# Summary of EIC Electroweak Working Group Workshop

**Williamsburg, VA**

**May 17-18, 2010**


## Kent Paschke


**EIC Detector Workshop**

**June 5, 2010**

Slides and content from K.Kumar, I.Cloet, M. Glatzmaier, M. Gonderinger, S.Mantry, W.Marciano, M.J. Ramsey-Musolf

# Topics from EW Working Group Workshop

These are interesting topics, and potentially very interesting - but not yet any obvious high-priority bullet point.

**Studies of the Electroweak Interaction**

- Charged Lepton Flavor Violation $\tau$ -> e
- Weak Neutral Current couplings

**Studies *using* the Electroweak Interaction**

- high-x structure functions - higher twist, charge symmetry violation, d/u of the proton
- PV EMC effect in nuclei, $F_3^{\gamma Z}$
- novel structure functions

**Workshop featured reports of significant theoretical progress**

Detailed studies of experimental feasibility have yet to be done!

# 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

# Identifying Tau Leptons


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

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

- If mixed in with hadron remnants, the tau would be boosted
- 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 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*** $e^- + p \rightarrow \mu^+ + X$ $e^- + p \rightarrow \tau^+ + X$

- Monte Carlo study to design cuts,efficiency and background rejection
- vertex tracker may be required

- some interest in starting this study at Stoney Brook (A. Deshpande)

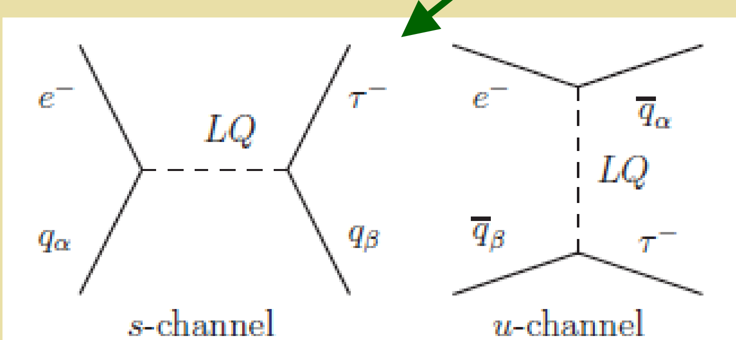
# BRW Leptoquark limits

**EIC @ 10 fb$^{-1}$ can decrease many existing limits by a factor of 2 to almost 2 orders of magnitude**

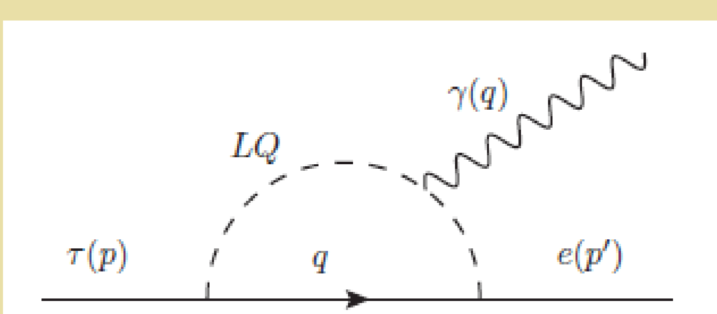
**Matt Gonderinger,**
**M Ramsey-Musolf**

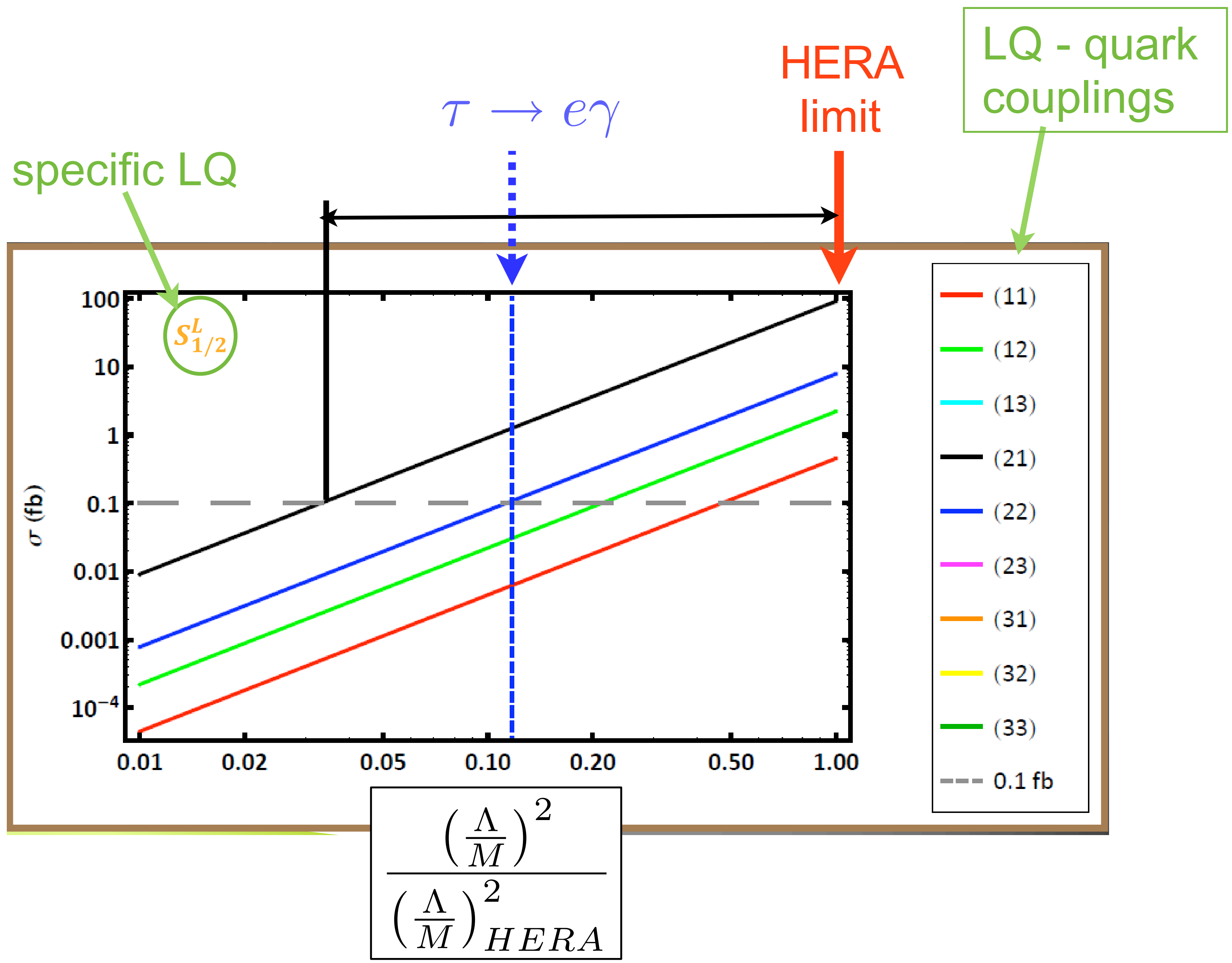
HERA & EIC

*τeqq eff op*




Rare Decays




@ luminosity of 10 fb$^{-1}$ :

~30x improvement for (21)

# High x Structure Functions

**$A_{PV}$ in Electron-Nucleon DIS:**

*polarized electron, unpolarized hadron*

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

***For 2H, assuming charge symmetry, structure functions largely cancel in the ratio at high x:***

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

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

**SOLID at JLab-12GeV**

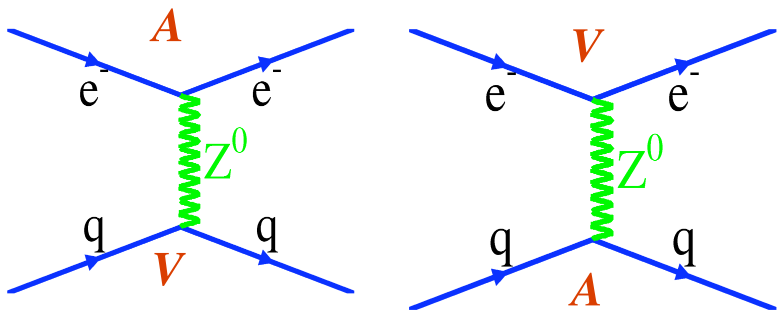
Program to map this out at high x (x~0.3-0.7) with high precision

- $C_{2q}$'s and $\sin^2\theta_w$
- CSV
- higher twist

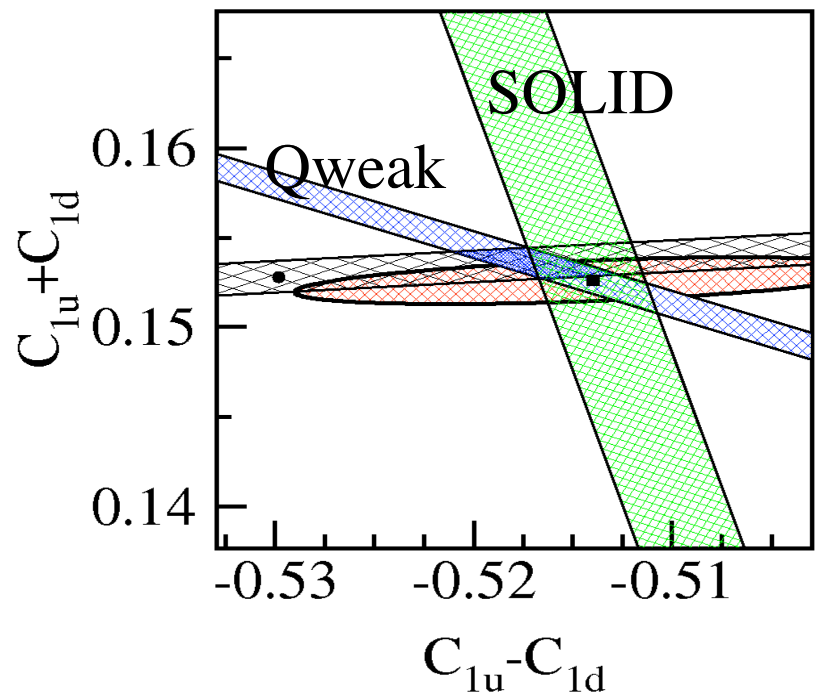
## Collider kinematics:

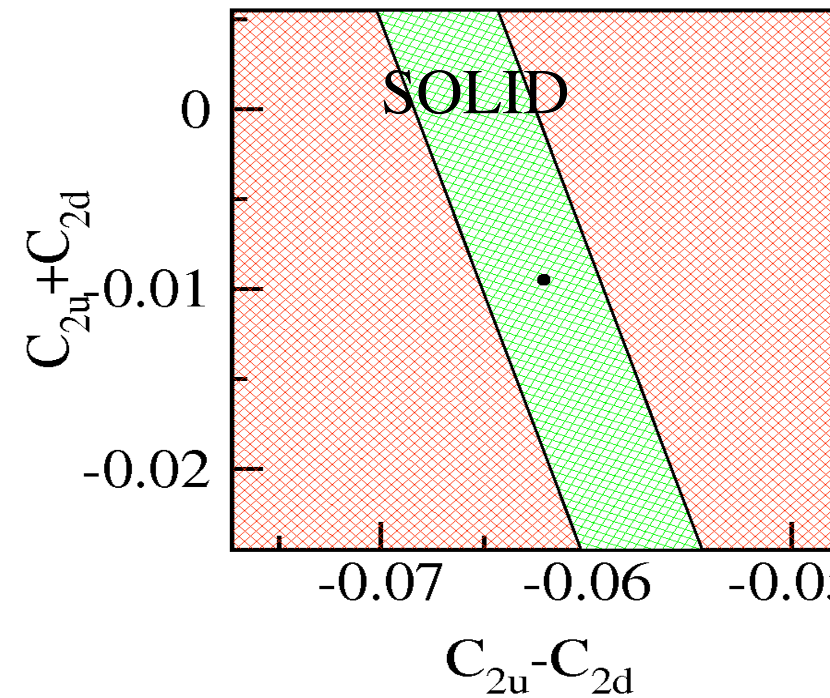
- At high $Q^2$:
  - "huge" asymmetries
  - large y range
- At low $Q^2$:
  - Very forward angle
  - small y; map out higher twist

# Weak Neutral Current Couplings



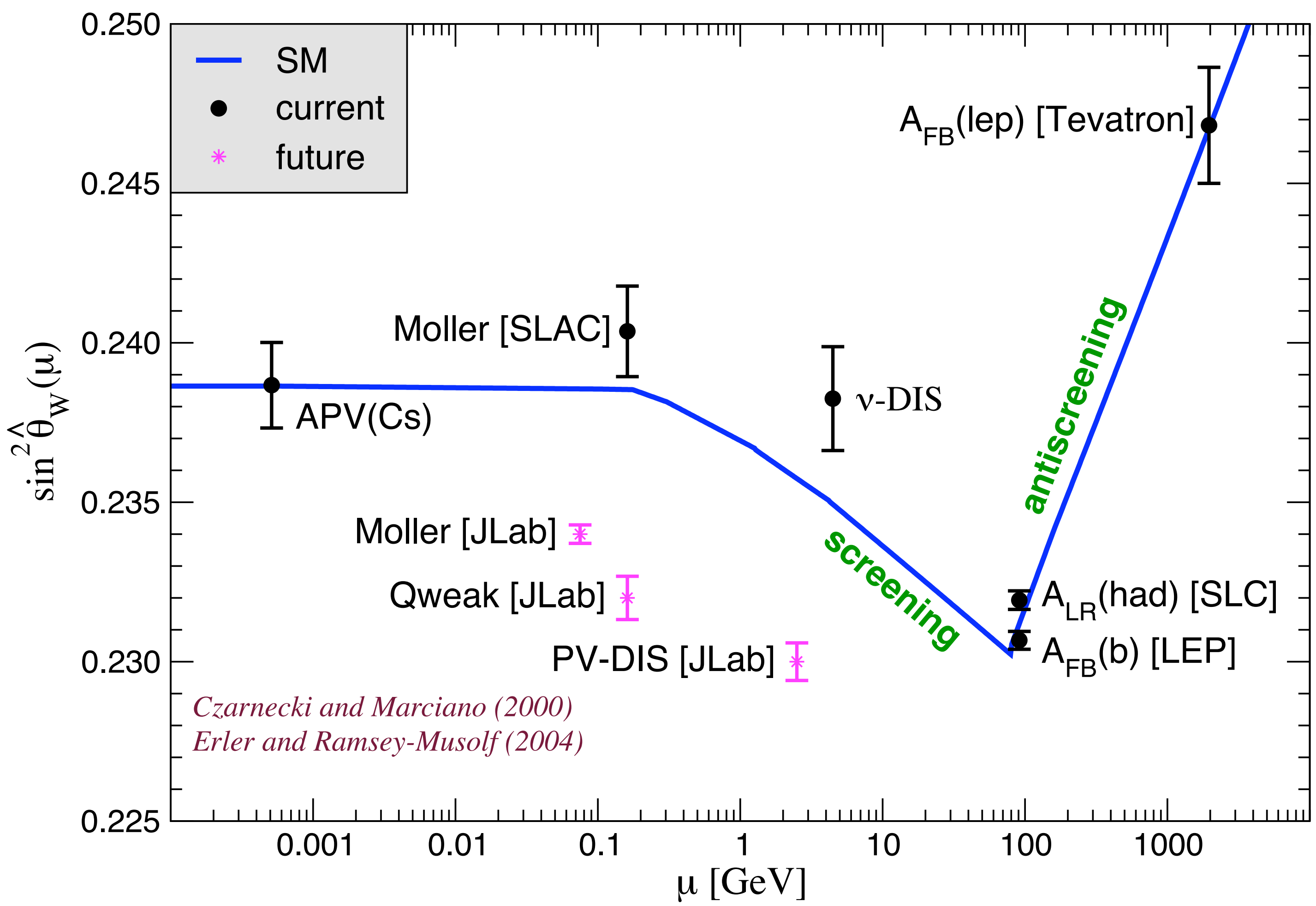

$C_{1i} \equiv 2 g_A^e g_V^i$ $\quad$ $C_{2i} \equiv 2 g_V^e g_A^i$




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

***At end of JLab program (Qweak, MOLLER, SOLID): Interest in couplings and in the weak mixing angle will depend on LHC results***

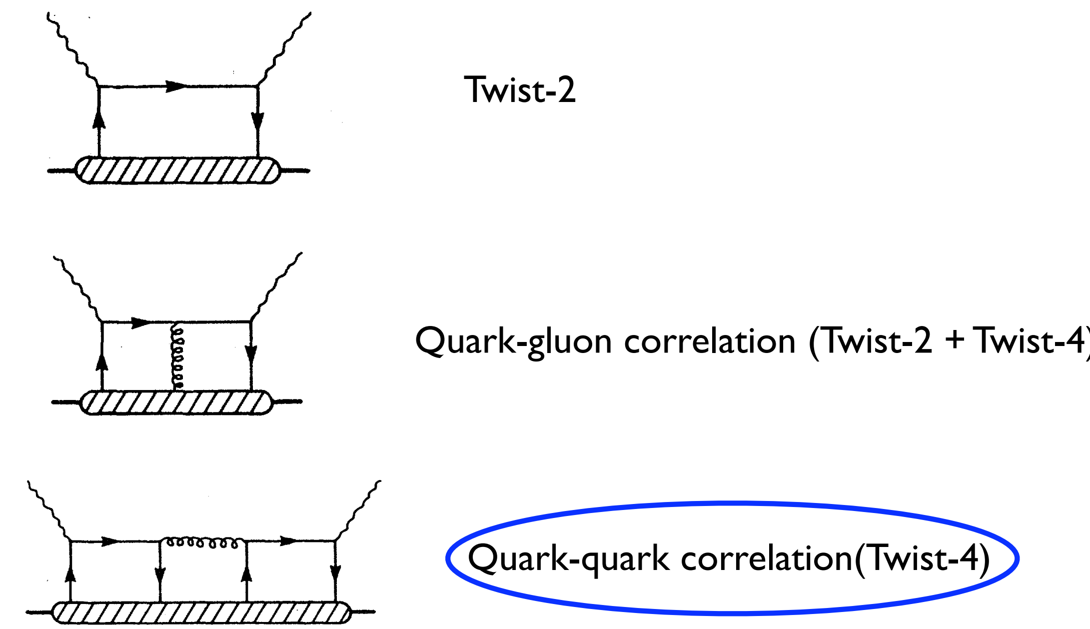


# Higher Twist Contributions to PV-DIS

**Sonny Mantry**, M.J. Ramsey-Musolf, G.F. Sacco arXiv:1004.3307

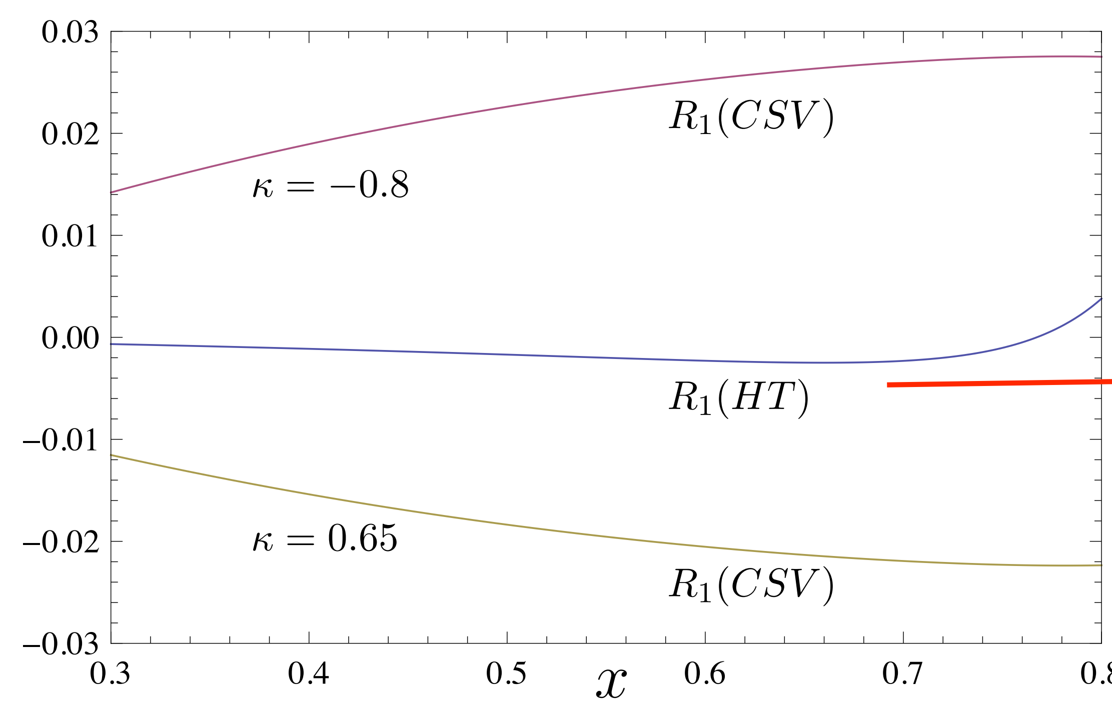
- **Twist-4 effects in vector WNC term come only from quark-quark correlations**
- A single 4-quark twist-4 matrix element contributes to the vector WNC term
- The relation $R^{\gamma Z} = R^{\gamma}$ holds true at twist-4 up to perturbative corrections

Operator Product Expansion




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

only quark-quark correlations given by a single matrix element




Bag model estimate of higher twist

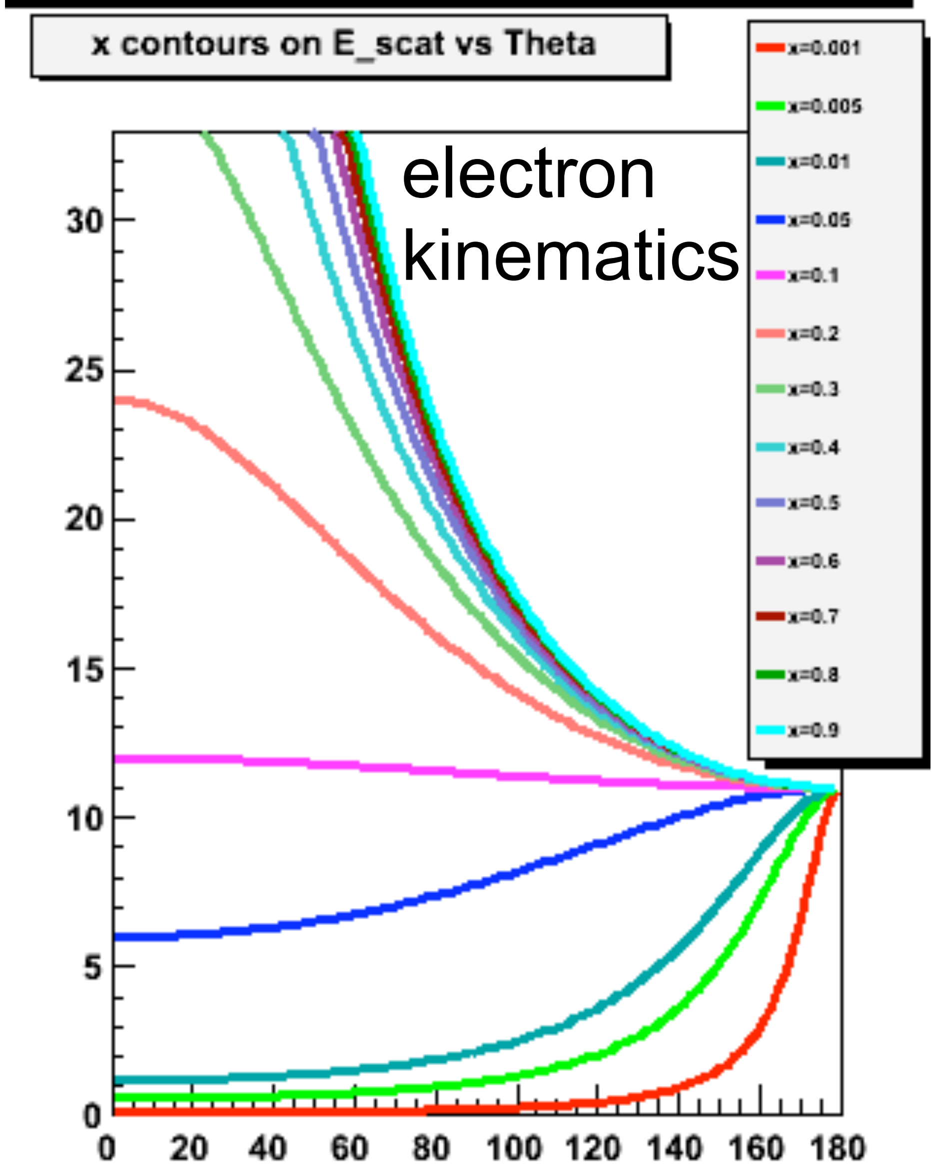
$$\delta u - \delta d = 2\kappa f(x), \qquad f(x) = x^{-1/2}(1-x)^4(x - 0.0909)$$

Collider kinematics:

- small y, good (low) $Q^2$ range; search for higher twist

# Quark Kinematics

High-x resolution requires measurement of hadronic flow

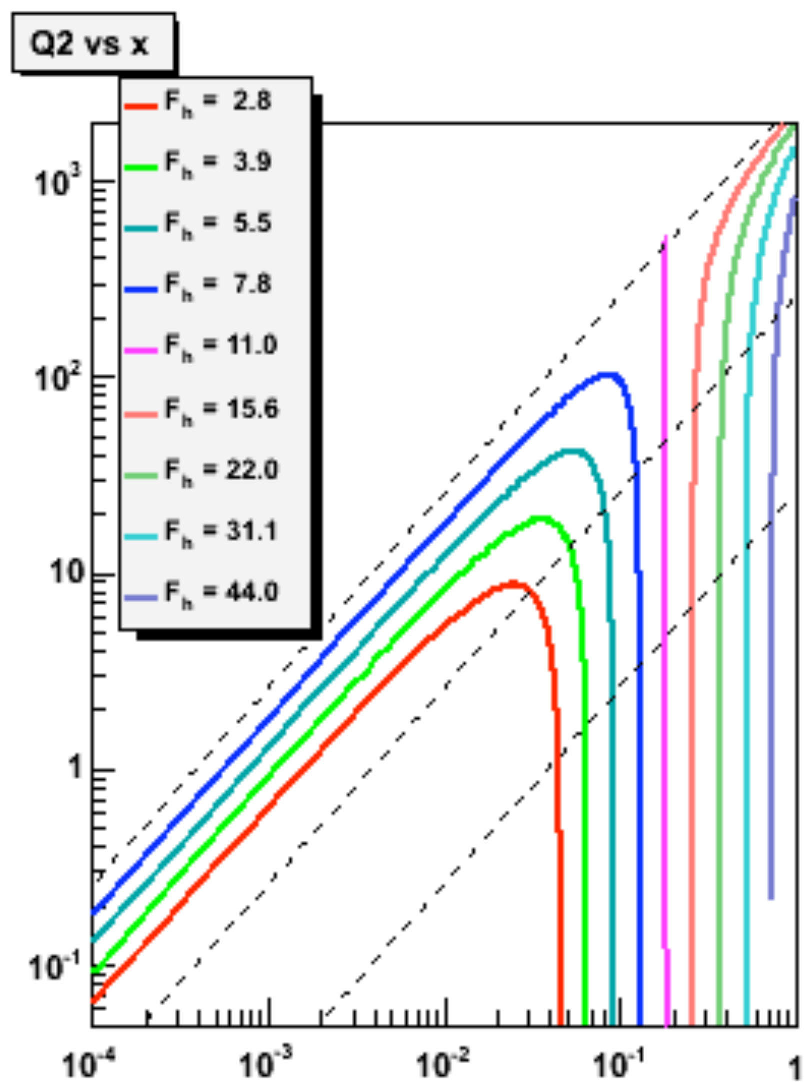


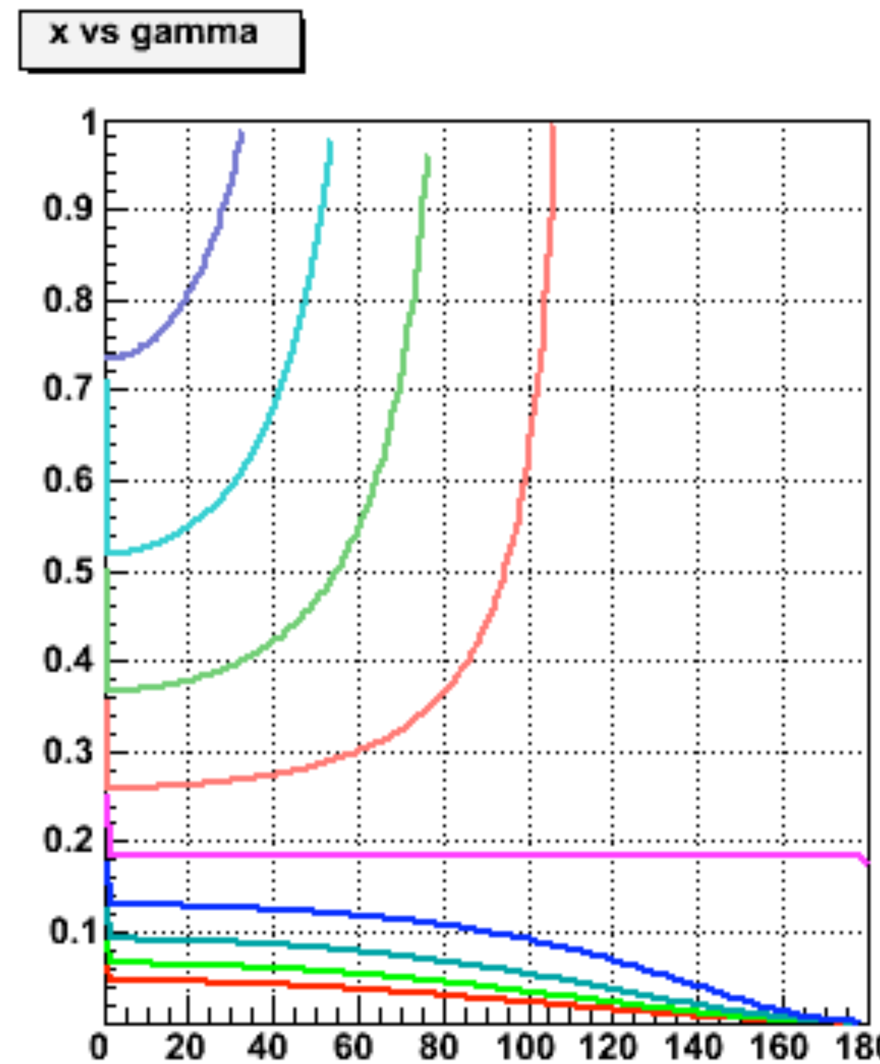

Jacquet-Blondel reconstruction

$$\cos\gamma_h = \frac{P_{T,h}^2 - (E_h - P_{z,h})^2}{P_{T,h}^2 + (E_h - P_{z,h})^2}$$

$$F_h = \frac{P_{T,h}^2 + (E_h - P_{z,h})^2}{2\,(E_h - P_{z,h})}$$

Constant $F_{JB}$ contours



# Plan for high x structure functions

## It is hard to beat fixed-target luminosity

- SOLID aims for many bins at measuring APV at 0.5%. At an EIC, this would seem to require $10^{35}$ $cm^{-2}$ at very high s.
  - **Not yet carefully checked... requires study for conclusion**
  - Potentially may provide the best independent constraint on $C_{2q}$'s

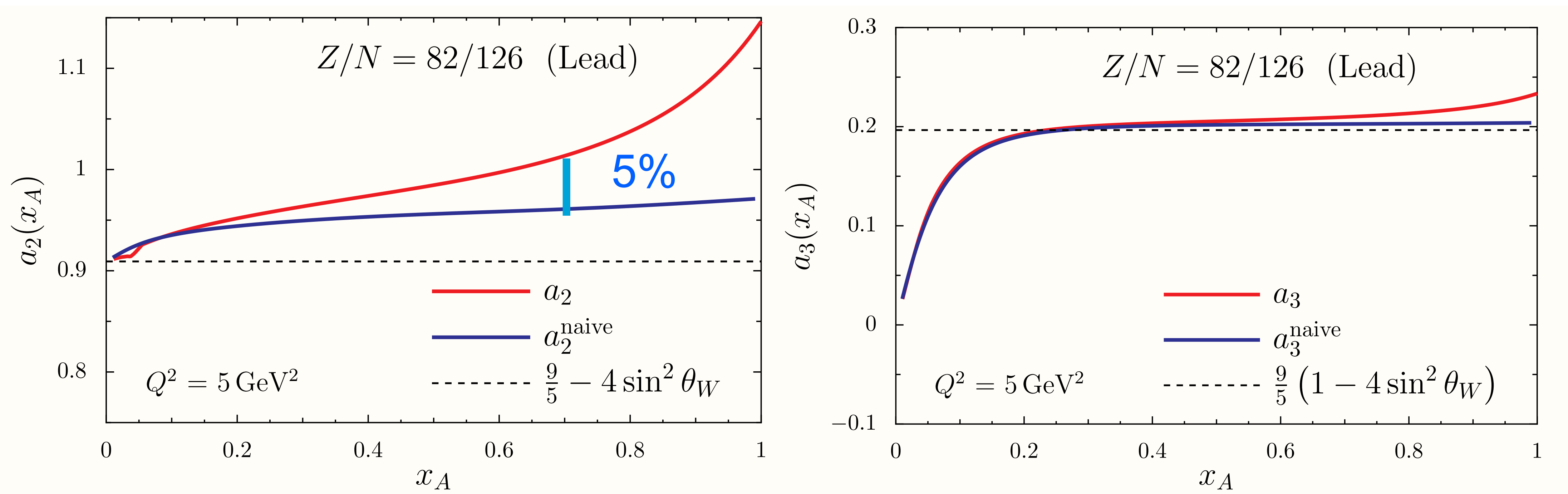
- collider gives $Q^2$ range with small y : measure 4-quark twist-4 operator
  - first-ever empirical bound on single HT quark-quark operator?

- additional topics in high-x p.d.f.'s: CSV (eD), d/u (ep), and sea quarks

# Nuclear Structure Functions

***Cloet**, Bentz, Thomas, arXiv 0901.3559*

- proposes that a neutron or proton excess in nuclei leads to an isovector–vector mean field dominated by ρ exchange
- shifts quark distributions: "apparent" CSV violation
- Isovector EMC effect: explain 1/2 of NuTeV anomaly
- Would be a smoking gun demonstration of medium modification




**More generally, $F_2^{(\gamma Z)}$ and $F_3^{(\gamma Z)}$ for nuclear DIS interesting and new**

- requires polarized e- with A
- inclusive rates for eA at low x, with y separation
- theoretical comment in nuclear $F_3^{\gamma Z}$

# Low-x Spin Structure Functions

*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 pieces*

★ *$^1H$, $^2H$ and $^3He$ measurements*

★ *Precise measurements to x ~ 0.01 at low s and x ~ 0.001 at high s*

| | y-independent | y-dependent |
|---|---|---|
| $^1$H | $\frac{2\Delta u^- + \Delta d^- + \Delta s^-}{4u^+ + d^+ + s^+}$ | $\frac{\Delta u^+ + \Delta d^+ + \Delta s^+}{4u^+ + d^+ + s^+}$ |
| $^2$H | $\frac{3\Delta u^- + 3\Delta d^- + 2\Delta s^-}{u^+ + d^+ + s^+}$ | $\frac{\Delta u^+ + \Delta d^+ + \Delta s^+}{u^+ + d^+ + s^+}$ |

- EW amplitudes measure a different linear combination of quark polarizations, allowing a determination of $\Delta s$ without $SU(3)_f$
- initial indications: very competive with semi-inclusive, phase 1 designs can make impact

# Low-x Spin Structure Functions

***New frontier in precision QCD tests in inclusive DIS:***

- **In the long term**, there are **15** different combinations that can be measured (EM, γZ, W)
- W production needs to be fully explored:
  - two structure functions $g_1$ and $g_5$
  - $^1H$ + $^2H$ with $e^-$ equivalent to $^1H$ with $e^-$ & $e^+$ ?
- New sum rules, new dynamics in $Q^2$ evolution, other implications?

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

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

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

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

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

**Start with focus on spin-dependent PDFs, Δs extraction**

# Topics from EW Working Group Workshop

**Most promising topics use the electroweak interaction to study QCD**

- high-x structure functions - higher twist, charge symmetry violation, d/u of the proton
- PV EMC effect in nuclei, $F_3^{\gamma Z}$
- $\Delta$**s**, other novel structure functions

*prospect for a phase 1 machine*

**Electroweak studies**

- WNC couplings — *hard to beat fixed target*
- Charged Lepton Flavor Violation $\tau$ -> e — *extensive MC study required*

Sufficient theoretical guidance to launch these topics - present bottleneck is getting the experimentalist time for rate studies and other calculations

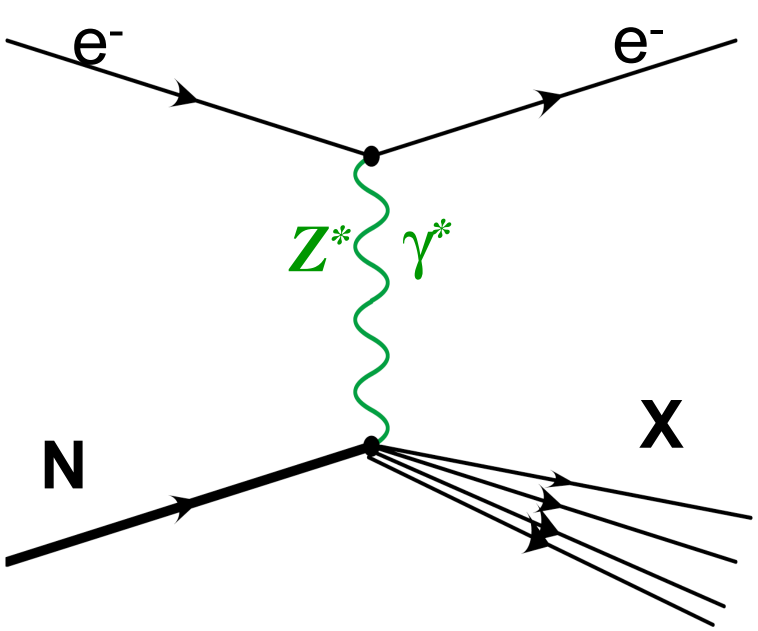
# Electroweak Structure Functions

$$\frac{1}{2m_N}W^i_{\mu\nu} = -\frac{g_{\mu\nu}}{m_N}F_1^i + \frac{p_\mu p_\nu}{m_N(p\cdot q)}F_2^i \qquad i \equiv \gamma, \gamma Z, Z$$

$$+ i\frac{\epsilon_{\mu\nu\alpha\beta}}{2(p\cdot q)}\left[\frac{p^\alpha q^\beta}{m_N}F_3^i + 2q^\alpha S^\beta g_1^i - 4xp^\alpha S^\beta g_2^i\right]$$

$$-\frac{p_\mu S_\nu + S_\mu p_\nu}{2(p\cdot q)}g_3^i + \frac{S\cdot q}{(p\cdot q)^2}p_\mu p_\nu g_4^i + \frac{S\cdot q}{p\cdot q}g_{\mu\nu}g_5^i$$

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




### *QPM Interpretation*

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

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

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

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

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