

# Electroweak Physics with Parity-Violating Electron Scattering

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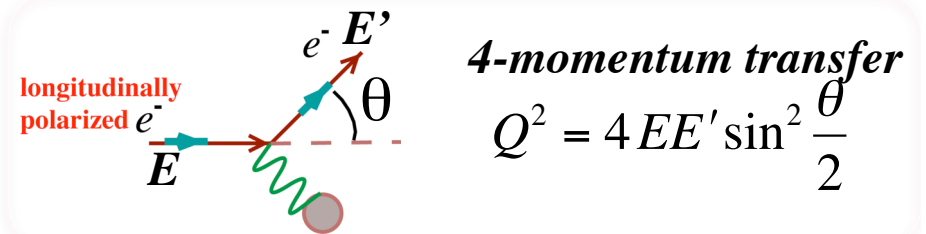
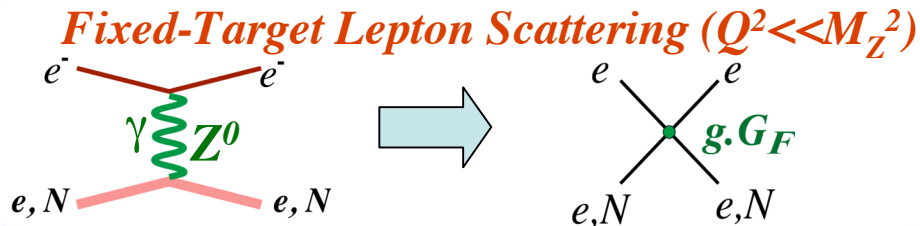
*DPF 2006*

*Honolulu, Hawaii, October 30, 2006*

## Outline

- *Physics Motivation*
- *SLAC E158: Møller ( $e^-e^-$ ) Scattering*
- *Future Measurements at Jefferson Laboratory*
- *Potential Fixed Target Experiment at the ILC*

# Weak Neutral Current (WNC) Interactions



$$\sigma \propto |A_{EM} + A_{weak}|^2$$

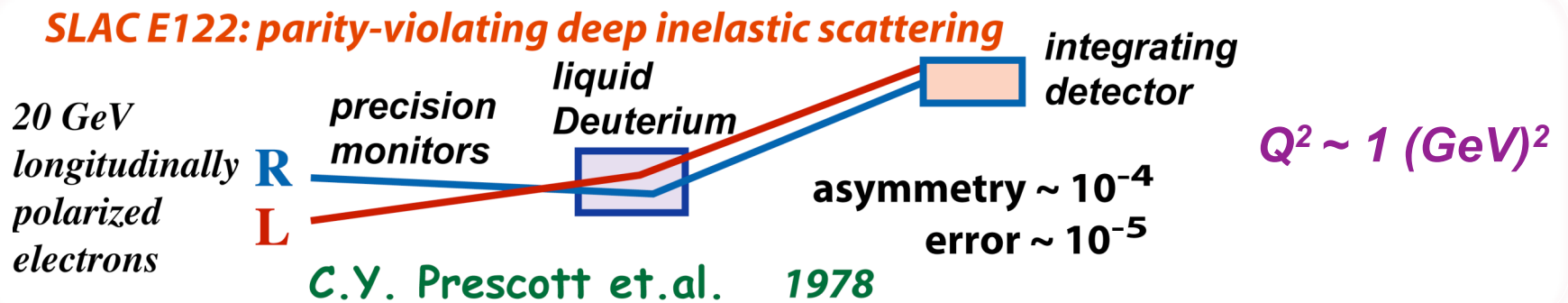
$$\sim |A_{EM}|^2 + \boxed{2A_{EM} A_{weak}^*} + \dots$$

*Parity-violating*

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

$$A_{PV} \sim g \cdot 10^{-4} \cdot Q^2 \text{ (GeV}^2\text{)}$$

$g$  is a function of the weak mixing angle  $\sin^2 \vartheta_W$



Modern experiments  $\Rightarrow$  Variety of physics topics

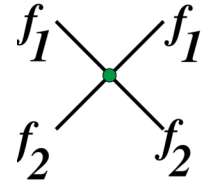
Part per billion systematic control

Large polarized luminosity

# 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  $f_1f_2 \rightarrow f_1f_2$

$$L_{f_1f_2} = \frac{g^2}{\Lambda^2} \sum_{i,j=L,R} \eta_{ij} \bar{f}_{1i} \gamma_\mu f_{1i} \bar{f}_{2j} \gamma^\mu f_{2j}$$


*$\Lambda$ '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  $\Lambda$ '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*

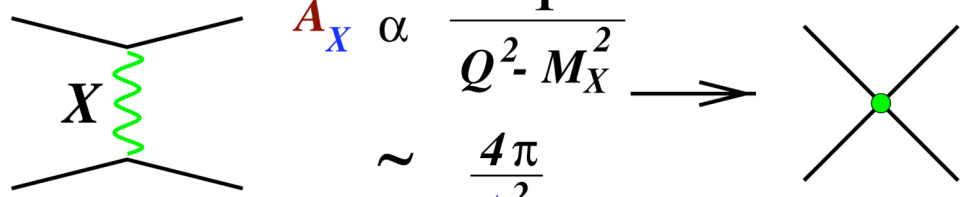
*LEP II, Tevatron access scales  $\Lambda$ 's  $\sim 10$  TeV*

*e.g. Tevatron dilepton spectra, fermion pair production at LEP II  
- L,R combinations accessed are parity-conserving*

*LEP & SLC accessed some parity-violating combinations but...*

# Colliders vs Low $Q^2$

*consider*



$A_X \propto \frac{1}{Q^2 - M_X^2} \rightarrow$  **Contact interaction**

$\sim \frac{4\pi}{\Lambda^2}$

$Q^2 \sim M_Z^2$  **on resonance:**  $A_Z$  *imaginary*  $\rightarrow A_Z^2 \left[ 1 + \frac{A_X^2}{A_Z^2} \right]$  **no interference!**

$$\frac{\delta A_Z}{A_Z} \propto \frac{\pi/\Lambda^2}{g G_F} \rightarrow \begin{cases} \delta(g)/g \sim 0.1 \\ \Lambda \sim 10 \text{ TeV} \end{cases}$$

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

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

In the mid-1990s, two promising techniques:

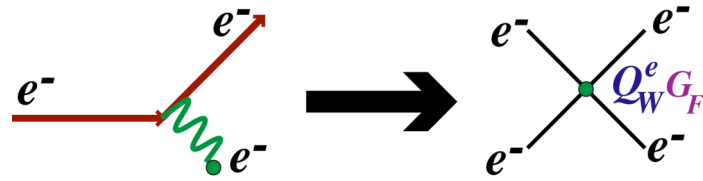
- Atomic Parity Violation Experiments
- Neutrino-Nucleon Deep Inelastic Scattering
- **Parity-Violating Electron Scattering can compete!**

*Need to measure  $A_{PV}$  that is proportional to  $1-4\sin^2 \theta_W$ :*

*Elastic electron-electron or electron-proton scattering*

$$\frac{\delta(\sin^2 \vartheta_W)}{\sin^2 \vartheta_W} \cong 0.05 \frac{\delta(A_{PV})}{A_{PV}}$$

# Møller Scattering



**Purely leptonic reaction!**

$$A_{PV} \approx 8 \times 10^{-8} E_{beam} (1 - 4 \sin^2 \vartheta_W)$$

**Tiny!**

$$\sigma \propto \frac{1}{E_{lab}}$$

*Figure of Merit rises linearly with  $E_{lab}$*



## SLAC E158: Parity-Violating Left-Right Asymmetry In Fixed Target Møller Scattering

$$A_{exp} \approx -2 \times 10^{-7} \times P_{beam}$$

*Goal: error small enough to probe TeV scale physics*

*~ 10 ppb statistical error*



*~ 0.4% error on  $\sin^2 \vartheta_W$*

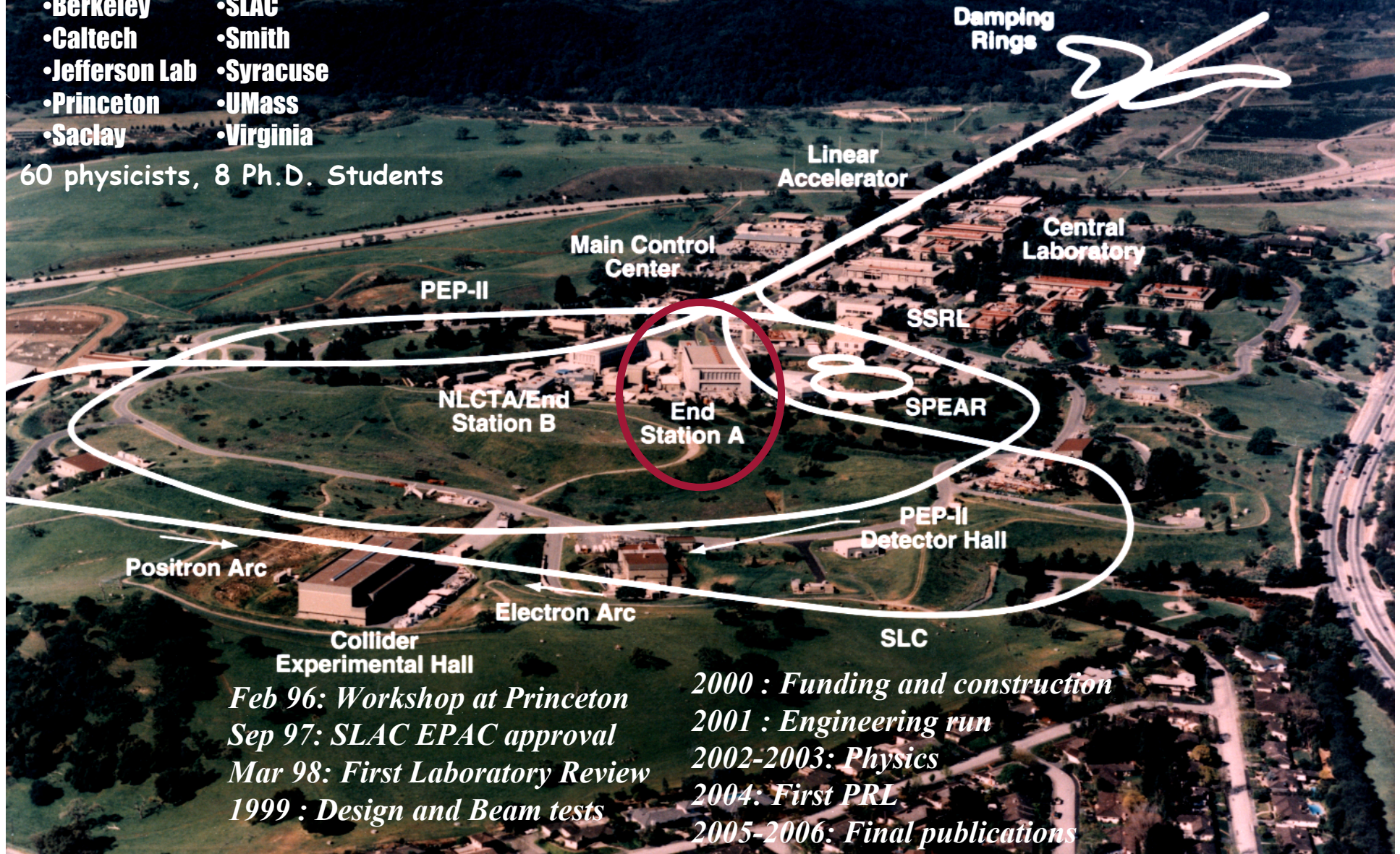
- Significant R&D effort on polarized beam production and monitoring
- Novel designs of target, spectrometer and detectors

# Stanford Linear Accelerator Center

## E158 Collaboration

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

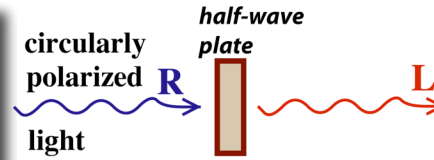
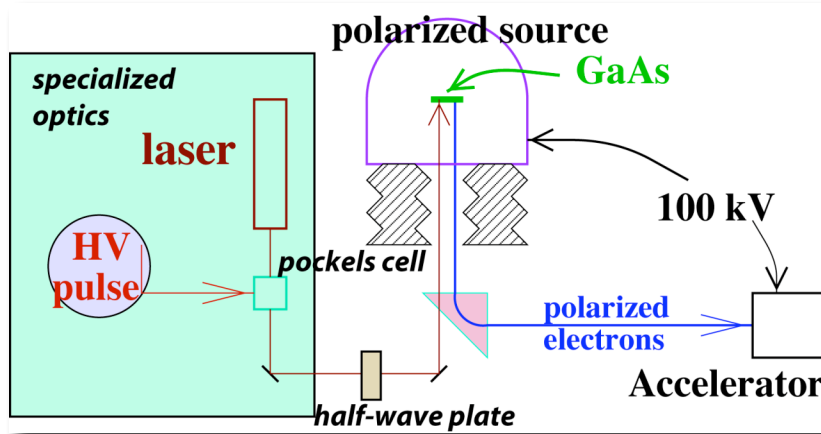
60 physicists, 8 Ph.D. Students



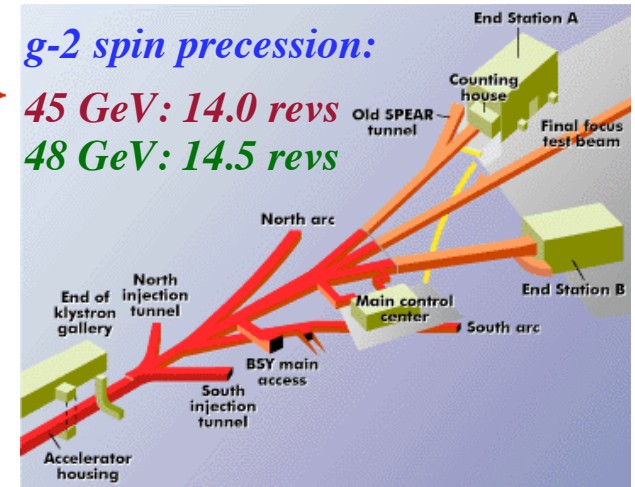
*Feb 96: Workshop at Princeton  
Sep 97: SLAC EPAC approval  
Mar 98: First Laboratory Review  
1999 : Design and Beam tests*

*2000 : Funding and construction  
2001 : Engineering run  
2002-2003: Physics  
2004: First PRL  
2005-2006: Final publications*

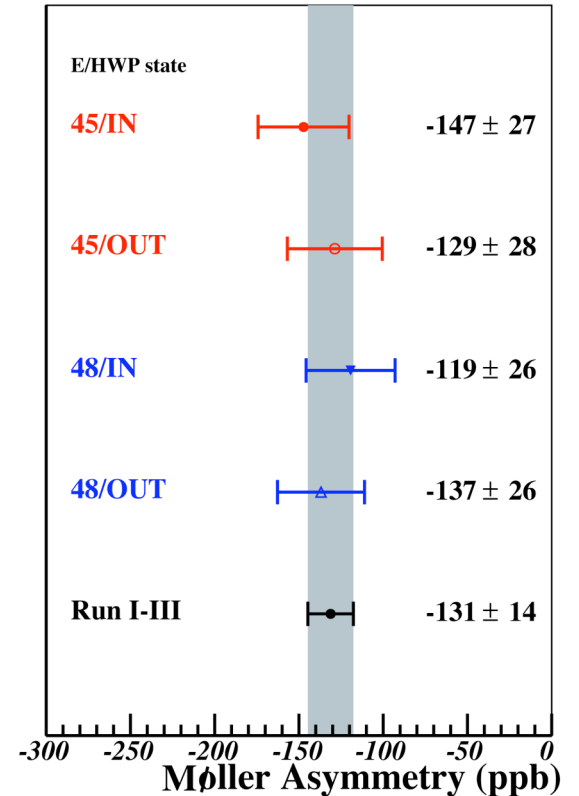
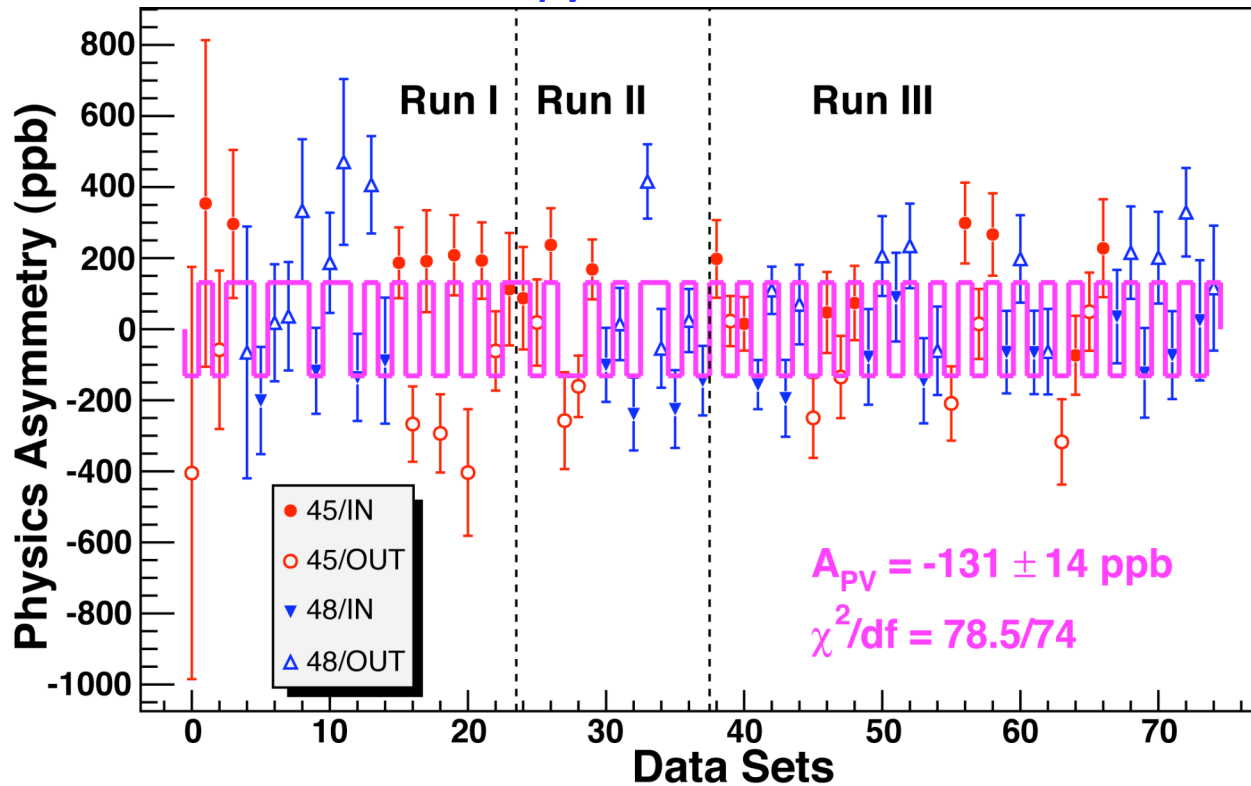
# SLAC E158: Final Result



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



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

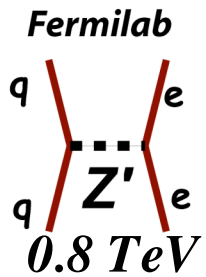
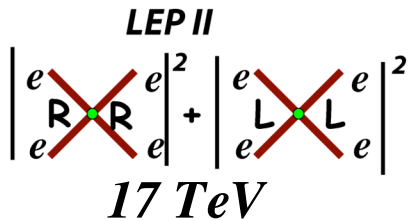


October 30 2006

Parity-Violating Electron Scattering

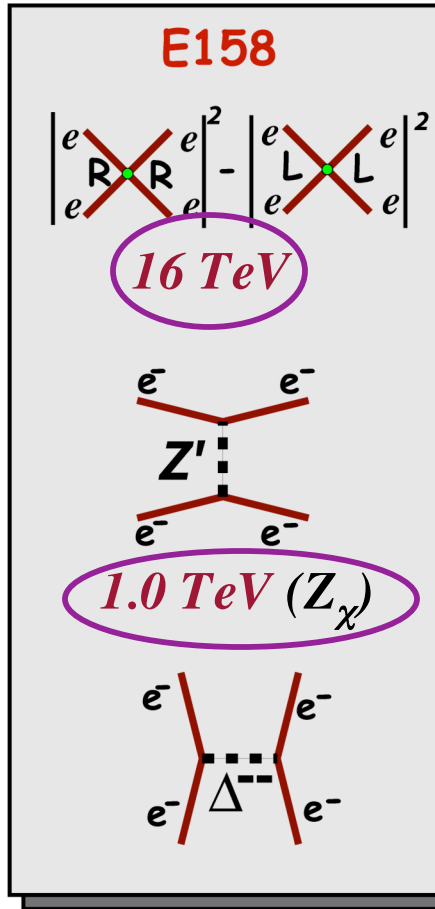
# Physics Implications

95% C.L.



doubly charged scalar exchange

$0.01 \cdot G_F$



## Atomic Parity Violation

•  $^{133}\text{Cs}$  6s to 7s transition

• Future: isotope measurements

## E158: purely leptonic

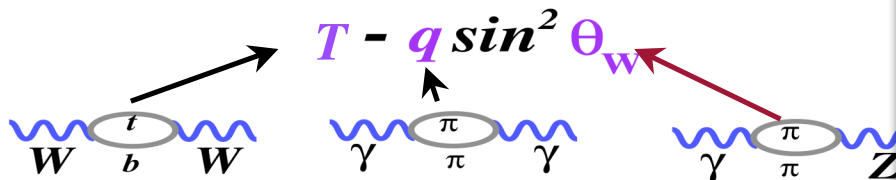
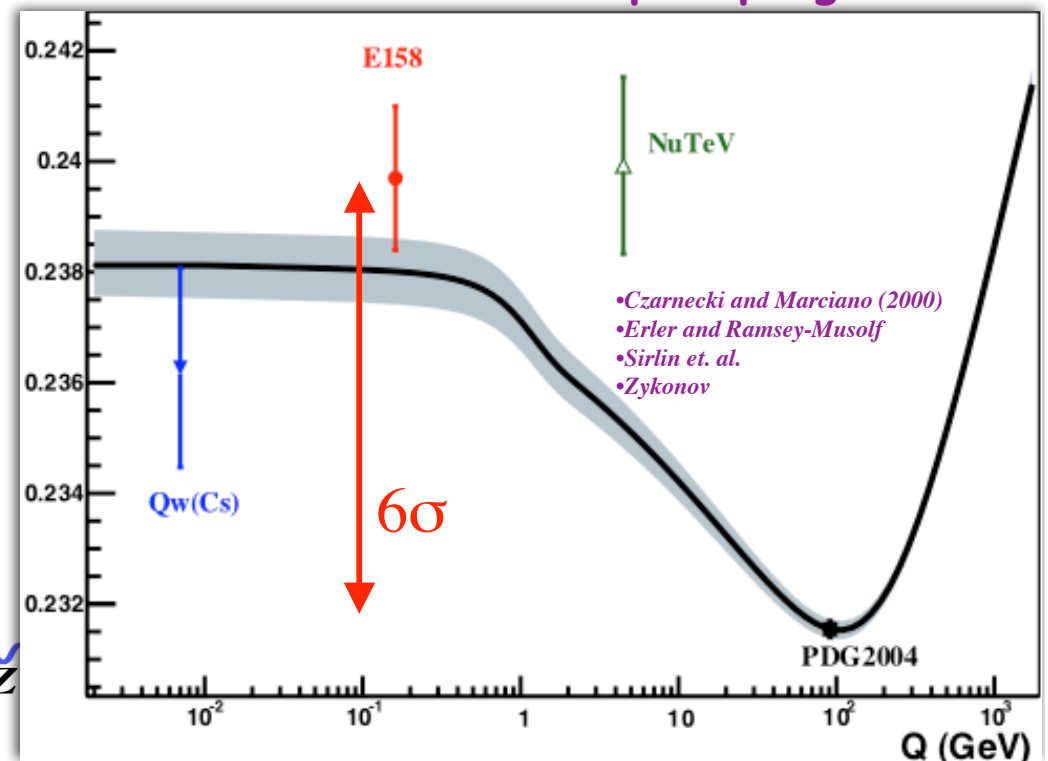
• Running of weak mixing angle

## Neutrino DIS: NuTeV

• 3  $\sigma$  deviation

• Many hadronic physics issues

• Look at other l-q couplings?

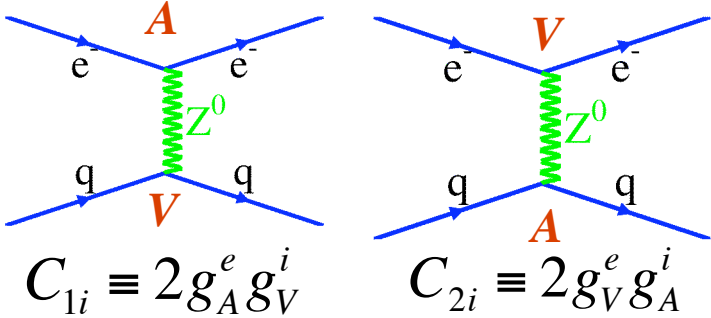




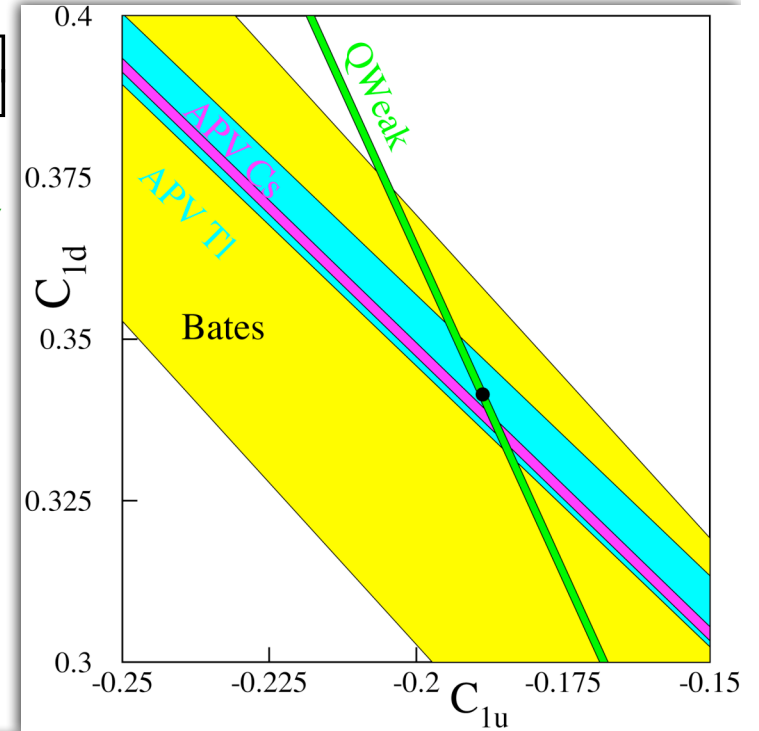
# Qweak at JLab

## $A_{PV}$ in elastic $e-p$ scattering

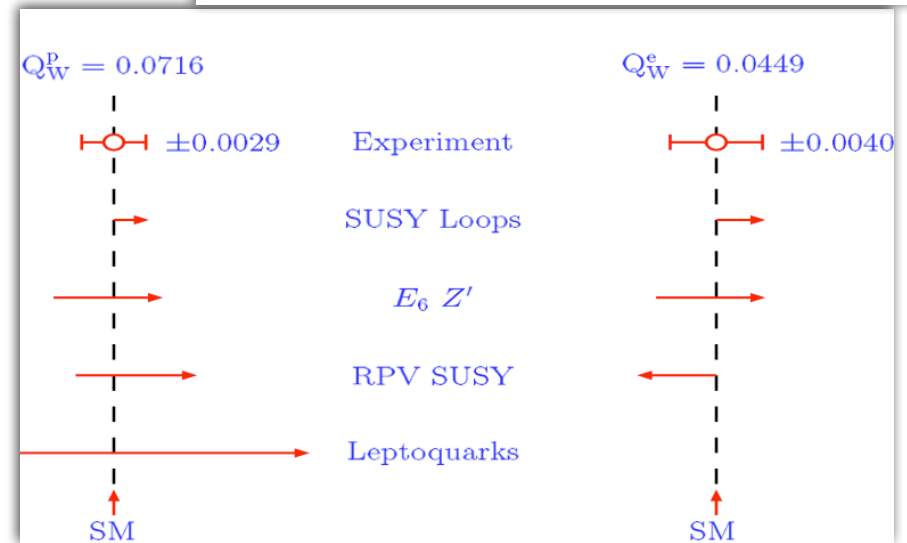
$$A(Q^2 \rightarrow 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}} \left[ Q^2 Q_{weak}^p + Q^4 B(Q^2) \right]$$



- $\delta(A_{PV}) \sim 3\%$
- $\delta(\sin^2 \theta_W) \sim \pm 0.0007$
- High luminosity
- Ultra-stable beam
- Design under way
- Data ~ 2010

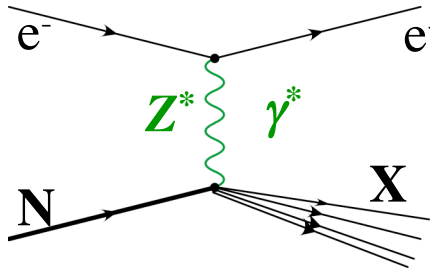


Jefferson Laboratory, Newport News, VA



# Precision Deep Inelastic Scattering

- $C_{2i}$ 's small & poorly known: difficult to measure in elastic scattering
- PV Deep inelastic scattering experiment with high luminosity  $\sim 10$  GeV beam
- Possible after 12 GeV upgrade of Jefferson Lab



$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha} [a(x) + f(y)b(x)]$$

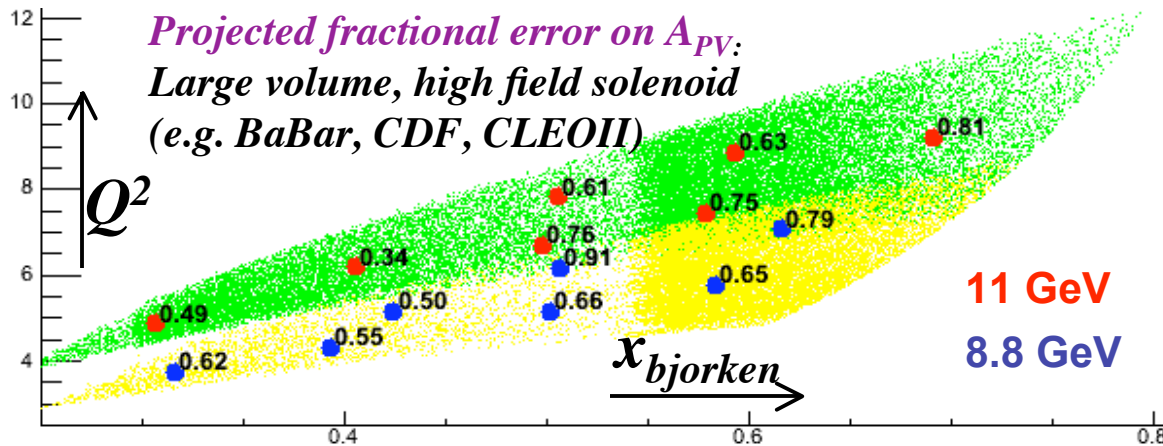
( $Q^2 \gg 1 \text{ GeV}^2$ ,  $W^2 \gg 4 \text{ GeV}^2$ ,  $x \sim 0.3-0.8$ )

$$a(x) = \frac{\sum_i C_{1i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)} \quad b(x) = \frac{\sum_i C_{2i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)}$$

$^2\text{H}$  target & charge symmetry: structure functions cancel

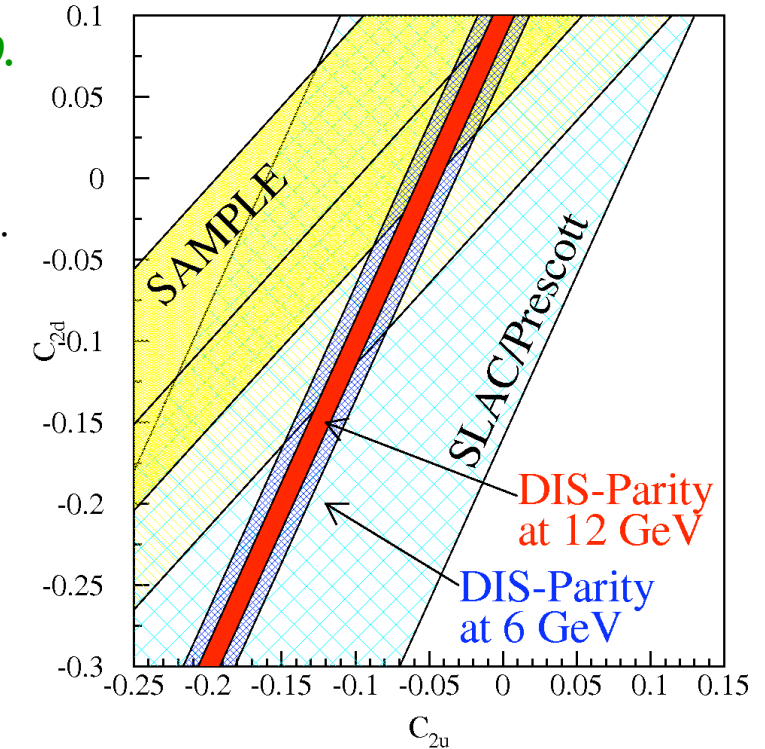
$$a(x) = \frac{3}{10} [(2C_{1u} - C_{1d})] + \dots \quad b(x) = \frac{3}{10} \left[ (2C_{2u} - C_{2d}) \frac{u_v(x) + d_v(x)}{u(x) + d(x)} \right] + \dots$$

- Must measure  $A_{PV}$  to 0.5% fractional accuracy!
- Must control QCD uncertainties



Projected fractional error on  $A_{PV}$ :  
Large volume, high field solenoid  
(e.g. BaBar, CDF, CLEOII)

11 GeV  
8.8 GeV



$C_{1u}$ ,  $C_{1d}$ ,  $C_{2u}$ ,  $C_{2d}$  measurements  
to provide precise constraints:  
help interpret LHC anomalies

# Precision High-x Physics with PV DIS

Charge Symmetry Violation (CSV) at High x:  
clean observation possible with  $^2\text{H}$  target?

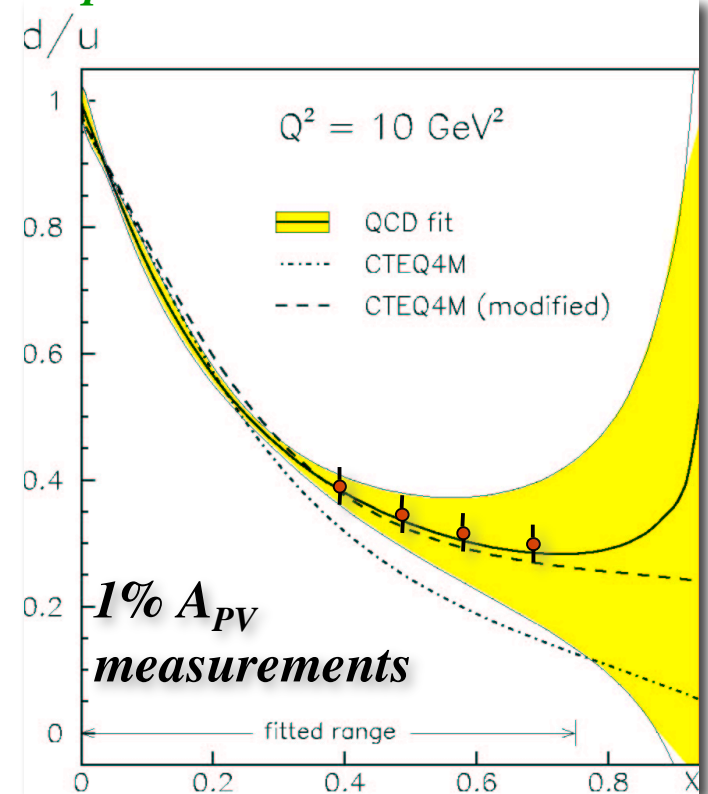
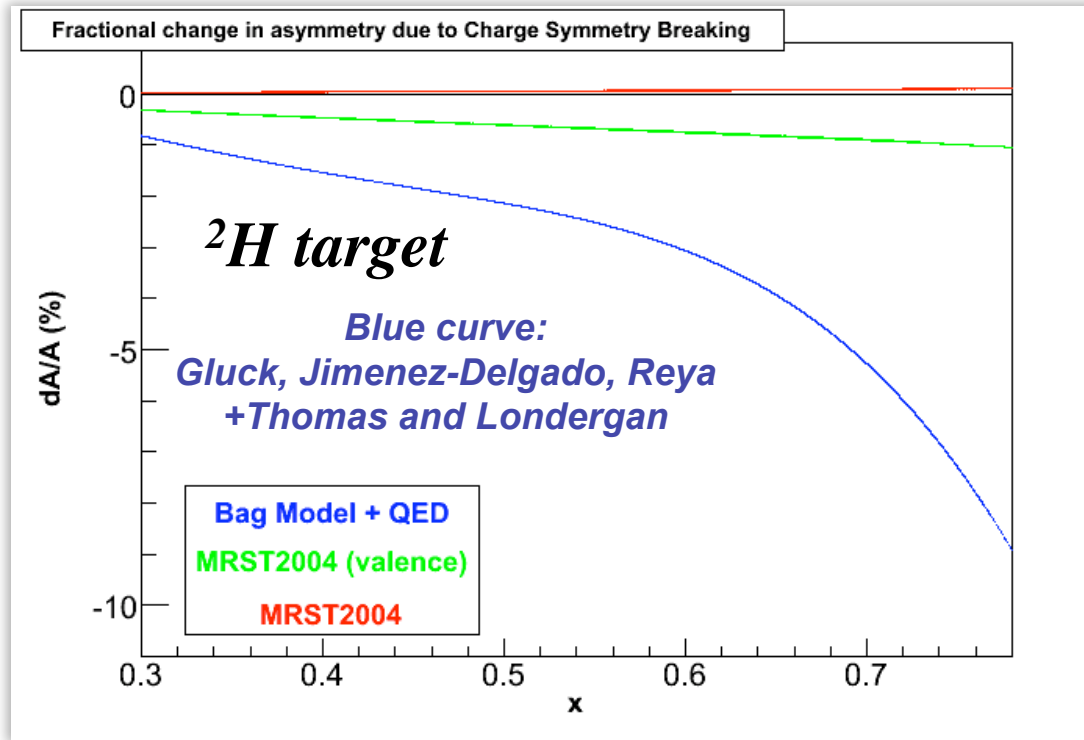
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha} [a(x) + f(y)b(x)]$$

$$\begin{aligned} \delta u(x) &= u^p(x) - d^n(x) & \frac{\delta A_{PV}(x)}{A_{PV}(x)} &= 0.3 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)} \\ \delta d(x) &= d^p(x) - u^n(x) \end{aligned}$$

**For  $^1\text{H}$ :**  $a(x) = \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$

- CSV structure functions important for LHC
- Discovery of CSV at partonic level is fundamental
- Could explain significant portion of NuTeV anomaly

- Allows  $d/u$  measurement on  $^1\text{H}$ , not  $^2\text{H}$
- Vector quark current!

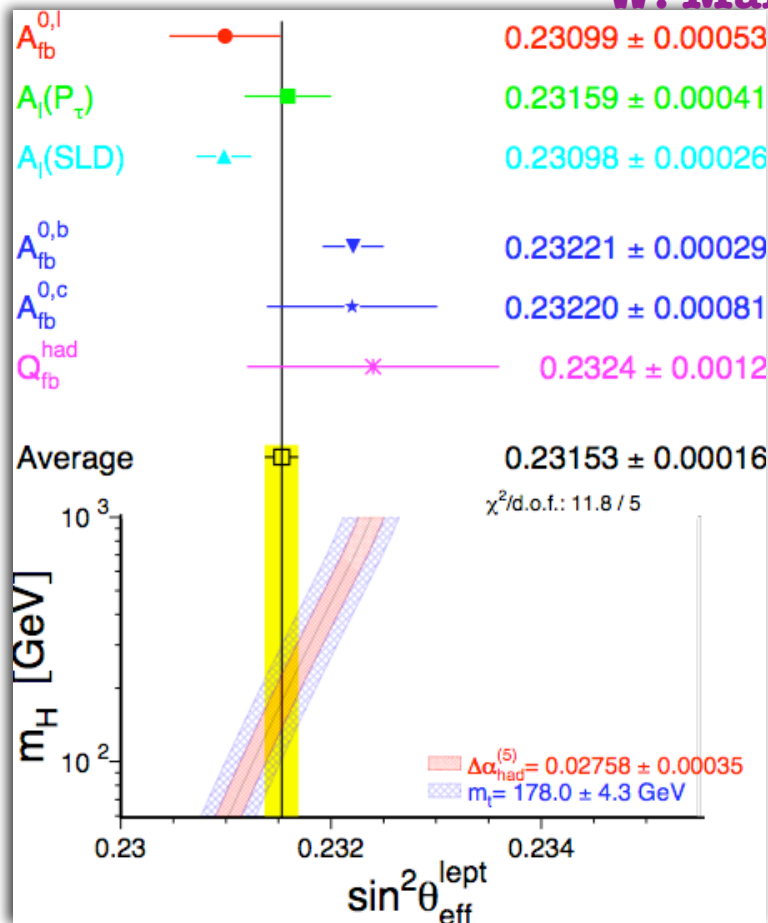


Longstanding issue:  $d/u$  as  $x \rightarrow 1$

# Weak Mixing Angle at HIGH Energy

W. Marciano, CIPANP06

Courtesy C. Kolda



The Average:  $\sin^2\theta_w = 0.23122(17)$

$\Rightarrow m_H = 89^{+38}_{-28} \text{ GeV}$   
 $\Rightarrow S = -0.13 \pm 0.10$

**3 $\sigma$  apart**

**Rules out Technicolor!**  
**Favors SUSY!**

$A_{LR}$

(also APV in Cs)

$\sin^2\theta_w = 0.2310(3)$



$m_H = 35^{+26}_{-17} \text{ GeV}$   
 $S = -0.11 \pm 17$

**Rules out the SM!**

$A_{FB}(Z \rightarrow b\bar{b})$

(also Moller @ E158)

$\sin^2\theta_w = 0.2322(3)$



$m_H = 480^{+350}_{-230} \text{ GeV}$   
 $S = +0.55 \pm 17$

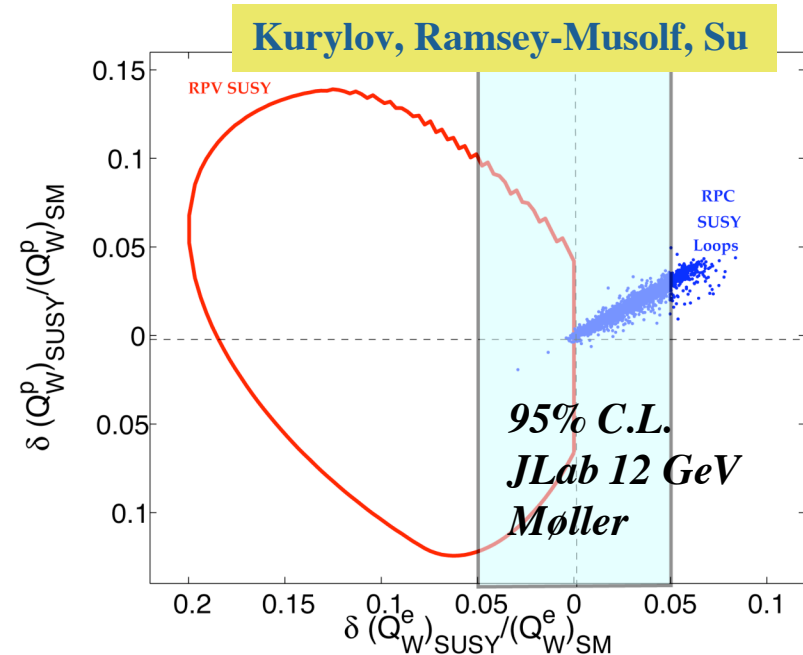
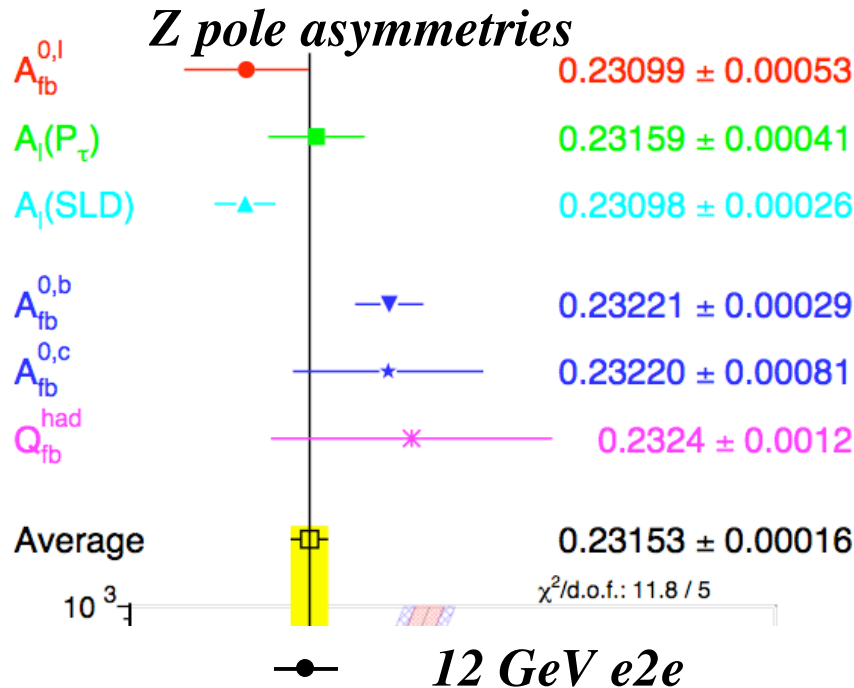
**Rules out SUSY!**  
**Favors Technicolor!**

- $\sin^2\theta_w$  improvements at hadron colliders very challenging
- Not a fashionable LHC topic: I hope some brave souls will try!
- “Giga-Z” option of ILC or neutrino factory are far in the future...

# Møller Scattering at Jefferson Lab

- *The 12 GeV upgrade project of Jefferson Laboratory is under way (~0.25B\$)*
- *A Møller scattering experiment could reach  $\delta(\sin^2\theta_W) \sim \pm 0.00025$  (on paper)*
- *Best low energy measurement until ILC or  $\nu$ -Factory*
- *Could be launched ~ 2012-13*

## Longstanding discrepancy between hadronic and leptonic Z asymmetries:

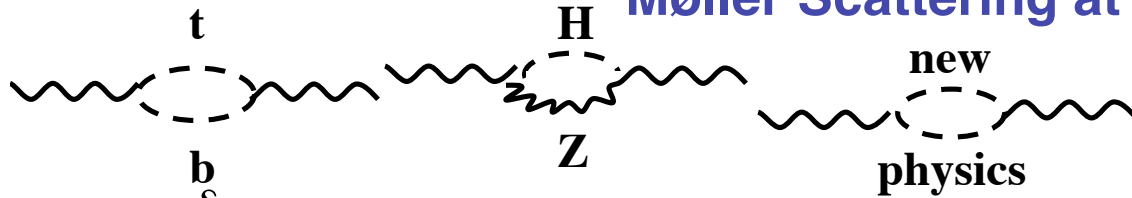


## Does Supersymmetry (SUSY) provide a candidate for dark matter?

- Neutralino is stable if baryon (B) and lepton (L) numbers are conserved
- B and L need not be conserved (RPV): neutralino decay

# Ultra-High Precision:

## Møller Scattering at the ILC



Measure contribution from scalars to oblique corrections

$$\frac{\delta m_H}{m_H} \approx 10\% \text{ for } \delta \sin^2 \theta_W \approx 0.00004$$

(world average  $\sim 0.00016$ )

Compare with masses of “bumps” at new colliders: *Critical crosscheck*

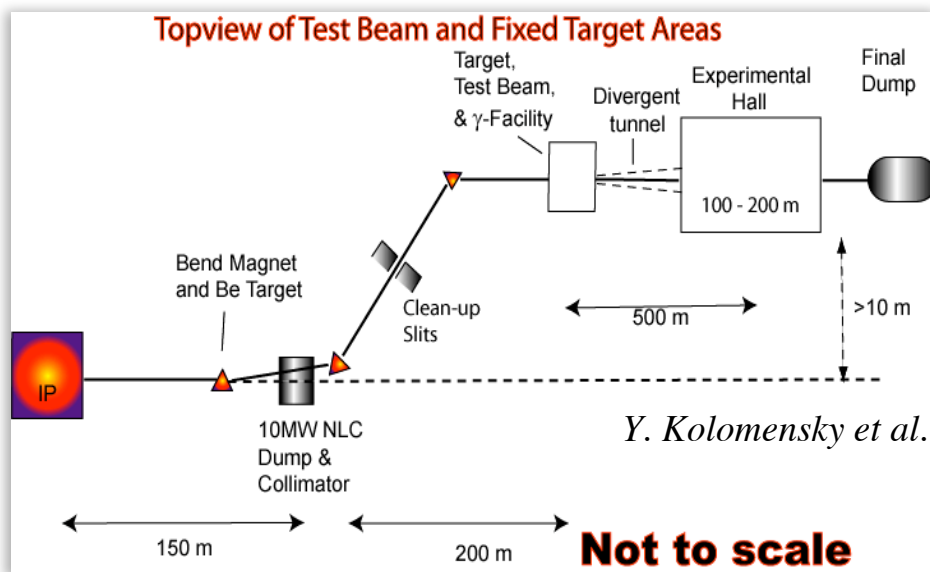
$A_{LR}$  and  $M_W$  at future colliders:

Systematics extremely challenging!

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

- Fixed target has advantages for systematics
- Could work with ILC “exhaust” beam

## Møller scattering at the ILC



|                           | E158                 | LC                  |
|---------------------------|----------------------|---------------------|
| Energy (GeV)              | 48                   | 250-500             |
| Intensity/pulse           | $4.5 \times 10^{11}$ | $14 \times 10^{11}$ |
| Pulse Rate (Hz)           | 120                  | 120                 |
| $P_e$                     | 85%                  | 90%                 |
| Time (s)                  | $5 \times 10^6$      | $2 \times 10^7$     |
| $A_{LR}$ (ppm)            | 0.15                 | 1-2                 |
| $\delta A_{LR}$ (ppm)     | 0.015                | 0.008               |
| $\delta \sin^2(\theta_W)$ | 0.001                | 0.00006-8           |

# Summary

- **SLAC E158's main physics result has been published:**
  - **Parity is violated in Møller scattering**
  - **Final result with all data:  $A_{PV}: -131 \pm 14 \pm 10$  ppb**
  - **Running of weak mixing angle established at  $6\sigma$**
  - **$\sin^2\theta_{eff} = 0.2397 \pm 0.0010 \pm 0.0008$**
  - **New constraints on TeV scale physics**
- **Next publications (by late 2006):**
  - **Inelastic e-p asymmetry at low  $Q^2$**
  - **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!**
- **Qweak will produce a complementary measurement in 2010**
- **Future 12 GeV JLab Møller: factor of 5 improvement**
- **High precision DIS measurements would probe l-q couplings**
- **An "ultimate" measurement could be done at the ILC, if a fixed-target beam can be run simultaneous with collisions**