SIDIS Spin-Flavor Decomposition Experiments in Halls A/C

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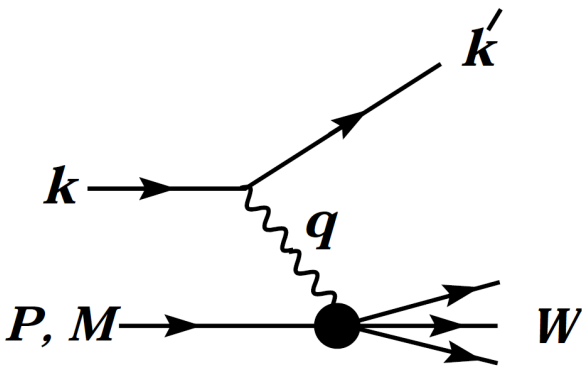
Workshop on High Luminosity Polarized Targets for the 12 GeV Era

6/18/2010

Outline:

- **DIS, SIDIS and Nucleon Spin Structure**
  - Inclusive data
  - Semi-inclusive data—HERMES, COMPASS, ...
  - pp data and ΔG
- **Flavor decomposition of unpolarized and polarized PDFs**
  - Global QCD analysis of polarized PDFs
- **Targets:**
  - p (NH_3, ...)
  - d (ND_3, LiD, ...)
  - n (^3He)
- **SIDIS spin-flavor decomposition using polarized targets @ JLab 12 GeV**
  - Hall A: BB+HRS and/or BB+SBS
  - Hall C: HMS + SHMS

Deep Inelastic Scattering (DIS)



- DIS reaction cross-section expressed in terms of ***structure functions*** describing the deviation of inelastic lepton-nucleon scattering from point-like scattering
- In the Bjorken limit, Q^2, $\nu \rightarrow \infty$, with x fixed, structure functions ***scale***, i.e., become independent of Q^2 at fixed x; indicating scattering from point-like nucleon constituents; i.e., ***quarks***

$$\frac{d^2\sigma}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\{y^2xF_1 + (1 - y - \frac{x^2y^2M^2}{Q^2})F_2$$

$$+ \lambda[-y(2 - y - 2x^2y^2\frac{M^2}{Q^2})xg_1 + 4x^3y^2\frac{M^2}{Q^2}g_2]\}.$$

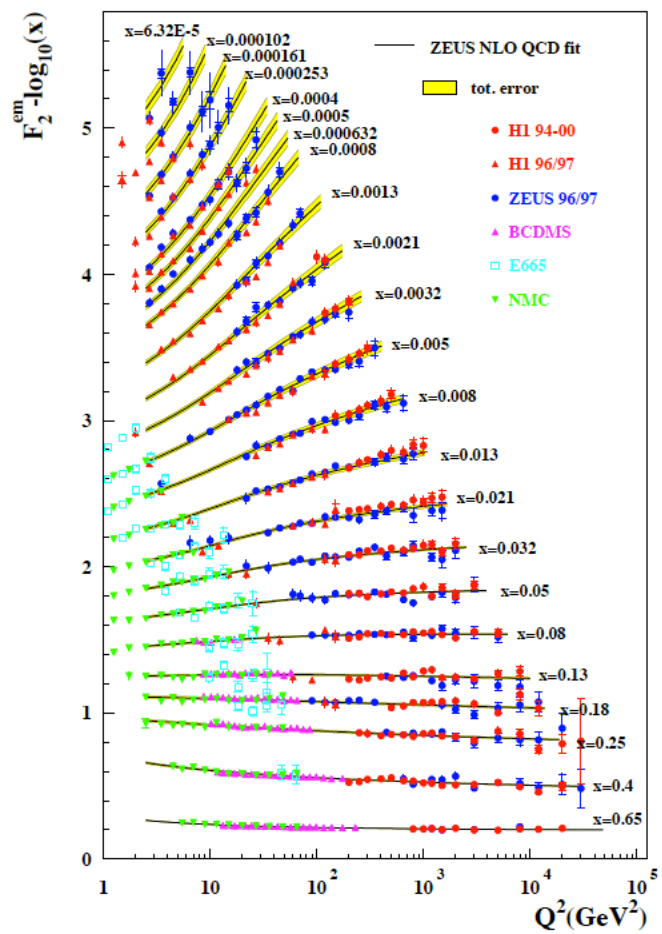
DIS in the quark-parton model

$$F_2 = 2xF_1 = x\sum_q e_q^2\left(q(x)+\bar{q}(x)\right)$$

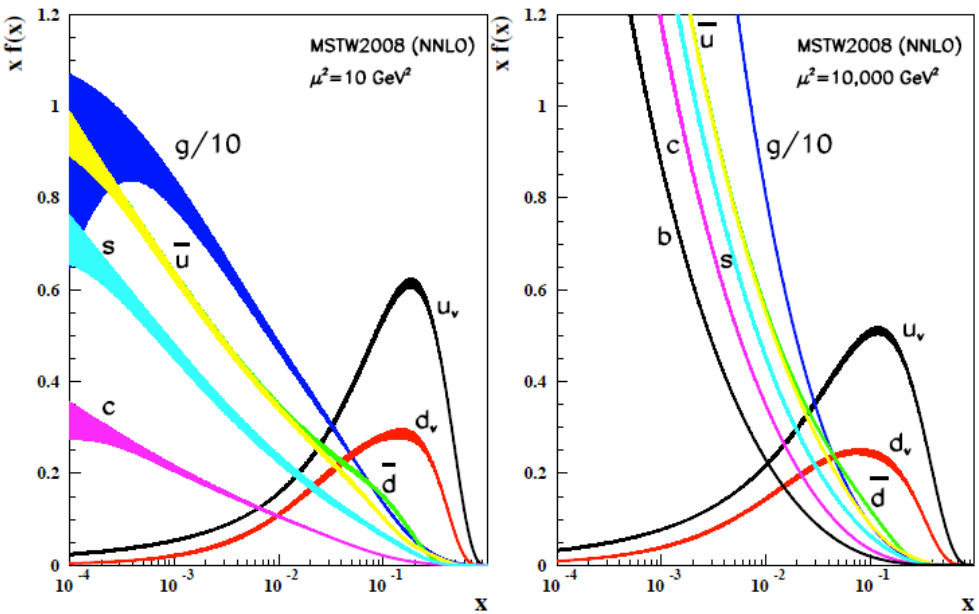
$$g_1 = \frac{1}{2}\sum_q e_q^2\left(\Delta q(x)+\Delta\bar{q}(x)\right)$$

$$g_2^{WW} = -g_1 + \int_x^1 g_1(y)\frac{dy}{y}$$

- Simplest naive quark-parton model: (e.m.) structure functions are charge-squared weighted incoherent sums of probability density for quark flavor q to carry momentum fraction x
- Callan-Gross relation between F_1 and F_2 implies $\sigma_L/\sigma_T \rightarrow 0$
- pQCD predicts logarithmic scaling violations: DGLAP evolution equations
- Right: F_2^p data with ZEUS NLO QCD fit



Extraction of unpolarized PDFs from global QCD analysis



MSTW2008 (arxiv:0901.0002) NNLO PDFs

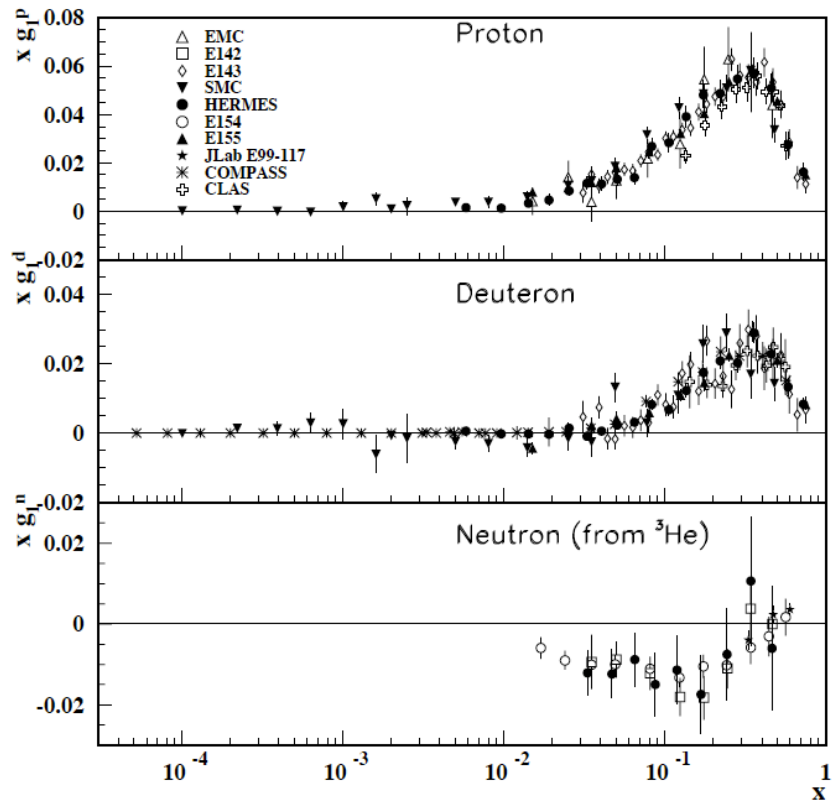
- Unpolarized parton densities rather well constrained from a wealth of structure function data over ~5 orders of magnitude in x and Q^2— now up to NNLO accuracy

Process	Subprocess	Partons	x range
$\ell^\pm\{p,n\} \to \ell^\pm X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
$\ell^\pm n/p \to \ell^\pm X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
$pp \to \mu^+\mu^- X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
$pn/pp \to \mu^+\mu^- X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
$\nu(\bar{\nu})\,N \to \mu^-(\mu^+)\,X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
$\nu\,N \to \mu^-\mu^+\,X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
$\bar{\nu}\,N \to \mu^+\mu^-\,X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
$e^\pm p \to e^\pm X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
$e^+ p \to \bar{\nu}\,X$	$W^+\{d,s\} \to \{u,c\}$	d, s	$x \gtrsim 0.01$
$e^\pm p \to e^\pm c\bar{c}\,X$	$\gamma^* c \to c,\ \gamma^* g \to c\bar{c}$	c, g	$0.0001 \lesssim x \lesssim 0.01$
$e^\pm p \to$ jet$+X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
$p\bar{p} \to$ jet$+X$	$gg, qg, qq \to 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
$p\bar{p} \to (W^\pm \to \ell^\pm\nu)\,X$	$ud \to W, \bar{u}\bar{d} \to W$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
$p\bar{p} \to (Z \to \ell^+\ell^-)\,X$	$uu, dd \to Z$	d	$x \gtrsim 0.05$

Inclusive DIS and Nucleon Spin Structure

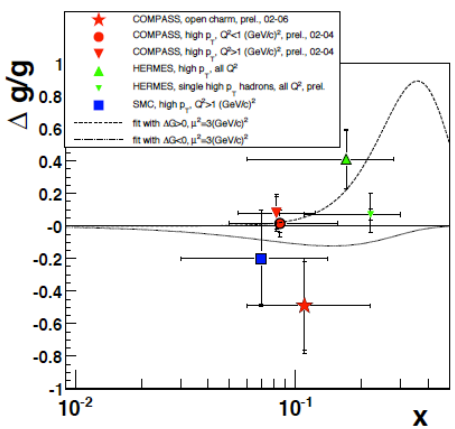
$$\frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} = A_{\parallel} \propto A_1 \approx \frac{g_1}{F_1}$$

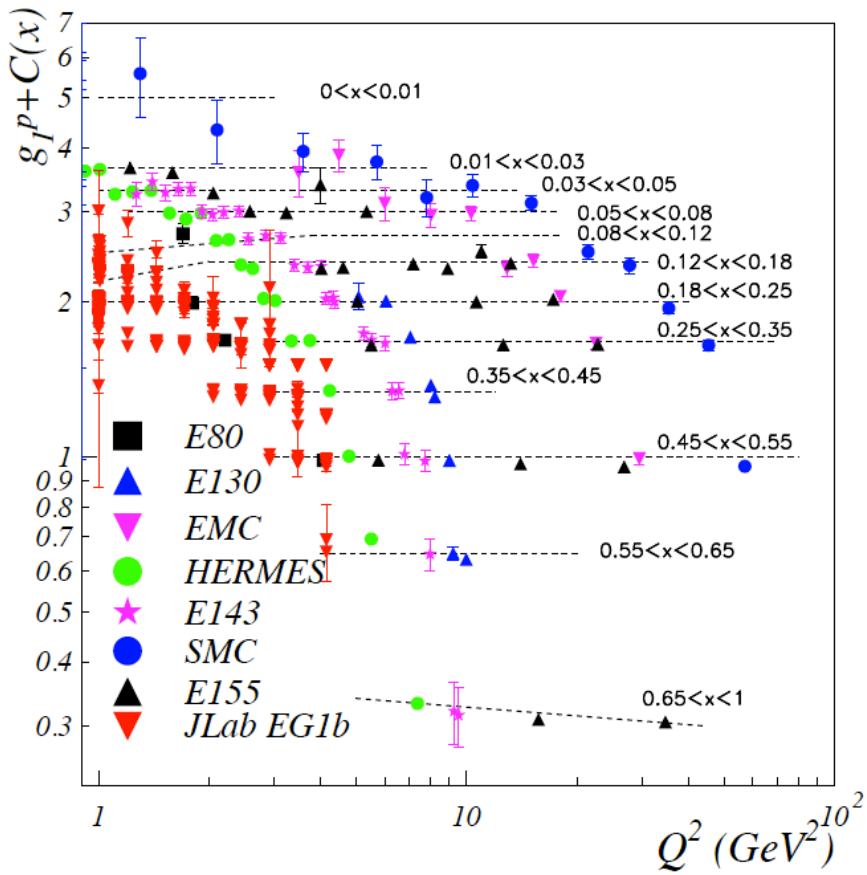
- Parallel-antiparallel asymmetry in the scattering of longitudinally polarized leptons on longitudinally polarized nucleons most sensitive to spin structure function g_1
- Virtually all data on $g_1^{p,n}$ obtained from fixed-target lepton scattering experiments with polarized beams/targets in the DIS region; Q^2, x coverage more limited than unpolarized data.
- Inclusive data only probes Δq+Δqbar
- Combined, proton, deuterium and ^{3}He data reasonably constrain u+ubar, d+dbar, and s+sbar
- Anti/sea quarks still poorly known



Inclusive DIS and Nucleon Spin Structure, cont.

- Q^2 range of polarized data ~2 orders of magnitude, with x range ~3-4 orders of magnitude
- "Mild" violations of scaling observed—extractions of gluon polarization from DIS data via Q^2 evolution have large uncertainties:





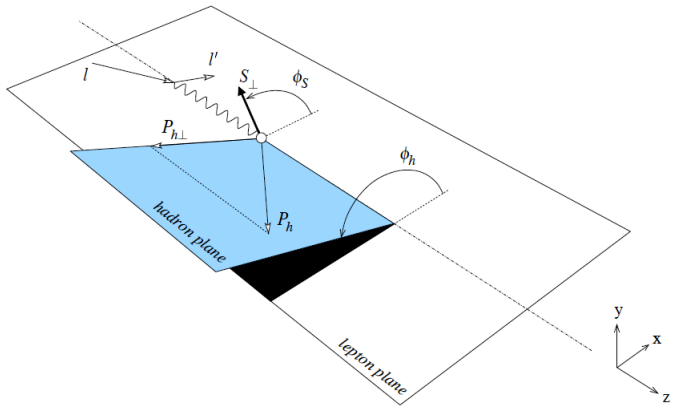
"Proton spin crisis"

$$\Sigma = \int_0^1 (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s}) \approx 0.3$$

- "Flavor singlet axial charge" Σ (a.k.a. a_0) is determined from 0th moment of g_1^p and experimentally known axial charge g_A and octet hyperon β decay constant "a_8"
- In the naive parton model, this is interpreted as the fraction of the proton spin carried by quarks and antiquarks.
- Original EMC value small, compatible with zero, in violation of Ellis-Jaffe sum rule
- Modern experimental value is close to 30% with experimental and theoretical uncertainties of a few percent
- **Recent reviews:**
  - **Thomas, PPNP 61, 219 (2008)**
  - **Kuhn, Chen, Leader, PPNP 63, 1 (2009)**

- **Where is the "missing" spin?**
  - Gluon polarization ΔG:
    - Indirect constraints from COMPASS g_1^d data, HERMES and COMPASS SIDIS data down to very low x and direct constraints from RHIC pp data constrain $|\Delta G| \leq 0.3$;
    - Unlikely to account for a significant fraction of the "missing" part
- **Quark+gluon orbital angular momentum**
  - Substantial evidence from a wide body of data suggest importance of OAM (another talk)

Semi-Inclusive DIS



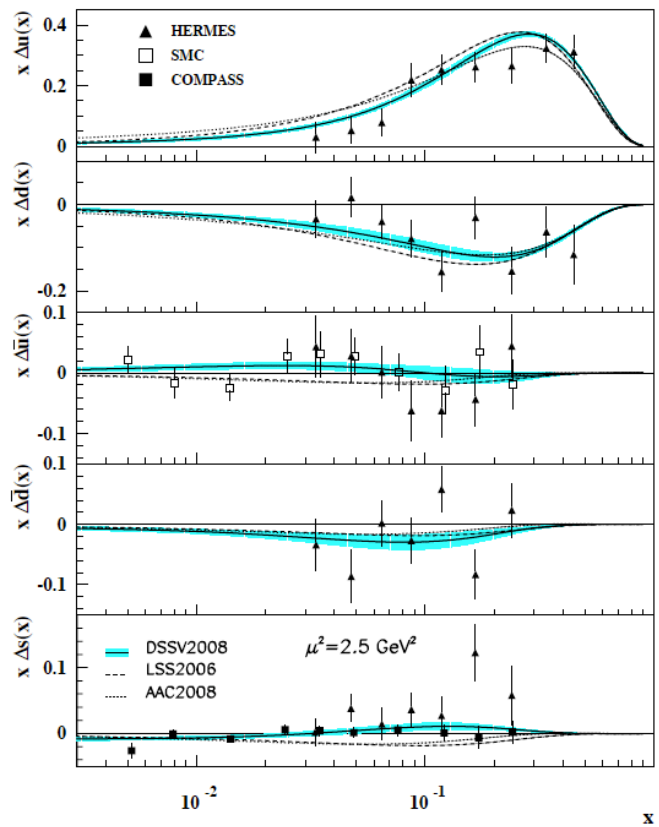
- Existing unpolarized SIDIS data included in NLO global analysis of fragmentation functions:
  - DSS2007 (PRD 75, 114010)
- Considerable and growing evidence for QPM interpretation of SIDIS data
- Still need to verify for JLab 12 (deferred PR-10-010)—using ideally CLAS12

- Detection of "leading" hadrons in lepton-nucleon DIS carrying a "large" (but not too large) fraction of the energy transfer presents the opportunity for "flavor tagging" the struck quark
- Different valence-quark content of different hadrons means different probabilities for production from hadronization of a given quark flavor q:
  - **"fragmentation functions"**
- In the QPM:

$$\frac{\left(\frac{d\sigma^h}{dxdydz}\right)}{\left(\frac{d\sigma}{dxdy}\right)} = \frac{\sum_q e_q^2 q(x) D_q^h(z)}{\sum_q e_q^2 q(x)}$$

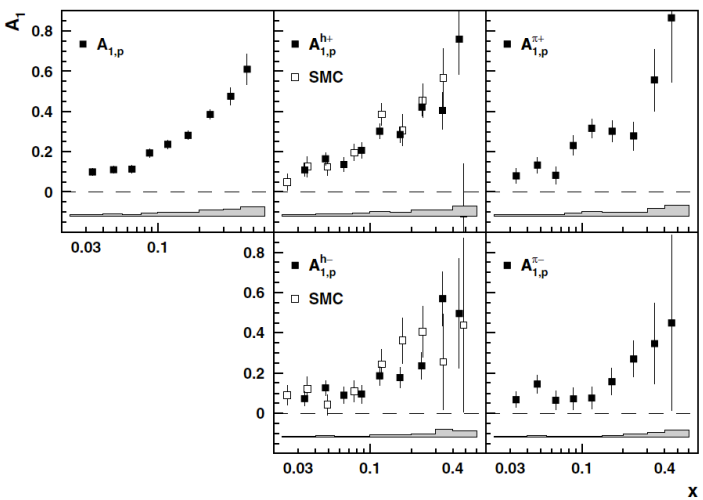
Flavor-separated helicity PDFs using SIDIS

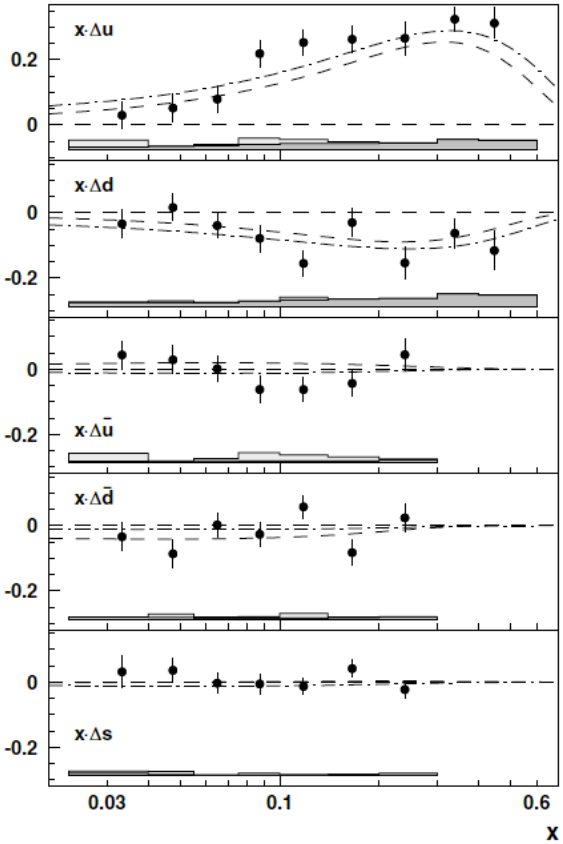
• PDG (right): comparison of polarized u, d, ubar, dbar extracted from HERMES +COMPASS+SMC data compared to various global analyses



HERMES spin-flavor SIDIS data

- A_1^h asymmetries from polarized p and d internal polarized gas targets
- h = $\pi^\pm$, $h^\pm$ for proton, $\pi^\pm$, $K^\pm$, $h^\pm$ for deuteron
- Insufficient statistics to separate kaons from hydrogen
- LO analysis using “purity method”





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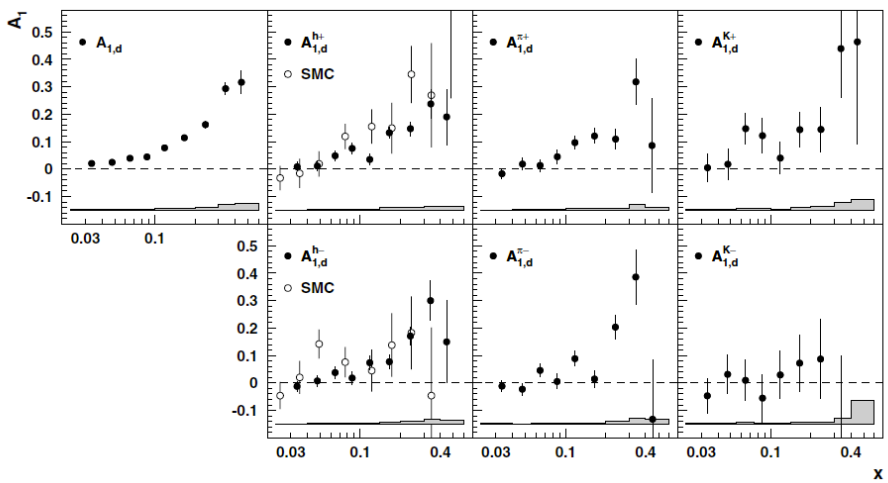
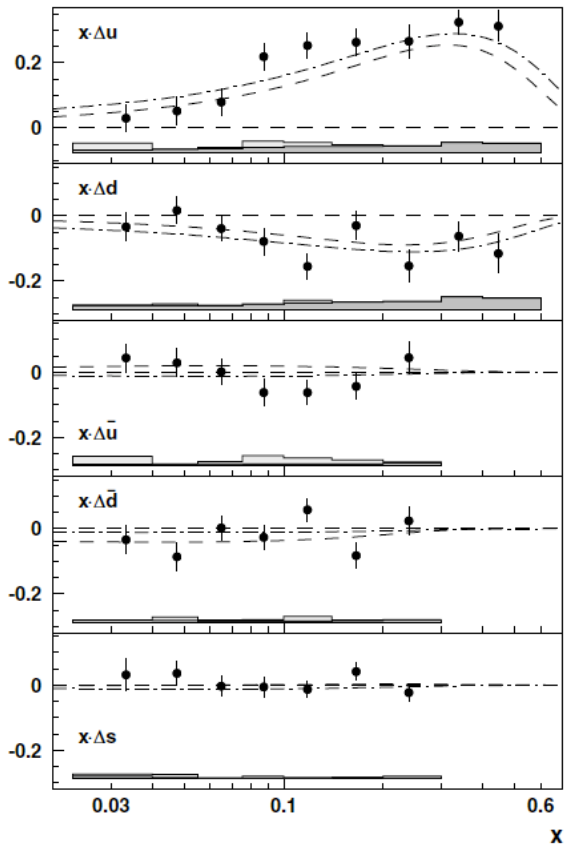
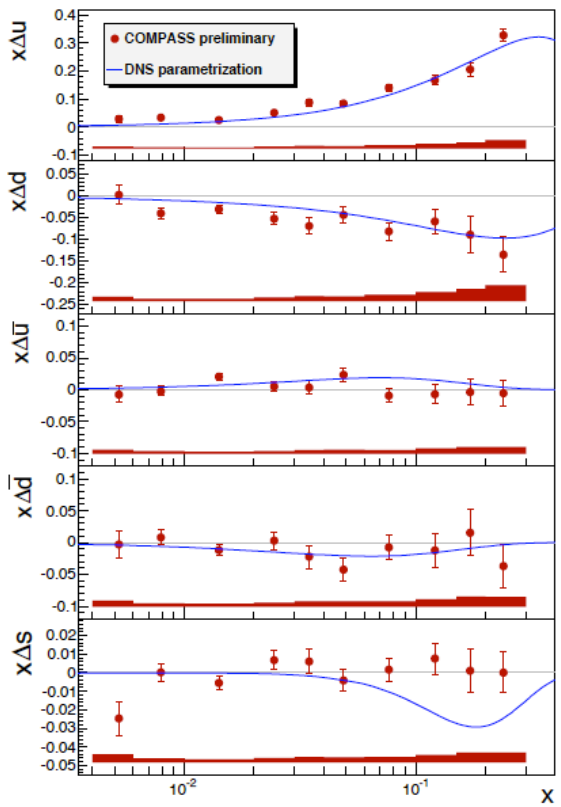
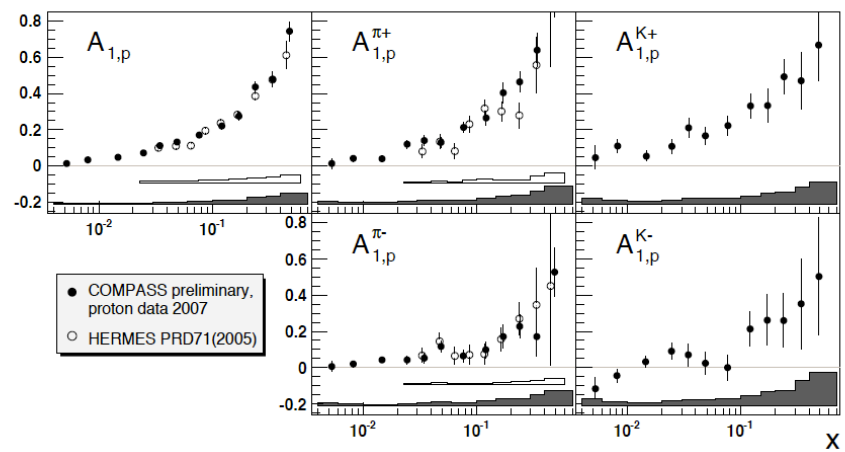




Preliminary COMPASS spin-flavor separation data



- Data for x<0.3, muons on polarized solid NH_3
- Unlike HERMES, also extracted $A_1^{p,K\pm}$
- u and d quark polarizations compatible with existing global analyses in measured x range
- sea quark polarizations compatible with zero over full measured range
- Also LO extraction of helicity PDFs

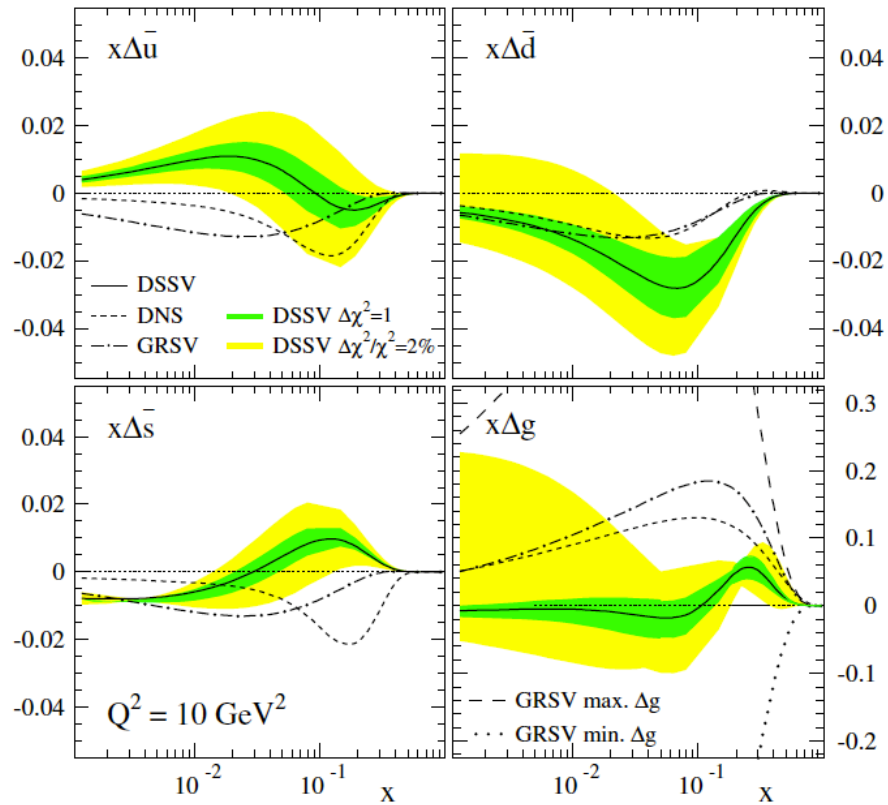


Global NLO QCD analysis of polarized PDFs: DSSV 2008

- De Florian, Sassot, Stratmann and Vogelsang:
  - PRL 101, 072001 (2008)
  - PRD 80, 034030 (2009)
- Included inclusive DIS, SIDIS, and pp data:

TABLE I. Data used in our analysis [2,4], the individual χ^2 values, and the total χ^2 of the fit. We employ cuts of Q, $p_T >$ 1 GeV for the DIS, SIDIS, and RHIC high-p_T data.

Experiment	Data fitted	χ^2
DIS: EMC, SMC, COMPASS, E142, E143, E154, E155, HALL-A, CLAS, HERMES	234	186
SIDIS $\pi^\pm$, $K^\pm$, $h^\pm$: SMC, HERMES, COMPASS	189	166.5
p-p 200 GeV, π^0: PHENIX (in part prel.)	20	21.3
p-p 62 GeV, π^0: PHENIX (prel.)	5	3.1
p-p 200 GeV, jet: STAR (in part prel.)	19	15.7
TOTAL:	467	392.6



Strange quark polarization and SIDIS Kaon production

- **Paraphrasing DSSV PRD 80, 034030 (2009):**
  - Fits to inclusive DIS data favor a “large” and negative strange quark polarization
  - DSSV fit favors a ***positive*** Δs at large x and negative at small x
    - Δs not constrained by data at small x; constraints from sum rules, beta decay, flavor SU(3)...
  - Within leading-twist, NLO framework employed by DSSV, kaon SIDIS data favor prefer small, ***positive*** Δs at medium x
  - Inclusive DIS and β decay constraints demand a ***negative*** integral of Δs; forces fit to turn negative at low x
  - Questions on reliability of kaon SIDIS data interpreted in a leading-twist framework, for both fragmentation functions and strangeness PDFs.
    - More kaon SIDIS data needed at lower x and at higher Q^2 for presently available x: natural for an EIC. What can we do @ JLab 12 GeV?
  - If first moment of Δs turns out to be small; large flavor SU(3) breaking implied
  - If flavor SU(3) not significantly broken, expect either Δs turns large and negative at low x, or that existing kaon SIDIS data are not reliable for extraction of Δs

Issues for SIDIS A_{LL} Measurements at JLab 12 GeV

- **Goal: develop a program of longitudinally polarized SIDIS measurements with maximal impact to global PDF analyses**
- **Issues:**
  - Targets:
    - luminosity
    - polarization
    - dilution
  - Detectors:
    - Rate capability: detectors and DAQ system
    - Acceptance
    - Resolution
    - Particle ID
- **Hall A vs. Hall C?**

Three-target measurement in Hall A and/or C

- **Proposal: in identical detector configuration, measure SIDIS asymmetries using three targets with 11 GeV beam.**
  - Maximize number of observables
  - Minimize point-to-point systematic uncertainties
- **Consider "existing" target technology as a baseline**
- **Targets:**
  - Polarized proton: NH_3 in UVA setup
  - Polarized deuterium: ^{6}LiD in UVA setup
  - Polarized ^{3}He (with GEN-II specs)
- **Hall A with BB as electron arm, SBS as hadron arm**
- **Hall C with HMS as electron arm, SHMS as hadron arm**

Assumptions on UVA Target Performance

- **NH_3:**
  - 80 nA, 85% polarized beam
  - 3 cm solid tgt. thickness
  - (Effective polarized proton luminosity approaching 10^{35} $cm^{-2}s^{-1}$)
  - 80% in-beam polarization
- **^{6}LiD:**
  - Same beam parameters
  - Same target thickness
  - 22% in-beam polarization
- **Nominal beam time:**
  - 30 days NH_3
  - 40 days 6LiD
  -

Assumptions on ^{3}He Target Performance (~GEN-II)

- 85% polarized beam at 40 μA
- 60 cm ^{3}He at 10 atm/amg
- 65% in-beam polarization
- Only assumptions not already achieved in previous experiments are high beam current (40 μA), and longer 60 cm cell (40 cm previously)
- GEN-II target being designed for 60+ μA
- Nominal 20 days beam-time assumption
- If all three targets run consecutively in the same kinematics/detector configuration, significant planning/installation effort to "switch out" UVA target for 3He target
- Logistically, may need to split into two separate proposals?

Hall A Setup: Kinematics

- BB @ 25 degrees
- SBS @ 7.5 degrees
- .1 < x < .6
- 2 < Q^2 < 8
- 2.4 < W < 4.2
- For central p_h, θ_h:
  - 1.6 < W' < 3.3
  - 0.4 < z < 0.6
- Stay in DIS region with large Q, W
- Avoid exclusive/resonance region via large W'
- large x_F insures dominance of current fragmentation
- Center hadron arm along the q-vector; i.e., $p_T^h = 0$

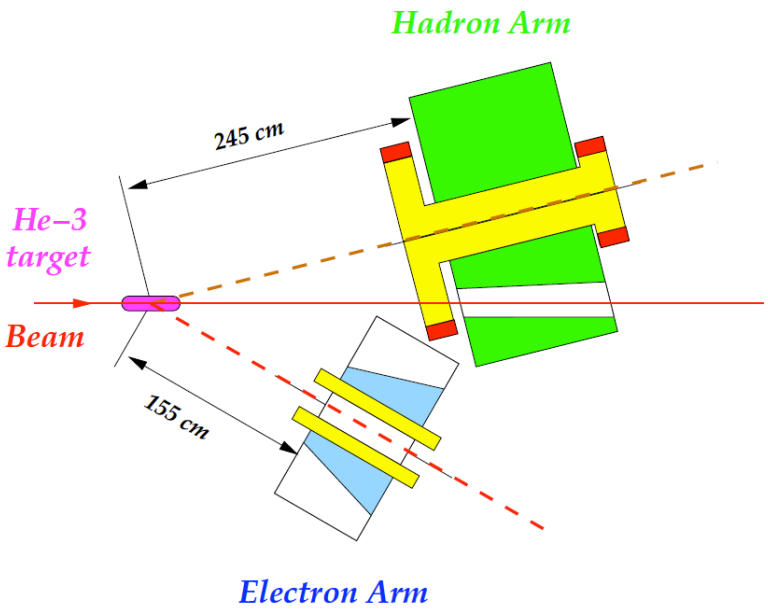
1 Choice of kinematics, rates and statistical uncertainties

E′ GeV	θ_e deg.	x	W GeV	Q^2 GeV^2	θ_q deg.	z_π	p_h GeV/c	W'_π GeV	η^π_{cm}	x^π_F
						$\theta_h = 7.5°$				
1.000	25.000	0.110	4.193	2.061	2.40	0.40	4.00	3.25	1.48	0.38
1.200	25.000	0.135	4.098	2.473	2.93	0.41	4.00	3.16	1.57	0.39
1.400	25.000	0.160	4.001	2.886	3.48	0.42	4.00	3.08	1.67	0.40
1.600	25.000	0.187	3.902	3.298	4.05	0.43	4.00	2.99	1.79	0.41
1.800	25.000	0.215	3.799	3.710	4.64	0.44	4.00	2.90	1.92	0.43
2.000	25.000	0.244	3.694	4.122	5.26	0.44	4.00	2.80	2.06	0.44
2.200	25.000	0.275	3.586	4.535	5.89	0.45	4.00	2.71	2.21	0.45
2.400	25.000	0.307	3.474	4.947	6.56	0.47	4.00	2.61	2.35	0.46
2.600	25.000	0.340	3.359	5.359	7.25	0.48	4.00	2.50	2.43	0.48
2.800	25.000	0.375	3.240	5.771	7.96	0.49	4.00	2.39	2.40	0.49
3.000	25.000	0.412	3.116	6.184	8.70	0.50	4.00	2.28	2.26	0.50
3.200	25.000	0.451	2.987	6.596	9.48	0.51	4.00	2.16	2.05	0.52
3.400	25.000	0.491	2.852	7.008	10.29	0.53	4.00	2.03	1.84	0.53
3.600	25.000	0.534	2.710	7.420	11.12	0.54	4.00	1.89	1.62	0.54
3.800	25.000	0.580	2.561	7.833	12.00	0.56	4.00	1.74	1.42	0.54
4.000	25.000	0.628	2.402	8.245	12.91	0.57	4.00	1.58	1.23	0.55

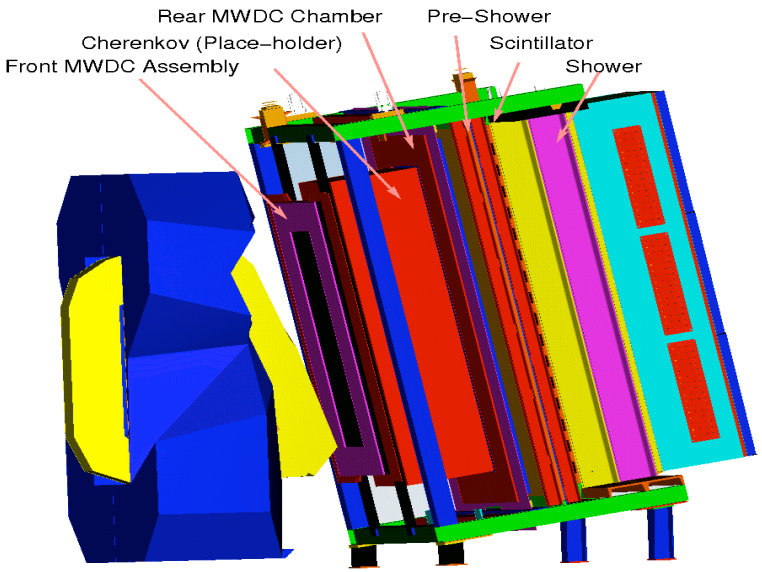
Table 1: The nominal kinematics for the central BigBite angle of 25° and SBS angle of 7.5°. The SBS momentum acceptance is assumed to be 3.0 GeV/c to 5.0 GeV/c, with the nominal centrual value (p_{SBS} = 4.00 GeV/c). The central z and W' values are also listed. Data of all x-bins will be collected simultaneously.

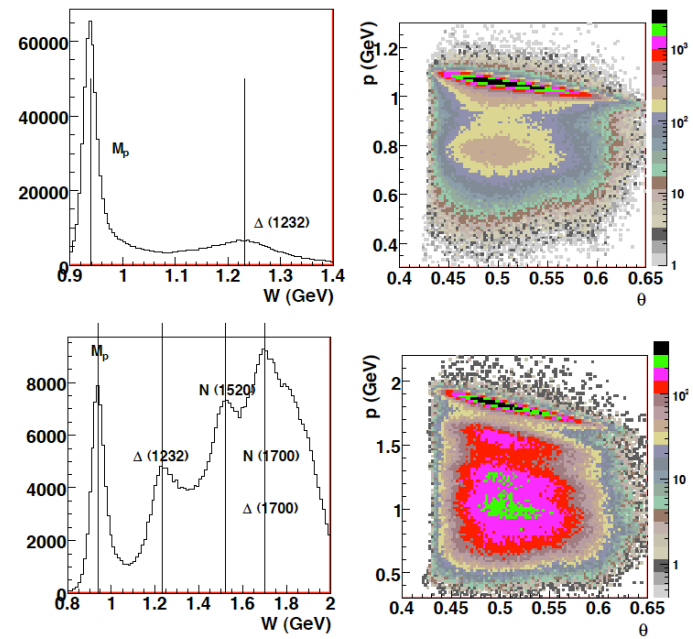
Hall A Setup: Spectrometers

- Reaction is the same as conditionally approved BB+SBS transversity proposal PR12-09-018, with similar resolution/PID requirements
- Highly similar kinematics for BigBite
- **Need smaller angle for SBS:**
    - In contrast to transversity measurements, where the interesting physics is expected to be found at large p_T, for spin-flavor decomposition, we center the hadron arm along the q-vector at p_T=0 in the interest of maximizing SIDIS statistics



BigBite Spectrometer

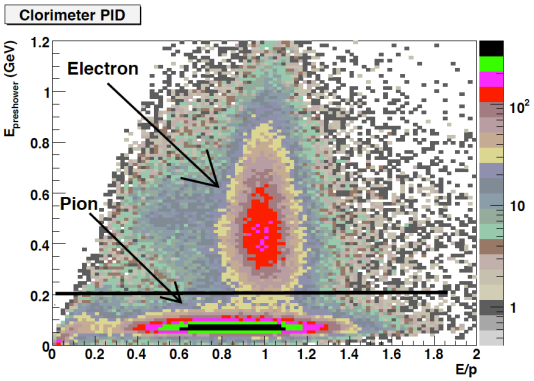


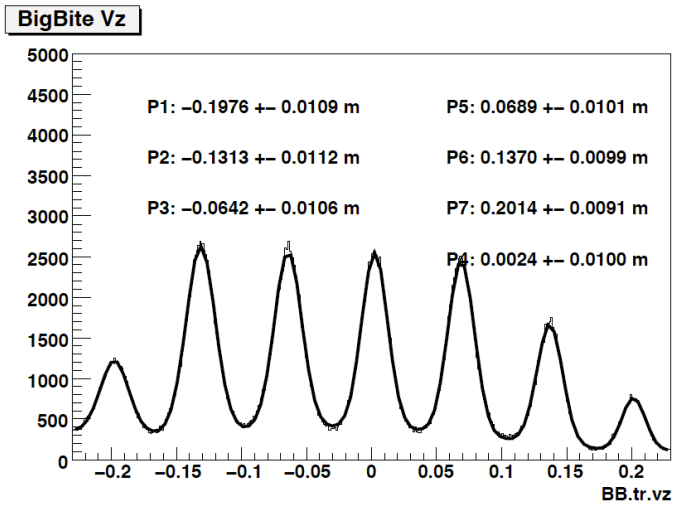


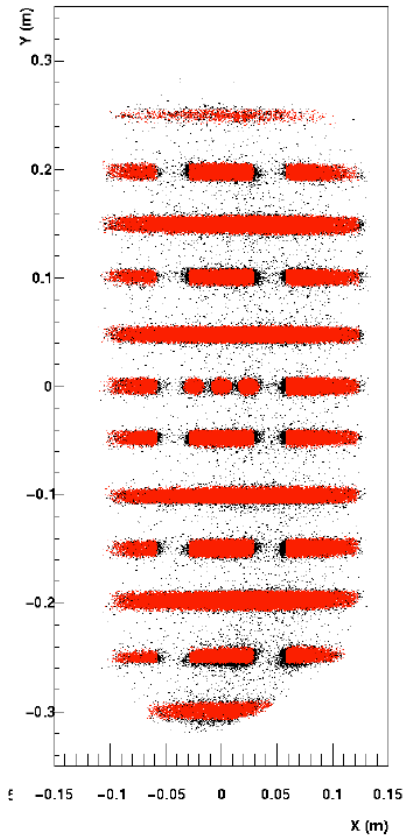
- BigBite performance in "electron-mode" well characterized in E06-010
- Detailed optics calibration by X. Qian; used to develop BigBite model for SIMC

BigBite momentum calibration in E06-010 for 1.2 GeV (1-pass) and 2.4 GeV (2-pass) beam using p(e,e')p

BigBite, continued...







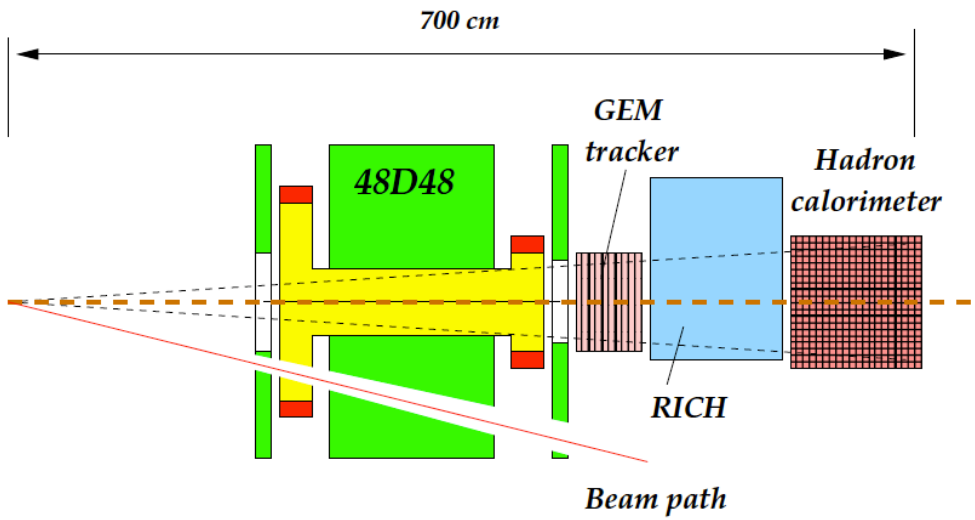
- Electron PID using preshower and shower E/p

- Vertex calibration using multifoil
- Angle calibration using sieve

BigBite, continued...

- **Planned improvements for GEN-II:**
  - Replacement of first two MWDCs with large-area GEM chambers to cope with higher rates (due to higher luminosity)
  - GEMs improve resolution at higher momenta; expect dp/p ~ 0.5% at p=3-4 GeV.
- **As this proposal assumes effectively the GEN-II target, we also assume the GEN-II detector package.**

SBS for SIDIS



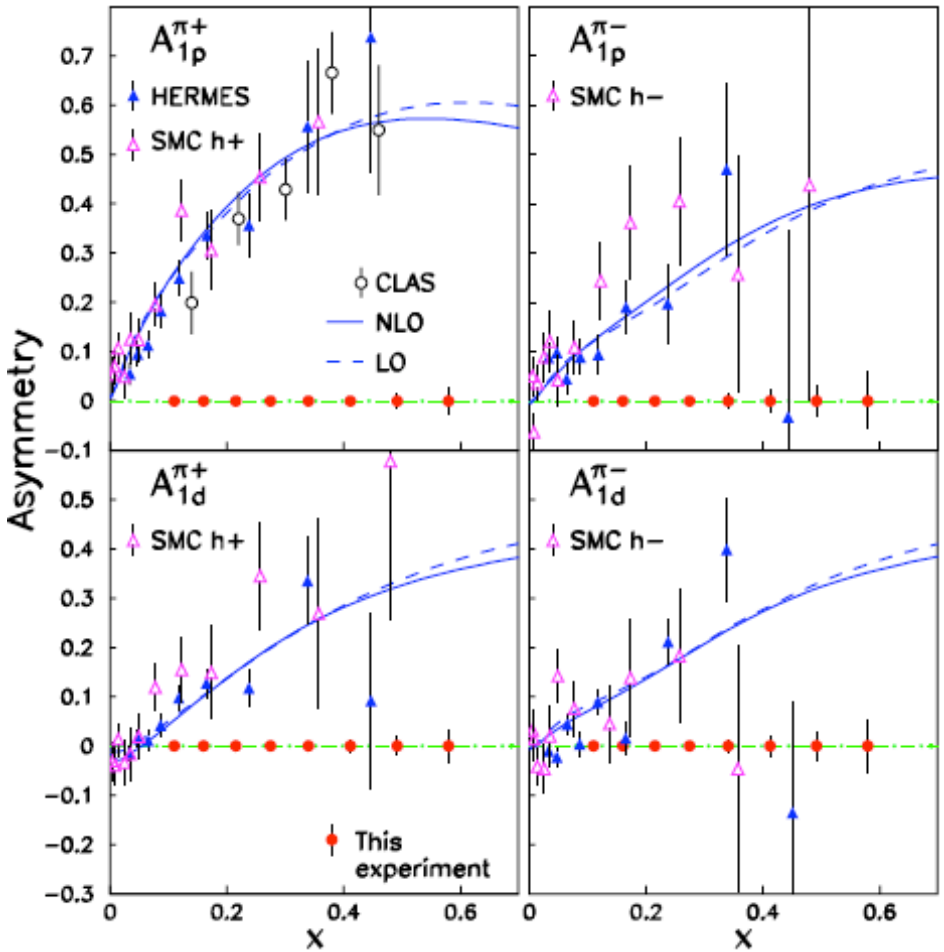
• Need to consider the detector performance at small scattering angles, particularly for RICH; rates per PMT may be too high—other possibilities for hadron PID?
• What about GEM rates and tracking capability?
• What kinematics could we cover at larger angles where RICH performance has been "demonstrated" as acceptable?

SBS performance parameters in SIDIS configuration

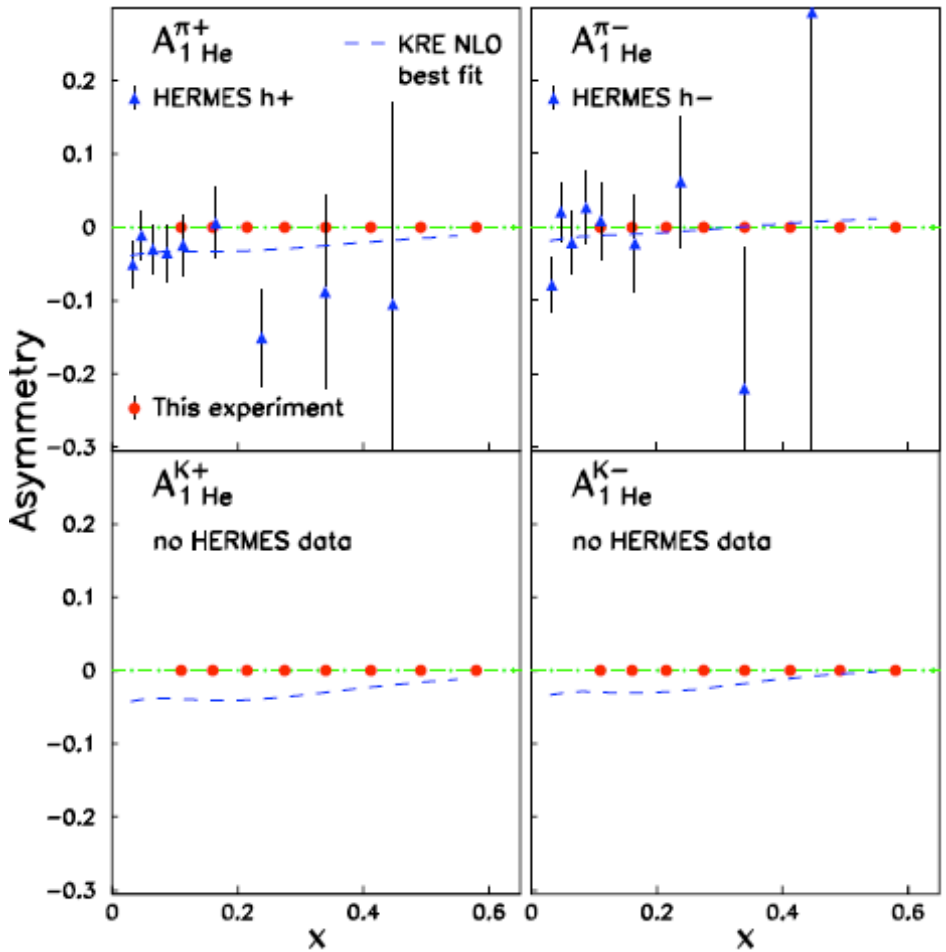
Distance from the target to the detector, cm	417
Central angle θ_c , degree	14
horizontal range: $\Delta\theta_h$, degree	± 3.6
vertical range: $\Delta\theta_v$, degree	± 12
angular resolution: σ_{θ_c}, degree	0.02
vertex resolution (along beam), cm	0.2
momentum resolution σ_p/p	$0.001 \times$p[GeV]

- Above numbers are for 14 degree central angle
- For 7.5 degree central angle, angle acceptance is smaller by almost a factor 2
- ~.3 mrad angular resolution
- ~0.1% momentum resolution

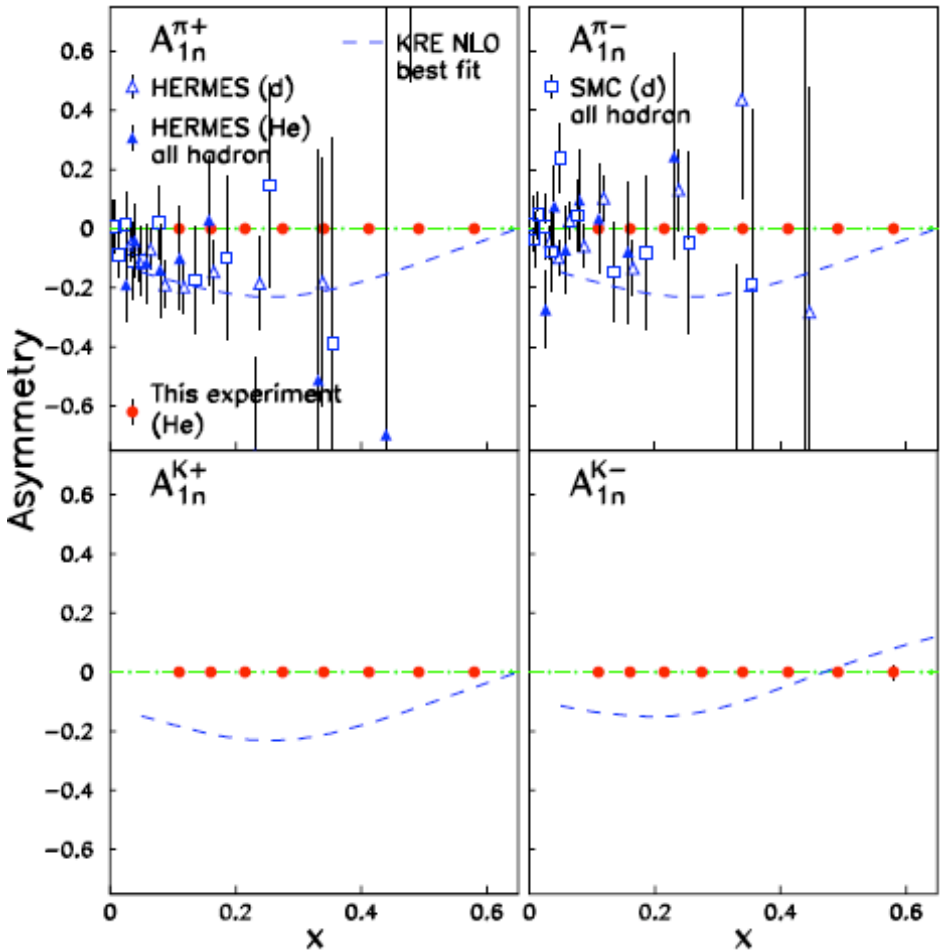
Expected Hall A Results: p and d pion asymmetries



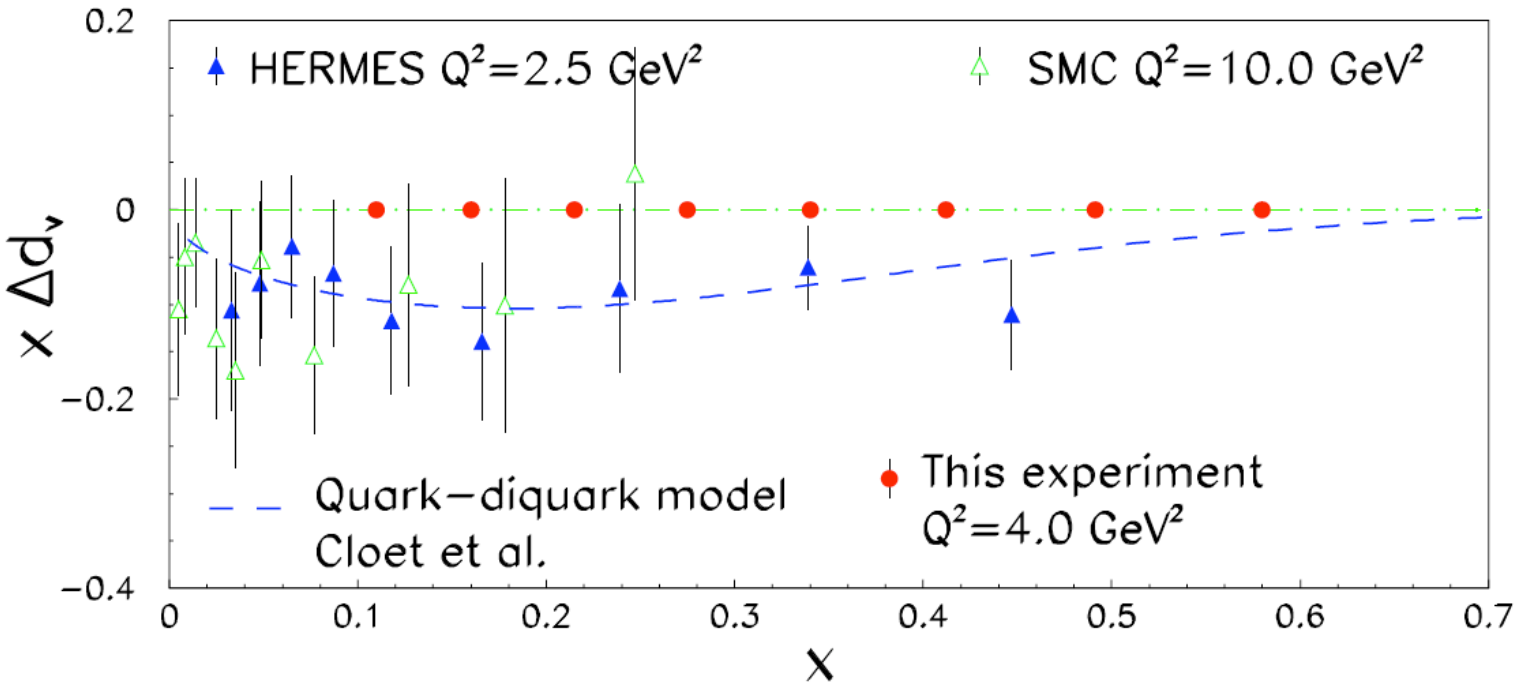
Expected Hall A results: Helium-3 pion and kaon asymmetries



Expected Results: pion and kaon neutron asymmetries (extracted from Helium-3)



Expected results: Δd_v



Advantages/Disadvantages of Hall C compared to Hall A

- **Obvious advantage is cleaner PID, better resolution, better understanding of (smaller) backgrounds**
- **Obvious disadvantage is much lower acceptance; significantly increasing required beamtime to cover similar kinematics—I have not done the calculations yet for HMS+SHMS configuration**
- **What about BigBite + HRS?**
  - Potential compromise between large acceptance electron arm vs. small acceptance (but well understood) hadron arm
  - Have not investigated in detail, but expect that small hadron acceptance may severely limit counting rates due to p_T distribution of SIDIS production
  - HRS momentum limited to ~4 GeV, limits to lower z/p_h values
- **We will soon investigate these options in depth using existing and new Monte Carlo tools**
- **SIMC modified to include new SIDIS physics and realistic BigBite (already written for E06-010 analysis) and SBS (will write) models**

Conclusion

- A SIDIS A_{LL} program, especially when different, complementary targets are run in the same detector configuration, can make a huge impact on the world database of flavor-separated helicity PDFs.
- Probably need separate proposals for 3He and UVA targets
- Orders of magnitude improvement in precision in overlap region with existing data
- Extend to higher x
- First kaon asymmetries for Helium-3 (correct me if I'm wrong)
- Improved constraints on strange quark polarization could have significant physics impact by discriminating between different scenarios for the first moment of Δs
- We are working with leading theorists to quantify the impact of these measurements on polarized PDF uncertainties in global analyses.