Accessing Polarized Sea Quark Flavor Asymmetry through Semi-Inclusive DIS at JLab-12GeV (and the Future EIC)

(Based on JLab Hall A Collaboration Proposal PR12-14-008)

Xiaodong Jiang, Los Alamos National Laboratory, Oct. 21st, 2014.

Semi-Inclusive double-spin asymmetry A_{LL} in ${}^3\vec{H}e(\vec{e}, e'h)$ $h = \pi^+, \pi^-, K^+, K^-(\pi^0)$

$$A^h_{LL,n} \propto A^h_{1n} = \Delta\sigma^h_n / \sigma^h_n$$

- Flavor tagging in SIDIS provides access to **Δq**.
- Existing SIDIS data on proton and deuteron lacks precision to constrain d-quarks, neutron (^{3}He) A^h_{1n} are most sensitive to $\mathbf{\Delta d},\ \mathbf{\Delta \bar{d}}$

This JLab proposal: precision A^h_{1n} and multiplicity data on a dense grid of (x,Q^2,z):

- Strong constraints on Δq through NLO QCD global fits.
- Leading-Order "purity"-method Δq extraction, as in HERMES and COMPASS.
- Self-consistency cross-checks to set limits on interpretation systematics.

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A JLab Hall A Collaboration Proposal, with SBS Collaboration's endorsement

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Collaboration carries extensive Hall A operation experiences, heavily involved in experiments such as:

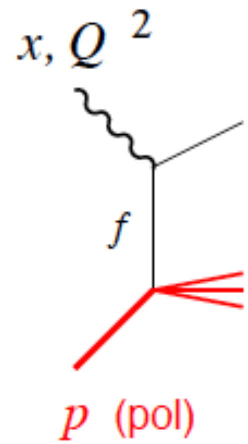
- **BigBite, Super-BigBite (SBS), GEp, GEn, Transversity, SoLID …**
- **with a polarized ^3He target.**
- **SIDIS spin asymmetry measurements.**

Nucleon Spin Flavor Decomposition

- Inclusive DIS access only $q_f + \bar{q}_f$:

$$g_1(x,Q^2) = \sum_{f=u,d,s} e_f^2 \, (\Delta q_f + \Delta \bar{q}_f)\,(x,Q^2)$$

$$\Delta u + \Delta \bar{u}, \Delta d + \Delta \bar{d}$$



LO approximation

$\Delta q_f, \Delta \bar{q}_f(x)$

- Inclusive DIS access gluon via Q^2 evolution, at NLO:

$$g_1 = \sum_{f=u,d,s} e_f^2 \, C_q \otimes (\Delta q_f + \Delta \bar{q}_f) \; + \; (\sum_f e_f^2) \, \alpha_s C_g \otimes \Delta G$$

involves gluons explicitly.

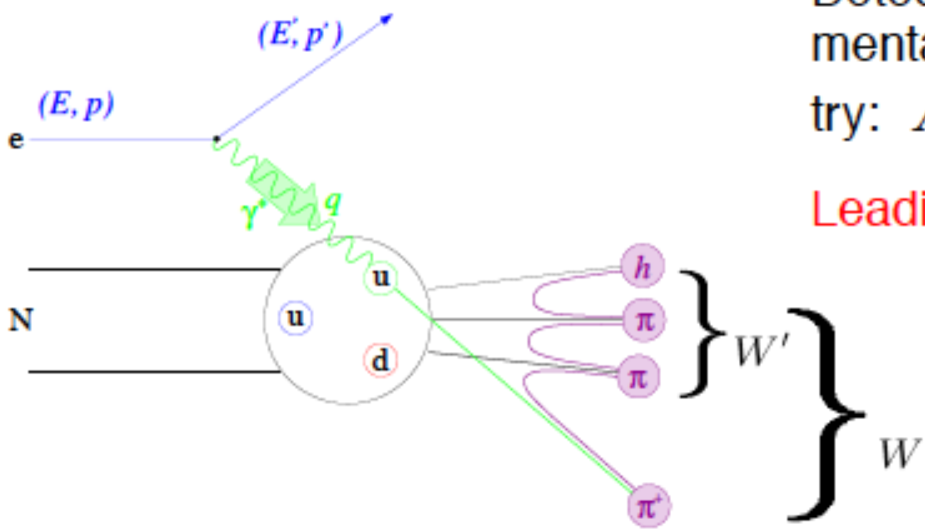
we wish to determine valence quarks' polarization:

$$\Delta u_v = \Delta u - \Delta \bar{u}, \;\; \Delta d_v = \Delta d - \Delta \bar{d}$$

and determine if sea quarks carry any polarization:

$$\Delta \bar{u} \stackrel{?}{=} 0, \Delta \bar{d} \stackrel{?}{=} 0, \Delta \bar{u} - \Delta \bar{d} \stackrel{?}{=} 0$$

Quark Flavor Tagging through SIDIS



$z = E_\pi / \nu$

Detect the leading hadron from the current fragmentation and measure double-spin asymmetry: $A_1^h = \Delta\sigma^h / \sigma^h$.

Leading order naive x-z separation:

$$\Delta\sigma^h = \sum_{f=q,\bar{q}} e_f^2 \, \Delta q_f(x) \, D_f^h(z)$$

Reaction on a "free quark":

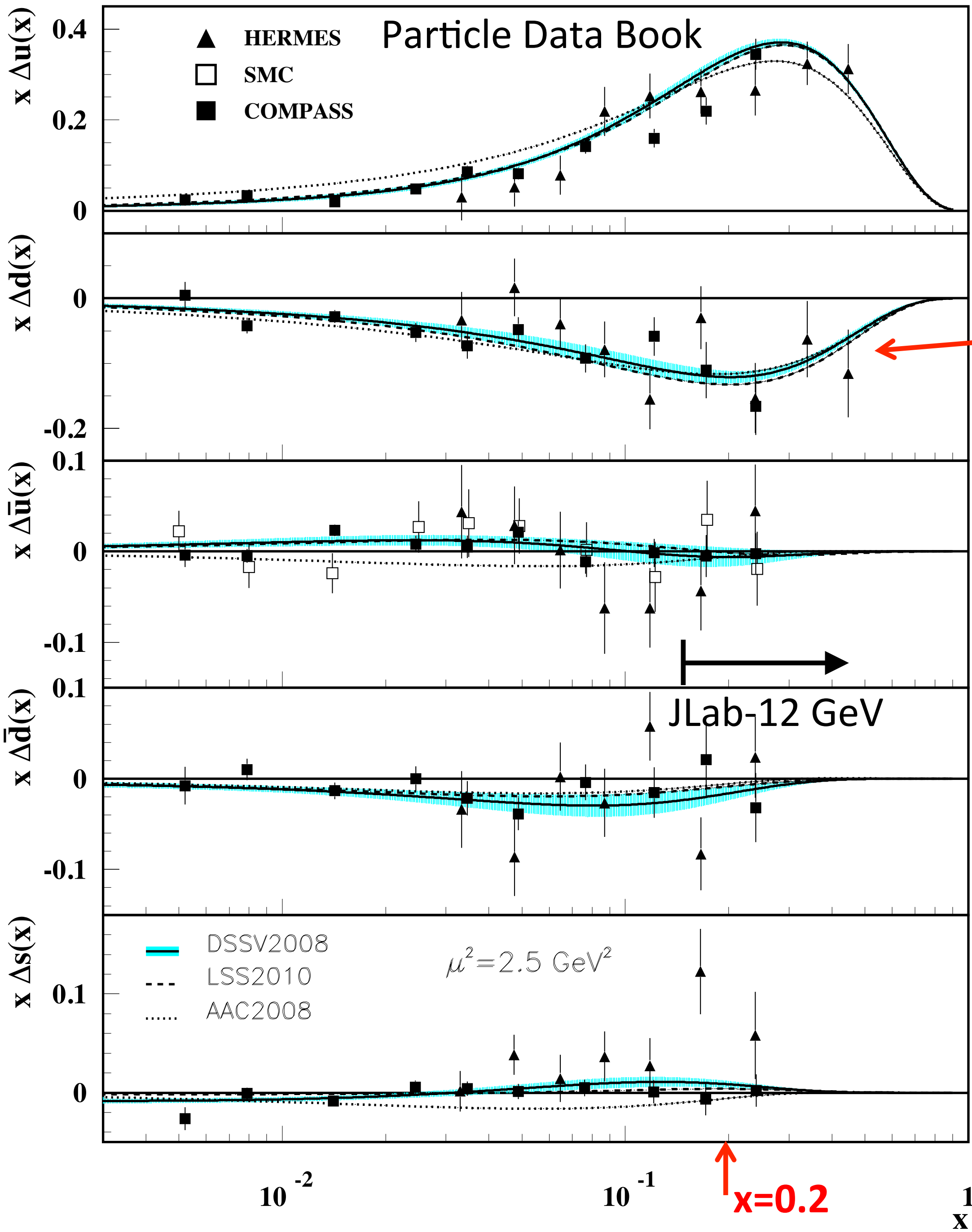
highest possible Q^2, W, p_π and W'.

HERMES calculated "purity" from a LUND based Monte Carlo:

$$A_1^h = \sum_a \underbrace{\frac{e_a^2 \, q_a(x) \, D_a^h(z)}{\sum_b e_b^2 \, q_b(x) \, D_b^h(z)}}_{P_a^h(x,z)} \frac{\Delta q_a(x)}{q_a(x)}$$

Fragmentation "tags" flavor

and charge of struck quark.



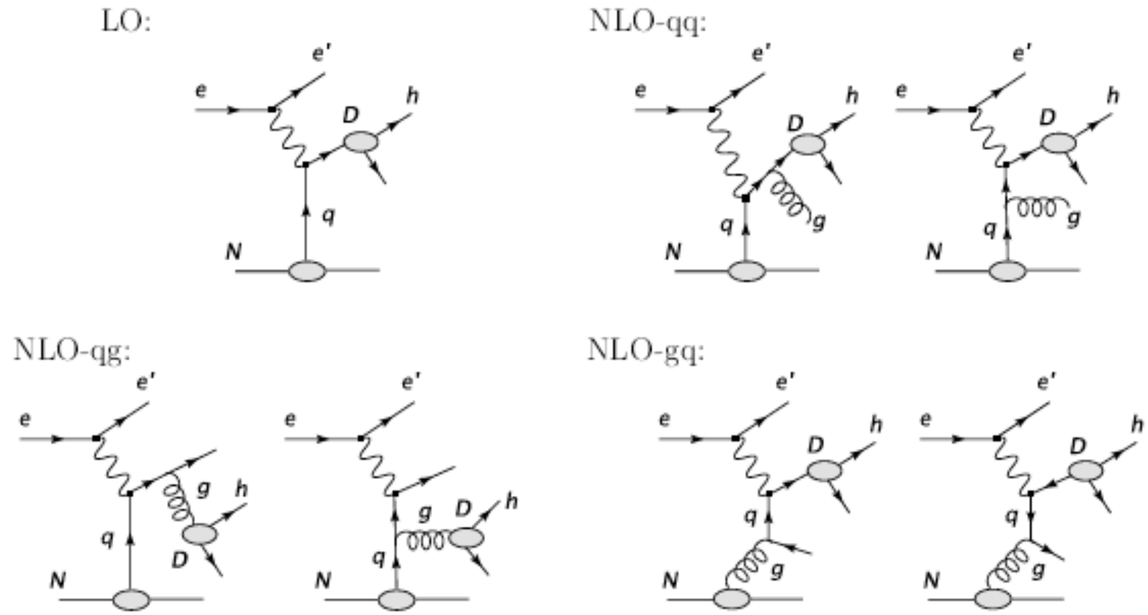
HERMES-2004 and COMPASS-2010

Leading-Order Δq extraction

Large uncertainties on Δd

sea quarks un-polarized ?

SIDIS at NLO



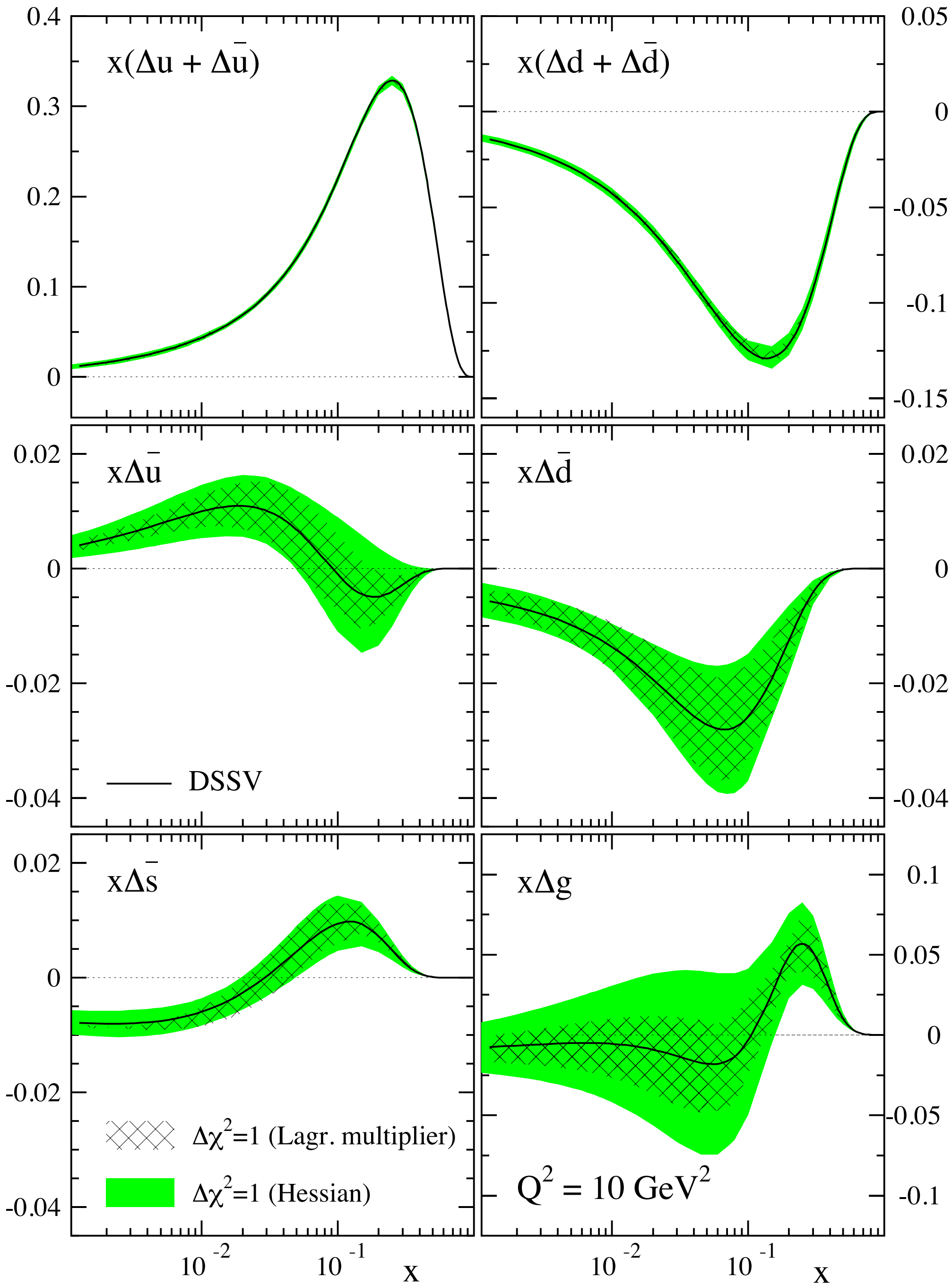
$$\Delta\sigma^h = \sum_i e_i^2 \Delta q_i \left[1 + \otimes \frac{\alpha_s}{2\pi} \Delta C_{qq} \otimes\right] D_{q_i}^h$$

$$+ \left(\sum_i e_i^2 \Delta q_i\right) \otimes \frac{\alpha_s}{2\pi} \Delta C_{qg} \otimes D_G^h + \Delta G \otimes \frac{\alpha_s}{2\pi} \Delta C_{gq} \otimes \left(\sum_i e_i^2 D_{q_i}^h\right)$$

- NLO global QCD-fit with inclusive and SIDIS data constrain Δq_i and ΔG.

NLO QCD global fits with inclusive DIS, SIDIS and p+p data, need inputs of:

- quark and gluon densities
- quark to hadron fragmentation functions
- gluon to hadron fragmentation functions



NLO Global -QCD Fit

DSSV2008

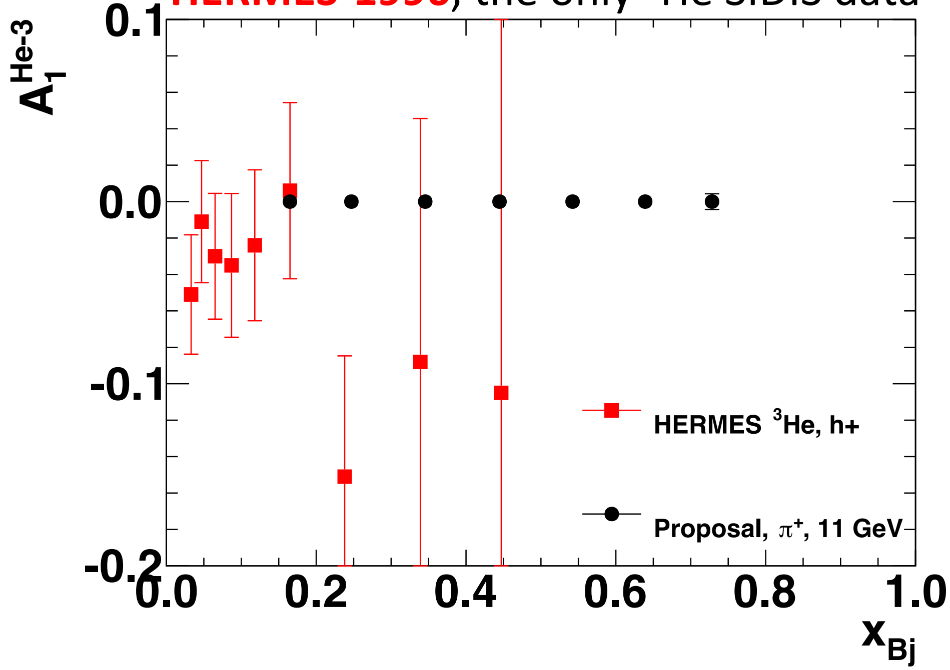
de Florian, Sassot, Stratmann, Vogelsang

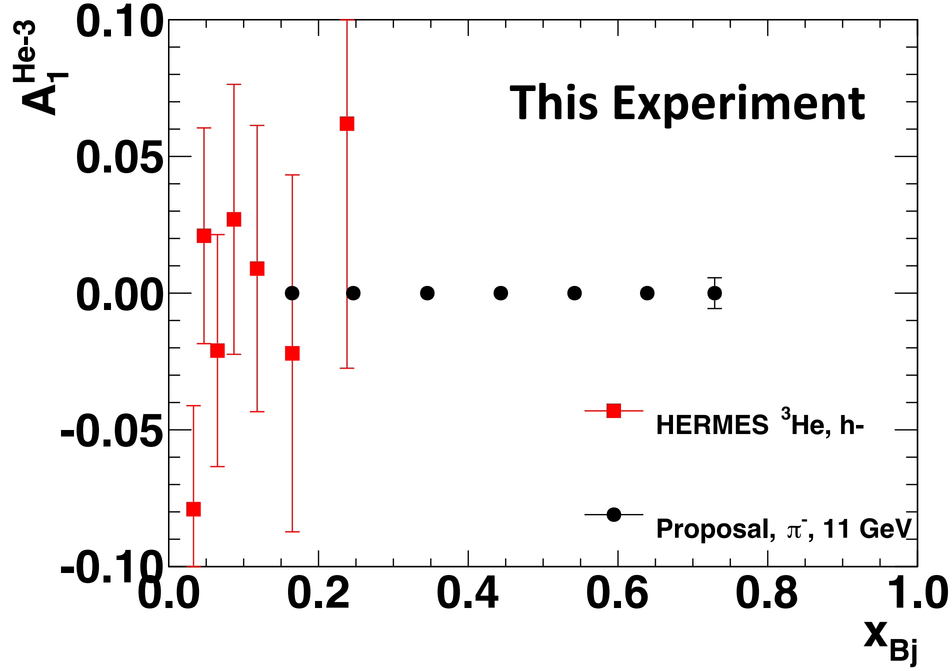
Phys. Rev. Lett., 101:072001, 2008

- Inclusive DIS and SIDIS data.
- p+p inclusive hadron, jets.
- Frag. Func. from e^+e^- data and fit to SIDIS multiplicities.

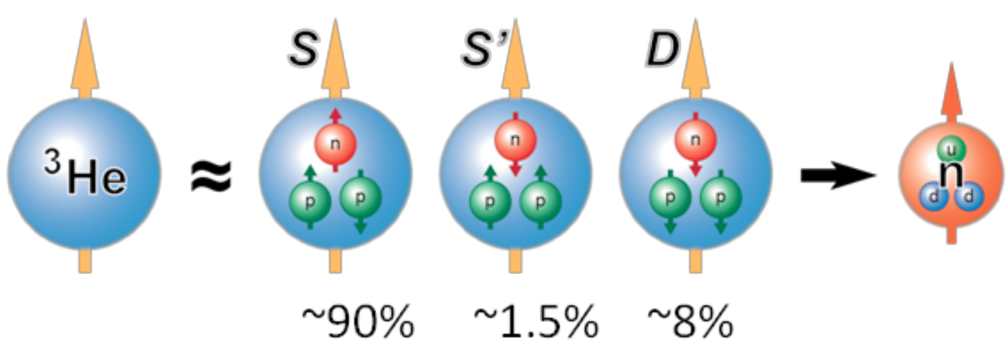
Urgently Need Precision SIDIS Data on Pol. ^{3}He

HERMES-1996, the only ^{3}He SIDIS data





Polarized ^{3}He is an "effective" neutron target:



effective polarization:

$$
\begin{aligned}
A_{^3\mathrm{He}} &= P_n(1-f_p)A_n + P_p f_p A_p \\
P_n &= 0.86^{+0.036}_{-0.02} \\
P_p &= -0.028^{+0.009}_{-0.004} \\
f_p &= \frac{2\sigma_p}{\sigma_{^3\mathrm{He}}}
\end{aligned}
$$

In Deep-Inelastic Scattering:
two protons in ^{3}He contribute a dilution factor

Neutron A^h_{1n} is sensitive to $\Delta d, \ \Delta \bar{d}$

Proton:	u	u	d		Notation: $d = u_n$			
e_q^2:	$\frac{4}{9}$	$\frac{4}{9}$	$\frac{1}{9}$					
Neutron:	d_n	d_n	u_n	$\Rightarrow$	u	u	d	
e_q^2:	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{4}{9}$		$\frac{1}{9}$	$\frac{1}{9}$	$\frac{4}{9}$	

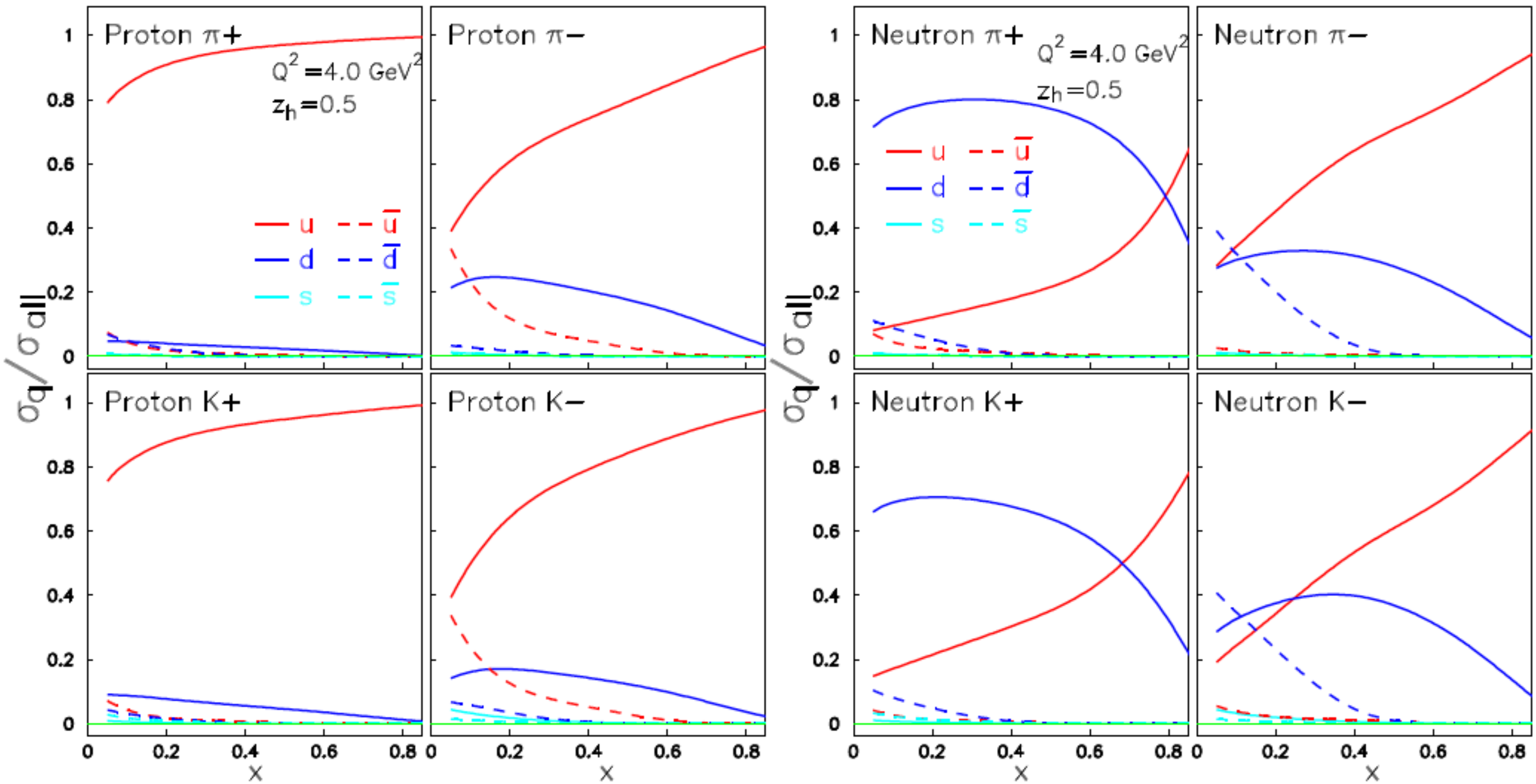
Polarized deuteron is not as good as ^{3}He:

pol. deuteron ≈ pol. proton + pol. neutron

- Spin effects likely to cancel between proton and neutron, leading to smaller asymmetry signals.
- u-quarks dominate in deuteron, less sensitive to d-quarks.
- ND_3 target lower polarization, lower luminosity, worse dilution factor.

Neutron A^h_{1n} is most sensitive to Δd, $\Delta \bar{d}$

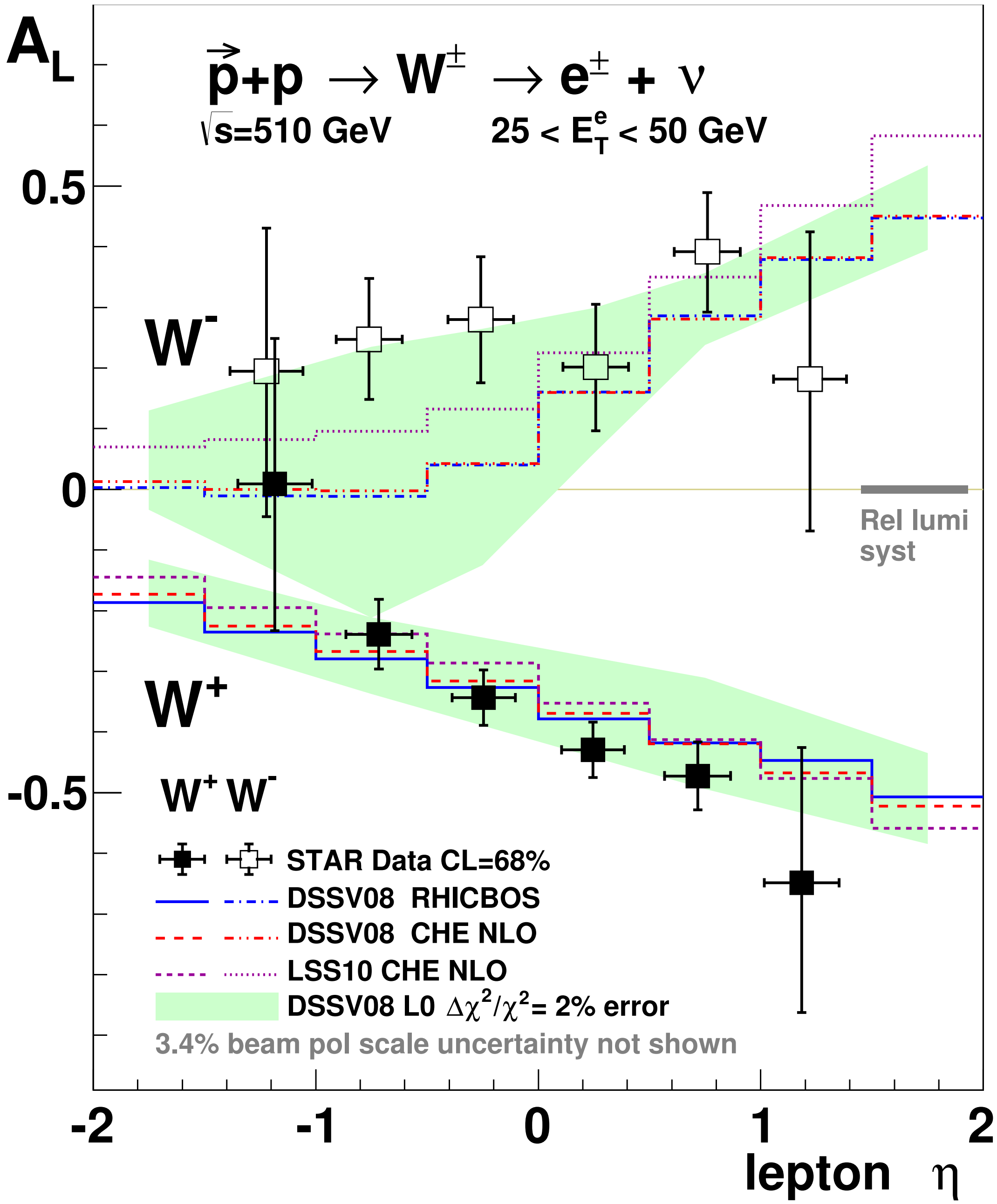
$$\sigma_q/\sigma_{all} = e_f^2 q_f \cdot D_f^h / \sum e_i^2 q_i \cdot D_i^h \qquad (@z_h = 0.5)$$



u-quark dominates in proton

d-quark's effects show up in neutron

STAR Run2012 arXiv:1404.6880



The Big News From STAR

$\Delta\bar{u}$ a shift away from the current best mean value was observed.

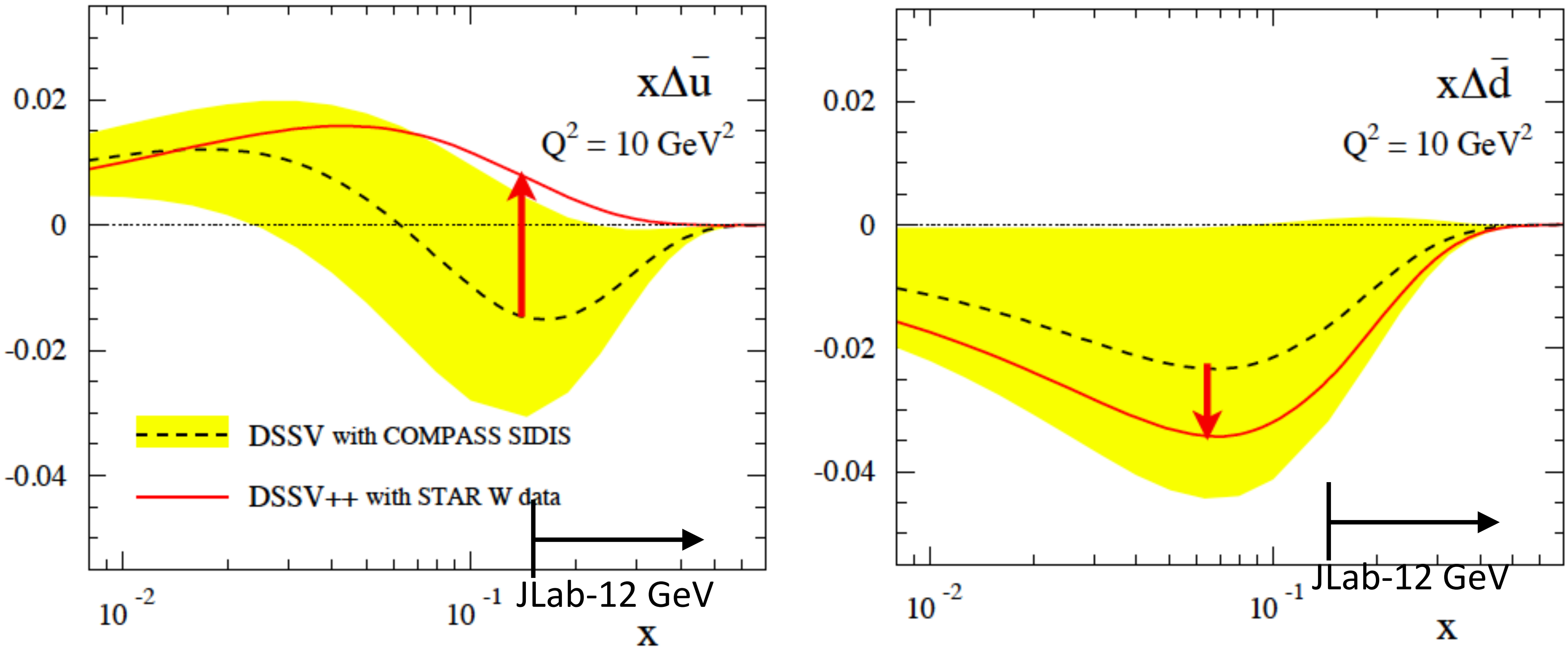
W^- data at η<0 tend to lie above central curve based on DSSV2008

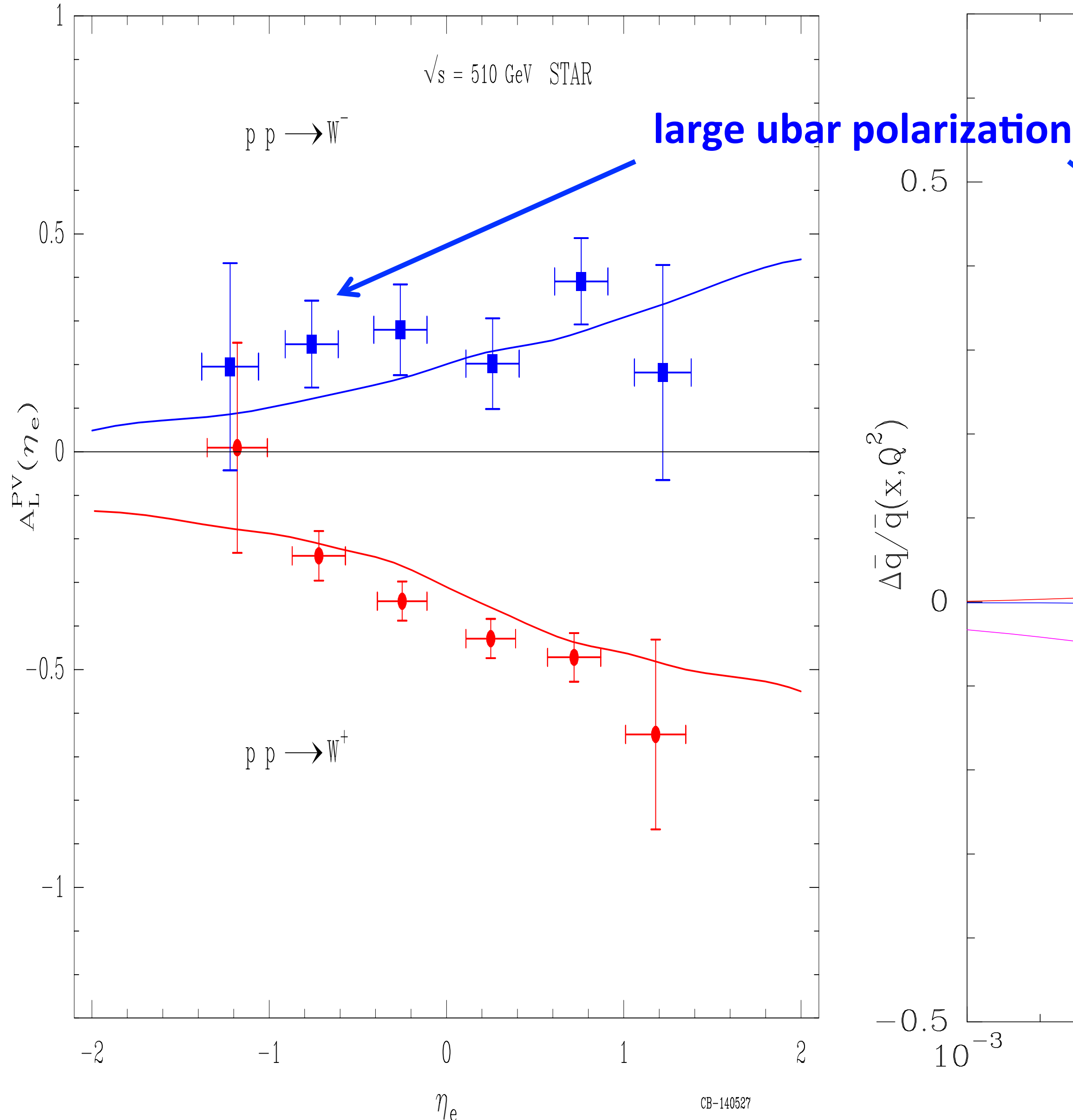
$\Delta\bar{u} > \Delta\bar{d}$ preferred for x =0.05 ~ 0.2.

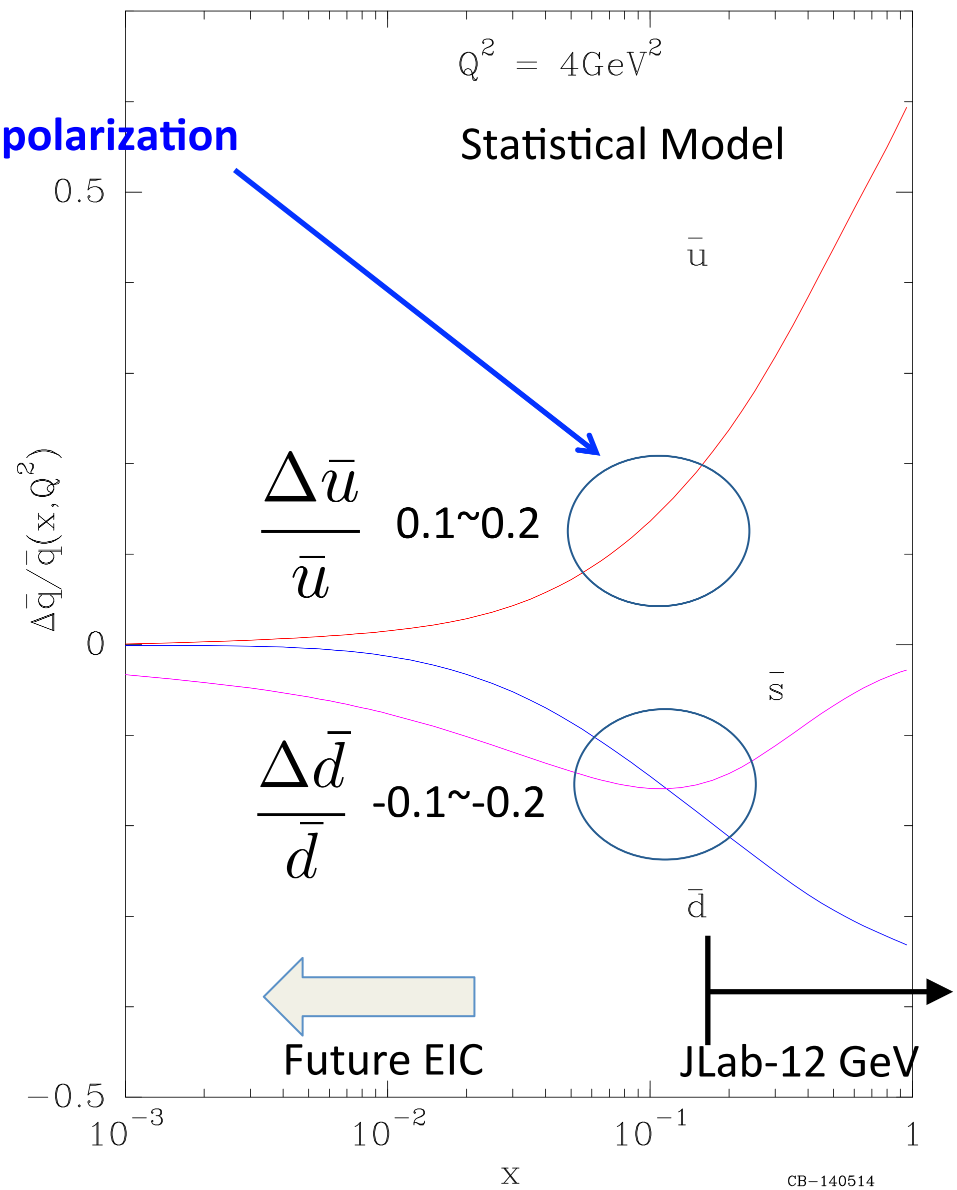
Strong indications of non-vanishing sea quark polarizations at x=0.05 ~0.2

A major effort at RHIC, DOE milestone. Both PHENIX and STAR are expected to release their final Run2011+Run2012+Run2013 W asymmetry results soon.

STRA W data introduced shifts to sea polarization in NLO global fit



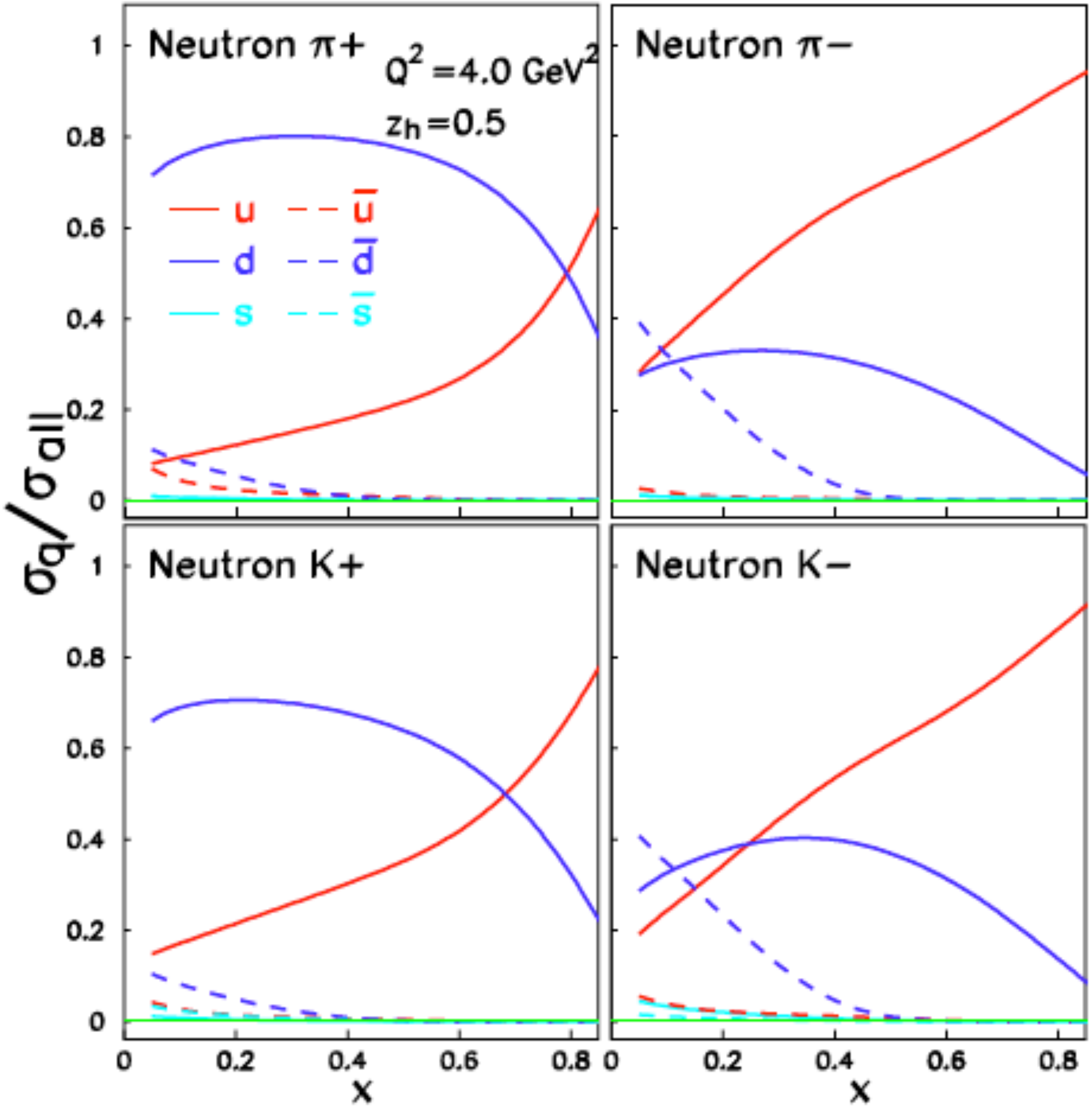




Statistical Model prediction.
Bourrely, Buccella, Soffer
PLB 726, 296 (2013)

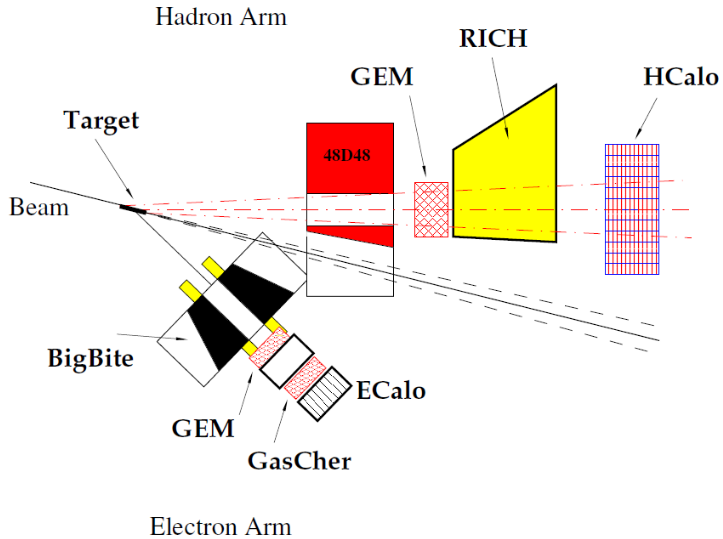
BBS2008: a rather large sea polarization 10~20%, strong flavor dependency.

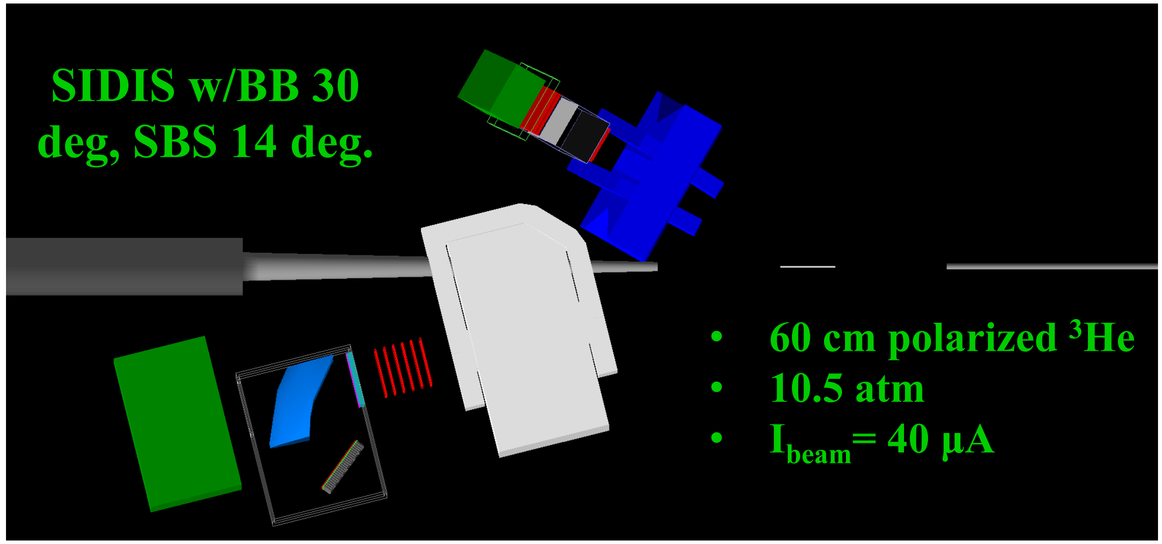
Neutron A^{h}_{1n} is most sensitive to $\Delta d,\ \Delta\bar{d}$

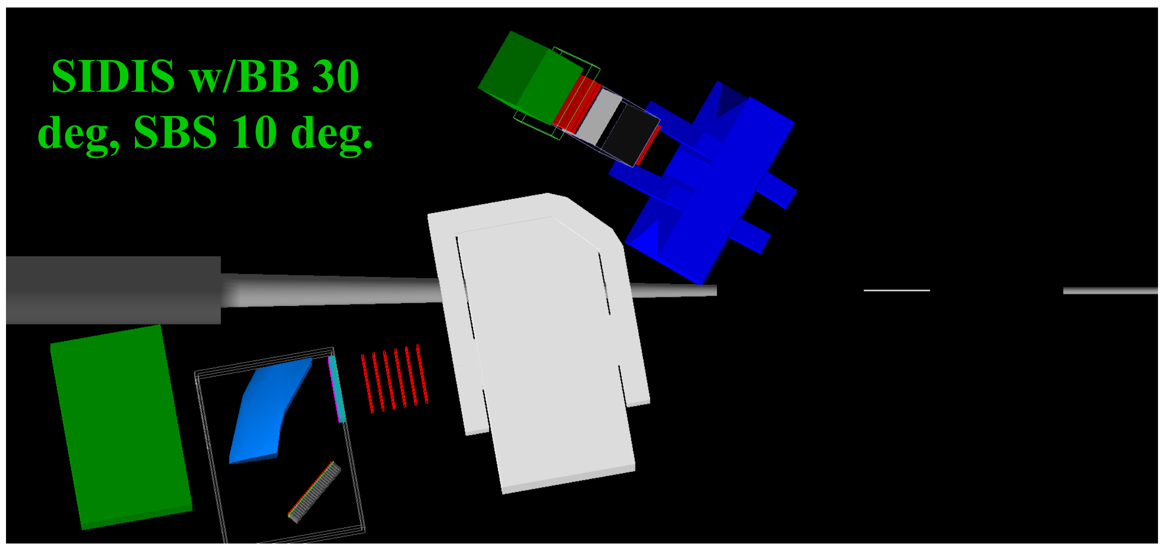


Urgently Need Precision SIDIS Data on Pol. Neutron (^{3}He).

Experiment Setup: BigBite+Super_BigBite





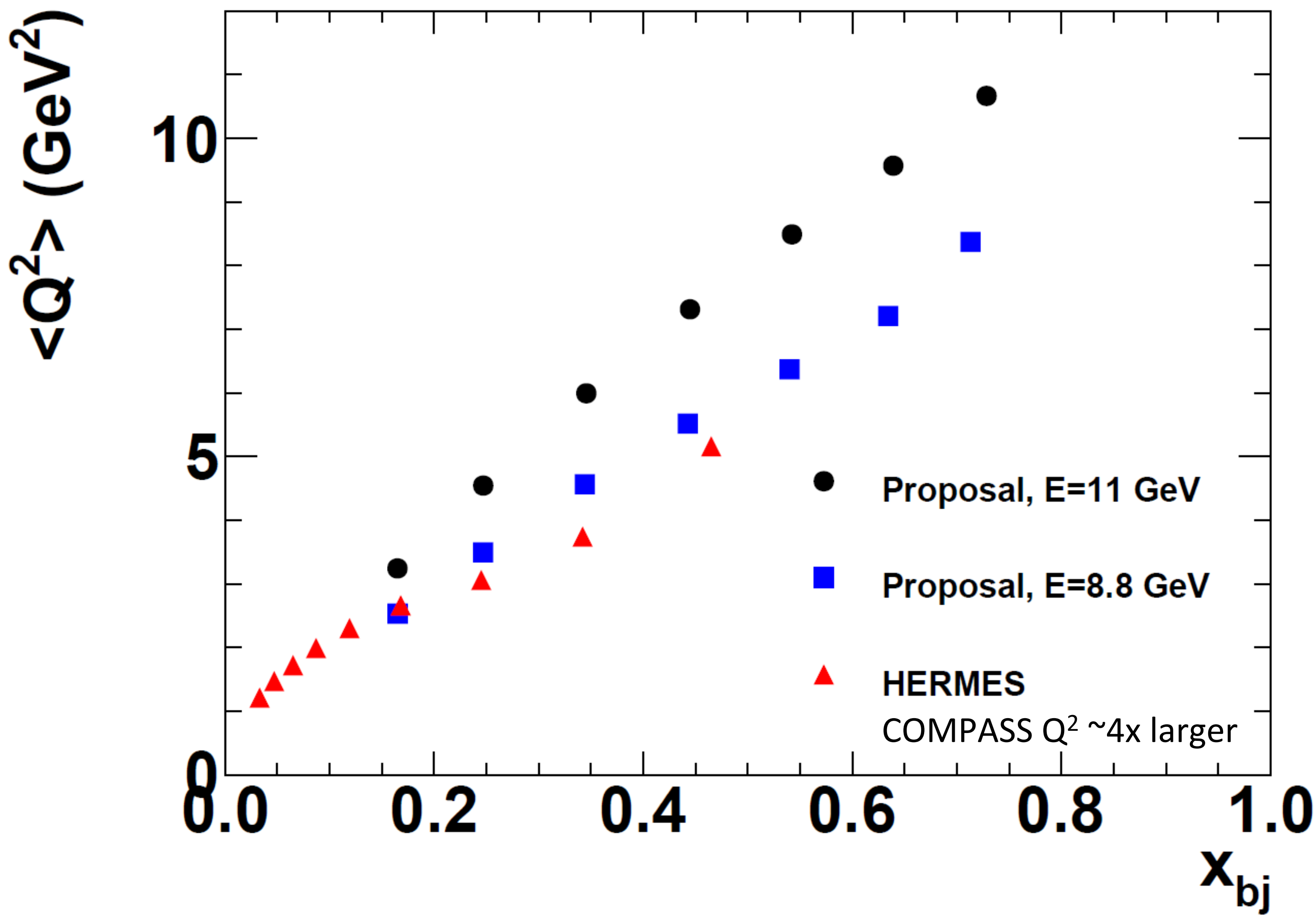


- Spectrometer layout of SIDIS
- ***Independent electron and hadron arms***:
  - Large momentum bite
  - Moderate solid angle
  - High-rate capability
  - Excellent PID
- ***h^+/h^- symmetric acceptance***

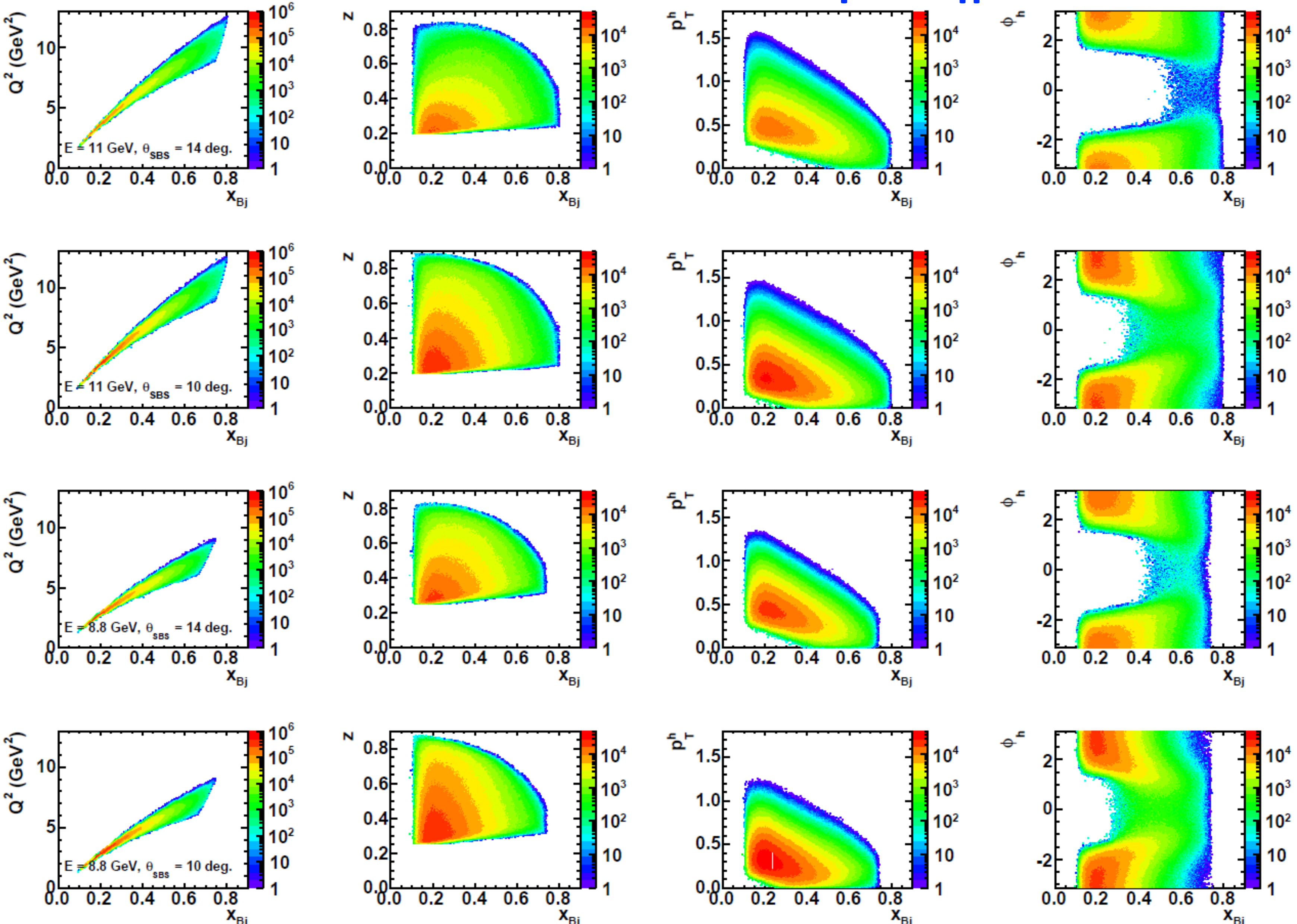
E_0=11, 8.8 GeV 30 days
SBS @14°, 10°

BigBite:electron-arm, SBS: hadron-arm

$\langle Q^2 \rangle$ of SBS+BB SIDIS: > HERMES, < COMPASS

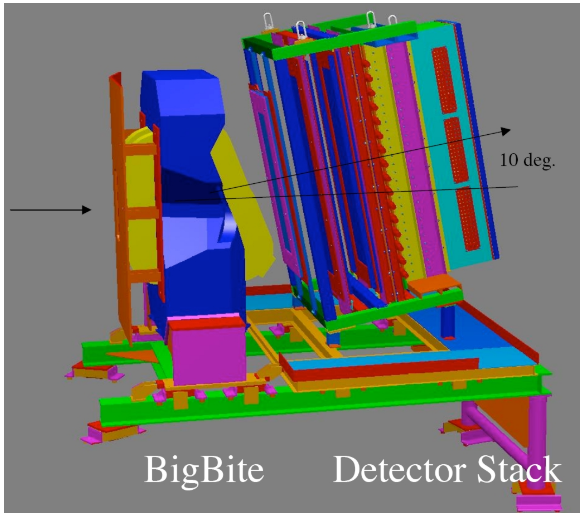


Acceptances: Q^2, z, p^h_T, ϕ_h vs x



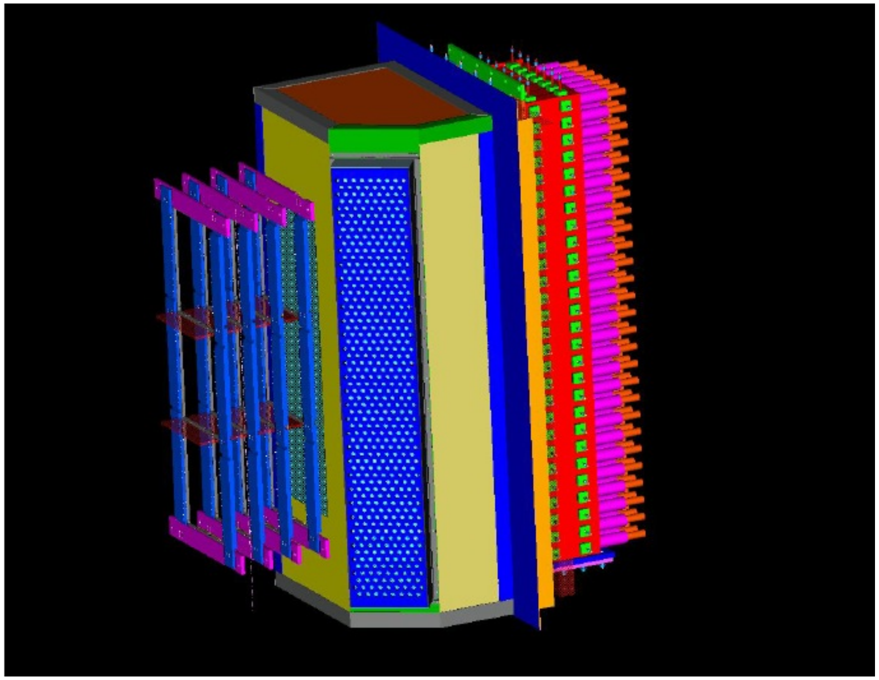
$$Q^2 \geq 1\ \text{GeV}^2, W \geq 2\ \text{GeV}, M_X \geq 1.5\ \text{GeV}, y \leq 0.9, P_h \geq 2\ \text{GeV}$$

Electron Arm—BigBite Spectrometer



BigBite @ 6 GeV (E06-010 transversity expt):

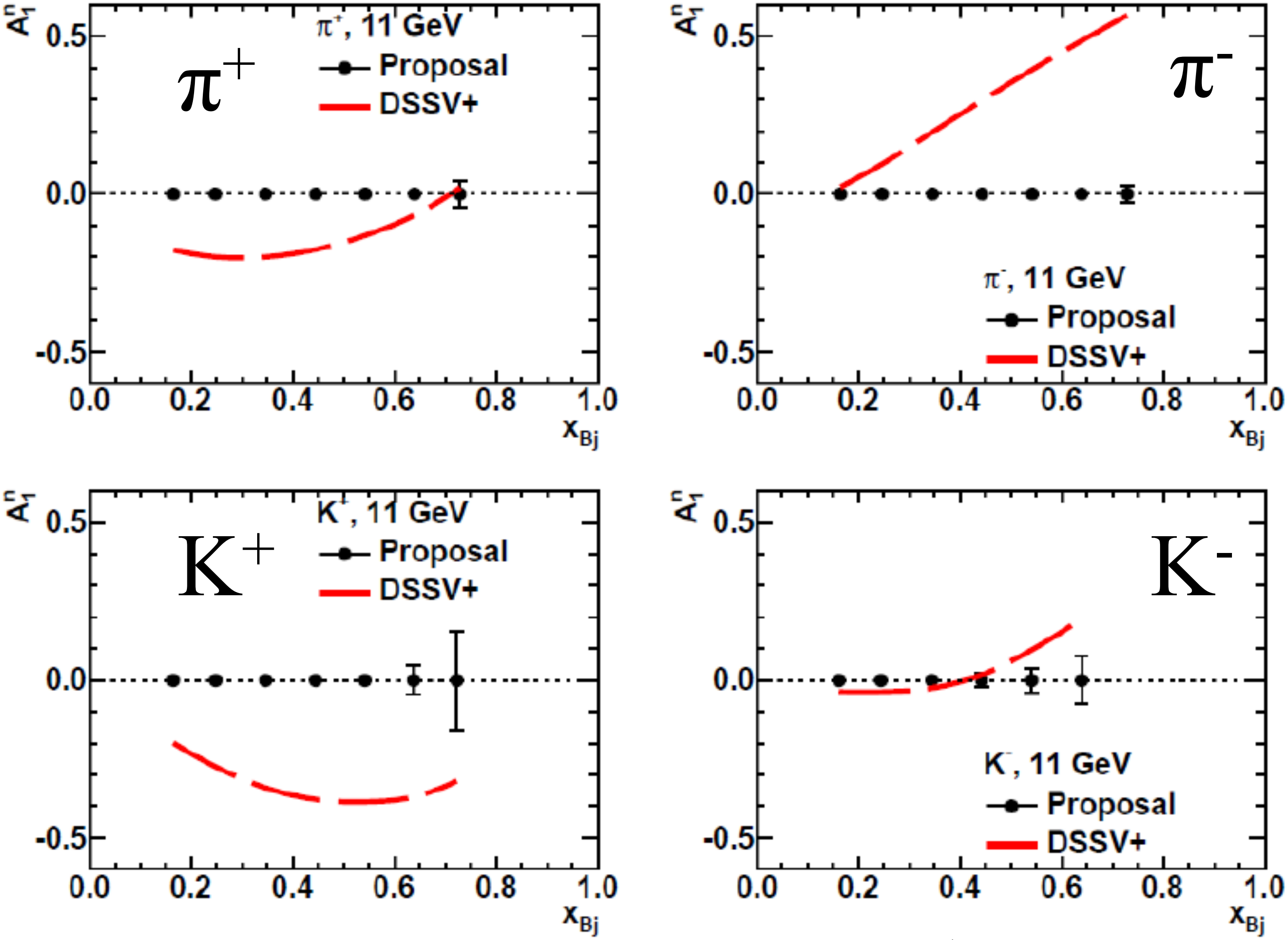
- Three MWDCs for tracking (18 wire planes)
- Pre-shower/shower calorimeter for trigger and PID
- Scintillator hodoscope for timing
- Dipole magnet: B*dl=1 T*m



BigBite @ 12 GeV:

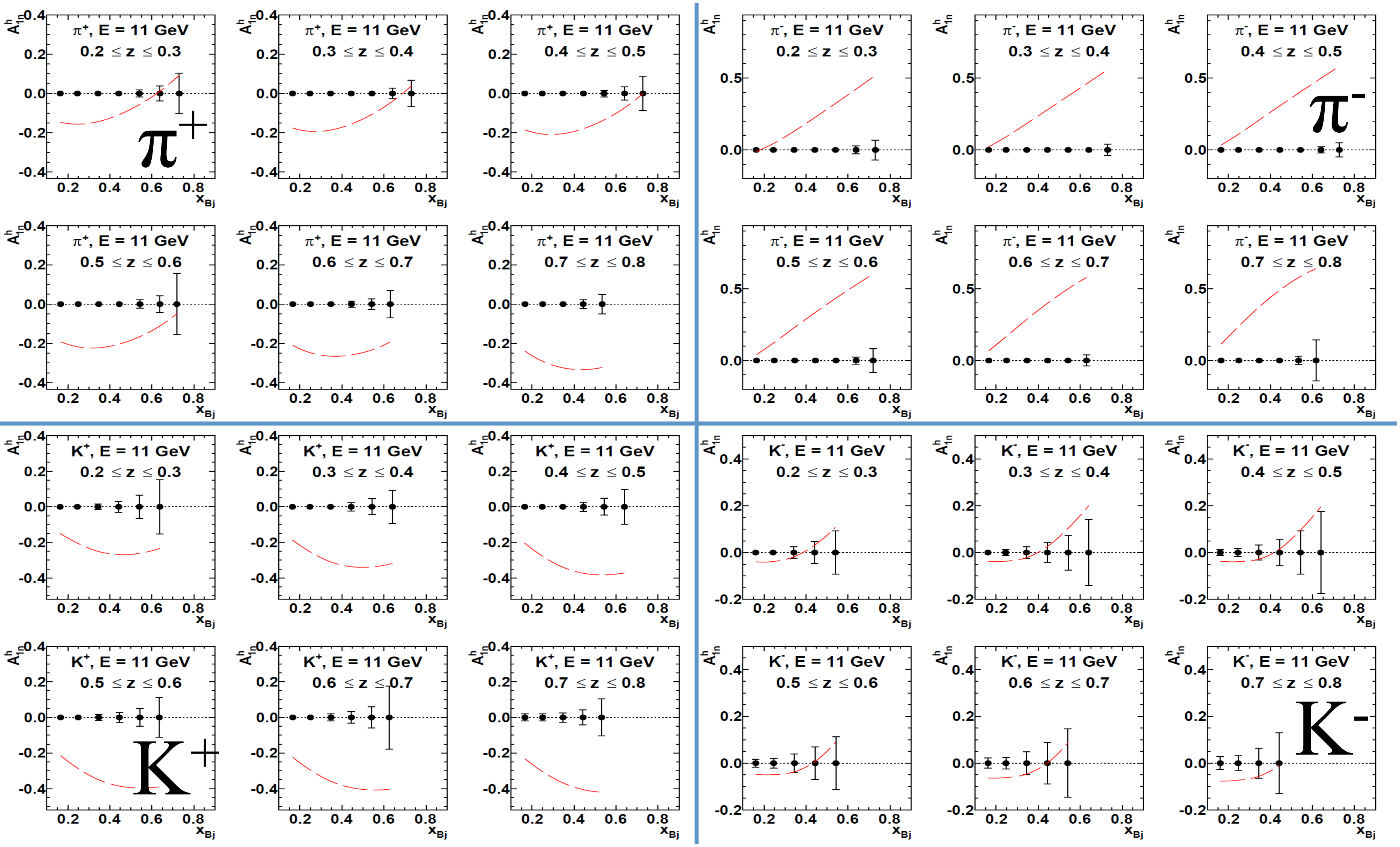
- Detector upgrades including:
  - GEM chambers for high-rate, high-resolution tracking (resolve higher electron momenta at same field integral)
  - Gas Cherenkov for higher-fidelity e/π separation
  - New detector support frame
- ***BigBite parameters in E12-14-008:***
  - ***Central angle = 30 deg.***
  - ***Target to magnet yoke distance = 1.5 m***

Projected Neutron Asymmetry-1D E_0=11 GeV

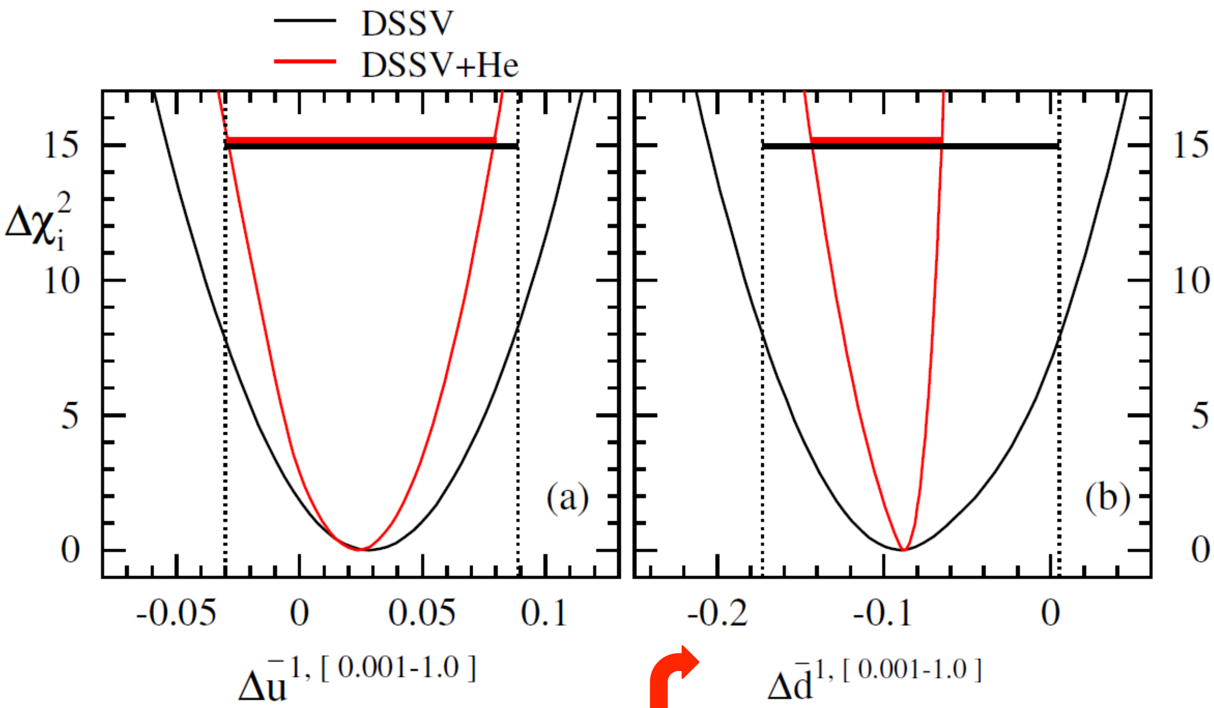


- Projected asymmetry precisions (stat. only) in A_{1n}^h vs x, integrated over z, p_T,
- Compared to prediction of "DSSV+" NLO global fit, arXiv:1108.3955

Projected Asymmetry Precision-2D (x, z), E_0=11 GeV

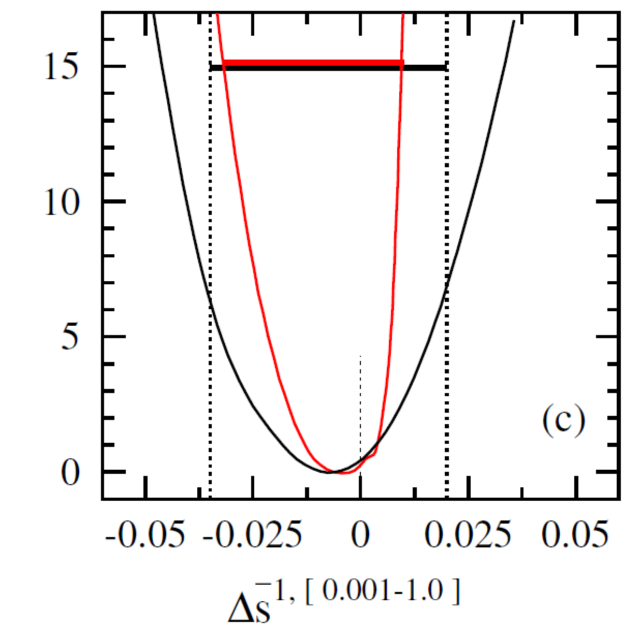


- High precision measurements on a dense grid of (x, z).
- **Consistent deviations from NLO QCD prediction ?**



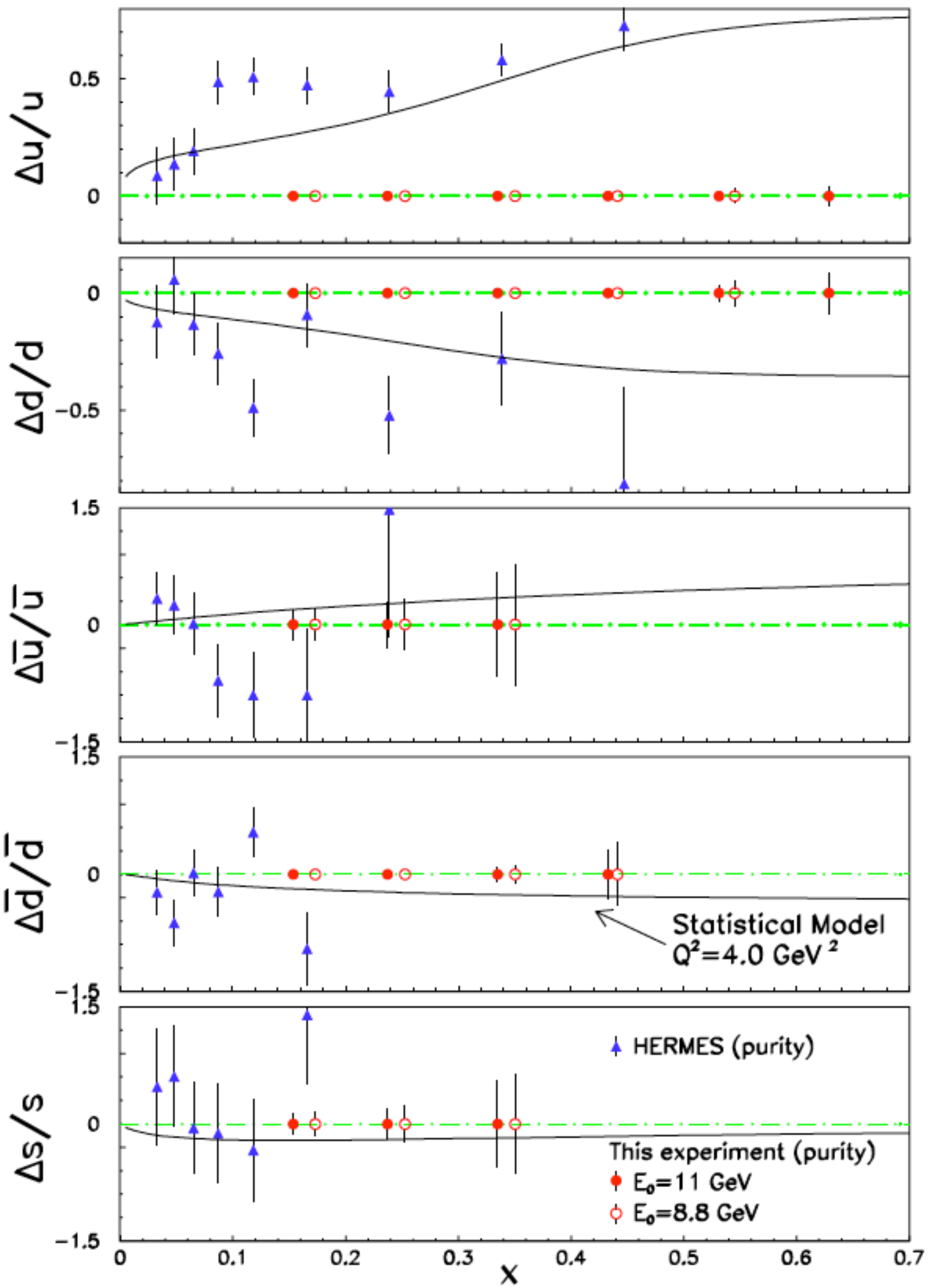
Black: width of parabolas at a 2% increase of the DSSV χ^2 (~ 1σ).

Red: adding this experiment.



Results of a DSSV study, impacts on error bands of sea quark polarization:

- ***Slight reduction on ubar***
- ***Very significant reduction on dbar***
- ***Noticeable reduction on s=sbar***



Physics Impacts:

Leading-Order "Purity" Method

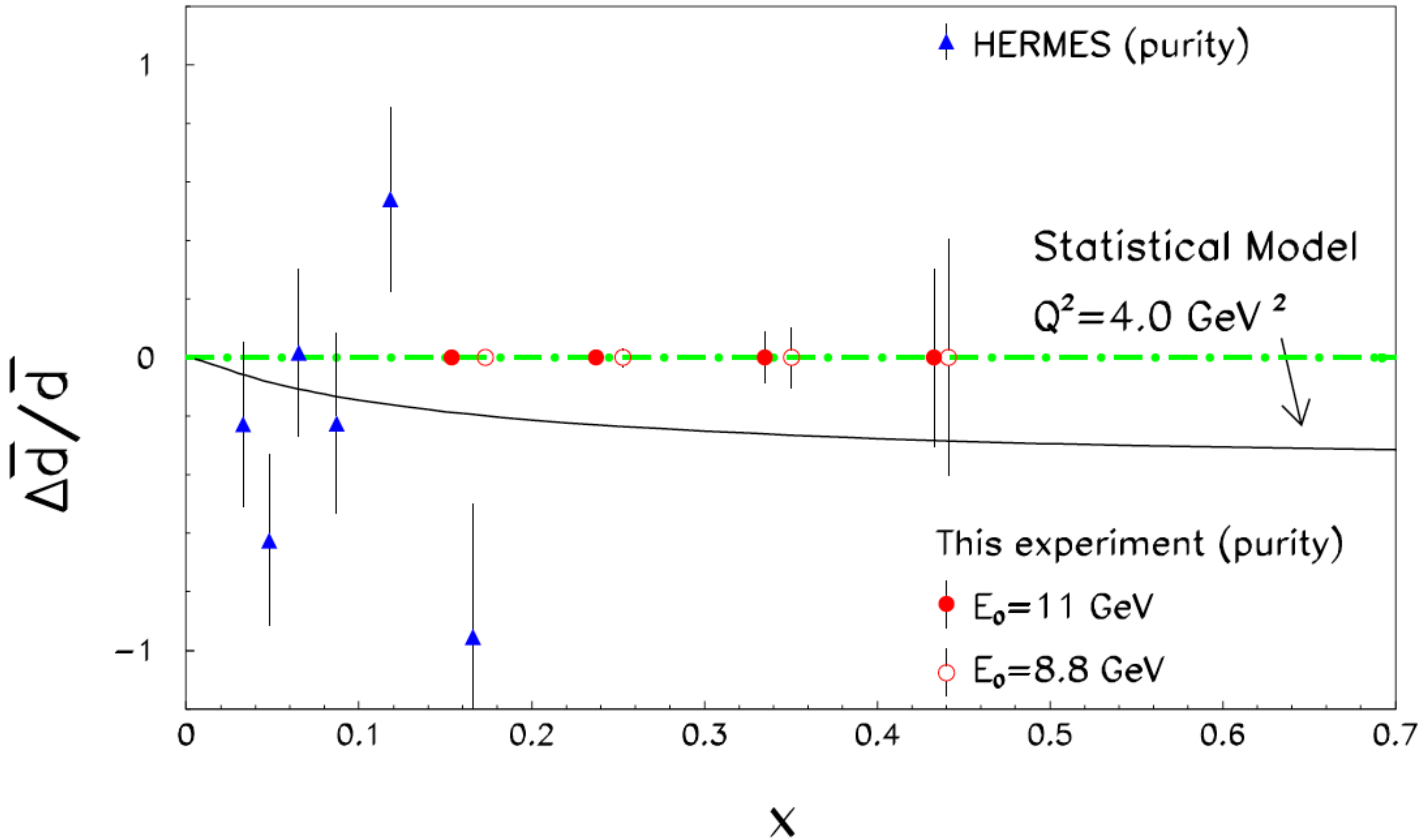
Precisely determine Δu/u and Δd/d

Significantly improve $\Delta\bar{u}/\bar{u}$

Potential of discovery:

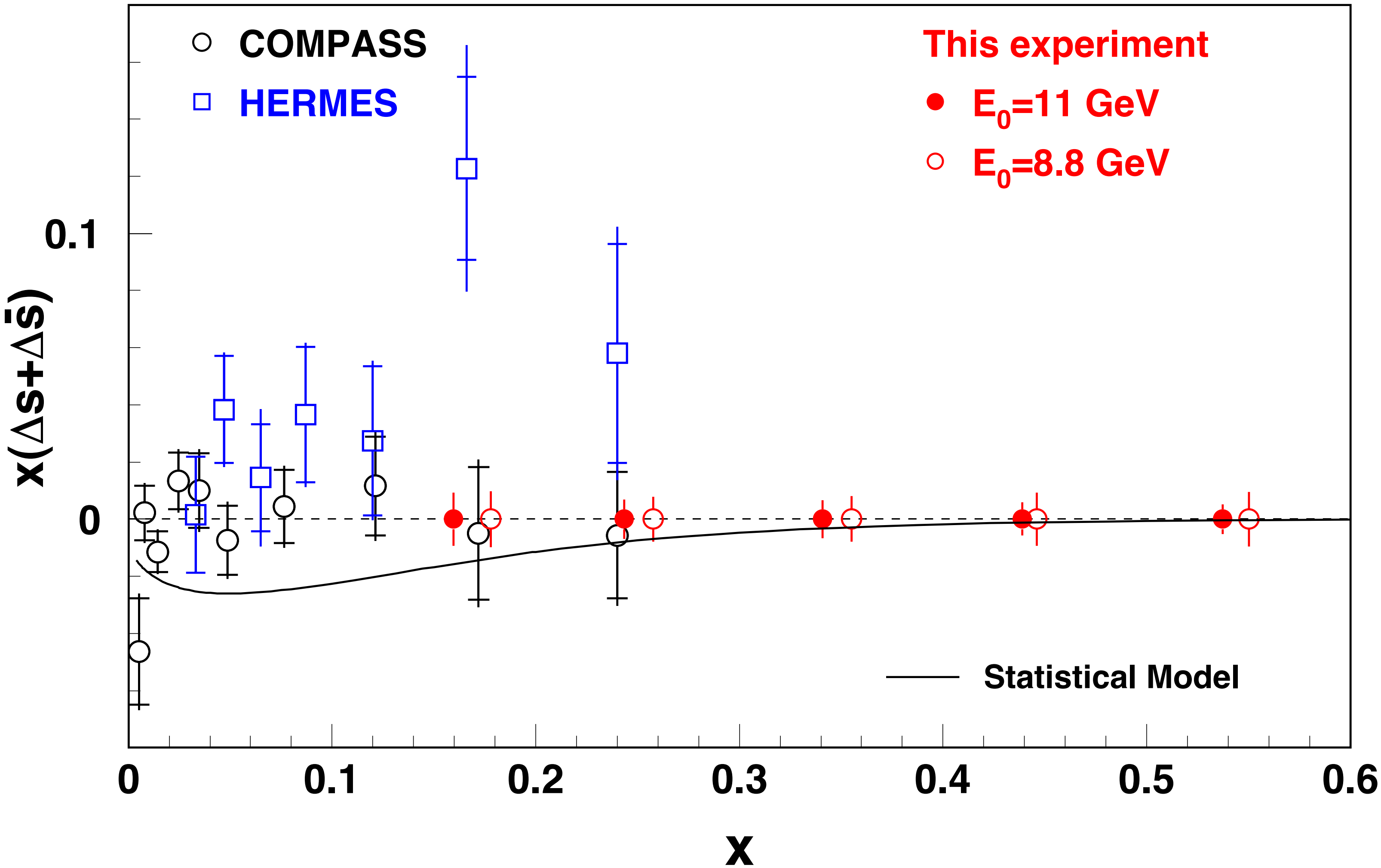
$$\Delta\bar{d}/\bar{d} \stackrel{?}{=} 0$$

Potential of Discovery $\Delta\bar{d}/\bar{d} \stackrel{?}{=} 0$

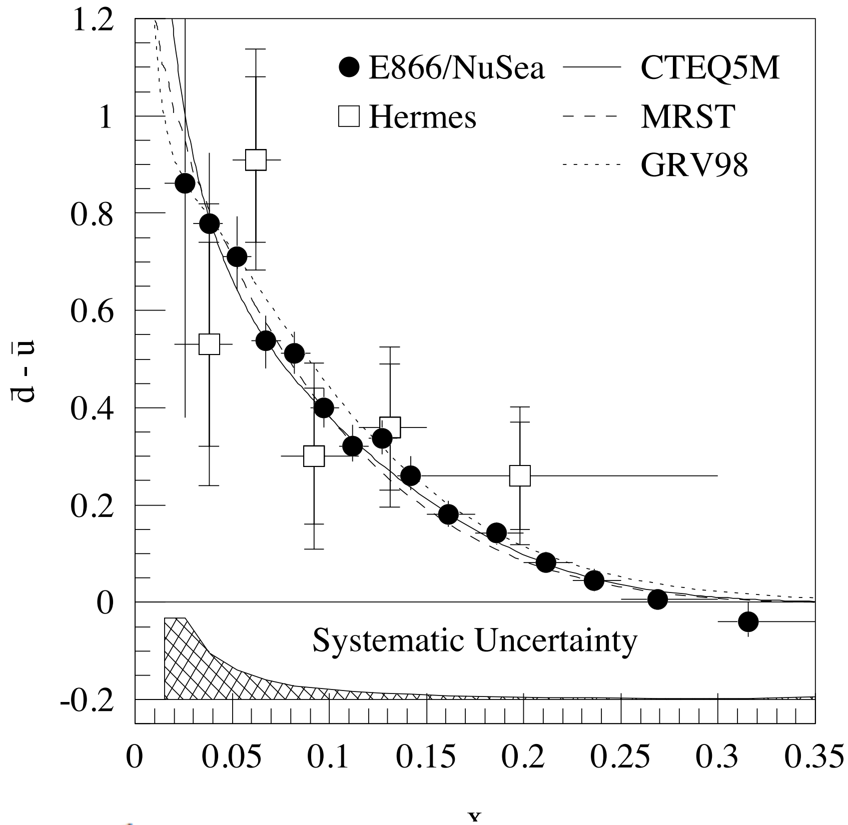


Leading-Order "Purity" Method

Sensitivity to Strangeness

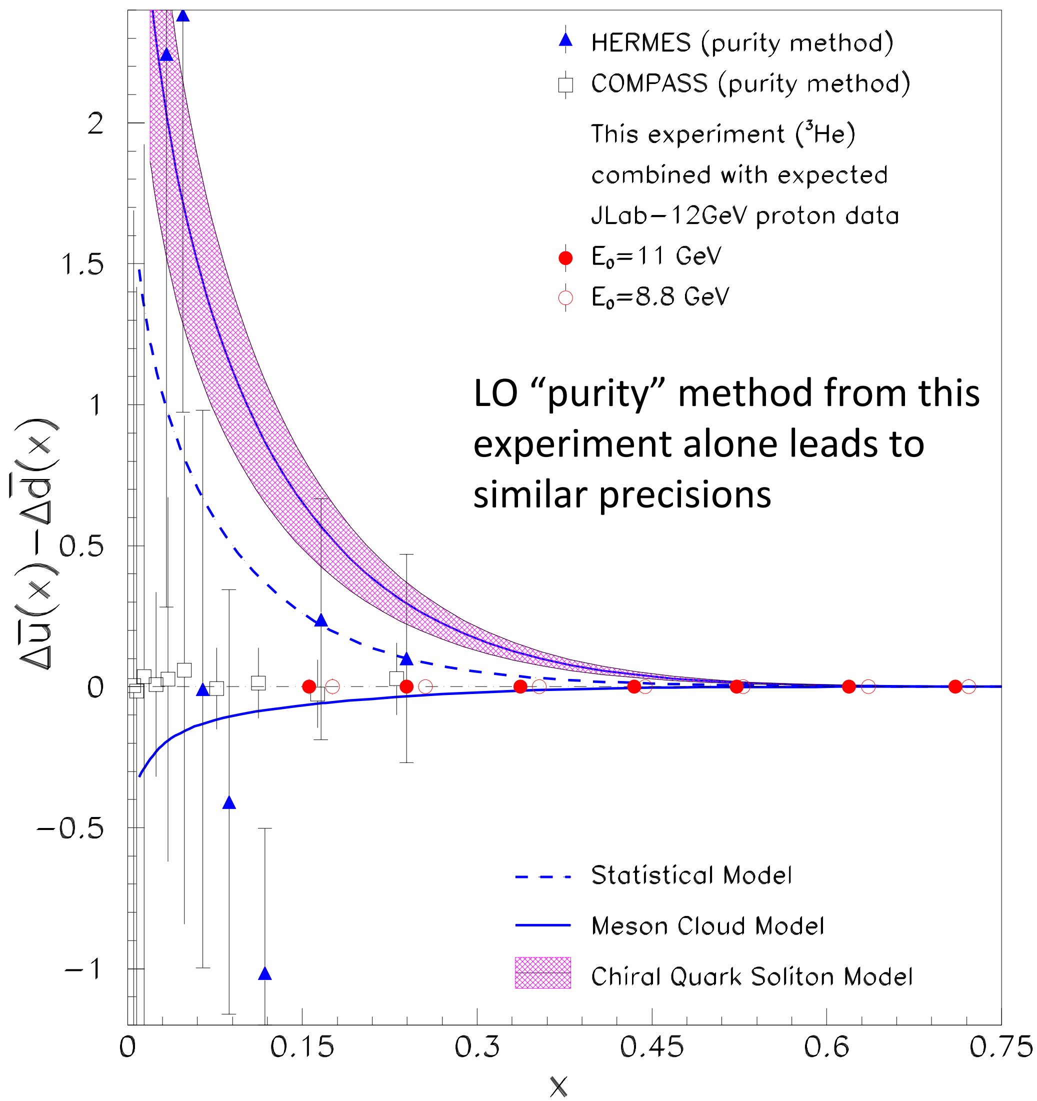


Assuming LO interpretation, and known Frag. Func.



$\int_0^1 (\bar{d} - \bar{u}) dx = 0.118 \pm 0.012.$

Many models explain $\bar{d} - \bar{u}$, including the meson-cloud model (π) which predicts $\Delta\bar{u} = \Delta\bar{d} = 0$.



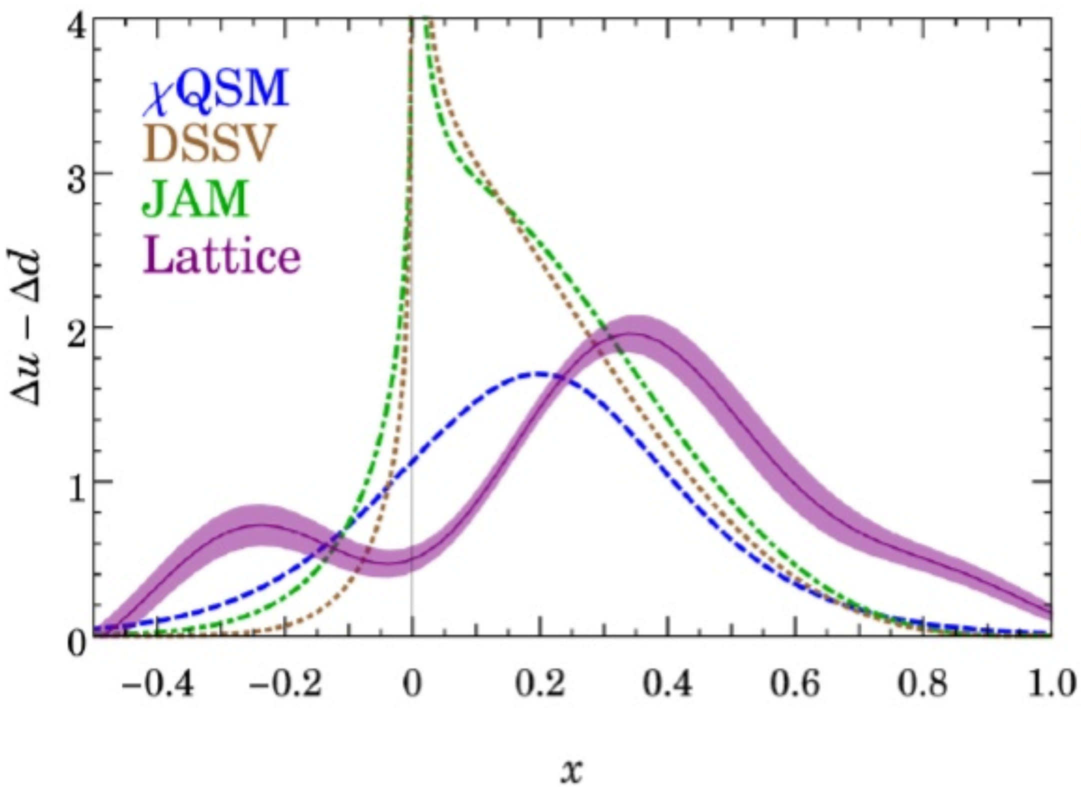
LO "purity" method from this experiment alone leads to similar precisions

Pauli-blocking model: $\int_0^1 [\Delta\bar{u}(x) - \Delta\bar{d}(x)] dx = \frac{5}{3} \cdot \int_0^1 [\bar{d}(x) - \bar{u}(x)] dx \approx 0.2.$

Polarized sea flavor asymmetry: non-perturbative in nature, intrinsic property of nucleon.

Helicity Distribution

§ Exploratory study



Removing
$O(M_N^n/P_z^n)$ errors + $O(\alpha_s)$

D. de Florian et al.
PRD 80, 034030 (2009)

P. Jimenez-Delgado et al.
arXiv:1310.3734 (2013)

- We found $\Delta\bar{u} > \Delta\bar{d}$ with large sea asymmetry

$$\int dx\, \left(\Delta\bar{u}(x) - \Delta\bar{d}(x)\right) \approx 0.24(6)$$

Summary: Δq Experiment

Precision A^h_{1n} and multiplicity data on a dense grid of (x,Q^2,z):

- Strong constraints on Δq through NLO QCD global fits.
- Leading-Order "purity"-method Δq extraction, as in HERMES and COMPASS.
- Flavor non-singlet observables which are only sensitive to valence Δq_v
- Self-consistency cross-checks to set limits on interpretation systematics.

Complimentary to CLAS12 SIDIS measurements on NH_3 and ND_3 targets.
Complimentary to SoLID ^3He target, with a higher-Q^2 coverage

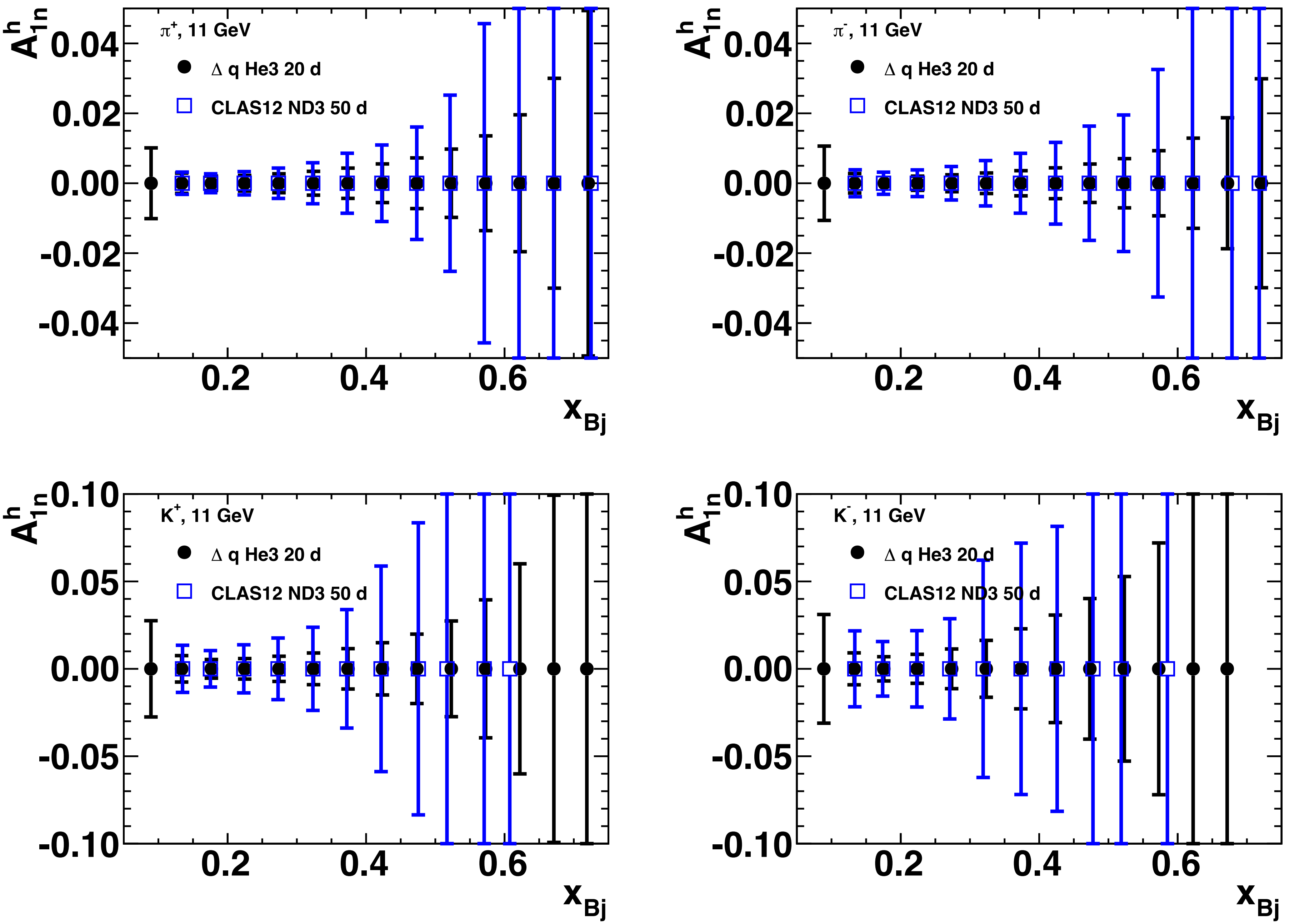
STAR W^- data suggests a non-vanishing sea polarization:

$\Delta\bar{u} > 0,\ \Delta\bar{u} > \Delta\bar{d}\ ?$ **a major effort at RHIC, a DOE milestone**

Neutron A^h_{1n} is most sensitive to $\Delta \mathrm{d},\ \Delta\bar{\mathrm{d}}$

Potential of Discovery $\Delta\bar{d}/\bar{d} \stackrel{?}{=} 0$

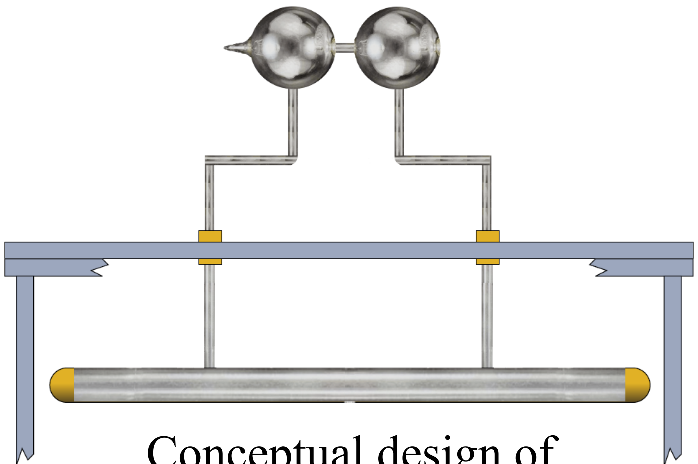
SBS project has been approved by DOE.
Target, spectrometer and detector constructions are underway.
Can run within the first five years of JLab-12GeV.



π+, 11 GeV
Δ q He3 20 d
CLAS12 ND3 50 d
π-, 11 GeV
K+, 11 GeV
K-, 11 GeV
A^h_{1n}
x_{Bj}

Backup Slides

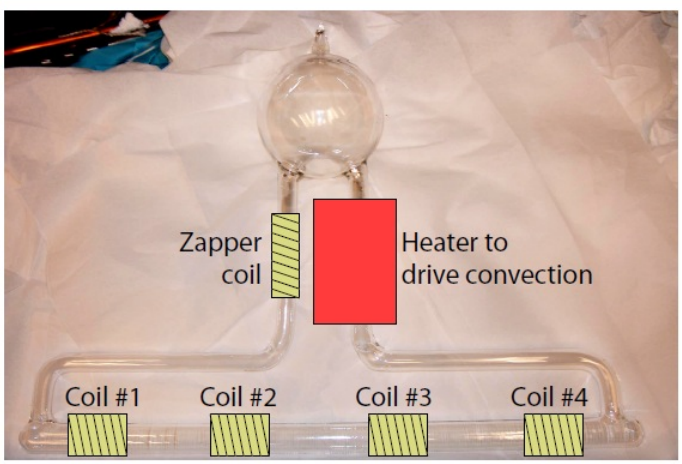
High-Luminosity Polarized ^{3}He Target

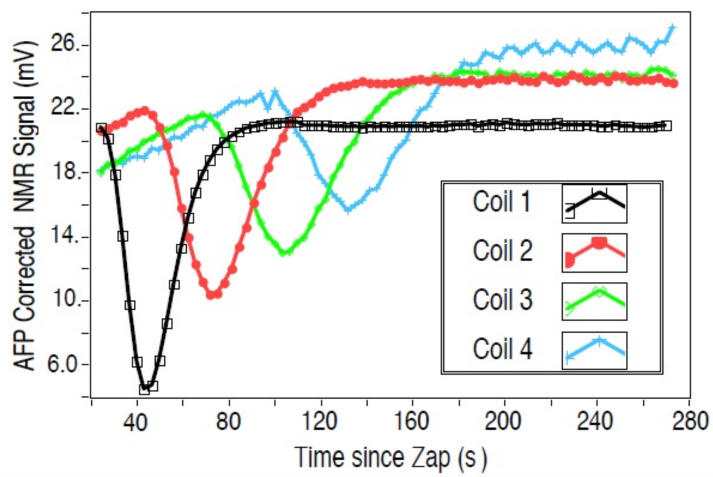


Conceptual design of SIDIS target w/metal end windows

Basic Target Parameters:

- Polarization: 60-65% based on alkali-hybrid spin-exchange optical pumping technology
- Beam current: 40 μA
- Target cell length along beam-line: 60 cm
- Electron-polarized neutron luminosity:
- Luminosity * Pol.^{2} capability upgraded (relative to previous targets) by using convection-driven circulation of gas between "pumping chamber" and "target chamber" (already demonstrated in bench tests) and metal end-windows to prevent cell rupture (under development)
- Spin orientation in "any" direction; holding field ~25 G
- Fast spin rotation: Change spin orientation every ~120 s.

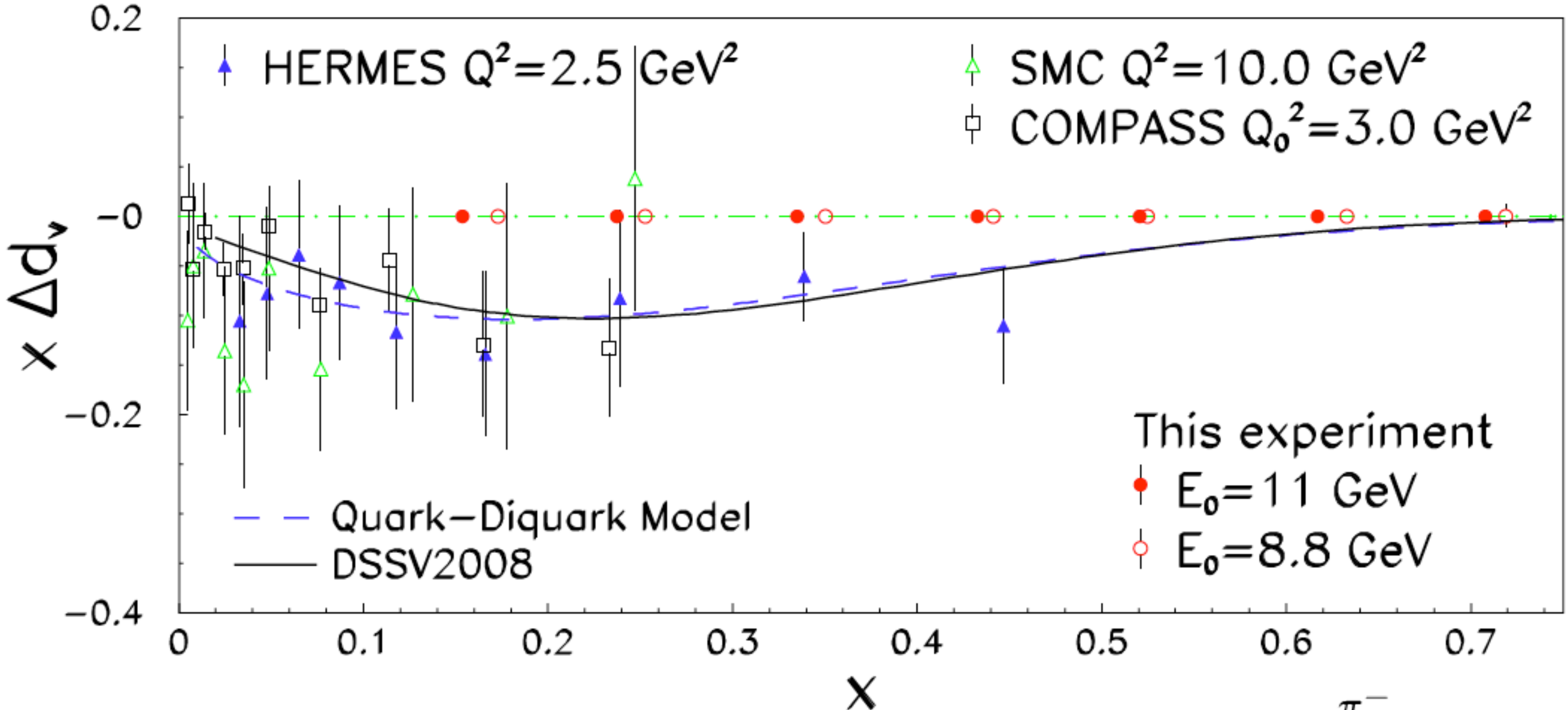




Same as in SBS-Transversity (E12-09-018), except target spin in longitudinal direction.

Leading-Order Christova-Leader Method

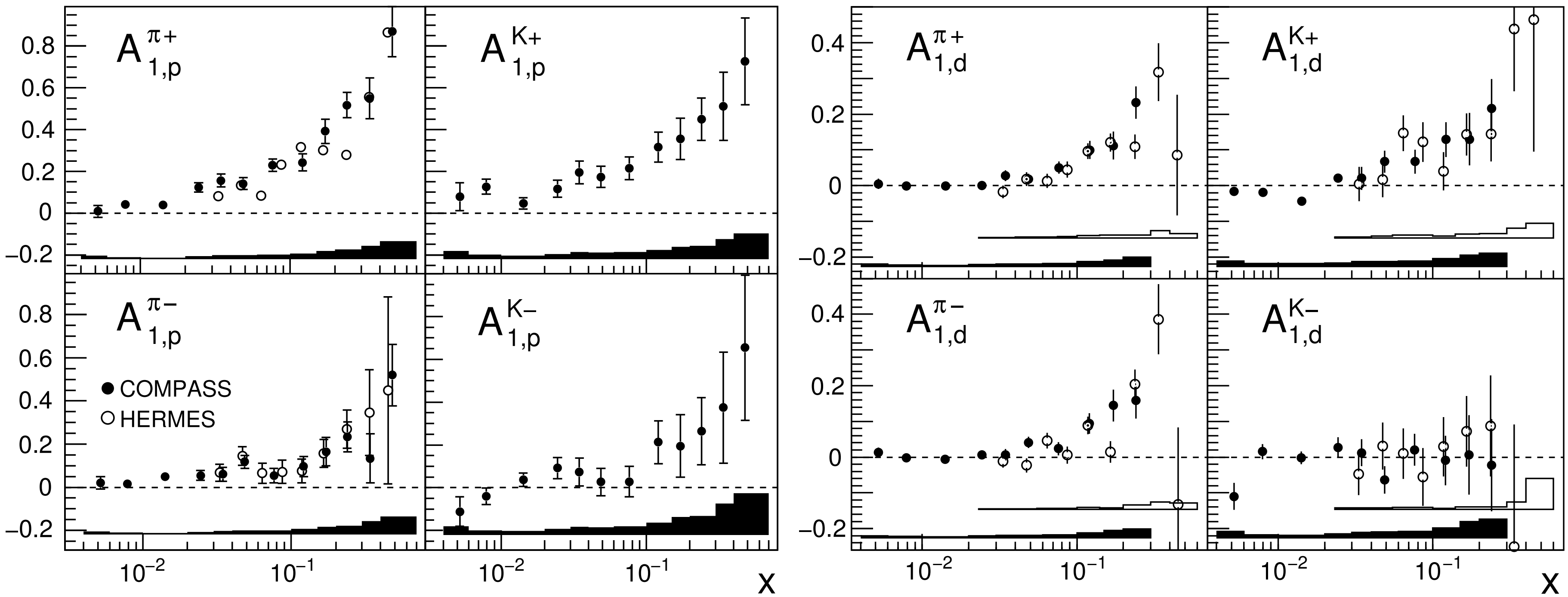
$$(\Delta d_v - \tfrac{1}{4}\Delta u_v)_{LO} = \frac{1}{4}(7u_v + 2d_v)\, A_{1He}^{\pi^+-\pi^-}$$



$$A_{1He}^{\pi^+-\pi^-} = \frac{\Delta\sigma_{He}^{\pi^+} - \Delta\sigma_{He}^{\pi^-}}{\sigma_{He}^{\pi^+} - \sigma_{He}^{\pi^-}} = \frac{A_{1He}^{\pi^+} - A_{1He}^{\pi^-}\cdot r}{1-r}. \quad r = \frac{\sigma_{He}^{\pi^-}}{\sigma_{He}^{\pi^+}}$$

$$[\Delta\bar{u}(x) - \Delta\bar{d}(x)]_{LO} = 3\,[g_1^p(x) - g_1^n(x))] - \frac{1}{2}(\Delta u_v - \Delta d_v)|_{LO}$$

HERMES and COMPASS A^h_{1N}



Solve for $\vec{A} = \mathcal{P}^h_f(x) \cdot \vec{Q}$

$$\vec{A} = \left(A^{\pi^+}_{1p}, A^{\pi^-}_{1p}, A^{\pi^+}_{1d}, A^{\pi^-}_{1d}, A^{K^+}_{1d}, A^{K^-}_{1d}, A_{1p}, A_{1d}\right)$$

Assume:

Leading order x-z separation and current fragmentation.

Isospin symmetry and charge conjugation.

Purity from Monte Carlo.