Parton Distributions from DIS (JLab/EIC)

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Workshop on Parton Distributions in Modern Era, Peking University, July 14-16, 2017

- Introduction
- Unpolarized PDFs: d/u @ high-x, sea asymmetry, strange sea
- Polarized PDFs: A1 @ high-x, d2 moments
- 3-d Structure Study: TMDs, GPDs
- JLab12 - SoLID Experiments
- Future - Electron Ion Collider
- Summary

Introduction

Nucleon Structure and DIS

JLab and 12 GeV Energy Upgrade

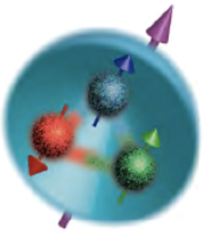
Nucleon Structure

- Nucleon: proton =(uud) , neutron=(udd) **_+ sea quarks + gluons_**
- Nucleon: **_99% of the visible mass in universe_**

➢ **Proton momentum (unpolarized PDFs)**

Quarks carry **~ 50%** of proton's momentum

Glue carry the rest of the momentum



➢ **Proton spin "puzzle" (polarized PDFs)**

Quarks carry $\sim 30\%$ of proton's spin

How does quark and gluon dynamics generate the rest of the proton spin?

➢ **3D structure of nucleon: 3D in momentum or (2D space +1 in momentum)**

Color Confinement Asymptotic freedom

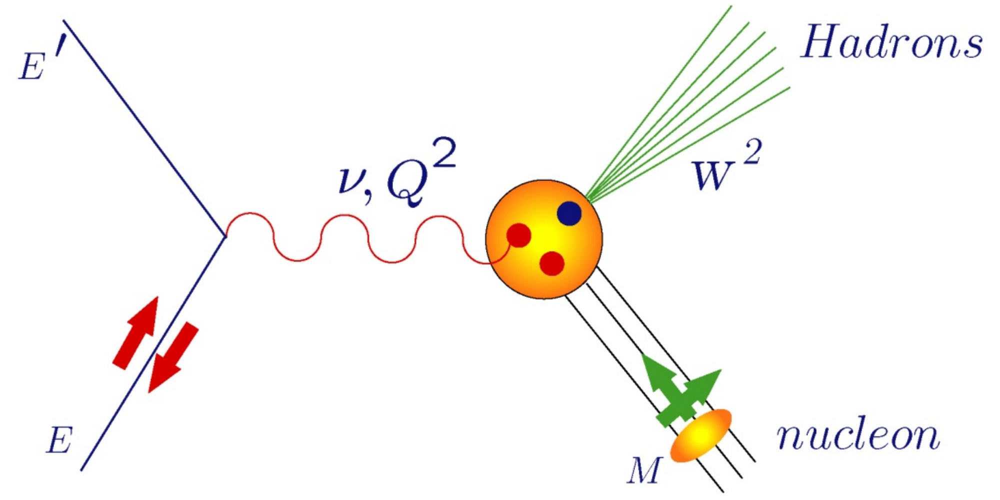
Q (GeV)

200 MeV (1 fm) 2 GeV (1/10)

Probing momentum

How does the glue bind quarks and itself into a proton and nuclei?
Can we scan the nucleon to reveal its 3D structure?

Polarized Deep Inelastic Electron Scattering



$x = \dfrac{Q^2}{2M\nu}$ Fraction of nucleon momentum carried by the struck quark

Q^2 = 4-momentum transfer of the virtual photon, ν = energy transfer, θ = scattering angle

- All information about the nucleon vertex is contained in

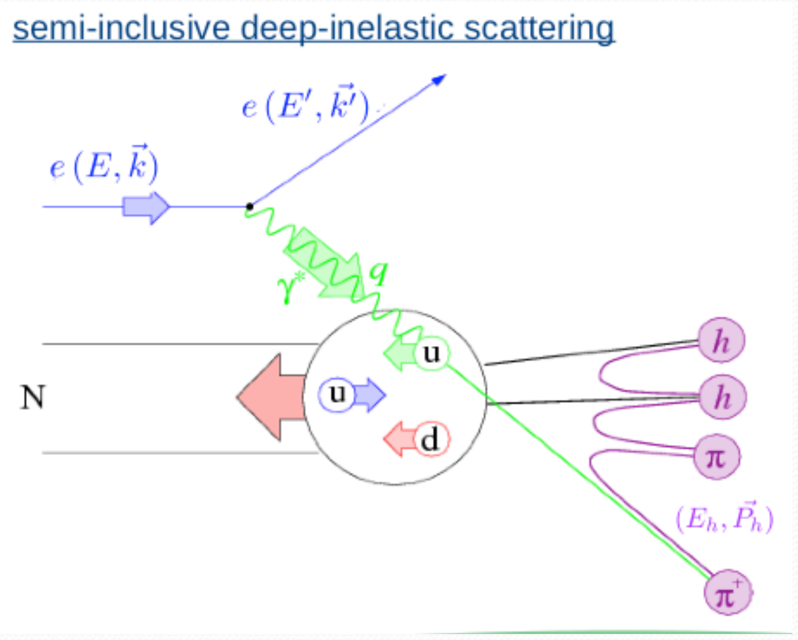
F_2 and F_1 the unpolarized (spin averaged) structure functions,

and

g_1 and g_2 the spin dependent structure functions

Inclusive, Semi-Inclusive and Exclusive Processes

- Inclusive electron scattering: only detect scattered electron
  - elastic: form factors
  - excitations: resonances, new states search
  - DIS: structure functions, parton distributions (PDFs), spin distributions (polarized PDFs)
- Semi-inclusive: detect one additional particle
  - SIDIS: flavor tagging, spin-flavor structure
  - transverse momentum dependent distributions (TMDs)
- Exclusive: all final states are determined
  - deep-virtual Compton Scattering (DVCS), …
  - → generalized parton distributions (GPDs)



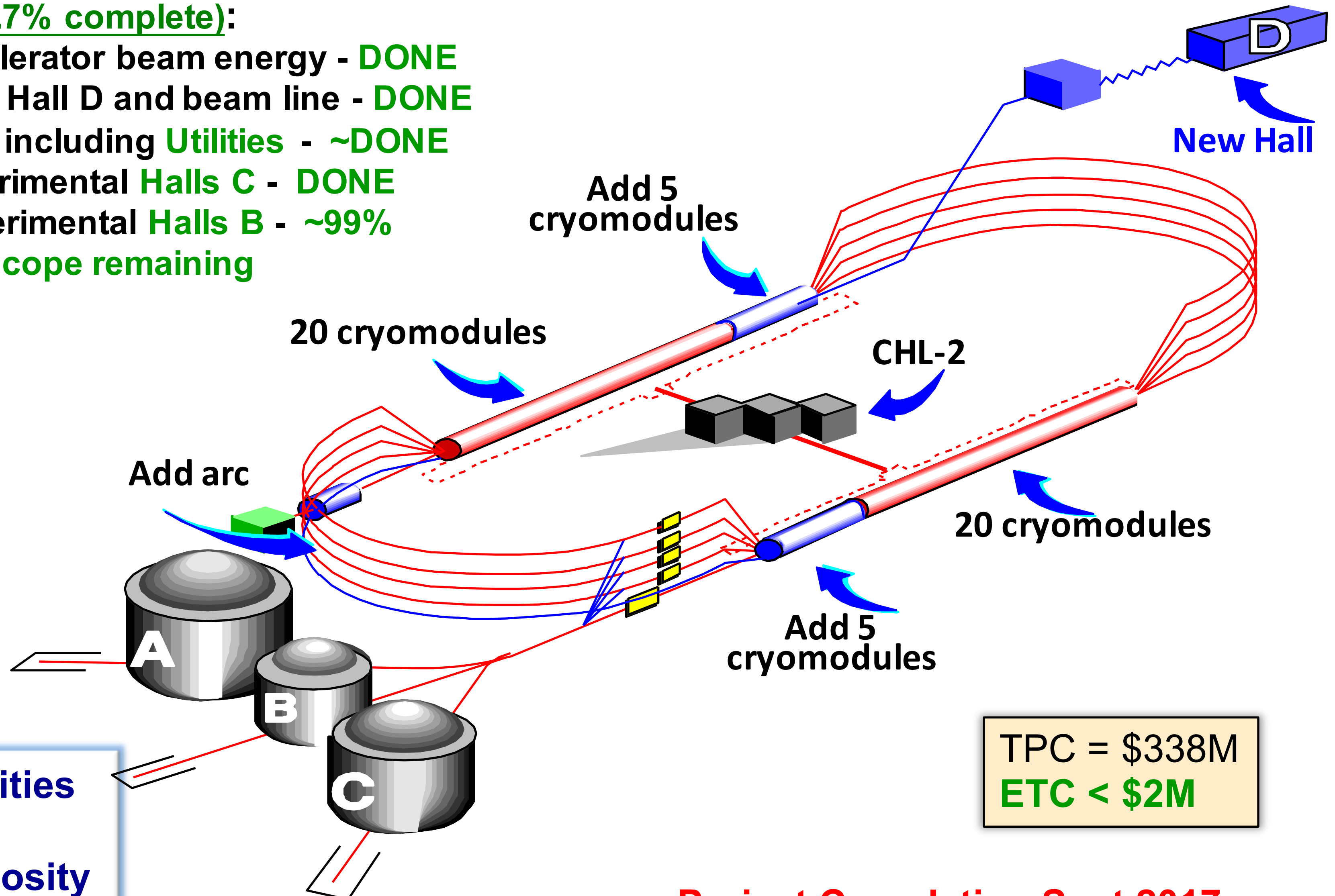
JLab and 12 GeV Energy Upgrade

Experimental Hall Detector Upgrade

12 GeV Upgrade Project

Project Scope (~99.7% complete):

- Doubling the accelerator beam energy - DONE
- New experimental Hall D and beam line - DONE
- Civil construction including Utilities - ~DONE
- Upgrades to Experimental Halls C - DONE
- Upgrades to Experimental Halls B - ~99%
  - Solenoid only scope remaining



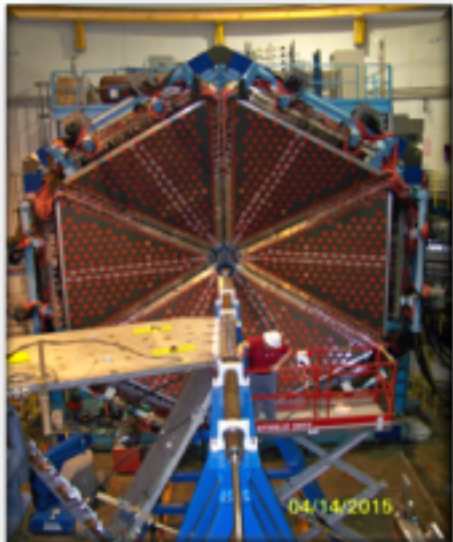
- Enhanced capabilities in existing Halls
- Increase of Luminosity 10^{35} - ~10^{39} cm^{-2}s^{-1}

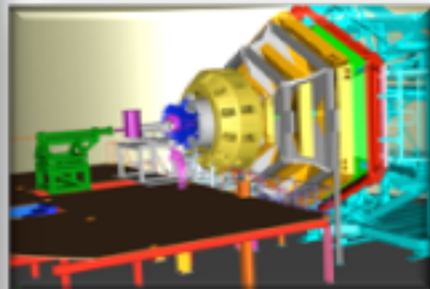
TPC = $338M
ETC < $2M

Project Completion Sept 2017

12 GeV Scientific Capabilities

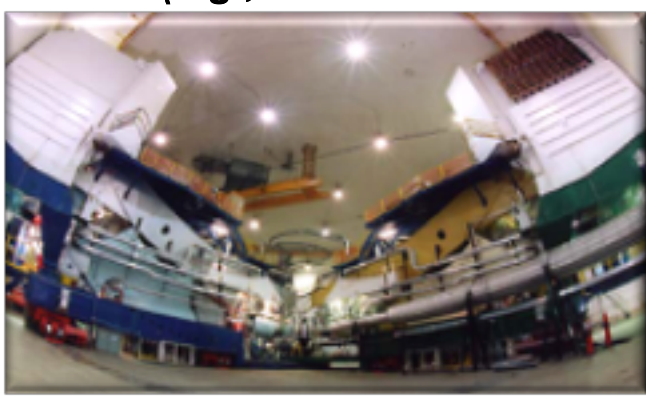
Hall B – understanding nucleon structure via generalized parton distributions

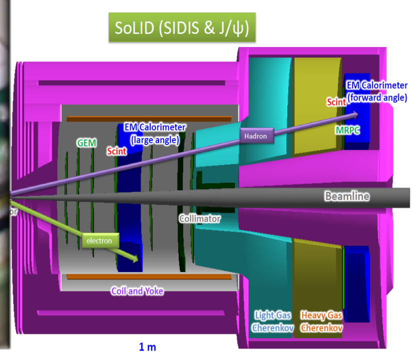




Hall D – exploring origin of confinement by studying exotic mesons

Hall A – form factors, future new experiments (e.g., SoLID and MOLLER)





Hall C – precision determination of valence quark properties in nucleons/nuclei

Unpolarized Parton Distributions

Valence Quark Structure: d/u @ High-x

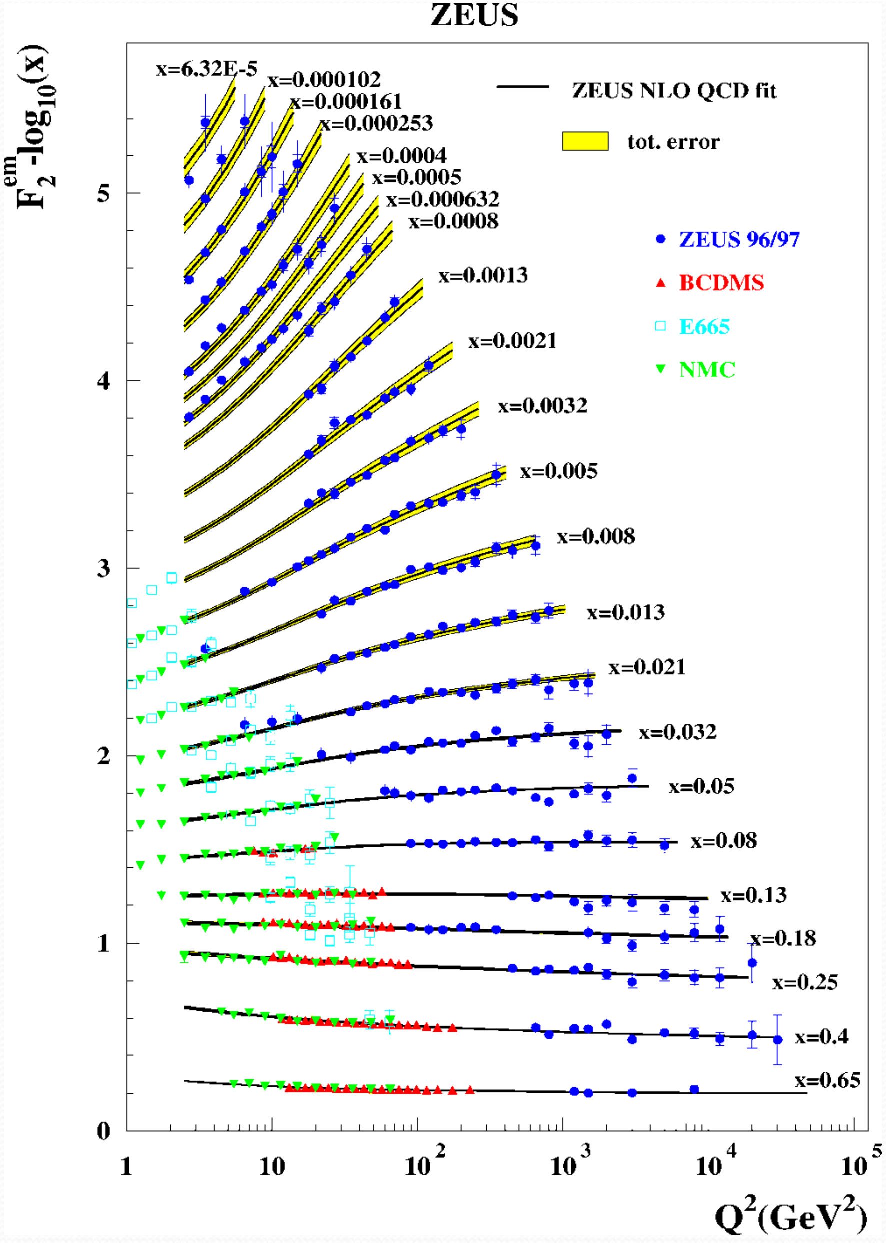
Sea Quark Flavor Distributions:

Light Sea Asymmetry, Strange Sea

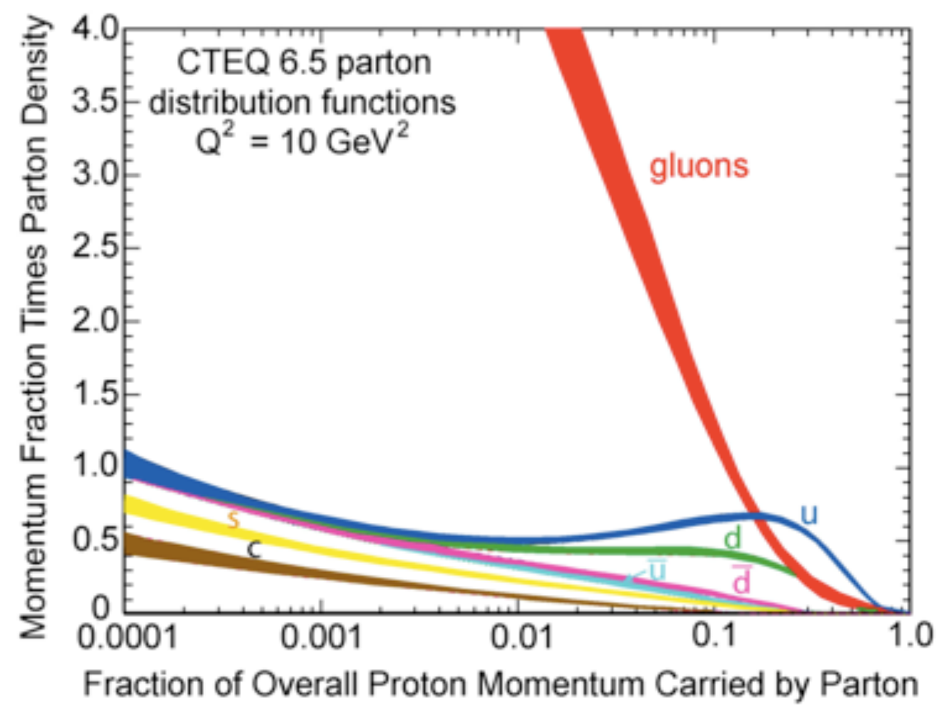
Unpolarized Structure Function F_2

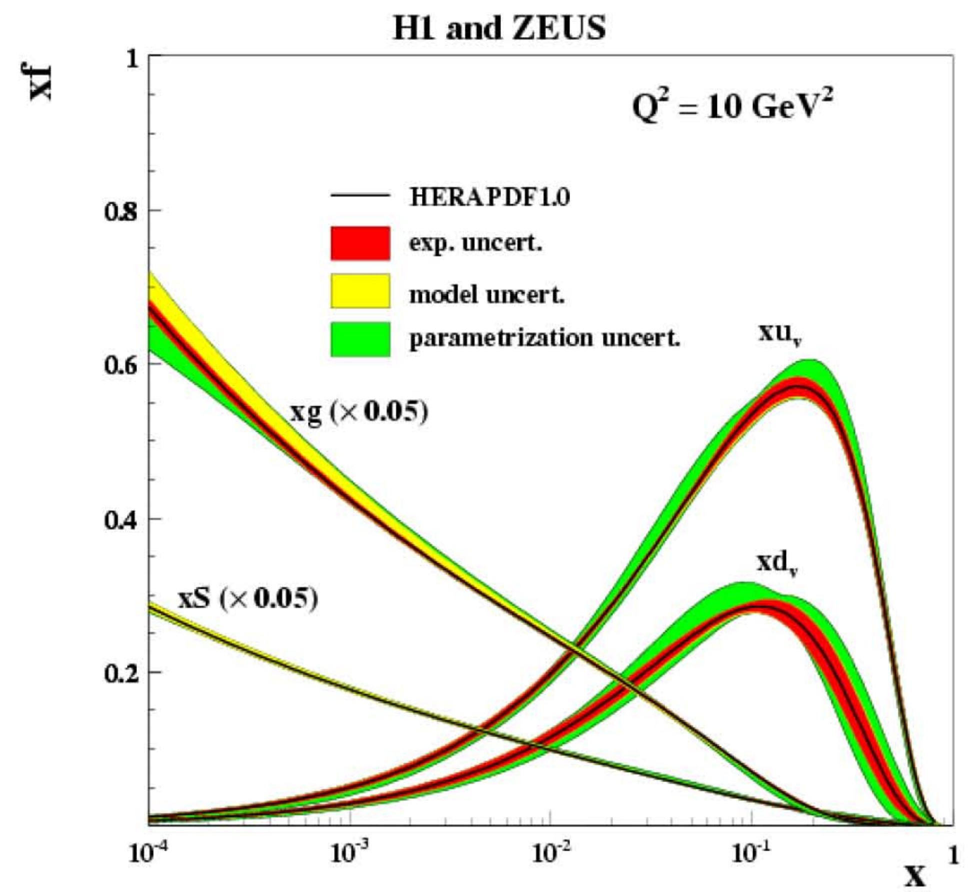
- **Bjorken Scaling**
- **Scaling Violation**
- **Gluon radiation –**
- **QCD evolution**

  NLO: Next-to-Leading-Order
- **One of the best experimental tests of QCD**



Unpolarized Parton Distribution Functions





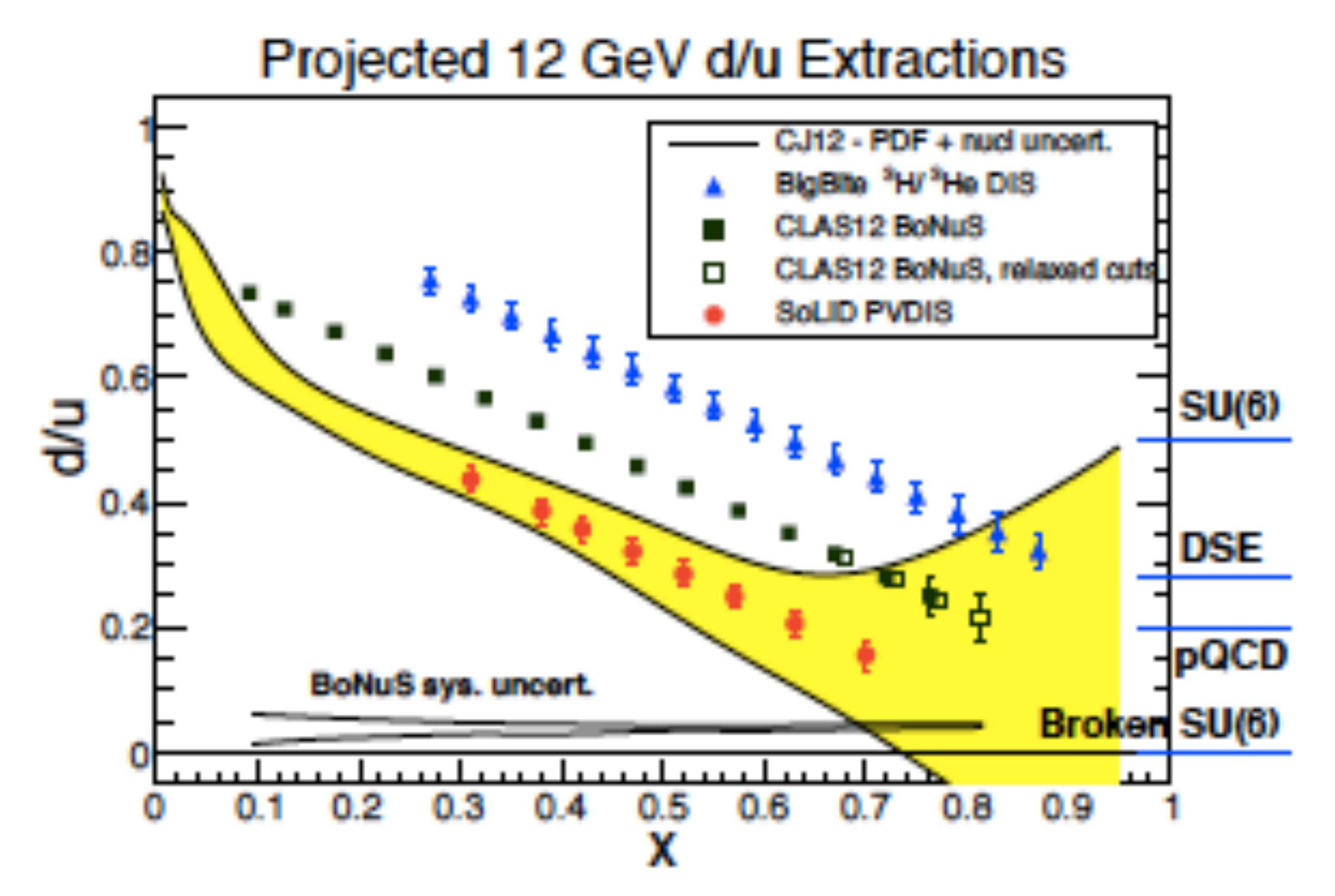
valence
region

Valence Quark Distributions: d/u@ High-x

High-x: valence quark dominating, clean region to study valence behavior

d/u at high-x, not well-known due to large nuclear effect using effective neutron target

JLab 12: 1) Hall A $^{3}H/^{3}He$; 2) BONUS @ CLAS12, 3) SoLID PVDIS-proton

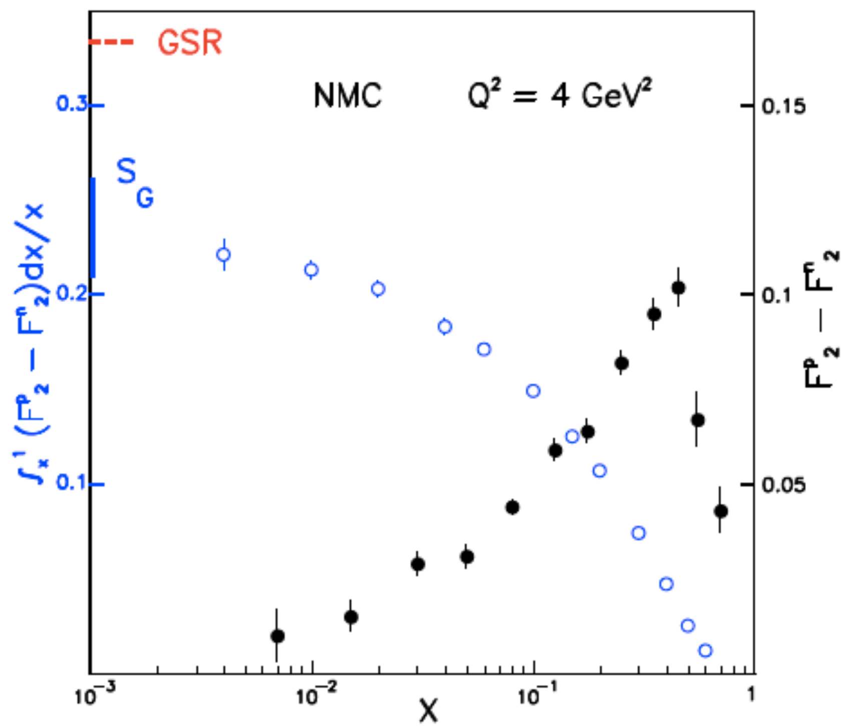


1) Hall A $^{3}H/^{3}He$: super ratio to minimize nuclear effect (this fall)
2) BONUS @ CLAS12 tag back scattering slow proton to minimize nuclear effect in deuteron
3) SoLID PVDIS-proton director probe d/u in proton using gamma and Z exchanges (without effective neutron)

Proton Sea not SU(3) Symmetric

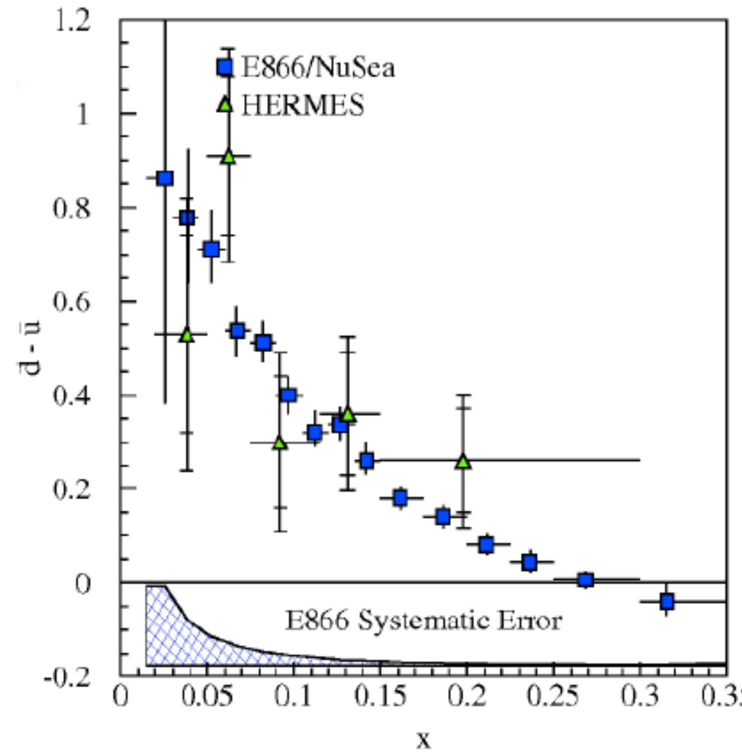
- The proton sea is not SU(3) symmetric!

Violation of Gottfried sum rule



$$S_G = \int_0^1 [(F_2^p(x) - F_2^n(x))/x]dx$$
$$= \frac{1}{3} + \frac{2}{3}\int_0^1 (\bar{u}_p(x) - \bar{d}_p(x))\ dx$$
$$= \frac{1}{3} \quad (if\ \bar{u}_p = \bar{d}_p) \quad \text{NMC: } S_G = 0.235 \pm 0.026$$

Confirmed by Drell-Yan exp't



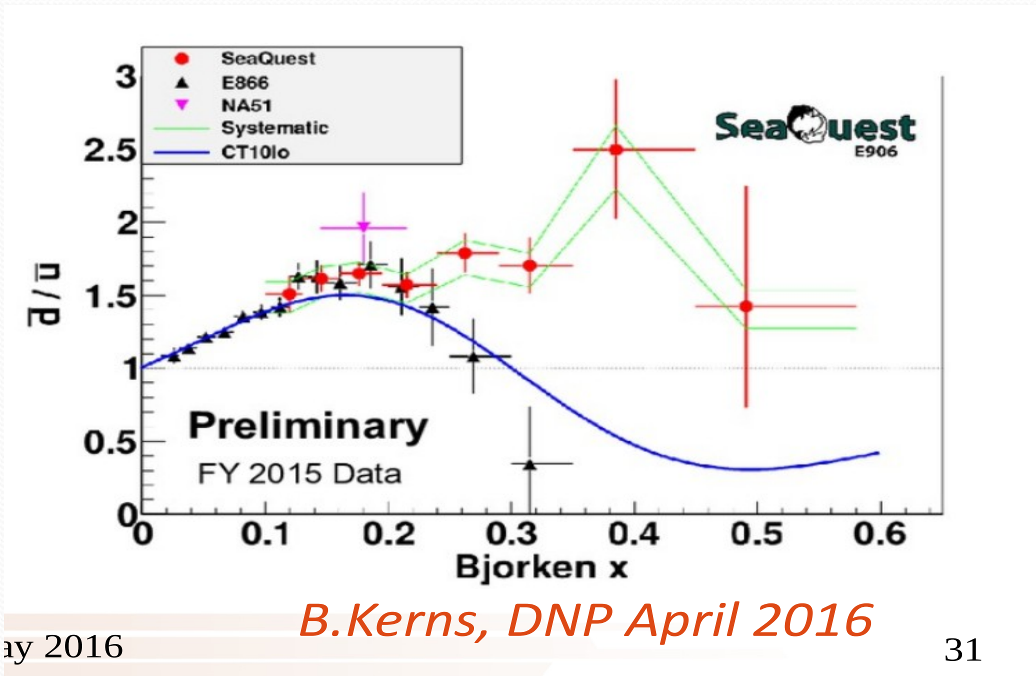
Why $\bar{d}(x) \neq \bar{u}(x)$ *?*

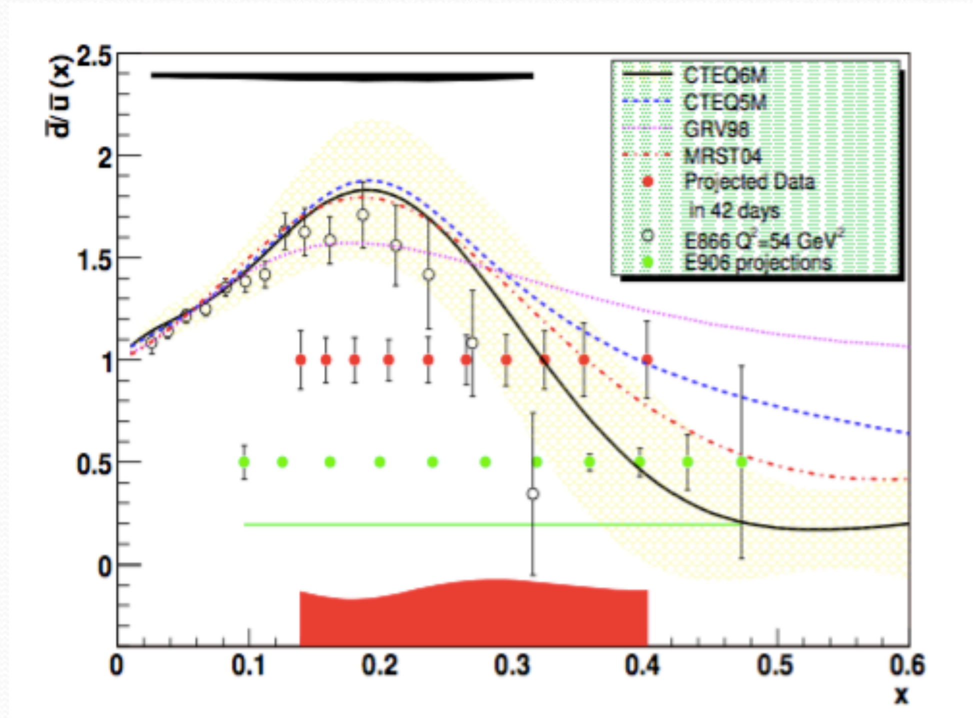
~~*Why*~~ *does* $\bar{d}(x) - \bar{u}(x)$ *change sign?*

Light Sea Quark Asymmetry: d_bar/u_bar

Fermi Lab SEAQUEST new results

JLab12: Possible SIDIS measurement,
Hall C proposal projections





Strange Sea

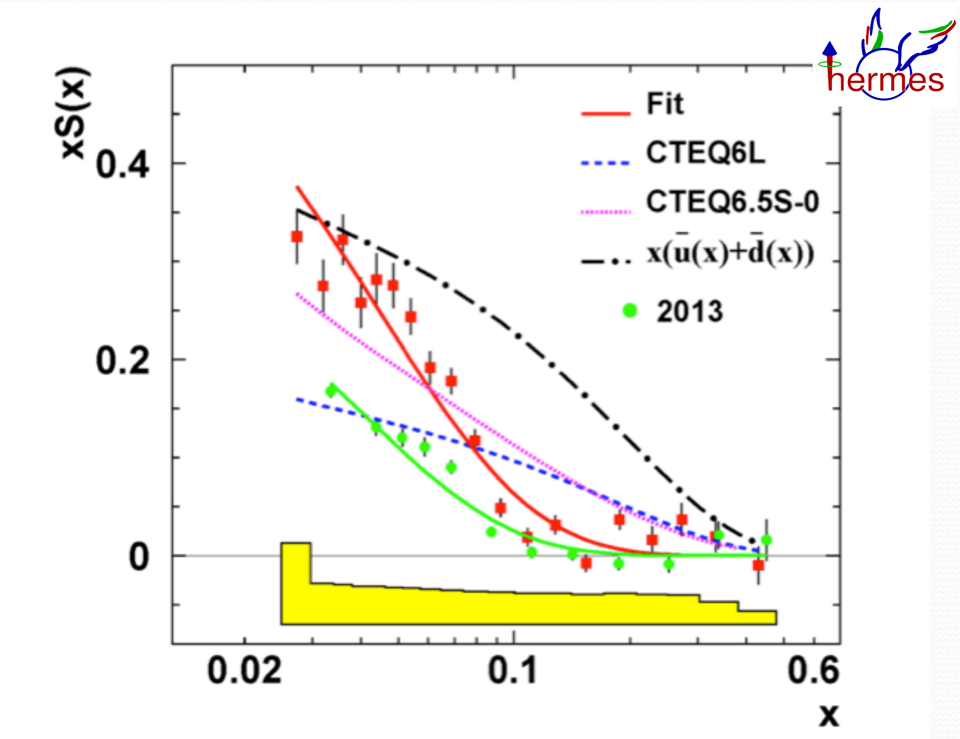
Need additional observable in addition to inclusive DIS on p and n

- ➢ Weak Interaction (Neutrino, PV) or SIDIS (Kaon)

SIDIS (Kaon): in current fragmentation region? HERMES, probably mostly not?

Issue with Kaon Fragmentation Function?

HERMES strange distributions: old vs new



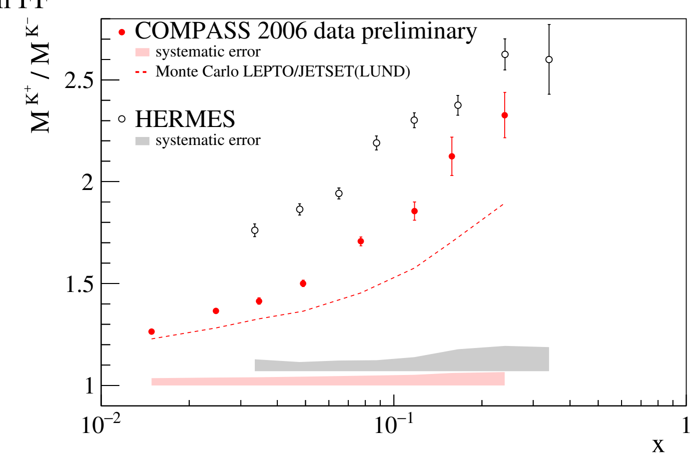
Comparison of Kaon Multiplicity Ratio

Kaon multiplicity ratio

- π case, there is a good agreement between COMPASS and HERMES for the π^+/π^- multiplicity ratio

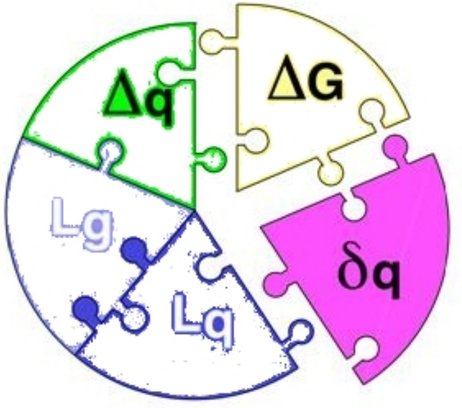
  Despite the difference in the shape of π multiplicity sum

- K case: clear discrepancy between COMPASS and HERMES even for the K^+/K^- multiplicity ratio
- DSS next fit of Kaon FF

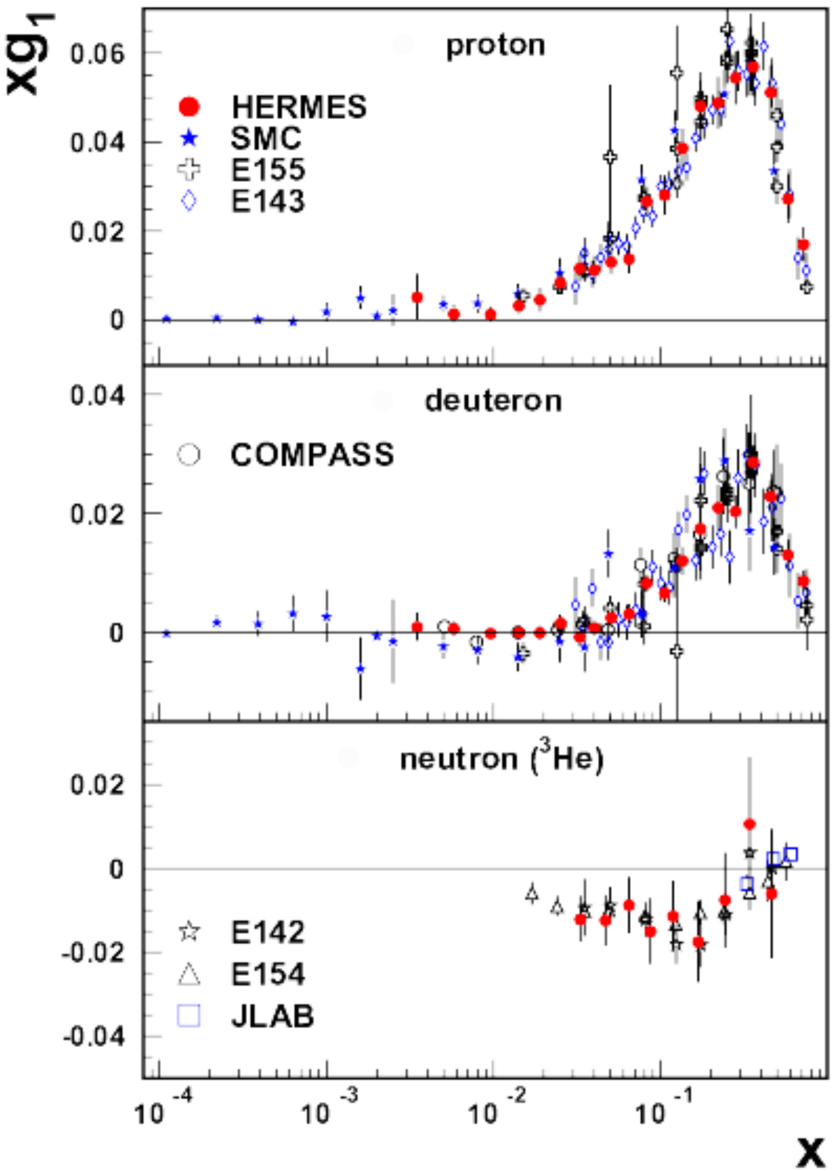


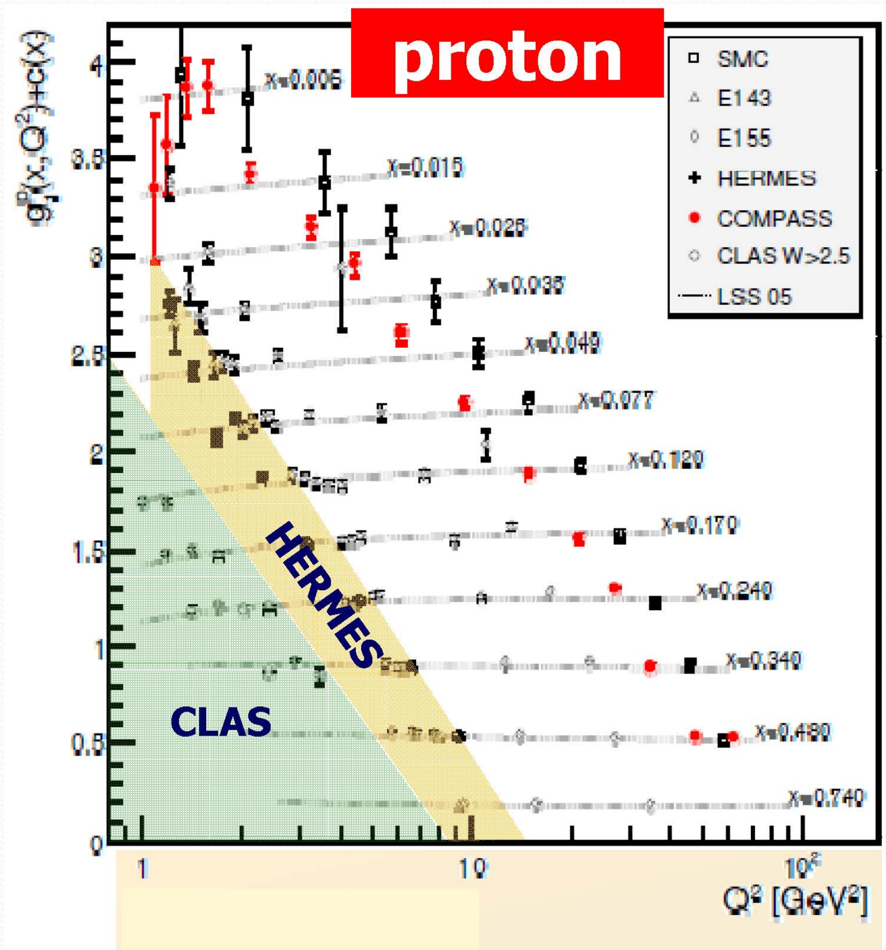
Nucleon Spin-flavor Structure

Valence Quark Flavor and Spin Distributions
Sea Quark Flavor-Spin Distributions
Gluon Spin Distribution



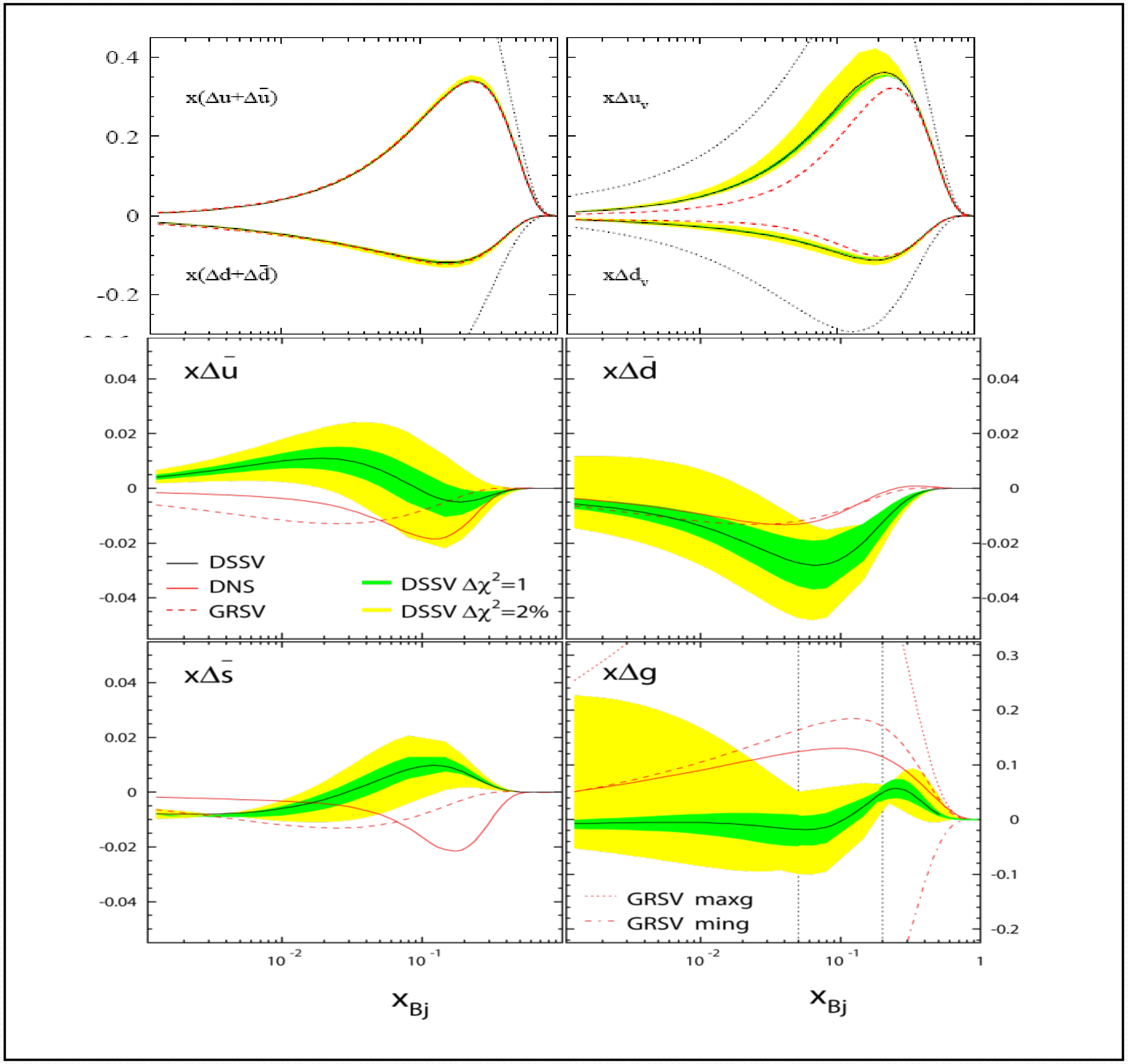
Polarized Structure functions





- Q^2 dependence of g_1 data

Polarized Parton Distributions



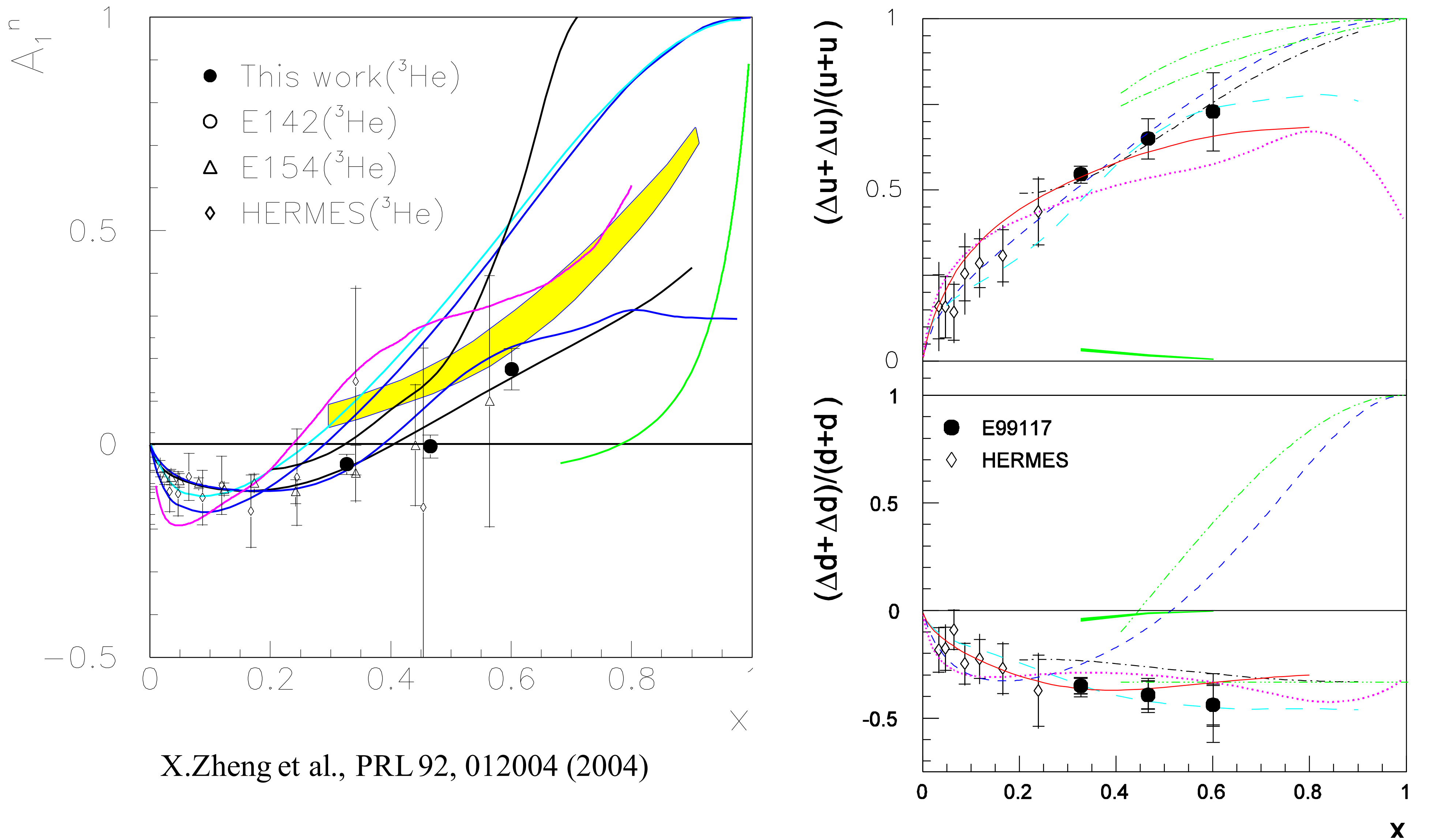
Nucleon Spin Structure Study

- 1980s: EMC (CERN) + early SLAC
  quark contribution to proton spin is very small
  $\Delta\Sigma$ = (12+-9+-14)%!   'spin crisis'
- 1990s: SLAC, SMC (CERN), HERMES (DESY)
  $\Delta\Sigma$ = 20-30%,   the rest: gluon and quark orbital angular momentum
  $$(1/2)\Delta\Sigma + L_q + \Delta G + L_G = 1/2$$
  gauge invariant $$(1/2)\Delta\Sigma + \mathcal{L}_q + J_G = 1/2$$
- 2000s: COMPASS (CERN), HERMES, RHIC-Spin, JLab, … :
  $\Delta\Sigma$ ~ 30%; ΔG contributes, orbital angular momentum significant
  Large-x (valence quark) behavior; Moments and sum rules
  Needs 3-d structure information to complete the proton spin puzzle

Reviews: Sebastian, Chen, Leader, arXiv:0812.3535, PPNP 63 (2009) 1;

JLab E99117: *Precision Measurement of A_1^n at High-x*

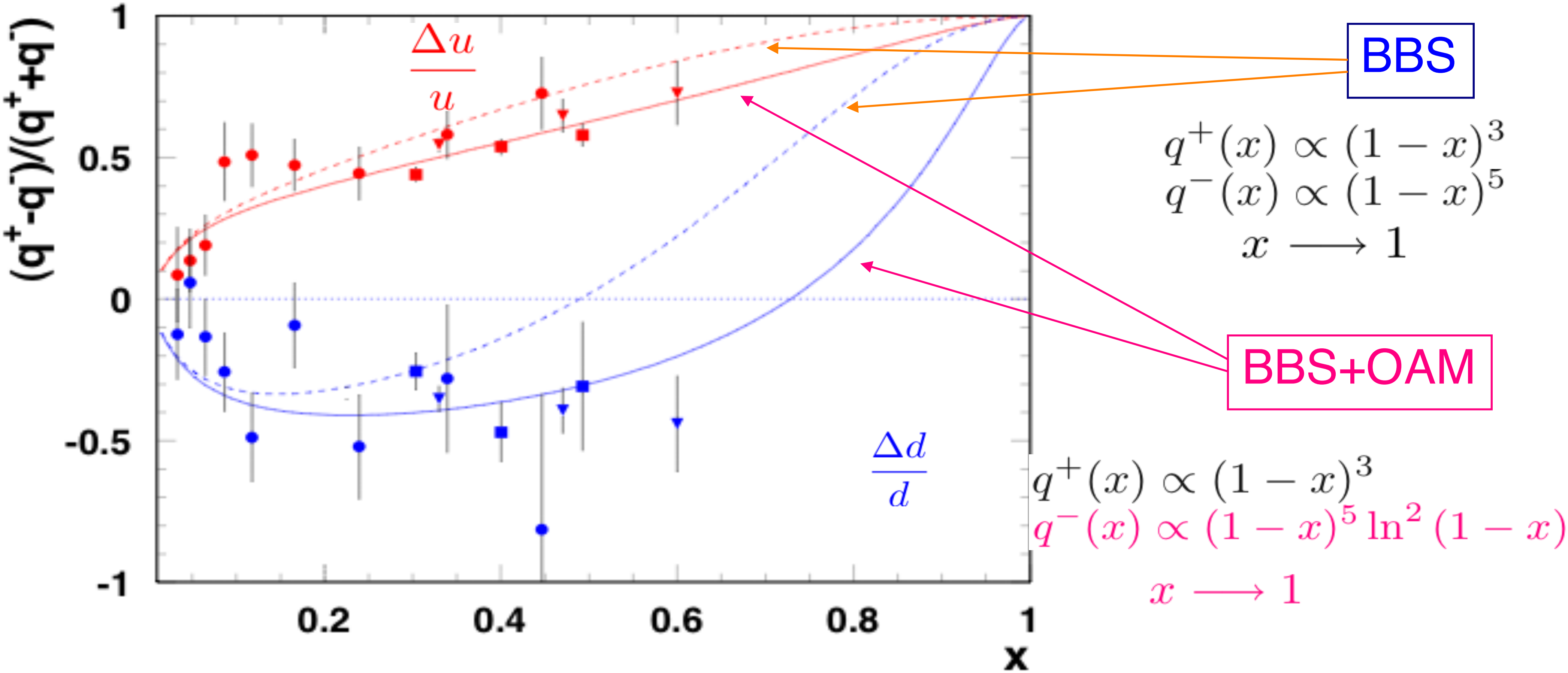
Valance Quark Flavor Separation



X.Zheng et al., PRL 92, 012004 (2004)

pQCD with Quark Orbital Angular Momentum

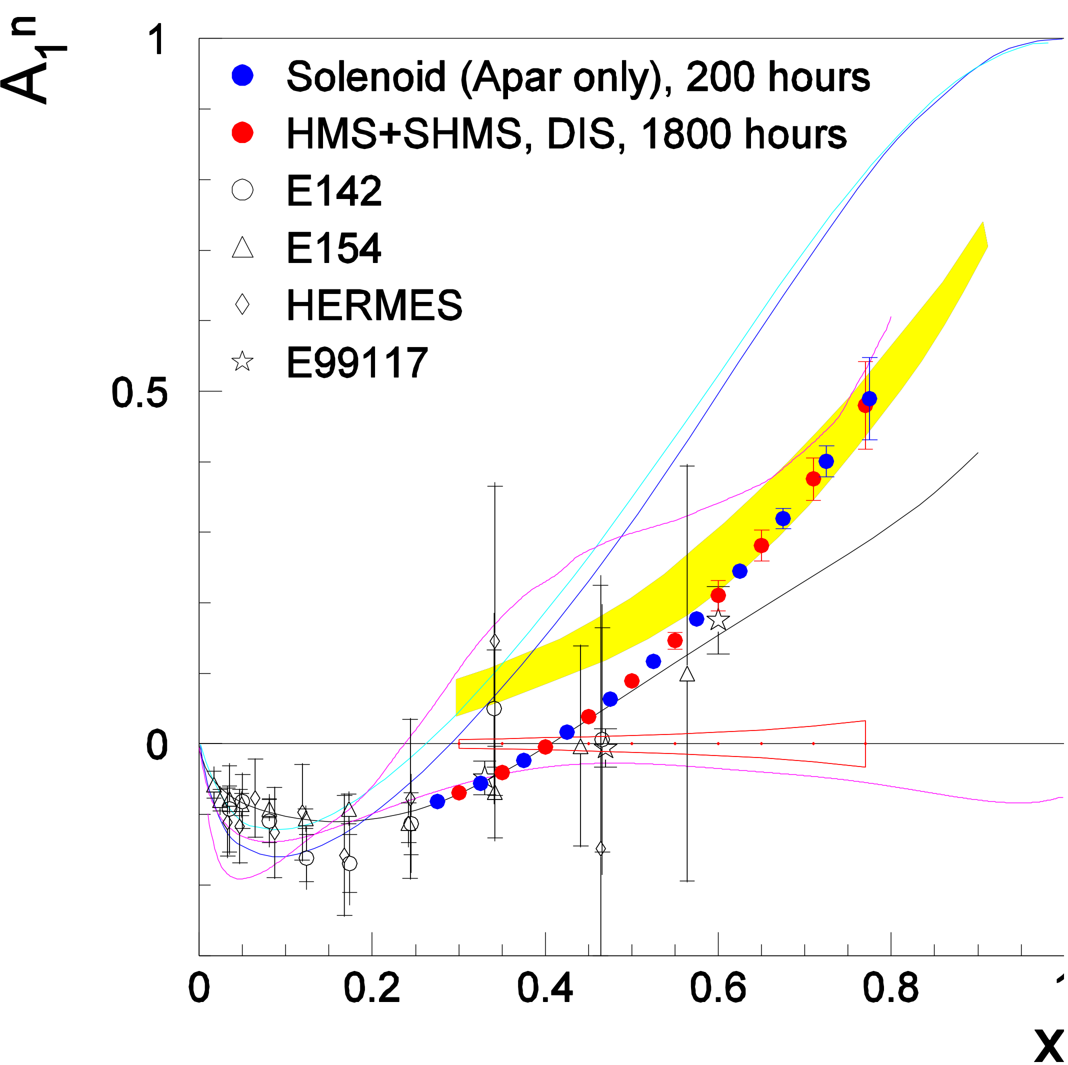
Inclusive Hall A and B and Semi-Inclusive Hermes



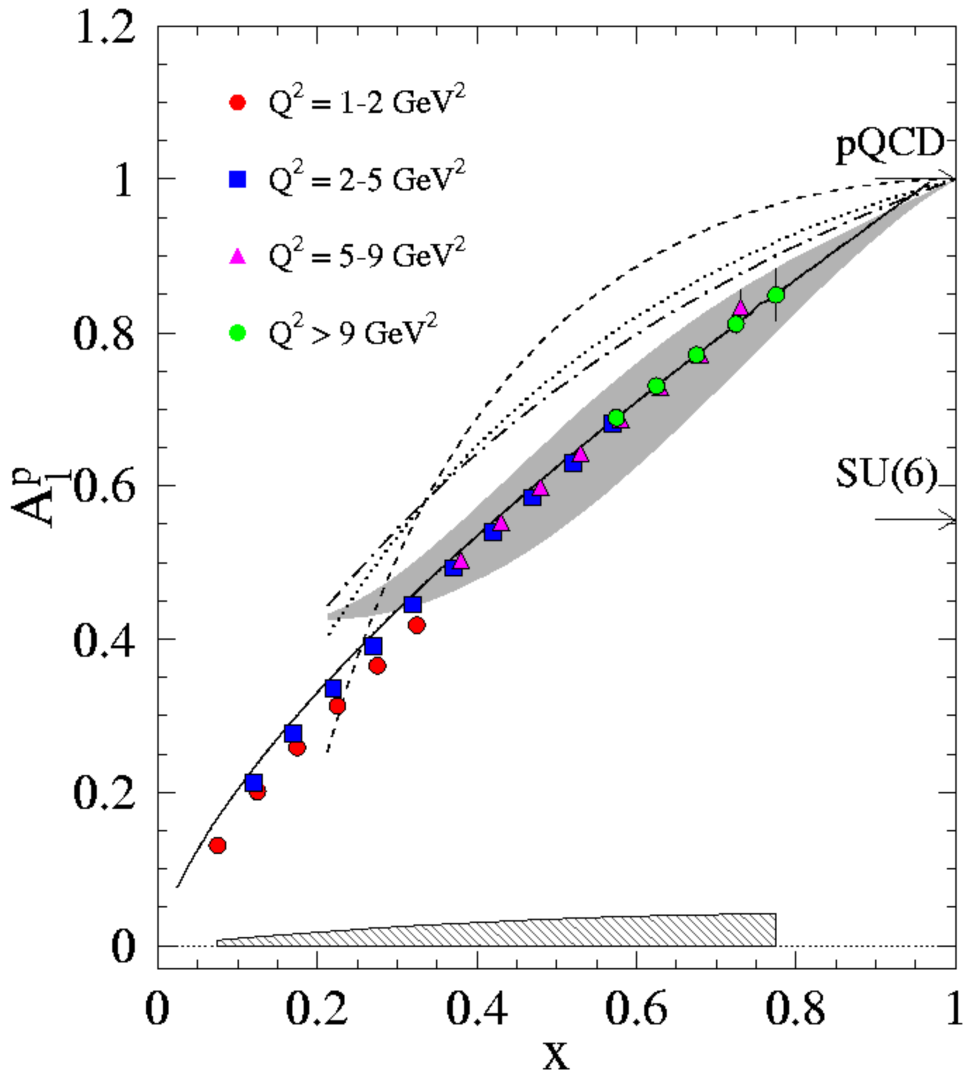
Avakian, Brodsky, Deur and Yuan,
PRL 99, 082001 (2007)

Projections for JLab at 11 GeV

A_1^n at 11 GeV



A_1^p at 11 GeV



g_2: twist-3, *q-g* correlations

- experiments: transversely polarized target

  SLAC E155x, (p/d)

  JLab Hall A (n), Hall C (p/d)

- g_2 leading twist related to g_1 by Wandzura-Wilczek relation

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(y,Q^2)\frac{dy}{y}$$

- $g_2 - g_2^{WW}$: a clean way to access twist-3 contribution

  quantify *q-g* correlations

Color Polarizability (Lorentz Force): d_2

- 2^{nd} moment of g_2-g_2^{WW}

  d_2: twist-3 matrix element

$$d_2(Q^2) = 3\int_0^1 x^2[g_2(x,Q^2) - g_2^{WW}(x,Q^2)]dx$$

$$= \int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx$$

d_2 and g_2-g_2^{WW}: clean access of higher twist (twist-3) effect: *q-g* correlations

Color polarizabilities χ_E, χ_B are linear combination of d_2 and f_2 *(X. Ji)*

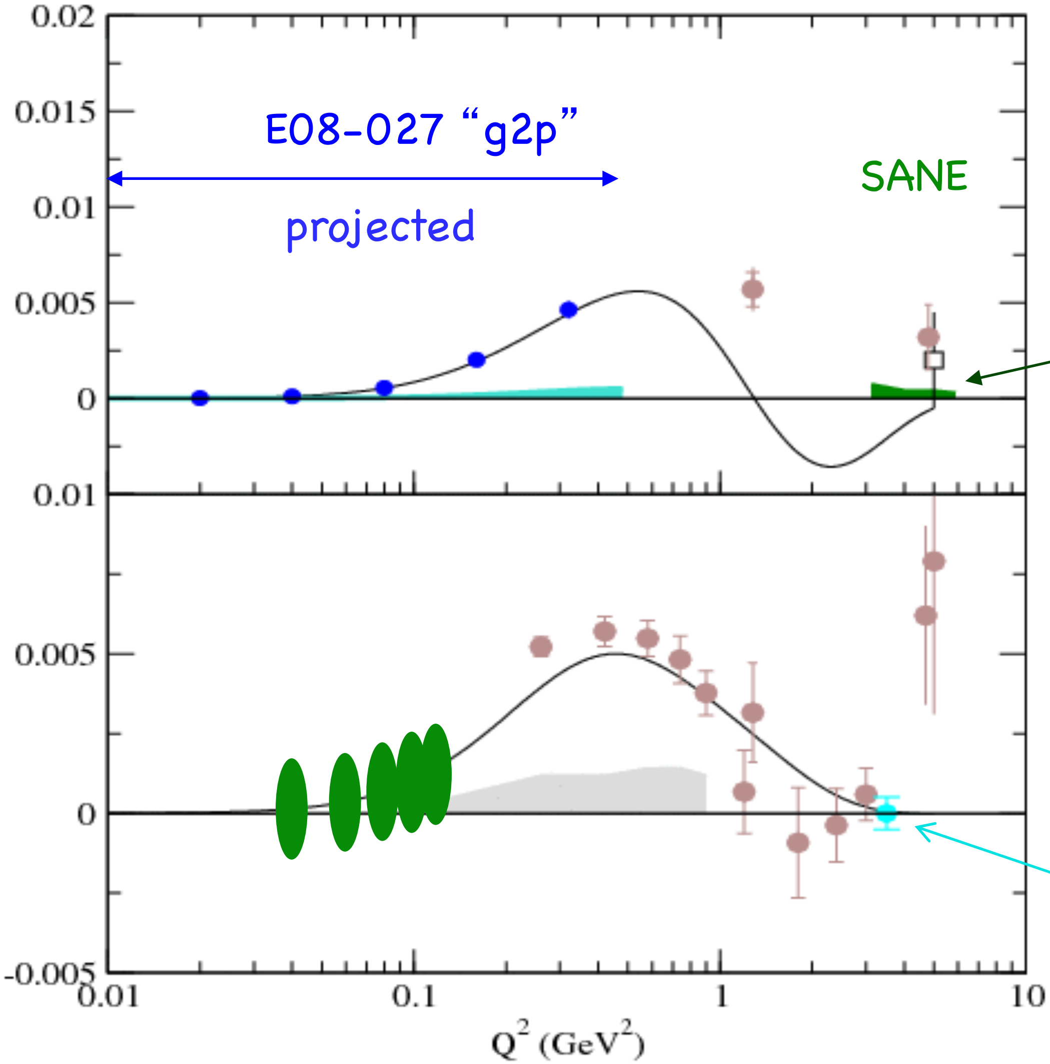
Provide a benchmark test of Lattice QCD at high Q^2

Avoid issue of low-*x* extrapolation

Color Lorentz (transverse) force *(M. Burkardt)*

Relation to Sivers and other TMDs

World Measurements of $d_2(Q^2)$



6 GeV Experiments

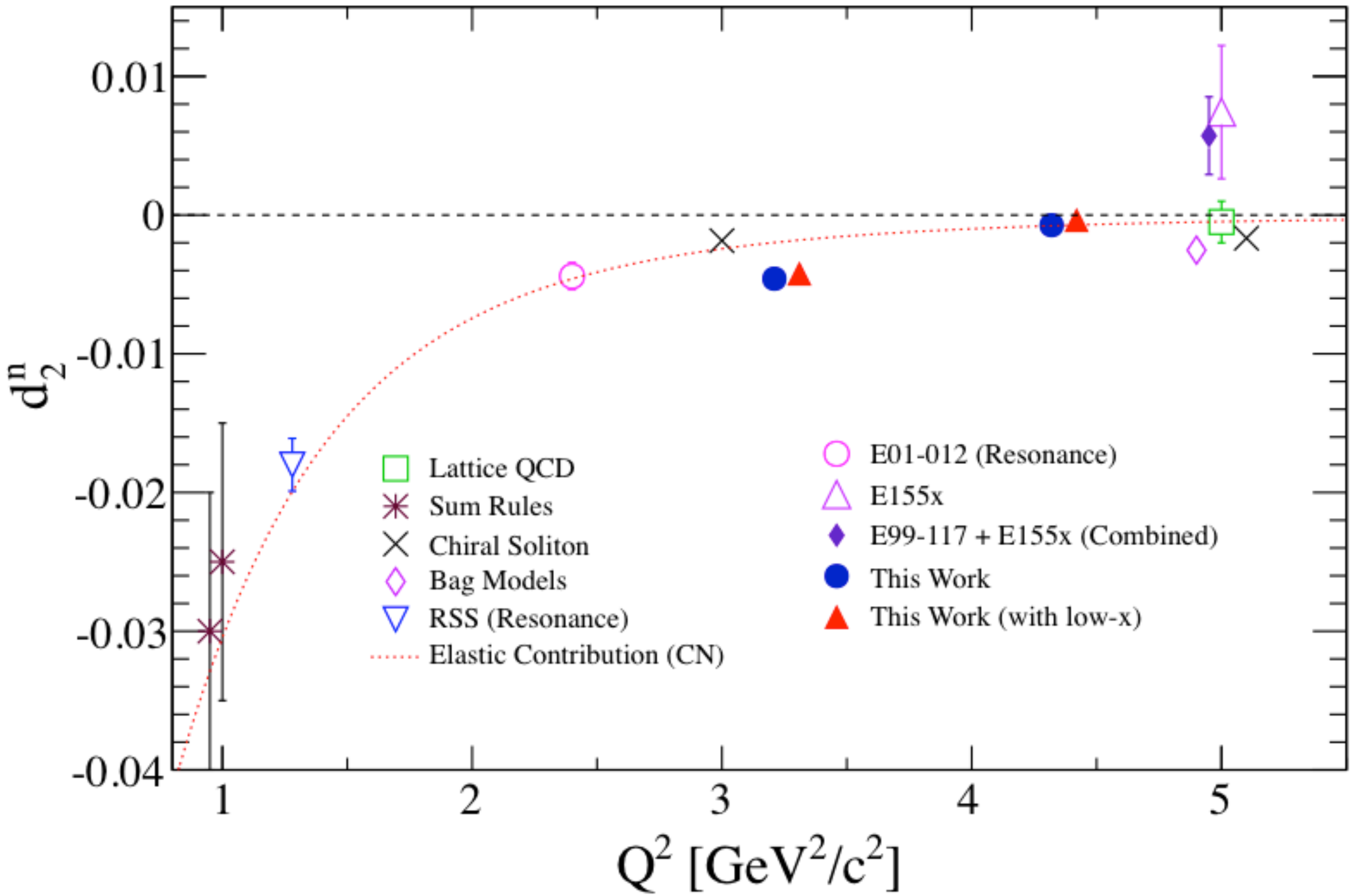
Sane: new in Hall C

"g2p" in Hall A, results soon

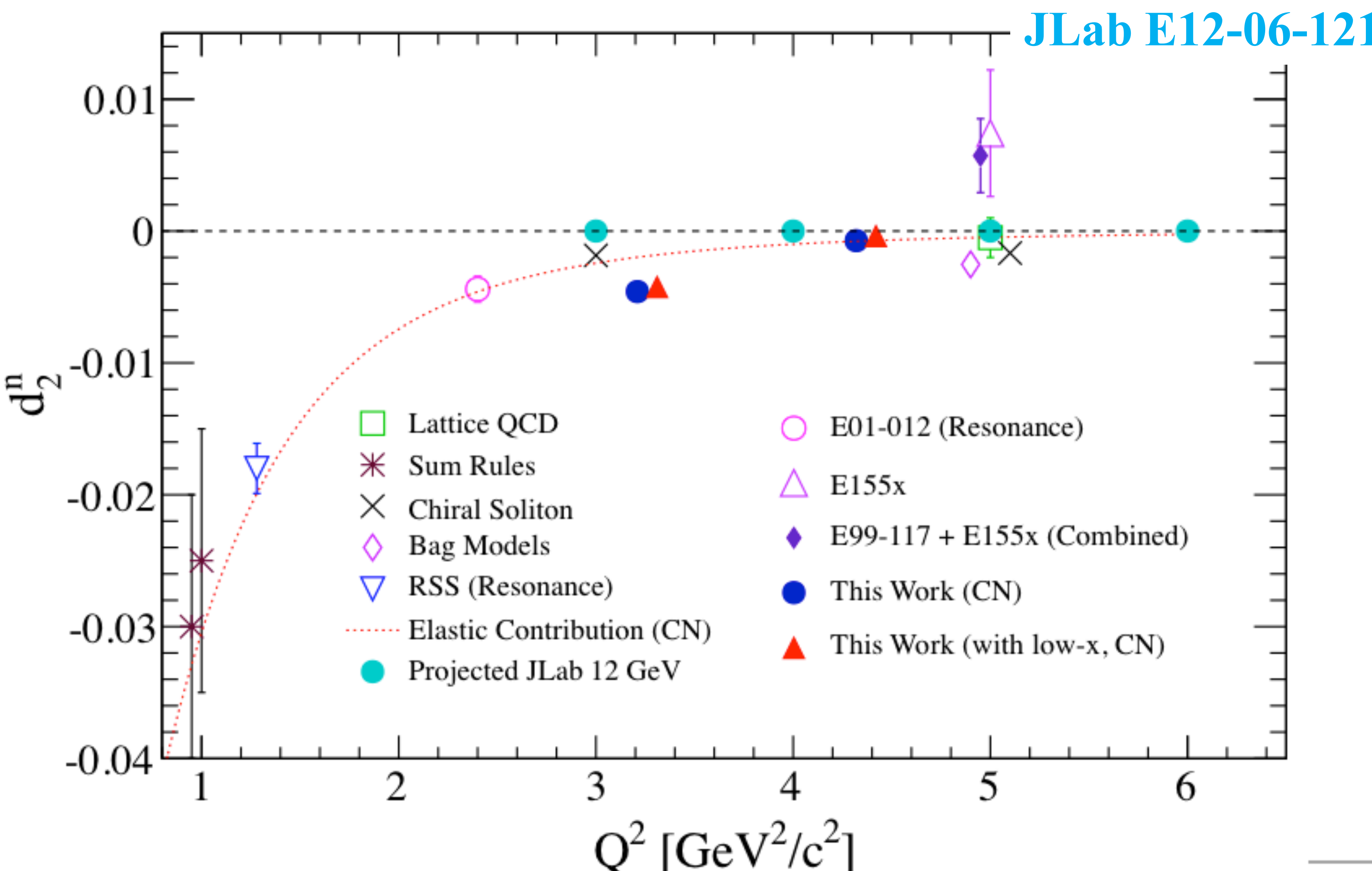
"d2n" (E06-014) new in Hall A

d_2^n Result from JLab E06-014

Posik et al., PRL 113 022002 (2014)



JLab 12 Projection of d_2^n



Sea Quark Spin-Flavor Study with EIC

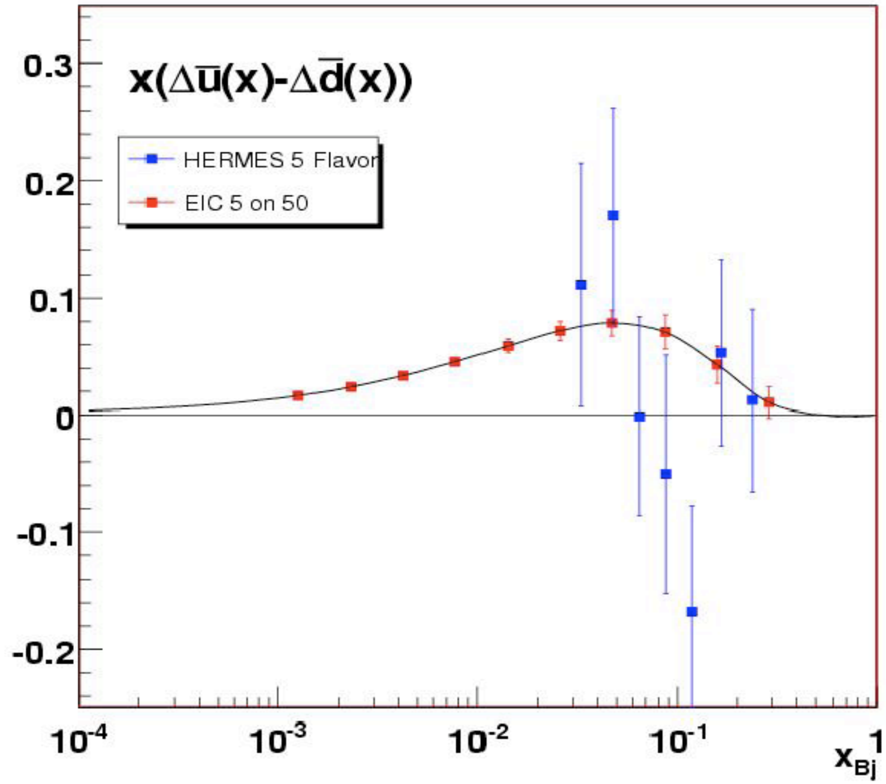
- Unique opportunity for Δs

  energy reach current fragmentation region for Kaon tagging in SIDIS

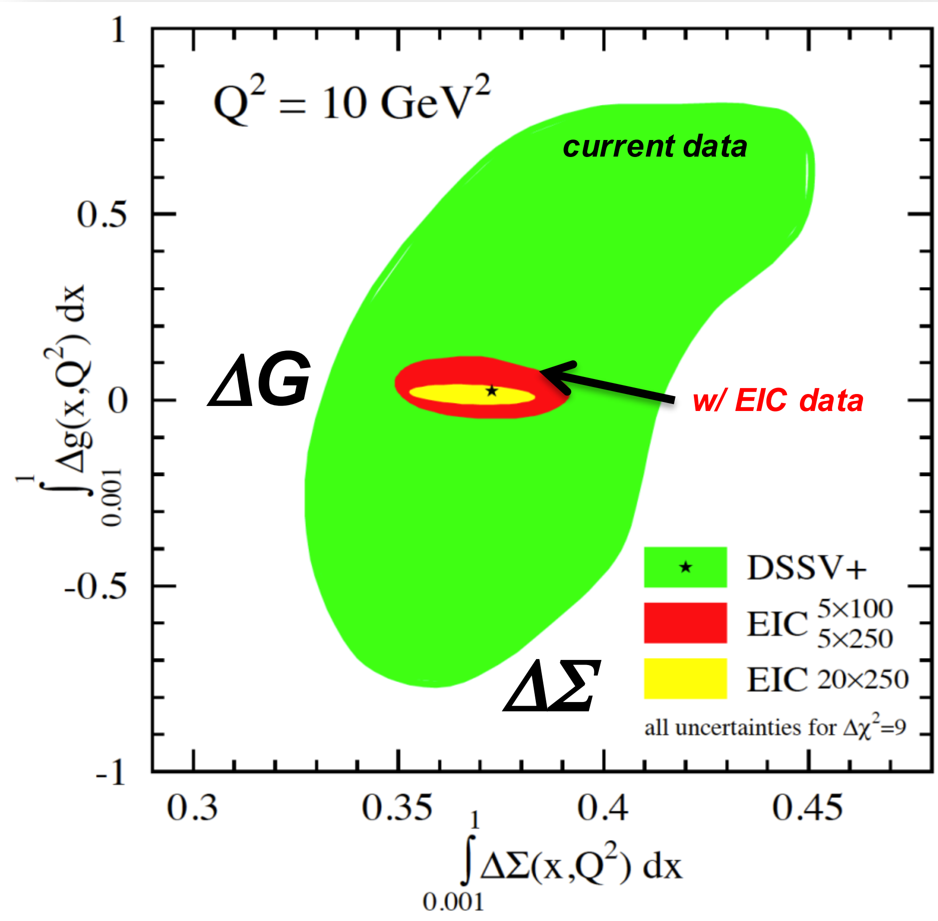
- Significant improvement for Δu_bar, Δd_bar from SIDIS

- Increase in Q^2 range/precision for g_1 (and g_2)

  constraint on Δg.



EIC: Probe Polarized Gluons

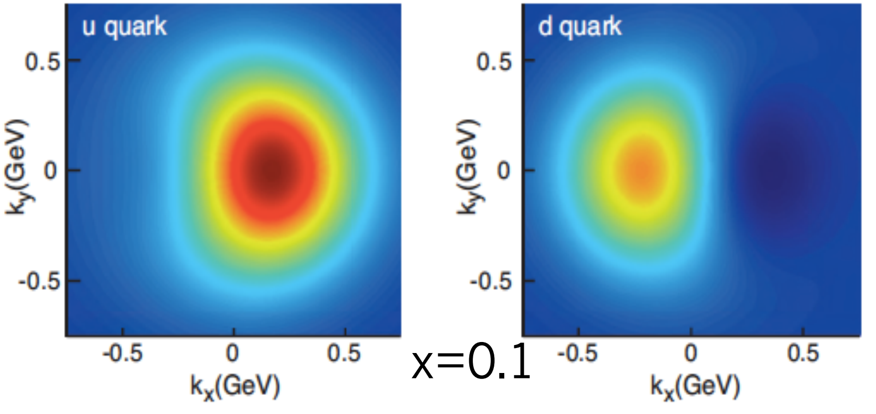


A Polarized EIC:

- ***Tremendous improvement on ΔG***
- ***Also improvement in ΔΣ***
- ***Spin Flavor decomposition of the Light Quark Sea***

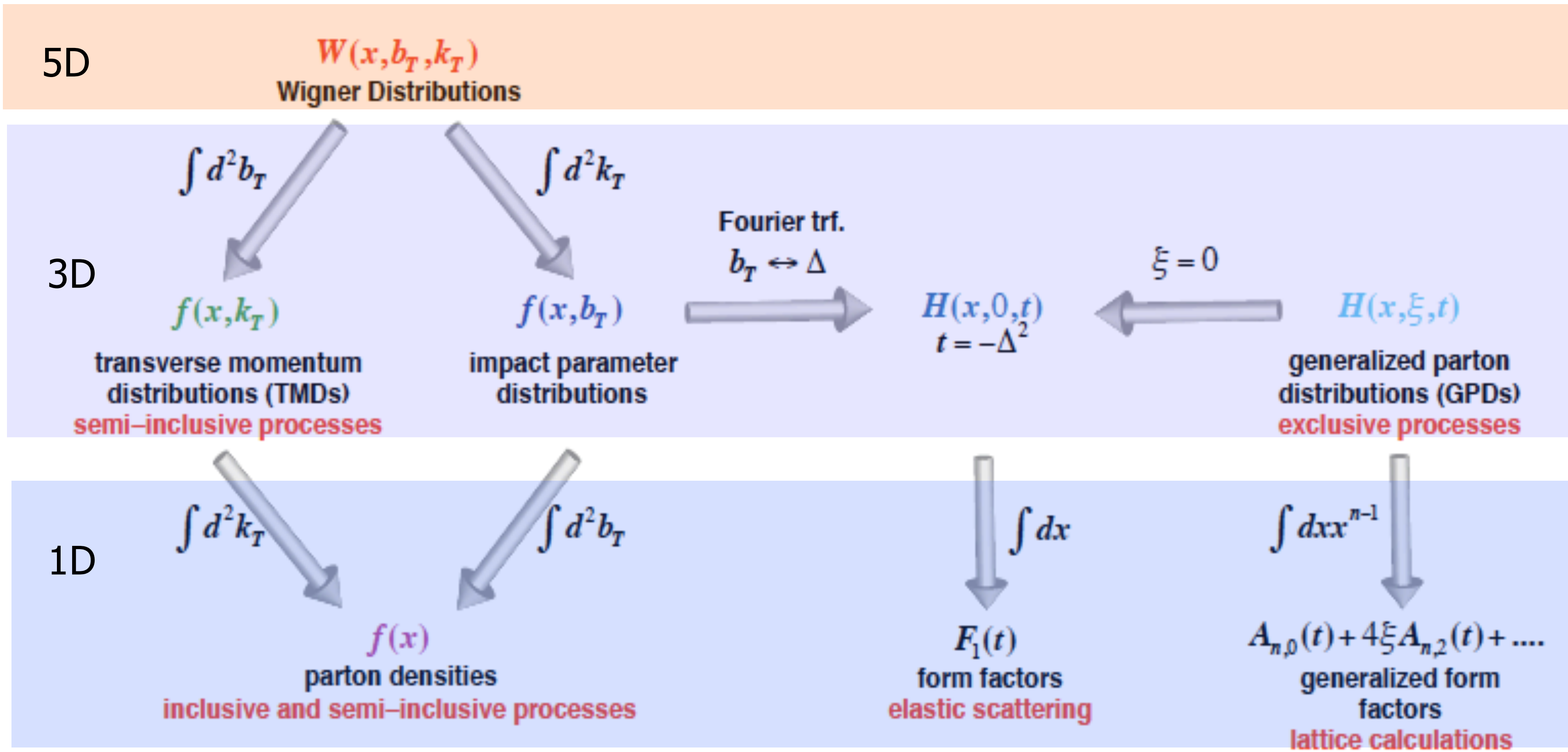
3-D Structure I

Transverse Momentum-Dependent Distributions



Unified View of Nucleon Structure

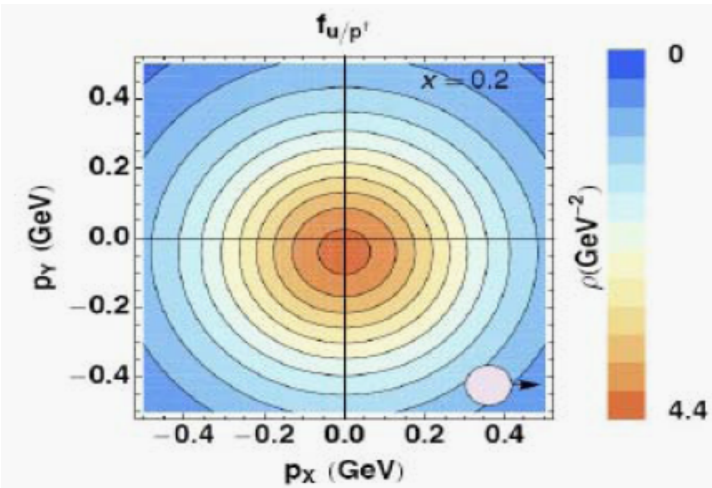
- Wigner distributions



Towards Imaging - Two Approaches

TMDs

2+1 D picture in **momentum space**

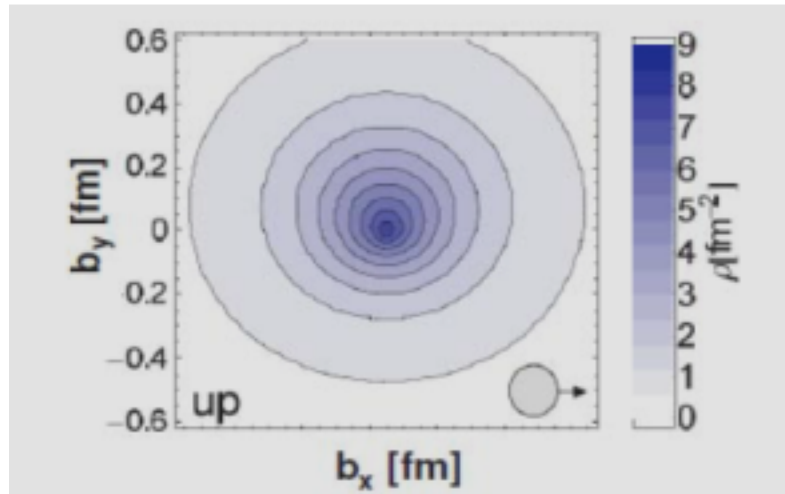


Bacchetta, Conti, Radici

- intrinsic transverse motion
- spin-orbit correlations- relate to OAM
- non-trivial factorization
- accessible in SIDIS (and Drell-Yan)

GPDs

2+1 D picture in **impact-parameter space**



QCDSF collaboration

- collinear but long. momentum transfer
- indicator of OAM; access to Ji's total $J_{q,g}$
- existing factorization proofs
- DVCS, deep exclusive meson production

Leading-Twist TMD PDFs

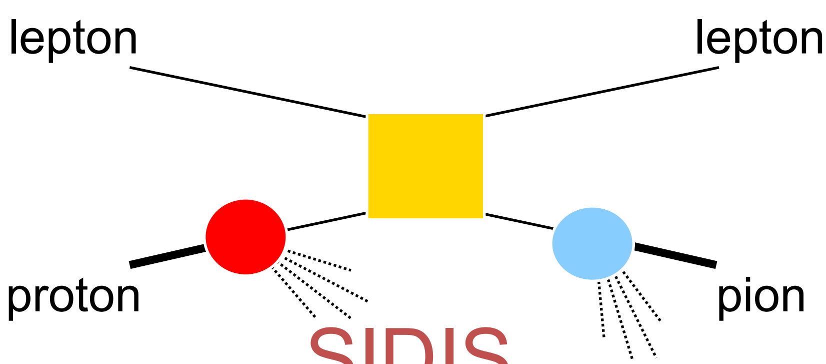
Nucleon Polarization		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
	U	$f_1 =$		$h_1^\perp = \quad - \quad$ Boer-Mulders
	L		$g_1 = \quad - \quad$ Helicity	$h_{1L}^\perp = \quad - \quad$ Worm Gear
	T	$f_{1T}^\perp = \quad - \quad$ Sivers	$g_{1T} = \quad - \quad$ Worm Gear	$h_1 = \quad - \quad$ Transversity $h_{1T}^\perp = \quad - \quad$ Pretzelosity

Nucleon Spin

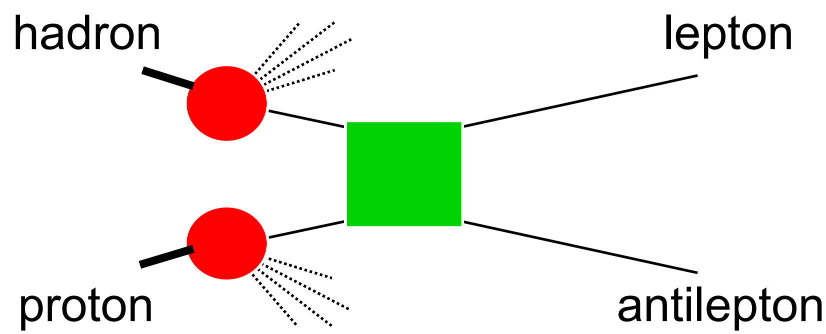
Quark Spin

: Survive trans. Momentum integration

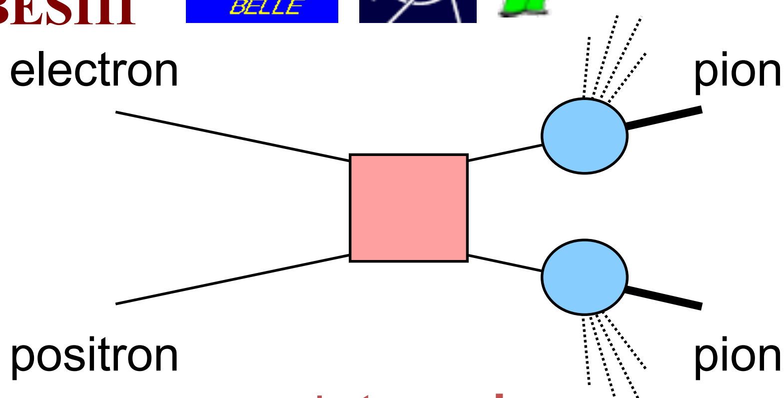
Access TMDs through Hard Processes



SIDIS



Drell-Yan

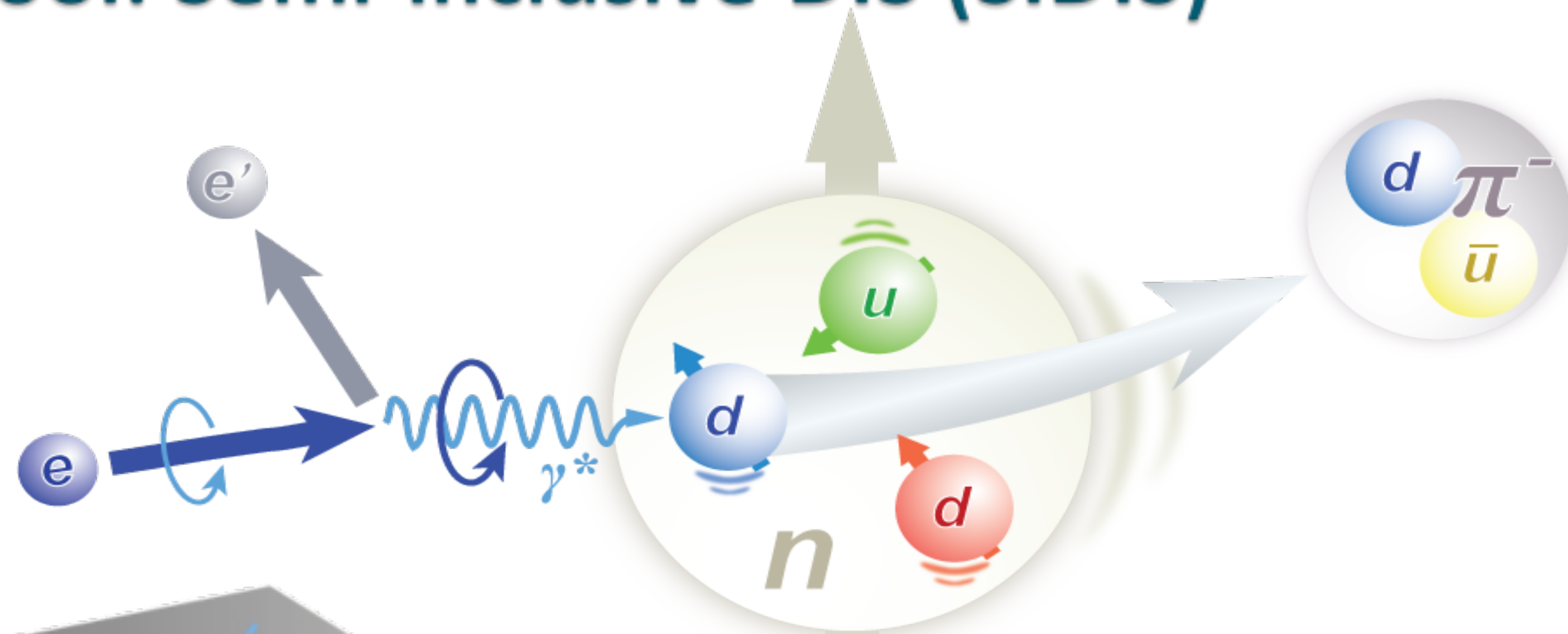


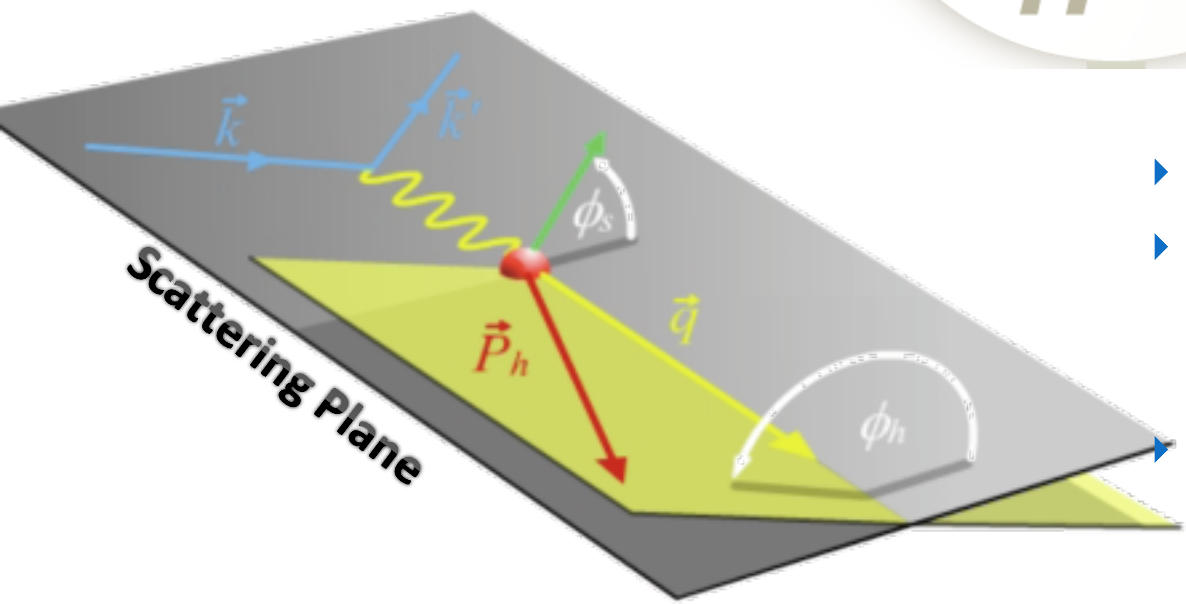
$e^{-}e^{+}$ to pions

- Partonic scattering amplitude
- Fragmentation amplitude
- Distribution amplitude

$$f_{1T}^{\perp q}(\mathrm{SIDIS}) = -f_{1T}^{\perp q}(\mathrm{DY})$$

Tool: Semi-inclusive DIS (SIDIS)





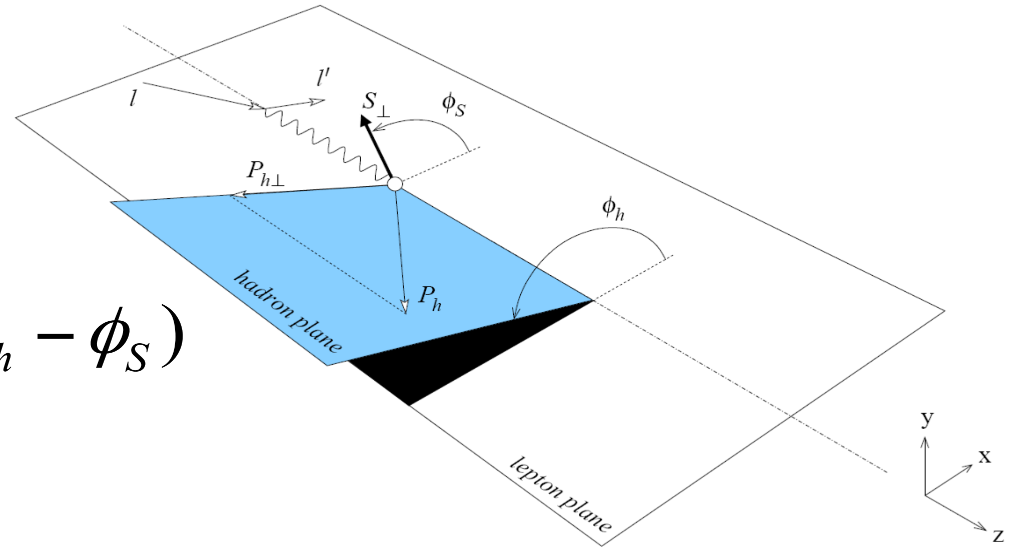
- Gold mine for TMDs
- Access all eight leading-twist TMDs through spin-comb. & azimuthal-modulations
- Tagging quark flavor/kinematics

Separation of Collins, Sivers and pretzelocity effects through angular dependence

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity}\sin(3\phi_h - \phi_S)$$

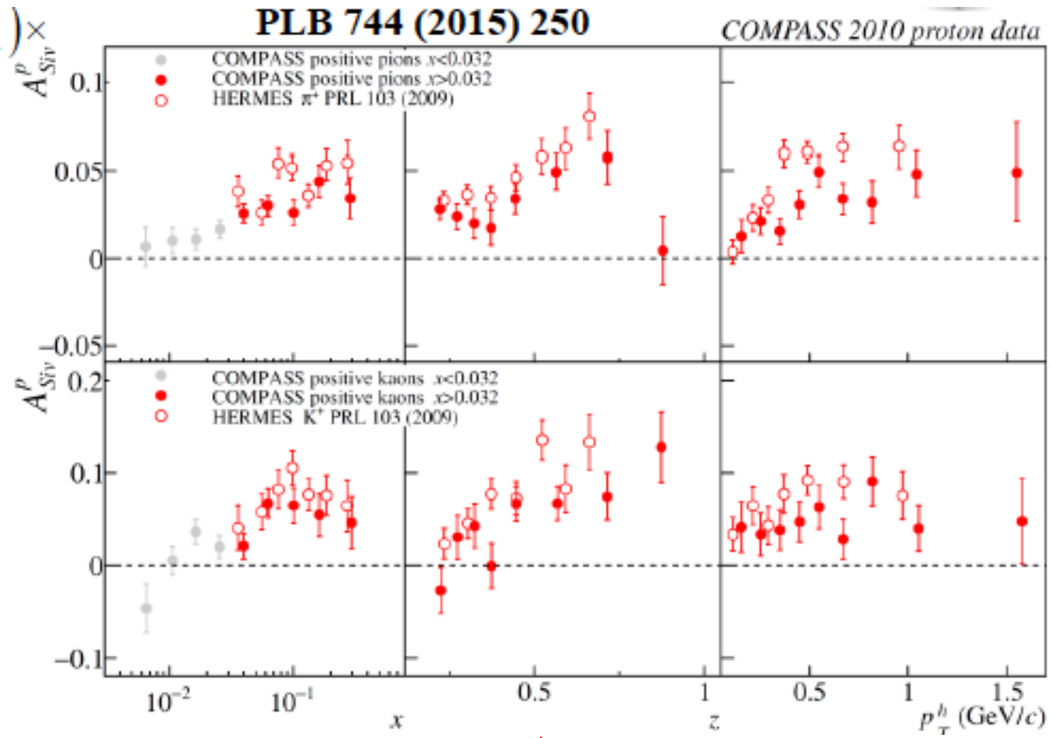


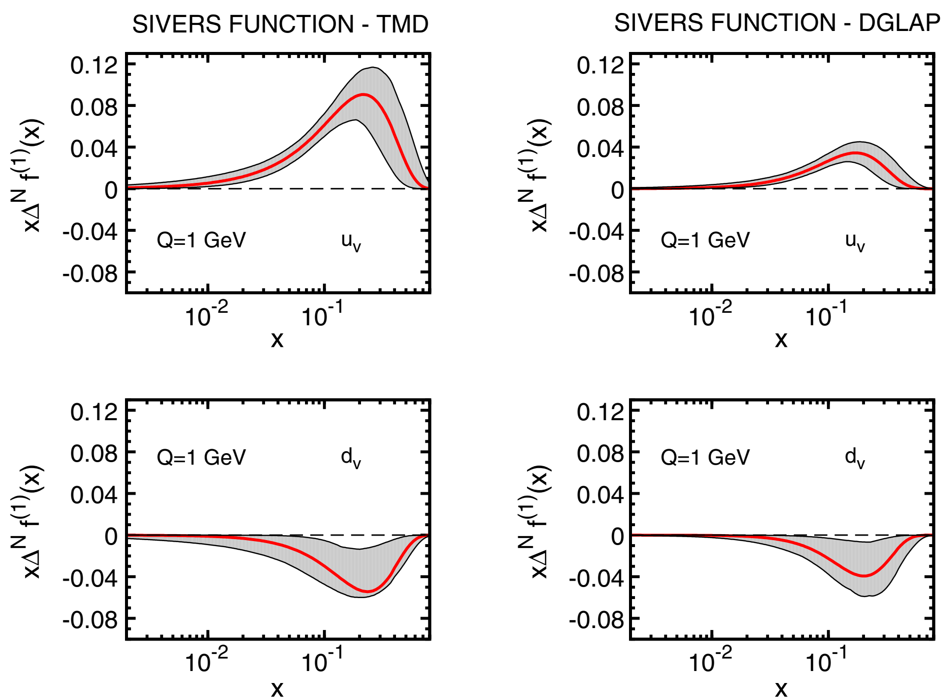
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

COMPASS/HERMES: *Sivers Asymmetries and Extraction of Sivers Function*





Also other TMDs.

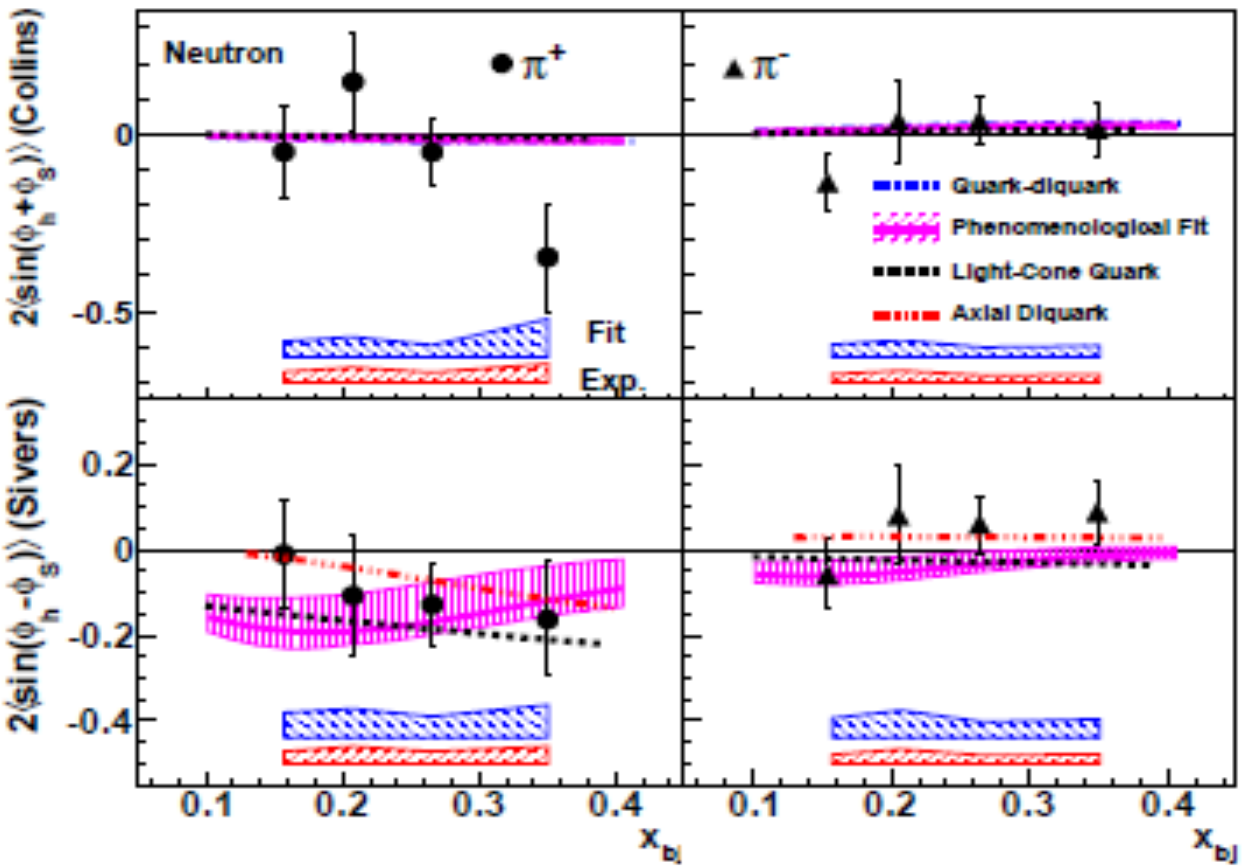
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

M. Anselmino, M. Boglione, and S. Melis
Phys. Rev. D 86, 014028 (2012)

^{3}He (n) Target Single-Spin Asymmetry in SIDIS

JLab E06-010 collaboration, X. Qian at al., **PRL 107:072003(2011)**

$$n^{\uparrow}(e,e'h), h = \pi^+, \pi^-$$



neutron Collins SSA small
Non-zero at highest x for π+

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

neutron Sivers SSA:
negative for π^+,
Agree with Torino Fit

Blue band: model (fitting) uncertainties
Red band: other systematic uncertainties

JLab 12 GeV Era: Precision Study of TMDs

- From exploration to precision study with 12 GeV JLab
- Transversity: fundamental *PDF*s, tensor charge
- *TMD*s: 3-d momentum structure of the nucleon
- → Quark orbital angular momentum
- Multi-dimensional mapping of *TMD*s
  - 4-d ($x,z,P_\perp,Q^2$)
  - Multi-facilities, global effort
- Precision → high statistics
  - high luminosity and large acceptance

Overview of SoLID

Solenoidal **L**arge **I**ntensity **D**evice

- **Full exploitation of JLab 12 GeV Upgrade**

  → A **Large Acceptance** Detector **AND** Can Handle **High Luminosity** (10^{37}-10^{39})

  Take advantage of latest development in detectors , data acquisitions and simulations

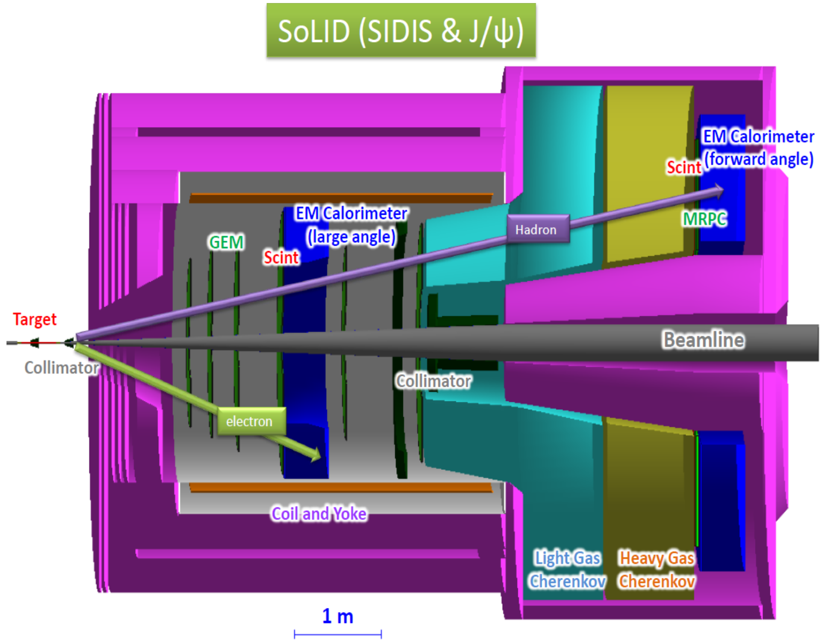
  Reach ultimate precision for SIDIS (TMDs), PVDIS in high-*x* region and threshold J/ψ

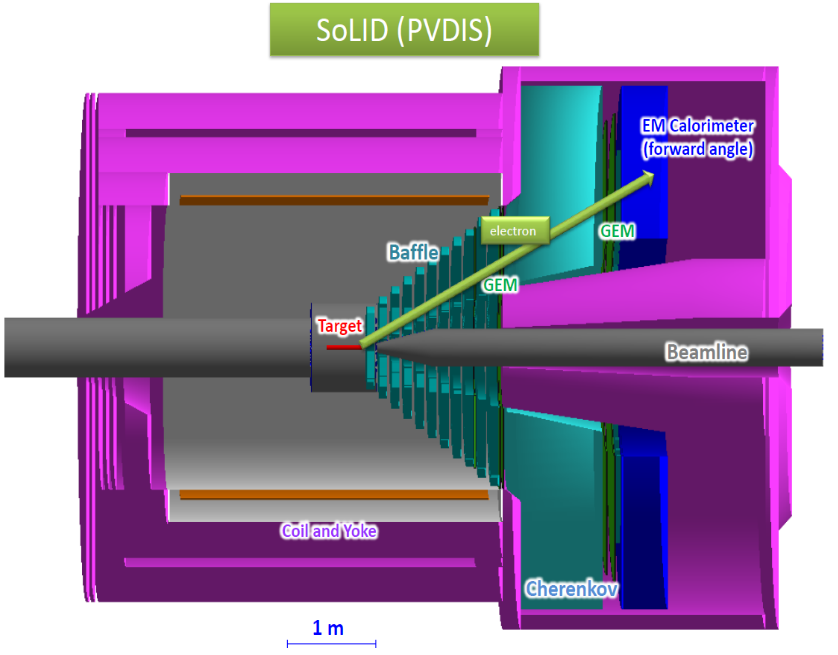
- **5 highly rated experiments approved**

  Three SIDIS experiments, one PVDIS, one J/ψ production (+ 4 run group experiments)

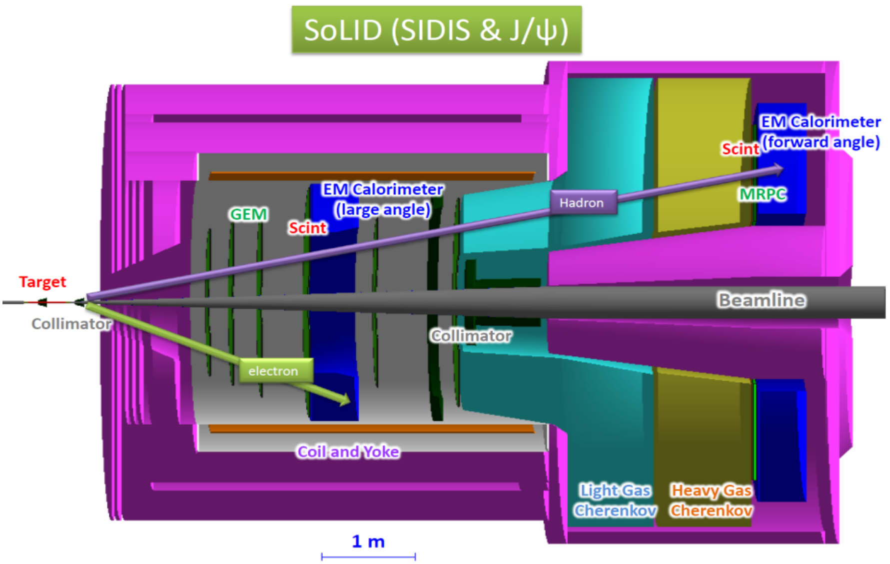
- **Strong collaboration** (250+ collaborators from 70+ institutes, 13 countries)

  International collaborations (significant Chinese contributions)





SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV

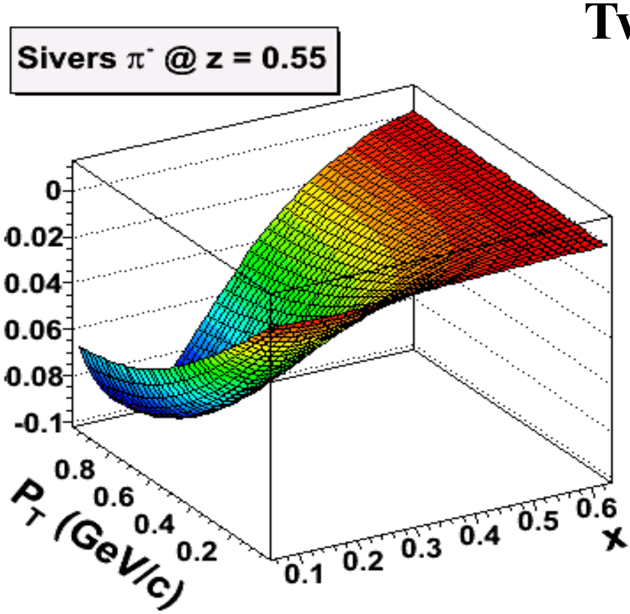


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He, **rating A**

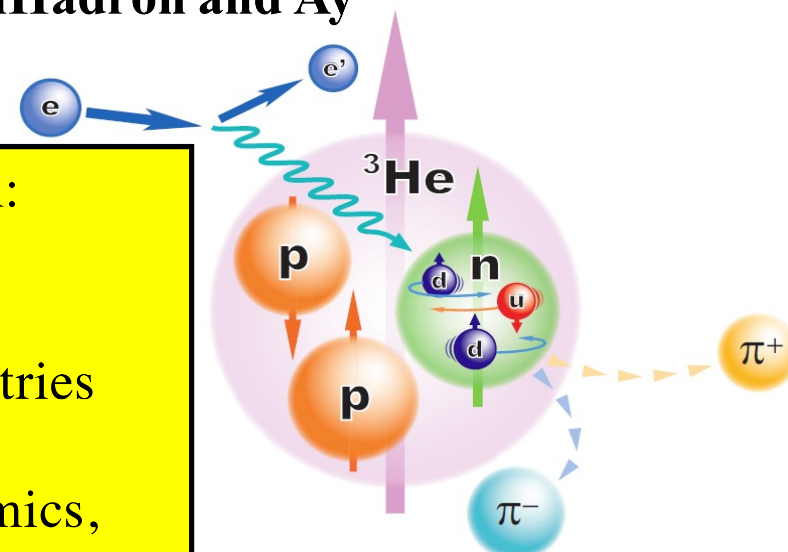
E12-11-007: Single and Double Spin Asymmetries on ^{3}He, **rating A**

E12-11-108: Single and Double Spin Asymmetries on Transverse Proton, **rating A**

Two run group experiments DiHadron and Ay



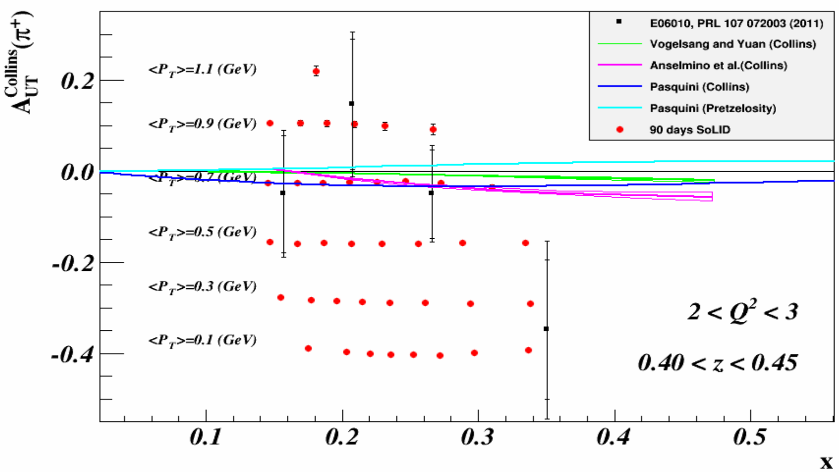
Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→ Lattice QCD, QCD Dynamics, Quark Orbital Angular Momentum, Imaging in 3-D momentum space.



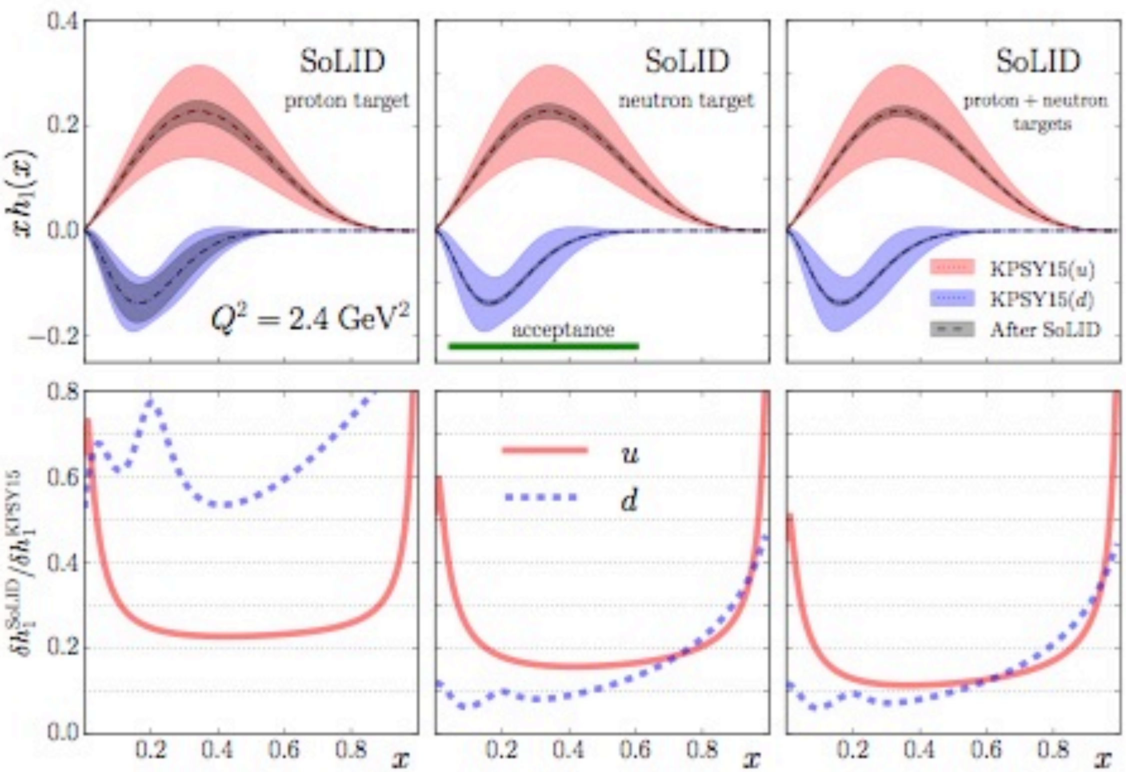
Transversity from SoLID

- Collins Asymmetries ~ Transversity (x) Collin Function
- **Transversity**: chiral-odd, not couple to gluons, **valence behavior**, largely unknown
- Global model fits to experiments (SIDIS and e+e-)
- SoLID with **trans polarized n & p** → Precision extraction of u/d quark transversity
- Collaborating with theory group (N. Sato, A. Prokudin, …) on impact study

Collins Asymmetries



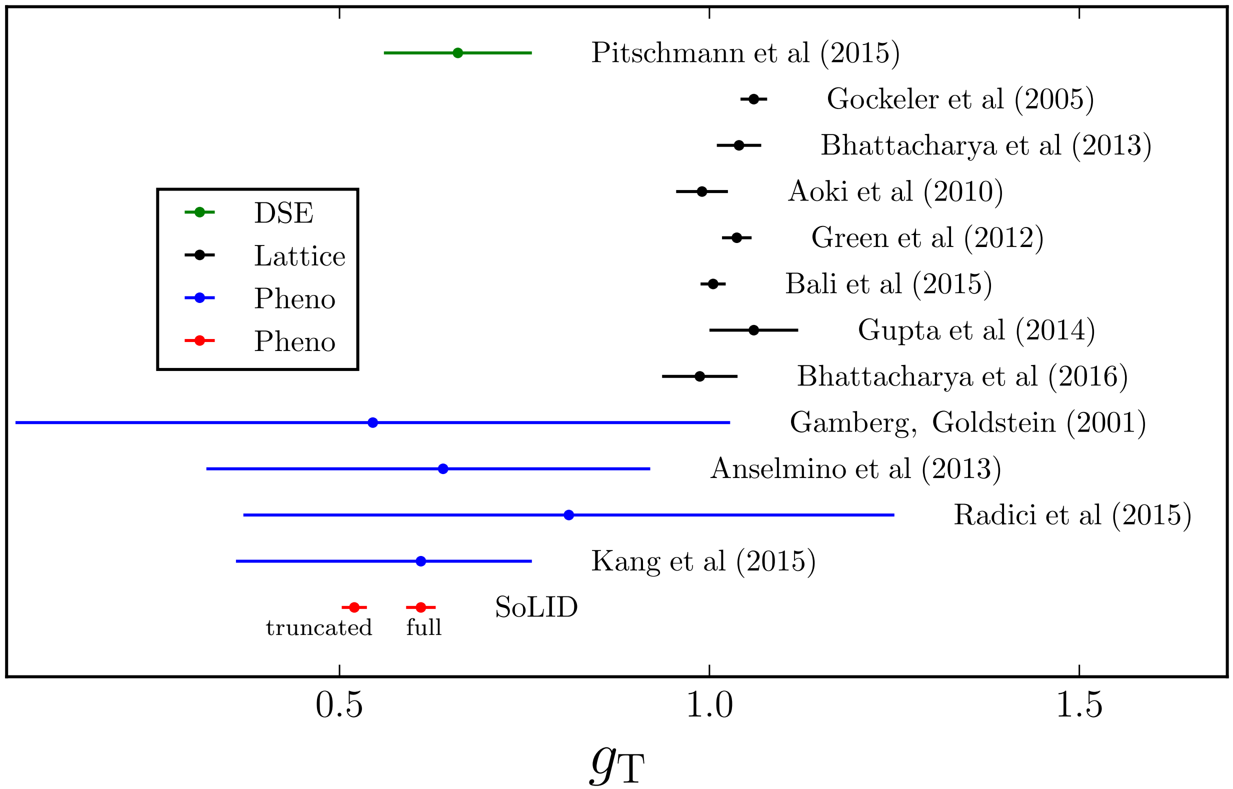
P_T vs. x for one (Q^2, z) bin
Total > 1400 data points



Z. Ye *et al.*, PLB 767, 91 (2017)

Tensor Charge from SoLID

- **Tensor charge (0th moment of transversity): fundamental property**
  Lattice QCD, Bound-State QCD (Dyson-Schwinger) , …
- **SoLID** with **trans polarized n & p** → determination of tensor charge



DSE

LQCD

Extractions from existing data

SoLID projections

Tensor Charges

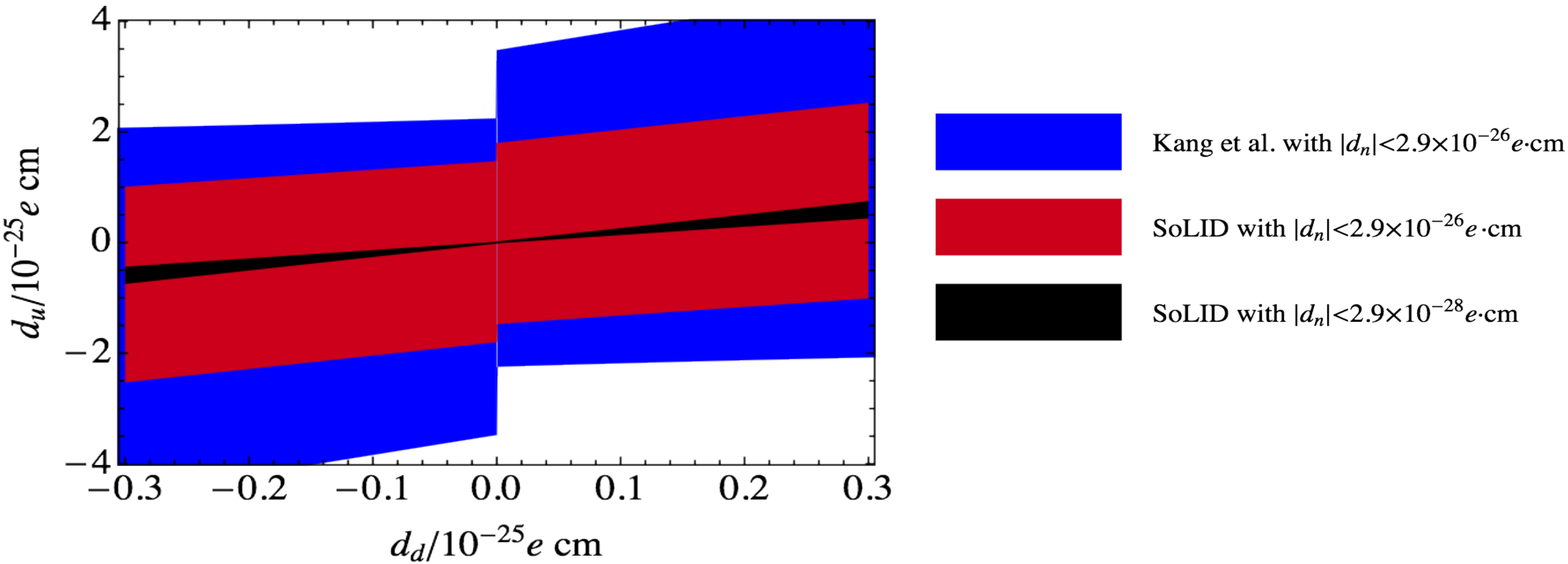
Projections with a model QCD evolutions included

Tensor Charge and Neutron EDM

Electric **D**ipole **M**oment

Tensor charge and EDM

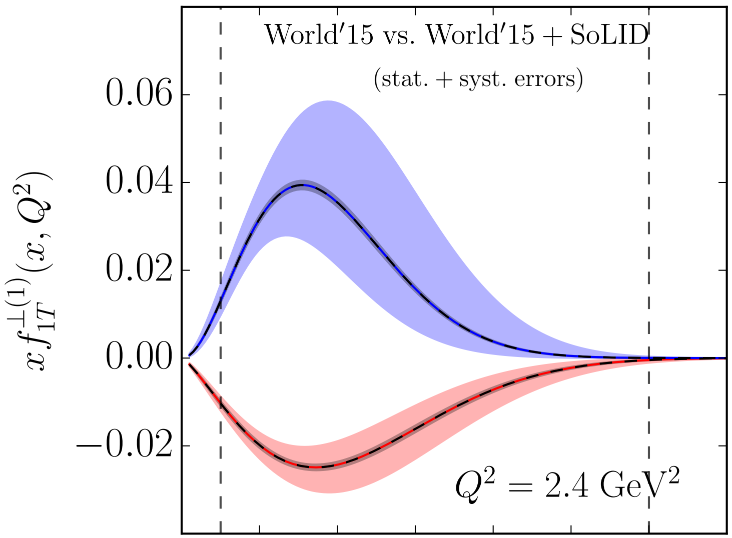
$$d_n = \delta_T u \, d_u + \delta_T d \, d_d + \delta_T s \, d_s$$



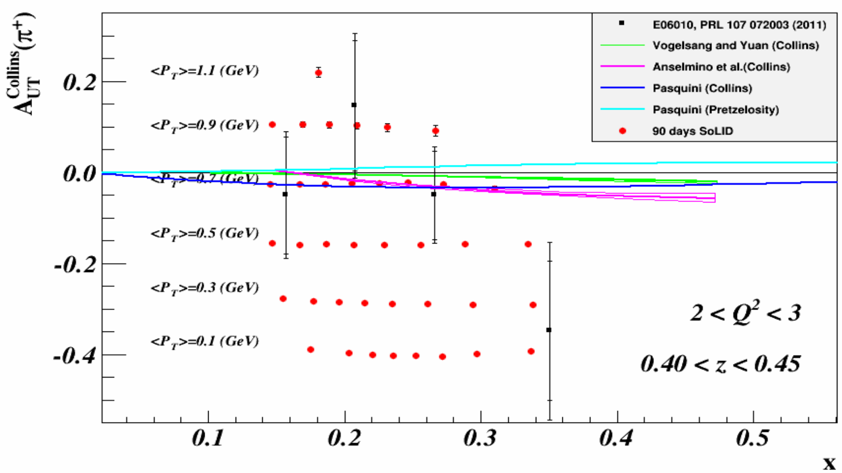
current neutron EDM limit $|d_n| < 2.9 \times 10^{-26} \, e \cdot \mathrm{cm}$

Mapping Sivers Asymmetries with SoLID

- Sivers Asymmetries ~ Sivers Function (x, k_T, Q^2) (x) Fragmentation Function (z, p_T, Q^2)
- Leading-twist/not Q power suppressed: Gauge Link/ QCD Final State Interaction
- Transverse Imaging
- QCD evolutions
- **SoLID**: precision multi-d mapping
- Collaborating with theory group: impact study

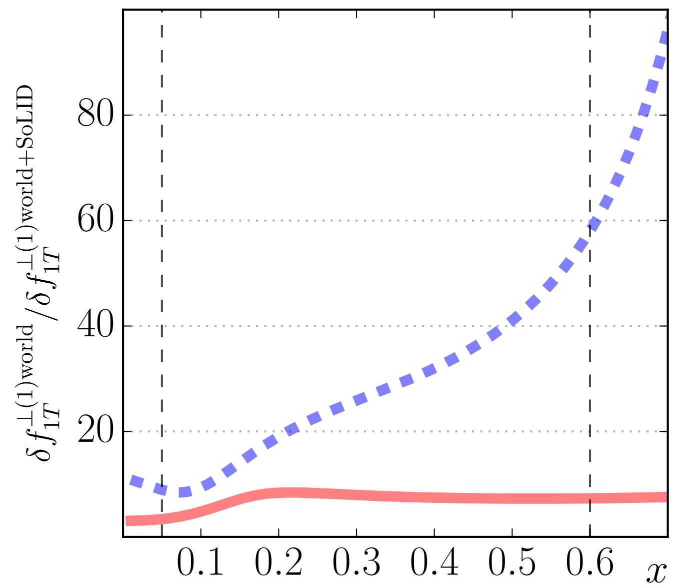


Sivers Asymmetries



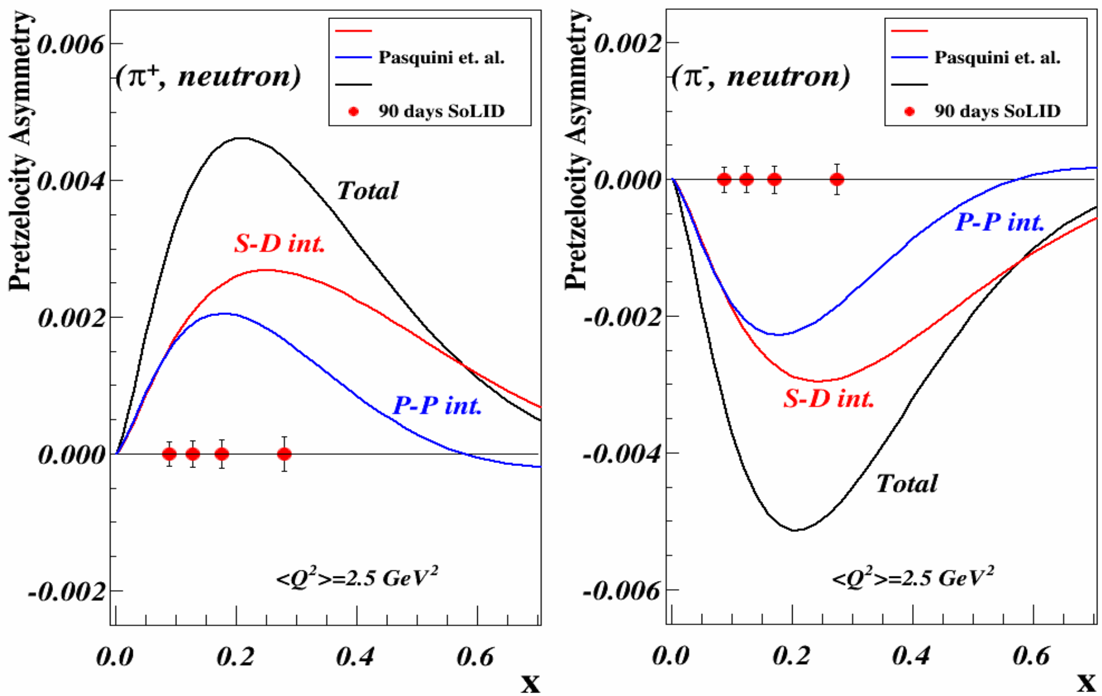
P_T vs. x for one (Q^2, z) bin
Total > 1400 data points

Liu, Sato, Prokudin,…



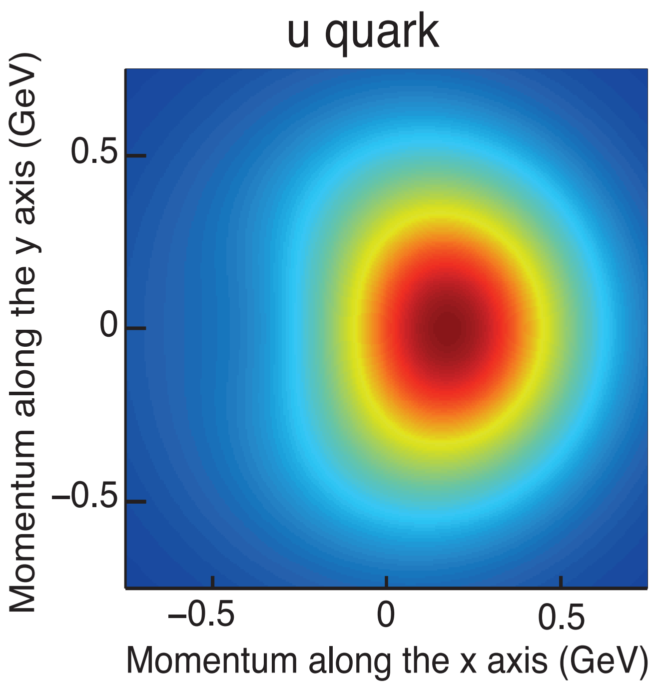
TMDs: Access Quark Orbital Angular Momentum

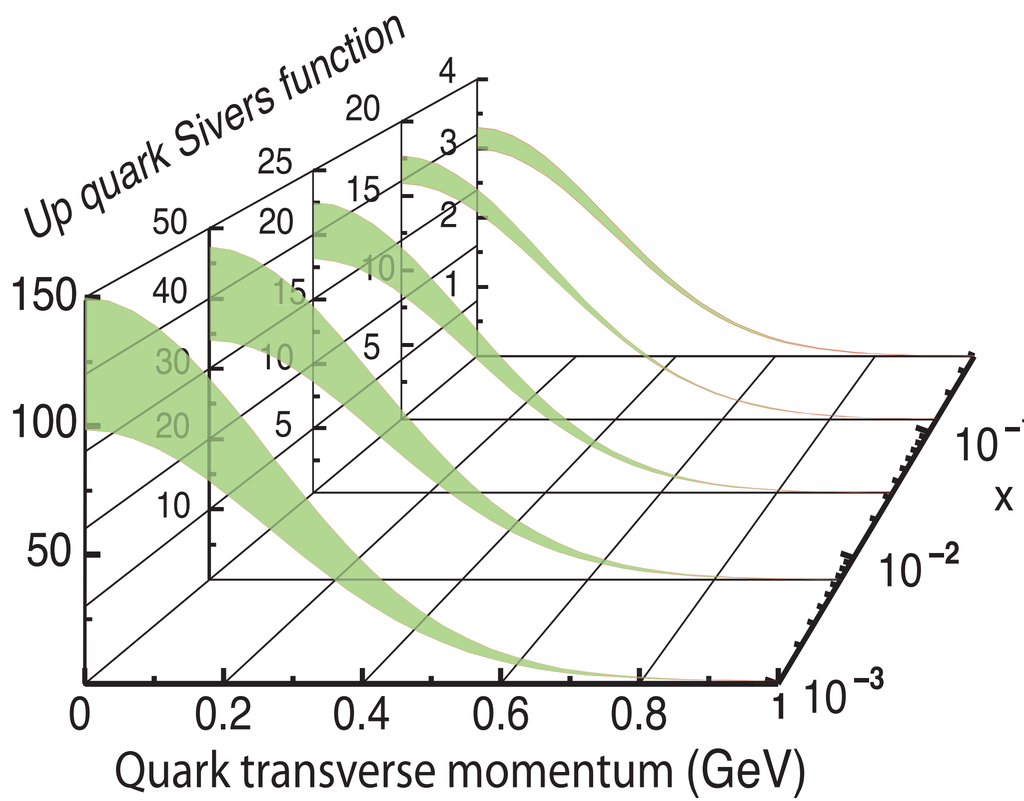
- TMDs : Correlations of transverse motion with quark spin and orbital motion
- **Without OAM, off-diagonal TMDs=0,**
  no direct model-independent relation to the OAM in spin sum rule yet
- Sivers Function: QCD lensing effects
- In a large class of models, such as light-cone quark models
  Pretzelosity: ΔL=2 (L=0 and L=2 interference , L=1 and -1 interference)
  Worm-Gear: ΔL=1 (L=0 and L=1 interference)
- **SoLID with trans polarized n/p → quantitative knowledge of OAM**



SoLID Projections Pretzelosity

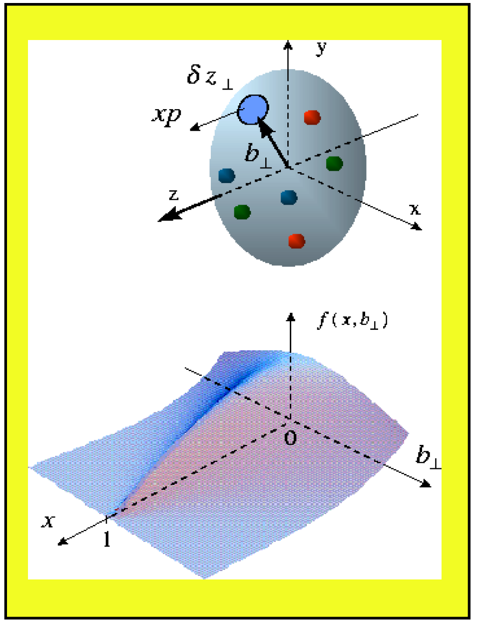
EIC Imaging in 3-d momentum space





3-D Structure II

Generalized Parton Distributions



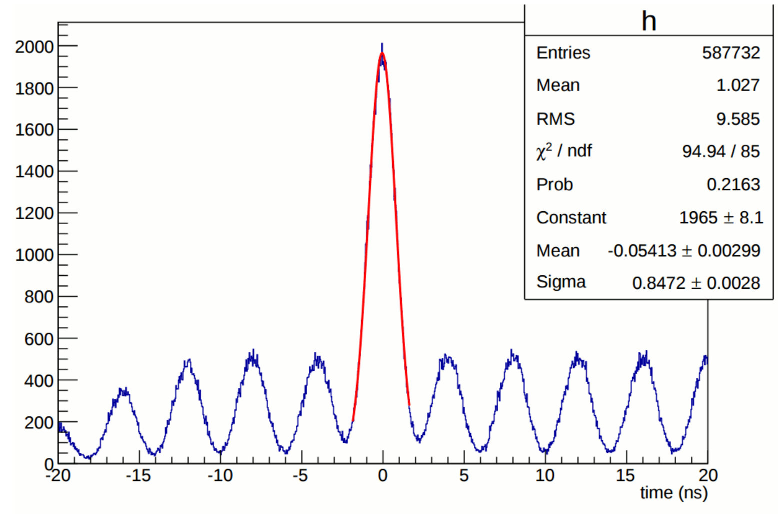
E12-06-114 DVCS in Hall A (first 12 GeV era experiment)

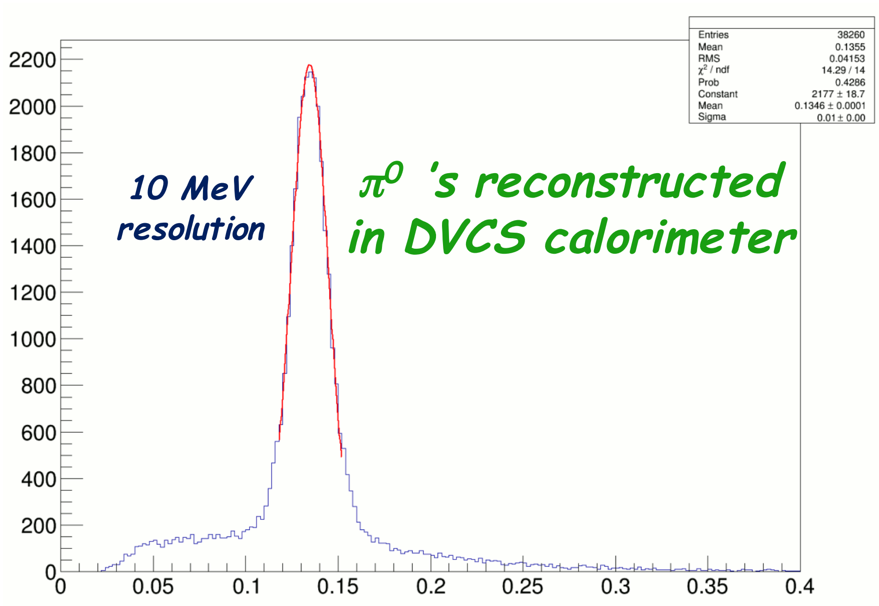
100 PAC days approved:

- ***High impact experiment for nucleon 3D imaging program***
- ***High precision scaling tests of the DVCS cross section at constant x_B***
- ***CEBAF12 will allow first time exploration of the high x_B region***

Planned 50% of experiment completed in 2014-2016

Excellent coincident time resolution:
250 MHz beam structure





Analysis path:

- ***Jun'17: Report at JLab Summer Meeting.***
- ***Jan'18: Preliminary results on π^0 at x_B=0.36***
- ***Apr'18: Preliminary results on DVCS***
- ***Jul'18 : Short paper submitted to PRL on π^0***
- ***Jan'19: Letter to PRL on DVCS***
- ***Jul'19: Long paper to PRC (DVCS & pi0)***

CLAS12 – DVCS/BH Target Asymmetry Projection

$$e\,\vec{p} \longrightarrow e p \gamma$$

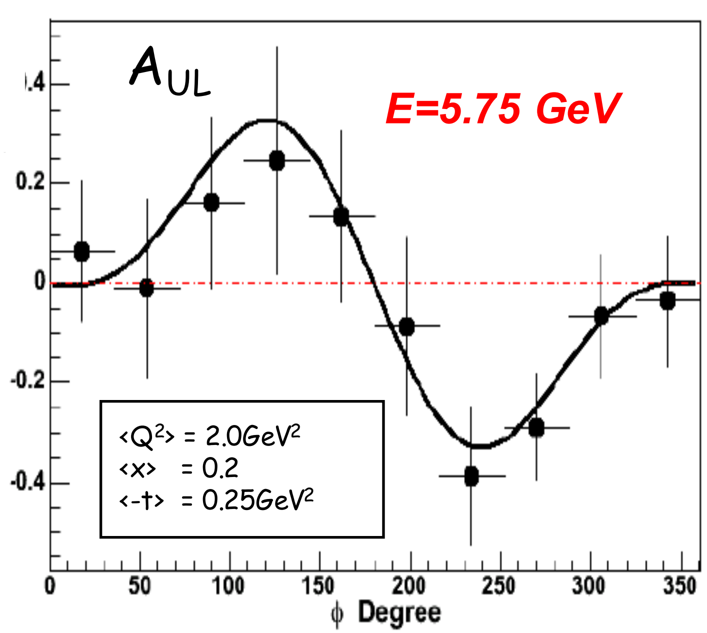
E = 11 GeV

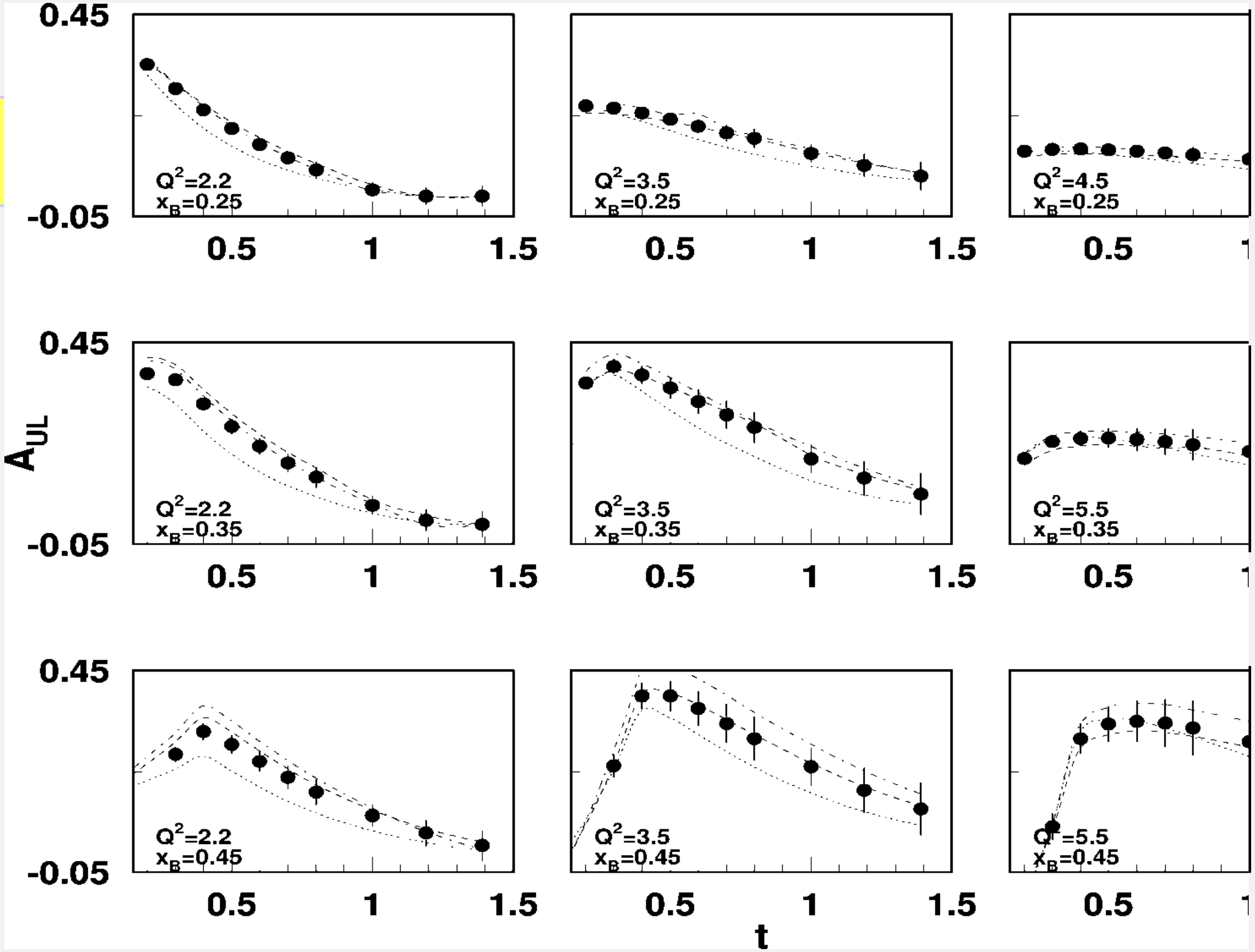
L = 2x10^{35} cm^{-2}s^{-1}
T = 1000 hrs
ΔQ^2 = 1GeV^2
Δx = 0.05

Longitudinally polarized target

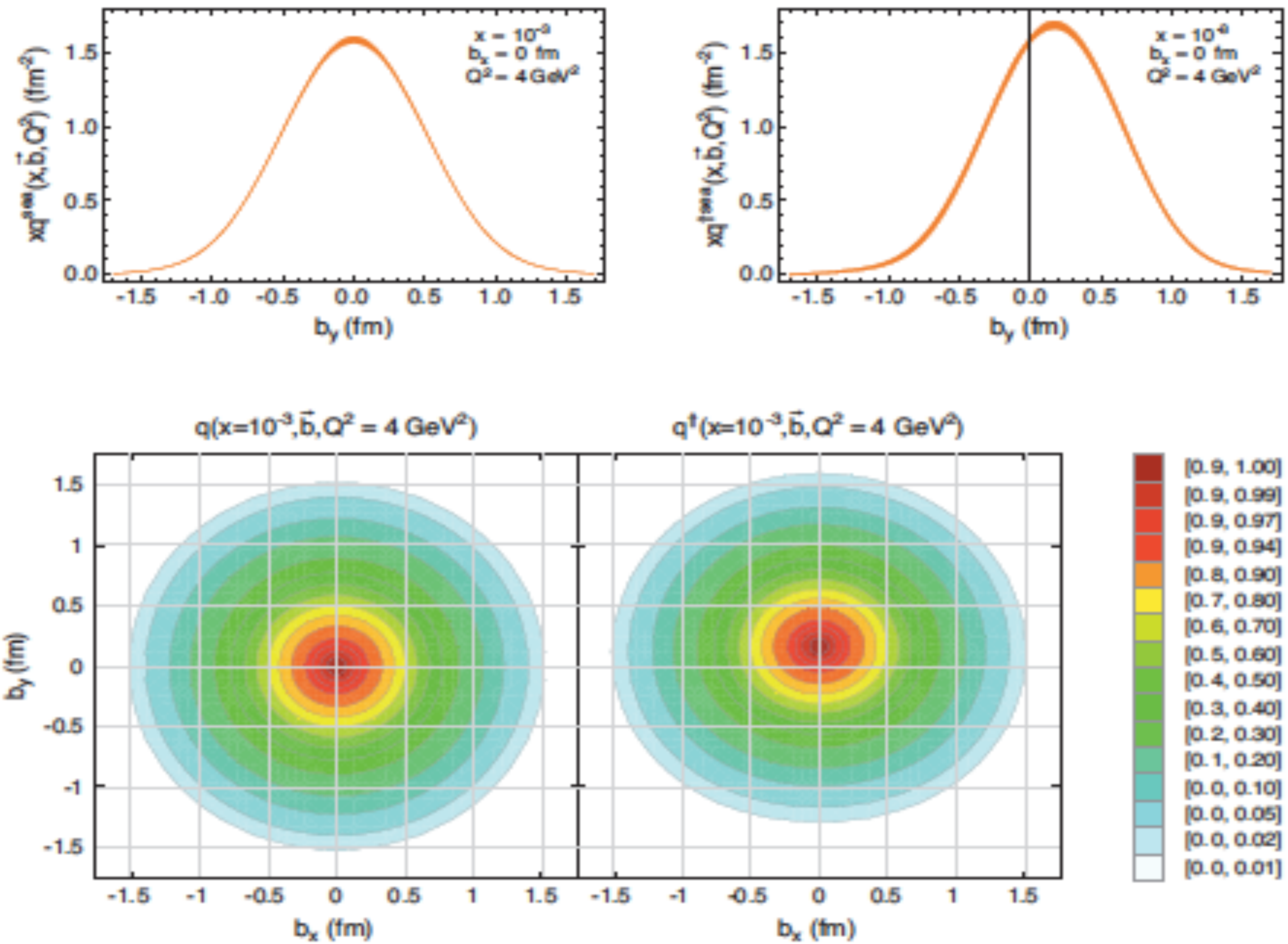
$$\Delta\sigma \sim \sin\phi\, \mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)H \ldots\}d\phi$$

CLAS preliminary





Polarized DVCS @ EIC



Electron Ion Collider

NSAC 2007 Long-Range Plan:

"An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia."

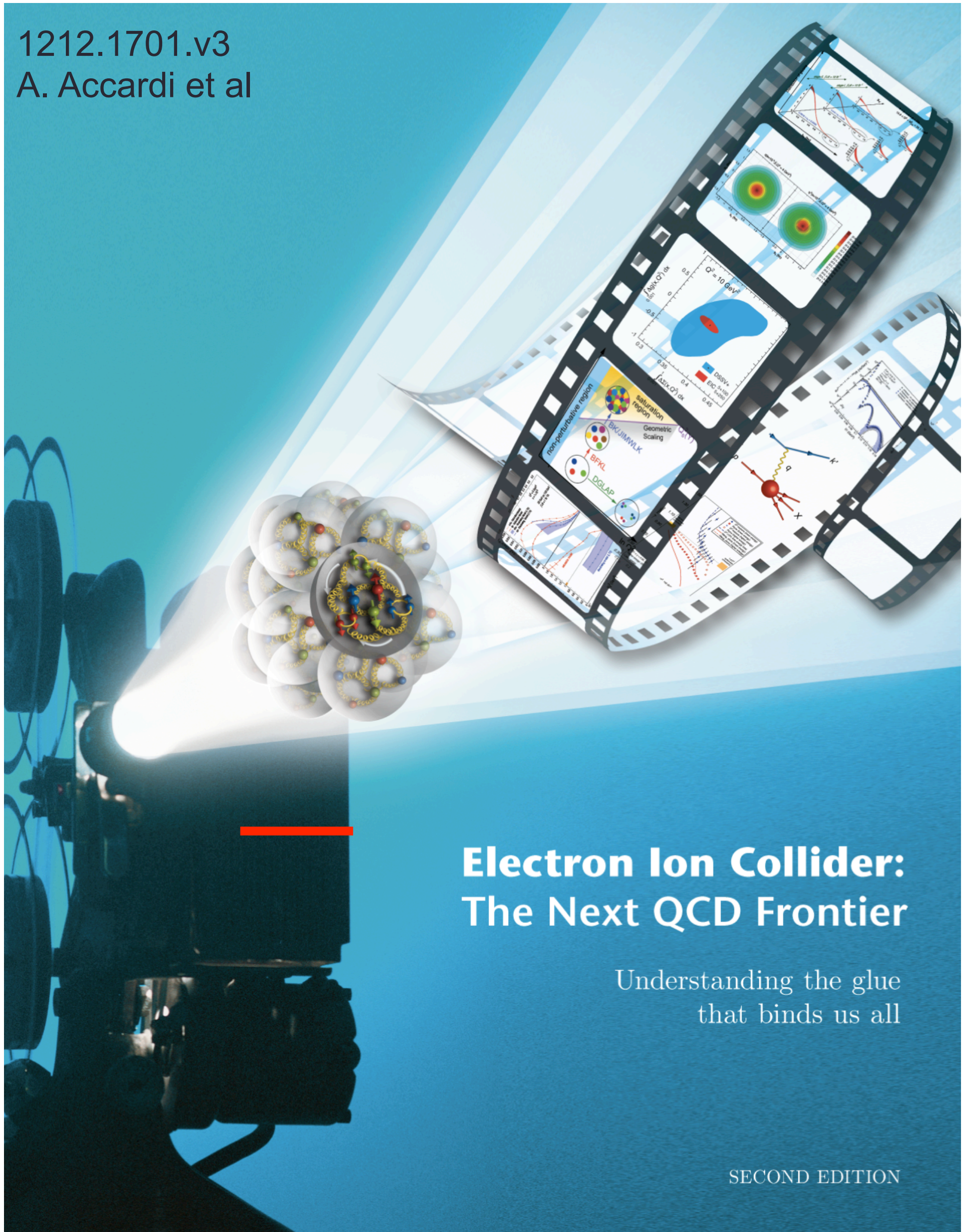
NSAC 2015 Long-Range Plan:

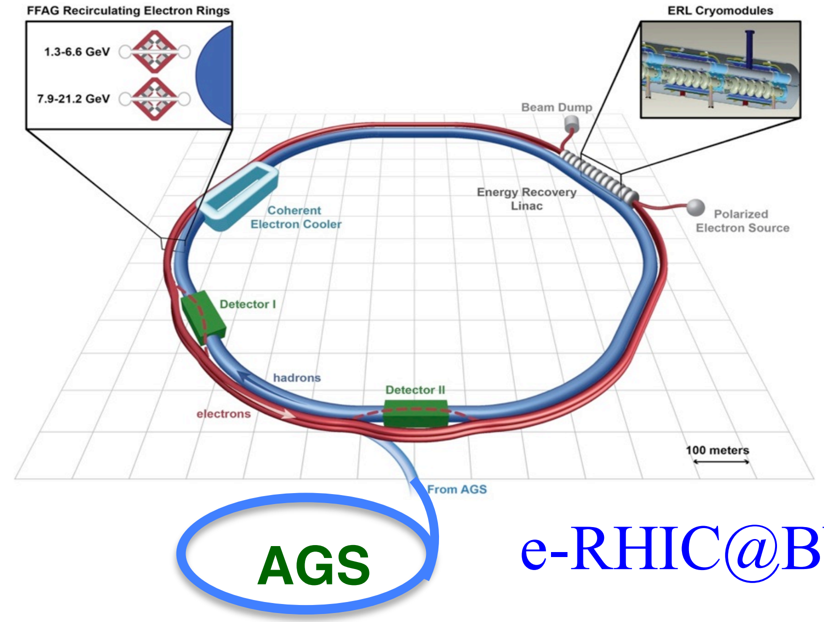
We recommend a high-energy high-luminosity polarized **EIC as the highest priority for new facility construction** following the completion of FRIB.

EIC Community White Paper arXiv:1212.1701v2

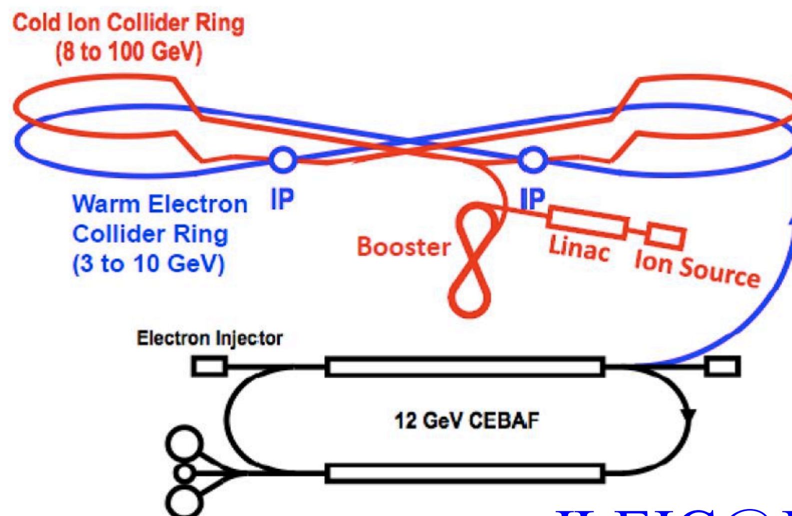
The Electron Ion Collider

Two proposals for realization of the Science Case





e-RHIC@BNL



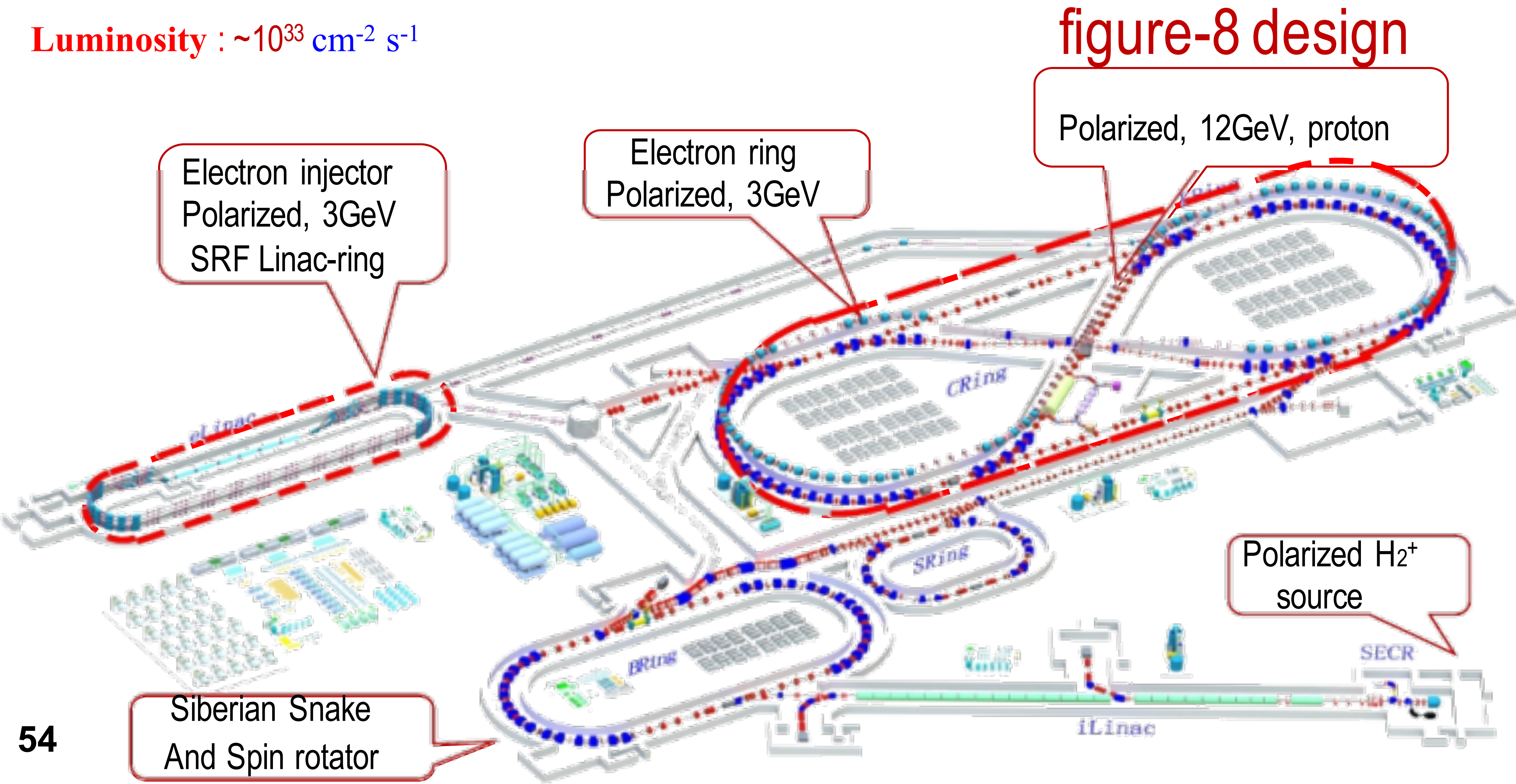
JLEIC@JLab

Second phase for HIAF: EIC (3 x 12 GeV) in China

- HIAF design maintains a well defined path for EIC
- **In HIAF I: EIC Ion pre-Booster $10^{14\sim15}$ ppp → Lower energy EIC (Update +ERL)**

See W. L. Zhan's talk@The 8th Workshop on Hadron Physics in China and Opportunities Worldwide (2016)

Luminosity : ~10^{33} cm^{-2} s^{-1}



Overview of EIC Experiments

A Key Question for EIC:

"How are the sea quarks and gluons, and their spins distributed in space and momentum inside the nucleon?"

- Spin and Flavor Structure of the Nucleon
- 3-d Structure in Momentum Space and Confined Motion of Partons inside the Nucleon
- 3-d Structure in Coordinator Space and Tomography of the Nucleon

Other Important Questions:

"Where does the saturation of gluon densities set in?

How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?"

Opportunity for Low Energy Search of Physics Beyond SM

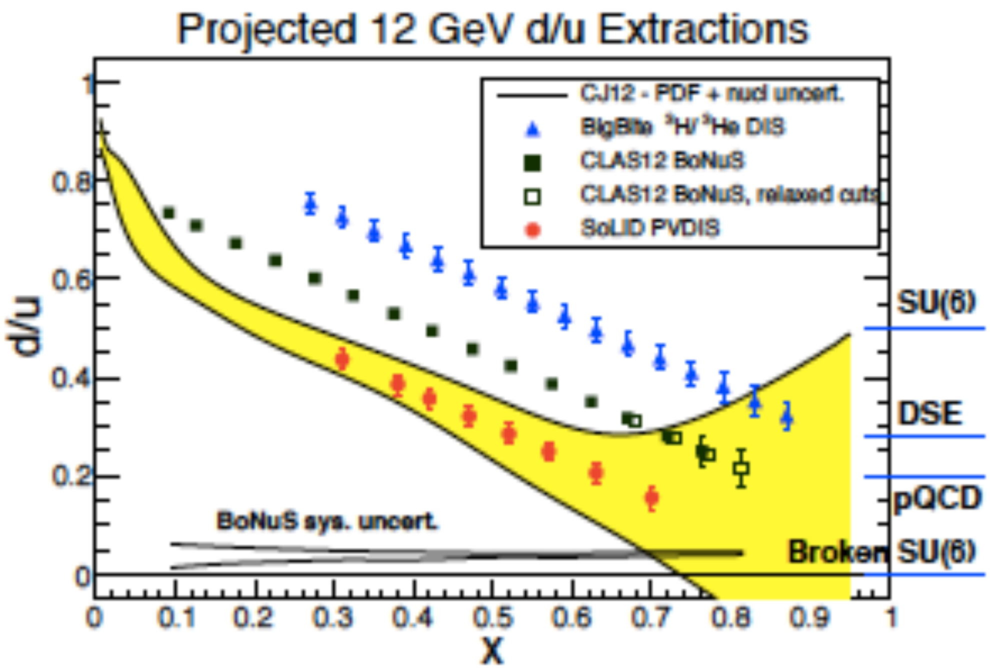
- Parity Violating e-N

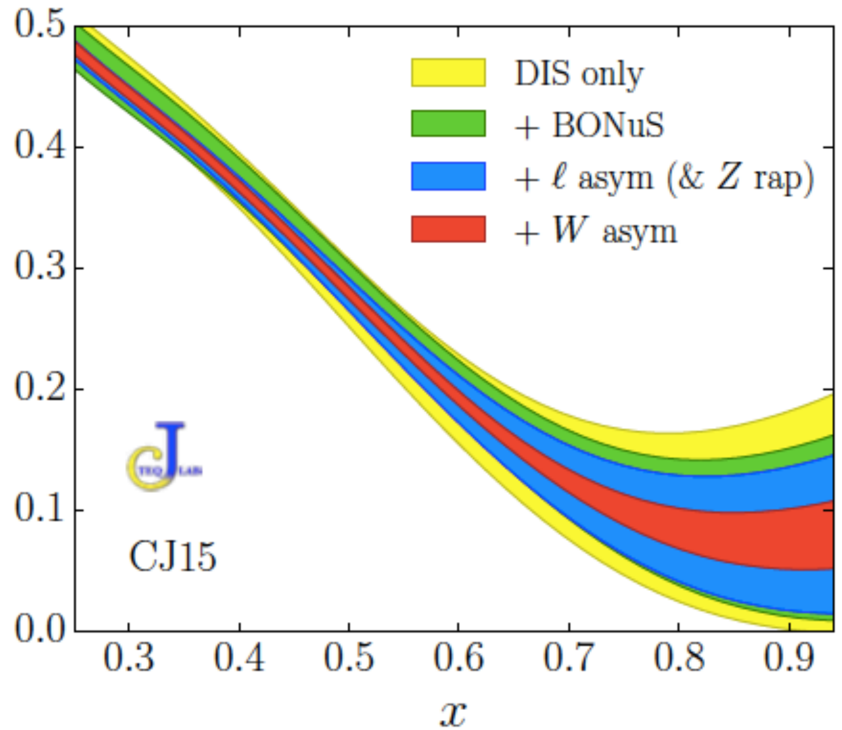
Summary

- Understand strong interaction/nucleon structure: A challenge
- JLab 12 GeV upgrade: Study Nucleon Structure in Valence Quark Region
- Highlights of JLab results and 12 GeV/SoLID program
  - Unpolarized PDF: d/u @ high-x, sea asymmetry d_bar/u_bar, strange sea
  - polarized PDF: A1n @high-x, d2 moments
  - 3-d Structure: TMDs and GPDs
- Future Electron-Ion Collider: understand sea quarks and gluons

Backup

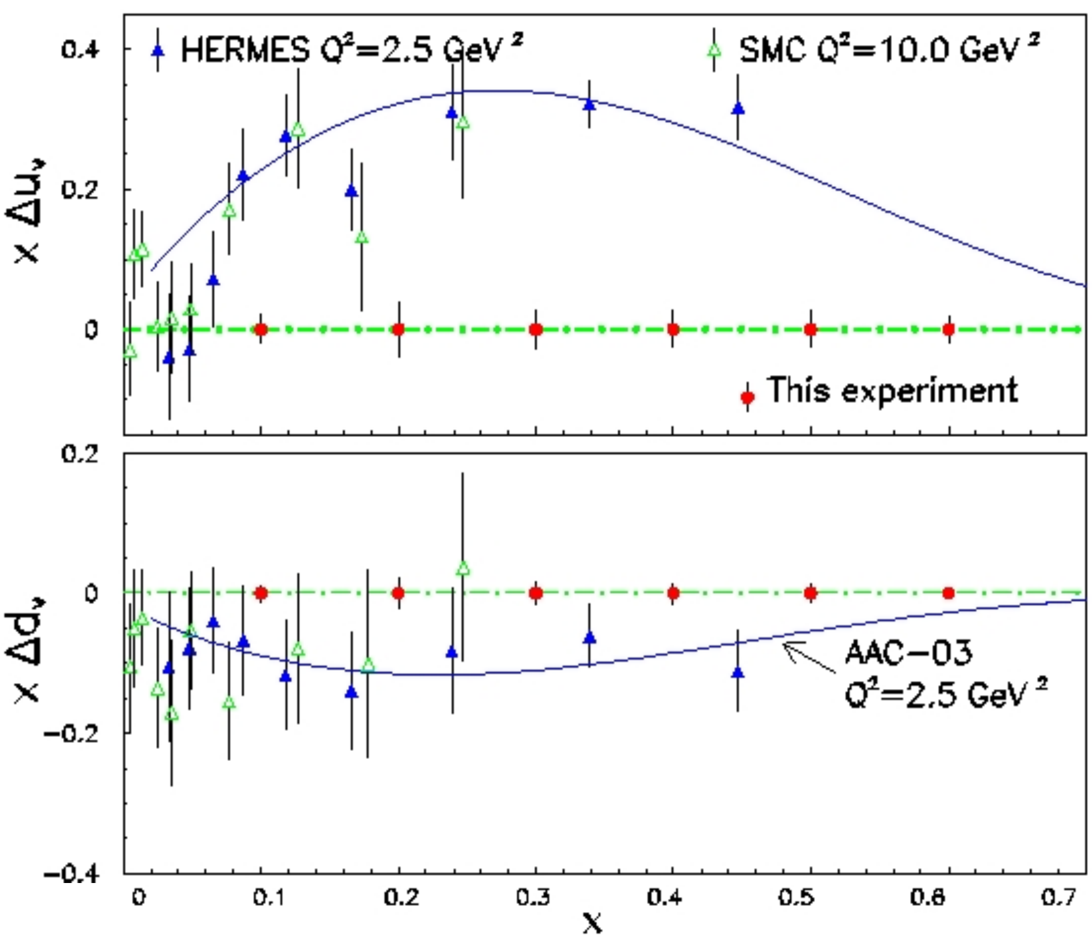
Valence Quark Distributions: d/u@ High-x



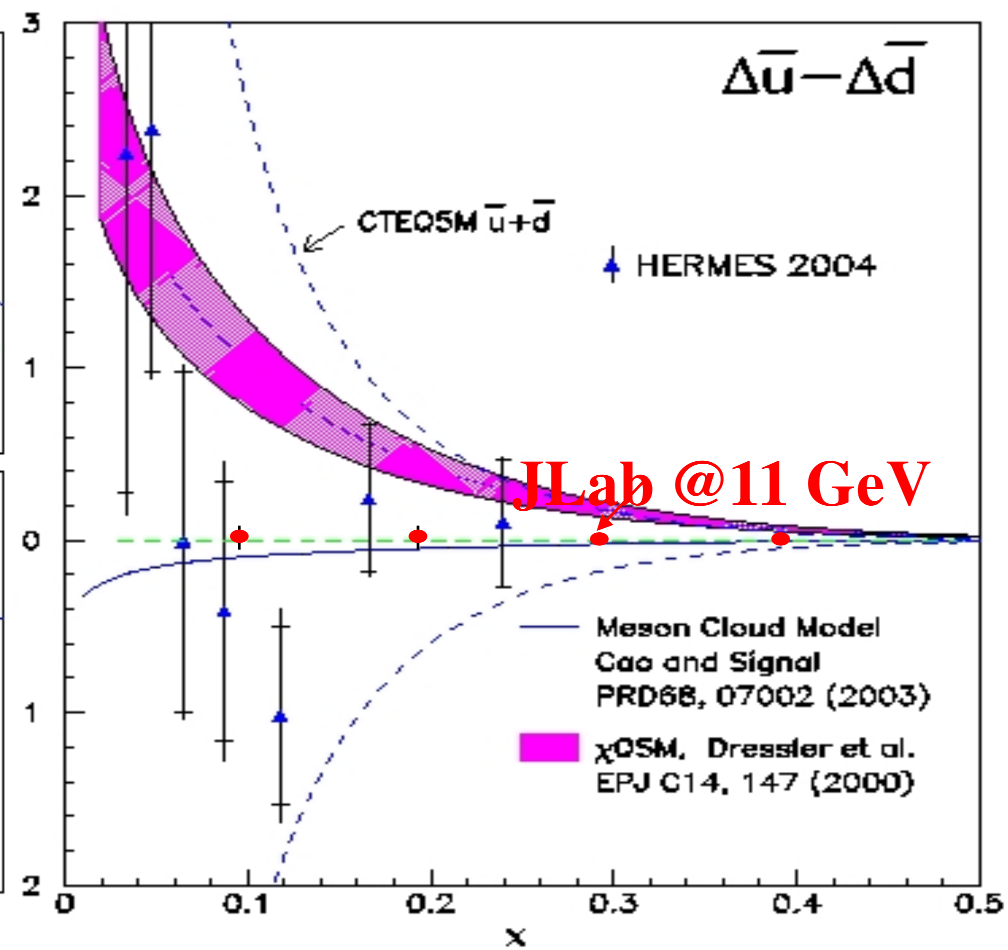


Flavor decomposition with SIDIS

Δu and Δd at JLab 11 GeV



Polarized Sea



known information on GPDs

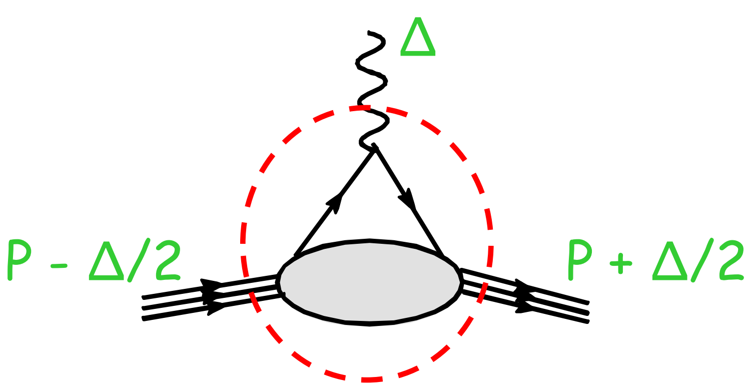
➡ forward limit : ordinary parton distributions

$$H^q(x,\xi=0,t=0) \quad = \quad q(x)$$ unpolarized quark distribution

$$\tilde{H}^q(x,\xi=0,t=0) \quad = \quad \Delta q(x)$$ polarized quark distribution

$E^q\ ,\ \tilde{E}^q$: do NOT appear in DIS ➡ additional information

➡ first moments : nucleon electroweak form factors



ξ independence : Lorentz invariance

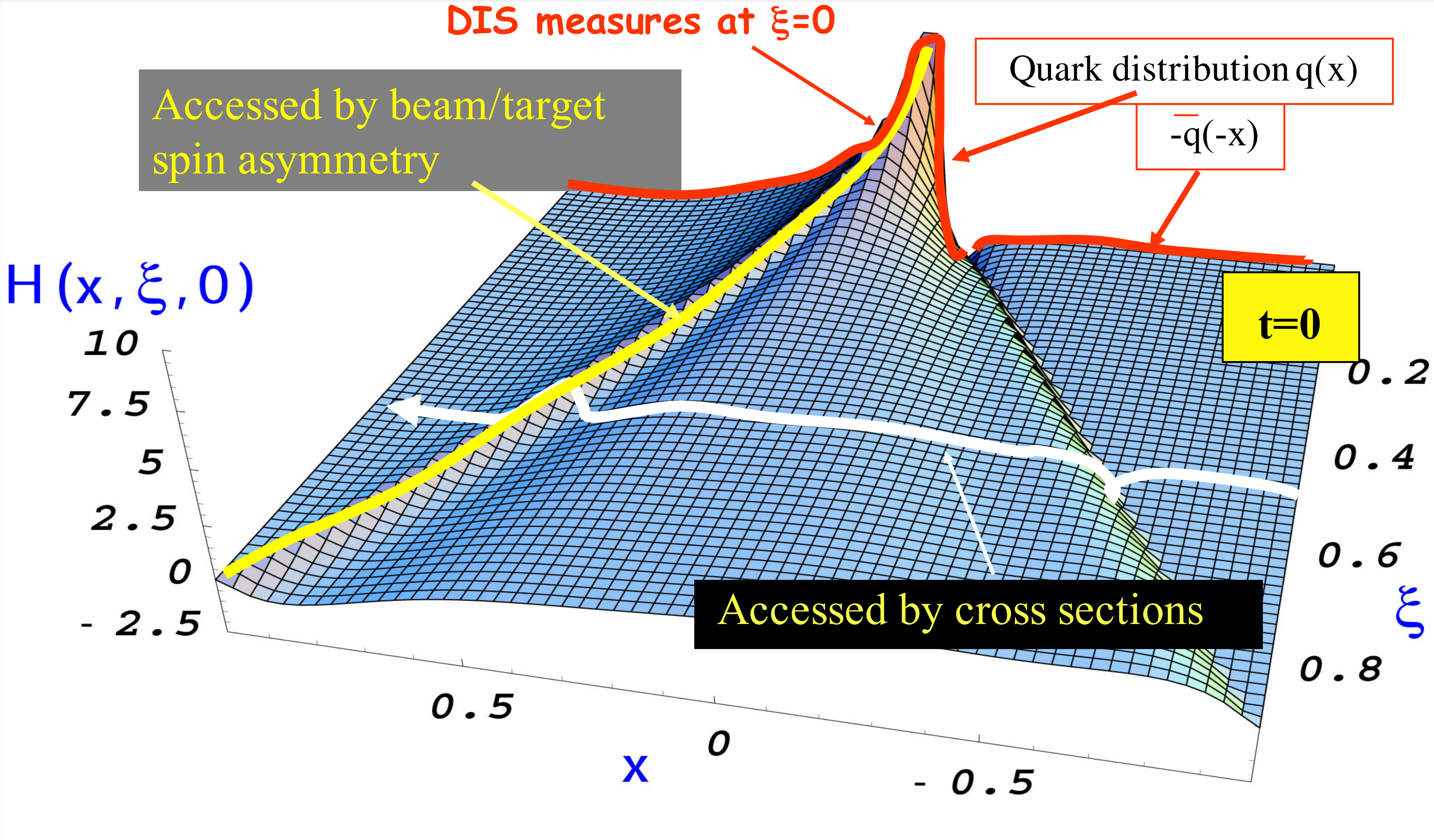
$$\int_{-1}^{1} dx\, H^q(x,\xi,t) \quad = \quad F_1^q(t)$$ Dirac

$$\int_{-1}^{1} dx\, E^q(x,\xi,t) \quad = \quad F_2^q(t)$$ Pauli

$$\int_{-1}^{1} dx\, \tilde{H}^q(x,\xi,t) \quad = \quad G_A^q(t)$$ axial

$$\int_{-1}^{1} dx\, \tilde{E}^q(x,\xi,t) \quad = \quad G_P^q(t)$$ pseudo-scalar

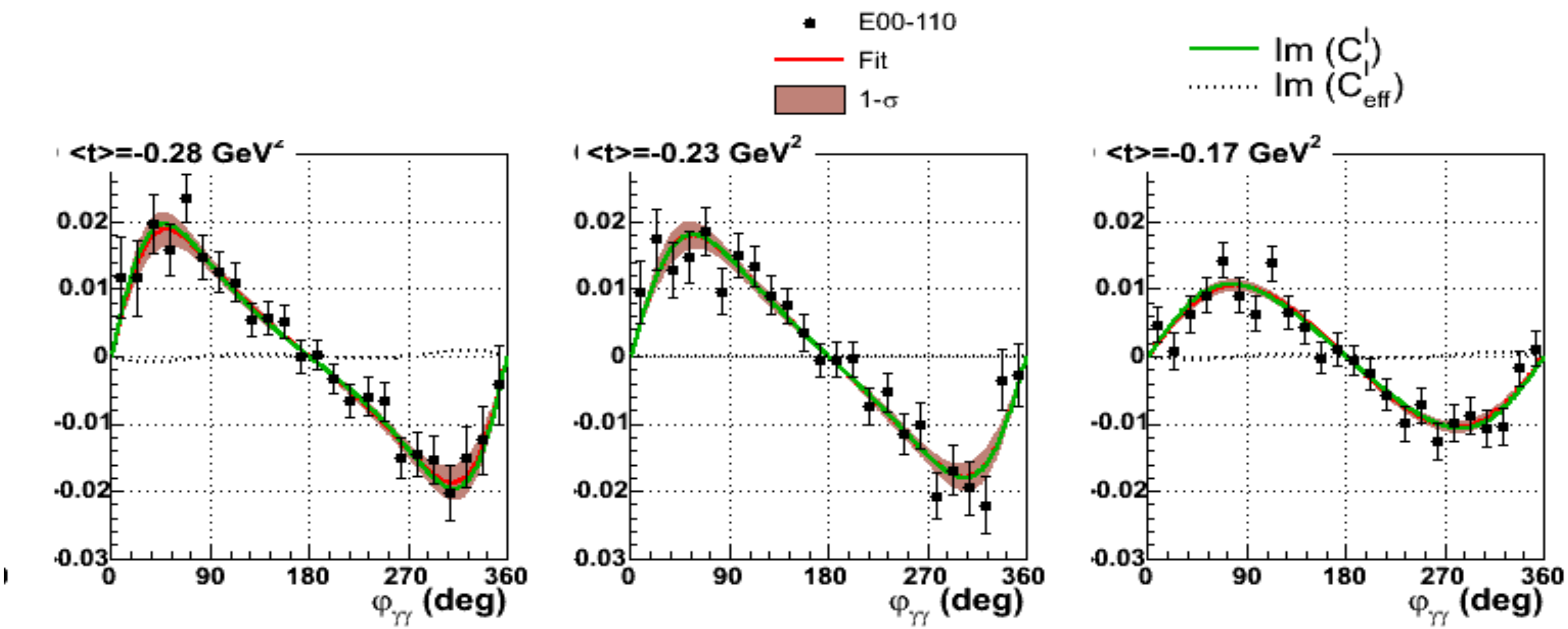
Access GPDs through DVCS x-section & asymmetries



Hall A DVCS Experiment

Handbag Dominance at Modest Q^2

$$\frac{d^4\sigma^+}{dx_B dQ^2 d\varphi\, dt} - \frac{d^4\sigma^-}{dx_B dQ^2 d\varphi\, dt} \quad [\mathrm{nb/GeV^4}]$$



Twist 2 contribution

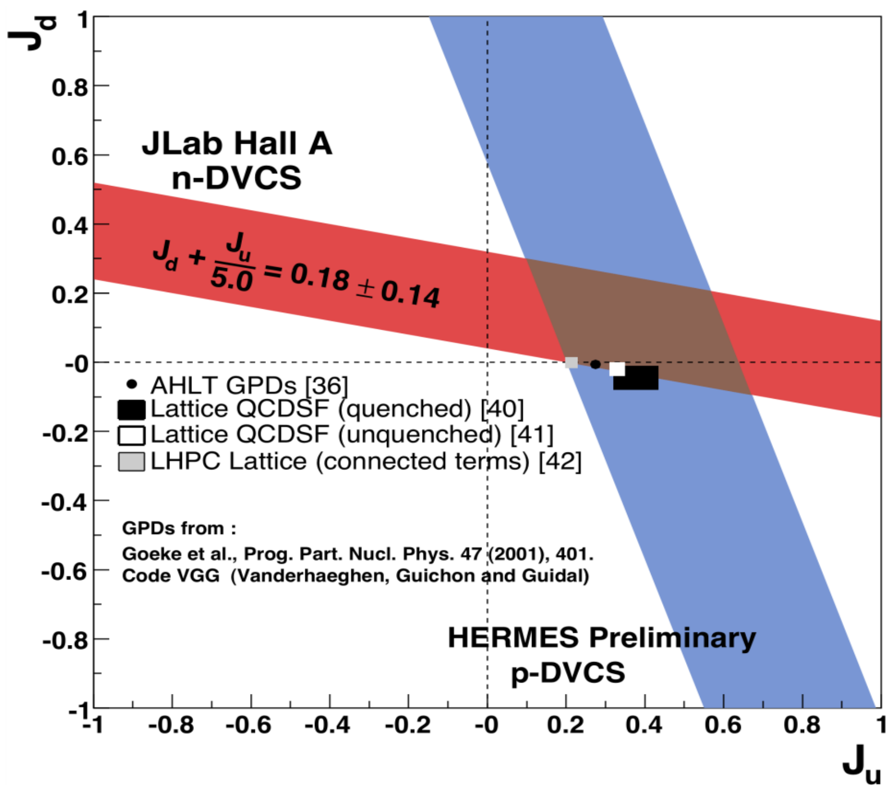
Twist 3 contribution strongly suppressed

The Twist-2 term can be extracted accurately from the cross-section difference

Dominance of twist-2 ⇒ handbag dominance ⇒ DVCS interpretation

Quark Angular Momentum

$$J^q(t) = \int_{-1}^{+1} dx x [H^q(x,\xi,t) + E^q(x,\xi,t)]$$



→ Access to quark orbital angular momentum

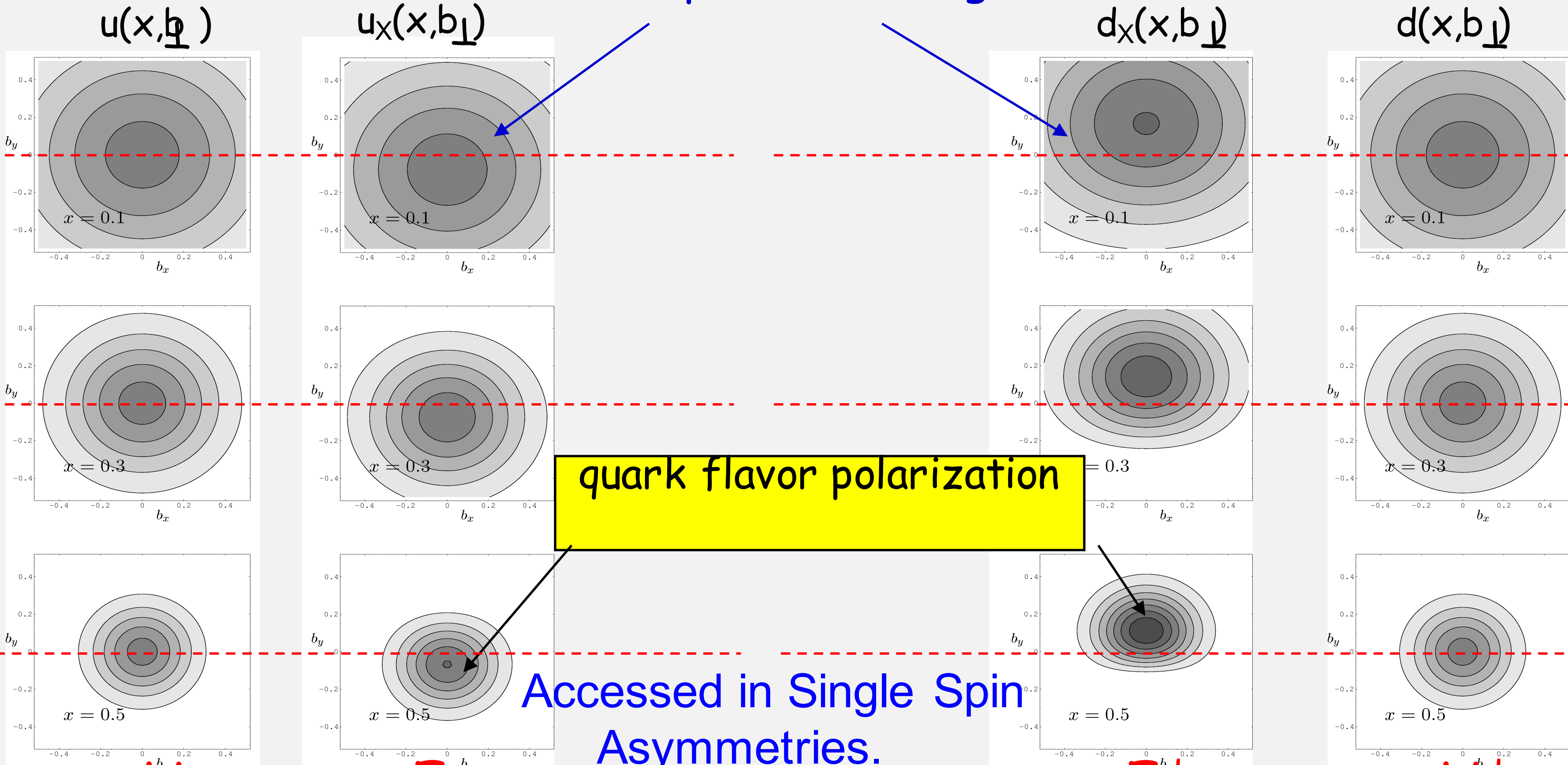
3D Images of the Proton's Quark Content

M. Burkardt PRD 66, 114005 (2002)

$$q(x,\mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{\Delta}_\perp \cdot \mathbf{b}_\perp} H(x,0,-\mathbf{\Delta}_\perp^2).$$

$\mathbf{b}_\perp$ - Impact parameter

transverse polarized target



quark flavor polarization

Accessed in Single Spin Asymmetries.

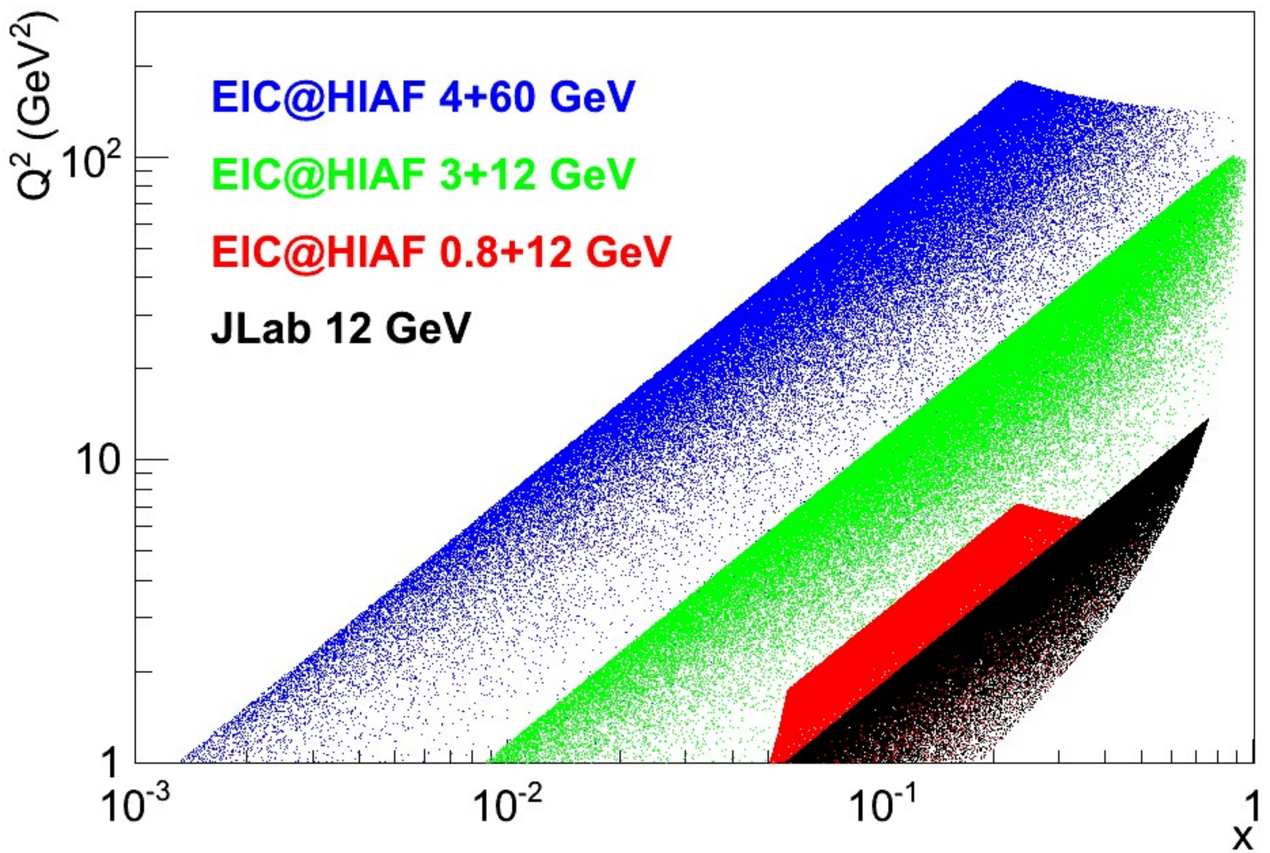
Needs: H^u E^u E^d H^d

EIC@HIAF Kinematic Coverage Comparison with JLab 12 GeV

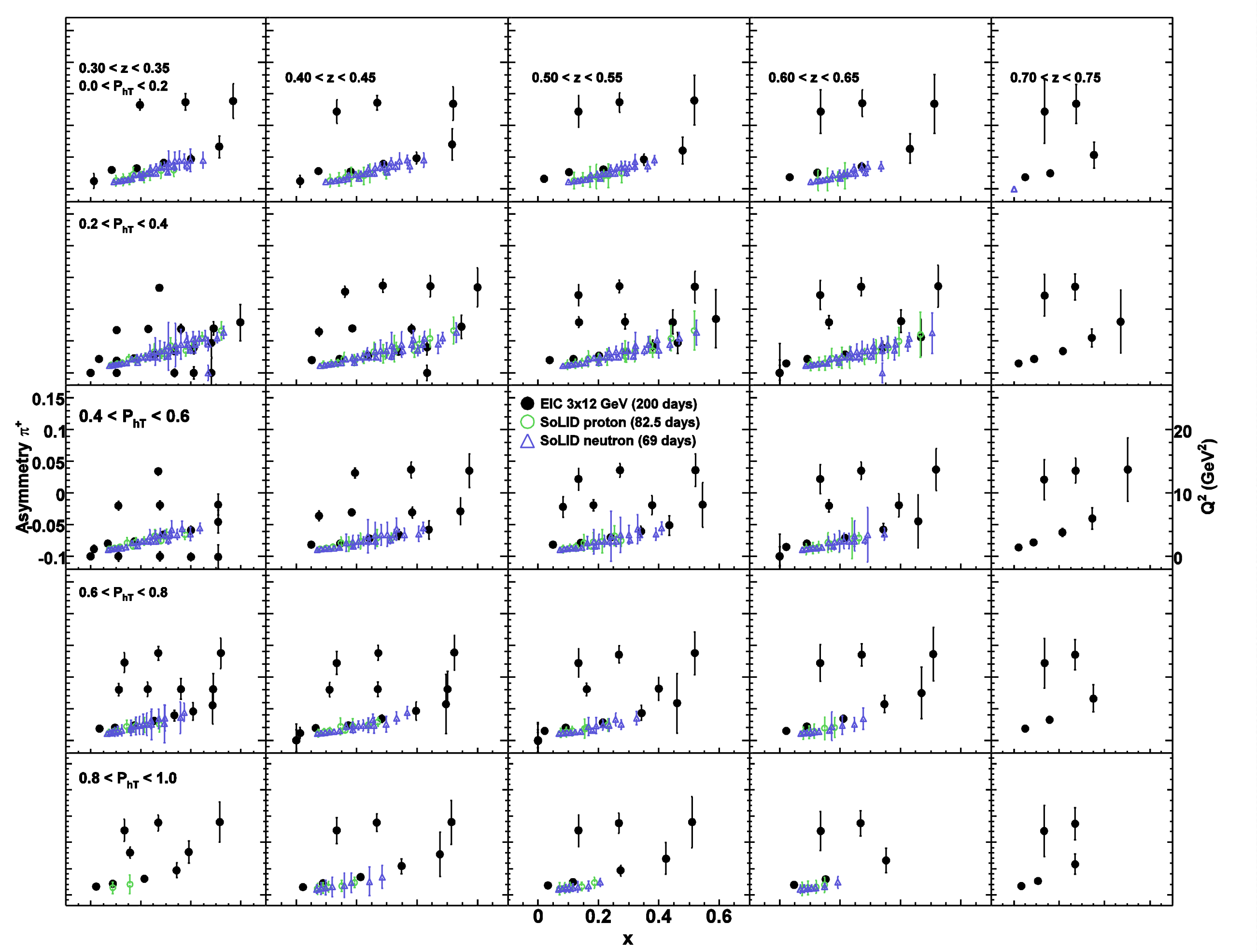
e(3GeV) +p(12GeV), both polarized, L(max)~ 10^{33}cm^2/s

EIC@HIAF:

- study sea quarks (x ~ 0.01)
- deep exclusive scattering at Q^2 > 5-10
- higher Q^2 in valance region
- range in Q^2 allows some study gluons



EIC@HIAF Projections for SIDIS Asymmetry π^+



EIC@HIAF reach high precision similar to SoLID at lower x, higher Q2 region

Green (Blue) Points: SoLID projections for polarized NH_3 ($^3He/n$) target
Luminosity: 10^{35} (10^{36}) (1/cm^2/s); Time: 120 (90) days

Black points: EIC@HIAF projections for 3 GeV e and 12 GeV p
Luminosity: 4 x 10^{32} /cm^2/s; Time: 200 days

GPD Study at EIC@HIAF

- Unique opportunity for DVMP (pion/Kaon)

  flavor decomposition needs DVMP

  energy reach $Q^2 > 5$-$10\ GeV^2$, scaling region for exclusive light meson production

  (JLab12 energy not high enough to have clean light meson deep exclusive process)

- Significant increase in range for DVCS

  combination of energy and luminosity

- Other opportunities: vector meson, heavy flavors?