Studying Strong and Electroweak Interactions with Electron Scattering at JLab

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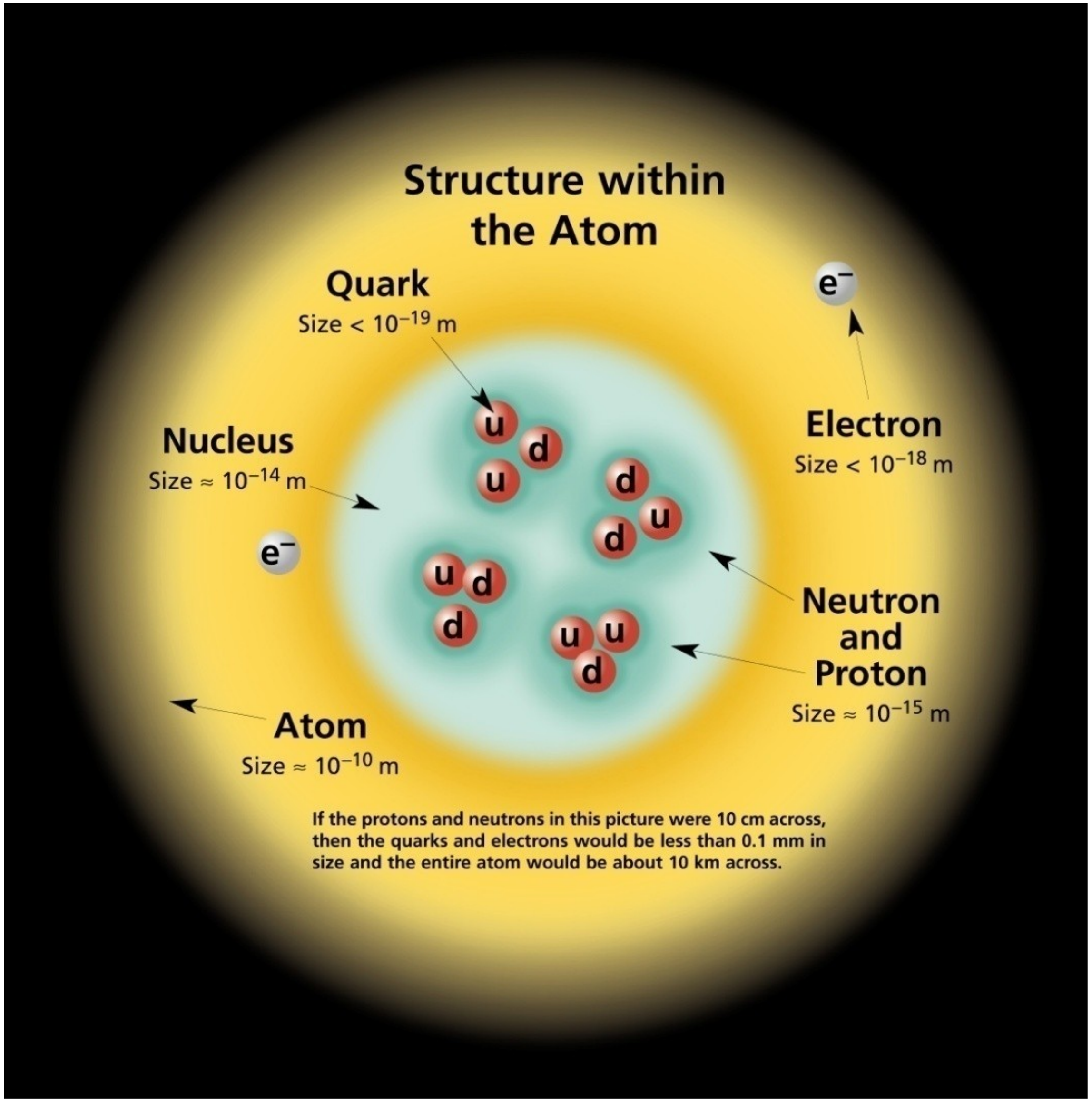
- Introduction — electron scattering and how it provides information on nucleon structure or electroweak interactions
- Parity Violating DIS at JLab 6 and 11 GeV
- (Nucleon spin structure study at JLab 6 and 11 GeV)
- Summary of research program and outlook

What is the Visible World Made of?



And How Do They Interact with Each Other?

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

$SU(2)_L \times U(1)_Y$ $SU(3)_C$

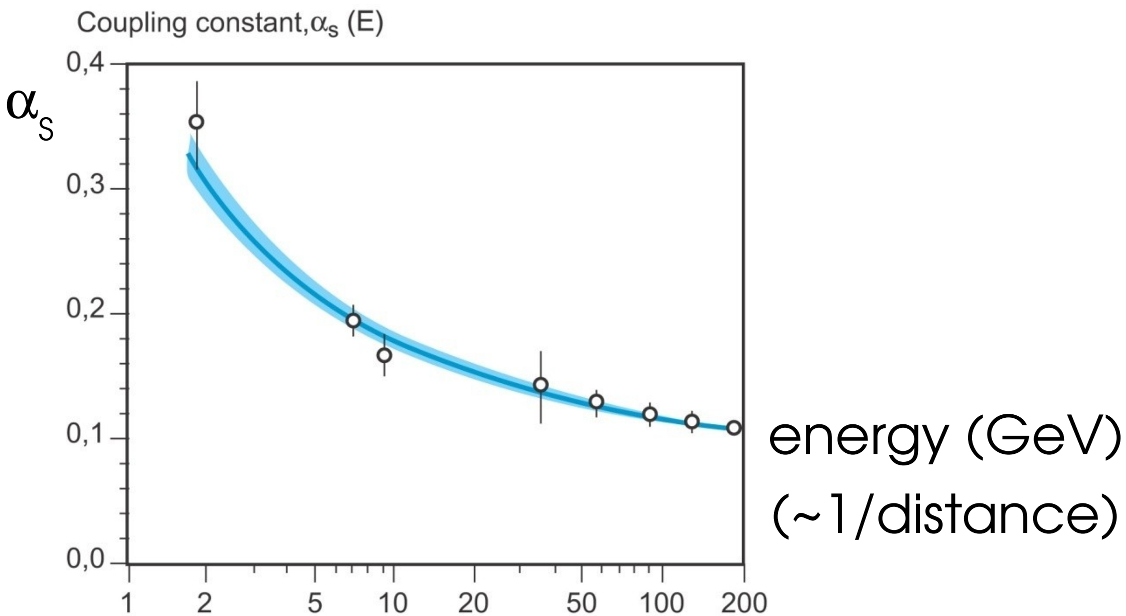
Standard Model of Particle Physics

- Success of the Standard Model
  - Electromagnetic and weak forces unified, electro-weak theory tested to very good precision
  - QCD tested in the high energy (perturbative) region

- Major Challenges ***to*** the Standard Model
  - Higgs mechanism yet to be tested (observed);
  - Cannot explain the observed non-zero mass of ν's;
  - Does not include gravity, neither does it explain dark matter/energy;
  - Requires too many parameters;
  - Conceptually, there is always "room" for New Physics.
  - Parity violation in lepton/electron scattering can help to test the Standard Model by looking for "signs" of new physics.

Standard Model of Particle Physics

- Major Challenges ***within*** the Standard Model
  - Understand and test QCD in extreme conditions (RHIC, LHC)
  - Understand and test QCD in "strong" interaction region (non-perturbative)
  - Understand the nucleon structure, how quarks and gluons form the nucleon's mass, momentum, and spin



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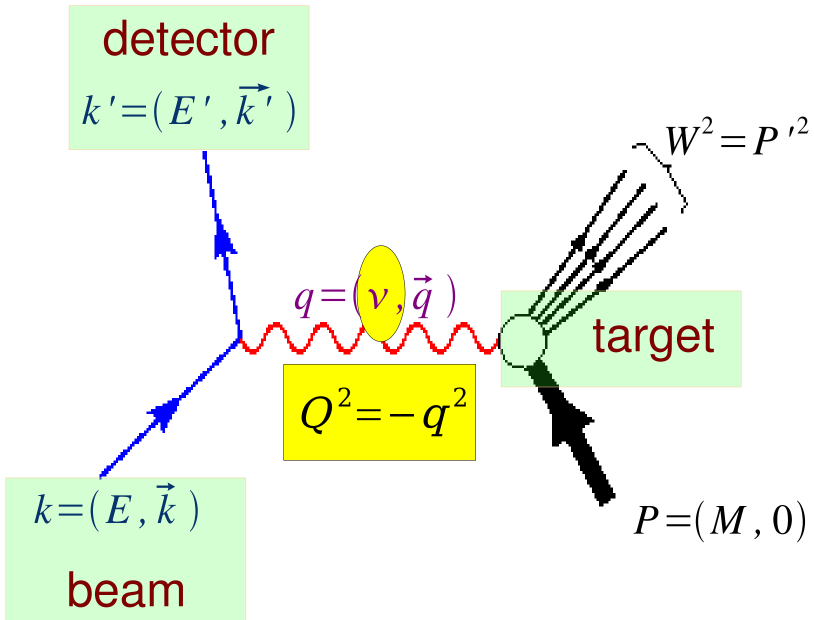
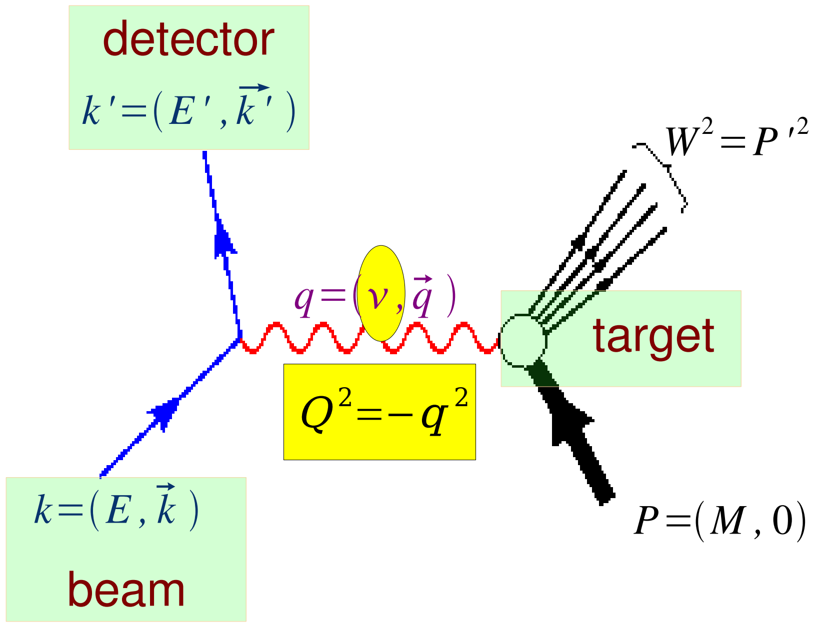
typically studied by lepton scattering on the nucleon/nucleus

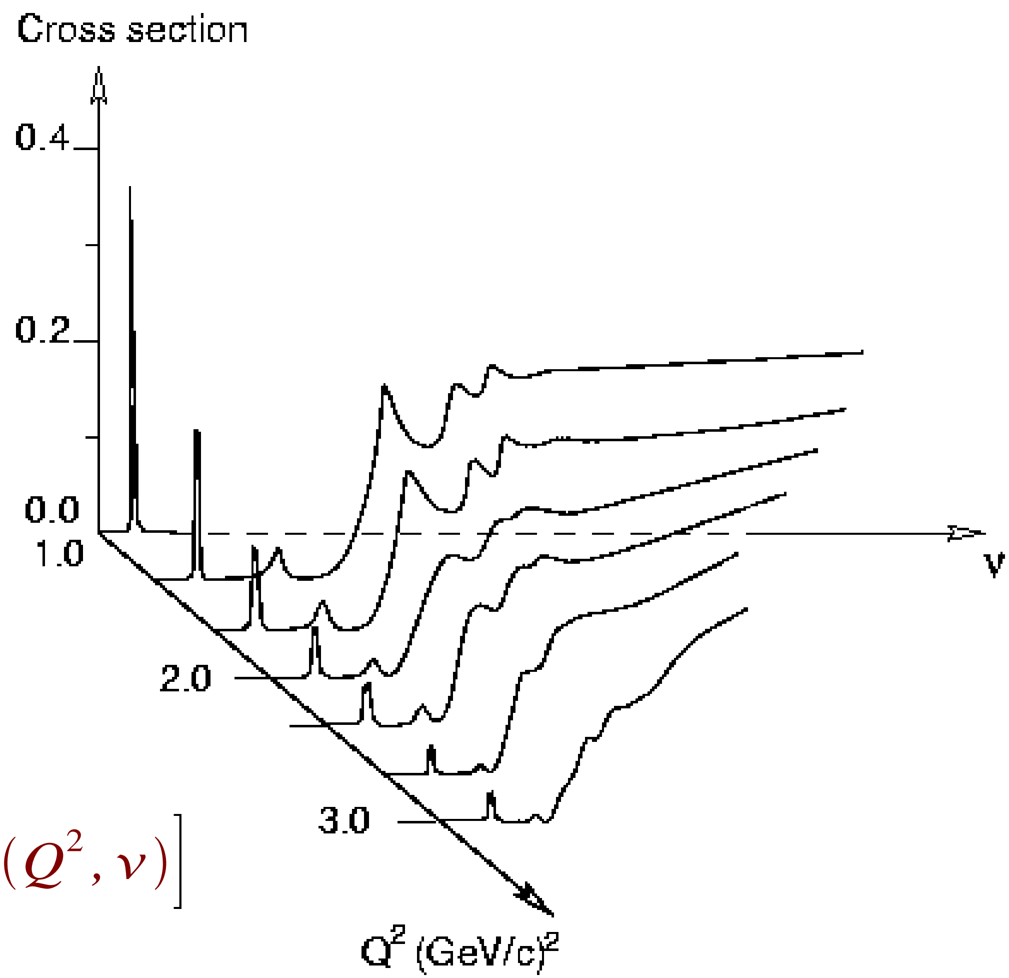
Exploring Nucleon Structure Using Electron Scattering



- *Electrons* intereract with the target by exchanging a "virtual" photon;
- Inclusive scattering: only scattered electrons are detected;
- Two variables to describe how the target behaves: $1/Q^2$ and ν. (also: W)

Exploring Nucleon Structure Using Electron Scattering





- The cross section:

$$\frac{d^2\sigma}{d\Omega\, dE'} = \sigma_{Mott}\left[\alpha F_1(Q^2,\nu)+\beta F_2(Q^2,\nu)\right]$$

For point-like target

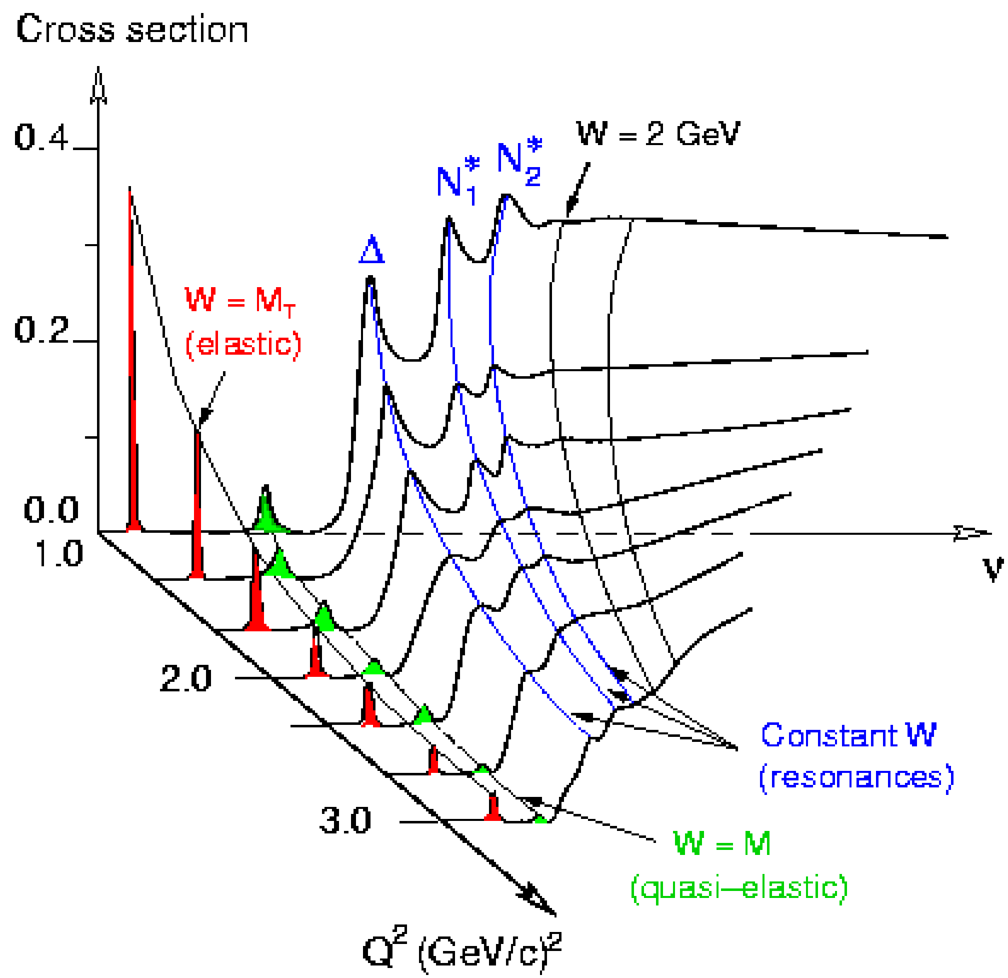
Exploring Nucleon Structure Using Electron Scattering

Elastic, quasi-elastic, resonances, deep inelastic

- (Quasi-) elastic – the nucleus (nucleon) appears as a rigid body $Q^2 = 2M_{T(N)}\nu \qquad (W = M_{T(N)})$

- Resonance region – quarks inside the nucleon react coherently to the γ^*

- Deep Inelastic Scattering (DIS):
  - Quarks start to react incoherently (start to see constituents of the nucleon)
  - Can test pQCD



(highly non-pertubative, phenomenology models)

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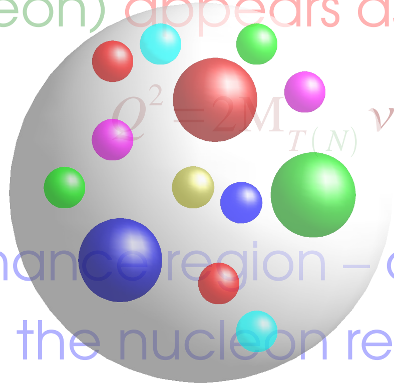
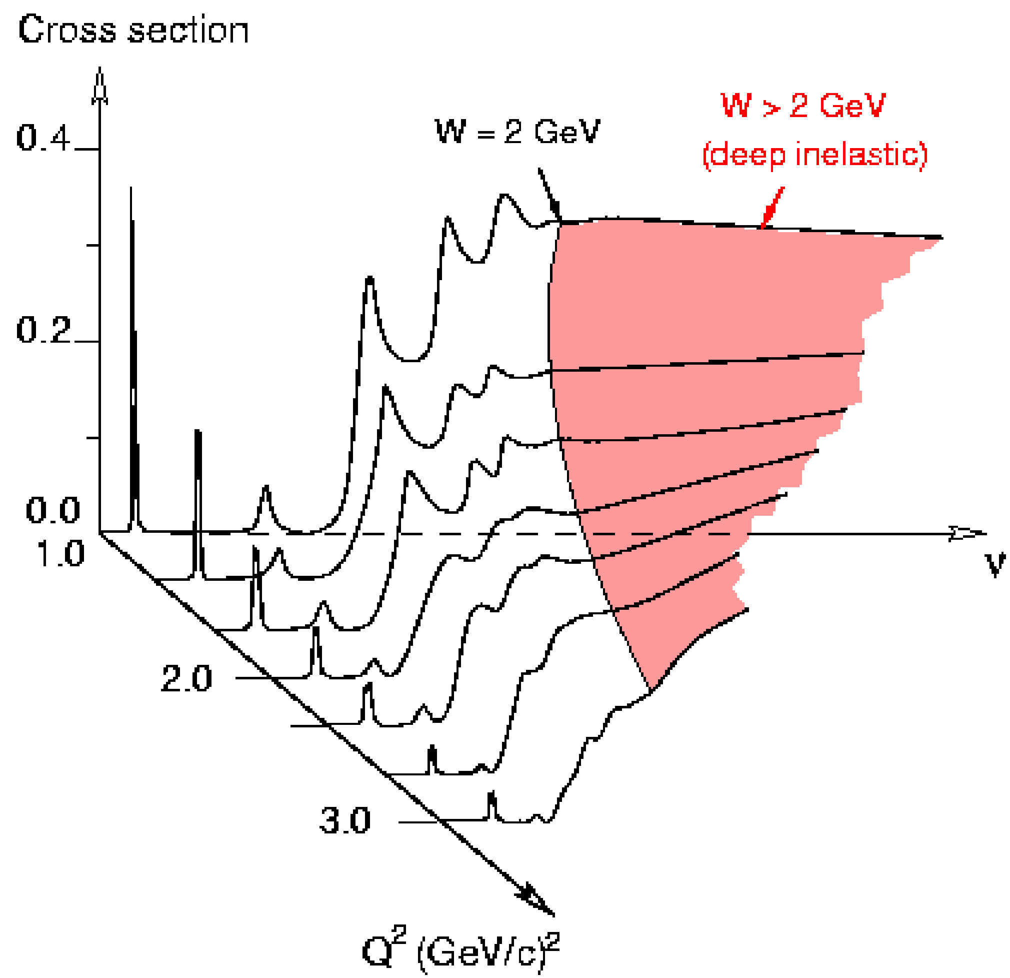


- Resonance region – quarks inside the nucleon react coherently to the γ^*

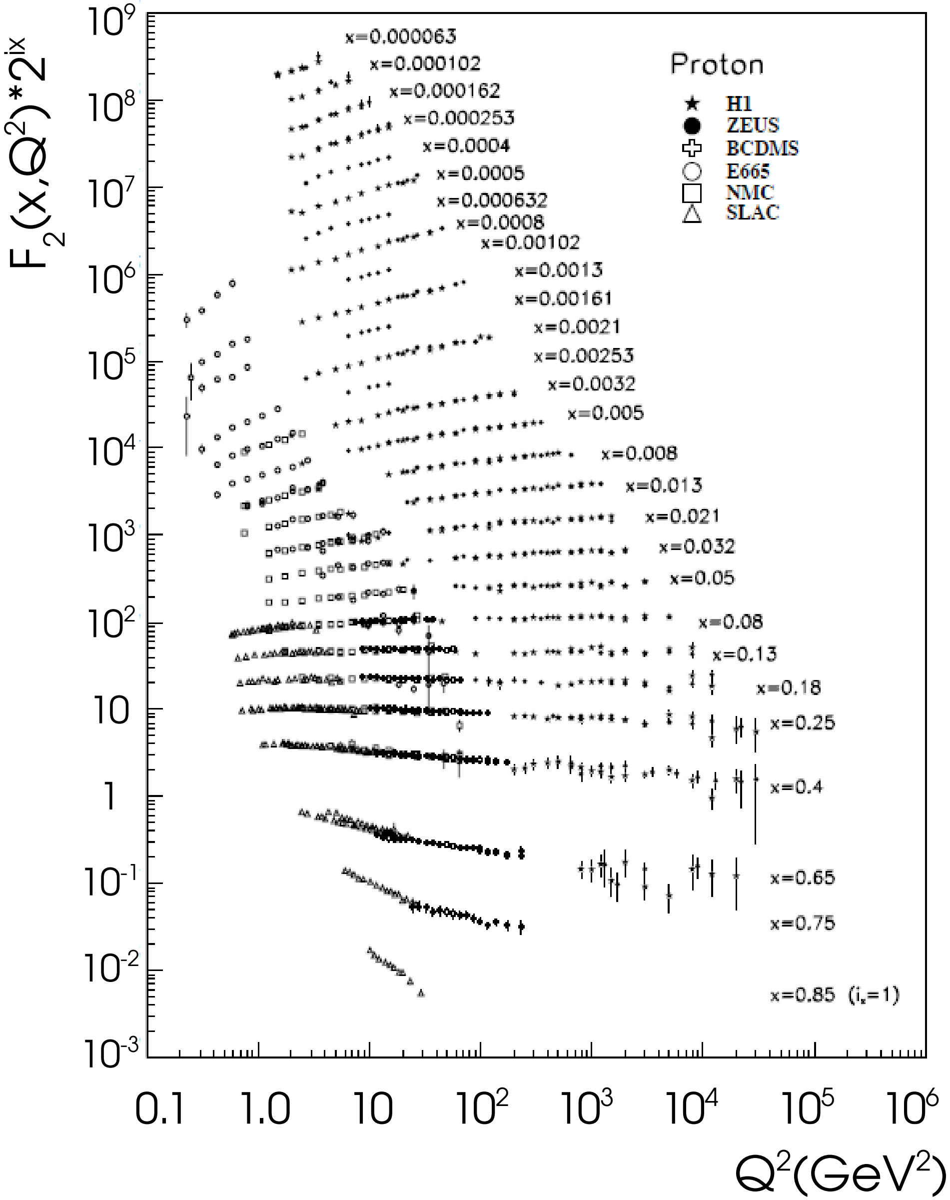
- **Deep Inelastic Scattering (DIS):**
  - Quarks start to react incoherently (start to see constituents of the nucleon); Because the interaction between quarks is not as strong:

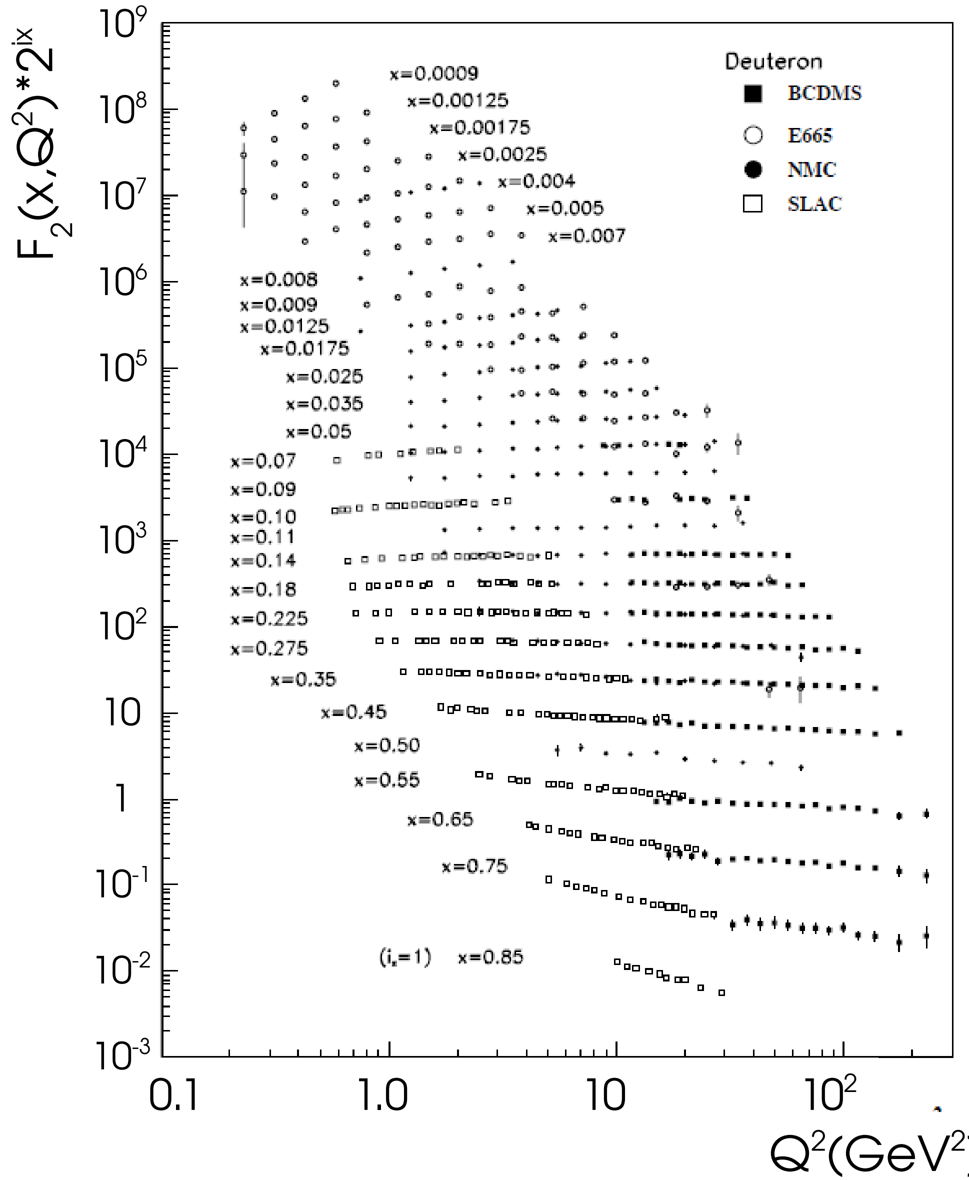
    Can test pertubative QCD



Current Knowledge of Nucleon Unpolarized Structure

$$\frac{d^2\sigma}{d\Omega\, dE'} = \sigma_{Mott}\left[\alpha F_1(Q^2,x) + \beta F_2(Q^2,x)\right] \qquad F_1 = \frac{F_2(1+\gamma^2)}{2x\left(1+R(Q^2,x)\right)} \qquad x_{Bj} = \frac{Q^2}{2M\nu}$$





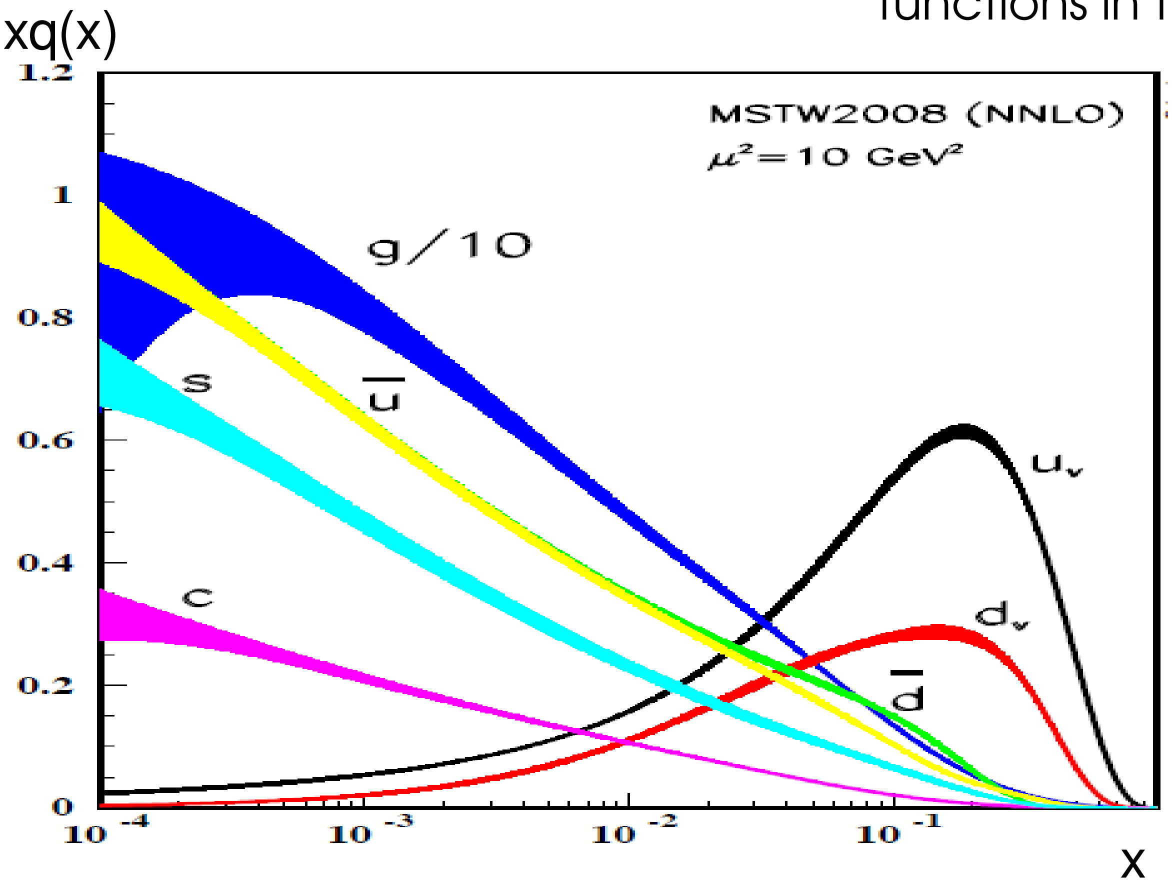
C. Amsler et al. (Particle Data Group), Phys. Lett. B667, 1 (2008)

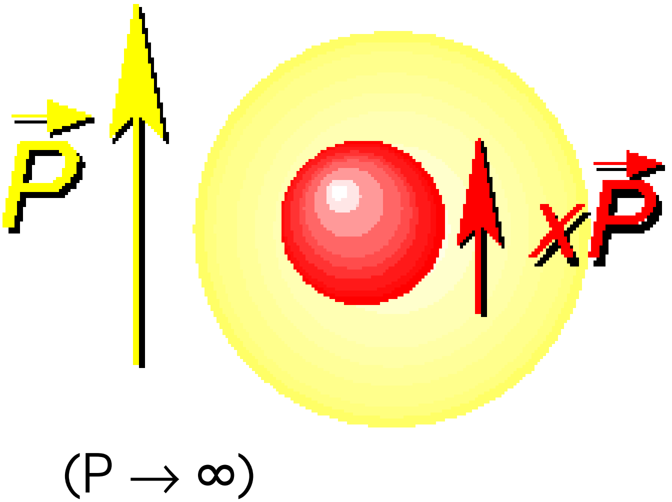
Current Knowledge of Nucleon Unpolarized Structure

$$F_1(x) = \frac{1}{2}\Sigma e_i^2[q_i(x)]$$

— can be related to parton distribution functions in the Quark-Parton Model and the infinite momentum frame (IMF)

A.D. Martin et al, Eur. Phys. J. C63, 189 (2009)

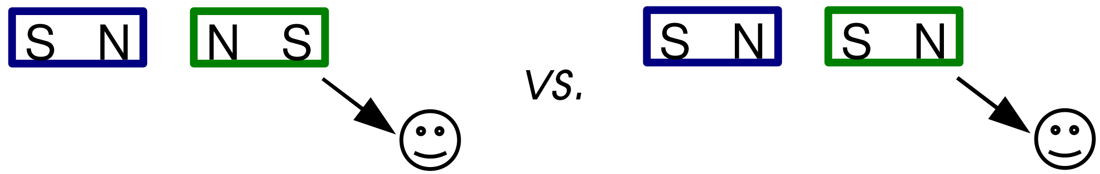




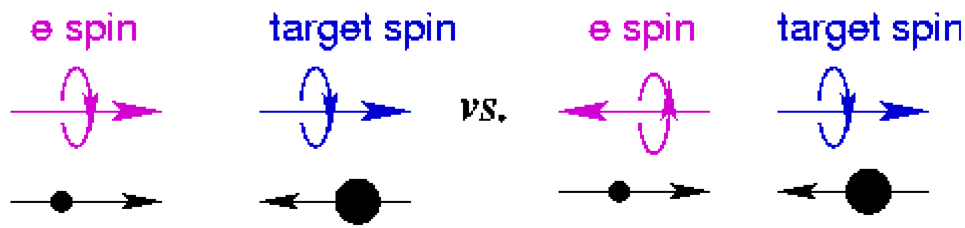
- After four decades of DIS experiments, the unpolarized structure of the nucleon is reasonably well understood (for moderate x_{Bj} region);
- *Similar status for spin structure of the nucleon from polarized DIS, though with less precision.*

Polarized DIS and Nucleon Spin Structure

- Scattering cross section is spin-dependent (imagine throwing two small magnets together)

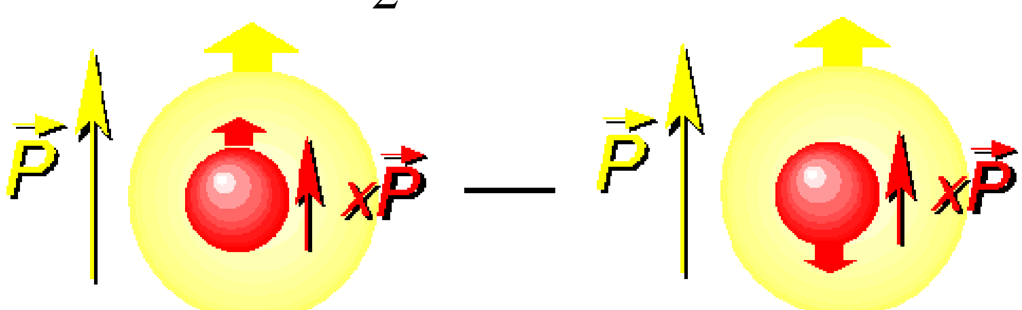


- Longitudinal:



$$\frac{d^2\sigma^{\uparrow\downarrow}}{d\Omega\, dE'} - \frac{d^2\sigma^{\uparrow\uparrow}}{d\Omega\, dE'} \propto \sigma_{point-like}[\alpha' g_1(x,Q^2) + \beta' g_2(x,Q^2)]$$

$$g_1(x) = \frac{1}{2}\Sigma e_i^2 [q_i^{\uparrow}(x) - q_i^{\downarrow}(x)] = \frac{1}{2}\Sigma e_i^2 [\Delta q_i(x)]$$



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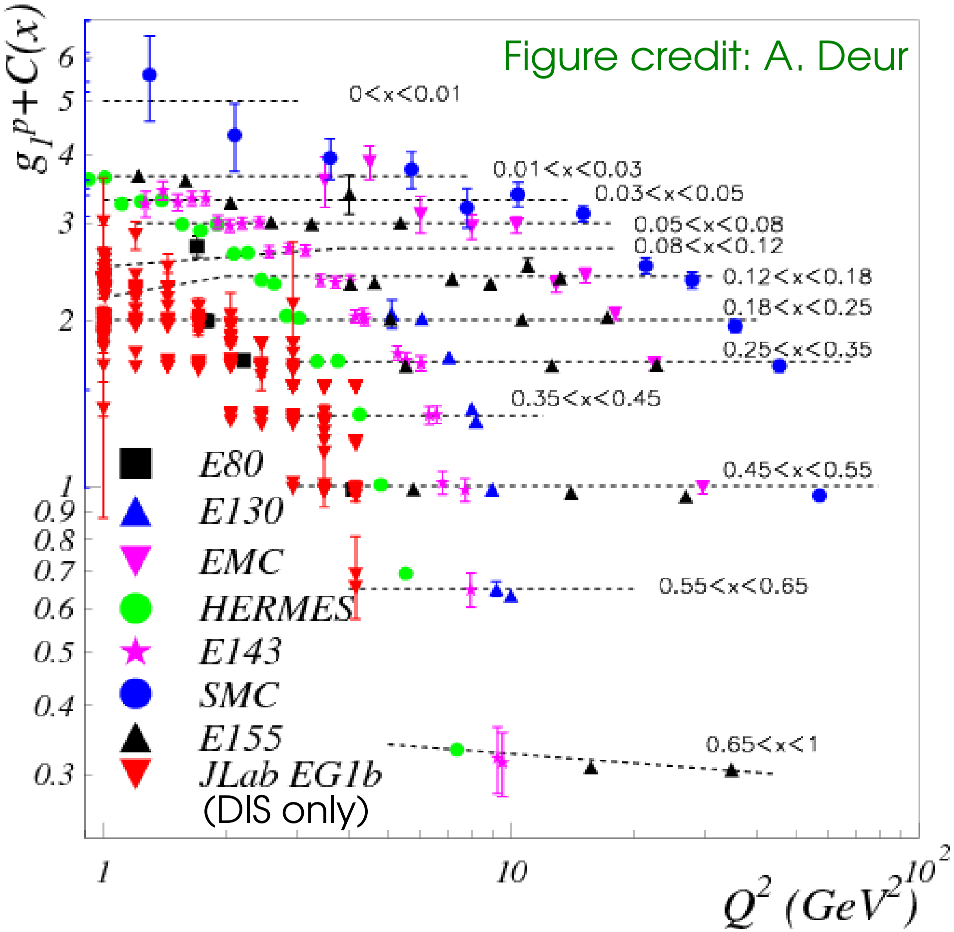
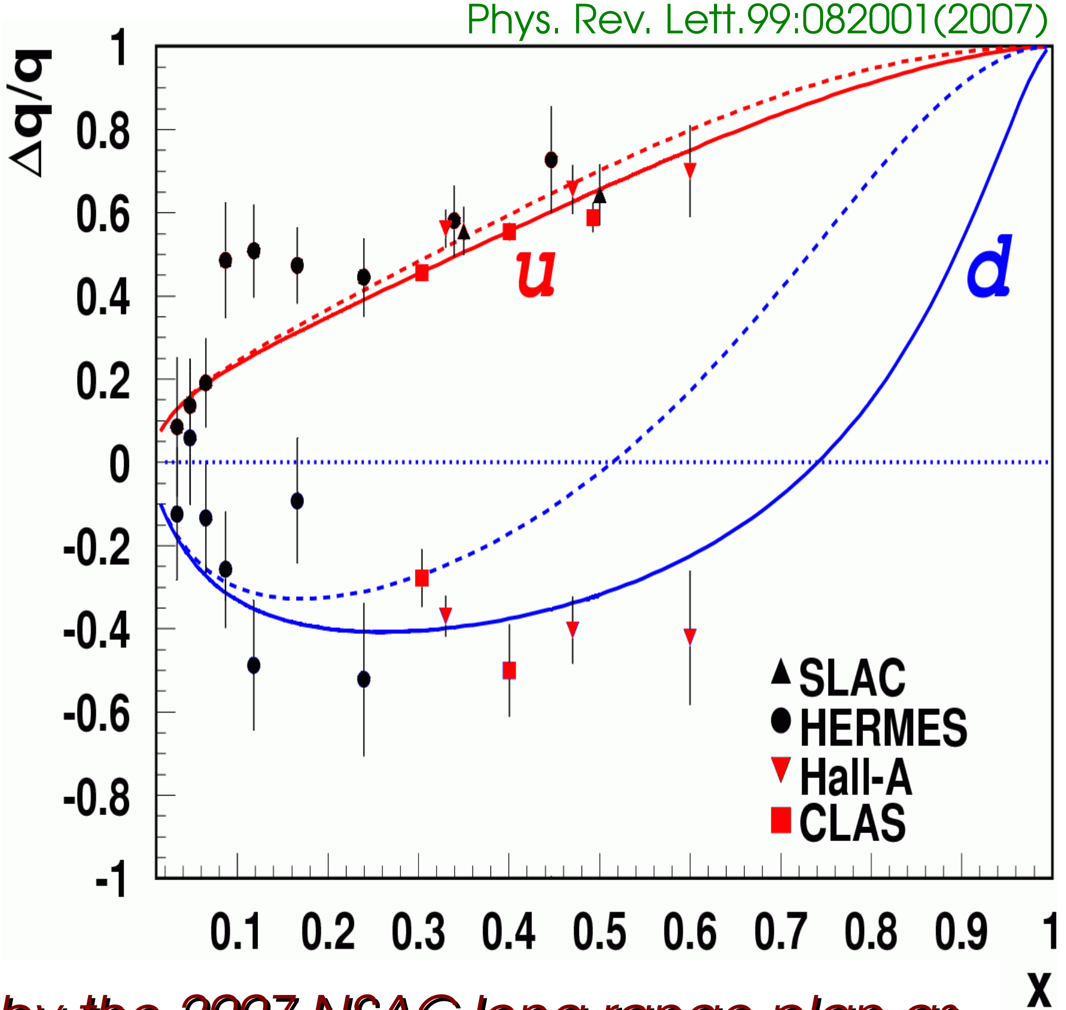
H. Avakian, S. Brodsky, A. Deur, F. Yuan, Phys. Rev. Lett.99:082001(2007)





- ***The JLab Hall A data were quoted by the 2007 NSAC long range plan as one of the "most important accomplishments since the 2002 LRP";***
- Extension planned for JLab 11 GeV.

Polarized PDF in the Valence Quark Region at JLab 11 GeV

- Combined results from Hall A (neutron) and B (proton) 11 GeV experiments

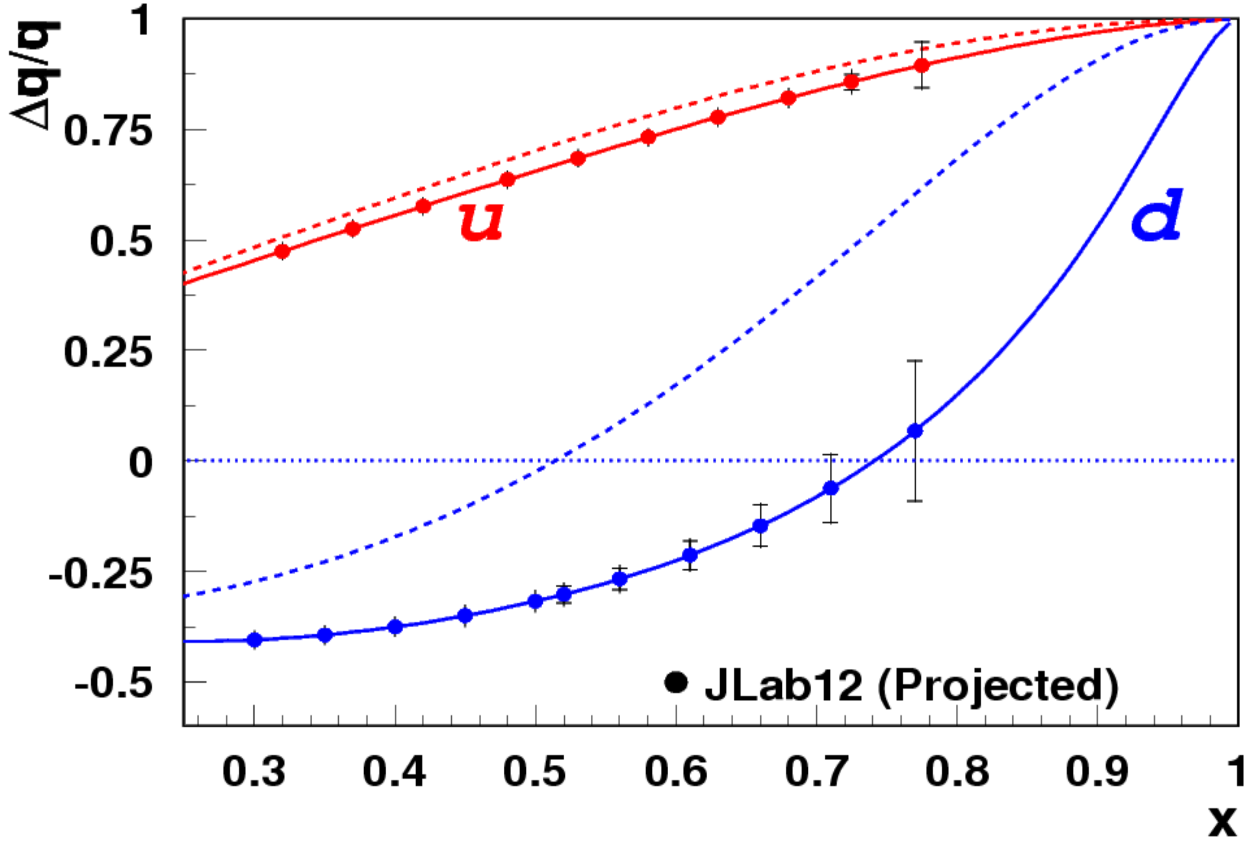


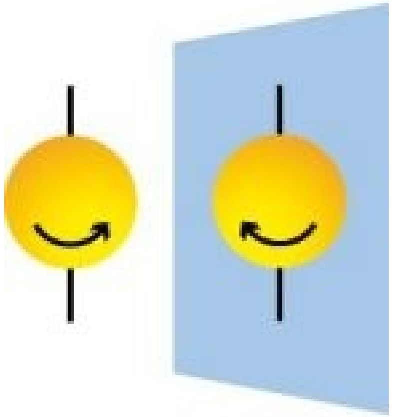
Figure from H. Avakian, S. Brodsky, A. Deur, F. Yuan, Phys. Rev. Lett.99:082001(2007)

- The Hall A program has 2 proposals so far, to be rated this summer. Our group will focus on R&D of the polarized 3He target first, and then run the experiments after the Upgrade.

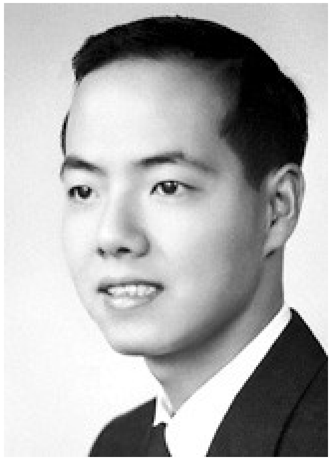
Weak Interactions in DIS
(Parity Violating DIS)

What is Parity Violation

- The parity symmetry: the physical laws behind all phenomena must be the same as those behind their mirror images;
- However this symmetry is broken in weak interactions;
- Weak interaction is carried by charged or neutral weak currents.



Chen-Ning Yang



Tsung-Dao Lee

Chien-Shiung Wu

1957 Nobel Prize in Physics:

"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"

Electroweak Interaction – The Standard Model

- Weak charged currents ($W^{\pm}$) were discovered first, described by a $SU(2)_L$ group with weak isospin *T*;
- When weak neutral current (Z^0) was discovered later, it could not be described by the same $SU(2)_L$ group. Must combine neutral currents from $SU(2)_L$ and QED ($U^{EM}(1)_\gamma$) to construct the proper description.

observable		theory	
j_μ^{em}	$\Leftrightarrow$	J_μ^3	← completes $SU(2)_L$
J_μ^{NC}		j_μ^Y	← $U(1)_Y$, *Y*: weak hyper charge

$$Q = T^3 + \frac{Y}{2}$$

photon →	A_μ	$\Leftrightarrow$	W_μ^3
Z^0 →	Z_μ		B_μ

(this is usually referred to as "unification of electromagnetic and weak nuclear forces")

Electroweak Interaction – The Standard Model

- Mixing of the $SU(2)_L$ and $U^{EM}(1)_\gamma$ is giving by: ... the Weak Mixing angle θ_W

$$A_\mu = B_\mu \cos\theta_W + W^3_\mu \sin\theta_W \qquad (m=0)$$
$$Z_\mu = -B_\mu \sin\theta_W + W^3_\mu \cos\theta_W \qquad (m\neq 0)$$

- Lepton neutral currents are given by vector and axial couplings

$$J^{NC}_\mu(\nu) = \frac{1}{2}\left(\bar{u}_\nu \gamma_\mu \frac{1}{2}(1-\gamma^5) u_\nu\right)$$

$$J^{NC}_\mu(q) = \left(\bar{u}_q \gamma_\mu \frac{1}{2}(c^q_V - c^q_A \gamma^5) u_q\right)$$

In the Standard Model

fermions	c^f_A	c^f_V
ν_e, ν_μ	$\frac{1}{2}$	$\frac{1}{2}$
e-, μ-	$-\frac{1}{2}$	$-\frac{1}{2}+2\sin^2\theta_W$
u, c	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$
d, s	$-\frac{1}{2}$	$-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W$

Testing the EW Standard Model – Running of $\sin^2\theta_W$ and the NuTeV Anomaly

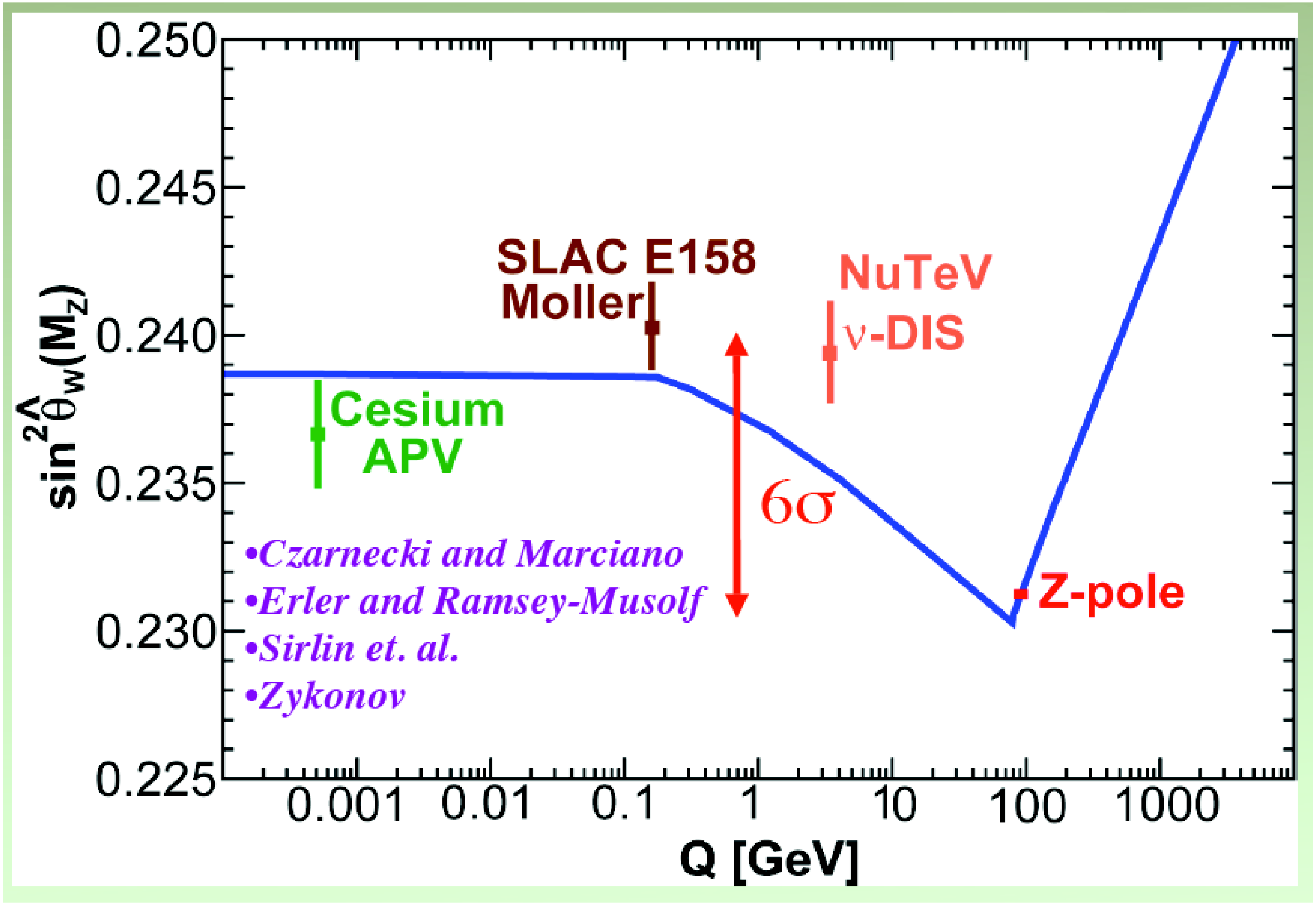
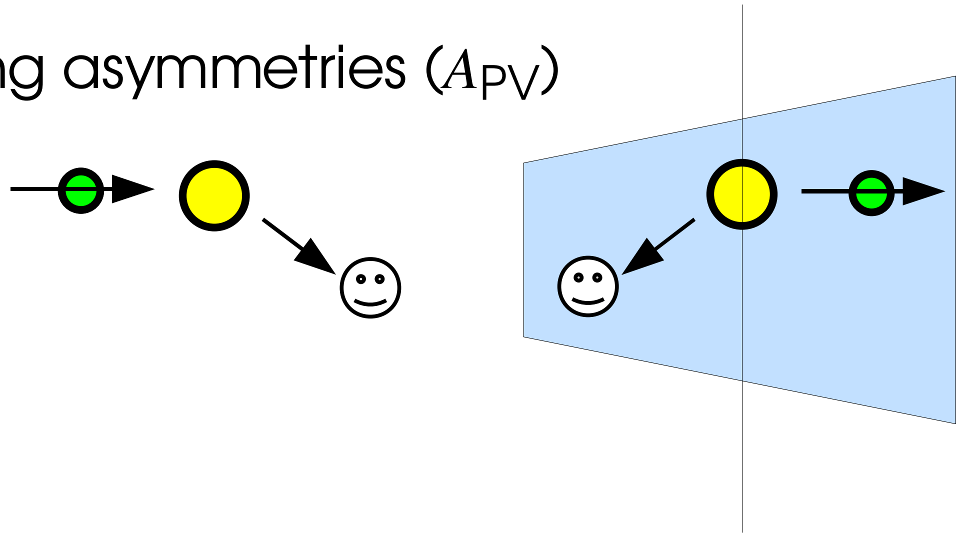


figure from K. Kumar, Seattle 2009 EIC Workshop EW talks

Parity Violating Electron Scattering

- Electromagnetic observables — cross sections and asymmetries...
- Weak observables — parity violating asymmetries ($A_{\rm PV}$)

  (polarized beam + unpolarized target)



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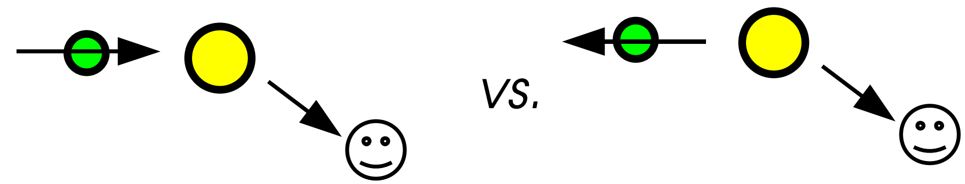
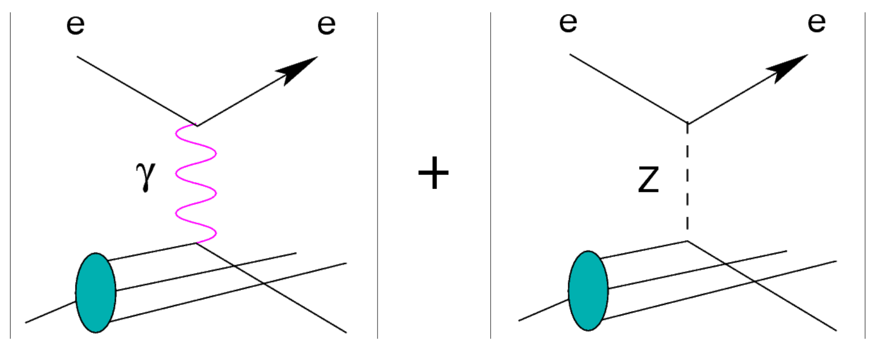


$A_{PV} =$

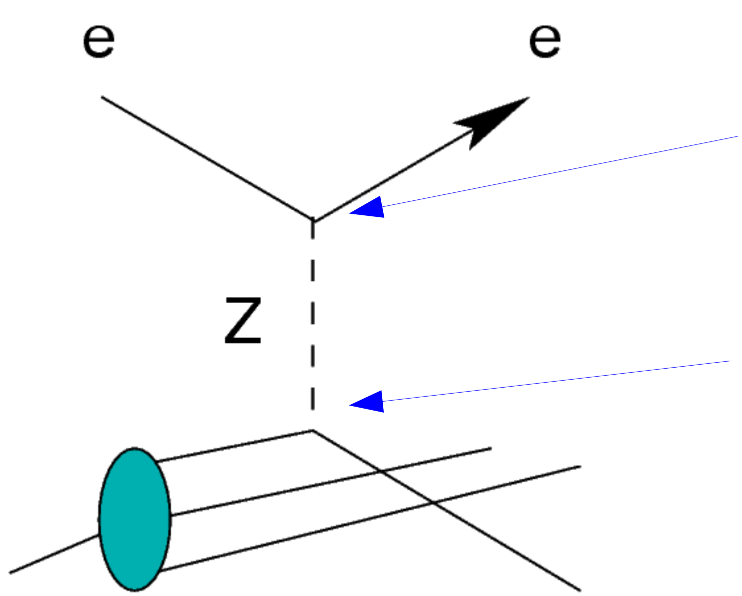


the asymmetry comes from the interference between the Z^0 and the photon exchanges

Neutral Weak Couplings from Charged Lepton Scattering

- Asymmetries (ratios) in charged lepton-nucleon scattering can be used to measure products of neutral weak couplings $c^e_{V,A} c^q_{V,A}$

$$L^{lepton\ scatt.}_{NC} = \sum_q \left[c^l_A c^q_V \bar{l} \gamma^\mu \gamma_5 l \bar{q} \gamma_\mu q + c^l_V c^q_A \bar{l} \gamma^\mu l \bar{q} \gamma_\mu \gamma_5 q + c^l_A c^q_A \bar{l} \gamma^\mu \gamma_5 l \bar{q} \gamma_\mu \gamma_5 q \right]$$



$$J^{NC}_\mu(e) = \left(\bar{u}_e \gamma_\mu \frac{1}{2} (c^e_V - c^e_A \gamma^5) u_e \right)$$

$$J^{NC}_\mu(q) = \left(\bar{u}_q \gamma_\mu \frac{1}{2} (c^q_V - c^q_A \gamma^5) u_q \right)$$

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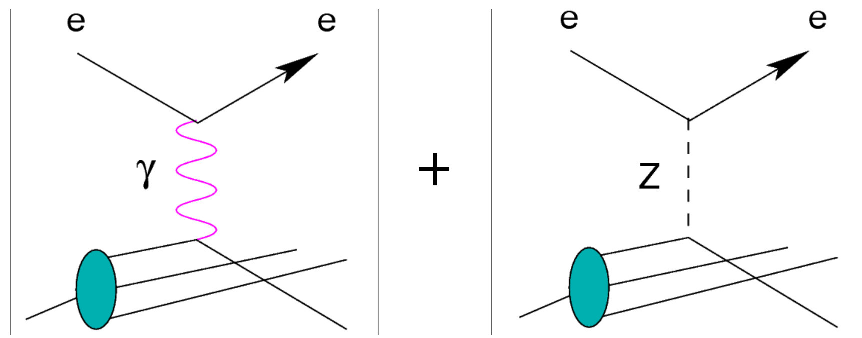
- $c^l_A c^q_V$ → C_{1q}
- $c^l_V c^q_A$ → C_{2q}
- $c^l_A c^q_A$ → C_{3q}

C_{1q}, C_{2q}: parity-violating, cause different e_L, e_R cross sections

C_{3q}: lepton charge conjugate-violating, cause difference in e_L, e^+_R cross sections

PVDIS Asymmetries

$A_{PV} =$ 

measurement so far not as precise as C_{1q}

- Deuterium:

$$A_d = (540\,ppm)\,Q^2 \frac{2C_{1u}[1+R_C(x)] - C_{1d}[1+R_S(x)] + Y(2C_{2u} - C_{2d})R_V(x)}{5 + R_S(x) + 4R_C(x)}$$

$1\text{ppm} = 10^{-6}$

- In contrast to parity violation experiments that measure elastic scatterings (A4@MAINZ, SAMPLE@BATES, G0 and HAPPEX@JLab), PVDIS is not sensitive to the (unknown) nucleon weak form factors, instead it depends directly on parton distribution functions that have been measured extensively from decades of DIS experiments. The hadronic uncertainty is therefore at a level smaller than or comparable to the electroweak uncertainties.

Current Knowledge of Nucleon Unpolarized Structure

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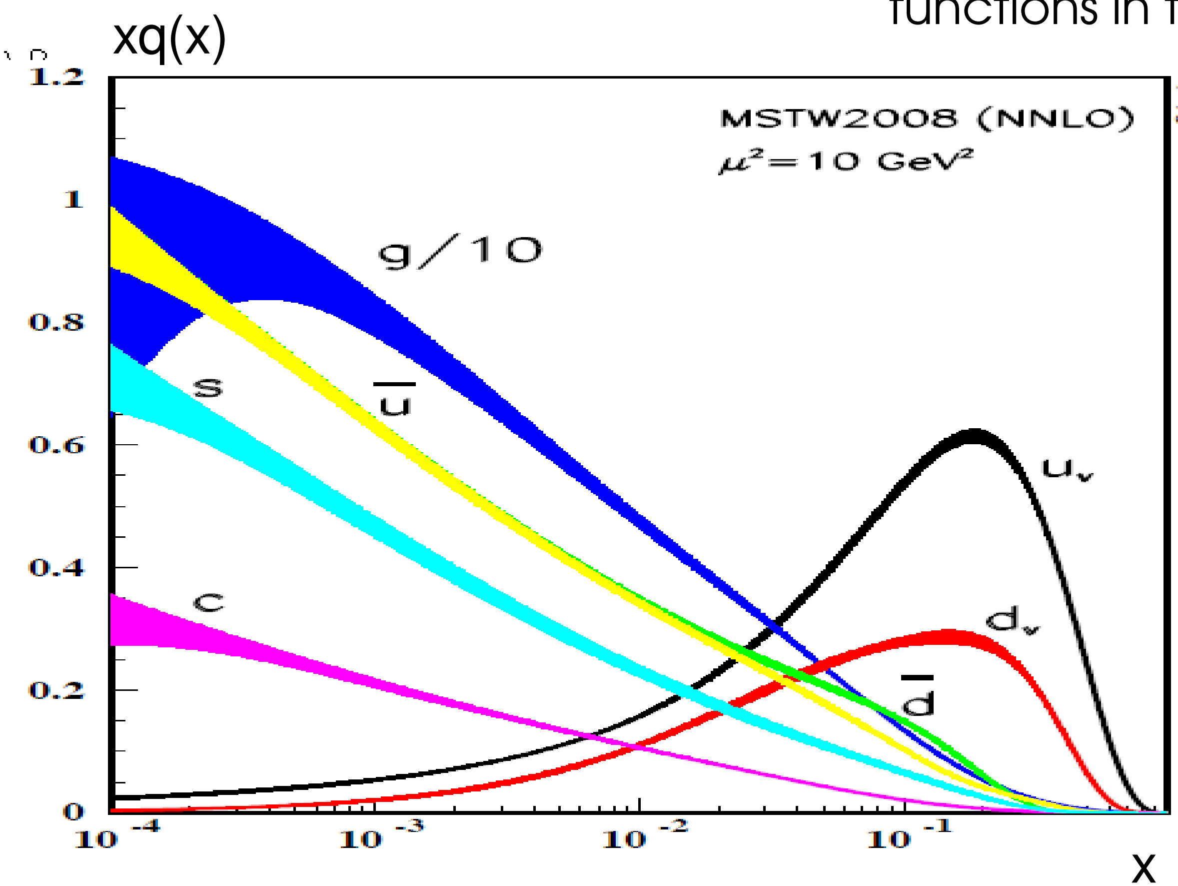
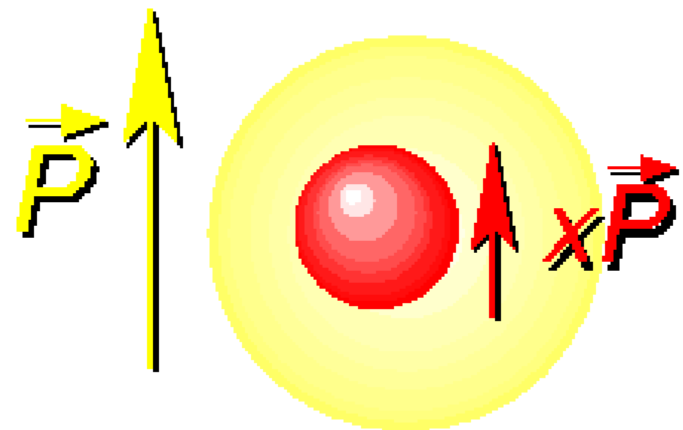
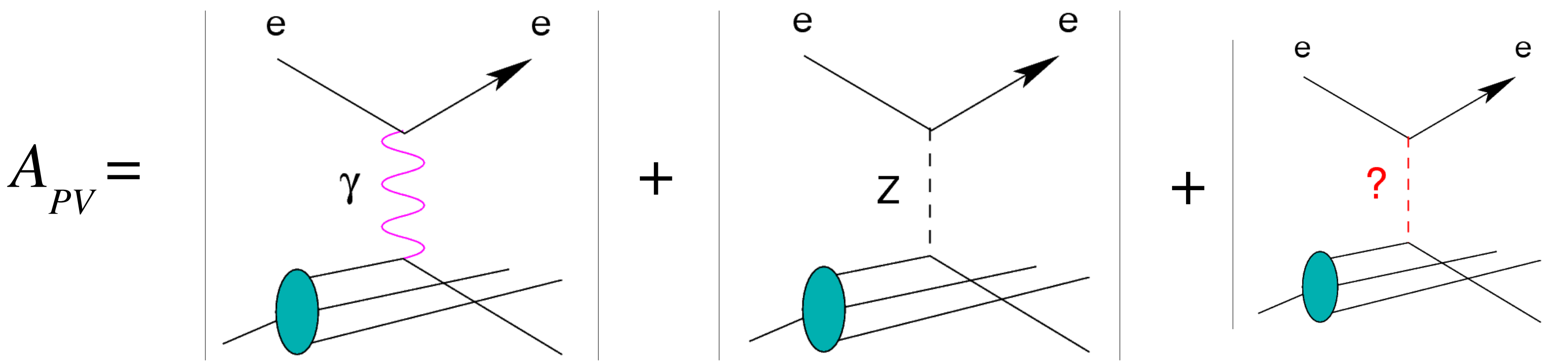




$(P \to \infty)$

- After four decades of DIS experiments, the ...olarized structure of the nucleon is reasonably well understood (for moderate x_{Bj} region);
- *Similar status for spin structure of the nucleon from polarized DIS, though with less precision.*

PVDIS Asymmetries



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- New physics sensitivity: $L = L_{SM}^{PV} + L_{NEW}^{PV}$

$$L_{SM}^{PV} = \frac{-G_F}{\sqrt{2}} \bar{e}\gamma_\mu e \sum_q C_{2q} \bar{q}\gamma^\mu\gamma^5 q \qquad L_{NEW}^{PV} = \frac{g^2}{4\Lambda^2} \bar{e}\gamma_\mu e \sum_f h_A^q \bar{q}\gamma^\mu\gamma^5 q$$

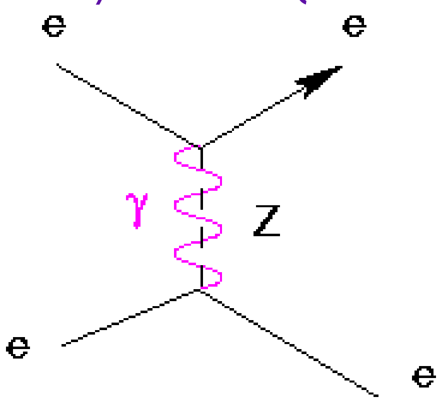
g: coupling constant, Λ: mass limit, h_A^q: effective coefficient

- Sensitive to: Z' searches, compositeness, leptoquarks
- Mass limit:

$$\Lambda / g \approx \left[\sqrt{8} G_F \left|\Delta(2C_{2u} - C_{2d})\right|\right]^{-1/2}$$

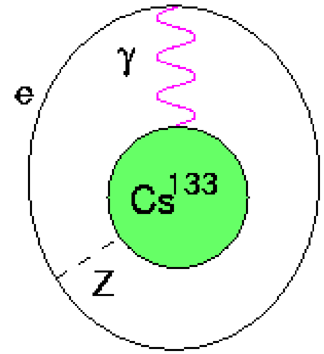
PV DIS and Other SM Test Experiments

- *E158/Moller (SLAC)*



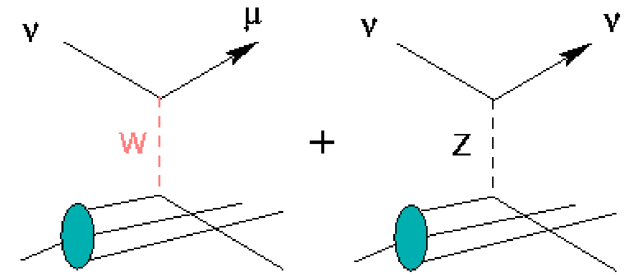
- Purely leptonic

- *Atomic PV*



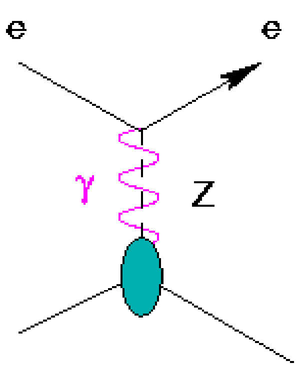
- Coherent Quarks in the Nucleus
- $-376C_{1u}-422C_{1d}$
- Nuclear structure?

- *NuTeV (FNAL)*



- Weak CC and NC difference
- Nuclear structure?
- Other hadronic effects?

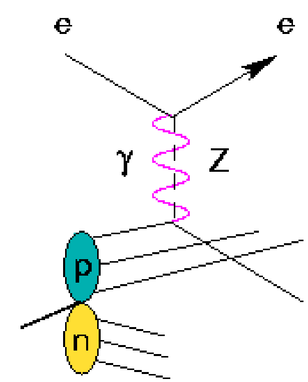
- *Qweak (JLab)*



- $2(2C_{1u}+C_{1d})$
- Coherent quarks in the proton

Different Experiments
Probe Different
Parts of Lagrangian,
PVDIS is the only one accessing C_{2q}

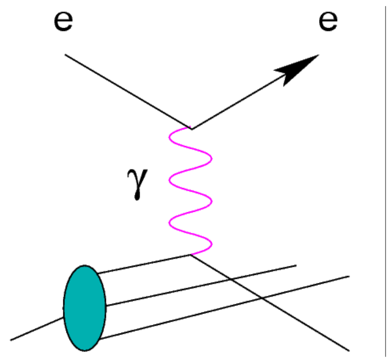
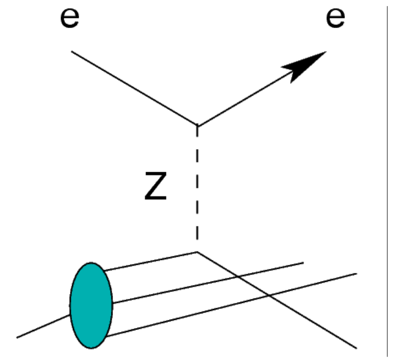
- *PVDIS (JLab)*



- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$
- Isoscalar quark scattering

Cartoons borrowed from R. Arnold (UMass)

PVDIS Asymmetries

$A_{PV} =$  + 

- Deuterium:

$$A_d = (540\,ppm)Q^2 \frac{2C_{1u}[1+R_C(x)] - C_{1d}[1+R_S(x)] + Y(2C_{2u} - C_{2d})R_V(x)}{5+R_S(x)+4R_C(x)}$$

$$R_S(x) = \frac{2[s(x)+\bar{s}(x)]}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)} \quad R_C(x) = \frac{2[c(x)+\bar{c}(x)]}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)} \quad R_V(x) = \frac{u_V(x)+d_V(x)}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)}$$

- Also sensitive to:
  - quark-gluon correlations (higher-twist effects)
  - Charge symmetry violation (CSV)

$$u^p(x) \neq d^n(x) \qquad d^p(x) \neq u^n(x)$$

PVDIS Experiment – Past, Present and Future

- 1970's, result from SLAC E122 consistent with $\sin^2\theta_W=1/4$, **established the Electroweak Standard Model;** C.Y. Prescott, *et al.*, Phys. Lett. B77, 347 (1978)

- PVDIS asymmetry has the potential to explore New Physics, study hadronic effects/CSV ...... However, hasn't been done since 1978.

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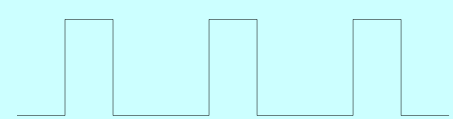
- PVDIS asymmetry has the potential to explore New Physics, study hadronic effects/CSV ...... However, hasn't been done since 1978.
  - (Re)start PVDIS at JLab 6 & 12 GeV
  - Difficulty: separate New Physics and hadronic effects

Medium & High Energy Physics Facilities for Lepton Scattering

Facilities	Accelerator	Beam	Energy, polarization	Luminosity ($cm^{-2}\,s^{-1}$)	Time	duty factor
FermiLab	Tevatron	$\vec{\mu}, \vec{\nu}$	1.96 TeV	low	1995 -	
SLAC	Stanford Linear Accelerator	$\vec{e}^-, \vec{e}^+$	50 GeV, 80%	10^{36}	1962 -	0.03%
JLab	Continuous Electron Beam Accelerator Facility (CEBAF)	$\vec{e}^-$	6 GeV, 85% 12 GeV, 85%	$10^{38\text{-}39}$	1985 - ... ... 2015 -	"CW"
CERN	Large e-/e+ Collider (LEP)	$\vec{\mu}, \vec{\nu}$	90-209 GeV	low	1989-2000	
DESY	Deutsches Elektronen Synchrotron	$\vec{e}^-, \vec{e}^+$	27.5 GeV	low	1987 - ... ... (DESY-II)	
MAINZ	Mainz Microtron MAMI	$\vec{e}^-, \vec{e}^+$	0.8/1.6 GeV	10^{38}	1979 -	"CW"
MIT Bates	MIT Bates Linear Accelerator	$\vec{e}^-$	0.8 GeV	10^{37}	1975-2005	

- *High luminosity, yet "continuous" polarized beam makes JLab an unique facility.*



~ns: "continuous"
>>ns: "pulsed"

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- PVDIS asymmetry has the potential to explore New Physics, study hadronic effects/CSV ...... However, hasn't been done since 1978.

- Do a first measurement at JLab 6 GeV — E08-011 (completed):
  - If observe significant deviation from the Standard Model value, it will definitely indicate something exciting;
  - *Indicate either electroweak new physics, or point out weakness in our understanding of strong interaction.*

– New electroweak Physics

– Non-perturbative QCD (higher-twist) effects ← Likely to be small, but need exp confirmation

– Charge symmetry violation ← Small from MRST fit (90% CL ~1%)

At the 6 GeV precision:

PVDIS Experiment – Past, Present and Future

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    - If observe significant deviation from the Standard Model value, it will definitely indicate something exciting;
    - *Indicate either electroweak new physics, or point out weakness in our understanding of strong interaction.*

  - At 12 GeV, a larger, well-planned PVDIS program could separate all three: New Physics, HT, CSV, *important information for both EW and Strong interaction study*.

work supported by NSF

The Collaboration

A. Afanasev, D.S. Armstrong, J. Arrington, T.D. Averett, E.J. Beise, W. Bertozzi, P.E. Bosted, H. Breuer, J.R. Calarco, A. Camsonne, G.D. Cates, J.-P. Chen, E. Chudakov, W. Deconinck, P. Decowski, **Xiaoyan Deng**, A. Deur, J. Erler, J.M. Finn, S. Gilad, K.A. Griffioen, K. Grimm, K. Hafidi, J.-O. Hansen, D.W. Higinbotham, R. Holmes, T. Holmstrom, R.J. Holt, J. Huang, P.M. King, W. Korsch, S. Kowalski, K. Kumar, N. Liyanage, A. Lukhanin, D.J. Mack, D.J. Margoziotis, P. Markowitz, D. McNulty, *R. Michaels* (co-spokesperson), B. Moffit, P. Monaghan, N. Muangma, V. Nelyubin, B.E. Norum, Kai Pan, K. Paschke, C. Perdrisat, A.J. Puckett, Y. Qiang, *P.E. Reimer* (co-spokesperson), J. Roche, A. Saha, B. Sawatzky, N. Simicevic, J. Singh, S. Sirca, *A. Shahinyan*, R. Snyder, P. Solvignon, P.A. Souder, N. Sparveris, **R. Subedi**, V. Sulkosky, W.A. Tobias, **Diancheng Wang,** K. Wang, S.P. Wells, *B. Wojtsekhowski*, X.-H. Zhan, *X.-C. Zheng* (co-spokesperon)

The Hall A Collaboration

ANL, Calstate, FIU, JLab, Kentucky, Louisiana Tech, U. of Ljubljana (Slovenia), MIT, UMD, UMass, UNH, Universidad Nacional Autonoma de Mexico, Ohio U., Randolph-Mason C., Smith C., Syracuse, Temple U., UVa, W&M, Yerevan Phys. Inst.(Armenia)

JLab 6 GeV Experiment 08-011

Co-spokesperson & contact: X. Zheng

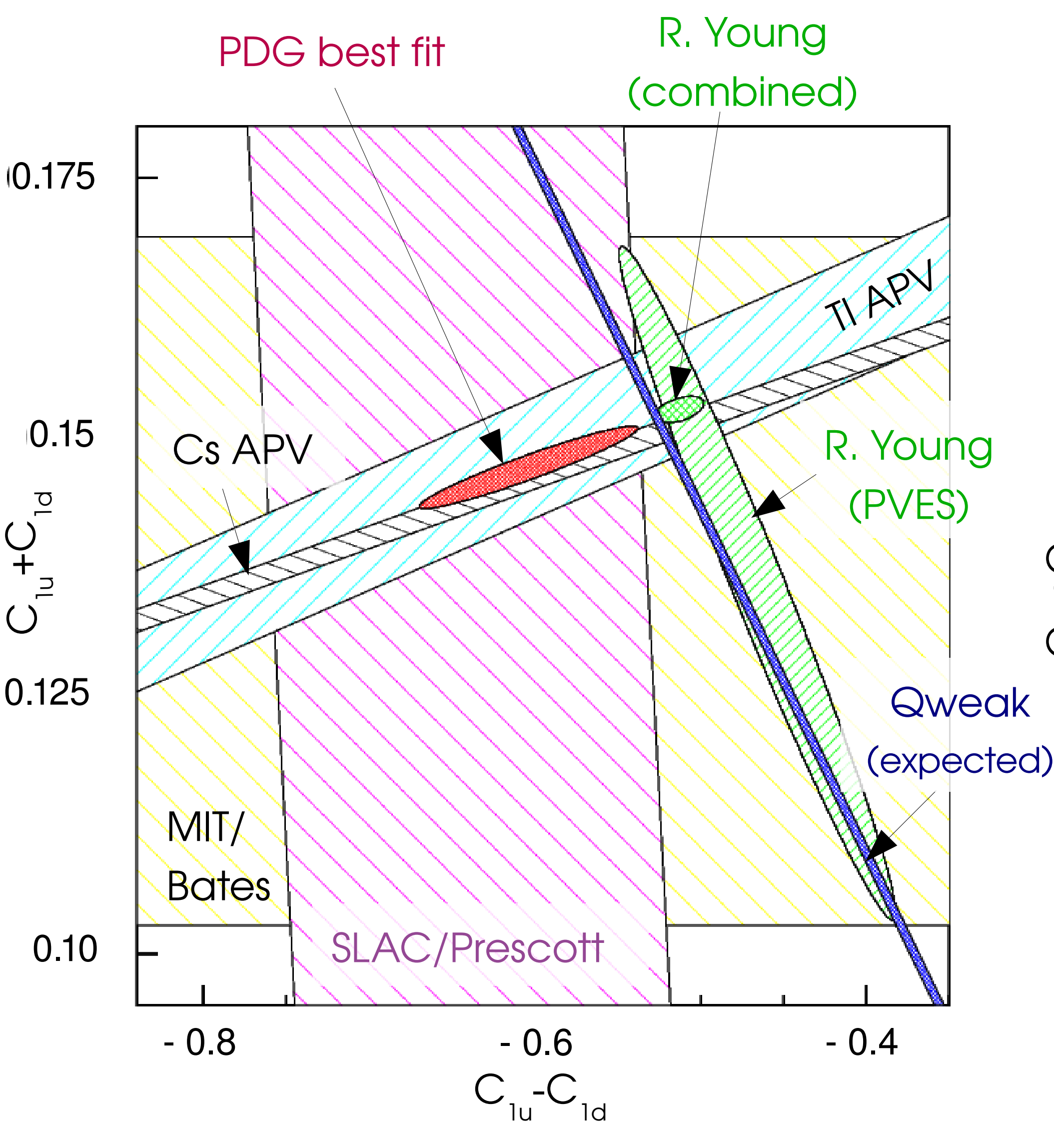
Co-spokesperson: P.E. Reimer, R. Michaels

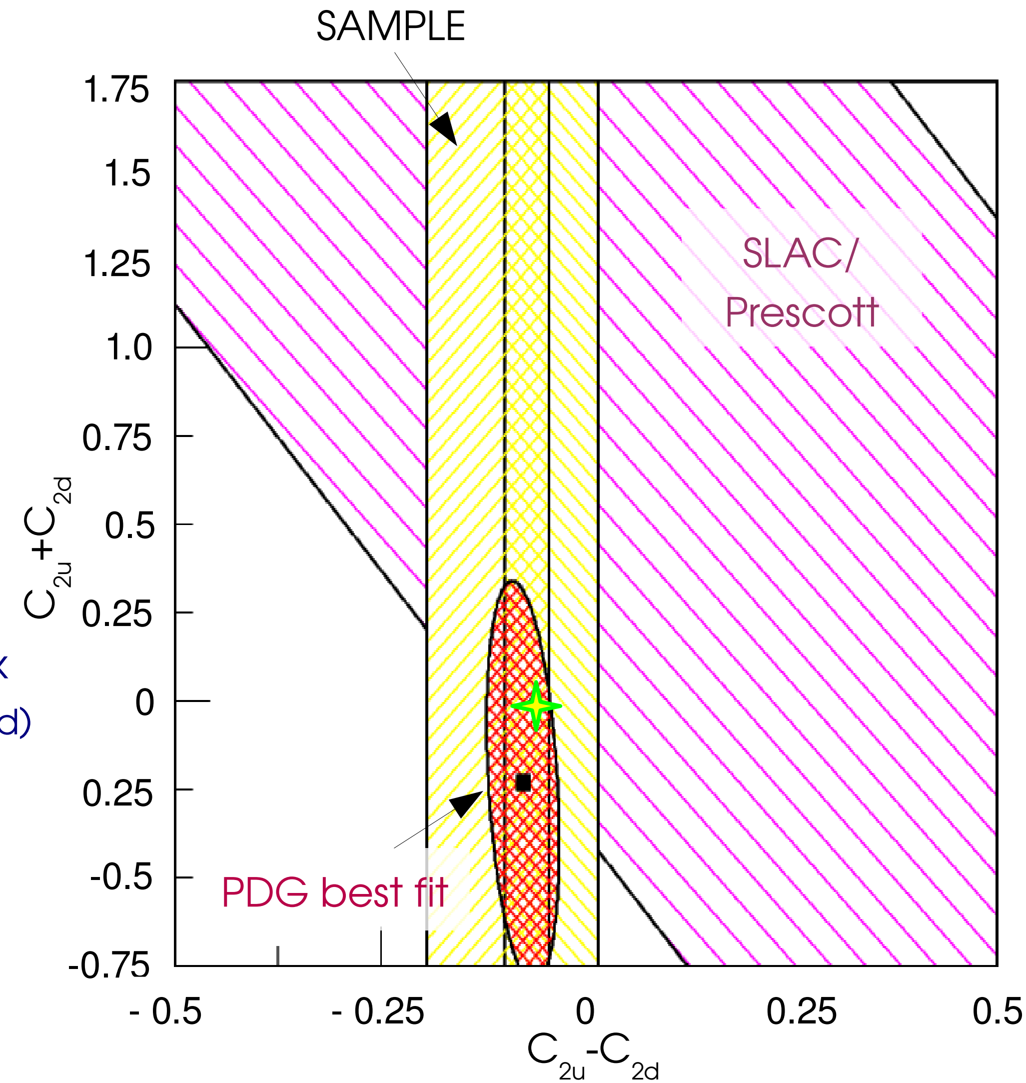
(Hall-A Collaboration Experiment, approved by PAC27; Re-approved by PAC33 for 32 days, rated A-; Ran Nov-Dec 2009)

- 100-105 µA, 6 GeV, 87% polarized beam on a 20-cm LD2 target;
- Two Hall A High Resolution Spectrometers detect scattered electrons;
- Measured PV asymmetry A_d at Q^2=1.10 and 1.90 GeV^2 to 3 and 4%(stat.), respectively.
  - A_d at Q^2=1.10 will set a limit on the higher twist effects;
  - If HT is small, can extract $2C_{2u}-C_{2d}$ from A_d at Q^2=1.90 to ±0.05-0.06 (or with reduced precision if higher twists are unexpectedly large)

Current Knowledge on $C_{1,2q}$

all are 1 σ limit

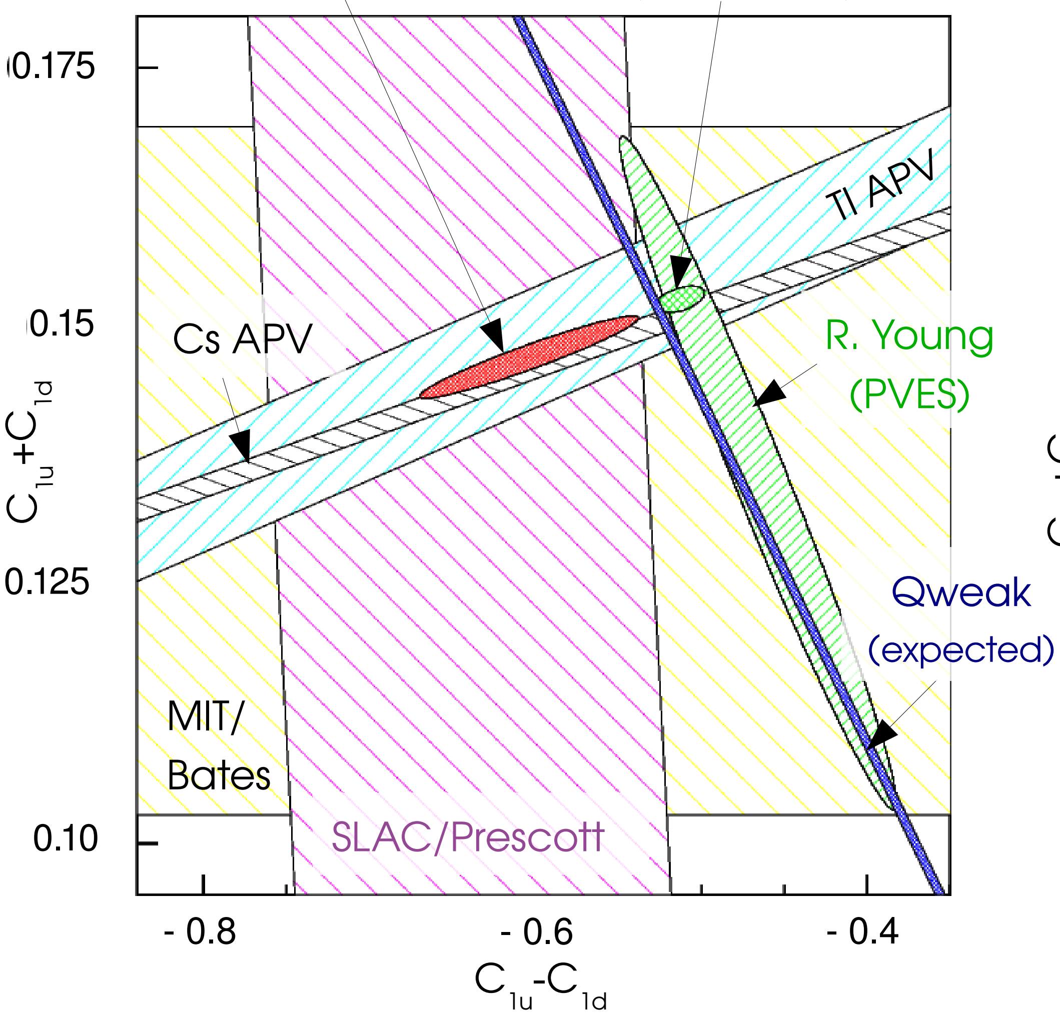


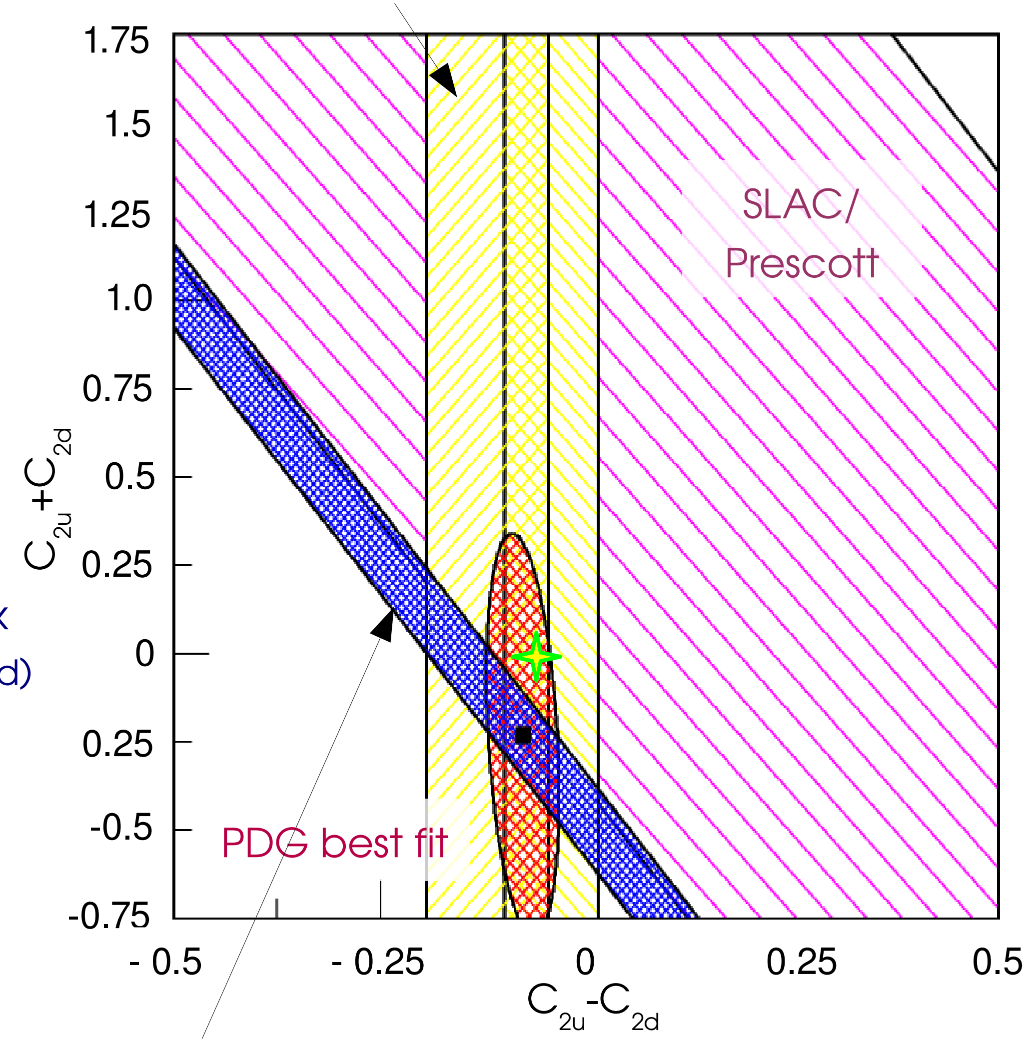


Best: $\Delta(2C_{2u}-C_{2d}) = 0.24$

The 6 GeV E08-011

all are 1 σ limit

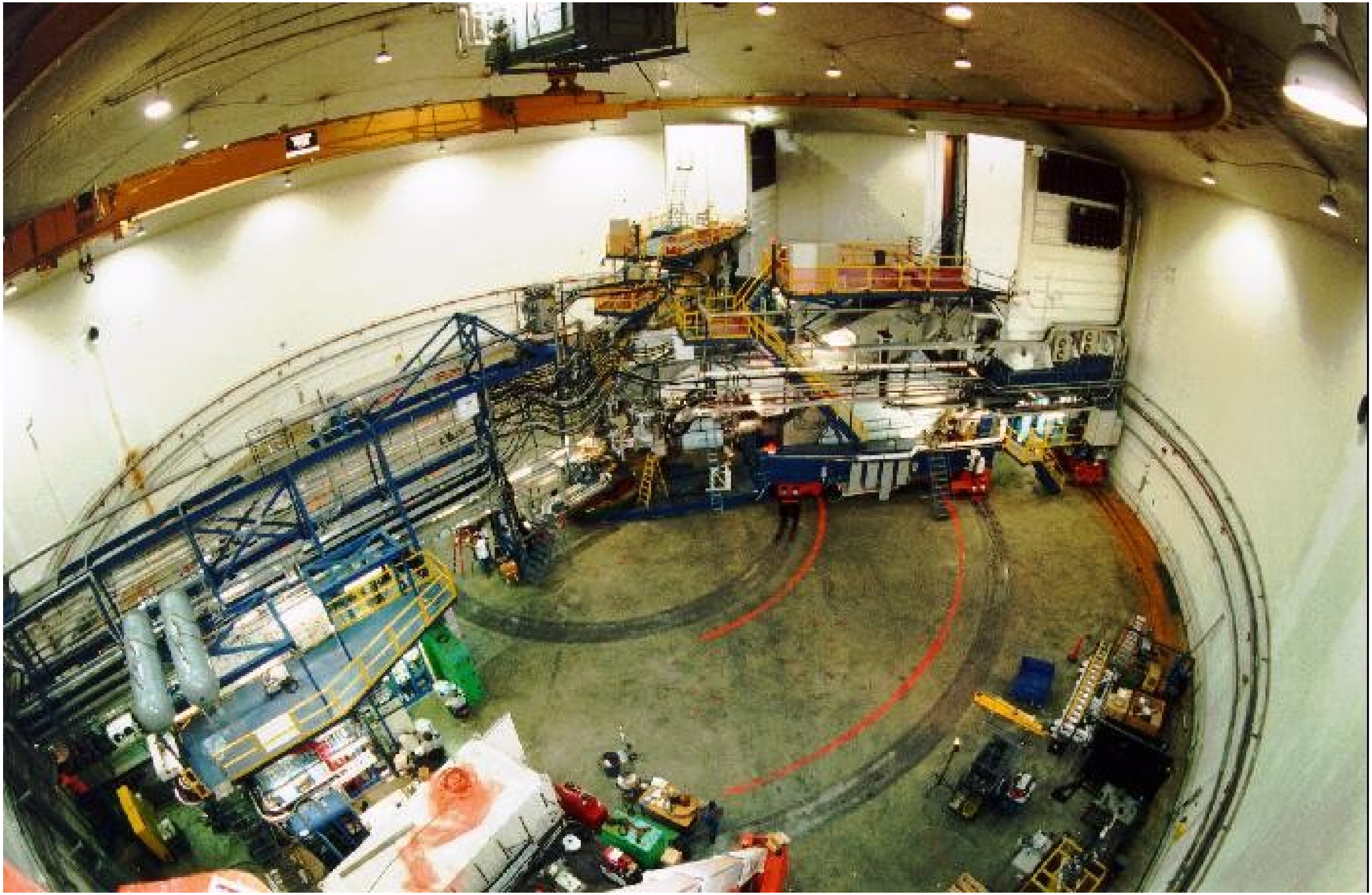




Best: $\Delta(2C_{2u}-C_{2d}) = 0.24$

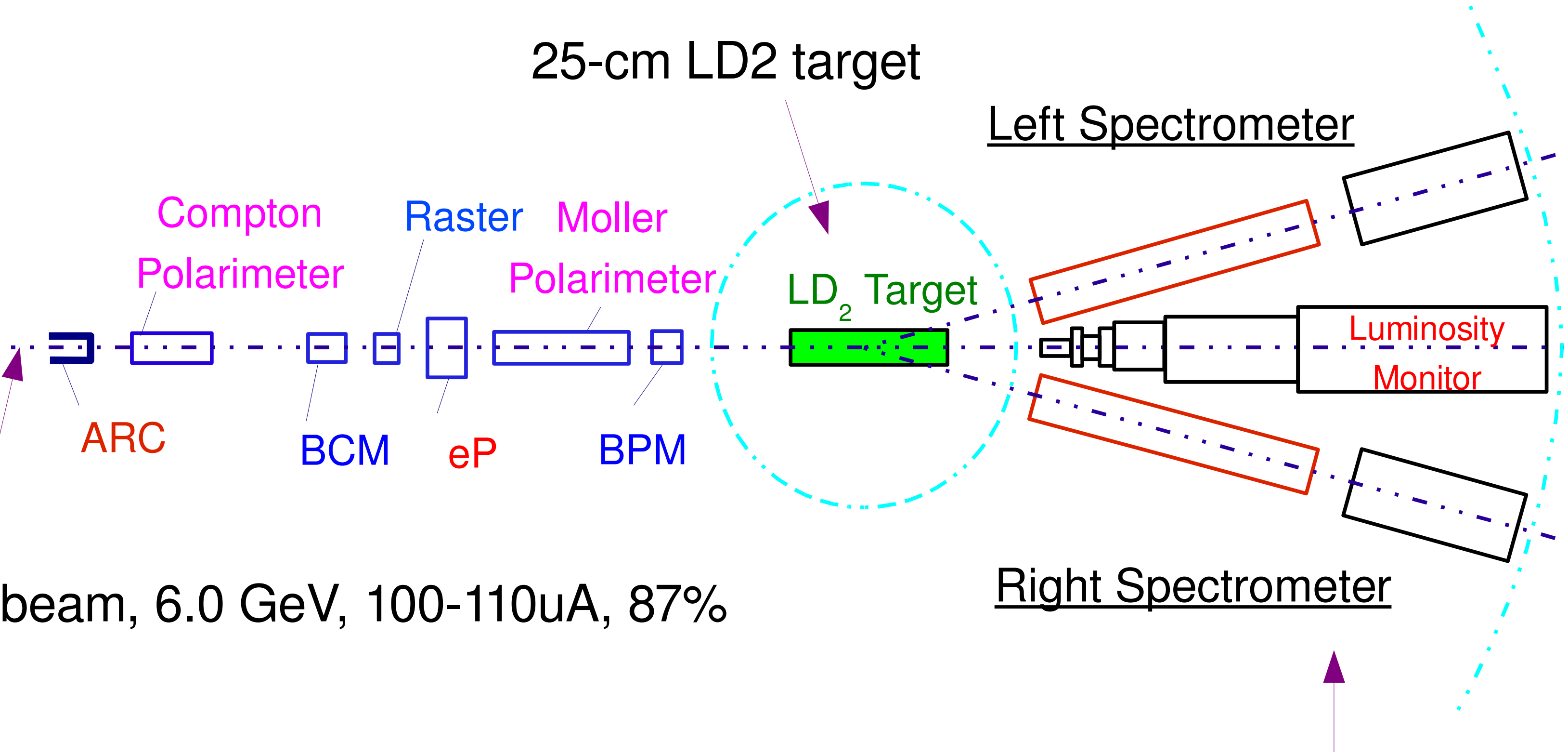
Expected: JLab 6 GeV PV-DIS E08-011 (assuming small hadronic effects and a 4% stat error on Ad)

Experimental Hall A



Overview of the Experimental Setup in Hall A

25-cm LD2 target



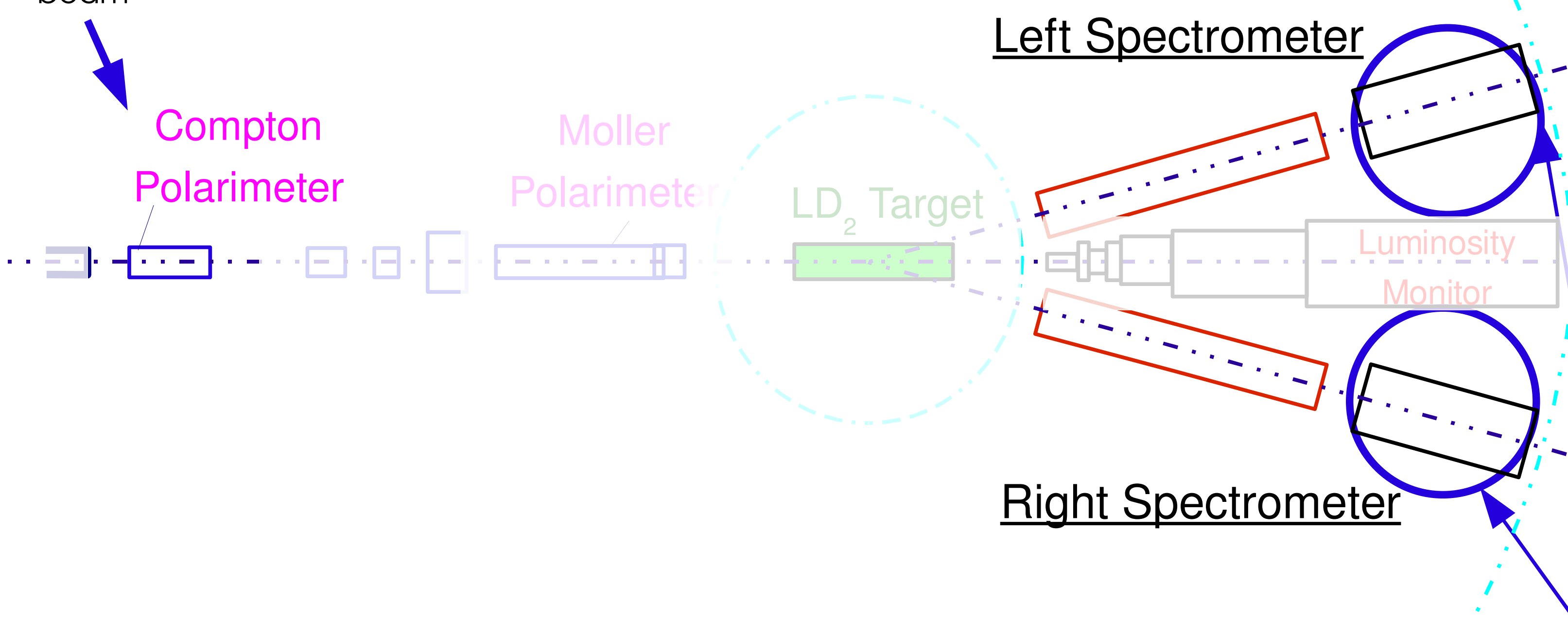
Pol e- beam, 6.0 GeV, 100-110uA, 87%

Electrons detected by the two spectrometers (HRS) independently

In Addition to the Standard Setup

- New methods used (photon integration and new electron detector): expect 2% precision on P_{beam} for E08-011

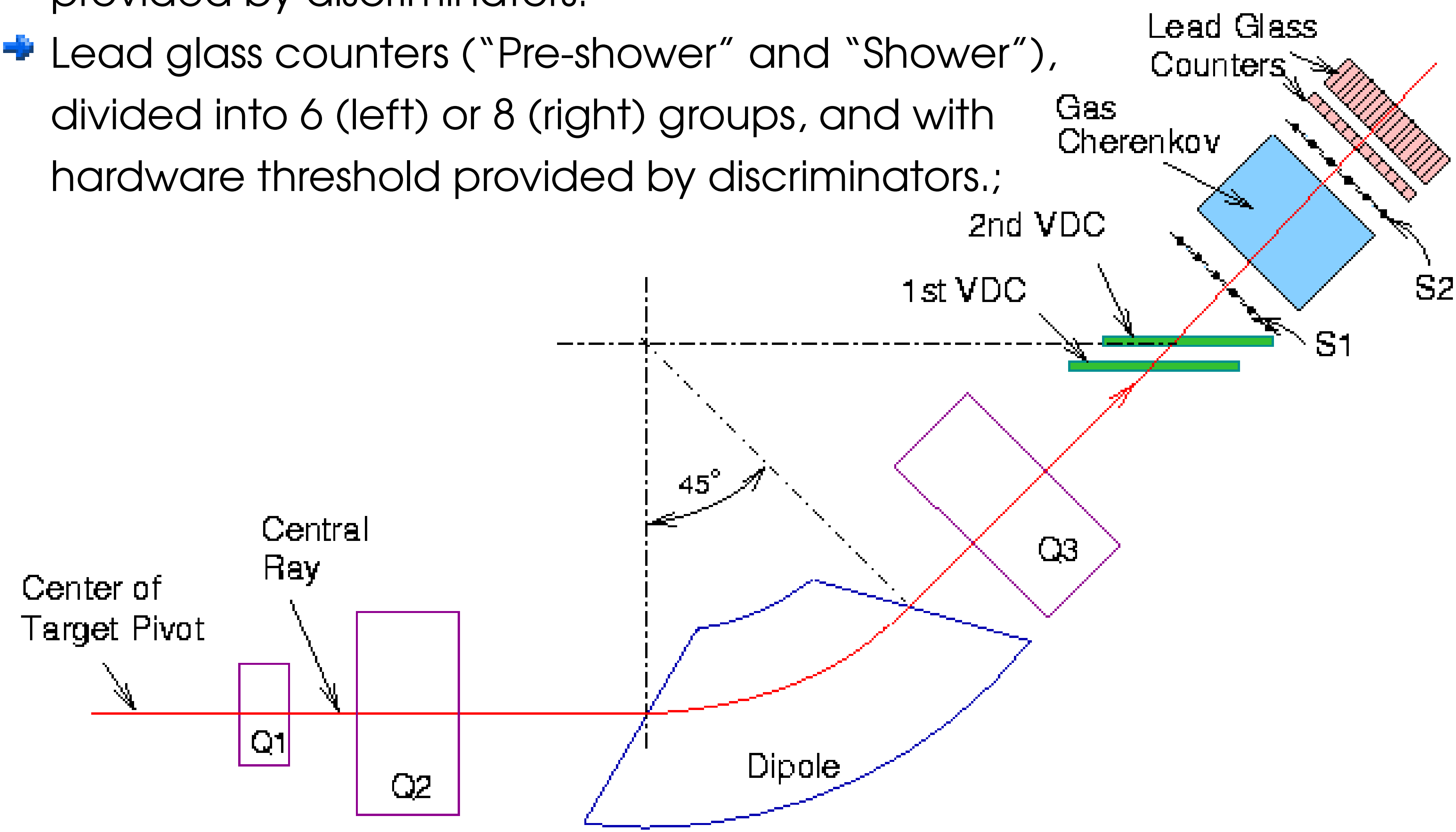
Also needed for two other PV experiments in Hall A (HAPPEX-III and PREX)



- Regular HRS data acquisition (DAQ) count up to 4KHz (expect 500KHz);
- Integration method won't work for DIS;
- Need a new fast-counting DAQ, design goal: 1MHz with on-line particle identification (PID); Never been done before!

A new fast-counting DAQ

- Inputs:
  - Scintillators (S1 and S2);
  - Gas cherenkov (GC), with hardware threshold provided by discriminators.
  - Lead glass counters ("Pre-shower" and "Shower"), divided into 6 (left) or 8 (right) groups, and with hardware threshold provided by discriminators.;



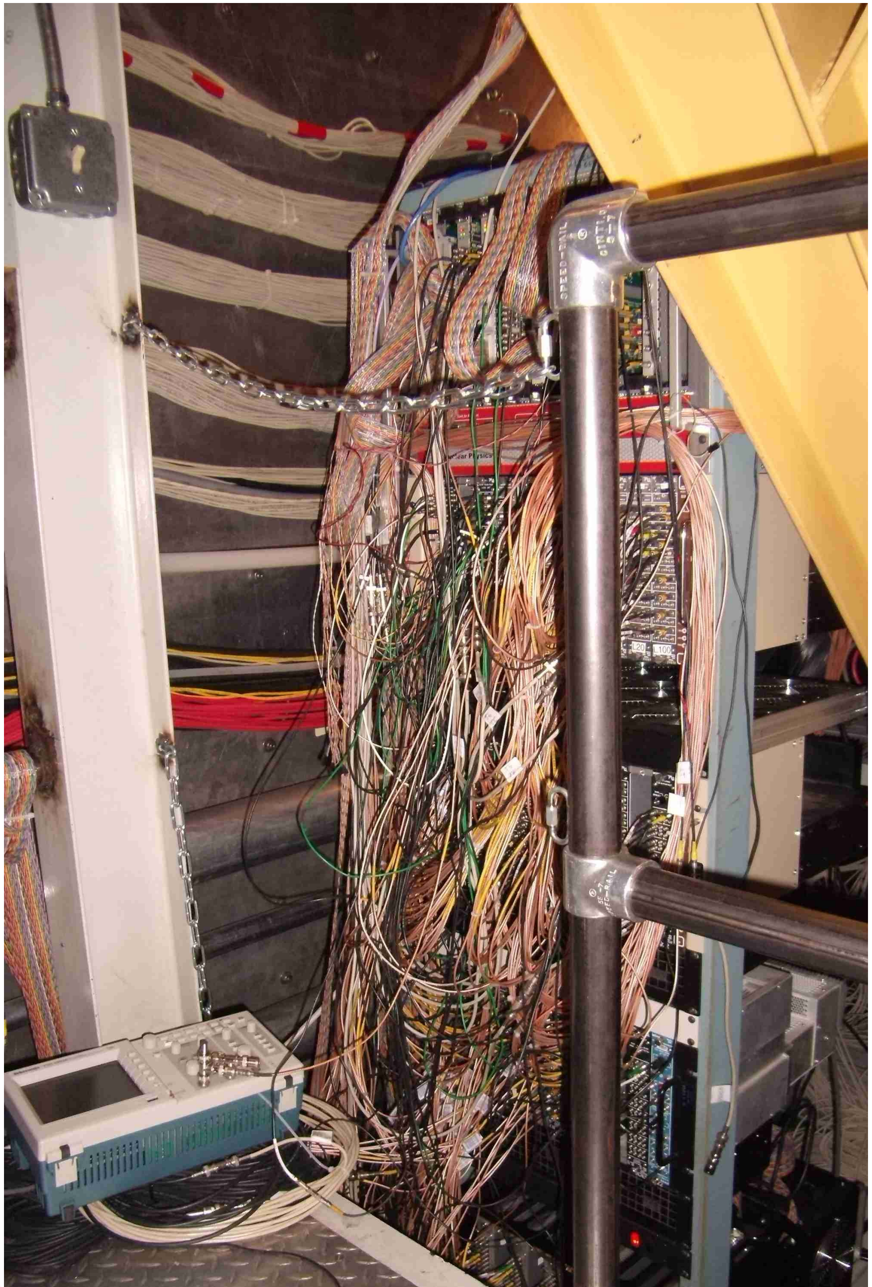
A new fast-counting DAQ

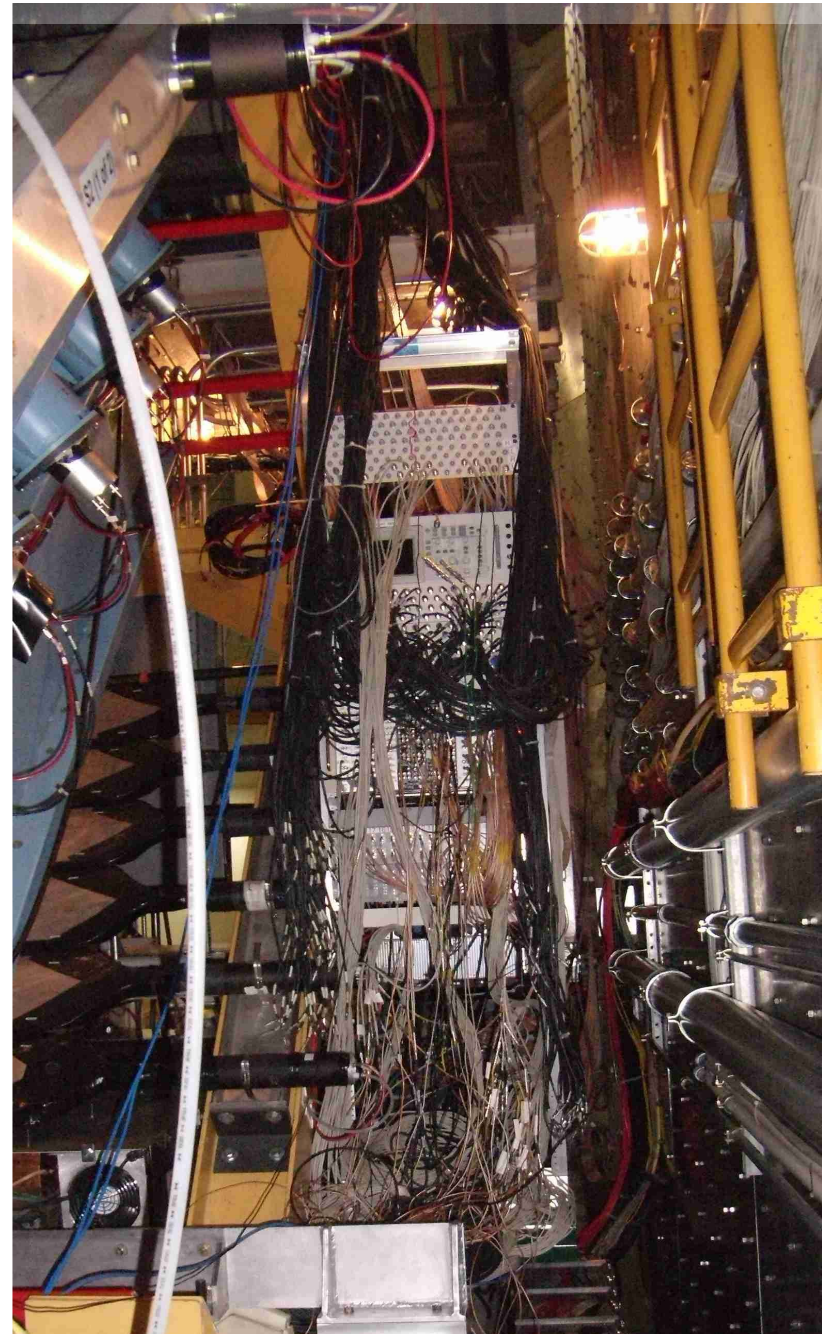
- Scaler-based: Helicity-gated scalers count e^- and π;
- Deadtime measured by multiple methods (goal: 0.3%)
  - Two resolution times (20, 100ns)
  - "tagger", TDC system

$$A_{PV} = \frac{A_{measured}}{P_b \eta_{DT}}$$

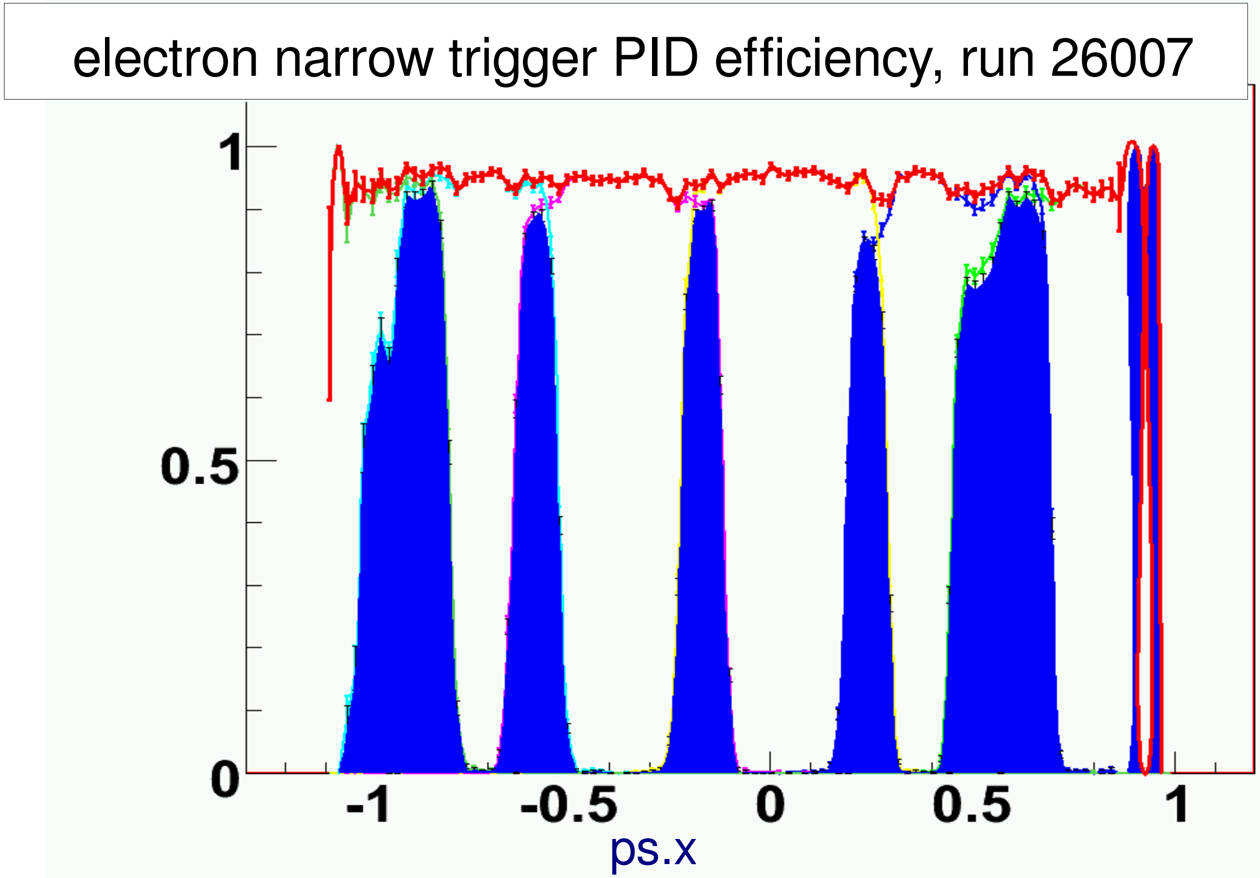
- Cross-check with regular DAQ at low rate for PID performance;
- Some channels with flash-ADCs, allow full sampling of signals for PID performance and pileup effects study.

- work started in spring 2008, underwent offline and online parasitic tests, here is how it looked like in the final stage (right HRS)

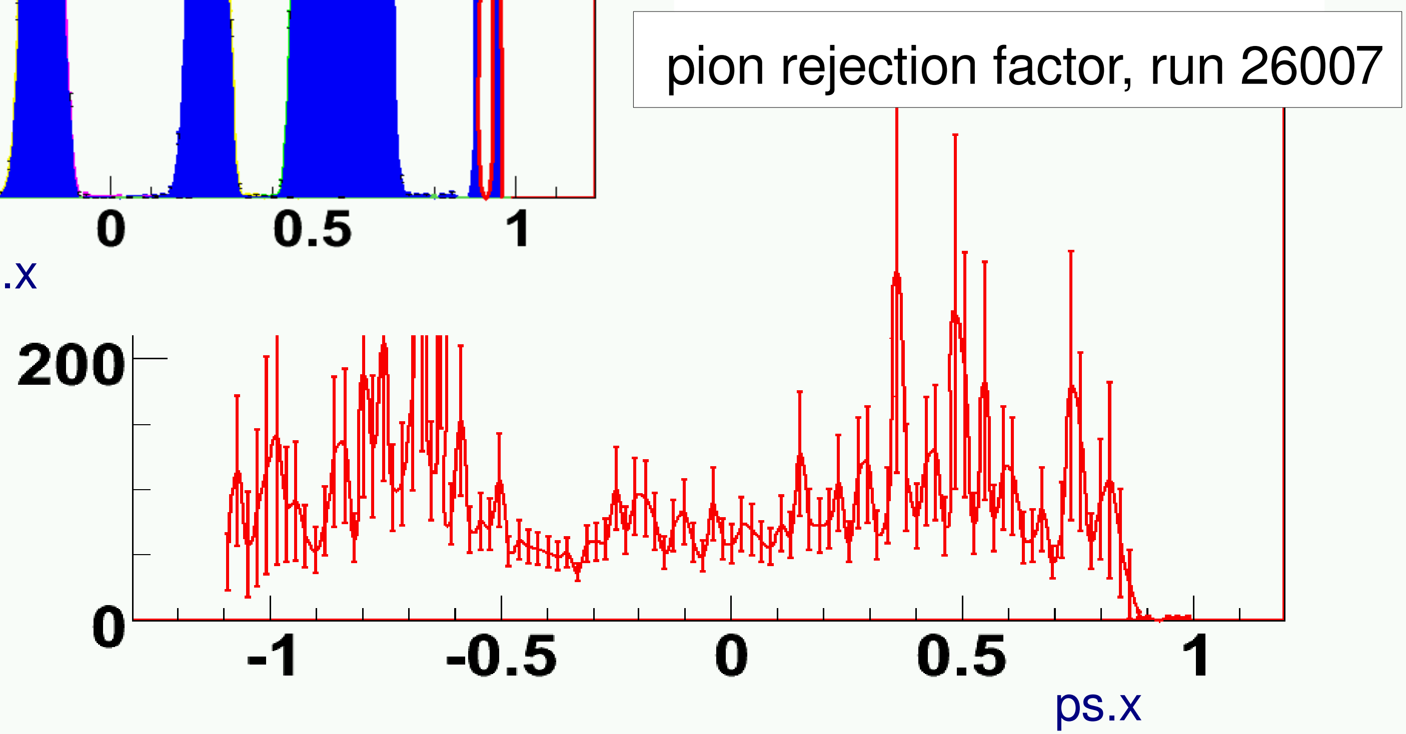




Lead Glass PID Check using fbTDC info in RHRS DAQ



- eff=N^e_1/N^e_0, electron samples N^e_0=(GC>800)
- rej=N^π_0/N^π_1, pion samples N^π_0=(GC<1)

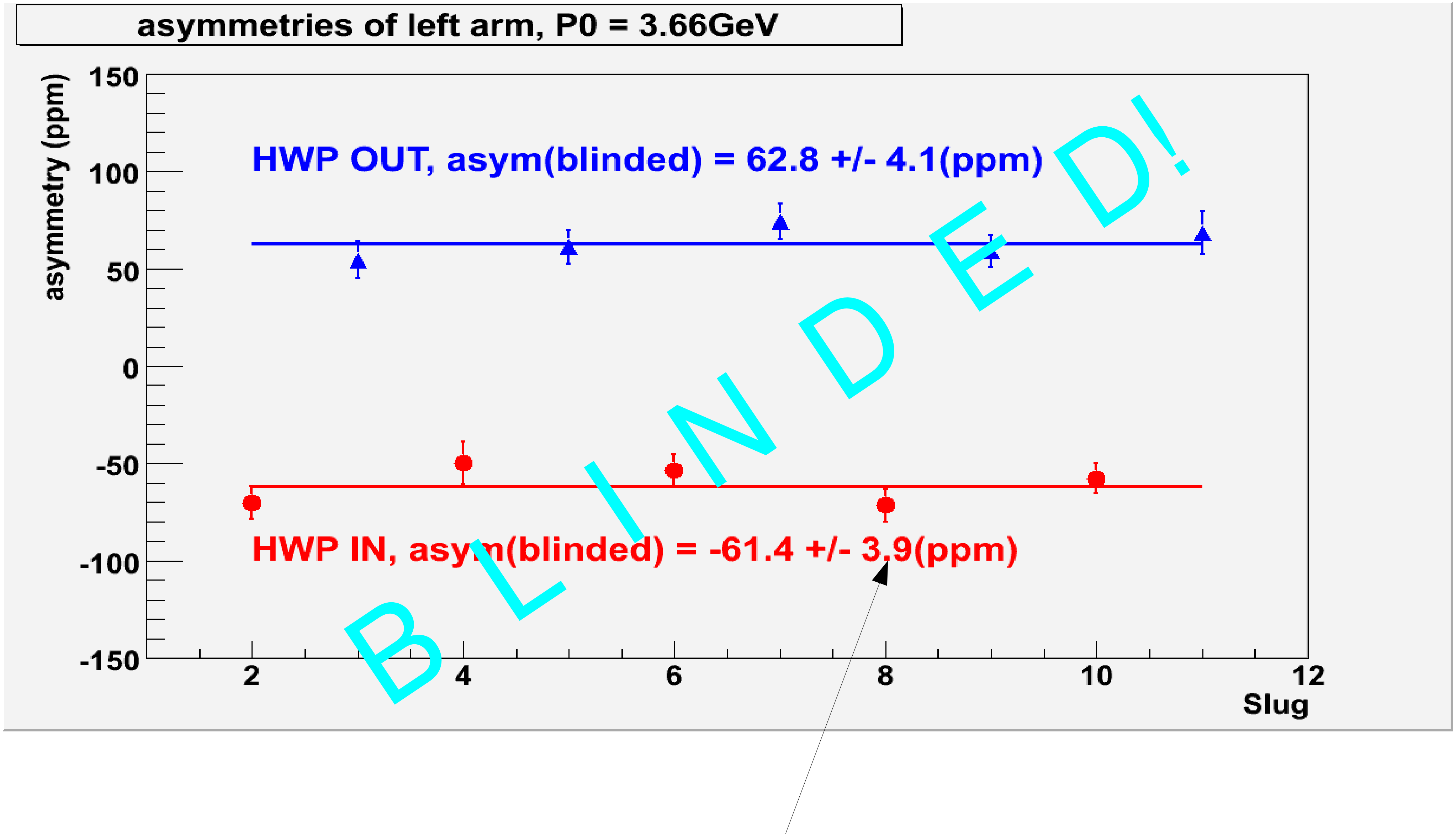


- Both agree with expectations
- Checked with VDC ON runs daily.

PVDIS General Run Information

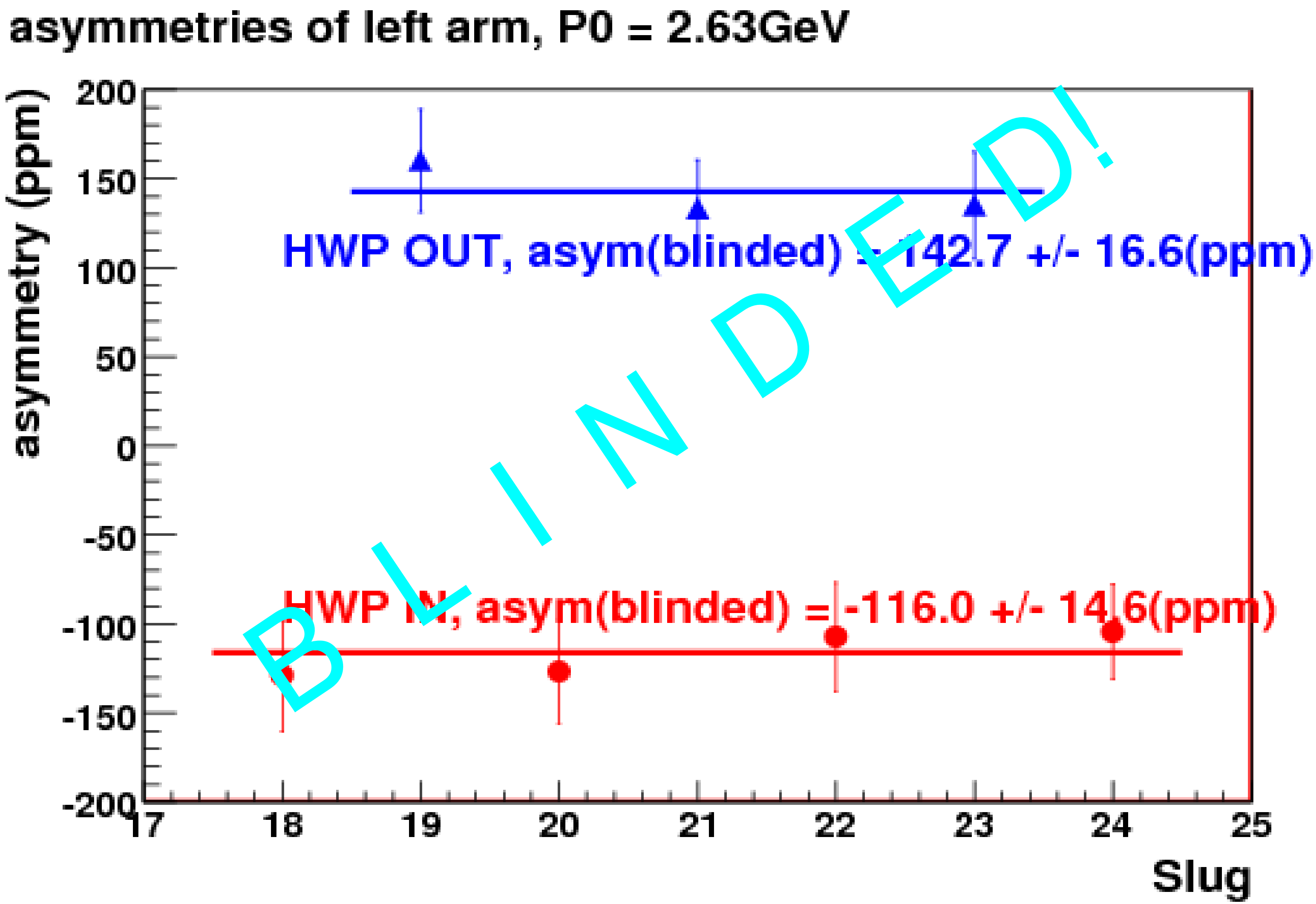
- Beam polarization shared with Hall B and monitored by Moller and Compton (photon-only). Moller results ~87%;
- Beam vertical polarization measured to be <2%;
- Beam charge asymmetry controlled by “parity feedback”;
- Target boiling noise monitored by Lumi;
- Beam IHWP switched every 1M helicity pairs (1 pair=66ms) (“slugs”);
- Deadtime measurement, analysis in progress;
- Other background or systematics measurements:
  - Pion asymmetries measured continuously by PVDIS DAQ, consistent with zero so far;
  - Al dummy and positive polarity runs (8 hours), rates agree with calculations;
  - Transverse beam polarization running (12 hours), *best DIS transverse measurement so far*, systematic uncertainty under control;
  - Random coincidence measurements.

Online Asymmetries, Q^2=1.1, Left arm only

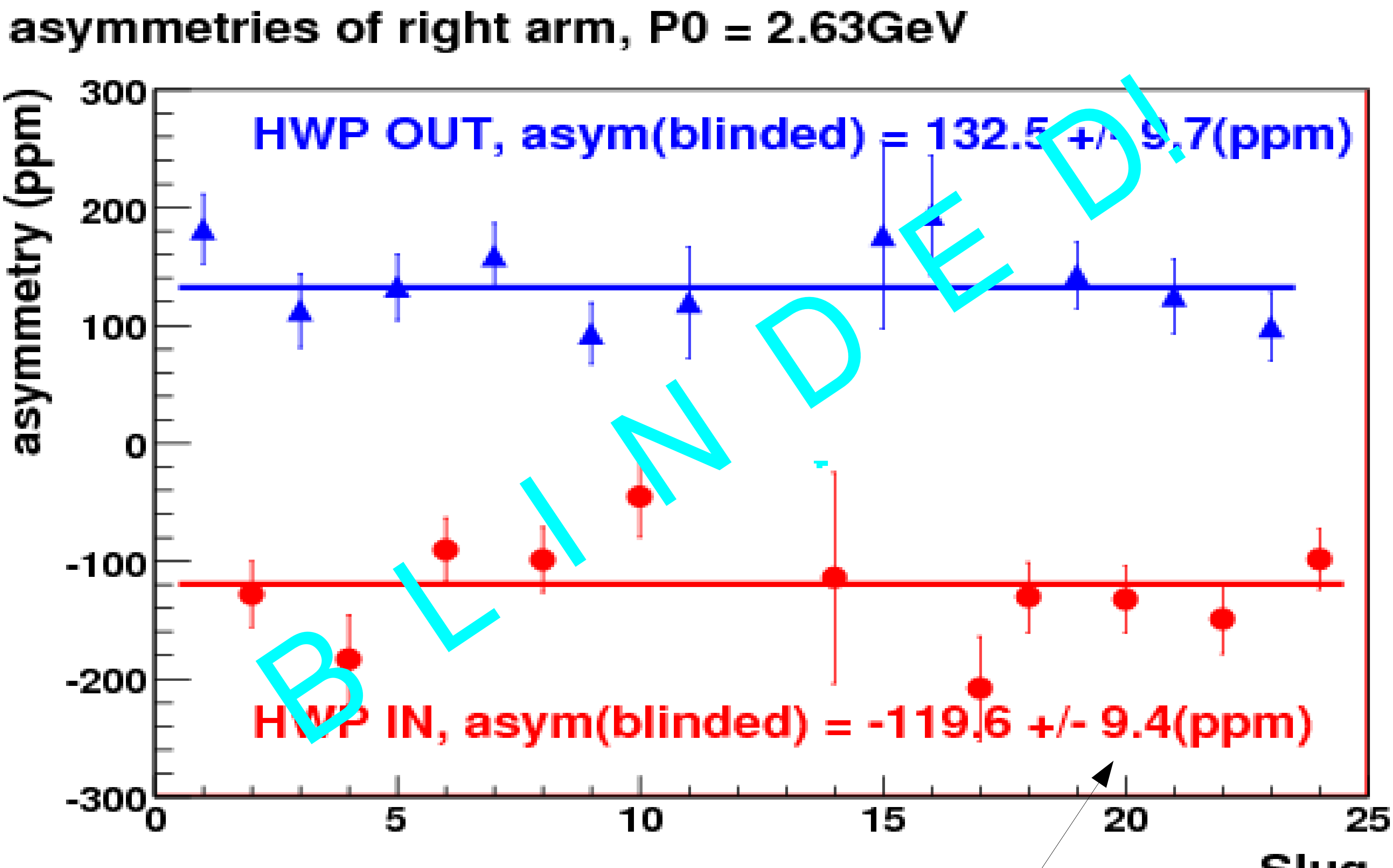


will provide a ~3% relative uncertainty compared to the calculated 90 ppm (note: we did not try to guess the blinding factor, not yet)

Online Asymmetries, Q^2=1.9, Left arm



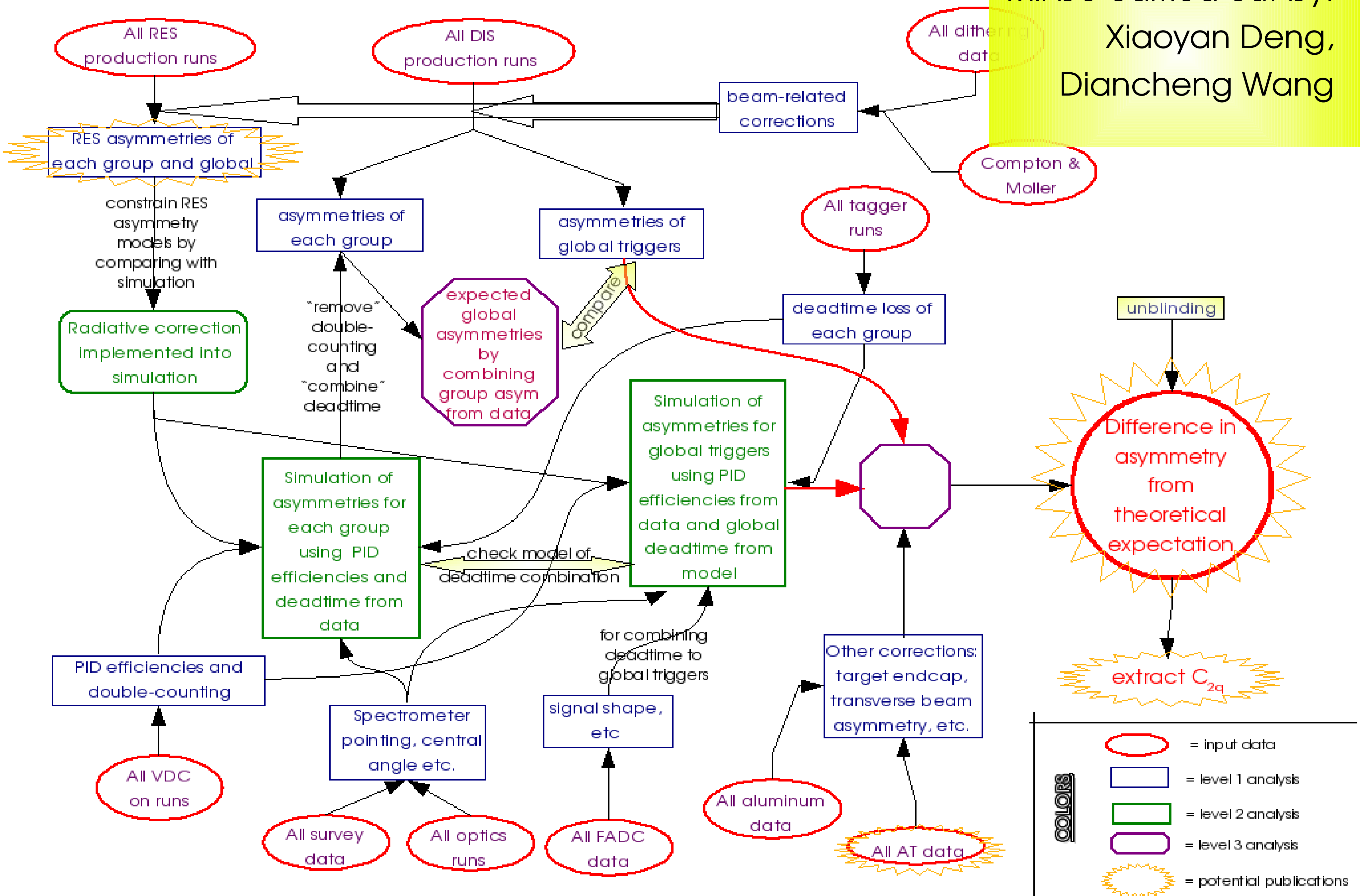
Online Asymmetries, Q^2=1.9, Right arm



will provide a ~4% relative uncertainty compared to the calculated 161 ppm (we did not try to guess the blinding factor, not yet)

E08-011 PVDIS Analysis Flow Chart

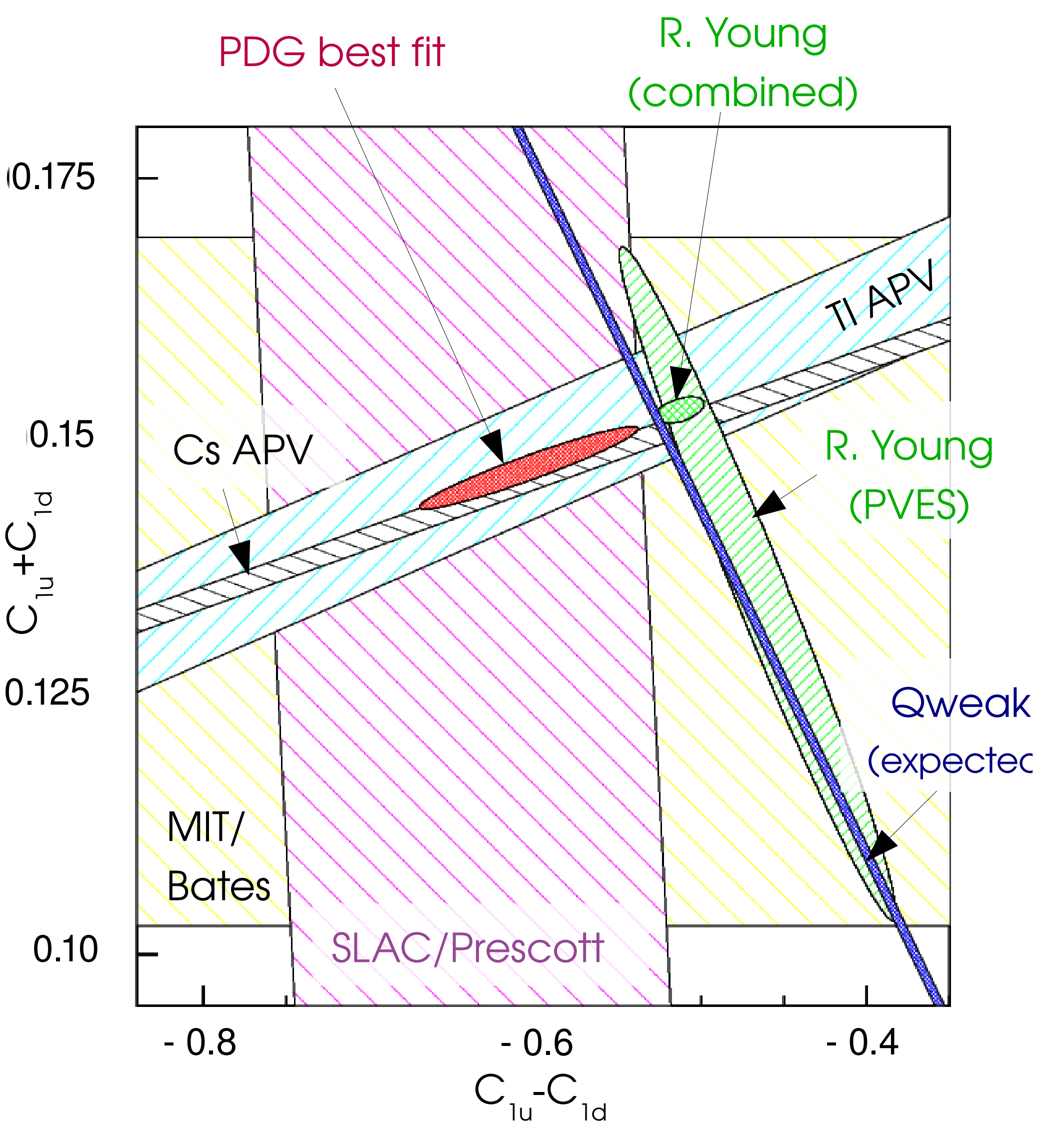
will be carried out by:
Xiaoyan Deng,
Diancheng Wang

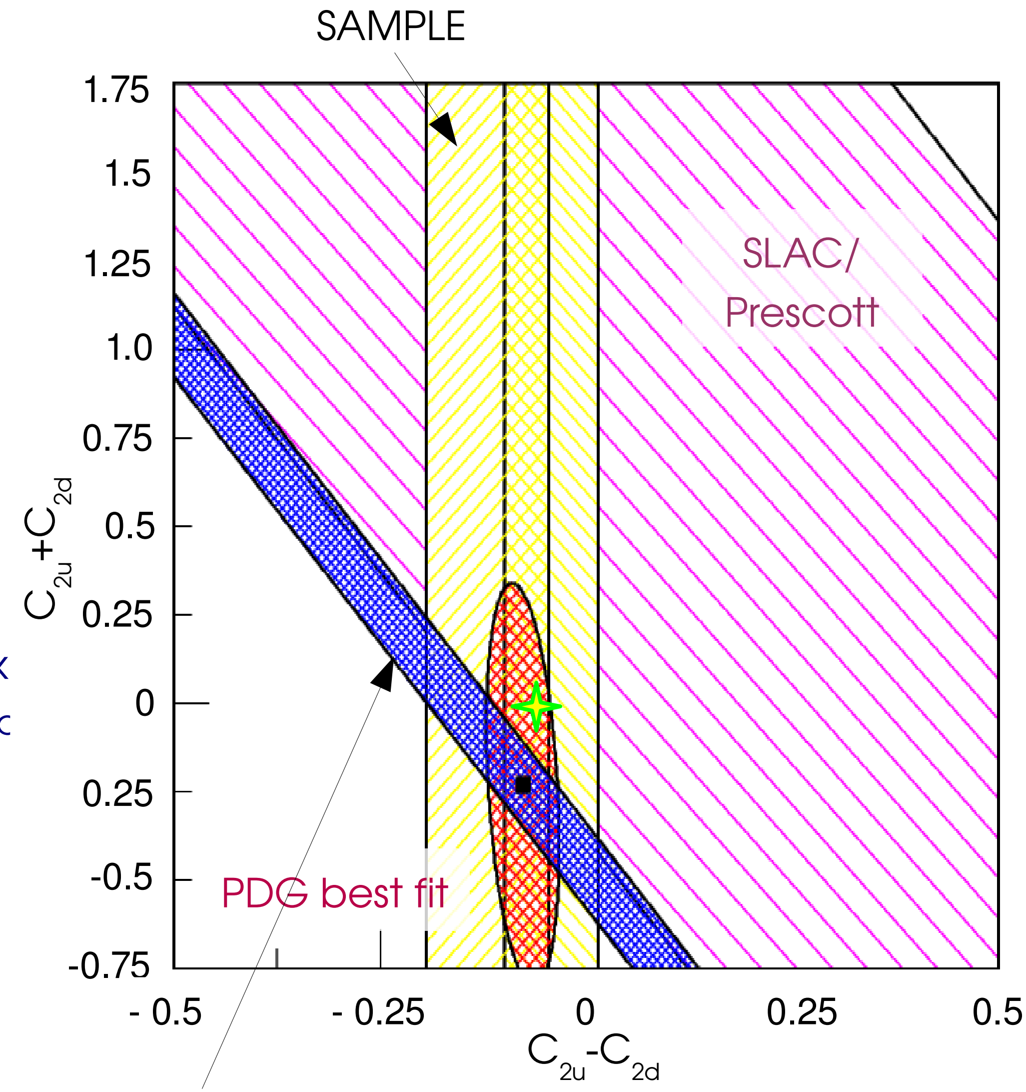


expect to unblind by late 2011, stay tuned!

The 6 GeV E08-011

all are 1 σ limit



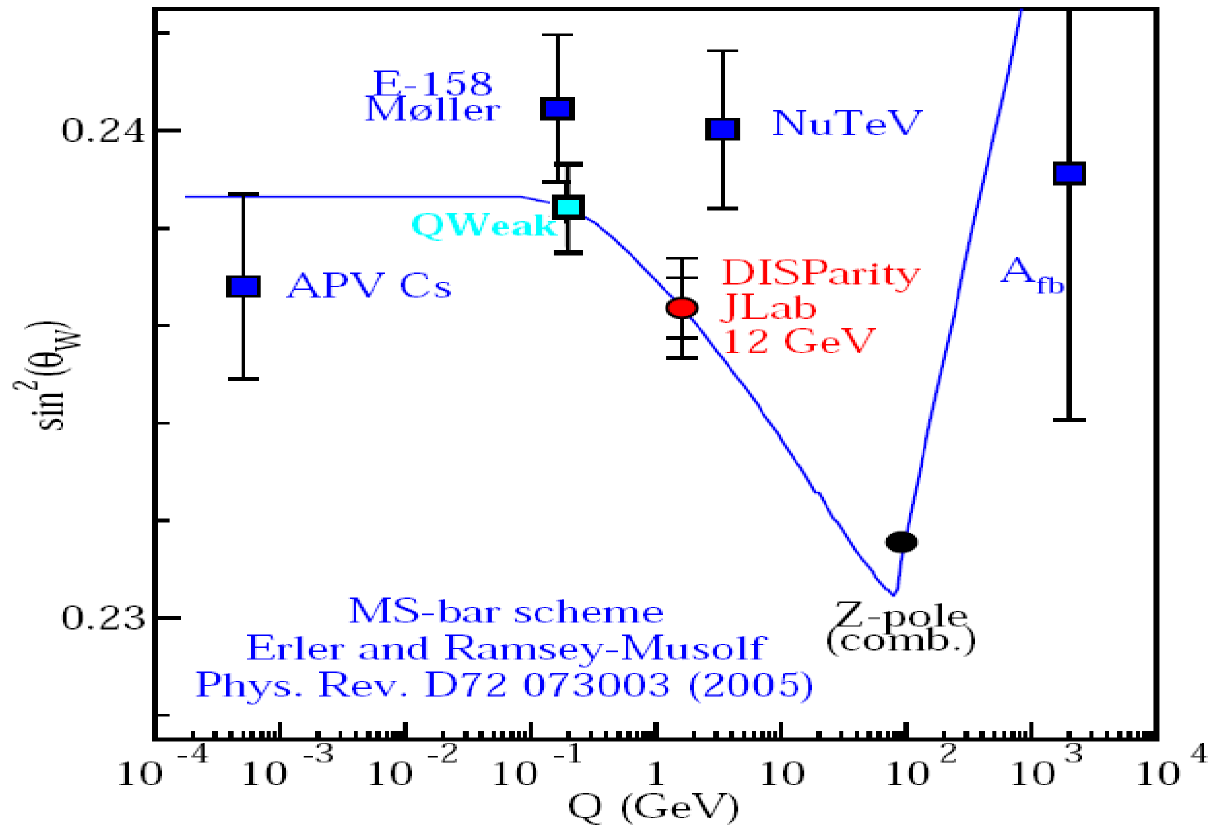


- Best: $\Delta(2C_{2u}-C_{2d}) = 0.24$

Expected: JLab 6 GeV PV-DIS E08-011 (assuming small hadronic effects and a 4% stat error on Ad)

PVDIS Program at JLab 12 GeV

- Higher precision, possibly sensitive to 1) New Physics beyond the SM; 2) Charge Symmetry Violation (CSV)
- Two approaches:
  - Hall C "baseline" SHMS+HMS: PR12-07-102 (P.E. Reimer, X-C. Z, K. Paschke,
    - 1% on A_d, extraction of C_{2q}, $\sin^2\theta_W$ (if higher-twists and CSV are negligible);
  - (conditionally approved)
    - Measure A_d to
      New Physics (v
    - Extract d/u at l
      effects;
    - Other hadronic ... DIS.



PVDIS Program at JLab 11 GeV

- Higher precision, possibly sensitive to 1) New Physics beyond the SM; 2) Charge Symmetry Violation (CSV)
- Two approaches:
  - Hall C "baseline" SHMS+HMS: PR12-07-102 (P.E. Reimer, X-C. Z, K. Paschke)
    - 1% on A_d, extraction of C_{2q}, $\sin^2\theta_W$ (if higher-twist and CSV are negligible);
  - Hall A large acceptance "solenoid" device: PR10-007 fully approved
    - Measure A_d to 1% for a wide range of (x,Q^2,y), clean separation of New Physics (via C_{2q} and $\sin^2\theta_W$), HT and CSV possible;
    - Extract d/u at large x from PVDIS on a proton target, free of nuclear effects;
    - Other hadronic physics study possible: A_1^n at large x, Semi-inclusive DIS.

Projected PVDIS Measurement with SOLID@11 GeV

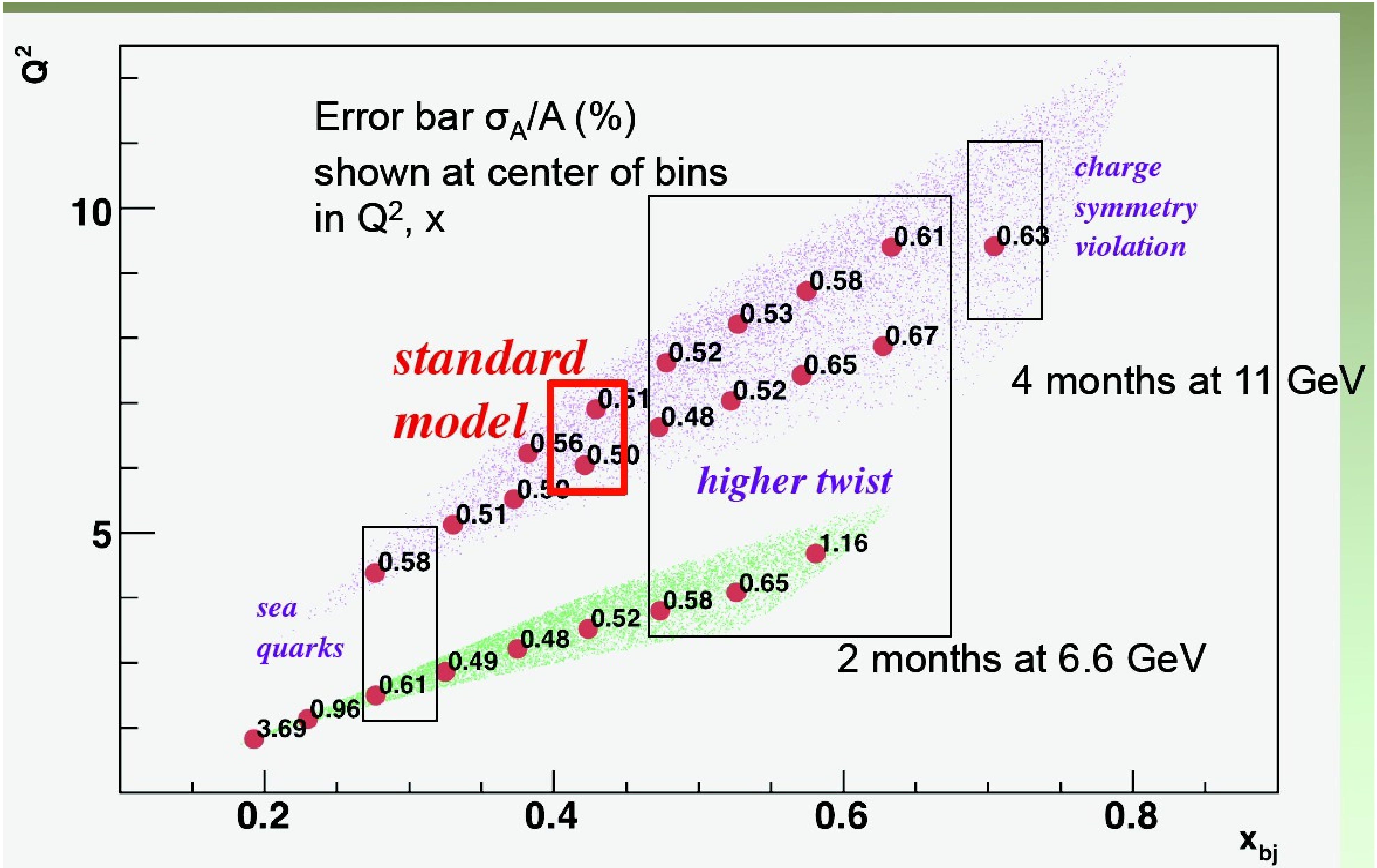


figure from K. Kumar, Seattle 2009 EIC Workshop EW talks

Projected PVDIS Measurement with SOLID@11 GeV

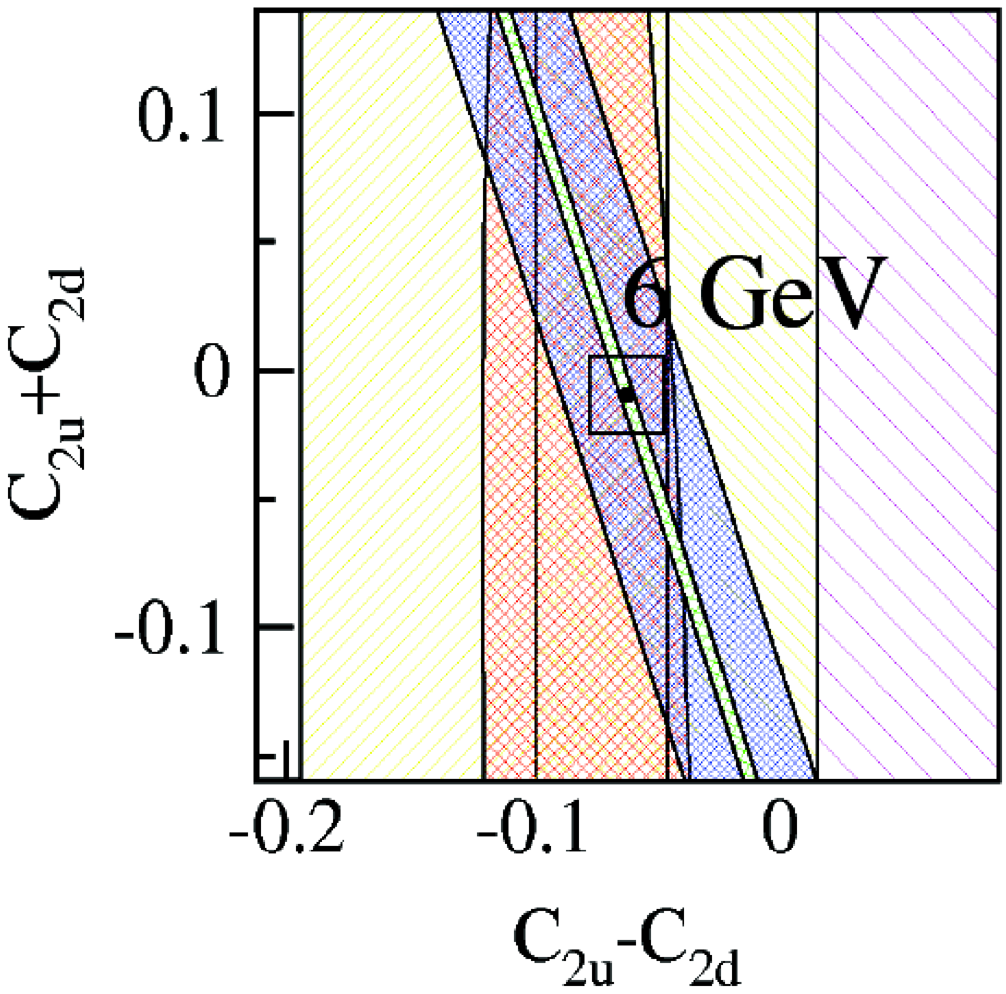


figure from K. Kumar, Seattle 2009 EIC Workshop EW talks

PVDIS Program at JLab 11 GeV

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- Two approaches:
  - Hall C "baseline" SHMS+HMS: PR12-07-102 (P.E. Reimer, X-C. Z, K. Paschke)
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    - Extract d/u at large x from PVDIS on a proton target, free of nuclear effects;
    - Other hadronic physics study possible: A_1^n at large x, Semi-inclusive DIS.

Research Summary (2009-2013) work will be supported by DoE

- Parity Violating DIS has the potential to study the Electro-weak Standard Model, and nucleon structure/QCD:
  - First step — JLab 6 GeV (E08-011): measured A_d at two Q^2 to 3 or 4% (stat.); analysis is expected to finish in 1-2 years; will attempt to extract $\Delta(2C_{2u}\text{-}C_{2d})$ to ± 0.05-0.06 (potential impact on electroweak Standard Model test);
  - With the upgraded 11 GeV beam and a new SOLID spectrometer, a brand-new program will be carried out to test the electroweak standard model and to study hadronic effects not measured before. Plan for the SOLID will focus on R&D of the calorimeter package.
- Extraction of low Q^2 A_{et} and A_t for single-pion electro-production $\vec{e}\,\vec{p} \to e'\pi^+ n$ from NH_3 and $\vec{e}\,\vec{n} \to e'\pi^- p$ from ND_3 using CLAS EG4 data;
- Plan for measurement of the neutron spin asymmetry A_1^n with the 11 GeV beam and a polarized ^{3}He target – 11 GeV "flagship" experiment. Target R&D will be carried out to improve its polarization and luminosity.

Research Summary (2013 -)

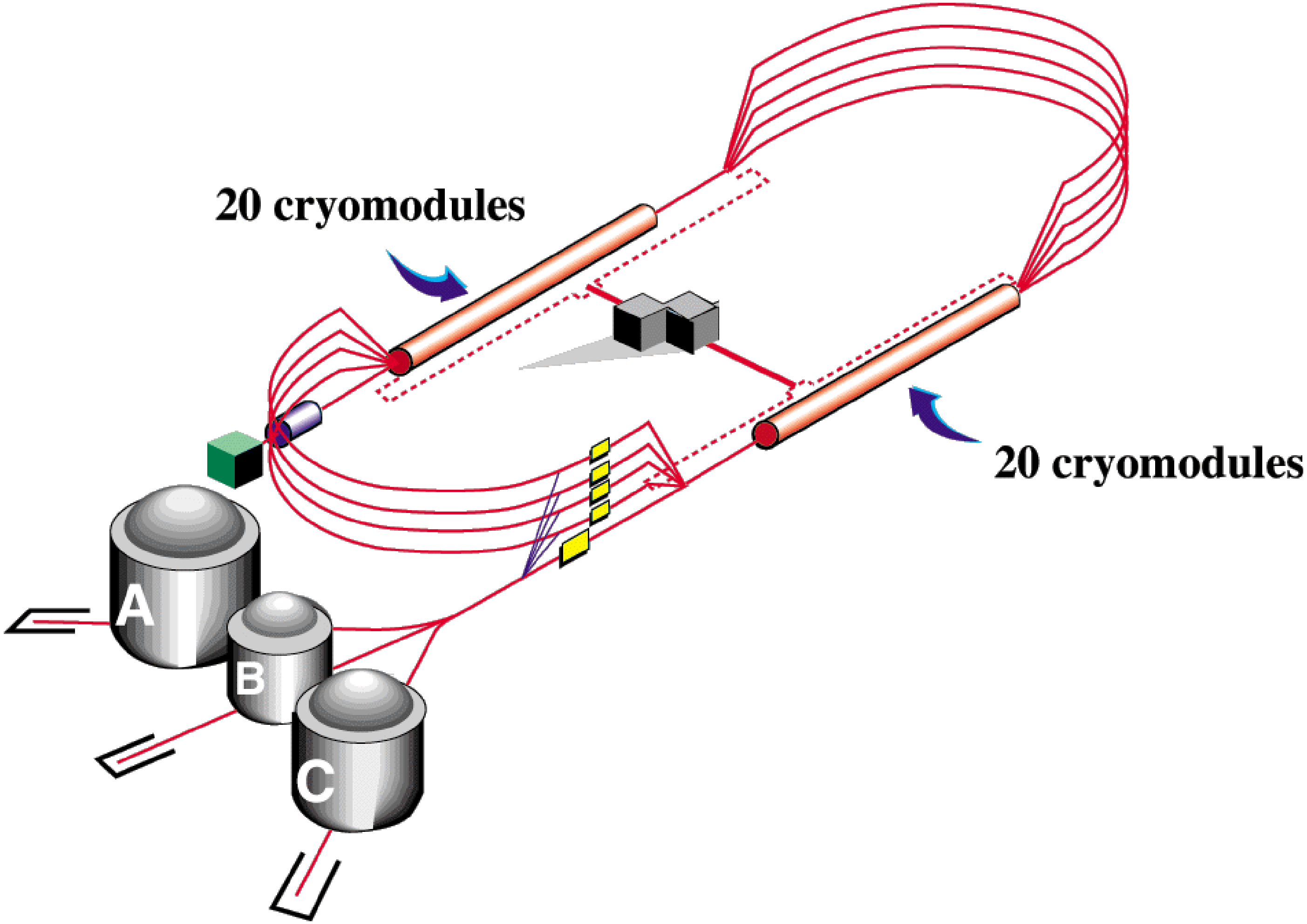
- Measurement of neutron asymmetry A_1^n in the valence quark region at JLab 12 GeV
  - Flagship experiment
  - If using baseline spectrometers, will be one of the first experiments to run (~2014?)
- SOLID program (2015 or later)
  - PVDIS at 11 GeV — ultimate goal: clean separation of New Physics and CSV
  - A_1^n, d/u measurements, SIDIS, etc.

Frontiers of Nuclear Science

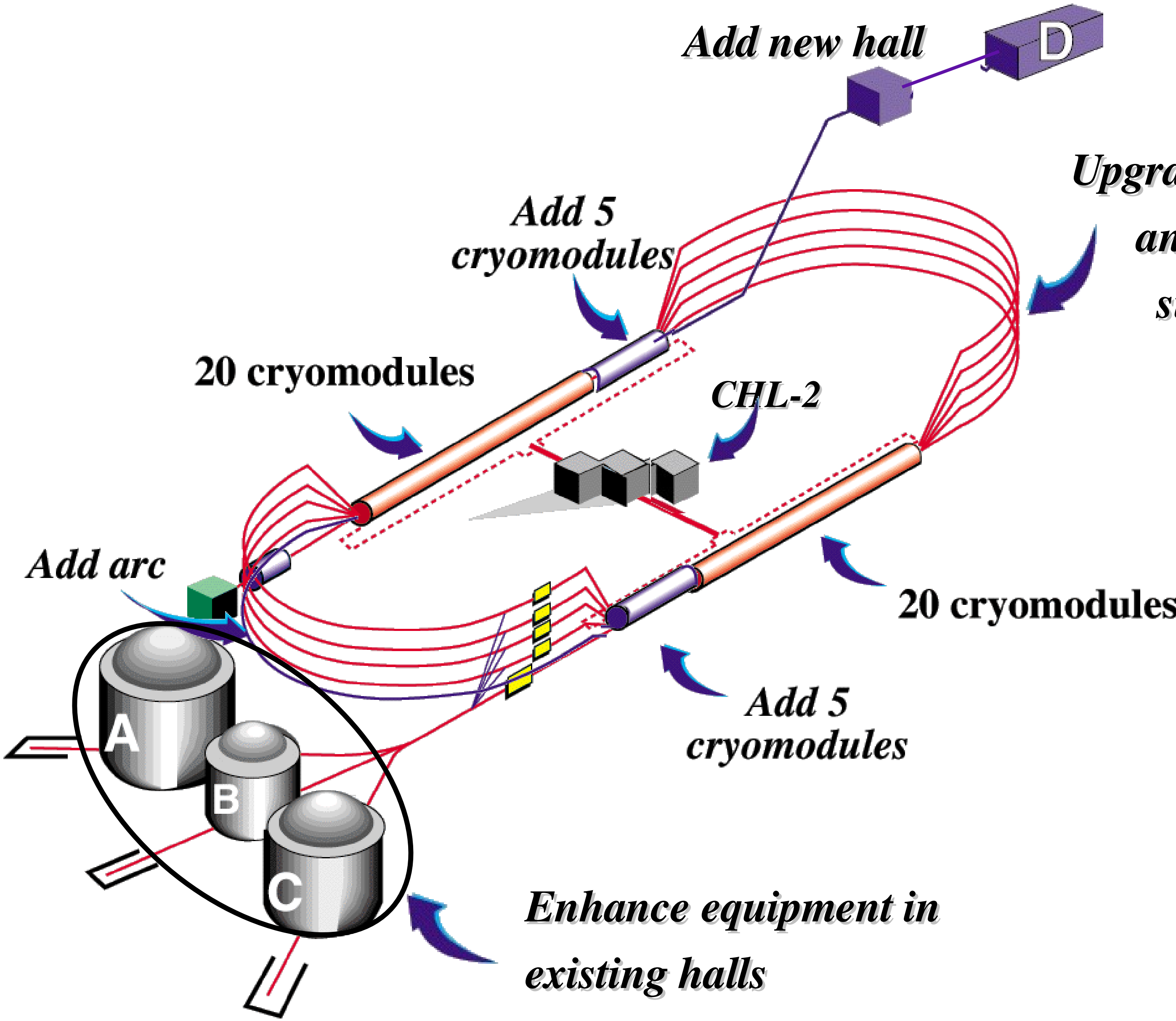
"Building on the foundation of the recent past, nuclear science is focused on three broad but highly related research frontiers: (1) QCD and its implications and predictions for the state of matter in the early universe, quark confinement, the role of gluons, and the structure of the proton and neutron; (2) the structure of atomic nuclei and nuclear astrophysics, which addresses the origin of the elements, the structure and limits of nuclei, and the evolution of the cosmos; and (3) developing a New Standard Model of nature's fundamental interactions, and understanding its implications for the origin of matter and the properties of neutrinos and nuclei."

Extra slides

Jlab 6 GeV



Jlab 12 GeV

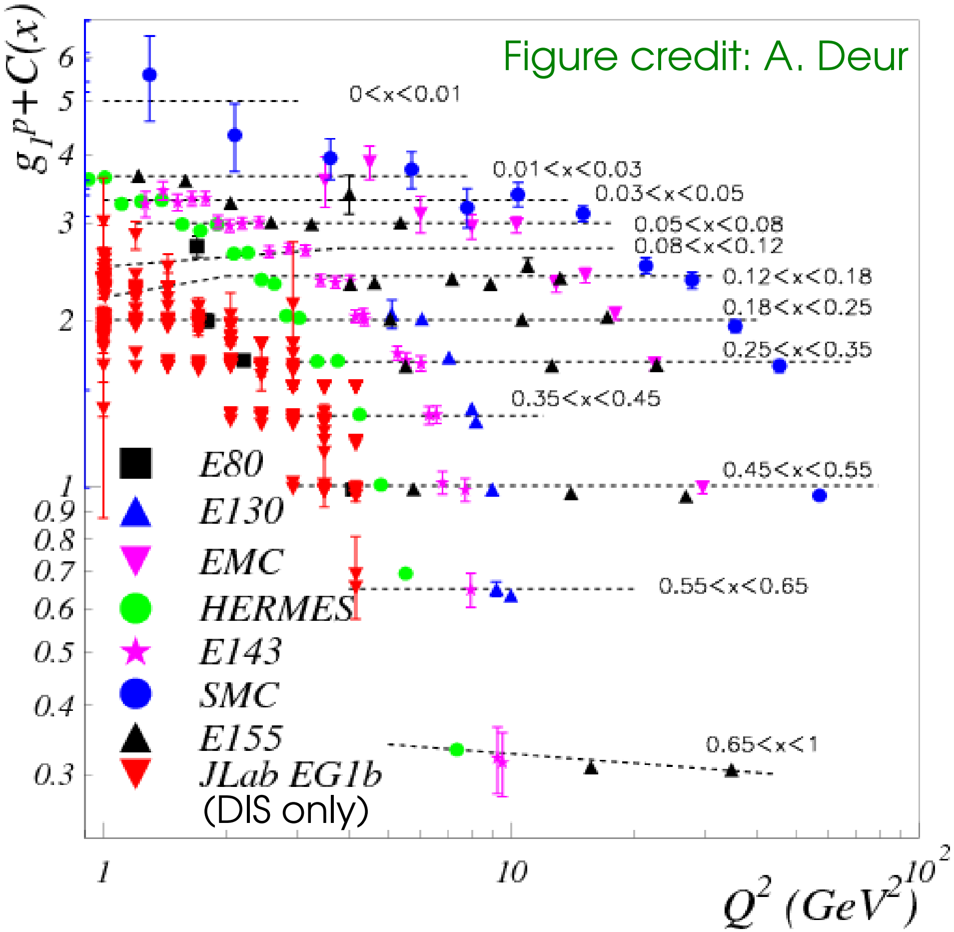


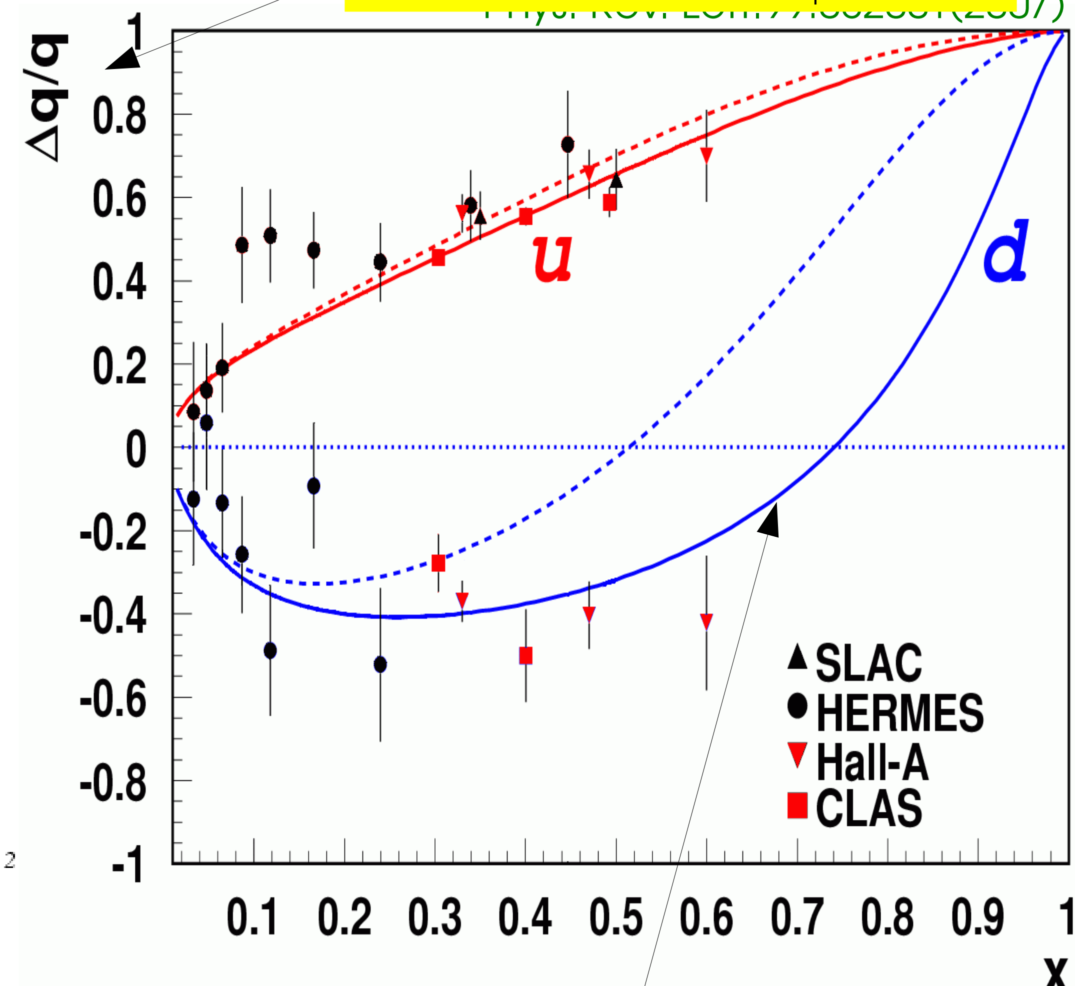
Add new hall
D
Upgrade magnets and power supplies
Add 5 cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
Add 5 cryomodules
A
B
C
Enhance equipment in existing halls

Nucleon Spin Structure in the Valence Quark Region

Polarized DIS and Nucleon Spin Structure

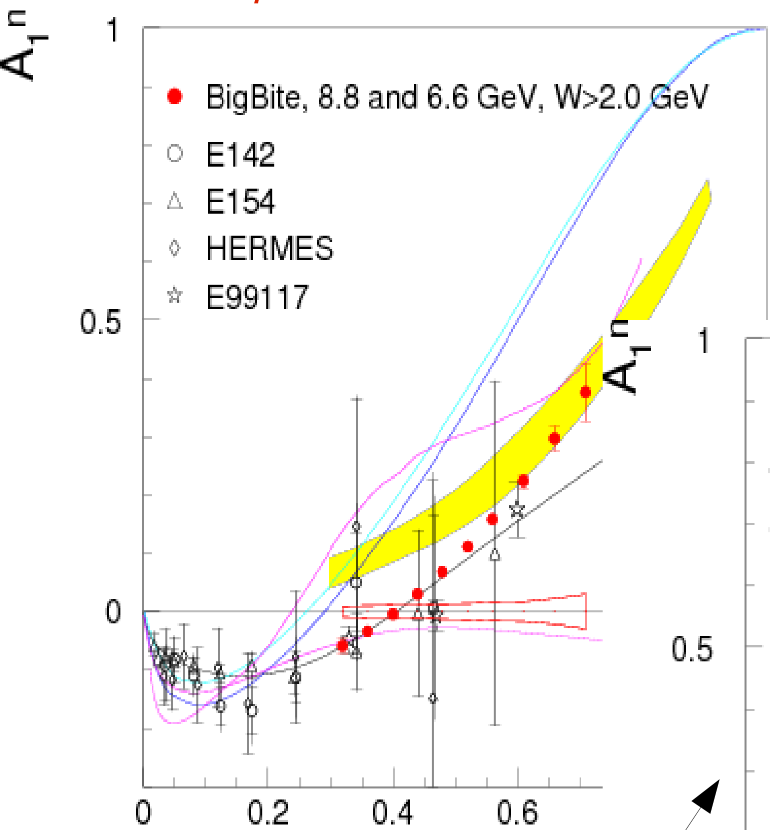
$$g_1(x) = \frac{1}{2}\Sigma e_i^2[q_i^{\uparrow}(x) - q_i^{\downarrow}(x)] = \frac{1}{2}\Sigma e_i^2[\Delta q_i(x)]$$



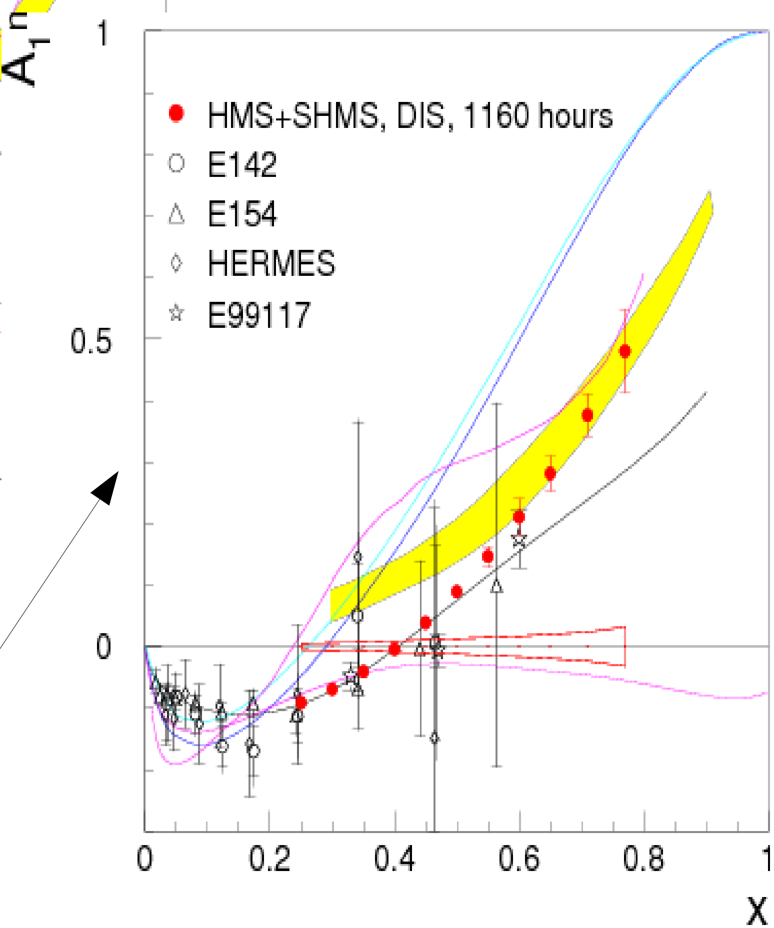


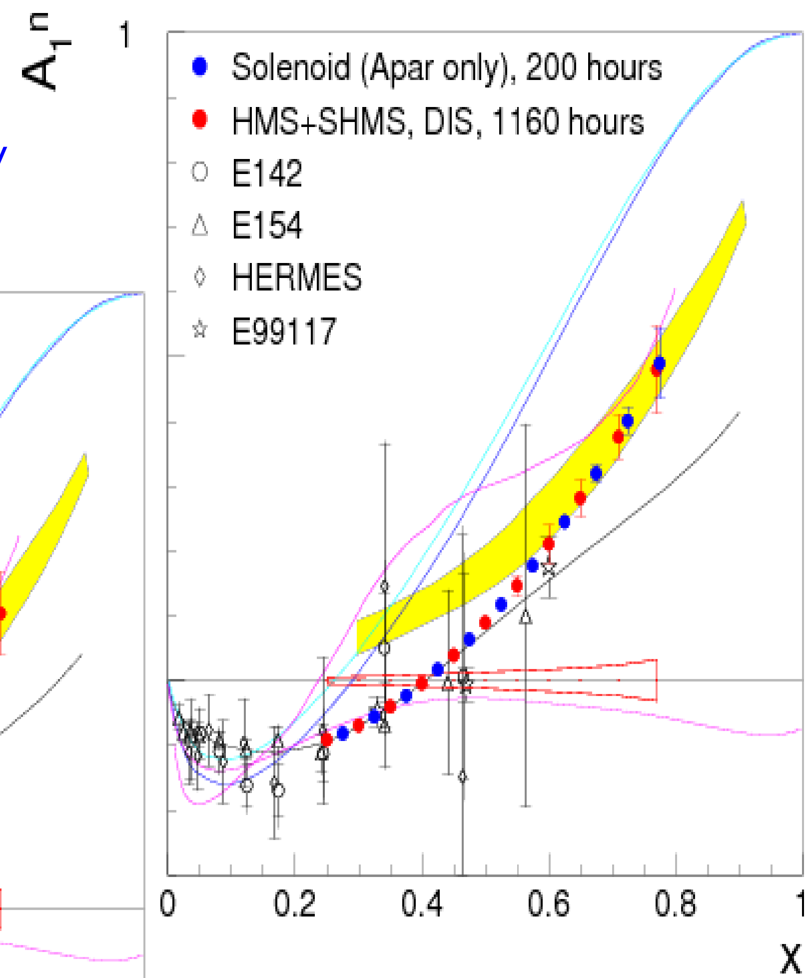
Will pQCD predictions (with quark OAM) work?

A_1^n in the Valence Quark Region at JLab 11 GeV



Hall C: PR12-06-110: conditionally approved



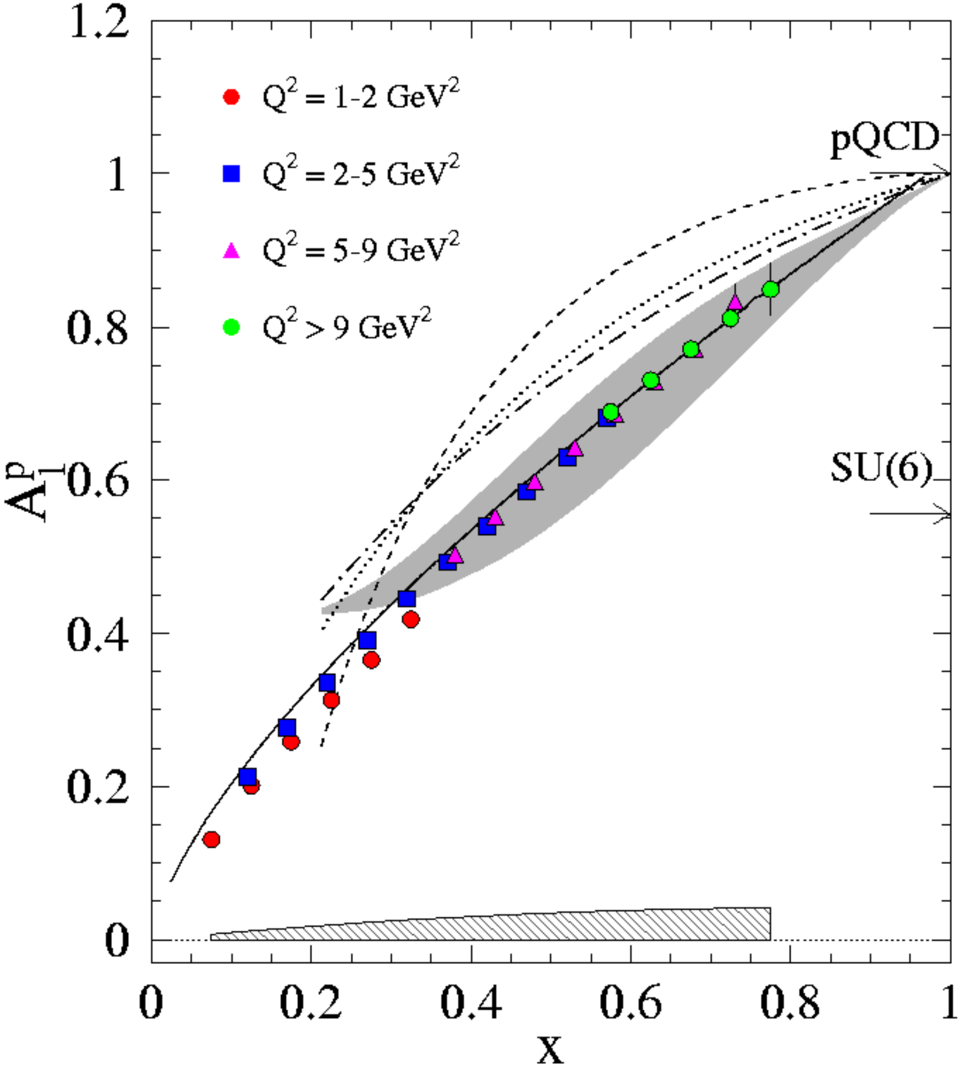


Hall A PR12-06-122: approved

Hall A+SOLID: to be proposed

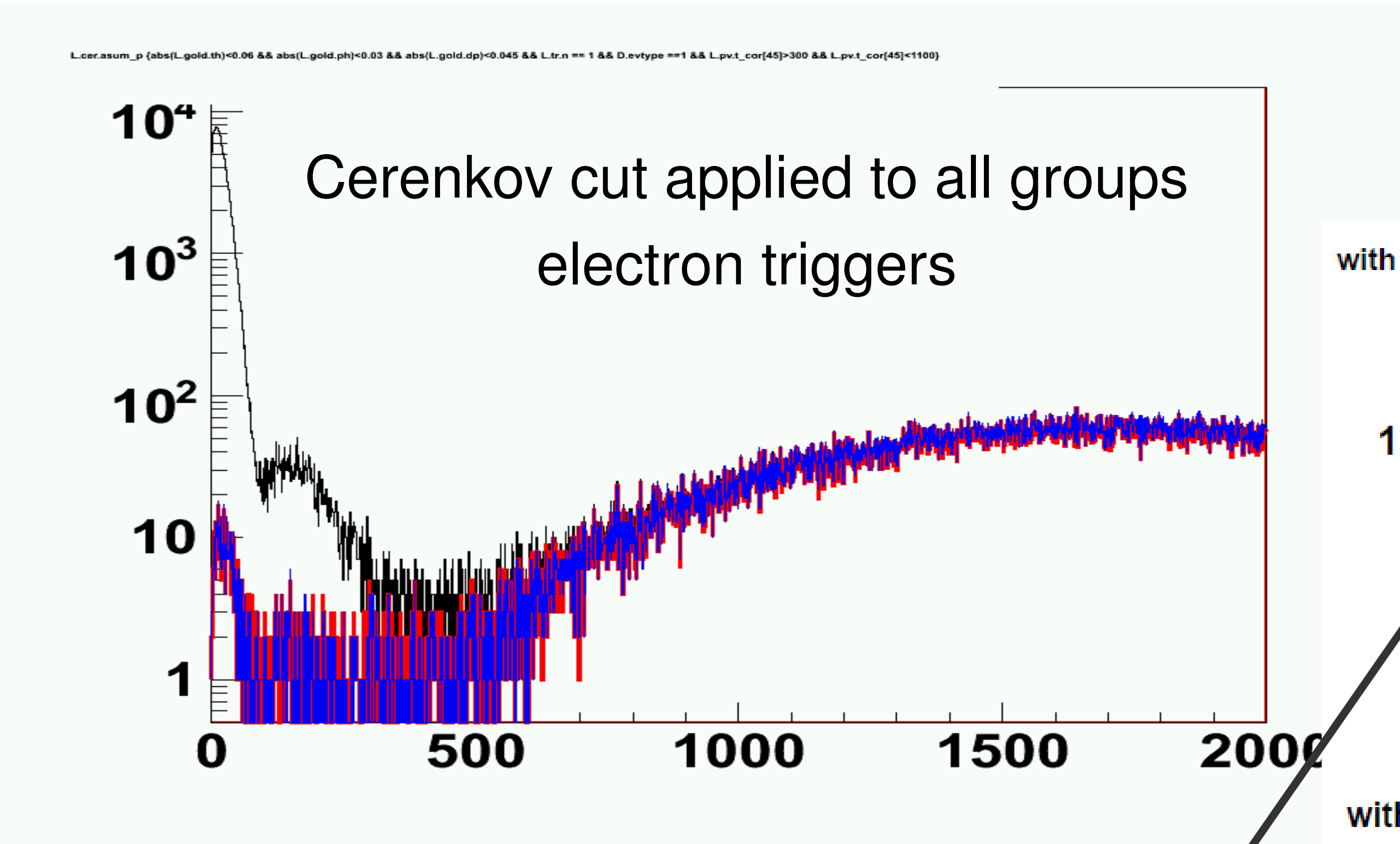
- To be rated August 2010

A_1^p at 11 GeV

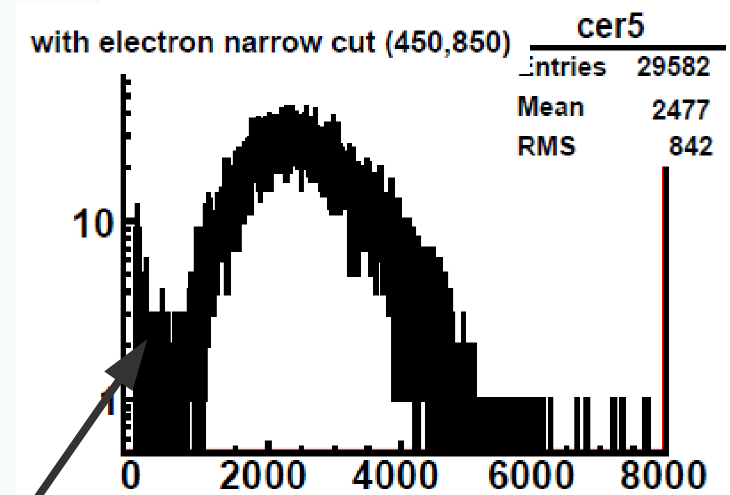


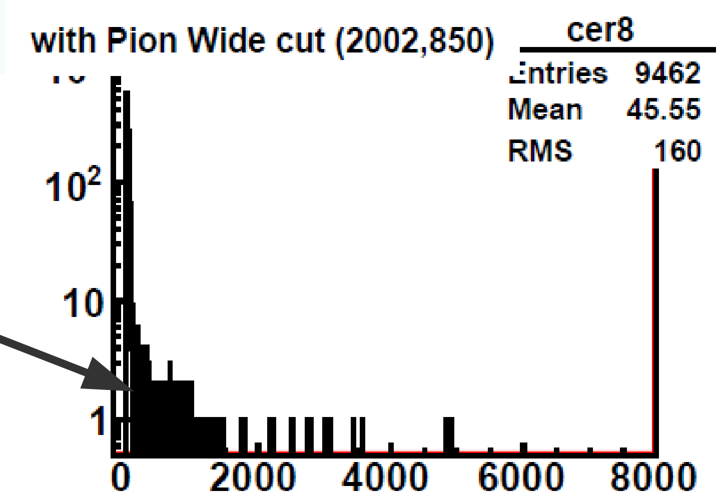
1.2
1
0.8
0.6
0.4
0.2
0
A_1^p
$Q^2 = 1\text{-}2\ GeV^2$
$Q^2 = 2\text{-}5\ GeV^2$
$Q^2 = 5\text{-}9\ GeV^2$
$Q^2 > 9\ GeV^2$
pQCD
SU(6)
0
0.2
0.4
0.6
0.8
1
x

Performance Check using fbTDC info in RHRS DAQ



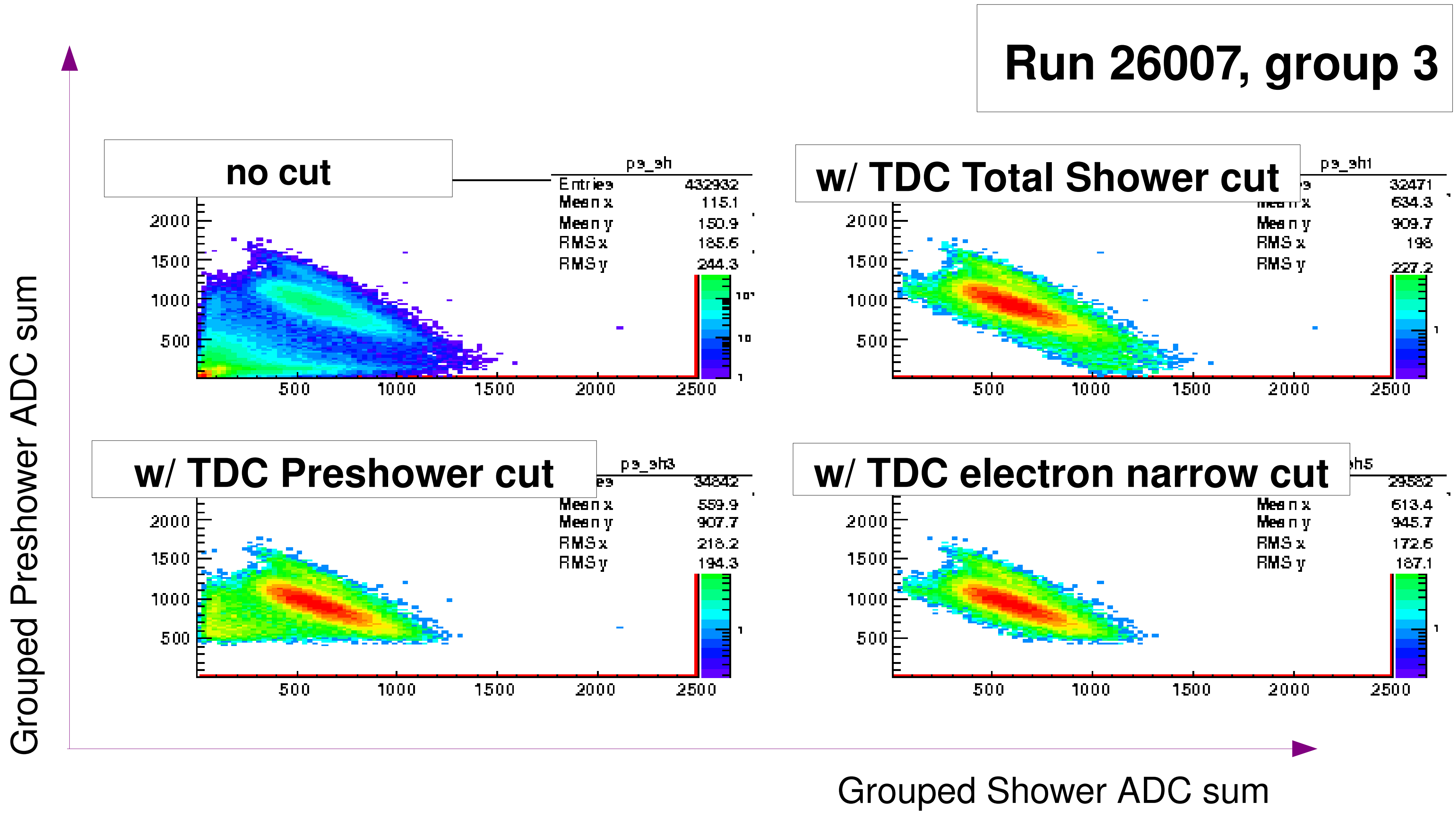
Run 26007





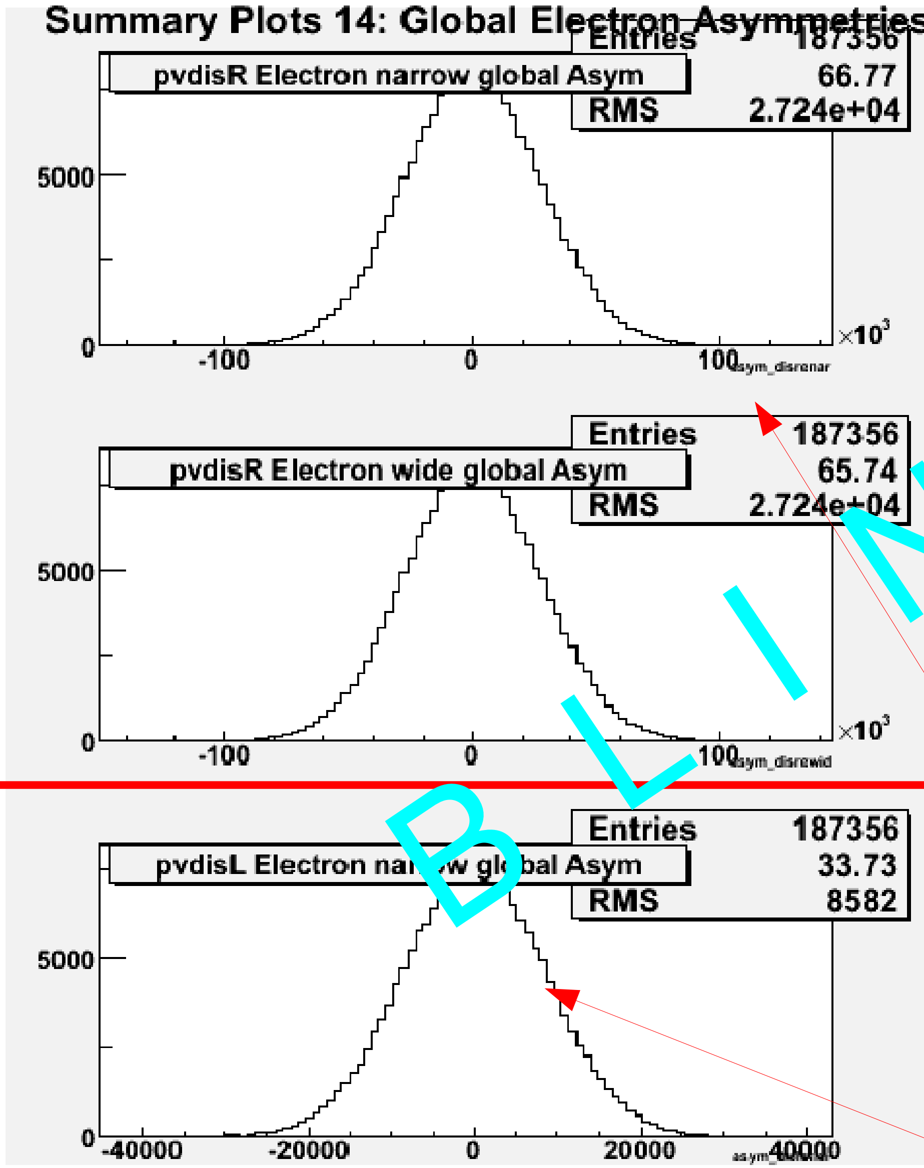
Group #3 electron
and pion triggers

Performance Check using fbTDC info in RHRS DAQ

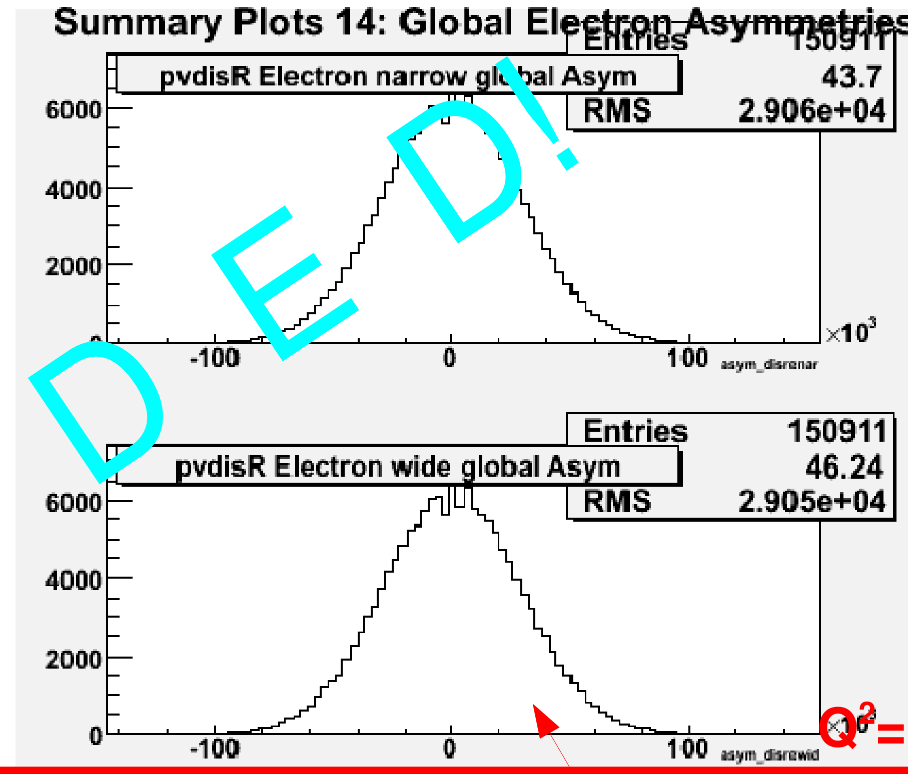


Transverse Beam Polarization (Dec. 2)

slug12



slug13



BLINDED!

Q^2=1.9

Q^2=1.1

$$\Delta A_T = \frac{2.724\text{E+4}}{\sqrt{187356}} \approx 63\ ppm$$

$$\Delta A_T = \frac{2.904\text{E+4}}{\sqrt{150911}} \approx 75\ ppm$$

$$\Delta A_T = \frac{8582}{\sqrt{187356}} \approx 20\ ppm$$

Deadtime Measurement

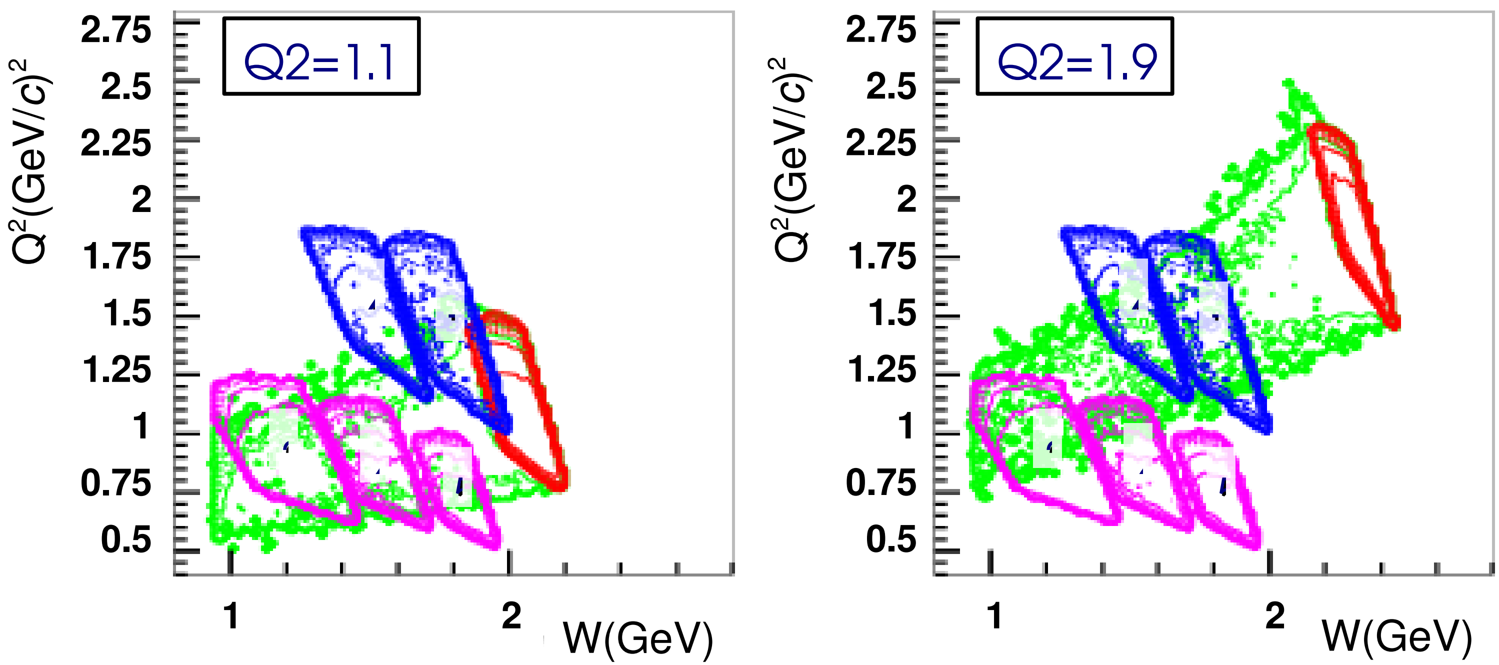
- Multiple methods planned:
  - tagger method (fractional loss + timing “pileup” correction);
  - rate scan method;
  - By observing TDC “deadzone”;
  - The DAQ consists of 2 “paths”, with discriminator width 30 and 100ns wide, respectively.

Deadtime Measurement

- Tagger method results:
  - Well understood, tagger "see" the same loss as electron signals;
  - Before Nov. 26, deadtime of all groups proportional to T1 rate, up to 1.4% loss on left arm. Error bar should be well below 0.5%.
  - After Nov. 26, deadtime proportional to group rates (Preshower or Total Shower).
    - "Narrow path" sees 50-70ns deadtime (dominated by input width);
    - "Wide path" sees 100-110ns deadtime (as expected).
    - Highest loss is for left arm at the lower Q^2 point: ~0.5%
    - Higher Q^2 point has much less deadtime: <0.05%.
    - Error bar should be a fraction of it (dominated by "pileup" correction").
- Rate scan method:
  - Need to know BCM nonlinearity.

Outlook (Resonance Runs: Dec. 17-22)

PVDIS at 6 GeV Simulation



adjusted to balance L/R HRS

Kine#	E (GeV)	θ	E' (GeV)	e- rate (KHz)	A_d (ppm)	$\Delta A_d/A_d$	Beam time (hours)
3	4.8	12.5	4.00(L)	1288	-68.7	5%	28.6
4	4.8	12.9	3.55(L)	888	-67.7	5%	42.6
~~5~~	~~4.8~~	~~12.9~~	~~3.10(R)~~	~~791~~	~~60.6~~	~~5%~~	~~59.8~~
6	4.8	19.0	2.77(R)	105	-120.7	8%	44.6

RES beam time: 4days

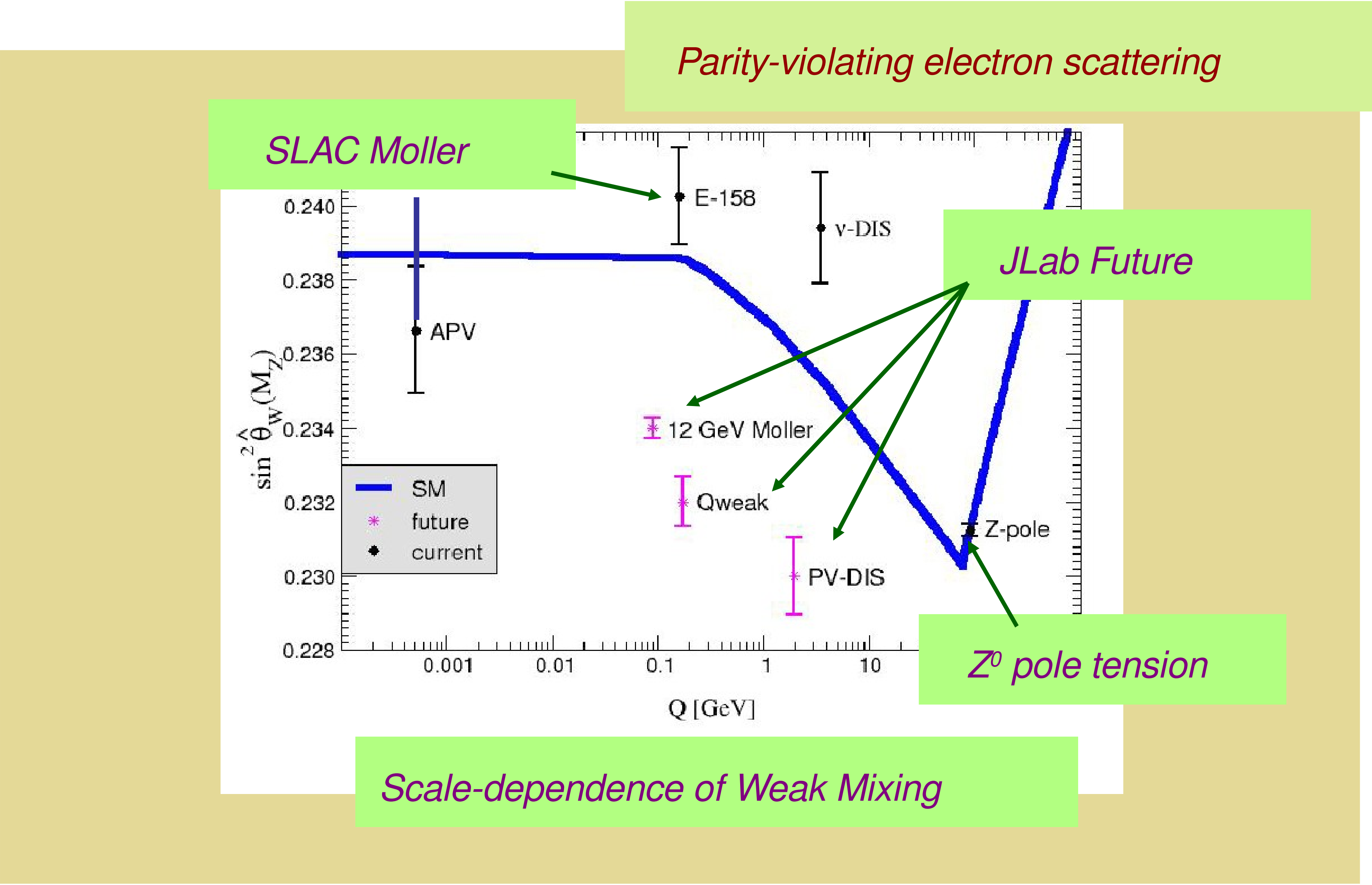
larger now by 50%

Expected Uncertainties on A_d

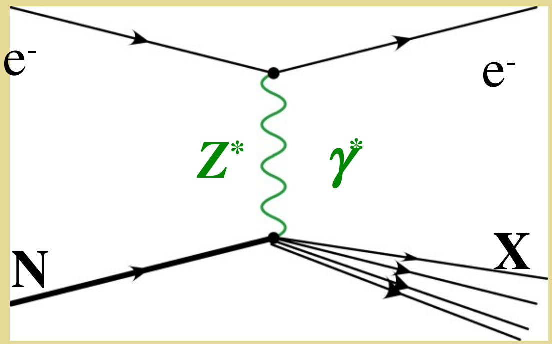
Source \ $\Delta A_d/A_d$	Q^2=1.1 GeV^2	Q^2=1.9 GeV^2
$\Delta P_b/P_b$=1%	1.0%	1.0%
Deadtime correction	0.3%	0.3%
Target endcap contamination	0.4%	0.4%
Target purity	<0.02%	<0.02%
Pion background	<0.2%	<0.2%
Pair production background	<0.2%	<0.2%
Systematics	1.36%	1.36%
Statistical	2.11%	2.09%
Total	2.52%	2.49%

now 5mil Al (was 3mil Be)

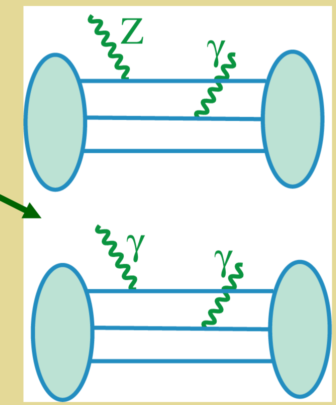
Weak Mixing in the Standard Model



Deep Inelastic PV: Beyond the Parton Model & SM



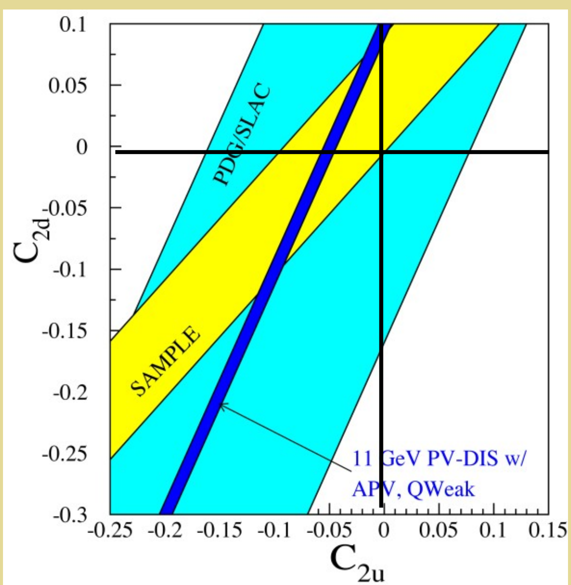
Higher Twist: qq and qqg correlations

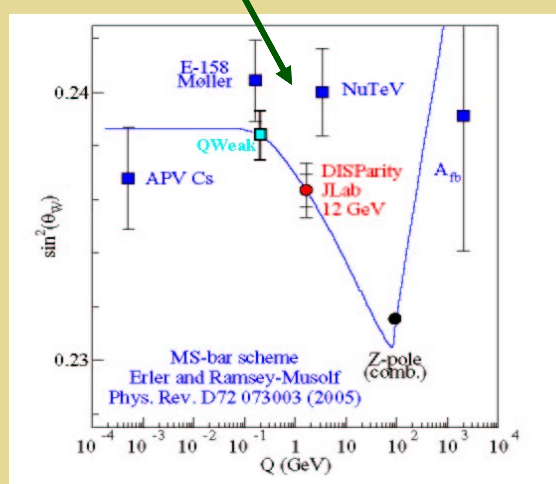


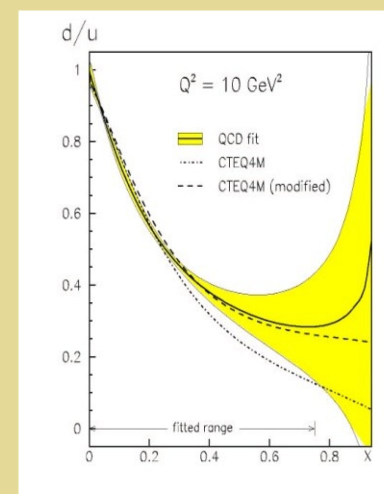
Charge sym in pdfs

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

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







Electroweak test: e-q couplings & $\sin^2\theta_W$

$d(x)/u(x)$: large x

Scorecard

	x	y	Q^2	p	d
Higher twist	Yes	No	Yes		X
Isospin	Yes	No	No		X
d/u	Yes	No	No	X	
New Physics	No	Yes	No		X

Apparatus Needed for PVDIS

Large Acceptance and High Luminosity

Large Angle Large Acceptance: Concept

JLab Upgrade

- Need high rates at high x

- *CW 90 μA at 11 GeV*
- *40-60 cm liquid H_2 and D_2 targets*
- *Luminosity > $10^{38}/cm^2/s$*

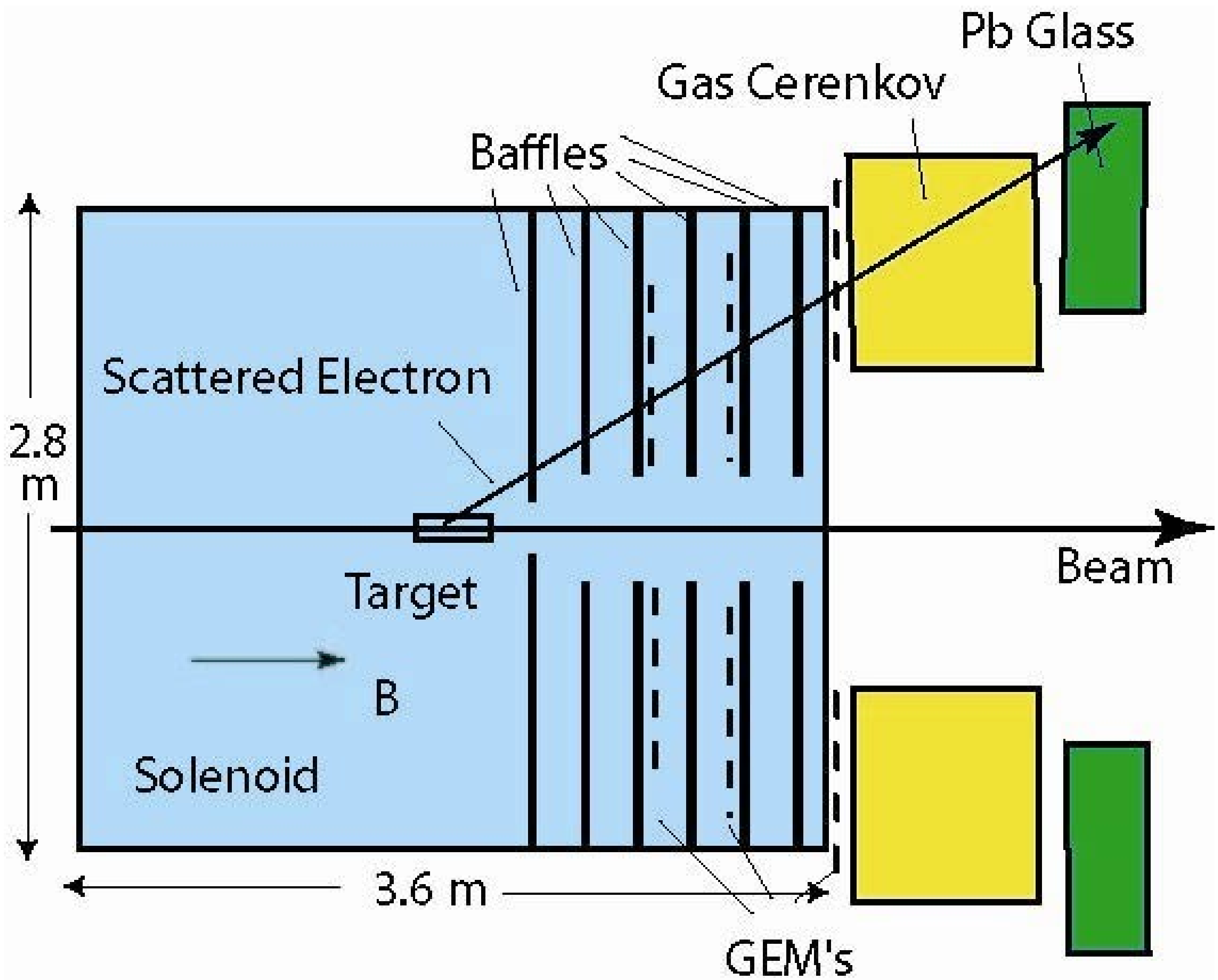
- For the first time: sufficient rates to make precision PV DIS measurements

- *solid angle > 200 msr*
- *Resolution<2%*
- *Count at 100 kHz*
- *online pion rejection of 10^2*

Need magnet to block γ's and low energy π's

Plan View of the Spectrometer

BaBar Solenoid?



Shashlyk (Shashlik) Calorimeter

- pi/e rejection $10^{(-2\sim-3)}$ at E=0.4~4 GeV/c based on energy resolution
- dE/E≤ 1.4+6.7%/sqrt(E(GeV))
- time resolution ≤1ns
- radiation hard
- can work in mag fields

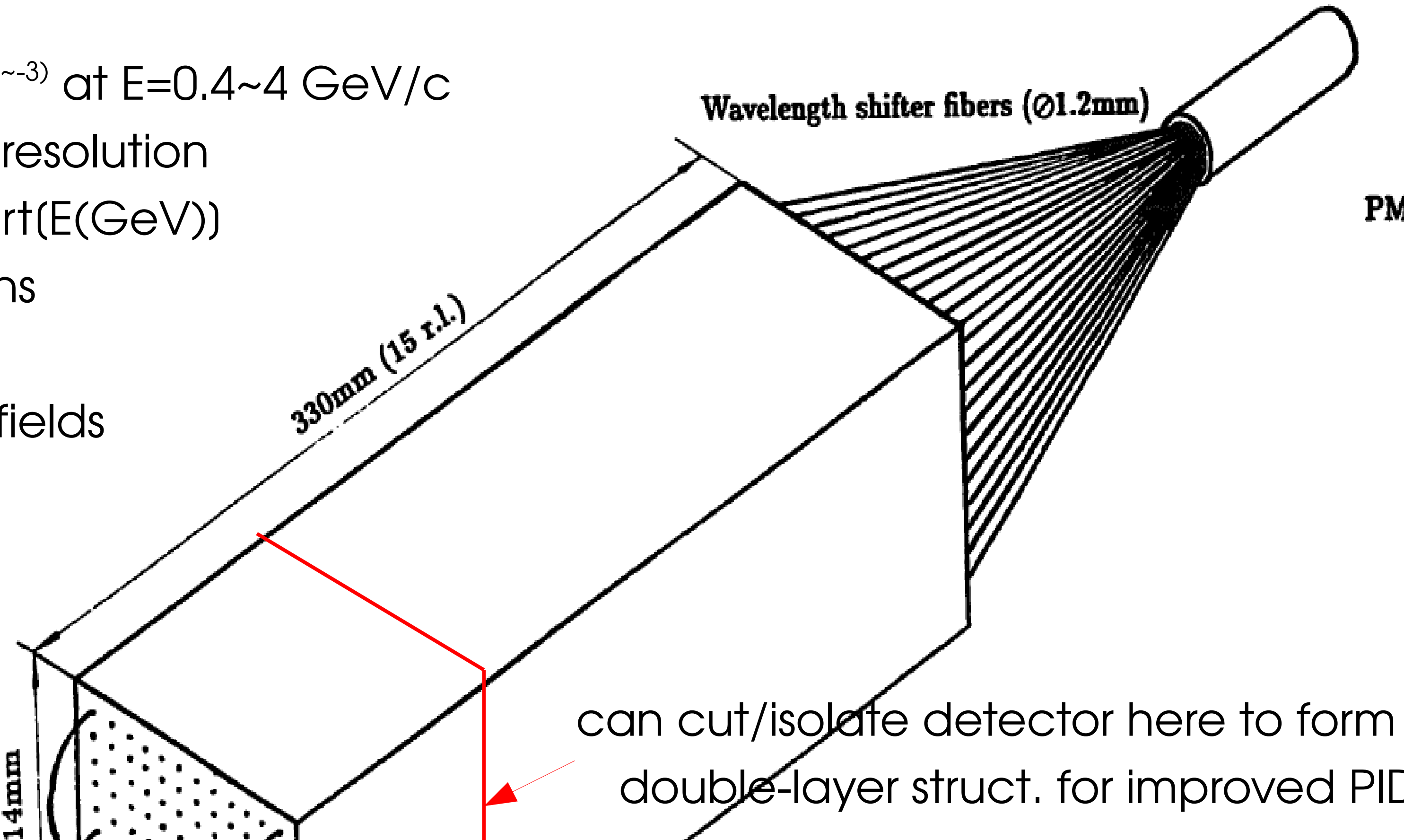


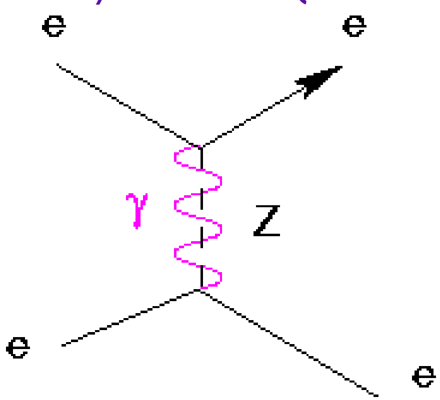
Fig. 1. Calorimeter module.

can cut/isolate detector here to form a double-layer struct. for improved PID

NIM A320, 144 (1992)

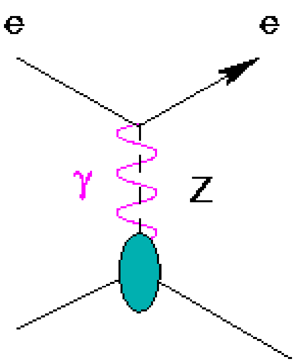
PV DIS and Other SM Test Experiments

E158/Moller (SLAC)



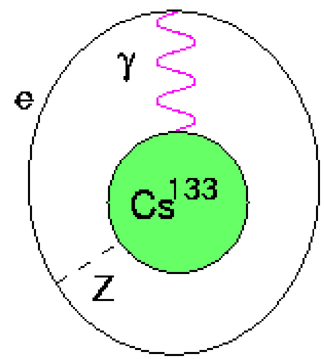
- Purely leptonic

Qweak (JLab)



- $2(2C_{1u}+C_{1d})$
- Coherent quarks in the proton

Atomic PV



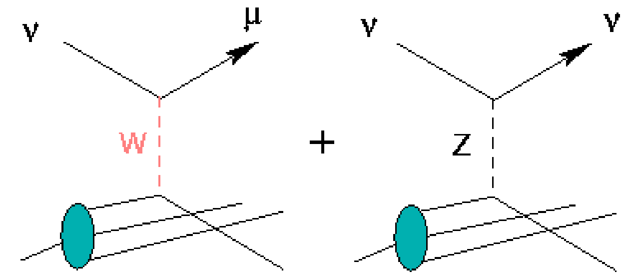
- Coherent Quarks in the Nucleus
- $-376C_{1u}-422C_{1d}$
- Nuclear structure?

Different Experiments Probe Different Parts of Lagrangian,

PVDIS is the only one accessing C_{2q}

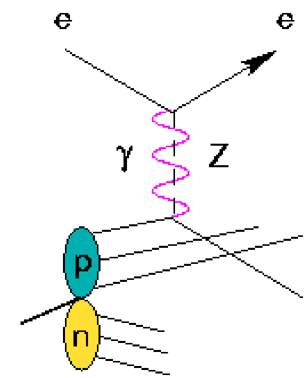
Cartoons borrowed from R. Arnold (UMass)

NuTeV (FNAL)



- Weak CC and NC difference
- Nuclear structure?
- Other hadronic effects?

PVDIS (JLab)



- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$
- Isoscalar quark scattering

Current Knowledge on Weak Coupling Coeffecients

$C_{1q} = g_A^e g_V^q$ $C_{2q} = g_V^e g_A^q$ $C_{3q} = g_A^e g_A^q$ J. Erler, M.J. Ramsey-Musolf, Prog. Part. Nucl. Phys. **54**, 351 (2005)

Facility	Process	Q^2	C_{iq} Combination	Result	SM Value
SLAC	e^--D DIS	1.39	$2C_{1u}-C_{1d}$	-0.90± 0.17	-0.7185
SLAC	e^--D DIS	1.39	$2C_{2u}-C_{2d}$	0.62± 0.81	-0.0983
CERN	$\mu^\pm$-D DIS	34	$0.66(2C_{2u}-C_{2d})+2C_{3u}-C_{3d}$	1.80± 0.83	1.4351
CERN	$\mu^\pm$-D DIS	66	$0.81(2C_{2u}-C_{2d})+2C_{3u}-C_{3d}$	1.53± 0.45	1.4204
MAINZ	e^--Be QE	0.20	$2.68C_{1u}-0.64C_{1d}+2.16C_{2u}-2C_{2d}$	-0.94± 0.21	-0.8544
Bates	e^--C elastic	0.0225	$C_{1u}+C_{1d}$	0.138±0.034	0.1528
Bates	e^--D QE	0.1	$C_{2u}-C_{2d}$	-0.042± 0.057	-0.0624
Bates	e^--D QE	0.04	$C_{2u}-C_{2d}$	-0.12± 0.074	-0.0624
JLab	e^--p elastic	0.03	$2C_{1u}+C_{1d}$	approved	-0.0357
	^{133}Cs APV	0	$-376C_{1u}-422C_{1d}$	-72.69±0.48	-73.16
	^{205}Tl APV	0	$-572C_{1u}-658C_{1d}$	-116.6±3.7	-116.8
Fit	e^--A	low	$C_{1u}+C_{1d}$	0.1358±0.0326	0.1528
All			$C_{1u}-C_{1d}$	-0.4659±0.0835	-0.5297
PVES			$C_{2u}+C_{2d}$	-0.2063±0.5659	-0.0095
Data			$C_{2u}-C_{2d}$	-0.0762±0.0437	-0.0621

new (R. Young, R. Carlini, A.W. Thomas, J. Roche, PRL 99, 122003 (2007) & priv. comm.)

A_1^n at 12 GeV in Hall C