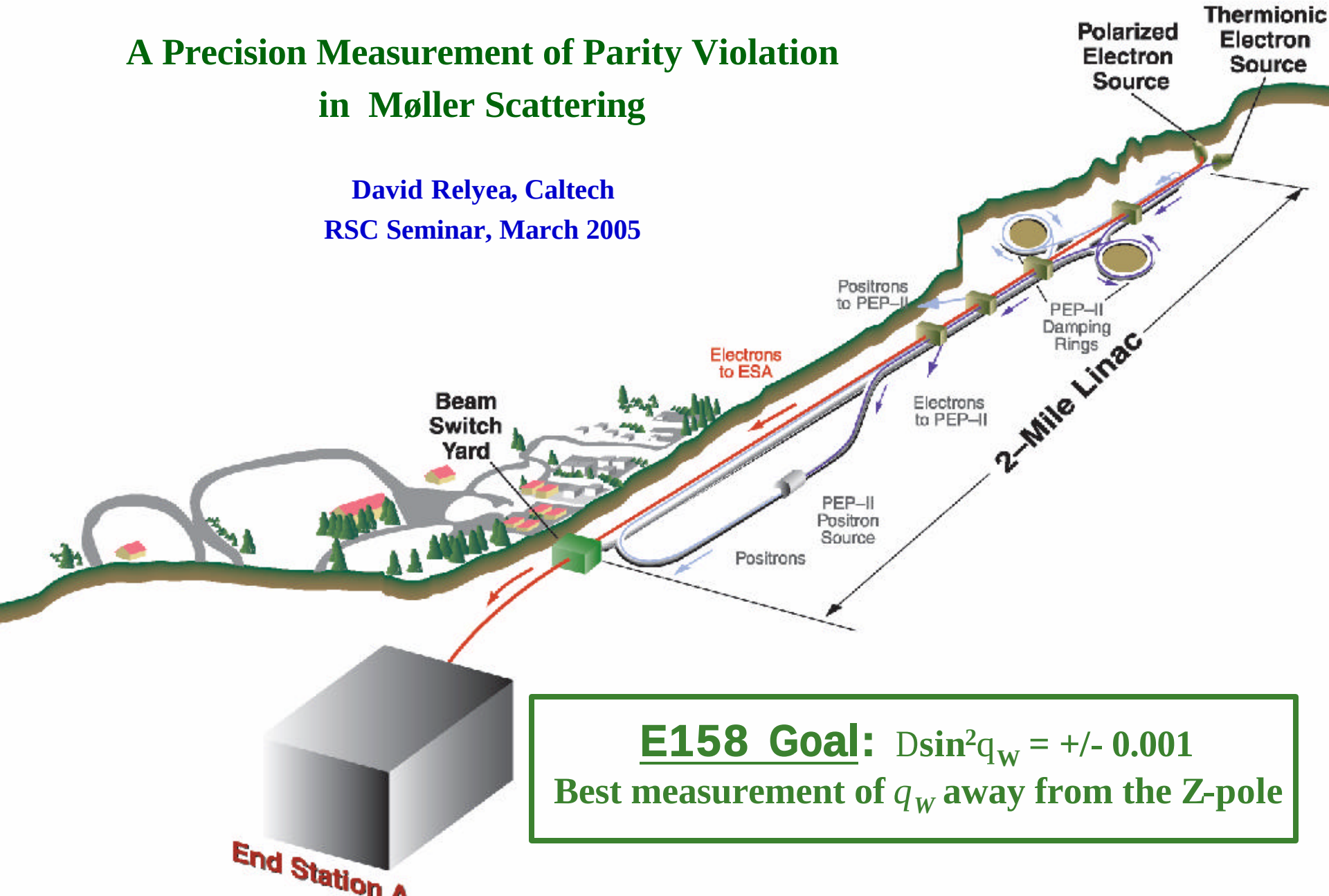
SLAC E-158

A Precision Measurement of Parity Violation in Møller Scattering

David Relyea, Caltech

RSC Seminar, March 2005



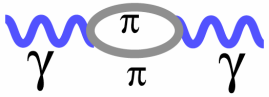
E158 Goal: $D\sin^2 q_W$ = +/- 0.001

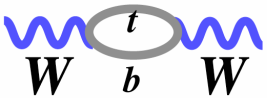
Best measurement of q_W away from the Z-pole

Physics Beyond the Standard Model

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

→ Complementary Approaches

α_{QED} G_F 



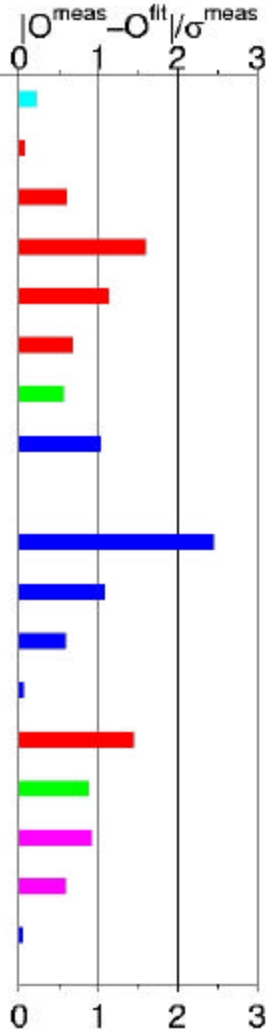
M_Z

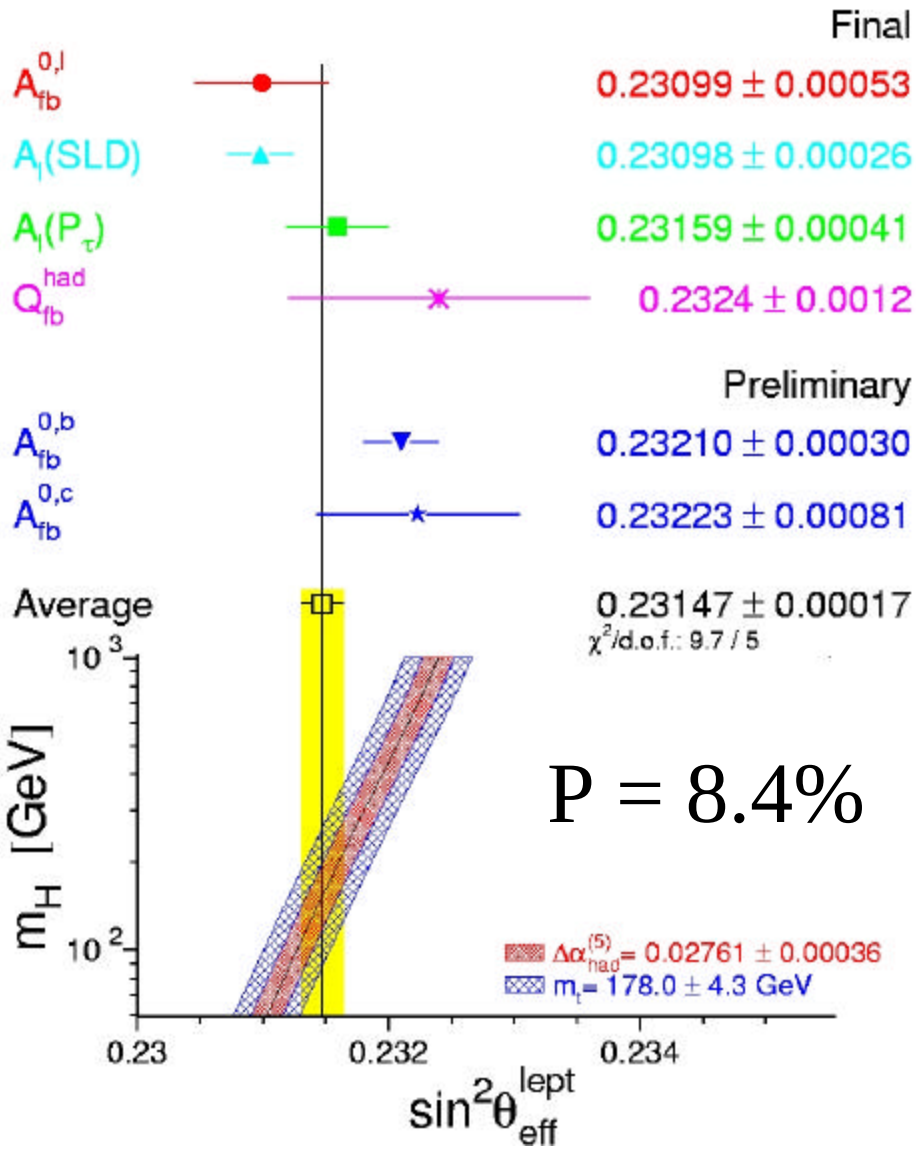
σ_Z M_W A_f

Latest World Electroweak Data

Summer 2004

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02769
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01650
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1483
R_b	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A^{0,b}_{fb}$	0.0998 ± 0.0017	0.1040
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0744
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1483
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.394
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.2

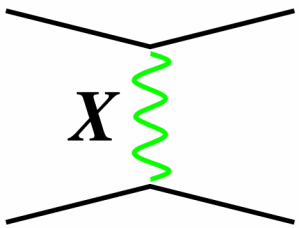




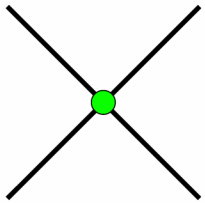
P = 8.4%

Search for New Physics: Electroweak Physics Away from the Z Pole

consider



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



Contact interaction

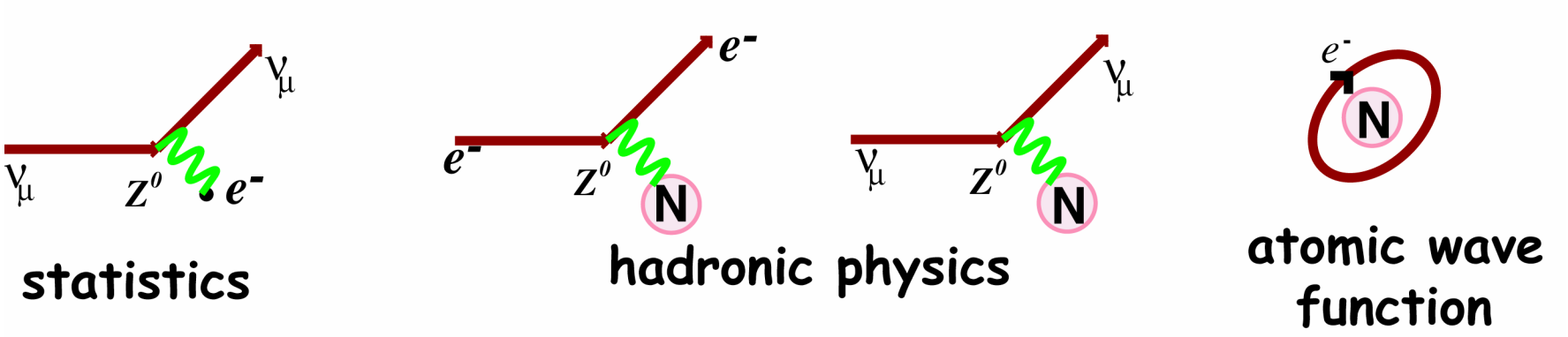
$Q^2 \sim M_Z^2$ **on resonance:** A_Z *imaginary* $\longrightarrow A_Z^2 \left[1 + \frac{A_X^2}{A_Z^2} \right]$

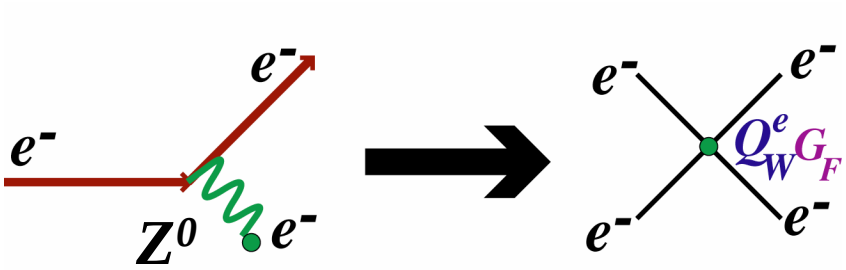
no interference!

- **Precision Z observables establish anchor points for SM**
- **Low energy observables probe interference between SM and new physics**
- **Current low energy experiments access scales beyond 10 TeV**
- **Eventually push to energies above the Z resonance**

(but for now…)

Measuring the Weak Neutral Current at Low Q^2





Purely leptonic reaction

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

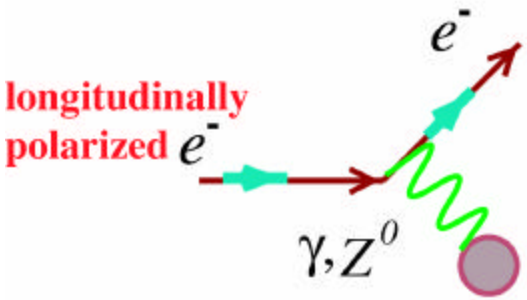
➔Fixed Target Møller Scattering

E158

E158 Collaboration / Timeline

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

Weak-Electromagnetic Interference in Electron Scattering



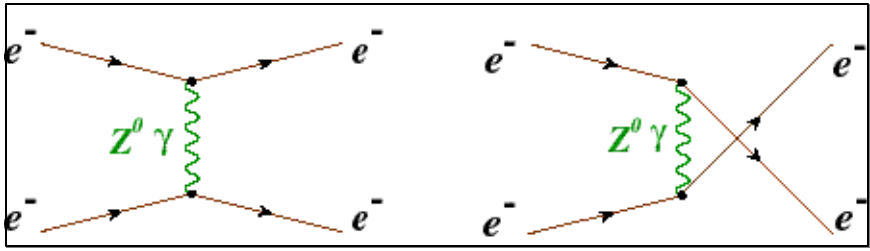
$$-A_{LR} = A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{\gamma}} \sim \frac{G_F Q^2}{4 \pi \alpha}$$

$$\sigma \;\; \alpha \; | A_{\gamma} + A_{weak} |^2 \qquad Q^2 \sim 0.01 - 1 \text{ GeV}^2 \longrightarrow A_{PV} \lesssim 10^{-7} - 10^{-4}$$

SLAC E122: lepton-nucleon deep inelastic scattering

C.Y. Prescott et.al. 1978

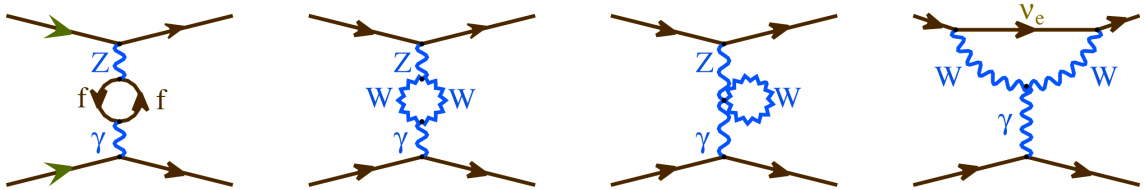
Parity Violation in Møller Scattering



- Scatter polarized 50 GeV electrons off *unpolarized* atomic electrons
- Measure $A_{PV} = \dfrac{s_R - s_L}{s_R + s_L}$
- Small tree-level asymmetry

$$A_{ee} = mE \frac{G_F}{\sqrt{2}pa} \frac{16\sin^2 q}{(3+\cos^2 q)^2} \overbrace{\left(\frac{1}{4} - \sin^2 q_W\right)}^{Q_W}$$

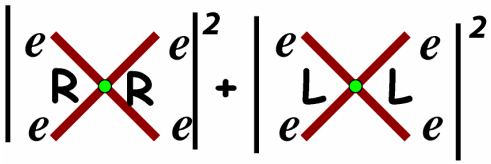
- At tree level, $A_{ee}(Q^2 = 0.03) \approx 3.2\times10^{-7} \quad (320\ ppb)$



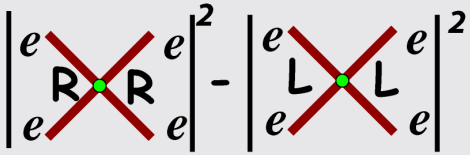
- Higher order corrections reduce asymmetry to **130 ppb**

E158 New Physics Reach

LEP II

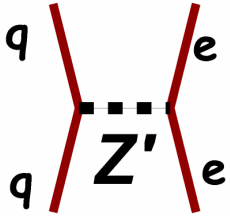


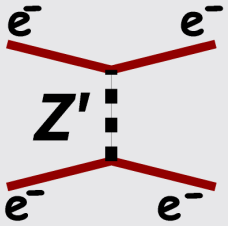
E158



15 TeV — compositeness

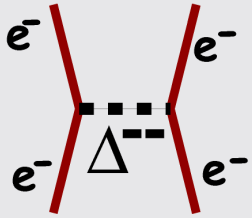
Fermilab





0.5-1.0 TeV — GUTs

0.5-2.5 TeV — extra dimensions



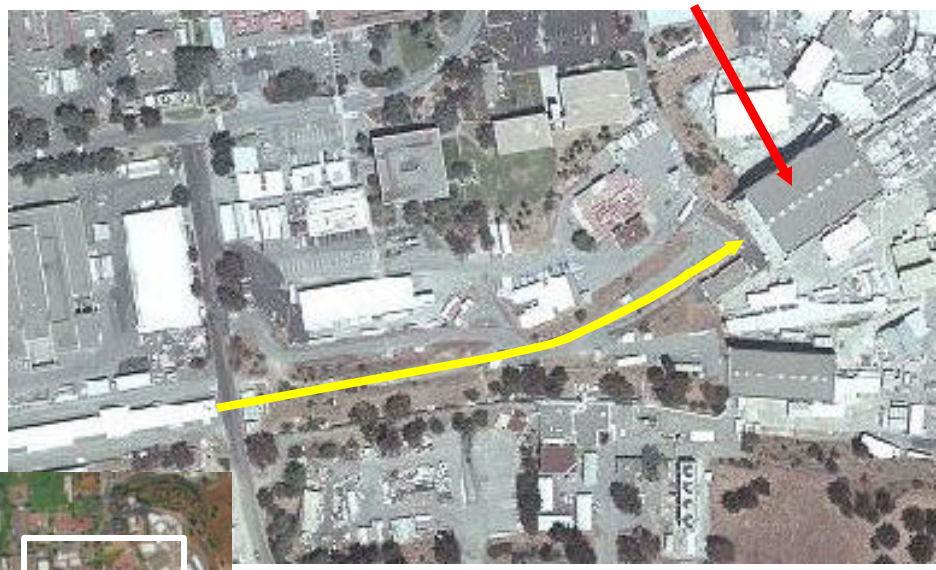
$$\frac{g^2}{2M_\Delta^2} < 0.01\ G_F$$

lepton flavor violation

doubly charged scalar exchange

Experimental Technique

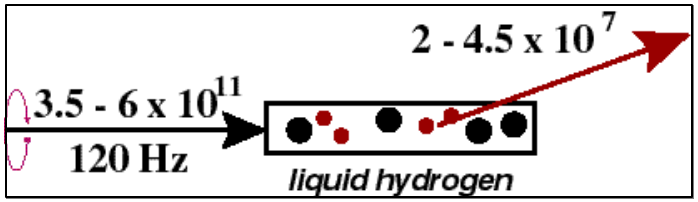
- Scatter polarized electrons off atomic electrons
  - High cross section (14 μBarn)
  - High intensity electron beam, ~85% polarization
  - 1.5 m LH2 target (0.18 r.l.)
    - ➡ Luminosity $4*10^{38}$ $cm^{-2}s^{-1}$
  - High counting rates (~2 GHz) ⇨ flux-integrating calorimeter
- Principal backgrounds:
  elastic and inelastic **ep** scatters
- Main systematics:
  - Helicity-correlated beam effects
  - Backgrounds
  - Beam polarization



Parity-Violating Asymmetry

1. Measure asymmetry for each pair of pulses,

$$A_{exp} = \frac{S_R - S_L}{S_R + S_L}$$



2. Correct for detector response to beam helicity differences:

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

beam intensity, position, angle, energy
R-L differences

coefficients determined by 1. fitting detector asymmetry to beam R-L differences, or
2. "dithering" beam and observing detector response

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

0. Measure a 100 ppb effect with a 10 ppb error

1. Electron Beam

i) high intensity
- 500 kW beam!

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

iii) small left-right helicity differences
- intensity
- position/angle
- energy

iv) high (>80%) polarization

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

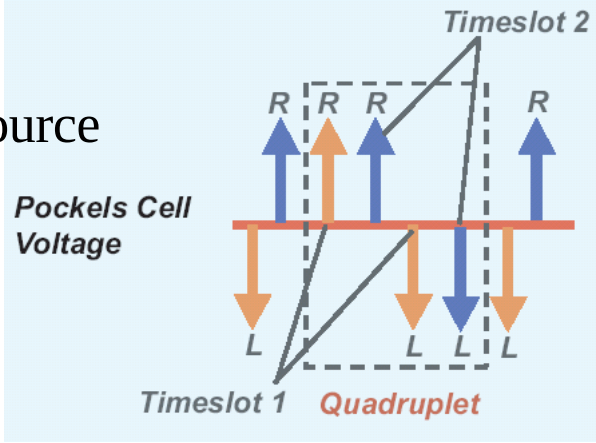
i) target density fluctuations: $<10^{-4}$ per pulse
ii) 18% radiation length
- absorbs 500W beam power

iii) Safety (largest LH2 target in the world)

4. Detectors

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

Laser/Electron Beam: Systematics



Beam helicity is generated pseudo-randomly at 120 Hz

- Use electro-optical Pockels Cell in Polarized Light Source
- Sequence of pulse quadruplets:

Beam R-L differences reduced using feedbacks

- Charge and position R-L differences nullified using electro-optical Pockels Cells in Source

Physics asymmetries can be reversed

- Insertable Halfwave Plate in Source
- (g-2) spin precession in A-Line (45 GeV and 48 GeV data)

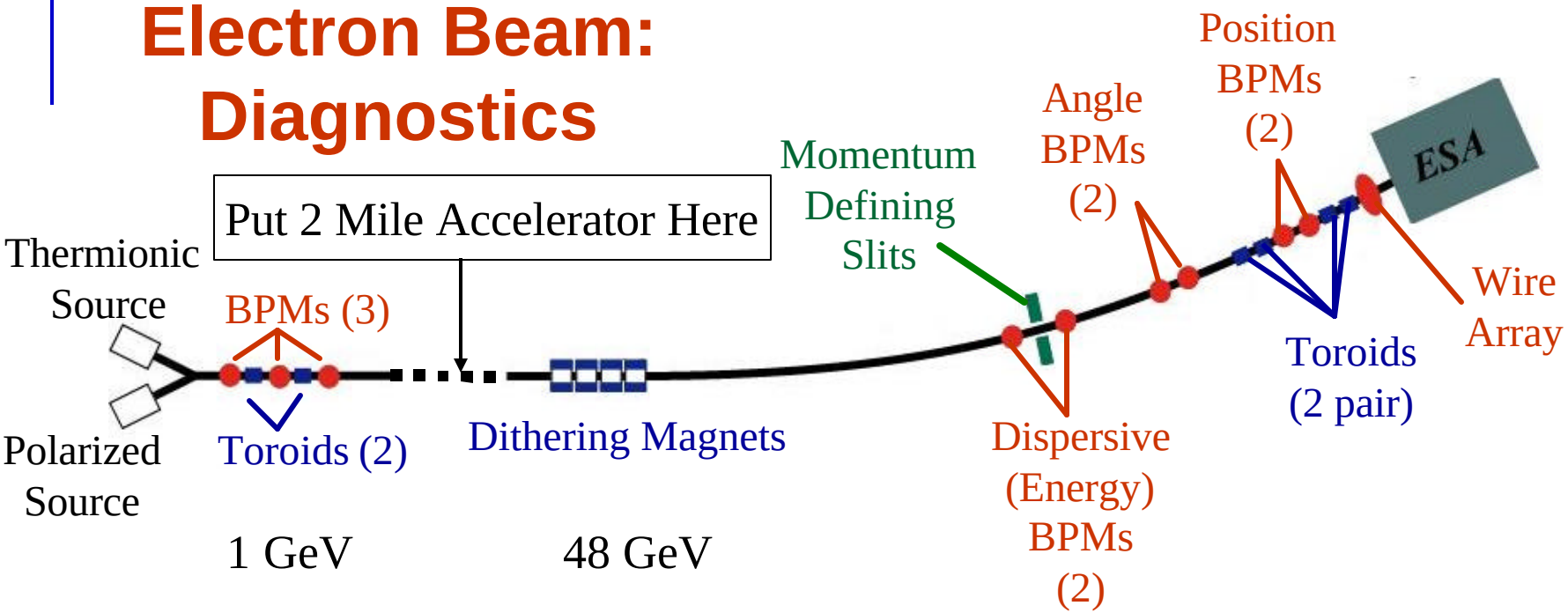
False asymmetry reversals

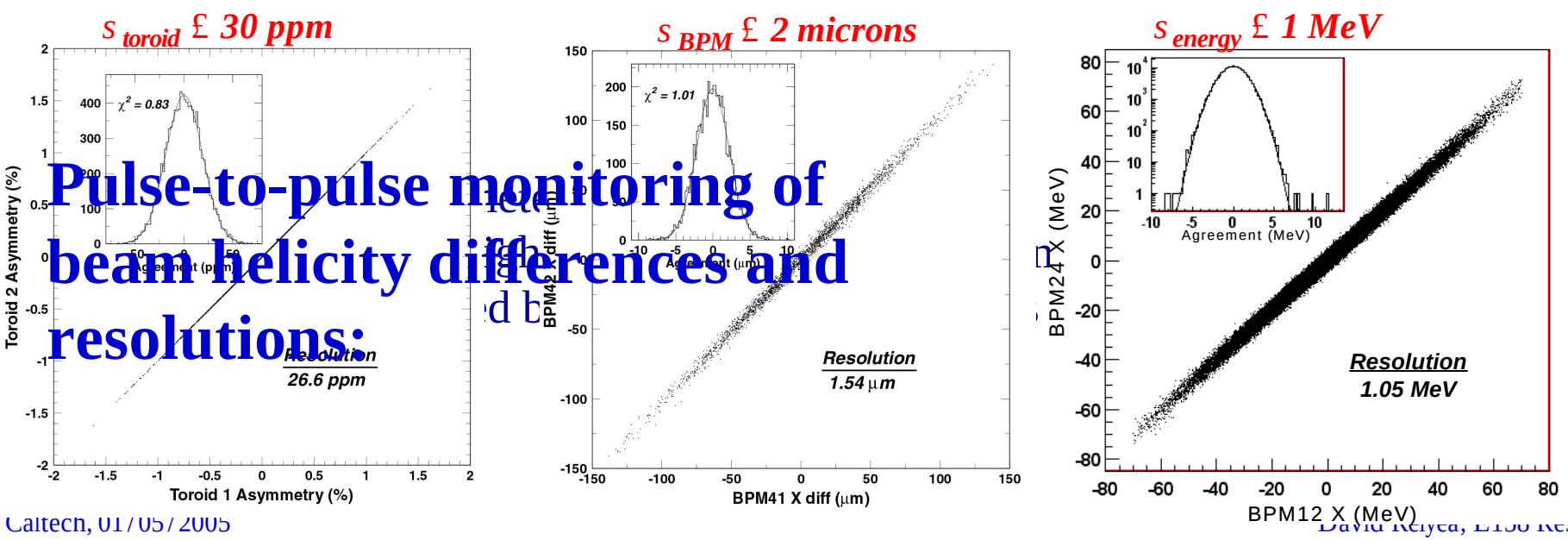
- Insert a four lens "-I/+I" inverter in the Source
- Reverses beam R-L differences
- Leaves physics asymmetry intact

'Null Asymmetry' cross-check is provided by a Luminosity Monitor

- measure very forward angle e-p (Mott) and Møller scattering

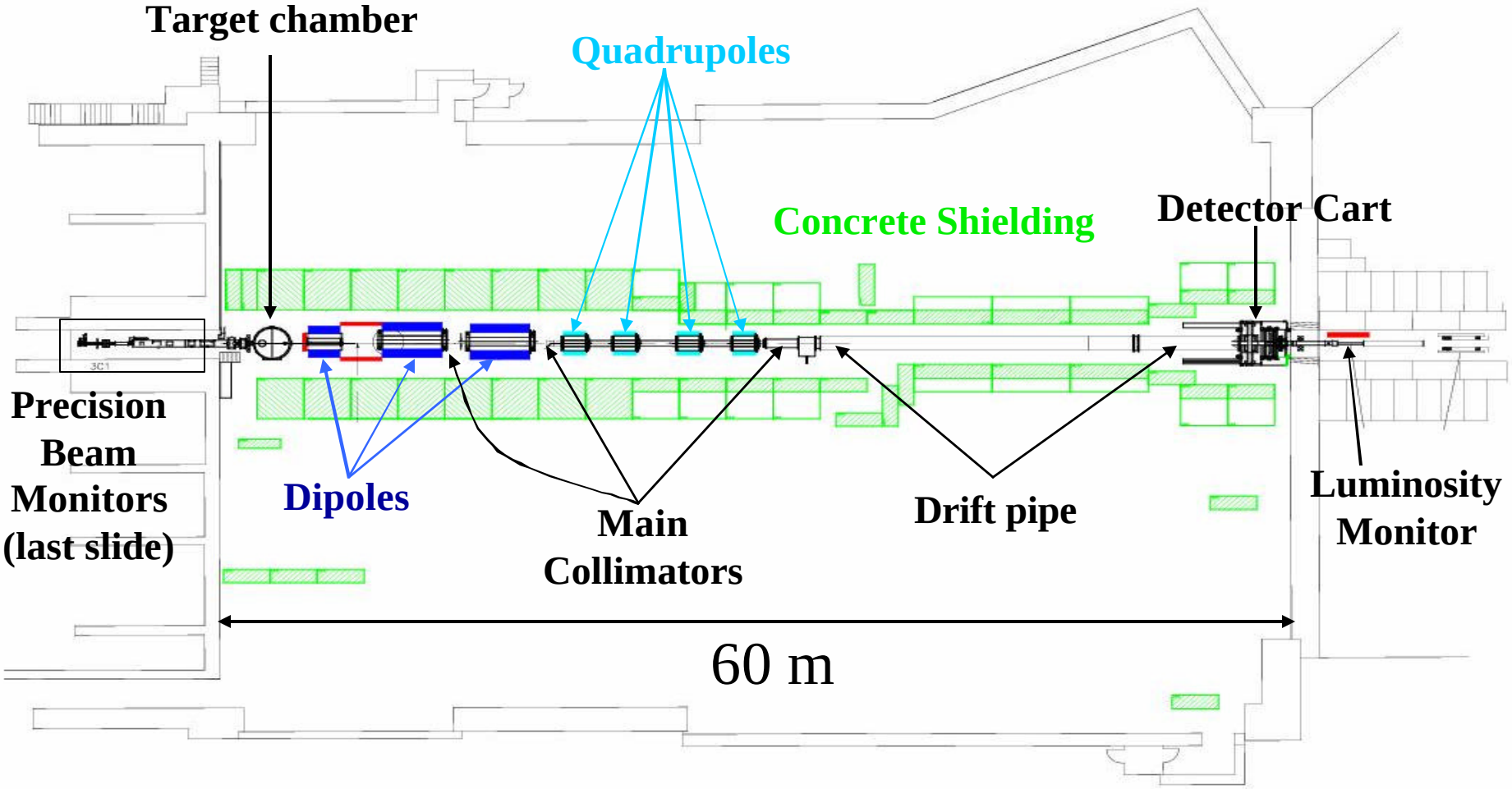
Electron Beam: Diagnostics

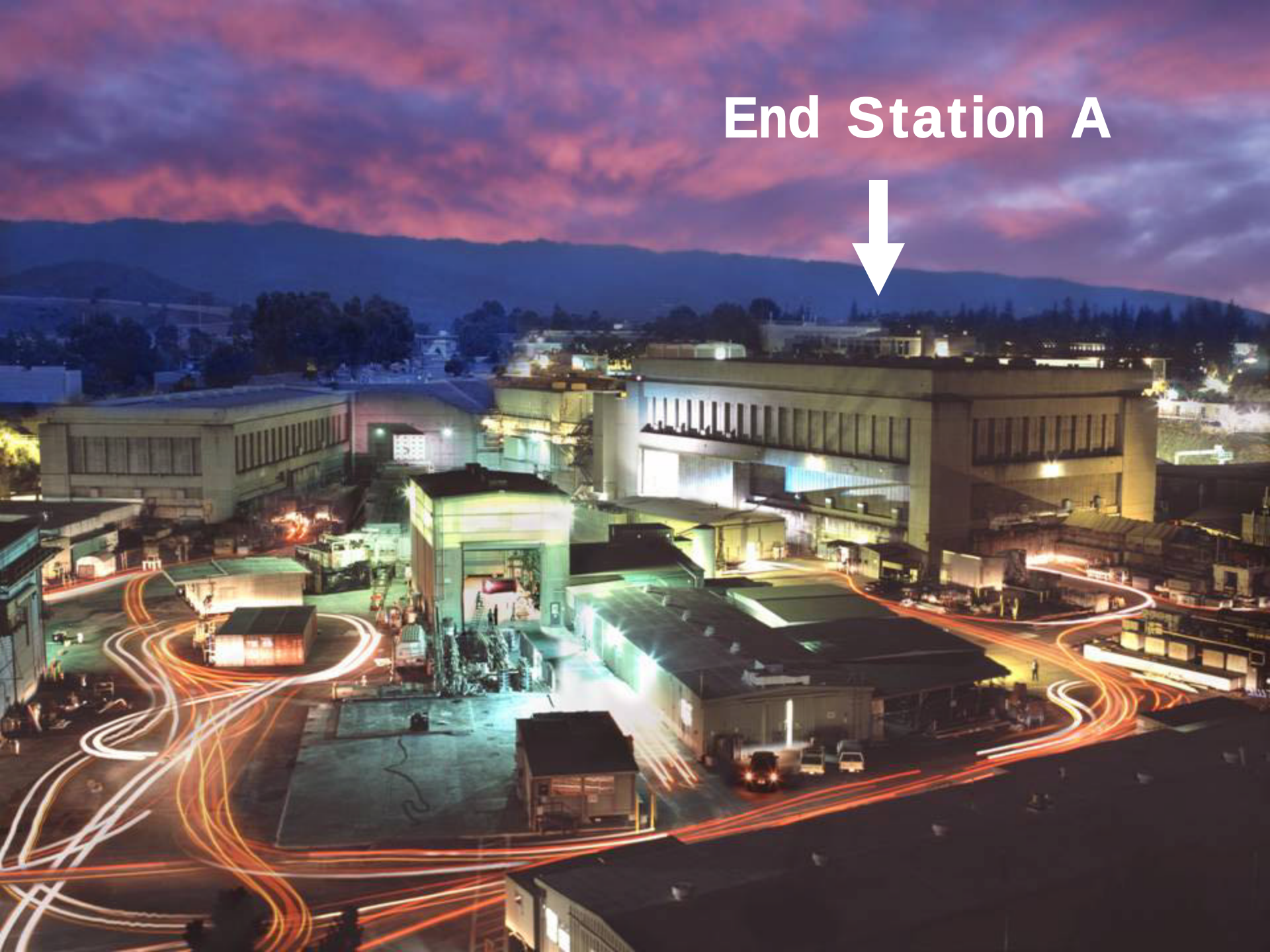




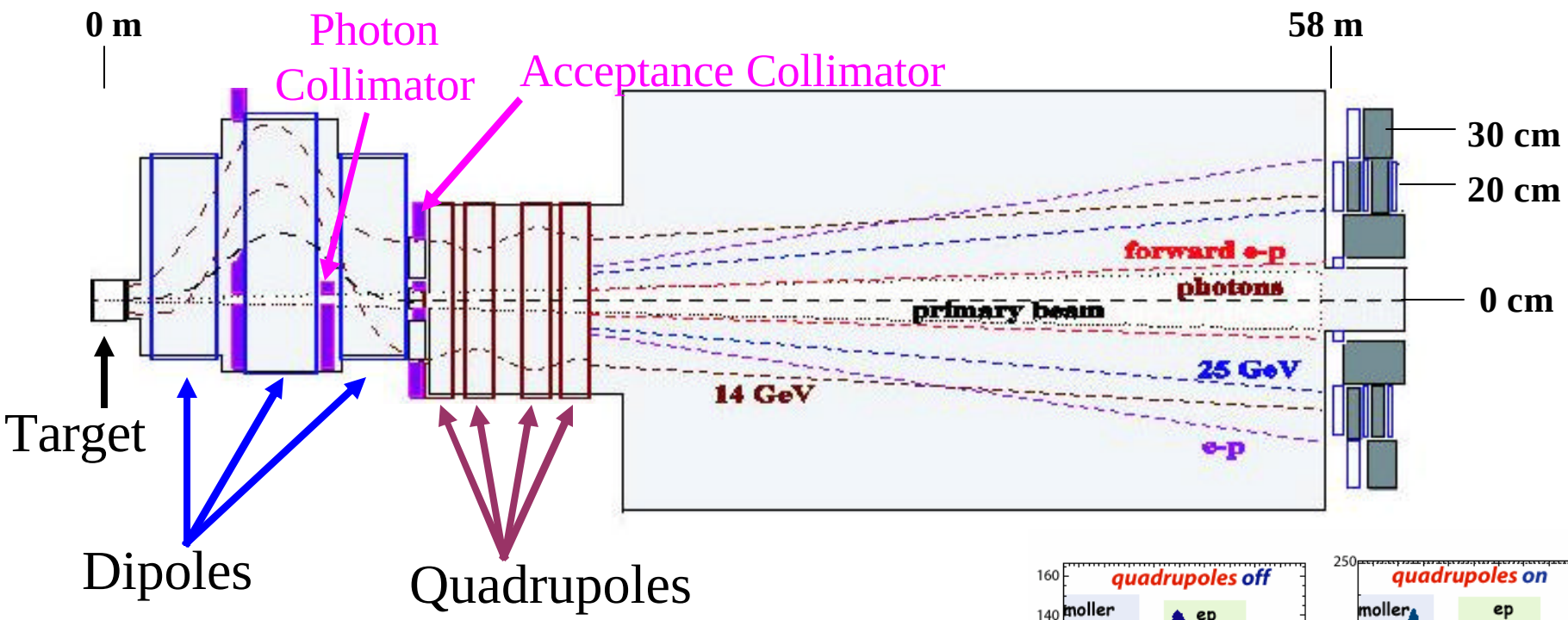
Pulse-to-pulse monitoring of beam helicity differences and resolutions:

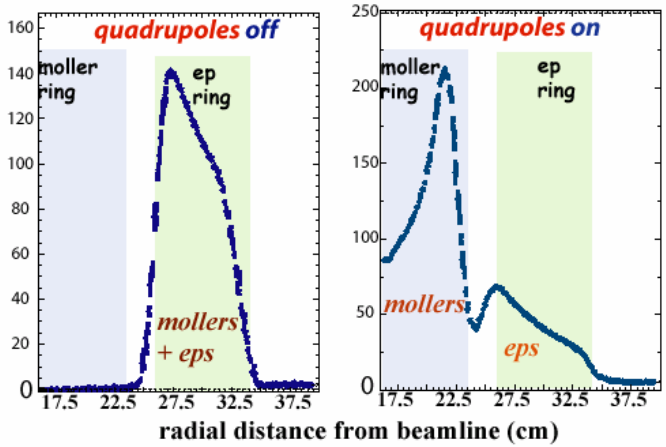
Experimental Layout: ESA




End Station A

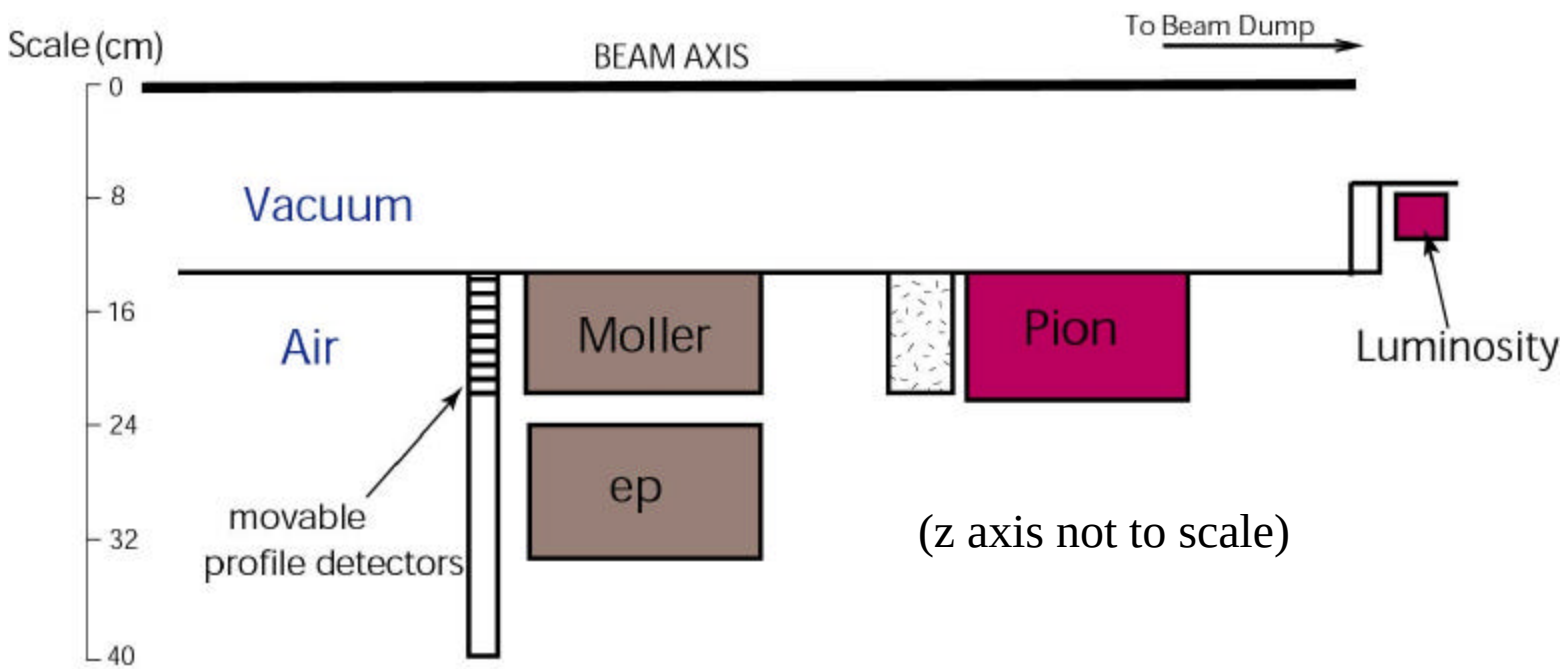
Experimental Layout: Spectrometer





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

Experimental Layout: Detectors



Møller, ep are (copper/fused silica fiber) calorimeters
Pion is a quartz bar Cherenkov
Luminosity is an ion chamber with Al pre-radiator

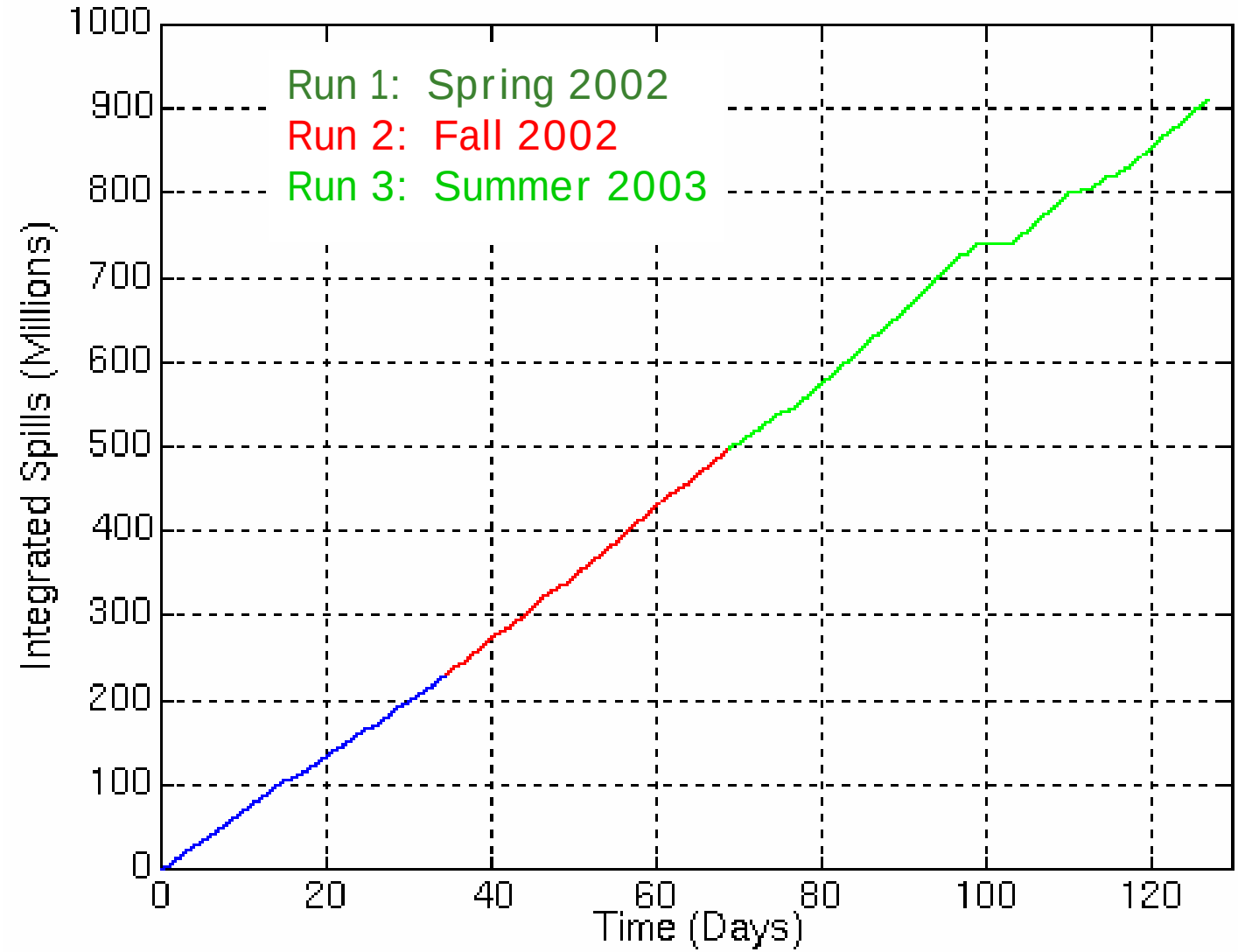
$$s^{MOLLER} \propto \frac{1}{Eq^4} \qquad s^{MOTT} \propto \frac{1}{E^2 q^4}$$

All detectors have azimuthal segmentation, and have photomultiplier tube (PMT) readout to a 16-bit ADC

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

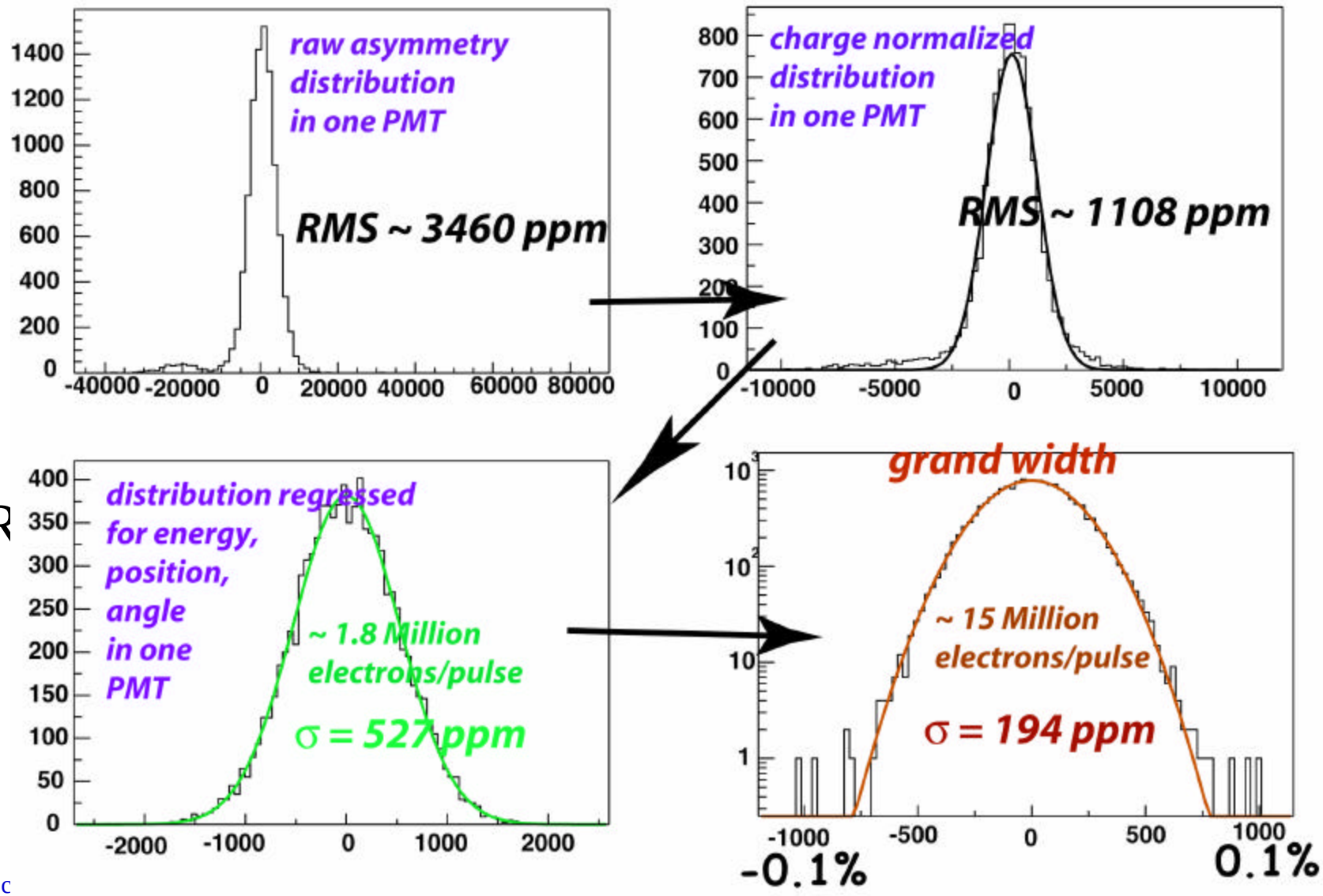
$$\left\langle q_{lab}^{MOLLER} \right\rangle = 6.0 mrad$$

E158 Runs


Run 1: Spring 2002
Run 2: Fall 2002
Run 3: Summer 2003
Integrated Spills (Millions)
Time (Days)
0
100
200
300
400
500
600
700
800
900
1000
0
20
40
60
80
100
120

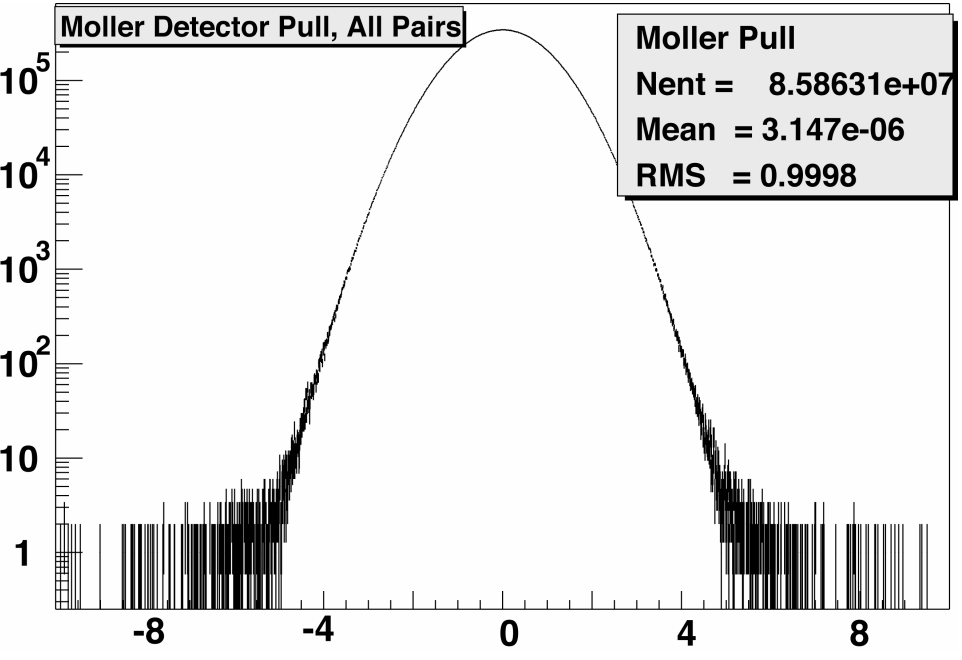
Møller Statistics and Fluctuations

observed left-right asymmetry distribution



Raw Asymmetry Statistics

per pulse pair (2 days, Run I only)

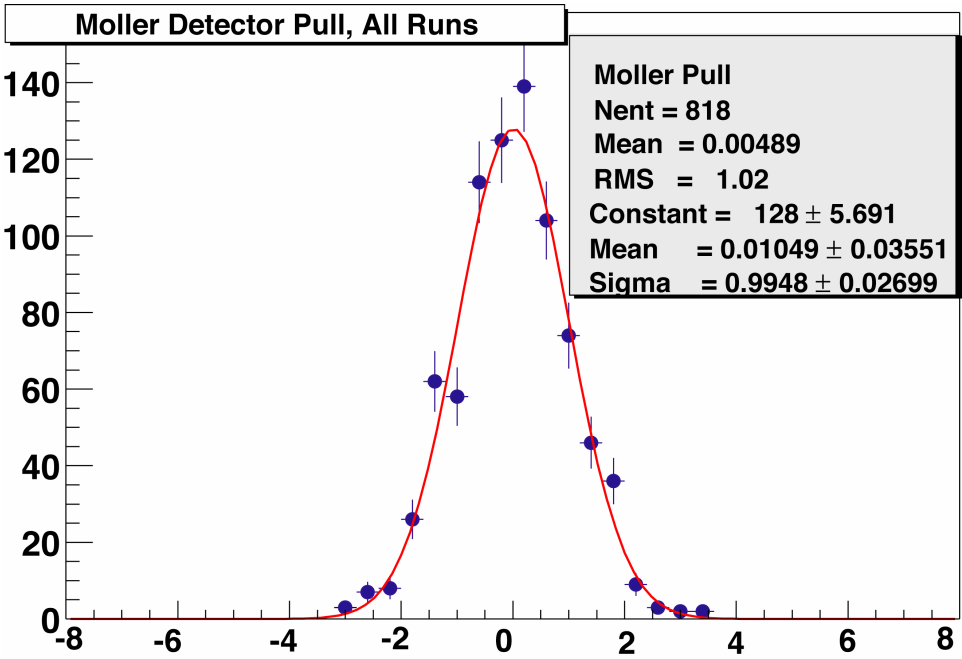


$$\frac{A_i - \langle \bar{A} \rangle}{s_i}$$

s_i ~ 200 ppm

N = 85 Million

per run (Run I only)



$$\frac{A_i - \langle \bar{A} \rangle}{s_i}$$

s_i ~ 600 ppb

N = 818

Raw Asymmetry Systematics

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

SLICES: Temporal Beam Profile

- SLICES readout in 10 bit ADCs

  Q : bpm31Q (4)

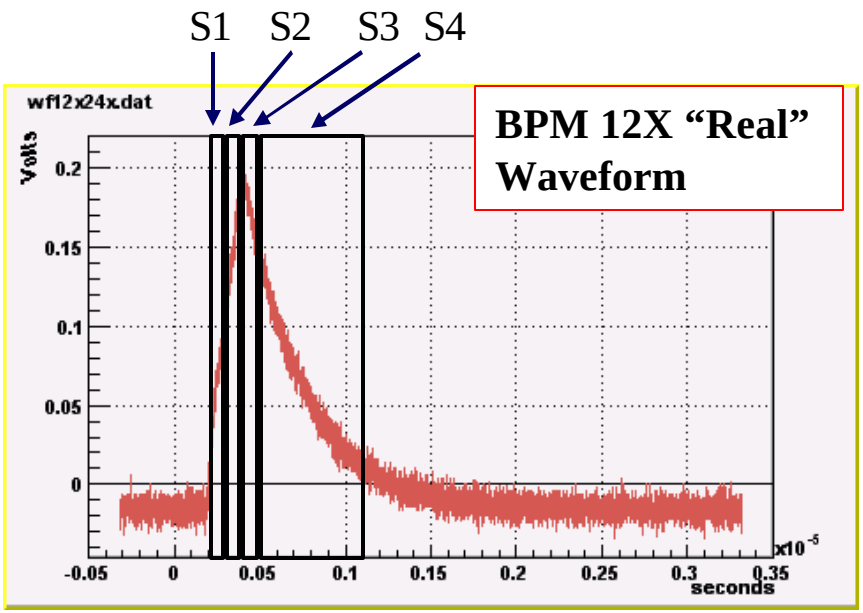
  E : bpm12X (3)

  X : bpm41X (4)

  Y : bpm41Y (4)

  dX : bpm31X (4)

  dY : bpm31Y (4)



Integration time :

S1 : 0 -100 ns

S2 : 100-200 ns

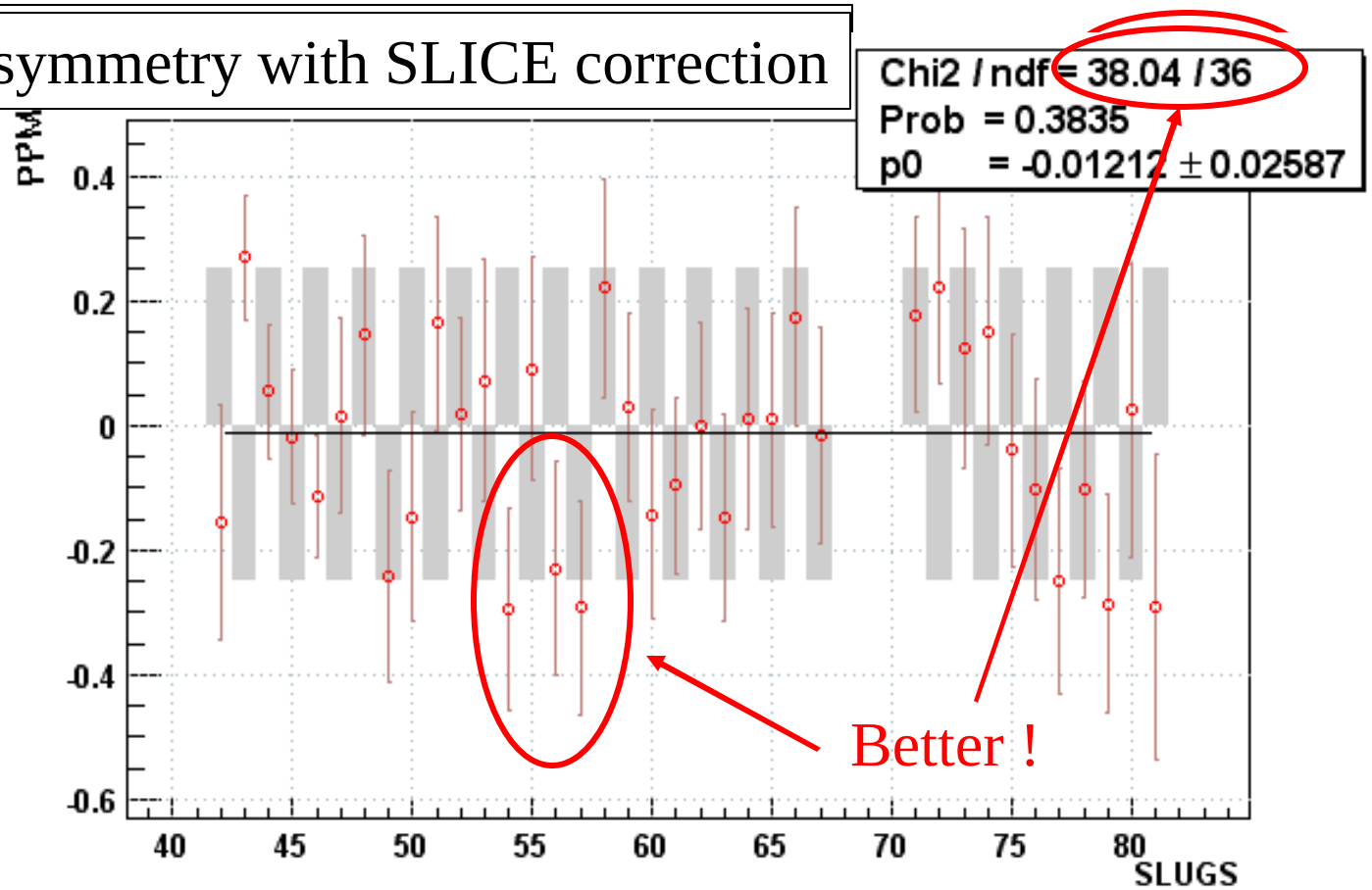
S3 : 200-300 ns

S3 : 300-1000 ns

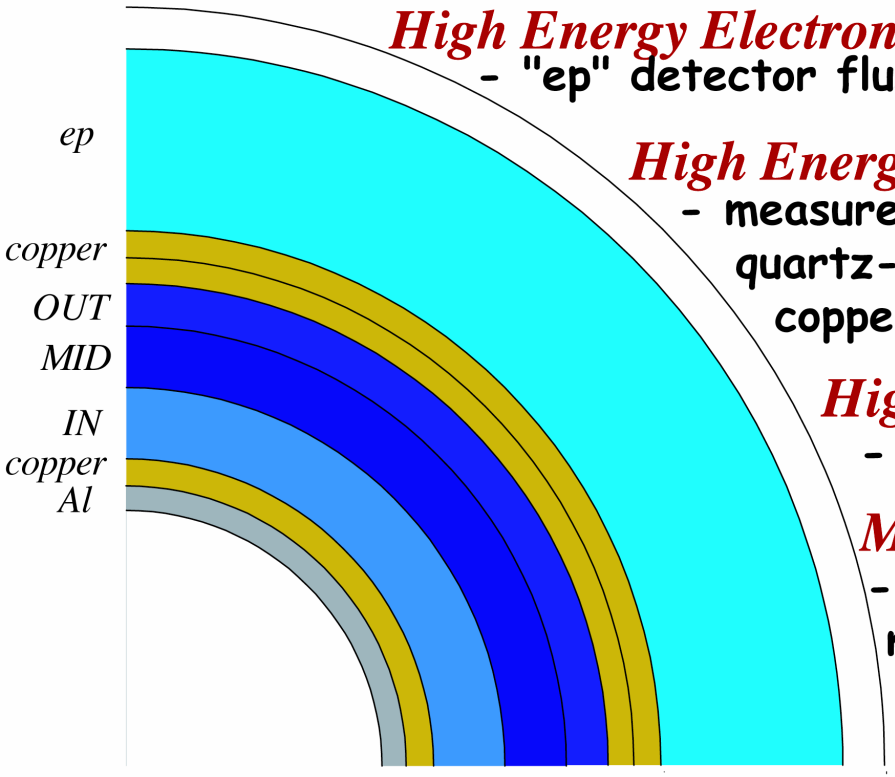
Additional Corrections

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

OUT asymmetry with SLICE correction



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

ep Asymmetry

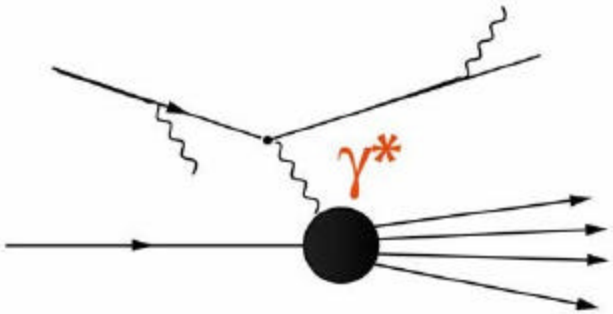
elastic scattering

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

in the ep detector:

$Q^2 \sim 0.06\ \mathrm{GeV}^2$:

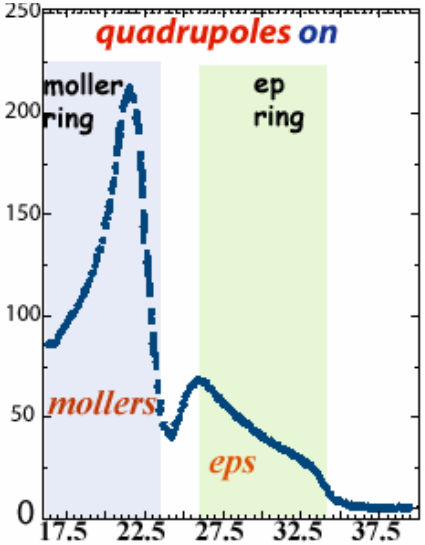
$A_{Raw} \sim 0.4 +/- 0.2$ ppm



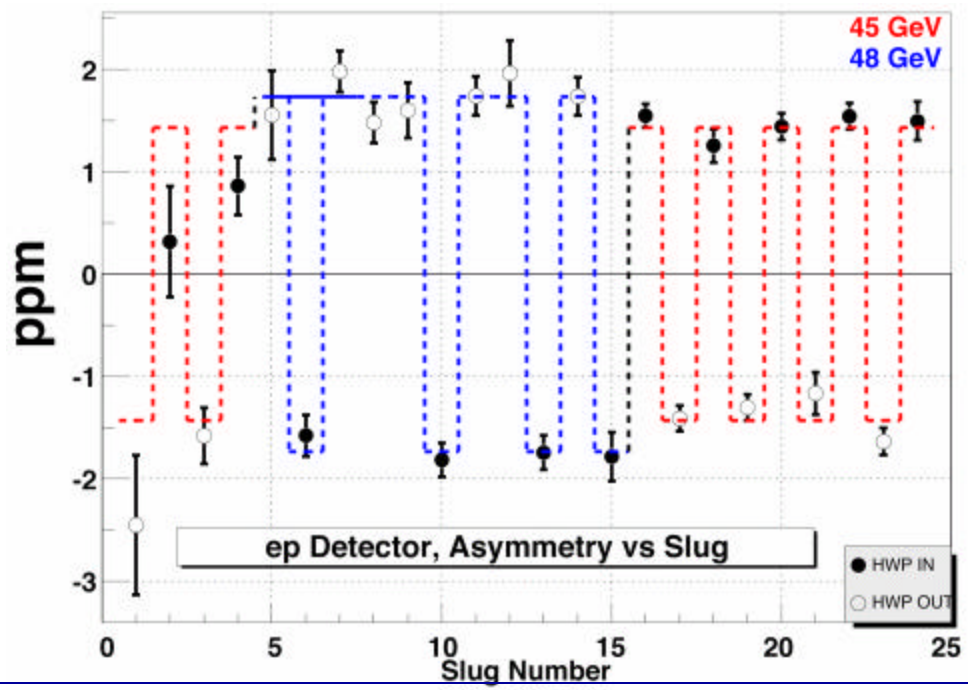
inelastic scattering

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

- radiative tail dominated by elastic scattering: ~ 8% under Moller peak
- additional 1% contribution from inelastic scattering



ep Detector Data (Run 1)



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

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

Ratio of asymmetries:

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

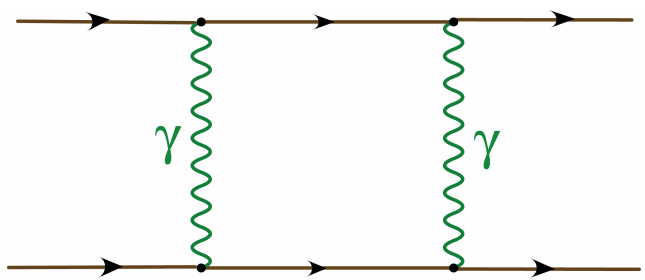
Consistent with expectations for inelastic ep asymmetry

Transverse Asymmetries

Beam-Normal Asymmetry in elastic electron scattering

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

$$A_T \equiv \frac{2p}{s^{\uparrow} + s^{\downarrow}} \frac{d(s^{\uparrow} - s^{\downarrow})}{df} \propto \vec{S}_e \cdot (\vec{k}_e \times \vec{k}'_e) \propto \sin f$$



Interference between one- and two-photon exchange

$$A_T \propto \frac{am_e}{\sqrt{s}} = -3.5 \text{ ppm} \bullet \sin f$$

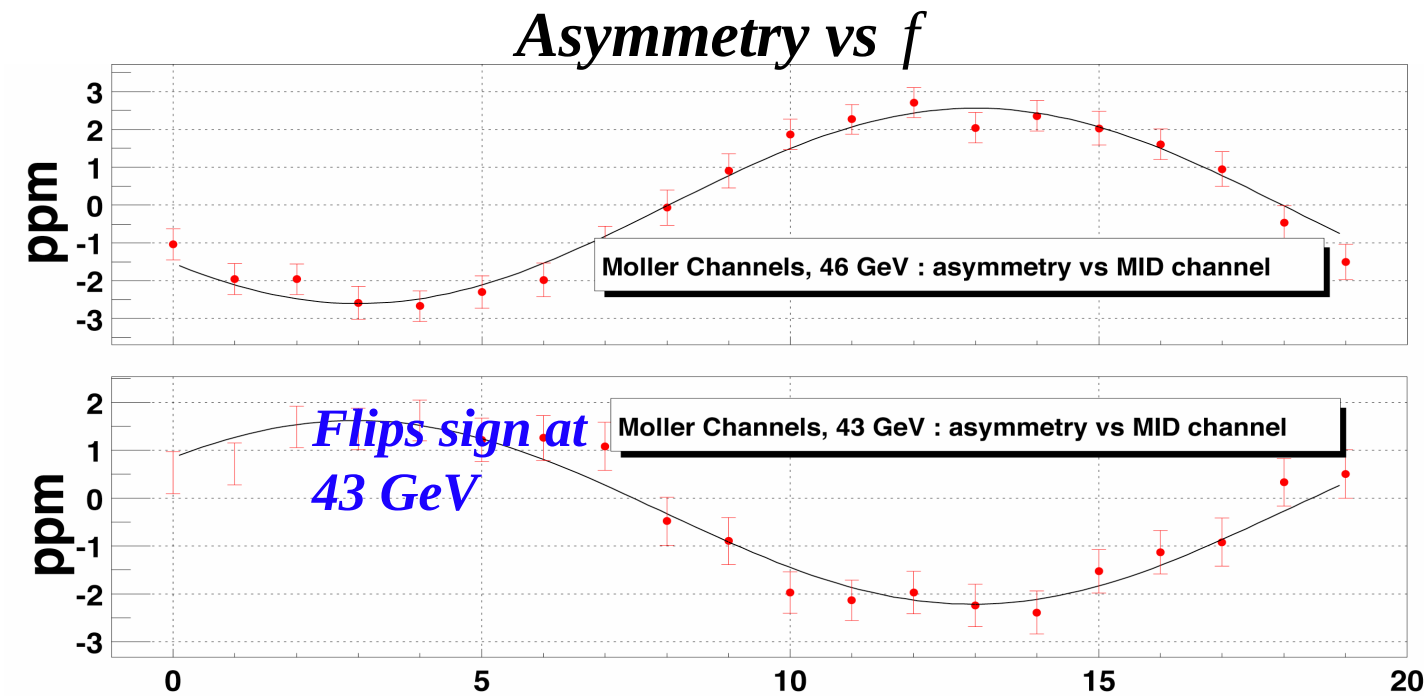
for Møller scattering at 43/46 GeV

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: PRD69:113001(2004)**

(Included bremsstrahlung corrections: few percent)

(Raw) Transverse ee Asymmetry



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

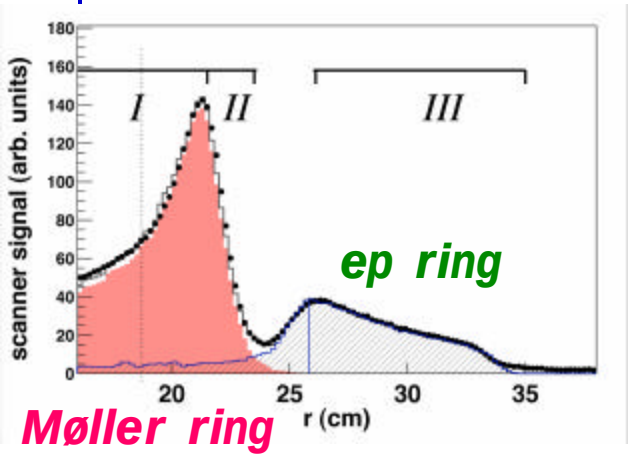
i) Interesting ***signal***

ii) Potential ***background*** for A_{PV} measurement

- Data carefully re-weighted to maintain azimuthal symmetry

iii) Studying its utility for ***calibration*** of polarization scale

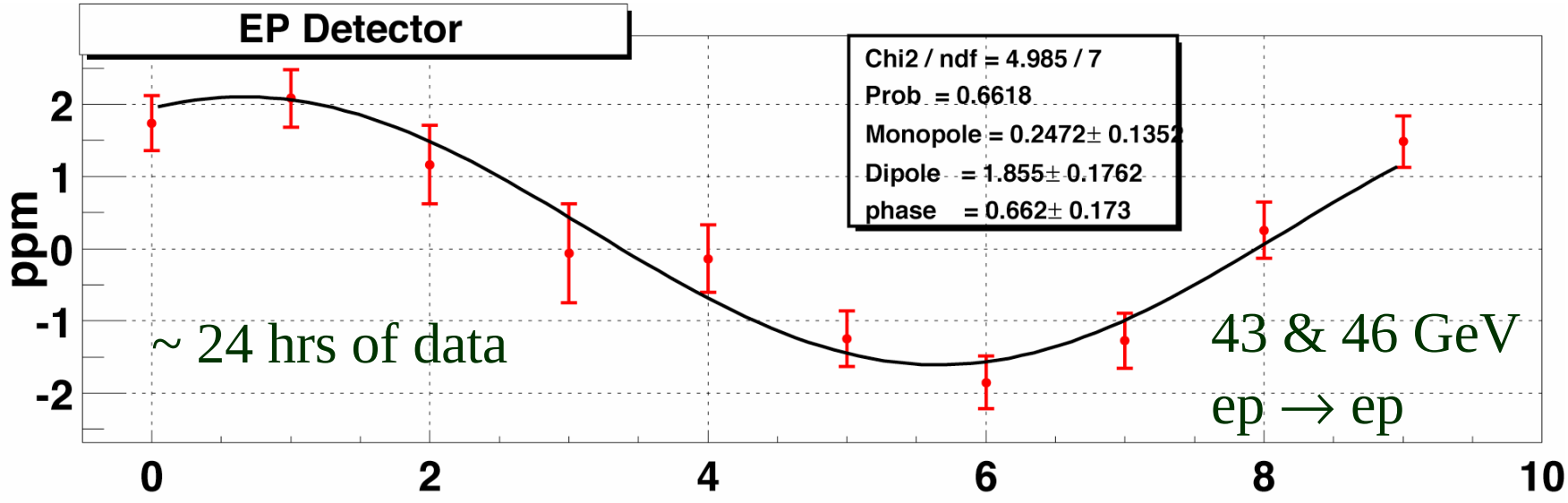
A_T^{ep} at E158



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

✓ Proton structure at E158 !

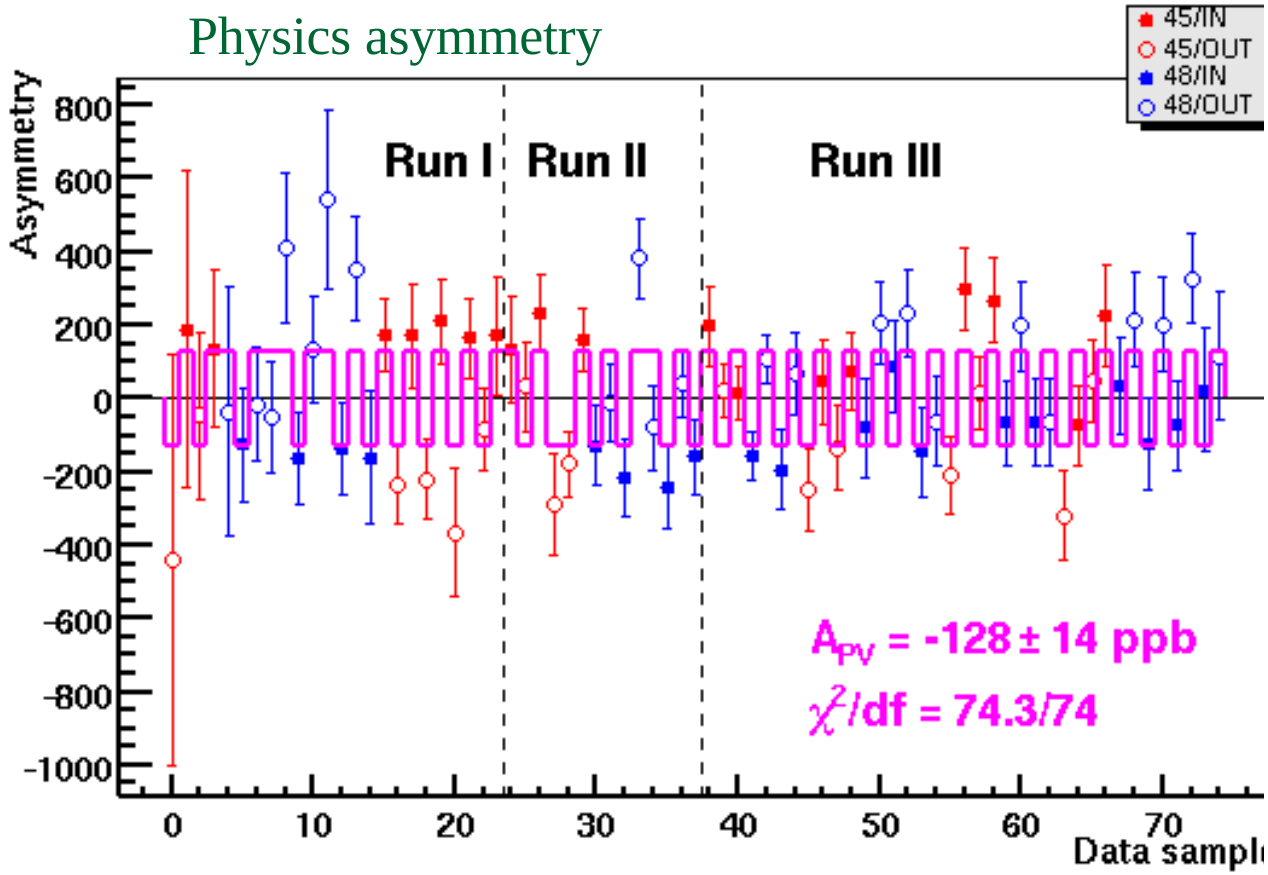
ϕ (Azimuthal angle)



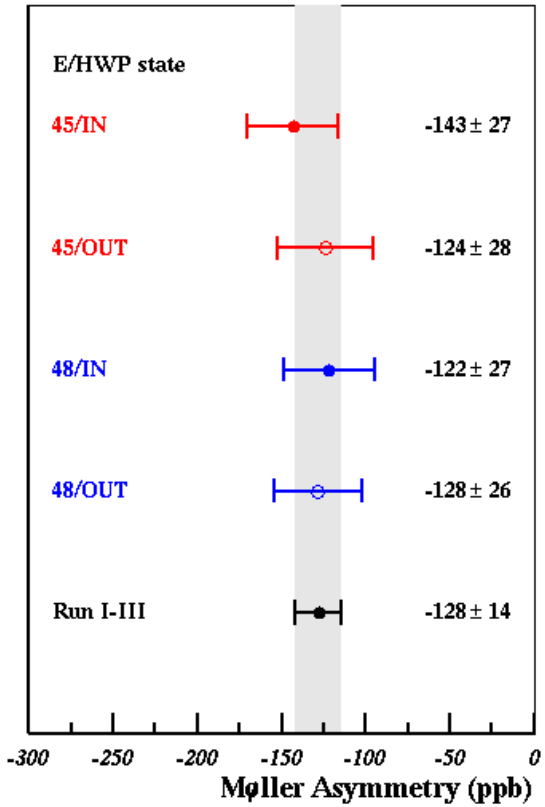
Møller Asymmetry

- Over 330M pulse pairs over 3 separate runs (2002-2003) at E_{beam}=45 and 48 GeV
- Passively flip helicity of electrons wrt source laser light ~every day to suppress spurious helicity-correlated biases

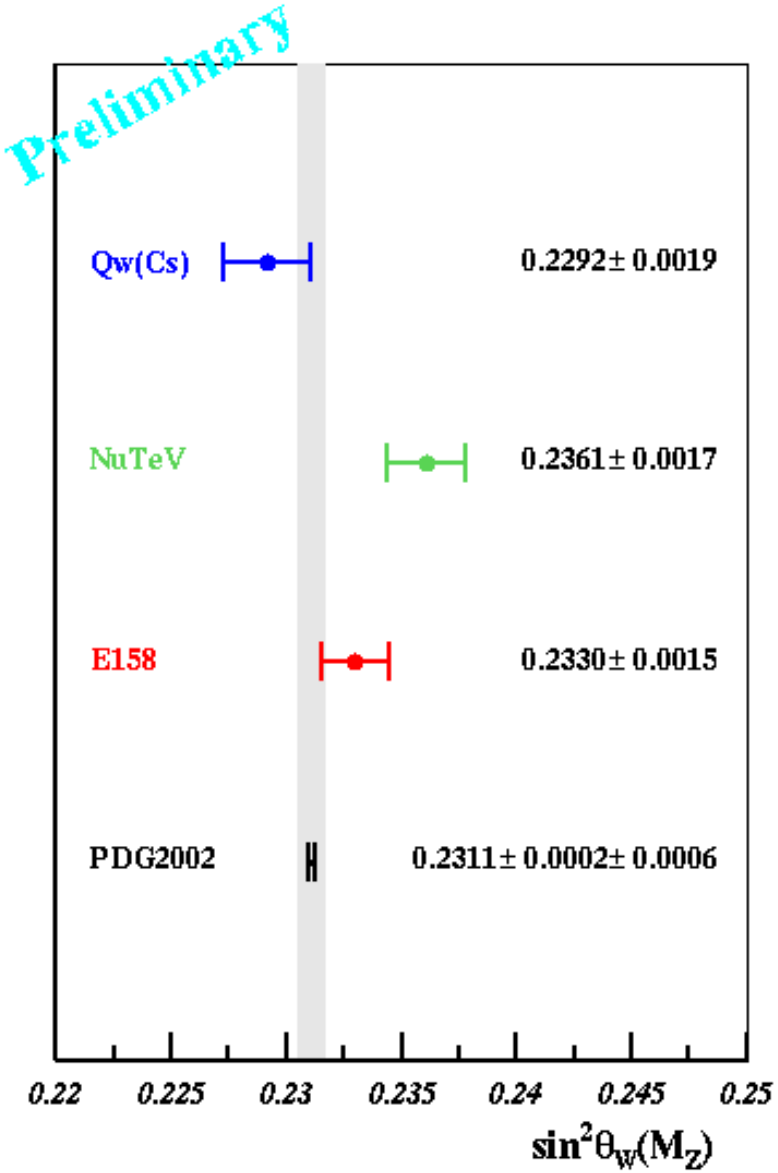
Physics asymmetry



Physics asymmetry

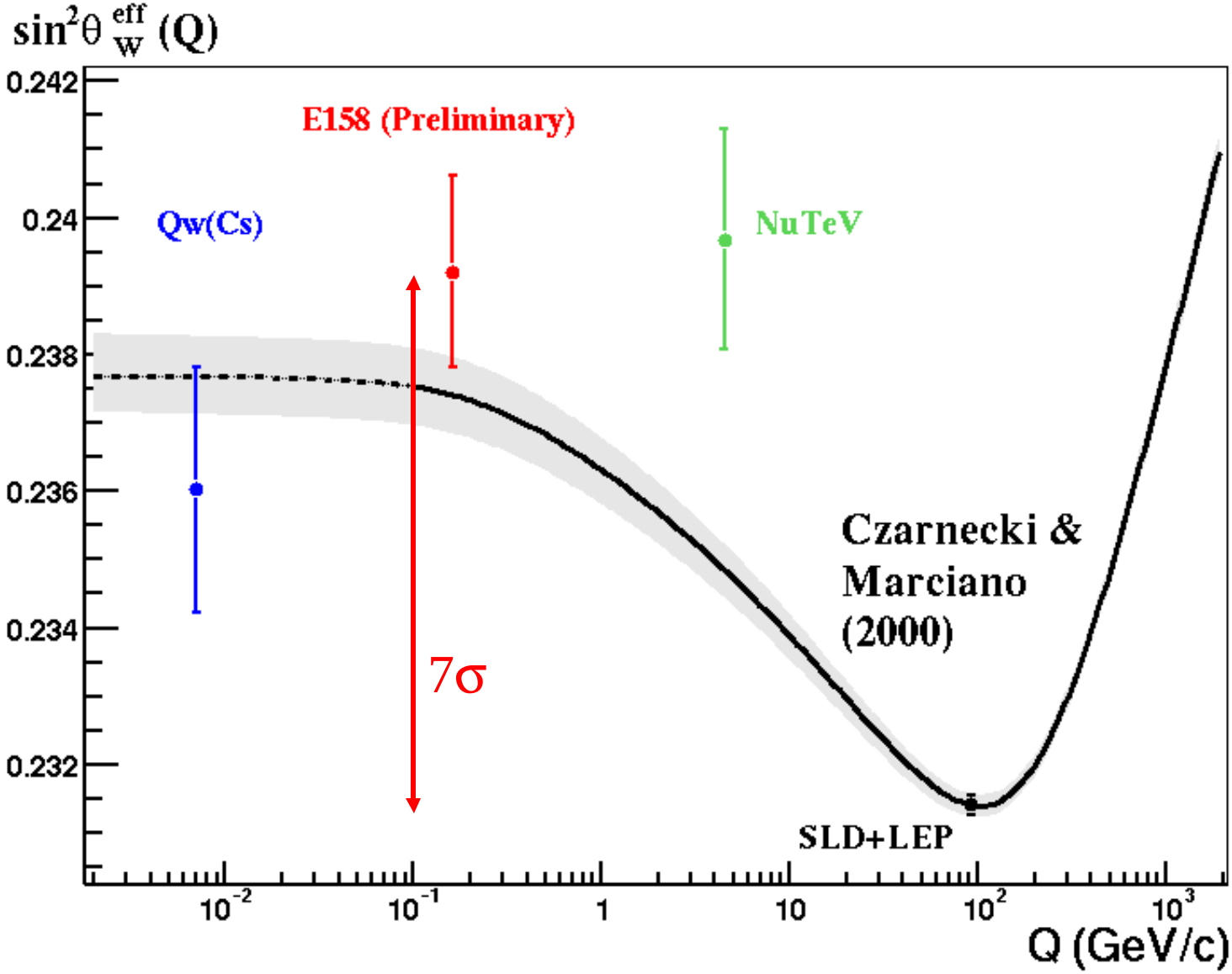


The Weak Mixing Angle



- General agreement between low Q^2 experiments, although NuTeV is still 3σ high compared to SM fit
- Stringent limits on new interactions at multi-TeV scales
- Parameterize as limit on 4-fermion contact term Λ_{LL} : 6-14 TeV limits for E158 alone (95% C.L.)
- Limit on SO(10) Z' at 900 GeV

Running of the Weak Mixing Angle



Summary: Physics Results

Electro-weak parity violation

- *first observation of parity violation in Møller scattering (8 s)*
- *running of the weak mixing angle established (7 s)*
- *Probing TeV-scale physics: ~10 TeV limit on L_{LL},*
  ~900 GeV limit on SO(10) Z'
- *inelastic e-p asymmetry consistent with quark picture*

Transverse asymmetries

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

Weak Mixing Angle

Preliminary Results using all data

$$A_{PV}(\text{Møller}) = (-128 \pm 14 \pm 12)\ \text{ppb}$$

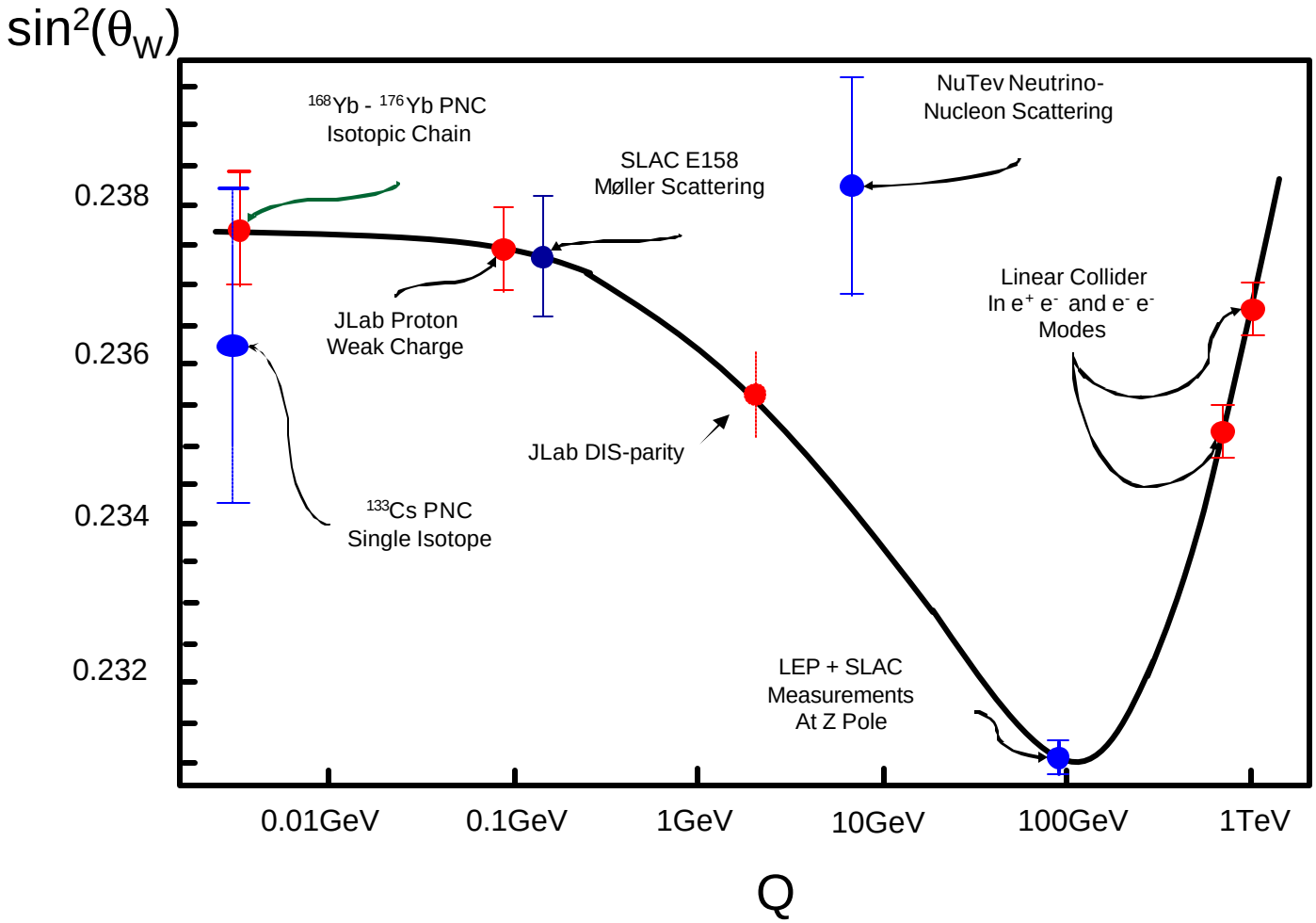
$$\sin^2 q_W^{MS}(M_Z^2) = 0.2330 \pm 0.0011\ (\text{stat}) \pm 0.0010\ (\text{syst})$$

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

Outlook

- Next set of precision measurements on the horizon
  - Neutrino-electron scattering
    - Reactor experiments (in conjunction with θ_{13}): cross section measurements to 0.7-1.3% would translate in $\sigma(\sin^2\theta_W)$ down to ~0.001
    - Ultimate measurements at the neutrino factory
  - Atomic parity violation
    - Ratios of APV in isotopes and hydrogenic ions could reach sensitivity of $\sigma(\sin^2\theta_W) \sim 0.001$
  - PV in electron scattering
    - Active program planned for JLab: PV in elastic ep scattering (~2007), Møller scattering, and DIS eD scattering (~2010) could reach below $\sigma(\sin^2\theta_W) \sim 0.001$ *per experiment*
  - e^+e^- and e^-e^- at the Linear Collider

Selected Future Measurements



EW Corrections to A_{LR} (Czarnecki-Marciano)

- LO expression:

g/Z mixing, anapole moment (factor of 1.03 in $\sin^2\theta_W$, -40% change in A_{LR})

EW Boxes (4% change in A_{LR})

$$A_{LR}(e^-e^-) = \frac{\rho G_\mu Q^2}{\sqrt{2}\pi\alpha}\frac{1-y}{1+y^4+(1-y)^4}$$

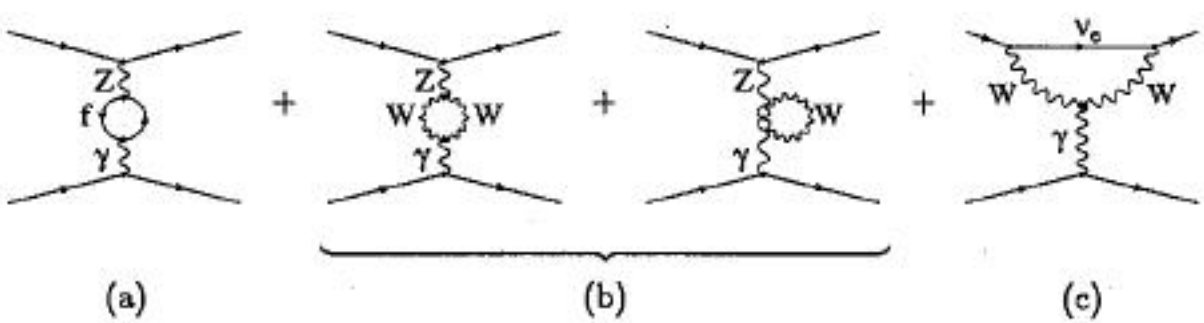
$$\times\left\{1 - 4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{MS}} + \frac{\alpha(m_Z)}{4\pi s^2}\right.$$

$$-\frac{3\alpha(m_Z)}{32\pi s^2 c^2}(1-4s^2)[1+(1-4s^2)^2]$$

$$\left.+F_1(y,Q^2)+F_2(y,Q^2)\right\}, \qquad (10)$$

where

(11)



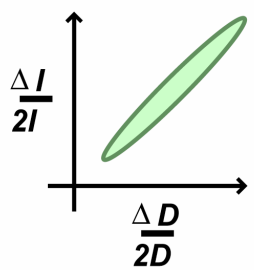
+ Inverted + crossed diagrams

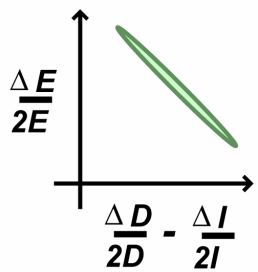
FIG. 2. γ-Z mixing diagrams (a) and (b), W-loop contribution to the anapole moment (c).

Eliminating Beam Helicity Effects

$$A_{\exp} = A_N - A_I + A_E + \sum a_i X_i$$

20 million Moller electrons per spill





Detector D, Current I: F = D/I

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

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

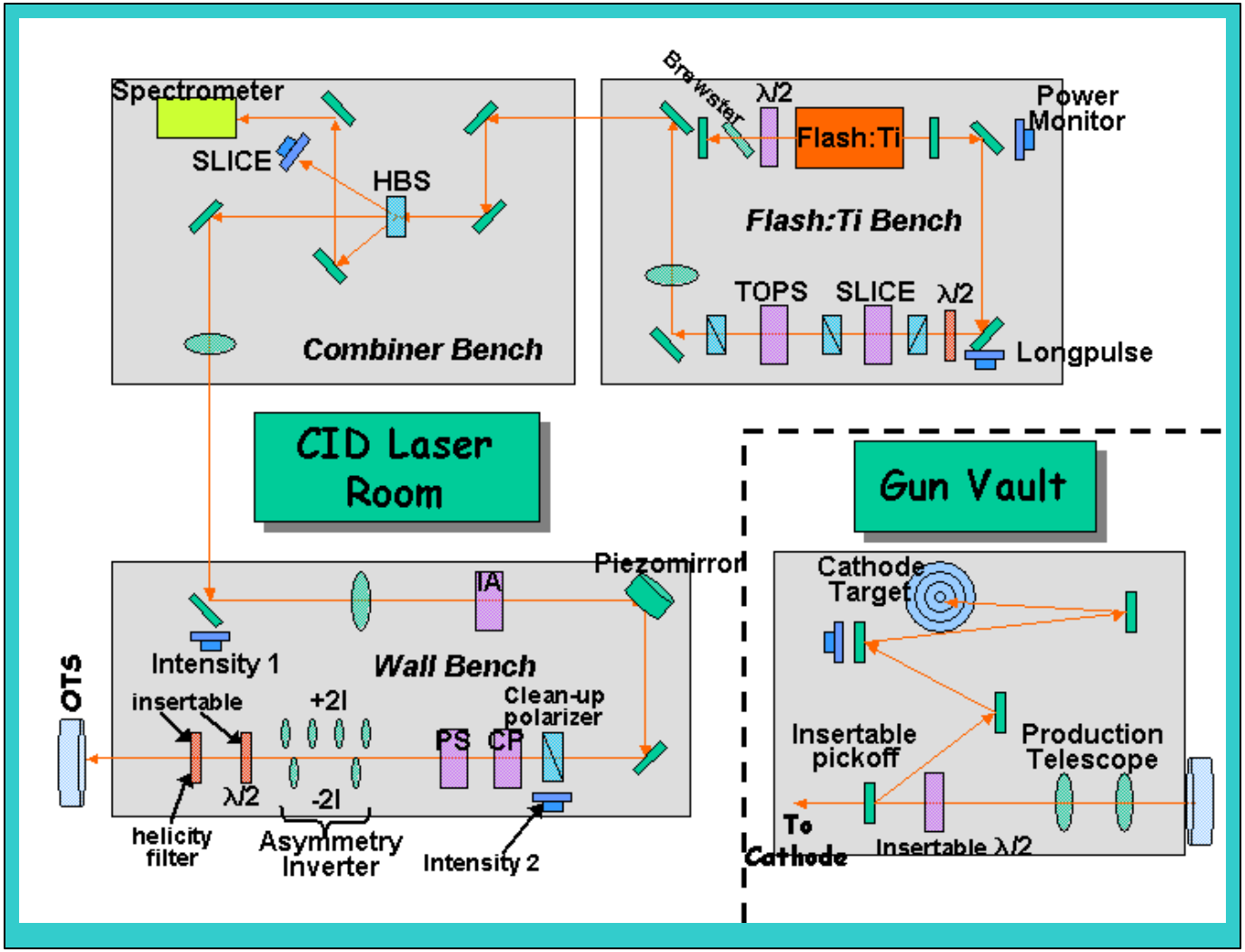
Integrate Detector response: Flux Counting

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

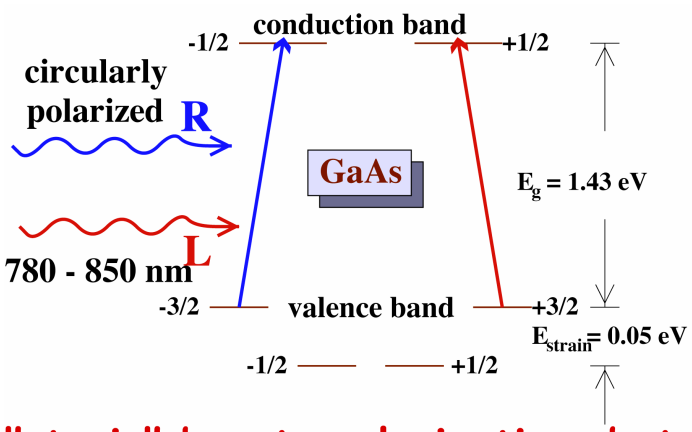
					linac tune
jitter (ppm)	200	5000	1000	500	
accuracy (ppm)		30	30	50	
cumulative (ppb)	110 +/-9	200 +/-1	20 +/-2	10 +/-2	

→ *precision monitoring and control of electron beam fluctuations*

Polarized Laser + GaAs cathode = Polarized Electron Beam

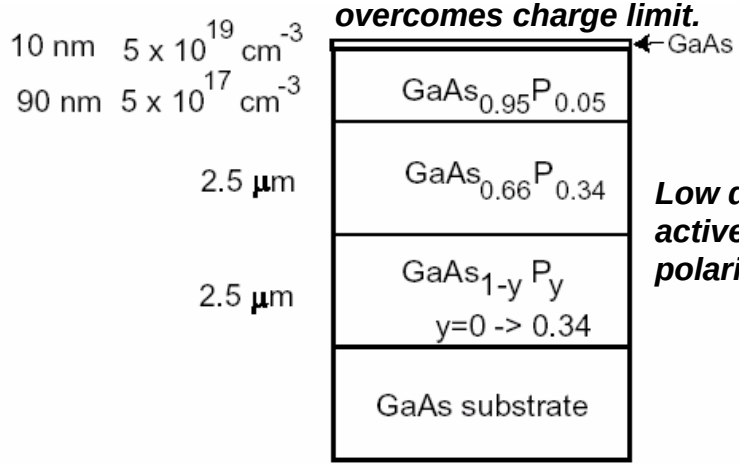


Polarized Source: GaAs cathode



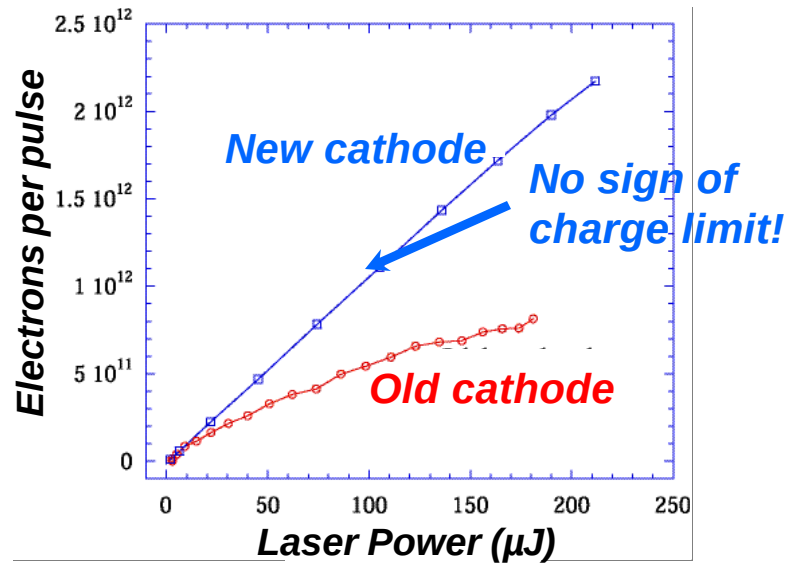
"strain" boosts polarization, but introduces anisotropy in response

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

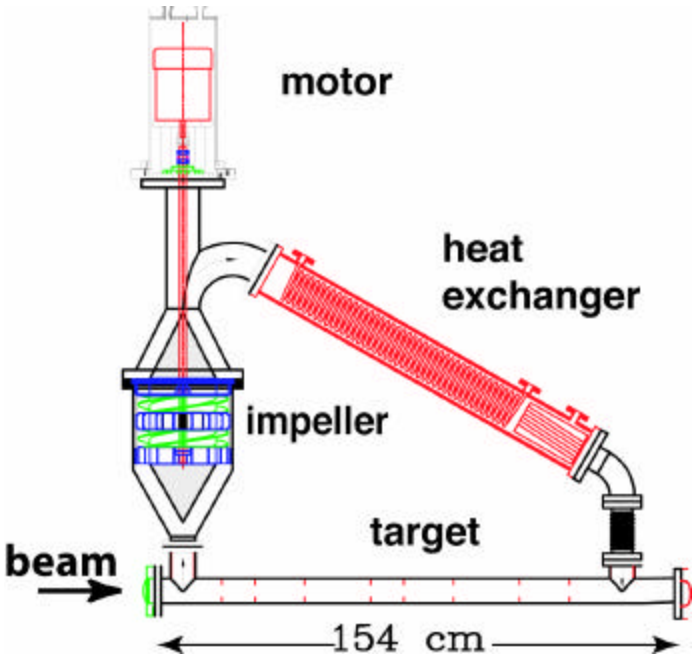


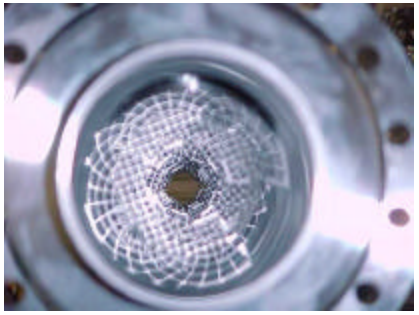
Low doping for most of active layer yields high polarization.

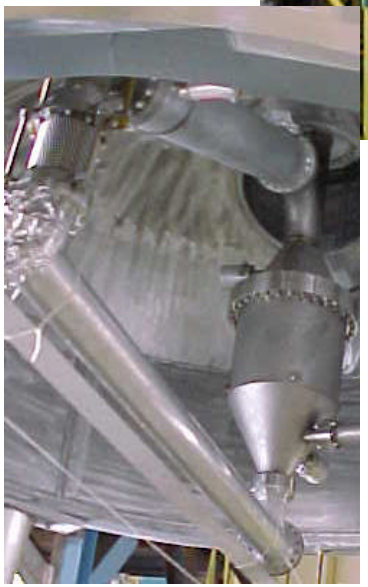
Parameter	E158	NLC-500
Charge/Train	6 x 10^{11}	14.3 x 10^{11}
Train Length	270ns	260ns
Bunch spacing	0.3ns	1.4ns
Rep Rate	120Hz	120Hz
Beam Energy	45 GeV	250 GeV
e^- Polarization	80%	80%



Liquid Hydrogen Target

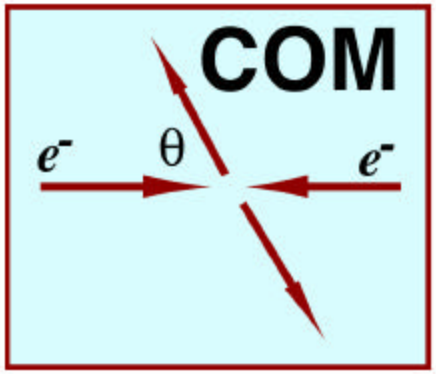


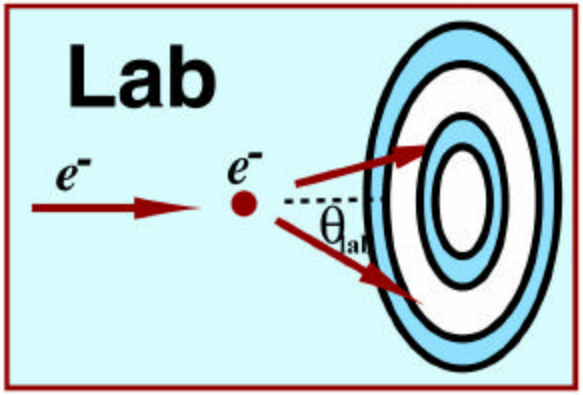


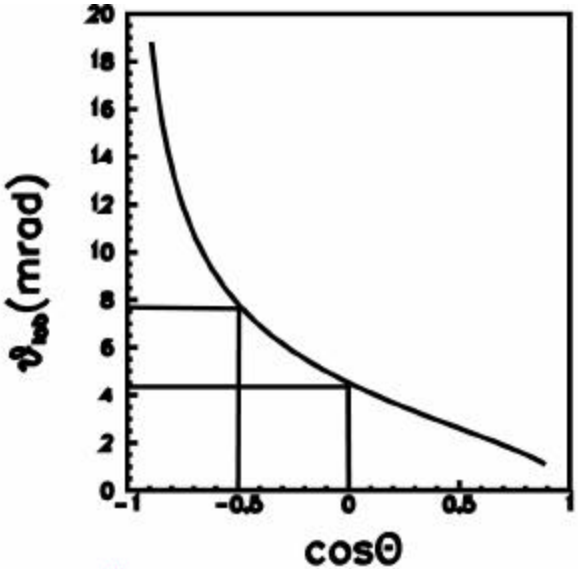


Refrigeration Capacity	**1 kW**
Operating Temperature	**20 K**
Length	**1.5 m**
Flow Rate	**5 m/s**
Vertical Motion	**6 inches**

Kinematics

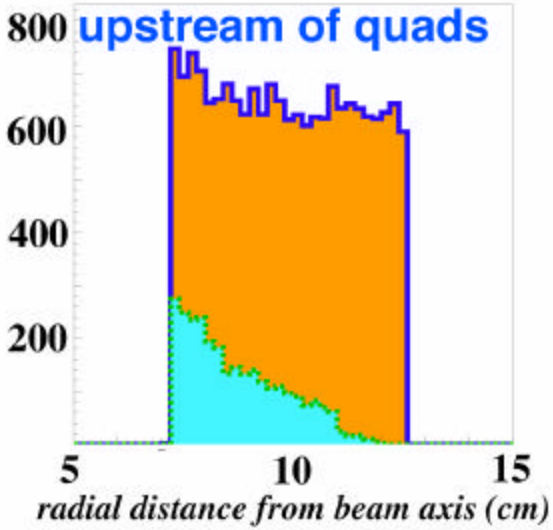


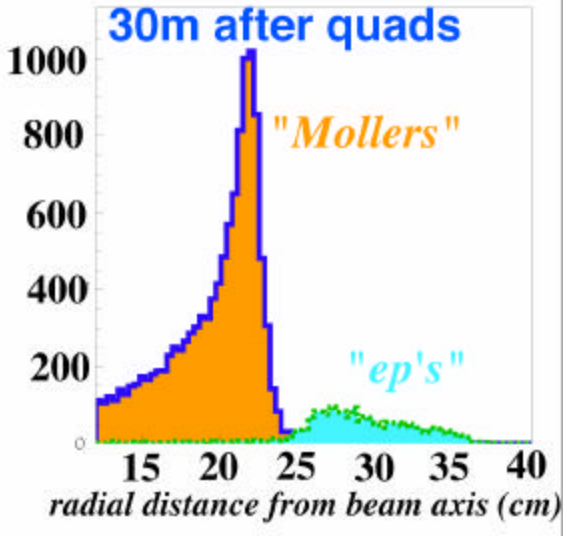




Quadrupole Quadruplet

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

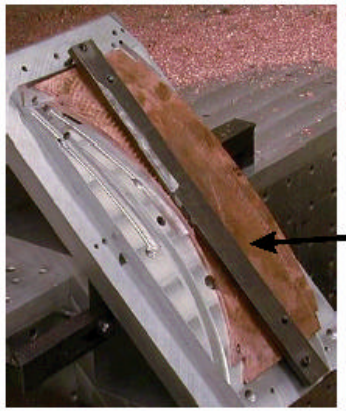


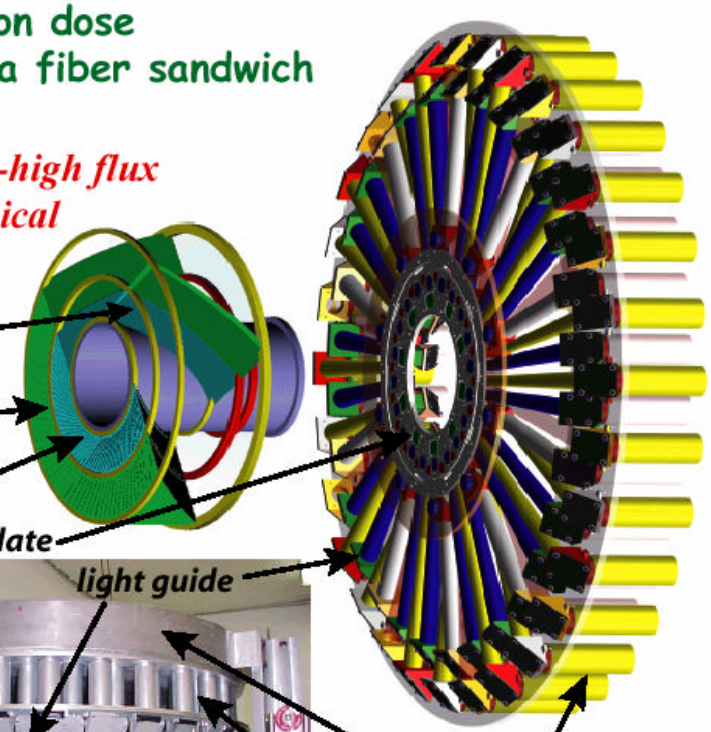


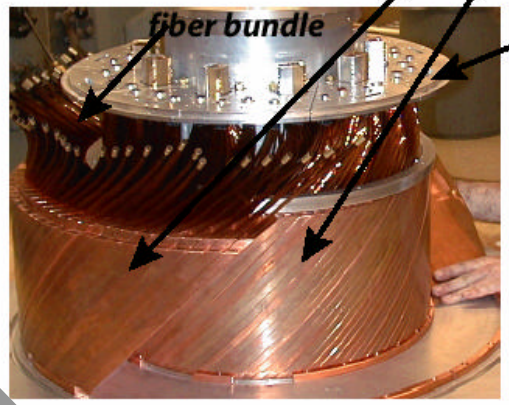
Møller Detector

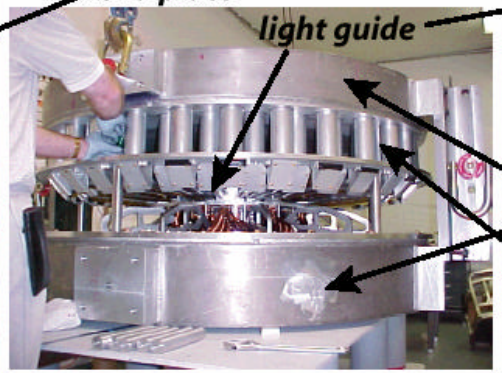
- 20 million electrons/pulse at 120 Hz
- 100 MRad radiation dose
- Copper/fused silica fiber sandwich

- state of the art in calorimetry at ultra-high flux
- challenging cylindrical geometry

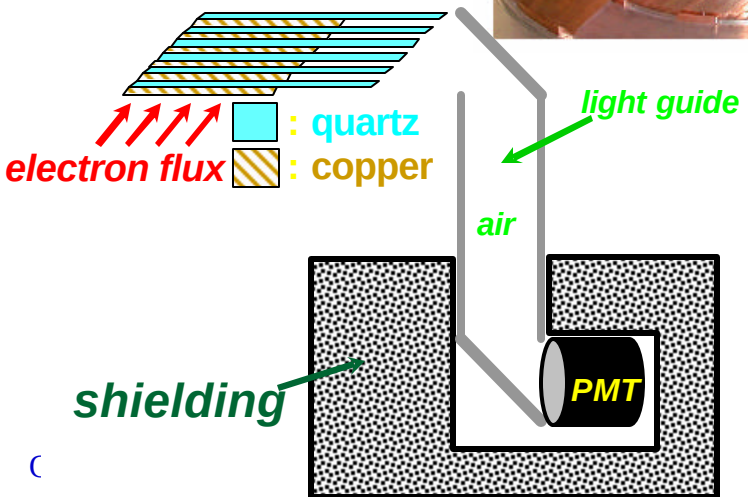








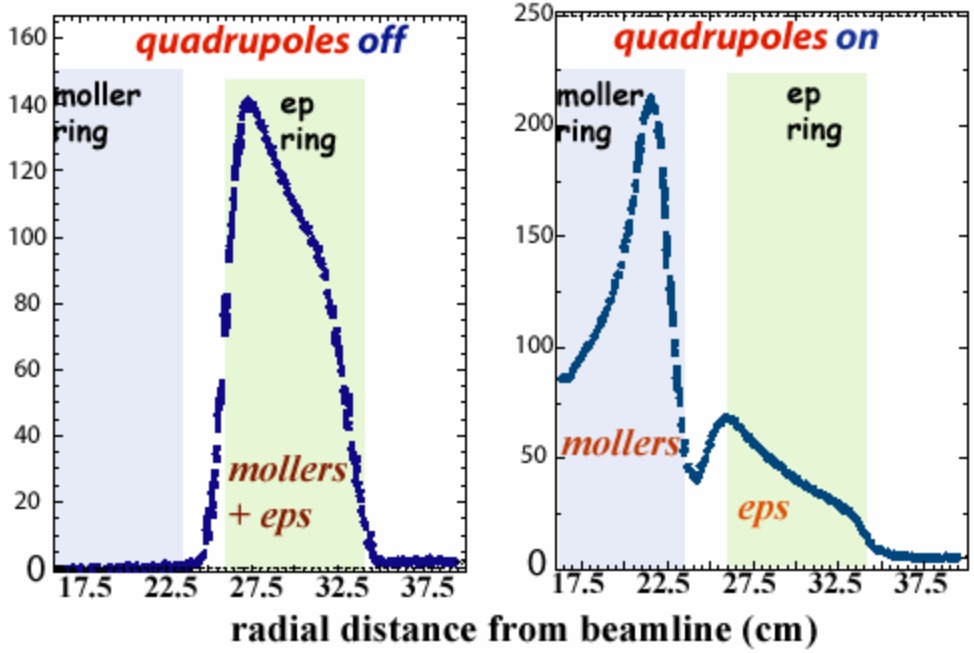
Basic Idea:

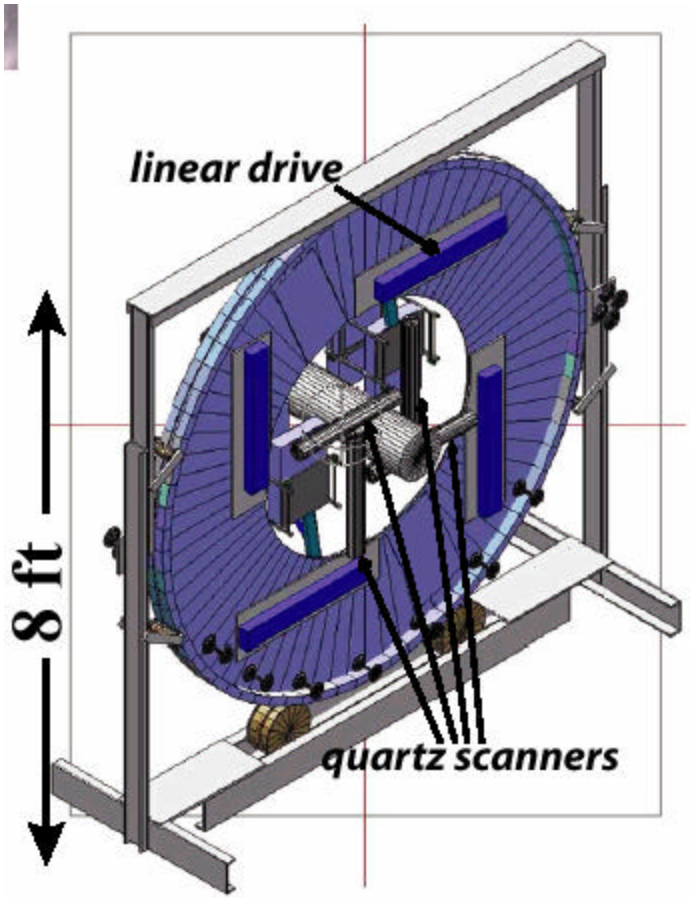


Profile Detector

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

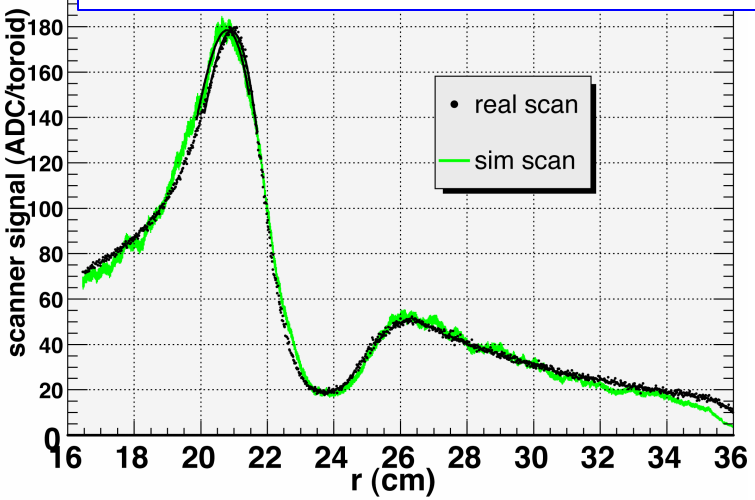
- Radial and azimuthal scans
  - collimator alignment, spectrometer tuning
  - background determination
  - Q^2 measurement



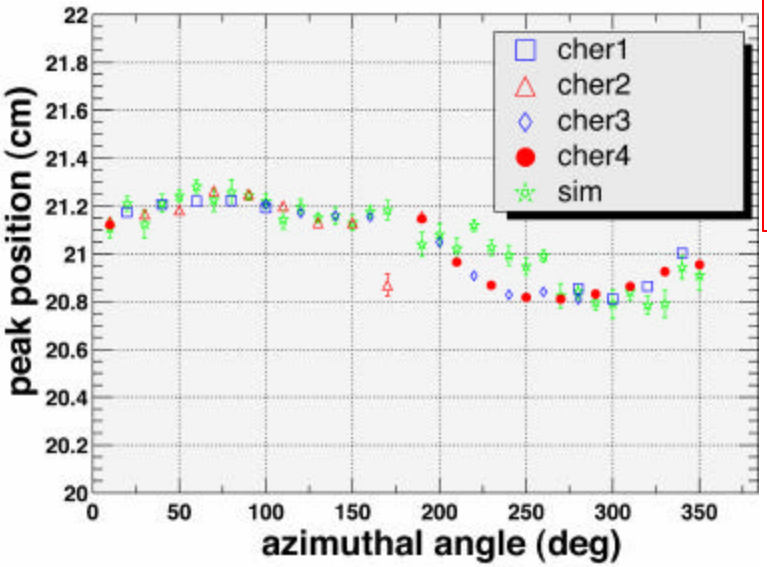


Scattered Flux Profile

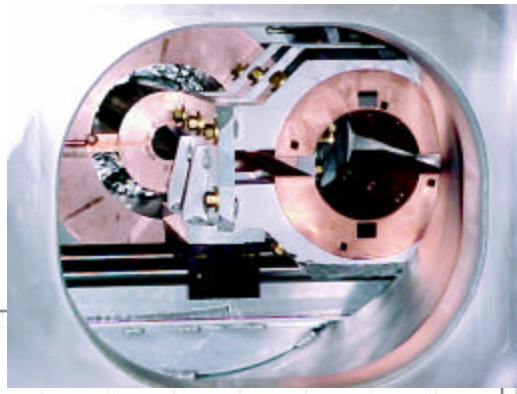
Møller peak scan: data vs **Monte Carlo**

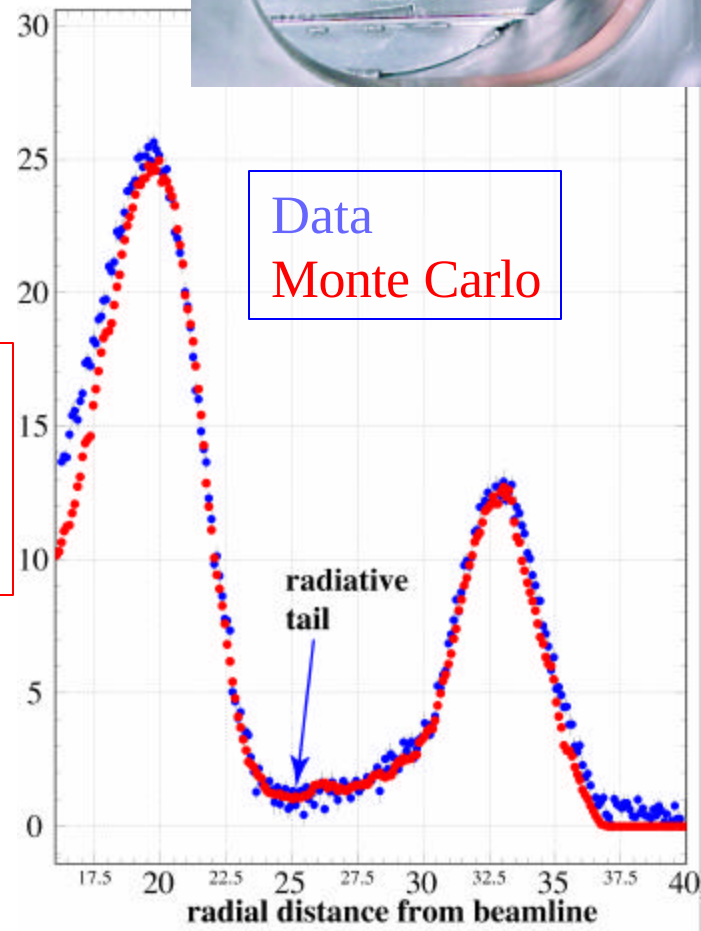


Møller scattering kinematics:
$\langle Q^2 \rangle = 0.026\ \mathrm{GeV}^{-2}$
$\langle y \rangle = 0.6$

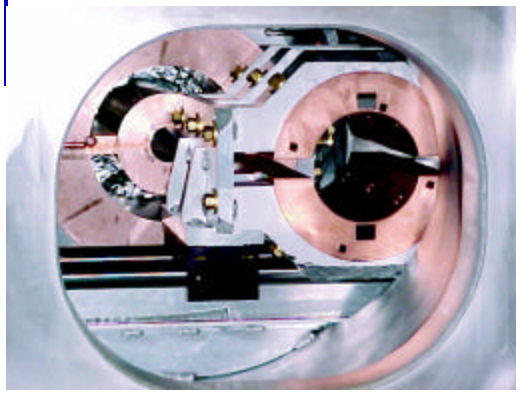


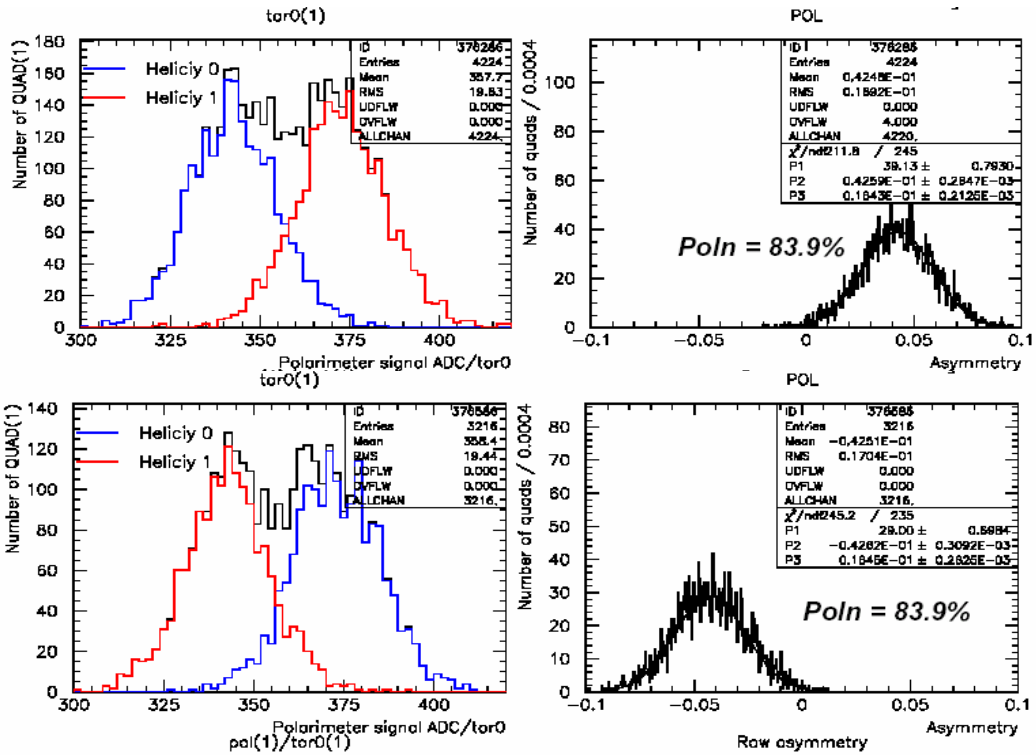
- ~2 mm geometry
- 1% energy scale
- Radiative tail
- <1% background

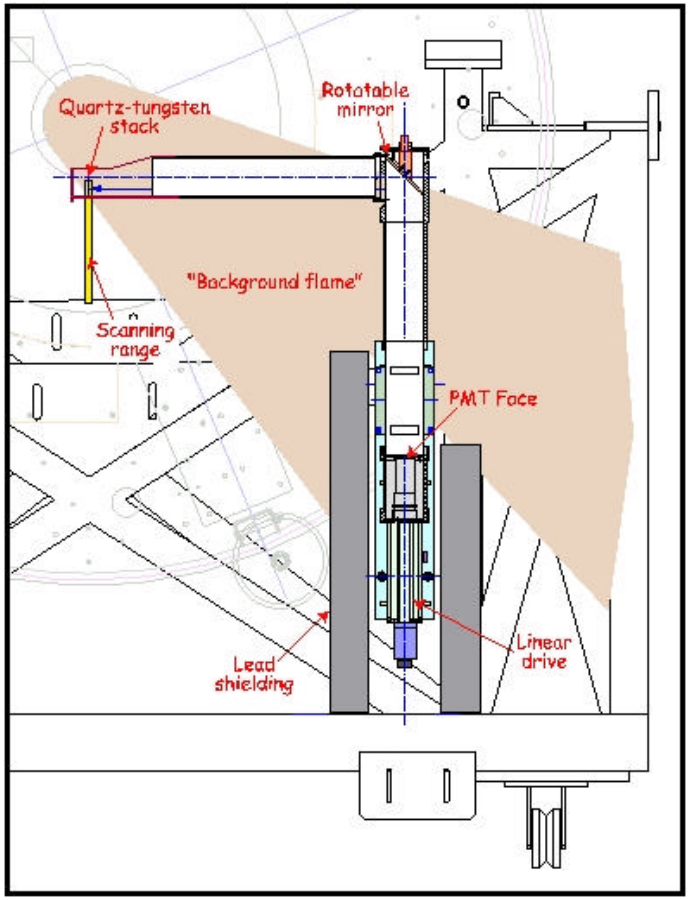




Polarimetry

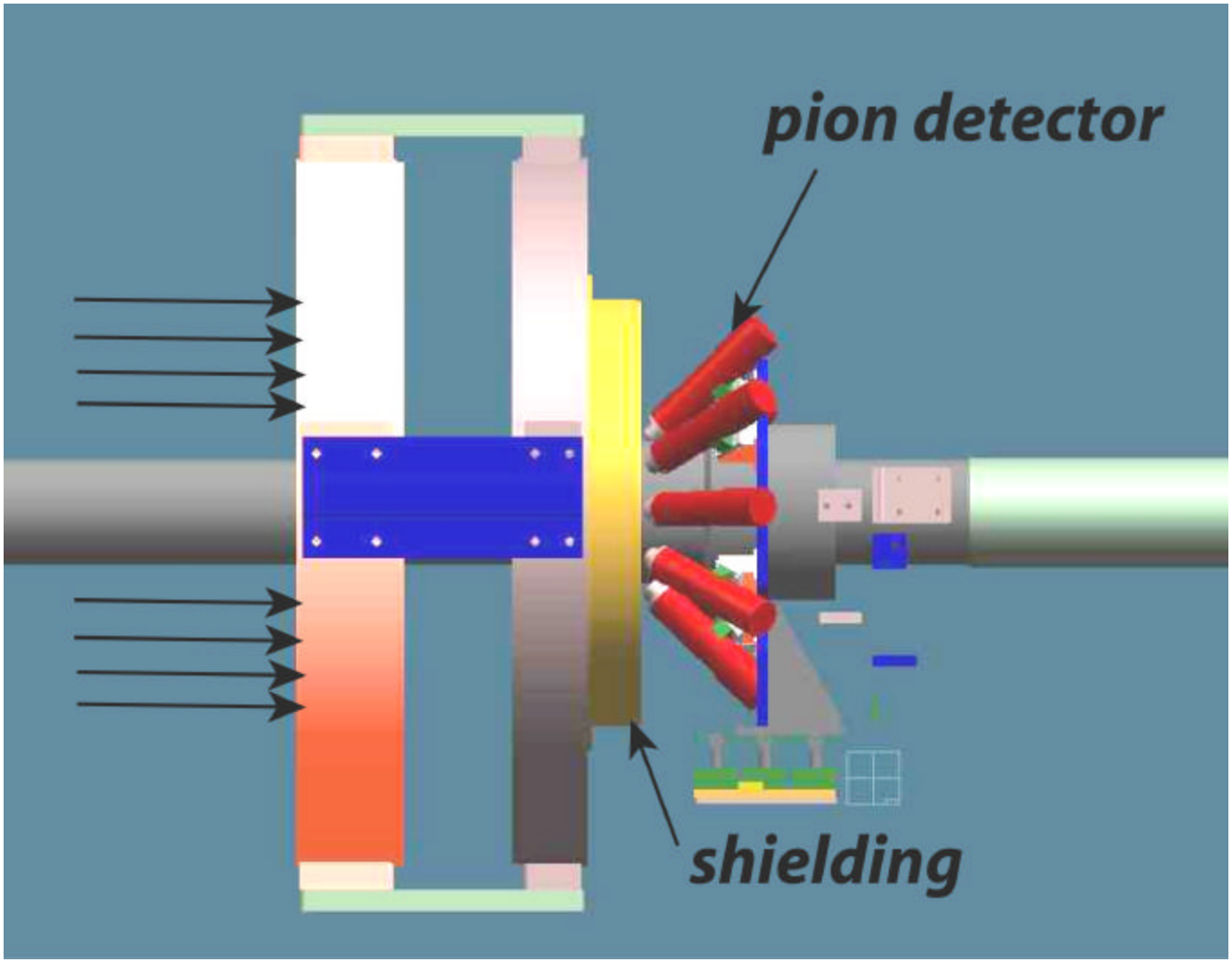






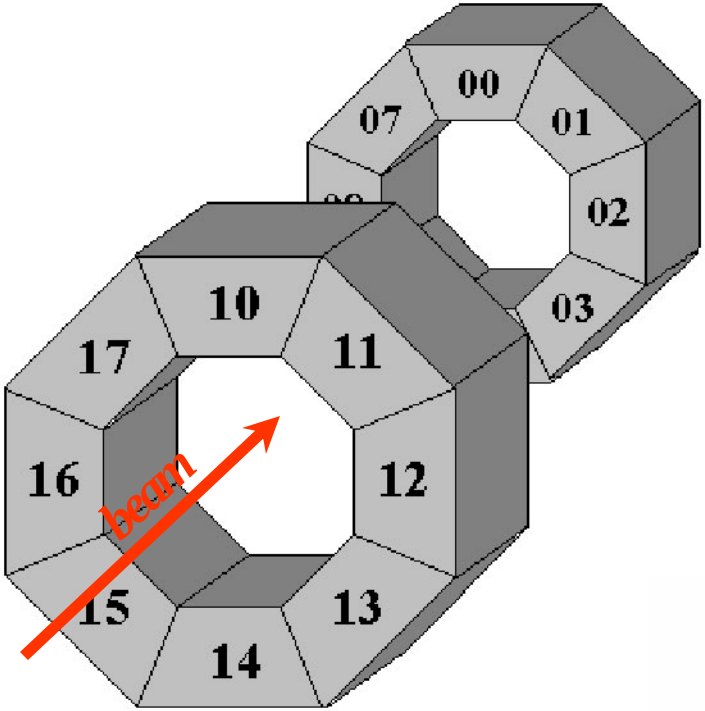
84.9 +/- 4.4 % polarization throughout Run I

Pion Detector



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

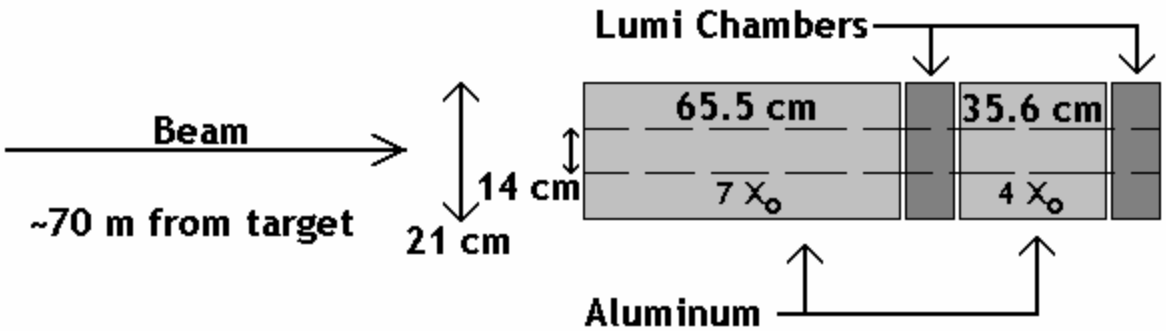
Luminosity Monitor



Segmented ion chamber detector with aluminum preradiator

500W incident power
(50W from synchrotron radiation)

Signal: eps and high energy Møllers
350M electrons per pulse;
<E> ~ 40 GeV
θ_{lab} ~ 1 mrad



- Null asymmetry measurement
- Enhanced sensitivity to beam and target density fluctuations

Asymmetry Corrections and Systematics

Correction	f_{bkg}	$\sigma(f_{bkg})$	A_{corr} (ppb)	$\sigma(A_{corr})$ (ppb)
Beam asymmetries	-	-	-	4
Beam spotsize	-	-	0	1
Transverse asymmetry	-	-	-4	2
ep elastic	0.058	0.007	-8	2
ep inelastic	0.009	0.003	-22	6
High energy photons	0.004	0.002	+3	3
Synchrotron photons	0.0015	0.0005	0	2
Neutrons	0.0006	0.0002	-1	1
Brem and Compton electrons	0.005	0.002	0	1
Pions	0.001	0.001	1	1
TOTAL	0.082	0.009	-27	8

- Scale factors:
  - Average Polarization 88 ± 5%
  - Linearity 99 ± 1%
  - Radiative corrections: 1.016 ± 0.005

Preliminary Results

$A_{PV}(e^-e^- \text{ at } Q^2=0.026\ \text{GeV}^2) = -128 \pm 14\ (\text{stat}) \pm 12\ (\text{syst})$ ppb

➔ *Significance of parity non-conservation in Møller scattering:* 8 σ

$\sin^2 q_{eff}(Q^2=0.026\ \text{GeV}^2) = 0.2403 \pm 0.0010\ (\text{stat}) \pm 0.0009\ (\text{syst})$

➔ *Most precise measurement at low Q^2*

➔ *Significance of running of* $\sin^2 q_W$: 7 σ

$\sin^2 q_W^{\overline{MS}}(M_Z) = 0.2330 \pm 0.0011\ (\text{stat}) \pm 0.0010\ (\text{syst})$

➔ *Standard Model pull:* **+1.2** s