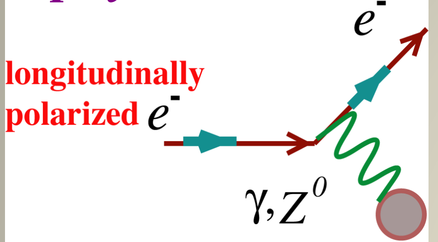
PVDIS at 11 GeV with SoLID

PV Electron Scattering

Continuous interplay between probing hadron structure and electroweak physics

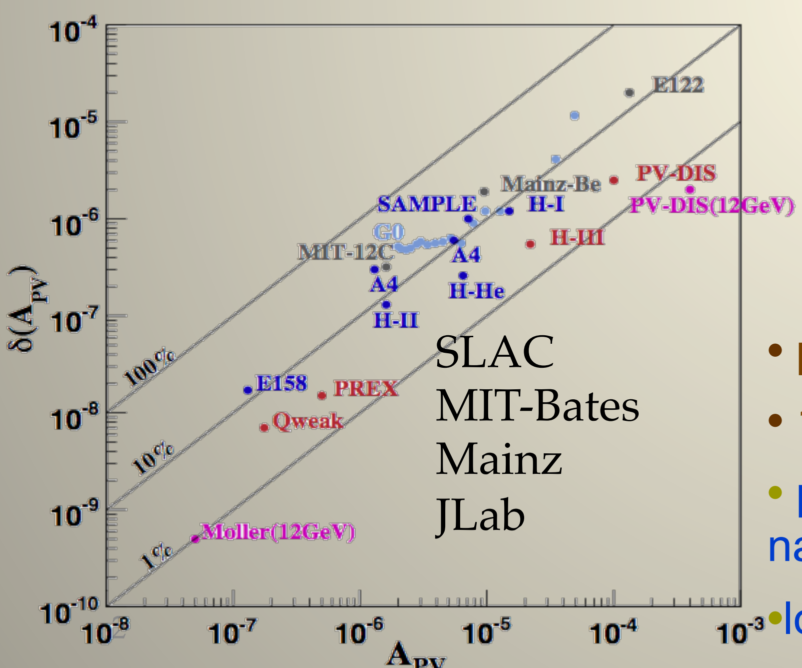


$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e g_V^T + \beta\, g_V^e g_A^T\right)$$

g_V is a function of $\sin^2\theta_W$

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

Parity-violating electron scattering has become a precision tool

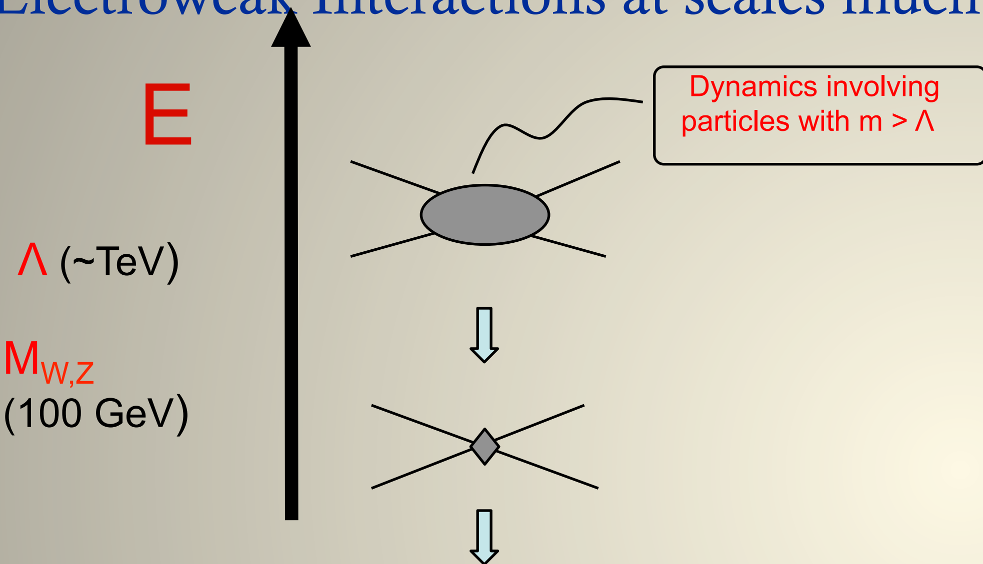


- Physics beyond Standard Model
- Strange quark form factors
- Neutron skin of a heavy nucleus
- QCD structure of the nucleon in PV DIS

- part per billion systematic control
- 1% normalization control
- photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics,
- low noise electronics, radiation hard detectors

Indirect Clues to TeV Physics

Electroweak Interactions at scales much lower than the W/Z mass



Many theories predict new forces that disappeared when the universe cooled

courtesy
V. Cirigliano
H. Maruyama

$$\mathcal{L}_{SM+\text{Heavy}}$$

$$\Downarrow$$

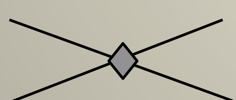
$$\boxed{\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots}$$

Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

higher dimensional operators can be systematically classified

- *flavor changing as well as flavor diagonal*
- *charged current as well as neutral current*

new contact interactions



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

must reach Λ ~ several TeV

Consider $f_1 f_2 \to f_1 f_2$ **or** $f_1 f_1 \to f_2 f_2$

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

Neutral Currents at Low Energy

Colliders AND Fixed Target

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

Colliders access scales Λ's ~ 10 TeV

Tevatron, LEP, SLC, LEP200, HERA

- L,R combinations accessed are mostly parity-conserving

Z boson production accessed some parity-violating combinations but…

on resonance: A_Z imaginary

$$\left|\mathbf{A_Z} + \mathbf{A_{new}}\right|^2 \to \mathbf{A_Z^2}\left[\mathbf{1} + \left(\frac{\mathbf{A_{new}}}{\mathbf{A_Z}}\right)^2\right]$$

no interference!

Low Energy: New Physics / Weak-Electromagnetic Interference

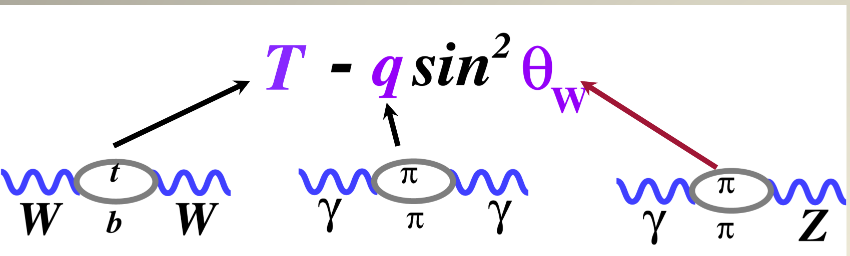
- opposite parity transitions in heavy atoms
- Spin-dependent electron scattering

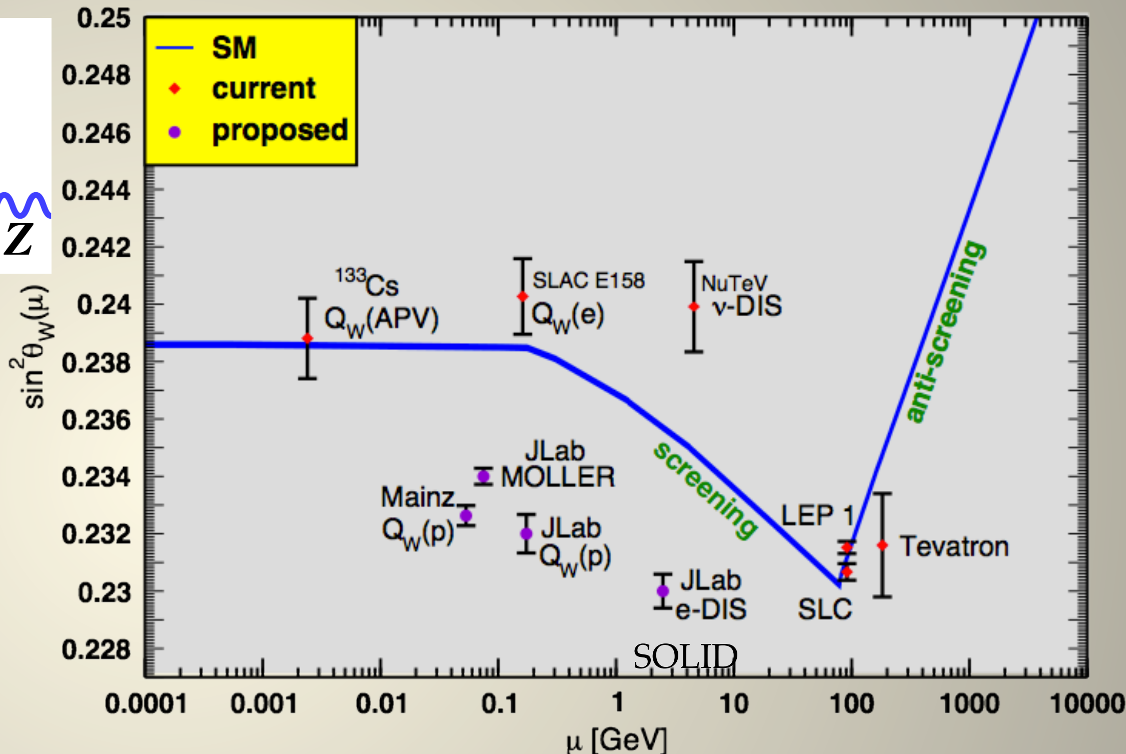
Electromagnetic amplitude interferes with Z-exchange as well as any new physics

$$\left|\mathbf{A_\gamma} + \mathbf{A_Z} + \mathbf{A_{new}}\right|^2 \to \mathbf{A_\gamma^2}\left[\mathbf{1} + \mathbf{2}\left(\frac{\mathbf{A_Z}}{\mathbf{A_\gamma}}\right) + \mathbf{2}\left(\frac{\mathbf{A_{new}}}{\mathbf{A_\gamma}}\right)\right]$$

The Weak Mixing Angle

Running of θ_W : Bookkeeping to check consistency of various measurements



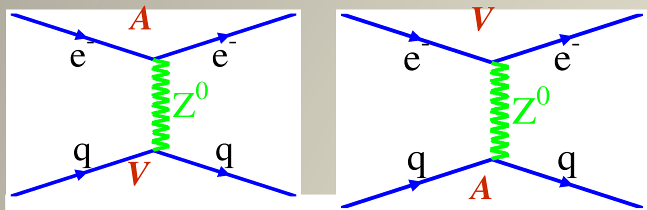


- *γ-γ loop is the running of α_{EM}*
- *W-W loop provides indirect m_t*
- *γ-Z loop is the running of $\sin^2\theta_W$*

- Published Measurements
  - SLAC E158
  - ^{133}Cs Atomic Parity Violation (APV)
  - NuTeV result requires careful consideration of nuclear corrections
- Current/Future PV Electron Scattering Measurements at JLab
  - e-q measurements: QWeak (elastic e-p) and SOLID (DIS)
  - Improve on E158 by a factor of 5 (MOLLER)

e-q coupling constants

4 phenomenological couplings: V, A & u, d combinations

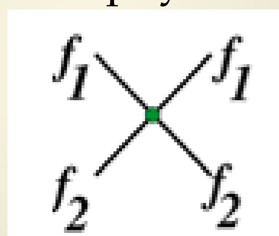


$C_{1i} \equiv 2 g_A^e g_V^i$ $\quad$ $C_{2i} \equiv 2 g_V^e g_A^i$

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

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

+ new physics



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

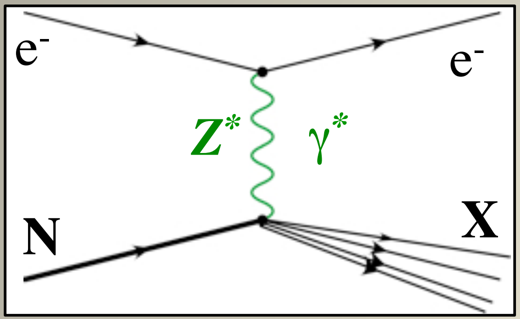
$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$ ⇨ PV elastic e-p scattering, Atomic parity violation

$$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$ ⇨ PV deep inelastic scattering

C_{2q}’s involve axial hadronic currents:
large theoretical uncertainties when accessed via elastic scattering

PV Deep Inelastic Scattering

off the simplest isoscalar nucleus and at high Bjorken x



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

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

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

$$x \equiv x_{Bjorken}$$

$$y \equiv 1 - E'/E$$

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

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

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

At high x, A_{iso} becomes independent of pdfs, x & W, with well-defined SM prediction for Q^2 and y

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

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

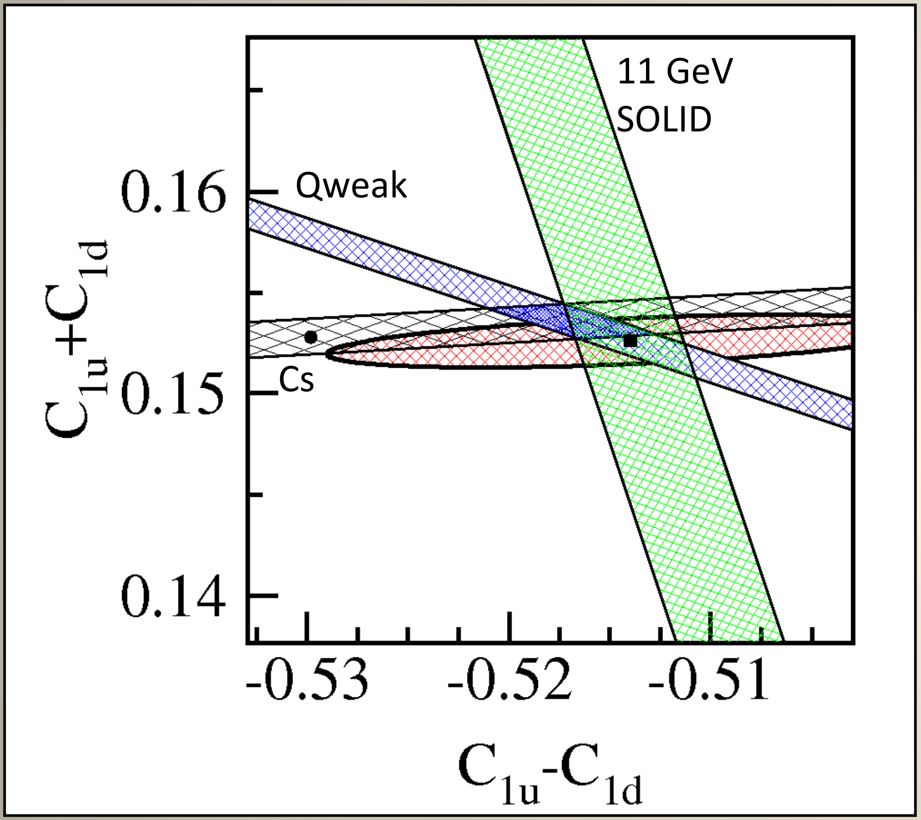
$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

Interplay with QCD

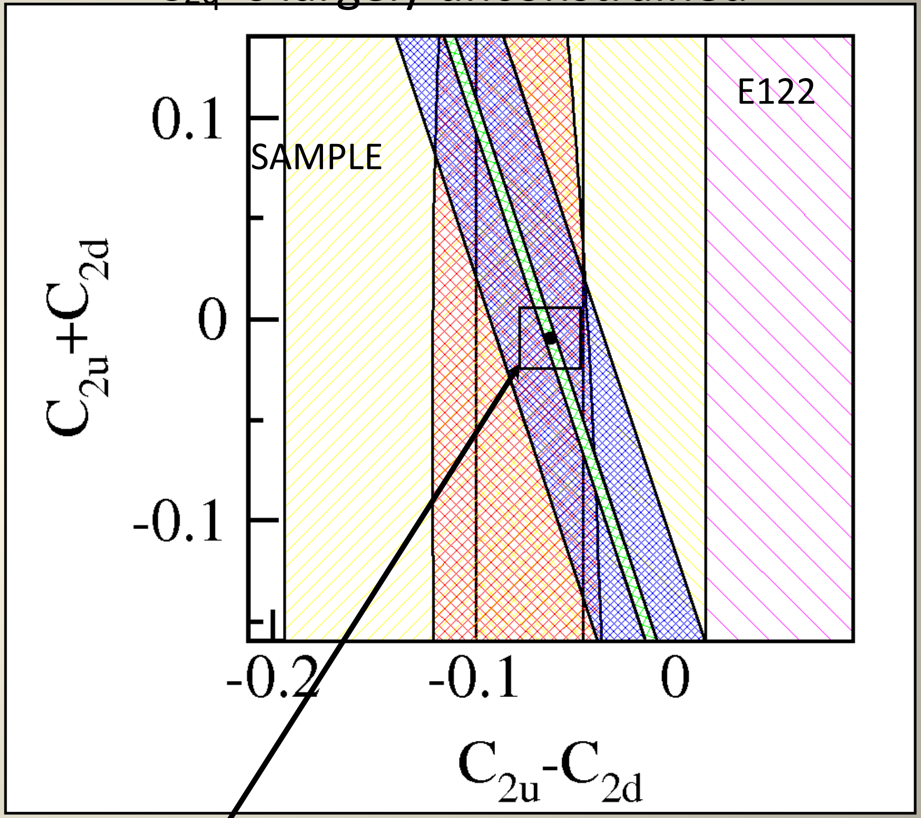
- Parton distributions (u, d, s, c)
- Charge Symmetry Violation (CSV)
- Higher Twist (HT)
- Nuclear Effects (EMC)

SOLID Goal on Couplings

Measure A_{PV} for e-^{2}H DIS to 0.6% fractional error (stat + syst + theory) at high x, y



C_{2q}' s largely unconstrained



This box matches the scale of the C_{1q} plot

Red ellipses are PDG fits

Blue bands represent expected data: Qweak (left) and PV-DIS-6GeV (right)

Green bands are the proposed measurement of SOLID

unique TeV-scale sensitivity

New Physics Examples

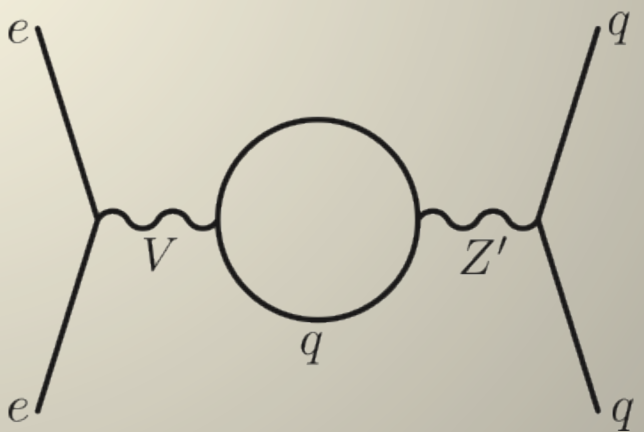
Leptophobic Z'

- ***Virtually all GUT models predict new Z's***
- ***LHC reach ~ 5 TeV, but....***
- ***Little sensitivity if Z' doesnt couple to leptons***
- ***Leptophobic Z' as light as 120 GeV could have escaped detection***

*Since electron vertex must be vector, the Z' cannot couple to the C_{1q}'s if there is no electron coupling: can only affect **C_{2q}'s***

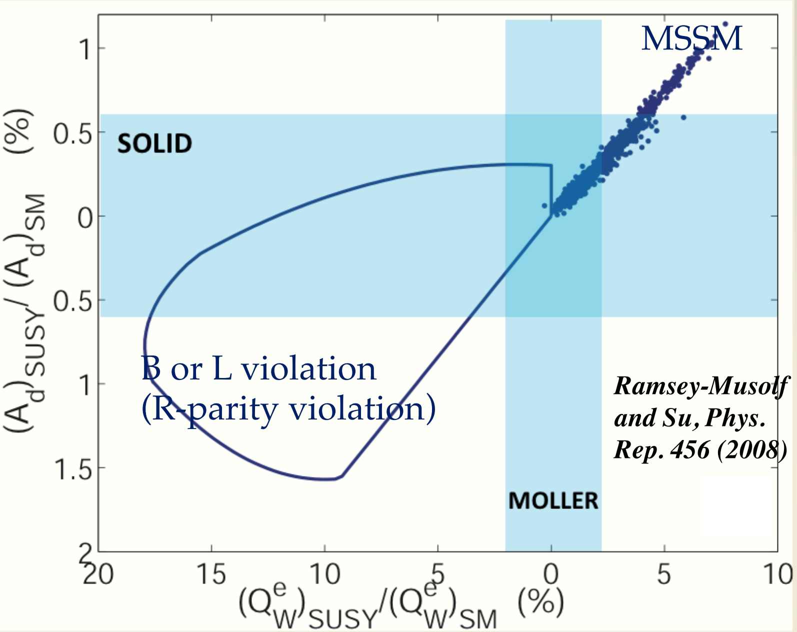
SOLID can improve sensitivity:
100-200 GeV range

arXiv:1203.1102v1
Buckley and Ramsey-Musolf

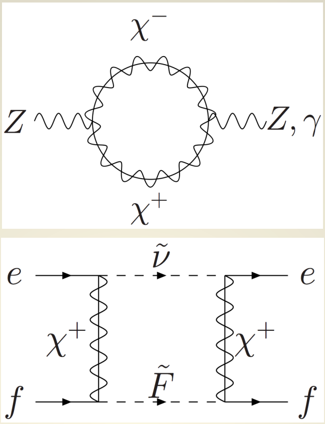


Other New Physics Examples

MSSM sensitivity if light super-partners, large tanβ



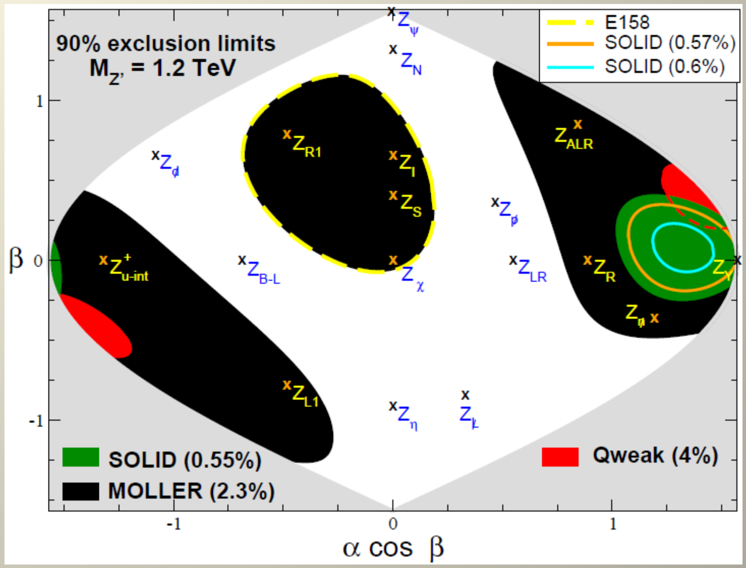
SUSY loops



Does Supersymmetry provide a candidate for dark matter?

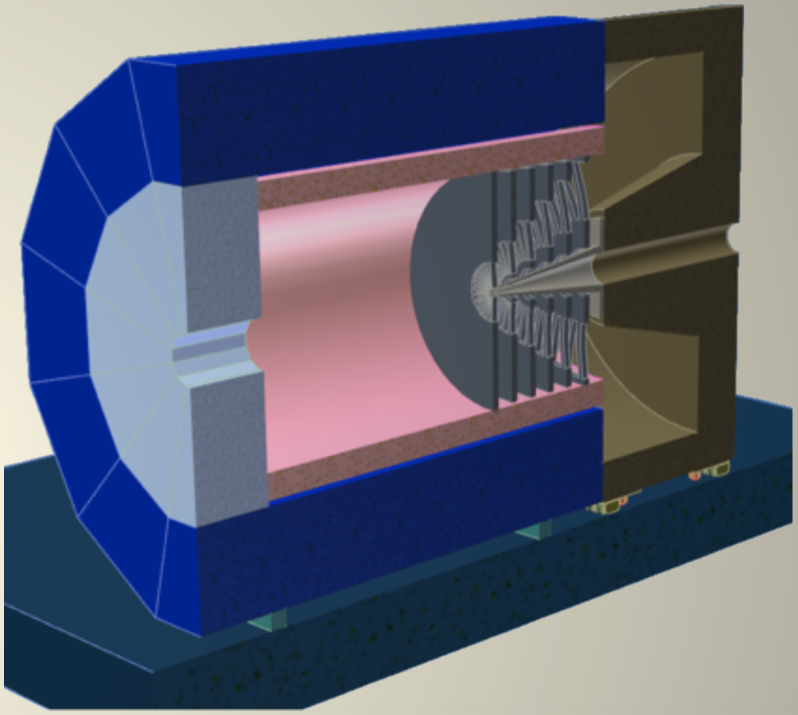
- B and/or L need not be conserved: neutralino decay
- Depending on size and sign of deviation: could lose appeal as a dark matter candidate

- Assume LHC sees
- 1.2 TeV Z'



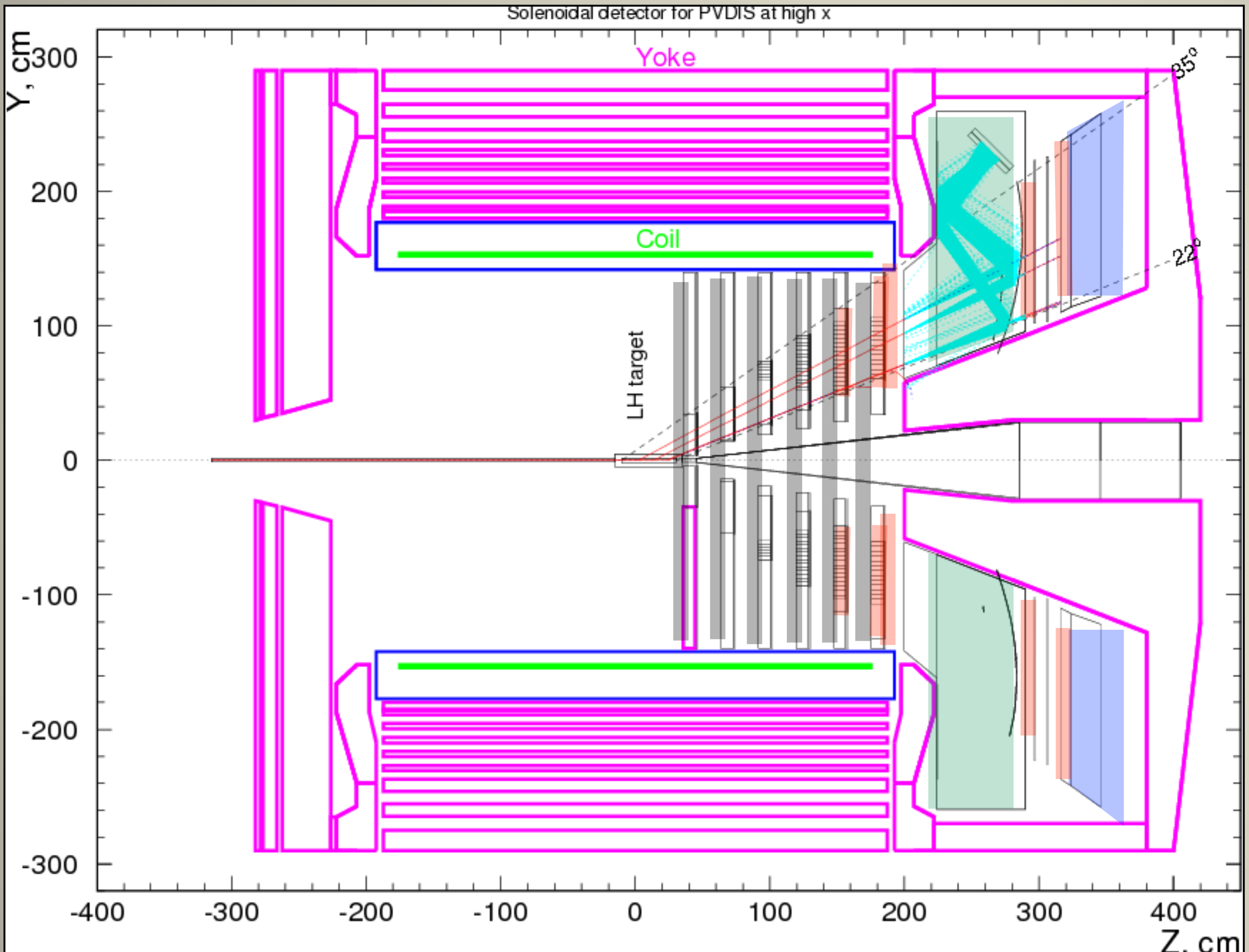
Extra Z's can have Different couplings (Jens Erler)

SOLID Apparatus

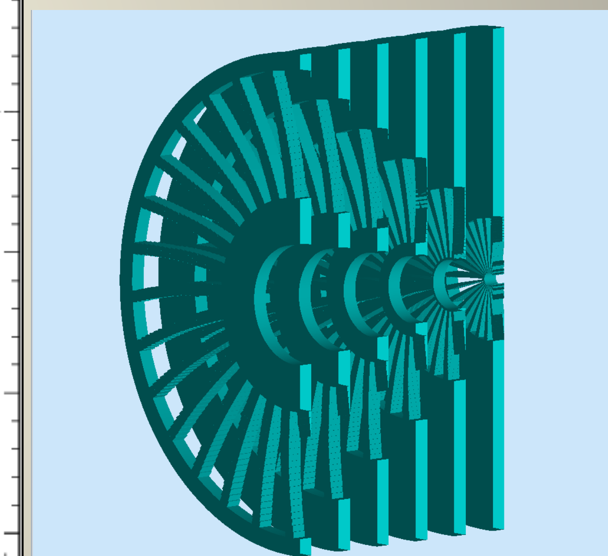


- Moderate running times
  - Large Acceptance
  - High Luminosity on LH2 & LD2
- Better than 1% errors for small bins
- Kinematics:
  - Large Q^2 coverage
  - x-range 0.25-0.75
  - $W^2 > 4\ \mathrm{GeV}^2$
- Requirements:
  - Solenoid contains low energy backgrounds (Møller, pions, etc)
  - Baffling to cut backgrounds: significant engineering
  - Trajectories measured after baffles
  - Fast tracking—GEM, particle ID, calorimetry, and pipeline electronics
  - Precision polarimetry (0.4%) Compton and atomic hydrogen Moller

SOLID Apparatus Overview

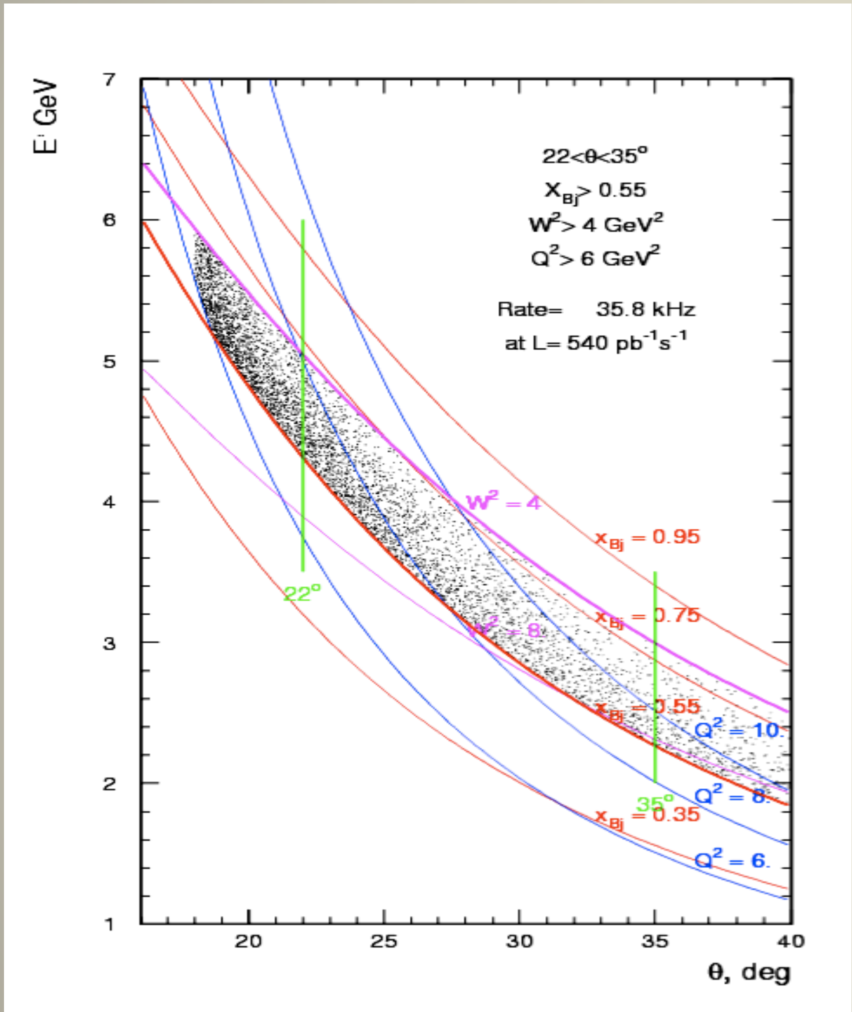


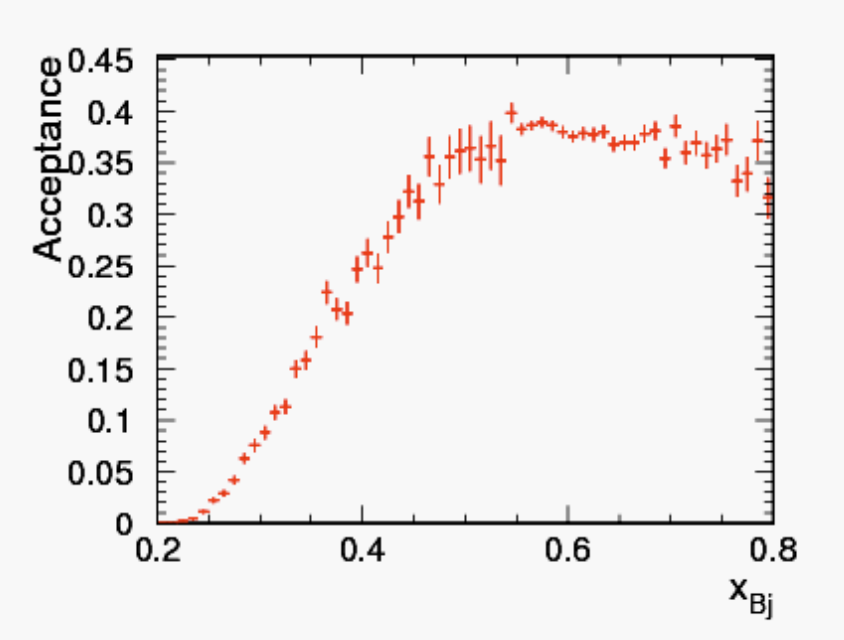
GEM
Sashlyk
gas Cerenkov
collimator



- 20° - 35°, E’ ~ 1.5 - 5 GeV δp/p ~ 2%
- some regions 10’s of kHz/mm², Pion rejection with Cherenkov + segmented calorimeter
- Several large solenoids would work (Zeus, Babar): present design focuses on CLEO-II

Spectrometer Acceptanace





Program of Measurements

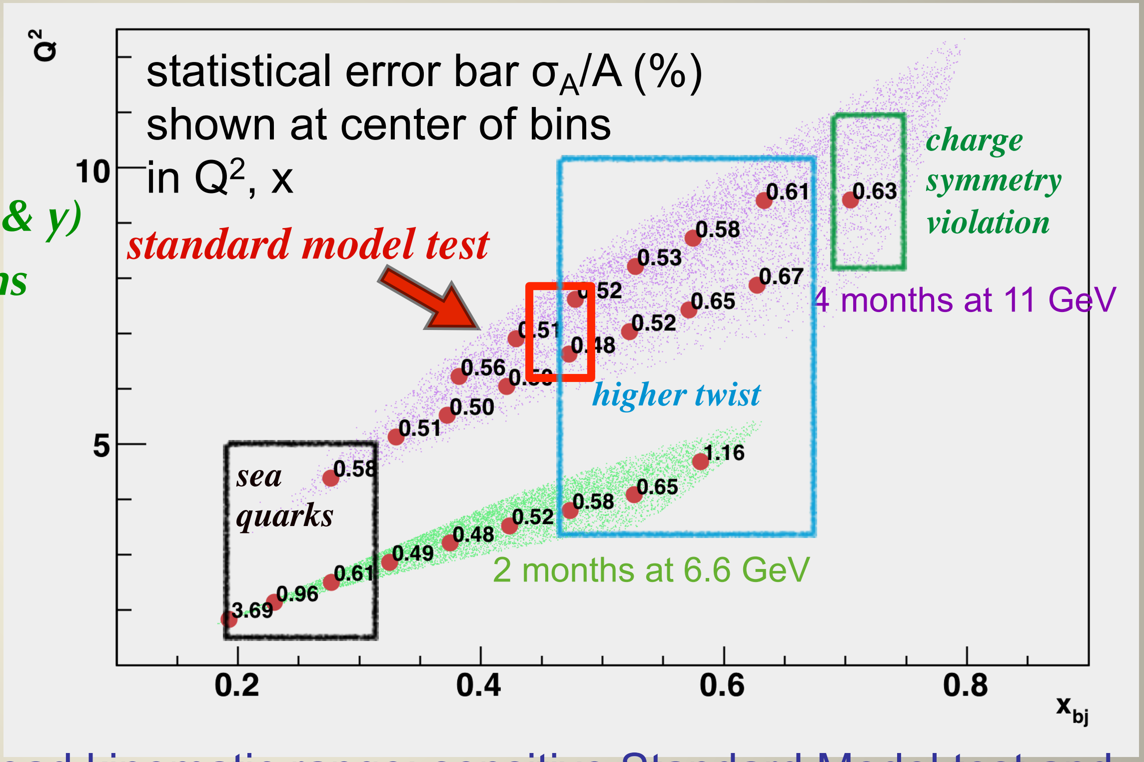
Requires 12 GeV upgrade of JLab and a large superconducting solenoid

Requirements

- *High Luminosity with E > 10 GeV*
- *Large scattering angles (for high x & y)*
- *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 at very high x)

- *Moderate running times*

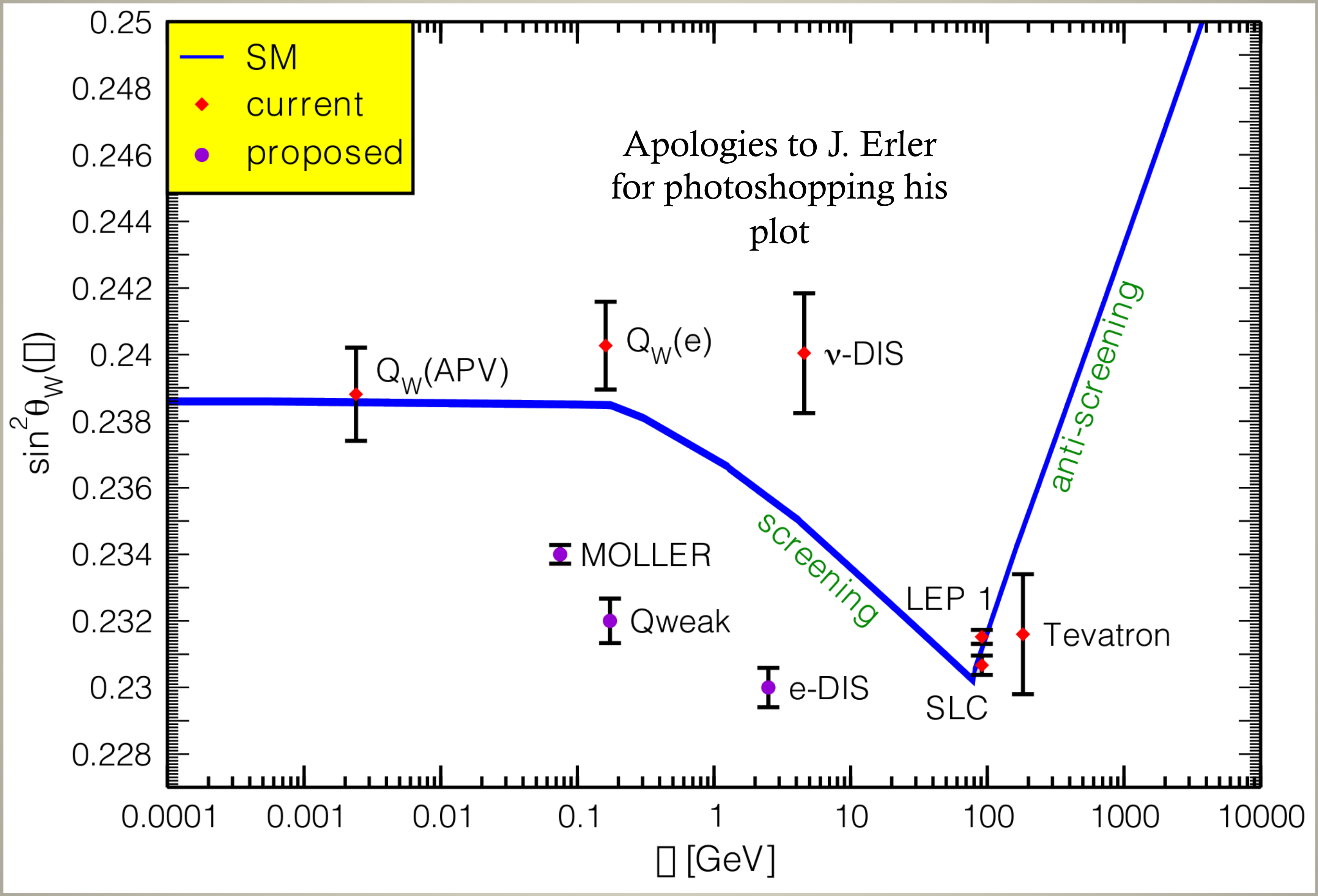


Strategy: sub-1% precision over broad kinematic range: sensitive Standard Model test and detailed study of hadronic structure contributions

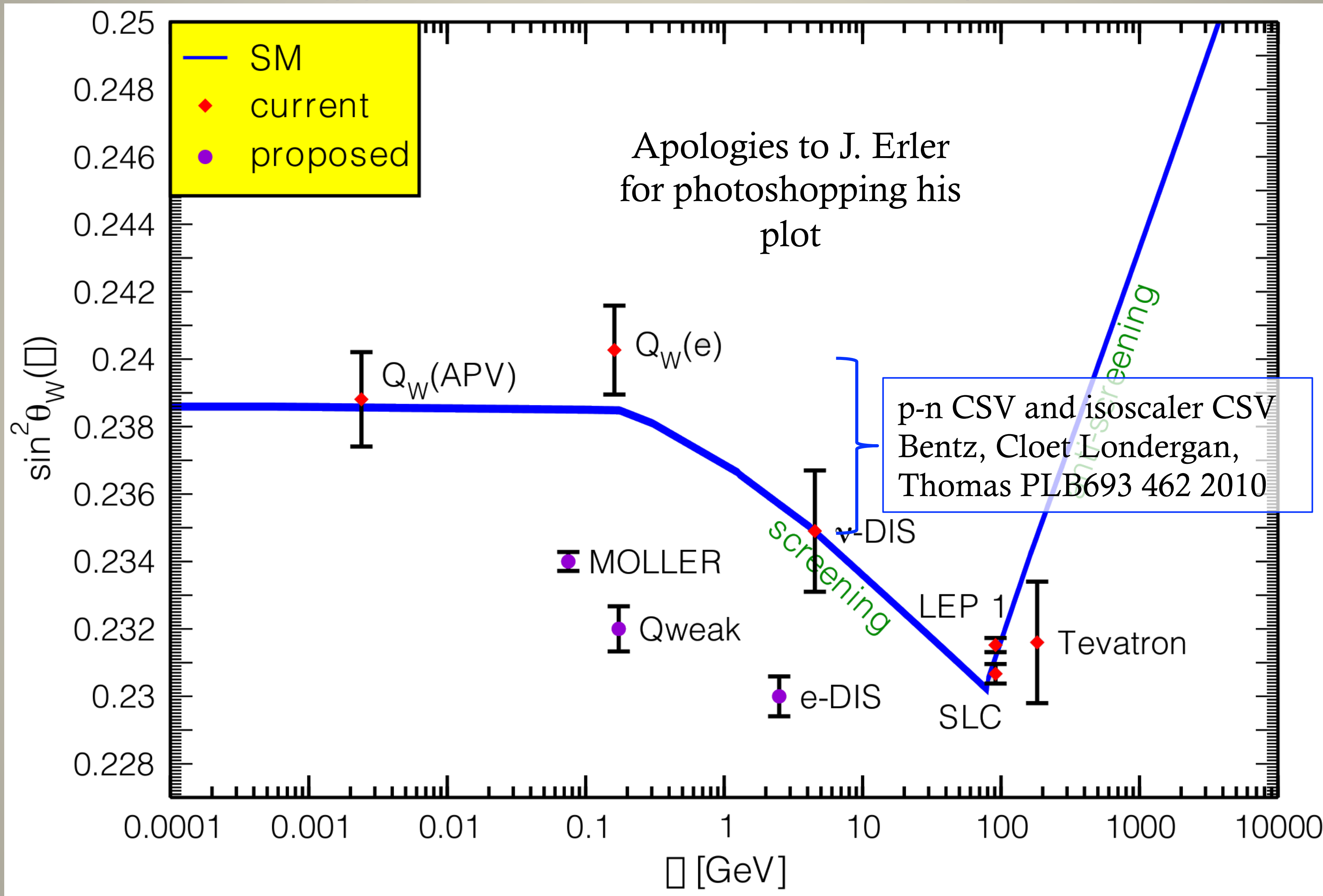
$$A = A\left[1 + \beta_{HT}\frac{1}{(1-x)^3 Q^2} + \beta_{CSV}x^2\right]$$

If no CSV, HT, quark sea or nuclear effects, ALL Q^2, x bins should give the same answer within statistics modulo kinematic factors!

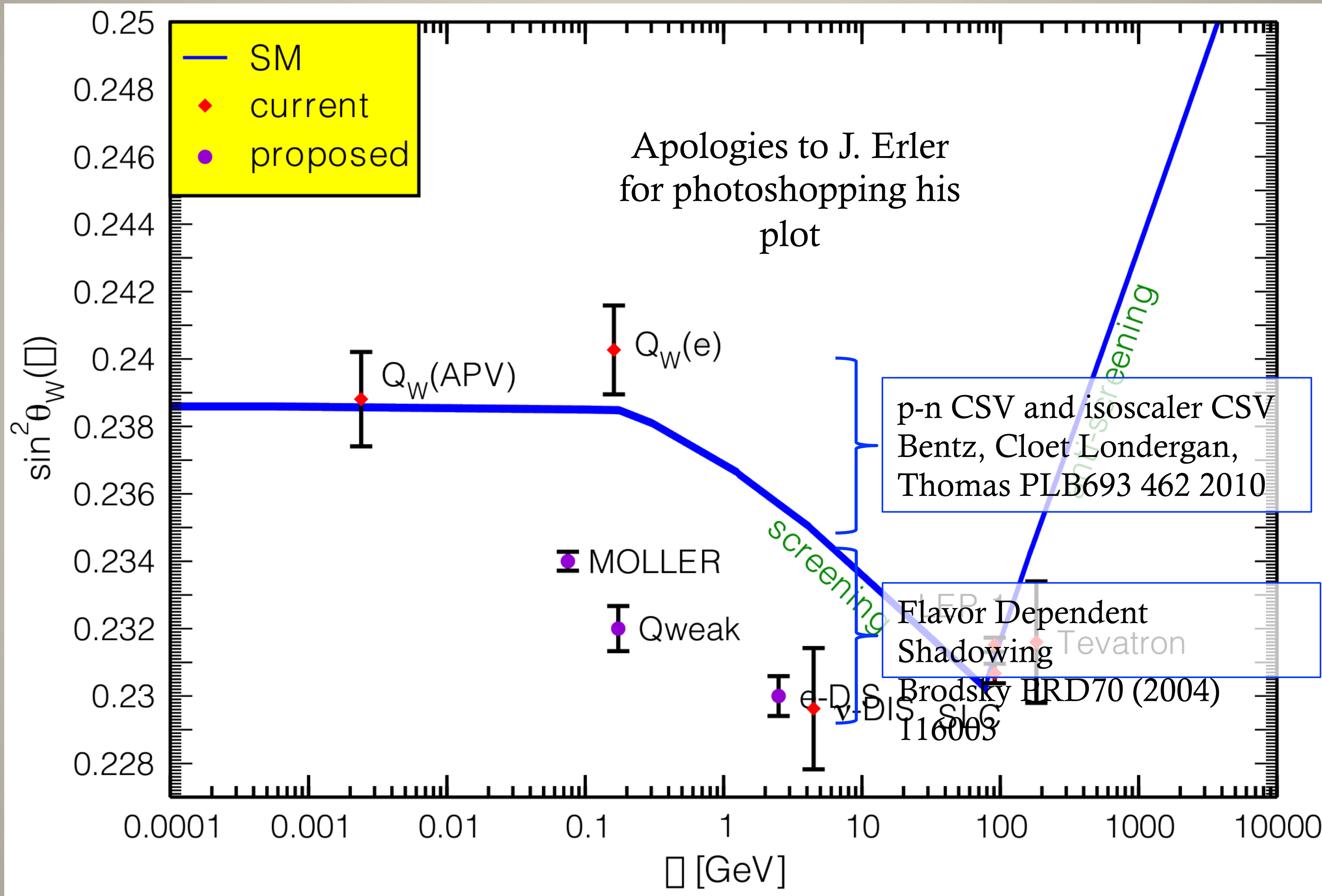
What about NuTeV?



What about NuTeV?



What about NuTeV?



Charge Symmetry Violation

We already know CSV exists:

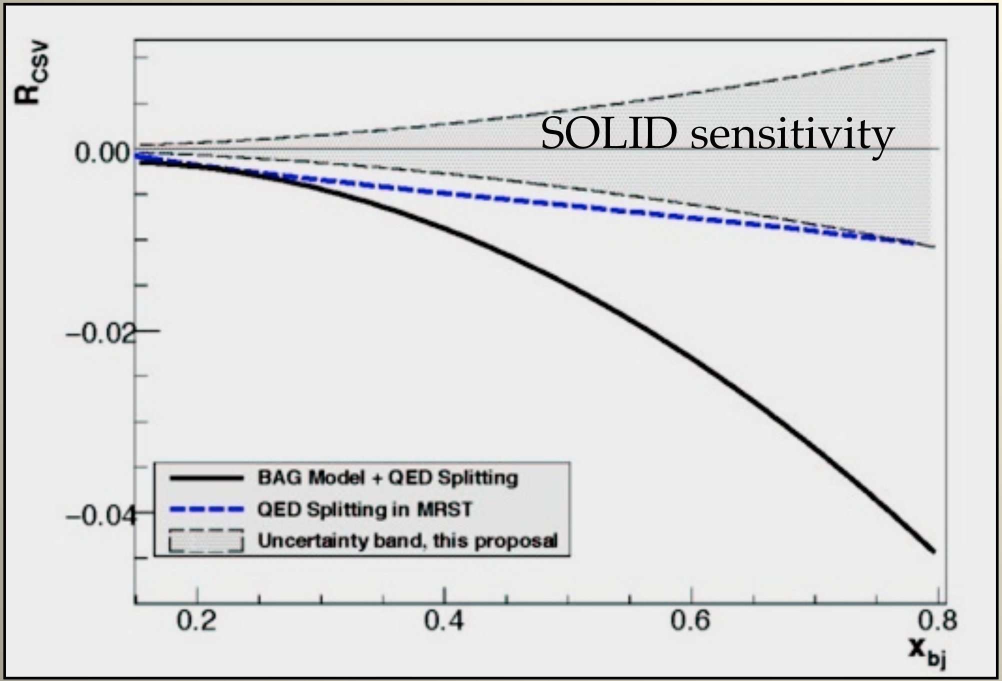
- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects

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

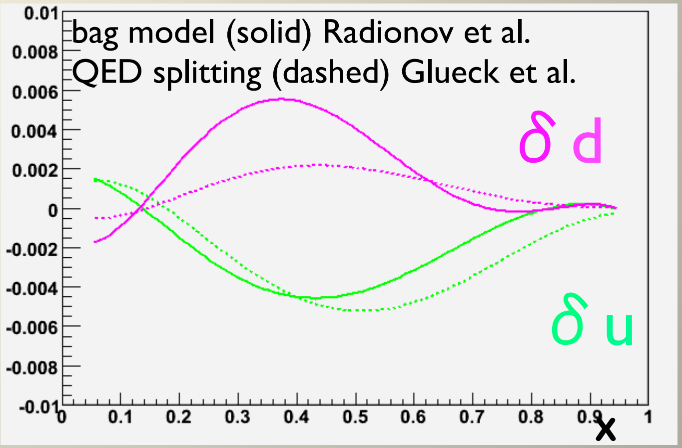
$$R_{CSV} = \frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

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

- Direct sensitivity to parton-level CSV
- Important implications for PDF's
- Could be partial explanation of the NuTeV anomaly



Sensitivity will be enhanced if u+d falls off more rapidly than δu-δd as x → 1



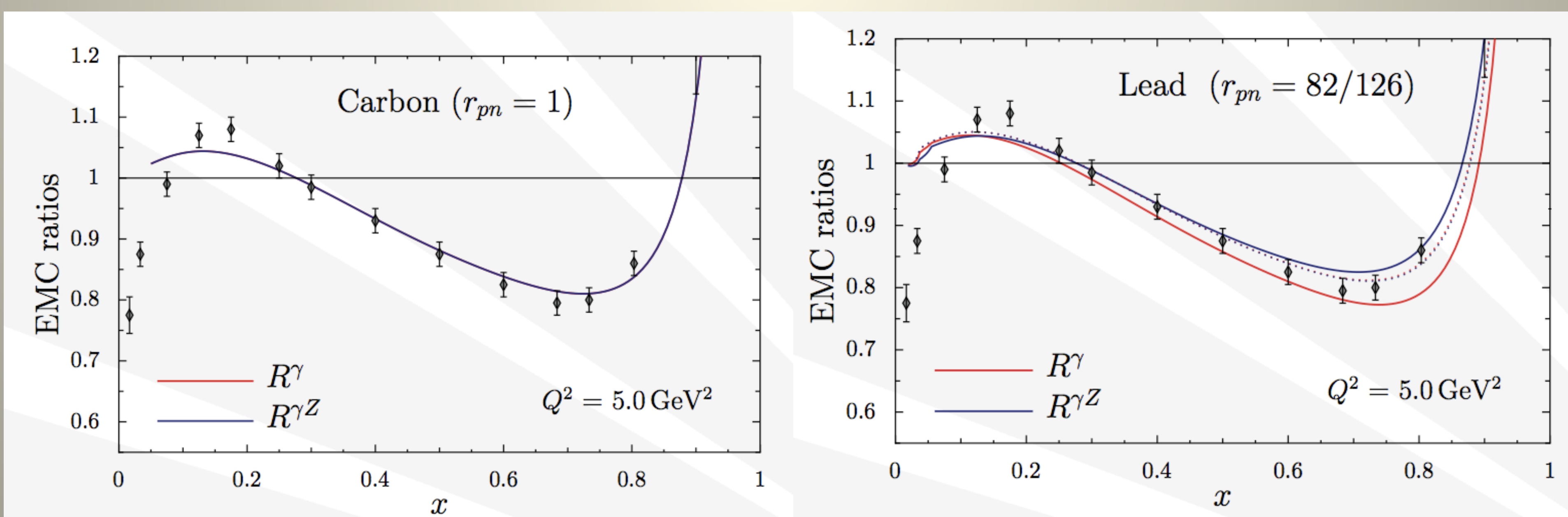
Significant effects are predicted at high x

Nuclear Medium Modification

Cloet, Bentz, Thomas, arXiv 0901.3559

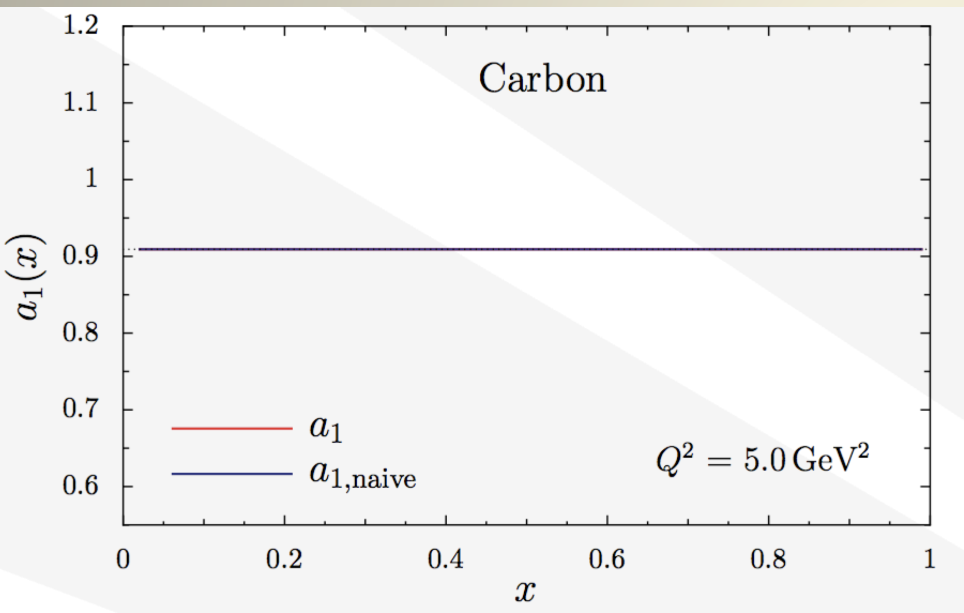
- They propose that a neutron or proton excess in nuclei leads to an isovector-vector mean field dominated by ρ exchange
- shifts quark distributions: "apparent" CSV violation
- Isovector EMC effect: explain 2/3 of NuTeV anomaly

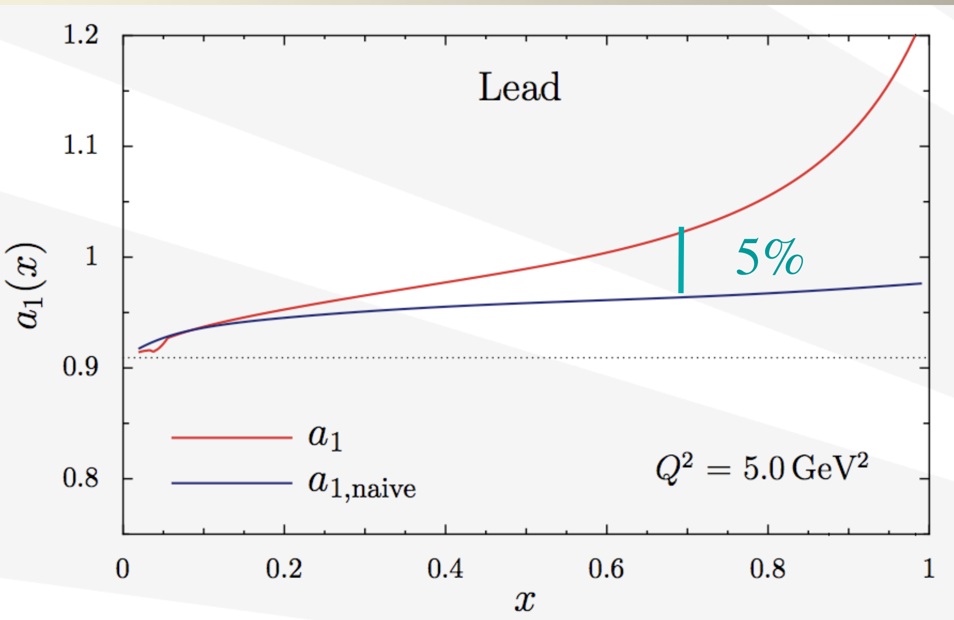
$$R^{\gamma} \sim \frac{4\,u_A(x)+d_A(x)}{4\,u_0(x)+d_0(x)} \quad \& \quad R^{\gamma Z} \sim \frac{1.16\,u_A(x)+d_A(x)}{1.16\,u_0(x)+d_0(x)}$$



Apparent CSV in Nuclei

- Suppose one completes a ^{2}H A_{PV} measurement, then repeat with ^{208}Pb
  - The ratio of ratios (heavy nucleus vs deuterium) as a function of x should show a measurable effect if model is correct
  - Measuring the EMC effect along a different isospin axis





- **Would be a smoking gun demonstration of nuclear medium modification of quark distributions**
- **Another classic example of interplay between EW and QCD physics**

A Special HT Effect

The observation of Higher Twist in PV-DIS would be exciting direct evidence for diquarks

following the approach of
Bjorken, PRD 18, 3239 (78),
Wolfenstein, NPB146, 477 (78)

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

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

Isospin decomposition before using PDF's

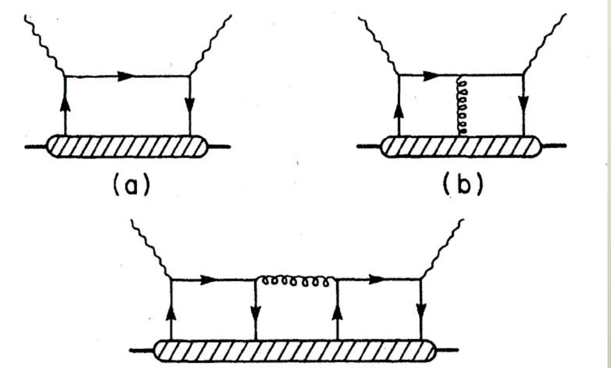
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

$$\delta = \frac{\langle VV \rangle - \langle SS \rangle}{\langle VV \rangle + \langle SS \rangle} \qquad a(x) \propto \frac{F_1^{\gamma Z}}{F_1^{\gamma}} \propto 1 - 0.3\delta$$

Higher-Twist valence quark-quark correlation

Zero in quark-parton model

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



Castorina & Mulders, '84

(c) type diagram is the only operator that can contribute to a(x) higher twist: theoretically very interesting!

σ_L contributions cancel

Use ν data for small b(x) term.

a_3 Term and Neutrino's

$$\frac{1-(1-y)^2}{1-y-y^2/2(1+R)}a_3(Q^2,\nu) \propto \frac{\sigma^{\nu}-\sigma^{\bar{\nu}}}{\sigma^{\nu}+\sigma^{\bar{\nu}}}$$

These hadronic corrections can be obtained from charged-current neutrino scattering data

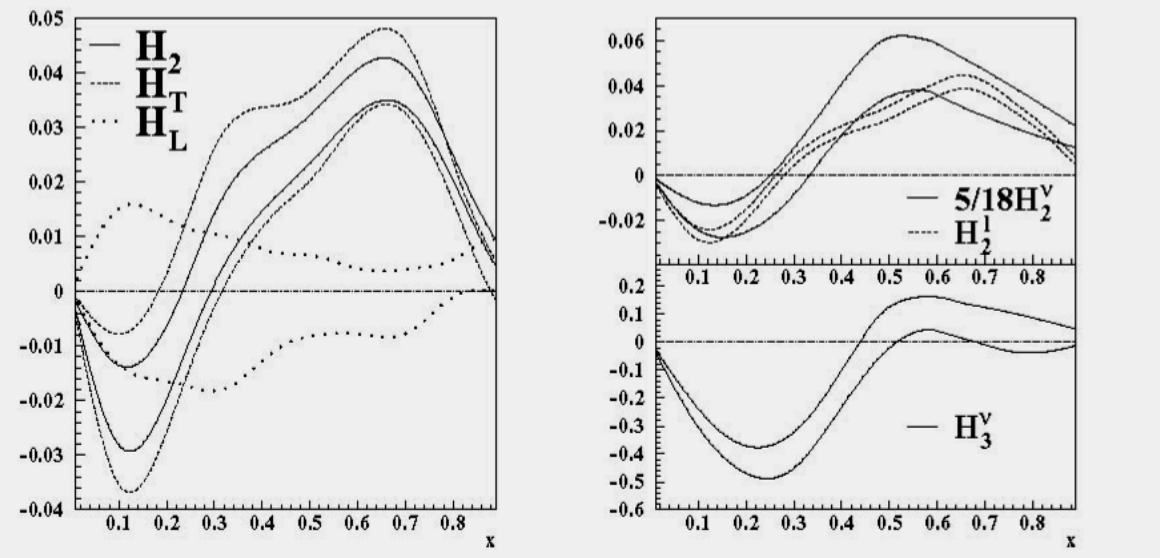


FIGURE 2. Left figure: the 1σ error bands for the high-twist terms in the isospin-symmetric combinations of different structure functions (solid lines: F_2, dashes: F_T, dots: F_L) for charged leptons. Right figure: corresponding 1σ bands for neutrino scattering off an isoscalar target (upper panel: F_2, lower panel: xF_3). The predictions for F_2 from charged leptons rescaled by the corresponding leading twist terms are also shown for comparison.

Error Budget (%)

Statistics	0.3
Polarimetry	0.4
Q2	0.2
Radiative Corrections	0.3
Total	0.6

Physics with Hydrogen

d(x)/u(x) as x→1

SU(6): d/u~1/2
Valence Quark: d/u~0
Perturbative QCD: d/u~1/5

Longstanding issue in proton structure

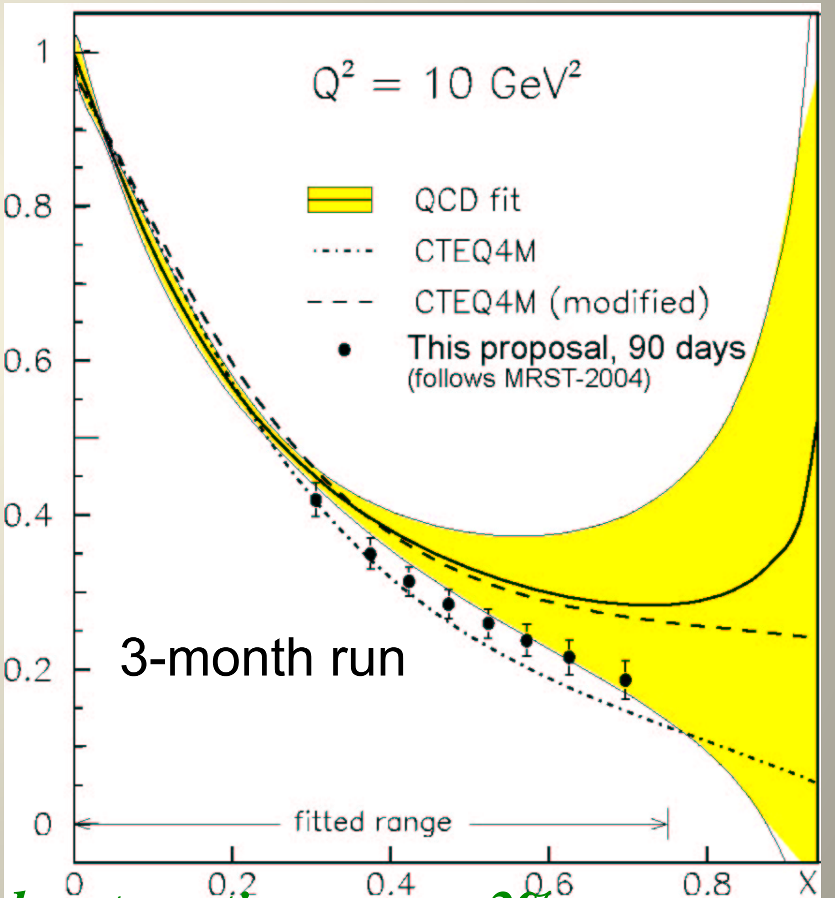
PV-DIS off the proton (hydrogen target)

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

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

Deuteron analysis has large nuclear corrections (Yellow)

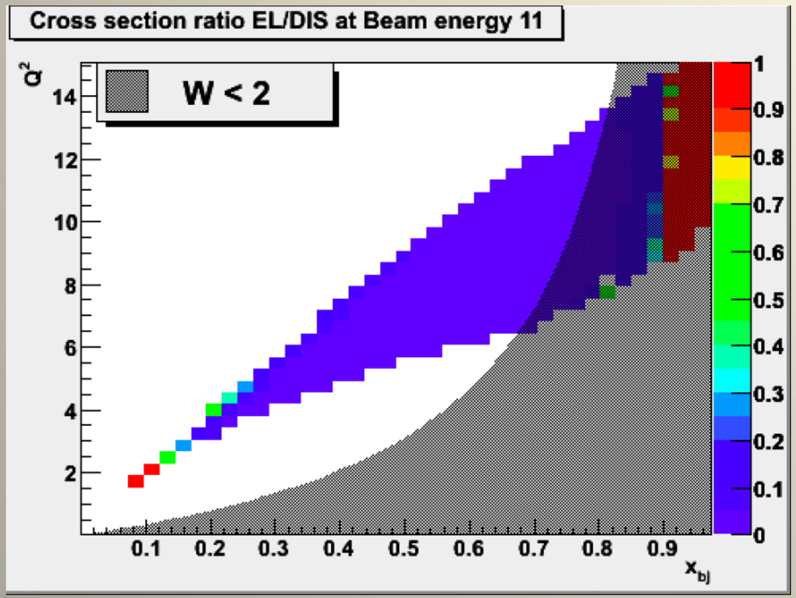
A_{PV} for the proton has no such corrections

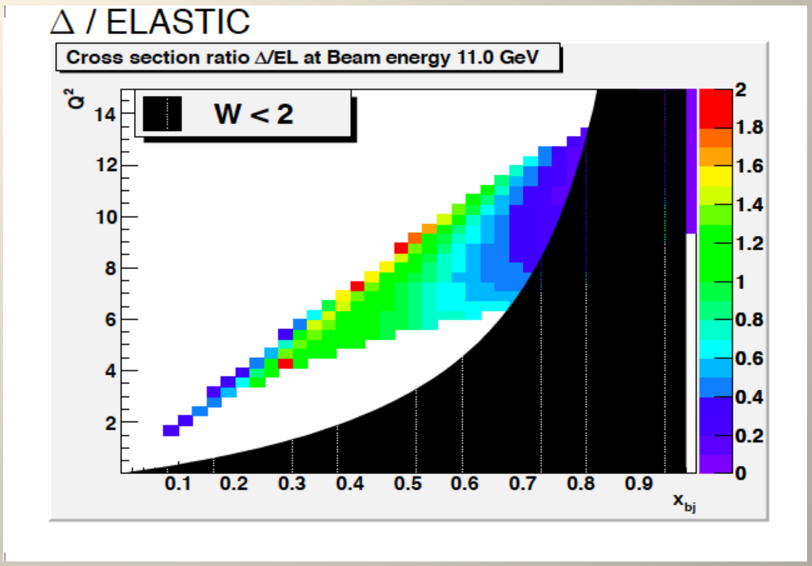


The challenge is to get statistical and systematic errors ~ 2%

Radiative Corrections

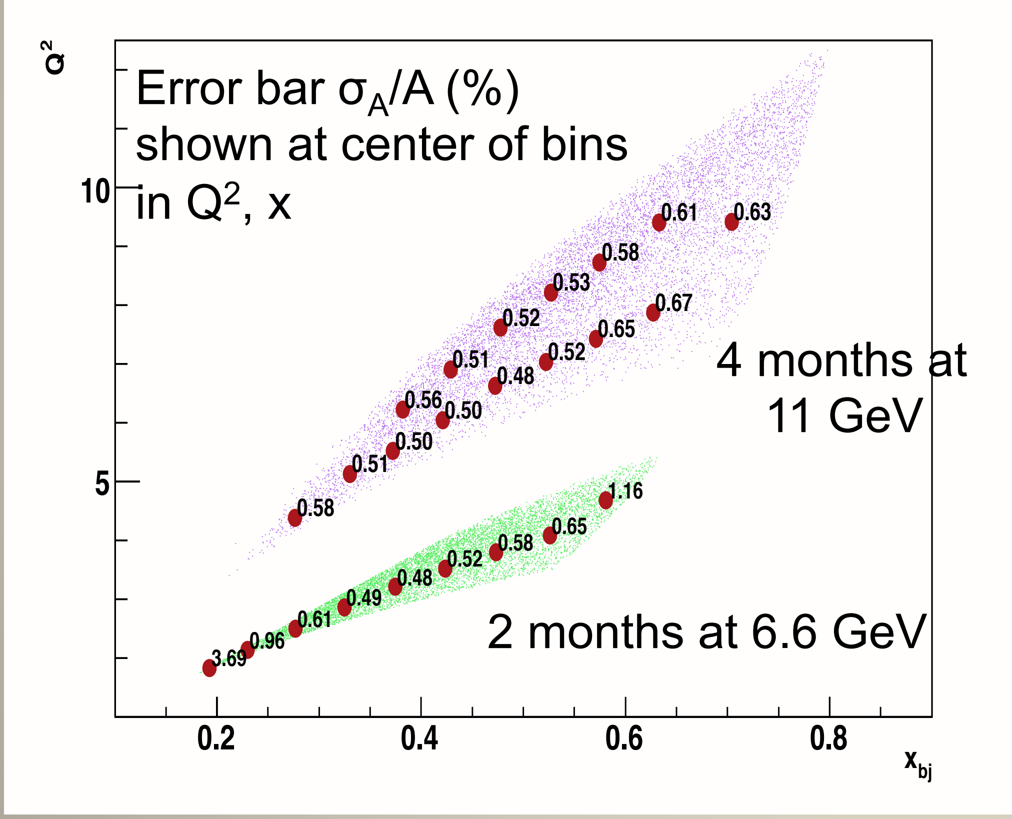
- Need coherent theory of all electromagnetic and elecroweak corrections at finite Q2.
- Radiative correction theory group is being assembled.
- Preliminary estimates have been made.





Running time

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



Untangle Physics with fit:

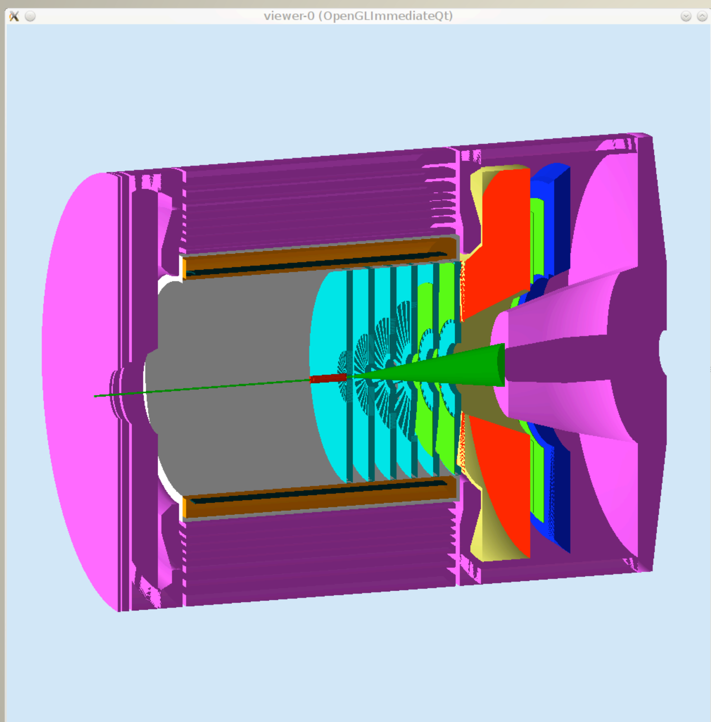
$$A = A\left[1 + \beta_{HT}\frac{1}{(1-x)^3 Q^2} + \beta_{CSV}x^2\right]$$

Beam Time Request:
LD_2: 245 Days
LH_2: 113 Days

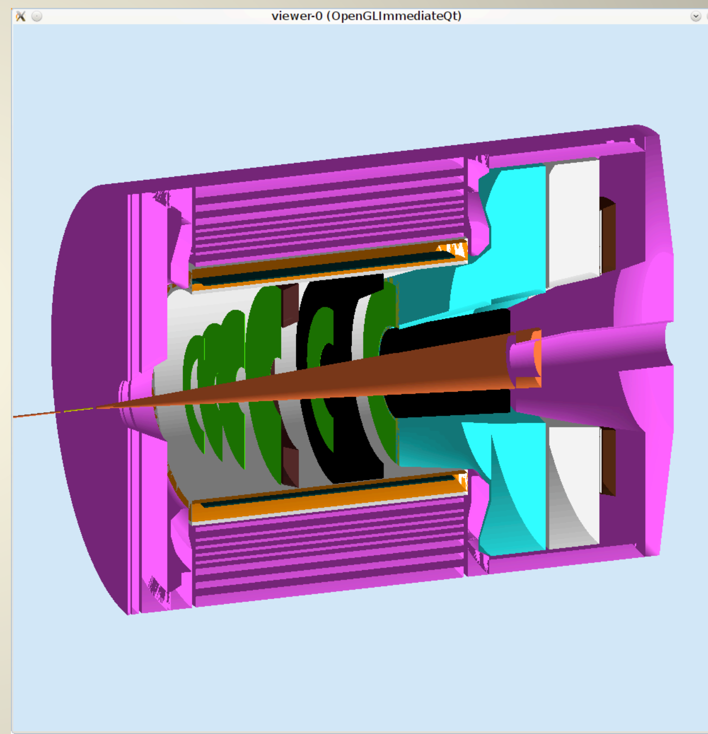
Energy(GeV)	4.4	6.6	11	Test
Days(LD2)	18	60	120	27
Days(LH2)	9	-	90	14

PVDIS vs SIDIS

PVDIS



SIDIS



Can you find six differences between these panels?

GEM Layout, Extra E-Cal, End Cap Longer

Target Location, Baffles (PVDIS), Cerenkov's,

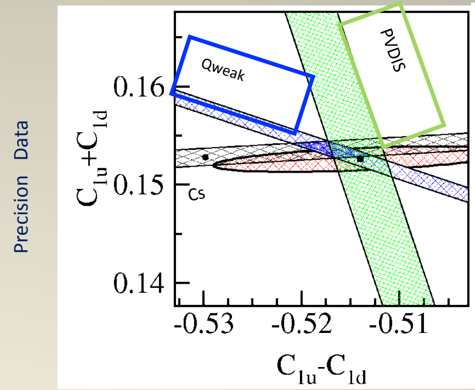
Summary

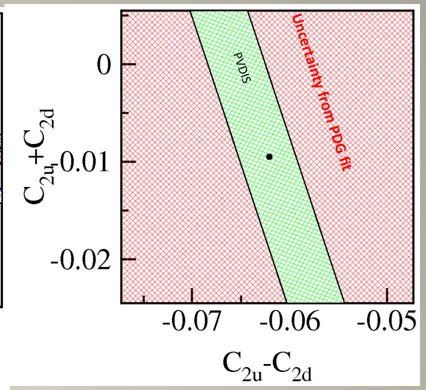
- Measurements of Parity Violation in Deep Inelastic Scattering contain a wealth of information about:
  - The Standard Model
  - Charge Symmetry (CSV)
  - Higher Twist (HT)

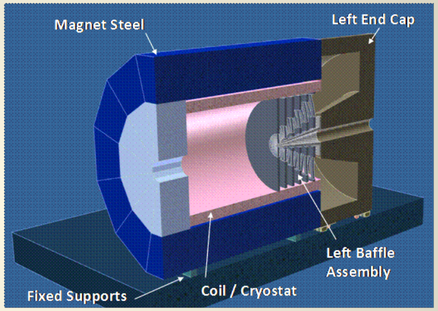
- For the complete picture—to unravel the full richness of the physics reach of this process a dedicated—a large-acceptance spectrometer is needed.

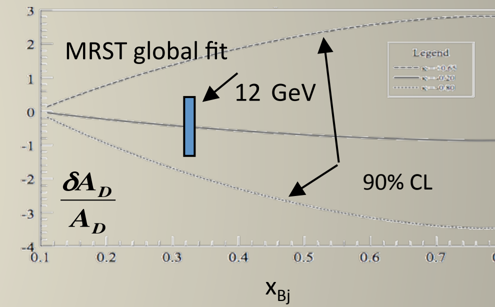
- SoLID will also provide critical nuclear structure test (NuTeV $\sin^2\theta_W$)

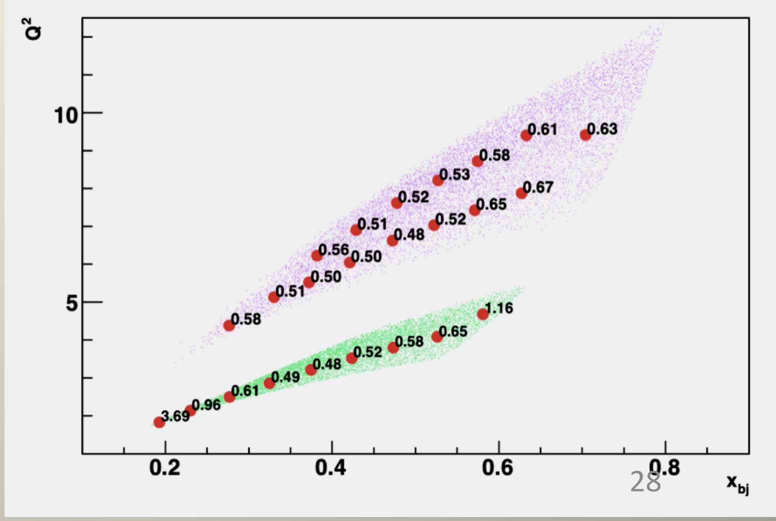
- Large additional program of SI-DIS planned for SoLID spectrometer







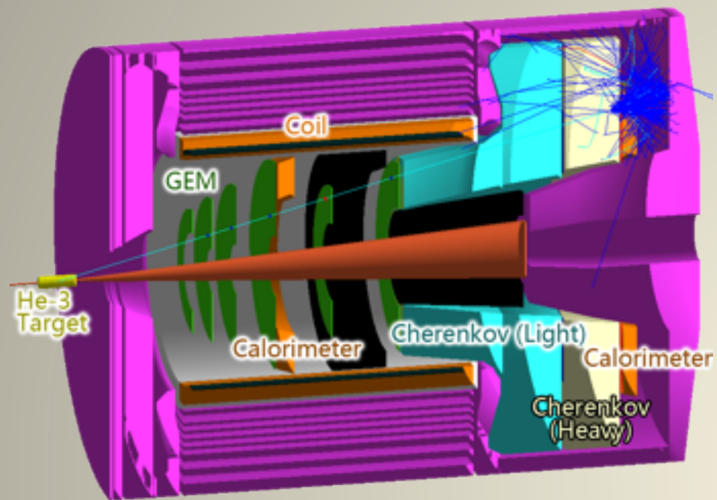




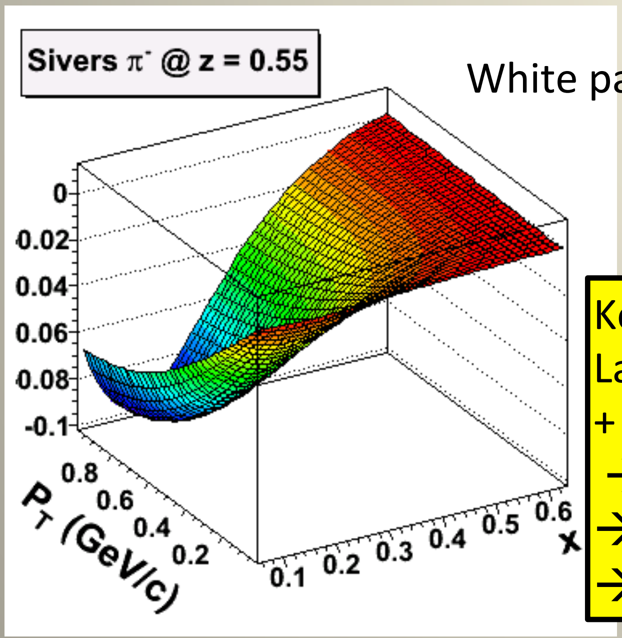
Junk

SOLID-Spin

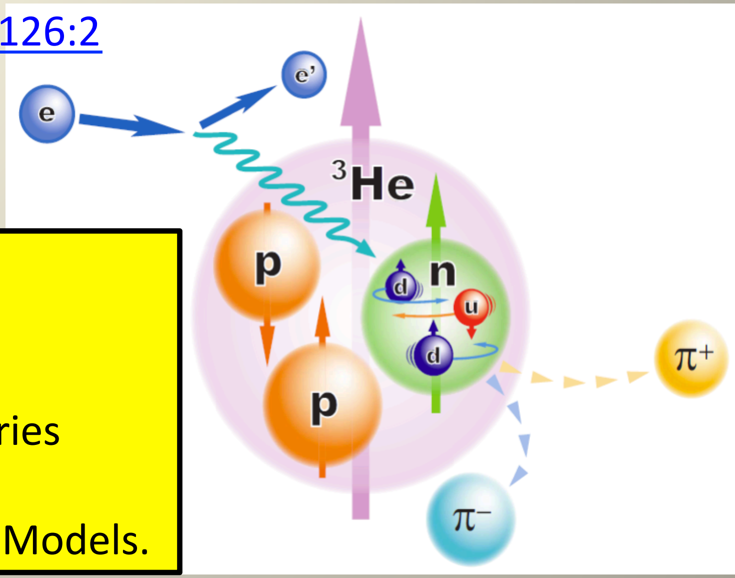
Double-Polarized Semi-Inclusive DIS on ^{3}He & ^{1}H at 11 GeV



- E12-10-006: Single Spin Asymmetry on Transverse ^{3}He @ 90 days
- E12-11-007: Single and Double Spin Asymmetry on ^{3}He @ 35 days
- PR12-11-108: Single and Double Spin Asymmetries on Transverse Proton (conditionally approved)

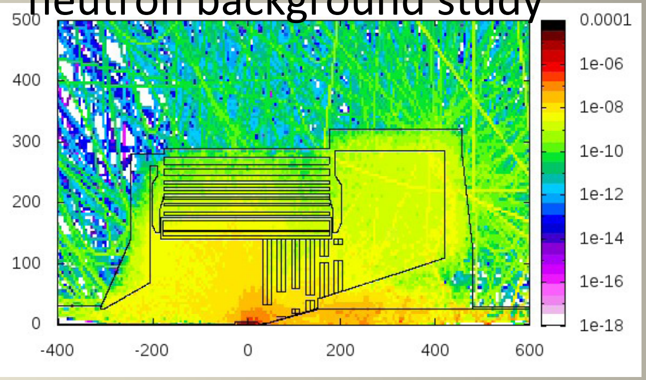


White paper: [Eur. Phys. J. Plus (2011) 126:2]



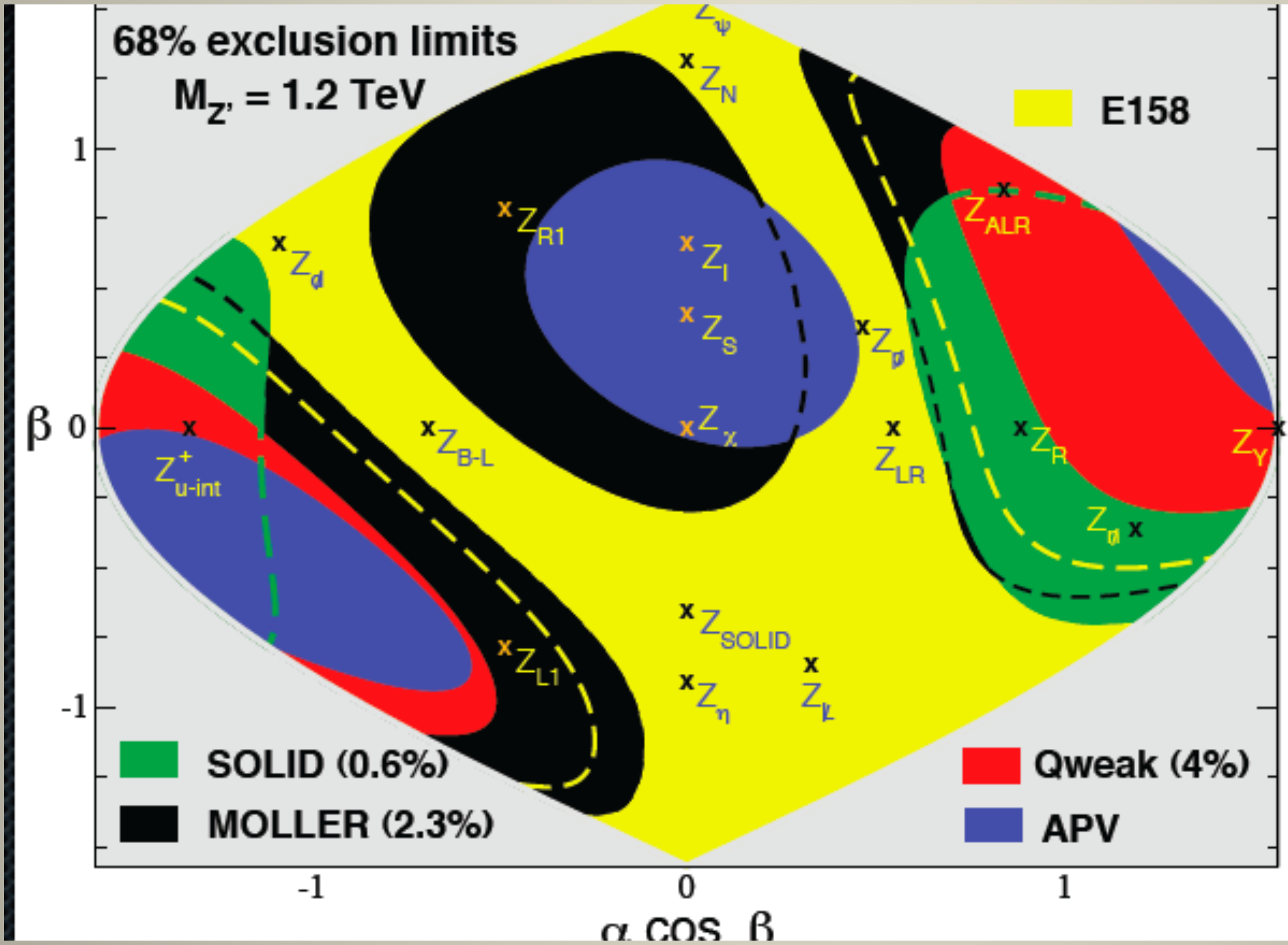
Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ 4-D mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.

SOLID Status



- Strong collaboration being formed
  - ~ 130 collaborators, ~ 35 institutions
  - Parity and DIS expertise
  - Significant international participation: Italy, Germany, China
  - ~ 5 Postdoc FTEs now focused on simulation and R&D
- Significant hardware R&D potential
  - GEMs, Shashlyk, pipeline electronics, collimator engineering….
- Timeline
  - Would run in Hall A on and off between 2016 and 2022
  - JLab is currently negotiating with Cornell to move CLEOII magnet ~ 2014
  - R&D and Design ~ 2-3 years
  - Funding strategies (total cost 20-25 M$)
    - unlikely to be a one CD-funded project
    - must consist of several sub-projects
    - JLab wants to single out hardware that might be of multi-purpose use

SoLID and extra Z's



- APV (Boulder)
- E158 (SLAC)
- MOLLER
- Qweak
- SOLID