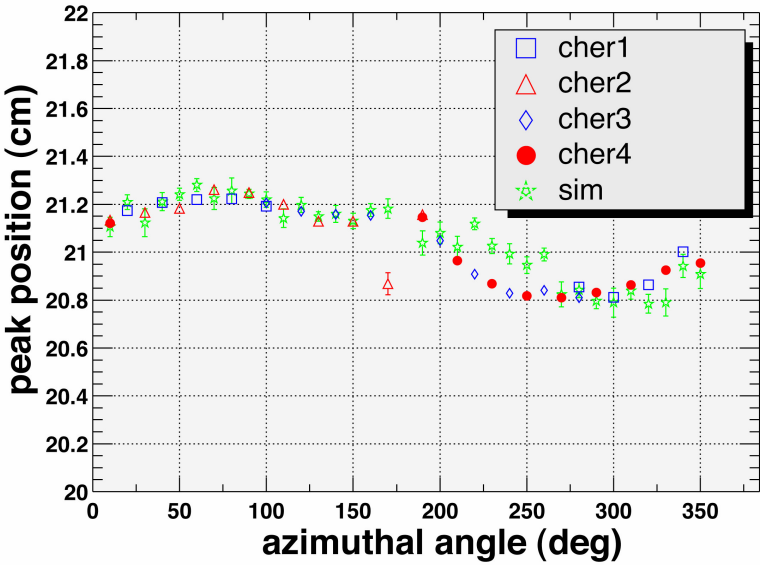




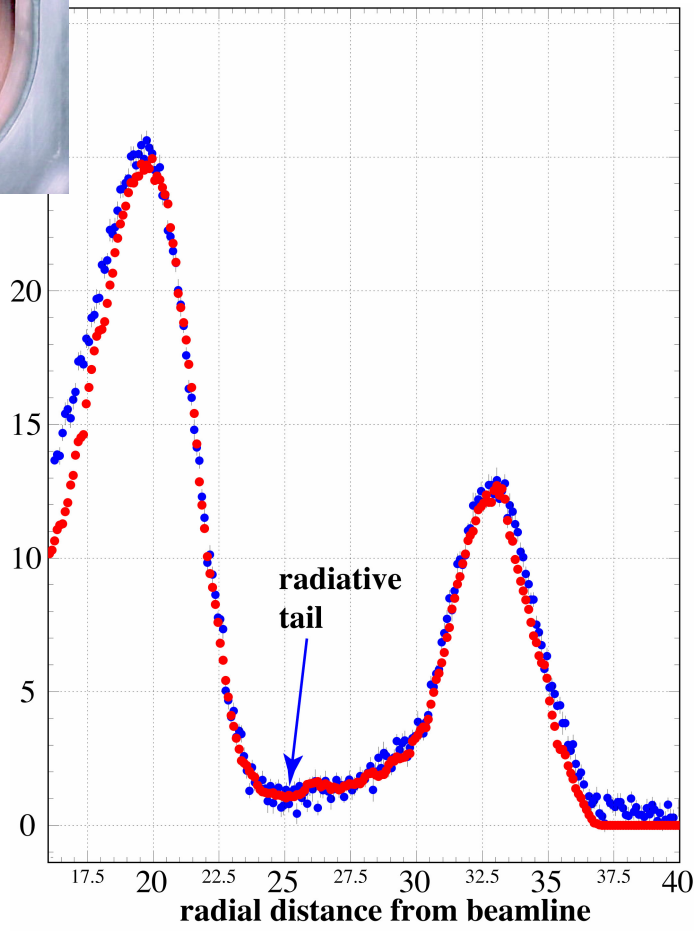
Scattered Flux Profile



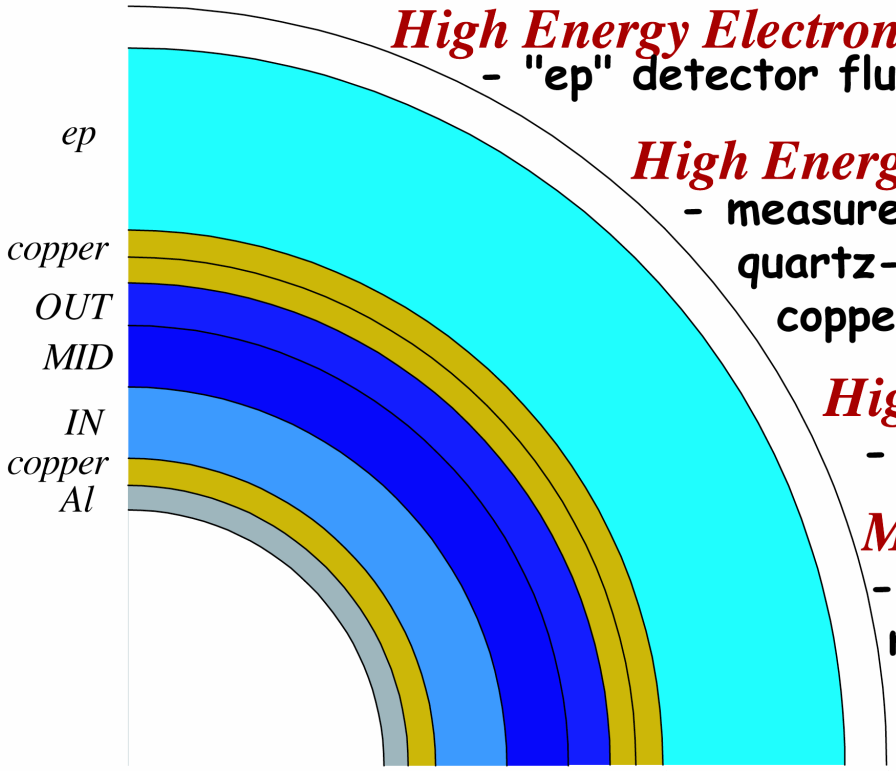




- *~ 2 mm geometry*
- *1% energy scale*
- *Radiative tail*
- *< 1% background*



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

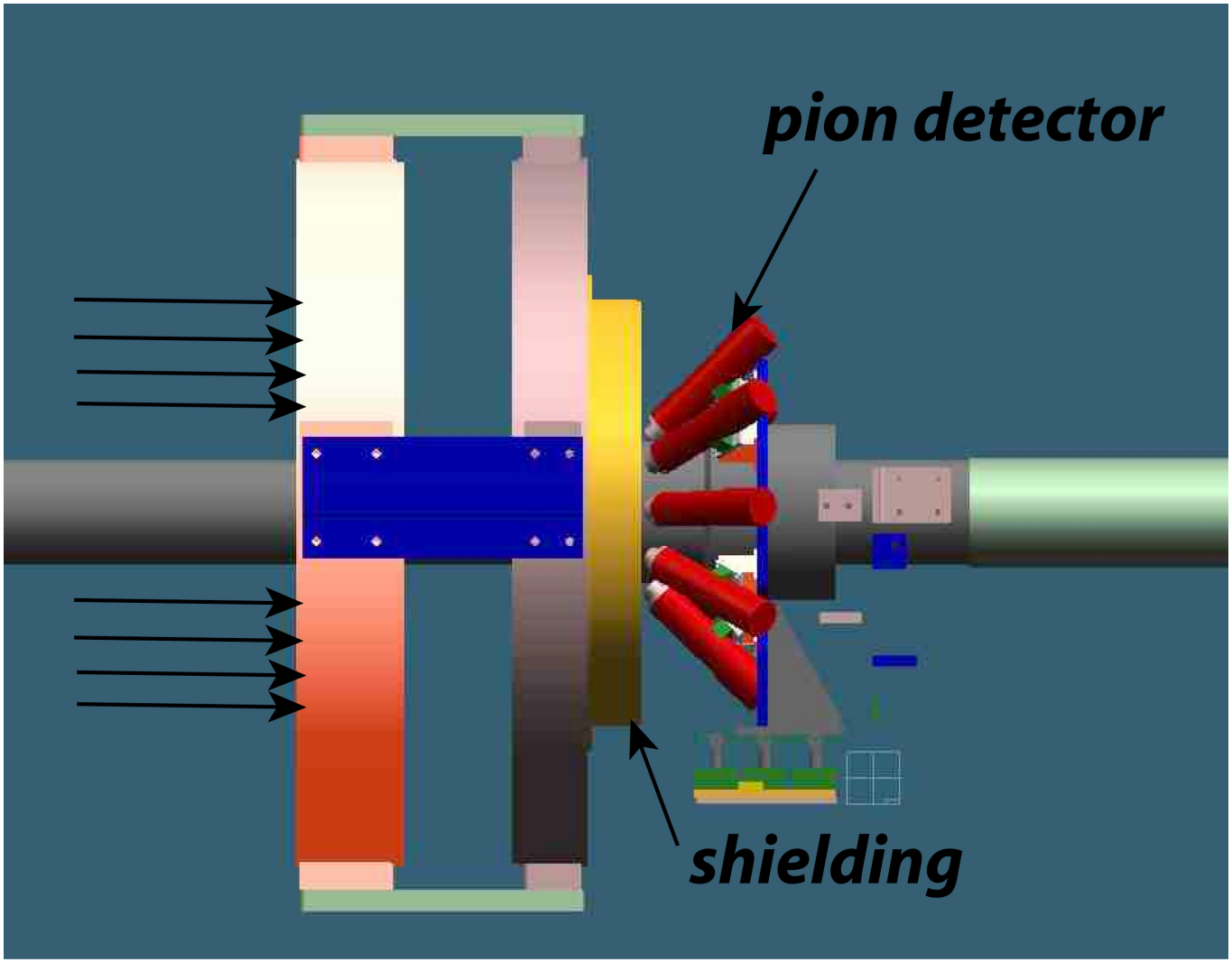
Multibounce Photons:
- Quads off/on data with main detector & profile detector

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

Pion Detector



- *~ 0.5 % pion flux*
- *~ 1 ppm asymmetry*
- *< 5 ppb correction*

SLICES: Temporal Beam Profile

- SLICES readout in 10 bit ADCs

  Q : bpm31Q (4)

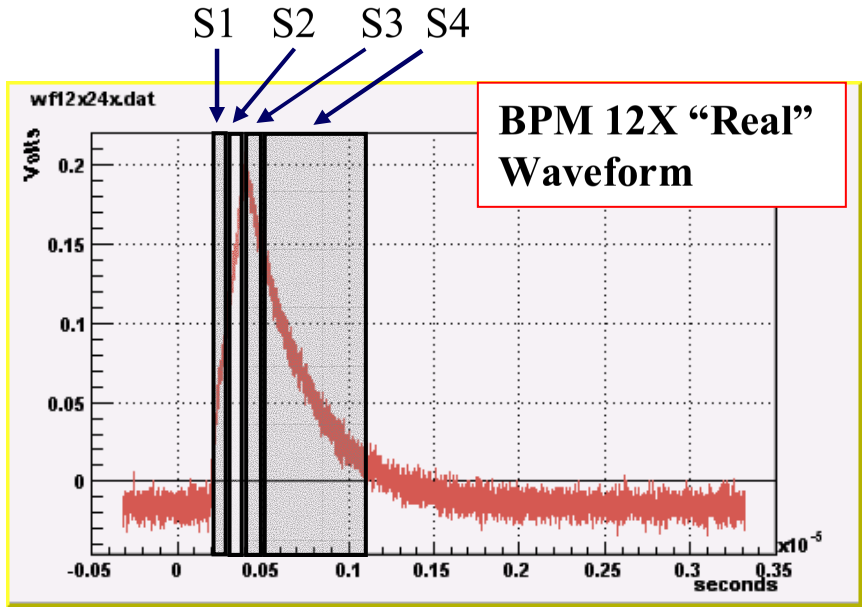
  E : bpm12X (3)

  X : bpm41X (4)

  Y : bpm41Y (4)

  dX : bpm31X (4)

  dY : bpm31Y (4)



Integration time :

S1 : 0 -100 ns

S2 : 100-200 ns

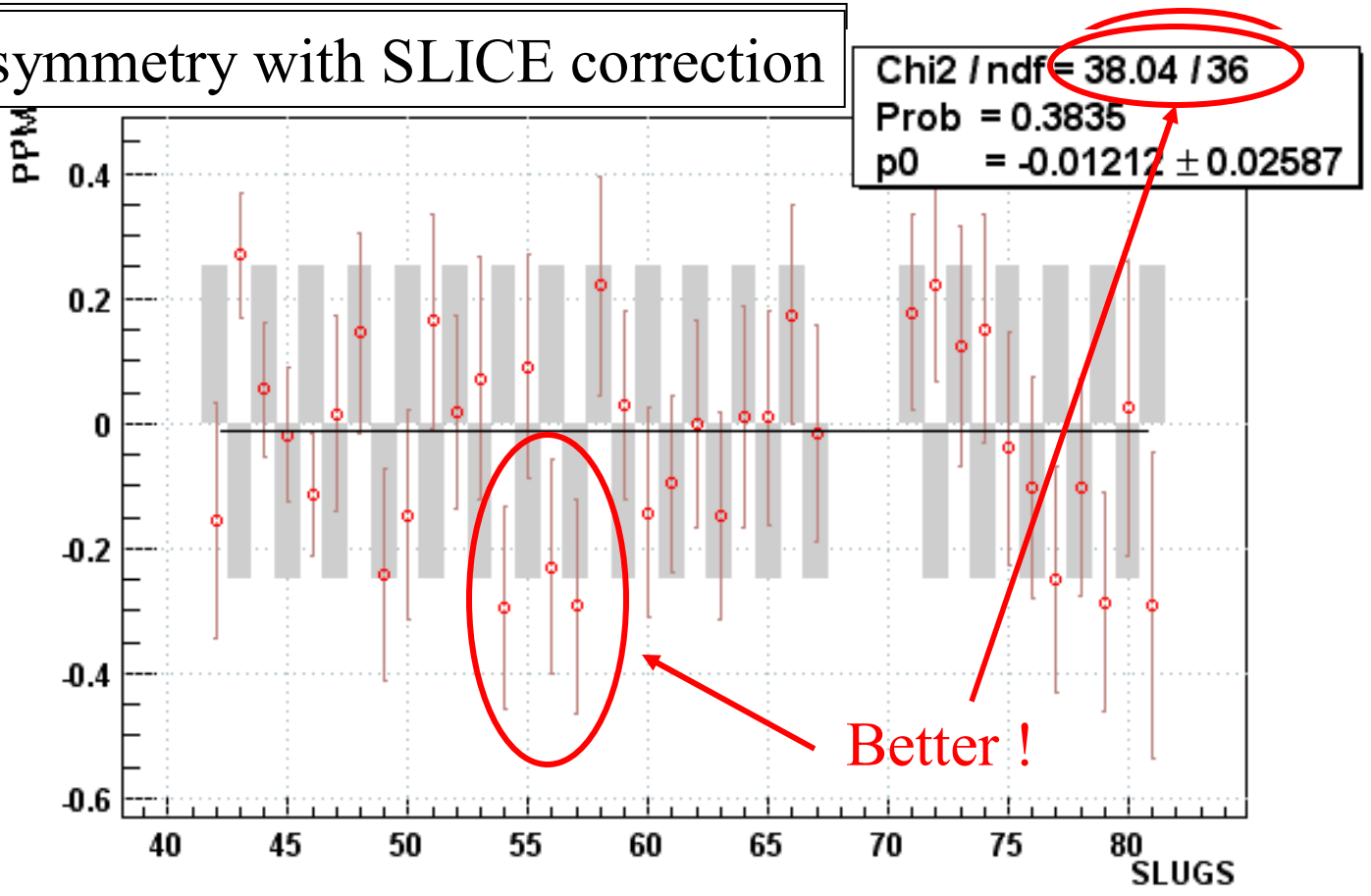
S3 : 200-300 ns

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



EP Sample: Summary

Preliminary (raw asymmetries)

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

Ratio of asymmetries:

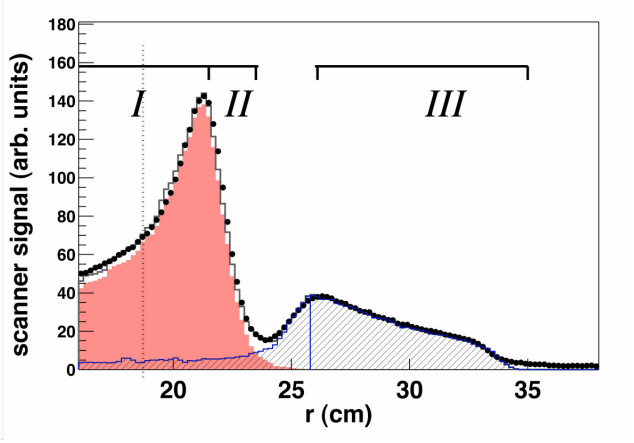
$A_{PV}(48\ GeV) / A_{PV}(45\ GeV) = 1.25 \pm 0.08\ (stat) \pm 0.03\ (syst)$

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

☞ 35±10 ppb correction to Møller asymmetry in Run I, below 20 ppb for Run II

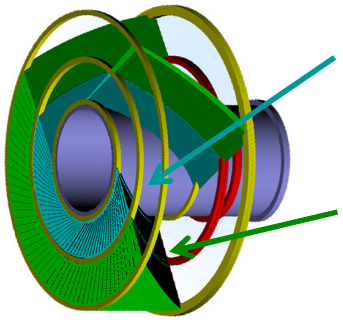
✓ Test of strong interactions in E158 ?

A_T^{ep} at E158



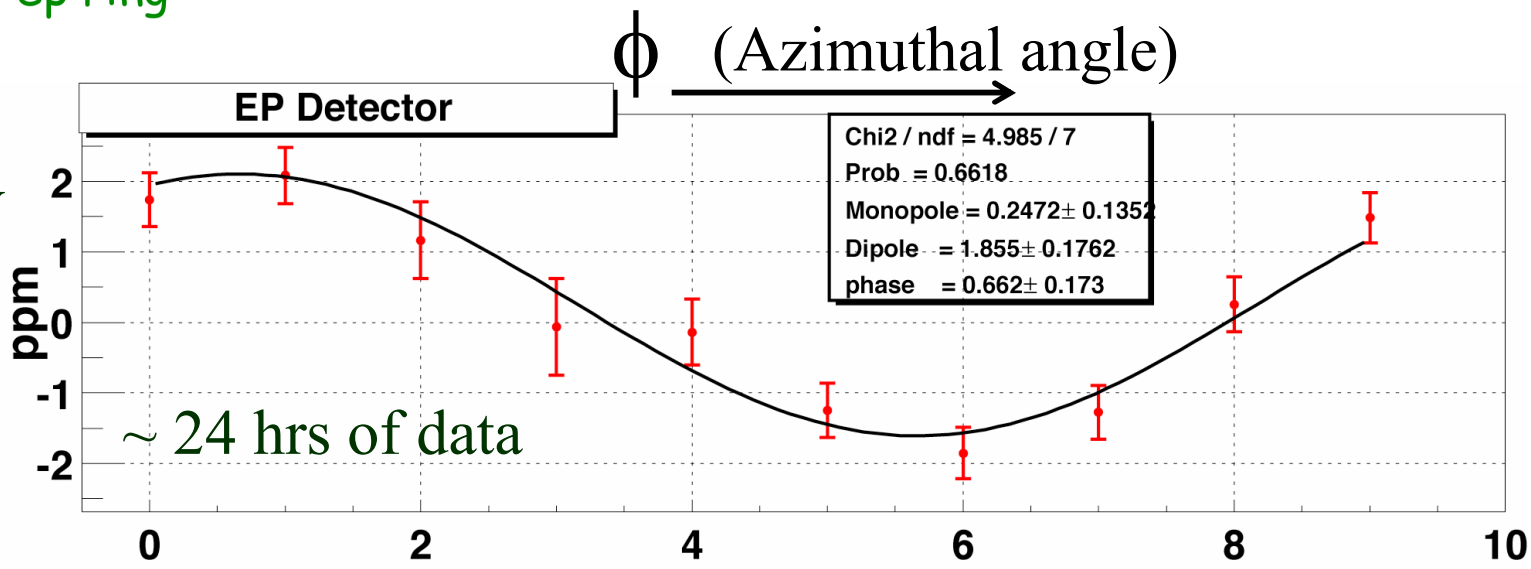
- Raw asymmetry!
- Has the opposite sign! (preliminary)
- Polarization & background corrections
- ~ 25% inelastic ep
- Few percent pions (asymmetry small)

✓ Proton structure at E158 !



43 & 46 GeV

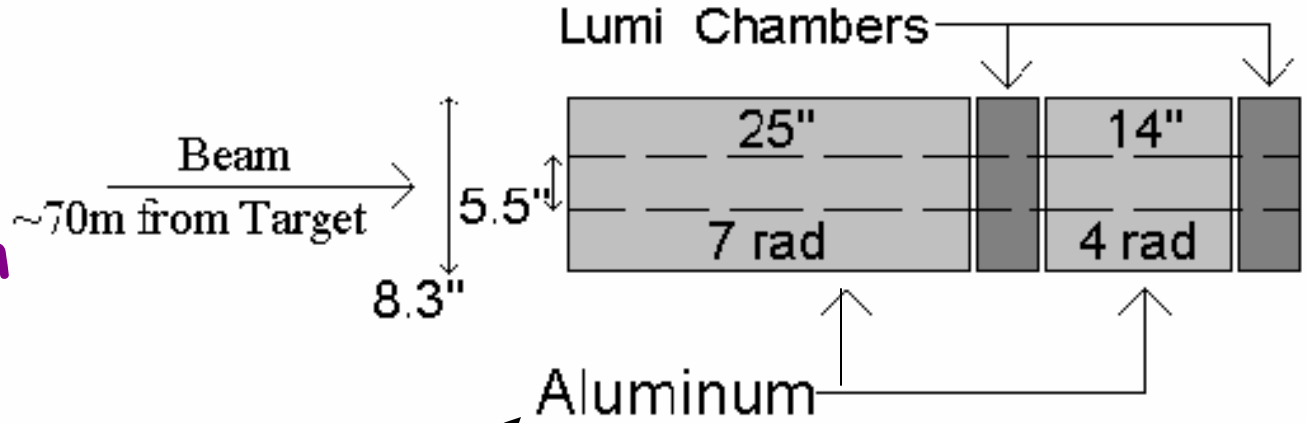
ep → ep

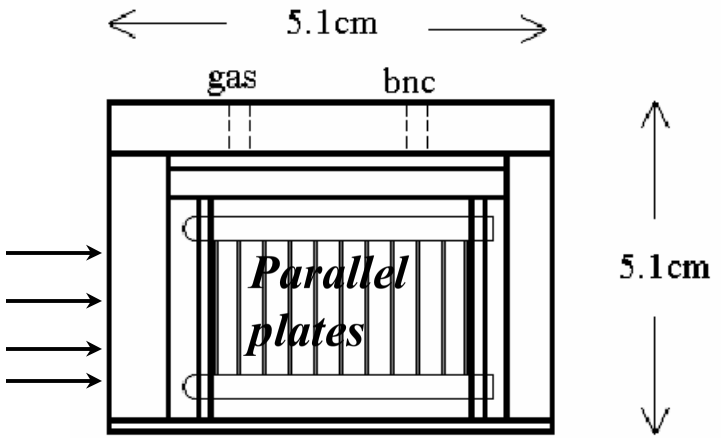


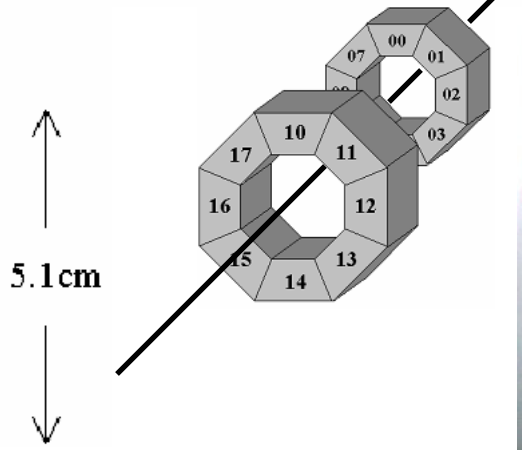
Luminosity Monitor

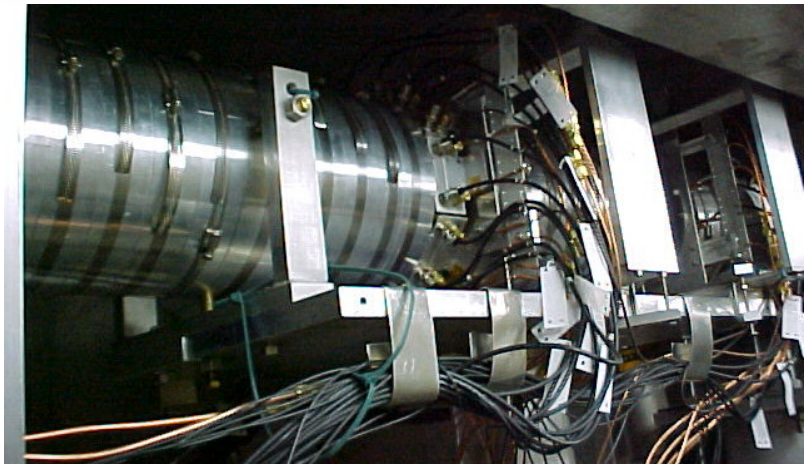
more than 10^8 scattered electrons per spill at $\theta_{lab} \sim 1$ mrad

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



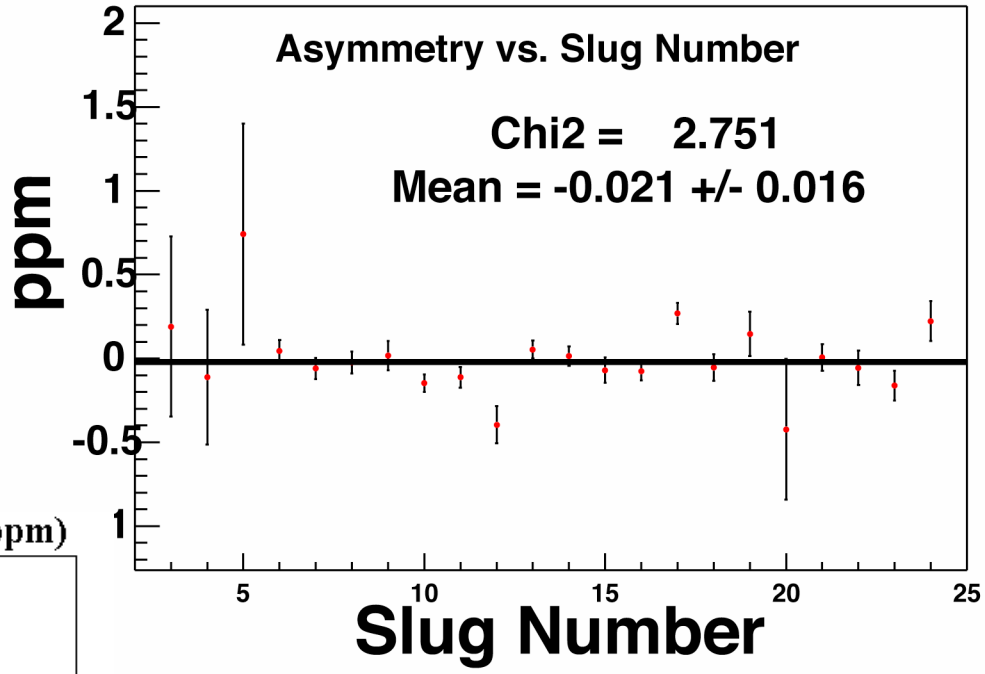


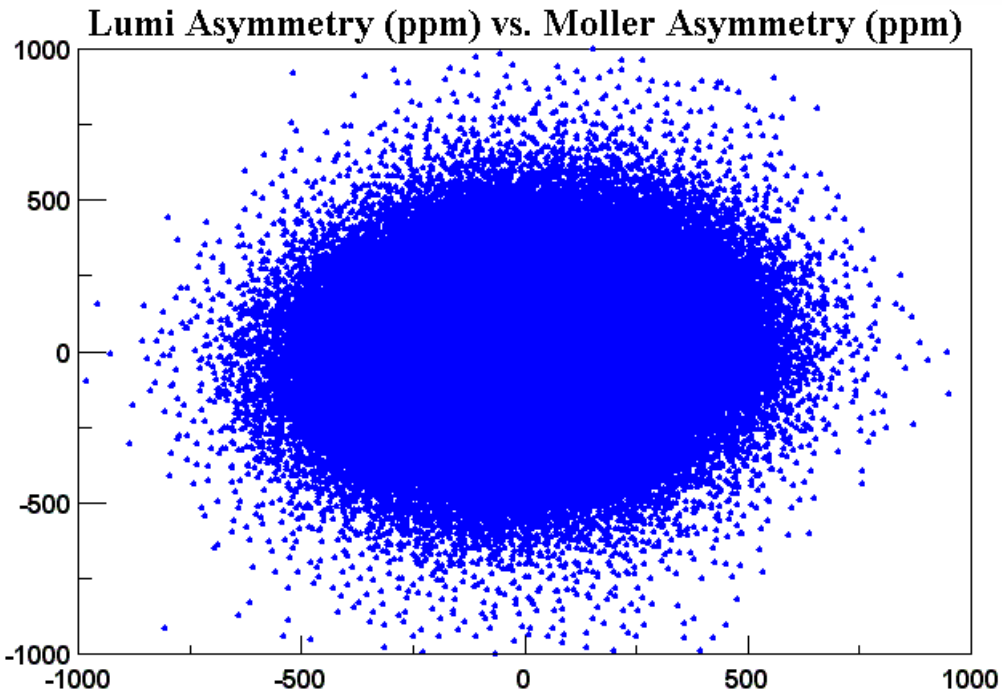




Luminosity Monitor Data

- Null test at level of 20 ppb





- Density fluctuations small
- Limits on second order effects