Parity Violating Deep Inelastic Scattering with the 12 GeV Upgrade

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Thanks to:
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DIS 2007, Munich, Germany

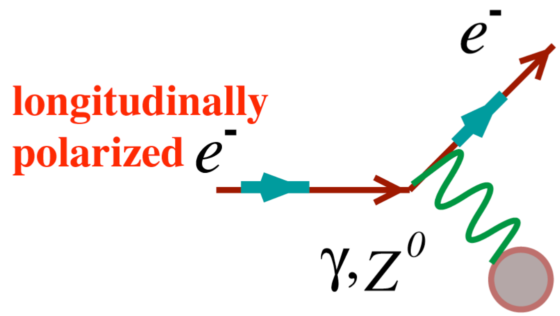
Outline

- *Introduction*
  - Weak Neutral Current Interactions
  - Parity-Violating Electron Scattering
- *Low Energy Searches for "New" Physics*
  - Why are new precision measurements relevant?
- *PV Deep Inelastic Scattering at JLab at 11 GeV*
  - Potential for complementary probes of "new" physics
  - Potential of precision studies of nucleon structure at high x
- *Aspects of the Experimental Design*
  - Novel, Large Acceptance Solenoidal Spectrometer
  - Precision Polarimetry
- *Outlook*

PV Asymmetries

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

Longitudinally Polarized Electron Scattering off Unpolarized Fixed Targets



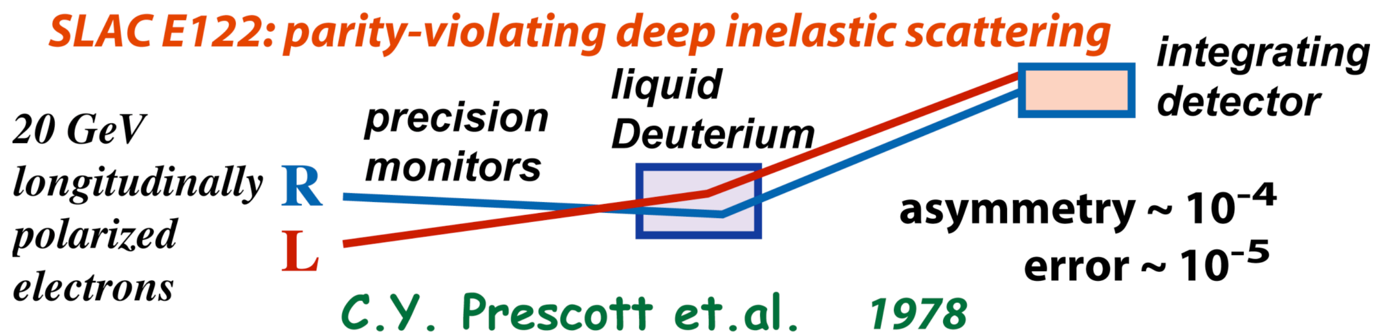
$$\sigma \quad \alpha \, | \, A_\gamma + A_{weak} |^2$$

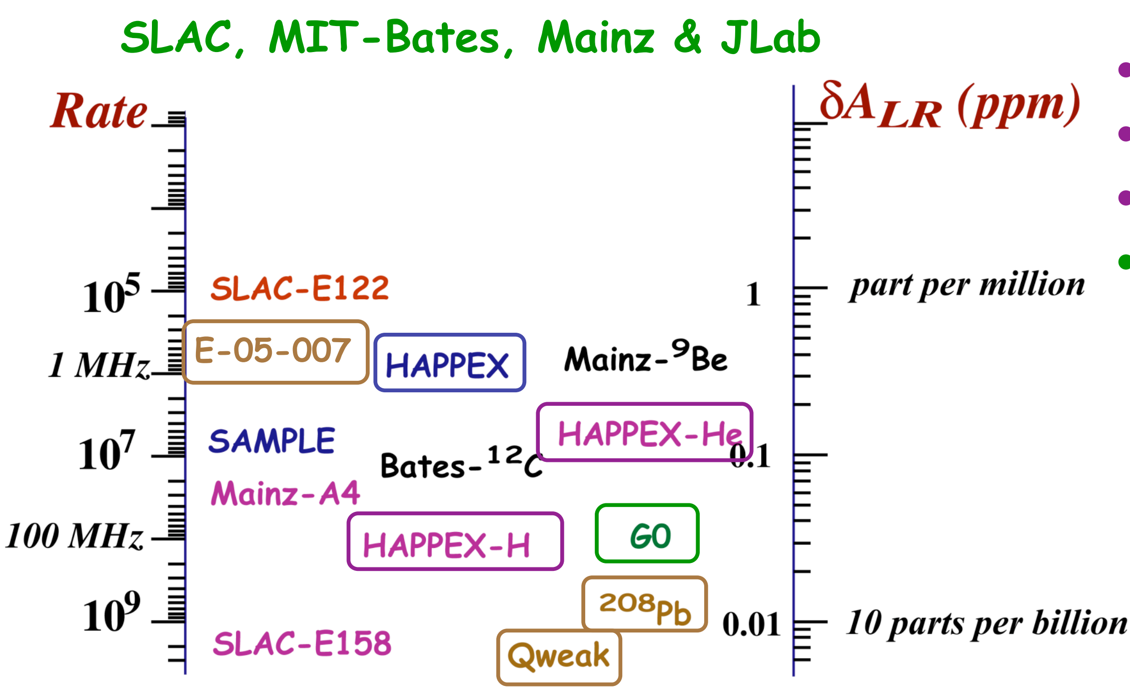
$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha} \left(g_A^e g_V^T + \beta g_V^e g_A^T\right)$$

- *The couplings g depend on electroweak physics as well as on the weak vector and axial-vector hadronic current*
- *With specific choice of kinematics and targets, one can probe new physics at high energy scales*
- *With other choices, one can probe novel aspects of hadron structure*

A_{PV} Measurements

$$A_{PV} \sim 10^{-5} \cdot Q^2 \quad \text{to} \quad 10^{-4} \cdot Q^2$$ ⇒ ~ 0.1 to ~100 ppm





- *Steady progress in technology*
- *part per billion systematic control*
- *1% normalization control*
- *JLab now takes the lead*
  - *-New results from HAPPEX*
  - *-Photocathodes*
  - *-Polarimetry*
  - *-Targets*
  - *-Diagnostics*
  - *-Counting Electronics*

21st Century Electroweak Physics

- New Particle Searches
- Rare or Forbidden Processes
- Symmetry Violations
- Electroweak One-Loop Effects

High Energy Colliders

as well as

Low Energy: $Q^2 \ll M_Z^2$

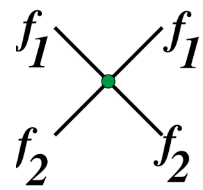
Low Q^2 offers complementary probes of physics at high energy scales

- *Neutrino Physics*
  - Oscillations and the MSNP matrix
  - Single and Double Beta Decay
- *Muon Physics*
  - g-2 anomaly
  - Precision muon decay parameter measurements
  - Charged lepton number violation searches
- *Semi-leptonic Weak Decays*
  - Standard Model CP Violation
  - Tests of CKM unitarity
  - Anomalous charged current interactions
  - Search for Proton decay
- *Dark Matter Searches*
- *Electric Dipole Moment Searches*
- *Neutral Weak Interaction Studies*

Comprehensive Search for New Neutral Current Interactions

Important component of indirect signatures of "new physics"

Consider $f_1\bar{f}_1 \rightarrow f_2\bar{f}_2$ or $f_1 f_2 \rightarrow f_1 f_2$



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

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 Λ > 10 TeV for as many $f_1 f_2$ and L,R combinations as possible

LEPII, Tevatron access scales Λ's ~ 10 TeV

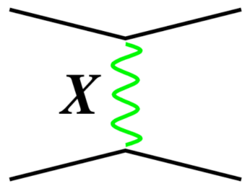
e.g. Tevatron dilepton spectra, fermion pair production at LEPII

- L,R combinations accessed are parity-conserving

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

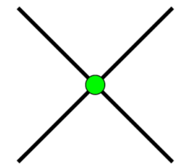
Colliders vs Low Q^2

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!

$\frac{\delta A_Z}{A_Z} \;\alpha\; \frac{\pi/\Lambda^2}{g\,G_F} \longrightarrow$ $\delta(g)/g \sim 0.1$, $\Lambda \sim 10\ TeV$

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

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

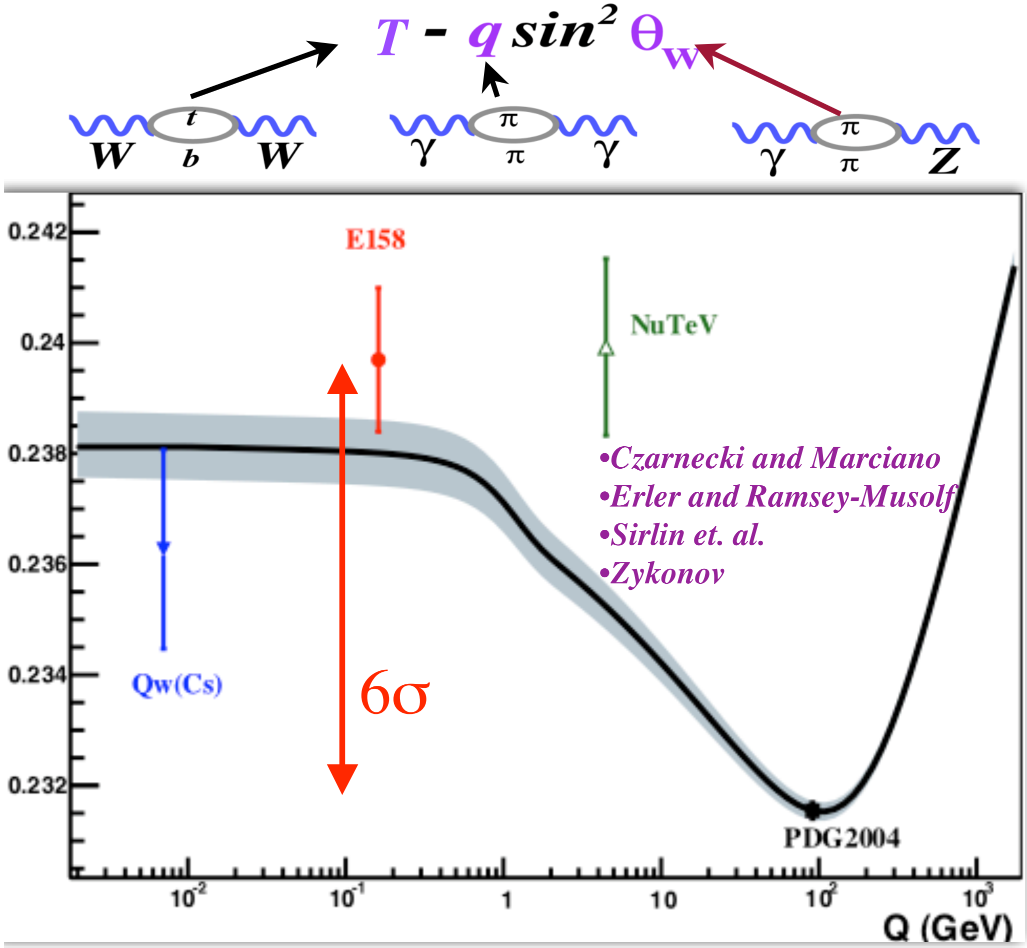
In the mid-1990s, two promising techniques:

- Atomic Parity Violation Experiments
- Neutrino-Nucleon Deep Inelastic Scattering
- Parity-Violating Electron Scattering can compete!

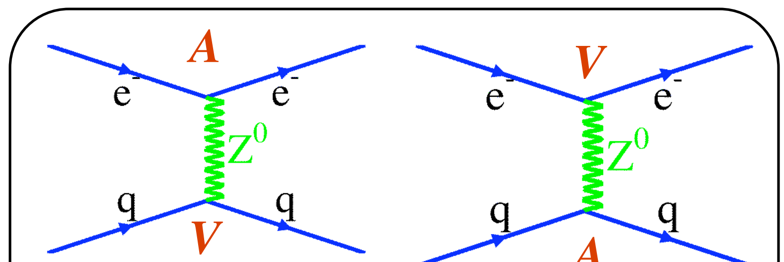
measure A_{PV} that is proportional to $1\text{-}4\sin^2\theta_W$:
electron-electron or elastic electron-proton scattering

$$\frac{\delta(\sin^2\vartheta_W)}{\sin^2\vartheta_W} \cong 0.05\,\frac{\delta(A_{PV})}{A_{PV}}$$

Current Status, Ongoing Efforts



- **Atomic Parity Violation**
  - ^{133}Cs 6s to 7s transition
  - Future: isotope measurements
- **E158: purely leptonic**
  - Running of weak mixing angle
- **Neutrino DIS: NuTeV**
  - 3 σ deviation
  - Many hadronic physics issues
  - Look at other l-q couplings?



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

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

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

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

Data ~ 2010

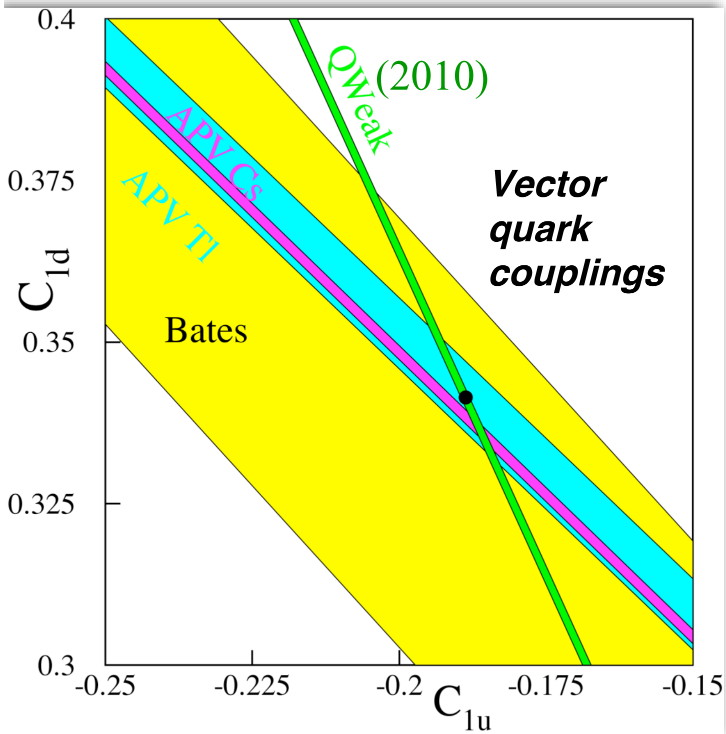
$$\delta(C_{1q}) \propto (+\eta_{RL}^{eq} + \eta_{RR}^{eq} - \eta_{LL}^{eq} - \eta_{LR}^{eq})$$

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

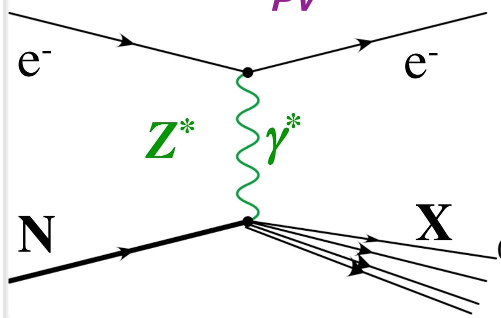
Complementary Constraints

provided $\delta(\sin^2\theta_W) \sim 0.001$

Unravelling the Quark WNC Couplings



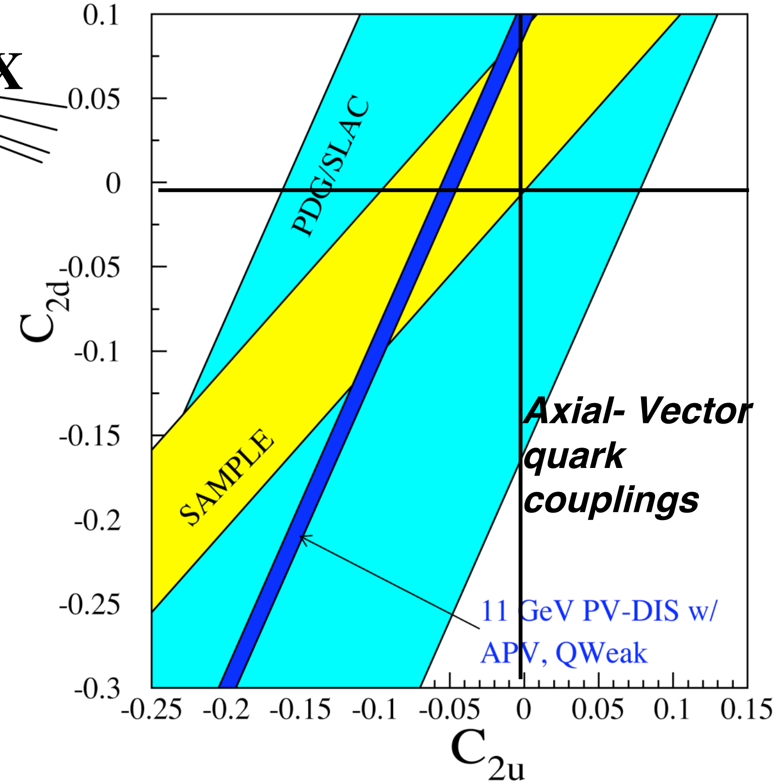
A_{PV} in Electron-Nucleon DIS:



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

$$a(x) = \frac{\sum_i C_{1i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)}$$

$$b(x) = \frac{\sum_i C_{2i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)}$$



For an isoscalar target like ^2H, structure functions largely cancel in the ratio:

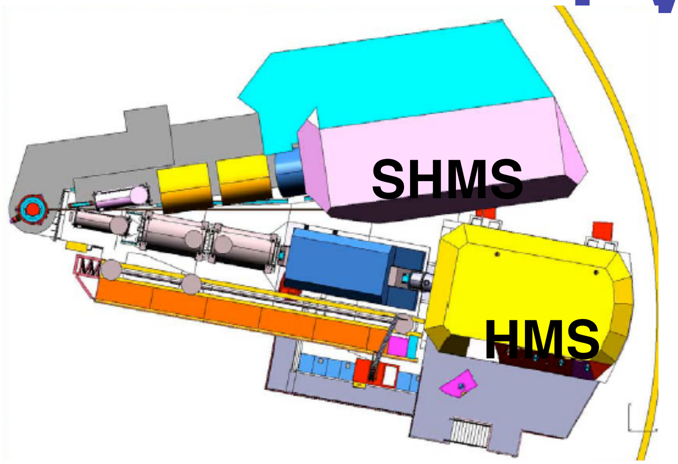
$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\right] + \cdots$$

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

- ***Must measure A_{PV} to 0.5% fractional accuracy!***
- ***Kinematics, luminosity and beam quality available at Jlab after the 12 GeV upgrade***

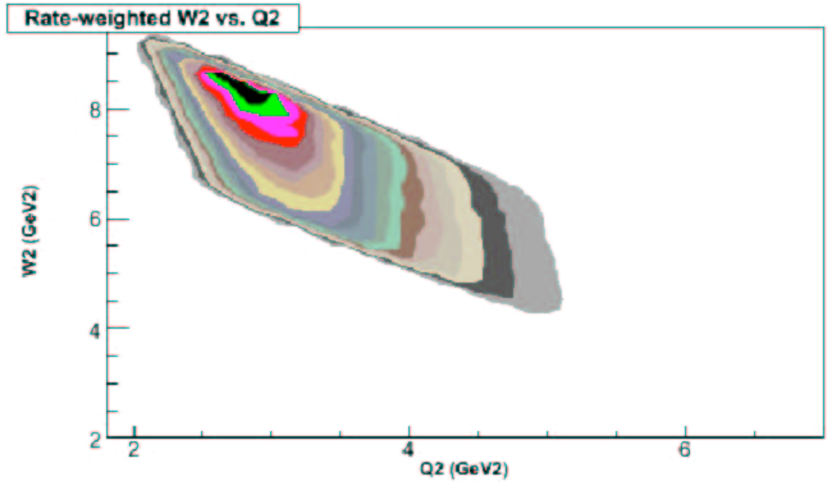
($Q^2 >> 1$ GeV^2 , $W^2 >> 4$ GeV^2, $x \sim 0.3$-0.6)

PV DIS Kinematics



- *Approved Experiment with 6 GeV beam*
- *Letter of Intent for 11 GeV Beam*

K.Paschke, P.Reimer, X.Zheng et. al



- *Use both HMS and SHMS at 11 GeV*
- *~0.5 MHz DIS rate, π/e ~ 0.1 - 1.0*

$x_{Bj} \sim 0.34$, $Q^2 \sim 3.3$ GeV^2, $W^2 \sim 7.3$ GeV^2

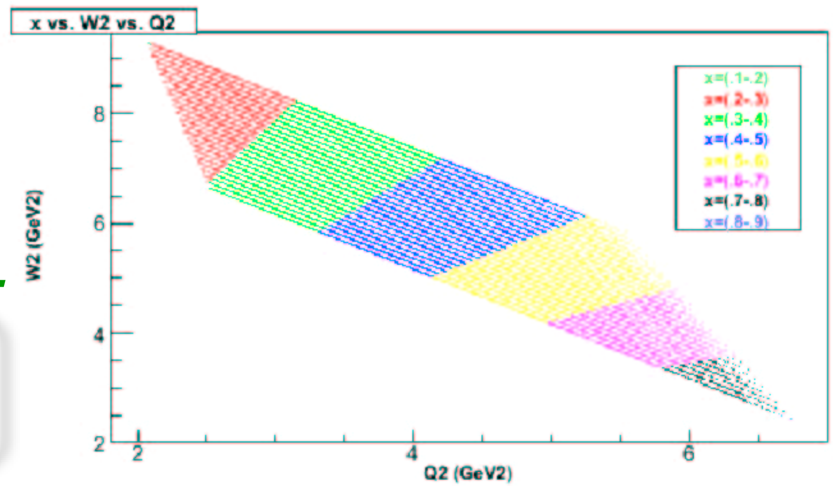
A_{PV} = 280 ppm ⇨ *30 days* ⇨ $\delta(A_{PV})_{stat}$=1.4 ppm

⇩

$\delta(2C_{2u}-C_{2d})_{stat}=\pm 0.009$

Theory: +0.0986

PDG (2004): -0.08 ± 0.24



Experimental systematics can be controlled…

Along with HERA & Atomic PV: important constraints to help decipher LHC anomalies

What about hadronic physics uncertainties?

With electron scattering, possibility to localize x,Q^2 bins, unlike neutrino scattering

Search for CSV in PV DIS

Charge symmetry violation (CSV) observed at nuclear & nucleon level: What about at the quark/parton level?

$$u^p(x) = d^n(x)?$$

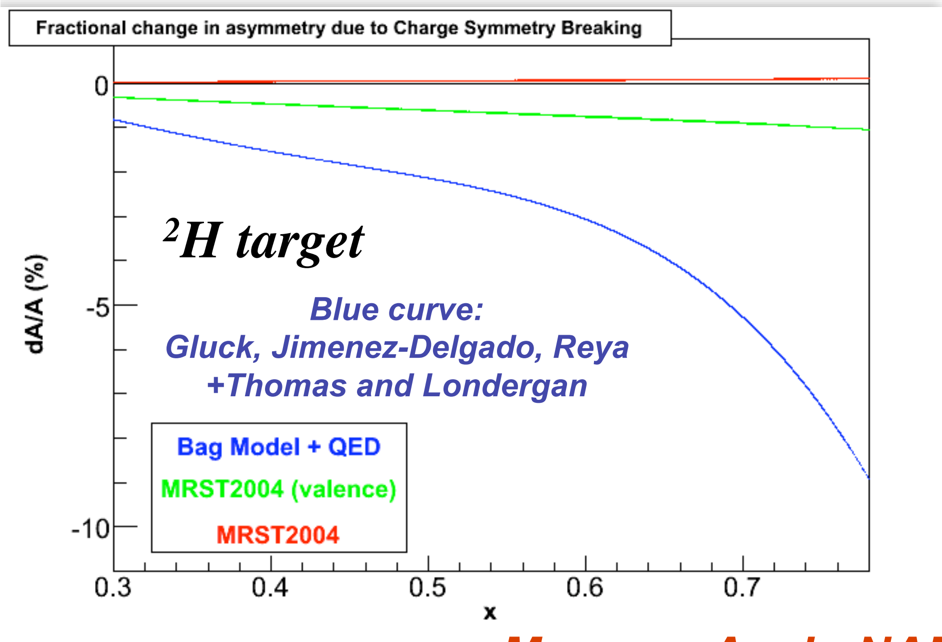
$$d^p(x) = u^n(x)?$$

- u-d mass difference
- electromagnetic effects

$$\delta u(x) = u^p(x) - d^n(x)$$

$$\delta d(x) = d^p(x) - u^n(x)$$

- *Direct observation of parton-level CSV would be very exciting!*
- *Important implications for high energy collider pdfs*
- *Could explain significant portion of the NuTeV anomaly*



u+d might fall off more rapidly than δu-δd as x → 1

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

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

	x	*y*	*Q^2*
New Physics	*no*	*yes*	*no*
Higher-Twist	*yes*	*no*	*yes*
CSV	*yes*	*no*	*no*

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***

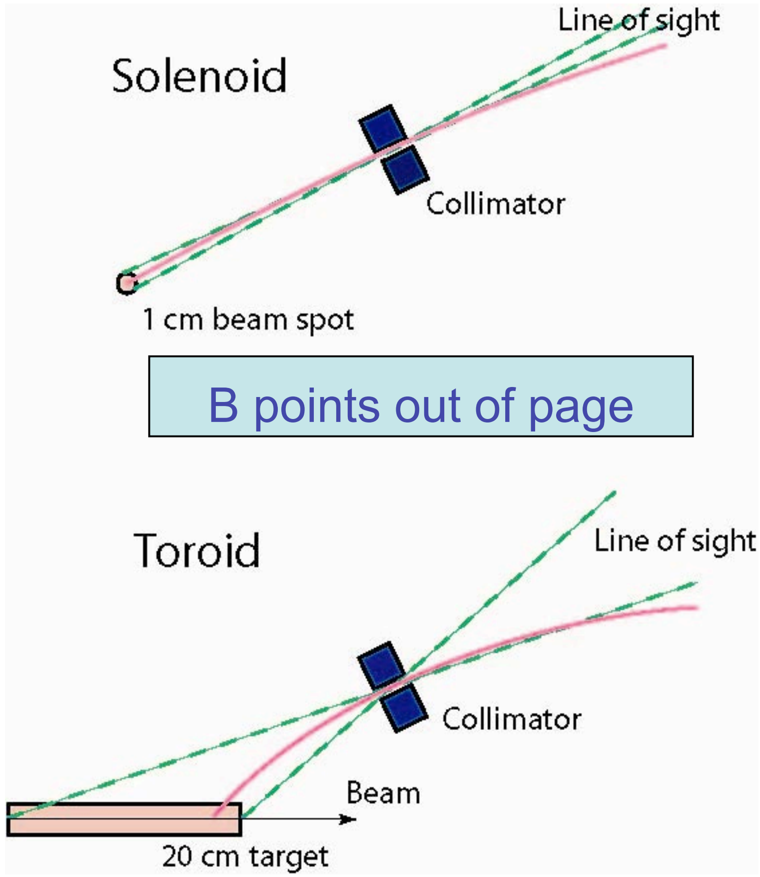
A Design for Precision PV DIS Physics

- *High Luminosity on long Cryotargets*
- *Better than 1% errors*
  - It is unlikely that any effects are larger than 5-6%
- *x-range 0.25-0.75*
- *W^2 well over 4 GeV^2*
- *Q^2 range a factor of 2 for each x*
  - (Except x~0.75)
- *Moderate running times*

•*CW 90 μA at 11 GeV*
•*40 cm liquid H_2 and D_2 targets*
•*Luminosity > $10^{38}/cm^2/s$*

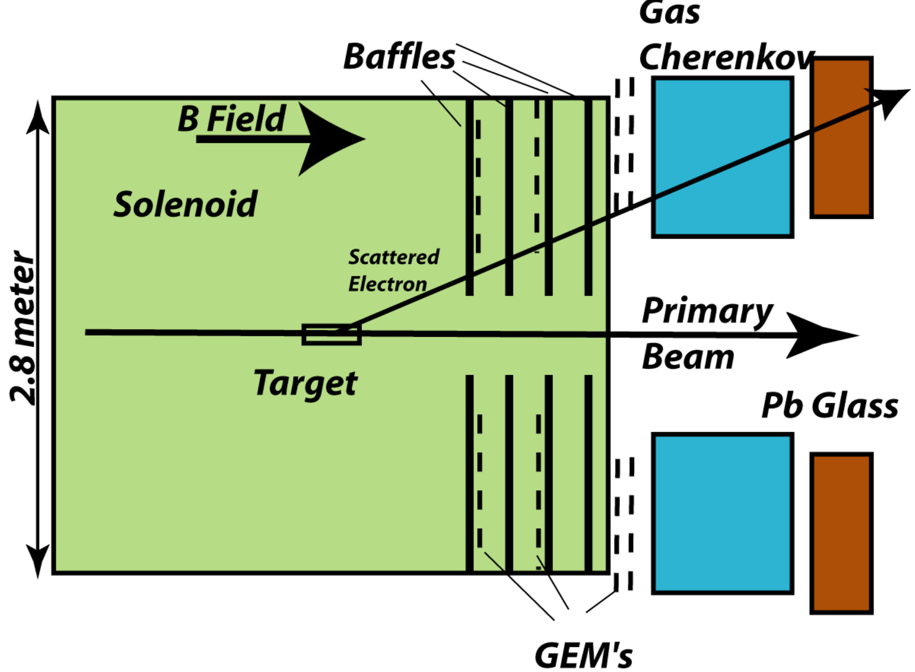
•*solid angle > 200 msr*
•*Count at 100 kHz*
• *online pion rejection of 10^2 to 10^3*

Problem: shield detector from line of sight photons

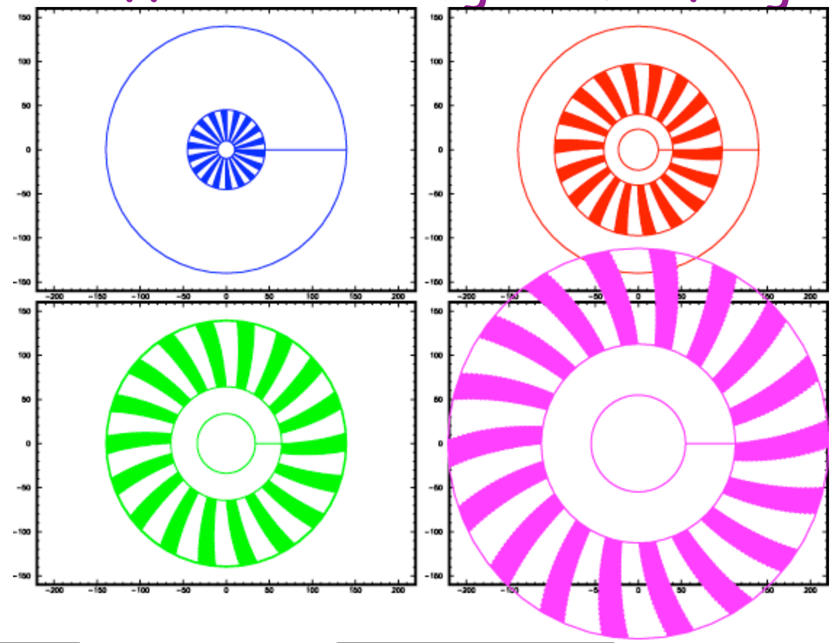


A Solenoidal Spectrometer Package

Solenoid takes advantage of the small beam spot; requires less bending



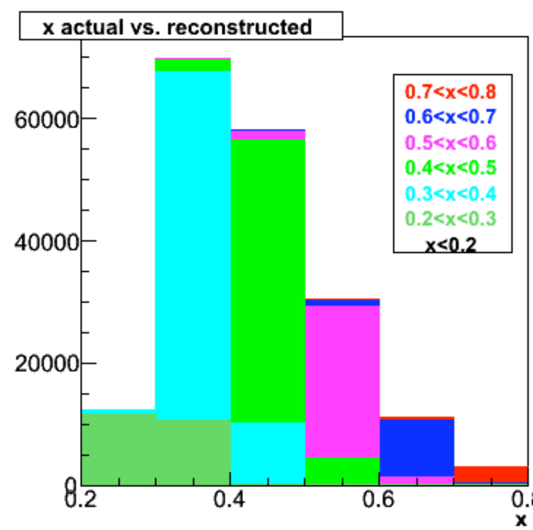
Baffles block target line of sight

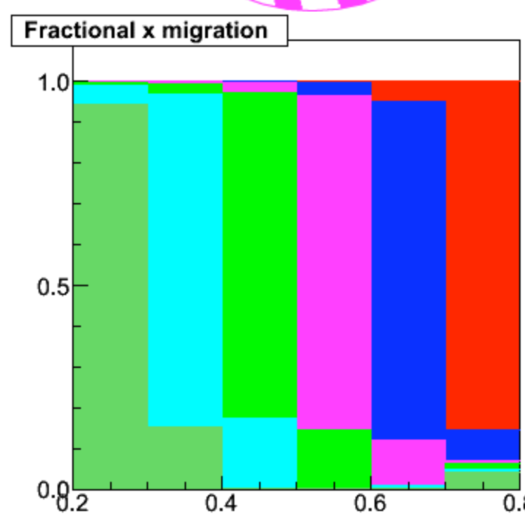


Existing solenoids which may fit

Experiment	B, T	Bore D, m	Length, m	MJ	X_0
BaBar	1.5	2.80	3.46	27	<1.4
Cleo-II	1.5	2.90	3.80	25	2.5

~ 2% momentum resolution achievable with 2 GEM planes outside solenoid





d(x)/u(x) as x→1: A New Method

Longstanding issue in proton structure

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

PV-DIS off the proton (hydrogen target)

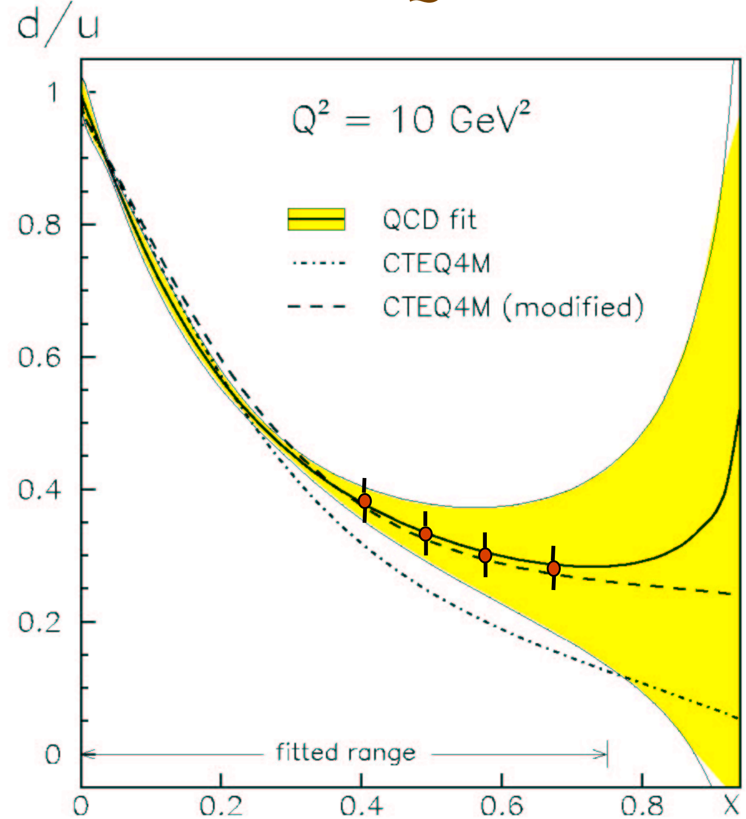
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

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

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

- *Allows d/u measurement on a single proton!*
- *Vector quark current! (electron is axial-vector)*

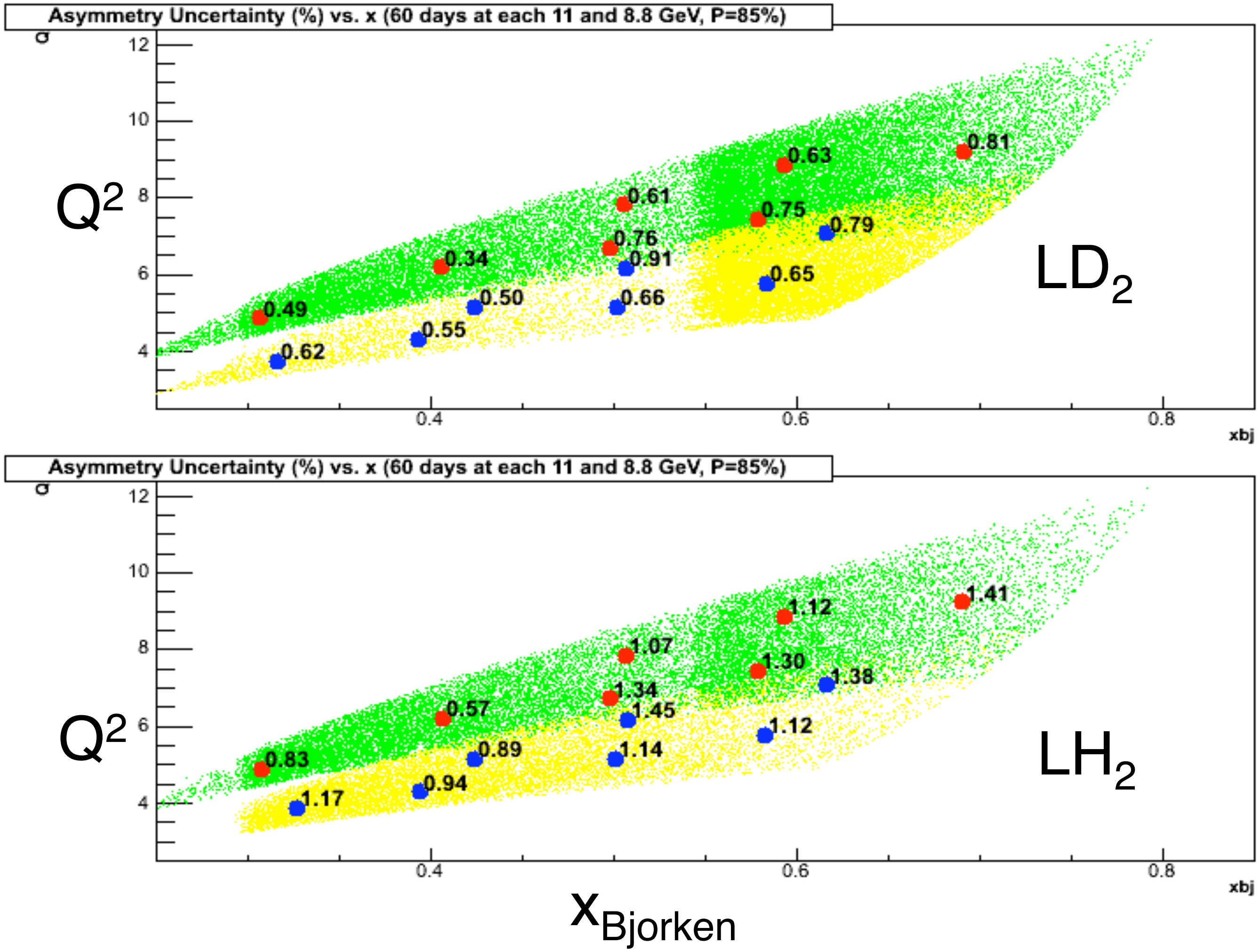
Also:
- ***Higher Twist Effects***
- ***F_3 structure function***



Solenoid Summary:

- *Need BaBar, CDF or CLEOII Solenoid*
- *refurbishing ~ 1-2 M$*
- *Total cost ~ 10M$*
- *diverse physics topics addressed:*
  - *Standard Model test, CSV, d/u, nuclear EMC effect, semi-inclusive physics, detailed studies of spin structure functions…*

Projected Statistical Errors



- 11 GeV
- 8.8 GeV

Simulations at two beam energies

Two runs of four calendar months

Successful Workshop at Jefferson Lab: Dec 13-14, 2006

Plan: Form a collaboration, start real design and simulations, and make pitch to US community: Nuclear Physics Long Range Planning (2007)

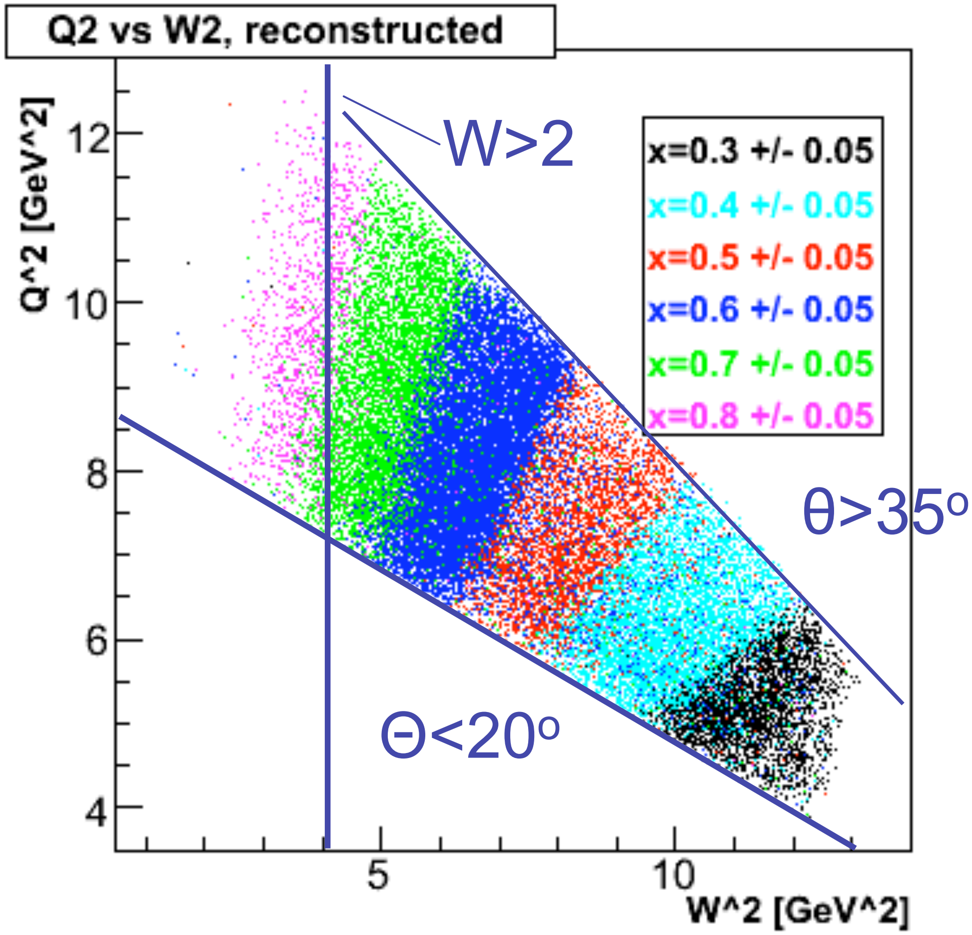
Summary

- ***Future Parity-Violating Electron Scattering Expts:***
  - New Precision Tests of the Standard Model
  - Important Complement of "Data Base" to confront LHC Data
- ***Parity-Violating Deep Inelastic Scattering***
  - Necessary for a Comprehensive Search for "New Physics"
- ***12 GeV Upgrade of Jefferson Laboratory***
  - Provides appropriate Beam Quality and Luminosity
  - Enables novel tests of nucleon structure and QPM picture
- ***Solenoidal Spectrometer Package***
  - Exploits Jlab Beam Conditions to provide unprecedented acceptance and resolution at x ~ 0.7
  - Many other physics topics would benefit
    - *d/u at high x*
    - *SIDIS with focus on TMDs*
    - *Nuclear EMC Effect*
    - *g_3 and g_5 structure functions*
- ***Come join us!***

Kinematic acceptance

11 GeV Incoming Beam Energy

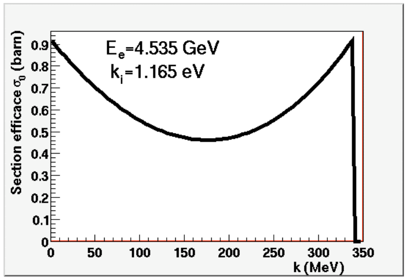
Large angles required for large x

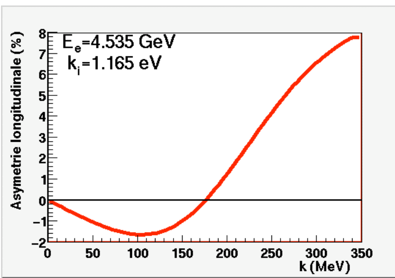


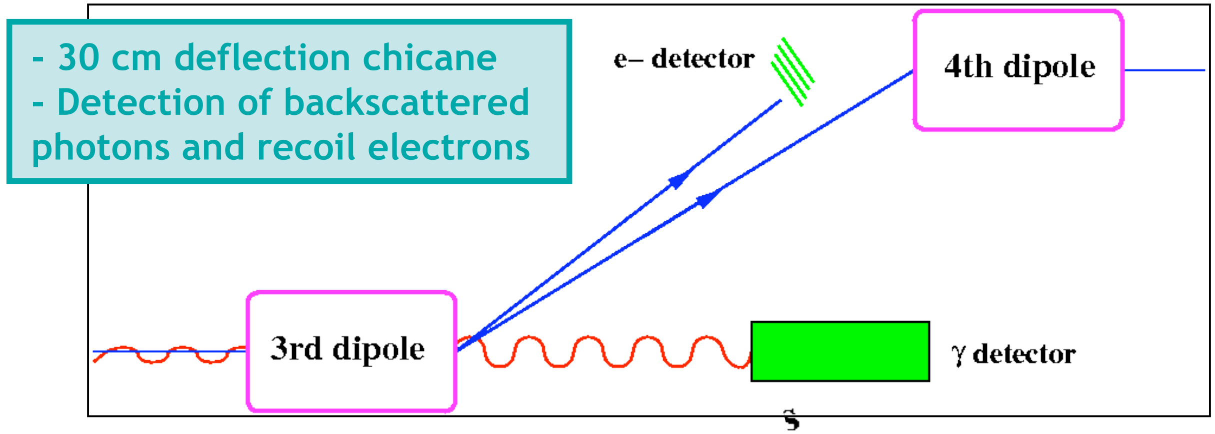
Good resolution needed to maintain integrity of the bins

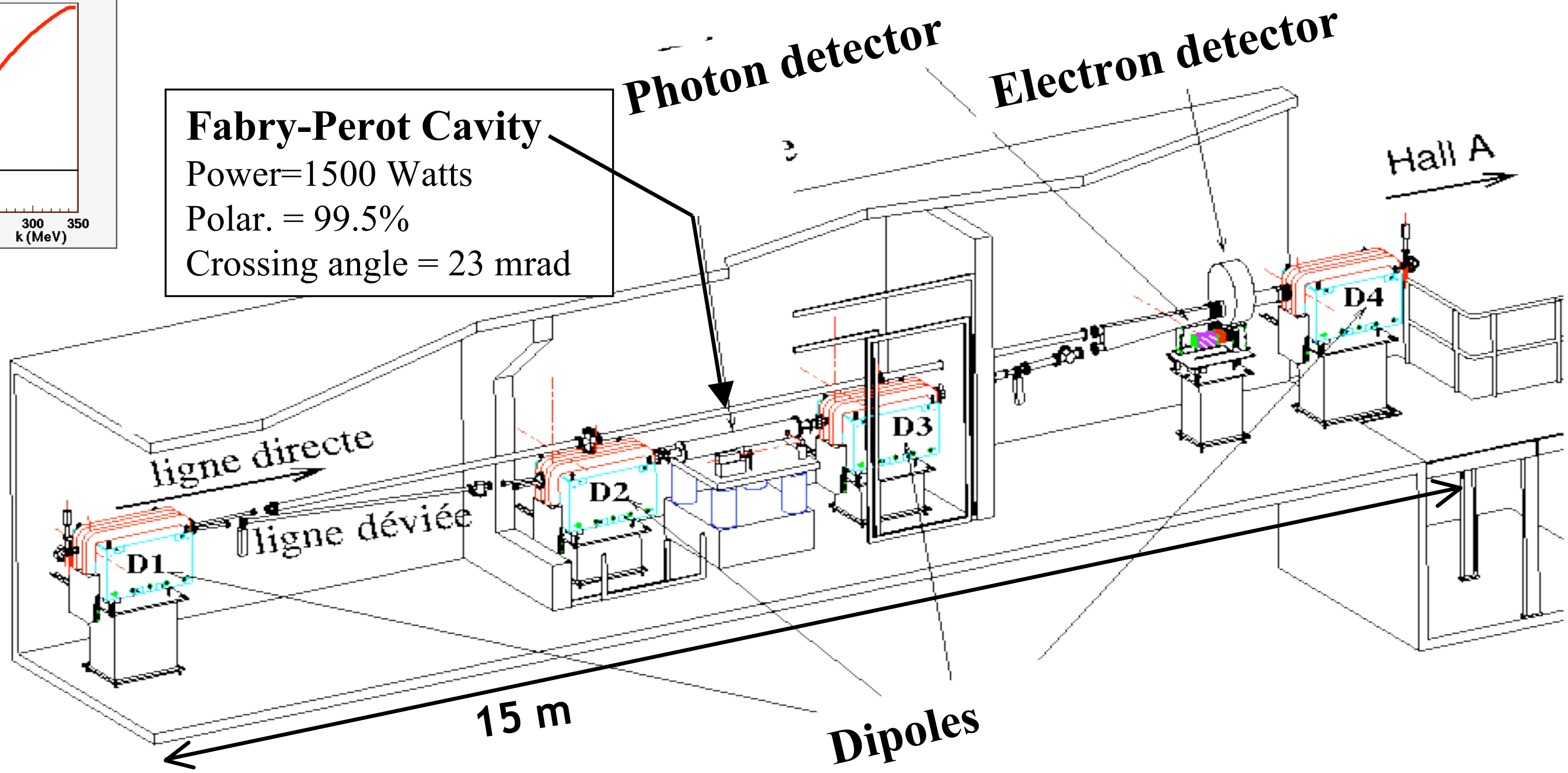
Hall A Compton Polarimeter

$$A_{exp} = \frac{n^+ - n^-}{n^+ + n^-} = P_\gamma \times P_e \times < A_{th} >$$







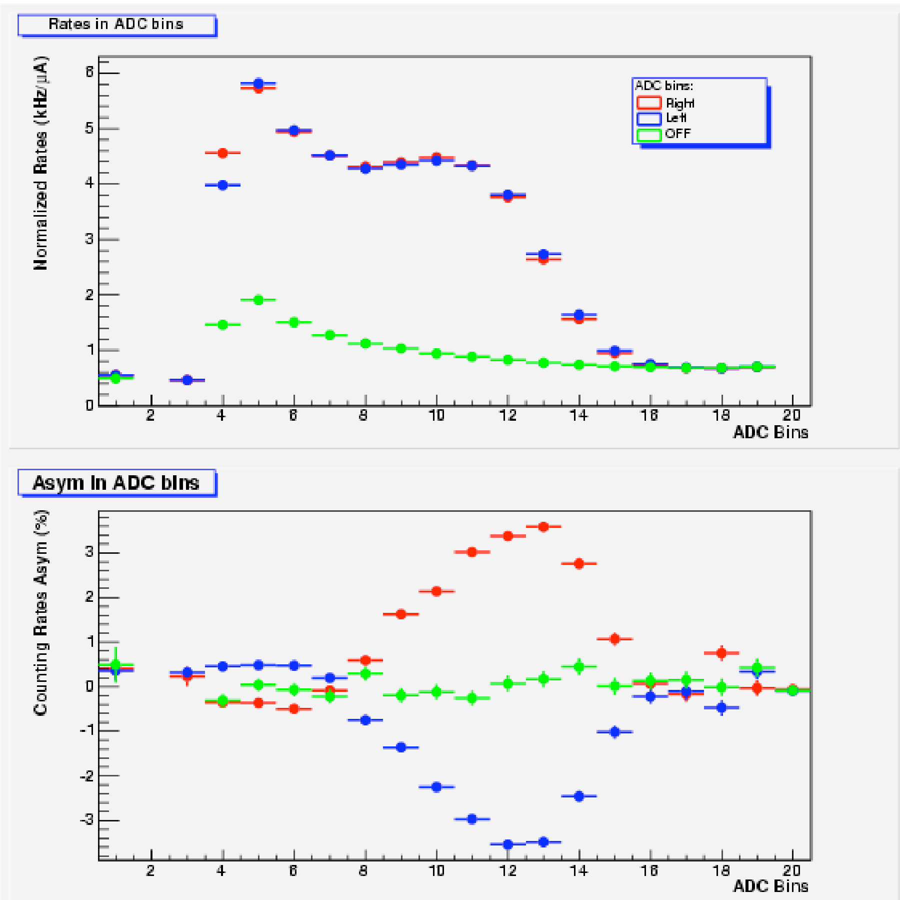


Hall A Compton Polarimetry Analysis

$$A_{\exp} = \frac{n^+ - n^-}{n^+ + n^-} = P_\gamma \times P_e \times < A_{th} >$$

requires energy calibration

Photon Detector Analysis



Energy resolution prevents self-calibration:

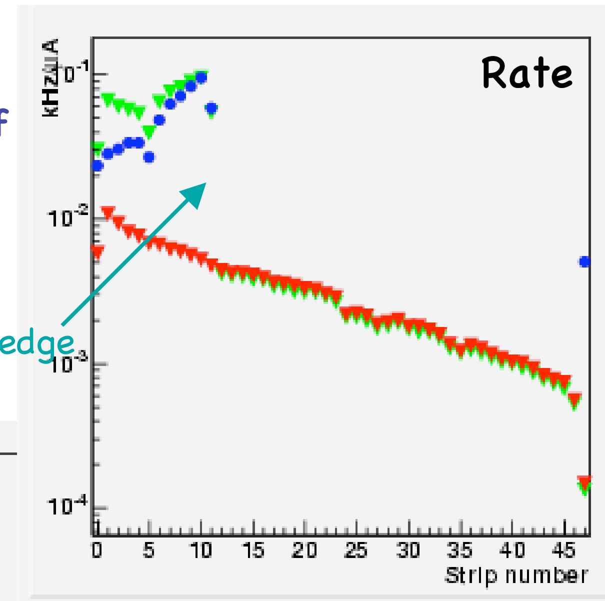
- Use electron detector to calibrate absolute energy.
- Skip energy calibration with integration technique

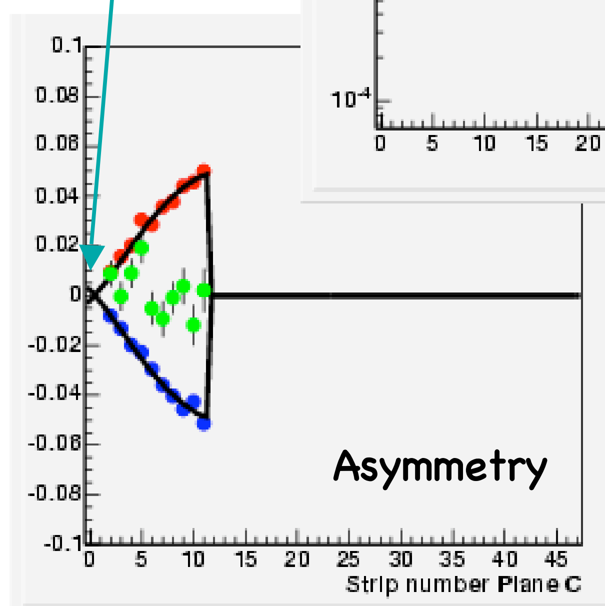
Electron Detector Analysis

Two Points of well-defined energy:

Zero crossing

Compton edge





Integrate between two known energy points, only sensitive to E_{beam}

Systematic Error Goals

Electron Method:

- $\delta(A_{exp})$
  dead time → 0.1%
- $\delta(\langle A_{th} \rangle)$
  Calibration
  (Strip Efficiency /
  Resolution /
  Spot Size) → 0.25%

Photon Analysis Method:

- $\delta(A_{exp})$
  dead time → 0.1%
- $\delta(\langle A_{th} \rangle)$
  Calibration → 0.25%
  Response Function → 0.40%
  Pile up → 0.20%

Common-Mode errors

- P_{laser} → 0.30%

Other uncertainties :

Backgrounds, Beam Asymmetries,
Radiative corrections (<0.05% each)

Acheivable: <0.5% polarimetry from electron detection,
<0.7% cross-check from photon detection

Polarimeter with Atomic Hydrogen

Replace existing Hall A Moller Target (keep spectrometer)

Expected depolarization → <2e-4

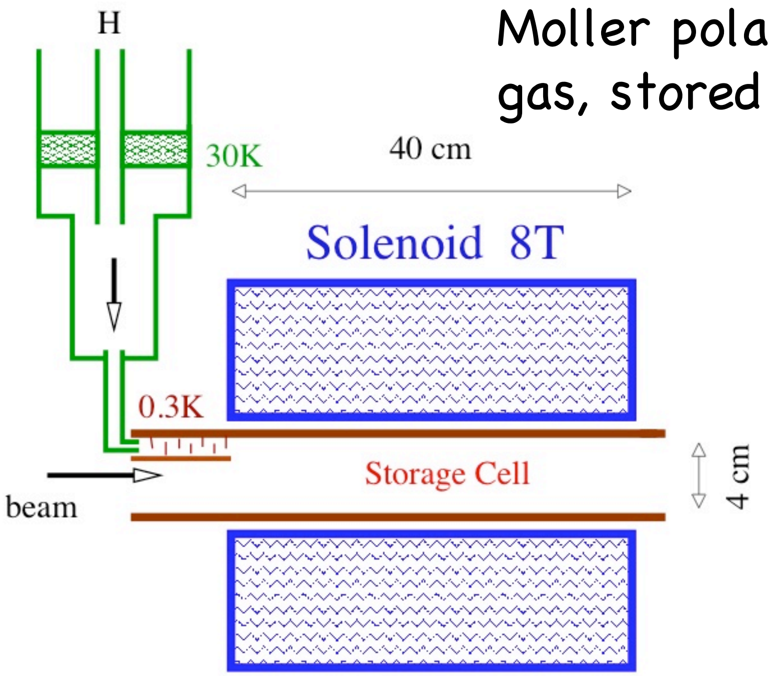
Expected contamination (residual gas + He, H_2, excited states, hyperfine states) → < 1%

Dominant systematic errors **total <0.5%**

- Analyzing power → <0.2%
- Background → <0.3%
- He dilution → <0.1%

Statistical error 1% in ~30 min (30 μA)

Atomic Hydrogen For Moller Target



Moller polarimetry from polarized atomic hydrogen gas, stored in an unltra-cold magnetic trap

- 100% electron polarization
- tiny error on polarization
- thin target (sufficient rates but no dead time)
- Non-invasive
- high beam currents allowed
- no Levchuk effect

10 cm, $\rho = 3 \times 10^{15}/cm^3$
in B = 7 T at T=300 mK

Brute force polarization

$$\frac{n_+}{n_-} = e^{-2\mu B/kT} \approx 10^{-14}$$

E. Chudakov and V. Luppov, IEEE Transactions on Nuclear Science, v 51, n 4, Aug. 2004, 1533-40

Atomic Hydrogen Trap Operation

H + H → H^2 recombination

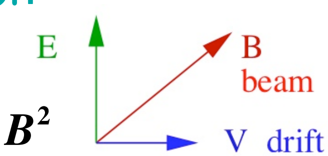
- suppressed for polarized gas
- surface must be coated (~50nm of superfluid ^{4}He)
- H_2 freezes to walls

Gas lifetime > 1 hour

Beam + RF ➔ 10^{-4}/sec ionizations (~20%/sec in beam)

- Ions purged by transverse electric field ~1 V/cm
- Cleaning (~20 μs) + diffusion ➔ <10^{-5} contamination

$$v = \vec{E} \times \vec{B} / B^2$$



Polarimetry Summary

Need major effort to establish unimpeachable credibility for 0.5% polarimetry → two separate measurements, with separate techniques, which can be cross-checked.

Methods from 6 GeV CEBAF may be applicable at 12 GeV

- High-Field Moller (Question: beam current extrapolation)
- Counting Compton (Question: 12 GeV e^- beam characteristics)

New methods may provide ultimate results

- Integrating Compton
  Major challenge: fully test simulated response functions/analyzing power
- Atomic Hydrogen Moller
  Least systematic uncertainty, but entirely novel application

Detectors

Calorimeter

- Lead glass $\sigma E/E \sim 0.06/\sqrt(E) \sim 3\%$
- Electrons $\sim$ 6 kHz/sector, pions $\sim$ 2 MHz/sector
- Time resolution $\sim$ 10 ns needed

Gas Cherenkov

Pion threshold $\sim$ 3 GeV/c 1 m long $\Rightarrow$ $>$ 10 ph.e.

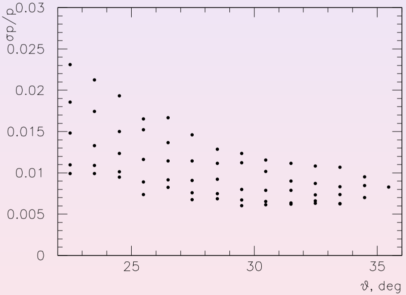
Tracking - GEM/straw

- GEM similar to COMPASS ($\sim$ 30 kHz/mm^2)
- Rate $<$ 1 kHz/mm^2, 10 MHz/sector
- Time resolution $\sim$ 40 ns $\Rightarrow$ 0.4 hits/sector
- Coordinate resolution $<$ 100 μm
- Mometum resolution $\sim$ 1-2%

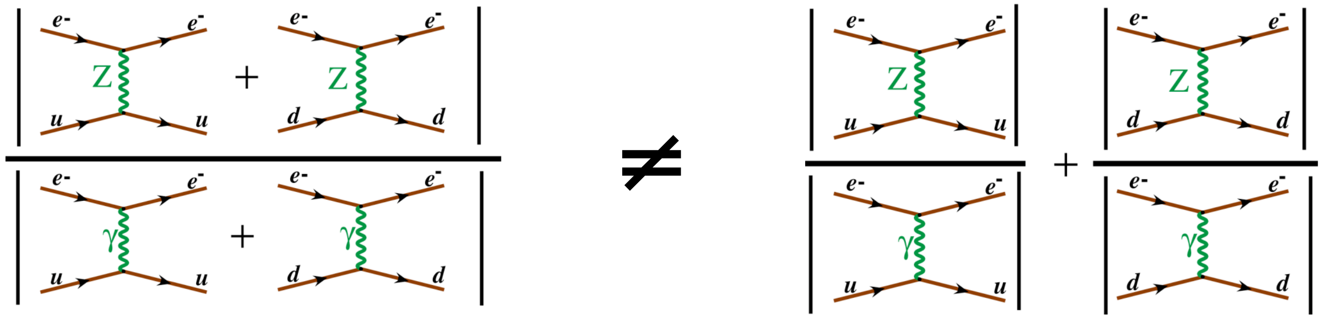
Where to place the coordinate detectors?

Tracking

- No need for planes inside the solenoid!
- Used - planes 6,8
- Parameters: $\Delta\phi^{-1}, r_6, r_8$
- Fit parameters in Δr_6 slices
- Coordinate resolution 0.2-0.4 mm - OK
- Calibration - ep at 6.6 GeV



Interpretation of Higher Twist



- A_{PV} sensitive to diquarks: ratio of weak to electromagnetic charge depends on amount of coherence
- Do diquarks have twice the x of single quarks?
- If Spin 0 diquarks dominate, likely only $1/Q^4$ effects
- On the other hand, some higher twist effects may cancel in ratio, so A_{PV} may have little dependence on Q^2.

Observing a clean higher twist operator has recently become very interesting.

Higher Twist without the QPM

Bjorken,
PRD 18, 3239 (78)

Wolfenstein,
NPB146, 477 (78)

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

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

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

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

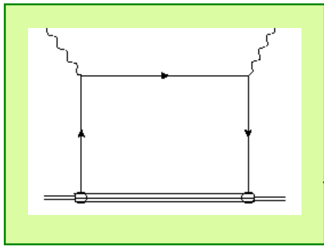
Zero in QPM

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

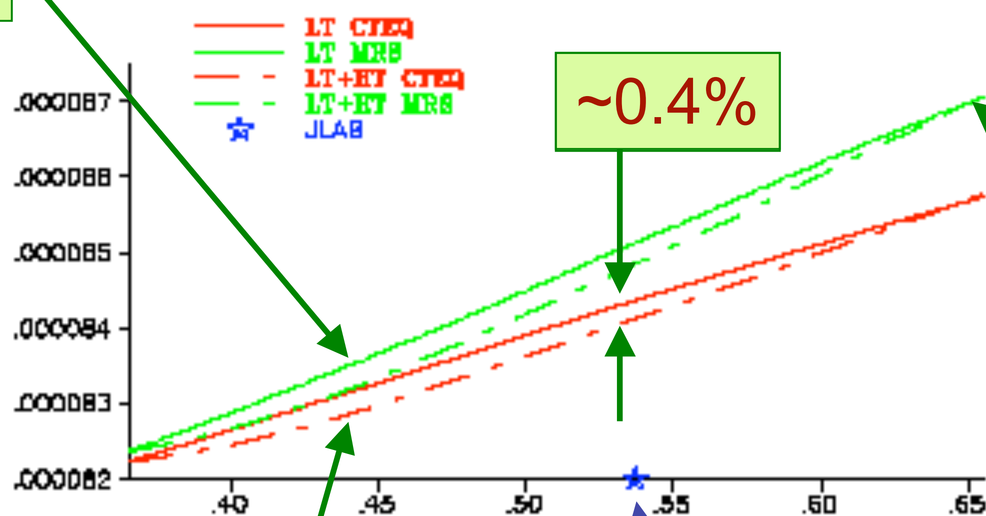
$$\delta = \frac{\langle VV\rangle - \langle SS\rangle}{\langle VV\rangle + \langle SS\rangle}$$

$$A \propto 1 - 0.3\delta$$

Probing Higher Twist with PV



PV Deep Ineslastic eD (J Lab 12 GeV)

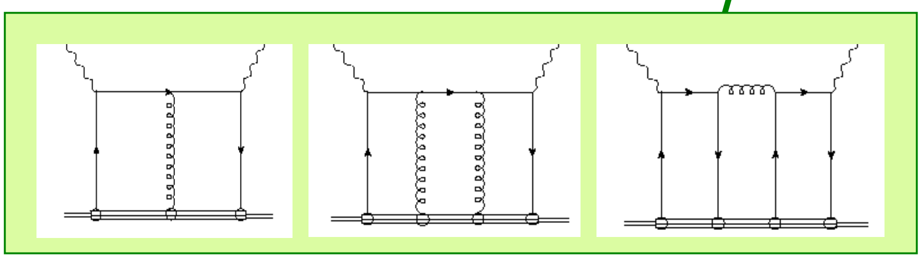


~0.4%

A_{PV}/Q^2

Different PDF fits

y



E=11 GeV
θ=12.5^0

Sacco, Ramsey-Mulolf preliminary

Effect is small at x~0.2

Testing Supersymmetry

Kurylov, Ramsey-Musolf, Su

Does Supersymmetry (SUSY) provide a candidate for dark matter?

- Neutralino is stable if baryon (B) and lepton (L) numbers are conserved
- B and L need not be conserved (RPV): neutralino decay