Electroweak Measurements at Low Q^2

Precision Tests of the Standard Model

Yury Kolomensky
UC Berkeley

Physics in Collision
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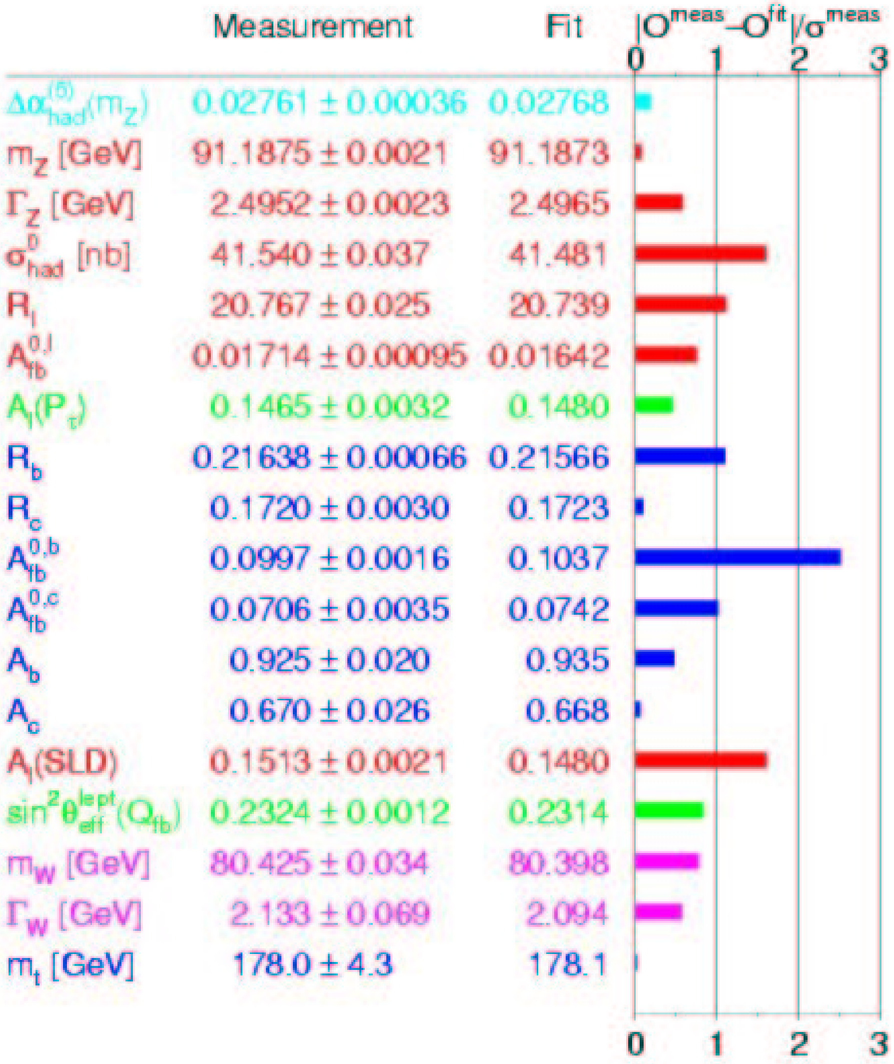
quark - lepton
Boston, MA - June 27-29, 2004

Outline

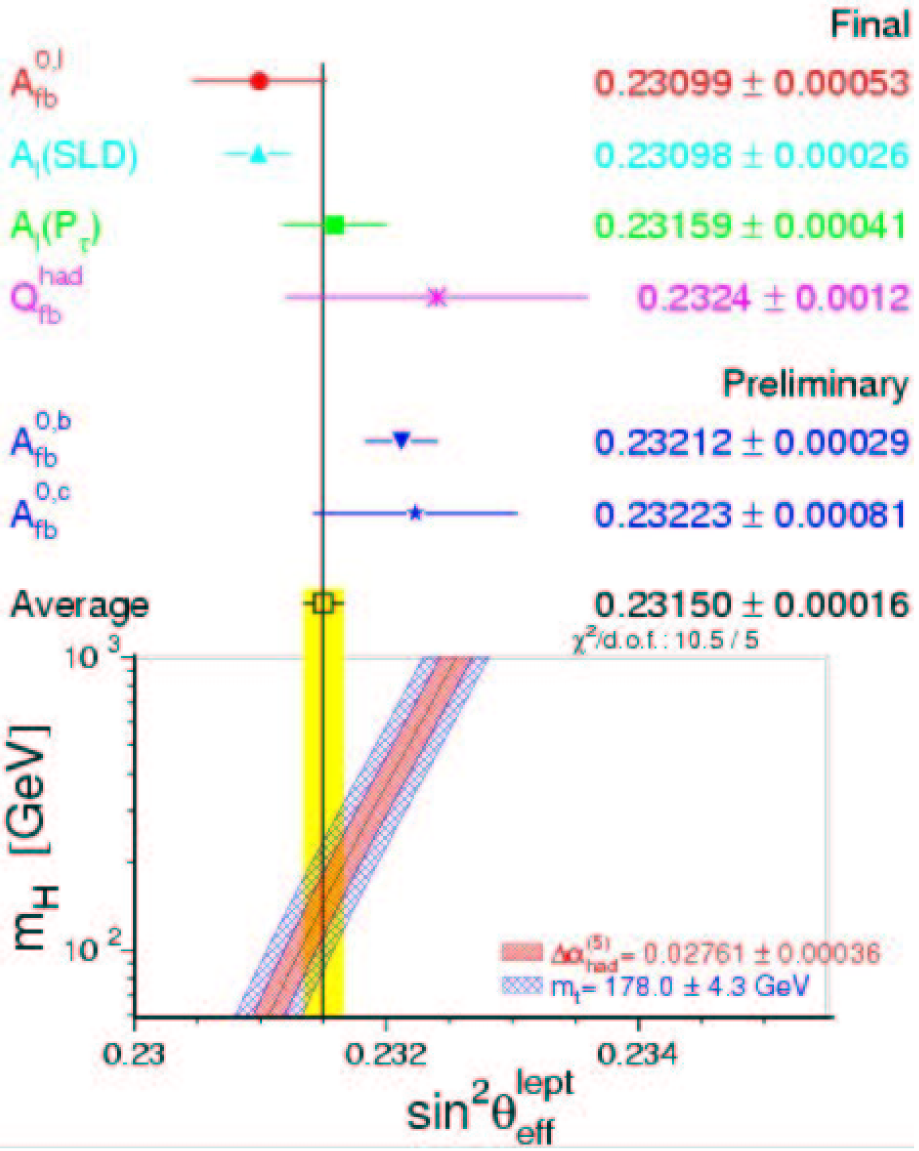
- Motivation
- Experiments (not covered by previous speakers ☺)
  - ☐ Atomic Parity Violation
  - ☐ Neutrino Scattering
  - ☐ PV in electron scattering
- New results from SLAC E158
- Outlook

“High Q^2” Electroweak Data

Winter 2004 (LEP EWWG)



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
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	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21638 ± 0.00066	0.21566
R_c	0.1720 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0742
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.398
Γ_W [GeV]	2.133 ± 0.069	2.094
m_t [GeV]	178.0 ± 4.3	178.1



"High Q^2" EW Data

- Spectacular precision
  - ❑ Quantum loop level (LO to NNLO)
  - ❑ Precise indirect constraints on top and Higgs masses
  - ❑ General consistency with the Standard Model
    - ☞ Few smoking guns
    - ☞ Leptonic and hadronic Z couplings seem inconsistent ?
- Direct searches have not yielded new physics phenomena (so far)

➔ Complementary sensitivity at low energies
  - ❑ Rare or forbidden processes
  - ❑ Symmetry violations
  - ➔ Precision measurements

Direct vs Indirect Searches

(according to Grimm Brothers)

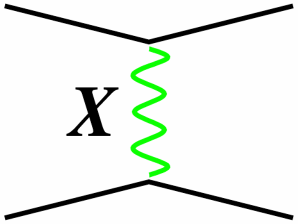
Classic Probes of Weak Interactions

- Charged current: beta decays
  - ❑ Muon beta decay: G_F
  - ❑ Neutron beta decay: universality
  - ❑ Parity Violation
- Neutral currents
  - ❑ Neutrino scattering (CERN, 1972)
  - ❑ Atomic Parity Violation (Novosibirsk, 1978)
  - ❑ PV in Electron Scattering (SLAC, 1978)

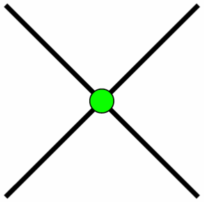
➔ Same techniques used today to look for physics beyond the Standard Model

Electroweak Physics Away from Z pole

consider



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



Contact interaction

$Q^2 \sim M_Z^2$

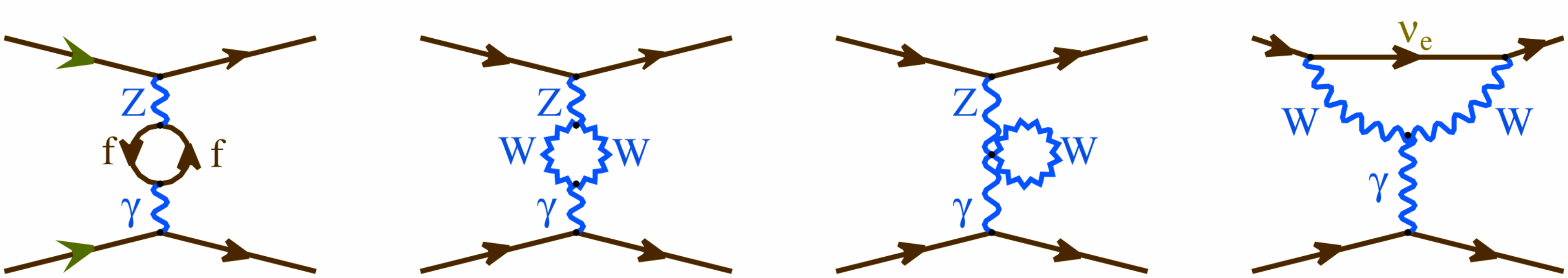
on resonance:
A_Z ***imaginary***

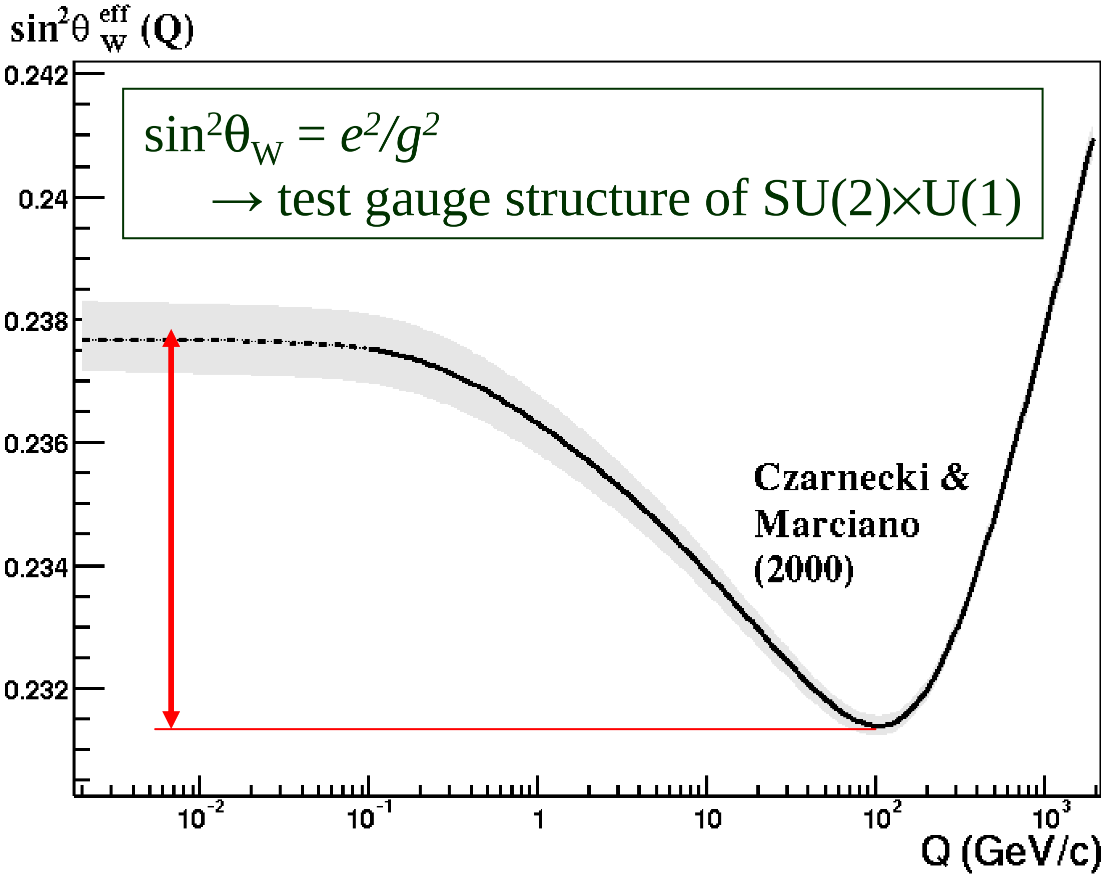
$$\longrightarrow A_Z^2\left[1+\frac{A_X^2}{A_Z^2}\right]$$

no interference!

- ➔ Precision Z observables establish anchor points for SM
- ➔ Low energy observables probe interference between SM and NP
- ➔ Current “low energy” experiments are accessing scales of beyond 10 TeV

Running of Weak Mixing Angle



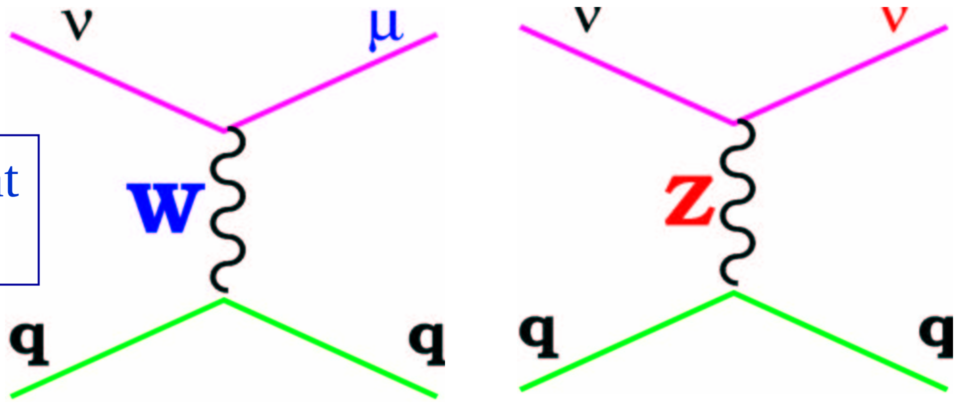


$\sin^2\theta_W = e^2/g^2$

→ test gauge structure of SU(2)×U(1)

Neutrino-Nucleon Scattering

Charged-Current (CC)



Neutral-Current (NC)

CC coupling ~ T_3

NC coupling ~ $T_3 - Q\sin^2\theta_W$

- Measure ν *NC/CC* ratio to extract ratio of weak couplings
  - ❑ Experimental and theoretical uncertainties for $\sin^2\theta_W$ suppressed in the ratio
- NuTeV uses both neutrino and anti-neutrino beams: form

Paschos - Wolfenstein Relation

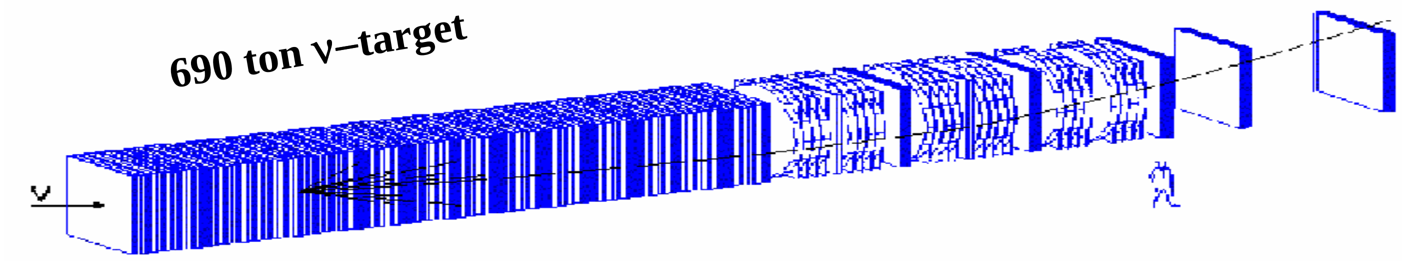
$$R^- = \frac{\sigma^\nu_{NC} - \sigma^{\bar\nu}_{NC}}{\sigma^\nu_{CC} - \sigma^{\bar\nu}_{CC}} = \rho^2\left(\tfrac{1}{2} - \sin^2\theta_W\right) = g_L^2 - g_R^2$$

$$g_{L,R}^2 \equiv u_{L,R}^2 + d_{L,R}^2$$

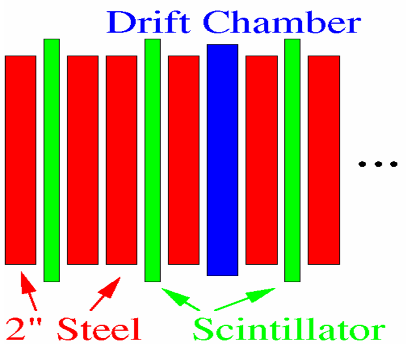
$$\sigma\left(\nu_\mu q_{sea}\right) - \sigma\left(\bar\nu_\mu \bar q_{sea}\right) = 0$$

$\Rightarrow$ Only valence quarks contribute

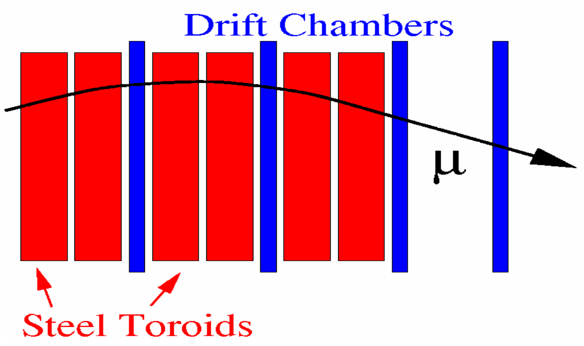
NuTeV Detector



Target / Calorimeter



Toroidal Spectrometer



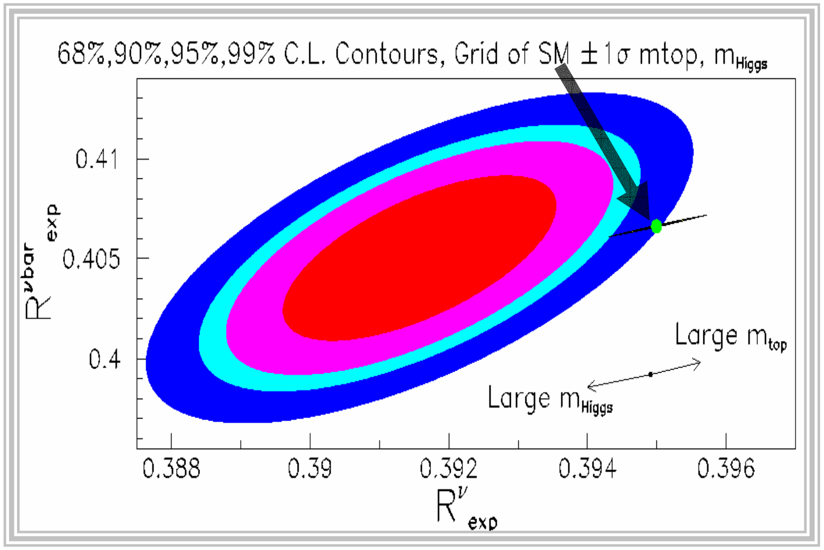
- 168 Fe plates provide mass
- 84 liquid scintillation counters
  - ❑ Trigger the detector
  - ❑ Measure: Visible energy, ν interaction point, Event length
- 42 drift chambers
  - ❑ Localize transverse vertex

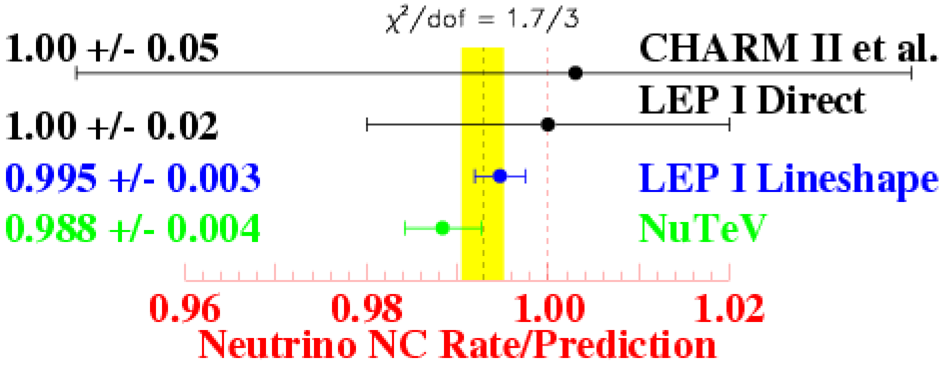
- Solid Fe magnet
  - ❑ Measures μ momentum/charge

NuTeV Result

NuTeV actually measures two ratios:

$$R^{\nu(\bar{\nu})} = \frac{\sigma_{NC}^{\nu(\bar{\nu})}}{\sigma_{CC}^{\nu(\bar{\nu})}} = \rho_0^2\left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\,(1+\frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}})\right)$$





Quote result in terms of

$$\sin^2\theta_W^{\text{on-shell}} = 0.2277 \pm 0.0013\ (\text{stat}) \pm 0.0009\ (\text{syst})$$

or

$$\sin^2\theta_W^{\overline{\text{MS}}}(M_Z) = 0.2361 \pm 0.0017\ (+3\sigma\ \text{SM pull})$$

New or Old Physics ?

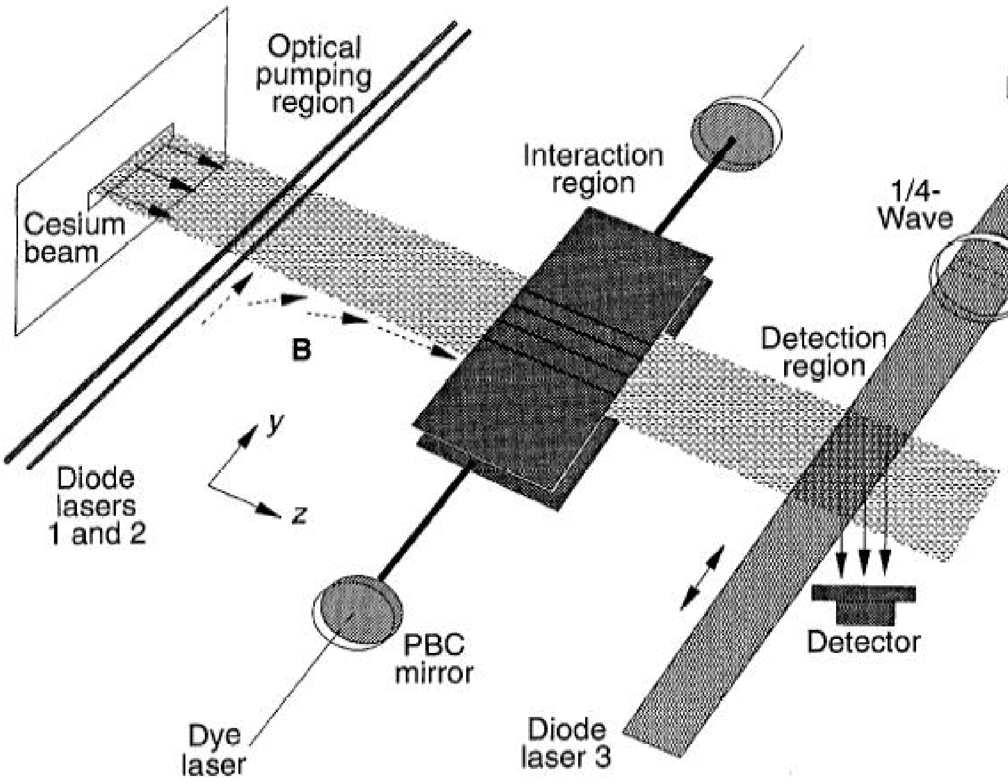
- Hard to explain NuTeV results with popular NP models
  - ❑ SUSY loops or RPV SUSY do not quite work
  - ❑ Hard to fit with leptoquarks
  - ❑ “Designer” Z’ is possible (need $g_L < g_R$)
- Possible “Old Physics” Explanations
  - ❑ Electroweak corrections
    - ☞ New calculations (hep-ph/0310364) claim significant shift in the result and underestimated uncertainties; being checked
  - ❑ QCD effects
    - ☞ Isospin violation ($u_p \neq d_n$) plausible, but large effect needed (O(5%) to move NuTeV result to Standard Model)

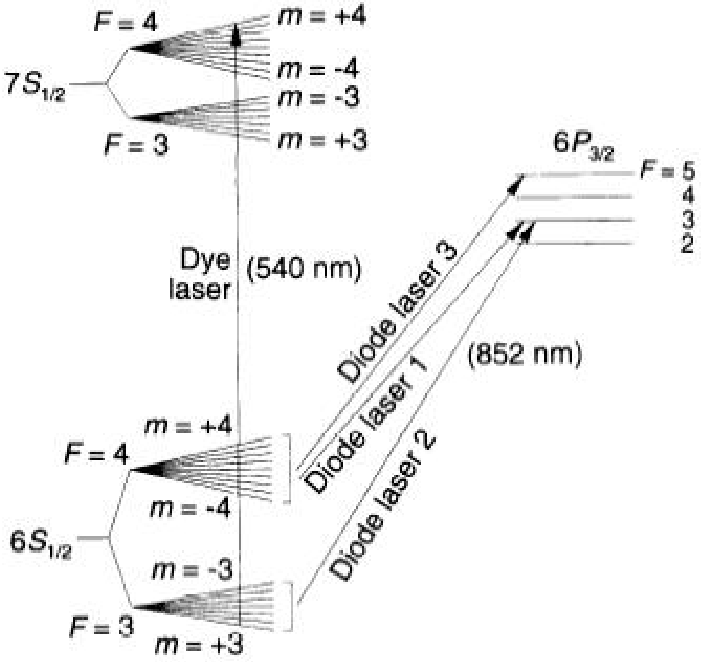
Atomic Parity Violation

- Weak neutral currents induce mixing of opposite-parity states
  - ❑ Ya. Zeldovich (1956)
  - ❑ Look for forbidden transitions
    - ☞ E.g. 1S→2S, caused by 2S-2P mixing
- Effect too small in Hydrogen atom but enhanced by Z^3 in heavy elements
  - ❑ Atomic theory simplest for alkali atoms
  - ❑ High-level transitions accessible by lasers
    - ☞ 6S →7S in Cs

Boulder Cs PNC Experiment

1982-1999





- P-odd, T-even correlation: $\boldsymbol{\sigma}\cdot [\boldsymbol{E} \times \boldsymbol{B}]$ (Stark interference)
- 5 reversals to distinguish PNC from systematics

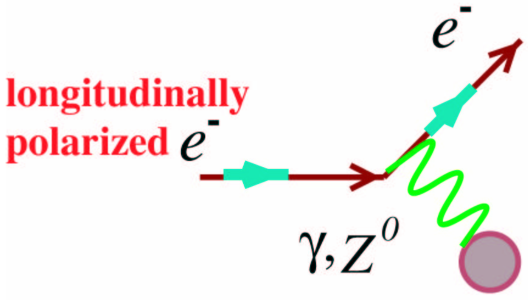
APV Results

- APV measures the “weak charge” (neutral current vector coupling) of the nucleus

$$Q_W = \rho\ [Z(1-4\sin^2\theta_W)-N]$$

- ❑ Standard Model: $Q_W(^{133}\text{Cs}) = -73.19 \pm 0.03$
- ❑ Experiment: $Q_W(^{133}\text{Cs}) = -72.69 \pm 0.48$
  - ☞ 0.4% experimental and 0.5% theoretical uncertainty, primarily from Cs atomic wave function
  - ☞ Equivalent to $\sin^2\theta_W(M_Z) = 0.2292 \pm 0.0019$ (-1σ SM pull)
- Future improvements:
- ❑ Isotope measurements (e.g. Yb)
  - ☞ 0.3% on Q_W(Yb) or ~0.001 on $\sin^2\theta_W$

Weak-Electromagnetic Interference in Electron Scattering

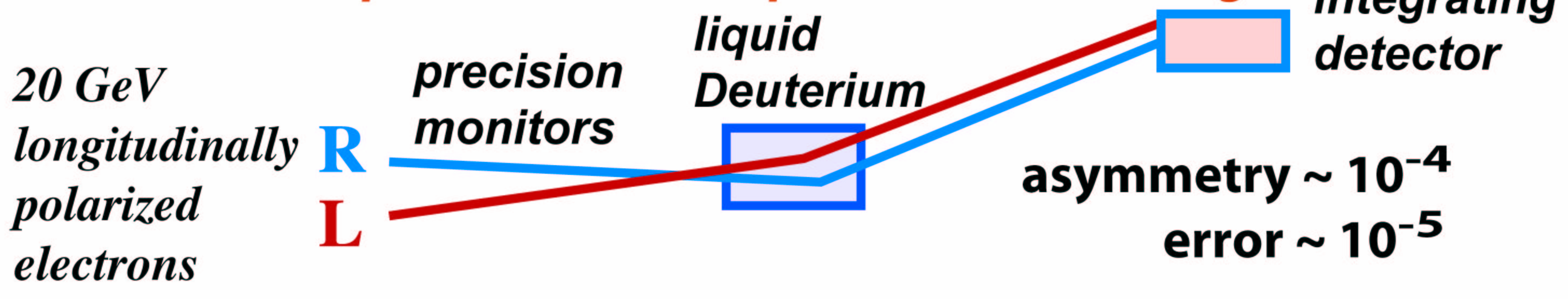


$$-A_{LR} = A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{\gamma}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

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

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

SLAC E122: lepton-nucleon deep inelastic scattering



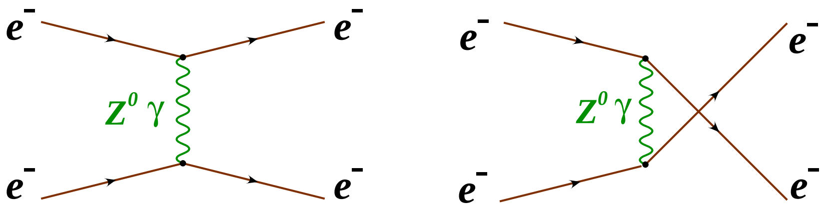
20 GeV longitudinally polarized electrons

asymmetry ~ 10^{-4}

error ~ 10^{-5}

C.Y. Prescott et.al. *1978*

Parity Violation in Møller Scattering



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

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

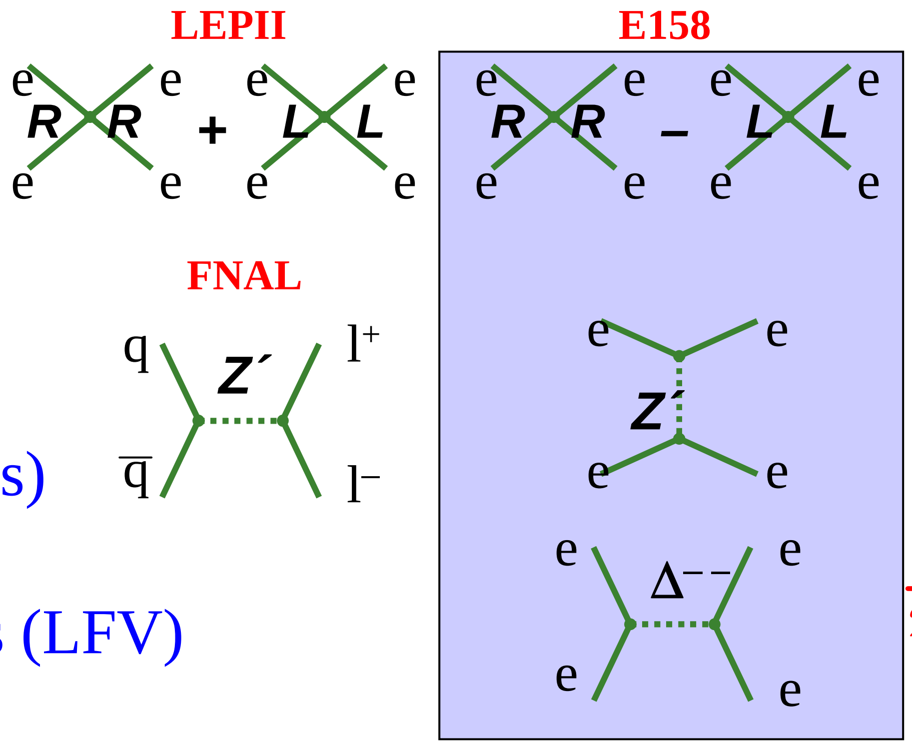
- At tree level, $A_{PV} \approx 280 \cdot 10^{-9}$
- Raw asymmetry about 130 ppb
  - ❑ Measure it with precision of 10%
  - ❑ Most precise measurement of $\sin^2\theta_W$ at low Q^2

E158: Physics Sensitivity

Compositeness

Neutral currents
(GUTs, extra dims)

Scalar interactions (LFV)



Λ~15 TeV

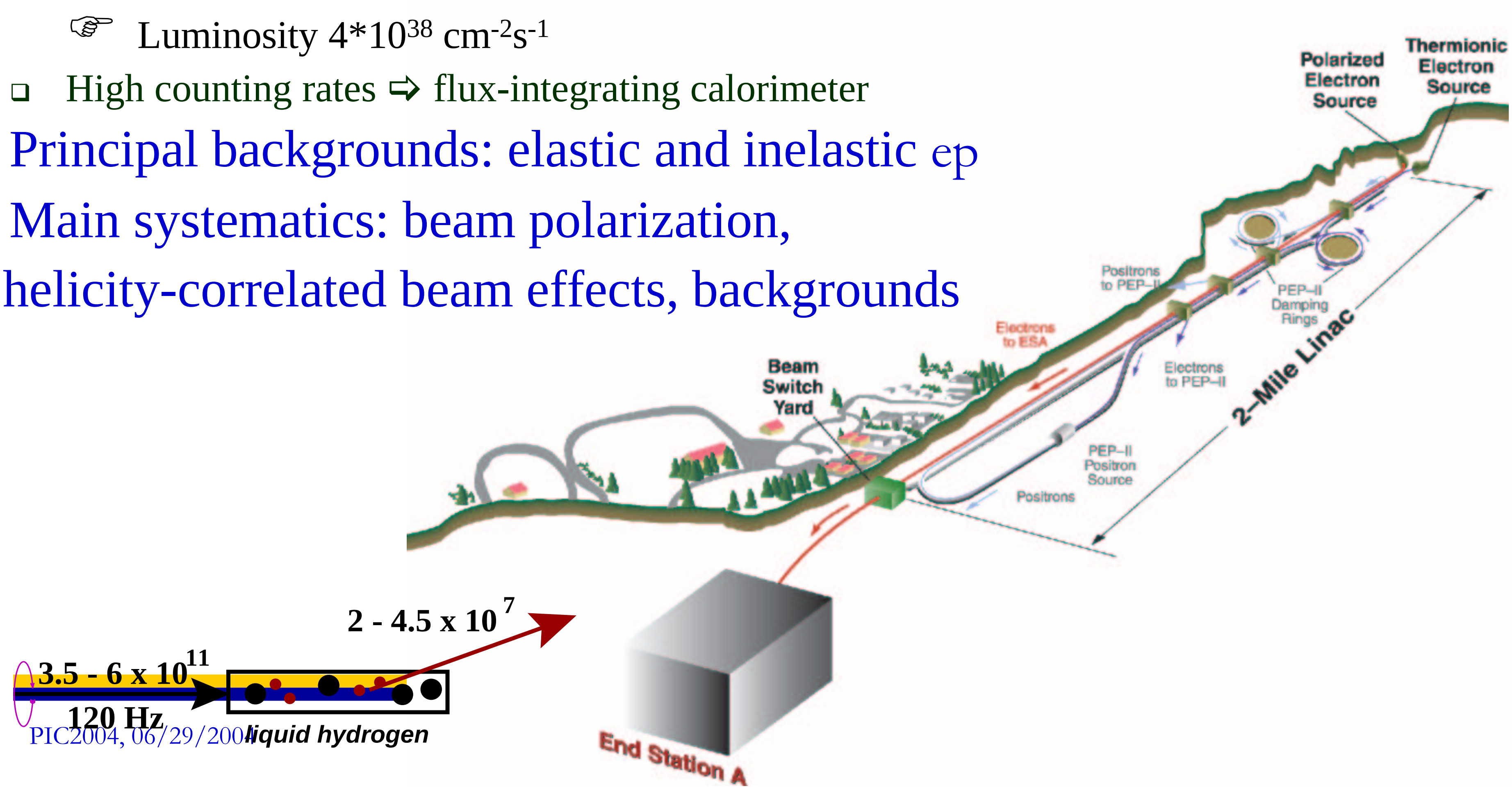
$M_{Z'}$~1 TeV

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

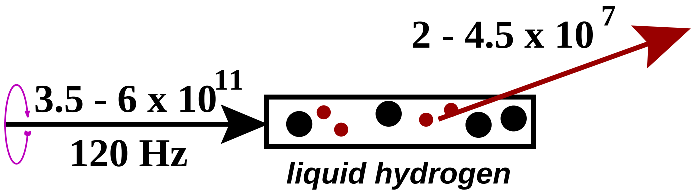
- ➔ Unique window of opportunity
- ➔ Complementary to collider searches

Experimental Technique

- Scattering of polarized electrons off atomic electrons
  - ❑ High cross section (14 μBarn)
  - ❑ High intensity electron beam, ~80% polarization
  - ❑ 1.5m LH2 target
    - ☞ 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



Rapidly flip electron helicity (120 Hz) and form pulse pairs of opposite helicity

Measure pulse-pair flux asymmetry:

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

Correct for difference in R/L beam properties:

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

charge, position, angle, energy R-L differences

coefficients determined experimentally

Physics asymmetry:

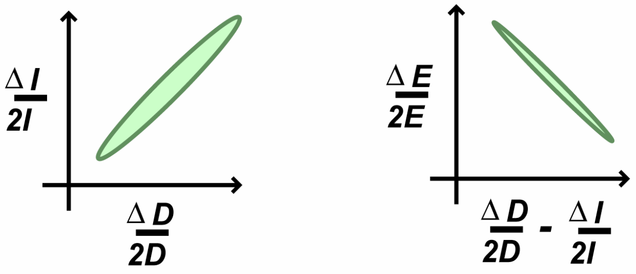
$$A_{PV} = \frac{1}{P_b} \frac{A_{raw} - f_{bkg} A_{bkg}}{1 - f_{bkg}}$$

backgrounds

beam polarization

Statistical and Systematic Fluctuations

20 million Moller electrons per spill



Detector D, Current I: F = D/I

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

Integrate Detector response: Flux Counting

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

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

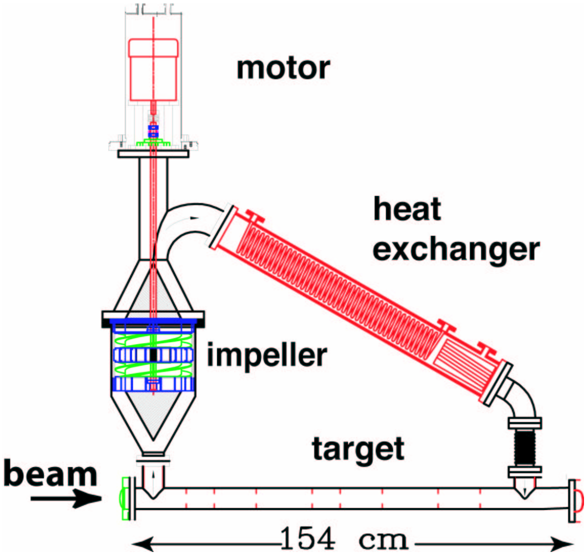
jitter (ppm)	*200*	*5000*	*1000*	*500*
accuracy (ppm)		*30*	*30*	*50*
cumulative (ppb)	110 +/-9	200 +/-1	20 +/-2	10 +/-2

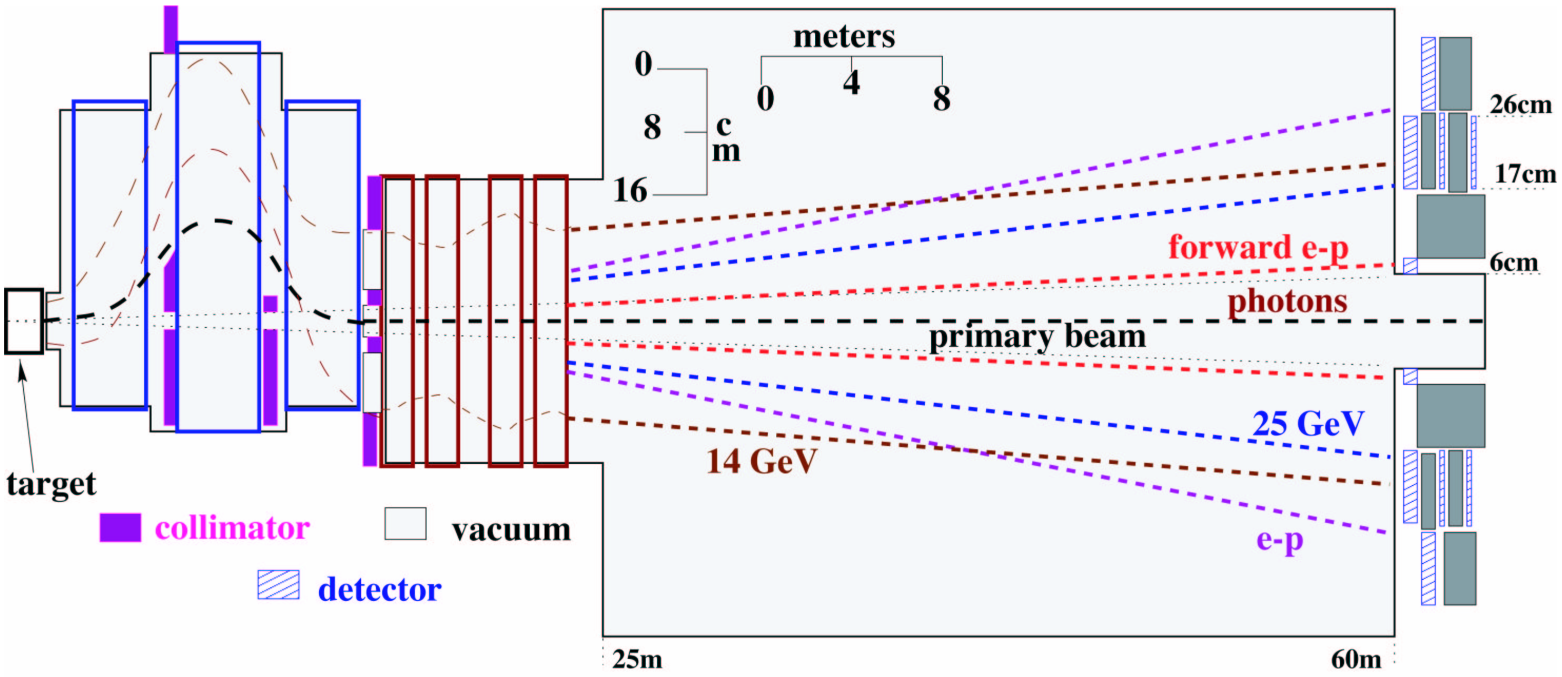
linac tune

→ ***precision monitoring and control of electron beam fluctuations***

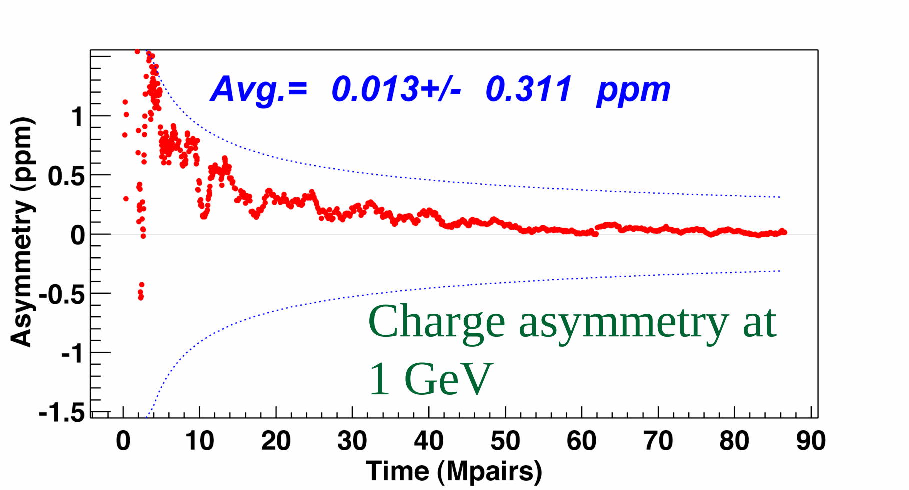
Key Ingredients

- High beam polarization and current
- Largest high-power LH2 target in the world
- Spectrometer optimized for Møller kinematics
- Stringent control of helicity-dependent systematics. Passive asymmetry reversals

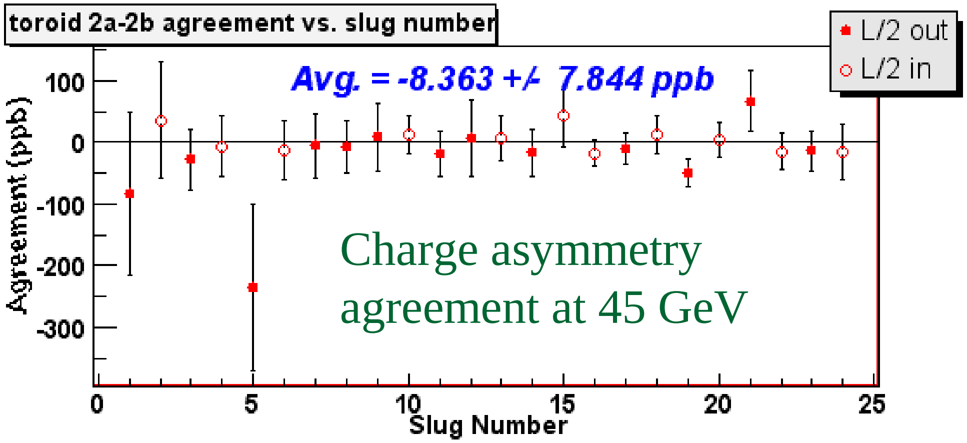




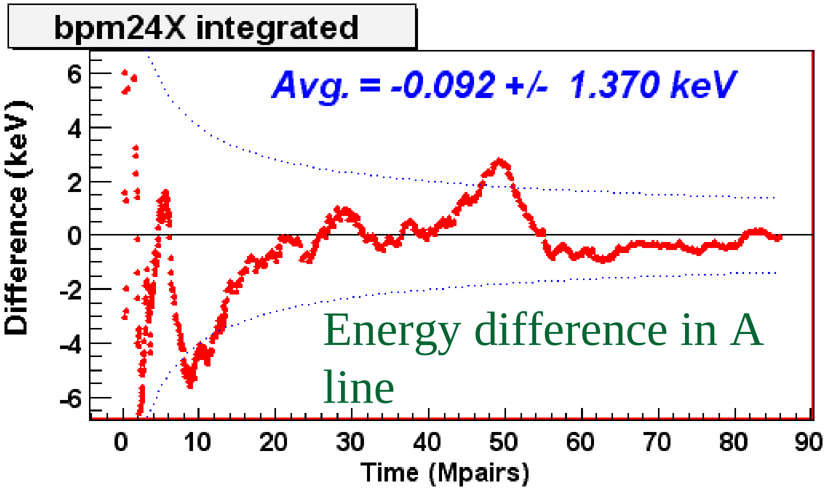
Beam Asymmetries



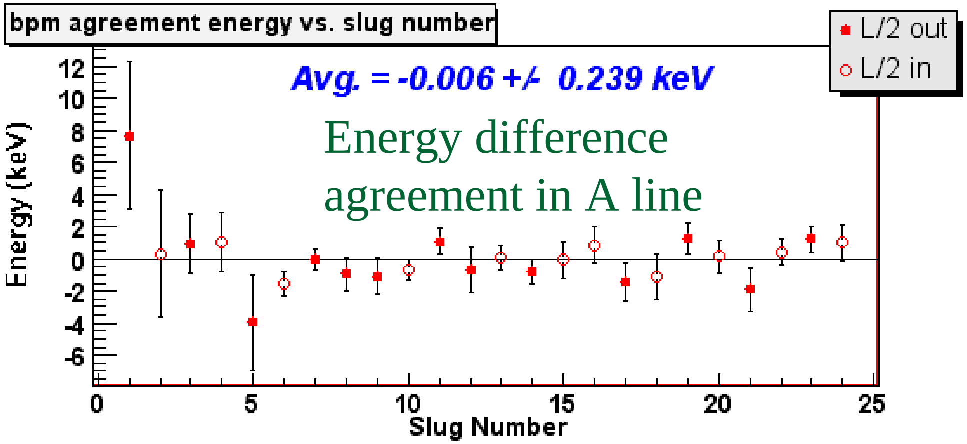
Charge asymmetry at 1 GeV



Charge asymmetry agreement at 45 GeV



Energy difference in A line

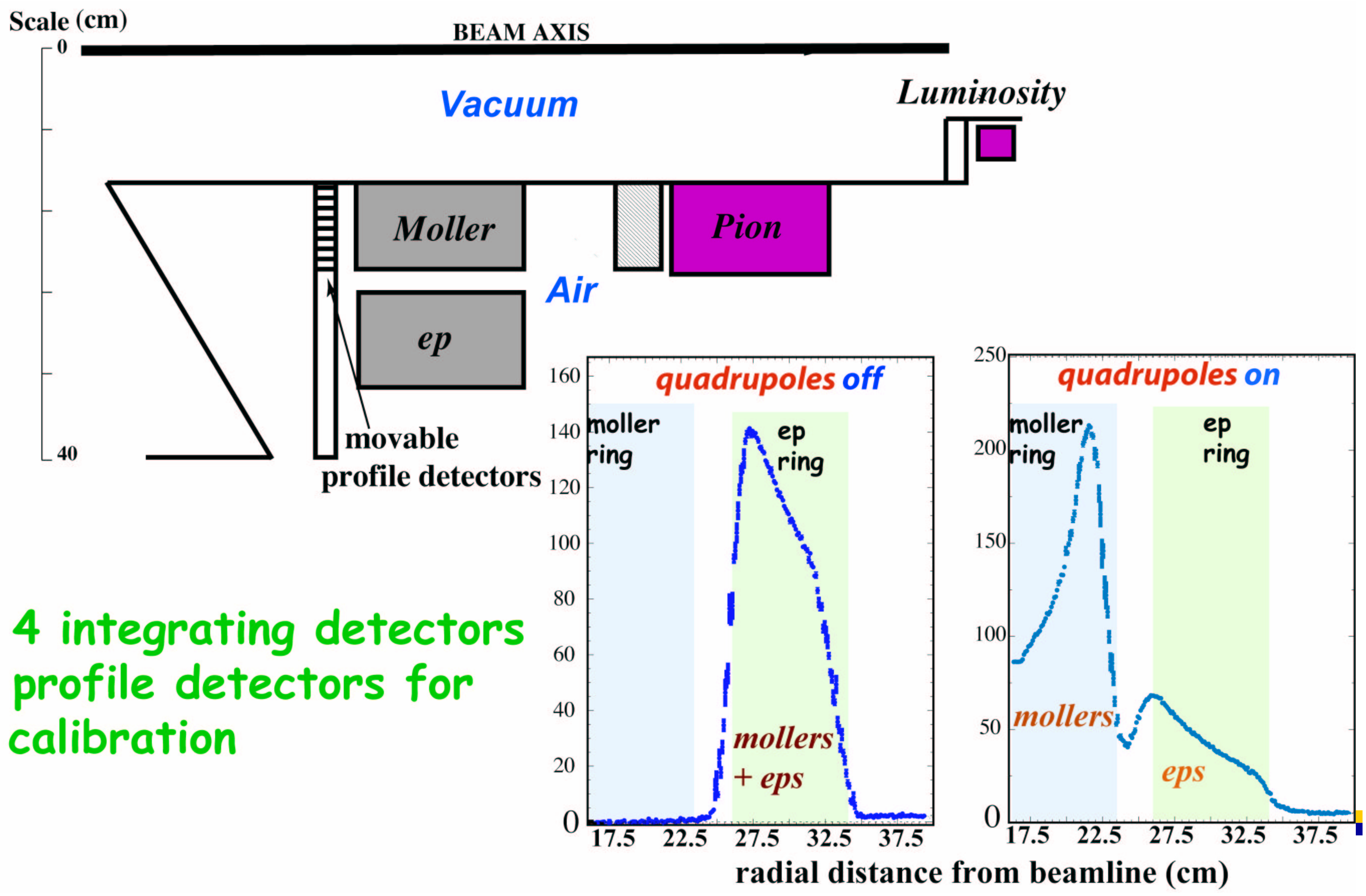


Energy difference agreement in A line

Position differences < 20 nm

Position agreement ~ 1 nm

Detector Concept



* 4 integrating detectors

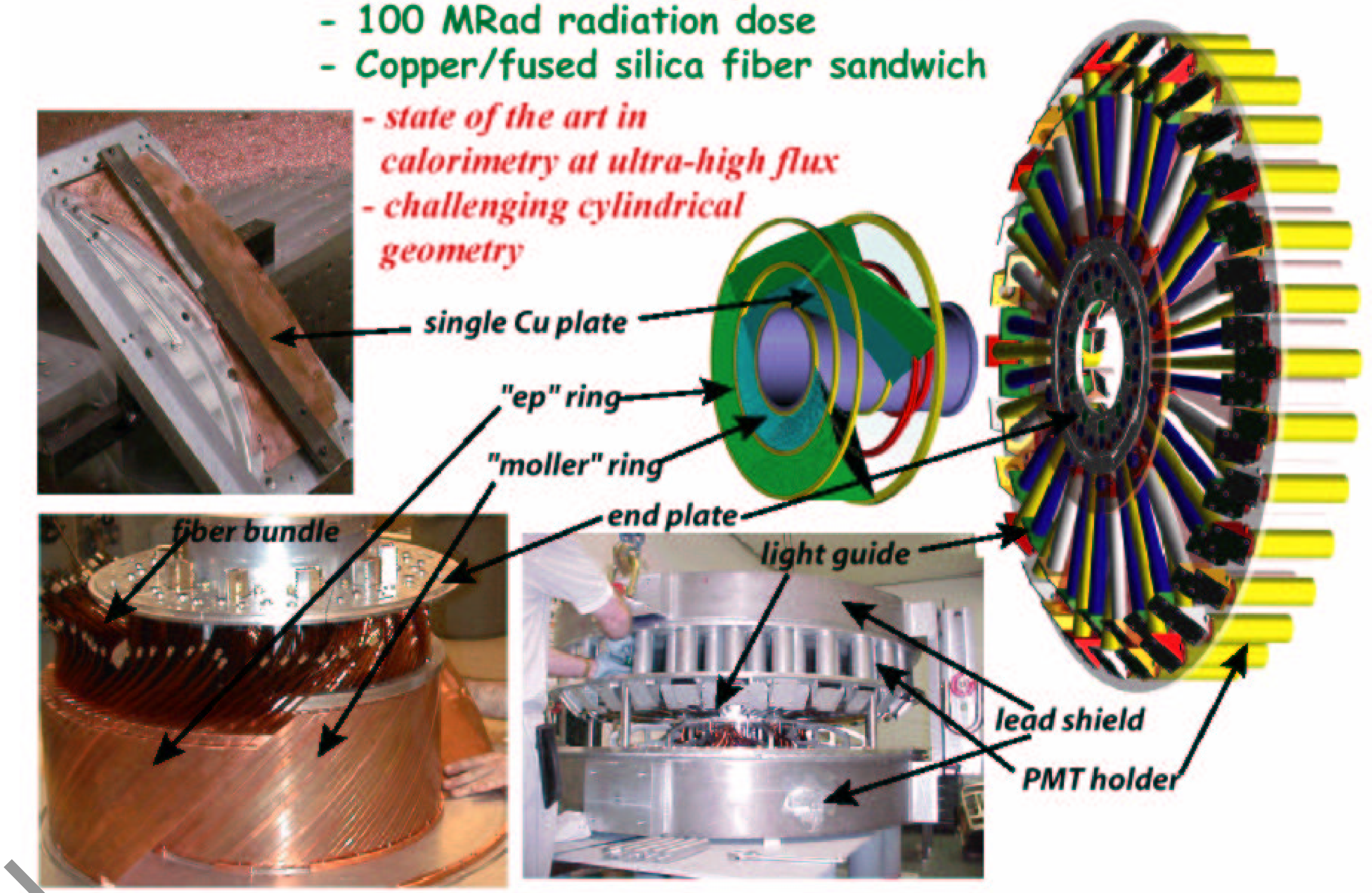
* profile detectors for calibration

MOLLER Detector

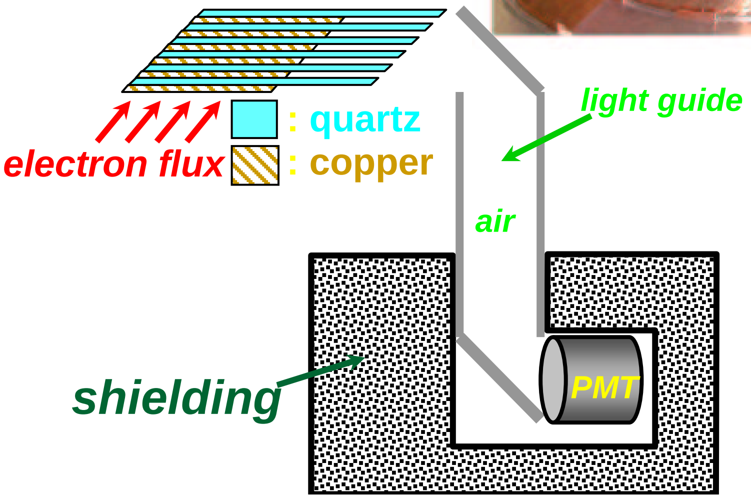
- 20 million electrons/pulse at 120 Hz
- 100 MRad radiation dose
- Copper/fused silica fiber sandwich

- state of the art in calorimetry at ultra-high flux

- challenging cylindrical geometry

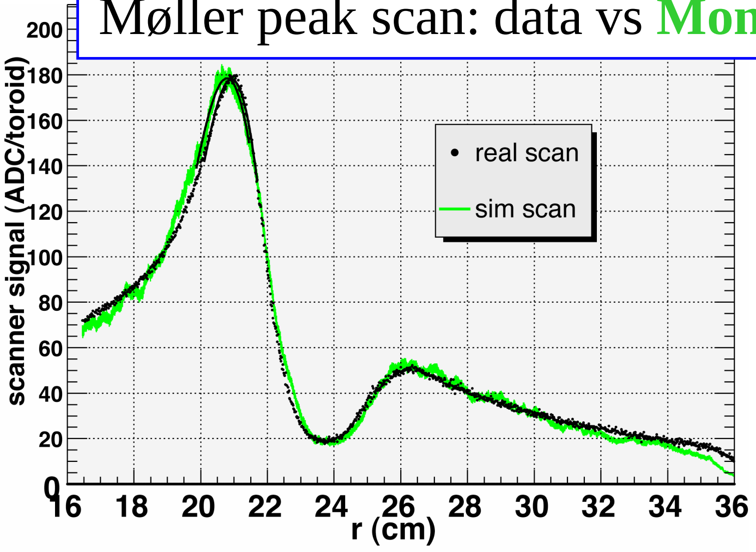


Basic Idea:

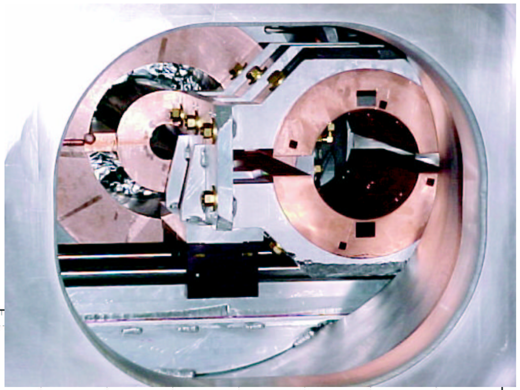


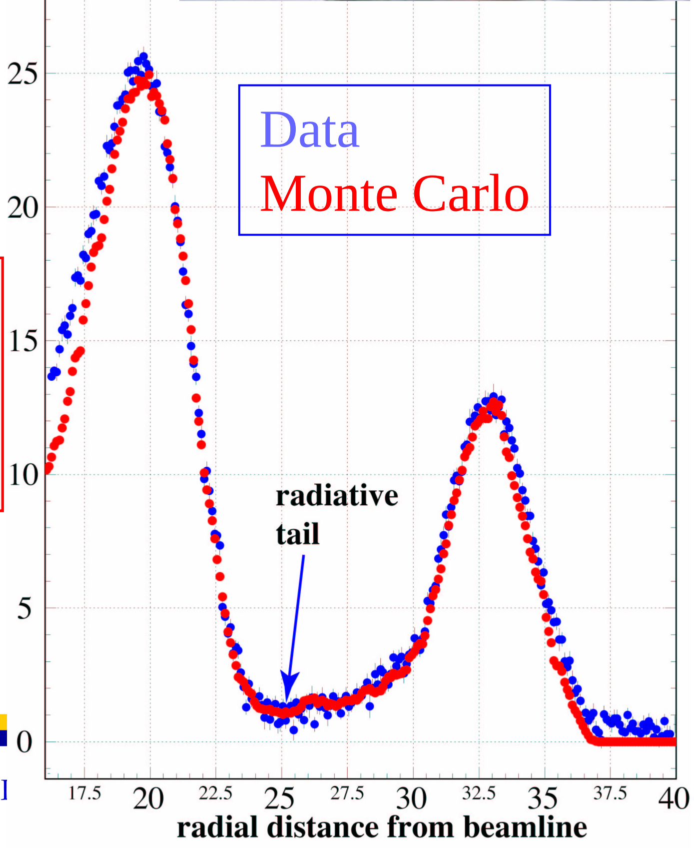
Scattered Flux Profile

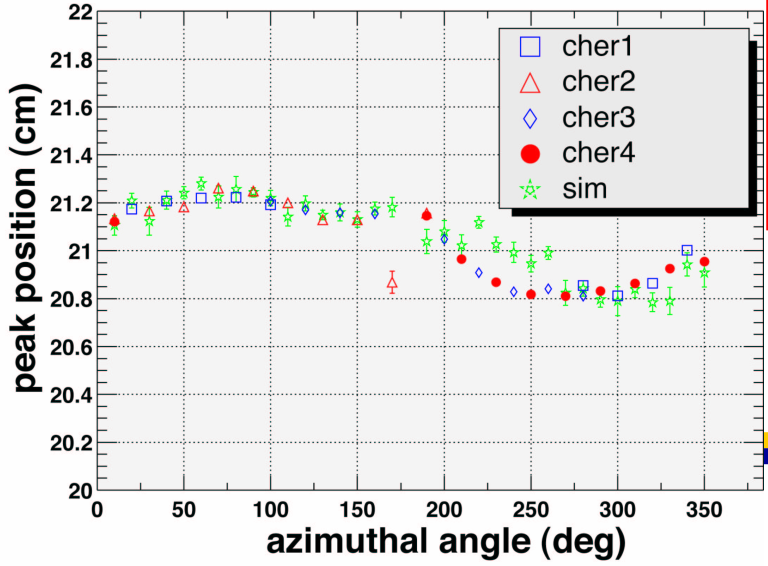
Møller peak scan: data vs **Monte Carlo**



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

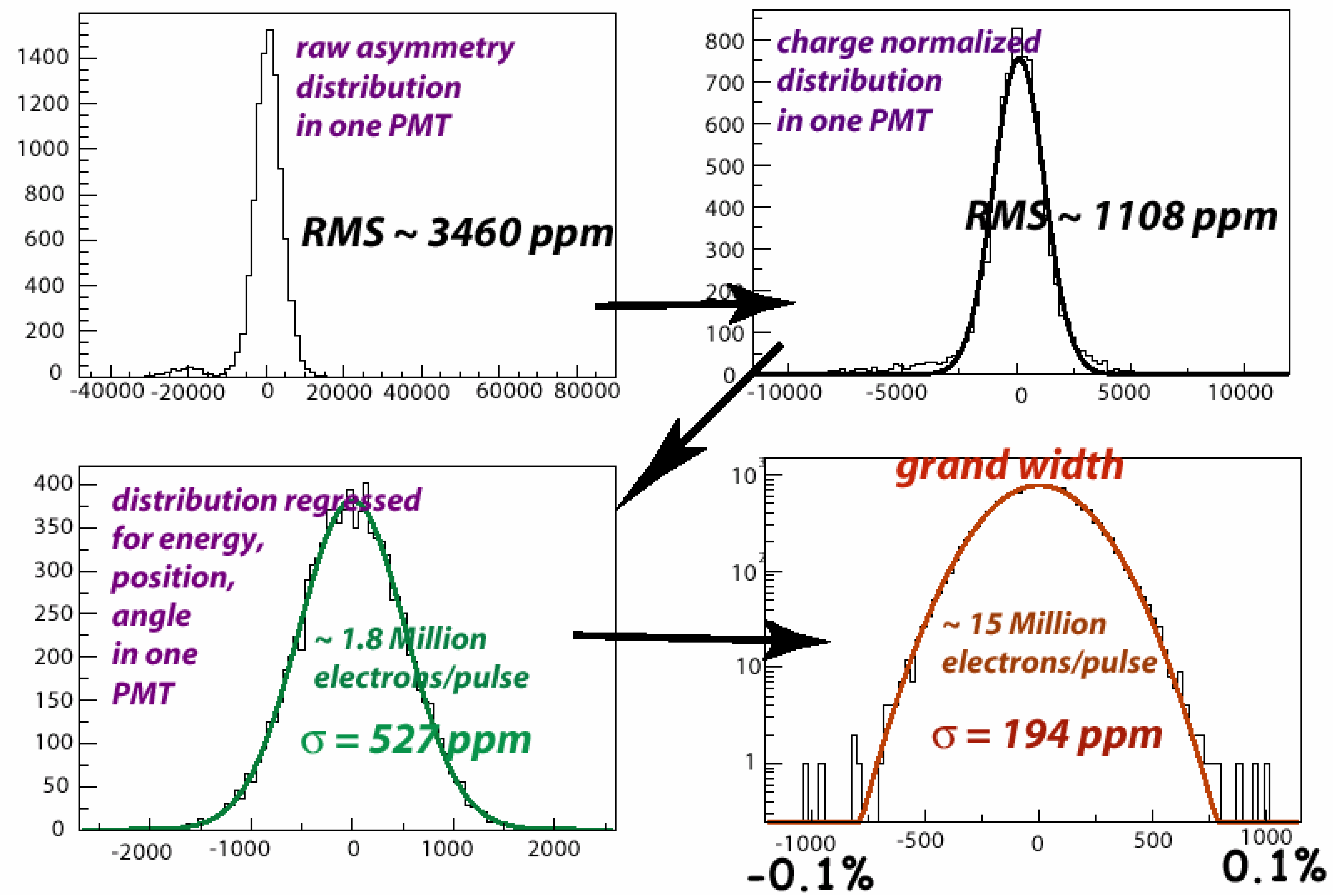






- ~2 mm geometry
- 1% energy scale
- Radiative tail
- <1% background

MOLLER Statistics and Fluctuations

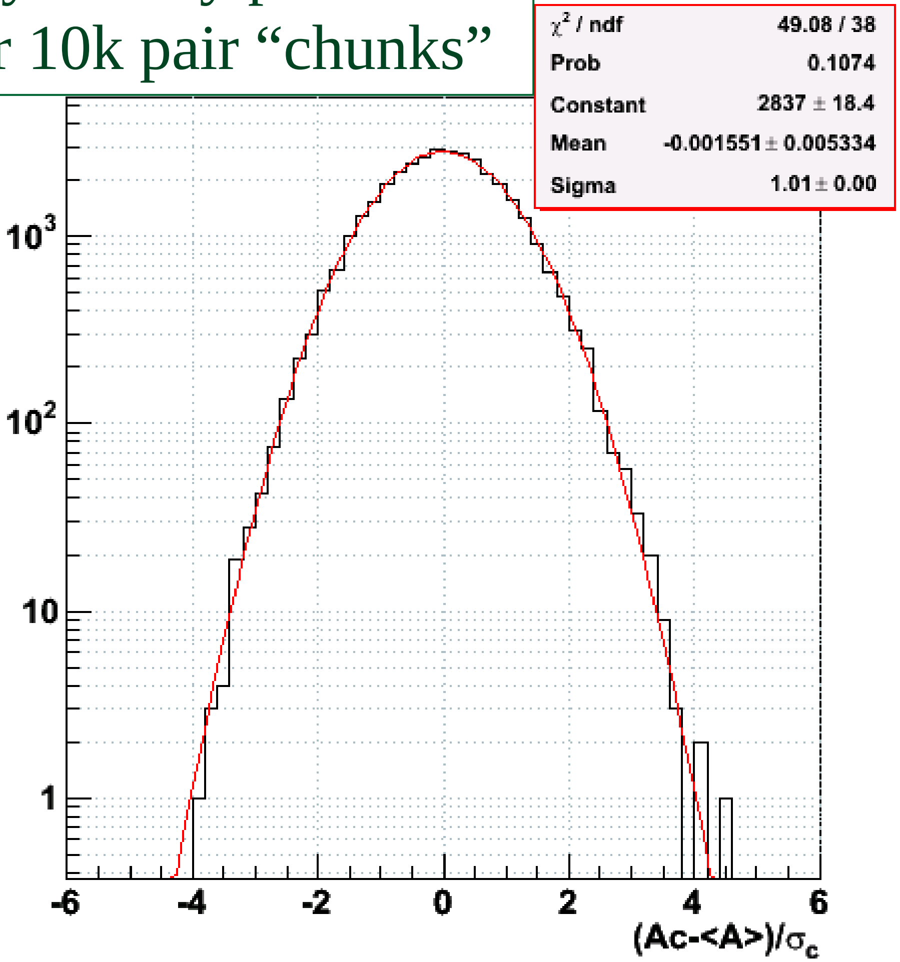


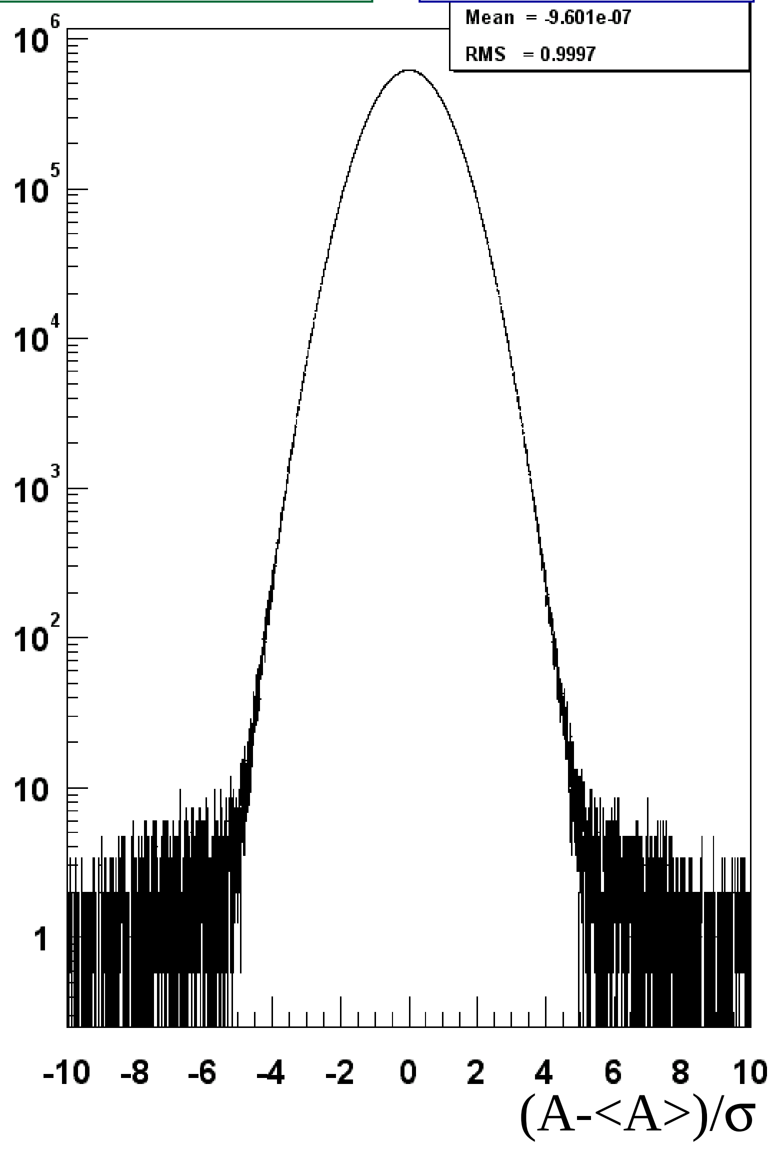
Raw Asymmetry Statistics

Asymmetry pulls per pulse pair:

150M pairs

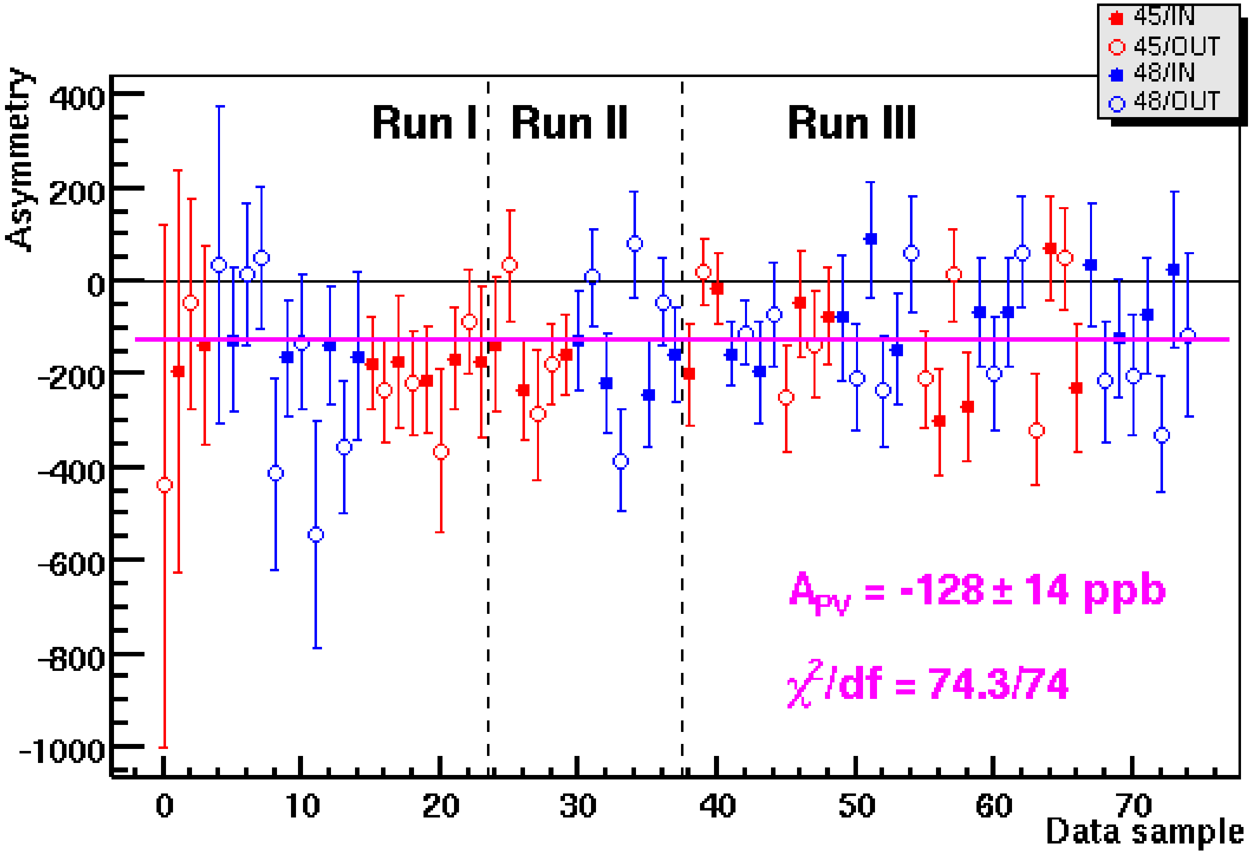
Asymmetry pulls per 10k pair “chunks”

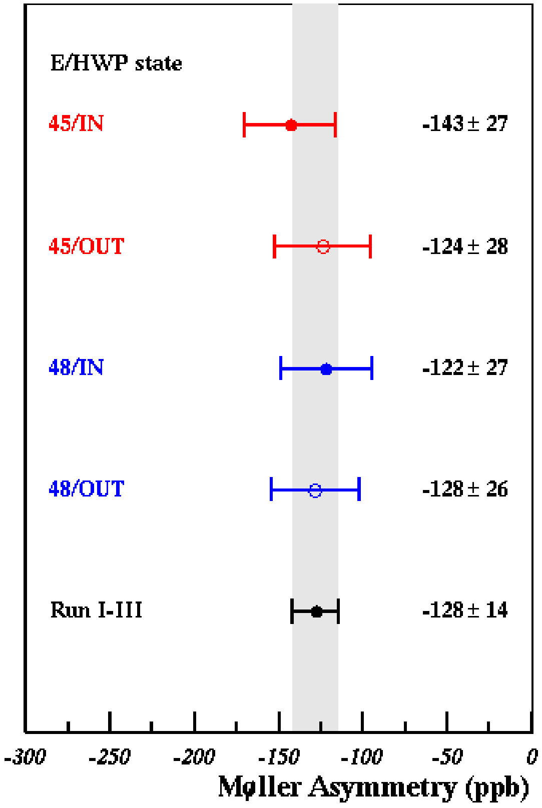




Møller Asymmetry

- Over 330M pulse pairs collected over 3 separate runs (2002-2003) at E_{beam}=45 and 48 GeV
- Passively flip helicity of electrons wrt source laser light ~every 2 days to suppress spurious helicity-correlated biases





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

Preliminary Results

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

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

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

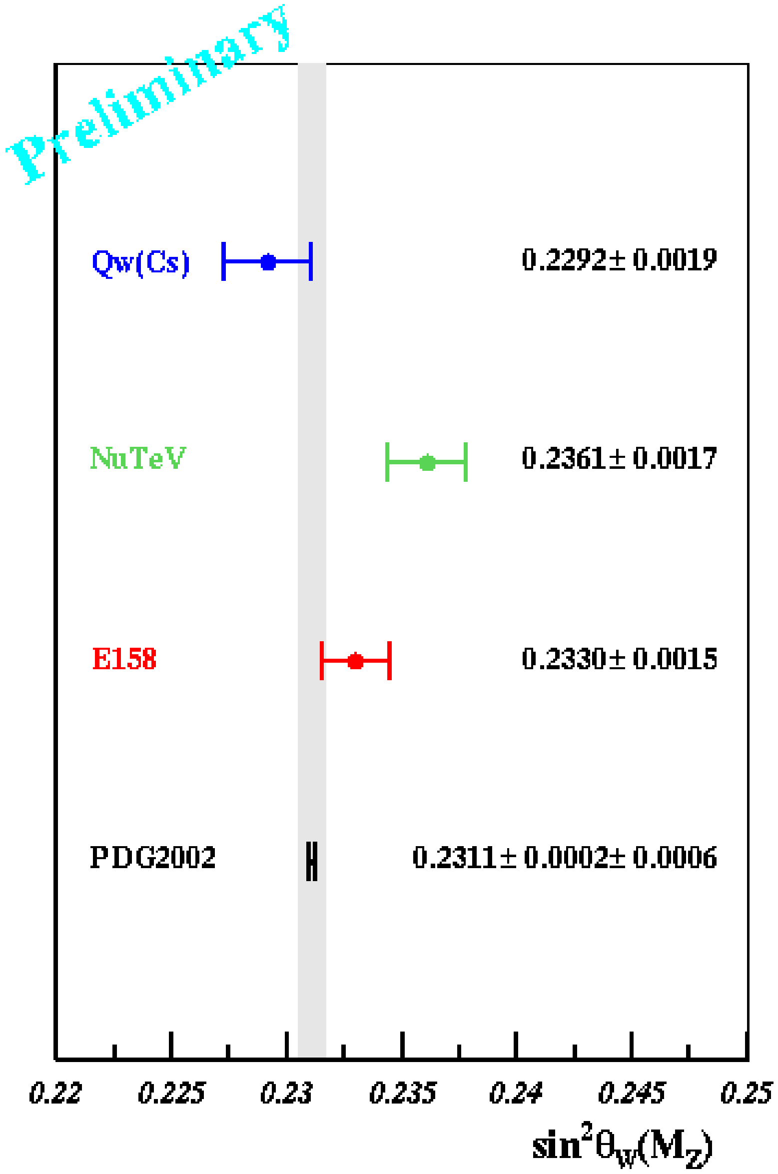
➔ *Most precise measurement at low Q^2*

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

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

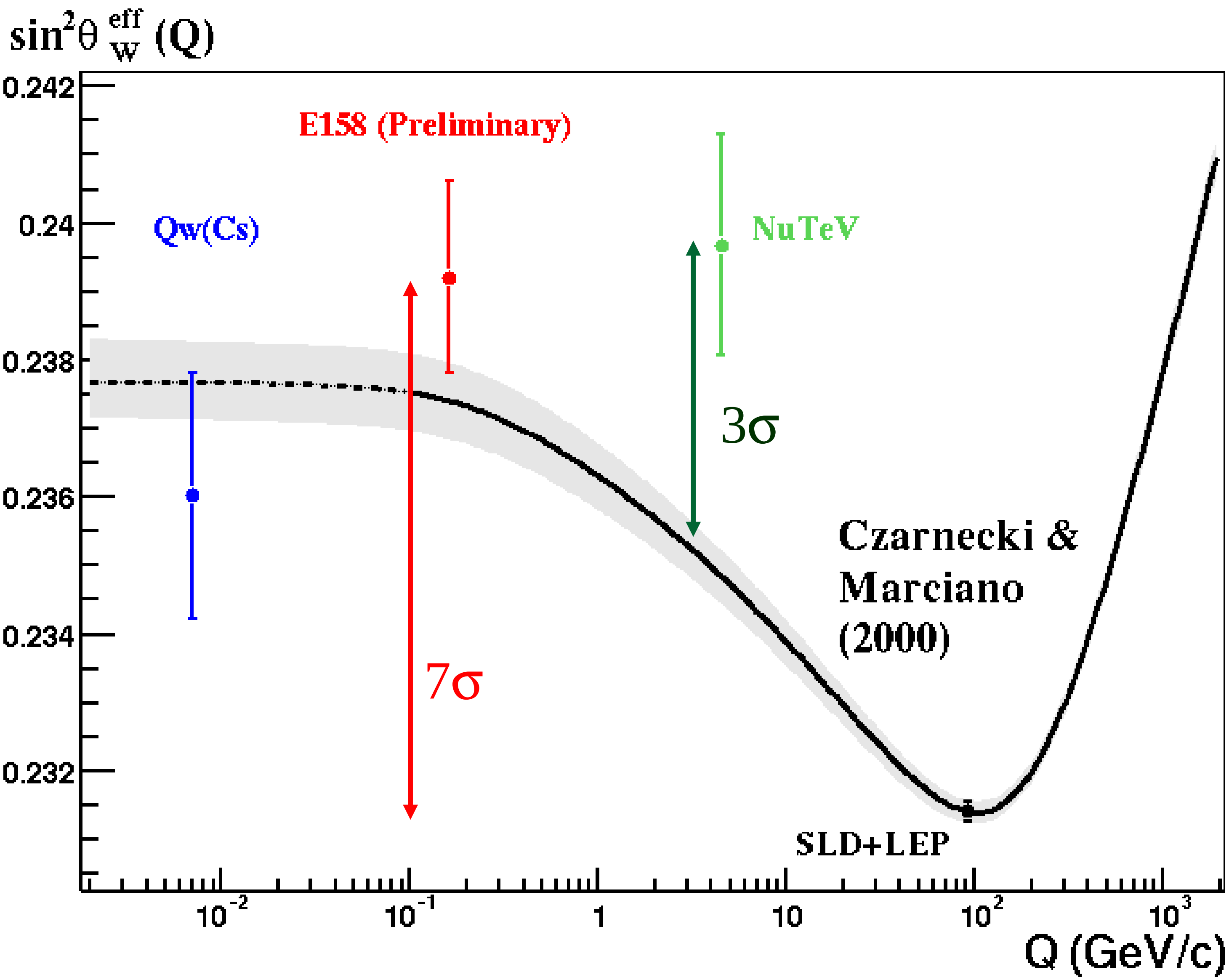
➔ *Standard Model pull:* +1.2 σ

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.)

Running of the Weak Mixing Angle



Outlook

- ☞ Precision experiments at low energies offer nontrivial constraints on the Standard Model and new physics at multi-TeV scales
- 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*

Stay tuned for PIC 2014 !