Measurement of Lepton-Lepton Electroweak Reaction
MOLLER

Physics Motivation & Experimental Strategy

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Director's Review, Jefferson Laboratory

Outline

- *Global Physics Context*
- *MOLLER Goal and Physics Impact*
- *Experimental Technique*
  - High flux parity experiments
  - MOLLER Design Choices
  - Technical Challenges/Requirements
  - Statistical and Systematic Errors

Worldwide Experimental Thrust in the 2010s: New Physics Searches

Compelling arguments for "New Dynamics" at the TeV Scale

A comprehensive search for clues requires:

Large Hadron Collider *as well as* **Lower Energy: $Q^2 << M_Z^2$**

Nuclear/Atomic systems address several topics; complement the LHC:

- ***Neutrino mass and mixing*** *$0\nu\beta\beta$ decay, θ_{13}, β decay, long baseline neutrino expts*
- ***Rare or Forbidden Processes*** *EDMs, charged LFV, $0\nu\beta\beta$ decay*
- ***Dark Matter Searches***
- ***Low Energy Precision Electroweak Measurements:***

Complementary signatures to augment LHC new physics signals

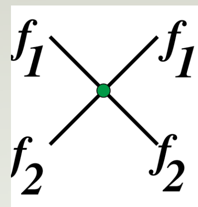
- ***Neutrons:*** *Lifetime, Asymmetries (LANSCE, NIST, SNS...)*
- ***Muons:*** *Lifetime, Michel parameters, g-2 (BNL, PSI, TRIUMF, FNAL, J-PARC...)*
- ***Parity-Violating Electron Scattering*** *Low energy weak neutral current couplings, precision weak mixing angle (SLAC, JLab)*

Comprehensive Search for New Neutral Current Interactions

Important component of indirect signatures of "new physics"

Consider $f_1\bar{f}_1 \rightarrow f_2\bar{f}_2$ or $f_1 f_2 \rightarrow f_1 f_2$

$$L_{f_1 f_2} = \sum_{i,j=L,R} \frac{4\pi}{\Lambda_{ij}^2} \eta_{ij} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma^\mu f_{2j}$$



Λ's for all f_1f_2 combinations and L,R combinations

Eichten, Lane and Peskin, PRL50 (1983)

Many new physics models give rise to non-zero Λ's at the TeV scale: Heavy Z's, compositeness, extra dimensions…

One goal of neutral current measurements at low energy AND colliders: Access $\Lambda > 10$ TeV for as many f_1f_2 and L,R combinations as possible

LEPII, Tevatron access scales Λ's ~ 10 TeV

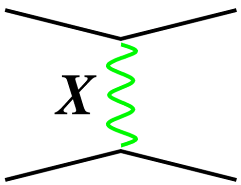
e.g. Tevatron dilepton spectra, fermion pair production at LEPII

- L,R combinations accessed are parity-conserving

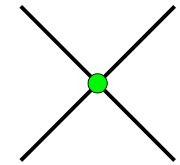
LEPI, SLC, LEPII & HERA accessed some parity-violating combinations but precision dominated by Z resonance measurements: ~ few TeV sensitivity

Colliders vs Low Q^2

consider



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



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!

Consider known weak neutral current interactions mediated by Z Bosons

$$\frac{\delta A_Z}{A_Z} \;\alpha\; \frac{\pi/\Lambda^2}{g\,G_F} \longrightarrow$$

$\delta(g)/g \sim 0.1$
$\Lambda \sim 10$ TeV

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

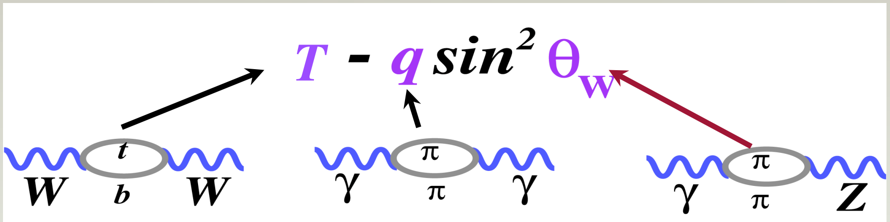
Window of opportunity for weak neutral current measurements at $Q^2 \ll M_Z^2$

Processes with potential sensitivity:

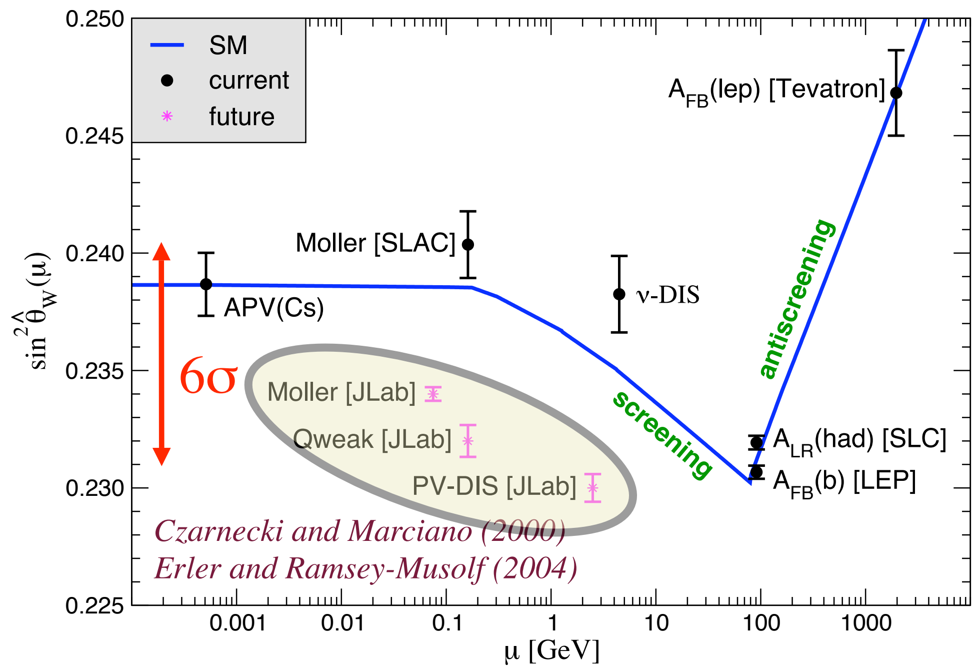
- ***neutrino-nucleon deep inelastic scattering***   *NuTeV at Fermilab*
- ***Atomic parity violation (APV)***   *^{133}Cs at Boulder*
- ***parity-violating electron scattering***

Published & Planned Projects

Running of θ_W: Bookkeeping for off-resonance measurements

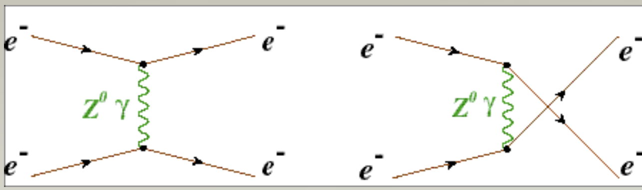


- γ-γ loop is the running of α_{EM}
- W-W loop provides indirect m_t
- γ-Z loop is the running of $\sin^2\theta_W$



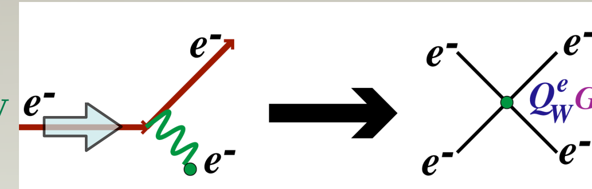
- **Published measurements**
  - Purely leptonic: SLAC E158 (e-e)
  - Semi-leptonic: APV (e-q) (atomic theory) & NuTeV (ν -q) (hadronic physics)
  - Important, complementary limits on new contact interactions
- **Future measurements search for new contact interactions**
  - Qweak (e-q), PVDIS (e-q) and MOLLER (e-e)
  - e-q measurements will further expand contact interaction reach
  - MOLLER, in addition, could potentially impact the central value of the $\sin^2\theta_W$ and its implications for m_H

MOLLER Goal



Derman and Marciano (1978)

$$A_{PV} = -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}Q^e_W$$



$$A_{PV} \propto m_e E_{lab}(1-4\sin^2\vartheta_W) \Rightarrow \frac{\delta(\sin^2\vartheta_W)}{\sin^2\vartheta_W} \cong 0.05\frac{\delta(A_{PV})}{A_{PV}}$$

E_{beam} = 11 GeV   75 μA   80% polarized ⇒ *(~ 2.5 yrs)* ⇒ *$\delta(A_{PV})$ = 0.73 ppb*

A_{PV} = 35.6 ppb ⇒ ***$\delta(Q^e_W)$ = ± 2.1 (stat.) ± 1.0 (syst.) %***

$\delta(\sin^2\theta_W)$ = ± 0.00026 (stat.) ± 0.00012 (syst.) ⇒ *~ 0.1%*

⇒ ***not just "another measurement" of $\sin^2\theta_W$***

Compelling opportunity with the Jefferson Lab Energy Upgrade:

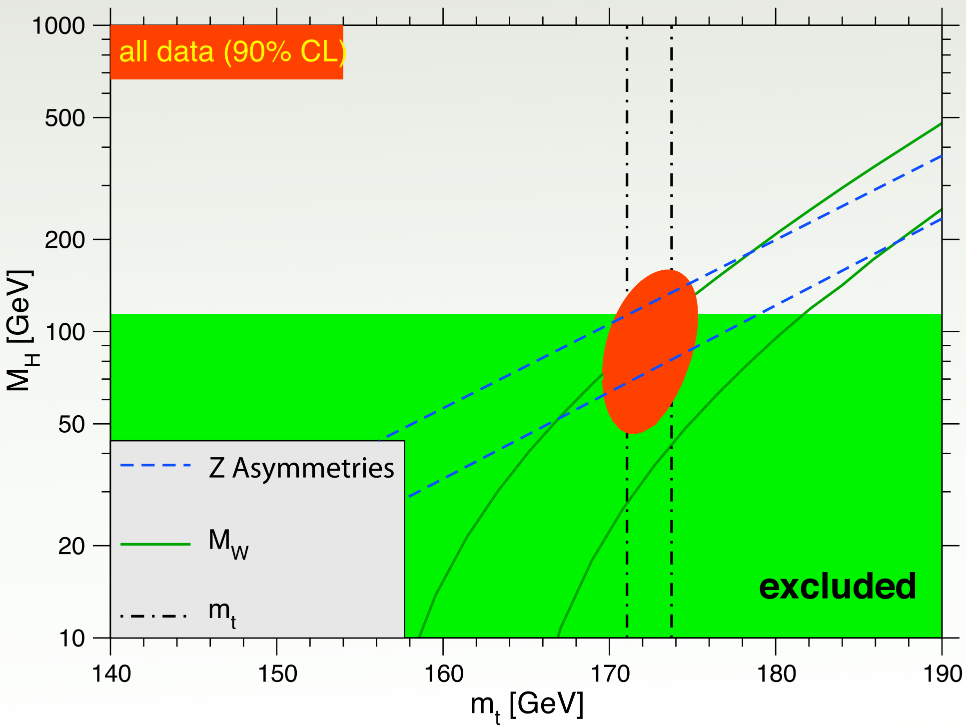
- Comparable to the two best measurements at colliders
- Unmatched by any other project in the foreseeable future
- At this level, one-loop effects from "heavy" physics

EW Physics at One-Loop

Three fundamental inputs needed: α_{em}, G_F and M_Z

Other experimental observables predicted at 0.1% level: sensitive to heavy particles via higher order quantum corrections

4th and 5th best measured parameters: $\sin^2\theta_W$ and M_W



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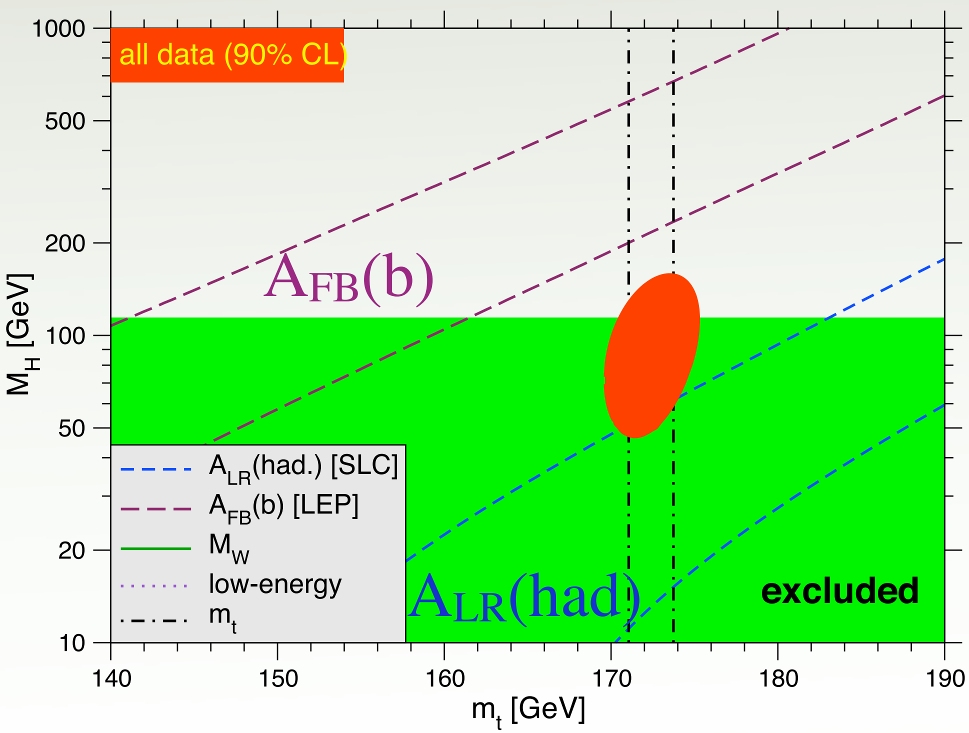
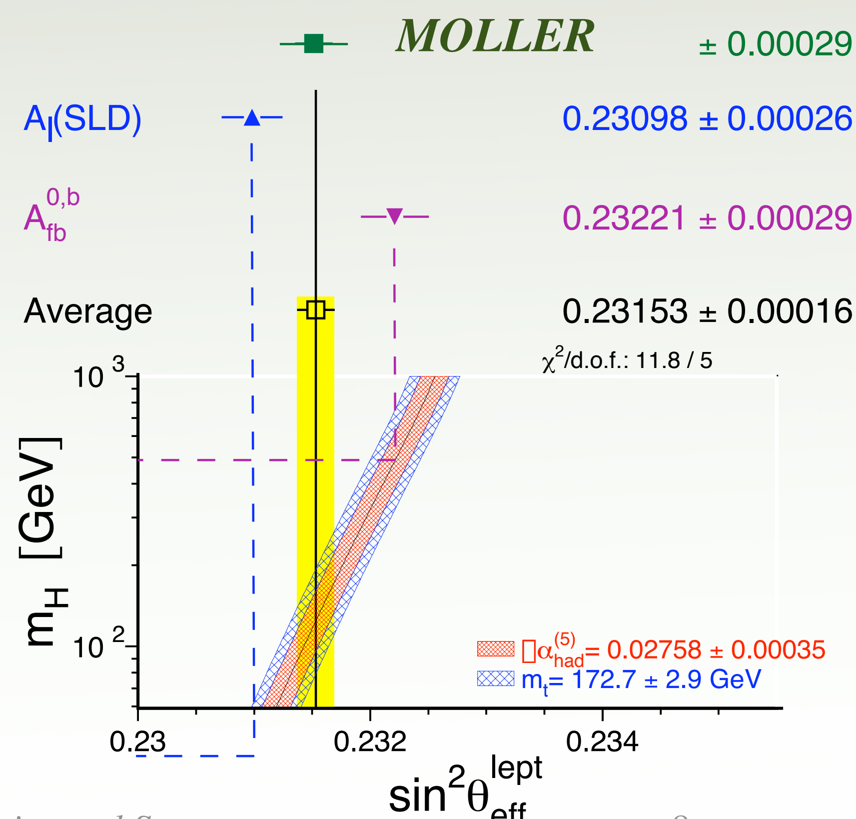
A_{FB}(b) measures product of e- and b-Z couplings

A_{LR}(had) measures purely the e-Z couplings

Proposed A_{PV} measures purely the e-Z couplings at a different energy scale





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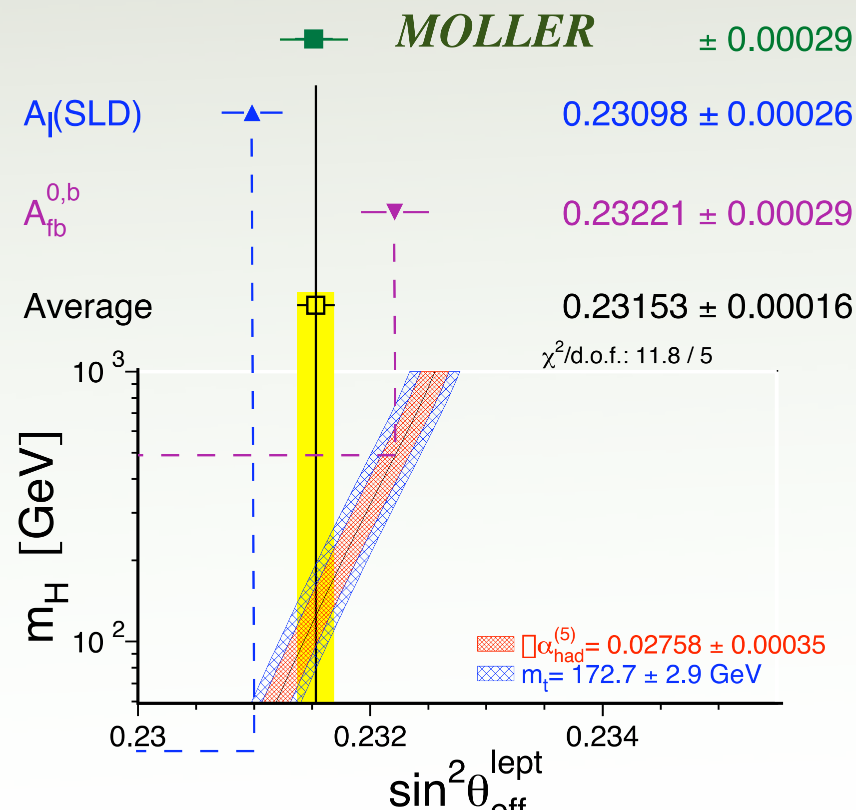
The moment one adds "new physics" (e.g. LHC anomaly), $\sin^2\theta_W$ becomes process-dependent (initial and final state fermion type), and Q^2-dependent



Contact Interaction Reach

$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j \quad \xrightarrow{A_{PV}} \quad \frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5 \text{ TeV}$$

If new contact interactions are to be folded in with the Standard Model processes, disentangling them requires several measurements of different processes off the Z resonance

Best current limits on 4-electron contact interactions: LEPII at 200 GeV

(Average of all 4 LEP experiments)

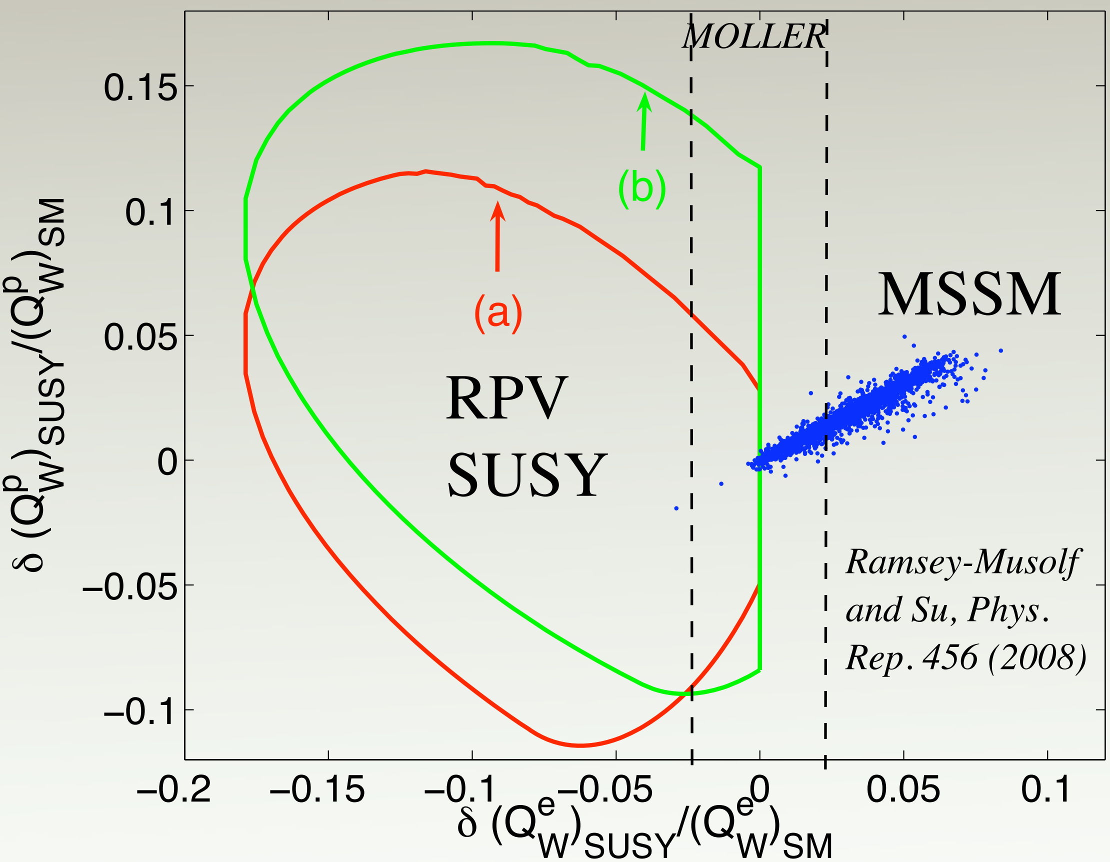
$$\frac{\Lambda}{\sqrt{|g_{RR}^2 + g_{LL}^2|}} = 4.4 \text{ TeV} \quad \text{OR} \quad \frac{\Lambda}{g_{RL}} = 5.2 \text{ TeV}$$

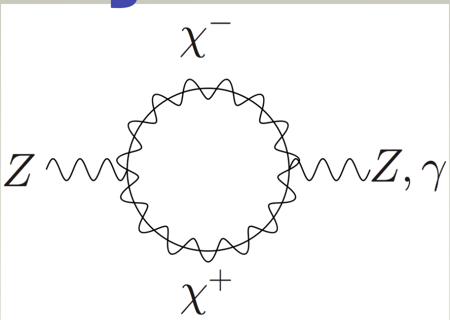
insensitive to $|g_{RR}^2 - g_{LL}^2|$

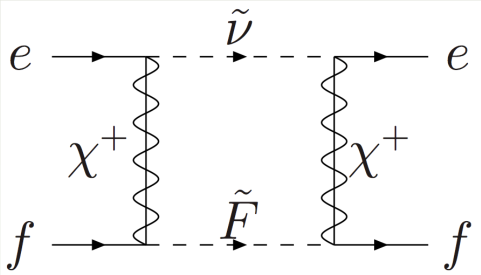
Compositeness scale: $\sqrt{|g_{RR}^2 - g_{LL}^2|} = 2\pi \Rightarrow \Lambda = 47 \text{ TeV}$

Length scale probed: 4×10^{-21} m

SUSY Sensitivity







MSSM sensitivity if light super-partners, large tanβ

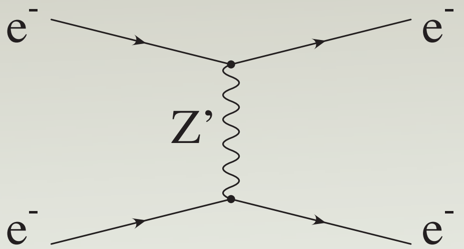
$$P_R = (-1)^{3(B-L)+2s}$$

Does Supersymmetry provide a candidate for dark matter?

- B and/or L need not be conserved (RPV): neutralino decay
  - neutralino then unlikely to be a dark matter candidate
  - neutrinos are Majorana

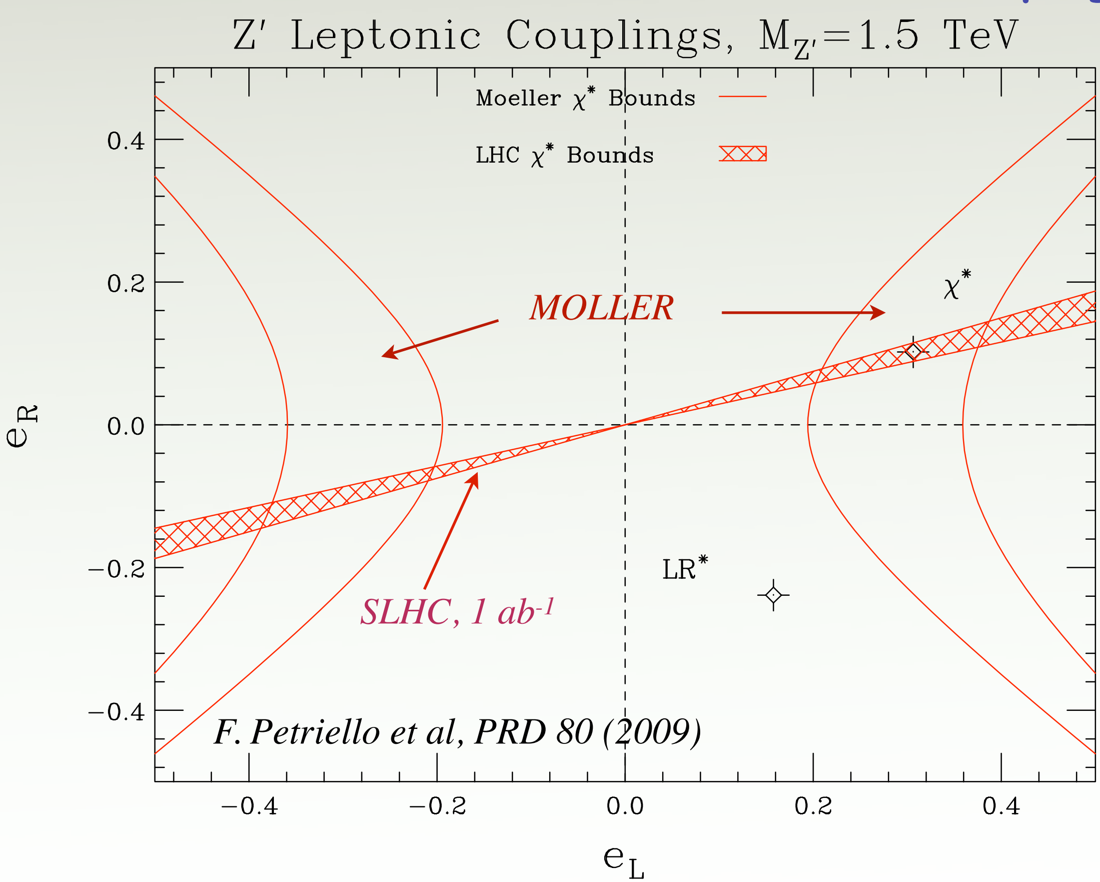
‘Light’ Z’ Complementarity

- *Virtually all GUT models predict new Z’s: LHC reach ~ 5 TeV*
- *With high luminosity at LHC, 1-2 TeV Z’ properties can be extracted*
- *A_{PV} can help separate left- and right-handed couplings*



Suppose a 1 to 2 TeV heavy Z’ is discovered at the LHC

- What are its vector- and axial-vector coupling?



$$\sqrt{2}G_F\delta(Q_W^e) = \frac{1}{(7.5\ \mathrm{TeV})^2}$$

$$= \frac{|g_{RR}^2 - g_{LL}^2|}{\Lambda^2} = \frac{e_R^2 - e_L^2}{M_{Z'}^2}$$

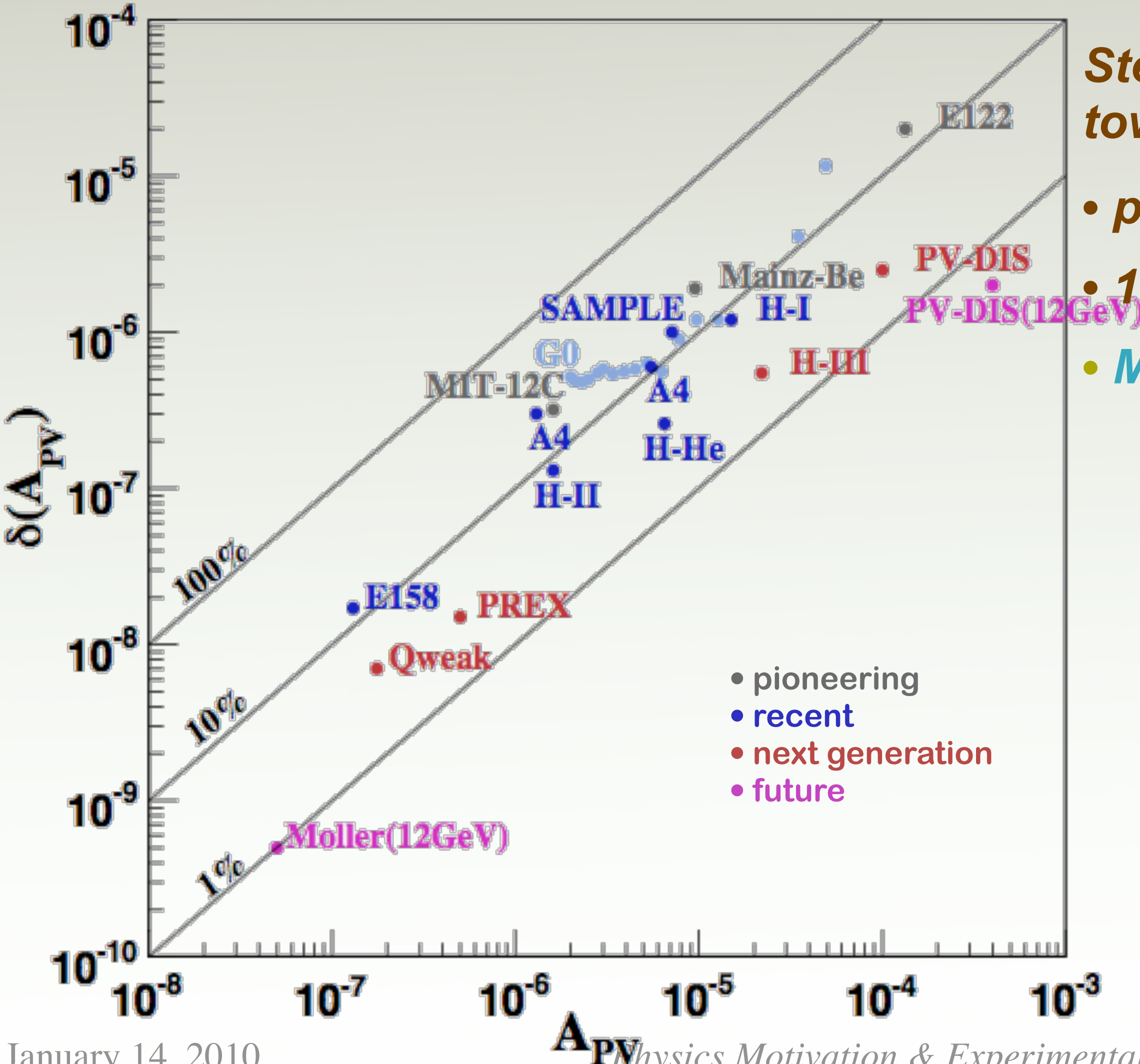
LHC data can extract the mass, width and $A_{FB}(s)$

→ ***constraint on e_R/e_L***

Experimental Technique:

Technical Improvements over 3 Decades

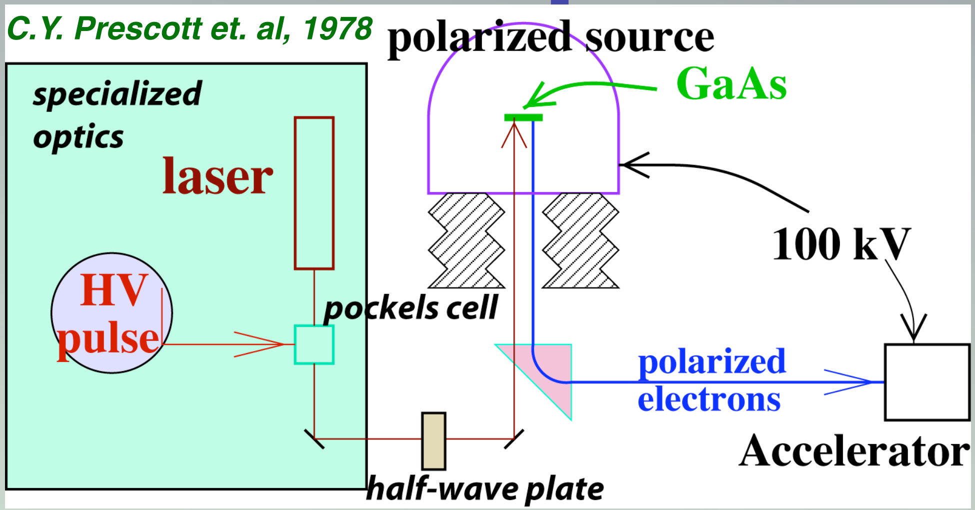
Parity-violating electron scattering has become a precision tool



Steady progress in technology towards:

- ***part per billion systematic control***
- ***1% systematic control***
- ***Major developments in***
  - ***photocathodes (I & P)***
  - ***polarimetry***
  - ***high power cryotargets***
  - ***nanometer beam stability***
  - ***precision beam diagnostics***
  - ***low noise electronics***
  - ***radiation hard detectors***

Optical Pumping



- Optical pumping of a GaAs wafer
- Rapid helicity reversal: change sign of longitudinal polarization ~ kHz to minimize drifts (like a lockin amplifier)
- Control helicity-correlated beam motion: under sign flip, keep beam stable at the sub-micron level

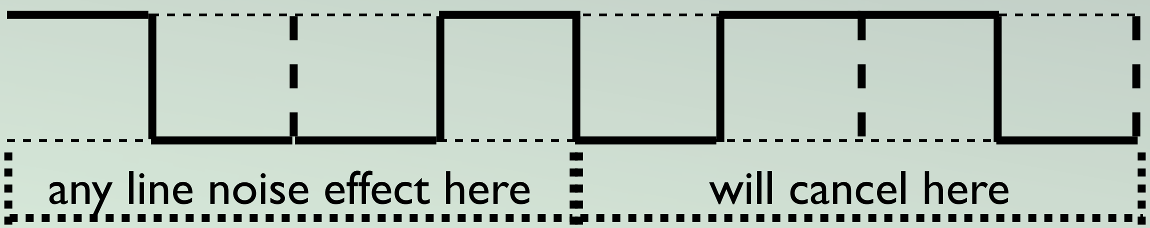
✧ **Beam helicity is chosen pseudo-randomly at multiple of 60 Hz**

- *sequence of "window multiplets"*

Example: at 240 Hz reversal

Choose 2 pairs pseudo-randomly, force complementary two pairs to follow

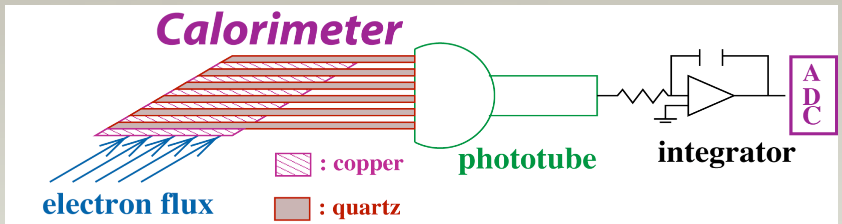
Analyze each "macropulse" of 8 windows together



MOLLER will plan to use ~ 2 kHz reversal; subtleties in details of timing

Noise characteristics have been unimportant in past experiments: Not so for PREX, Qweak and MOLLER....

Flux Integration



"Flux Integration": very high rates

direct scattered flux to background-free region

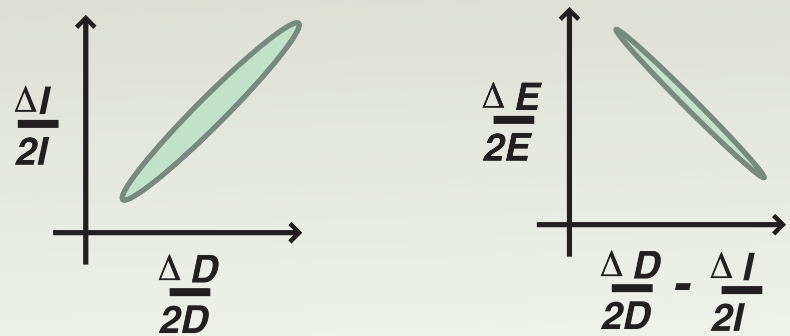
Detector D, Current I: F = D/I

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

$$A_{pair} = \frac{\Delta F}{2F} + \Delta A$$

I order: x, y, θ_x, θ_y, E

II order: e.g. spot-size



After corrections, variance of A_{pair} must get as close to counting statistics as possible: ~ 80 ppm (2kHz) & central value reflects A_{phys}

Experimental Challenge & Systematic Control

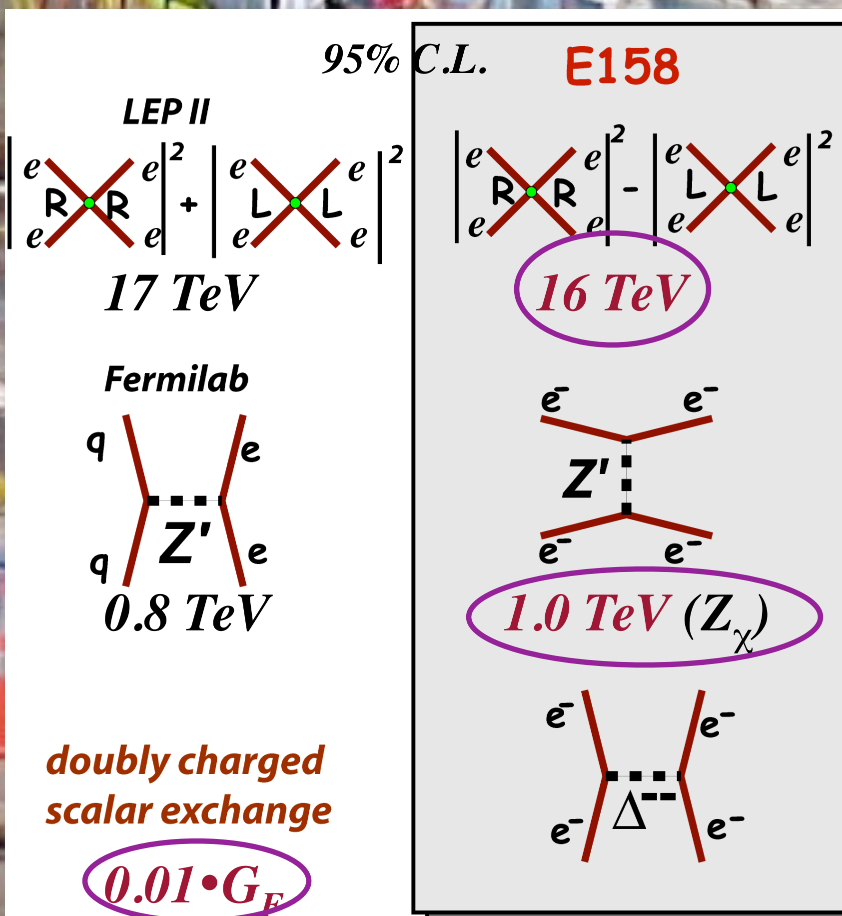
Talks by M. Pitt and G. Cates

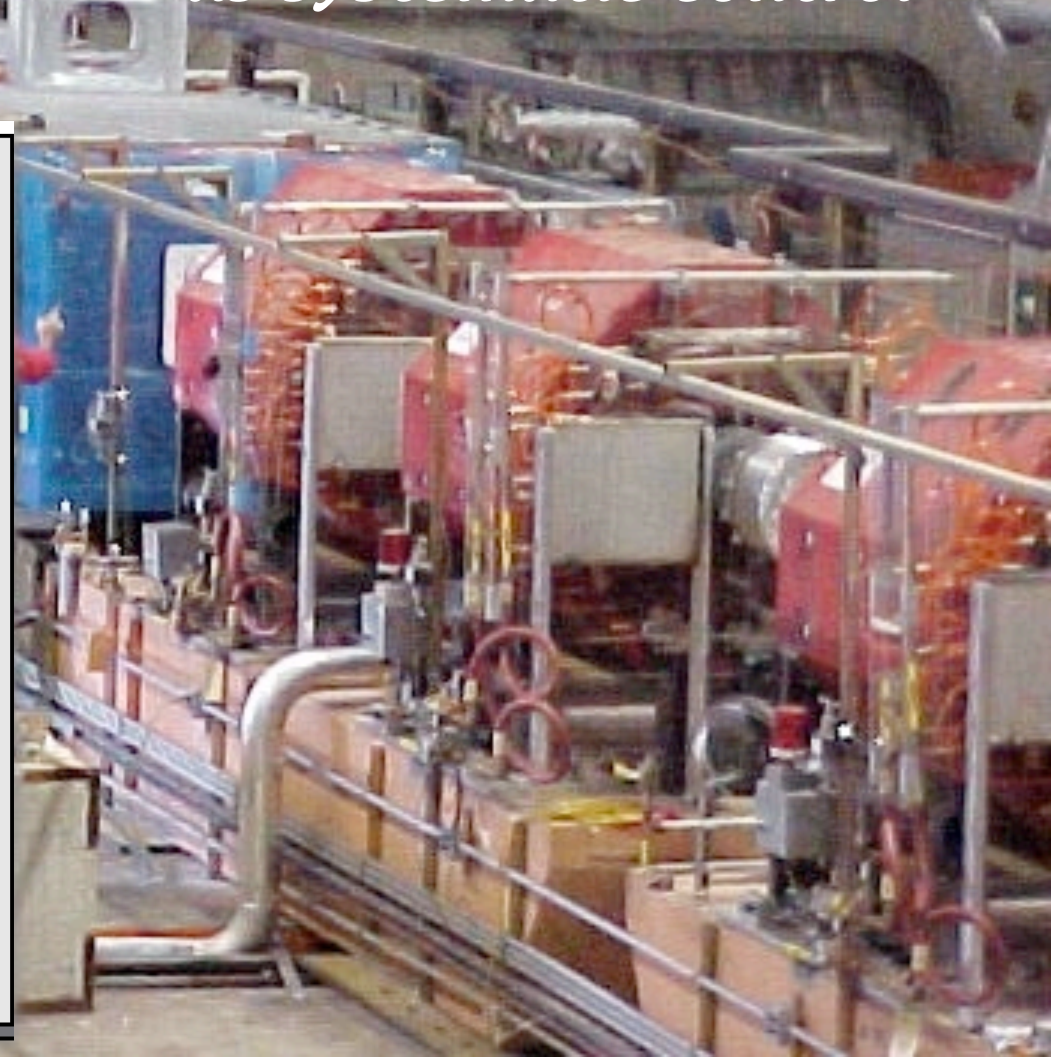
- ***Must minimize both random and helicity-correlated fluctuations in the integrated window-pair monitor response of electron beam trajectory, energy and spot-size.***

SLAC E158

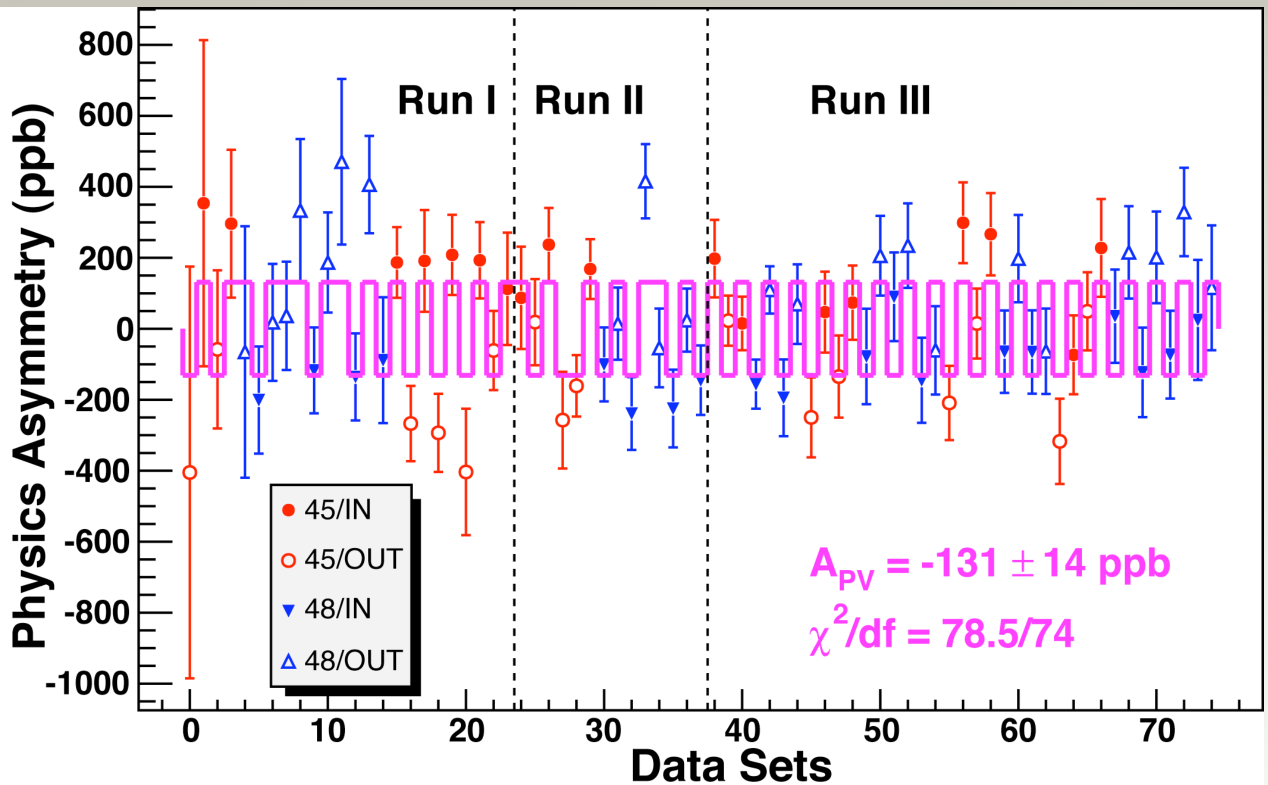
Experience relevant for apparatus design as well as systematic control

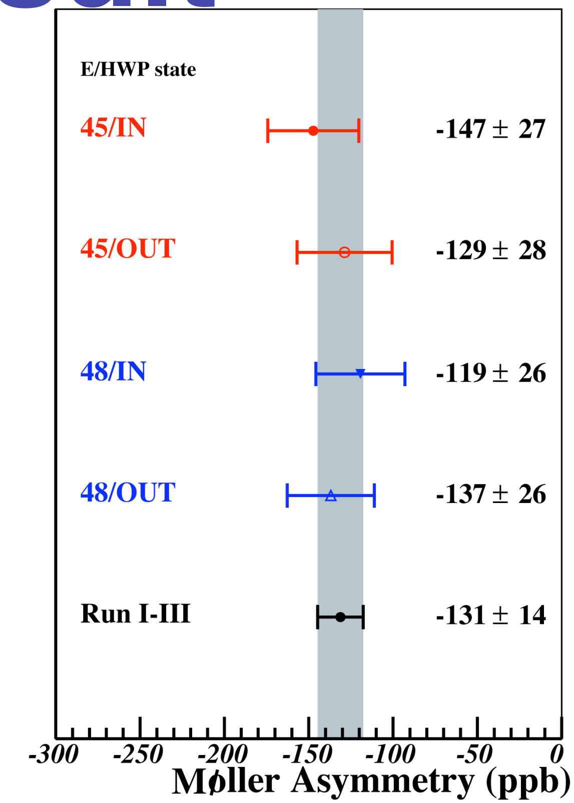
Limits on "New" Physics



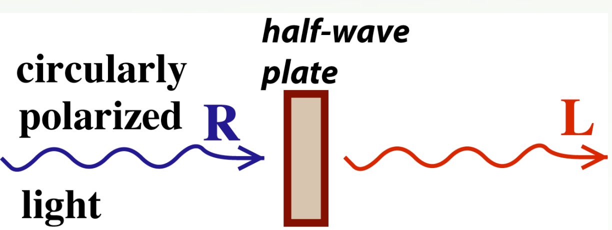


SLAC E158 Result





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

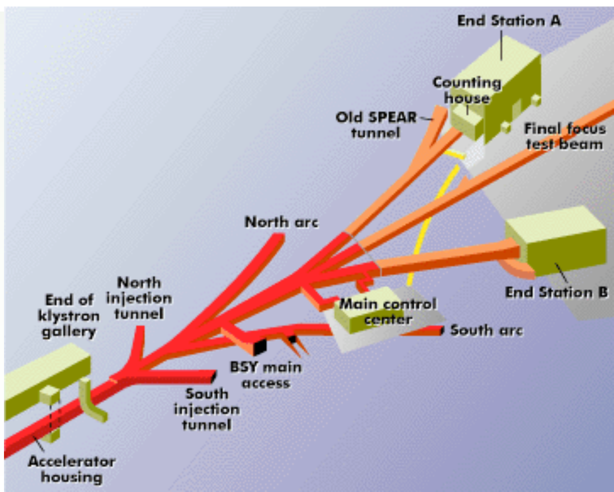


g-2 spin precession

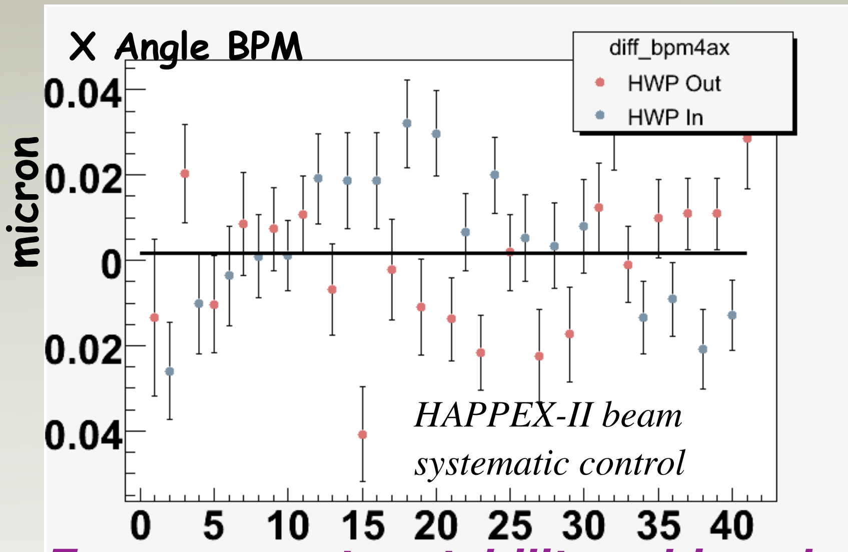
45 GeV: 14.0 revs

48 GeV: 14.5 revs

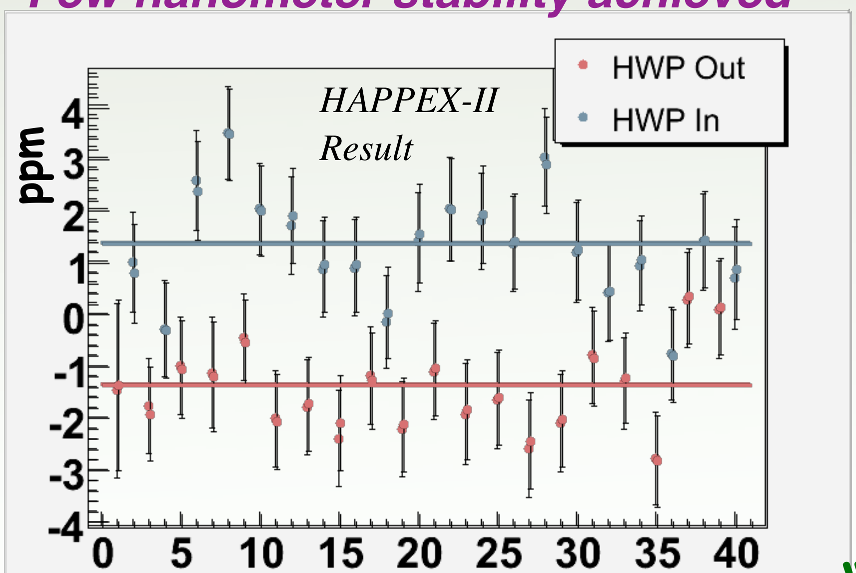
Phys. Rev. Lett. **95** 081601 (2005)



Parity Violation at JLab



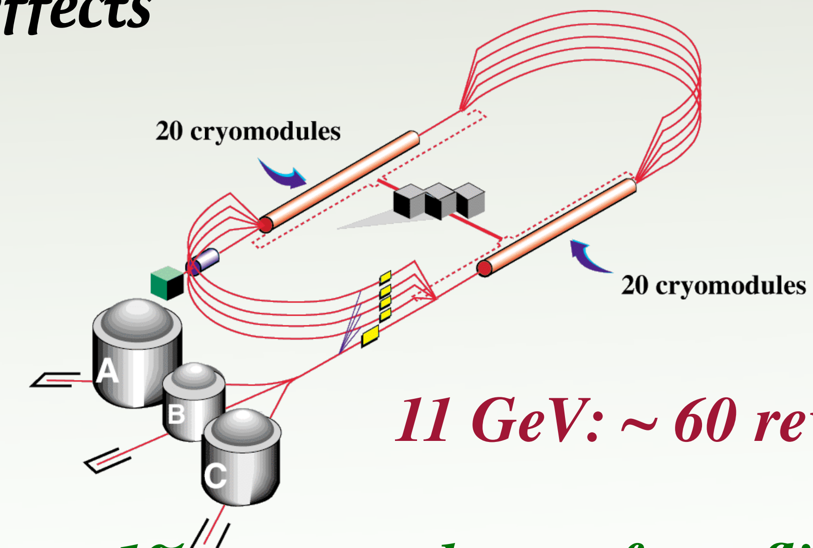
Few nanometer stability achieved



A_{PV} = -1.58 ± 0.12 (stat) ± 0.04 (syst) ppm

- Excellent collaborations formed between experimenters, EGG group and Acc. Ops.
- Pushing the envelope with PREX/Qweak
- MOLLER constitutes the 4th generation:

Build in two powerful new flips: cross-check of control of II order effects

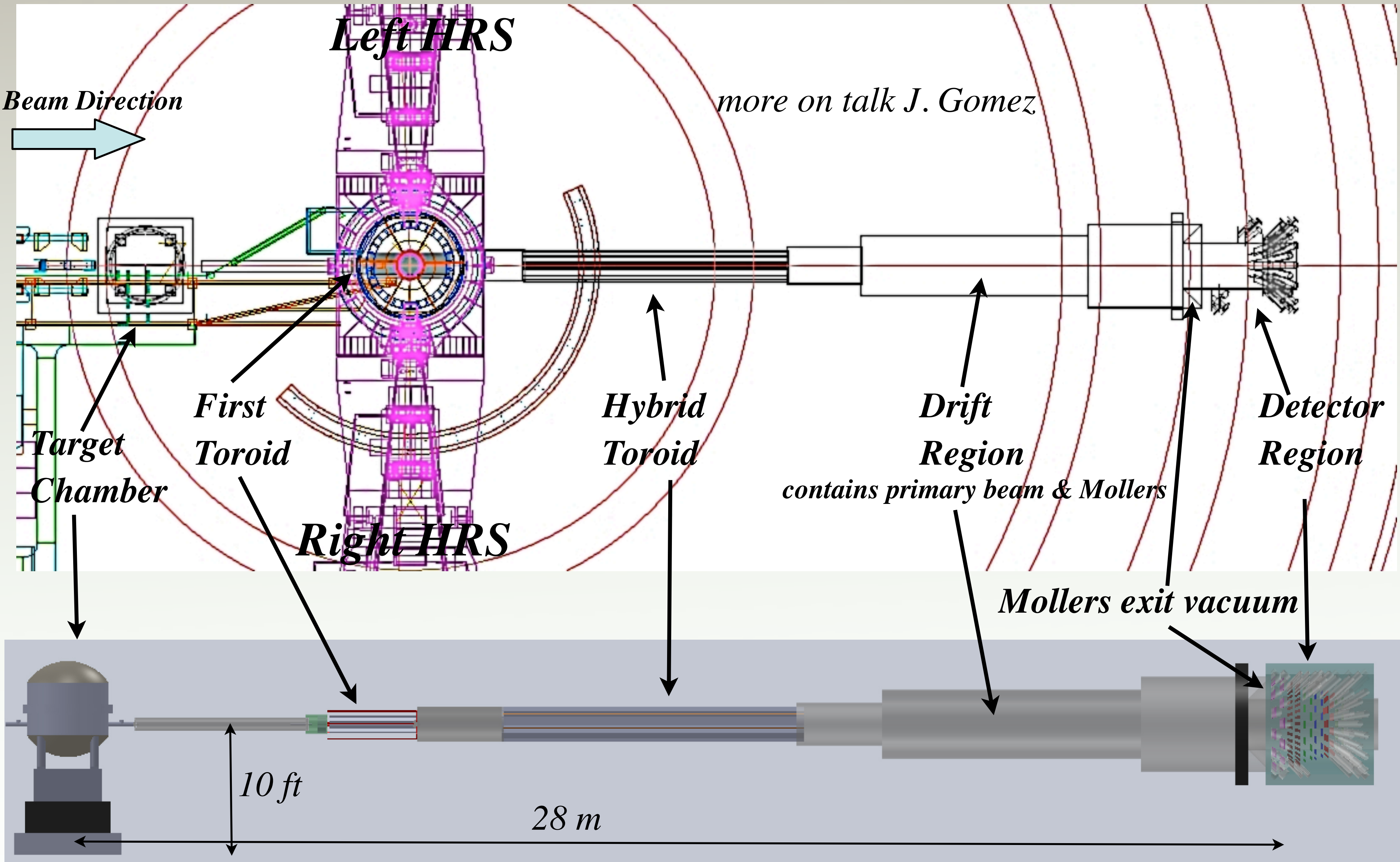


11 GeV: ~ 60 revs!

~ 1% energy change for a flip

"Double-Wien" flip equally powerful

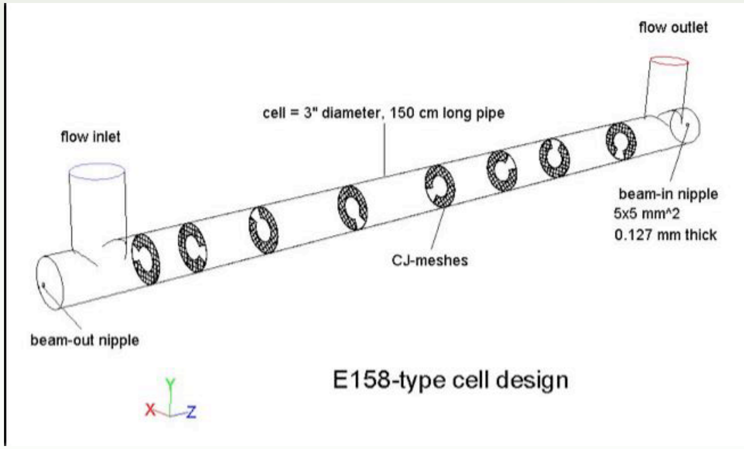
MOLLER Hall Layout



Target: Liquid Hydrogen

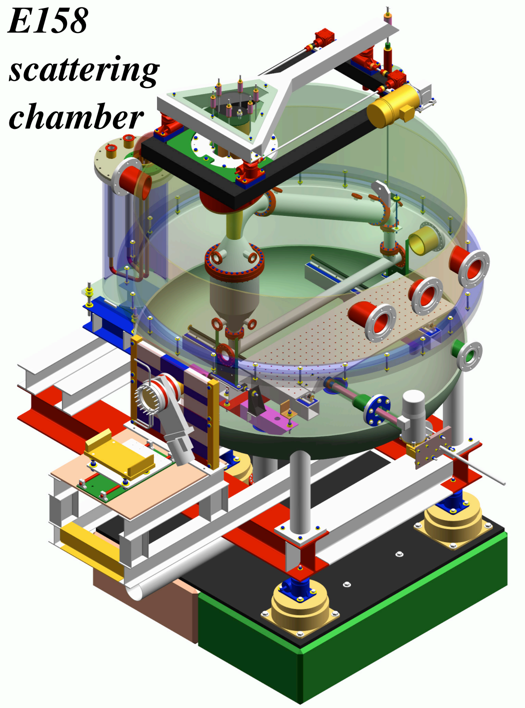
- *Most thickness for least radiative losses*
- *No nuclear scattering background*
- *Not easy to polarize*

- *Need as much target thickness as technically feasible*
- *Tradeoff between statistics and systematics*
- *Default: Same geometry as E158*

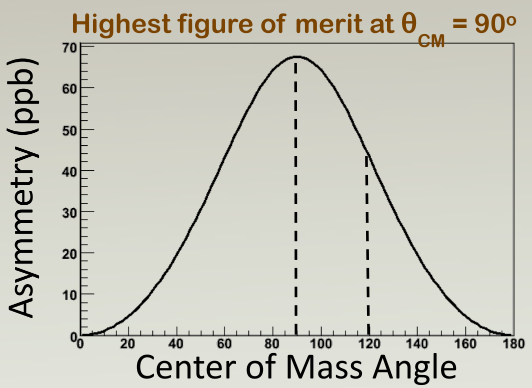


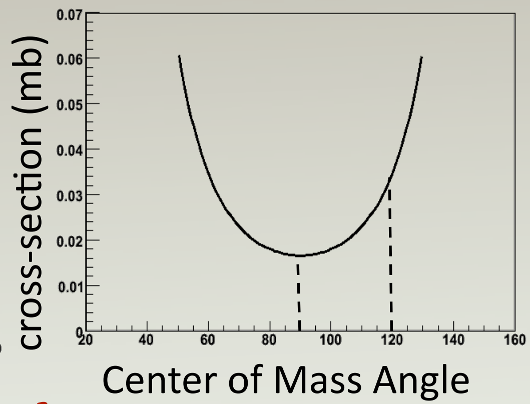
parameter	value
length	150 cm
thickness	10.7 gm/cm^2
X_0	17.5%
p,T	35 psia, 20K
power	5000 W

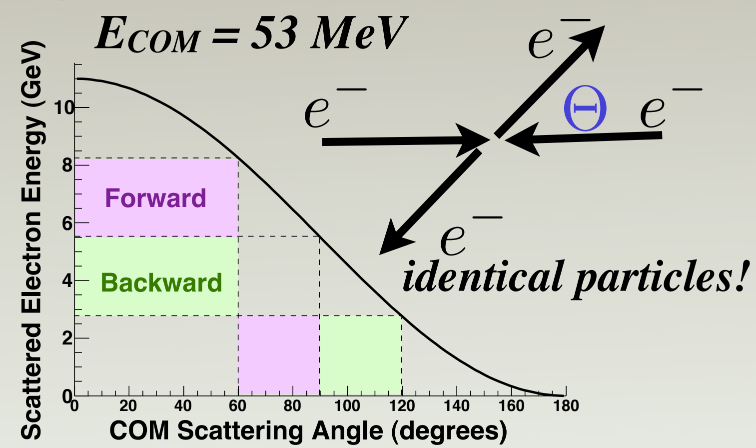
E158 scattering chamber



Spectrometer Choice

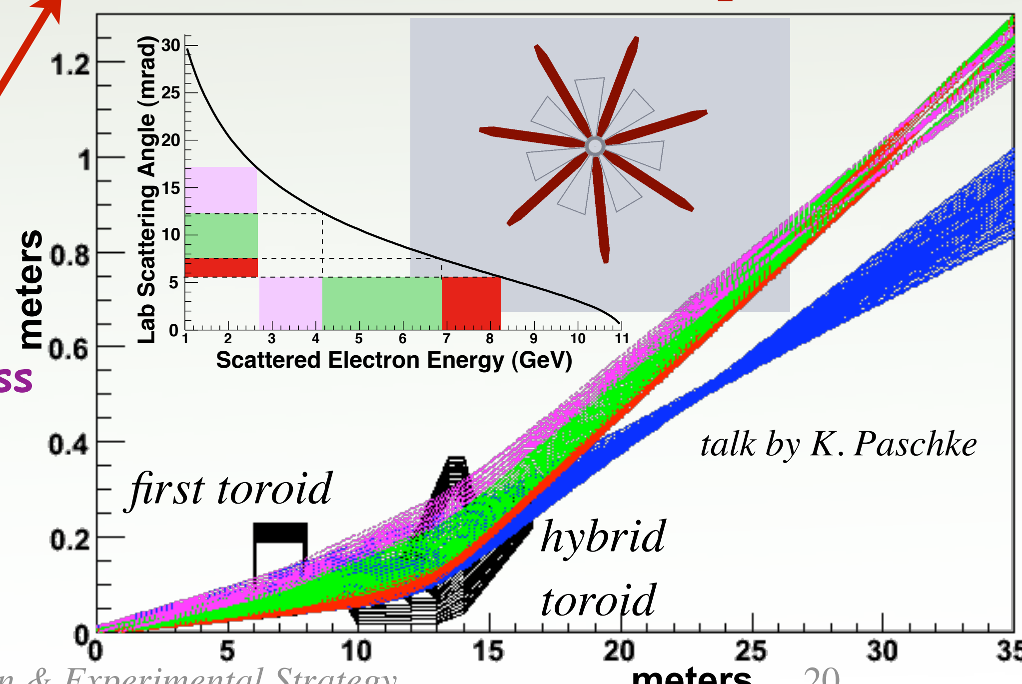




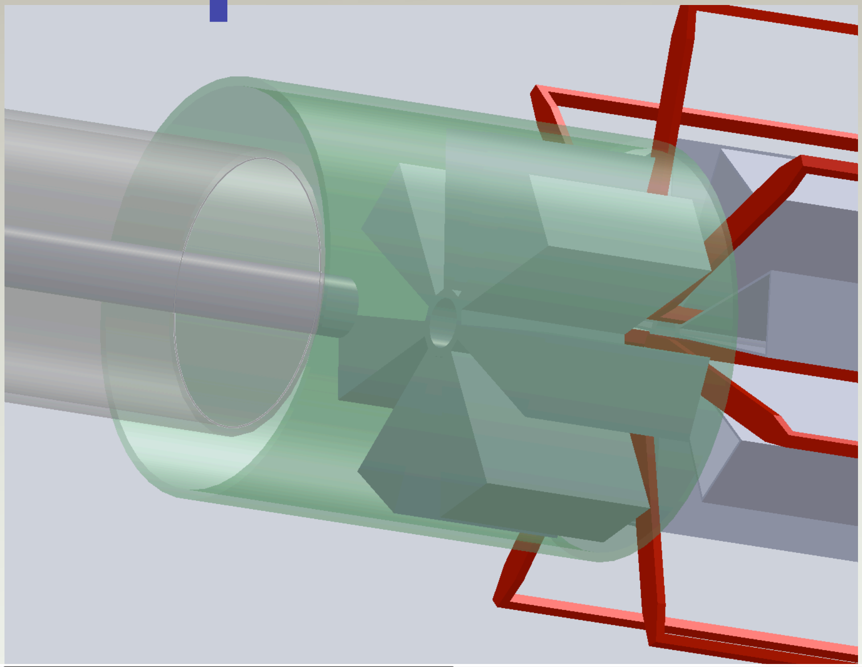


- ***Avoid superconductors***
  - ~150 kW of photons from target
  - Collimation extremely challenging
- ***Quadrupoles a la E158***
  - high field dipole chicane
  - poor separation from background
  - ~ 20-30% azimuthal acceptance loss
- ***Two Warm Toroids***
  - 100% azimuthal acceptance
  - better separation from background

Odd number of coils: both forward & backward Mollers in same phi-bite

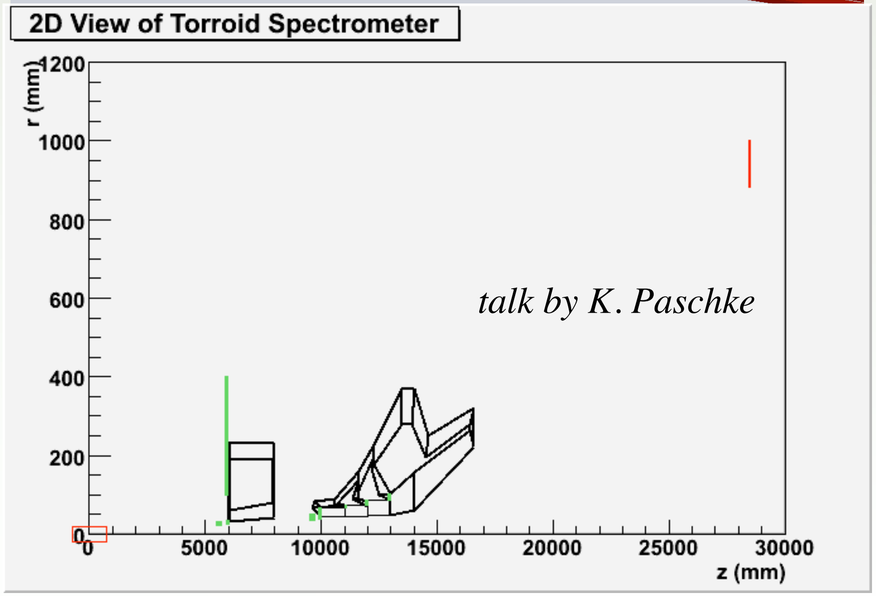


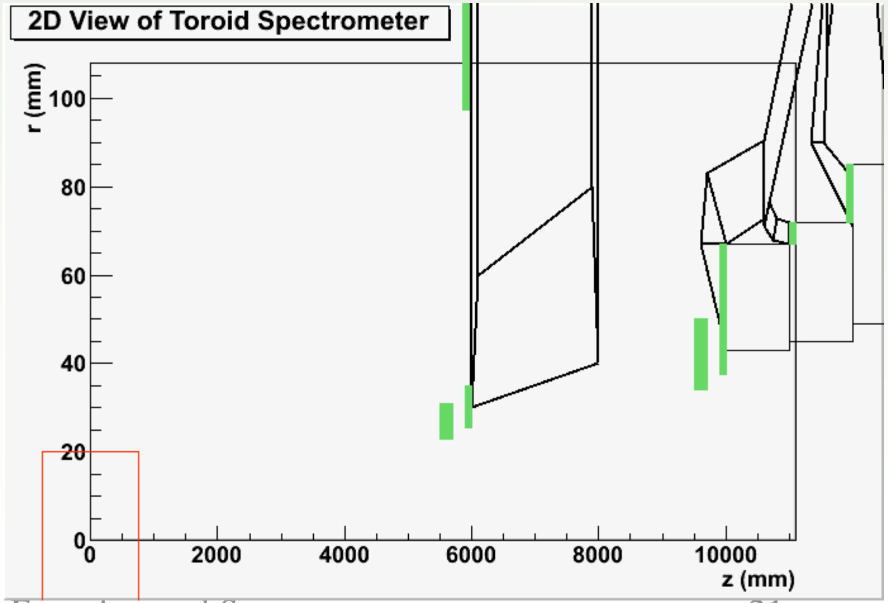
Spectrometer Collimation



Learn from E158 experience

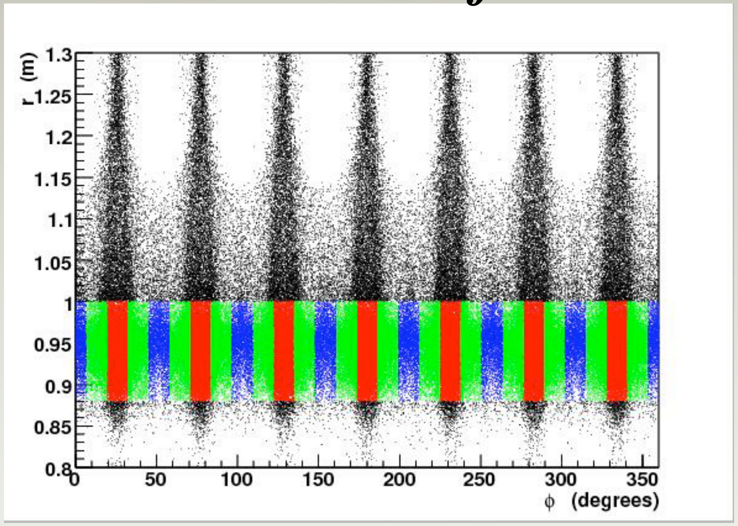
- *One-Bounce Photons*
- *Power Dissipation*
- *Precision Alignment*
- *Radiation Protection*

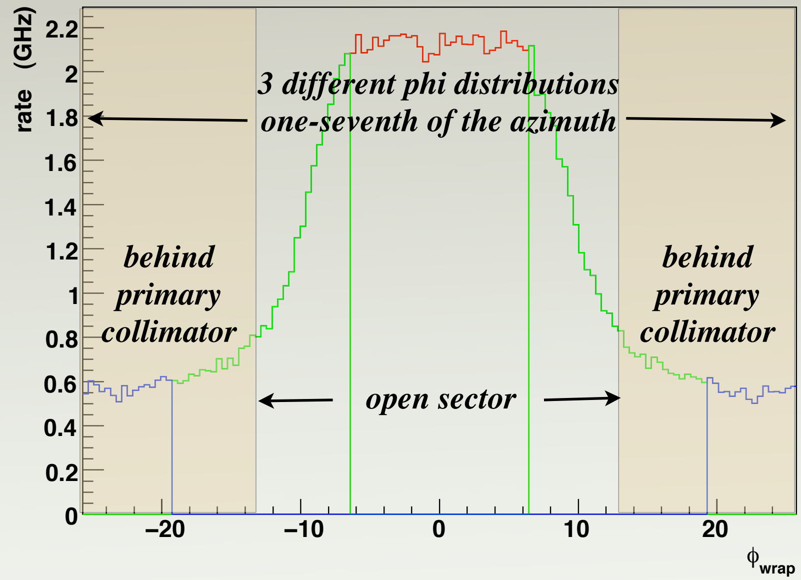


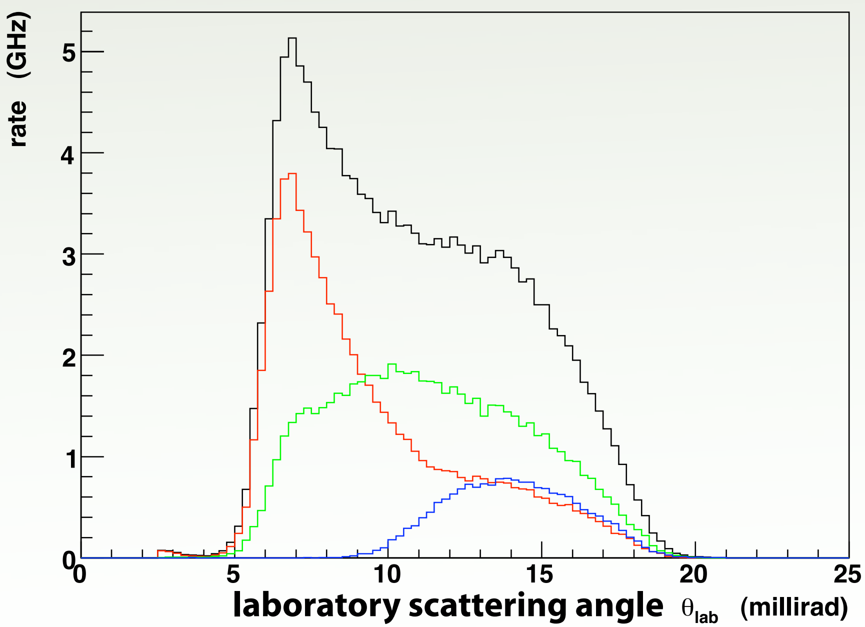


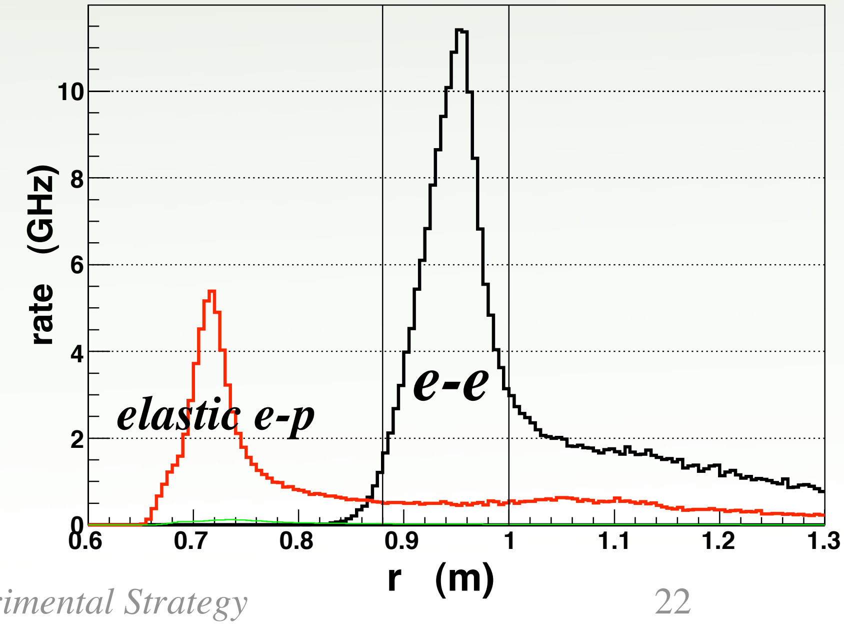
Simulations

Initial and final state radiation effects in target

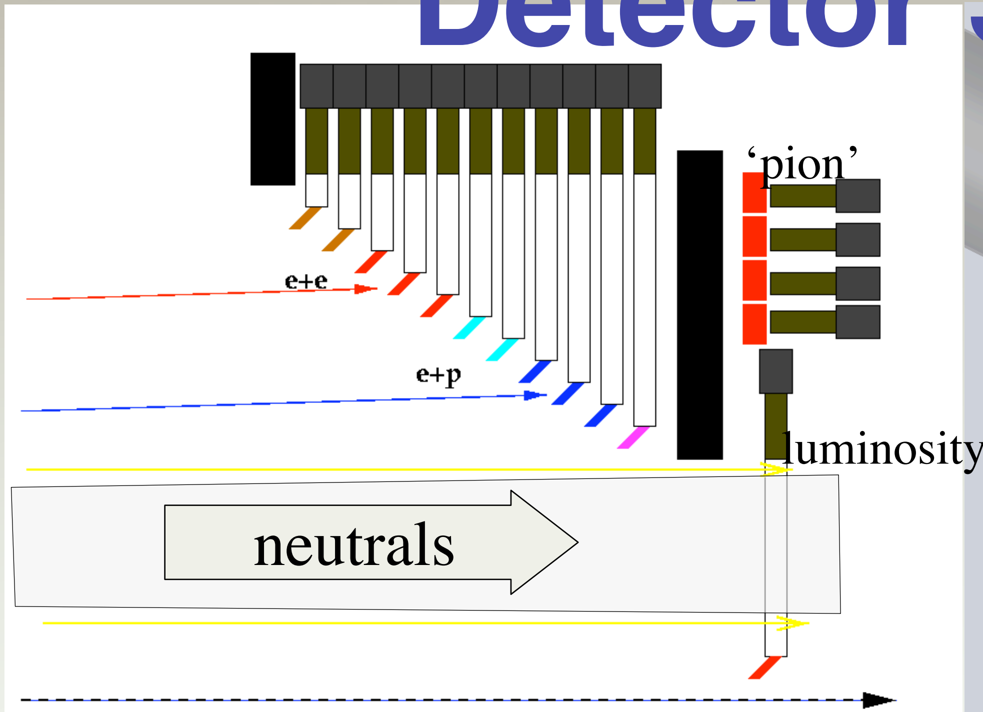


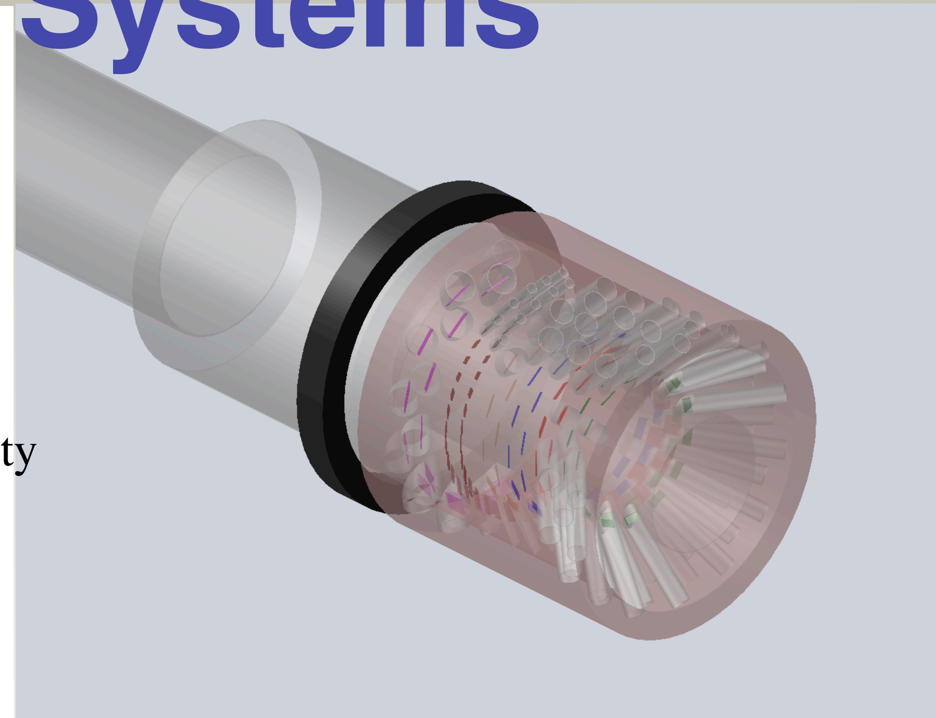






Detector Systems





- ***Integrating Detectors:***

  talk by D. Mack

  - **Moller and e-p Electrons:**
    - *radial and azimuthal segmentation*
    - *quartz with air lightguides & PMTs*
  - **pions and muons:**
    - *quartz sandwich behind shielding*
  - **luminosity monitors**

- ***Other Detectors***

  talk by D. Armstrong

  - **Tracking detectors**
    - *3 planes of GEMs/Straws*
    - *Critical for systematics/ calibration/debugging*
  - **Integrating Scanners**
    - *quick checks on stability*

Signal & Backgrounds

parameter	*value*
cross-section	45.1 μBarn
Rate @ 75 μA	135 GHz
pair stat. width (1 kHz)	82.9 ppm
$\delta(A_{raw})$ (6448 hrs)	0.544 ppb
$\delta(A_{stat})/A$ (80% pol.)	2.1%
$\delta(\sin^2\theta_W)_{stat}$	0.00026

- ***Statistical Error***
  - 83 ppm @ 75 μA
  - table assumes 80% Pe and no degradation of statistics from other noise sources
  - realistic goal ~ 90 ppm
  - potential for recovering running time with higher Pe, higher efficiency, better spectrometer focus....

Backgrounds: *talk by P. Souder*

- ***photons and neutrons***
  - mostly 2-bounce collimation system
  - dedicated runs to measure "blinded" response
- ***pions and muons***
  - real and virtual photo-production and DIS
  - prepare for continuous parasitic measurement
  - estimate 0.5 ppm asymmetry @ 0.1% dilution
- ***Elastic e-p scattering***
  - well-understood and testable with data
  - 8% dilution, 7.5±0.4% correction
- ***Inelastic e-p scattering***
  - sub-1% dilution
  - large EW coupling, 4±0.4% correction
  - variation of A_{PV} with r and ϕ

Technical Challenges

- ~ 150 GHz scattered electron rate
  - Design to flip Pockels cell ~ 2 kHz
  - 80 ppm pulse-to-pulse statistical fluctuations
    - *Electronic noise and density fluctuations < 10^{-5}*
    - *Pulse-to-pulse beam jitter ~ 10s of microns at 1 kHz*
    - *Pulse-to-pulse beam monitoring resolution ~ 10 ppm and few microns at 1 kHz*
- 1 nm control of beam centroid on target
  - Modest improvement on control of polarized source laser transport elements
  - Improved methods of "slow helicity reversal"
- > 10 gm/cm² target needed to achieve desired luminosity
  - 1.5 meter Liquid Hydrogen target: ~ 5 kW @ 85 μA
- Full Azimuthal acceptance with θ_{lab} ~ 5 mrad
  - novel two-toroid spectrometer
  - radiation hard, highly segmented integrating detectors
- Robust and Redundant 0.4% beam polarimetry
  - Plan to pursue both Compton and Atomic Hydrogen techniques

Systematics Overview

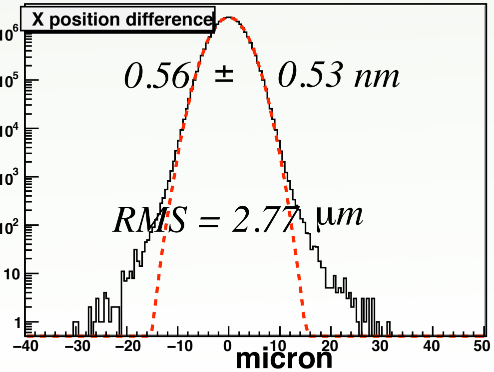
source of error	% error
absolute value of Q^2	0.5
beam second order	0.4
longitudinal beam polarization	0.4
inelastic e-p scattering	0.4
elastic e-p scattering	0.3
beam first order	0.3
pions and muons	0.3
transverse polarization	0.2
photons and neutrons	0.1
Total	**1.0**

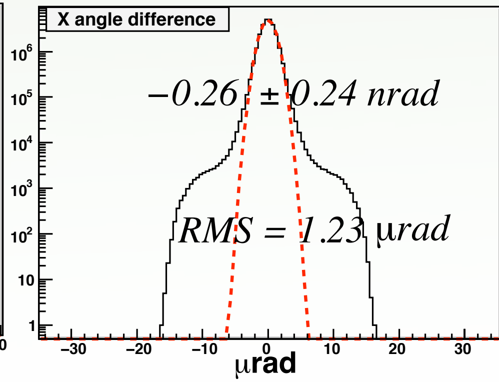
- ***longitudinal beam polarization*** *E. Chudakov and K. Paschke*
  - Goal: redundant, continuous monitoring with Compton & Atomic Hydrogen Moller
  - Redundancy backup plan: High field Moller
- ***transverse beam polarization*** *K. Paschke & Y. Kolomensky*
  - kinematic separation allows online monitoring
  - slow feedback using Wien filter
- ***Absolute value of Q^2*** *D. Armstrong*
  - dedicated tracking and scanning detectors
  - experience with HAPPEXII & Qweak

G. Cates and M. Pitt

- ***I order beam helicity correlations***
  - position to 0.5 nm, angle to 0.05 nrad
  - active intensity, position and angle feedback
- ***II order beam helicity correlations***
  - control laser spotsize fluctuations to 10^{-4}
  - slow flips with Wien filter and g-2 energy flip

HAPPEXII





Motivation Summary

- *Projected Result from an A_{PV} measurement in Møller Scattering*

A_{PV} = 35.6 ppb $\delta(A_{PV})$ = 0.73 ppb $\delta(Q^e_W) = \pm$ 2.1 (stat.) $\pm$ 1.0 (syst.) %

$\delta(\sin^2\theta_W) = \pm$ 0.00026 (stat.) $\pm$ 0.00012 (syst.) ⇨ ~ 0.1%

- *Opportunity with high visibility and large potential payoff*
  - The weak mixing angle is a fundamental parameter of EW physics
  - A cost-effective project has been elusive until now
    - *expensive ideas reach perhaps 0.2% (reactor or accelerator ν's, LHC Z production...)*
    - *sub-0.1% requires a new machine (e.g. Z- or ν-factory, linear collider....)*
  - physics impact on nuclear physics, particle physics and cosmology
    - *pin down parameter for other precision low energy measurements*
    - *help decipher potential LHC anomalies at the TeV scale*
    - *shed light on feasibility of SUSY dark matter via search for R-Parity violation*
- *NSAC Long Range Plan strongly endorsed the physics*
  - part of fundamental symmetries initiative to tune of 25M$
- *11 GeV JLab beam is a unique instrument that makes this feasible*

Outlook

- ***Aggressive physics goal***
  - conservative design choices
  - reasonable extrapolations on existing/planned III generation technologies
- ***Strong, committed collaboration***
  - Experience from E158, G0, HAPPEX
  - Major roles in Qweak & PREX (the best kind of MOLLER R&D!)
- ***No engineering yet***
  - Spectrometer design is the heart of the apparatus
    - *launching coherent plan with dedicated physicist/engineering manpower (absent in 2009)*
- ***Cost range: 12-16 M$***
  - Very generous on engineering/design manpower and contingency
  - far from WBS but much better than canonical x2 underestimate
- ***Begun process of devising a coherent R&D Plan***
  - Assuming green light, launch parallel effort to CD0 process in 2010