Precision Measurements of Parity-Violation in Deep Inelastic Scattering using SoLID

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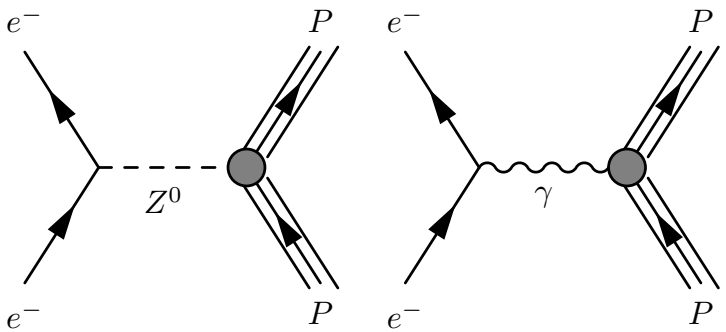
April 29^{th}, 2015

Outline

Parity Violating Electron Scattering



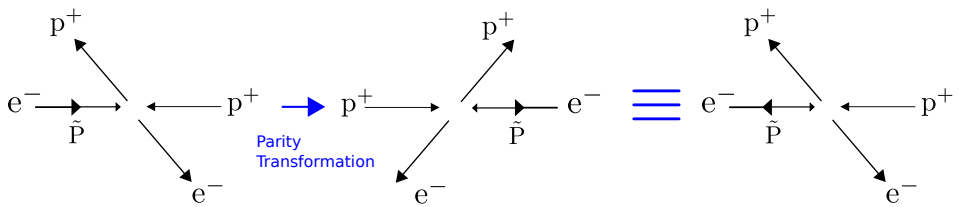
$$\mathrm{M}^{\mathrm{EM}} = \frac{4\pi\alpha}{\mathrm{Q}^2}\mathrm{Q}_\ell \not{l}^\mu \mathrm{J}^{\mathrm{EM}}_\mu$$

$$\mathrm{M}^{\mathrm{NC}} = \frac{-\mathrm{G_F}}{2\sqrt{2}}(\mathrm{g}^\ell_{\mathrm{V}} \not{l}^\mu + \mathrm{g}^\ell_{\mathrm{A}} \not{l}^{\mu 5})(\mathrm{J}^{\mathrm{NC}}_\mu + \mathrm{J}^{\mathrm{NC}}_{\mu 5})$$

Differential scattering cross section,

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \propto |\mathrm{M}^{\mathrm{Total}}|^2 \simeq |\mathrm{M}^{\mathrm{EM}}|^2$$

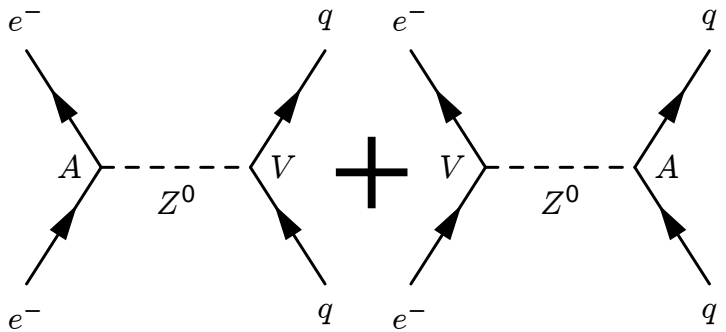
Due to PV nature of the neutral current, the differential cross section is dependent on the helicity of the electron

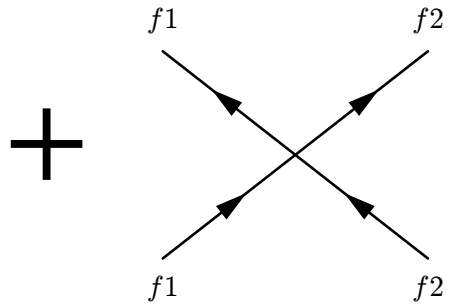


The difference in helicity correlated scattering cross section is known as the PV asymmetry,

$$\mathrm{A_{LR}} = \frac{\frac{\mathrm{d}\sigma^{\mathrm{R}}}{\mathrm{d}\Omega} - \frac{\mathrm{d}\sigma^{\mathrm{L}}}{\mathrm{d}\Omega}}{\frac{\mathrm{d}\sigma^{\mathrm{R}}}{\mathrm{d}\Omega} + \frac{\mathrm{d}\sigma^{\mathrm{L}}}{\mathrm{d}\Omega}} \propto \frac{\mathrm{M}^{\mathrm{EM}} \cdot \mathrm{M}^{\mathrm{NC}}}{|\mathrm{M}^{\mathrm{EM}}|^2}$$

Electron-Quark Couplings





EW neutral current interaction

New physics

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

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

Vector hadronic currents: PV elastic e-p scattering, Atomic PV

Axial hadronic currents: PV deep inelastic scattering

$$\mathrm{C_{1u}} = -\frac{1}{2} + \frac{3}{4}\sin^2\theta_\mathrm{W} \simeq -0.19$$

$$\mathrm{C_{1d}} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_\mathrm{W} \simeq 0.35$$

$$\mathrm{C_{2u}} = -\frac{1}{2} + 2\sin^2\theta_\mathrm{W} \simeq -0.04$$

$$\mathrm{C_{2d}} = \frac{1}{2} - 2\sin^2\theta_\mathrm{W} \simeq 0.04$$

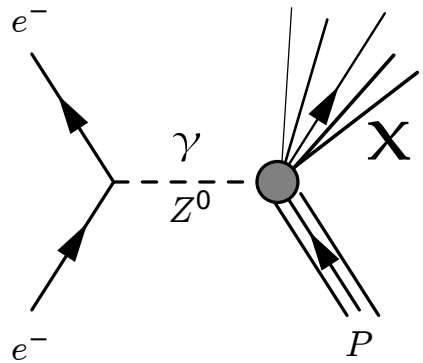
Parity Violating Deep Inelastic Scattering Asymmetry

$$A_{PV}^{DIS} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}[2g_A^e Y_1(y)\frac{F_1^{\gamma Z}}{F_1^Z} + 2g_V^e Y_3(y)\frac{F_3^{\gamma Z}}{F_1^Z}]$$

For $Q^2 >> 1$ GeV^2 and $W^2 > 4$ GeV^2

$$= \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}[a_1(x)Y_1(y) + a_3(x)Y_3(y)]$$

$$\text{Where, } Y_1 \simeq 1; Y_3 \simeq \frac{1-(1-y)^2}{1+(1-y)^2}$$



Isocalar Target Approx.

For isoscalar (deuteron) target, PVDIS asymmetry becomes independent of PDFs, x and W; SM makes well-defined predictions for Q^2 and y variations for the asymmetry

$$a_1^D(x) = \frac{6}{5}(2C_{1u} - C_{1d})(1 + \frac{0.6s^+}{u^+ + d^+})$$

$$a_3^D(x) = \frac{6}{5}(2C_{2u} - C_{2d})(\frac{u^- + d^-}{u^+ + d^+})$$

Where $f_i^{\pm} = f_i \pm \bar{f}_i, y = \frac{\nu}{E}$

Parity Violating Deep Inelastic Scattering Asymmetry

$$A_{PV}^{DIS} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[2g_A^e Y_1(y)\frac{F_1^{\gamma Z}}{F_1^Z} + 2g_V^e Y_3(y)\frac{F_3^{\gamma Z}}{F_1^Z}\right]$$

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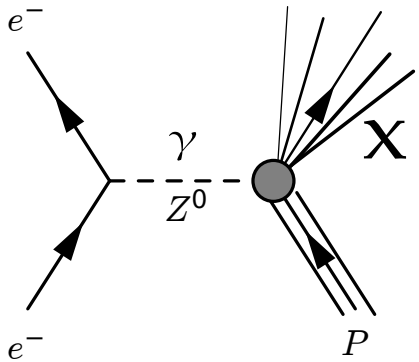


The QCD interactions at play

- Flavor dependent quark distributions (u,d, and s)
- Charge symmetry violations
- Higher twist effects
- Nuclear medium effects (EMC)

SoLID-PVDIS Physics Motivation

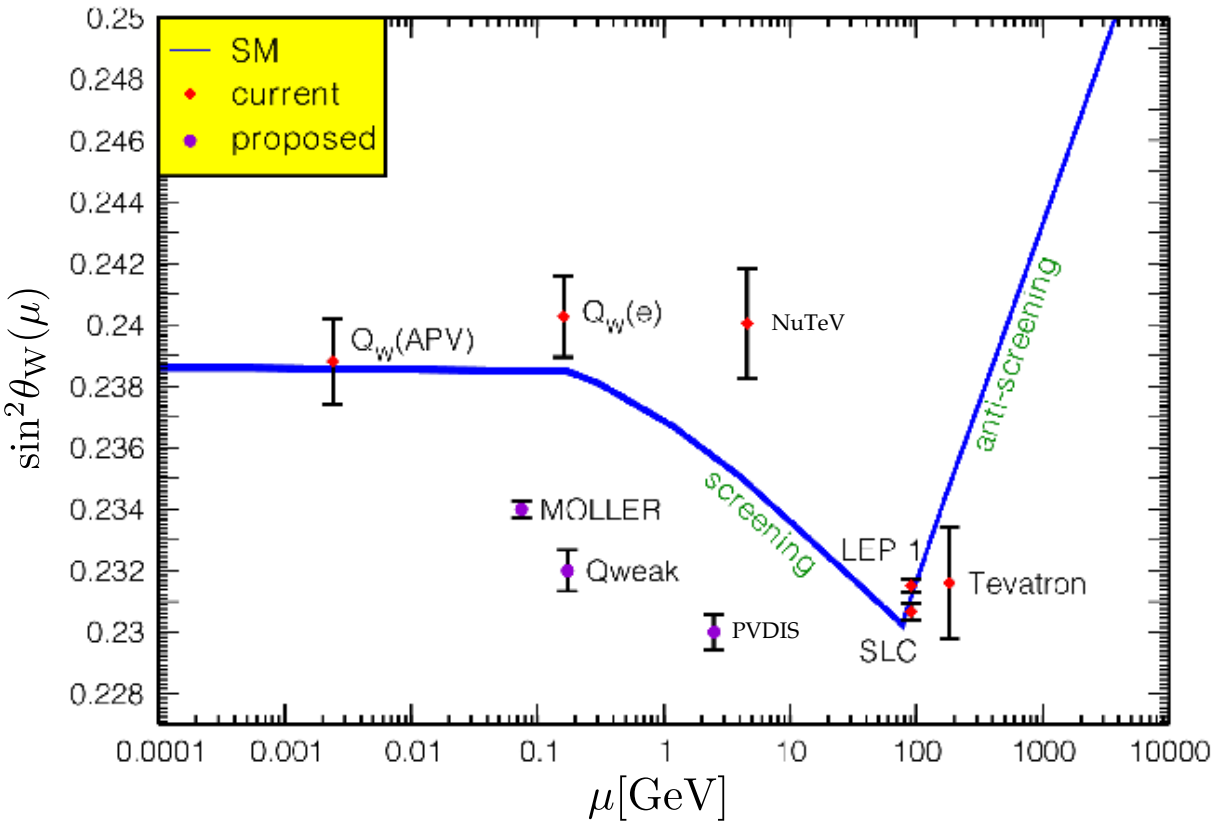
- A precision test of the Standard Model
- Search for Charge Symmetry Violation (CSV)
- Test of QCD higher twist corrections (quark quark correlations)
- Quark Flavor Dependent Effects on Proton

PVDIS features:

- Large PV asymmetries (at large Q^2 values)
- Manageable backgrounds
- Ability to reach higher precision beam polarimetry with high beam energies of DIS

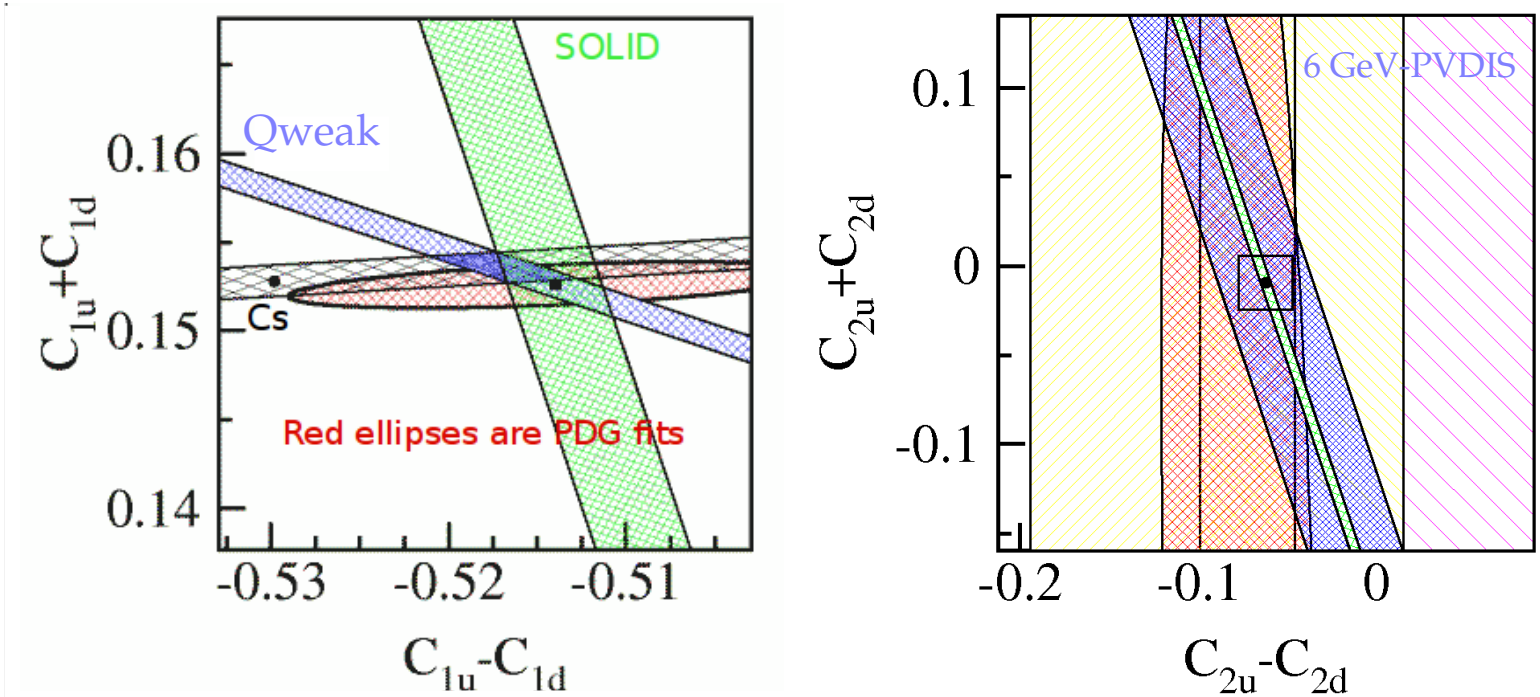
The running of Weak-Mixing Angle

SM prediction verified by low energy measurements



- NuTeV: Potential corrections due to Isovector medium corrections and CSV
  - p-n CSV and isoscaler CSV; Bentz et. al. PLB693 462 2010 and Flavor Dependent Shadowing; Brodsky PRD70 (2004) 116003

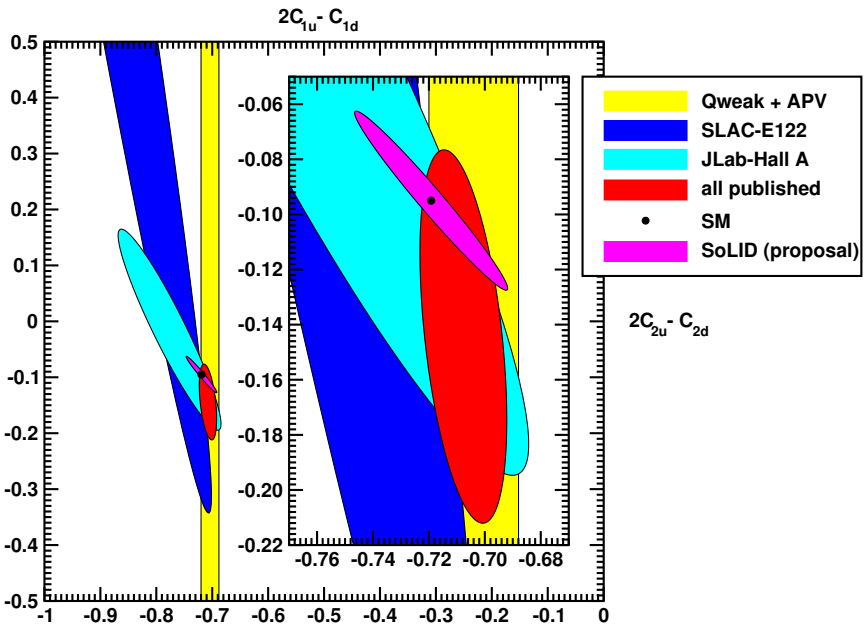
Quark Coupling Constants

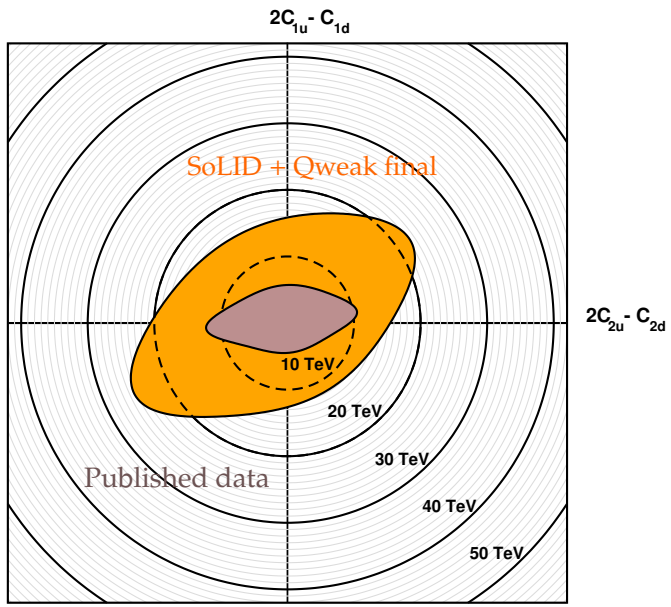


Set of PVDIS asymmetry measurements to 0.6% fractional error (stat + syst + theory) at high x, y

- will provide constraints on quark coupling constants C_{2i} (unique TeV-scale sensitivity)
- Green bands are projections to the proposed measurement of SOLID

Projected Electroweak Constraints from SoLID PVDIS



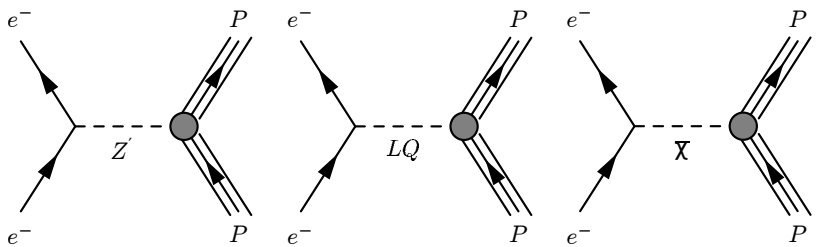


Constraints on quark coupling constants and updated limits on new physics beyond SM when SoLID PVDIS projections are included

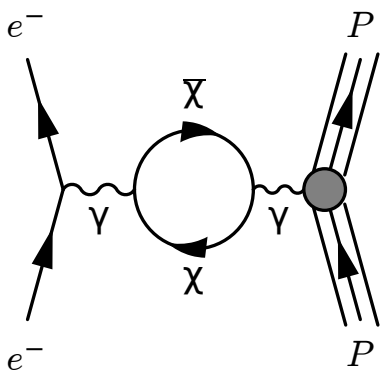
New Physics Beyond SM

TeV scale model independent constraint on PV new physics

- Tree level interactions
  - Extra Z-bosons
  - Leptoquarks
  - Supersymmetric particles



- probe new physics radiative corrections
  - Leptophobic Z' where SoLID can improve the sensitivity in 100-200 GeV range (arXiv:1203.1102v1 Buckley and Ramsey-Musolf)



Hadron Physics with PVDIS

- Hadron physics reach:
  - Charge Symmetry Violation (CSV) in PVDIS
  - Higher Twist (HT) effects in PVDIS
  - Quark Flavor Dependent Effects
- Hadron physics in PVDIS asymmetry depends critically on Bjorken x and Q^2
- We use the full statistical power of the PVDIS dataset to probe hadron physics effects
- Proposal in the making for heavy nuclei ($^{48}\mathrm{Ca}$) PVDIS to observe isovector EMC effects

Charge Symmetry Violation

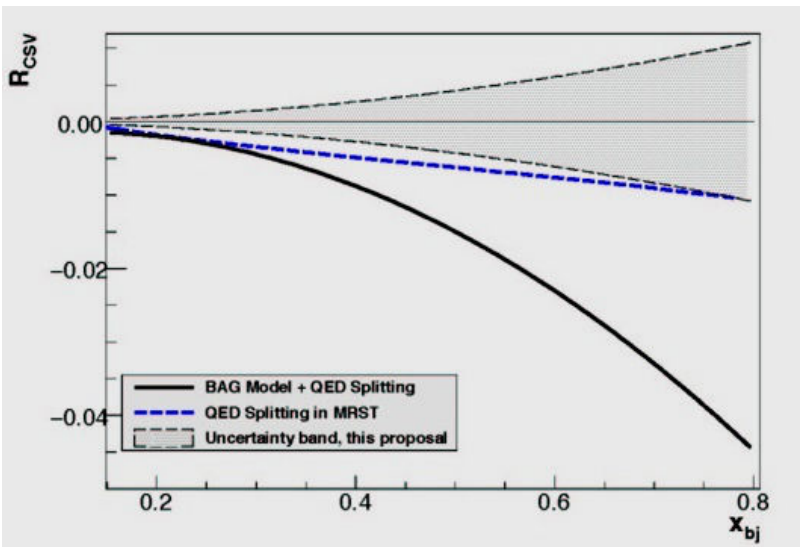
Direct observation of parton level CSV from PVDIS

- Charge symmetry $\rightarrow \mathrm{u^p} = \mathrm{d^n}; \mathrm{u^n} = \mathrm{d^p}$
- Fractional change in $\mathrm{A_{PV}}$ due to CSV from different models is plotted
- The uncertainty band in the plot is from the PVDIS figure-of-merit

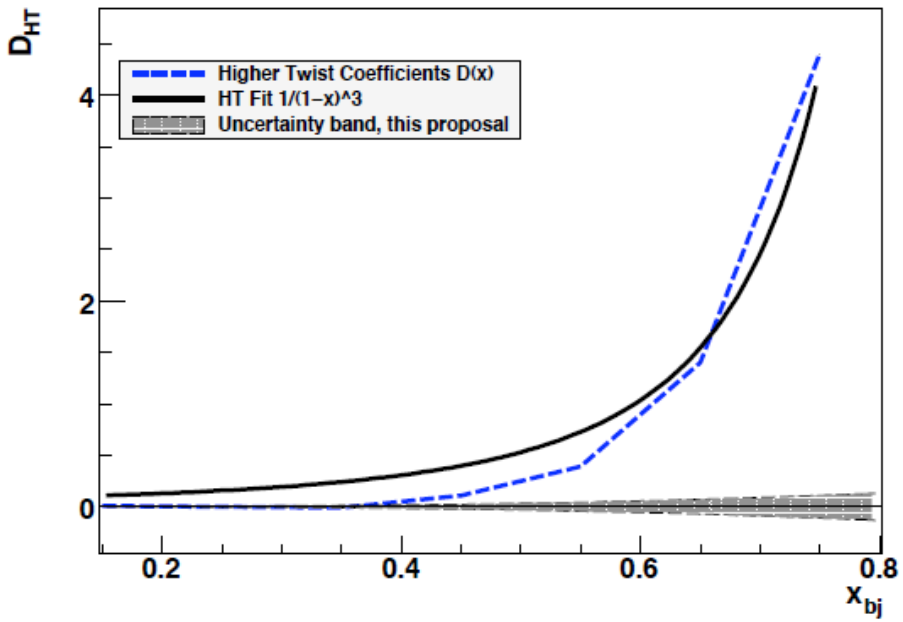
Sensitivity to CSV

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

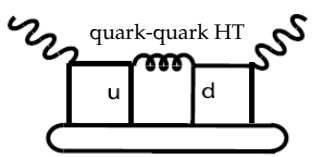
where
$\delta \mathrm{u} \equiv \mathrm{u^p} - \mathrm{d^n}; \delta \mathrm{d} \equiv \mathrm{d^p} - \mathrm{u^n};$

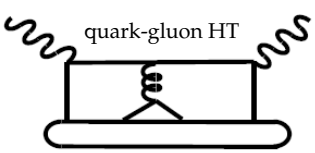


Higher Twist Effects in PVDIS



- To go from Quark Parton Model (QPM) to QCD
  - Add DGLP evolution
- Higher order terms in the Operator Product Expansion (OPE)
  - Higher Twists (HT) terms





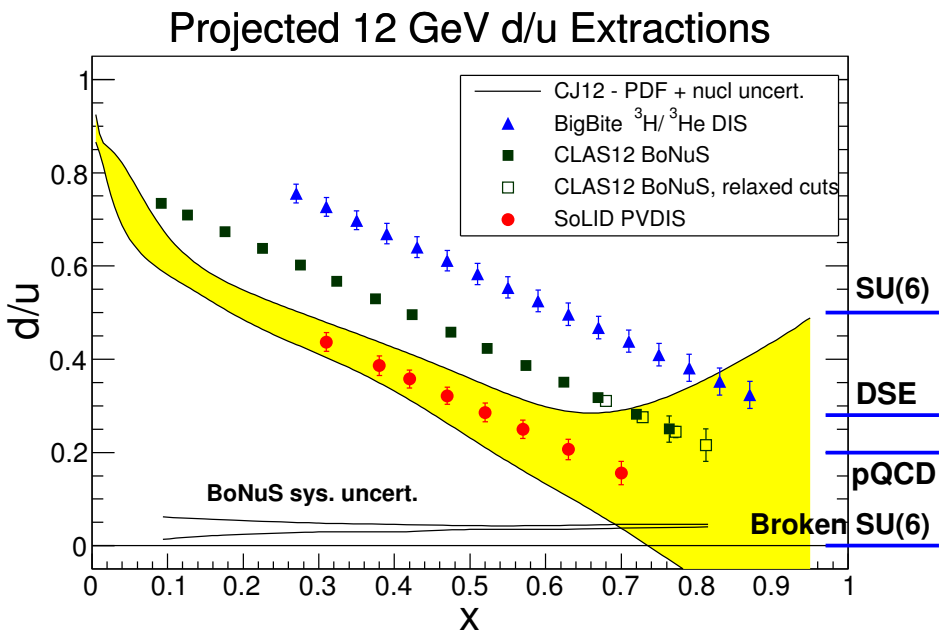
- PVDIS experimental signature is the variation of $\mathrm{Y_1 a_1^D}$ part of the asymmetry with x and $\mathrm{Q^2}$

Quark Flavor Dependent Effects on Proton

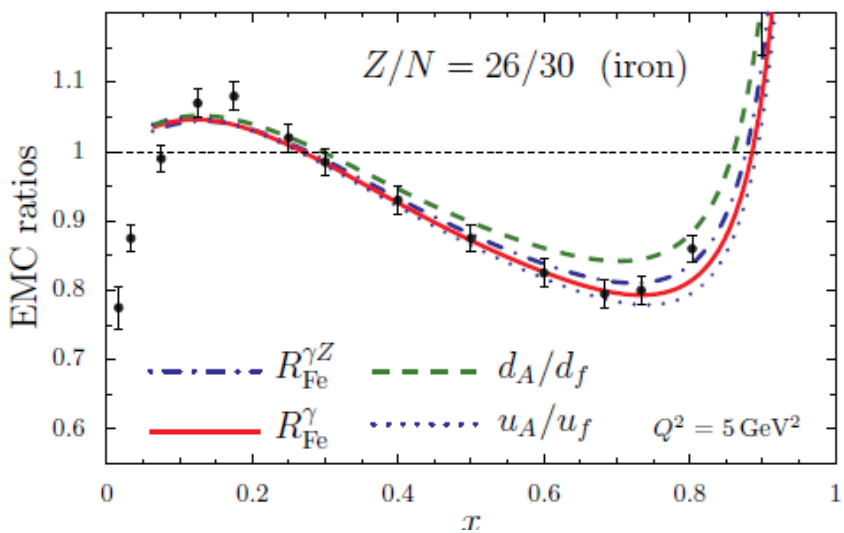
- Measurement of d(x)/u(x) ratio for the proton at high x

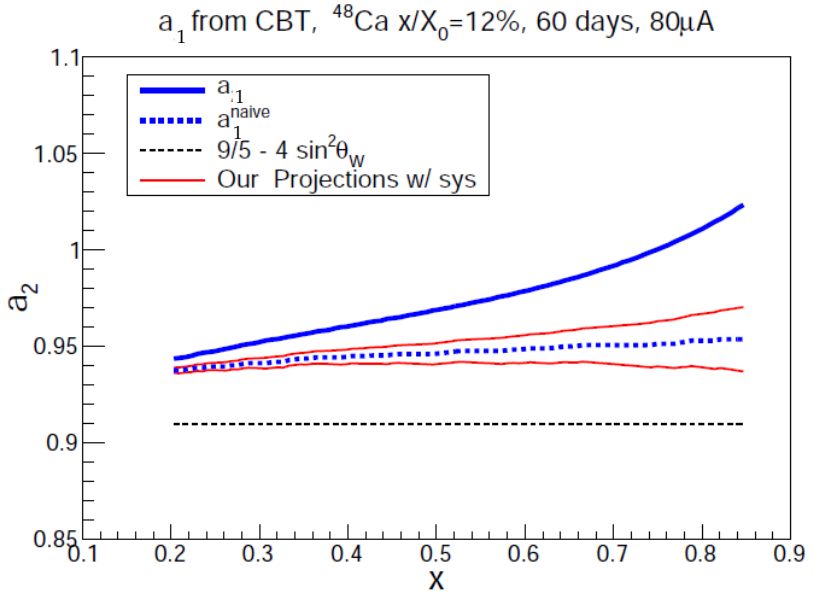
$$a_1^p(x) \sim \frac{u(x) + 0.912d(x)}{u(x) + 0.25d(x)}$$

- A clean measurement free from any nuclear corrections
- Uncertainties of set of PVDIS measurements are shown in the plot (red dots)
  - Provides high precision measurements in range of x



Flavor Dependent Model EMC Predictions





- PVDIS with neutron rich nuclei (^{48}Ca) can constrain possible flavor-dependent nuclear medium modification effects on quarks
  - PVDIS asymmetry is a direct measurement of differences in the quark flavors

$$a_1 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+}$$

Physics Program Summary

- Use $x > 0.4$ high Q^2 data to test the SM
- Search for CSV with x dependence of PVDIS asymmetry
- Cover broad Q^2 range for $0.3 < x < 0.6$ to constraint HT

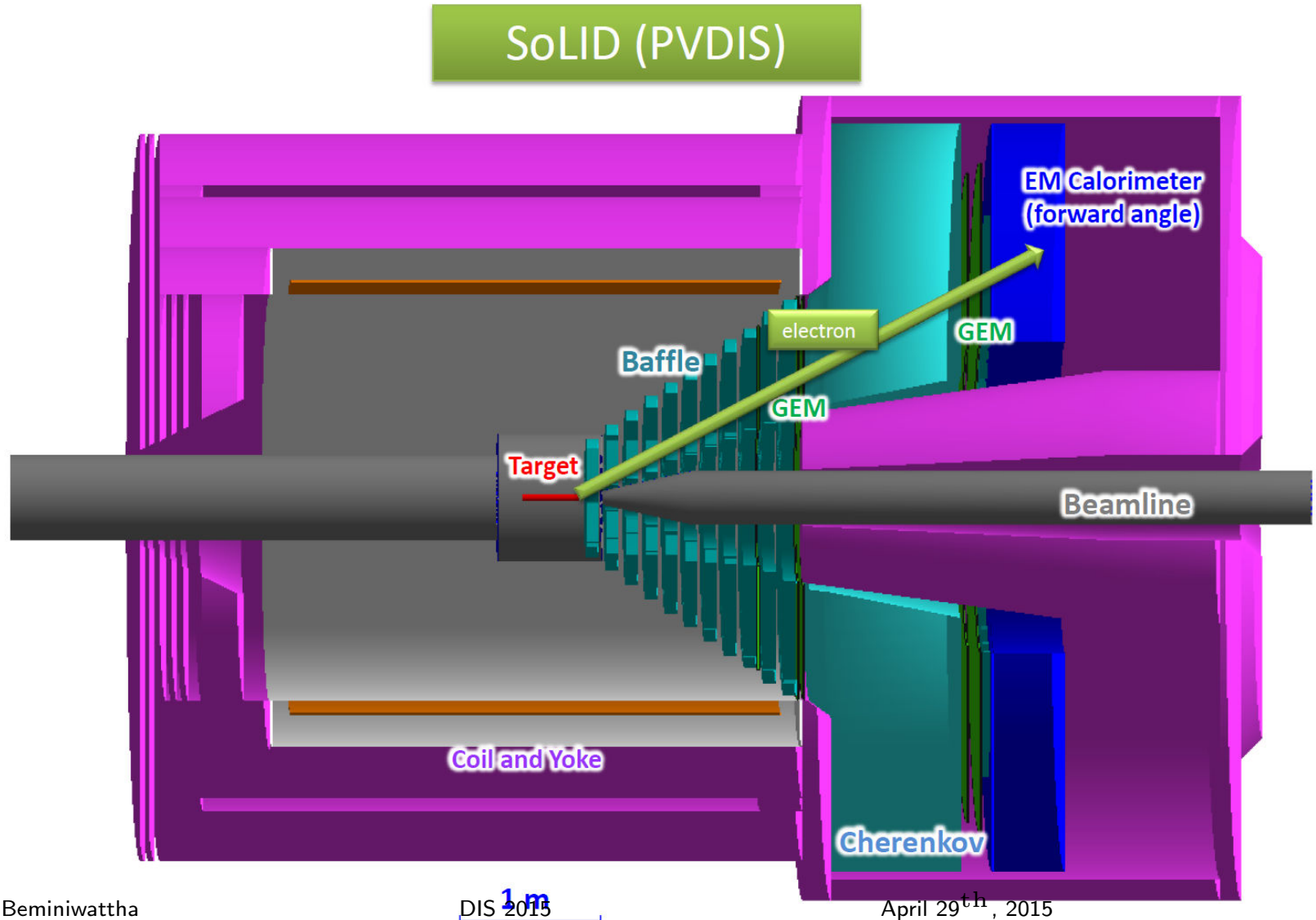
	x	y	Q^2
New Physics		YES	
CSV	YES		
Higher Twist	YES		YES

Error budget for PVDIS asymmetry at $x = 0.4$,

Source	Error (%)
Statistics	0.3
Polarimetry	0.4
Q^2	0.2
Radiative corrections	0.3
Total	0.6

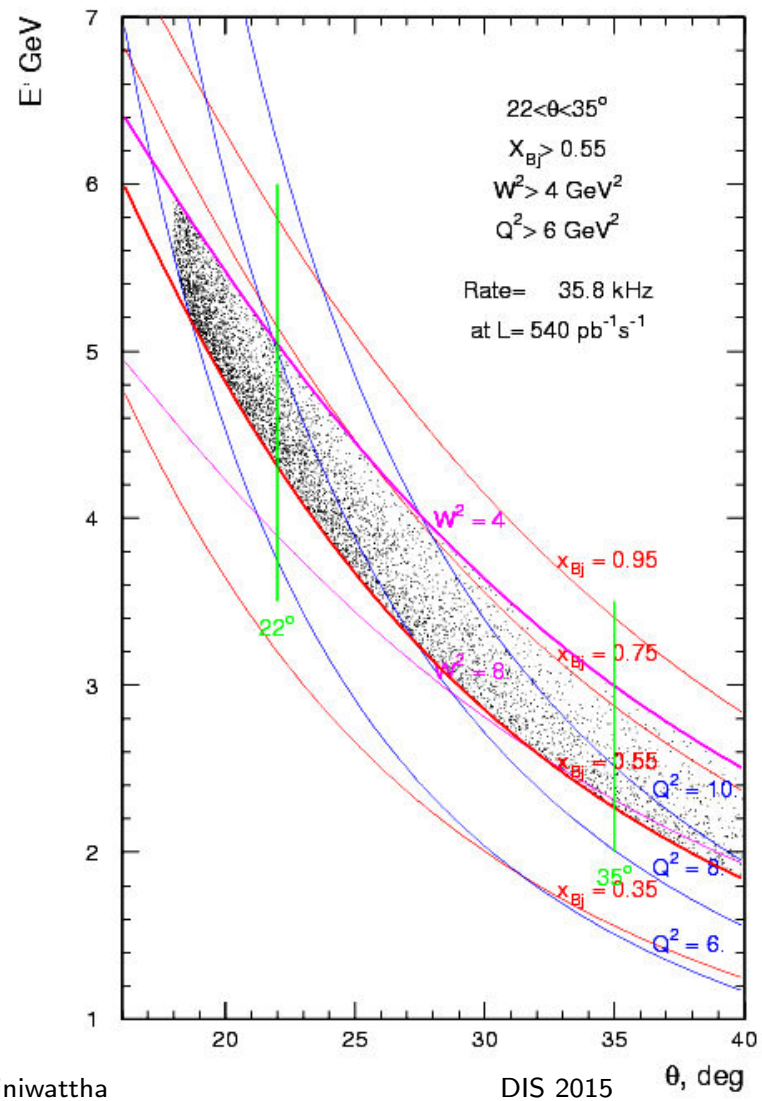
Solenoidal Large Intensity Device (SoLID)

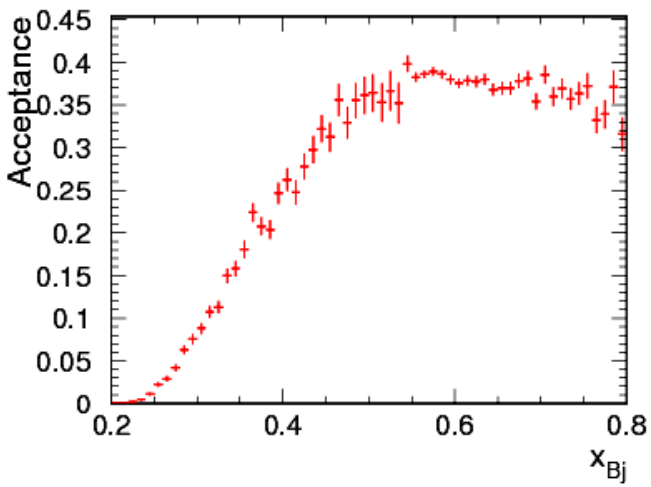
Apparatus



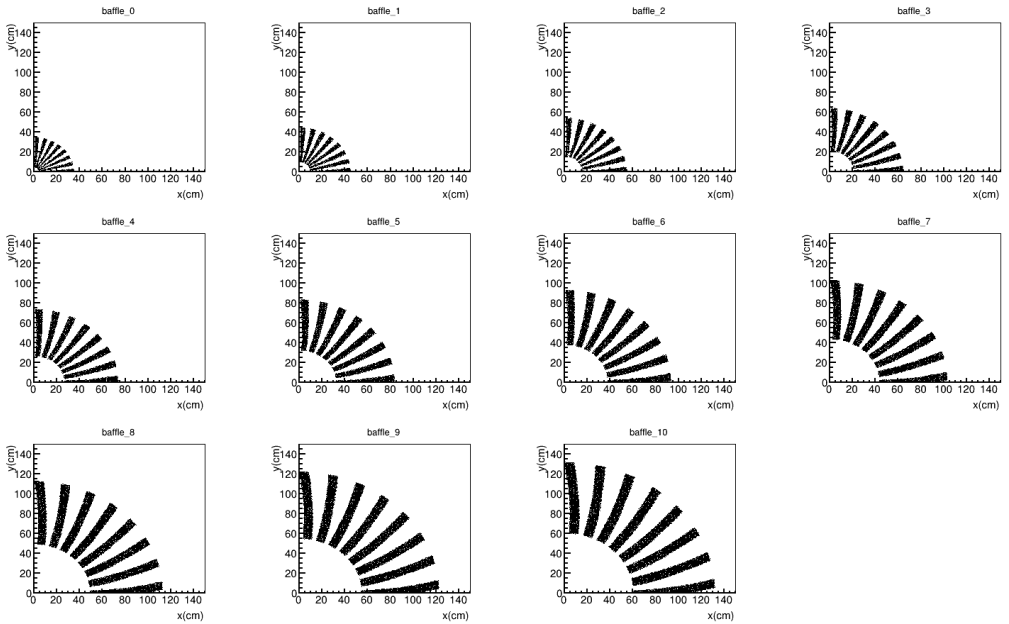
Solenoidal Large Intensity Device (SoLID)

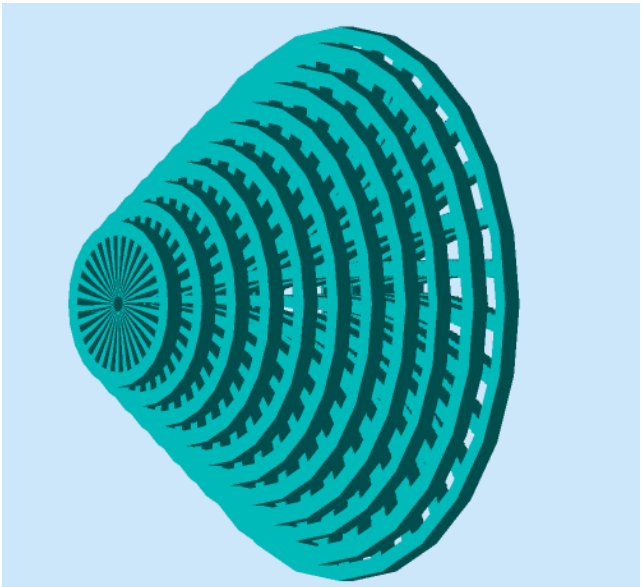
Acceptance





SoLID Baffle Design





- High luminosity at target generate high rate and radiation dose on detectors
- Baffle shields low energy photons from target
- Charged particles bent in the solenoid field
- Baffle system provide 30 12 deg. azimuthal sectors $\rightarrow 30\%$ coverage

SoLID Specs. and Figure-Of-Merit

Specifications

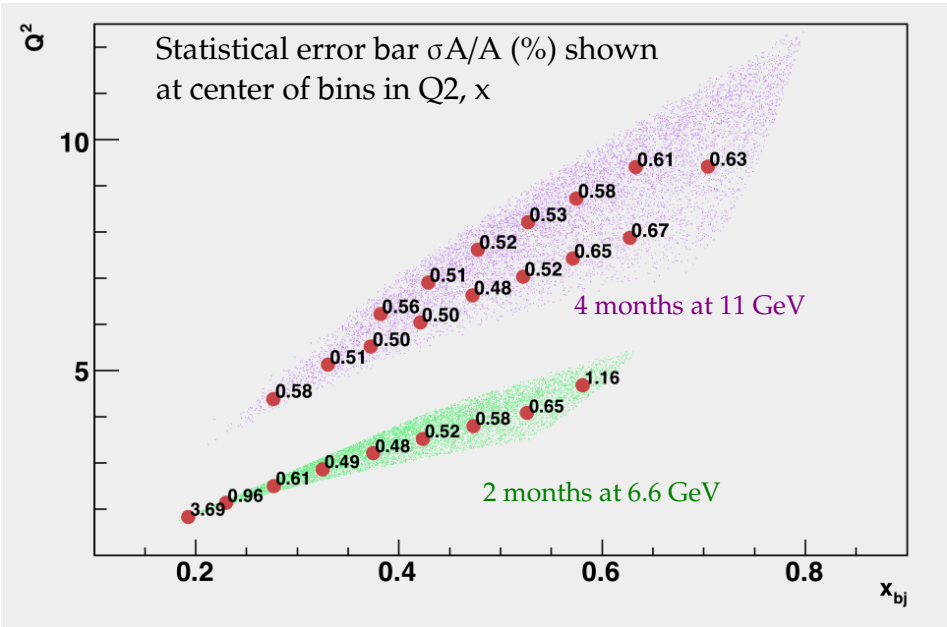
Using Thomas Jefferson National Accelerator Facility (TJNAF),

- High Luminosity ($10^{39}/\mathrm{cm}^2/\mathrm{s}$)
- Beam current $50\ \mu\mathrm{A}$ and polarization $\sim 85\%$
- Large scattering angles for high x & y access
- With moderate running times,
  - X-range of 0.25 to 0.75
  - $\mathrm{W}^2 > 4\mathrm{GeV}^2$
  - Q^2 range a factor of 2 for each x

SoLID Specs. and Figure-Of-Merit

FOM

sub 1 % precision over broad kinematic range: A Standard Model test and a detailed study of hadronic structure contributions



$$A_{PV}^{D} = A_{PV}^{EW}(1 + \beta_{HT}\frac{1}{(1-x)Q^2} + \beta_{CSV}x^2)$$

If no CSV, HT, quark sea, or nuclear effects, All (Q^2, x) bins should give the asymmetry within statistics and kinematic factors

SoLID-PVDIS Summary

- A set Parity Violation in Deep Inelastic Scattering (PVDIS) asymmetry measurements will provide:
  - A test of the Standard Model
  - Charge Symmetry Violation (CSV)
  - Higher Twist (HT) effects
  - Nucleon medium effects on quark distributions in heavy nucleii
- For this rich set of the physics reach, high luminosity, large angle, large-acceptance spectrometer is needed : proposal for SoLID apparatus
- Semi-Inclusive Deep Inelastic Scattering (SIDIS) and J/ψ physics are planned for SoLID apparatus, See talk by Zhihong

SoLID Progress

- Successfully completed Jefferson Lab director's review for initial conceptual design report
- Spectrometer magnet acquired, planning for dissemble and transportation
- Detailed detector background simulation
- Detector pre-R&D for EM calorimeter, gas Cherenkov and GEM