DIS and Electroweak Physics:

Experimental Opportunities at a Polarized Electron-Ion Collider

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EIC Meeting at LBL, Berkeley

Opening Thoughts

- *Any new machine that pushes the intensity frontier is of interest to the precision EW community*
- *EIC with its high luminosity projections should not be an exception*
- *This study is motivated by the desire to explore what we can do in the area of precision EW physics with the proposed EIC machine parameters*
  - What SHOULD be the parameters of the collider to make it interesting for such precision tests and new physics?
  - What would it take to get there in terms technology, cost etc. etc…..

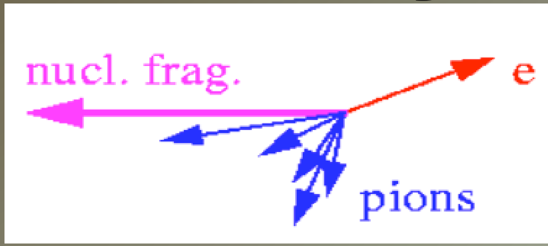
Outline

- *Lepton Flavor Violation*
- *Precision weak mixing angle measurement*
- *Parity Violating deep inelastic scattering*
- *Electroweak Physics at the EIC*
  - First look at BSM reach
  - Full Slate of EW Observables
    - *Relationship to Charged Current*
  - Two specific applications to nucleon structure
    - *EMC effect*
    - *Quark Helicity Distributions*
- *Preliminary Conclusions and Homework*

Lepton Flavor Violation

- *Mike has given you several aspects of the physics motivation*
- *From the experimental side, LFV physics is undergoing a revival*
  - LFV searches are ongoing at existing facilities (e.g. PSI), and are also being looked at seriously for the future (e.g. J-PARC, Fermilab)
  - The muon-to-electron conversion experiment is being designed for Fermilab Project-X: The recent P5 report in the US gave mu2e at Fermilab the highest near term priority in HEP
- *Thus, it is interesting to see if EIC has a role to play in this subfield*

Identifying Tau Leptons



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

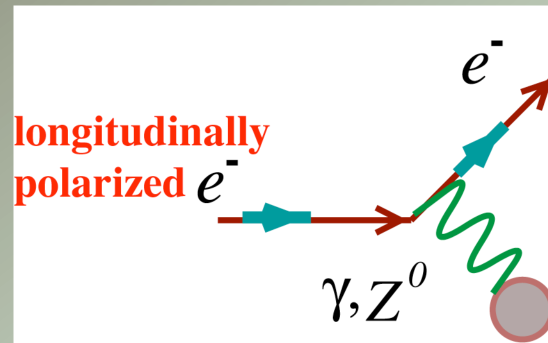
Topology: DIS event, except electron replaced by tau lepton

- *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*
- *In either case:*
  - look for single pion, three pions in a narrow cone, single muon: should be able 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

PV Asymmetries

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

Longitudinally Polarized Electron Scattering off Unpolarized Targets



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

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e g_V^T +'' g_V^e g_A^T\right)$$

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:

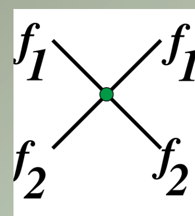
- *In mid 70s, goal was to show $\sin^2\theta_W$ was the same as in neutrino scattering*
- *Early 90s: target couplings carry novel information about hadronic structure*
- *Now: precision measurements with carefully chosen kinematics can probe physics at the multi-TeV scale*

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 $f_1 f_2 \to f_1 f_2$

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



Eichten, Lane and Peskin, PRL50 (1983)

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

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

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

LEPII, Tevatron access scales Λ's ~ 10 TeV

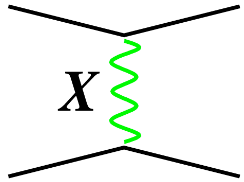
e.g. Tevatron dilepton spectra, fermion pair production at LEPII

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

LEPI, SLC, LEPII & HERA accessed some parity-violating combinations but precision dominated by Z resonance measurements

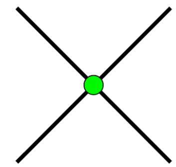
Colliders vs Low Q^2

consider



$$A_X \;\alpha\; \frac{1}{Q^2 - M_X^2} \longrightarrow$$

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



Contact interaction

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

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

$\delta(g)/g \sim 0.1$

$\Lambda \sim 10$ TeV

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

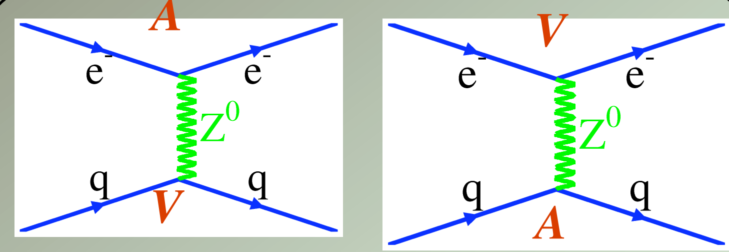
Window of opportunity for weak neutral current measurements at $Q^2 \ll M_Z^2$

Processes with potential sensitivity:

- ***neutrino-nucleon deep inelastic scattering***
- ***Atomic parity violation***
- ***parity-violating electron scattering***

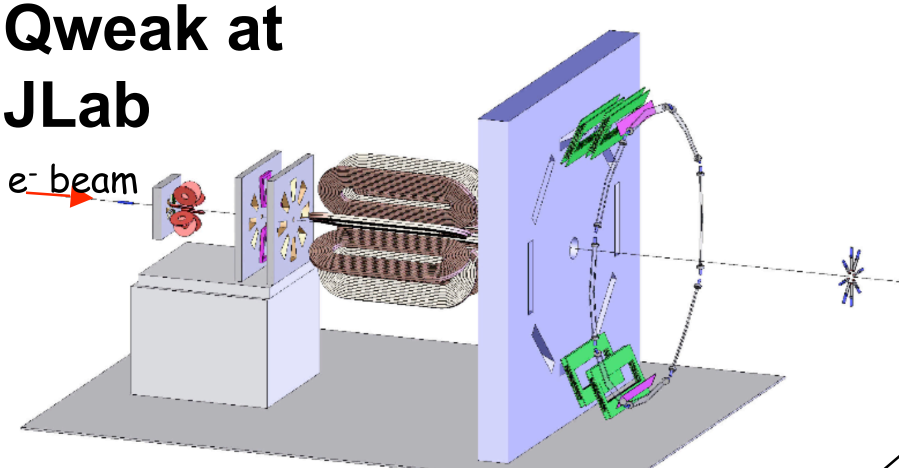
Lepton-Quark WNC Couplings

- **Atomic Parity Violation**
- ^{133}Cs 6s to 7s transition
- Future: isotope measurements
- **Neutrino DIS: NuTeV**
- 3 ℘ deviation
- Many hadronic physics issues
- Look at other l-q couplings?



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

Qweak at JLab



$$\delta(C_{1q}) \propto (+\eta_{RL}^{eq} + \eta_{RR}^{eq} - \eta_{LL}^{eq} - \eta_{LR}^{eq})$$

$$\delta(C_{2q}) \propto (-\eta_{RL}^{eq} + \eta_{RR}^{eq} - \eta_{LL}^{eq} + \eta_{LR}^{eq})$$

Will measure one combination

But elastic scattering cannot determine C_{2q}'s precisely

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

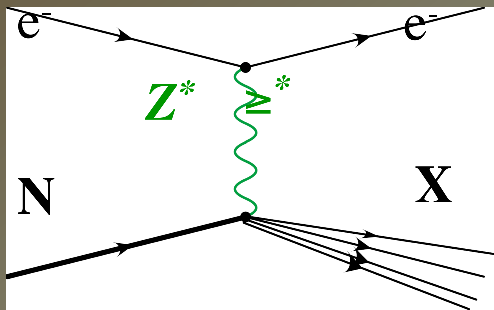
$$A(Q^2 \to 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}}\left[Q^2 Q^p_{weak} + Q^4 B\left(Q^2\right)\right]$$

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

Data ~ 2010

We need ***Deep Inelastic Scattering***

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 a ^{2}H target, assuming charge symmetry, structure functions largely cancel in the ratio:

$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\right] + \ldots$$

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

SMALL

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

12 GeV JLab Projections

Also: ***PV-DIS off the proton (hydrogen target)***

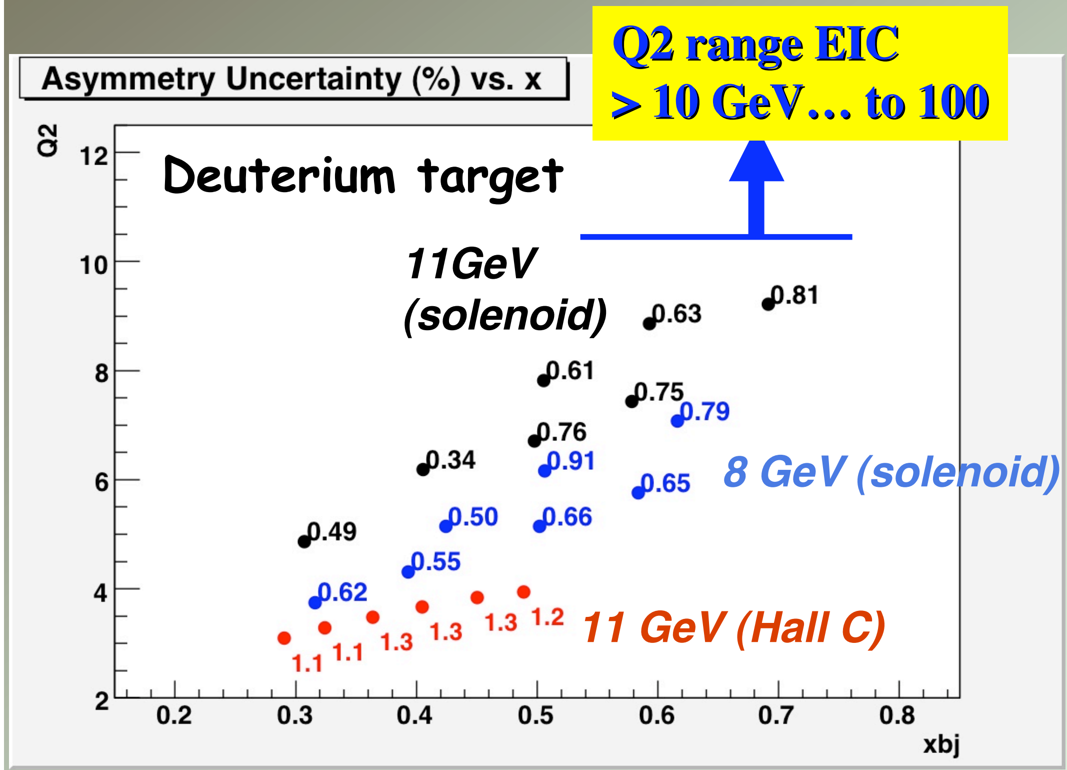
$$a(x) = \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$

Very sensitive to d(x)/u(x)

•Allows d/u measurement on a single proton, Vector quark current!

Strategy:

- *Measure A_{PV} in NARROW x,Q^2 bins, EACH with 1% accuracy*
- *measure or constrain higher twist effects at x ~ 0.5-0.6*
- *precision measurement of A_{PV} at x ~ 0.7 to search for CSV*

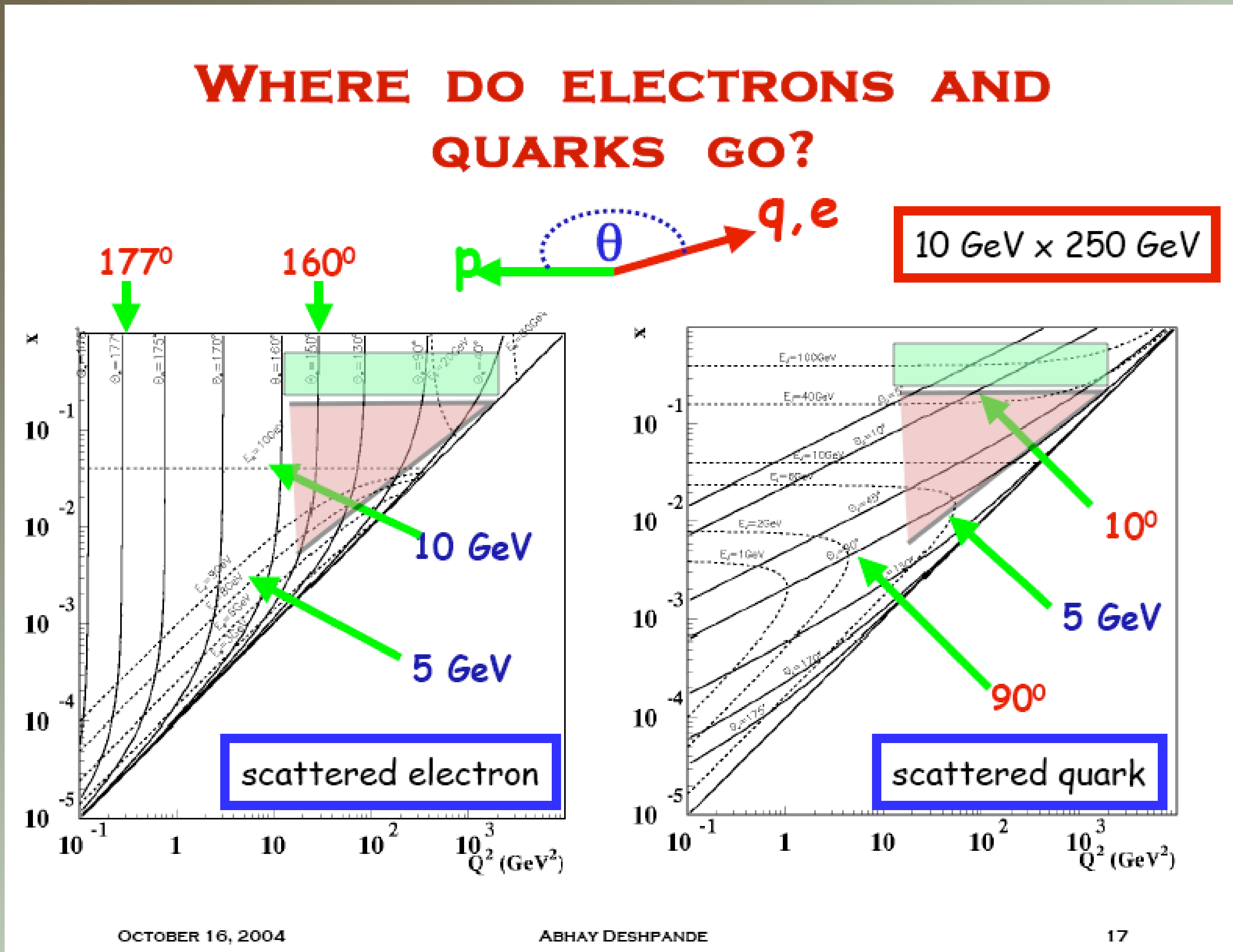


Fractional errors shown

For JLAB:

- ***Simulation and design development begun***
- ***Letter of Intent targeted for Jan 2009***

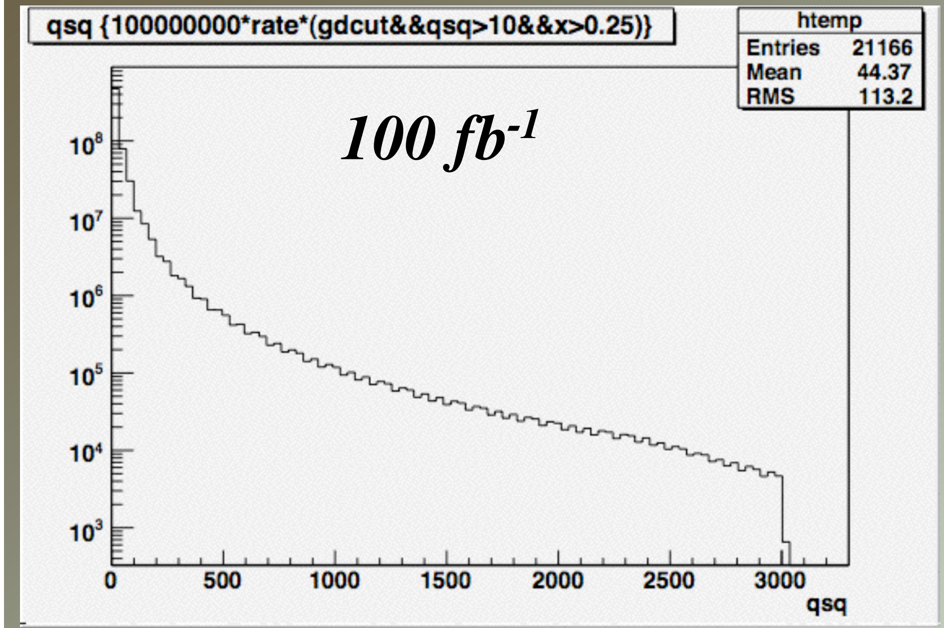
EIC DIS Kinematics



PV DIS at the EIC

- *Confine to $Q^2 > 10$ GeV^2*
- *Below 100 GeV^2 , will need hadron jet to extract x:*
  - can one keep asymmetry systematics at ppm level?
- *To avoid sticky trigger systematics, keep lepton energy > 5 GeV and scattering angle between 10 and 170 degrees*
- *Figure of merit ($A^2\sigma$) roughly flat vs Q^2*
- *Measurements at different y for same x very useful*
- *Two Q^2 ranges: 10 to 100 GeV^2 & > 100 GeV^2 : y range*
- *Assume a 100 fb^{-1} data set: Would much prefer to have at least 3-4x10^{33} luminosity!*
- *Comment: 10^{33} lumi at 10 wks operation, 70% detector, 70% machine uptime means ~5 fb-1/yr*
  - 50 fb-1 in 10 (10-wk)-years

First Look at Statistics



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

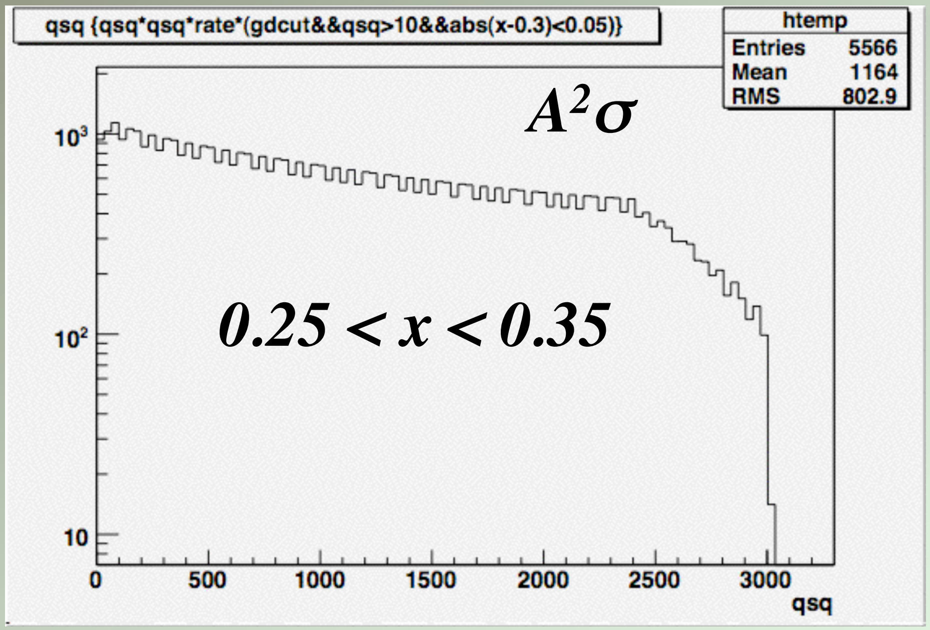


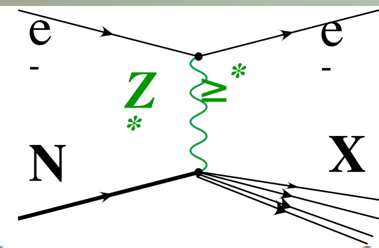
figure of merit vs Q^2 (GeV^2)

- ~ billion events at Q^2 ~ 10 GeV^2
- ~ few hundred thousand events at ~ 200 GeV^2
- 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?*
  - At EIC devoid of complications which may arise from lower Q^2 (HT)
- *Can one control polarimetry syst. error at that level?*
  - Initial studies (EIC WS at Michigan already), details to be worked out, not only on the techniques but also on integrating polarimetry in Machine Design
- *Is there a double-spin asymmetry calculation that makes the effective polarization large and the systematic error small? (home work for KK & AD)*
- *Our 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 and JLab 12 GeV measurements
  - 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



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

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

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

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

QPM Interpretation

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

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

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

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

$$g_3^{\gamma Z} = 2x \sum_q e_q (g_A)_q (\Delta q - \Delta\bar{q}) \qquad 2x g_5^{\gamma Z} = g_3^{\gamma Z}$$

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**

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

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

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

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

- ***Jefferson Lab 12 GeV can begin exploration***
- ***A high luminosity EIC is a new opportunity***
  - *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!*
  - *Effective polarization error might be significantly reduced: peculiarity of measuring parity-violating asymmetries between relativistic particles*
  - *All three asymmetries could be measured simultaneously*

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?

Possible Novel Aspect of the EMC Effect

- *Suppose one completes a polarized electron-unpolarized deuteron run and measure A_{PV} precisely as a function of x*
- *Now suppose we switch to a heavy nucleus for an e-A run and maintain a polarized electron beam*
  - To first order, DIS rate should be the same: measure A_{PV}
- *A_{PV} is in itself a ratio (weak to EM amplitude)*
  - What would the ratio of ratios (deuterium to nucleus) look like as a function of x?
  - Measuring the EMC effect along a different isospin axis
  - Major contributions to the radiative corrections would cancel in the ratio of ratios
  - Intriguing theory question: How is F_L(gamma-Z) related F_L(gamma)? Perhaps F_L effects cancel?

Preliminary Conclusions and Outlook (I)

- ***Lepton Flavor Violation***
  - DIS tau lepton conversion possible at EIC kinematics with high efficiency and large background rejection
  - With vertexing and 100 fb^{-1} : ~10^{-10} sensitivity
  - Detailed detector simulations (GEANT) needed…
- ***Precision weak mixing angle measurement***
  - EIC with highest luminosity scenarios may allow precision beyond anything conceived for next decade
  - Several technical issues:
    - *Polarization flips*
    - *longitudinal polarization stability*
    - *luminosity fluctuations and monitoring*
    - *…*

Preliminary sensitivity figures exist (see previous EIC meetings) Devil is in the Details

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!*
    - *Is the polarization systematic suppressed to 0.1%? (Very challenging)*
  - An optimized 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*
    - *Critical for disentangling new physics in W asymmetries*
  - e-A with polarized electrons
    - *novel probe of EMC effect?*
    - *different systematics? e.g. radiative corrections, F_L*

My outlook:

- *If "precision EW" physics at EIC holds a promise, we are obliged to explore it*
- *It is clear this will push the luminosity & systematic uncertainty requirements to its limit… but that is the fun in exploring something new….*
- *With advice & input from MRM & KK, I hope we can explore this: we will be initiating some of the simulation studies in January 2009. Join us if you are interested…*