Fundamental Symmetries, Neutrinos, Neutrons and related Nuclear Astrophysics
Long-Range Plan Town Meeting
Chicago
September 28-29, 2014

## *Parity Violating Electron Scattering (PVES)*

# Recent Results and Future Prospects


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Acknowledgments: A. Deshpande, J. Erler, W. Marciano, K. Paschke, M. Pitt, M. Ramsey-Musolf, P. Souder, X. Zheng

# Context for Polarized Electron Scattering

**A comprehensive strategy to understand the origin of matter requires:**

**The Large Hadron Collider, astrophysical observations** ***as well as*** **Lower Energy: $Q^2 \ll M_Z^2$**

***Nuclear/Atomic* systems address several topics; unique & complementary:**

- ***Neutrino mass and mixing*** *$0\nu\beta\beta$ decay, $\theta_{13}$, $\beta$ decay, long baseline neutrino expts…*
- ***Rare or Forbidden Processes*** *EDMs,* ***other LNV, charged LFV****, $0\nu\beta\beta$ decay…*
- ***Dark Matter Searches*** *direct detection, dark photon searches…*
- ***Precision Electroweak Measurements:*** *$(g-2)_\mu$, charged &* ***neutral current amplitudes***

## *Experimental Facilities/Initiatives/Programs*

- ***Neutrons:*** *Lifetime, Asymmetries (LANSCE, NIST, SNS…)*
- ***Underground Detectors:*** *Dark Matter, Double-Beta Decay*
- ***Nuclei:*** *Precision Weak Decays, Atomic Parity Violation, EDMs (MSU, ANL, TAMU, Tabletop…)*
- ***Muons, Kaons, Pions:*** *Lifetime, Branching ratios, Michel parameters, g-2 , EDMs (BNL, PSI, TRIUMF, FNAL, J-PARC...)*
- ***Electron Beams:*** *Weak neutral current couplings, precision weak mixing angle, dark photons (JLab, Mainz)*

**FRIB ~ 2020; EIC?**

**Electroweak Interactions at scales much lower than the W/Z mass**

# TeV-Scale Probe: Indirect Clues

**NP: Fundamental Symmetries; HEP: The Intensity/Precision Frontier**

## Interplay between electroweak and hadron dynamics

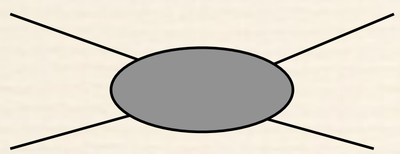
## High Energy Dynamics

E

$\Lambda$ (~TeV)

$M_{W,Z}$ (100 GeV)

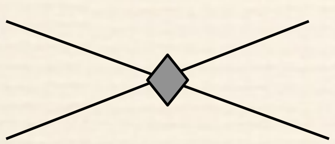
courtesy V. Cirigliano, H. Maruyama, M. Pospelov

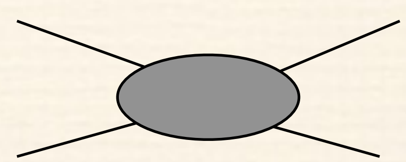


***SM amplitudes can be very precisely predicted***

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

higher dimensional operators can be systematically classified

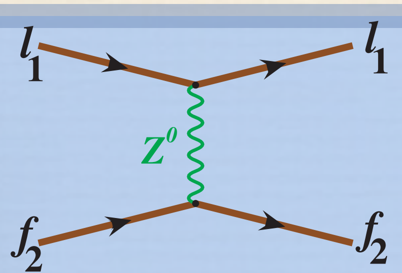




## Dark Sector

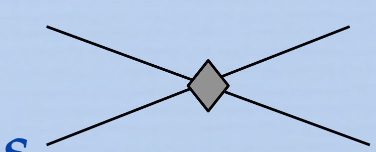
$(\text{coupling})^{-1}$

**Heavy Z's, light (dark) Z's, technicolor, compositeness, extra dimensions, SUSY...**




**Search for new flavor diagonal neutral currents**

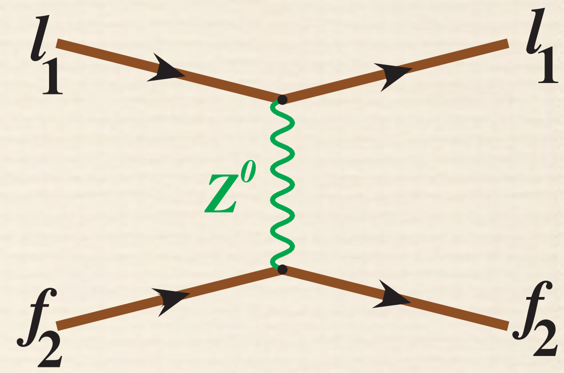
*Look for tiny but measurable deviations from precisely calculable predictions for SM processes*



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

**must reach $\Lambda$ ~ 10 TeV**

# Weak Neutral Current Interactions

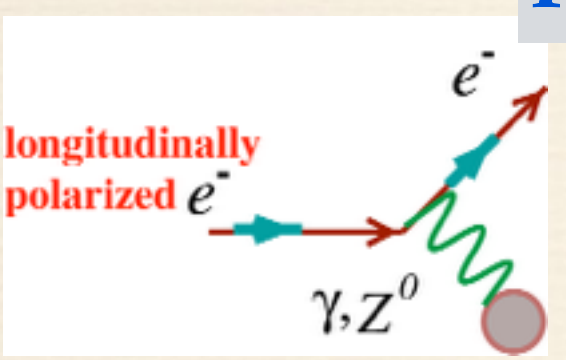



✦Precision Neutrino Scattering

✦New Physics/Weak-Electromagnetic Interference

- *opposite parity transitions in heavy atoms*
- *Spin-dependent electron scattering*

## Parity-violating Electron Scattering




$$-A_{LR} = A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{\gamma}} \sim \frac{G_F Q^2}{4\pi\alpha} (g_A^e g_V^T + \beta\, g_V^e g_A^T)$$

*$g_V$ and $g_A$ are function of $\sin^2\theta_W$*

$$A_{PV} \sim 10^{-5} \cdot Q^2 \quad \textit{to} \quad 10^{-4} \cdot Q^2$$

**Specific choices of kinematics and target nuclei probes different physics:**

- ***In mid 70s, goal was to show $\sin^2\theta_W$ was the same as in neutrino scattering***
- ***Since early 90's: target couplings probe novel aspects of hadron structure (strange quark form factors, neutron RMS radius of nuclei)***
- ***Future: precision measurements with carefully chosen kinematics can probe physics at the multi-TeV scale, and novel aspects of nucleon structure***

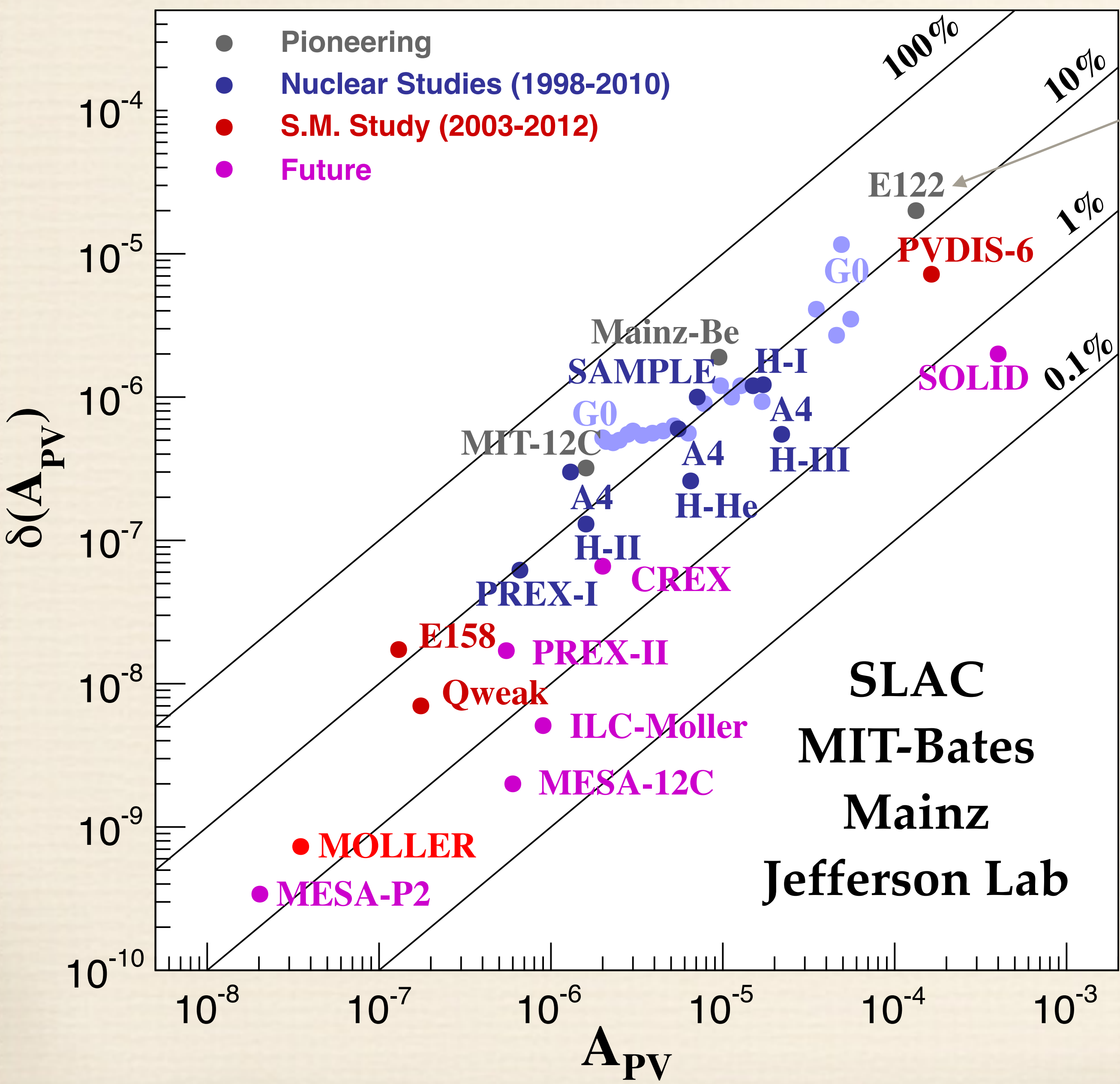
*Continuous interplay between probing hadron structure and electroweak physics*

# 4 Decades of Progress

**Parity-violating electron scattering has become a precision tool**

***photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors***

PVeS Experiment Summary




**Pioneering electron-quark PV DIS experiment SLAC E122**

## State-of-the-art:

- ***sub-part per billion statistical reach and systematic control***
- ***sub-1% normalization control***

## Physics Topics

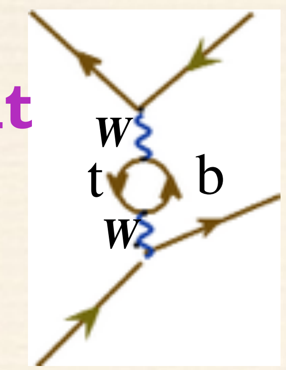
- *Strange Quark Form Factors*
- *Neutron skin of a heavy nucleus*
- *Indirect Searches for New Interactions*
- *Novel Probes of Nucleon Structure*
- *Electroweak Structure Functions at the EIC*
- *Charge Lepton Flavor Violation at the EIC*

# Weak Mixing Angle at 1-Loop

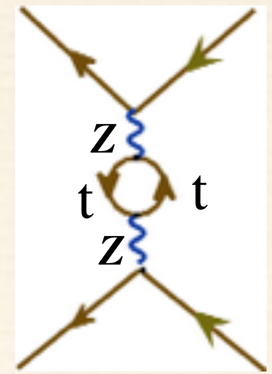
**For electroweak interactions, 3 input parameters needed:**

1. **Rb-87 mass + Ry constant**
2. **The muon lifetime**
3. **The Z line shape**

$\alpha_{QED} \quad G_F \quad M_Z$

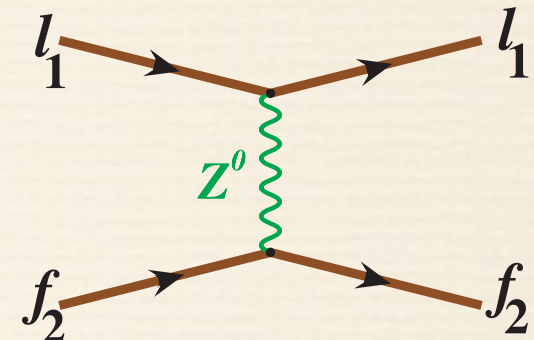



*Muon decay*




*Z production*

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




Weak Neutral Current interactions

***LEP-I, SLC, LEP-II, Tevatron***

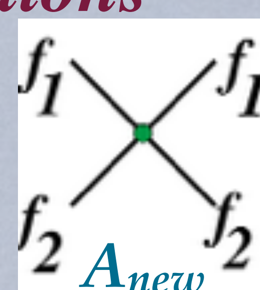
$$\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.23125(16)$$

$$M_W = 80.385(15)\ \text{GeV}$$

*Flavor Diagonal Contact Interactions*

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

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




**New heavy physics that does not couple directly to SM gauge bosons**

New flavor diagonal interactions mediated by a new light boson such as the "dark Z"

*on resonance: $A_Z$ is imaginary*

$$\left|A_Z + A_{new}\right|^2 \rightarrow A_Z^2\left[1 + \left(\frac{A_{new}}{A_Z}\right)^2\right]$$

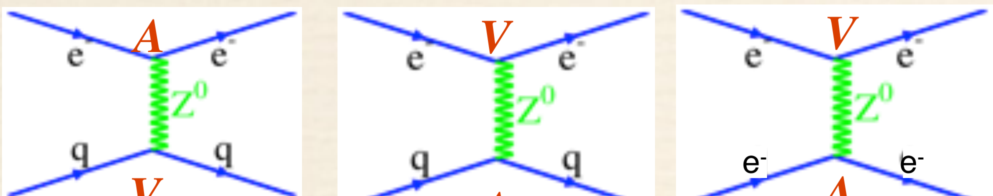
no interference!

$$Q^2 \ll M_Z^2$$

## Elastic and deep-inelastic PV scattering

# Weak Neutral Current Couplings

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d)$$
$$+\bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)$$
$$+C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

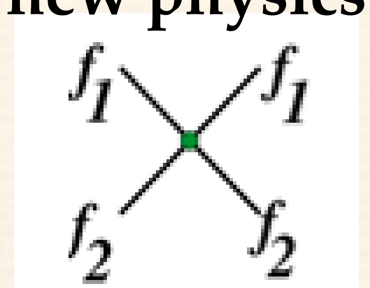



$C_{1i} \equiv 2g_A^e g_V^i$ $\quad C_{2i} \equiv 2g_V^e g_A^i$ $\quad C_{ee} = 2g_V^e g_A^e$

| | | | | |
|---|---|---|---|---|
| $C_{1u}$ | $=$ | $-\frac{1}{2}+\frac{4}{3}\sin^2\theta_W$ | $\approx$ | $-0.19$ |
| $C_{1d}$ | $=$ | $\frac{1}{2}-\frac{2}{3}\sin^2\theta_W$ | $\approx$ | $0.35$ |
| $C_{2u}$ | $=$ | $-\frac{1}{2}+2\sin^2\theta_W$ | $\approx$ | $-0.04$ |
| $C_{2d}$ | $=$ | $\frac{1}{2}-2\sin^2\theta_W$ | $\approx$ | $0.04$ |

$$C_{ee} = \frac{1}{2} - 2\sin^2\theta_W \approx 0.02$$

+ **new physics**




$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$ ⇒ ***PV elastic e-p scattering, Atomic parity violation***

$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$ ⇒ ***PV deep inelastic scattering***

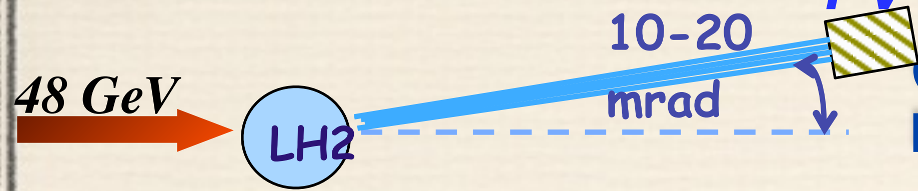
$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2$ ⇒ ***PV Møller scattering***

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

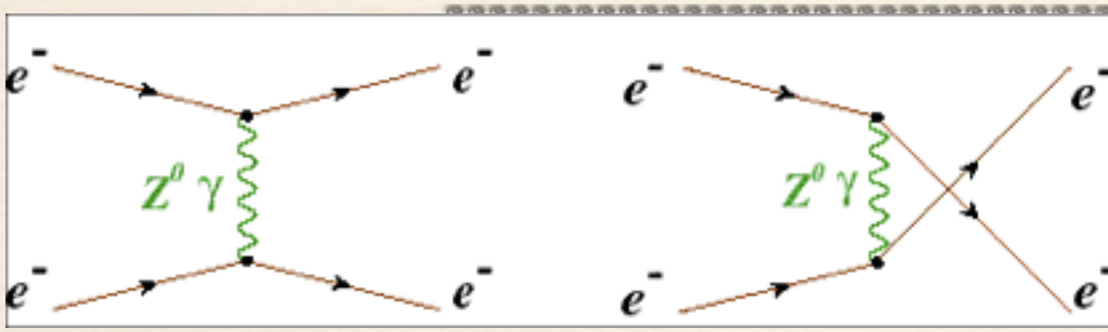
# SLAC E158

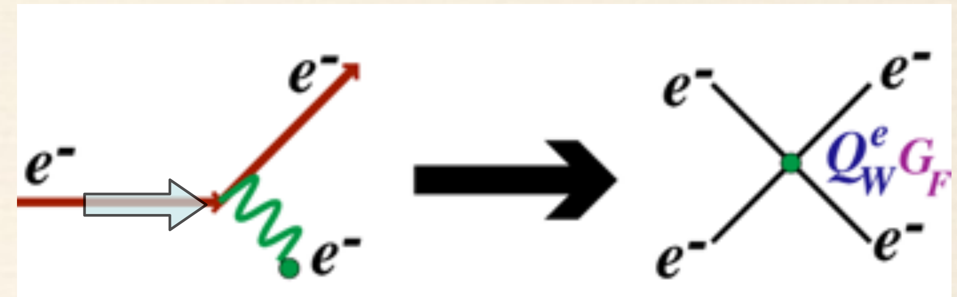
1997-2004

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




## *Parity-Violating Møller scattering: first to reach TeV-scale sensitivity*

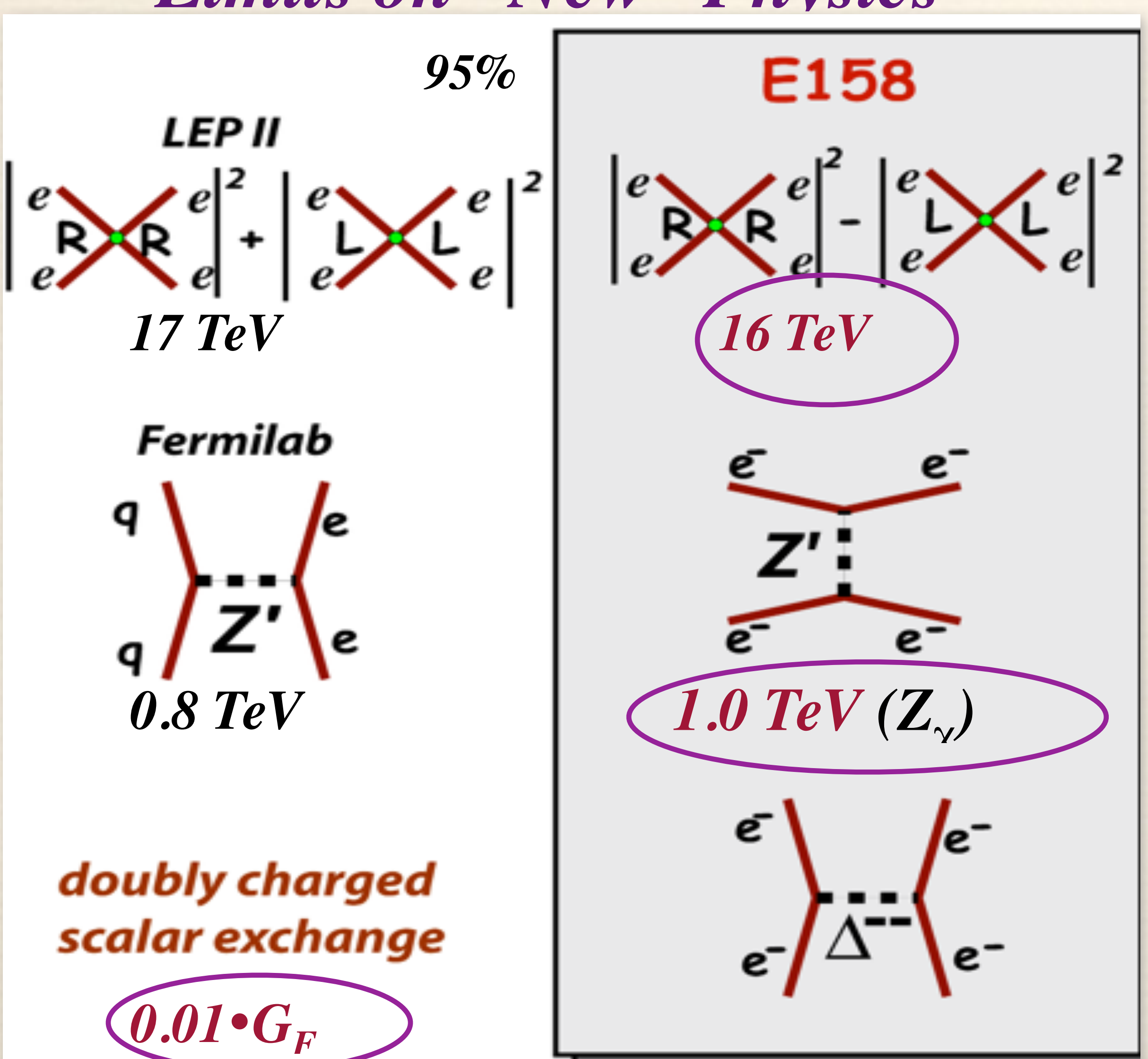



$$A_{PV} = -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}Q^e_W$$

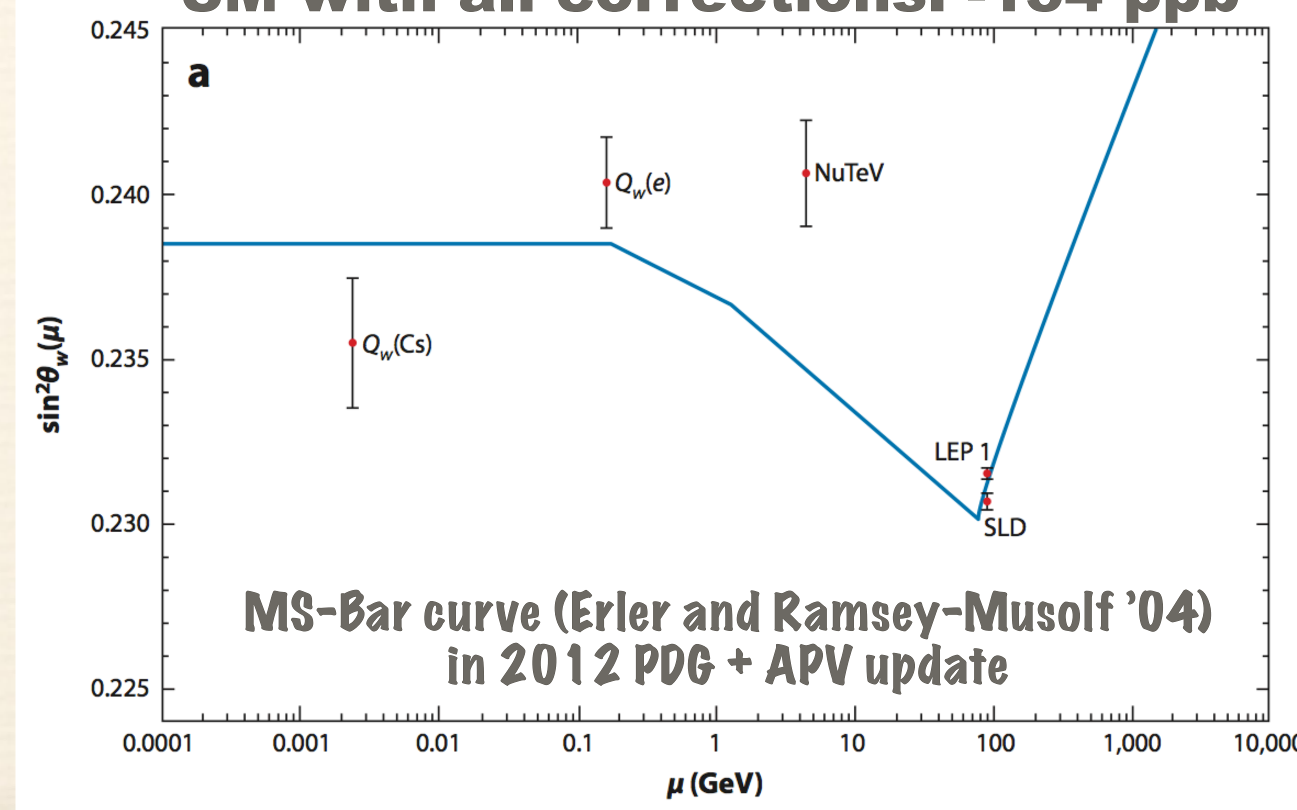
$$Q^e_W = 1 - 4\sin^2\theta_W \sim 0.075 \Longrightarrow 0.045$$

## *Limits on "New" Physics*



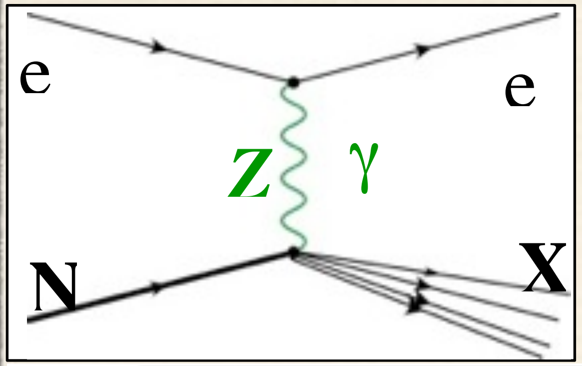

Tree-level prediction: ~ -270 ppb

**SM with all corrections: -154 ppb**



# Deep Inelastic Scattering on $LD_2$

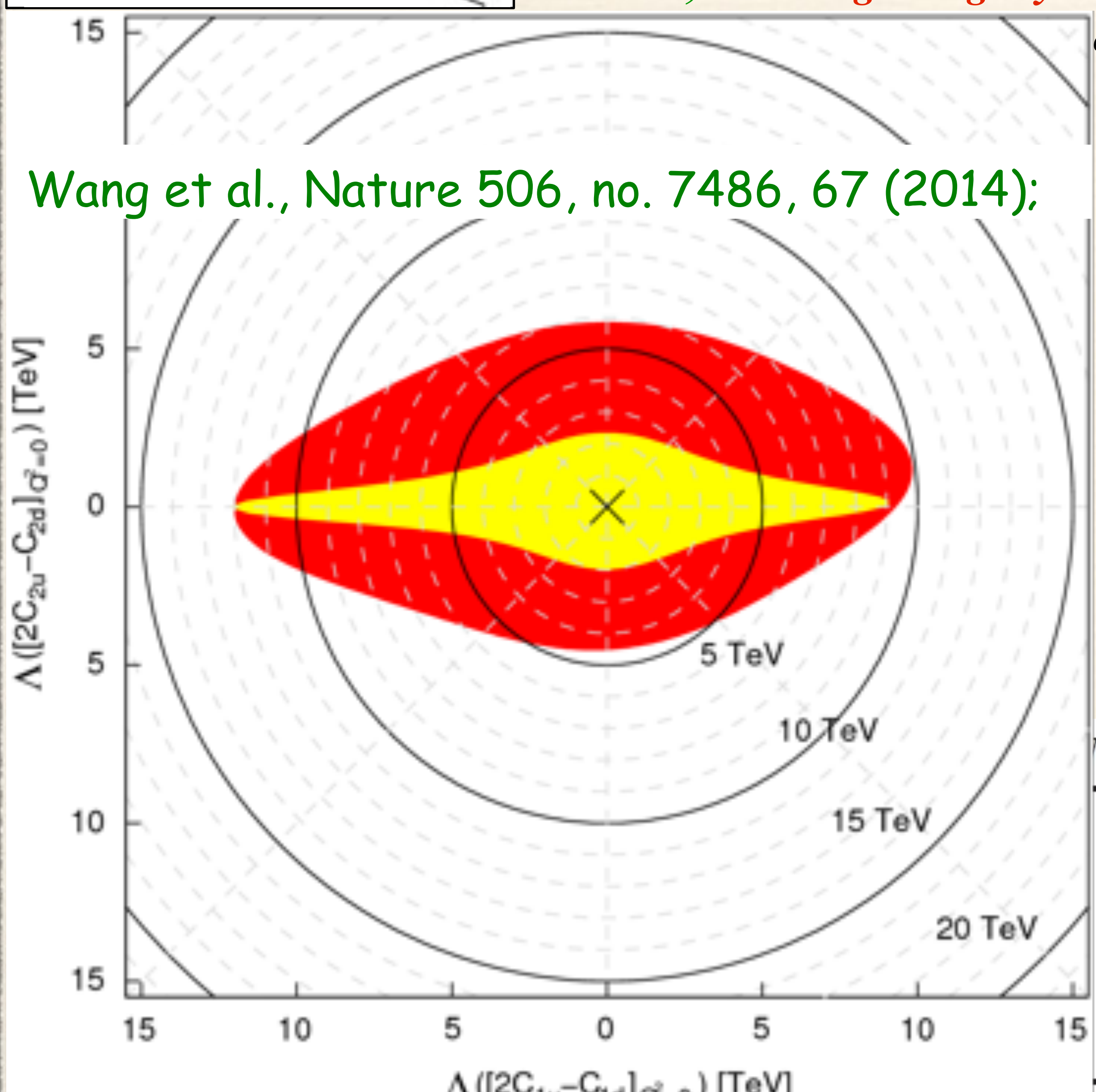
***$A_{PV}$ in deep inelastic e-D scattering:***



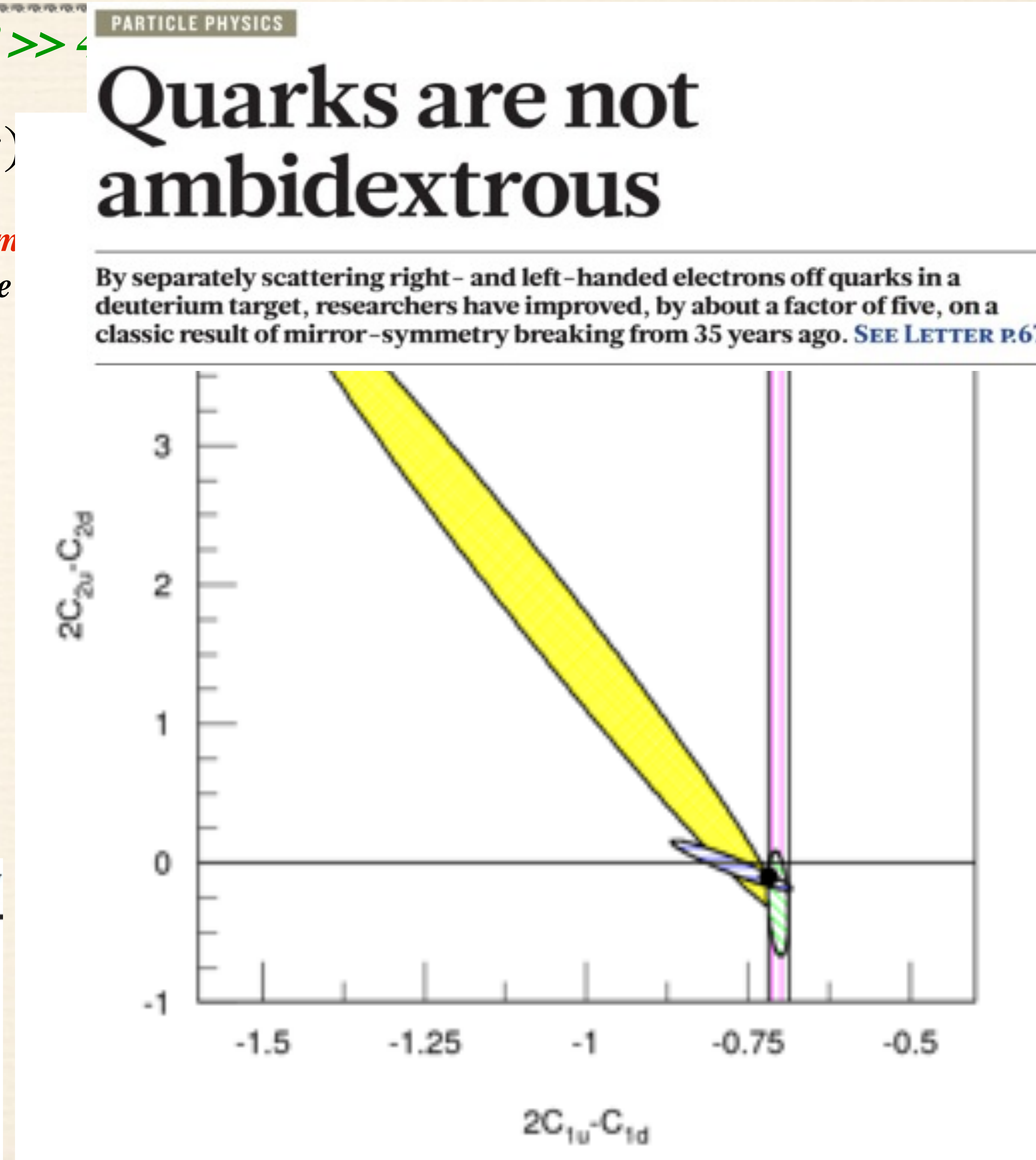

*$Q^2 >> 1\ GeV^2$ , $W^2 >>$*

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x)\right.$$

*For $^2H$, assuming charge symm*

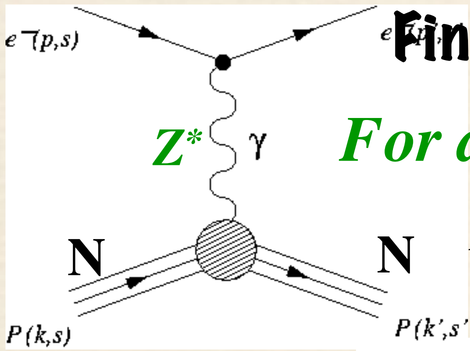



Wang et al., Nature 506, no. 7486, 67 (2014);



## $A_{PV}$ in elastic e-p scattering: Qweak at JLab

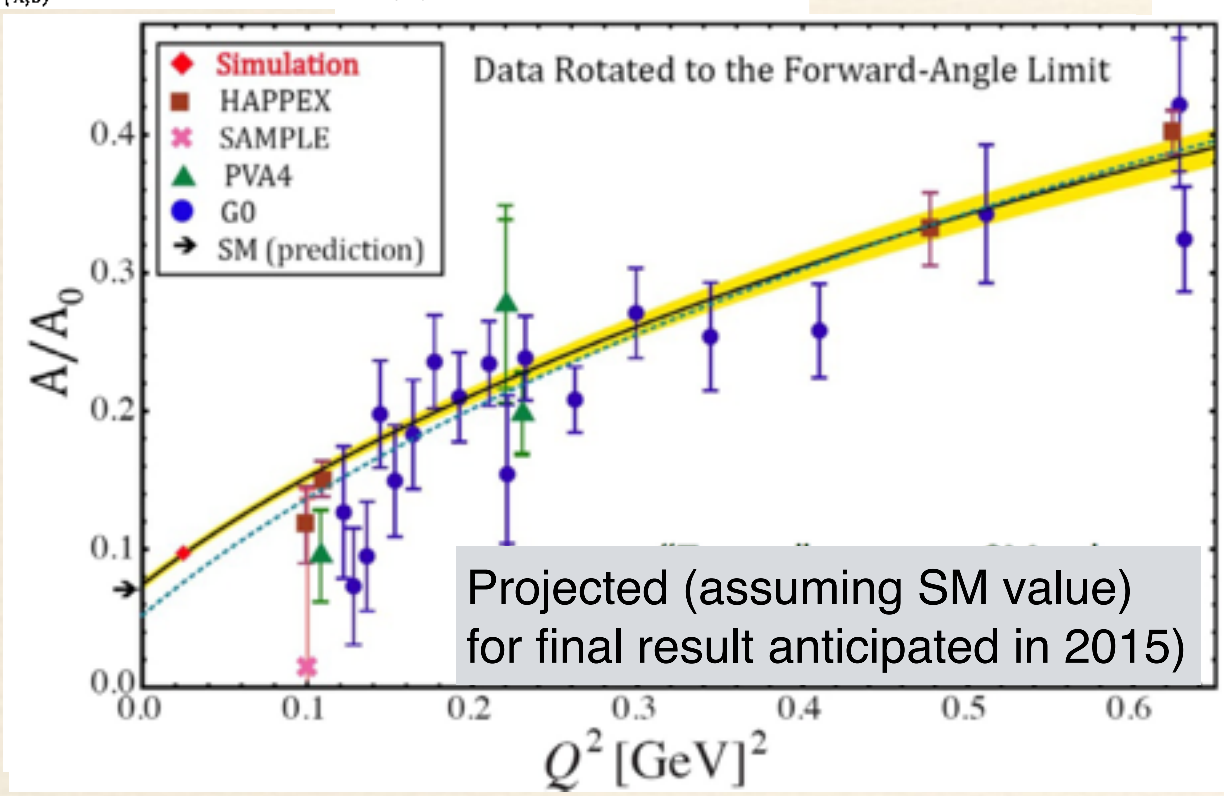
# The Weak Charge of the Proton

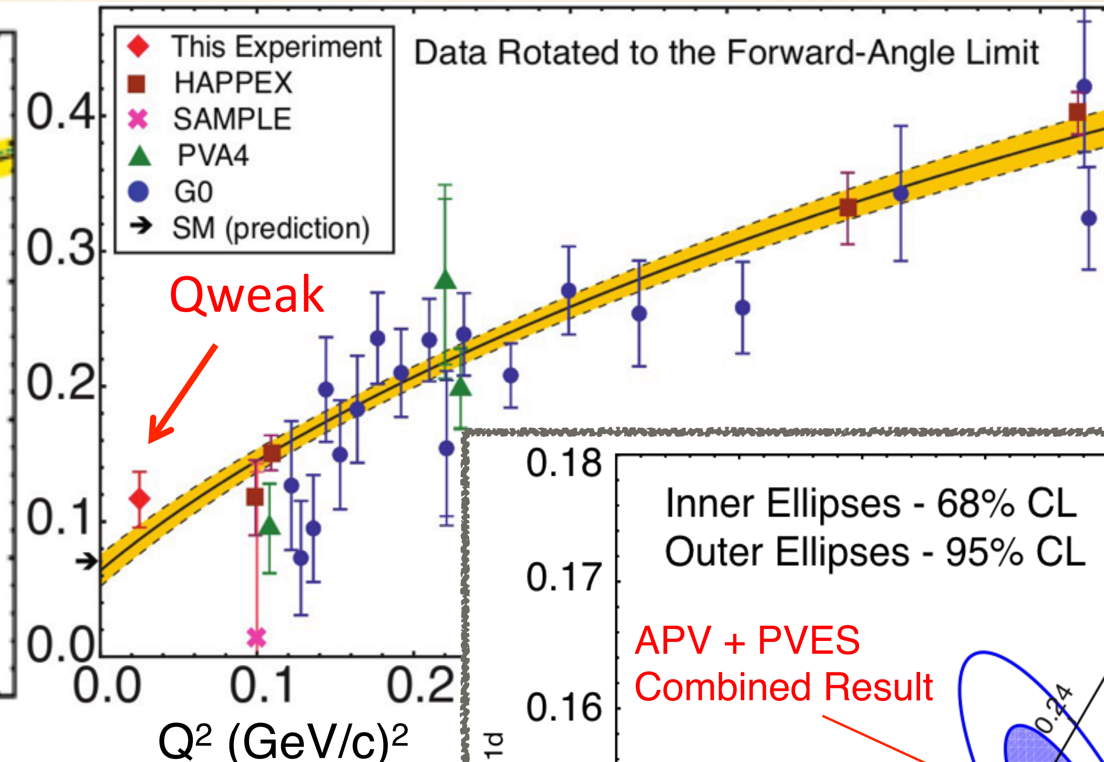


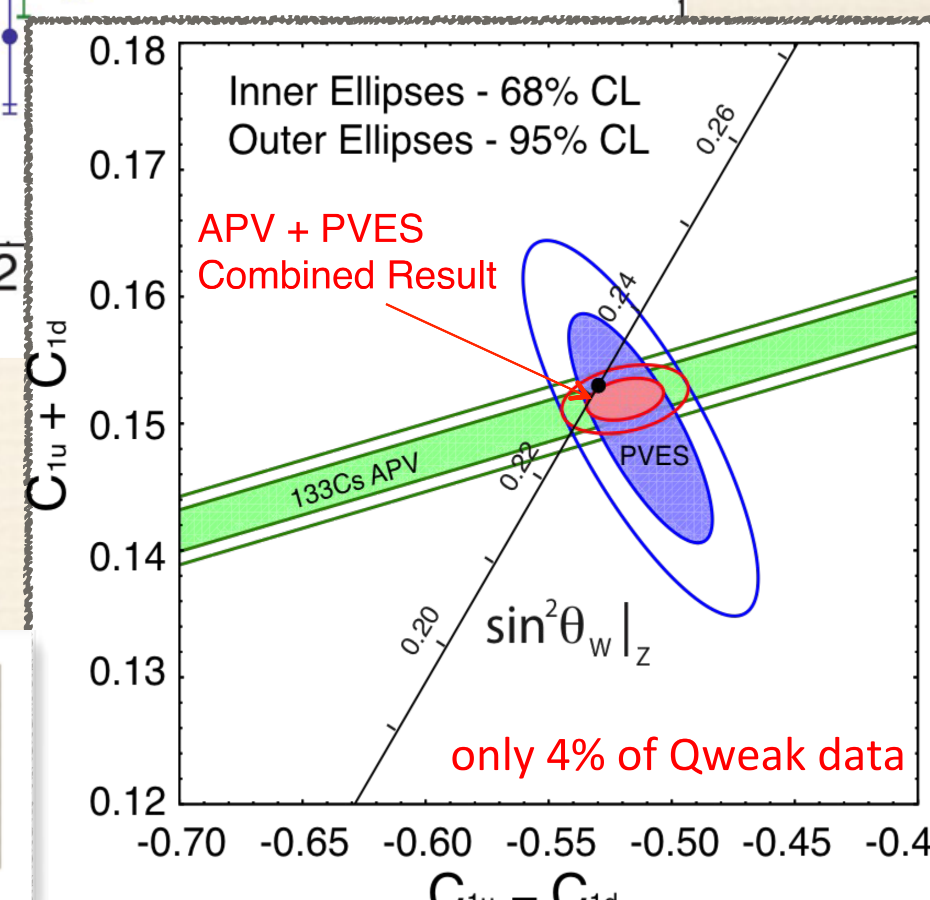

**Final result with the full accumulated statistics is anticipated in 2015**

*For a ¹H target, nucleon structure contribution well-constrained from measurements*

$$A(Q^2 \to 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}}\left[Q^2 Q^p_{weak} + Q^4 B(Q^2)\right] \qquad Q^p_{weak} = 2C_{1u} + C_{1d} \propto 1 - 4\sin^2\vartheta_W$$




**Two Production Runs: Feb-May '11, Nov '11-May '12**

Run 0 Results (1/25th of total dataset) – published in PRL **111**, 141803 (2013)

$$A_{ep} = -279 \pm 35(\text{stat}) \pm 31(\text{syst})\ \text{ppb} \quad \text{at} \quad \langle Q^2 \rangle = 0.0250\ (\text{GeV}/c)^2$$

$$Q^p_W(\text{PVES}) = 0.064 \pm 0.012 \qquad Q^p_W(\text{SM}) = 0.0710 \pm 0.0007$$

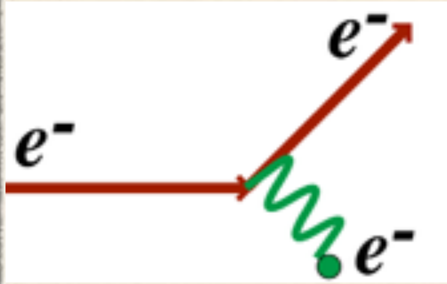
First determination of proton's weak charge in good agreement with Standard Model

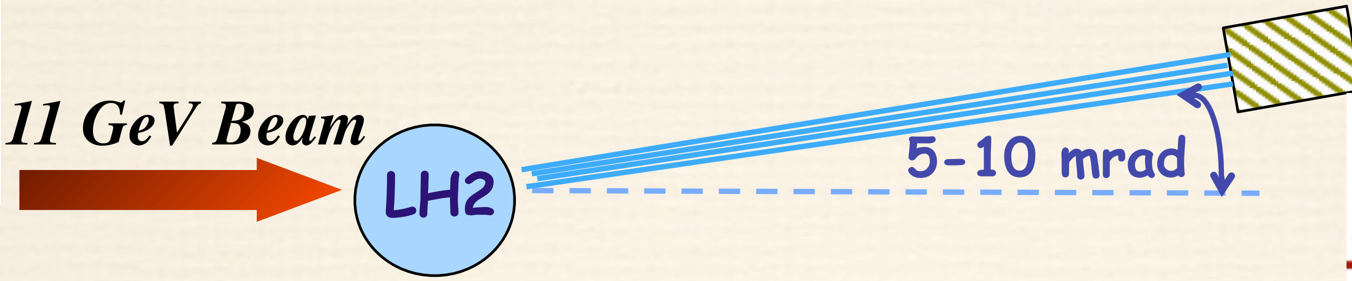
*Using Møller scattering (purely leptonic!), improve on E158 by a factor of 5*

***11 GeV Møller scattering***

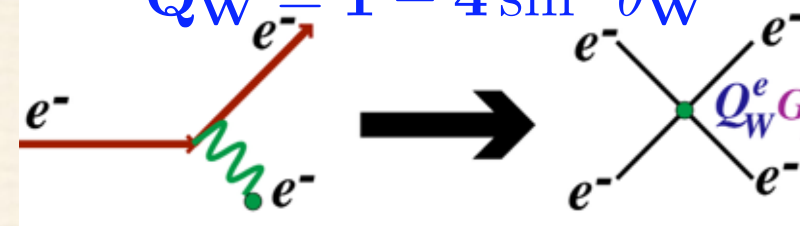
# MOLLER at JLab

## Measurement Of Lepton Lepton Electroweak Reaction

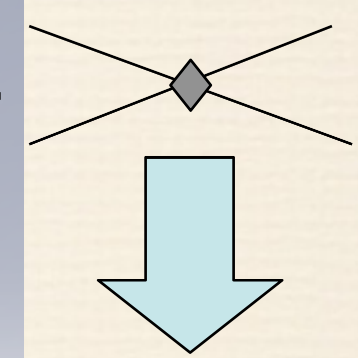



$$Q_W = 1 - 4\sin^2\theta_W$$



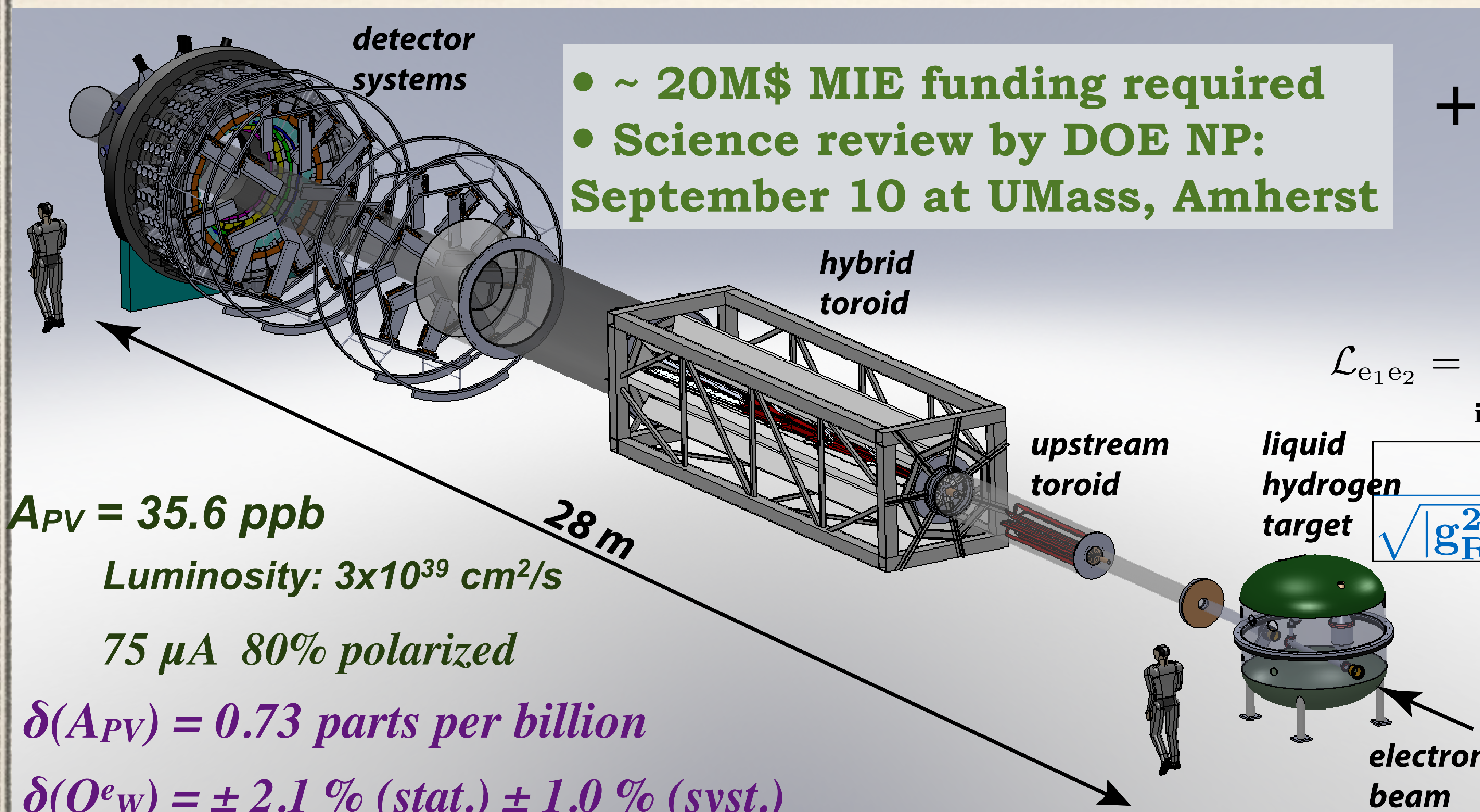
$$+ \quad \frac{1}{\Lambda^2}\mathcal{L}_6$$



$$\mathcal{L}_{e_1e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2}\bar{e}_i\gamma_\mu e_i \bar{e}_j\gamma^\mu e_j$$

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5 \text{ TeV}$$

- ~ 20M$ MIE funding required
- Science review by DOE NP: September 10 at UMass, Amherst




$A_{PV}$ = 35.6 ppb

Luminosity: 3x10$^{39}$ cm$^2$/s

75 μA 80% polarized

$\delta(A_{PV})$ = 0.73 parts per billion

$\delta(Q^e_W)$ = ± 2.1 % (stat.) ± 1.0 % (syst.)

Unique opportunity leveraging the 12 GeV Upgrade investment

# Best Low $Q^2$ Reach in Next Decade

$\delta(\sin^2\theta_W) = \pm 0.00024$ (stat.) $\pm 0.00013$ (syst.) → ~ 0.1%

$Q^e_W \sim 0.045$

$\frac{\delta Q^e_W}{Q^e_W} = 2.4\%$ → $A_{new} \sim 0.001 \cdot G_F$

unprecedented sensitivity

LEP200

$\Lambda^{ee}_{VV} \sim 17.7$ TeV

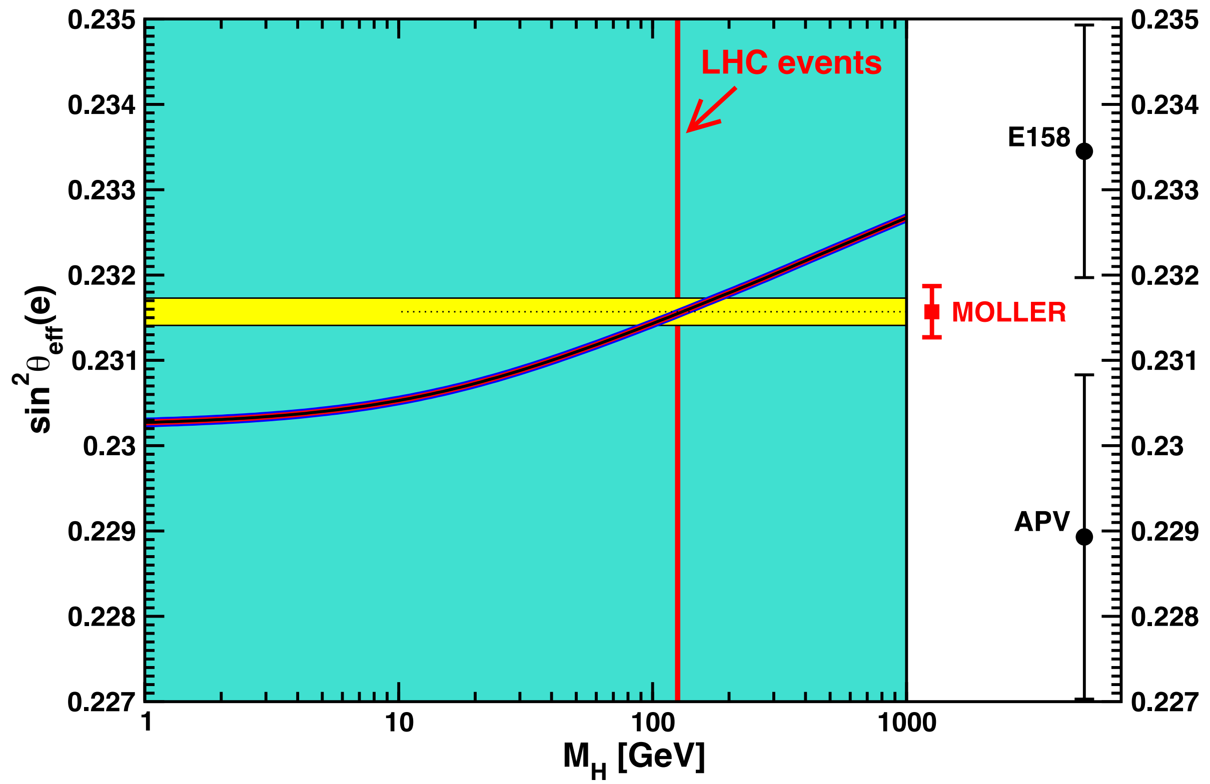
E158 Reach

$\Lambda^{ee}_{RR-LL} \sim 17$ TeV

MOLLER Reach

$\Lambda^{ee}_{RR-LL} \sim 38$ TeV

± 10σ discovery potential at $Q^2 \ll M_Z^2$




**Future projections, similar time scale:**

**Mainz P2: ~ 0.00034**

**Final Tevatron: ~ 0.00041**

**LHC 14 TeV, 300 fb$^{-1}$ : ~ 0.00036**
**Note: systematics-dominated (pdf uncertainties)**

**MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory**

Expertise from several generations of successful parity experiments

# MOLLER Status

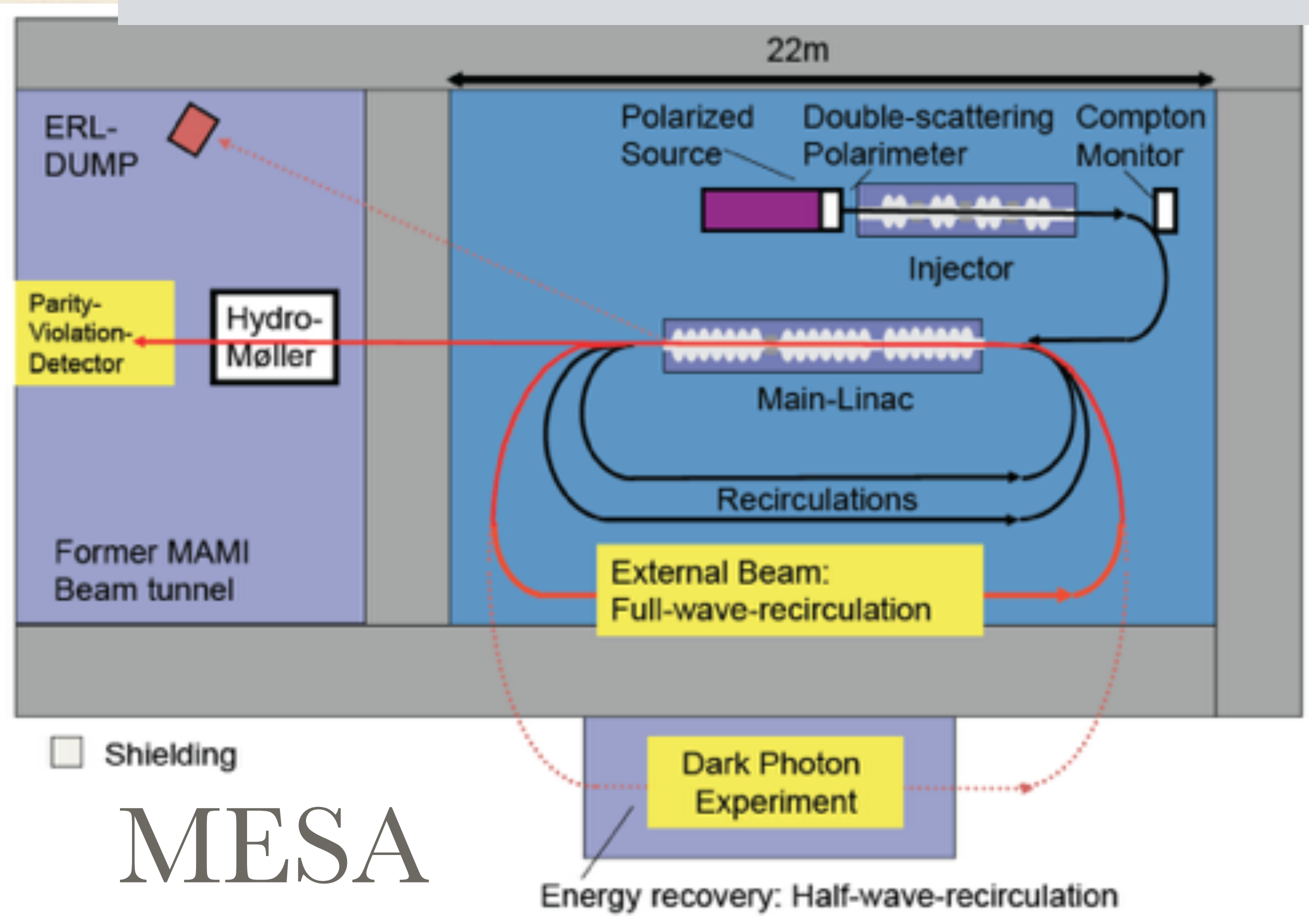
*~120 Collaborators, 30 institutions, 6 countries*

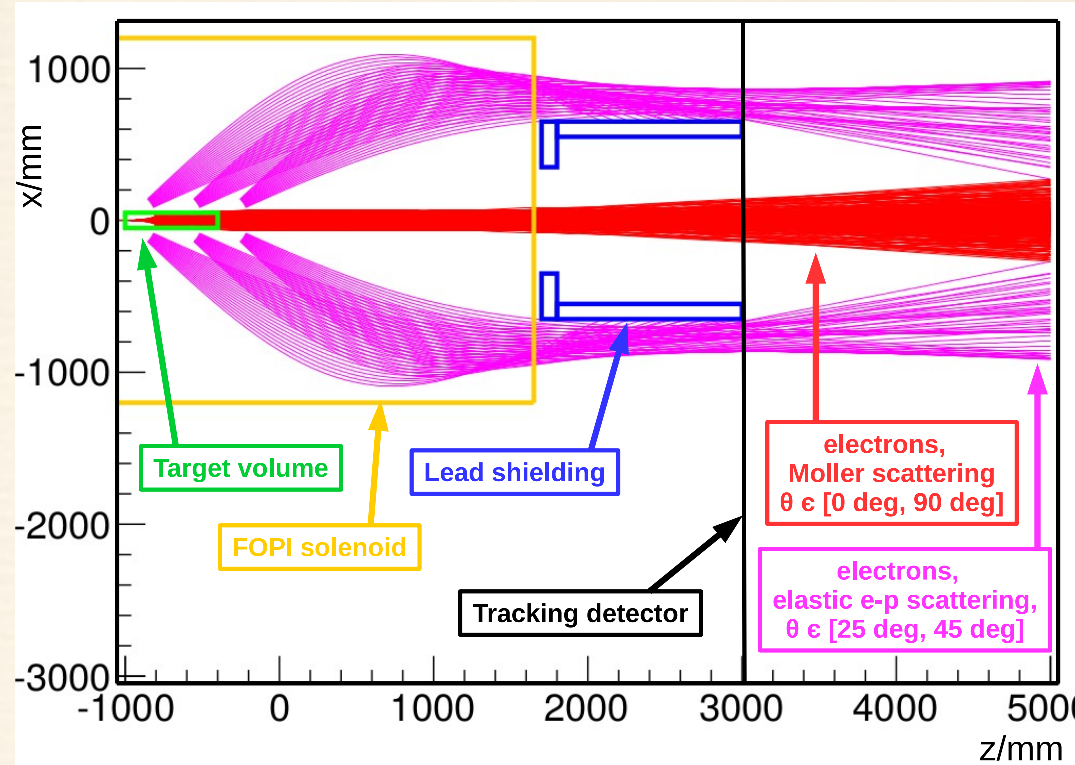
- **MOLLER Concept Developed ~ 2007**
  - Conceptual breakthrough: 100% acceptance toroidal spectrometer
  - Mentioned in 2007 LRP for Fundamental Symmetries investment
  - JLab Director's Review chaired by C. Prescott in 2010
    - *strongly endorsed physics case and commended experimental team and approach*
  - JLab PAC Ranking and Beamtime allocation in 2011
    - *enthusiastic endorsement, "…flagship…", full request (344 PAC days) allocated*
  - Tribble Subcommittee Report in 2012 (LRP Implementation)
    - *MOLLER listed in suite of recommended Fundamental Symmetries investments*
- **DOE NP conducted a Science Review on Sept 10, 2014**
  - 6 Panelists: T.W. Donnelly, D. Hertzog, C. Horowitz, Z-T. Lu, M. Perelstein, T. Rizzo
  - Outcome of the Review was positive (closeout comments)
    - *Highlighted unique opportunity: strong support to carry out the measurement*
    - *MUST achieve proposed error bar; theoretical cleanliness (purely leptonic!)*
    - *No homework: looking forward to receiving final review report and moving on…*

Improve Qweak by a factor of 2.5: *$\delta(\sin^2\theta_W) = \pm\, 0.00030$ (stat.) $\pm\, 0.00017$ (syst.)*

# P2 at MESA, U. Mainz, Germany

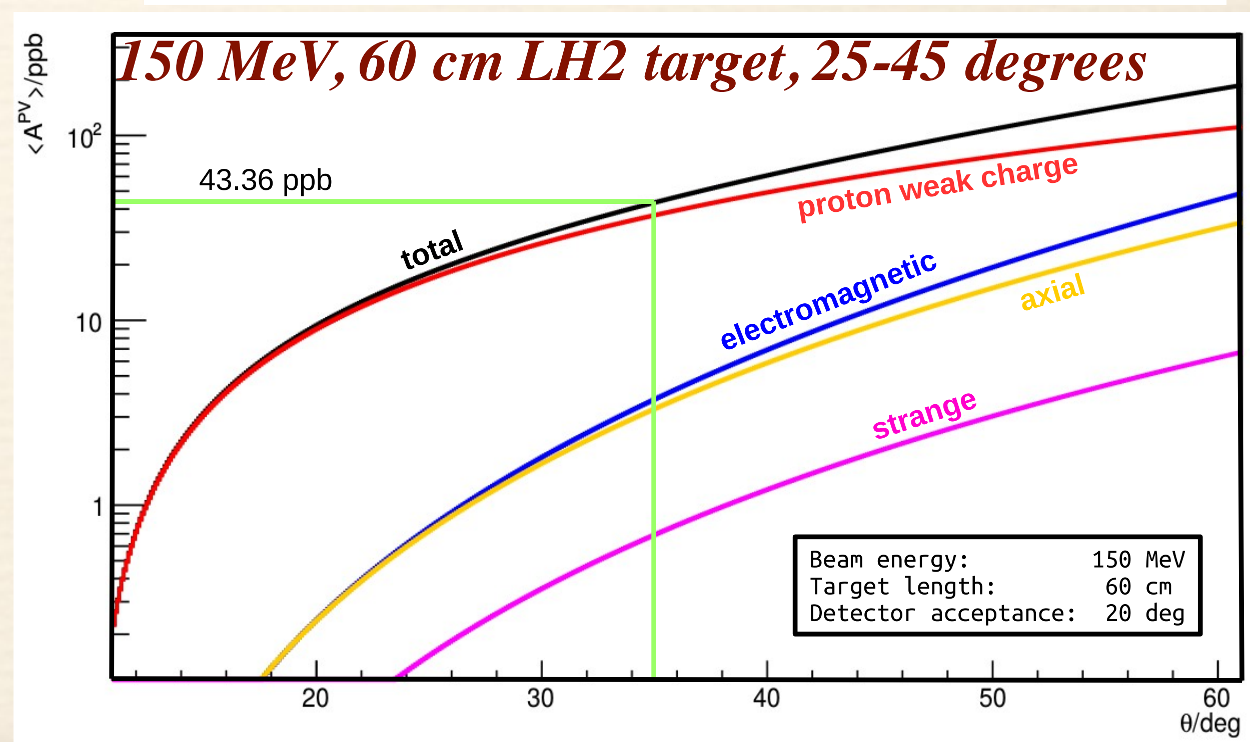
## Theory error smaller with E=150 MeV; requires novel polarimetry technique



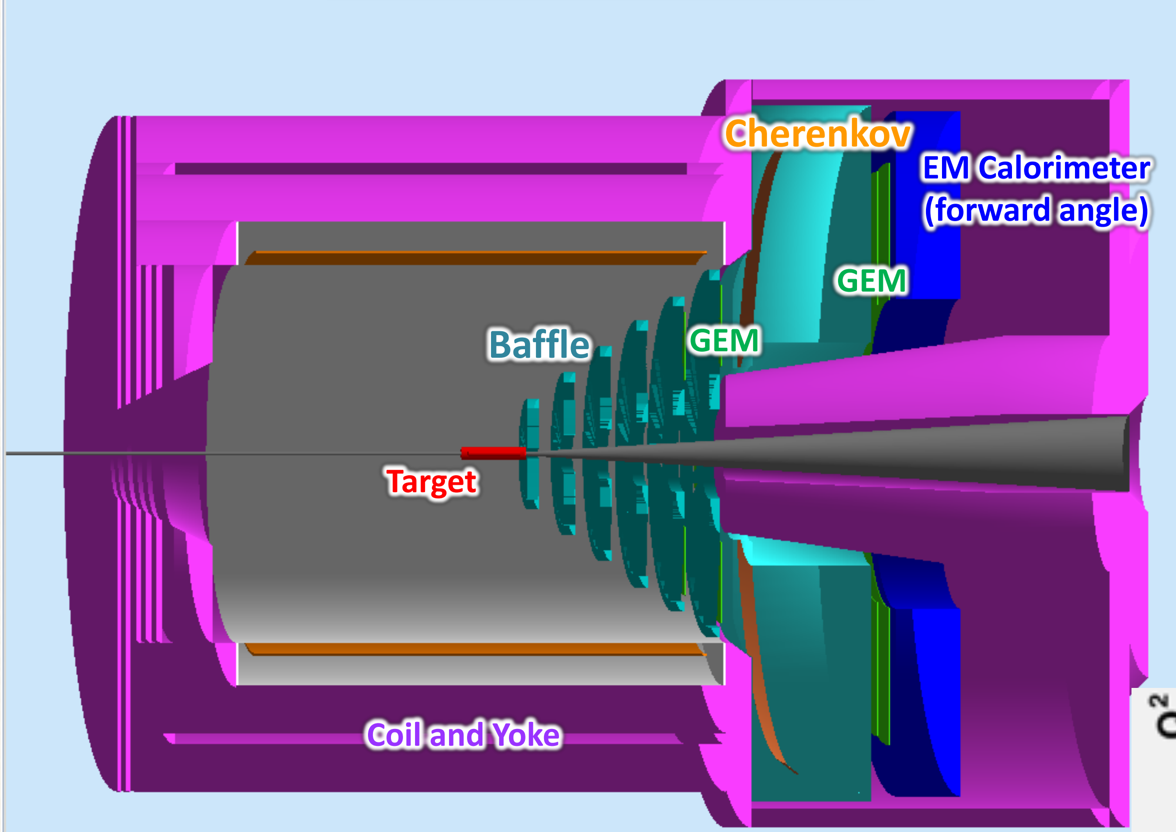

- Funding approval from DFG
- R&D in progress
- Aim to run from 2017-20

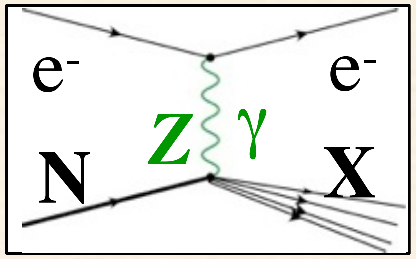
**Technically challenging: great synergy with JLab program**




**Recent joint beam test of integrating quartz detectors successful**

# SOLID with the 12 GeV Upgrade



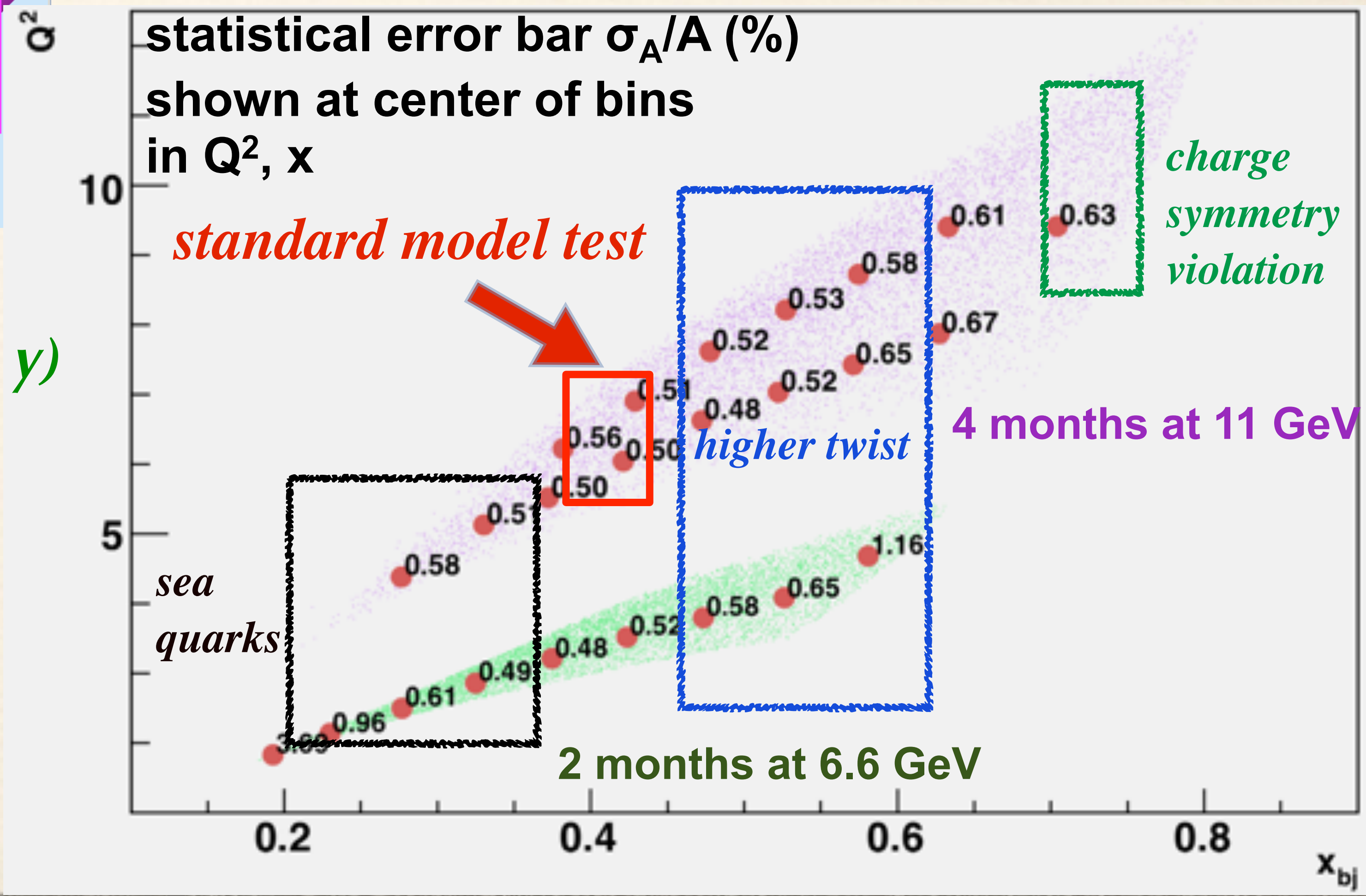




$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

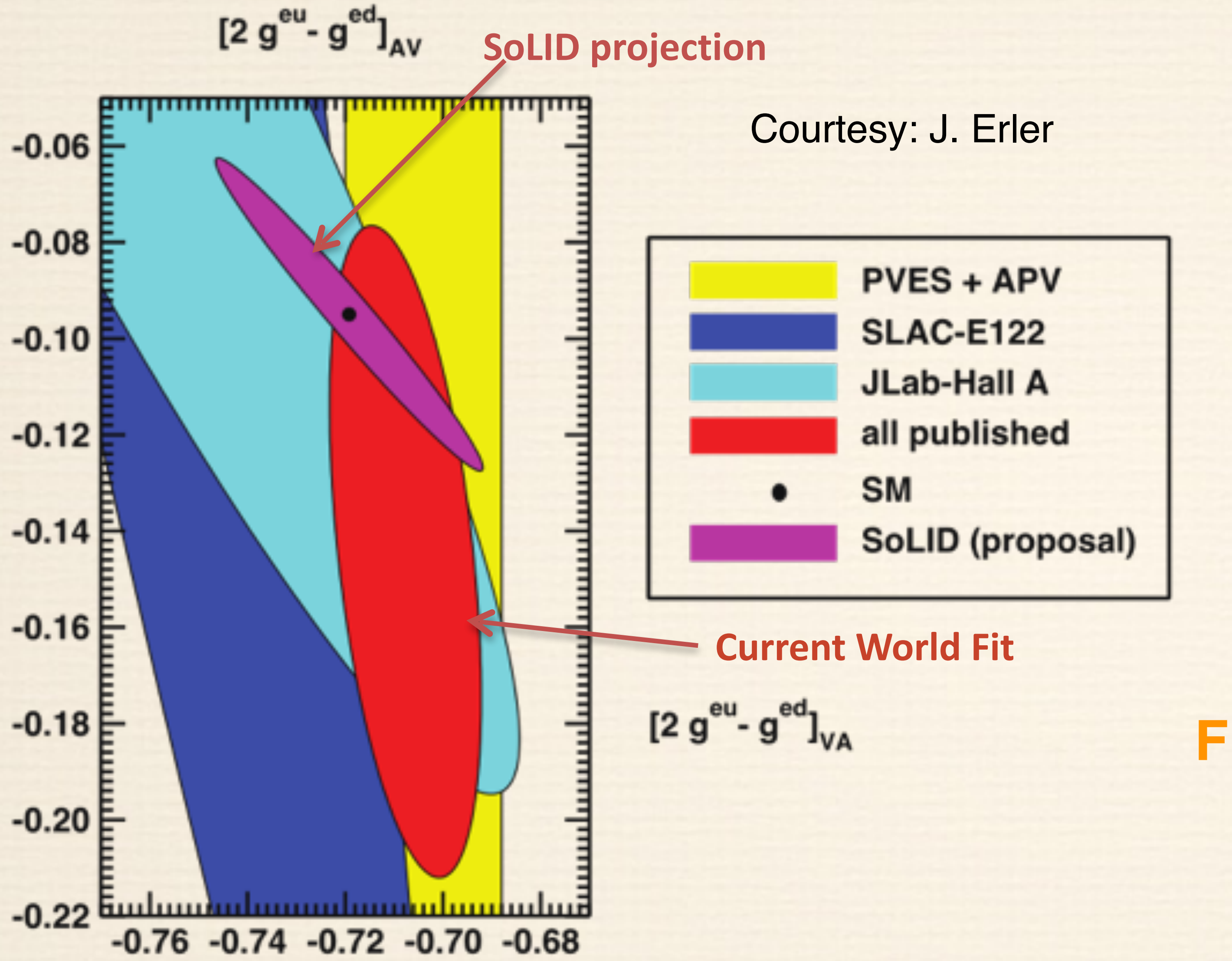
**Strategy:** **sub-1% precision** over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**

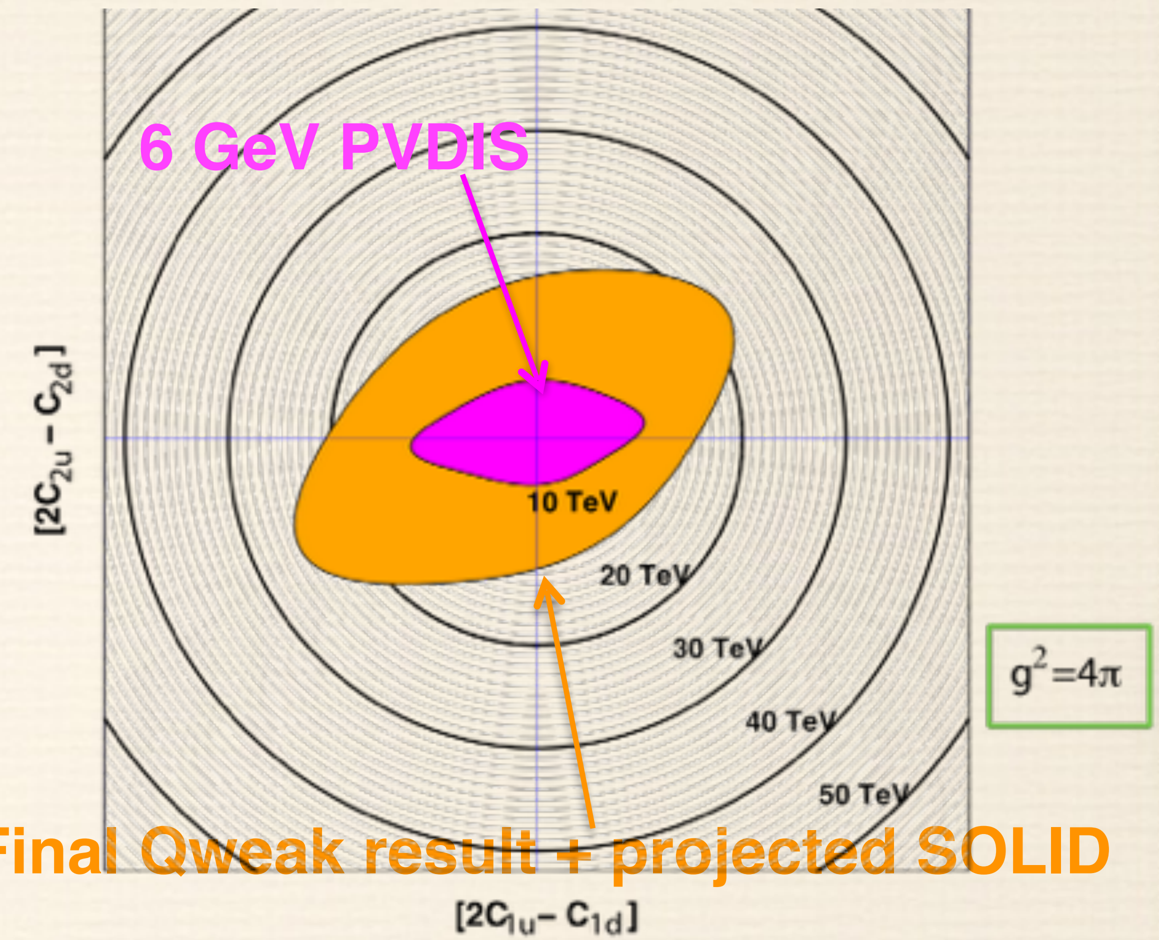
## *Requirements*

- *High Luminosity with E > 10 GeV*
- *Large scattering angles (for high x & y)*
- *Better than 1% errors for small bins*
- *x-range 0.25-0.75*
- *$W^2$ > 4 $GeV^2$*
- *$Q^2$ range a factor of 2 for each x*
  - (Except at very high x)
- *Moderate running times*

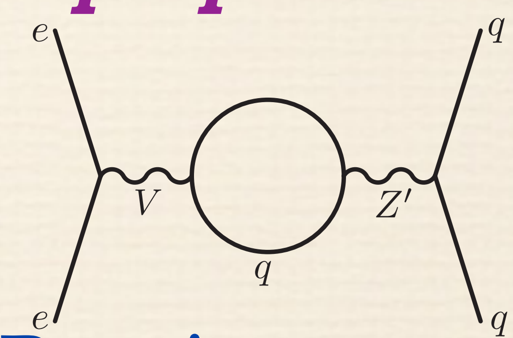


# SOLID New Physics Sensitivity




***Leptophobic Z'***




**Qweak and SOLID will expand sensitivity that will match high luminosity LHC reach with complementary chiral and flavor combinations**

SOLID can improve sensitivity: 100-200 GeV range

## “Parasitic” Opportunity: Electroweak & BSM Physics

# The Electron Ion Collider

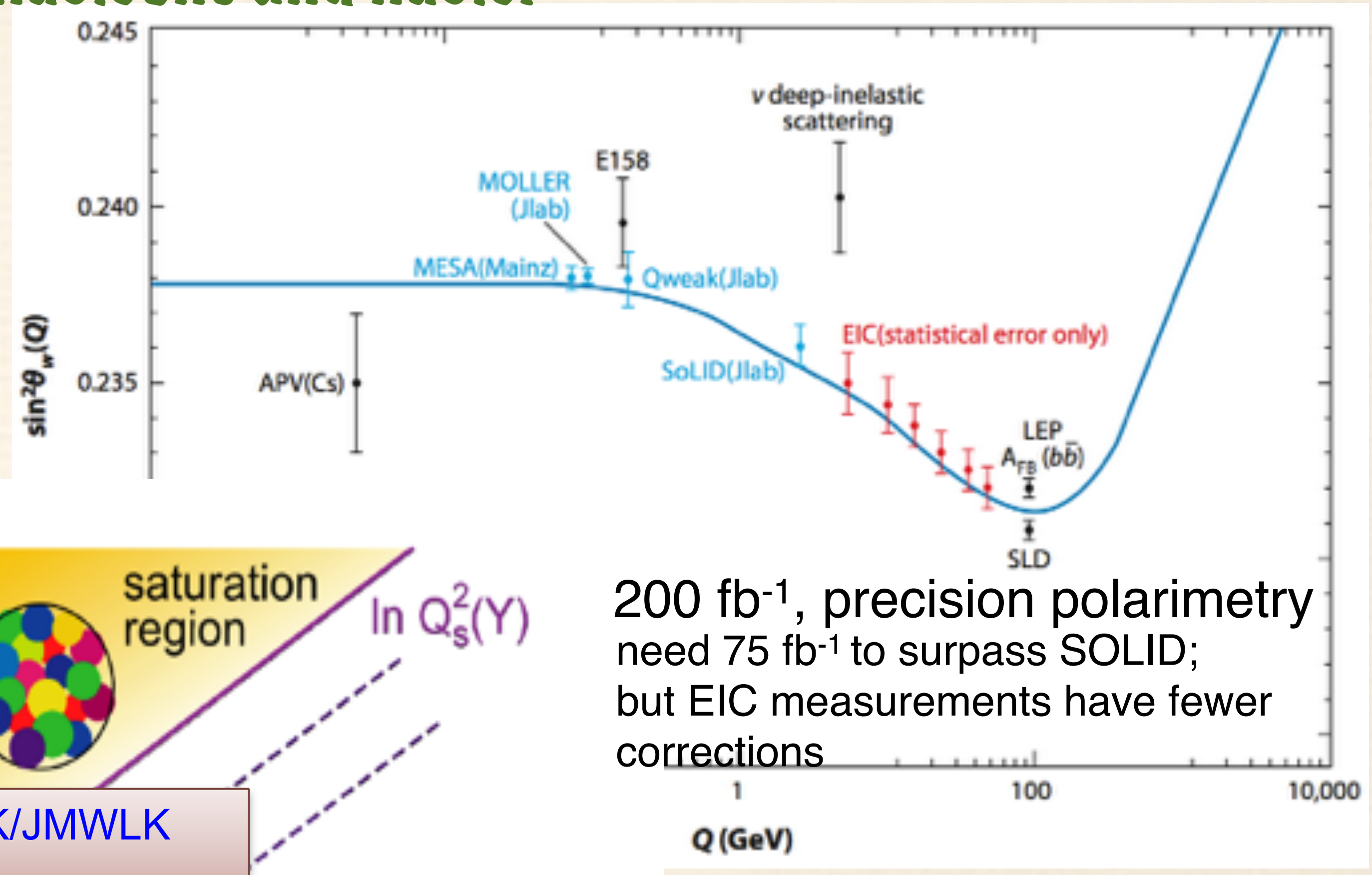
eRHIC at Brookhaven National Laboratory MEIC at Jefferson Laboratory

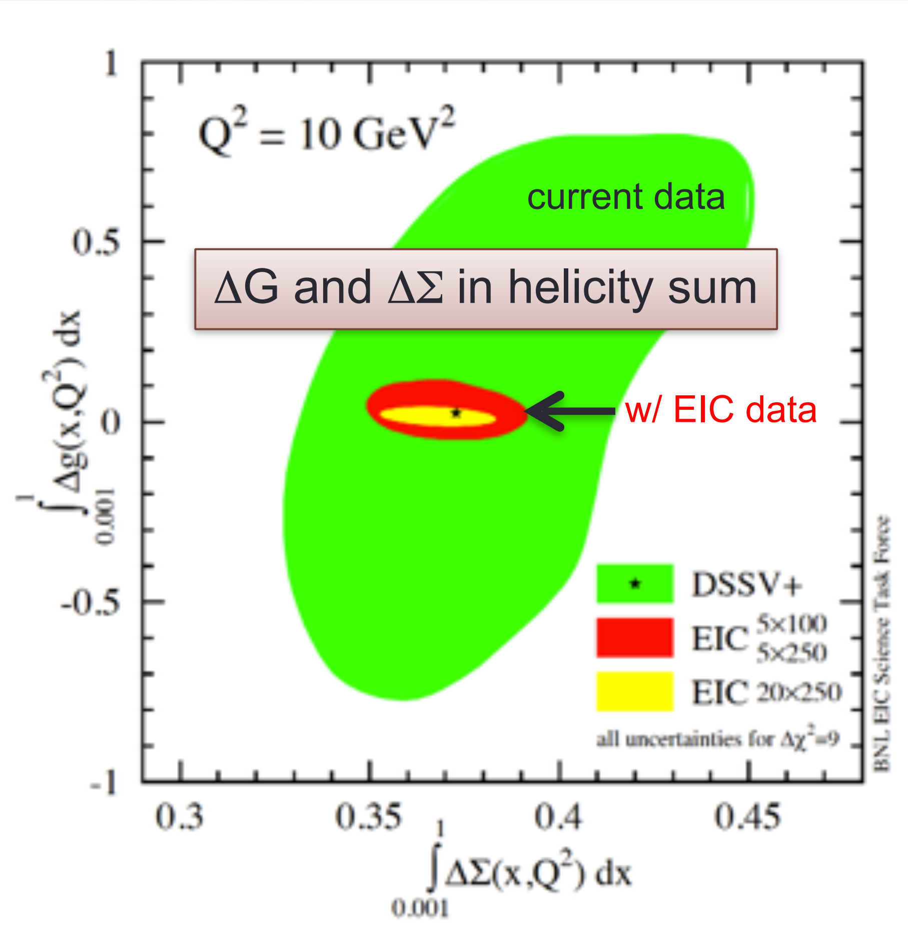
– **Unique facility for the study of gluons and sea quarks in QCD**

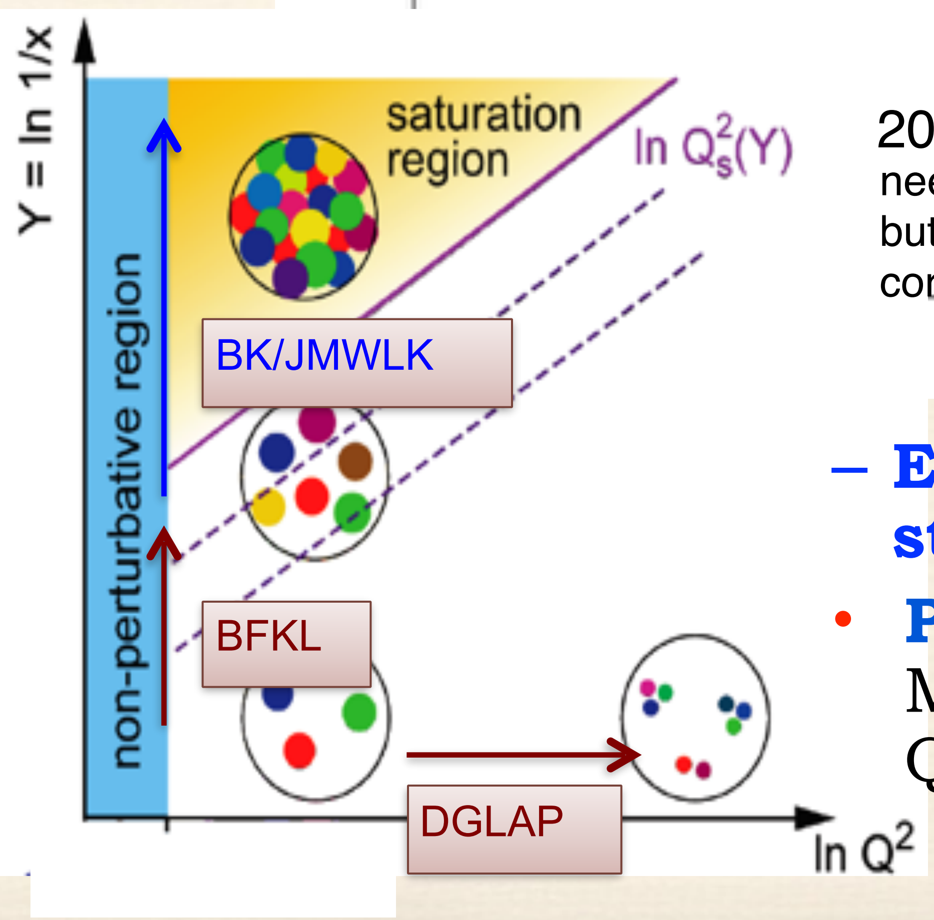
- Polarized electron DIS on polarized nucleons and nuclei

### Two Machine Designs

- $\mathrm{Sqrt}(S_{ep})$ = 20-100 (140) GeV




– **Electroweak (spin) structure functions**

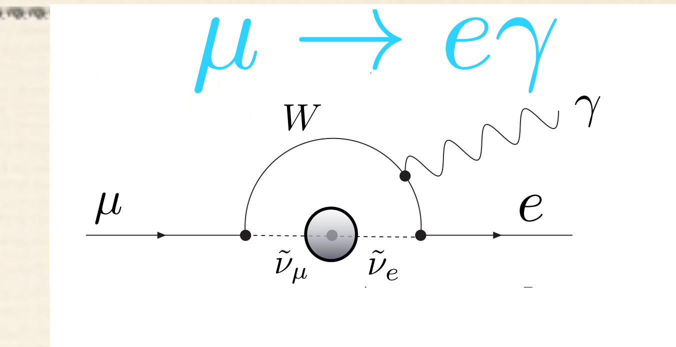
- **Parity violating DIS**: Measurements at higher $Q^2$ than SOLID

Is Lepton Flavor Conserved? No! Neutrino Oscillations!

# Charged Lepton Flavor

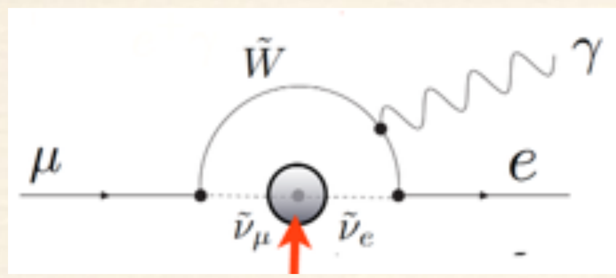
But how BIG is the effect?

$\mu \to e\gamma$




**First to Third Generation signals could be further enhanced and are experimentally more challenging to access**

Slepton mixing in SUSY




$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

$$\mathrm{BR}(\mu \to e\gamma) \sim 10^{-15}$$

tiny standard model branching fraction

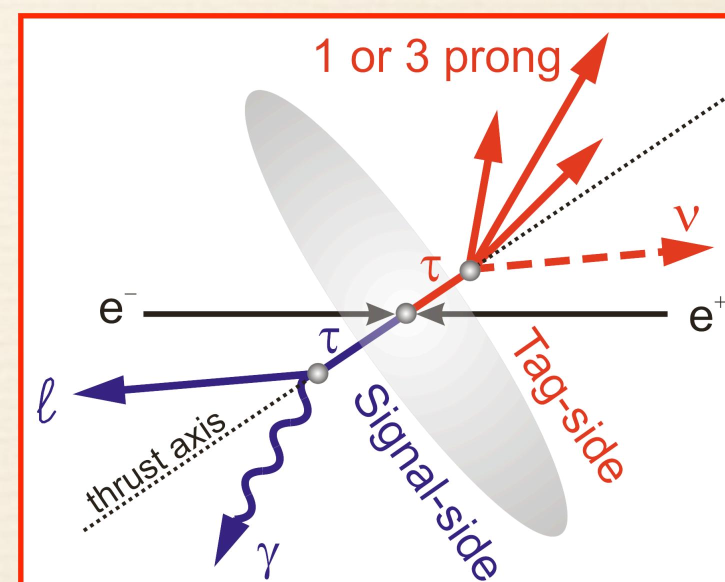
Major experimental searches are ongoing; mass reach depends on flux and sensitivity of technique

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{C_{\mu e}}{\Lambda^2}\bar{e}_L\sigma^{\alpha\beta}\mu_R\Phi F_{\alpha\beta}$$

μ or τ → eγ, μ-e conversion, $e^+e^-e$, $K_L \to \mu e$, ...

Need very high fluxes for required statistical reach

New high intensity kaon & muon beams and high luminosity e+e- colliders all over the world



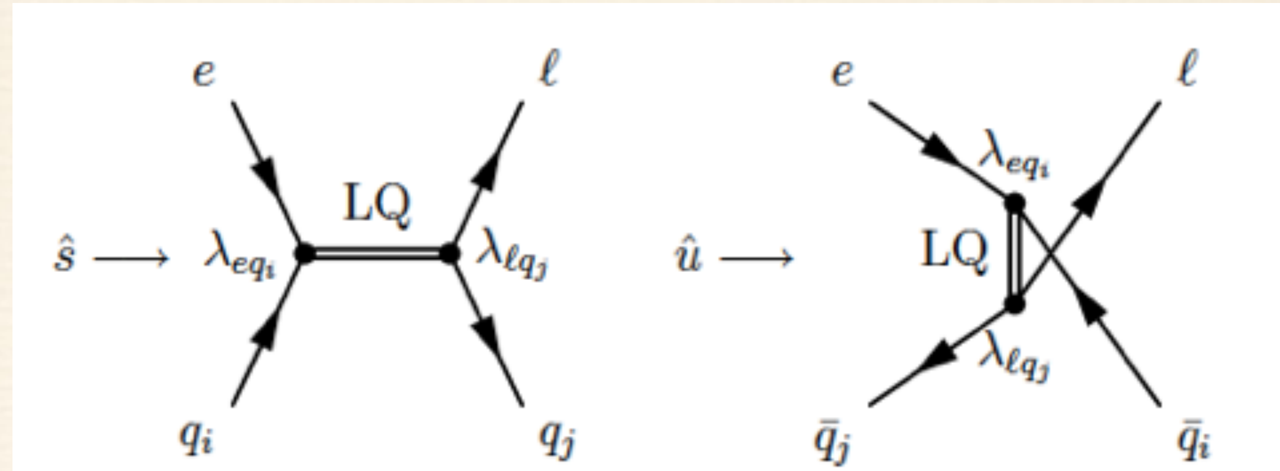

Tau Decays at e+e- colliders

Even a decade from now, the EIC can compete in the first-to-third generation searches

# e-τ Conversion Search

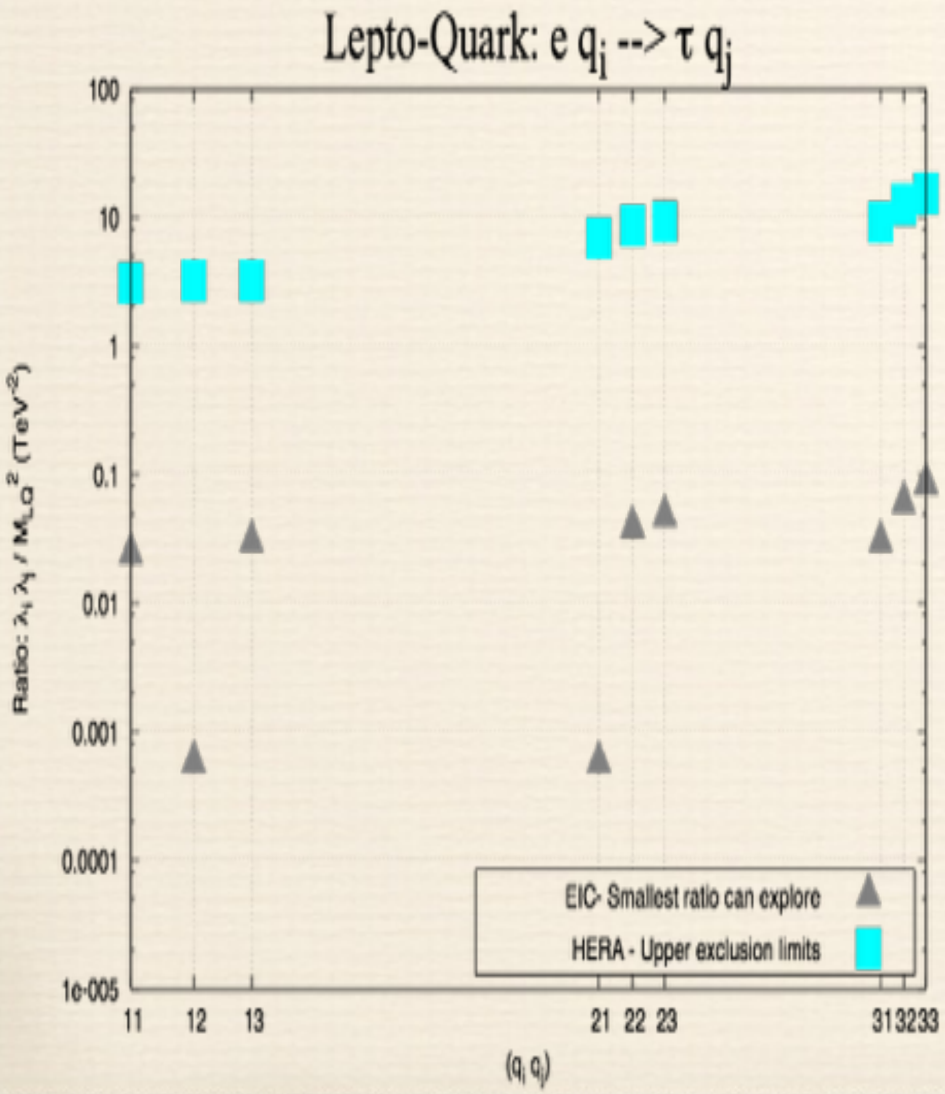
$$e^- + p \rightarrow \tau^- + X$$

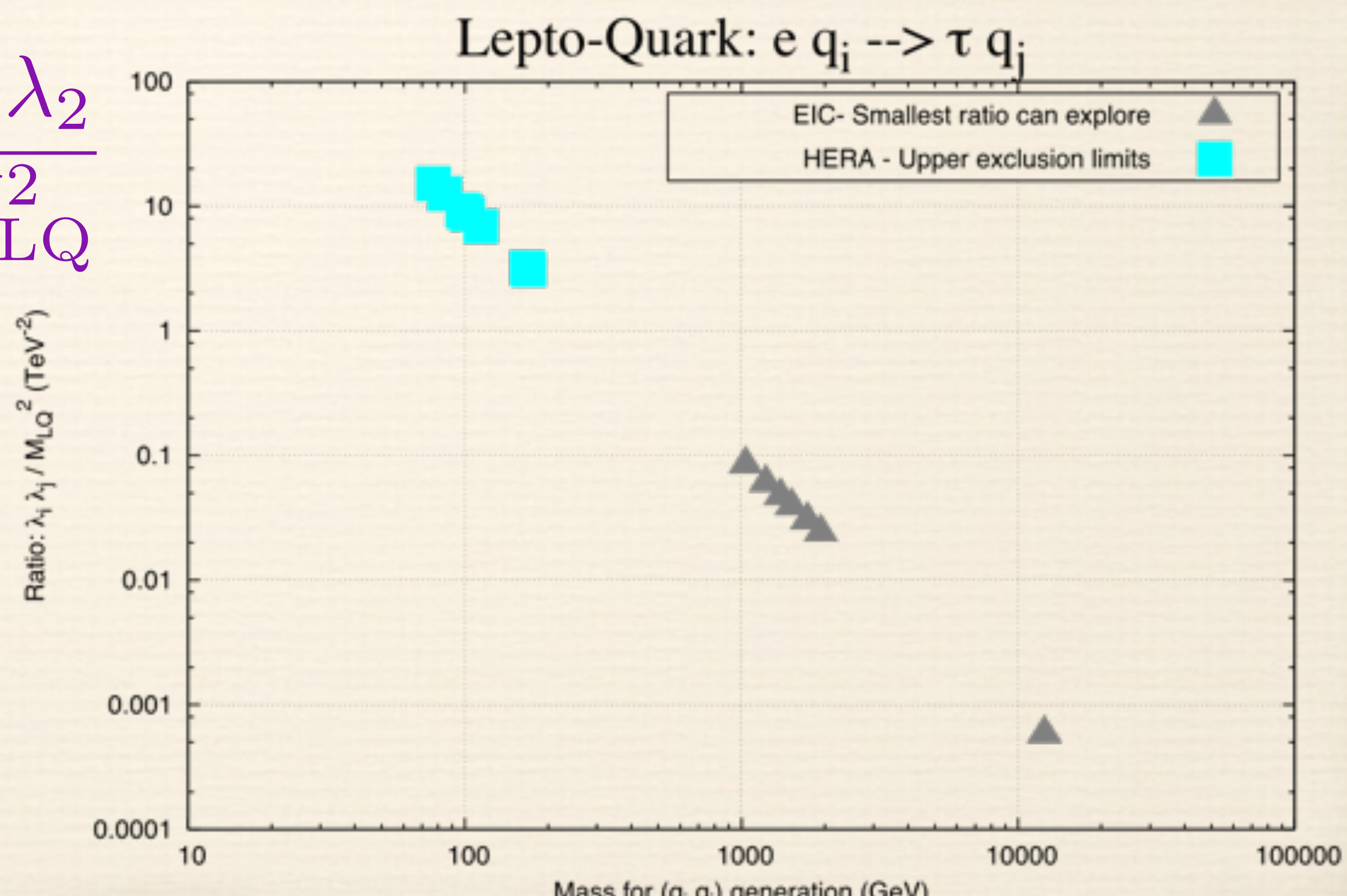

*Topology: neutral current DIS event; except that the electron is replaced by tau lepton*




Gonderinger and Ramsey-Musolf, arXiv: 1006.5063

$$\frac{\lambda_1 \lambda_2}{M_{\rm LQ}^2}$$



*Parity Violating Electron Scattering:*

# Summary

*Rich Physics Program Yields Flagship Experiments in Electron Accelerators*

- **Parity Violating Electron Scattering: QCD Applications continue….**
  - Strange Quark Form Factor Program: Important QCD Input and Technical Improvements
  - Neutron RMS Radii of Heavy Nuclei: Important input to nuclear symmetry energy constraints
- **Search for BSM Physics has reached multi-TeV scale sensitivity**
  - PV Elastic Scattering: Qweak final results soon, future: MOLLER at JLab & P2 at Mainz
    - *best weak mixing angle uncertainties in the next decade*
    - *best CP/Flavor-conserving amplitude sensitivity and complementary LNV sensitivity*
  - PV Deep Inelastic Scattering with Deuterium: 6 GeV PVDIS published, future: SOLID at JLab
    - *first experimental establishment of non-zero axial quark couplings*
    - *SOLID: Complementary TeV-scale sensitivity*
- **Nucleon Structure Topics Enabled by SOLID**
  - $^2$H: Access to a dynamically interesting higher-twist effect
  - $^2$H: Precise constraint of possible parton-level charge symmetry violation at high-x
  - $^1$H: Precision high-x constraints on d/u with no nuclear corrections
  - $^{48}$Ca: Clean, precise inclusive measurement would facilitate flavor decomposition of EMC dynamics
- **New PV Measurements Enabled by the EIC**
  - Natural evolution of the JLab PVDIS Program
  - Novel parity-violating structure functions will provide new insights into nucleon QCD dynamics
  - Unique Sensitivity to electron-tau lepton conversion to search for charge lepton flavor violation

# Perspective on Future PVES

## MOLLER, SOLID, P2

**Sensitive discovery reach over the next decade for CP-/flavor-conserving and LNV scattering amplitudes**

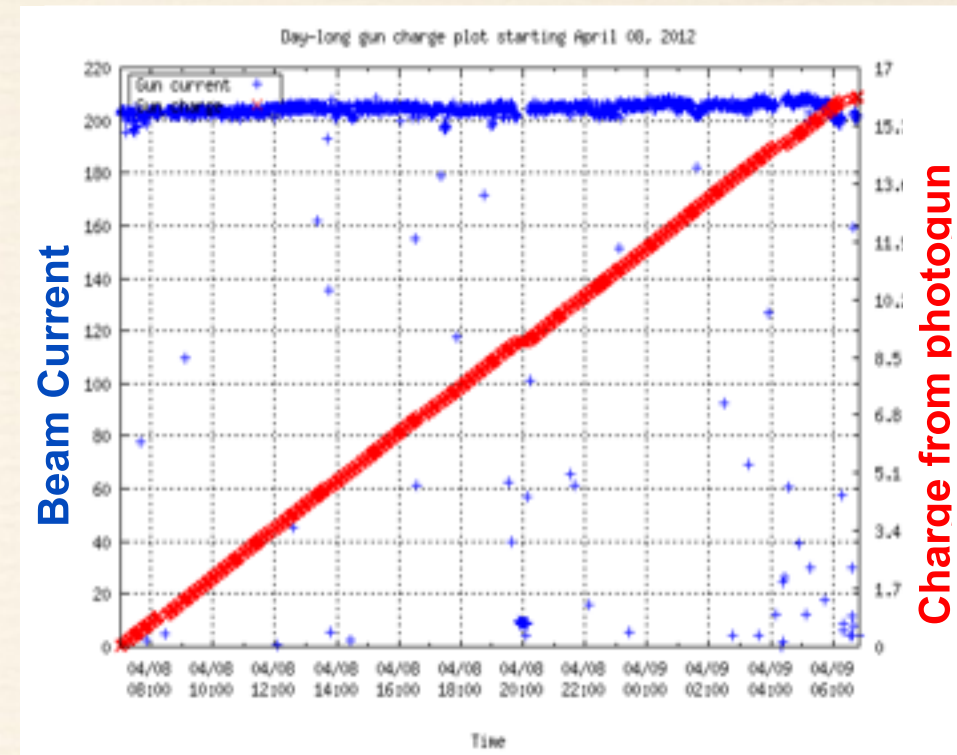
- **If LHC sees ANY anomaly in Runs 2 or 3 (~2022)**
  - The unique discovery space probed will become a pressing need, along with other sensitive low energy probes (e.g. g-2 anomaly)
- **Discovery scenarios beyond LHC signatures**
  - Hidden weak scale scenarios
  - Lepton Number Violating Amplitudes
  - Light Dark Matter Mediators
  - ...

# *Backup*

# Polarized Source at JLab

B. Matthew Poelker
2011 E. O. Lawrence Award

**Record Performance (2012):**
**180 $\mu$A at 89% polarization**




24 Hours

## Electron Gun Requirements

- Ultrahigh vacuum
- No field emission
- Maintenance-free

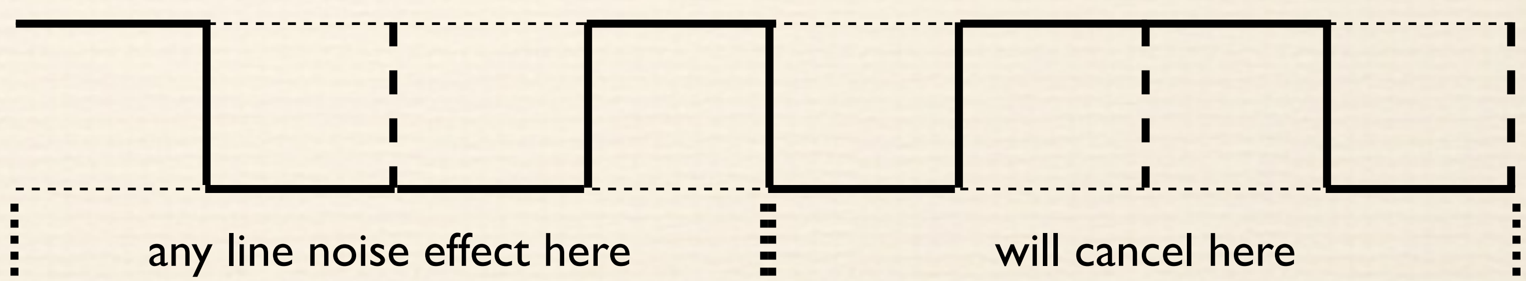
✧ **Beam helicity is chosen pseudo-randomly at multiple of 60 Hz**

- *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 1.96 kHz reversal; subtleties in details of timing (e.g. 64-plet)*

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

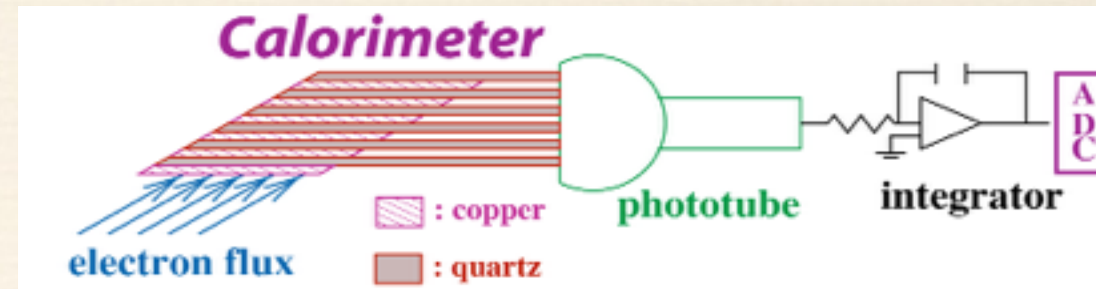
## Instantaneous Signal Rate ~ 100 GHz

# Flux Integration

1 kHz Pulse Pair Width: ~100 ppm ➡ 10 Billion Pairs: 1 ppb (average $10^7$ s)

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

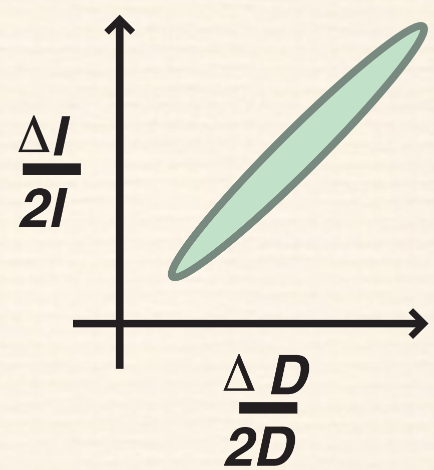
$$A_{pair} = \frac{\Delta F}{2F} + \Delta A$$

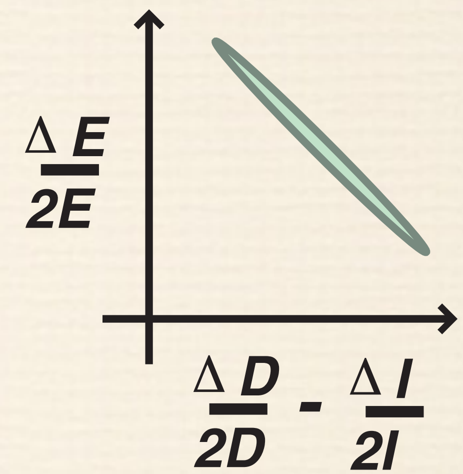



Detector D, Current I: $F = D/I$

*I order: $x, y, \theta_x, \theta_y, E$*

*II order: e.g. spot-size*




*After corrections, variance of $A_{pair}$ must get as close to counting statistics as possible: ~ 100 ppm (1kHz pairs); central value then reflects $A_{phys}$*

**Must minimize (both) random and helicity-correlated fluctuations in average window-pair response of electron beam trajectory, energy and spot-size.**

**The characteristics of the JLab beam, both at the 2 kHz time scale (~ppm, microns), to grand averages over several days (~ppb, nm), are critical to extracting a measurement which is dominated by statistical fluctuations.**

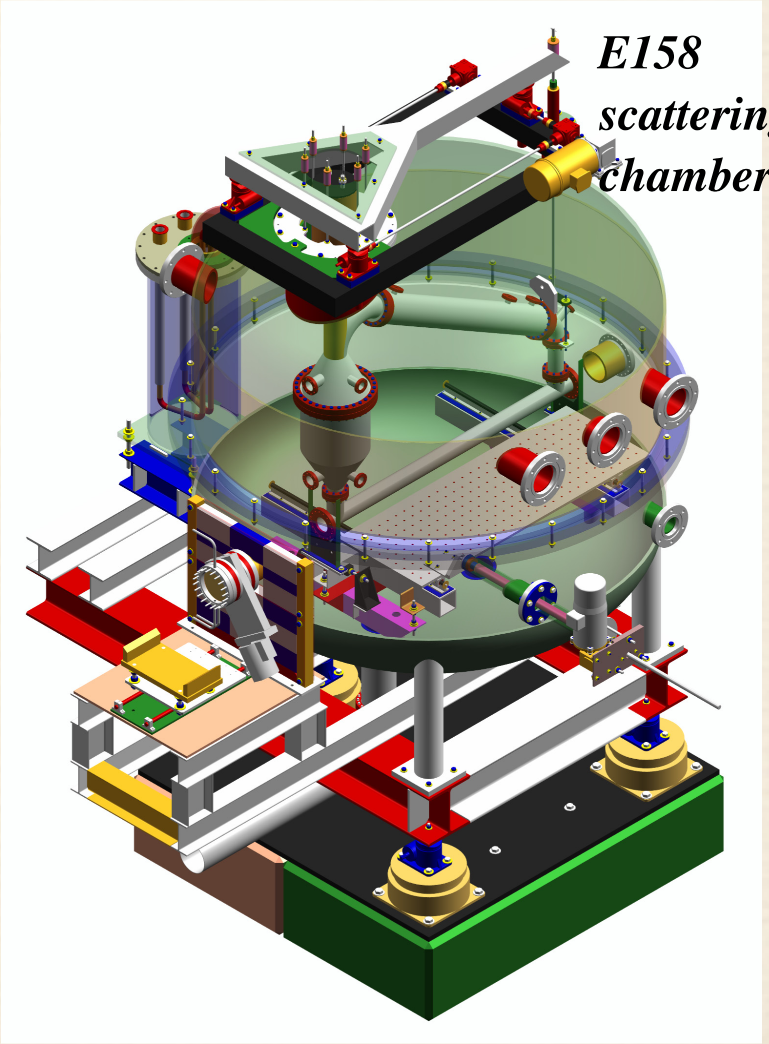
# Liquid Hydrogen Target

- **Most thickness for least radiative losses**
- **No nuclear scattering background**
- **Small sensitivity to EM field induced polarization**

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

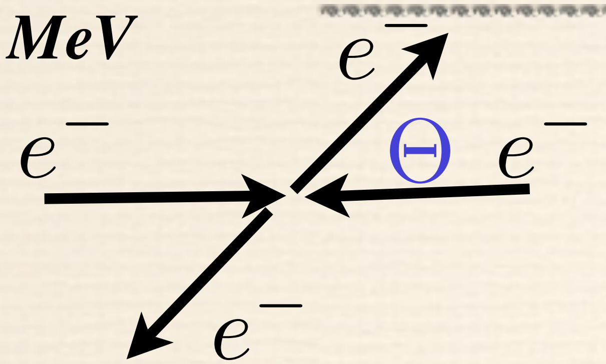
| parameter | value |
|---|---|
| *length* | *150 cm* |
| *thickness* | *10.7 gm/cm* |
| *X* | *17.5%* |
| *p,T* | *35 psia, 20K* |
| *power* | *5000 W* |

**Progressive evolution of sophistication over generations of PVES experiments; most recently, Qweak**

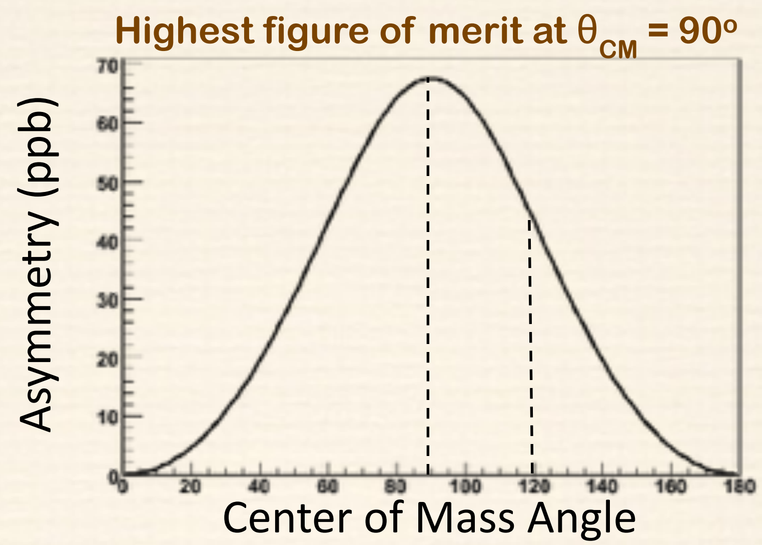


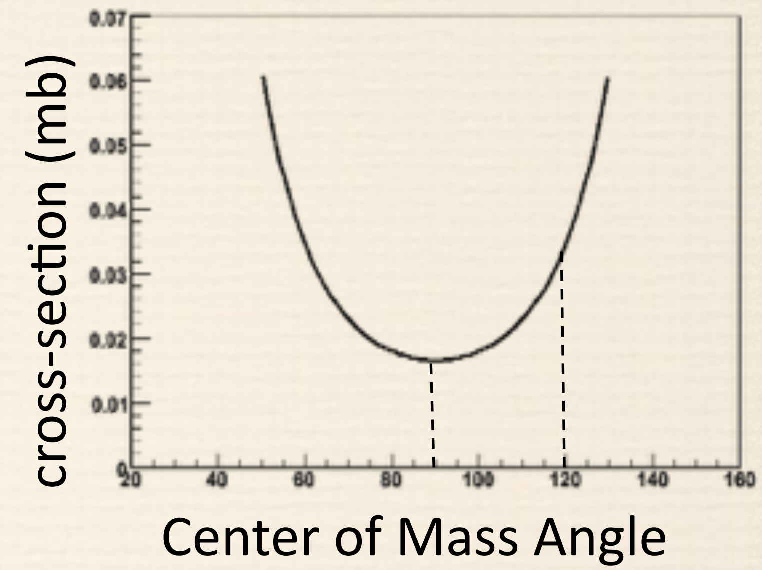
# Møller Kinematics

$E_{COM} = 53$ MeV

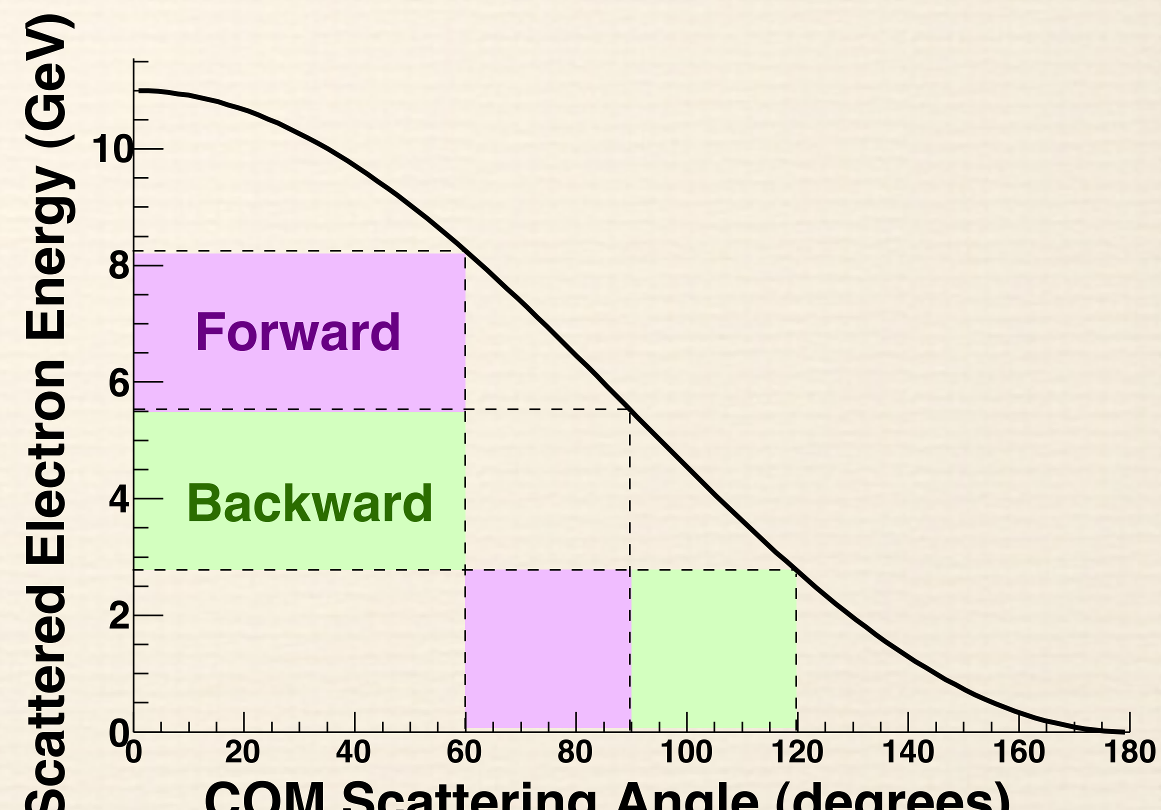



*identical particles!*




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



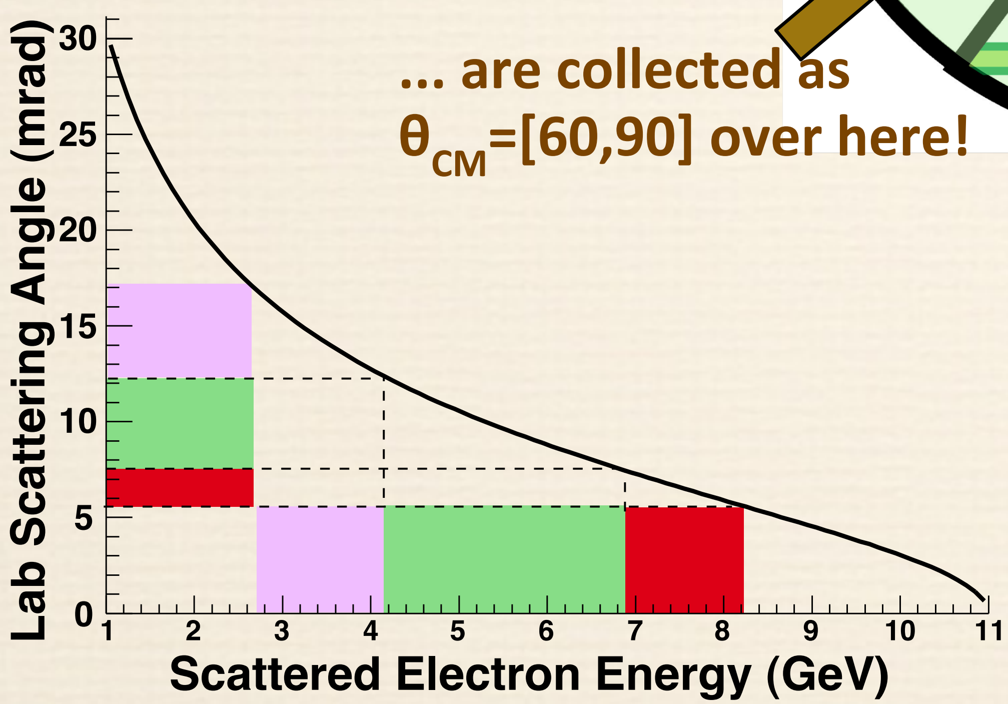
# 100% Acceptance

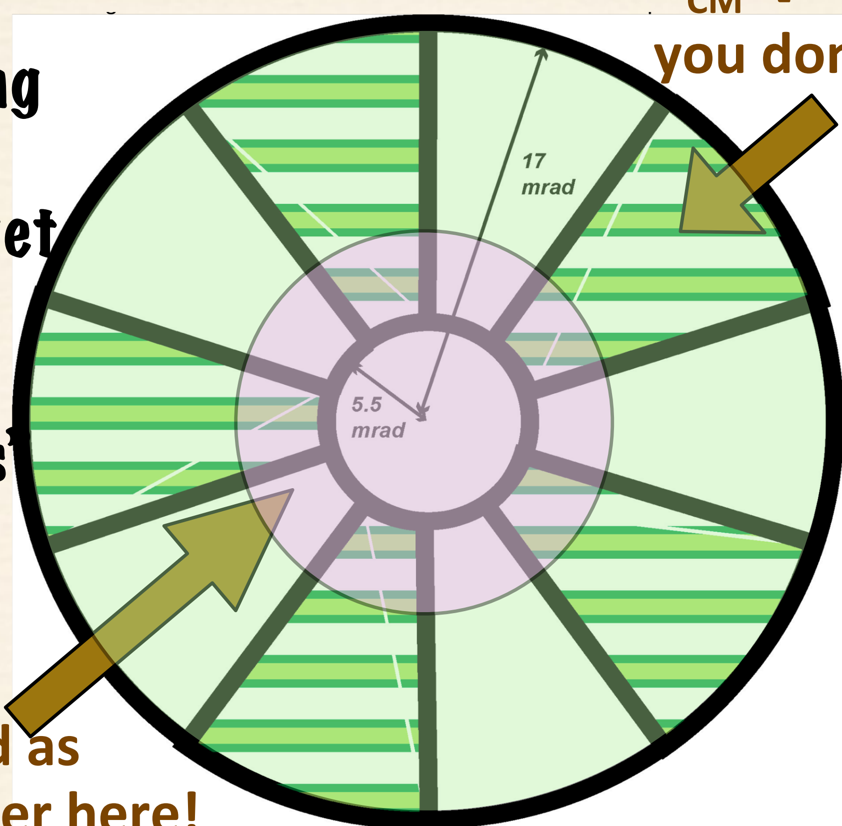
**Electrons from elastic scattering off target protons separated from elastic scattering off target electrons (Møllers); electrons from inelastic scattering dominate in between two "rings"**

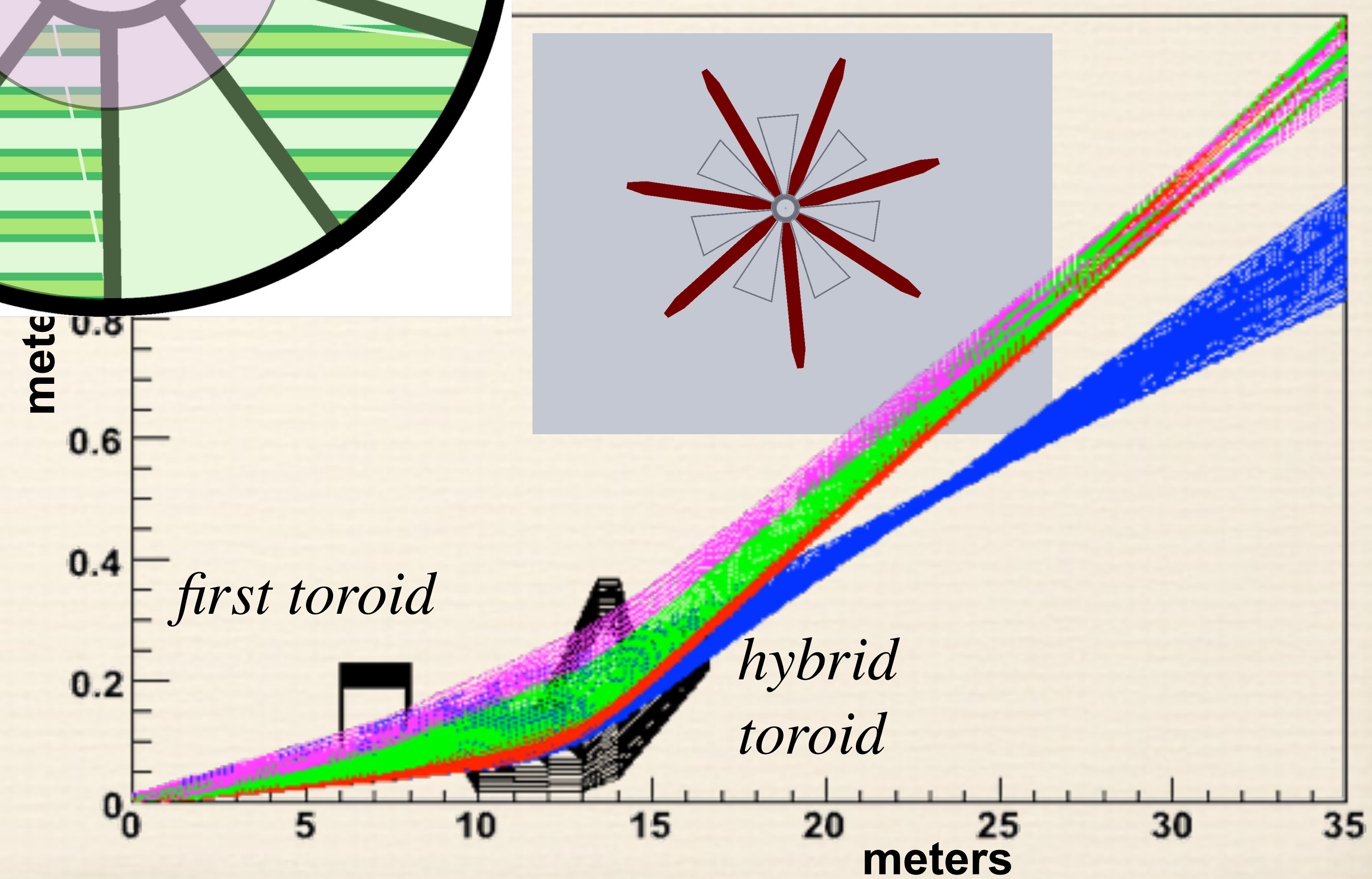
All of those rays of $\theta_{CM}$=[90,120] that you don't get here...

... are collected as $\theta_{CM}$=[60,90] over here!

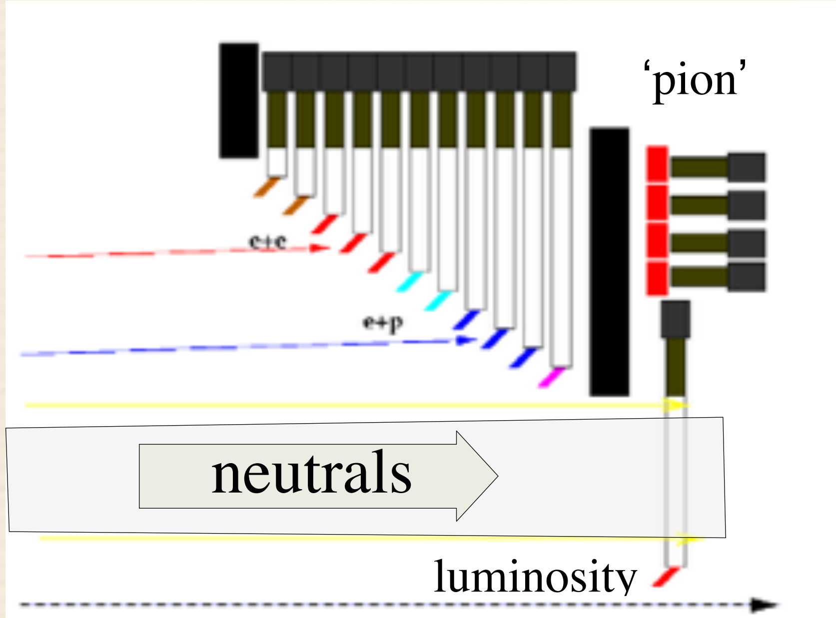
*Odd number of coils: both forward & backward Møllers in same phi-bite*

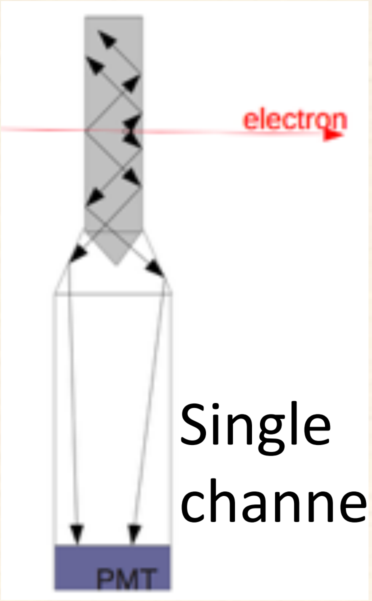


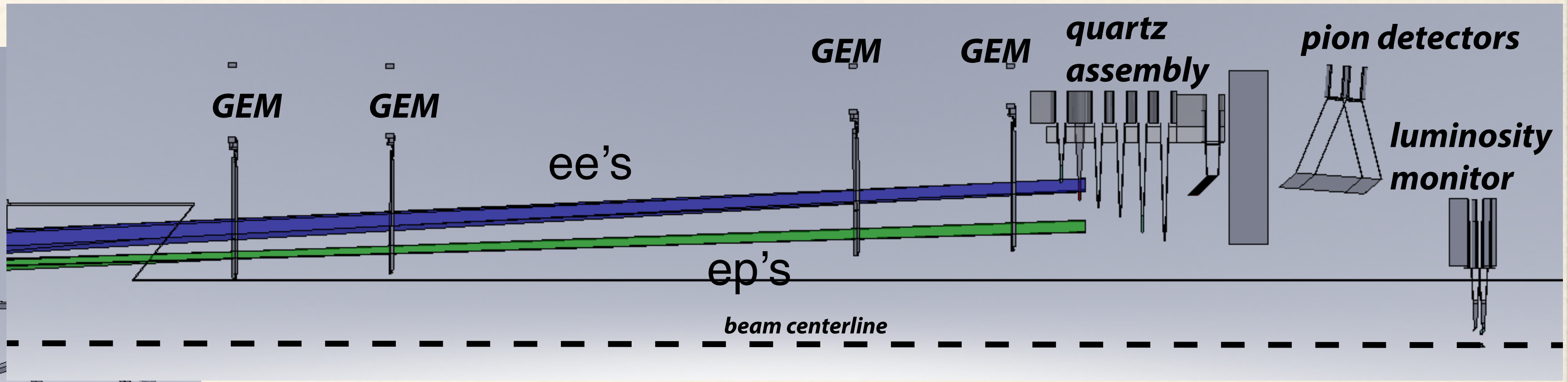



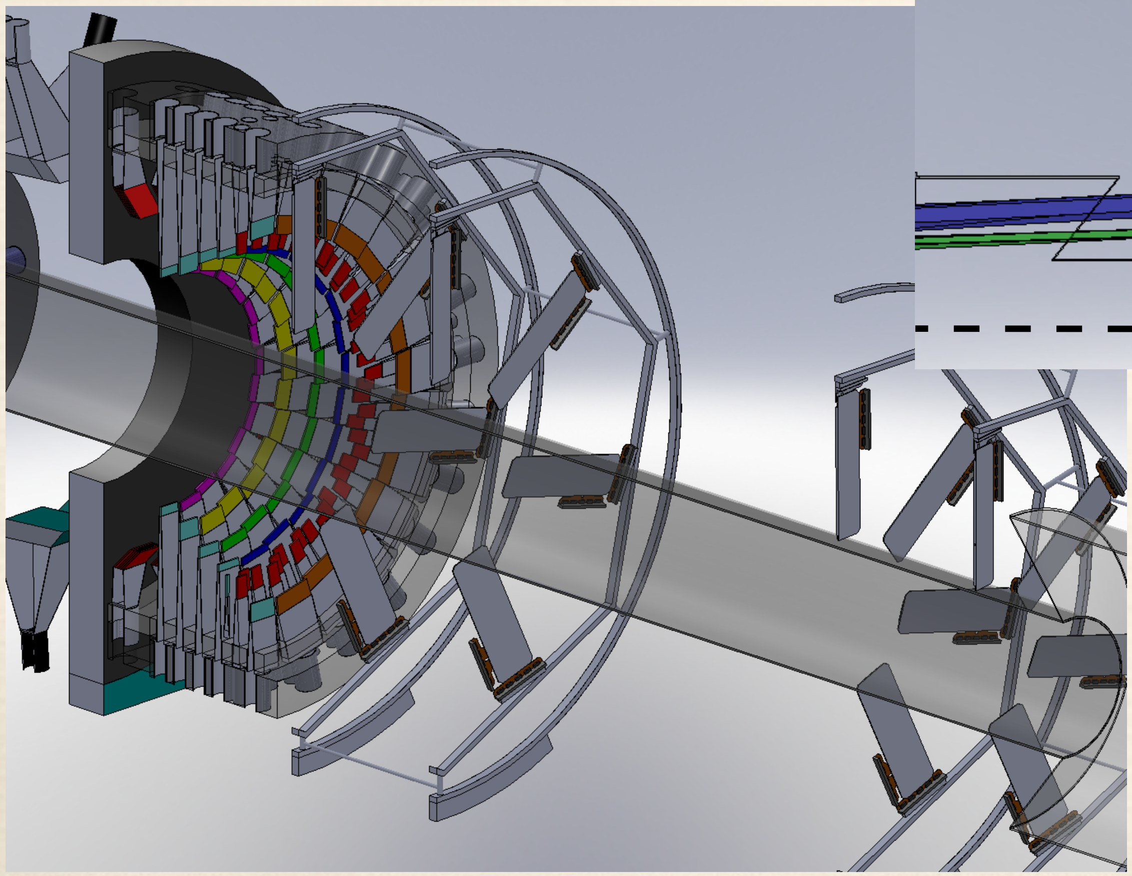
# Integrating Detector Concept



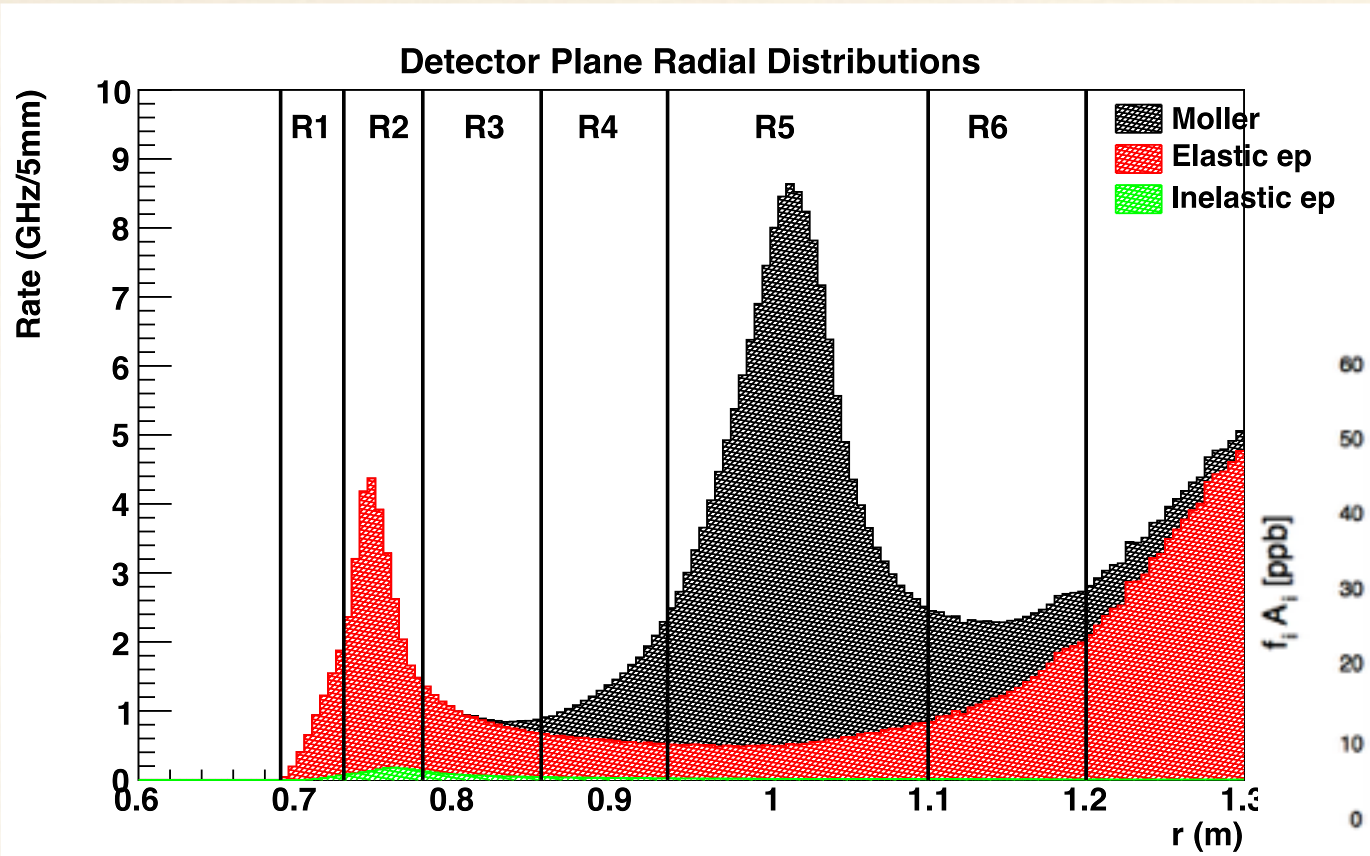

- **Møller and e-p electrons:**
  - radial and azimuthal segmentation
  - quartz with air lightguides & PMTs
- **Pions and muons:**
  - quartz sandwich behind shielding
- **Luminosity monitors**
  - beam & target density fluctuations



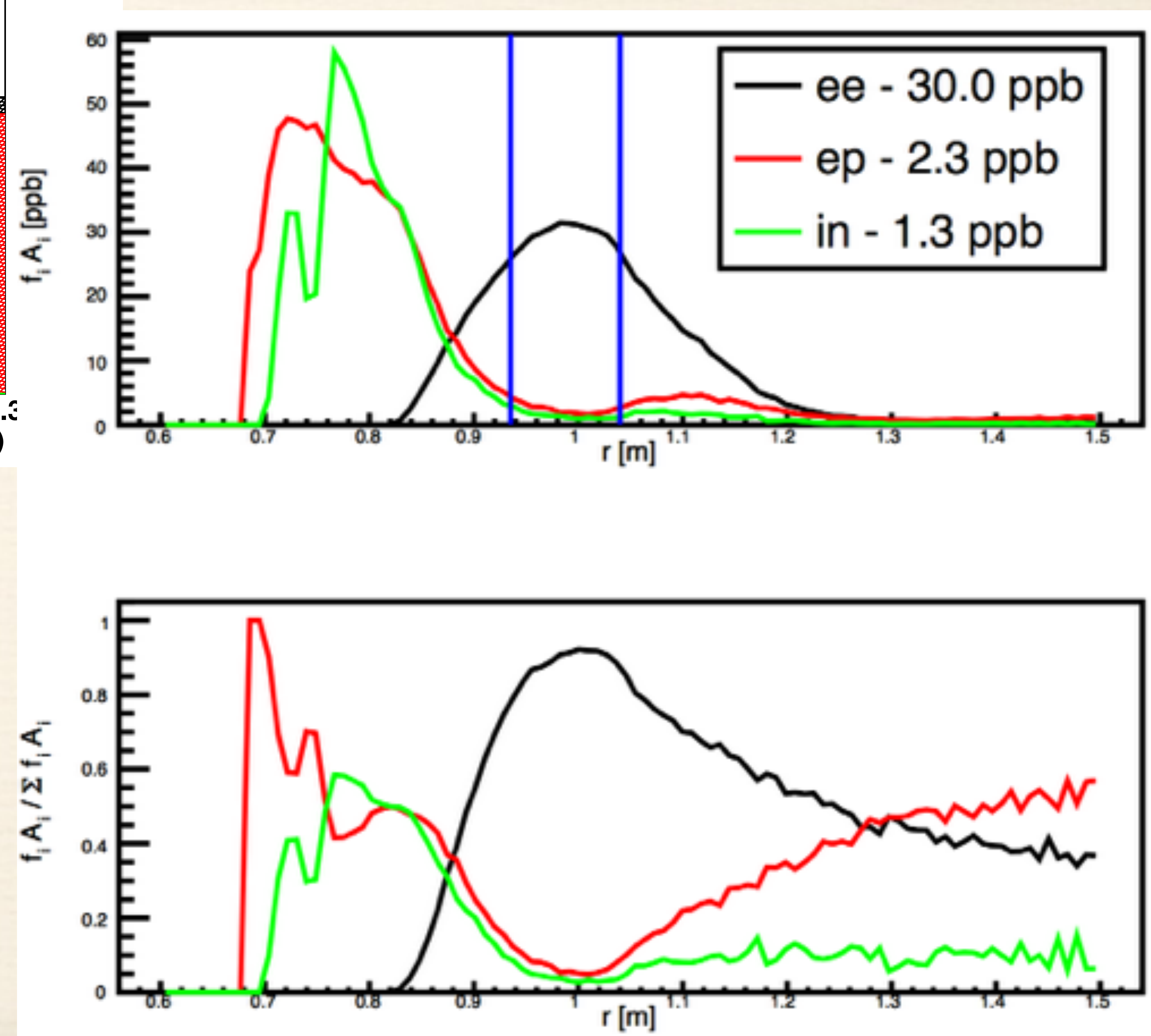



Evolutionary pre-R&D has continued using fractions of student and postdoc FTE's focused on Qweak and PREX; indeed these experiments are MOLLER "test beams"!

# Backgrounds




**The primary irreducible backgrounds are from electrons scattering elastically and inelastically off target protons**




- photons and neutrons
  - 2-bounce collimation system
- pions and muons
  - real and virtual photo-production and DIS
  - continuous parasitic measurement: guards against potential hyperon background

# MOLLER Auxiliary Measurements

- $A_{PV}$ in Inelastic Electron Proton Scattering
  - The intermediate rings will directly constrain the weak neutral current proton coupling in diffractive kinematics
  - New input to improved constraints on the box diagram uncertainties for calculation of the proton weak charge
  - Interesting QCD dynamics: related to quark-hadron duality
- Transverse Asymmetry Measurements
  - Dedicated Møller vector analyzing power measurements with transversely polarized beams: exquisite check of our understanding of the apparatus

# Statistics and Systematics: Summary

| Beam Property | Assumed Sensitivity | Accuracy of Correction | Required 2 kHz random fluctuations | Required cumulative helicity-correlation | Systematic contribution |
|---|---|---|---|---|---|
| Intensity | 1 ppb / ppb | $\sim$1% | $<$ 1000 ppm | $<$ 10 ppb | $\sim$ 0.1 ppb |
| Energy | -1.4 ppb / ppb | $\sim$10% | $<$ 108 ppm | $<$ 0.7 ppb | $\sim$ 0.05 ppb |
| Position | 0.85 ppb / nm | $\sim$10% | $<$ 47 $\mu$m | $<$ 1.2 nm | $\sim$ 0.05 ppb |
| Angle | 8.5 ppb / nrad | $\sim$10% | $<$ 4.7 $\mu$rad | $<$ 0.12 nrad | $\sim$ 0.05 ppb |

| Error Source | Fractional Error (%) |
|---|---|
| Statistical | **2.1** |
| Absolute Normalization of the Kinematic Factor | 0.5 |
| Beam (second order) | 0.4 |
| Beam polarization | 0.4 |
| $e + p(+\gamma) \rightarrow e + X(+\gamma)$ | 0.4 |
| Beam (position, angle, energy) | 0.4 |
| Beam (intensity) | 0.3 |
| $e + p(+\gamma) \rightarrow e + p(+\gamma)$ | 0.3 |
| $\gamma^{(*)} + p \rightarrow (\pi, \mu, K) + X$ | 0.3 |
| Transverse polarization | 0.2 |
| Neutral background (soft photons, neutrons) | 0.1 |
| Total systematic | **1.1** |

All systematics required at sub-1% level

# MOLLER Subsystems

**Expressions of Interest by Collaborating Instituions**

- Polarized source: UVa, JLab, Miss.St.
- Hydrogen Target: JLab, CalState LA, Miss.St.
- Spectrometer Magnets: Canada, ANL, MIT, SBU, UVa
- Focal Plane Detectors: Syracuse, Canada, JLab, UNC A&T, VaTech, SBU
- Luminosity Monitors: VaTech, Ohio
- Pion Detectors: SBU, LATech, UNC A&T
- Tracking Detectors: William & Mary, Canada, SBU, UVa, INFN Roma, MIT
- Electronics: Canada, JLab, UMass
- Beamline Instrumentation: SBU, JLab, VaTech
- Polarimetry: UVa, Syracuse, JLab, CMU, ANL, Miss.St., Clermont-Ferrand, Mainz, William & Mary, Temple
- Data Acquisition: Ohio, Rutgers, JLab
- Simulations: SBU, UMass, Canada, Berkeley, Idaho State, UVa, LaTech

# MOLLER Workforce

- **MOLLER: IV Generation JLab PVES project**
  - **III Generation Experiments Qweak and PREX**
    - *critical evolutionary development of all technical requirements*
    - *majority of both collaborations are committed to MOLLER*
    - *combined Hall A/C PVES: 12 PD FTE's and 25 Ph.D. students at peak*
    - *funding from DOE NP, NSF and NSERC (Canada)*
  - **7-8 faculty/lab staff positions in last decade in US NP**
    - *Critical training and expansion of expert workforce*
- **MOLLER Workforce Outlook:**
  - **Estimate 12-15 PD FTEs and 25 Ph.D. students at peak**
    - *A majority of the User funding would be redirected from existing grants*
    - *Restore PVES User funding to 2010-11 levels; it is down ~20%*
    - *New foreign participation will help offset losses at the ~10% level*

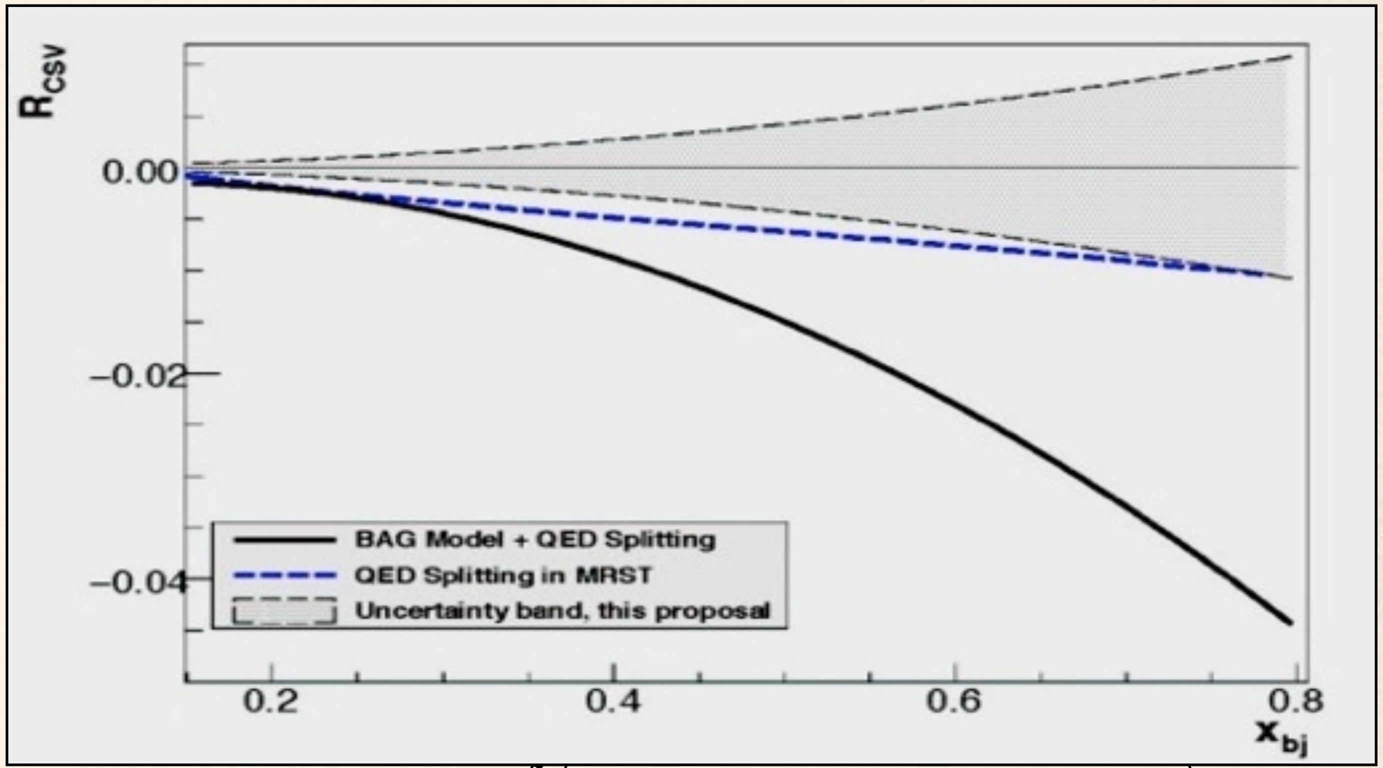
# QCD Dynamics in Precision $D_2$ PVDIS

$$u^p(x) \stackrel{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$
$$d^p(x) \stackrel{?}{=} u^n(x) \quad \Rightarrow \quad \delta d(x) \equiv d^p(x) - u^n(x)$$

$$R_{CSV} = \frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

**We already know CSV exists:**

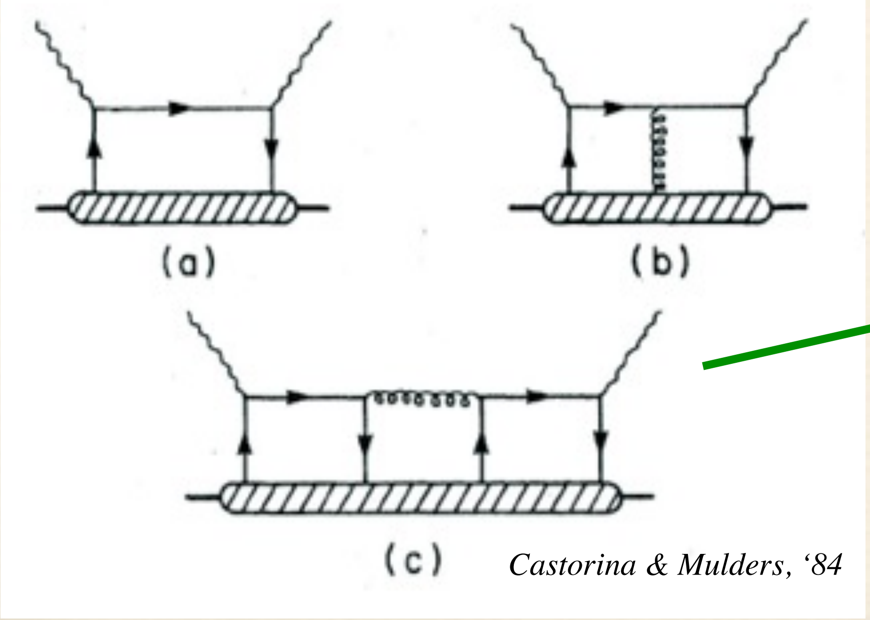
- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects




- **Direct sensitivity to parton-level CSV**
- **Important implications for PDF's**
- ***Could be* partial explanation of the NuTeV anomaly**

$$\langle VV \rangle - \langle SS \rangle = \langle (V-S)(V+S) \rangle \propto l_{\mu\nu} \int \langle D | u(x) \gamma^\mu u(x) d(0) \gamma^\nu d(0) \rangle e^{iqx} d^4x$$

**Zero in quark-parton model**



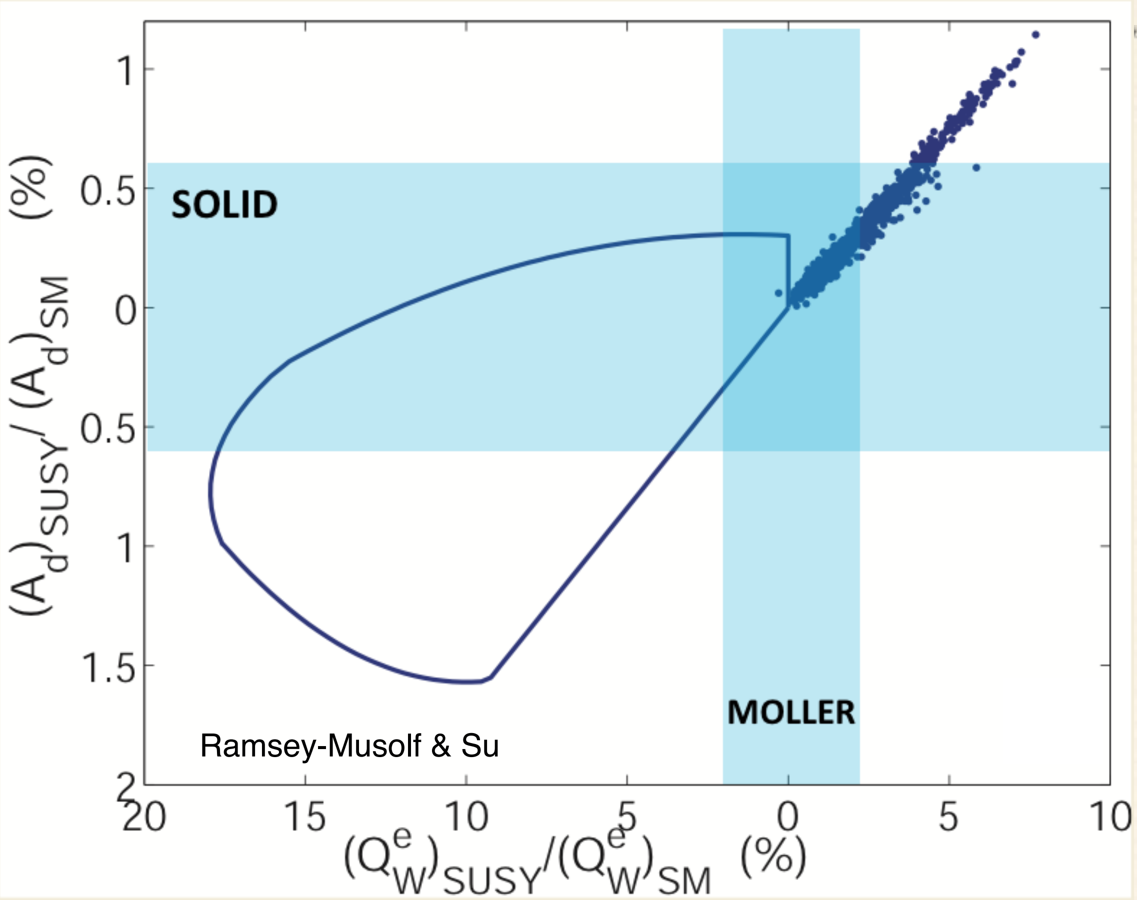

*Castorina & Mulders, '84*

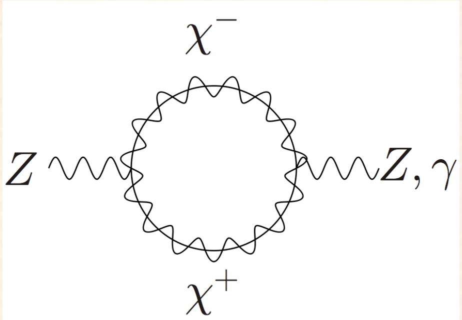
**Higher-Twist valence quark-quark correlation**

**(c) type diagram is the only operator that can contribute to a(x) higher twist: theoretically very interesting!**

**$\sigma_L$ contributions cancel**

# SOLID Sensitivity




***Does Supersymmetry provide a candidate for dark matter?***

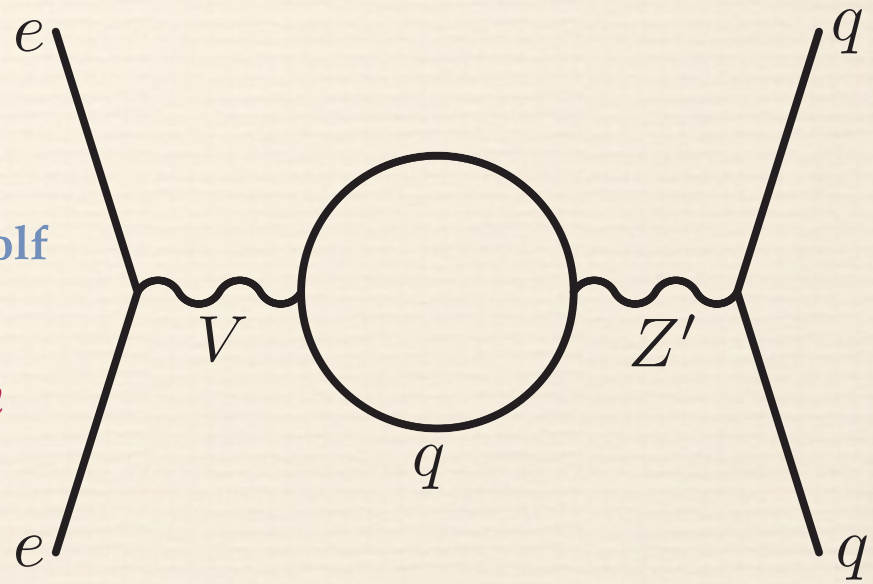
- B and/or L need not be conserved: neutralino decay
- Depending on size and sign of deviation: could lose appeal as a dark matter candidate

## *Leptophobic Z'*

arXiv:1203.1102v1

Buckley and Ramsey-Musolf

- *Virtually all GUT models predict new Z's*
- *LHC reach ~ 5 TeV, but....*
- *Little sensitivity if Z' doesnt couple to leptons*
- *Leptophobic Z' as light as 120 GeV could have escaped detection*



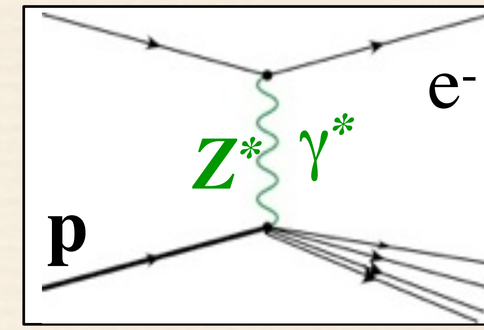

*Since electron vertex must be vector, the Z' cannot couple to the $C_{1q}$'s if there is no electron coupling: can only affect* **$C_{2q}$'s**

**SOLID can improve sensitivity: 100-200 GeV range**

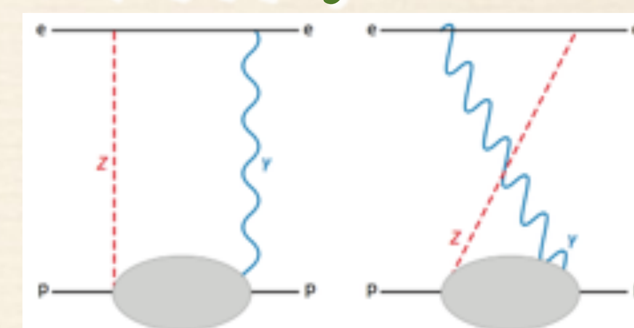
# EW Physics and QCD Interplay

- ✦ **Strange Quark Form Factors**

electrons on $LH_2$

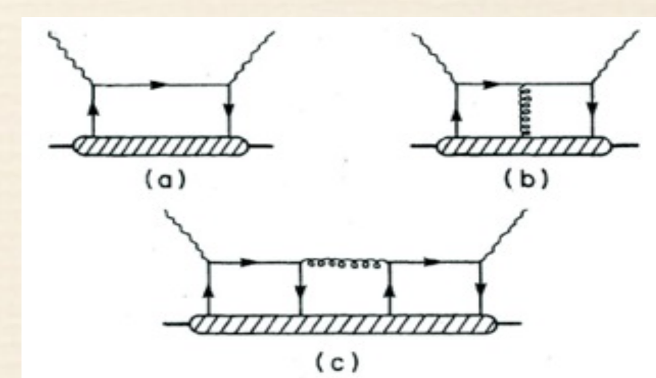



- ✦ **Inelastic backgrounds**
  - ★ Inelastic e-p scattering in diffractive region ($Q^2 << 1$ GeV$^2$, $W^2 > 2$ GeV$^2$) pollutes the Møller peak



- ✦ **Box diagram uncertainties**
  - ★ Proton weak charge modified; inelastic intermediate states
- ✦ **Parton dynamics in nucleons and nuclei**

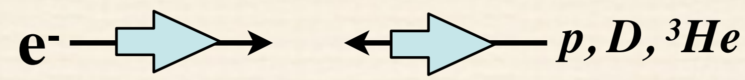
**Physics of SOLID**




  - ★ Higher twist effects
  - ★ charge symmetry violation in the nucleon
  - ★ "EMC" style effects: quark pdfs modified in nuclei

*High luminosity: precision measurements of PV observables*

# EW Structure Functions at EIC




$$\frac{1}{2m_N}W^i_{\mu\nu} = -\frac{g_{\mu\nu}}{m_N}F^i_1 + \frac{p_\mu p_\nu}{m_N(p\cdot q)}F^i_2$$
$$+ i\frac{\epsilon_{\mu\nu\alpha\beta}}{2(p\cdot q)}\left[\frac{p^\alpha q^\beta}{m_N}F^i_3 + 2q^\alpha S^\beta g^i_1 - 4xp^\alpha S^\beta g^i_2\right]$$
$$-\frac{p_\mu S_\nu + S_\mu p_\nu}{2(p\cdot q)}g^i_3 + \frac{S\cdot q}{(p\cdot q)^2}p_\mu p_\nu g^i_4 + \frac{S\cdot q}{p\cdot q}g_{\mu\nu}g^i_5$$

Ji, Vogelsang, Blümlein, ...
Anselmino, Efremov & Leader,
Phys. Rep. **261** (1995)

***polarized* electron, *unpolarized* hadron**

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A\frac{F_1^{\gamma Z}}{F_1^\gamma} + g_V\frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^\gamma}\right]$$

***unpolarized* electron, *polarized* hadron**

$$A_{TPV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V\frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A f(y)\frac{g_1^{\gamma Z}}{F_1^\gamma}\right]$$

**proton**

**similar expressions for the neutron:** $u \leftrightarrow d$

$$g_1^{W^-} = (\Delta u + \Delta\bar{d} + \Delta\bar{s} + \Delta c)$$
$$g_1^{W^+} = (\Delta\bar{u} + \Delta d + \Delta s + \Delta\bar{c})$$
$$g_5^{W^+} = (\Delta\bar{u} - \Delta d - \Delta s + \Delta\bar{c})$$
$$g_5^{W^-} = (-\Delta u + \Delta\bar{d} + \Delta\bar{s} - \Delta c)$$

$$\int_0^1 dx[g_5^{W^-,n} - g_5^{W^-,p}] = g_A\left(1 - \frac{2\alpha_s}{3\pi}\right)$$

**new sum rules**

**proton**

$$F_1^{\gamma Z} \propto u + d + s$$
$$F_3^{\gamma Z} \propto 2u_v + d_v$$
$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$
$$g_5^{\gamma Z} \propto 2\Delta u_v + \Delta d_v$$

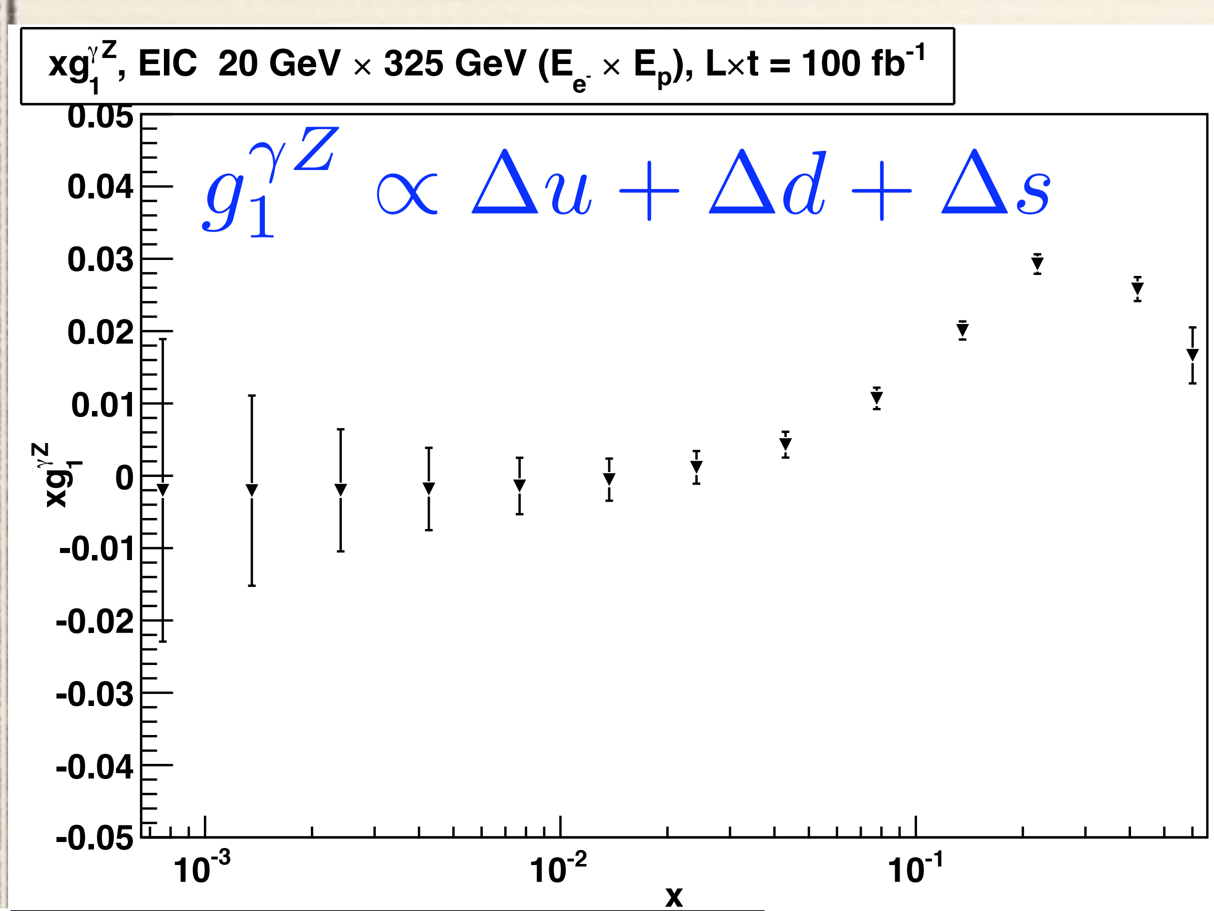
**deuteron**

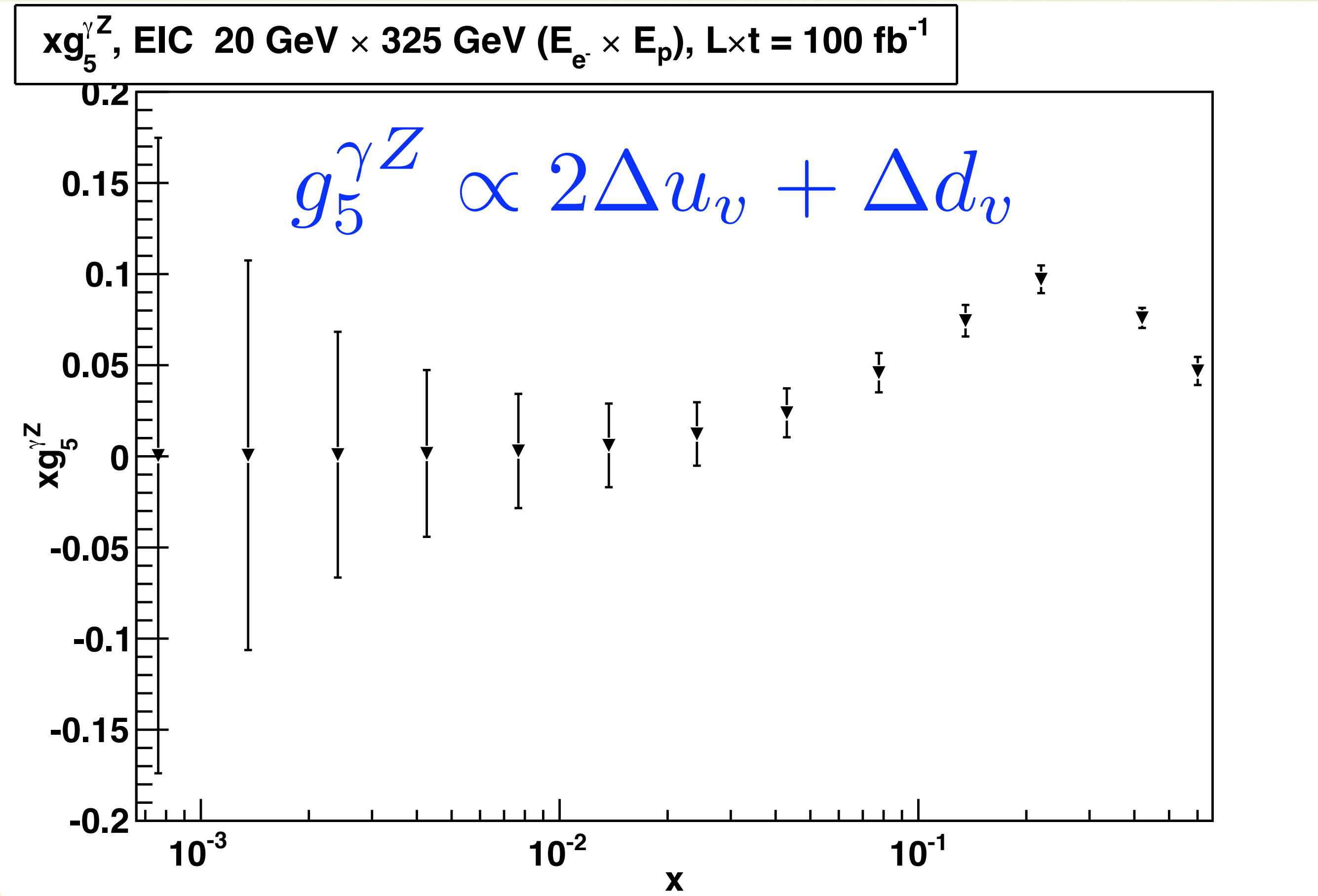
$$F_1^{\gamma Z} \propto u + d + 2s$$
$$F_3^{\gamma Z} \propto u_v + d_v$$
$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$
$$g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v$$

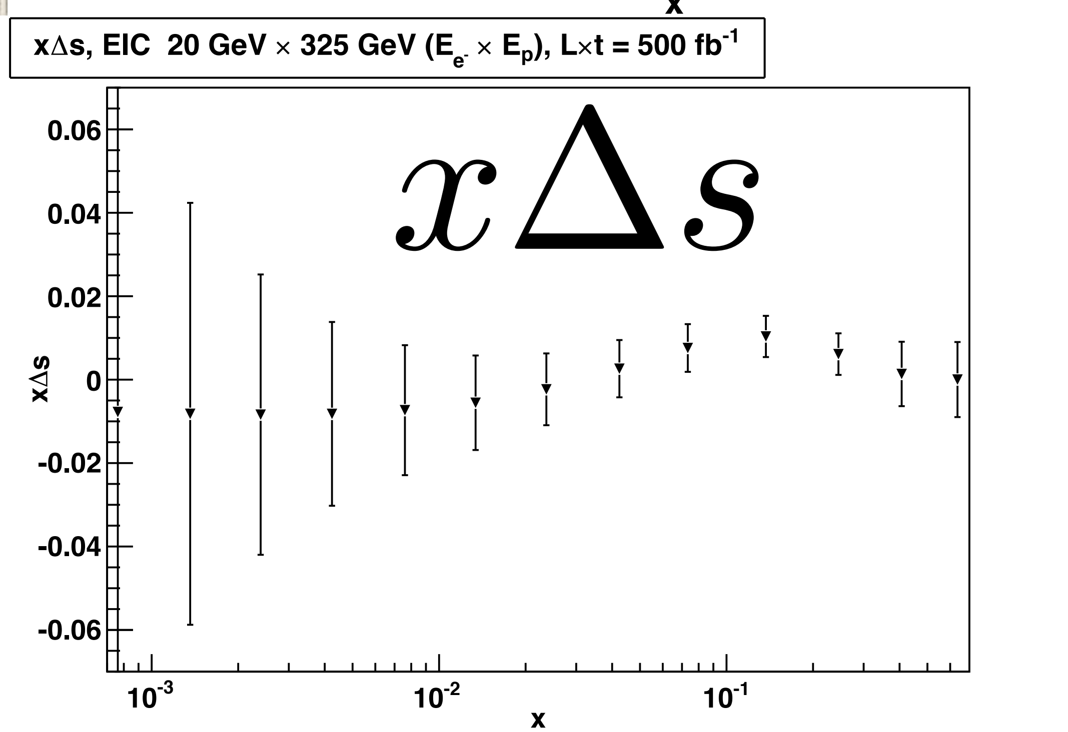
**Similar expressions for neutral current structure functions**

*Including quark and anti-quark polarizations*

# Help 6-Flavor Separation



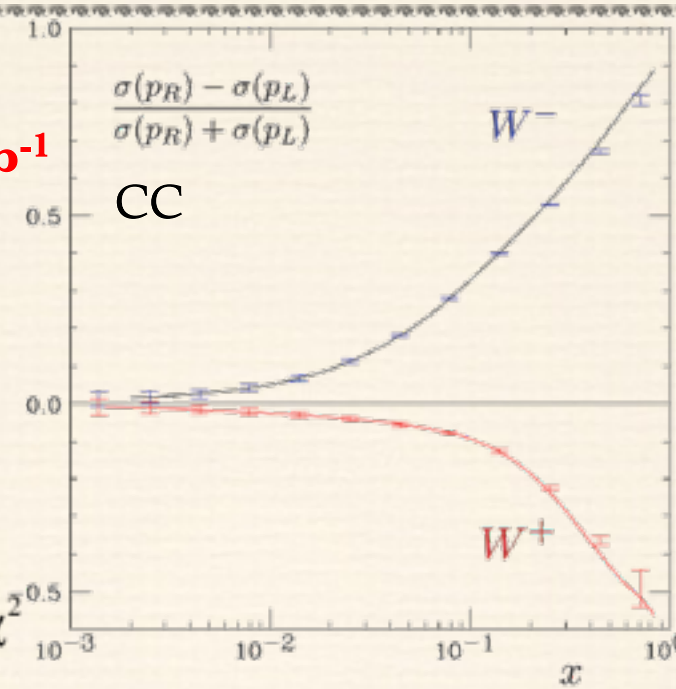

*A cross-check showing unambiguously non-zero delta-s in an inclusive measurement?*

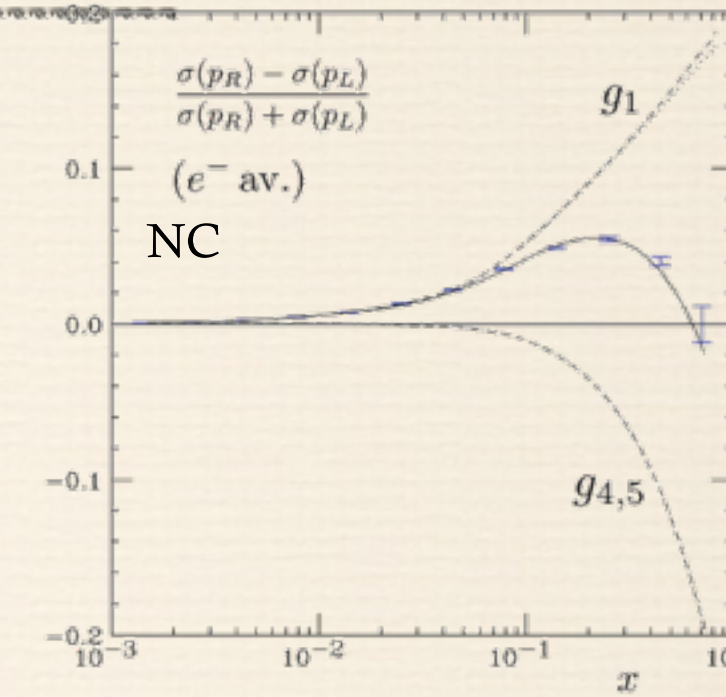
***Semi-inclusive measurements lose statistical power at x ~ 0.1, and have significant theoretical interpretation issues***

# Examples of Projected Results

$20 \times 250$ GeV, $Q^2 > 1$ GeV$^2$, $0.1 < y < 0.9$, **10 fb$^{-1}$**

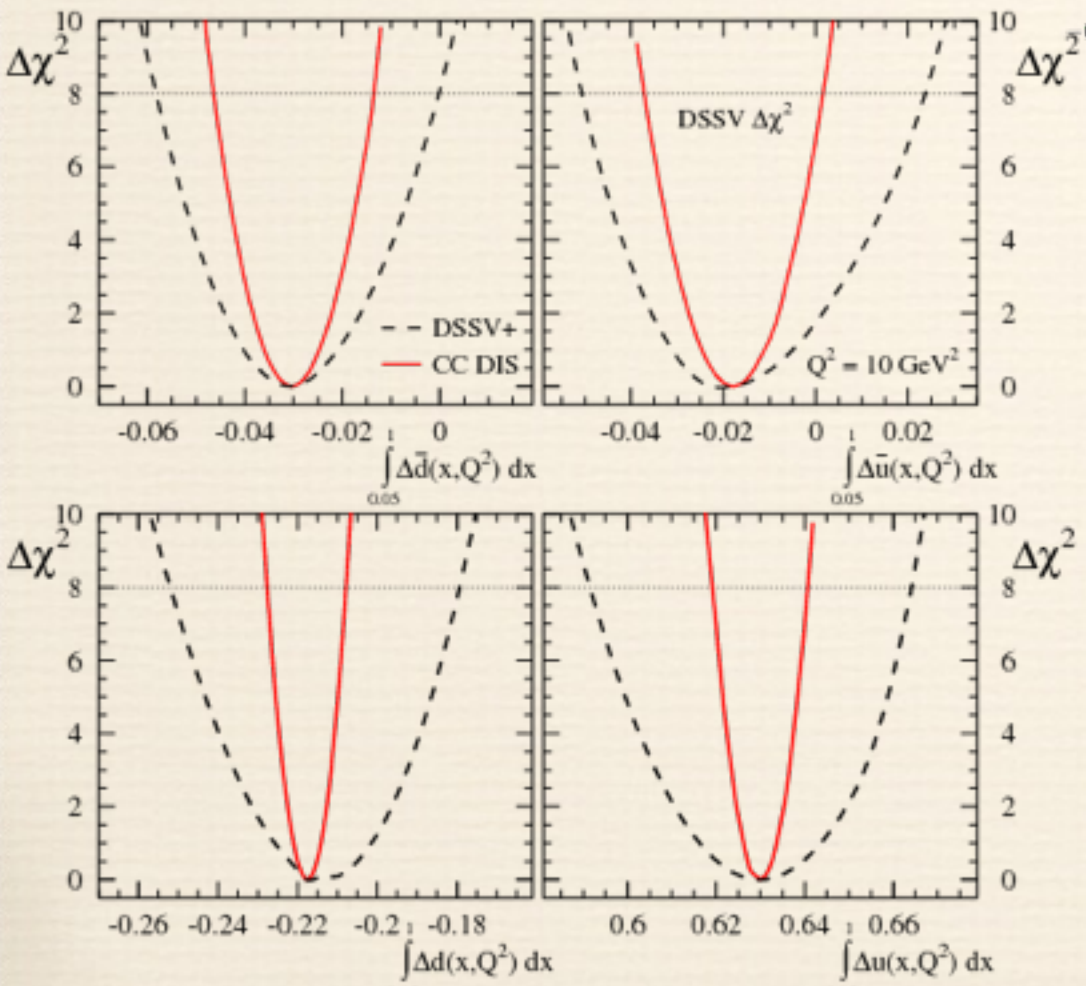
**(Could begin the program with 5x250 GeV i.e "Stage 1" of the EIC)**

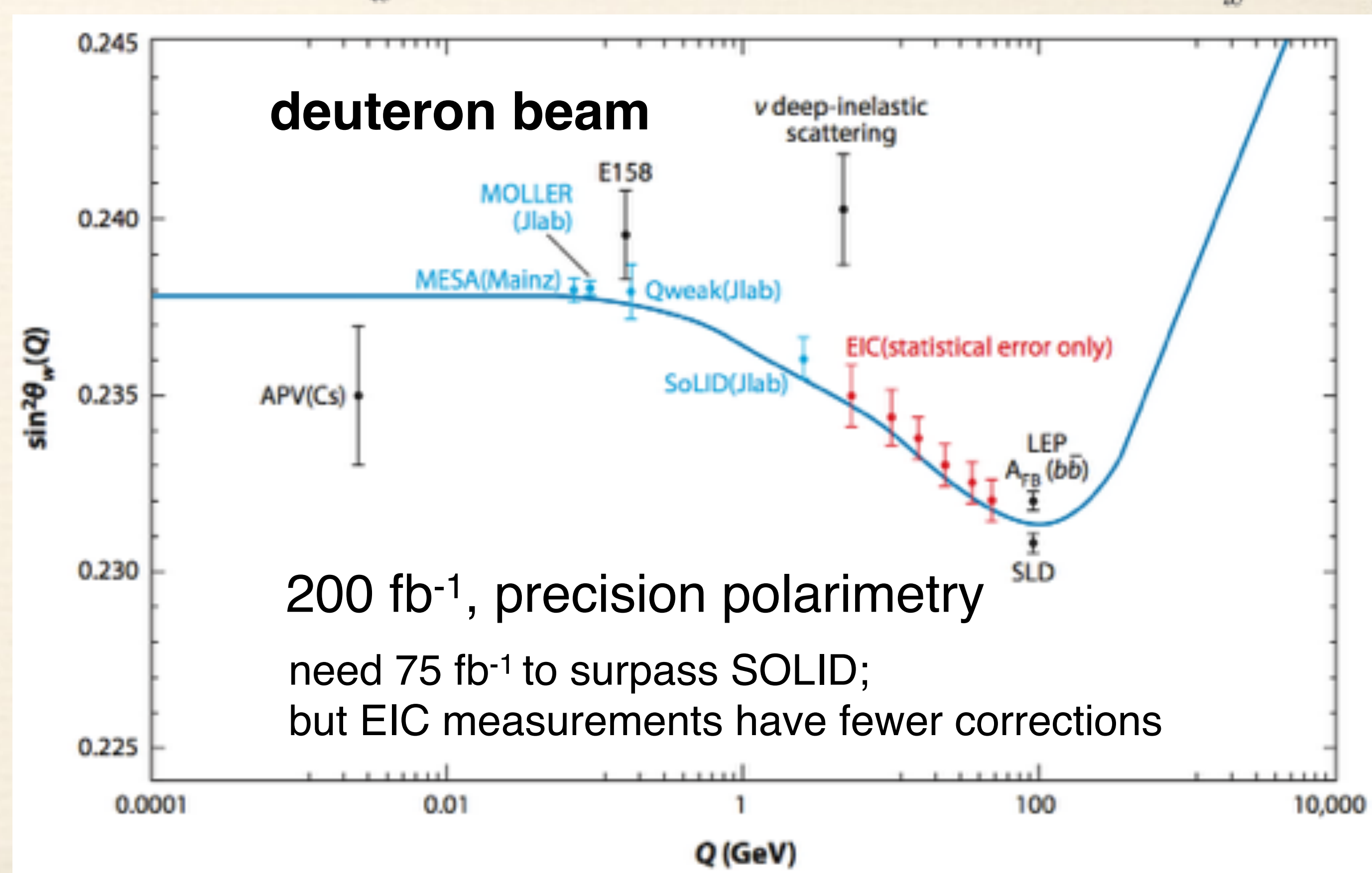



***Full analysis of charged current events including radiative corrections***

Aschenauer et al, PRD **88**, 114025 (2013)



*Longstanding issue in proton structure*

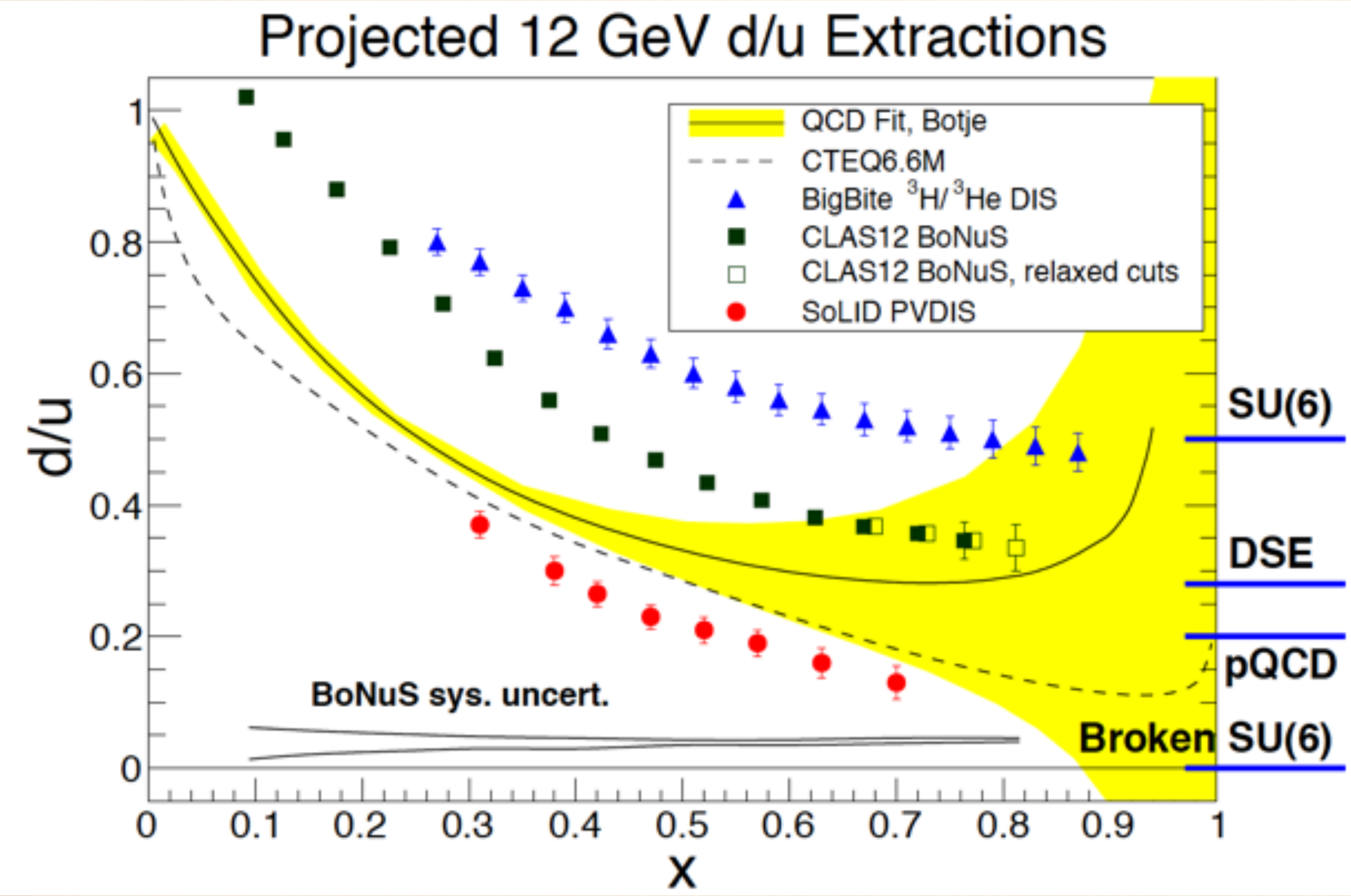
# Proton PVDIS: d/u at high x

*(high power liquid hydrogen target)*

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

*SU(6): d/u~1/2*
*Broken SU(6): d/u~0*
*Perturbative QCD: d/u~1/5*

$$a^P(x) \approx \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$




- Three JLab 12 GeV experiments:
  - CLAS12 BoNuS - spectator tagging
  - BigBite - DIS $^3$H/$^3$He Ratio
  - SoLID - PVDIS *ep*
- The SoLID extraction of $d/u$ is made directly from *ep* DIS: *no nuclear corrections*

*Cloet, Bentz, Thomas, arXiv 0901.3559*

# $^{48}$Ca PVDIS

## *Consider PVDIS on a heavy nucleus*

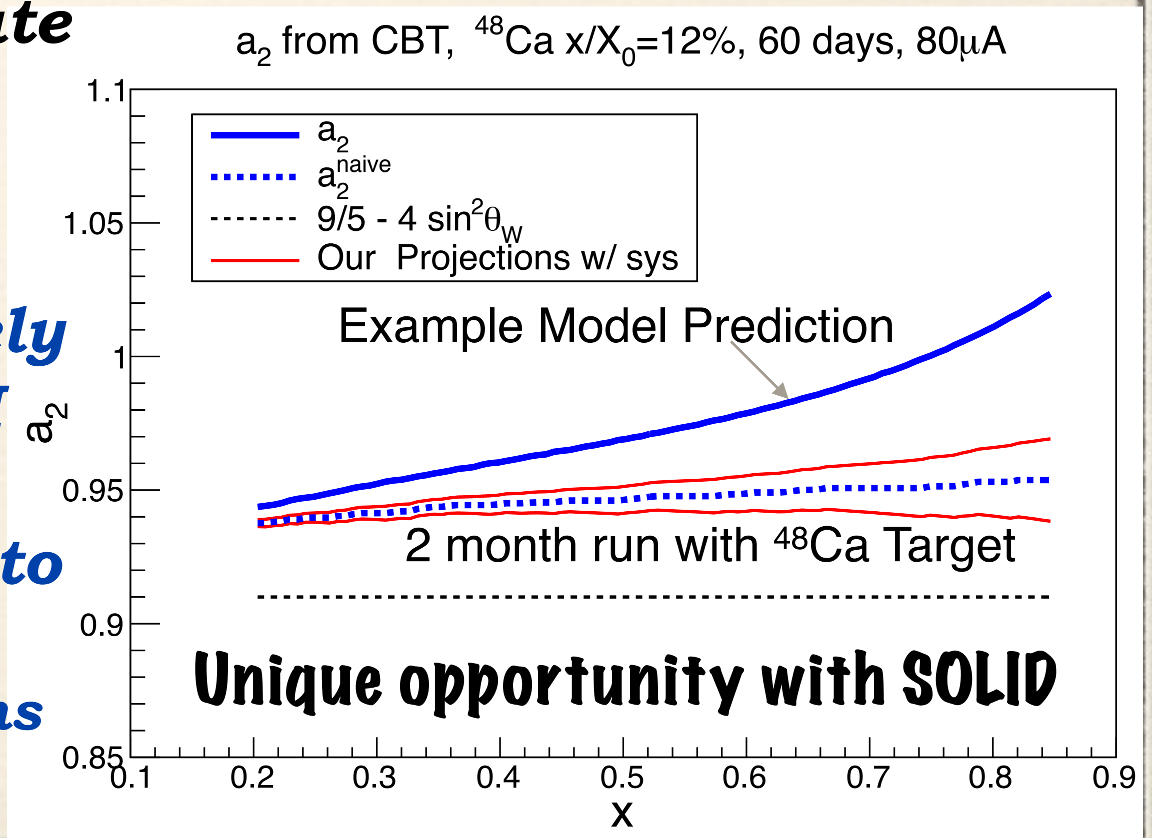
- Neutron or proton excess in nuclei leads to a isovector-vector mean field (ρ exchange)
- shifts quark distributions: "apparent" charge symmetry violation
- Isovector EMC effect: explain additional 2/3 of NuTeV anomaly

- **new insight into medium modification of quark distributions**

$$a_2 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + \cdots$$

**Great leverage for a clean isospin decomposition of the EMC effect in an inclusive measurement**

- ***Flavor separation: clean data sparse to date***
- ***With hadrons in the initial or final state, small effects are difficult to disentangle (theoretically and experimentally)***
- ***Precise isotope cross-section ratios in purely electromagnetic electron scattering: MUCH reduced sensitivity to the isovector combination; potentially see small effects to discriminate models***
  - ***a flavor decomposition of medium modifications is extremely challenging***

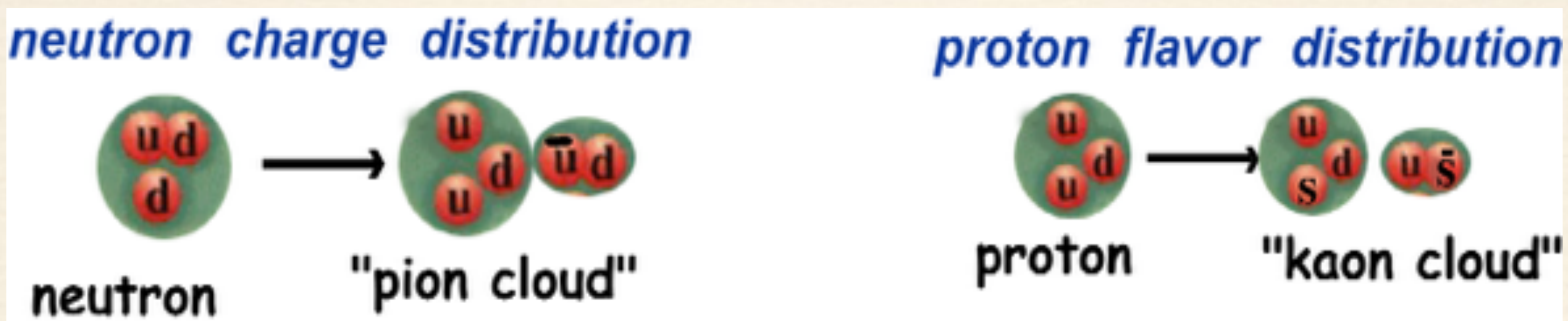


# Strange Quarks in the Nucleon

Quark Model ⟺ ? QCD *Late 1980's*

***Strange quarks carry nucleon momentum: Other external properties affected?***

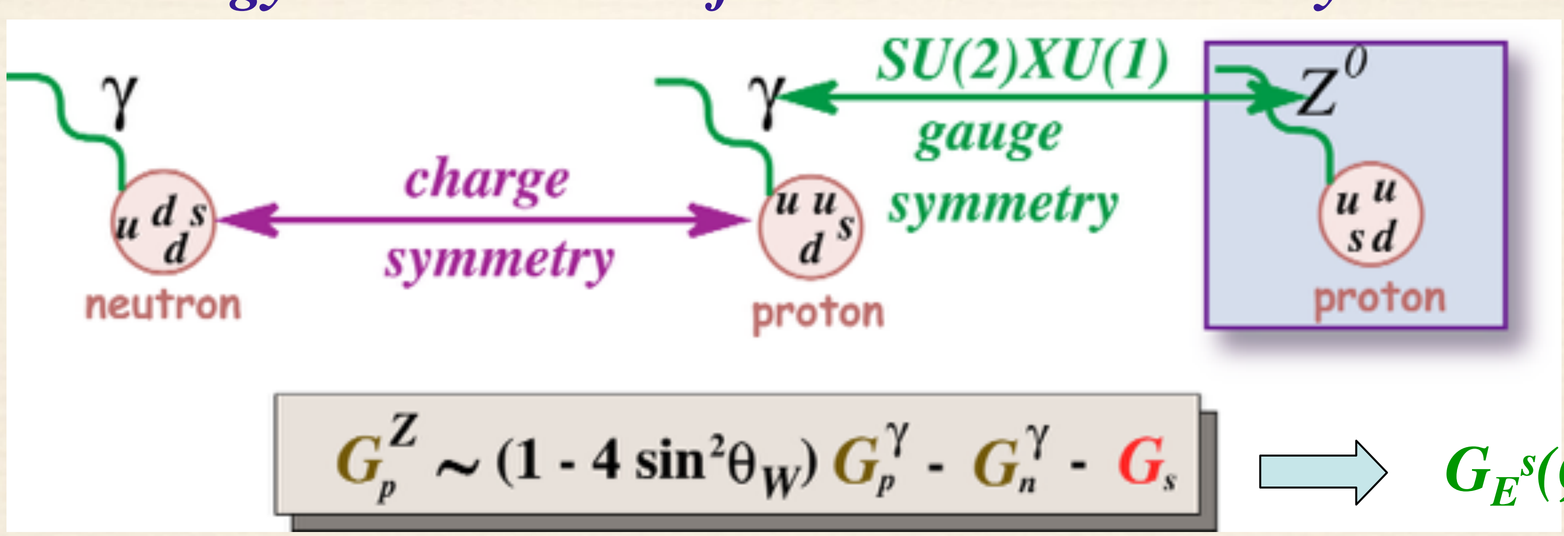
**A pressing question after discovery of EMC effect and the spin crisis**




?

***Even with broken $SU(3)_f$, potentially large effects for vector current predicted***

*Theorists originally proposed using neutrino scattering; parity-violating electron scattering technology & the success of the electroweak theory led to a new strategy*




Kaplan & Manohar (1988)
McKeown (1989)
Beck (1990)

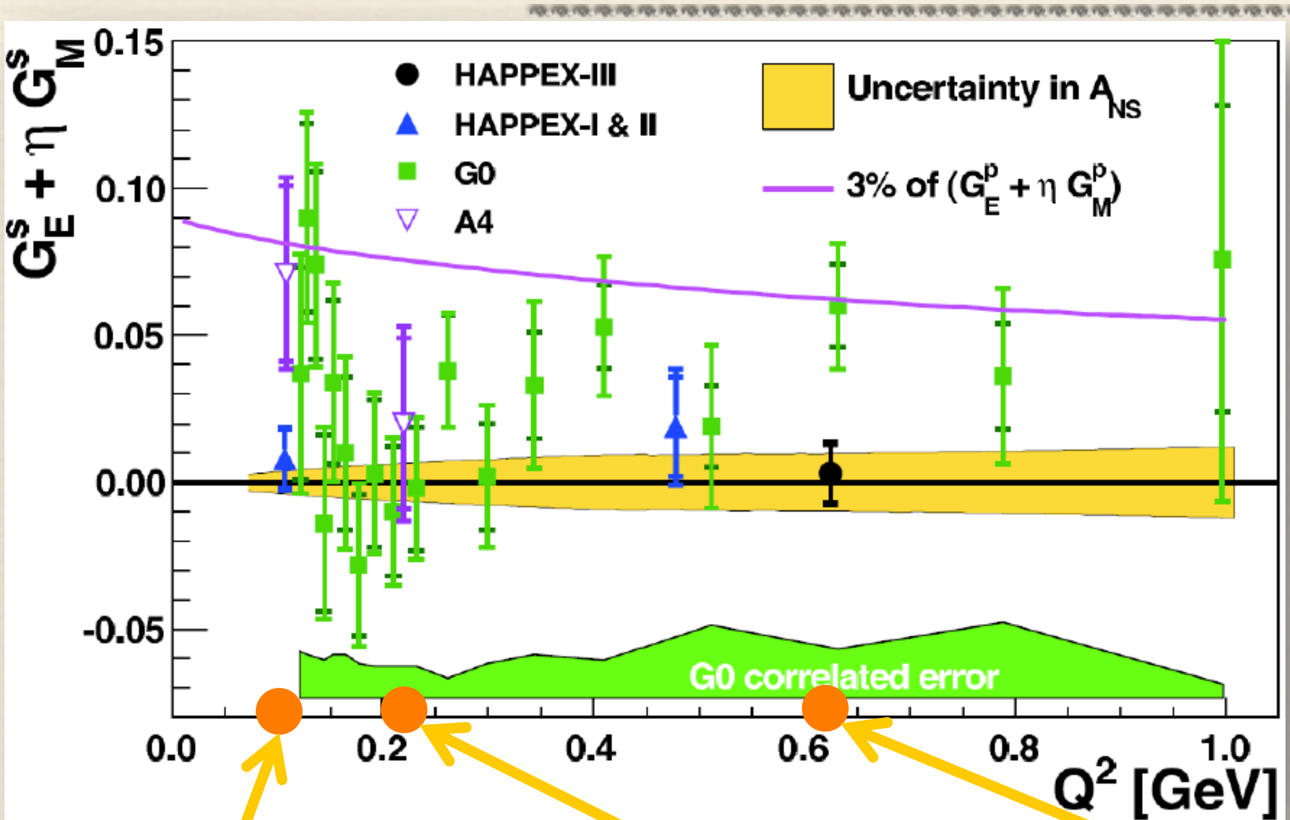
⇒ $G_E^s(Q^2), G_M^s(Q^2)$

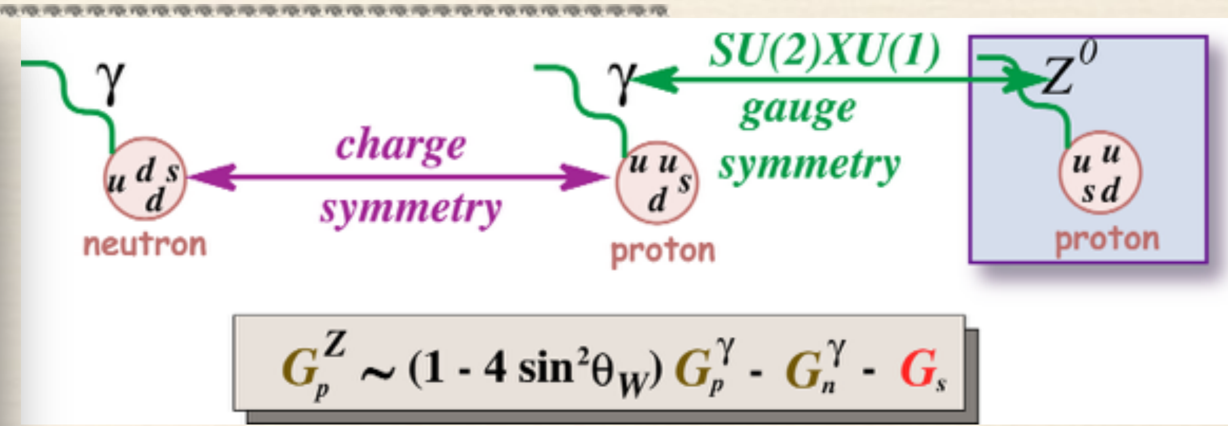
*$^4$He target: Unique $G_E$ sensitivity* *$^2$H: Enhanced $G_A$ sensitivity*

## 2011: Completion of a 2-decade program

# Strange Quarks Form Factors

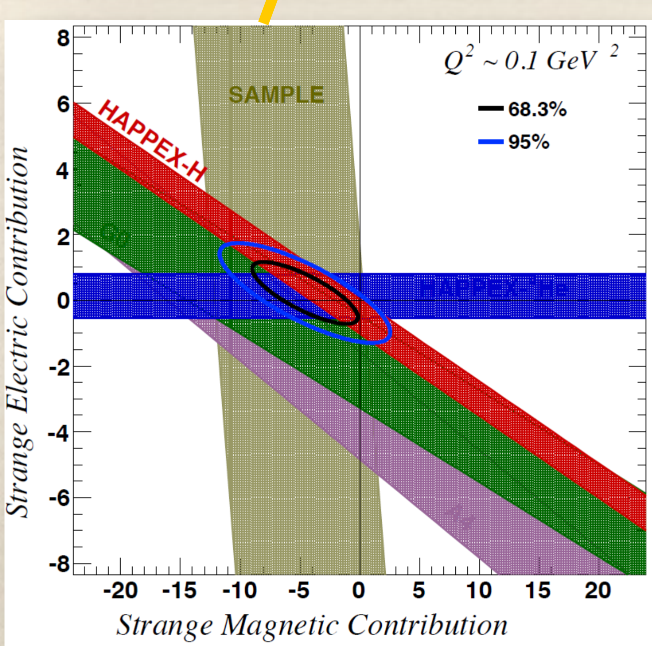
### SC Milestone HP4 on Flavor Separated Form Factors at $Q^2 < 1$ GeV$^2$

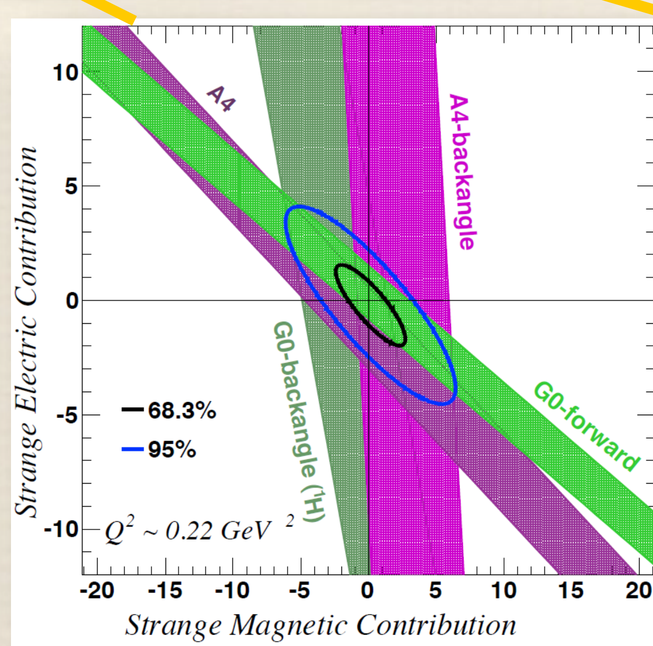


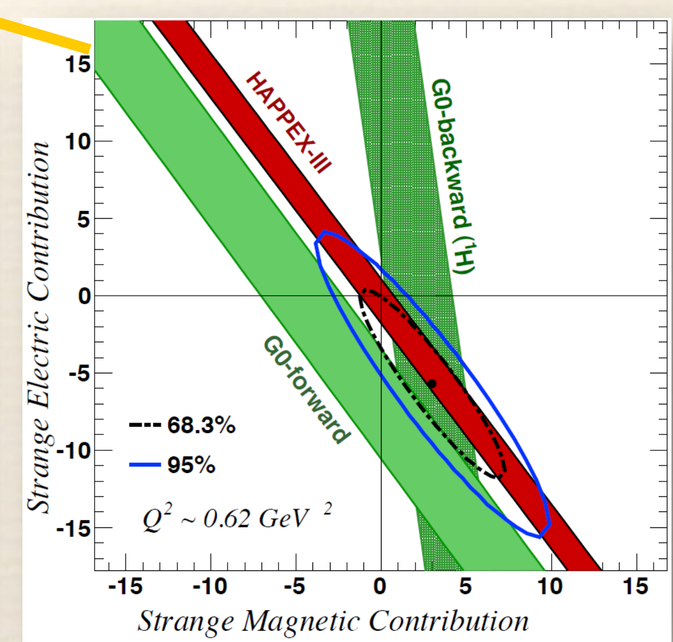




$\Rightarrow\ G_E^s(Q^2), G_M^s(Q^2)$

- Sensitive Flavor separation at 3 $Q^2$ values
- No more than few % of EM structure
- Recent lattice results in agreement

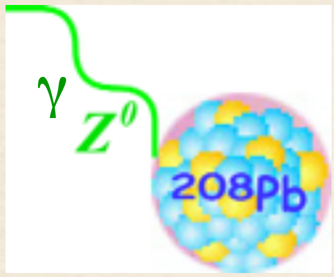


Pb-Radius EXperiment

# EW Probe of Neutron Densities




$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2) \qquad M_{PV}^{NC} = \frac{G_F}{\sqrt{2}}\left[\left(1-4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

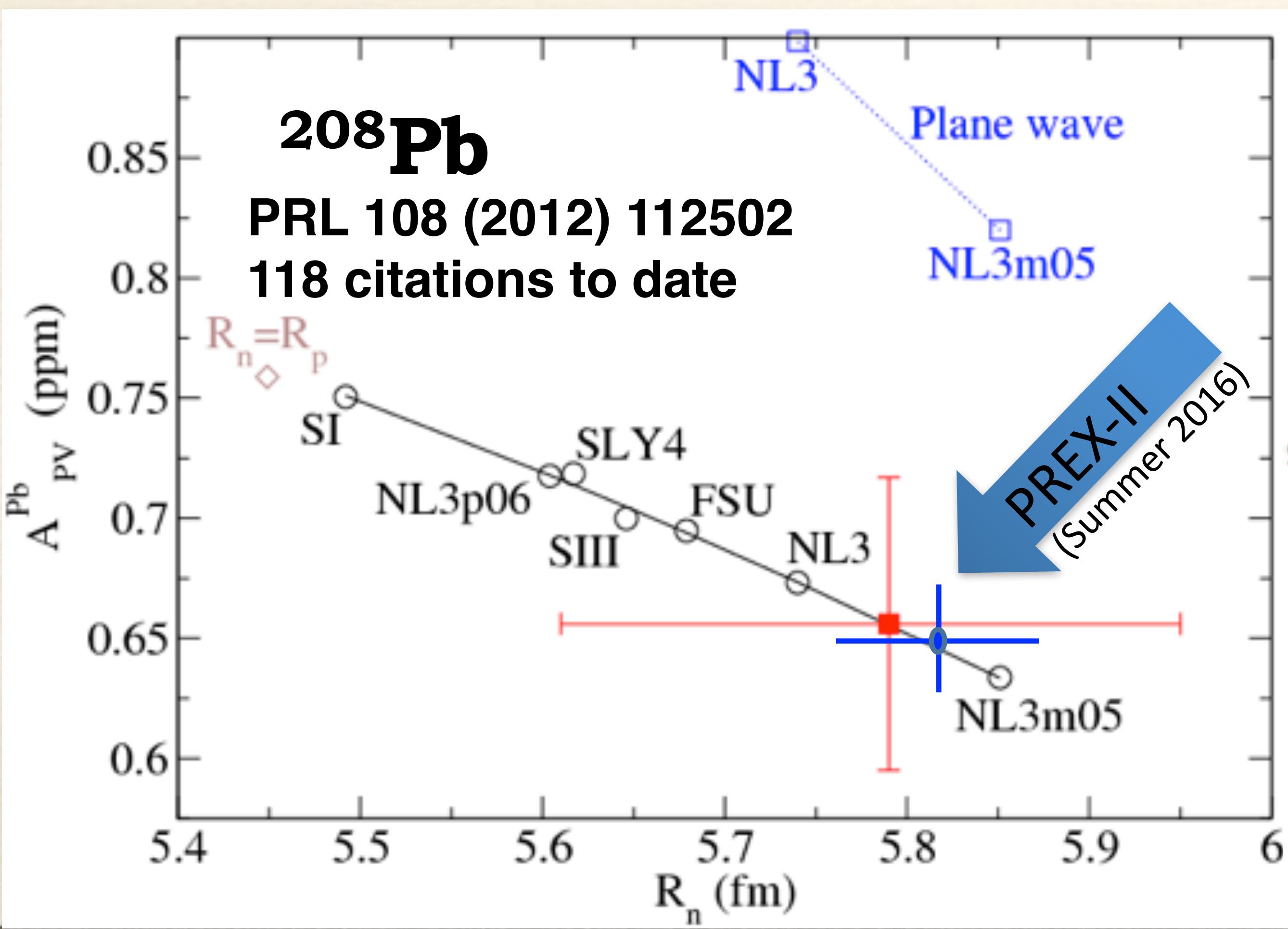
$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

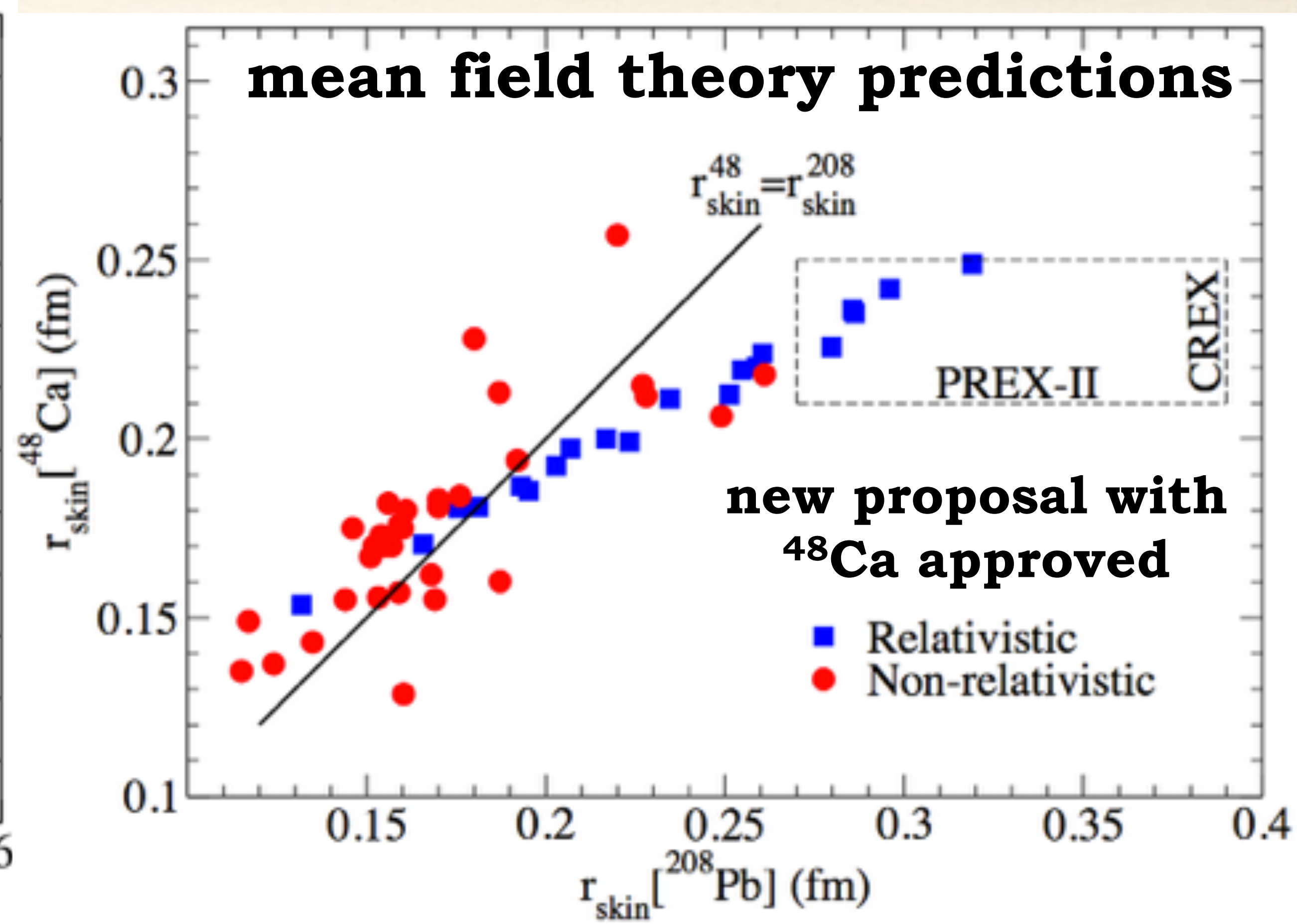
$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

$\delta(A_{PV})/A_{PV} \sim 3\%$

$\delta(R_n)/R_n \sim 1\%$

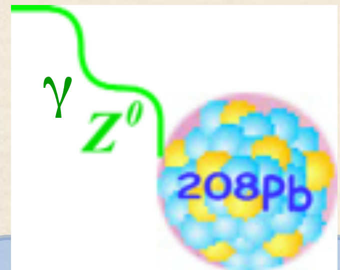
$\delta(R_n) \sim \pm\, 0.06\ fm$



Pb-Radius EXperiment

# EW Probe of Neutron Densities




$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

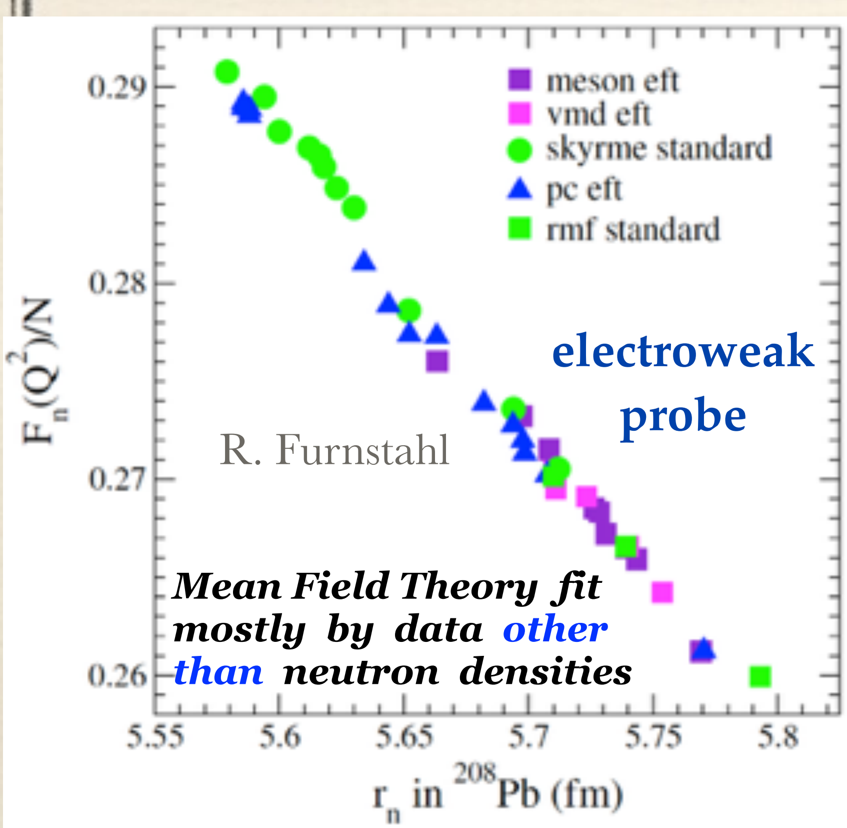
$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2) \qquad M^{NC}_{PV} = \frac{G_F}{\sqrt{2}}\left[\left(1-4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

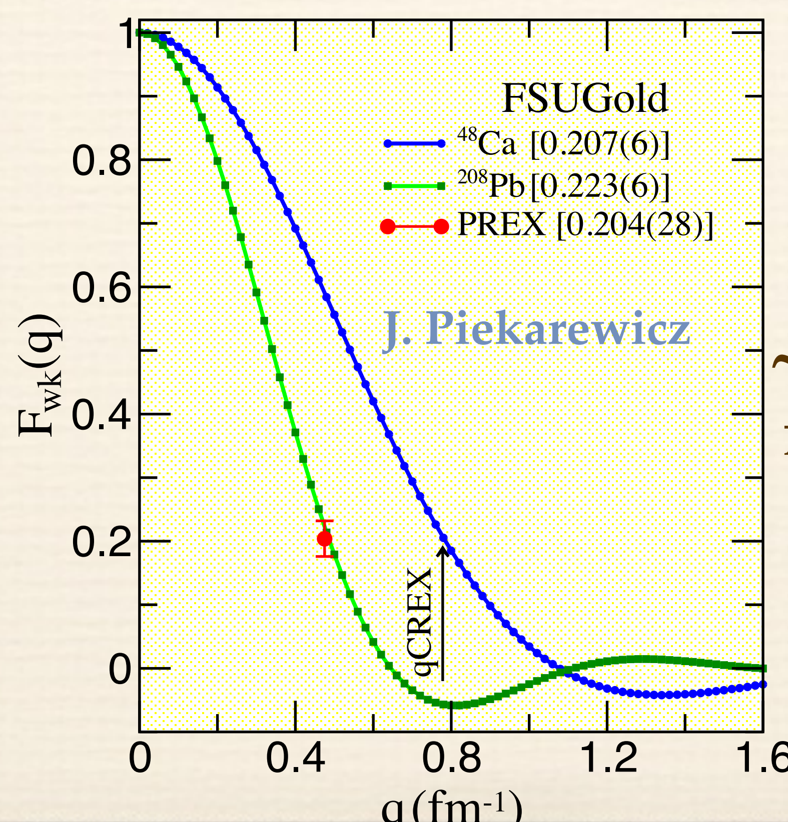
$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

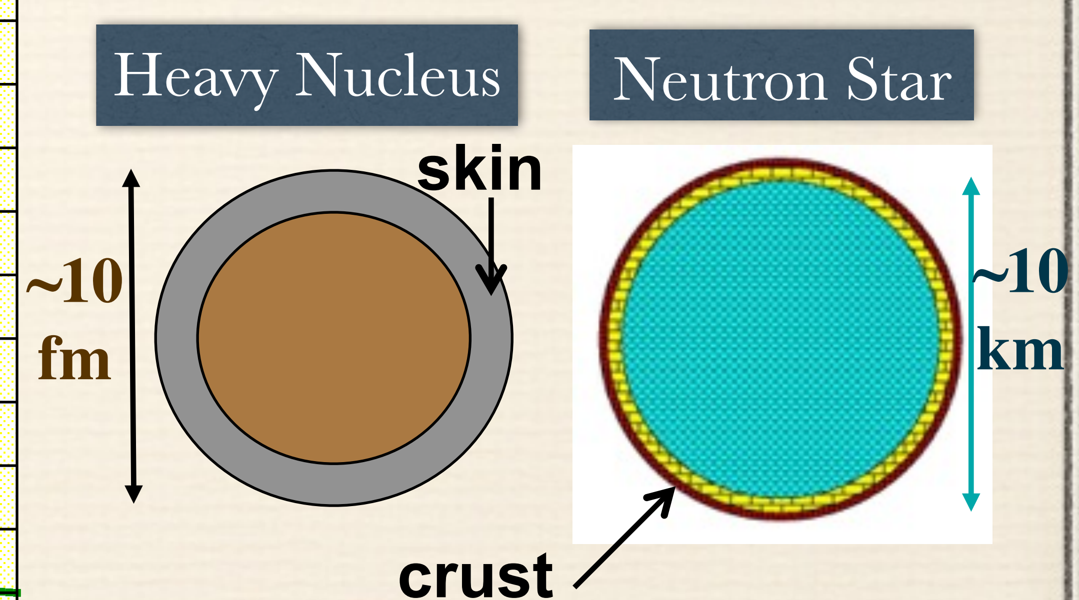
**$Q^2 \sim 0.01$ GeV$^2$**
$5^o$ scattering angle

**$A_{PV} \sim 0.6$ ppm**
**Rate ~ 1 GHz**
**$\delta(A_{PV}) \sim 20$ ppb!**

| | proton | neutron |
|---|---|---|
| Electric charge | 1 | 0 |
| Weak charge | ~0.08 | -1 |




Horowitz and Piekarewicz, PRL 86 (2001)

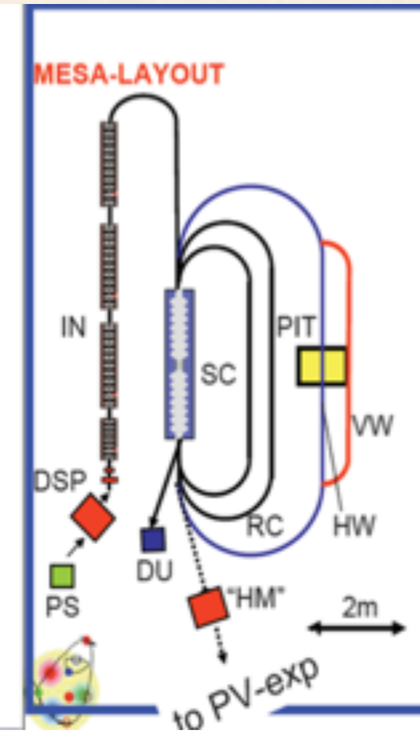
# Weak Charge and Neutron Skin at Mainz

## Future: MESA/P2 at Mainz

**New ERL complex will also support a high-current extracted beam suitable for a PV measurement of proton weak charge**

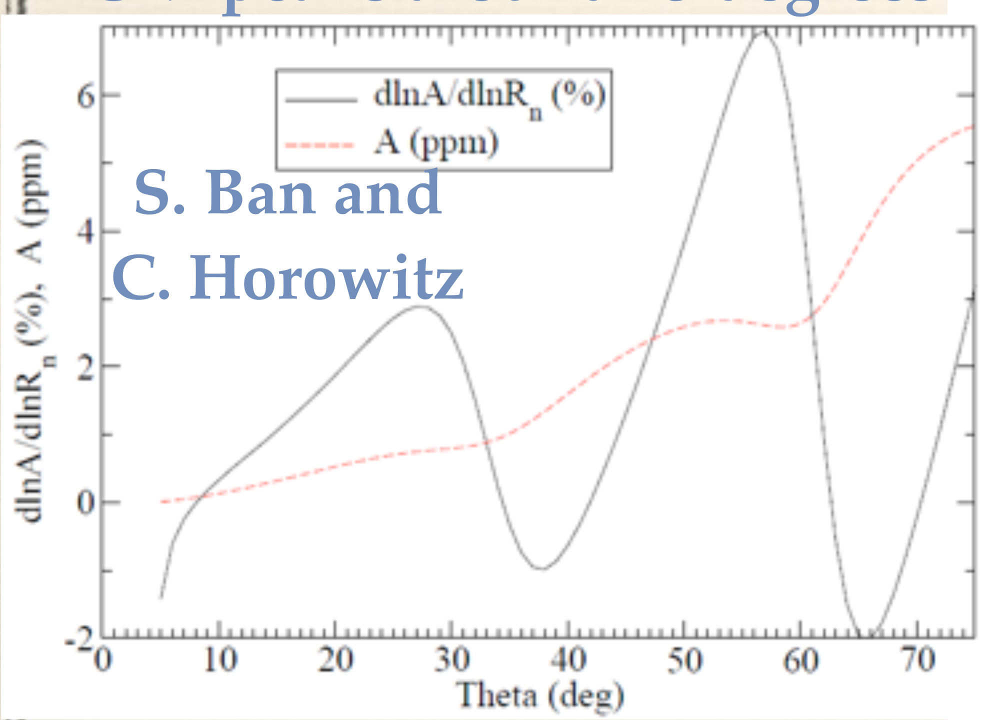
- $A_{PV}$ = -20 ppb to 2.1% (0.4ppb)
- $\delta(\sin^2\theta_W)$ = 0.2%

- Funding approved from DFG
- Development starting now
- Planned running 2017-2020



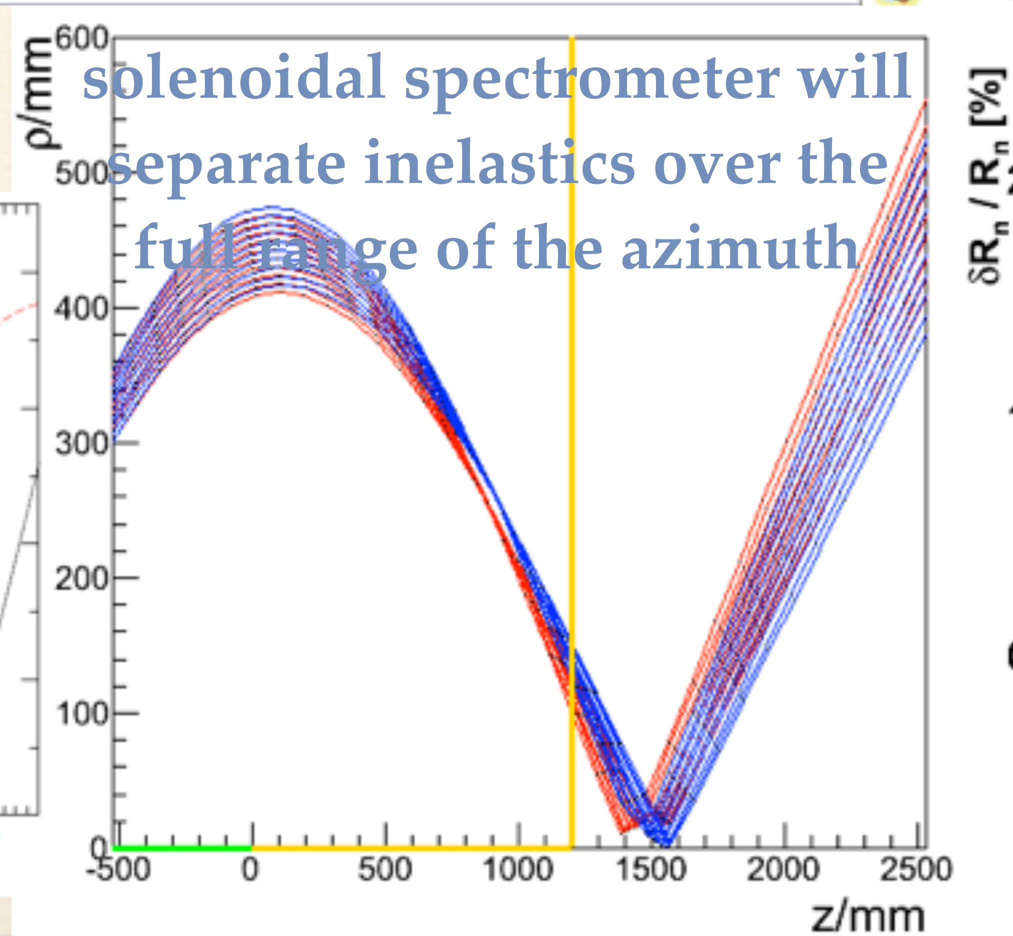

**Explore a PREX-style measurement using same solenoidal magnet to be used for P2**

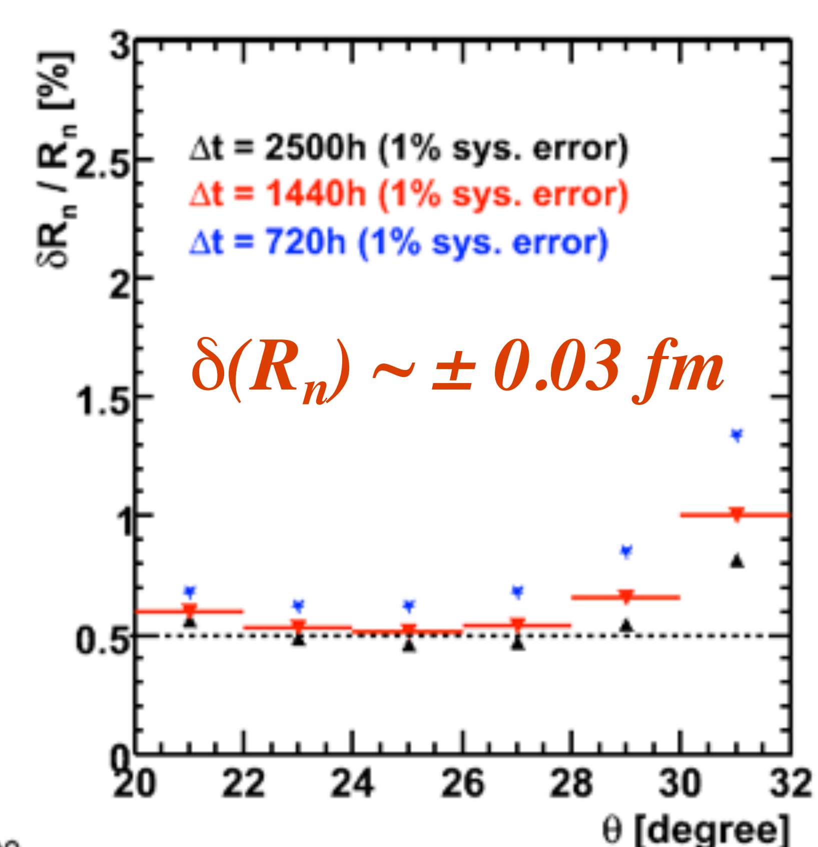
200 MeV
FOM peaks around 25 degrees




S. Ban and C. Horowitz

solenoidal spectrometer will separate inelastics over the full range of the azimuth

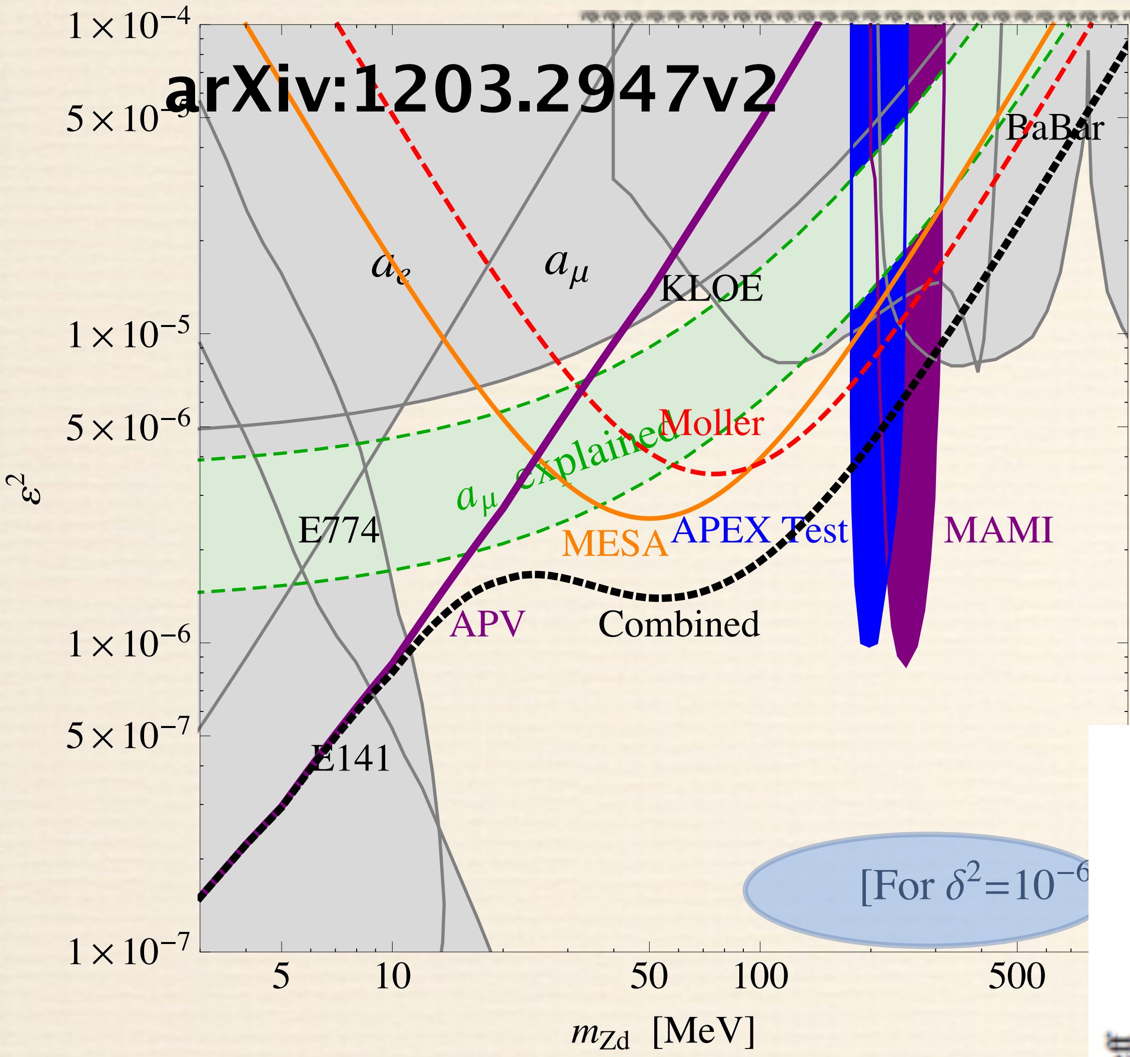



$\delta(R_n) \sim \pm 0.03$ fm

# Dark Z to Invisible Particles

Davoudiasl, Lee, Marciano




***Dark Photons:***

***Beyond kinetic mixing; introduce mass mixing with the $Z^0$***

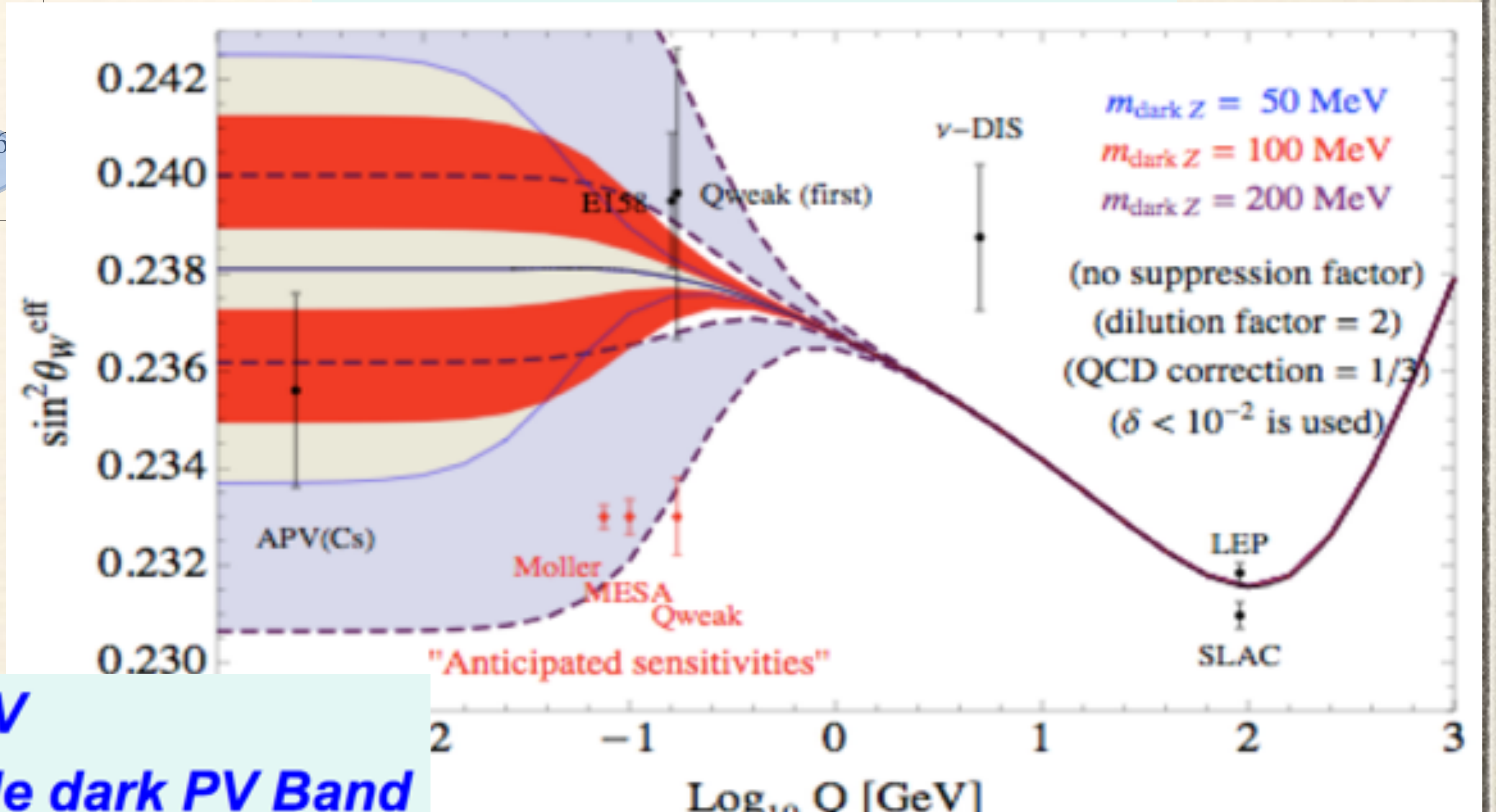
$$\epsilon_Z = \frac{m_{Z_d}}{M_Z}\delta$$

- Potentially Observable Effects (for $\delta \geq 10^{-3}$)

  APV & Polarized Electron Scattering at low <Q>

  $BR(K \rightarrow \pi Z_d) \approx 4\times10^{-4}\delta^2$ $BR(B \rightarrow K Z_d) \approx 0.1\delta^2$

***$\delta^2$ roughly probed to $10^{-6}$***




***$K \rightarrow \pi Z_d \rightarrow \pi$+"missing energy"***

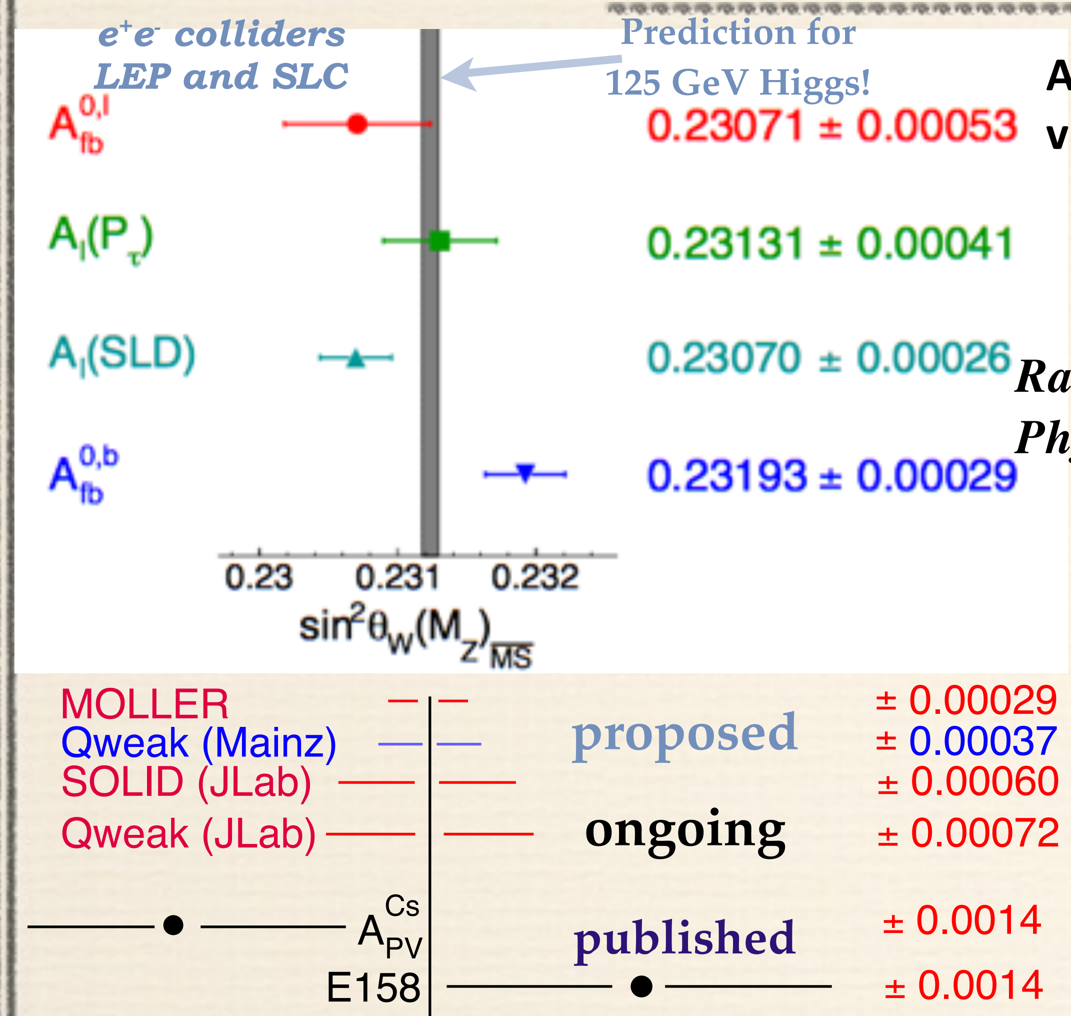
***ε and δ effects could partially cancel!***

***Suppression by ~1/6 allows $Z_d$~100MeV***

***Combined with muon g-2 → observable dark PV Band***

# Physics Examples: Beyond LHC

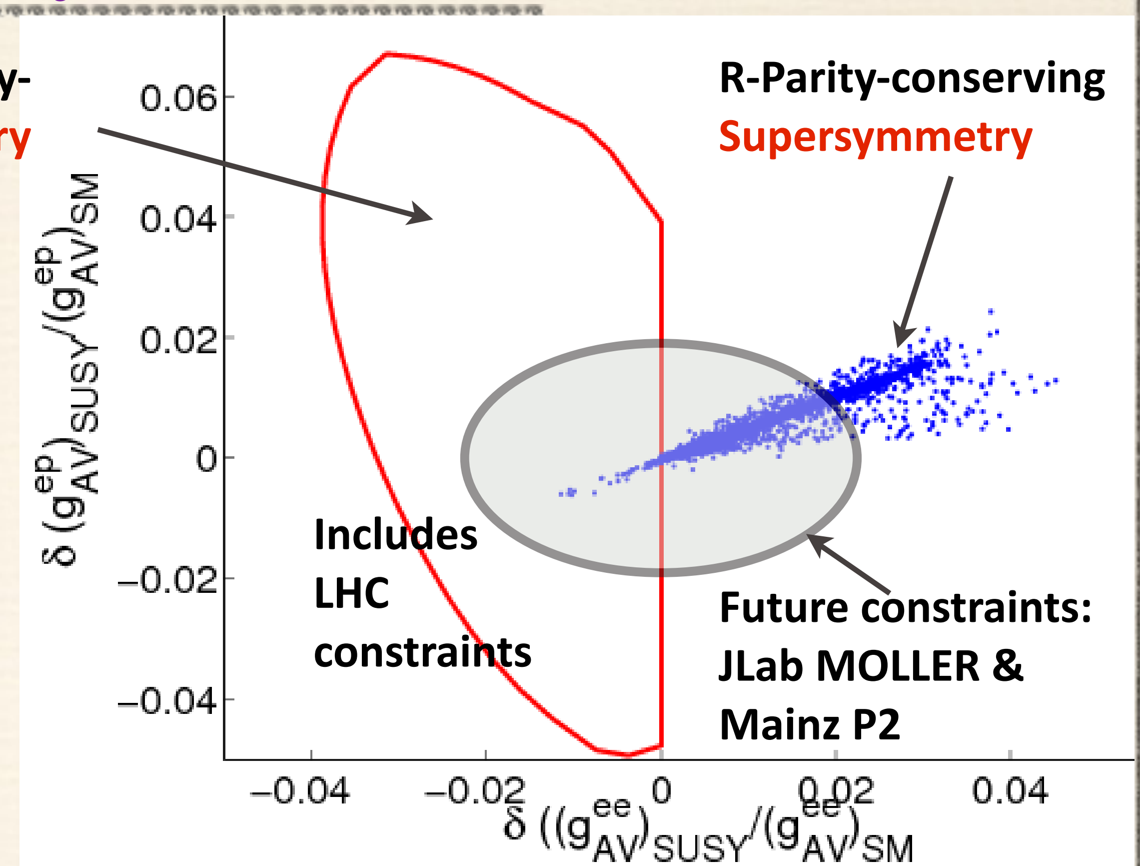
**Z resonance measurements: little sensitivity to new contact interactions**




Allowed region: R-Parity-violating Supersymmetry

*Ramsey-Musolf and Su, Phys. Rep. 456 (2008)*

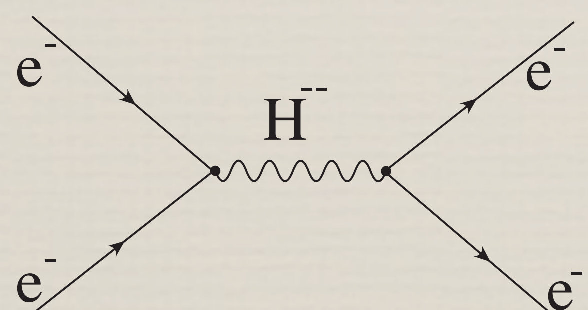
*Erler and Su, arXiv:1303.5522*




## Lepton Number Violation

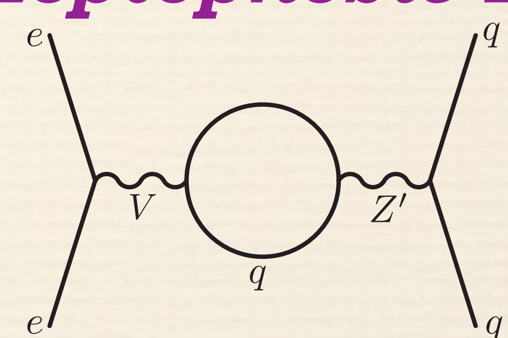
***Λ > 5 TeV***

***Doubly-Charged Scalars***




**Significant reach beyond LEP-200**

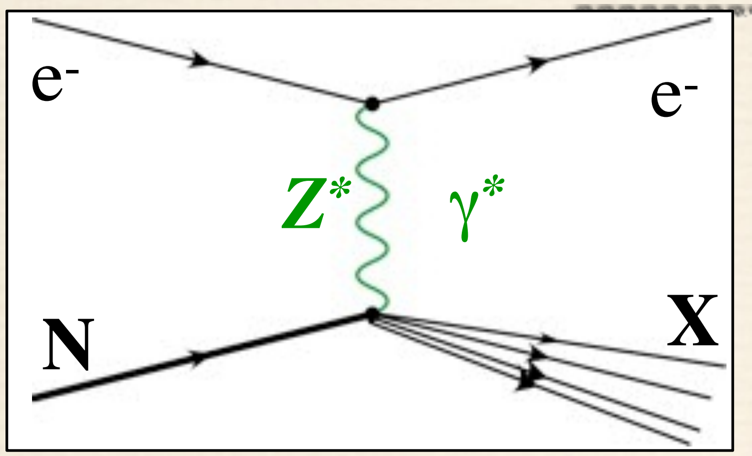
## *Leptophobic Z'*




**SOLID can improve sensitivity: 100-200 GeV range**

# PV Deep Inelastic Scattering

## off the simplest isoscalar nucleus and at high Bjorken $x$




$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

$x \equiv x_{Bjorken}$

$y \equiv 1 - E'/E$

$Q^2 >> 1\ GeV^2$ , $W^2 >> 4\ GeV^2$

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

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\frac{R}{R+1}}$$

$$R(x,Q^2) = \sigma^l/\sigma^r \approx 0.2$$

$$A_{\rm iso} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} = -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5 + R_s}$$

**At high x, $A_{iso}$ becomes independent of pdfs, x & W, with well-defined SM prediction for $Q^2$ and y**

$$R_s(x) = \frac{2S(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 0$$

$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

### Interplay with QCD

- Parton distributions (u, d, s, c)
- Charge Symmetry Violation (CSV)
- Higher Twist (HT)
- Nuclear Effects (EMC)