Parity Violation and Beyond Standard Model Aspects:

Opportunities at a Polarized Electron-Ion Collider

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EIC Workshop

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Preface

- Any new machine that pushes the intensity frontier is of interest to the precision EW community
- The EIC, especially with potentially high luminosity projections, is no exception
- We have just launched a study with the motivation to explore potentially interesting and unique EW physics with the projected EIC machine parameters
  - **What SHOULD be the parameters of the collider be to make it uniquely interesting for precision EW tests and searches for physics beyond the standard model?**
  - **What are the detector capabilities and resources required to achieve the required sensitivity and precision?**

In this talk, we describe the motivation; the questions above would be addressed in a dedicated study if there is enough interest/quorum

Outline

- Weak Neutral Current Interactions
  - **indirect effects of new TeV-scale dynamics**
- Parity Violating deep inelastic scattering (PVDIS)
  - **The Developing Jefferson Lab 12 GeV PV Program**
- Electroweak Physics at the EIC
  - **Advantages over fixed target**
  - **New PV observables**
  - **Two specific applications to nucleon structure**
    - ***quark helicity distributions***
    - ***Isovector EMC effect***
- Lepton Flavor and Number Violation
  - **electron-tau lepton conversion**
- Conclusions & Outlook

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: $Q^2 << M_Z^2$**

Low Q^2 experiments address four broad 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 decipher LHC new physics signals

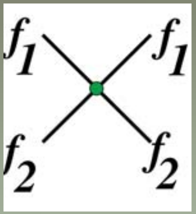
- ***Neutrons:*** *Lifetime, Asymmetries (LANSCE, NIST, SNS...)*
- ***Muons:*** *Lifetime, Michel parameters, g-2 (BNL, PSI, TRIUMF, FNAL, J-PARC...)*
- ***Parity-Violating Electron Scattering*** *Low energy weak neutral current couplings, precision weak mixing angle (SLAC, JLab, EIC?)*

Comprehensive Search for New Neutral Current Interactions

Important component of indirect signatures of "new physics"

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

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



⊄'s for all $f_1 f_2$ combinations and L,R combinations

Eichten, Lane and Peskin, PRL50 (1983)

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

One goal of neutral current measurements at low energy AND colliders: Access ⊄ > 10 TeV for as many $f_1 f_2$ and L,R combinations as possible

LEPII, Tevatron access scales ⊄'s ~ 10 TeV

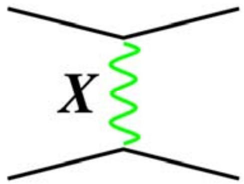
e.g. Tevatron dilepton spectra, fermion pair production at LEPII

- ***L,R combinations accessed are parity-conserving***

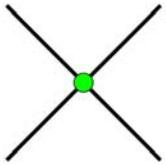
LEPI, SLC, LEPII & HERA accessed some parity-violating combinations but precision dominated by Z resonance measurements: ~ few TeV sensitivity

Colliders vs Lower Q^2

consider



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



Contact interaction

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

$$\frac{\delta A_Z}{A_Z} \propto \frac{\pi/\Lambda^2}{g\,G_F} \longrightarrow \begin{array}{l} \delta(g)/g \sim 0.1 \\ \Lambda \sim 10\ TeV \end{array}$$

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

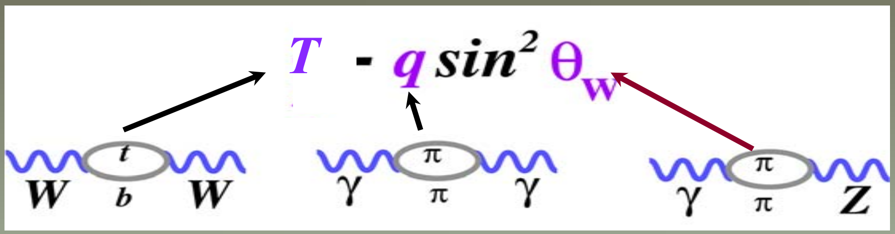
Window of opportunity for weak neutral current measurements at $Q^2 << M_Z^2$

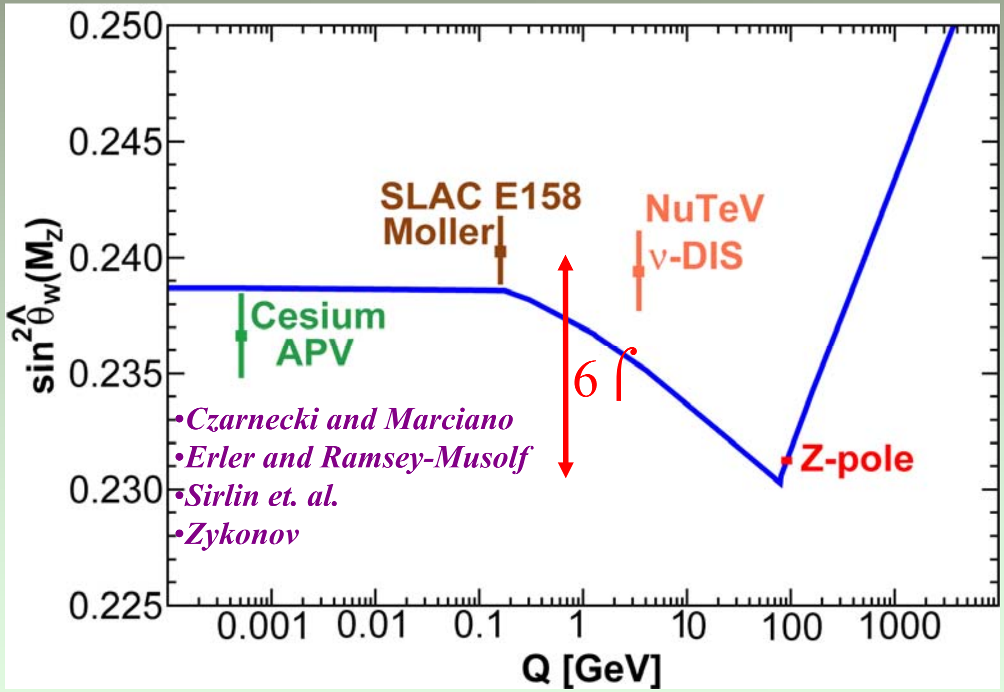
Processes with potential sensitivity:
- neutrino-nucleon deep inelastic scattering
- Atomic parity violation
- parity-violating electron scattering

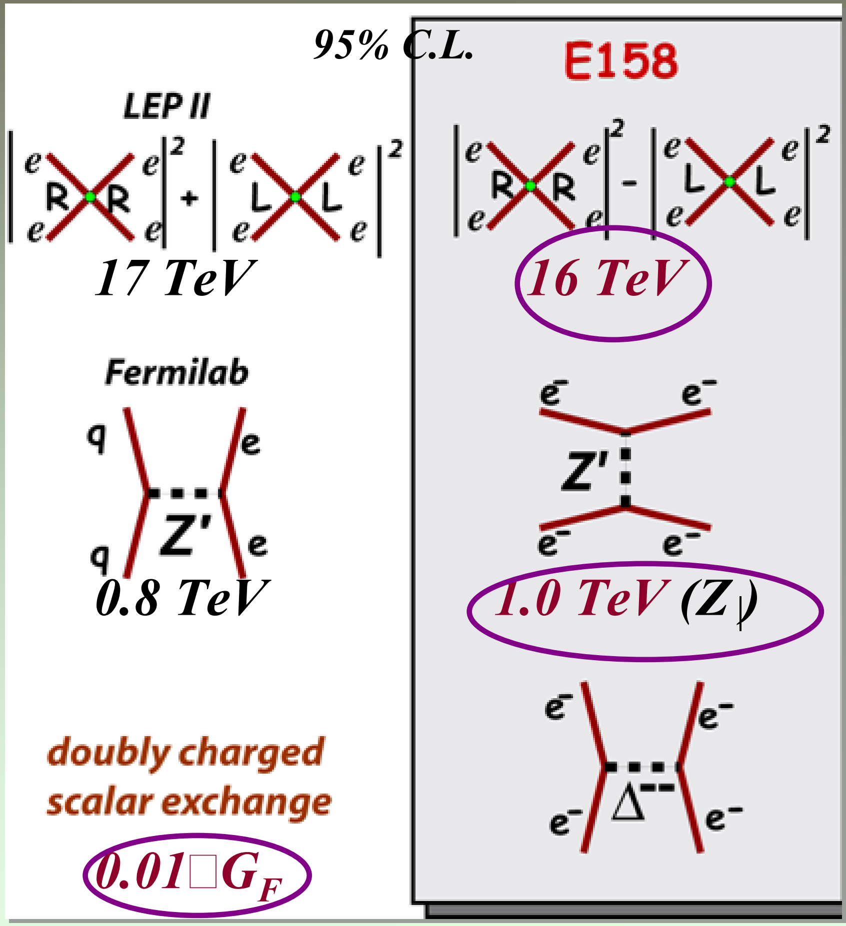
Published Measurements

Running of sin$^2\theta_W$ established to 6σ

Limits on "New" Physics

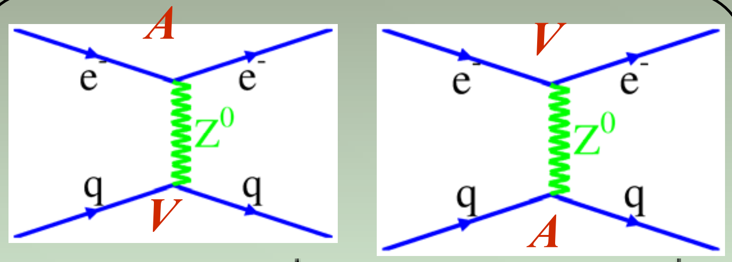






Lepton-Quark Z^0 Couplings

- **Atomic Parity Violation (APV)**
  - ^{133}Cs 6s to 7s transition: first low energy measurement sensitive enough to access the TeV scale
- **Neutrino DIS: NuTeV**
  - 2 to 3 ∫ deviation
  - Many hadronic physics issues
  - Motivates close look at e-q couplings



$$C_{1i} \equiv 2 g_A^e g_V^i \qquad C_{2i} \equiv 2 g_V^e g_A^i$$

$$C_{1u} = -\tfrac{1}{2} + \tfrac{4}{3}\sin^2(\theta_W) + \delta C_{1u} \approx -0.19$$
$$C_{1d} = \tfrac{1}{2} - \tfrac{2}{3}\sin^2(\theta_W) + \delta C_{1d} \approx 0.35$$
$$C_{2u} = -\tfrac{1}{2} + 2\sin^2(\theta_W) + \delta C_{2u} \approx -0.030$$
$$C_{2d} = \tfrac{1}{2} - 2\sin^2(\theta_W) + \delta C_{2d} \approx 0.025$$

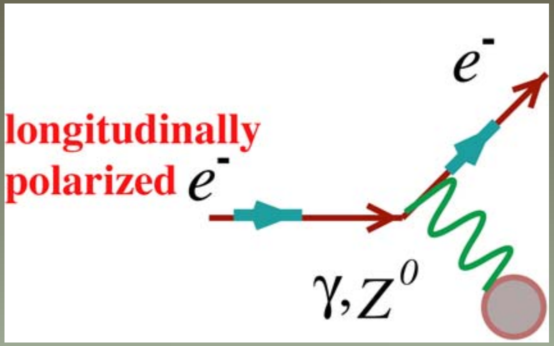
$$\delta(C_{1q}) \propto (+\eta_{RL}^{eq} + \eta_{RR}^{eq} - \eta_{LL}^{eq} - \eta_{LR}^{eq})$$ → ***PV elastic e-p scattering, APV***

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

Parity-Violating Asymmetries

Weak Neutral Current (WNC) Interactions at $Q^2 \ll M_Z^2$

Longitudinally Polarized
Electron Scattering off
Unpolarized Targets



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

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

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

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

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***
- ***Early 90s: target couplings carry novel information about hadronic structure***
- ***Now: precision measurements with carefully chosen kinematics can probe physics at the multi-TeV scale***

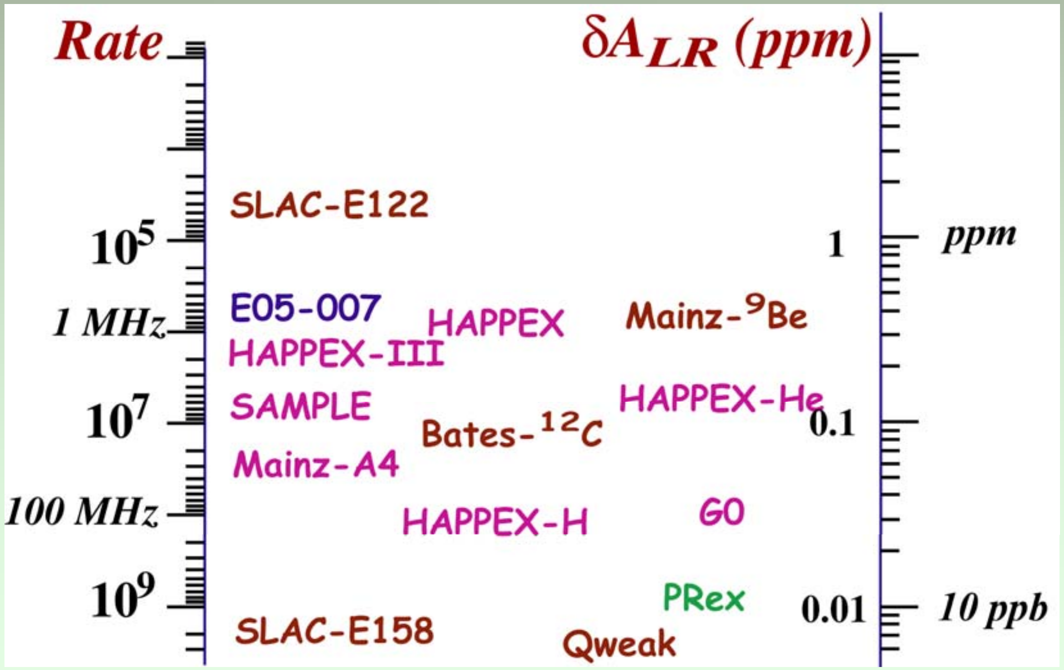
Today: MeV to TeV Physics

Parity-violating electron scattering has become a precision tool

Physics over a range of energy scales:

- ***Many-body nuclear physics: Neutron skin of ^{208}Pb***
- ***Nucleon structure: strangeness contribution to form factors***
- ***Valence quark structure: Deep inelastic scattering at high-x***
- ***Search for new TeV physics: Precision electroweak parameters***

Four electron scattering laboratories: SLAC, MIT-Bates, Mainz & JLab



- *Steady progress in technology*
- *part per billion systematic control*
- *1% normalization control*
- *Intensive R&D on:*

-Photocathodes
-Polarimetry
-High Luminosity cryotargets
-Nanometer beam stability
-Precision Beam Diagnostics
-Counting Electronics
-Radiation hard detectors

Qweak at JLab & Beyond

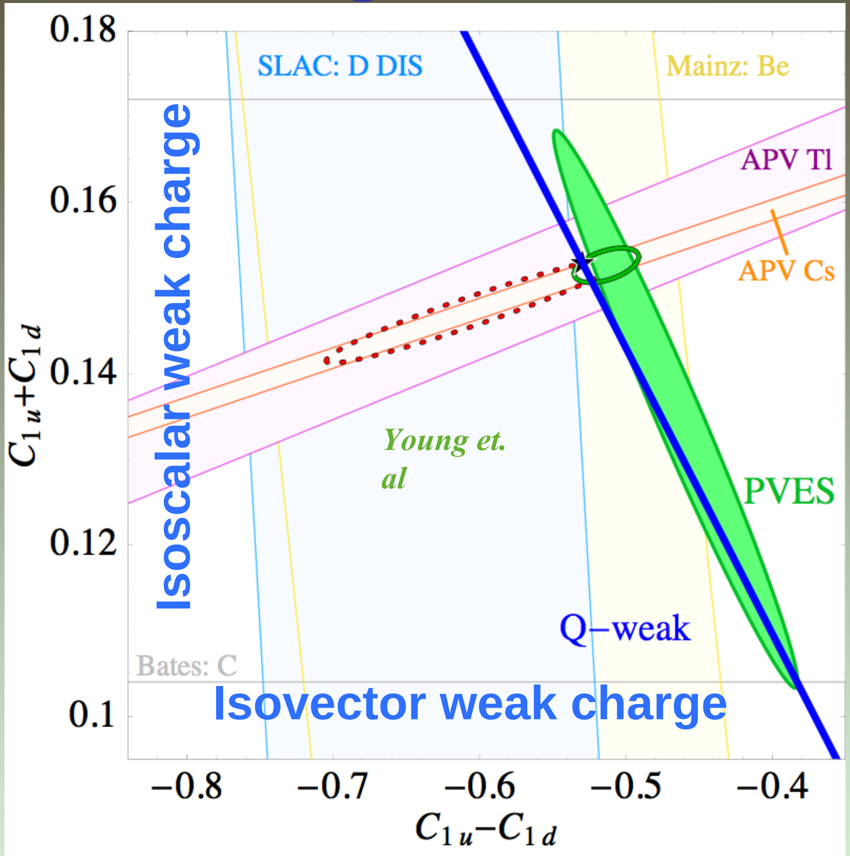
Qweak at Jefferson Laboratory

A_{PV} in elastic e-p scattering:

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

$$Q^p_{weak} = 2C_{1u} + C_{1d} \propto 1 - 4\sin^2\vartheta_W$$

Contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$,
Extracted using global fit
of existing PVES experiments!



- **Data ~ 2010 thru mid-2012**

New, complementary constraints on lepton-quark interactions at the TeV scale

Future:

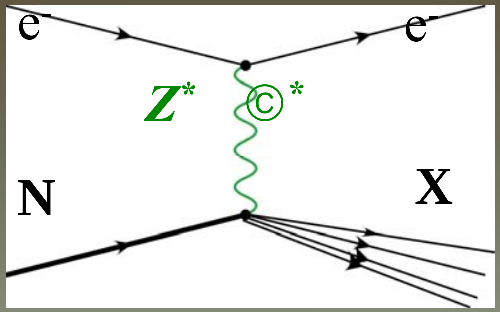
- ***Ultra-high precision with MOLLER proposal (factor of 5 better than E158)***

- ***C_{2u} and C_{2d} are small and poorly known: one combination can be accessed in PV DIS***

New physics such as compositeness, leptoquarks:

Deviations to C_{2u} and C_{2d} might be fractionally large

PV Deep-Inelastic Scattering



A_{PV} in Electron-Nucleon DIS:

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

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

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

For ^2H, assuming charge symmetry, structure functions largely cancel in the ratio:

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

Must measure A_{PV} to 0.5% fractional accuracy!

Feasible at 6 GeV at Jlab → ***luminosity > $10^{38}/cm^2/s$***

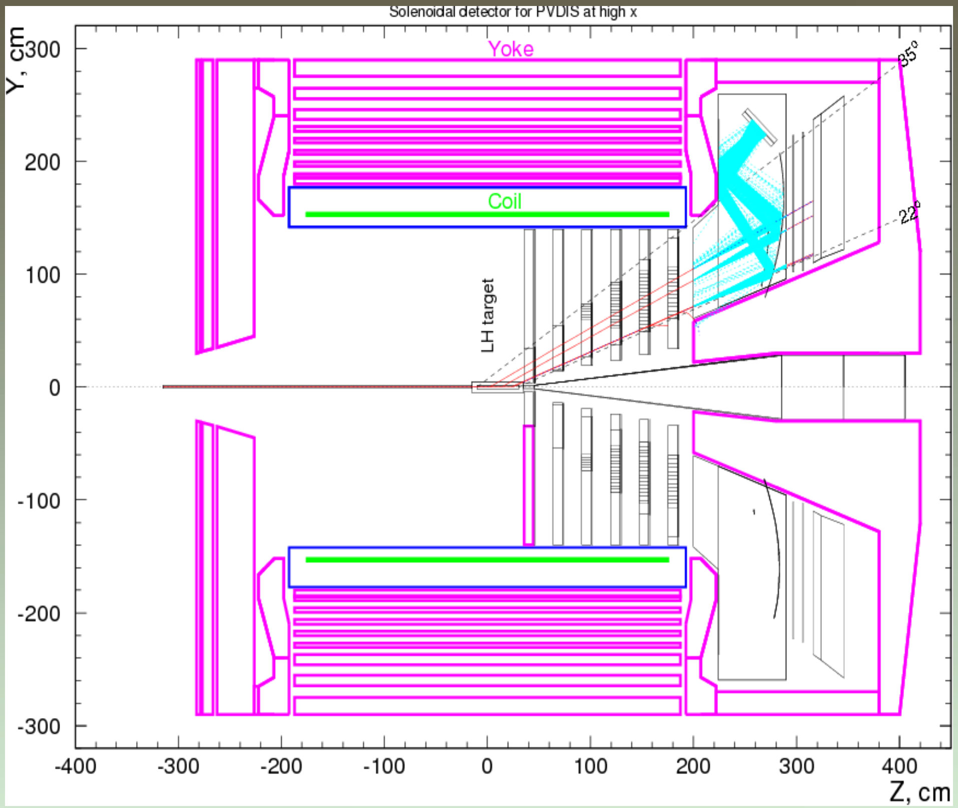
well-suited for 11 GeV after the upgrade

A Design for Precision PV DIS Physics at JLab

SoLiD Spectrometer at JLab

- *High Luminosity on LH_2 & LD_2*
- *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 x~0.75)
- *Moderate running times*

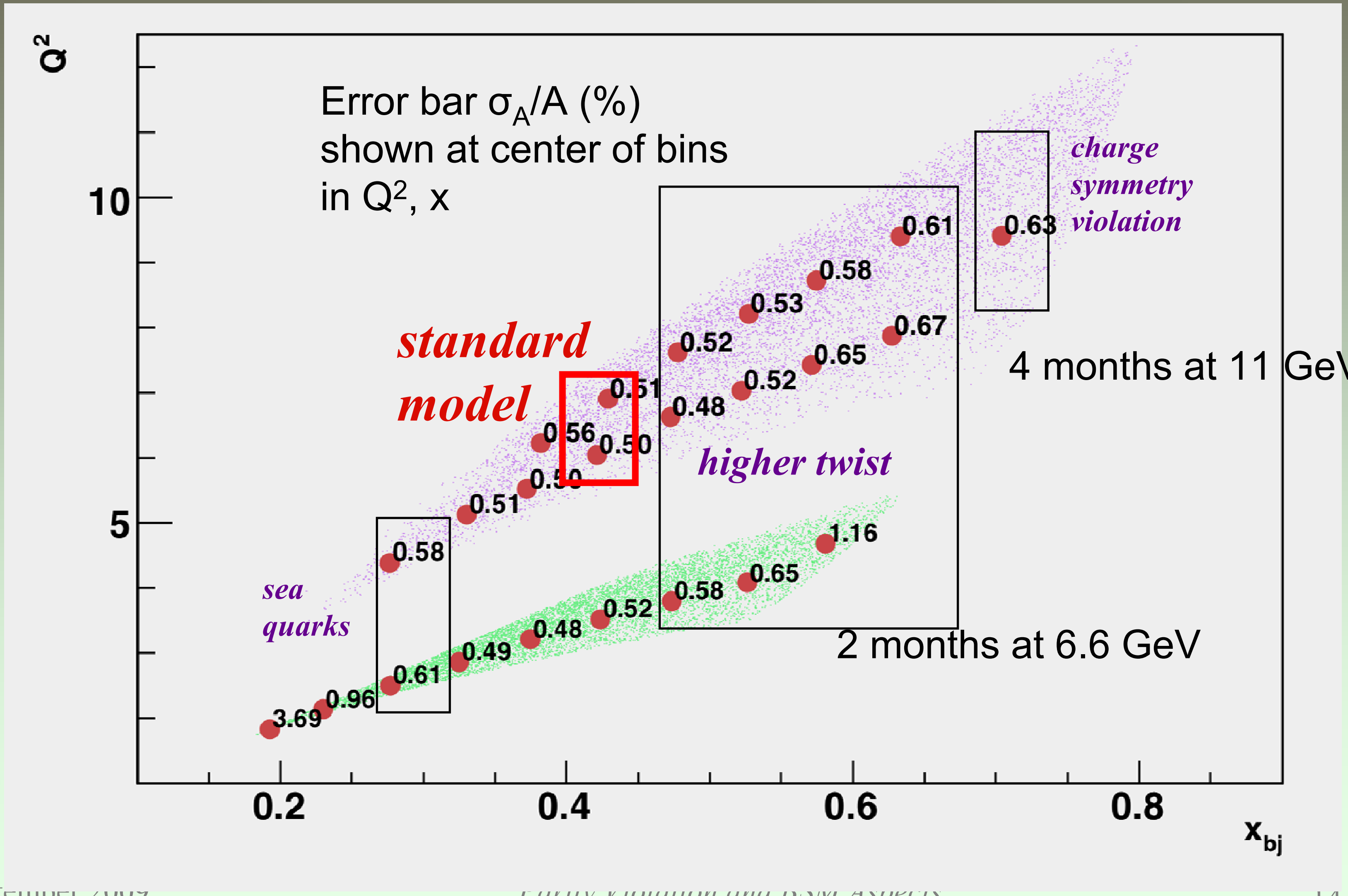
Proposal received conditional approval in January 2009



- *Solenoid (from BaBar, CDF or CLEOII)*
  contains low energy backgrounds (Moller, pions, etc)
  trajectories measured after baffles
- *Fast tracking, particle ID, calorimetry, and pipeline electronics*
- *Precision polarimetry (0.4%)*

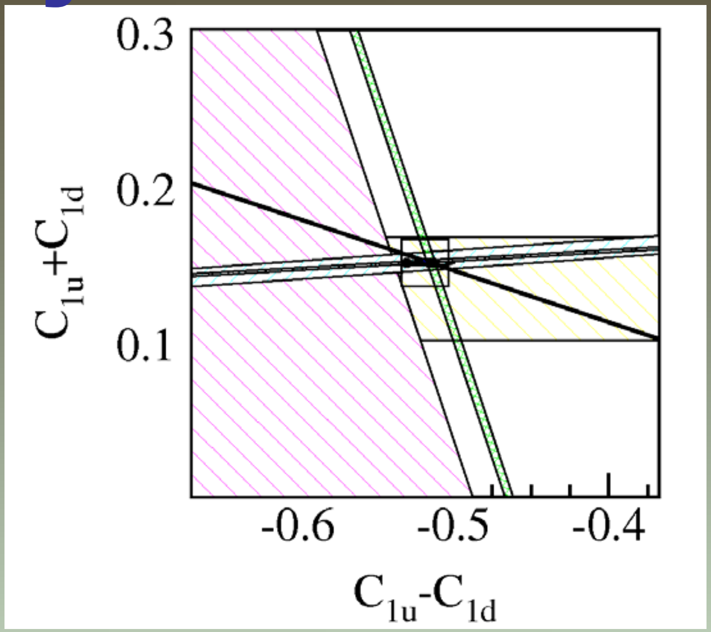
Proposed SoLiD Dataset

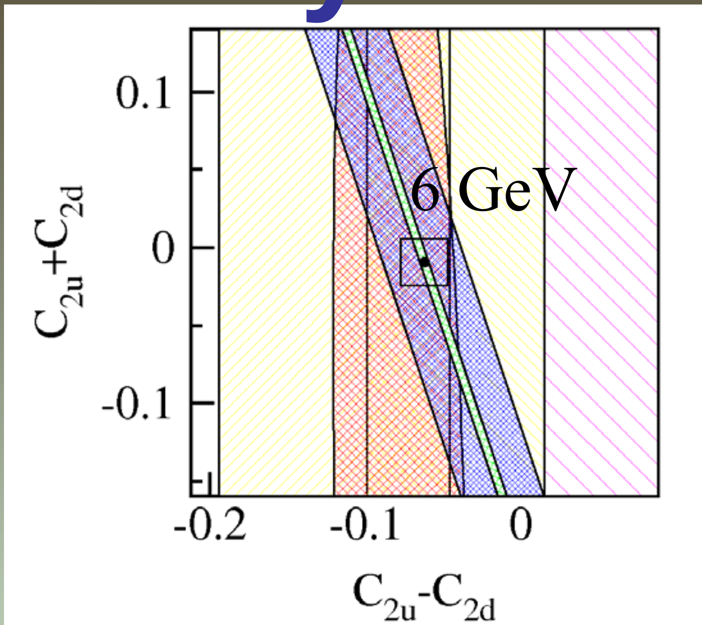
Strategy: **sub-1% precision** over broad kinematic range for **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**



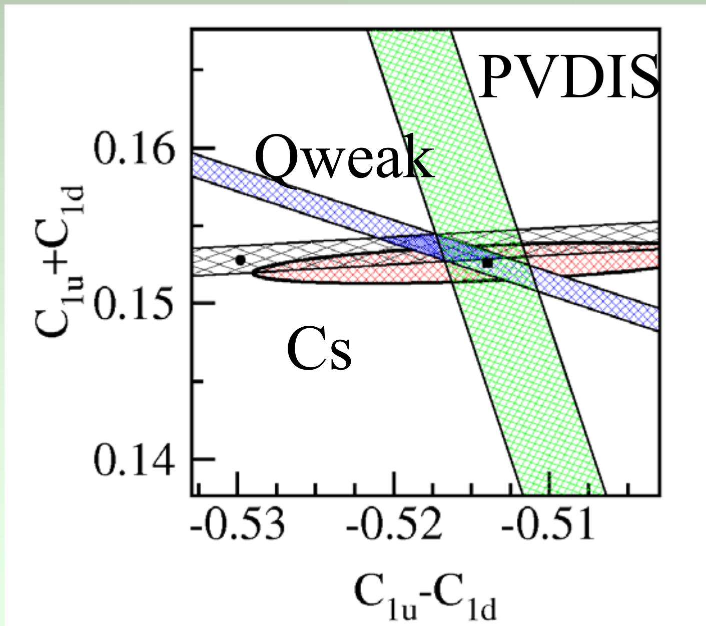
Projected Sensitivity

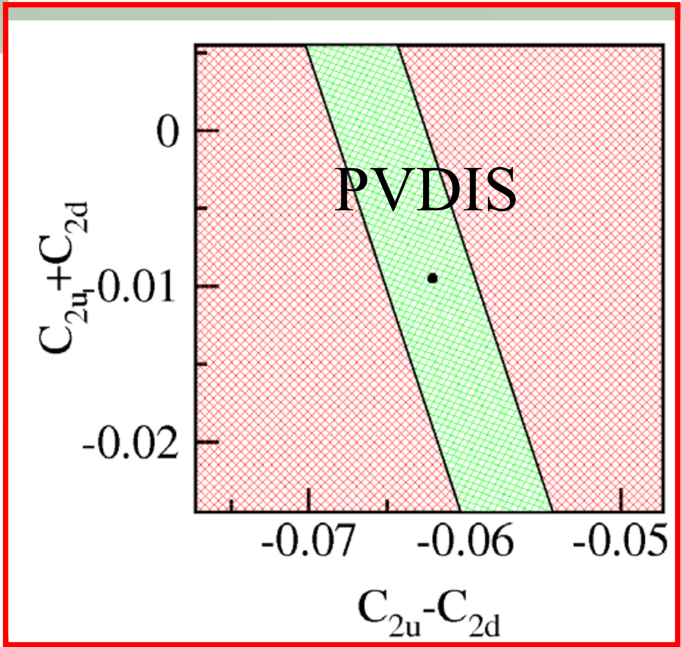
World's data





Precision Data





New, unique sensitivity to TeV scale physics

CSV with PVDIS

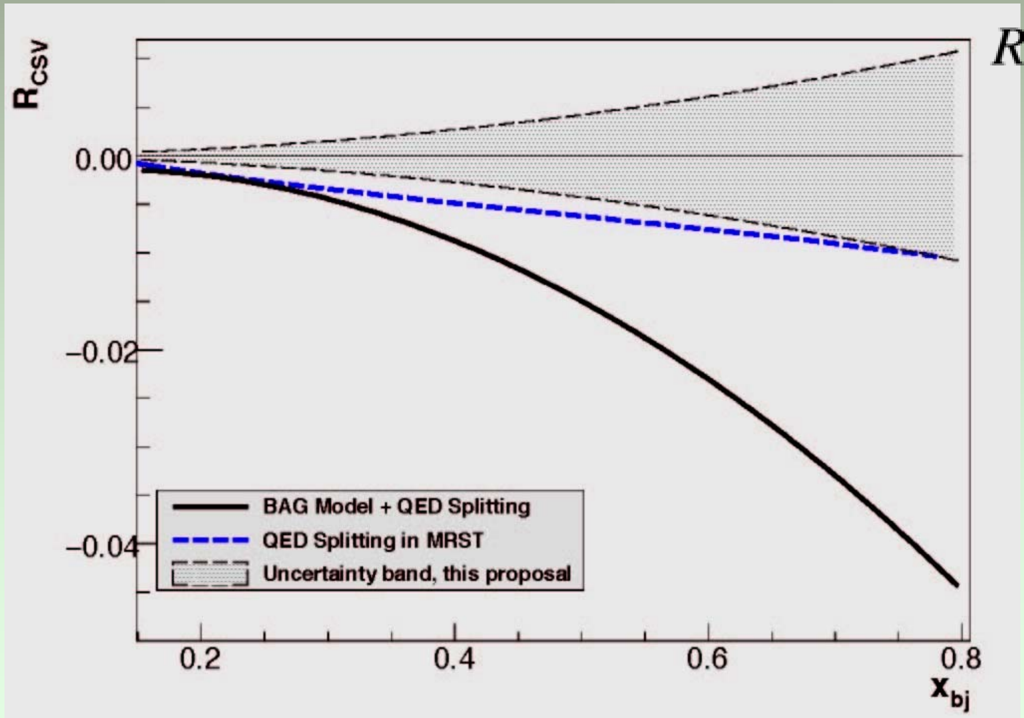
Parton-level charge symmetry assumed in deriving $^2H\ A_{PV}$

Charge Symmetry Violation

$$\delta u(x) = u^p(x) - d^n(x)$$

$$\delta d(x) = d^p(x) - u^n(x)$$

- u,d quark mass difference
- electromagnetic effects



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

- Direct observation of parton-level CSV would be very exciting!
- Important implications for high energy collider pdfs
- Could explain significant portion of the NuTeV anomaly

Proposed Strategy

Fit data to:

$$A = A\left[1 + \beta_{HT}\frac{1}{(1-x)^3 Q^2} + \beta_{CSV}x^2\right]$$

- Measure A_D in NARROW bins of x, Q^2 with 0.5% precision
- Cover broad Q^2 range for x in [0.3,0.6] to constrain HT
- Search for CSV with x dependence of A_D at high x
- Use x>0.4, high Q^2, and to measure a combination of the C_{iq}'s

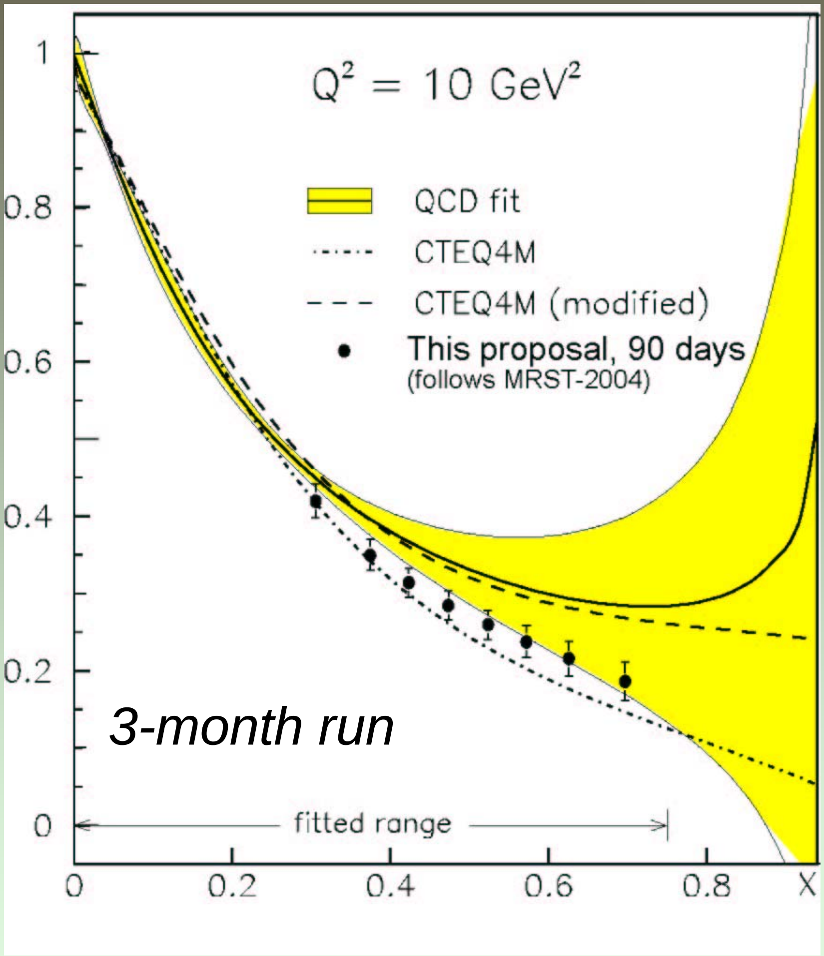
	x	y	Q^2
New Physics	no	yes	no
CSV	yes	no	no
Higher Twist	yes	no	yes

PVDIS on the Proton: d/u at High x

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

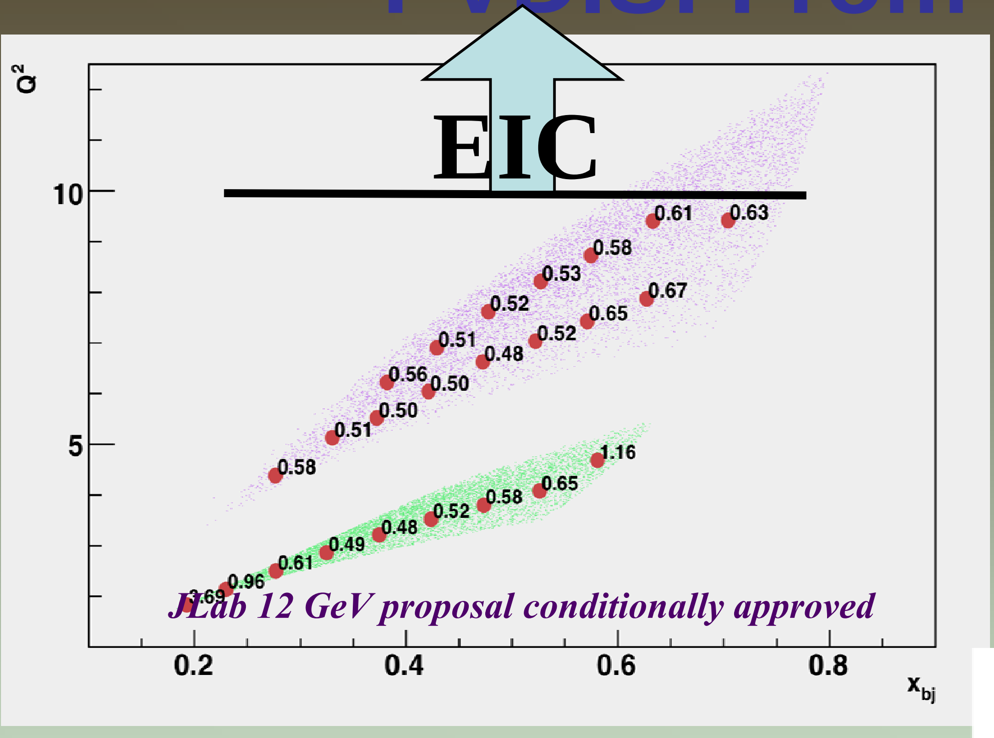
Deuteron analysis has large nuclear corrections (Yellow)

A_{PV} for the proton has no such corrections



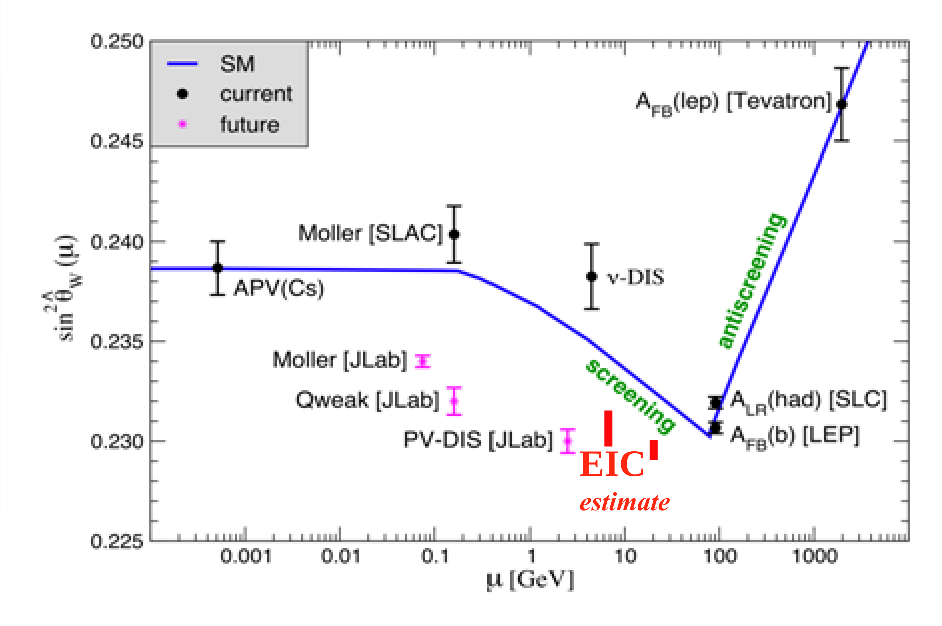
The challenge is to get statistical and systematic errors ~ 2%

PVDIS: From JLab to EIC

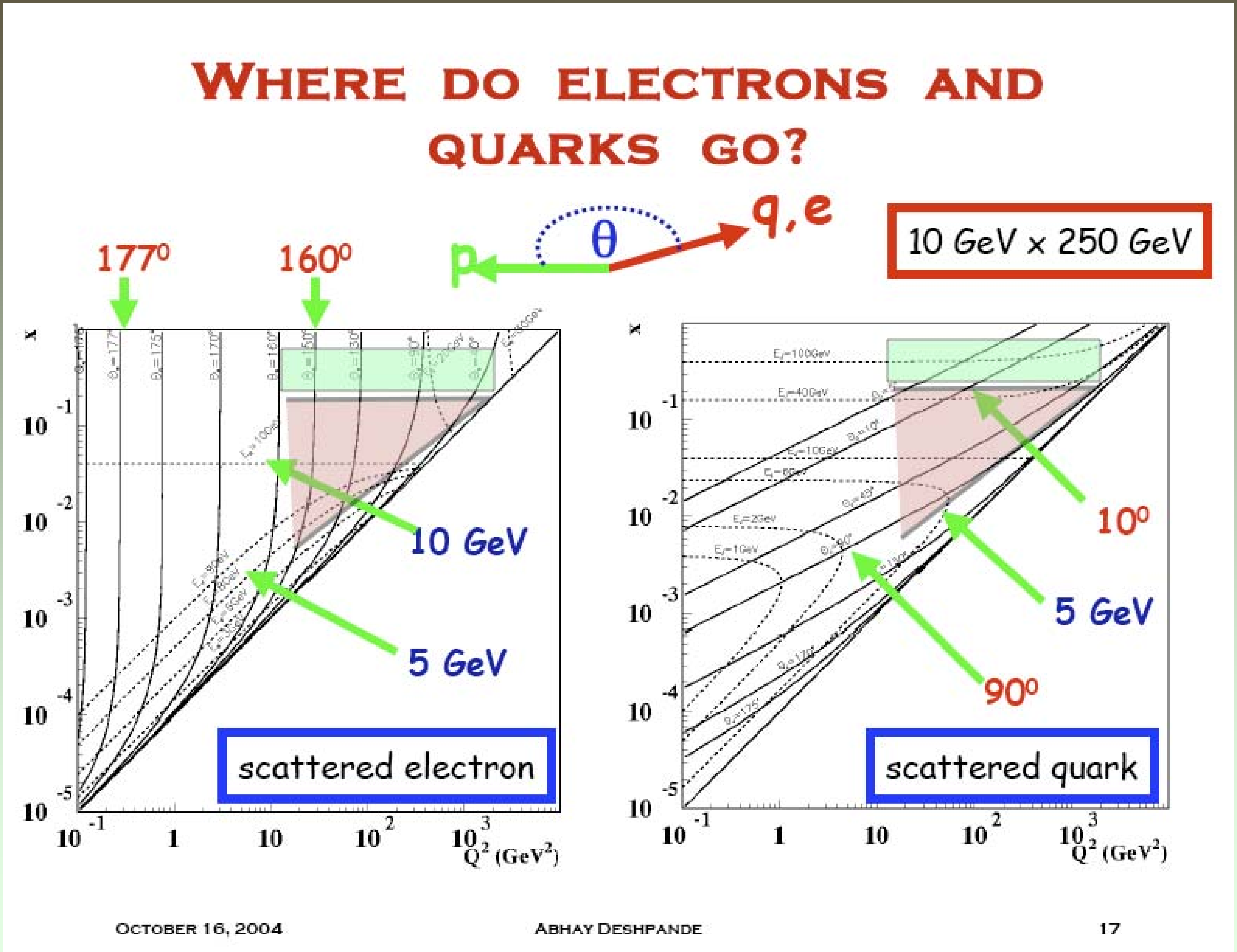


At EIC, one can consider a high statistics runs with polarized e-D collisions and polarized e-p collisions

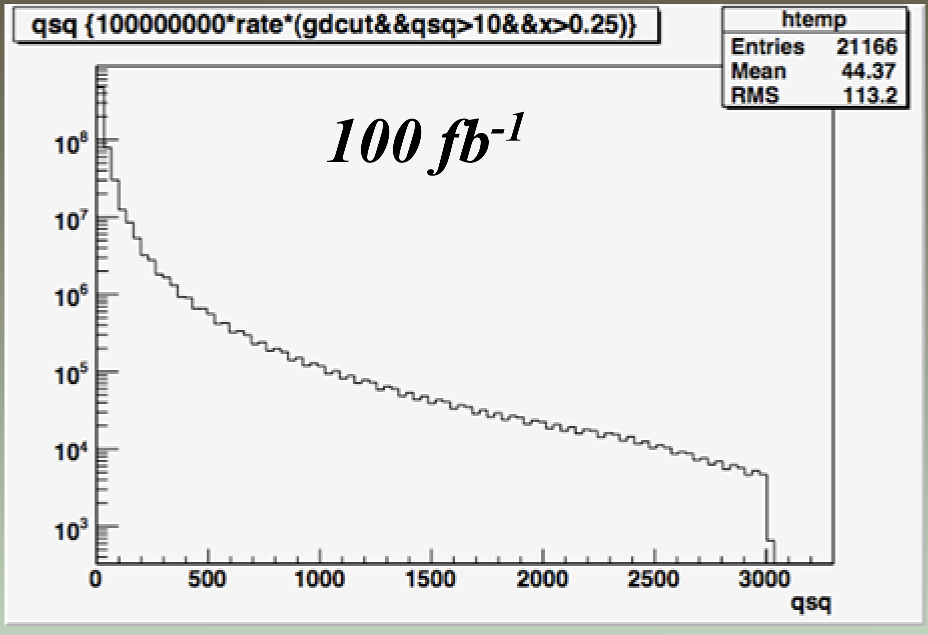
- Much high Q^2: no higher twist issues
- "Huge" Asymmetries
- Large range in y
- can unfold c_1 & c_2 couplings
- At highest Q^2, couplings affected by pure Z exchange: different linear combination of couplings



EIC DIS Kinematics



First Look at Statistics



Number of events vs Q^2 (GeV^2)

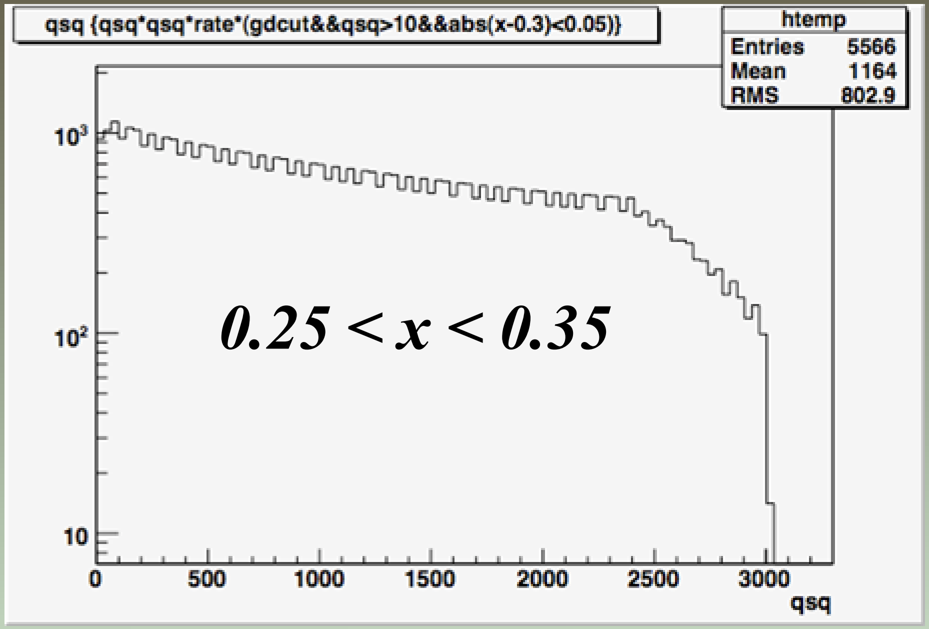


figure of merit vs Q^2 (GeV^2)

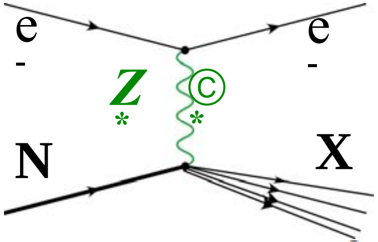
- ~ 100 M events at Q^2 ~ 100 GeV^2: $A_{PV} \sim 10^{-2}$
- ~ few 100K events at ~ 1000 GeV^2: A_{PV} ~ 0.1
- figure of merit is roughly flat for fixed x
- y is virtually zero for small Q^2 sample

Some Comments

- sub-1% stat. error at $x = 0.3$ and $Q^2 > 100\ GeV^2$, independent sub-2% measurement, same x & $Q^2 = 10\ GeV^2$
- sub-2% stat error at $x = 0.6$: stringent tests of charge symmetry violation and d/u?
  - **devoid of complications such as higher twist effects**
- Can one control polarimetry syst. error at 0.5% level?
  - **Initial studies (e.g. Michigan workshop) showed 1% possible but detailed systematics analysis & integration with machine design needed**
- Preliminary conclusions:
  - **A 100 fb^{-1} data set with e-d collisions can provide sensitivity to standard model EW couplings at an interesting level: one would have to revisit this after LHC data. Such measurements could potentially become vital and JLab results might ignite further interest**
  - **A similar data set with e-p collisions would measure d/u precisely and the combination of the two data sets would provide new limits on charge symmetry violation at $x = 0.6$ and $Q^2 = 300\ GeV^2$**

General EW Hadronic Tensor

$$\frac{1}{2m_N}W^i_{\mu\nu} = -\frac{g_{\mu\nu}}{m_N}F^i_1 + \frac{p_\mu p_\nu}{m_N(p\cdot q)}F^i_2$$



$$+\, i\frac{\epsilon_{\mu\nu\alpha\beta}}{2(p\cdot q)}\left[\frac{p^\alpha q^\beta}{m_N}F^i_3 + 2q^\alpha S^\beta g^i_1 - 4xp^\alpha S^\beta g^i_2\right]$$

$$-\,\frac{p_\mu S_\nu + S_\mu p_\nu}{2(p\cdot q)}g^i_3 + \frac{S\cdot q}{(p\cdot q)^2}p_\mu p_\nu g^i_4 + \frac{S\cdot q}{p\cdot q}g_{\mu\nu}g^i_5$$

Ji, Nucl. Phys. B 402 (1993)
Anselmino, Gambino and Kalinoski, hep-ph/9401264v2
Anselmino, Efremov & Leader, Phys. Rep. **261** (1995)

QPM Interpretation

$$F_1^{\gamma Z} = \sum_q e_q (g_V)_q (q + \bar{q}) \qquad F_2^{\gamma Z} = 2xF_1^{\gamma Z}$$

$$F_3^{\gamma Z} = 2\sum_q e_q (g_A)_q (q - \bar{q})$$

$$g_1^{\gamma Z} = \sum_q e_q (g_V)_q (\Delta q + \Delta\bar{q})$$

$$g_2^{\gamma Z} = g_4^{\gamma Z} = 0$$

$$g_3^{\gamma Z} = 2x\sum_q e_q (g_A)_q (\Delta q - \Delta\bar{q}) \qquad 2xg_5^{\gamma Z} = g_3^{\gamma Z}$$

New Structure Functions

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y) b(x)\right] \qquad a(x) = \frac{\sum_i C_{1i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)} \qquad b(x) = \frac{\sum_i C_{2i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)}$$

QED Double-spin Asymmetry

$$A_{\parallel} = \frac{f(y) g_1^{\gamma}}{F_1^{\gamma}}$$

polarized electron, unpolarized hadron

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

New opportunity at EIC:

g_V and g_A are the electron vector- and axial-vector couplings

unpolarized electron, polarized hadron

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

- ***Enough y range to separate vector and axial-vector couplings***
- ***Could go down in x as low as 0.01***
- ***electroweak g_1 is complementary to electromagnetic g_1: weights of up, down and strange quark helicity distributions differently: could eliminate the need for input from Hyperon decays for extracting strange quark helicity distributions!***

Homework on Observables

- There are 3 beam PV asymmetries and 3 target PV asymmetries that can be measured (p, ^{3}He, ^{2}H)
- There are equal number of W asymmetries that can be measured
- Within the standard model and the quark-parton model i.e. with no physics beyond the standard model and no novel QCD effects, these observables will form an over-constrained set.
- Is there a clever set of these observables that optimizes sensitivity for testing QCD models as well as TeV scale BSM models, and at the same time reduce sensitivity to common systematic errors such as beam polarization?

Isovector EMC Effect

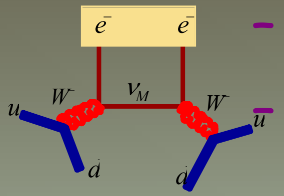
Cloet, Bentz, Thomas, arXiv 0901.3559

- They propose that a neutron or proton excess in nuclei leads to an isovector-vector mean field: shifts quark distributions and leads to “apparent” CSV
- Explains 2/3 of NuTeV anomaly (due to N≠Z in Fe target)
- Suppose one completes a polarized electron-deuteron run and measure A_{PV} precisely as a function of x
- Switch to e-Pb collisions, with polarized electrons
  - **To first order, DIS rate should be the same: measure A_{PV}**
- A_{PV} is in itself a ratio (weak to EM amplitude)
  - **The ratio of ratios (deuterium to heavy nucleus) as a function of x should show a measurable effect if model is correct?**
  - **Measuring the EMC effect along a different isospin axis**
  - **Major contributions to the radiative corrections would cancel in the ratio of ratios**

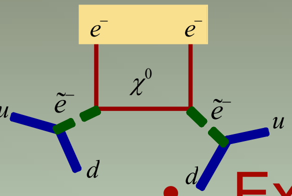
Charged Lepton Flavor Violation

Theoretical motivation w.r.t. EIC initiated by M. Ramsey-Musolf

- The discovery of neutrino mass and mixing



  - **lepton number violation theoretically favored**
  - **potentially enhanced charge lepton flavor violation within reach of proposed experiments**



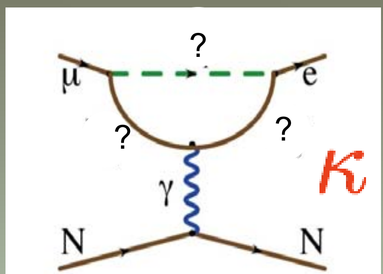
    - ***help decipher the mechanism of neutrinoless double beta decay***
    - ***R-parity violating Supersymmetry***

- Experimental LFV searches undergoing revival
  - **Ongoing at existing facilities (PSI, B-Factories), and also being looked at seriously for the future (J-PARC, Fermilab)**
  - **The Mu2e project at Fermilab was given the highest near-term priority in the recent P5 report for US HEP**
- Thus, it is interesting to see if EIC has a role to play in this subfield

Decay vs Scattering

$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

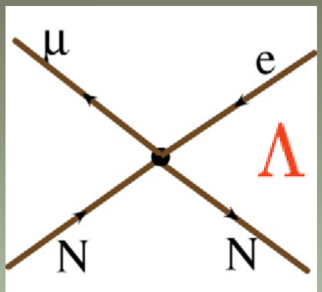
"Loops"



Supersymmetry and Heavy Neutrinos

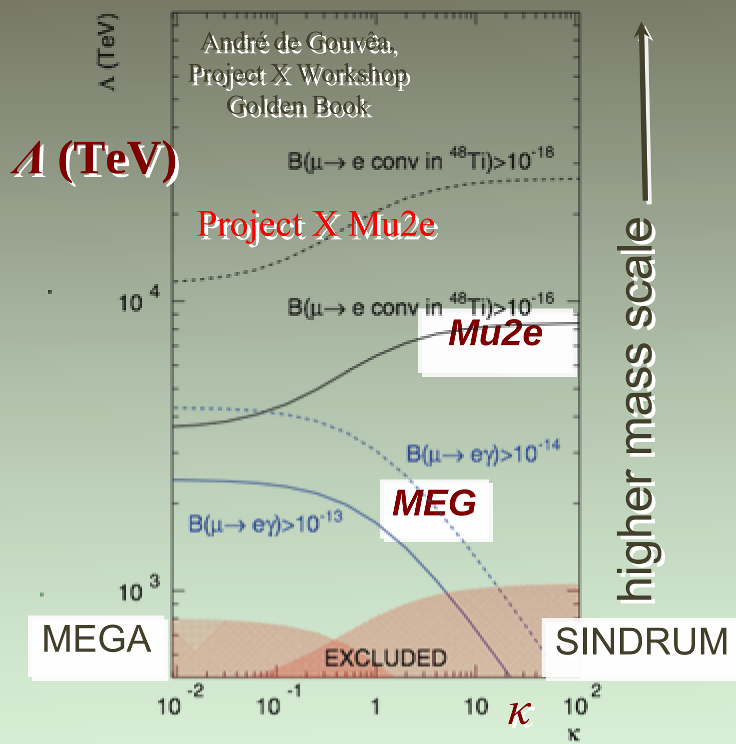
ributes to μ→eγ

"Contact Terms"



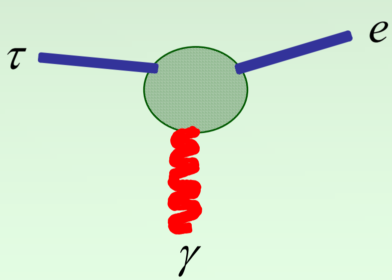
Exchange of a new, massive particle

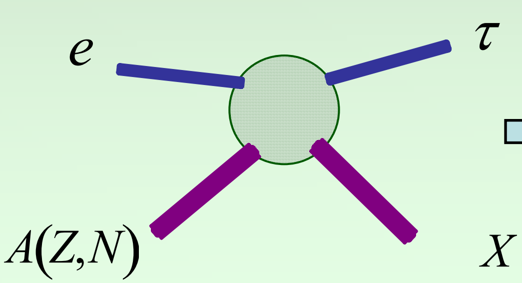
Does not produce μ→eγ



Similarly

Exp: $B_{\tau\text{->}e\gamma} \sim 1.1 \times 10^{-7}$

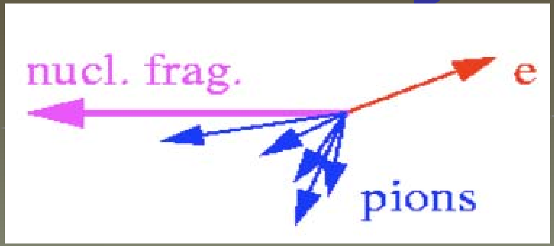




100 to 1000 fb^{-1} DIS dataset at EIC energies competitive

(Theory input from M.J. Ramsey-Musolf)

Identifying Tau Leptons



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

- If mixed in with hadron remnants, the tau would be highly boosted (10 to 50 GeV)
- If forward in the incident electron direction, the tau would be isolated
- Potential for clean identification with high efficiency:
  - **look for single pion, three pions in a narrow cone, single muon: should be able to devise several good triggers**
  - **tau decay is self-analyzing: should study polarization dependence**
  - **tau vertex displaced 200 to 3000 microns: would greatly help background rejection and maintain high efficiency if vertex detector is included in EIC detector design**

Must also investigate the sensitivity and motivation for

Lepton Number Violation $e^- + p \to \mu^+ + X$ $e^- + p \to \tau^+ + X$

Preliminary Conclusions (I)

- Lepton Flavor Violation
  - **DIS tau lepton conversion detectable at EIC kinematics with high efficiency and large background rejection**
  - **With vertexing and 1000 fb^{-1} : possibly 10^{-10} sensitivity**
- Lepton-Quark Weak Neutral Current Couplings
  - **EIC with highest luminosities may allow precision beyond planned facilities, both for BSM physics and nucleon stucture**
  - **Several technical issues:**
    - ***Polarization flips***
    - ***longitudinal polarization stability***
    - ***luminosity fluctuations and monitoring***
    - ***trigger and other biases for asymmetry systematics at ppm level***
    - ***…***

Preliminary Conclusions (II)

- Parity Violating deep inelastic scattering at EIC
  - **100 fb^{-1} data set with polarized e-d collisions needed**
    - *sensitivity would reach beyond 12 GeV JLab program*
    - *interest level might be magnified depending on LHC results and results of the JLab program*
    - *theoretically very clean (e.g. higher twist effects)*
    - *detailed look at experimental systematics needed!*
    - *Can electron polarization be measured to 0.1%?*
  - **An optimized (smaller) data set with polarized proton and He-3**
    - *new parity-violating structure functions*
    - *separation of quark helicity distributions from $x = 0.01$ to 0.5*
    - *Possibly critical for disentangling new physics in W asymmetries*
  - **e-A with polarized electrons**
    - *novel probe of EMC effect?*
    - *available "for free" during e-A running if properly instrumented*

Outlook

- If "precision EW" physics at EIC has unique potential for discovery, we are obliged to explore it
- It is already clear that this will push luminosity, systematics and detector capabilities to the limit: physics payoff must justify the effort
- We are forming a small group to evaluate the physics and determine sensitivities: more people interested?