Parity Violation in Deep Inelastic Scattering

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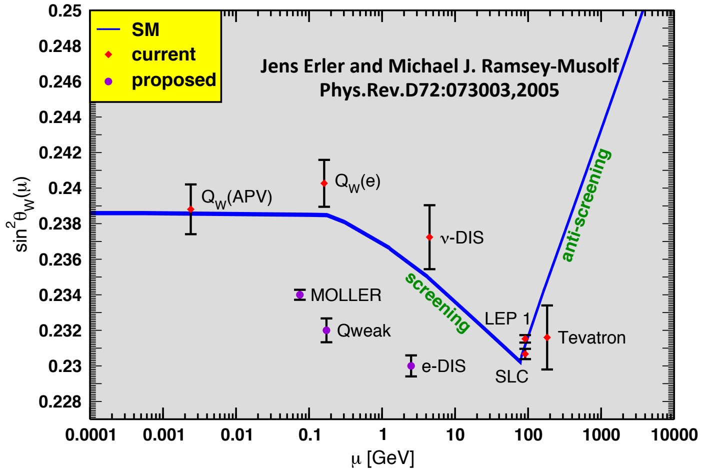
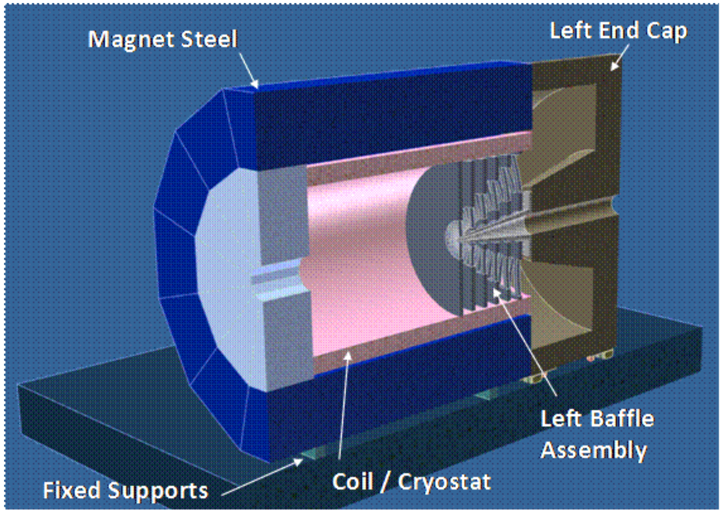
9 November 2010

Representing the SoLID Collaboration

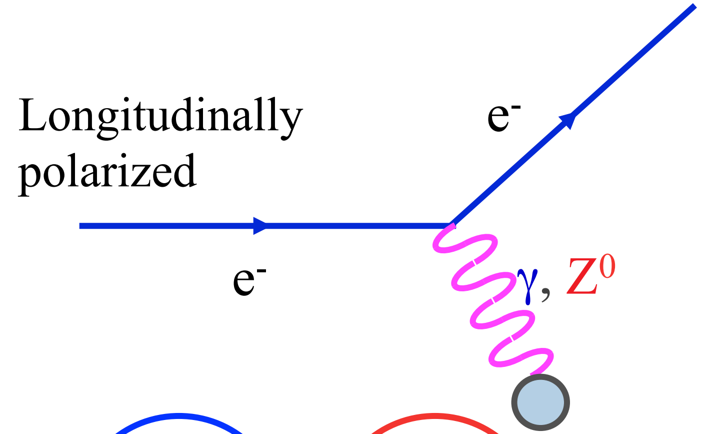


I. Parity Violation
II. PVDIS Physics Potential
    A. Electroweak Couplings
    B. Charge Symmetry
    C. Higher Twist
    D. Other Physics and Targets: d_v/u_v ; Isoscaler EMC effect
III. Experiments: JLab Hall A 6 GeV, JLab Hall C 12 GeV and JLab Hall A SOLID
IV. SIDIS w/SoLID@JLab



This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

Why measure of parity violation in electron scattering?



- Because it's hard and physicists like challenges.
- PV gives access to the weak interaction at low energy (well below the mass of the Z^0).

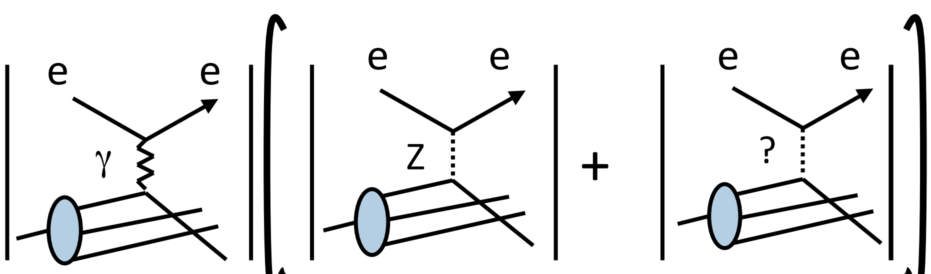
$$\sigma^l \propto \left|\mathcal{M}_\gamma + \mathcal{M}^l_{Z^0}\right|^2 \qquad \sigma^r \propto \left|\mathcal{M}_\gamma + \mathcal{M}^r_{Z^0}\right|^2$$

large

Tiny

$$A_{\mathrm{PV}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{\mathcal{M}^l_{Z^0} - \mathcal{M}^r_{Z^0}}{\mathcal{M}_\gamma}$$

A_{PV} ~



Graphic from Ray Arnold

1^{st} Generation PV experiment PV-DIS in 1977

PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING ☆

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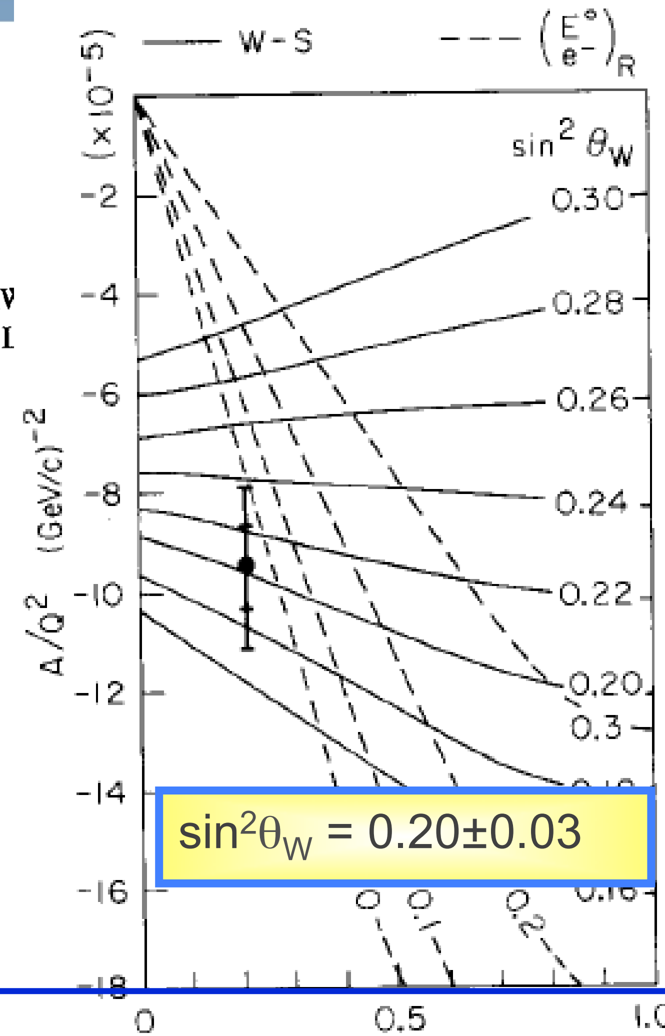
Received 14 July 1978

Phys. Lett. 77B, 347 (1979)



$\sin^2\theta_W = 0.20 \pm 0.03$

Abstract
We have measured parity violating asymmetries in the inelastic scattering of longitudinally polarized electrons from deuterium and hydrogen. For deuterium near $Q^2 = 1.6\ (GeV/c)^2$ the asymmetry is $(-9.5\times10^{-5})Q^2$ with statistical and systematic **uncertainties each about 10%**

PVDIS variables

Weak PV

Electromagnetic

$$A_{\rm PV} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{\mathcal{M}^l_{Z^0} - \mathcal{M}^r_{Z^0}}{\mathcal{M}_\gamma}$$

Kinematic factor

$$\propto -\left(\frac{G_{\rm F} Q^2}{4\pi\alpha}\right)\left(g^e_A g^T_V + \beta g^e_V g^T_A\right)$$

- The couplings g depend on electroweak physics as well as on the weak vector and axial-vector hadronic current.
- Both new physics at high energy scales as well as interesting features of hadronic structure come into play.
- A program with many targets and a broad kinematic range can reveal the physics.

Is the glass half full or half empty?

PVDIS variables

Cahn and Gilman, PRD **17** 1313 (1978) polarized electrons on deuterium

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

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

$$A_{\text{iso}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r}$$

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

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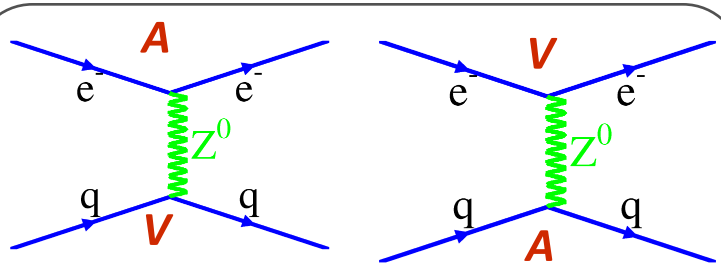
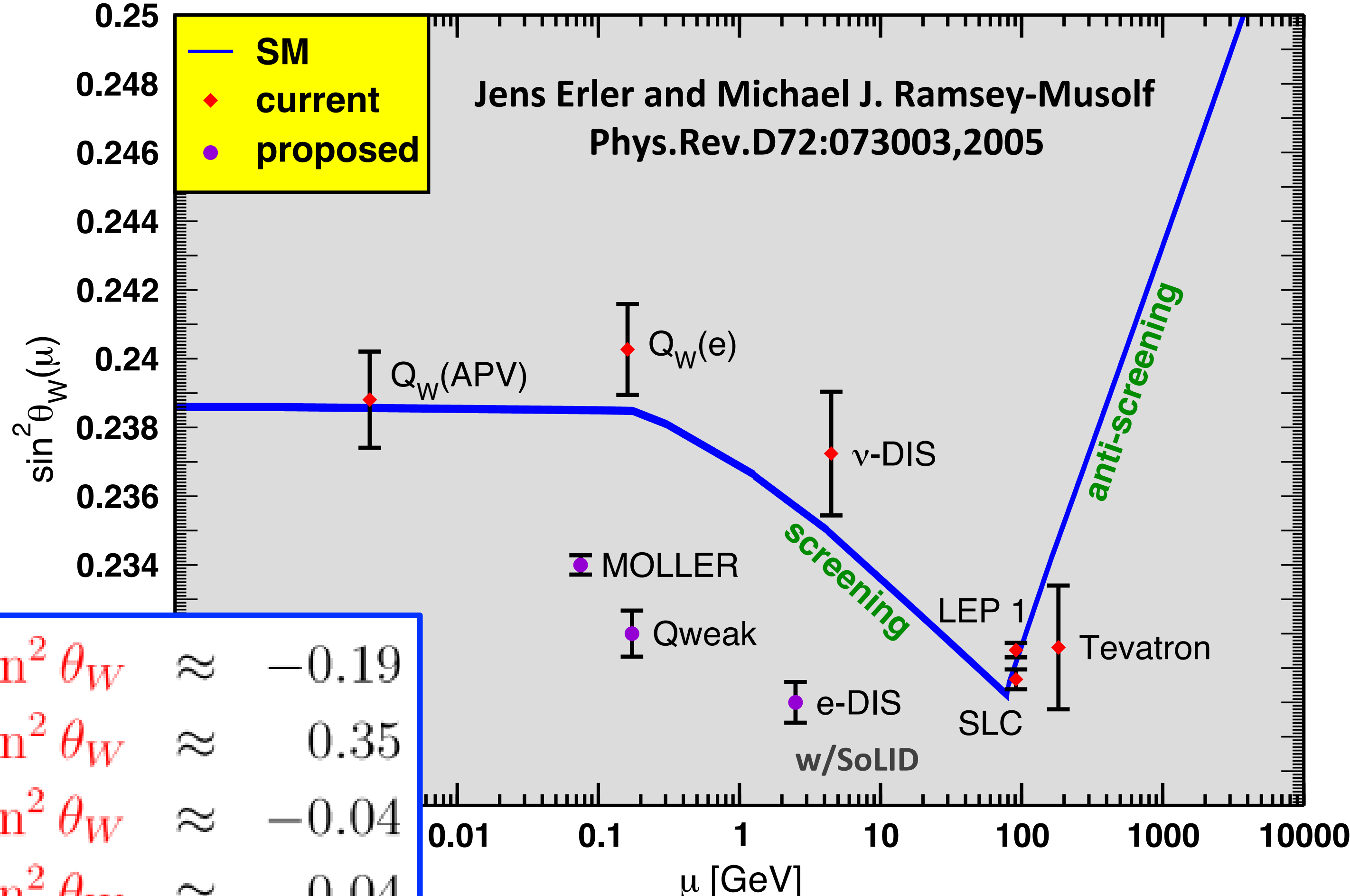


$C_{1i} \equiv 2g_A^e g_V^i$ $\qquad$ $C_{2i} \equiv 2g_V^e g_A^i$

Z_{SoLID}? (See talk by J. Erler)

$$\begin{aligned}
C_{1u} &= -\tfrac{1}{2}+\tfrac{4}{3}\sin^2\theta_W &\approx& -0.19\\
C_{1d} &= \tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W &\approx& 0.35\\
C_{2u} &= -\tfrac{1}{2}+2\sin^2\theta_W &\approx& -0.04\\
C_{2d} &= \tfrac{1}{2}-2\sin^2\theta_W &\approx& 0.04
\end{aligned}$$

PVDIS—Electroweak couplings and $\sin^2\theta_W$



$$
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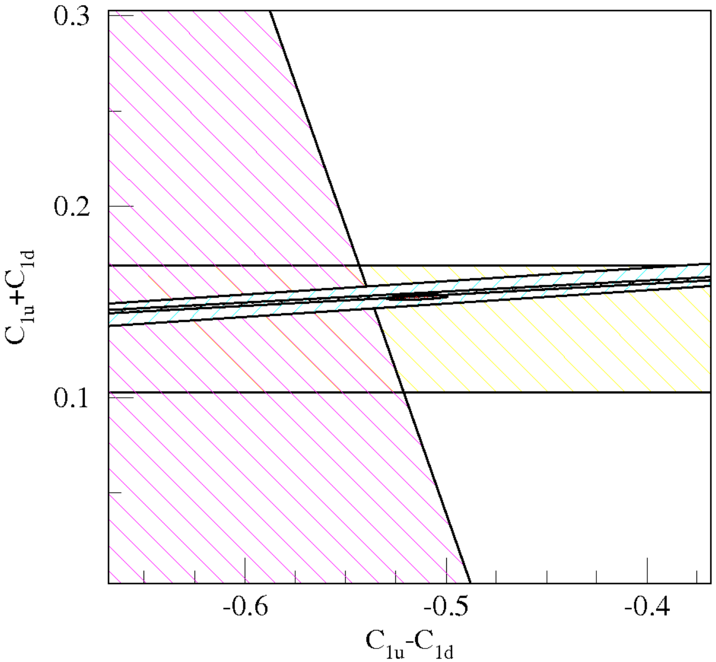
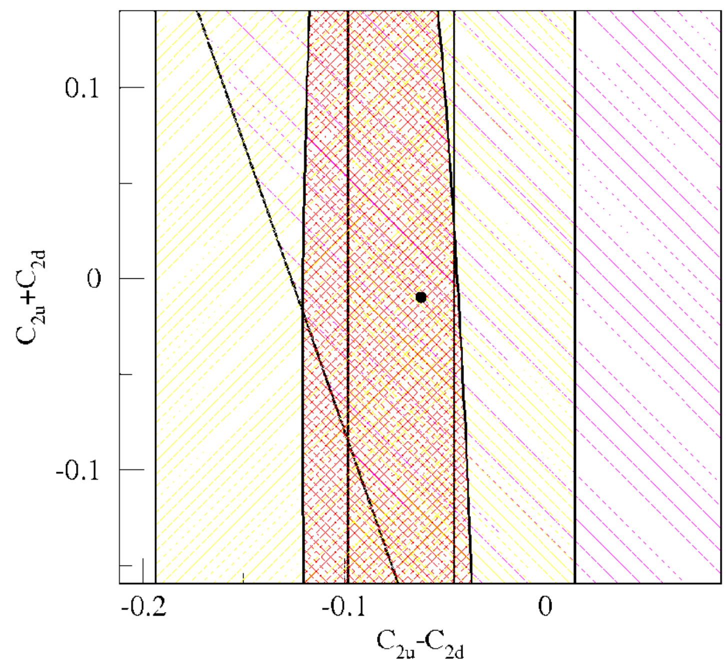
C_{2d} &= \tfrac{1}{2}-2\sin^2\theta_W \approx 0.04
\end{aligned}
$$

Recall: $\sin^2\theta_W$ projects couplings onto Standard Model—measurements of couplings to elucidate extensions to the S.M.

Sensitivity: C_1 and C_2 Plots

World's data





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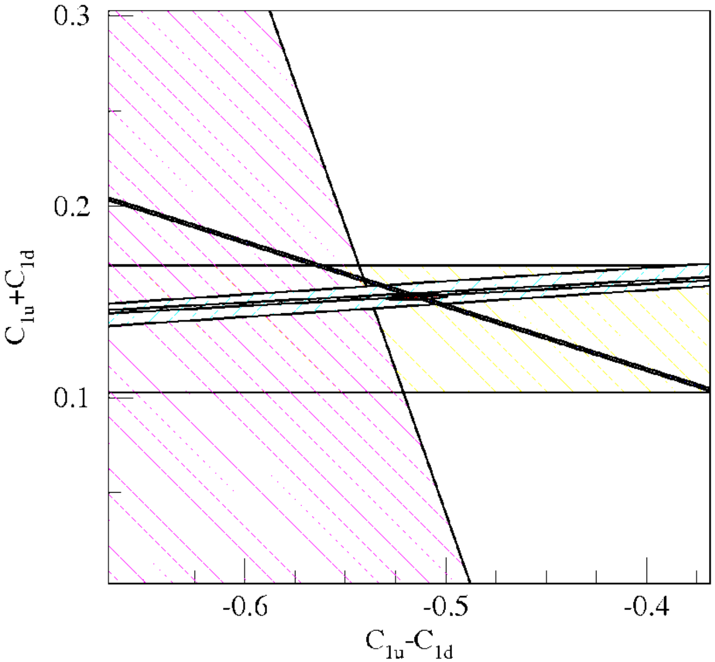

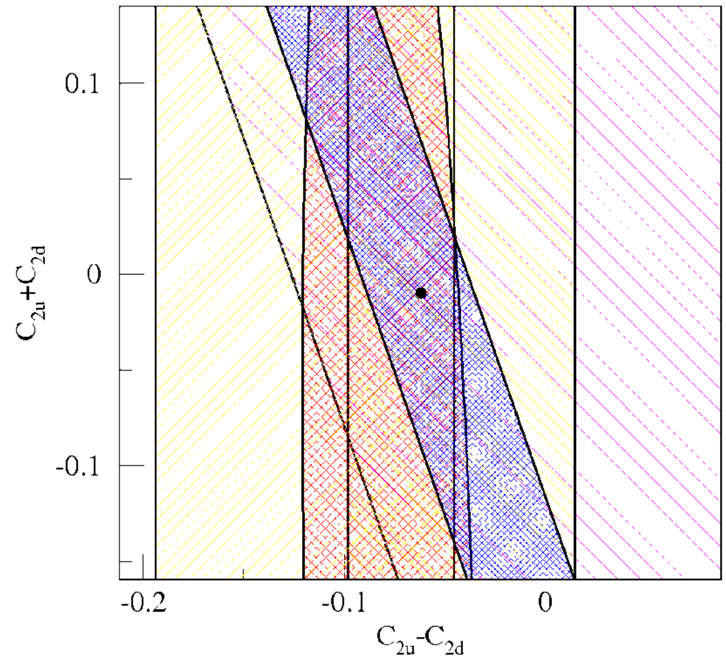

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$$R_s(x) = \frac{2S(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 0$$

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

QCD

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

QCD: Charge Symmetry Violation

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

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

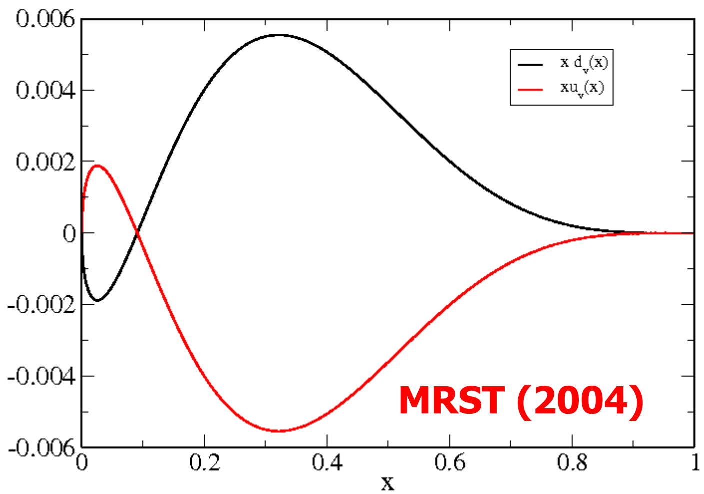
We already know CSV exists:

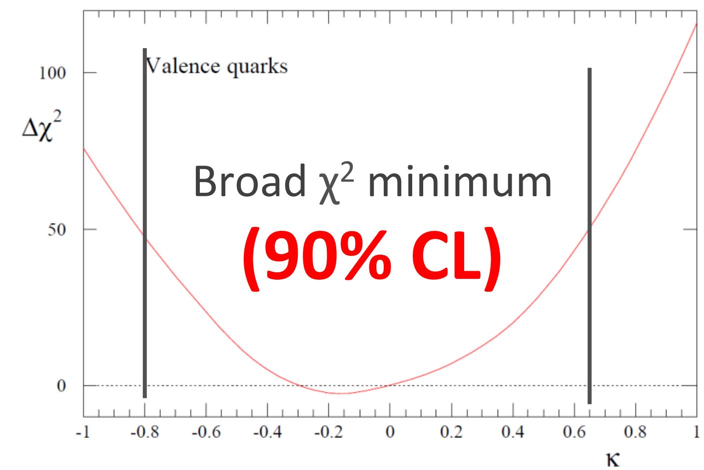
- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects
- Direct observation of CSV—very exciting!
- Important implications for PDF's
- *Could be a* partial explanation of the NuTeV anomaly

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

For A_{PV} in electron-^{2}H DIS:

MRST PDF global with fit of CSV
Martin, Roberts, Stirling, Thorne Eur Phys J C**35**, 325 (04)





QCD:
Charge Symmetry Violation

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

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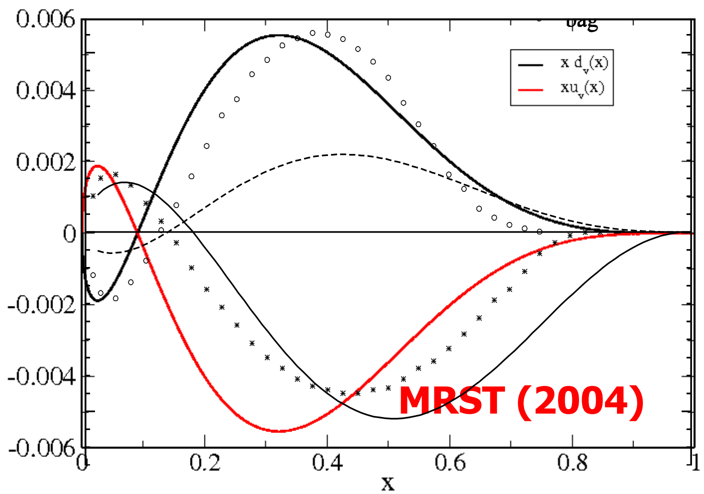
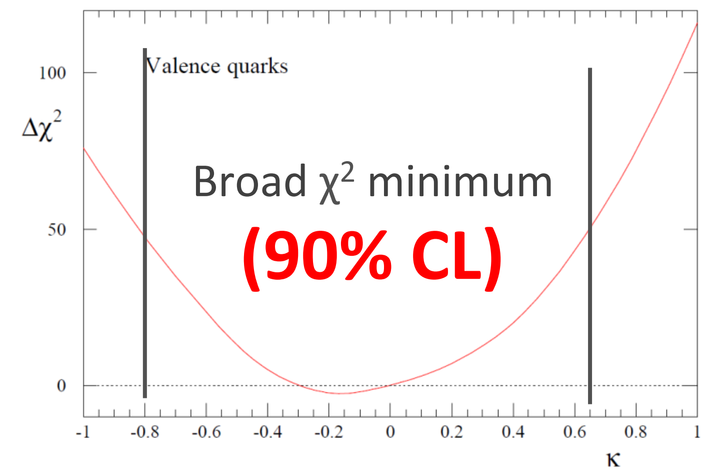
MRST PDF global with fit of CSV
Martin, Roberts, Stirling, Thorne Eur Phys J C**35**, 325 (04)

Londergan and Thomas
hep-ph/0407247
(analytic model)





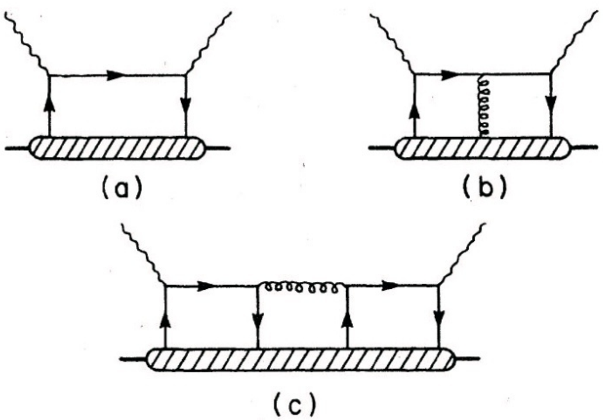
QCD:
Higher Twist

From the Quark Parton Model (QPM) to QCD

1. Add DGLAP evolution
2. Add higher order terms in the Operator Product Expansion (OPE)⟷Higher Twist Terms

Parton Model—leading twist

Quark-gluon diagram



Di-quarks

What is a true quark-gluon operator?

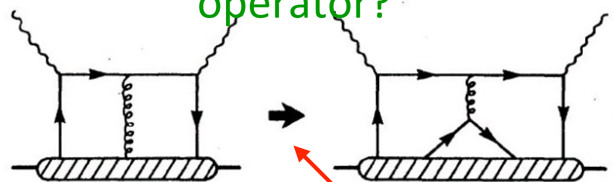


FIG. 3. The only gluon operator that we keep is the operator O^9, which can be expressed as a four-quark operator using the equations of motion.

Quark-gluon operators correspond to transverse momentum

QCD equations of motion

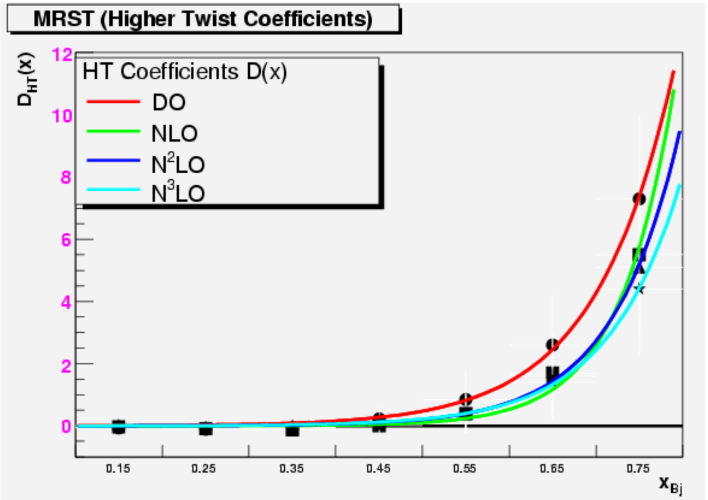
QCD:
Higher Twist--MRST Fits

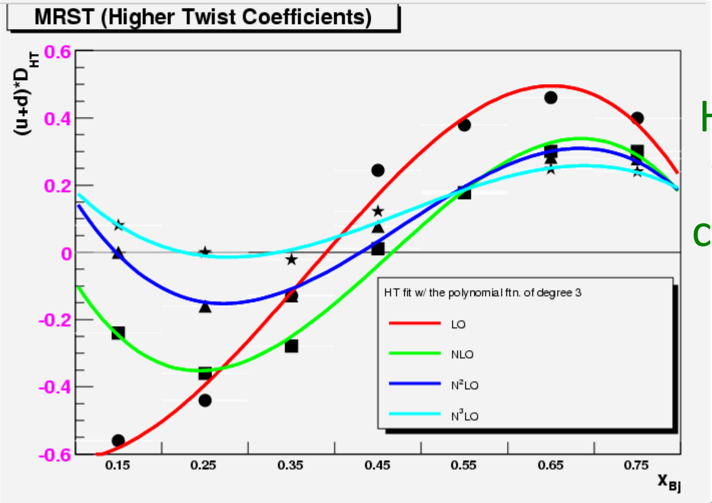
MRST, PLB582, 222 (04)

Order of DGLAP influences size of HT

$F_2(x,Q^2)=F_2(x)(1+D(x)/Q^2)$ $Q^2=(W^2-M^2)/(1/x-1)$ $Q^2_{min}=Q^2(W=2)$

x	Q^2_{min}	D(x)		D/Q^2_{min} (%)	
		LO	N^3LO	LO	N^3LO
0.1-0.2	0.5	-.007	0.001	-14	2
0.2-0.3	1.0	-.11	0.003	-11	0.0
0.3-0.4	1.7	-.06	-0.001	-3.5	-0.5
0.4-0.5	2.6	.22	0.11	8	4
0.5-0.6	3.8	.85	0.39	22	10
0.6-0.7	5.8	2.6	1.4	45	24
0.7-0.8	9.4	7.3	4.4	78	47





$$A_{\rm meas.} = A_{\rm PV}\left[1+\frac{C(x)}{Q^2}\right]$$

If C(x)~D(x), there is large sensitivity al large x.

Higher twist falls slowly compared to PDF's at large x.

Need Full Phenomenology

$$\left[\frac{d^2\sigma}{dxdy}\right]_{EM} \propto 2xyF_1^{\gamma} + \frac{2}{y}\left(1 - y - \frac{xyM}{2E}\right)F_2^{\gamma}$$

$$F_1^{\gamma} = F_2^{\gamma}(1+R) \rightarrow R = \frac{\sigma_L}{\sigma_T}$$

$$\left[\frac{d^2\sigma}{dxdy}\right]_{\gamma Z}^{V} \propto \frac{G}{2\sqrt{2\pi\alpha}}\left\{-g_A\left[2xyF_1^{\gamma Z} + \frac{2}{y}\left(1 - y - \frac{xyM}{2E}\right)F_2^{\gamma Z}\right]\right\}$$

$$\left[\frac{d^2\sigma}{dxdy}\right]_{\gamma Z}^{A} \propto \frac{G}{2\sqrt{2\pi\alpha}}\left[-g_V x(2-y)F_3^{\gamma Z}\right]$$

There are 5 relevant structure functions

Isospin rotation of νd charge current

$$F_3^{\gamma Z} = \frac{5}{18}F_3^{\nu}$$

$$A_B^{PV} = \frac{\sigma_{\gamma Z}^{V} + \sigma_{\gamma Z}^{A}}{\sigma_{EM}}$$

BIG

Small; use ν data (Higher twist workshop at Madison, Wisconsin)

Why HT in PVDIS is Special

Bjorken,
PRD 18, 3239 (78)
Wolfenstein,
NPB146, 477 (78)

$$A \propto \frac{l_{\mu\nu}\int\langle D\,|\,j^{\mu}(x)J^{\nu}(0)+J^{\mu}(x)j^{\nu}(0)\,|\,D\rangle e^{iq\cdot x}d^4x}{l_{\mu\nu}\int\langle D\,|\,j^{\mu}(x)j^{\nu}(0)\,|\,D\rangle e^{iq\cdot x}d^4x}$$

$$V_\mu = \left(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d\right) \Leftrightarrow S_\mu = \left(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d\right)$$

$$\langle VV\rangle = l_{\mu\nu}\int\langle D\,|\,V^{\mu}(x)V^{\nu}(0)\,|\,D\rangle e^{iq\cdot x}d^4x$$

Isospin decomposition before using PDF's

$$A = \frac{(C_{1u}-C_{1d})\langle VV\rangle + \frac{1}{3}(C_{1u}+C_{1d})\langle SS\rangle}{\langle VV\rangle + \frac{1}{3}\langle SS\rangle}$$

Zero in QPM

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

HT in F_2 may be dominated by quark-gluon correlations

Higher-Twist valance quark-quark correlations

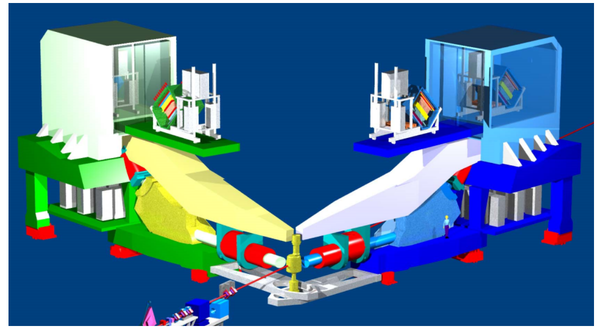
Vector-hadronic piece only

Use ν data for small b(x) term.

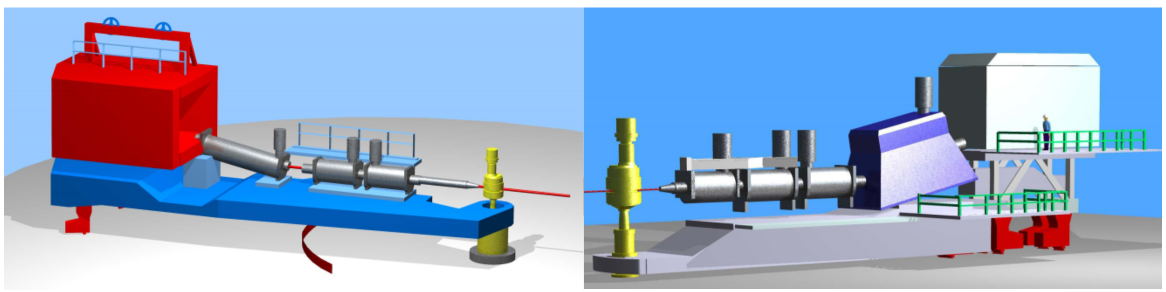
Future PVDIS Measurements at JLab

- JLab Hall A 6 GeV

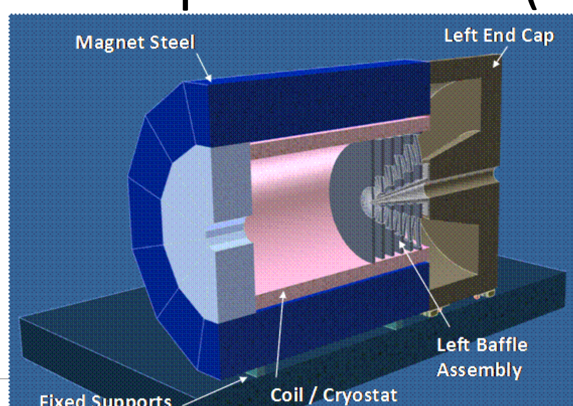
  See talk by Xiaochao Zheng

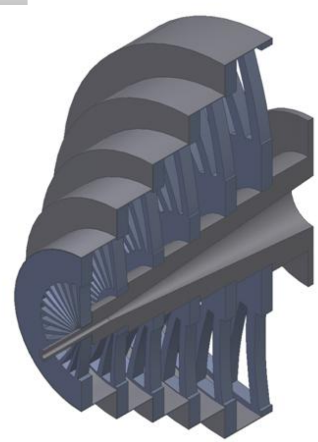


- JLab Hall C Baseline Spectrometers (12 GeV)

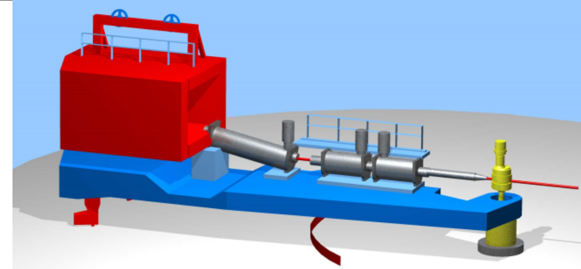


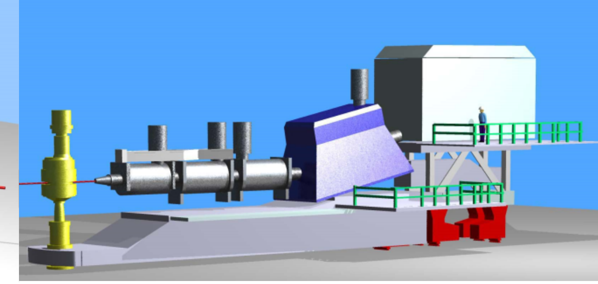
- JLab Hall A SOLID Spectrometer (12 GeV)





12 GeV Hall C Baseline equipment

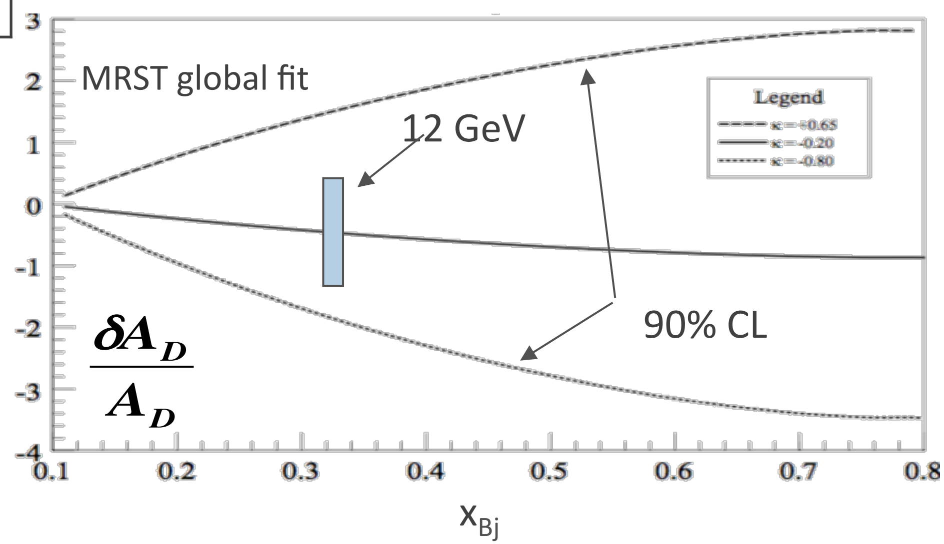




- Measurement with baseline spectrometers
- Sensitive to both Hadronic effects and to Standard Model effects

Approximate Kinematics					
x_{Bj}	Q^2 (GeV^2)	E' (GeV)	Θ (deg)	W^2 (GeV)	A_d (ppm)
0.35	3.3	6.0	13.5	7.1	-285

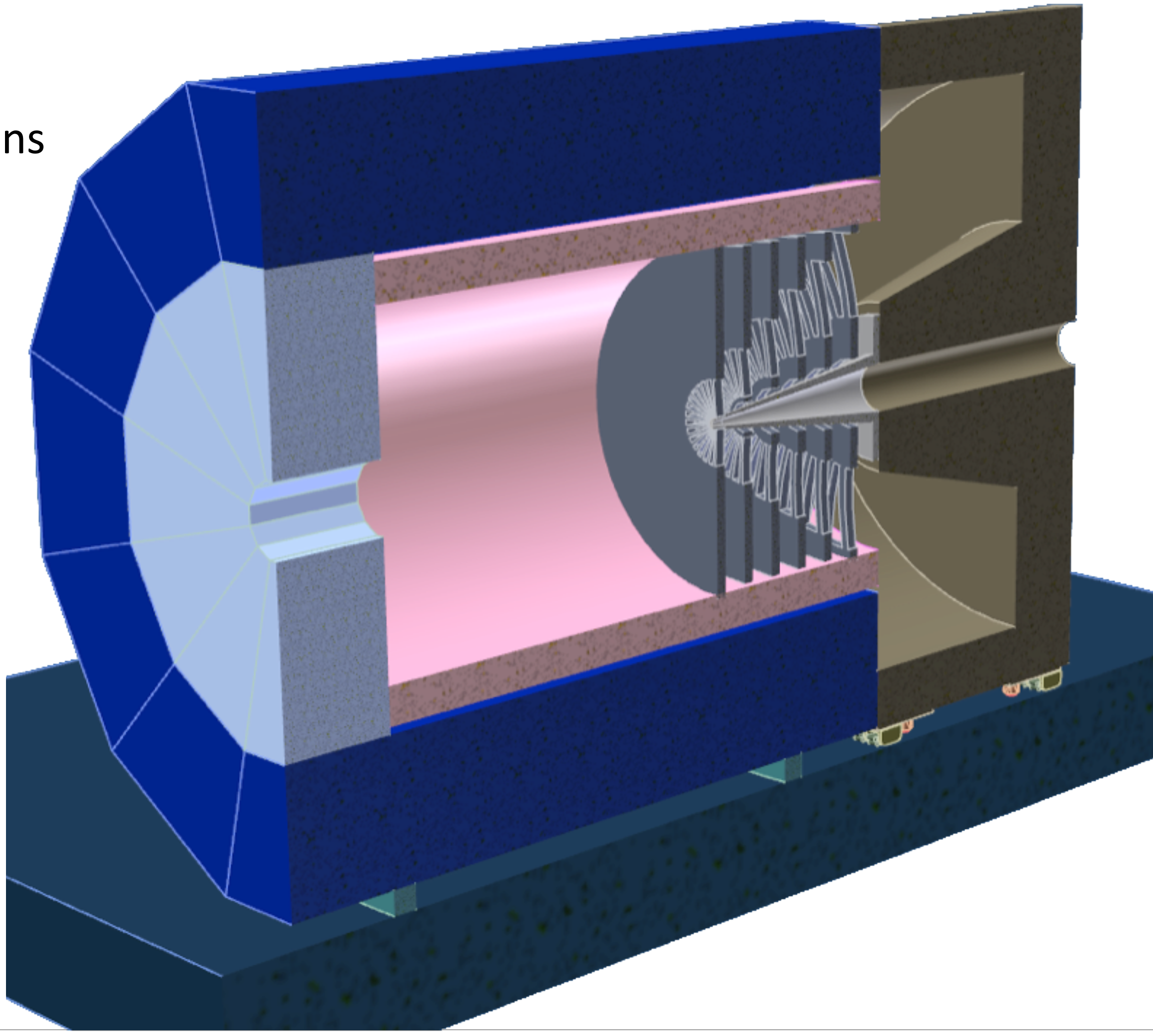
Uncertainty ($\delta A_d/A_d \times 10^{-3}$)		
Statistical		5.0
Systematic		
	Polarimetry	5
	Q^2	4
	Rad. Corr.	4
	Total Syst.	7.6



If there is something interesting (Charge Symmetry Violation or Standard Model deviation) the experiment may be able to see it—but baseline equipment expt. cannot tell the difference.

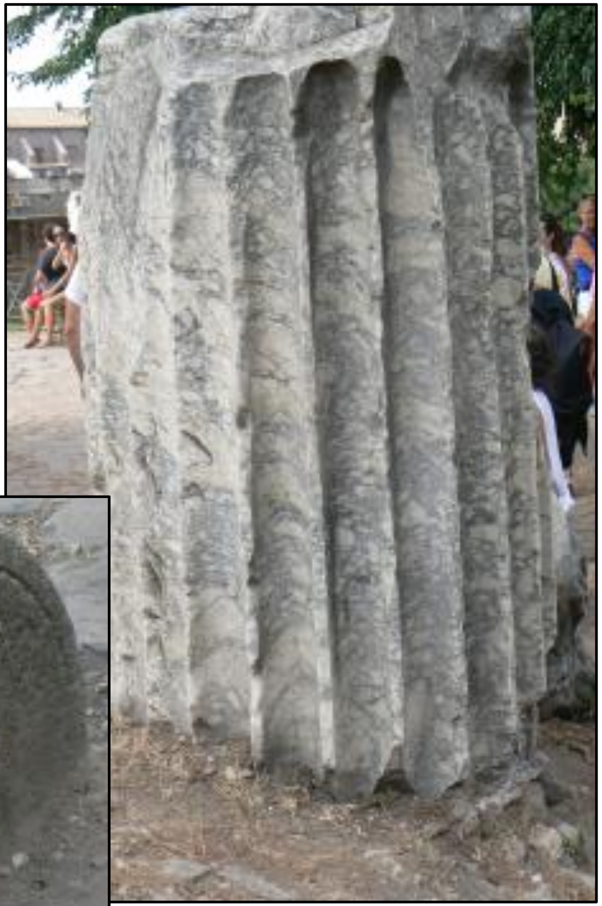
SoLID: A large acceptance apparatus for JLab Hall A

- **Moderate running times**
  - **Large Acceptance**
  - High Luminosity on LH2 & LD2
- Better than 1% errors for small bins
- Kinematics:
  - Large Q^2 coverage
  - x-range 0.25-0.75
  - $W^2 > 4\ \text{GeV}^2$
- Spectrometer requirements:
  - Solenoid contains low energy backgrounds (Møller, pions, etc)



Search for a Solenoid

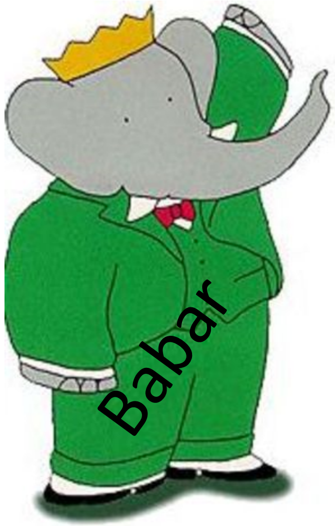
- There are a number of Solenoids available right around Rome



Search for a Solenoid

- There are a number of Solenoids available right around Rome
- And even period appropriate transportation schemes

Step 1: Find a solenoid—"The usual suspects"



CDF

- MEGA (Hall D)
- New Hall D design
- All could work within the constraints of our physics needs
- **Present effort focused on CLEO Magnet**

SoLID: A large acceptance apparatus

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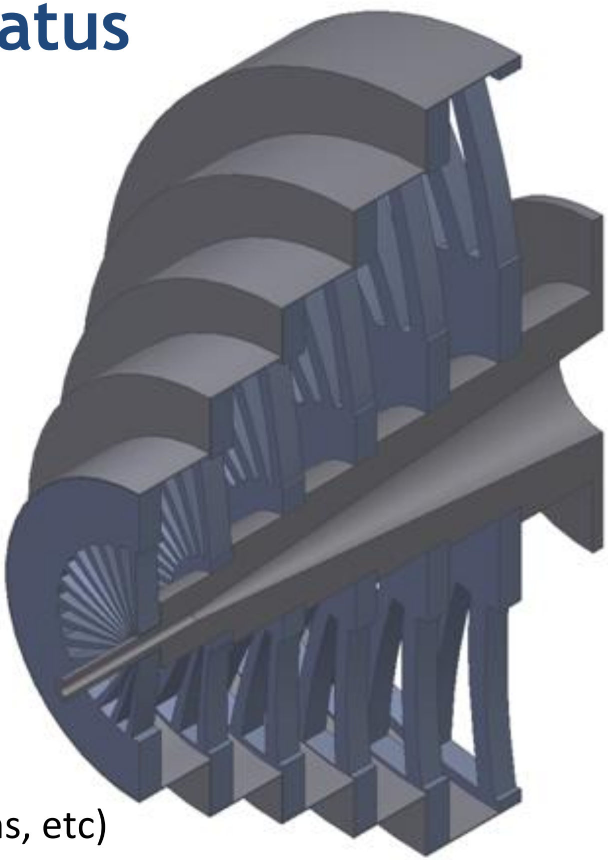
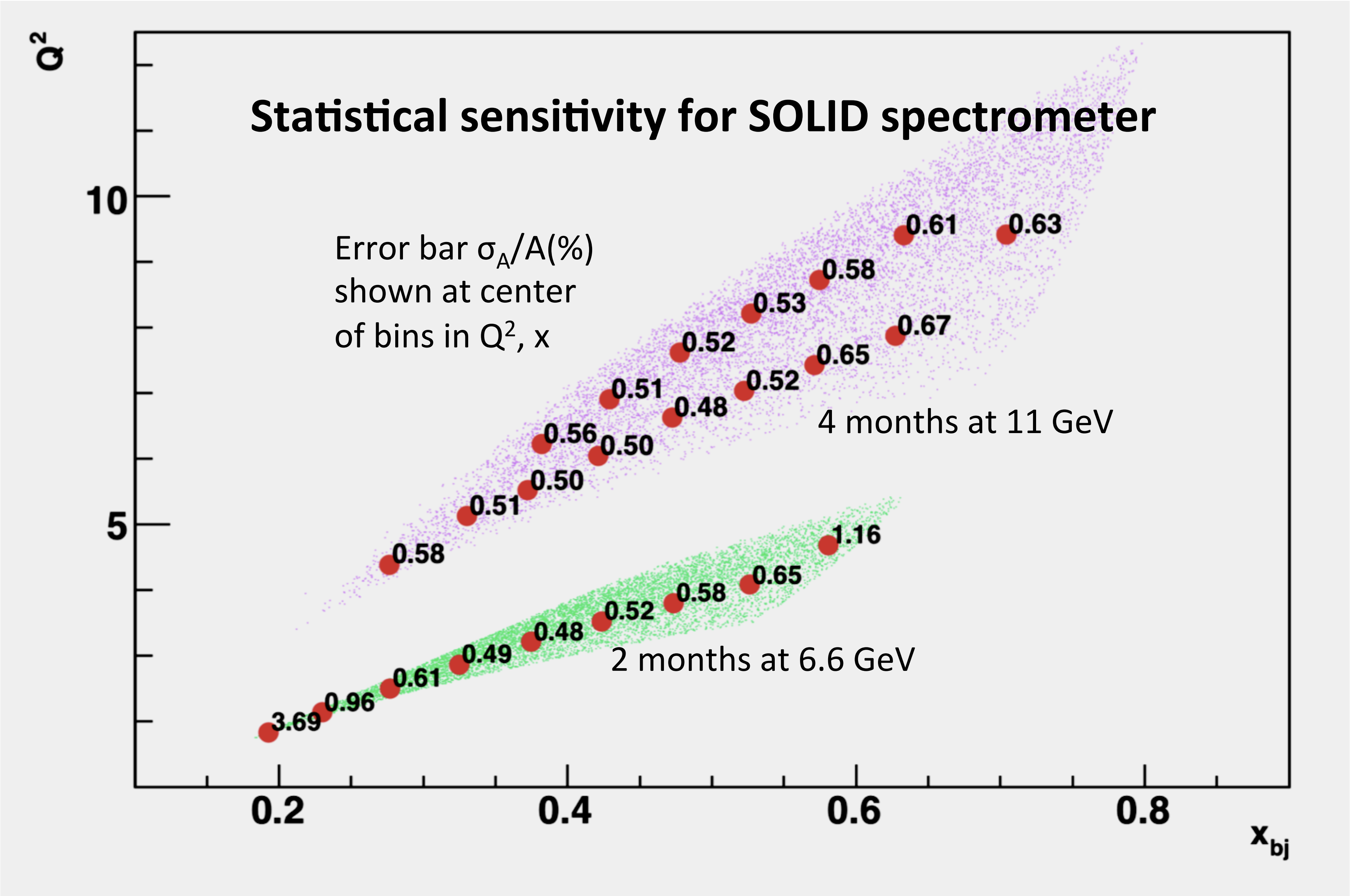


- Spectrometer requirements:
  - Solenoid contains low energy backgrounds (Møller, pions, etc)
  - Polarized e^- beam (M. Poelker, M. Pitt)
  - Trajectories measured after baffles
  - Fast tracking—GEM (E. Cisbani), particle ID, calorimetry, and pipeline electronics
  - Precision polarimetry (0.4%) (see talks by S. Glamazdin, E. Chudakov, K Aulenbacher A. Narayan, M. Friend)

Statistical Errors (%) vs. Kinematics



Coherent Program of PVDIS Study

Strategy: requires precise kinematics and broad range

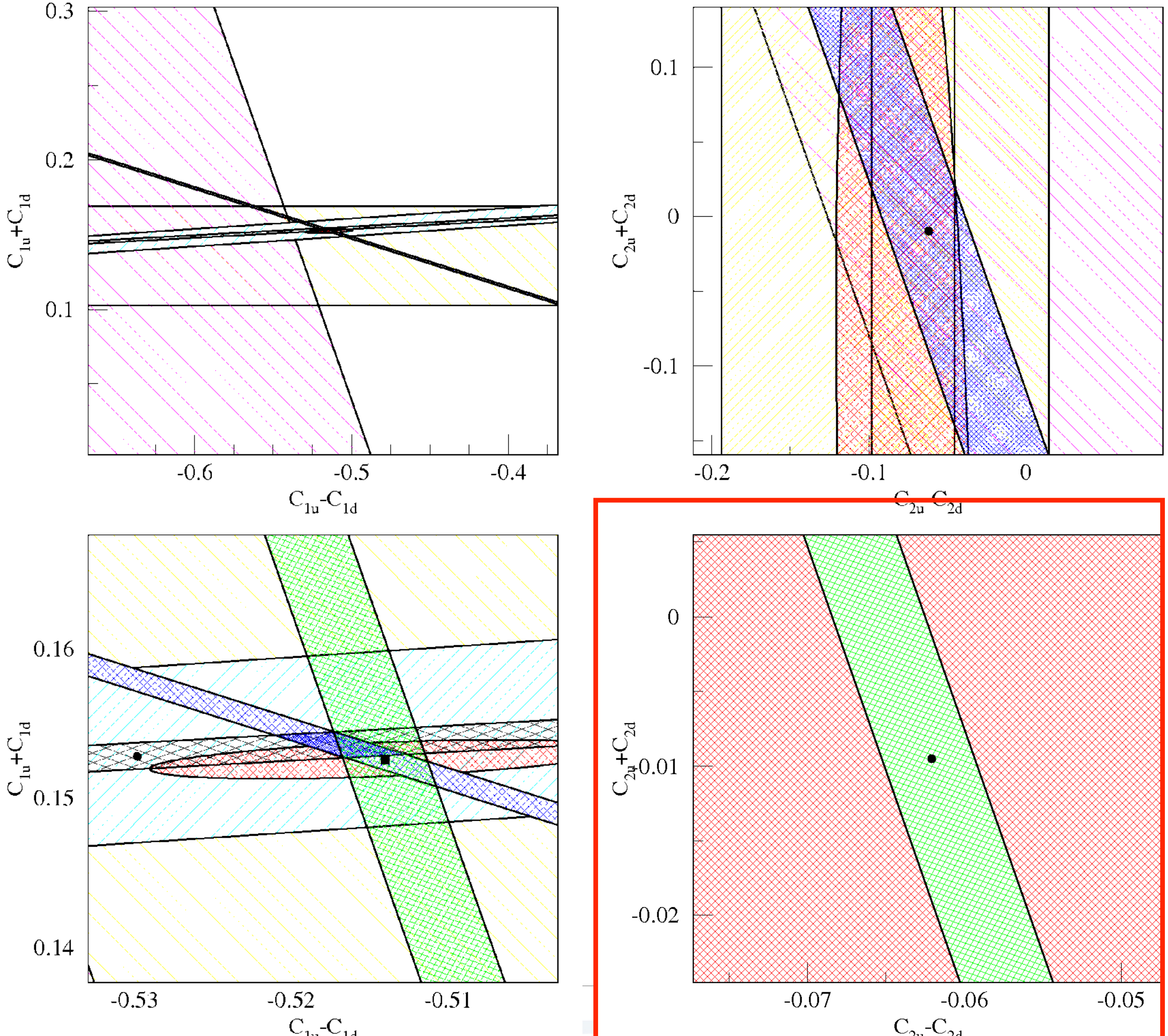
	x	Y	Q^2
New Physics	no	yes	no
CSV	yes	no	no
Higher Twist	yes	no	yes

- 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 to measure a combination of the C_{iq}'s

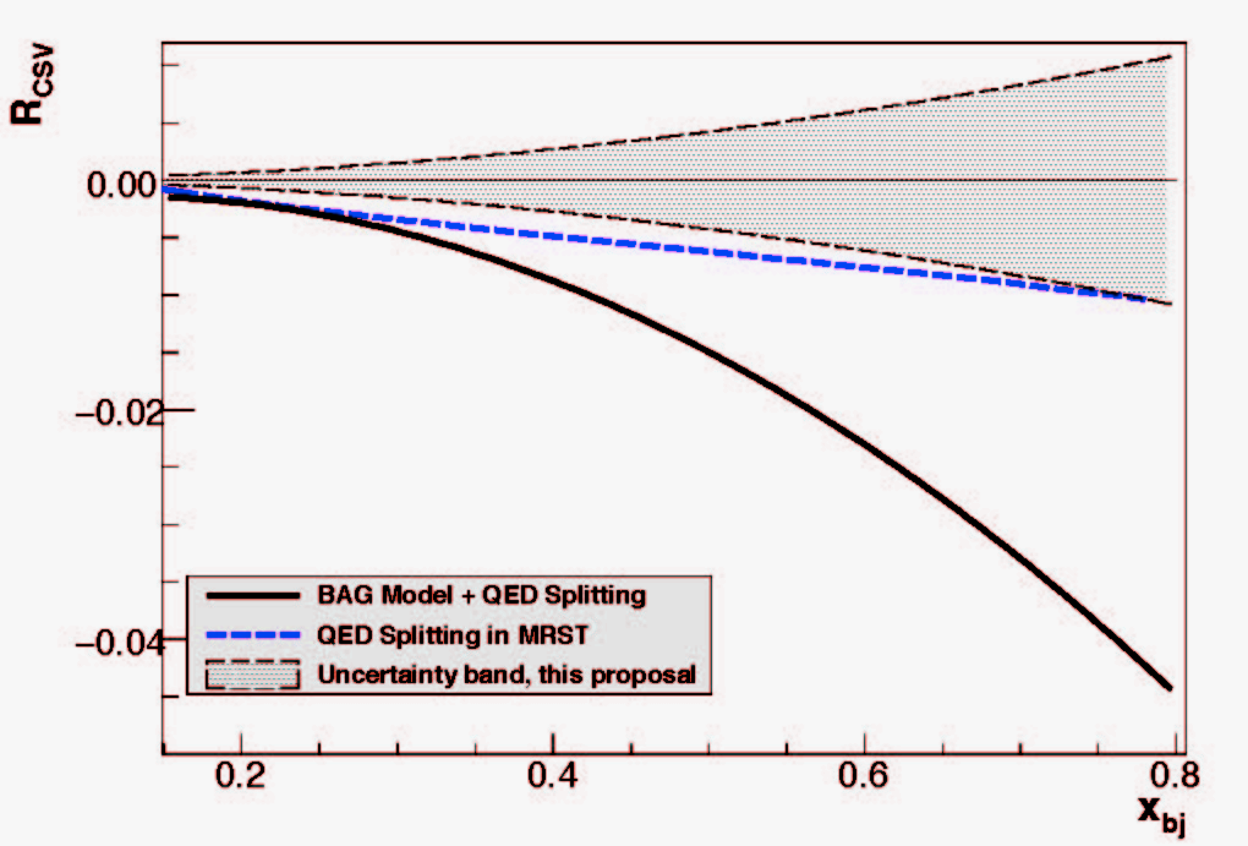
Fit data to: $$A_{\mathrm{Meas.}} = A_{\mathrm{SM}}\left[1 + \frac{\beta_{\mathrm{HT}}}{(1-x)^3 Q^2} + \beta_{\mathrm{CSV}} x^2\right]$$

Sensitivity: C_1 and C_2 Plots

World's data



QCD:
Charge Symmetry Violation



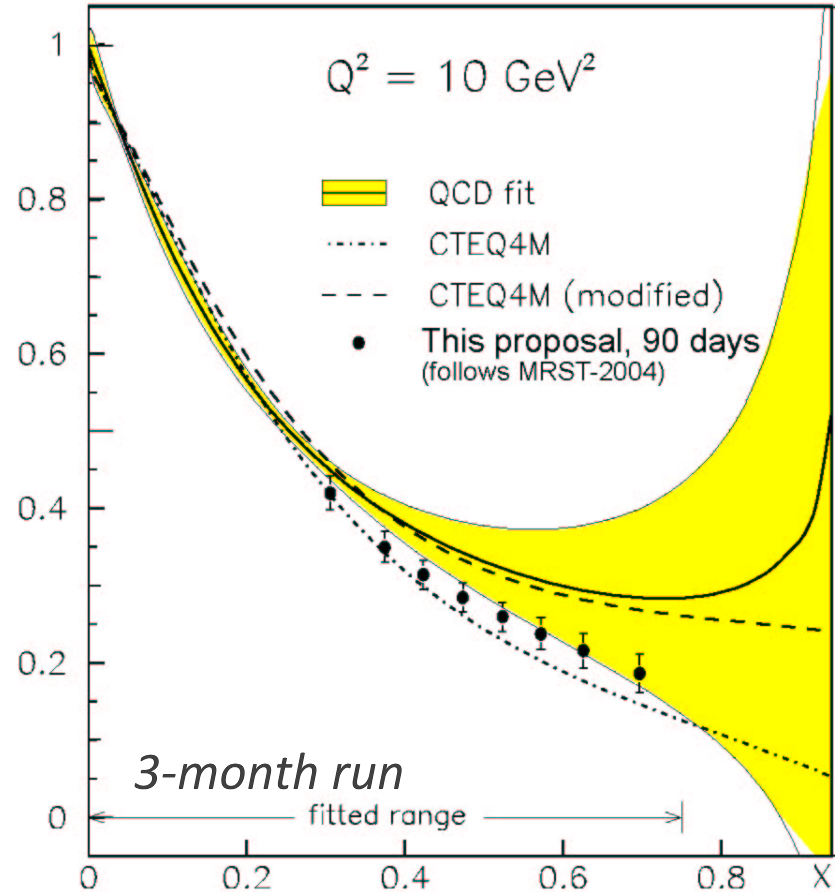
$$\frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

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 (complementary to BONUS)

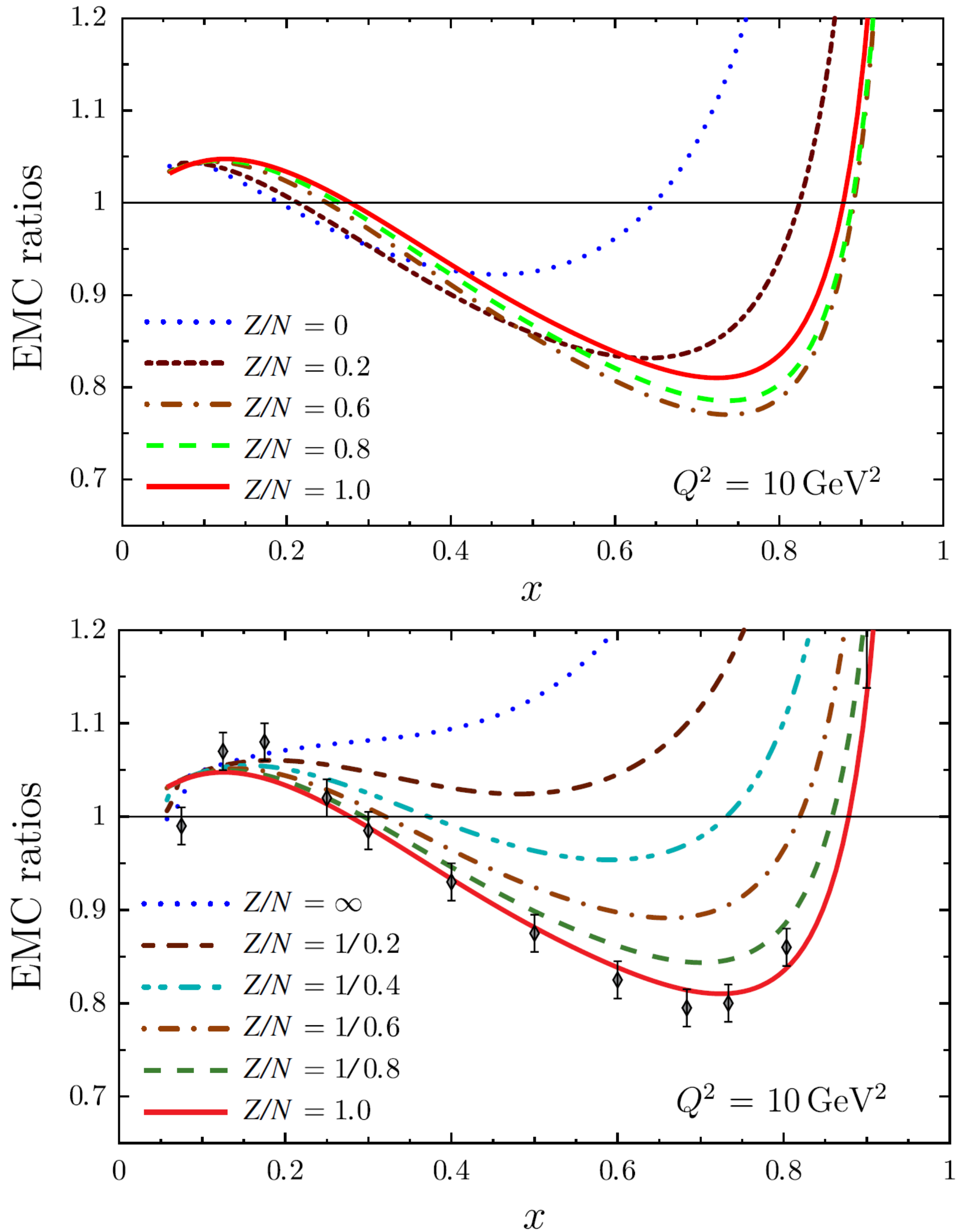


CSV in Heavy Nuclei: EMC Effect

Isovector EMC Effect and the NuTeV Anomaly

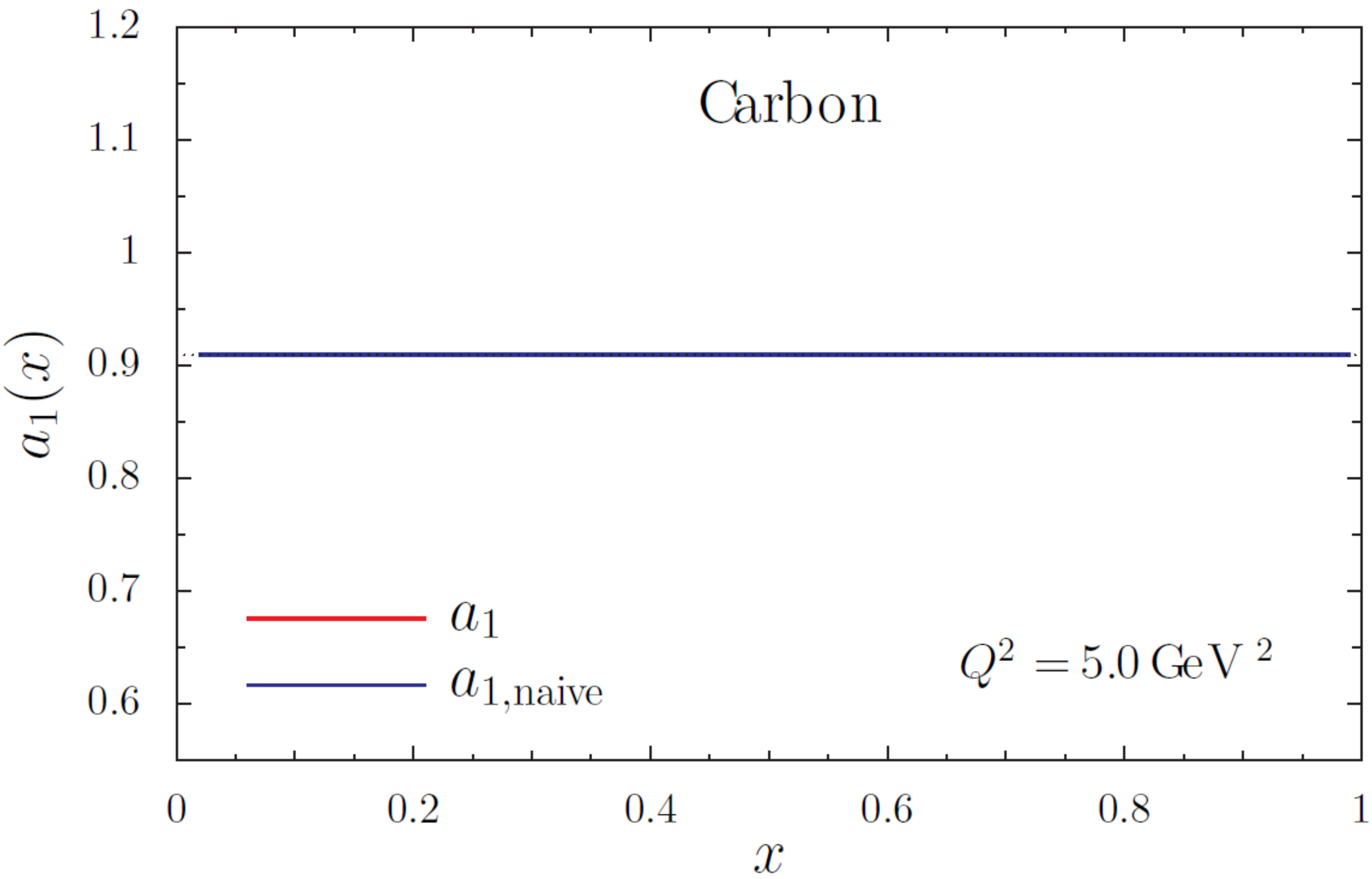
I. C. Cloët,[1] W. Bentz,[2] and A. W. Thomas[3]

PRL **102**, 252301 (2009)

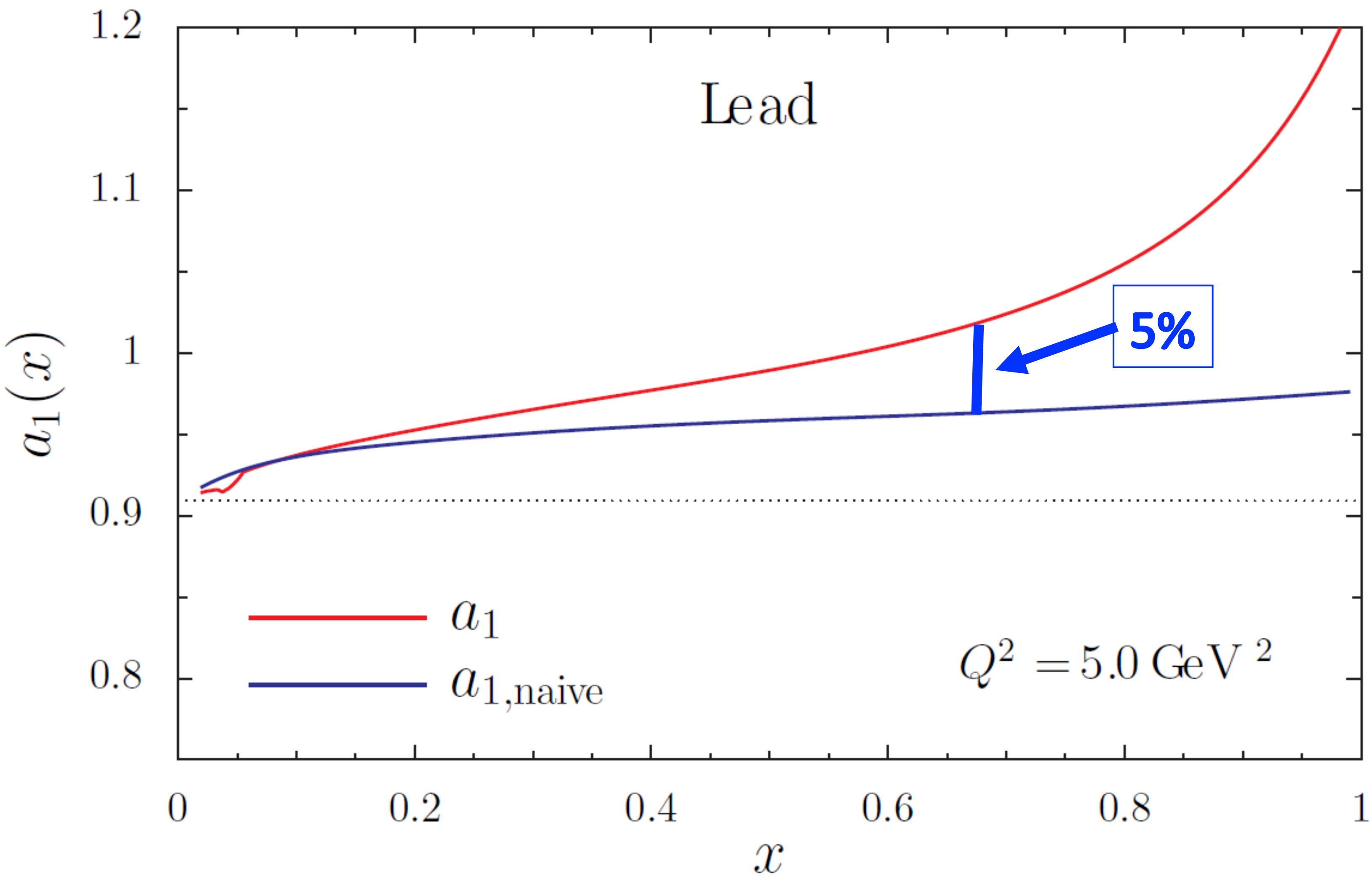


- Mean Field approach to estimate an EMC-like effect for N ≠ Z nuclei
- Possible explanation for NuTeV anomaly which used iron target.

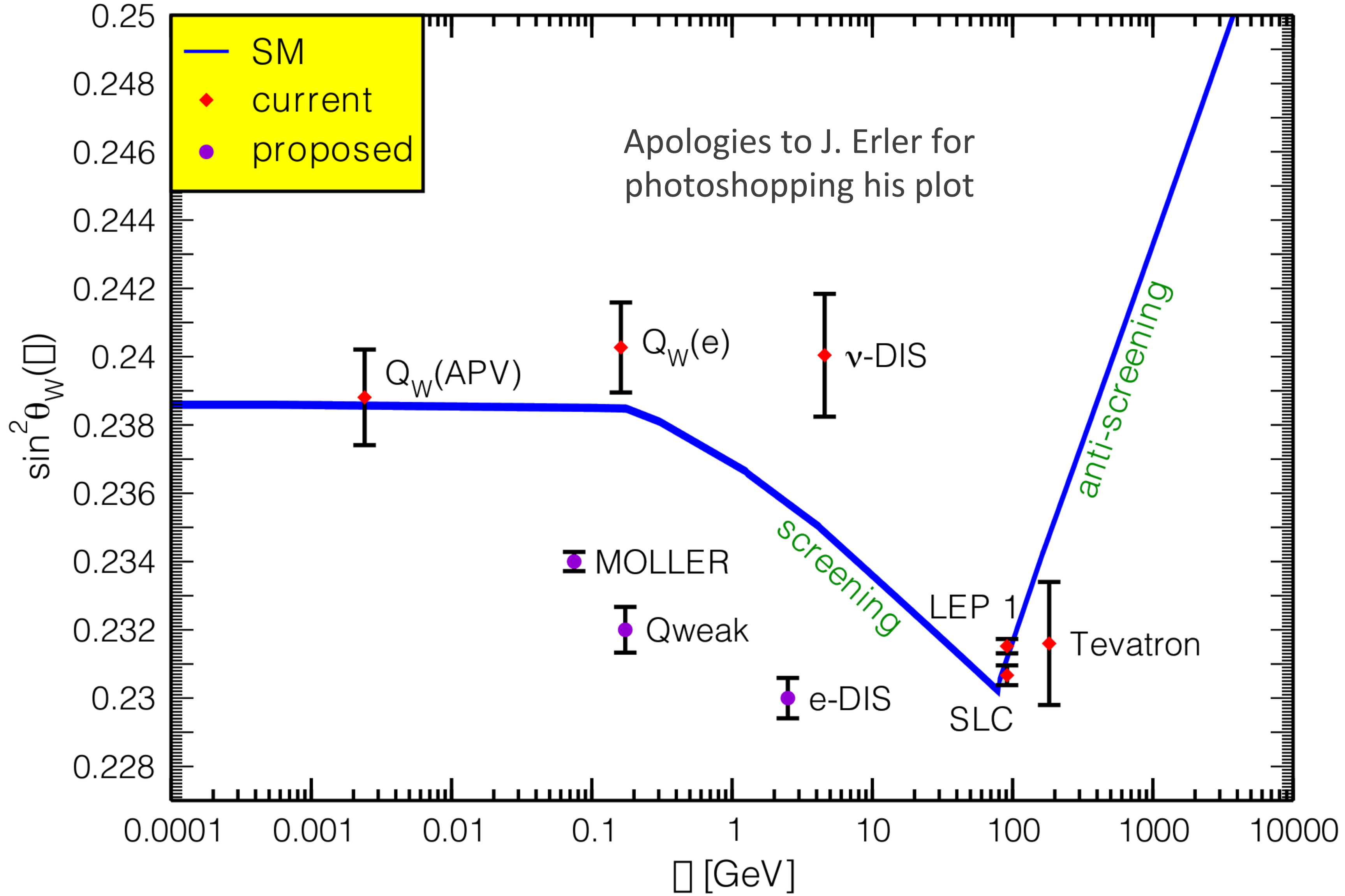
CSV in Heavy Nuclei: EMC Effect



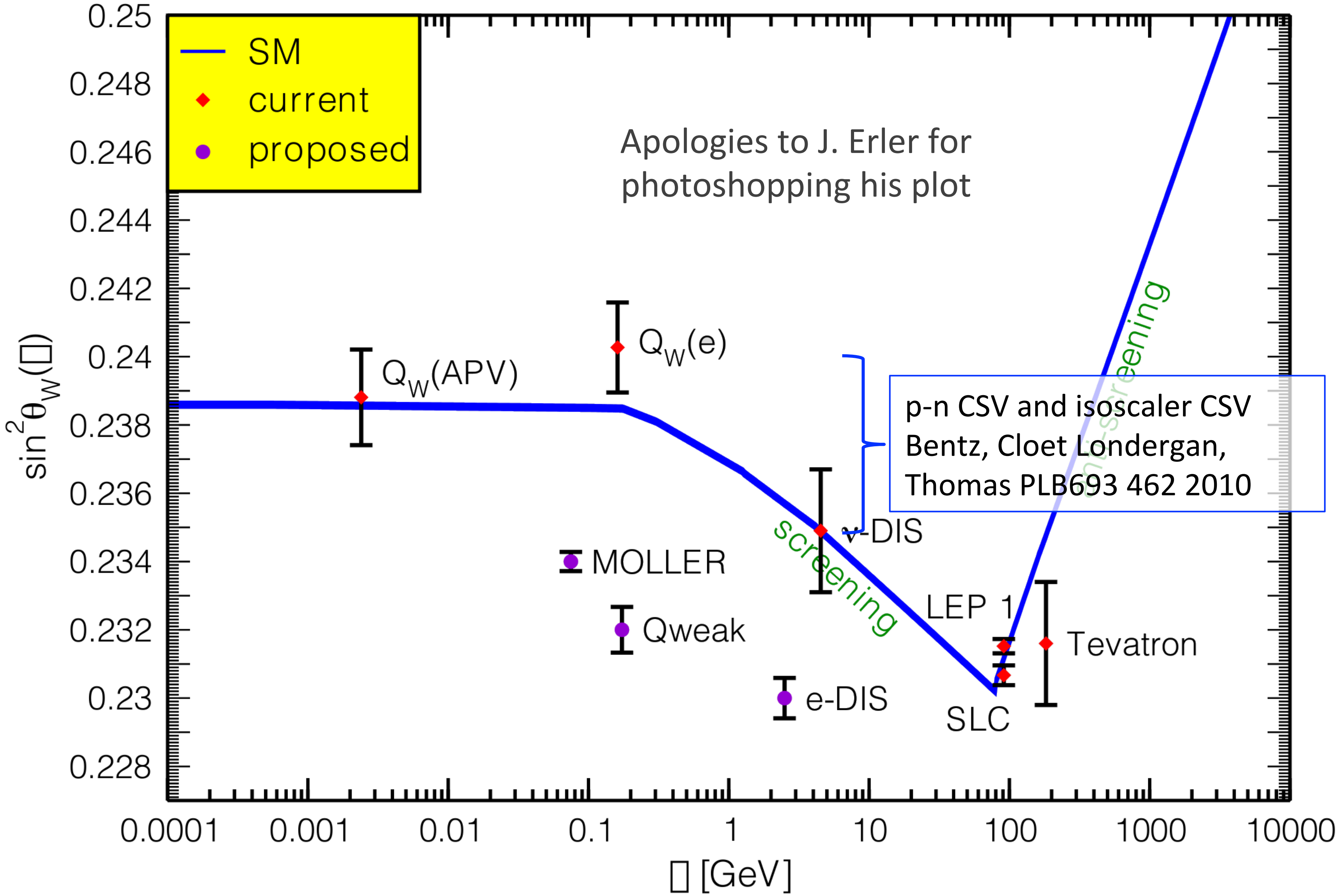
CSV in Heavy Nuclei: EMC Effect



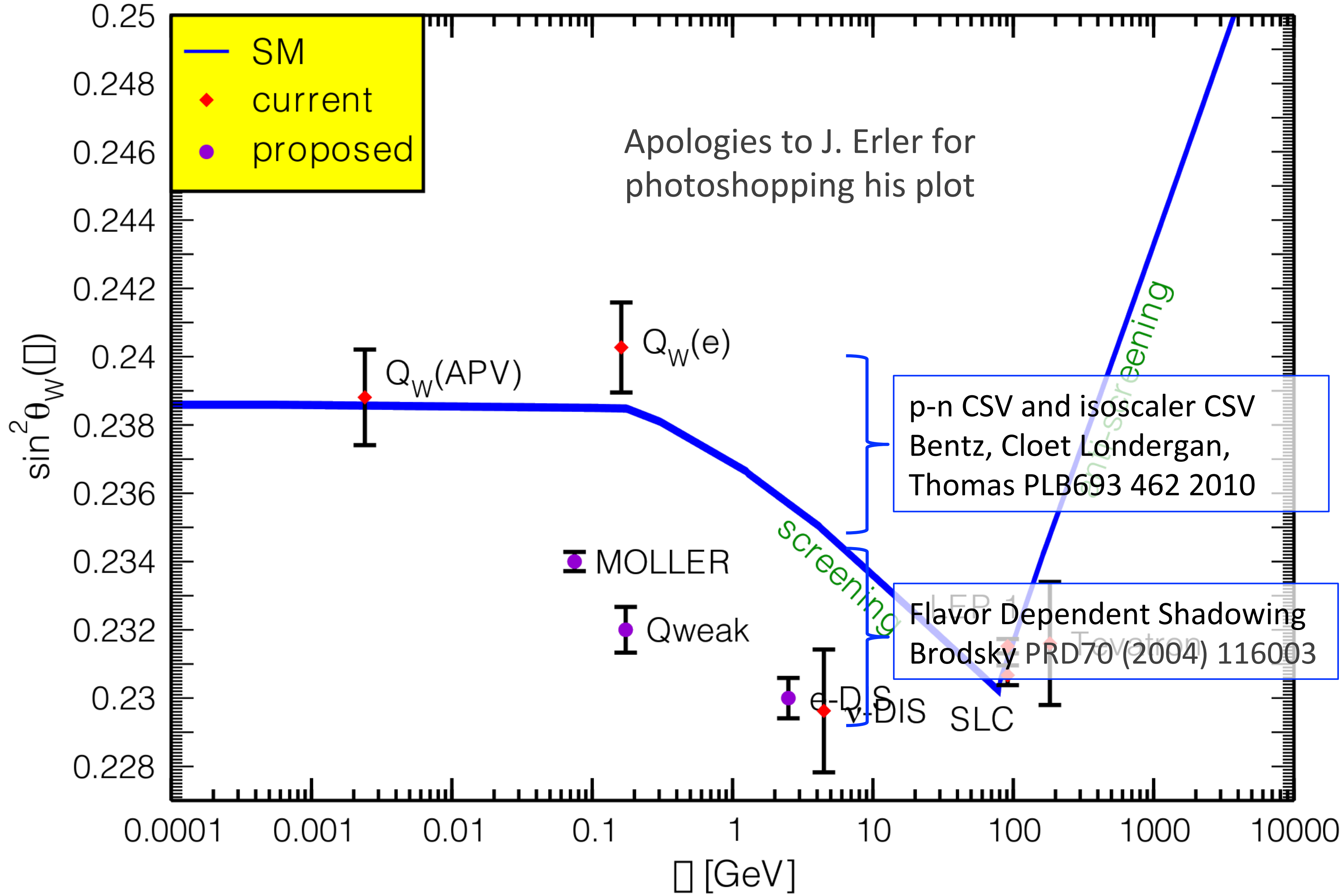
What about NuTeV?



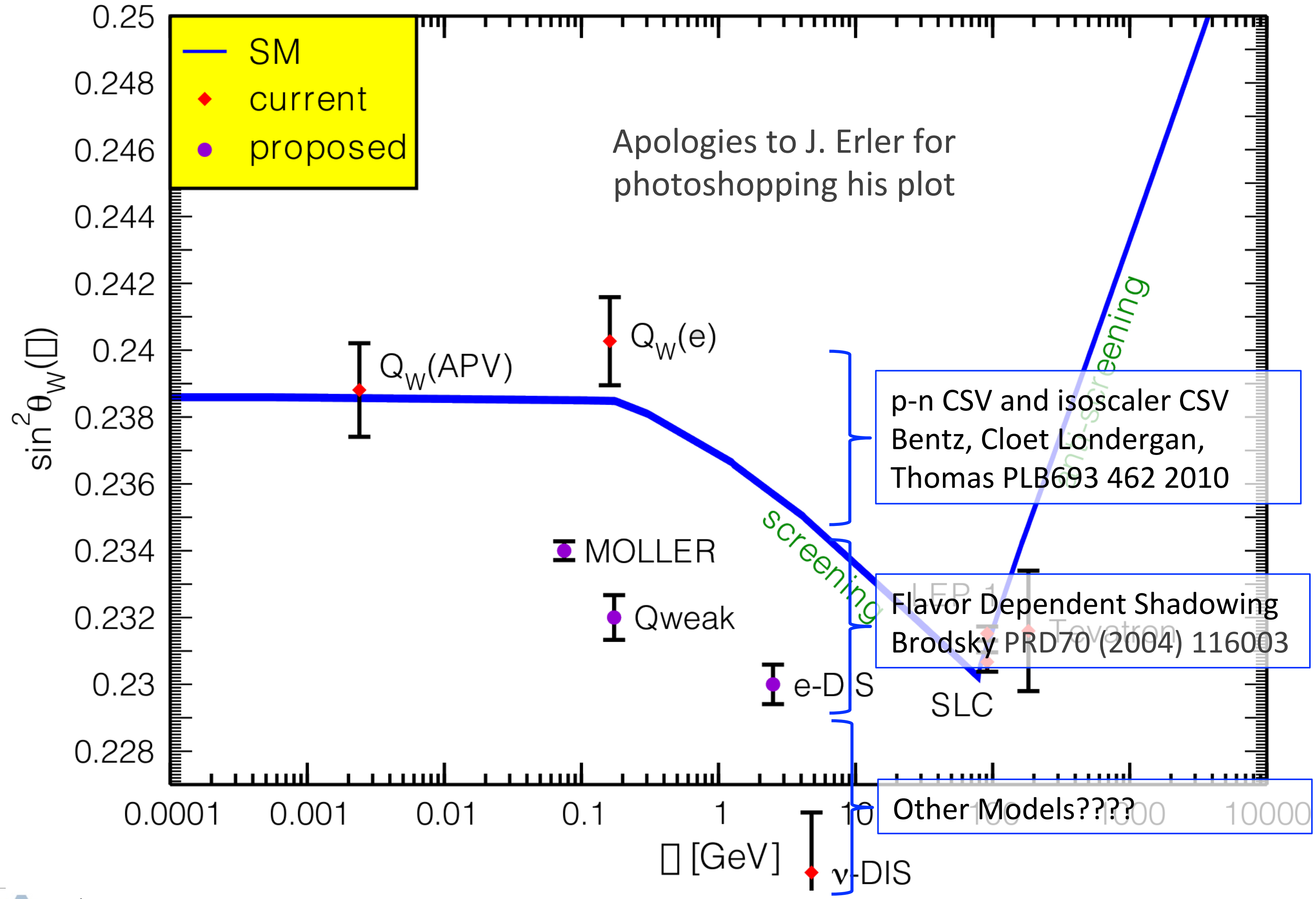
What about NuTeV?



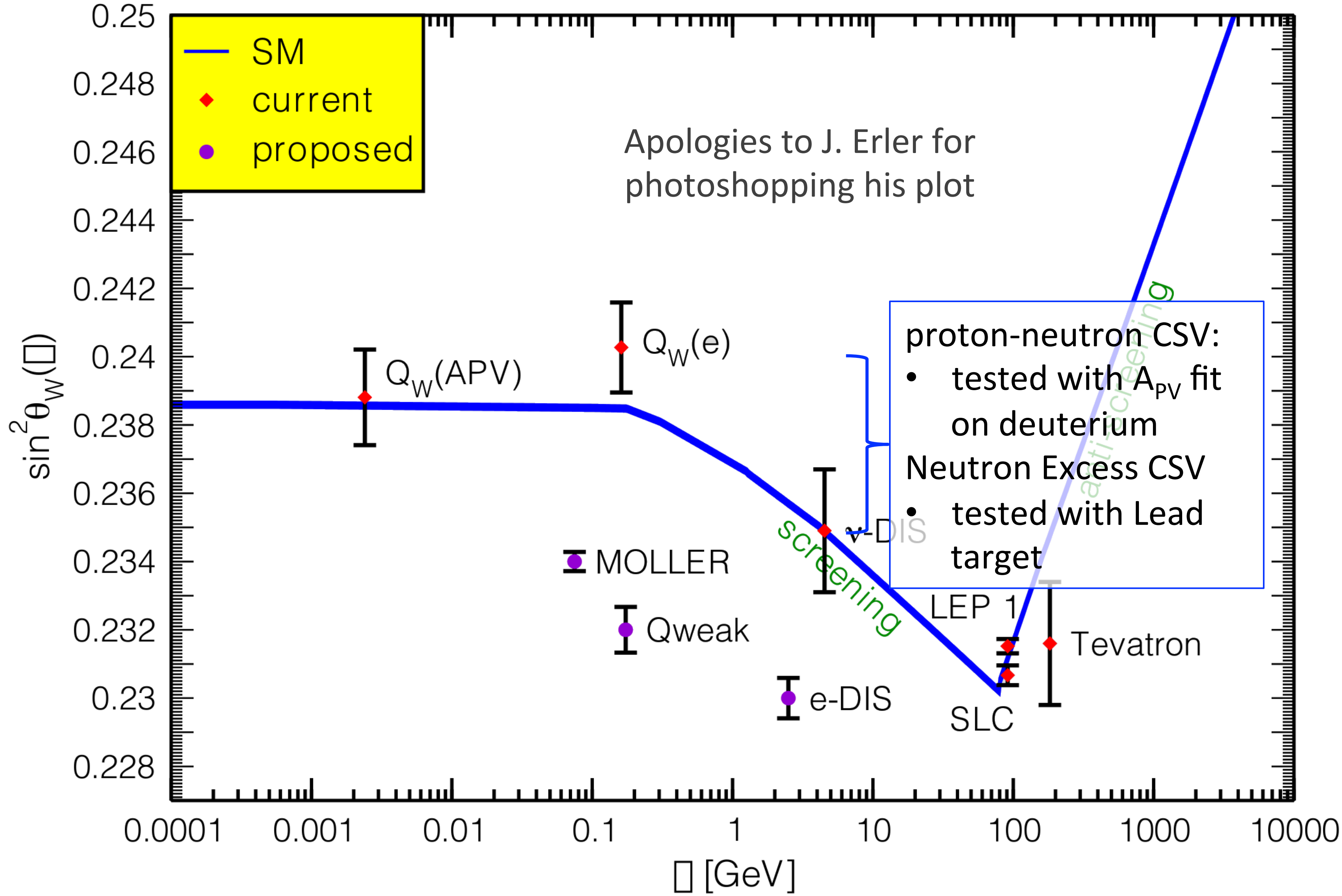
What about NuTeV?



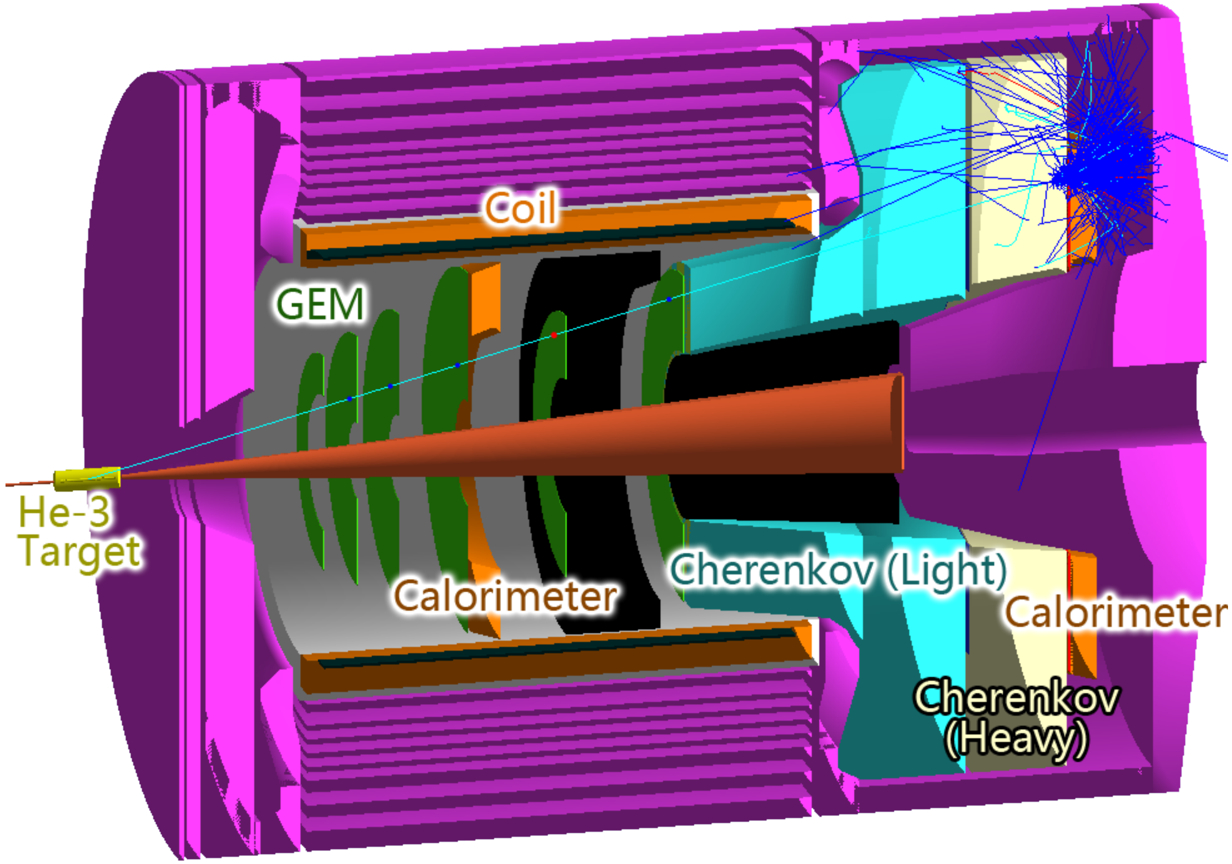
What about NuTeV?



What about NuTeV?



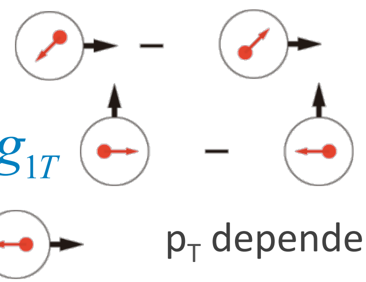
SIDIS and Transverse Spin with the SoLID Spectrometer



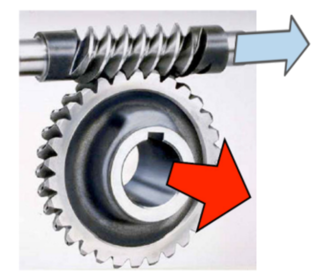
E12-11-007: SIDIS using Longitudinally Pol. ^{3}He and SoLID

a study of spin-orbital correlation

- **Semi-Inclusive DIS $\pi^{\pm}$ production**
  - **Longitudinally Pol. ^{3}He target** effective pol. neutron target, achieved world-best performance
  - **SoLID** large symmetric acceptance detector, high statistics and better angular modulation separation
- **Extraction of novel TMDs**
  - $A_{UL}(\sin(2\phi_h)) \to h_{1L}^{\perp}$
  - $A_{LT}(\cos(\phi_h - \phi_S)) \to g_{1T}$
  - $A_{LL} \to g_{1L}$



WORM-GEAR distributions, interference of OAMs: Re $[(L=0)_q \times (L=1)_q]$



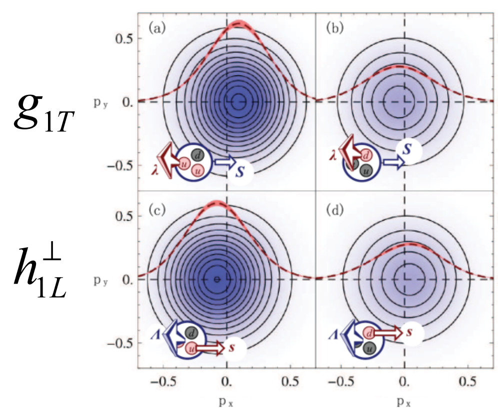
p_T dependent helicity distribution

- **Many predictions available**
  - First Lattice QCD calculation
  - Light-cone quark model and others
- **No GPD Correspondence**
  - Genuine sign of intrinsic transverse motion
- **Links to Collinear PDFs**

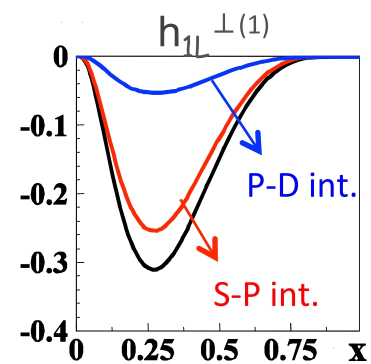
$$h_{1L}^{\perp q(1)}(x) \overset{WW-type}{\approx} -x^2 \int_x^1 \frac{dy}{y^2} \cdot h_1^q(y)$$

$$g_{1T}^{q(1)}(x) \overset{WW-type}{\approx} x \int_x^1 \frac{dy}{y} \cdot g_1^q(y)$$

hep-ph/0603194



Lattice QCD, arXiv:0908.1283



Light-Cone CQM, arXiv:0806.2298

Summary

- Measurements of Parity Violation in Deep Inelastic Scattering contain a wealth of information about:
  - The Standard Model
  - Charge Symmetry (CSV)
  - Higher Twist (HT)

- For the complete picture—to unravel the full richness of the physics reach of this process a dedicated—a large-acceptance spectrometer is needed.

- SoLID will also provide critical nuclear structure test (NuTeV $\sin^2\theta_W$)

- Large additional program of SI-DIS planned for SoLID spectrometer