Frontiers in Hadron (Nucleon) Structure

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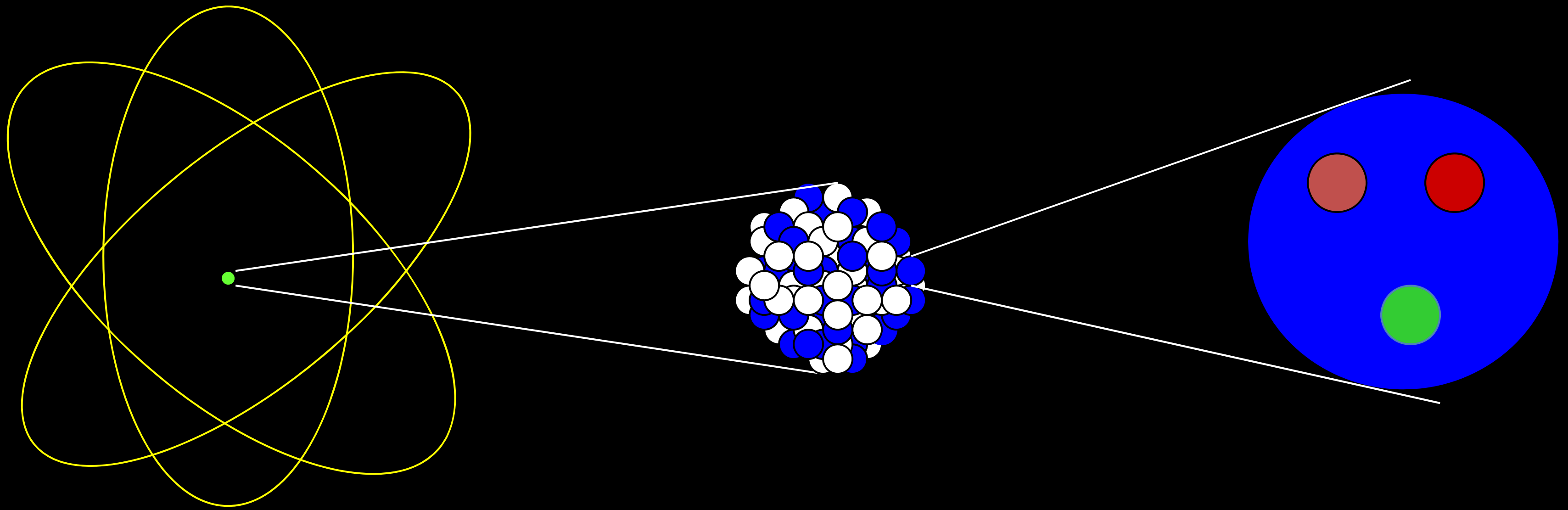
Outline

- Introduction
- Nucleon transverse spin and structure
- **The JLab E06-10 experiment**
- Summary and outlook

Nuclear physics is the study of the structure of matter

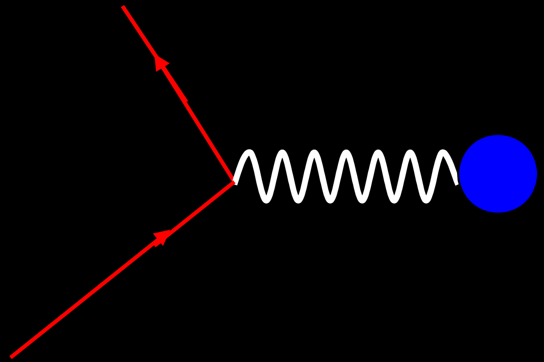
- Most of the mass and energy in the universe around us comes from nuclei and nuclear reactions.
- The nucleus is a unique form of matter in that all the forces of nature are present : (strong, electromagnetic, weak).



atom: 10^{-10} m

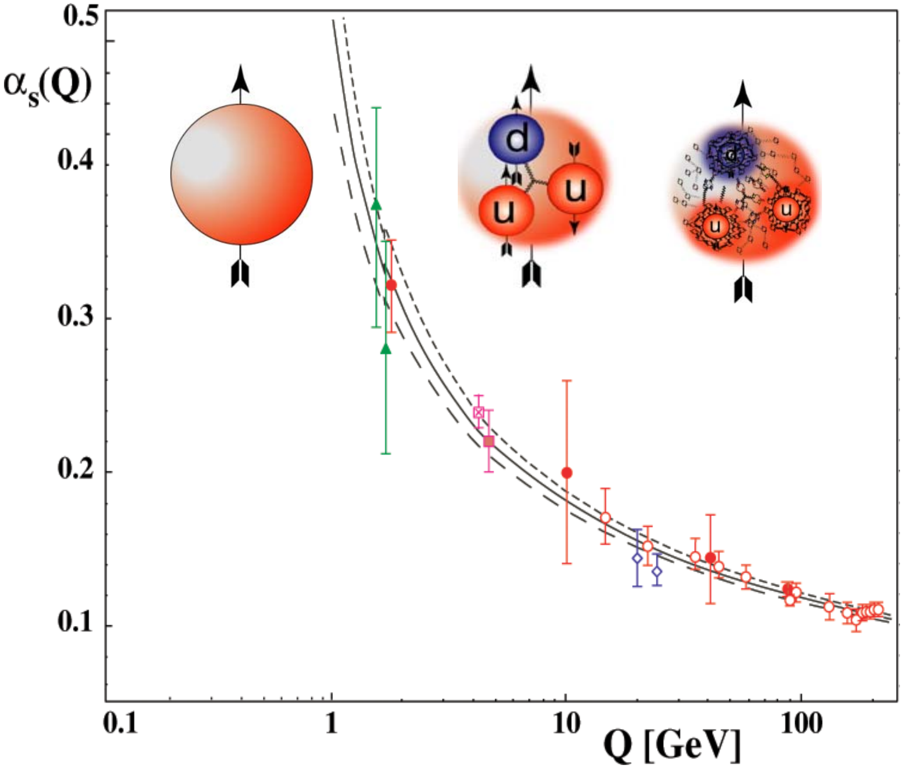
nucleus: 10^{-14} m

nucleon: 10^{-15} m



$$\lambda \approx \frac{h}{p}$$

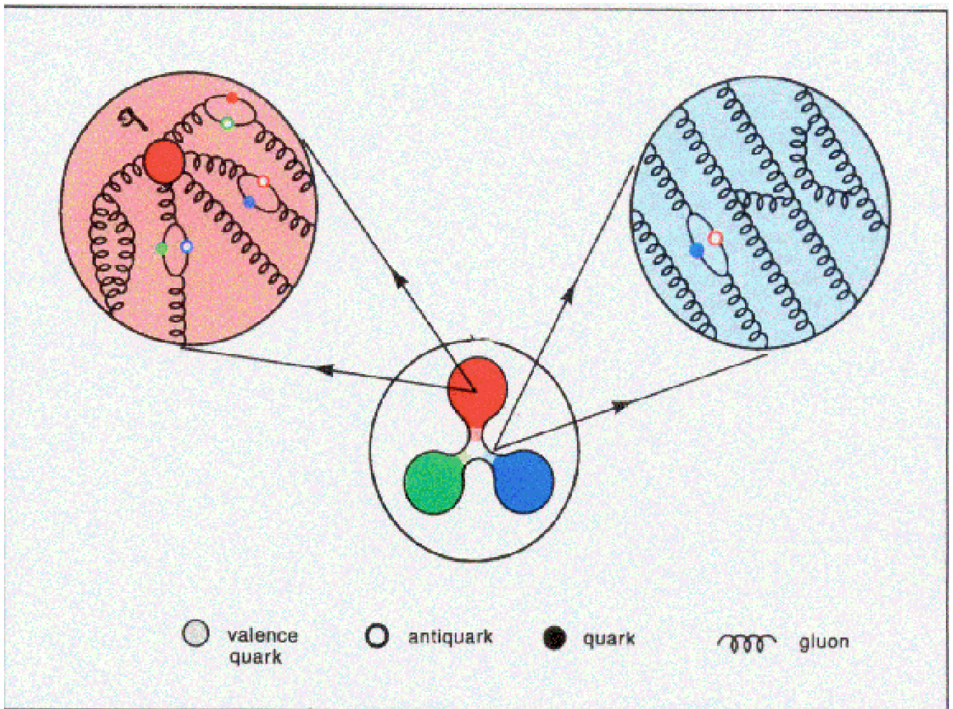
QCD: still unsolved in non-perturbative region



Gauge bosons: gluons (8)

- *2004 Nobel prize for ``asymptotic freedom''*
- *non-perturbative regime QCD ?????*
- *One of the top 10 challenges for physics!*
- *Nucleon structure is one of the most active areas*

Nucleons: Building blocks of matter



- Nucleon anomalous magnetic moment ***(Stern, Nobel Prize 1943)***
- ***Electromagnetic form factors from electron scattering (Hofstadter, Nobel Prize 1961)***
- Deep-inelastic scattering, quark underlying structure of the nucleon ***(Friedman, Kendall, Taylor, Nobel Prize 1990)***

- Current quark mass is negligible
- Quark contributes 50% of momentum

Understanding the underlying nucleon structure from quantum chromodynamics is important
Understanding QCD in the confinement region

Lepton scattering: powerful microscope!

- Clean probe of hadron structure
- Electron point-like particle, electron vertex is well-known from quantum electrodynamics
- One-photon exchange dominates, ***higher-order exchange diagrams are suppressed***
- ***One can vary the wave-length of the probe to view deeper inside the hadron***

Resolution $\propto h/Q$

–Q ≈ 20 MeV λ ≈ 10 fm nucleus

–Q ≈ 200 MeV λ ≈ 1 fm nucleon

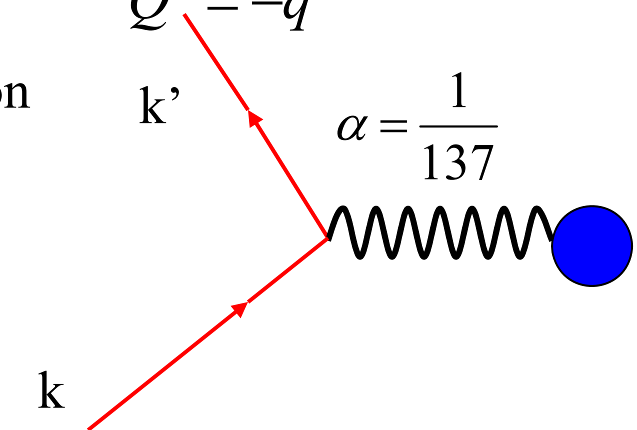
–Q≈ 2 GeV λ ≈ 0.1 fm inside nucleon

–Q≈ 20 GeV λ ≈ 0.01 fm quark

Virtual photon 4-momentum

$$q = k - k' = (\vec{q}, \omega)$$

$$Q^2 = -q^2$$

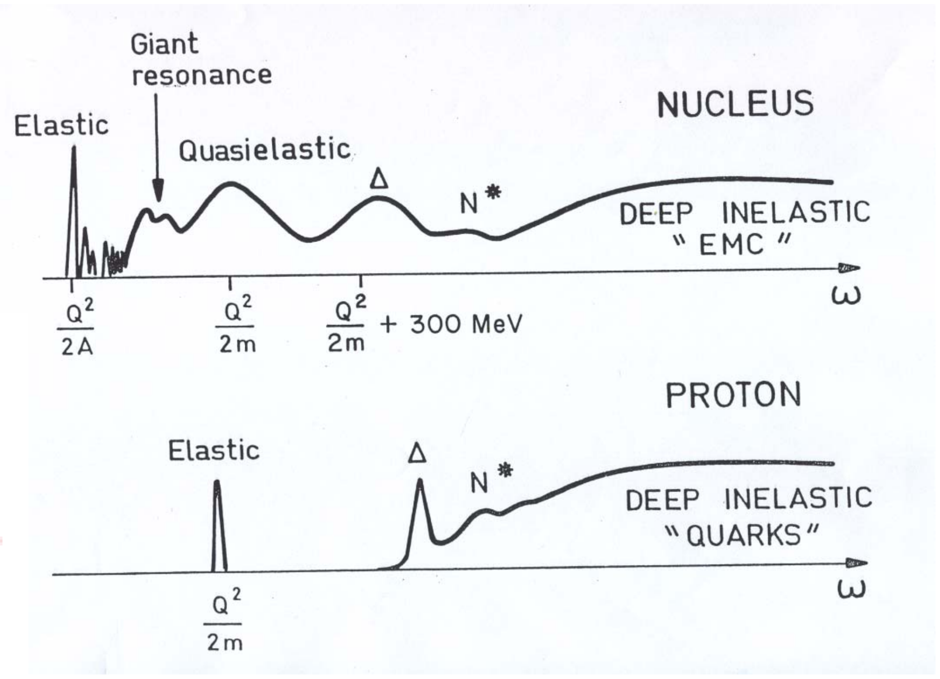


Using electron scattering as example

Electron-nucleon scattering

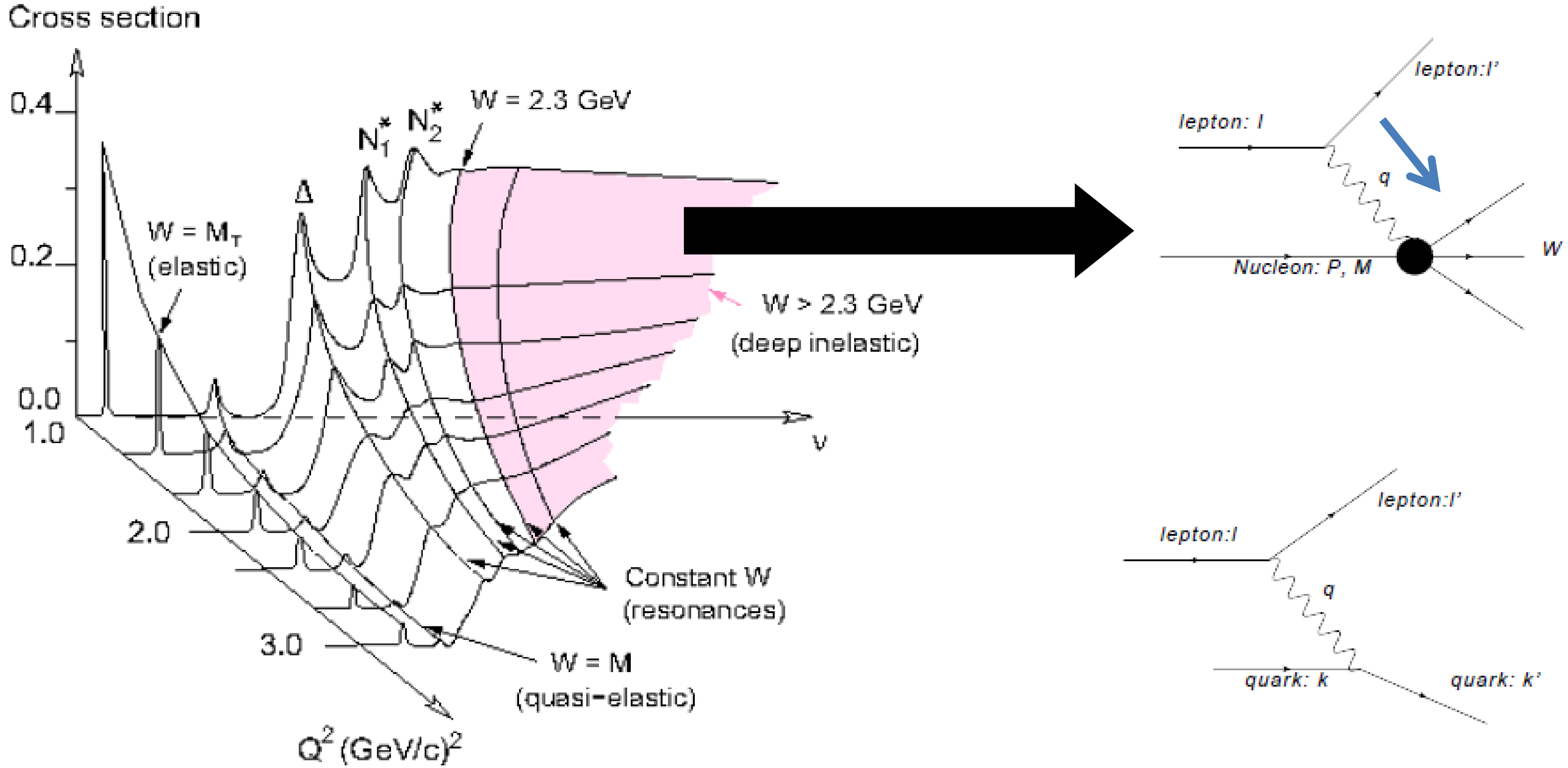
- Low Q^2 elastic scattering, $x=1=Q^2/2m\omega$
- As Q^2 increases inelastic effects dominates
- As Q^2 further increases, deep-inelastic scattering off quarks inside

m: mass of the nucleon



Electron energy transfer

Lepton Scattering ----- *A powerful tool*



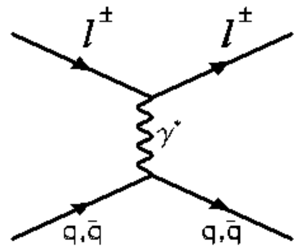
$$Q^2 = -q^2 = -(l - l')^2$$ 4-momentum transfer squared: resolution.

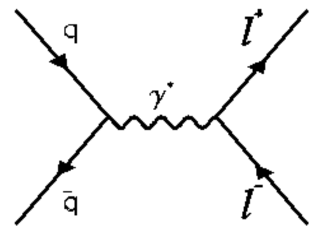
$$\nu = E_l - E_{l'}$$ Energy transfer.

$$x_{Bjorken} = \frac{Q^2}{2m\nu}$$ Longitudinal momentum fraction of parton in the light cone frame.

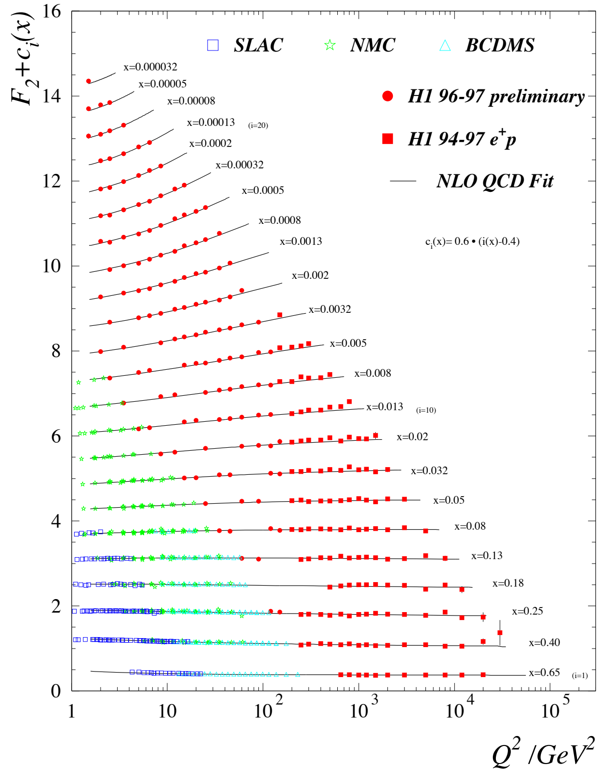
Universal Parton Distribution

DIS

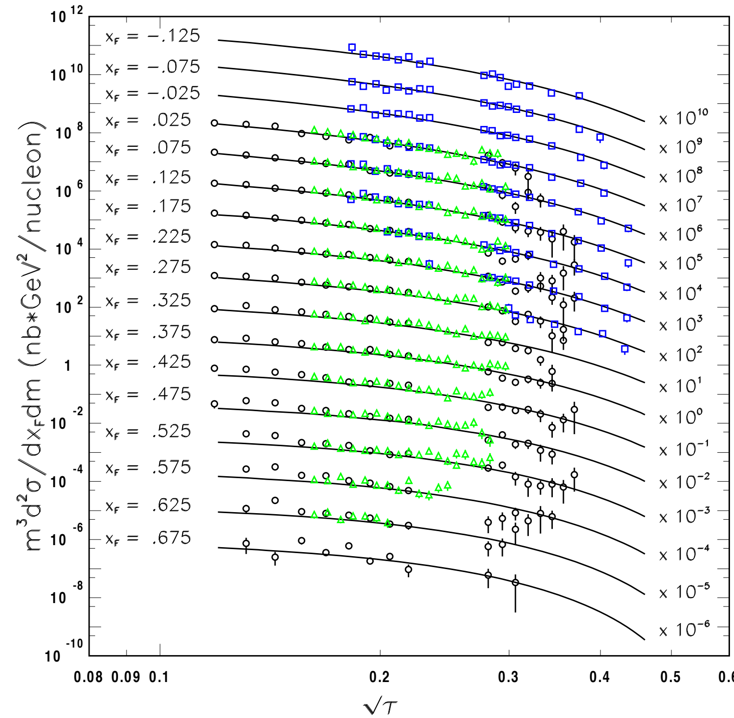




Drell-Yan



$p\,A \rightarrow \mu^+\mu^-\,X$



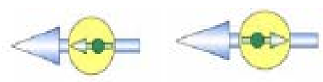
Drell-Yan and DIS cross sections are well described by Next-to-Leading Order QCD

Spin as a knob

- Spin Milestones: (Nature)
  - 1896: Zeeman effect (milestone 1)
  - 1922: Stern-Gerlach experiment (2)
  - 1925: Spinning electron (Uhlenbeck/Goudsmit)(3)
  - 1928: Dirac equation (4)
  - Quantum magnetism (5)
  - 1932: Isospin(6)
  - 1935: Proton anomalous magnetic moment
  - 1940: Spin–statistics connection(7)
  - 1946: Nuclear magnetic resonance (NMR)(8)
  - 1971: Supersymmetry(13)
  - 1973: Magnetic resonance imaging(15)
  - 1980s: “Proton spin crisis”
  - 1990: Functional MRI (19)
  - 1997: Semiconductor spintronics (23)
  - 2000s: “New breakthrough in spin physics”?

Nucleon Spin Structure

- Understand Nucleon Spin in terms of quarks and gluons (QCD).
  - **Nucleon spin is ½ at all energies.**

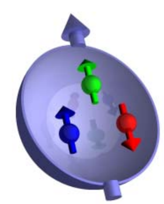


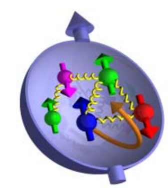
Nucleon's spin
Ji's Sum Rule

$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + J_g$$

J_q

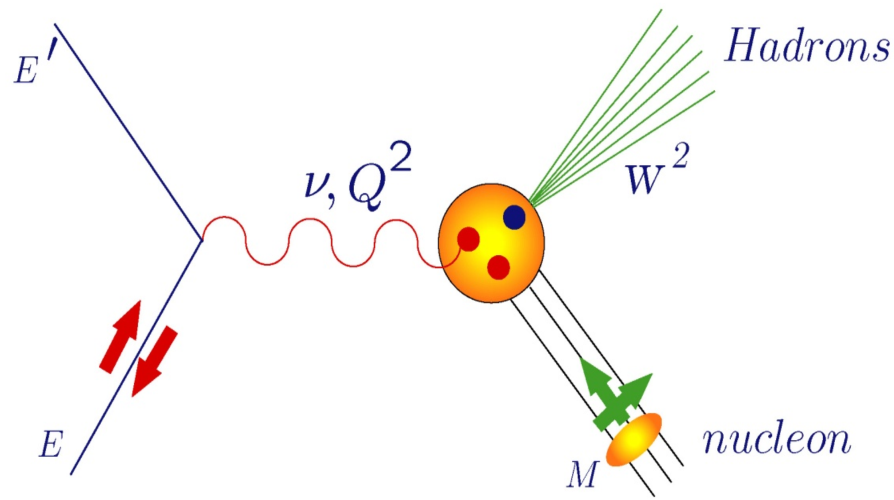
~30% from data
"spin crisis"





  - Small contribution from quarks and gluons' intrinsic spin
  - Orbital angular momentum of quarks and gluons is important
    - **Understanding of spin-orbit correlations.**

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,

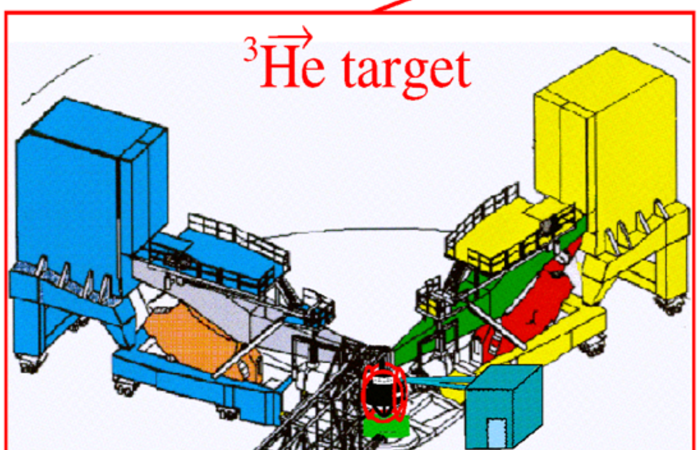
and

g_1 and g_2 the spin dependent structure functions

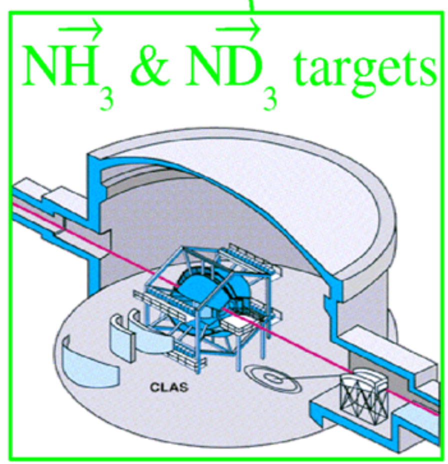
Jefferson Lab Experimental Halls

6 GeV polarized
CW electron beam
Pol=85%, 180μA

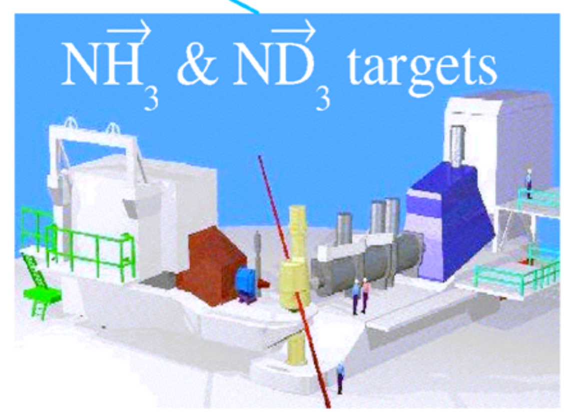
Will be upgraded to
12 GeV by ~2014



HallA: two HRS’

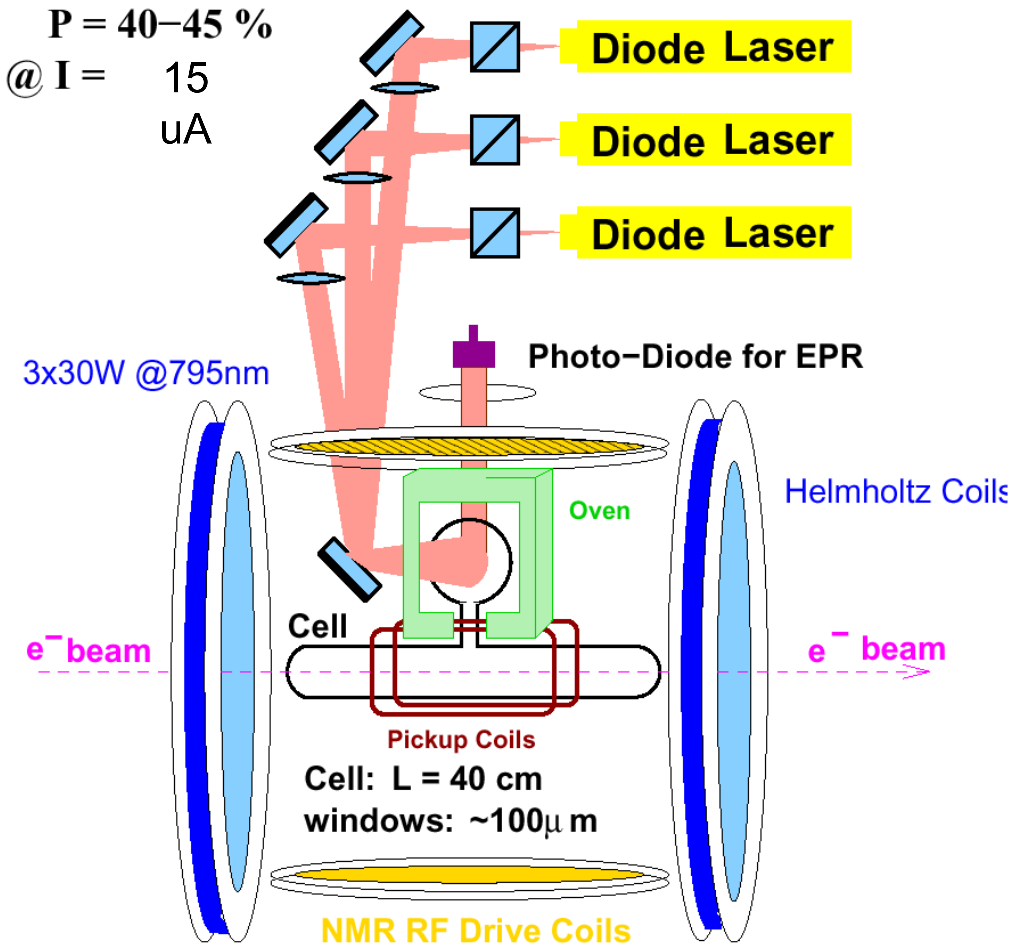


Hall B:CLAS



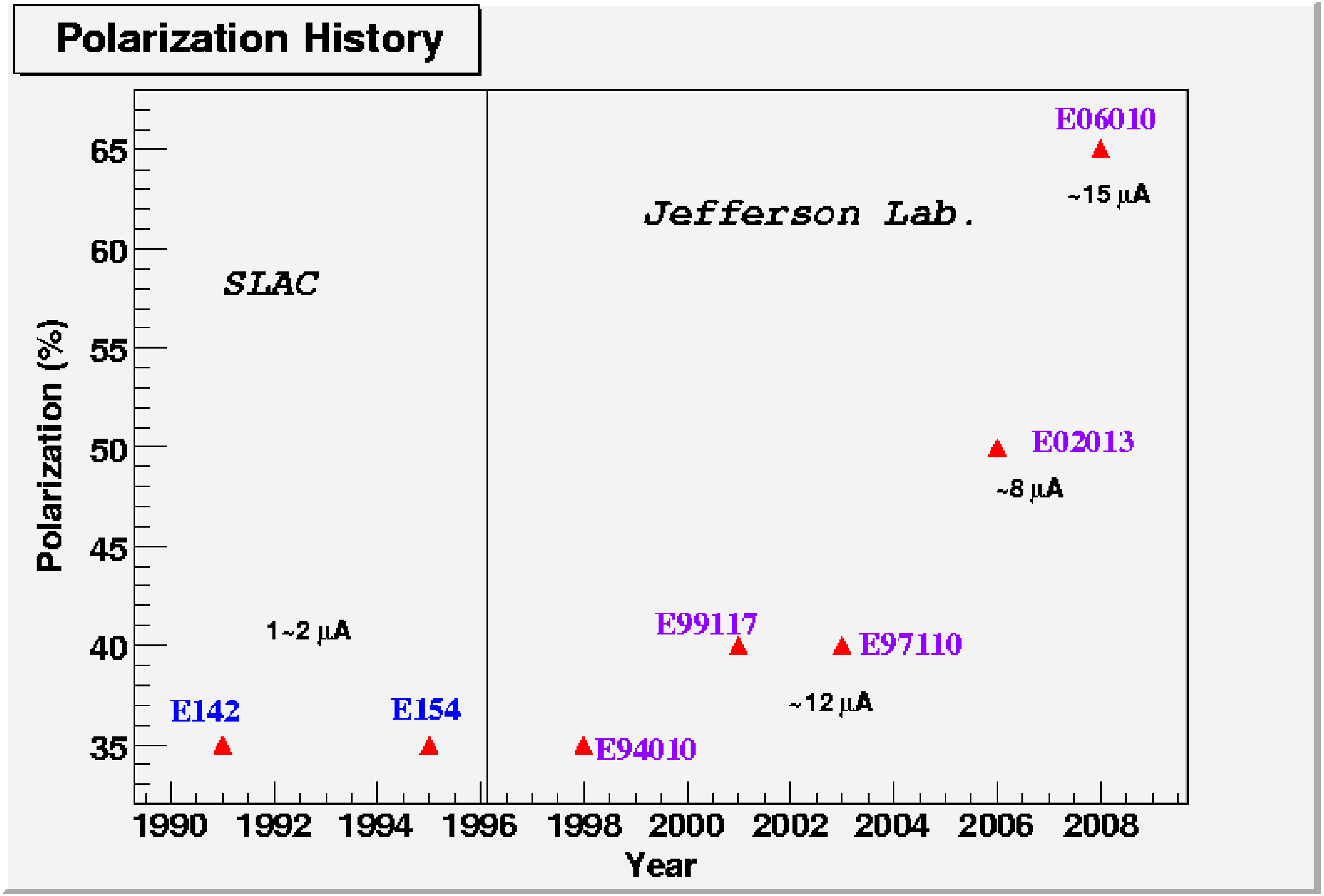
Hall C: HMS+SOS

Hall A polarized ^{3}He target



- ✓longitudinal, transverse and vertical
- ✓Luminosity=10^{36} (1/s) (highest in the world)
- ✓High in-beam polarization ~ 65%
- ✓Effective polarized neutron target
- ✓13 completed experiments
  7 approved with 12 GeV (A/C)

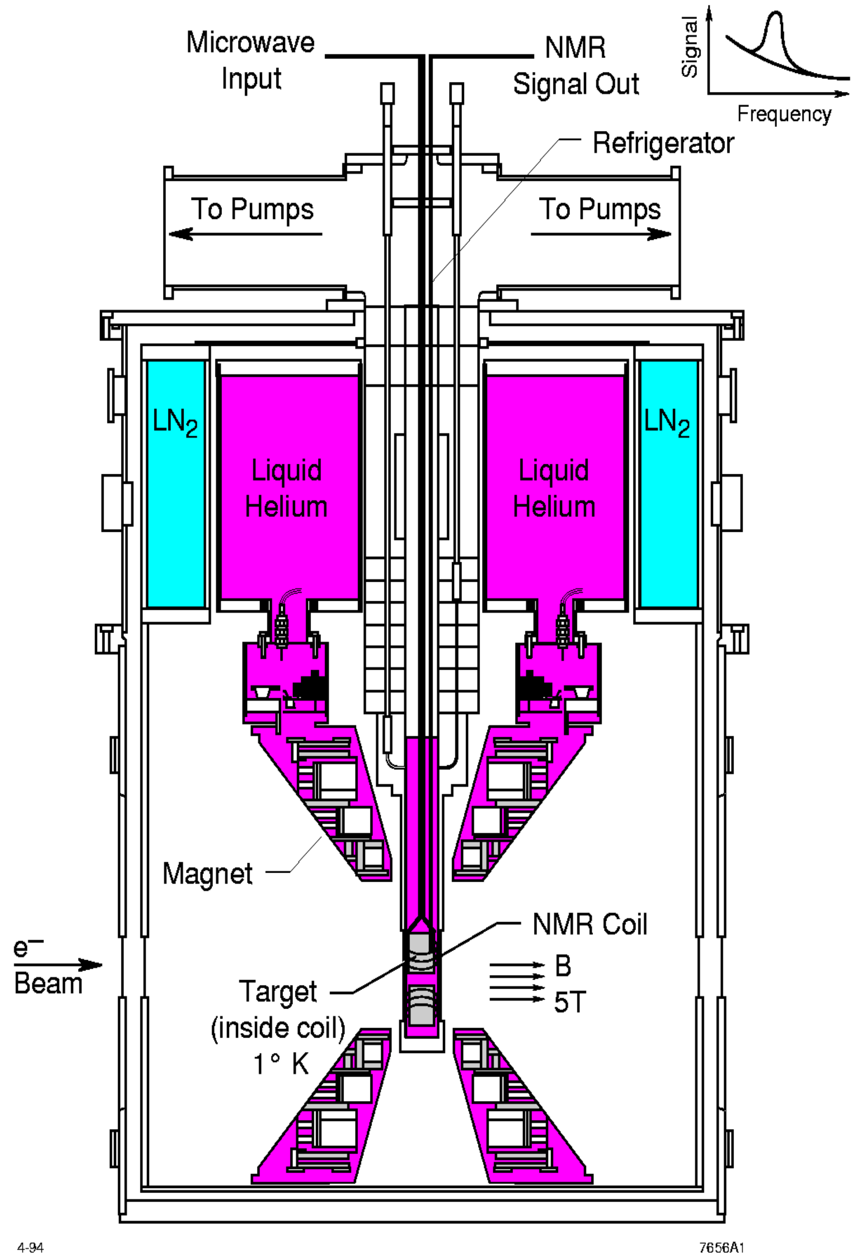
Polarized ^{3}He Progress



Hall B/C Polarized proton/deuteron target

- Polarized NH_3/ND_3 targets
- Dynamical Nuclear Polarization

- In-beam average polarization
  - 70-90% for p
  - 30-40% for d
- Luminosity up to
  - ~ 10^{35} (Hall C)
  - ~ 10^{34} (Hall B)



Three Decades of Spin Structure Study

- 1980s: EMC (CERN) + early SLAC

  quark contribution to proton spin is very small

  $\Delta\Sigma = (12+-9+-14)\%$! 'spin crisis'

  (Ellis-Jaffe sum rule violated)

- 1990s: SLAC, SMC (CERN), HERMES (DESY)

  $\Delta\Sigma = 20-30\%$

  the rest: gluon and quark orbital angular momentum

  $A^+=0$ (light-cone) gauge $(½)\Delta\Sigma + L_q + \Delta G + L_g = 1/2$ (Jaffe)

  gauge invariant $(½)\Delta\Sigma + \mathcal{L}q + J_G = 1/2$ (Ji)

  Bjorken Sum Rule verified to <10% level

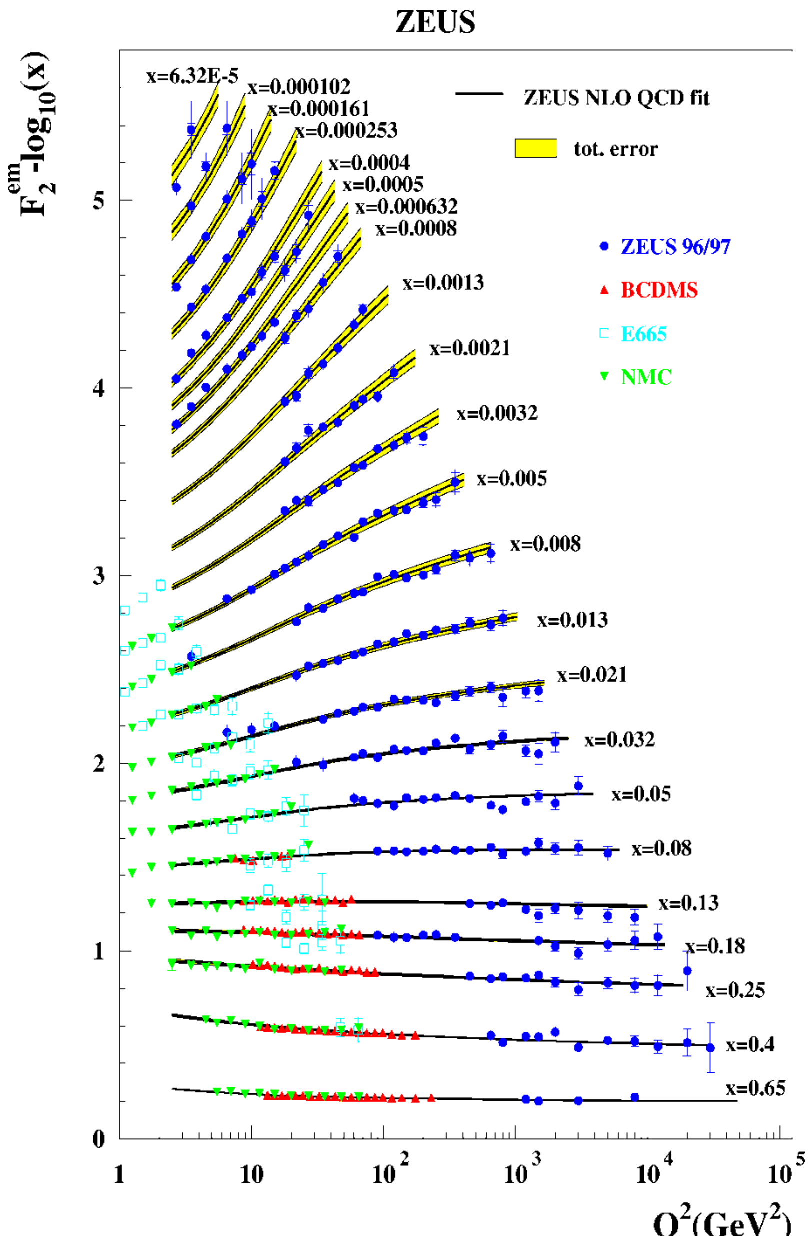
- 2000s: COMPASS (CERN), HERMES, RHIC-Spin, JLab, Mainz, HIGS, …

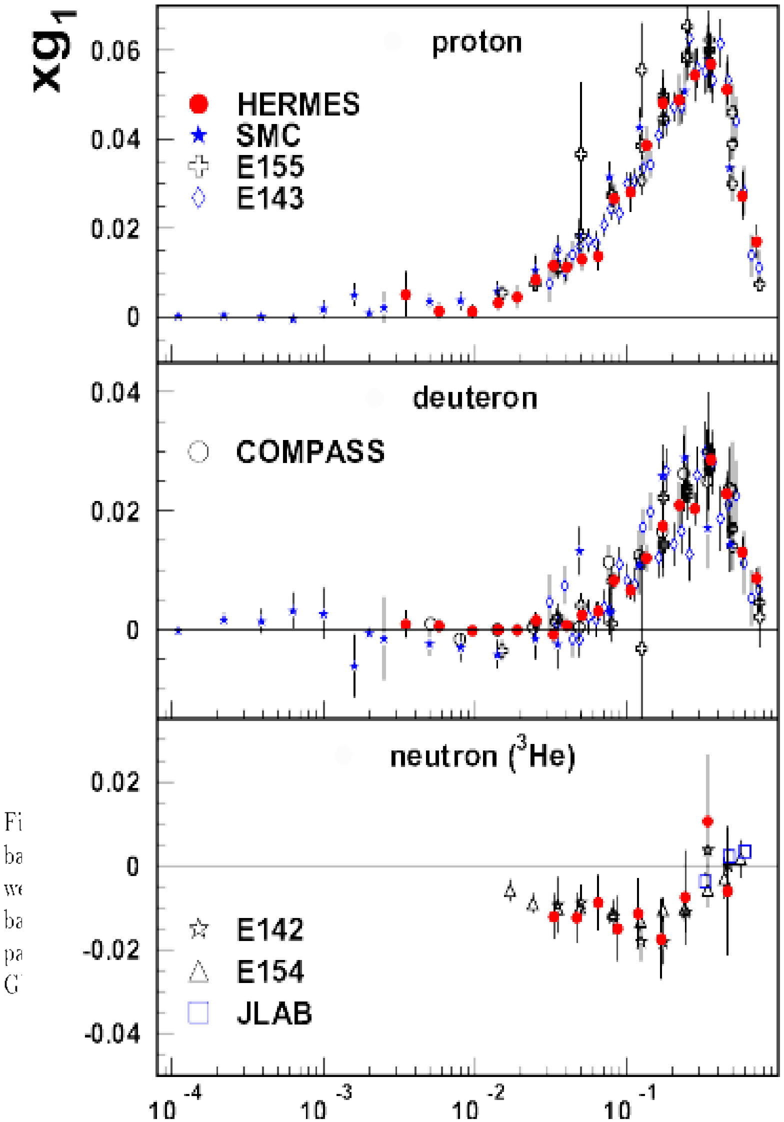
  $\Delta\Sigma \sim 30\%$;

  ΔG probably small, orbital angular momentum probably significant

  Transversity, Transverse Momentum Dependent distributions (TMDs) and Generalized Parton Distributions (GPDs)

Unpolarized and Polarized Structure functions





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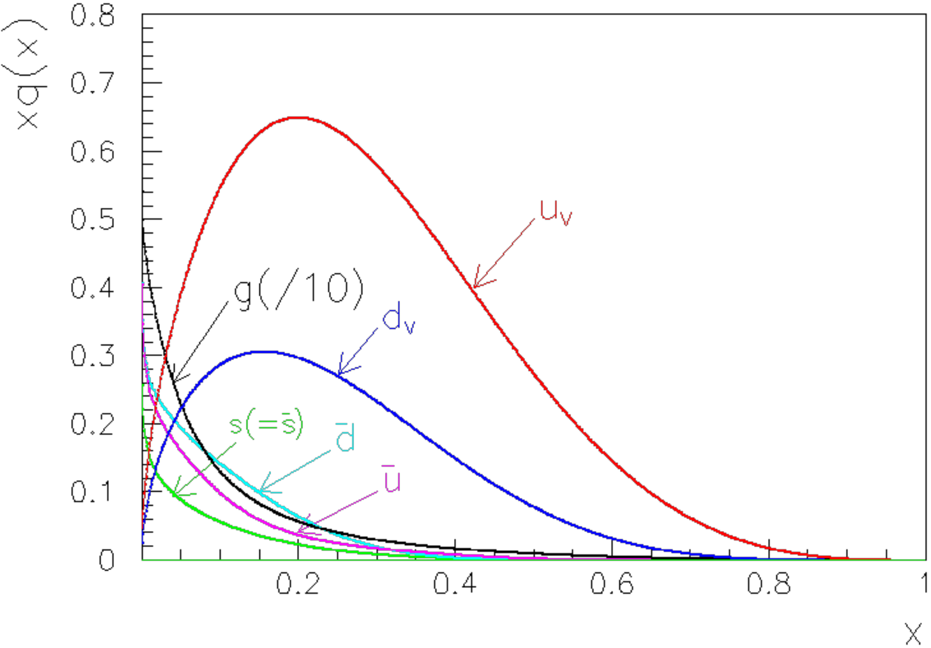
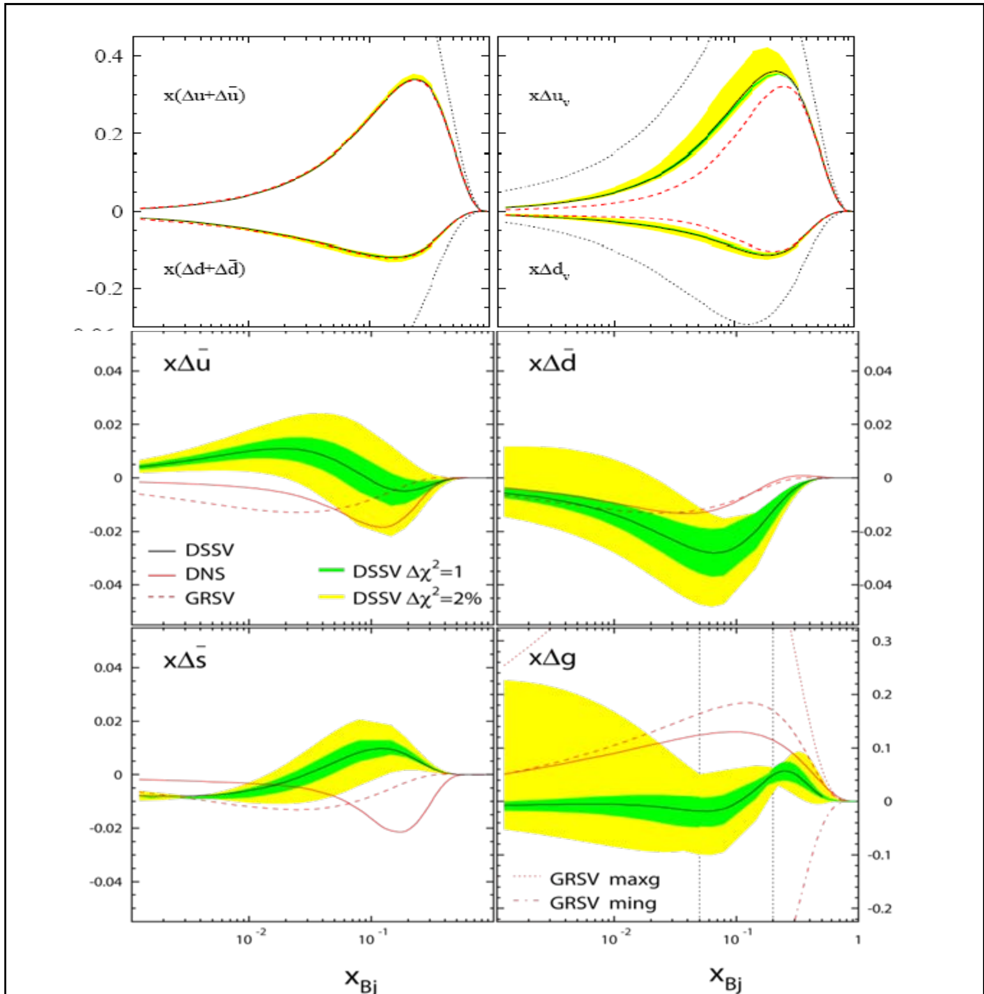
Parton Distributions (CTEQ6 and DSSV)

Unpolarized PDFs



CTEQ6, JHEP 0207, 012 (2002)

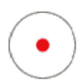
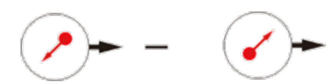
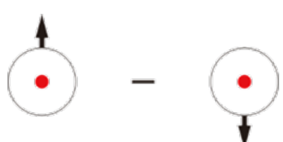
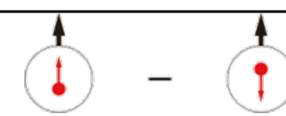
Polarized PDFs



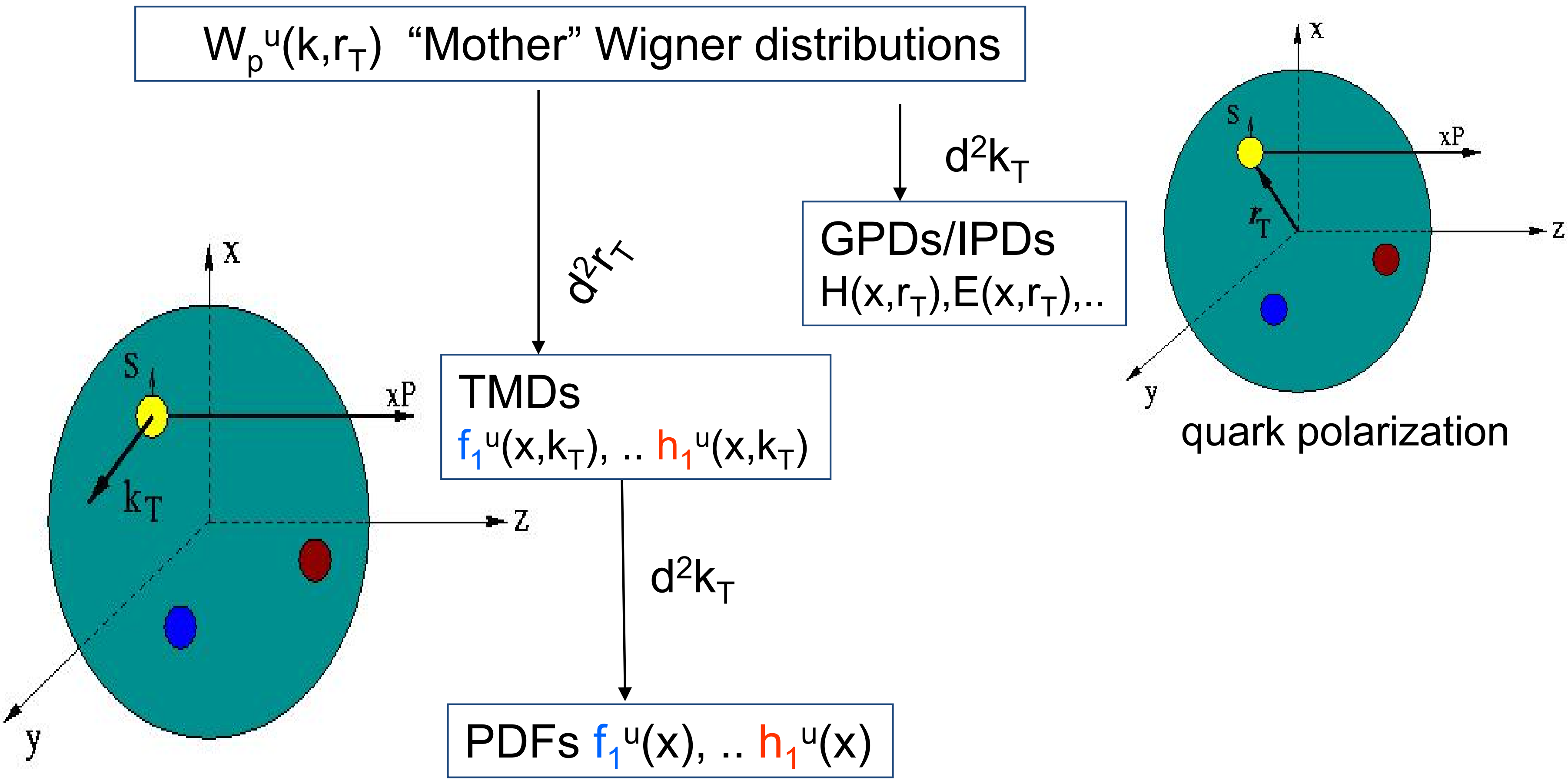
DSSV, PRL101, 072001 (2008)

Leading Twist Transverse Momentum Dependent Parton Distributions (TMDs)

→ Nucleon
→ Quark Spin

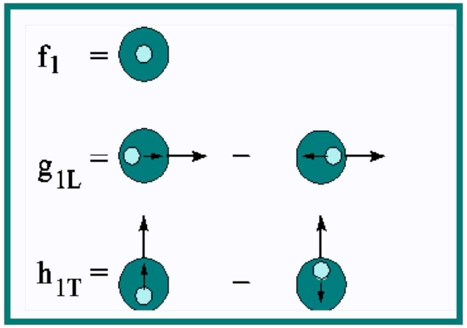
Nucleon Polarization	Quark polarization: Un-Polarized	Quark polarization: Longitudinally Polarized	Quark polarization: Transversely Polarized
U	f_1 = 		$h_1^{\perp}$ =  Boer-Mulder
L		g_1 =  Helicity	$h_{1L}^{\perp}$ = 
T	$f_{1T}^{\perp}$ =  Sivers	$g_{1T}^{\perp}$ = 	h_{1T} =  Transversity $h_{1T}^{\perp}$ =  Pretzelosity

Multi-dimension Distributions



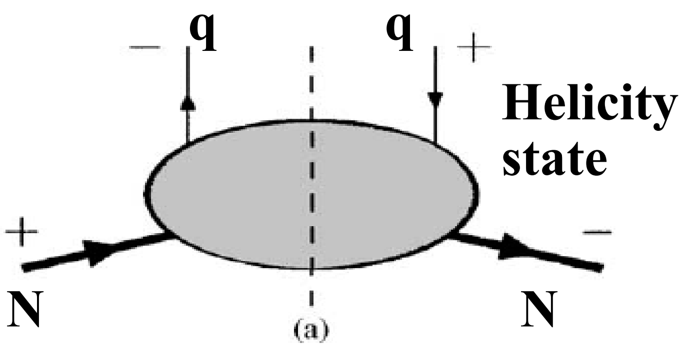
- Gauge invariant definition (Belitsky,Ji,Yuan 2003)
- Universality of k_T-dependent PDFs (Collins,Metz 2003)
- Factorization for small k_T. (Ji,Ma,Yuan 2005)

More on Transversity

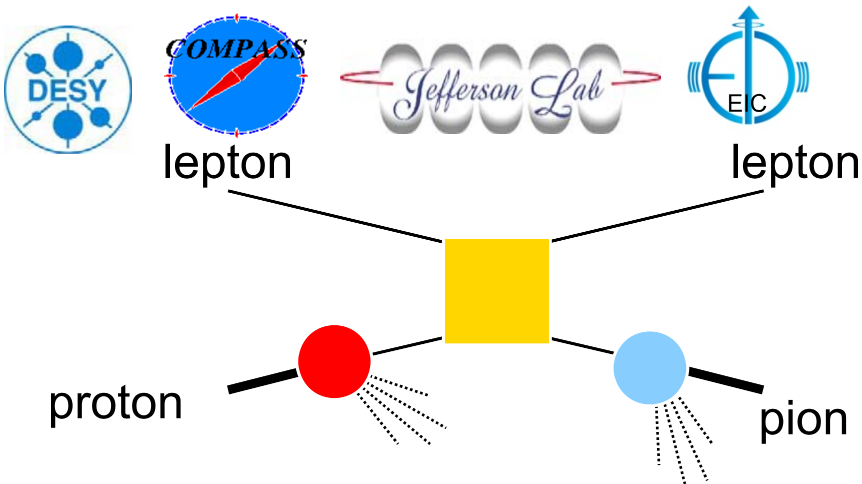


- Some characteristics of transversity
  - $h_{1T} = g_{1L}$ for non-relativistic quarks
  - No gluon transversity in nucleon
  - Chiral-odd → difficult to access in inclusive DIS
  - Soffer's bound
    - $|h_{1T}| <= (f_1+g_{1L})/2$

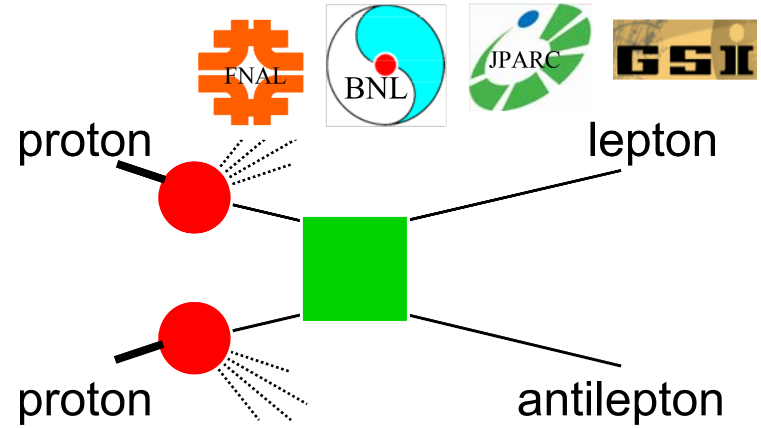
- Tensor Charge:
  - Integration of transversity over
  - An important quantity of nucle



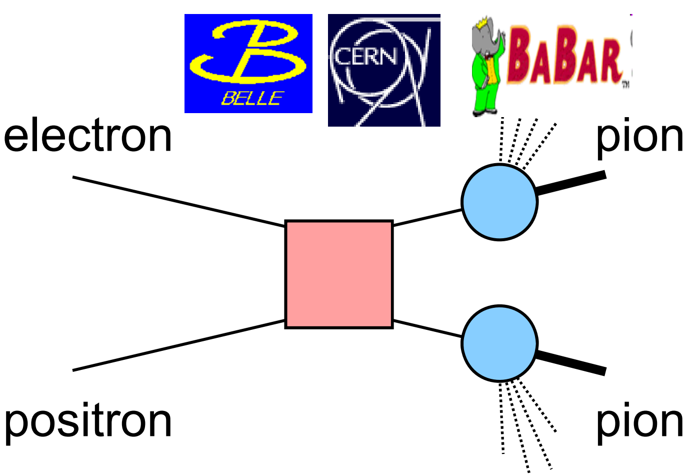
Access TMDs through Hard Processes



SIDIS



Drell-Yan



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

Partonic scattering amplitude

Fragmentation amplitude

Distribution amplitude

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

$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY})$$

Conventions in SIDIS

resolution Q^2

ν: energy transferred into the system

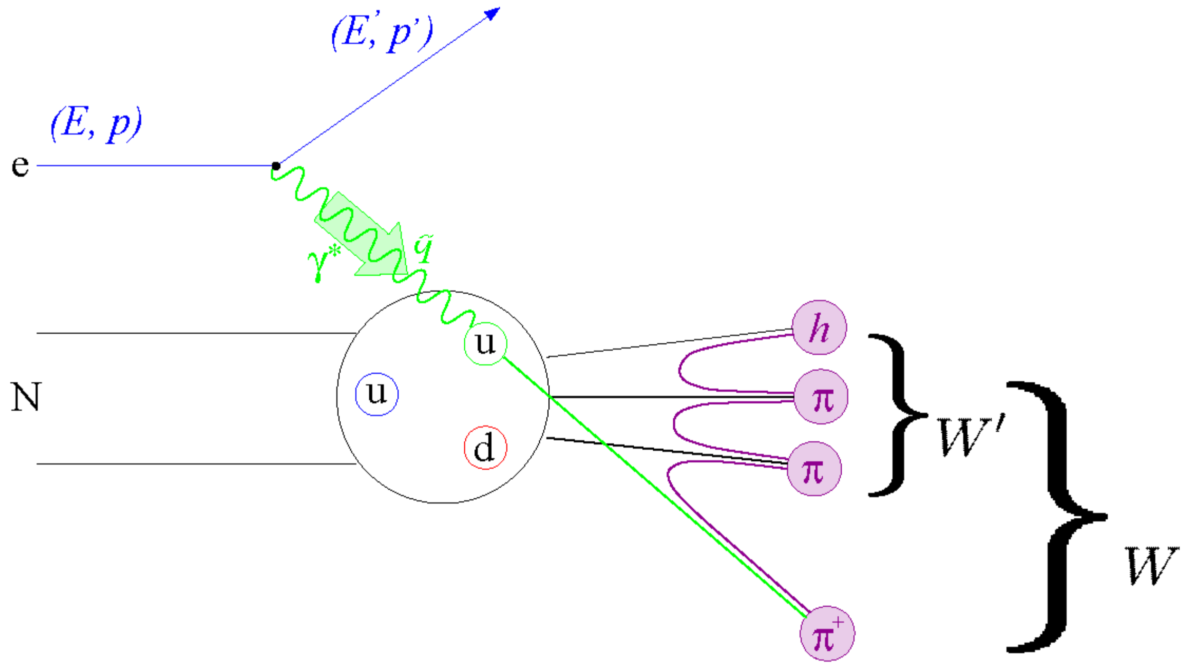
Bjorken x: $Q^2/2m\nu$ momentum fraction of parton of nucleon at light cone frame

W: invariant mass of the system

W': invariant mass of the residual system

z: energy fraction of the leading hadron with respect to ν

k_T (P_T): transverse momentum



$$z = E_\pi / \nu$$

Use E&M interaction (well known) to understand strong force and "strong material".
Light-cone frame - infinite momentum frame.

Access Parton Distributions through Semi-Inclusive DIS

$$\frac{d\sigma}{dxdyd\phi_S dzd\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\cdot$$

$$\{F_{UU,T} + \ldots$$

$$+\varepsilon\cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots$$

Unpolarized

$$+S_L[\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$$

$$+S_T[\varepsilon\sin(\phi_h+\phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+\sin(\phi_h-\phi_S)\cdot(F_{UL}^{\sin(\phi_h-\phi_S)} + \ldots)$$

$$+\varepsilon\sin(3\phi_h-\phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]$$

Polarized Target

$$+S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$

$$+S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]\}$$

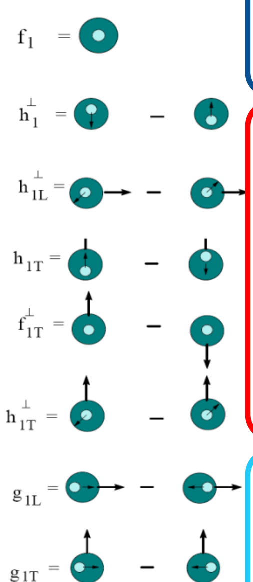
Polarized Beam and Target

Boer-Mulder

Transversity

Sivers

Pretzelosity



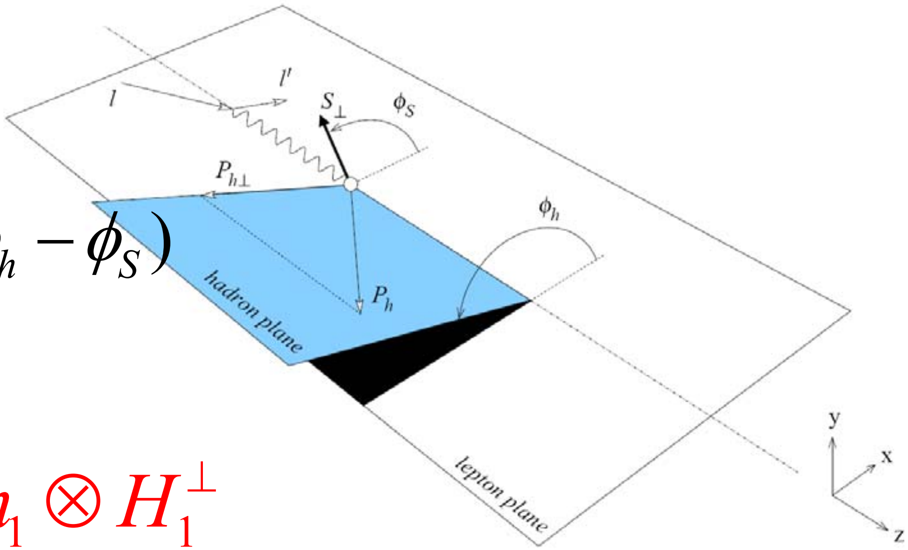
S_L, S_T: Target Polarization; λ_e: Beam Polarization

Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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



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

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

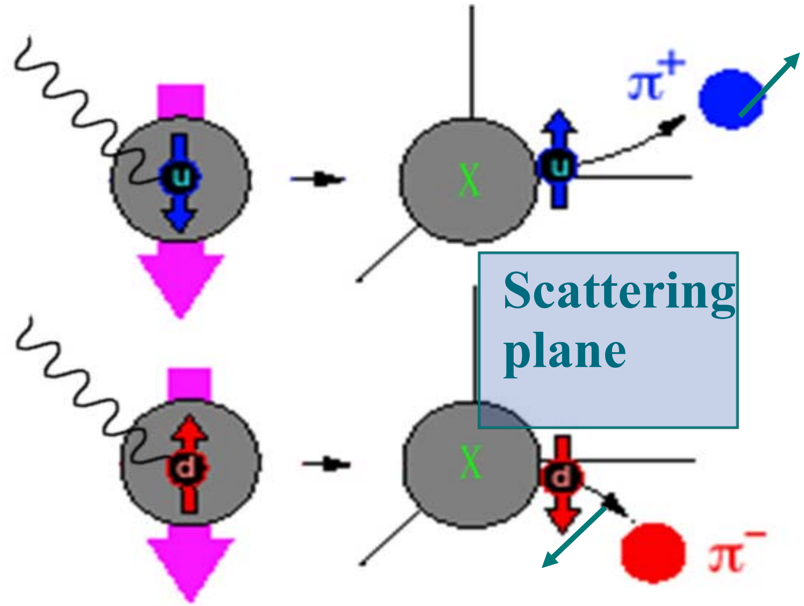
$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)
Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.

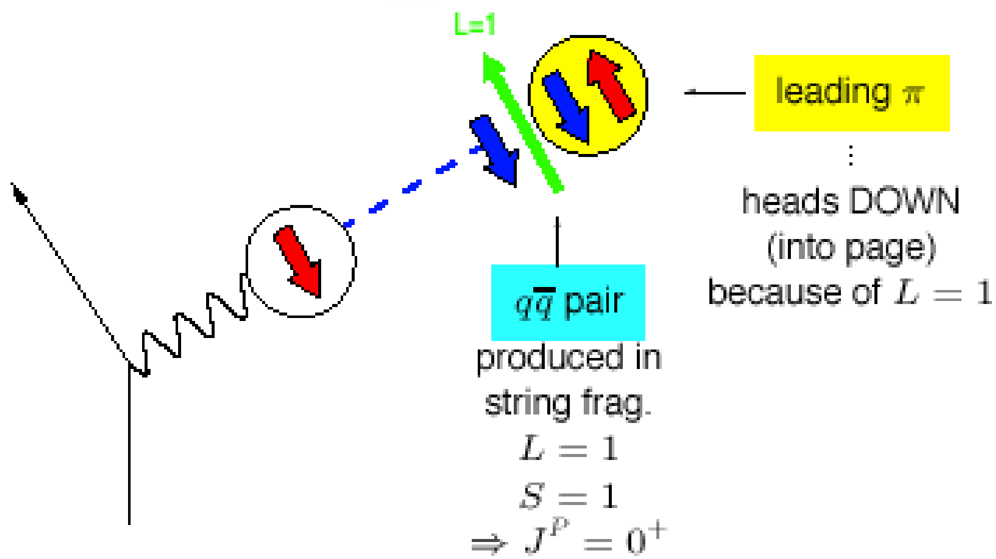
SSA in SIDIS with polarized target ----- Collins effect

- Access to transversity
  - Collins fragmentation
  - Correlation between transverse spin of the quark with the P_T.

$$A \sim h_{1T} H_1^{\perp}$$

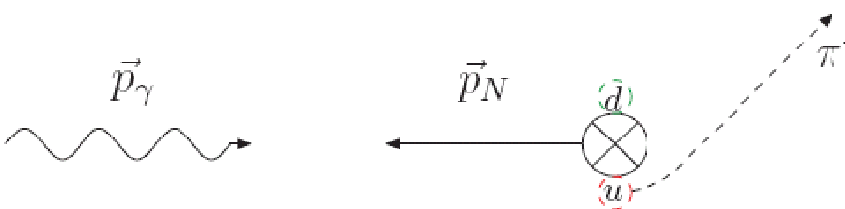


- Artru model
  - Based on LUND fragmentation picture.

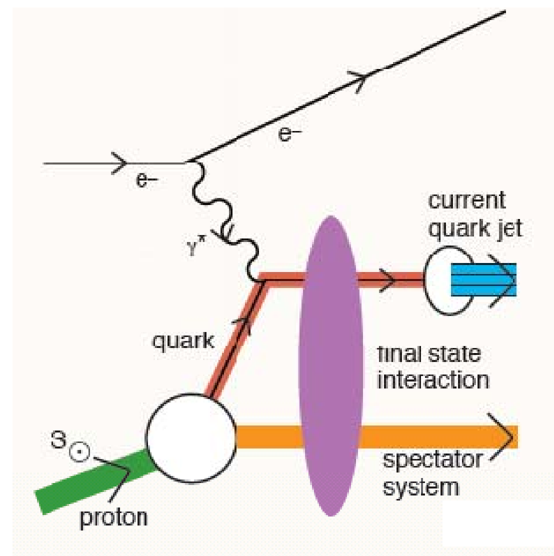


SSA in SIDIS with polarized target ----- Sivers effect

- Sivers effect $A \sim f_{1T}^{\perp} D_1$
- Correlation between nucleon spin with quark angular momentum ⇨ a new type distribution function
- Matrix element related to anomalous magnetic moment.



Burkhardt : chromodynamic lensing



Stan Brodsky, SLAC

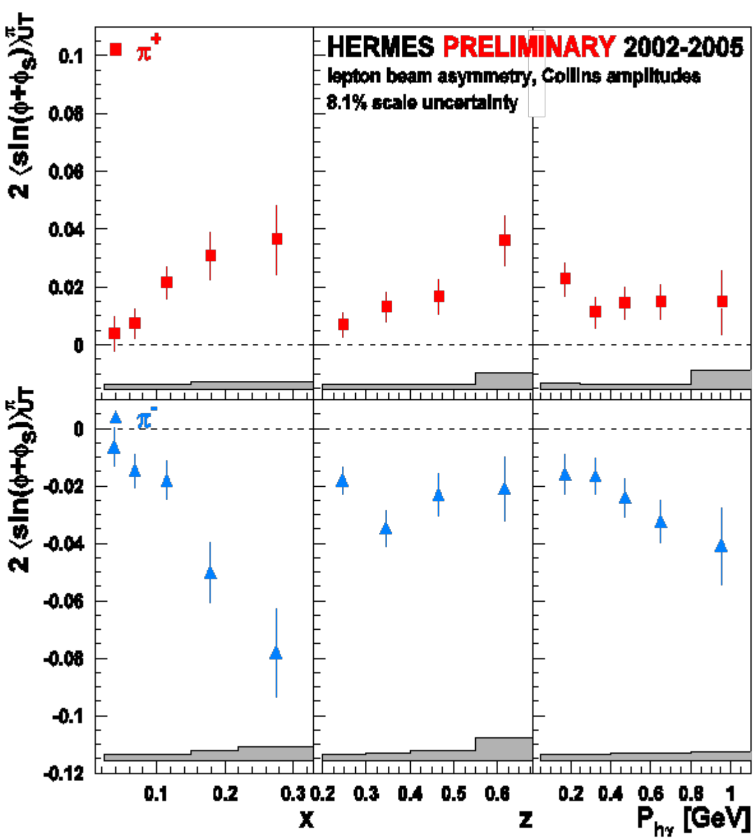
$$f_{1T}^{\perp q}\Big|_{SIDIS} = -f_{1T}^{\perp q}\Big|_{D-Y}$$

Important test for Factorization

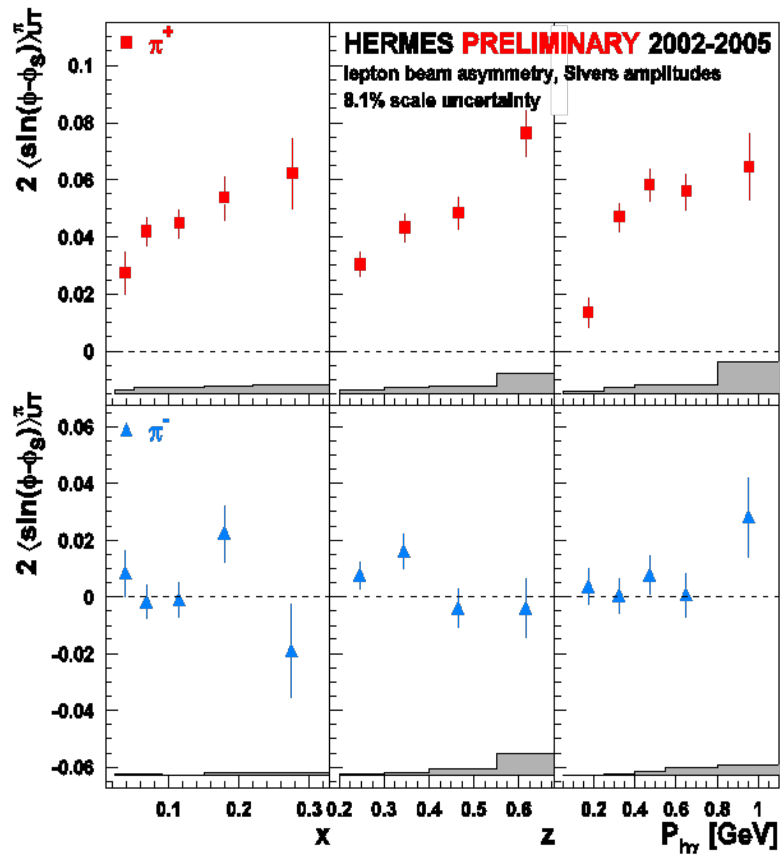
Final-State-Interaction

$A_{UT}^{\sin(\phi)}$ from transv. pol. H target

`Collins' moments



`Sivers' moments



- Non-zero Collins asymmetry
- Assume $\delta q(x)$ from model, then

  H_1_unfav ~ $-H_1$_fav

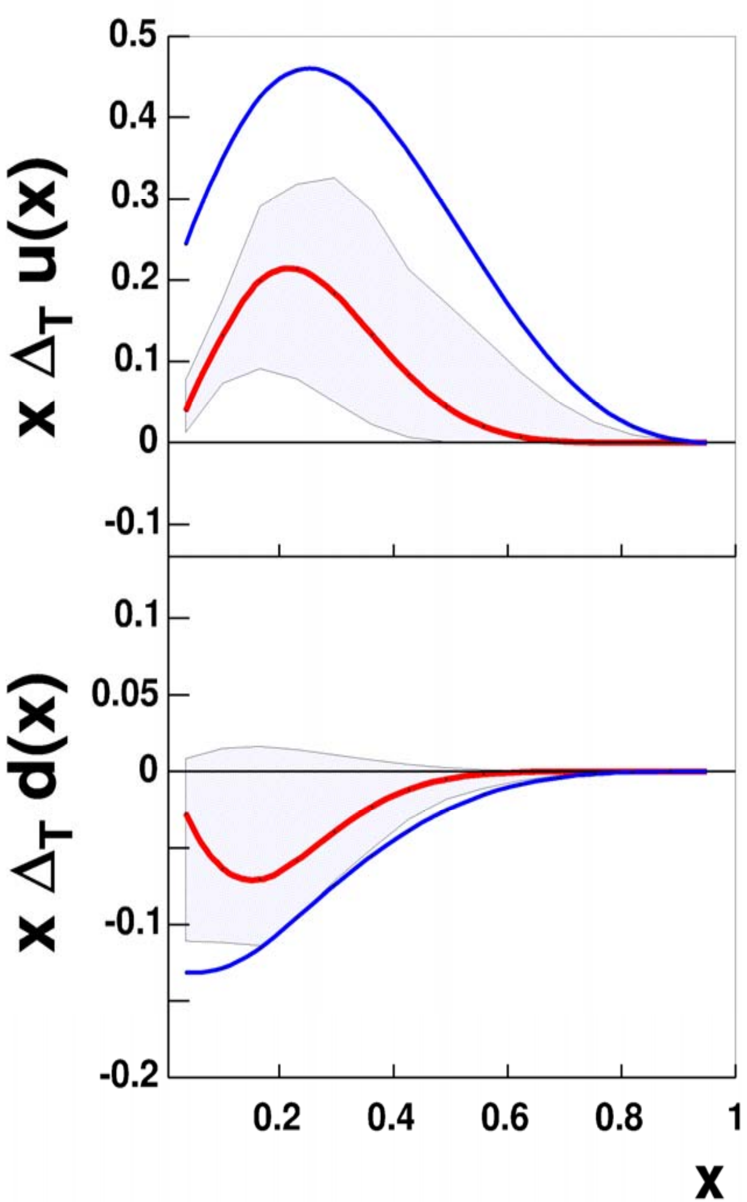
- H_1 from Belle (arXiv:0805:2975)

- Sivers function nonzero (π^+)→ orbital angular momentum of quarks
- Regular flagmentation functions

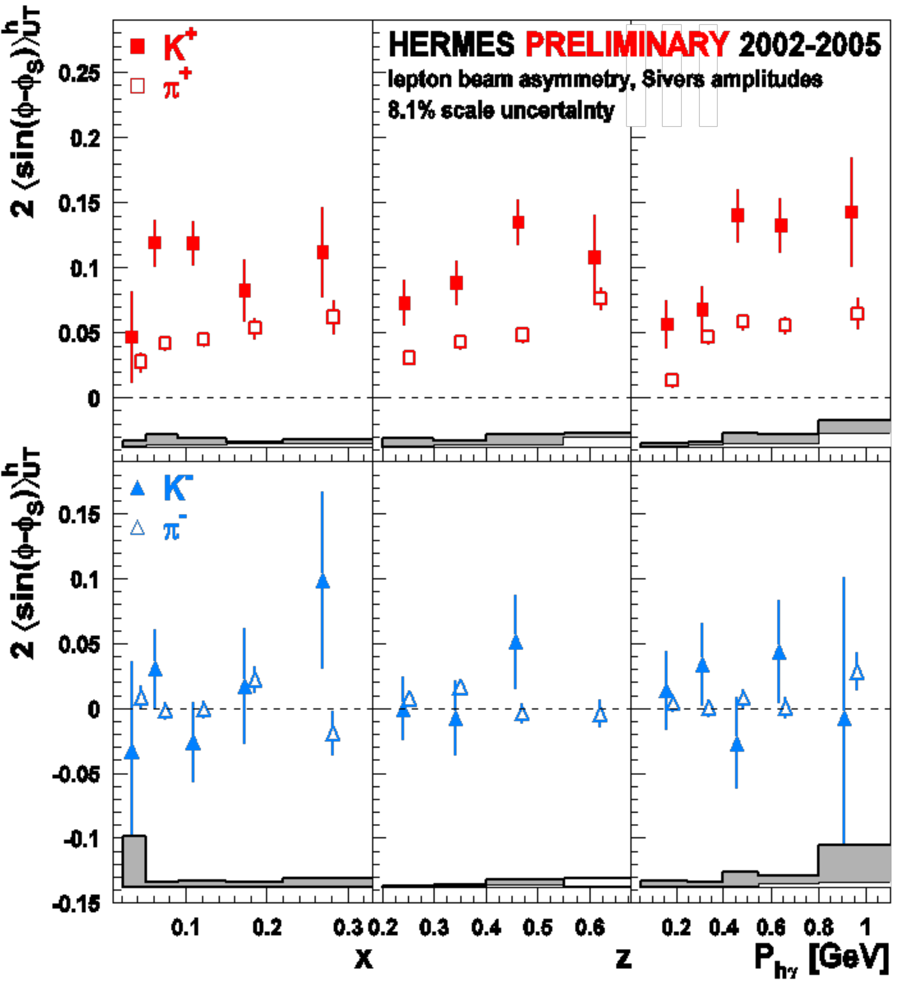
Transversity Distributions

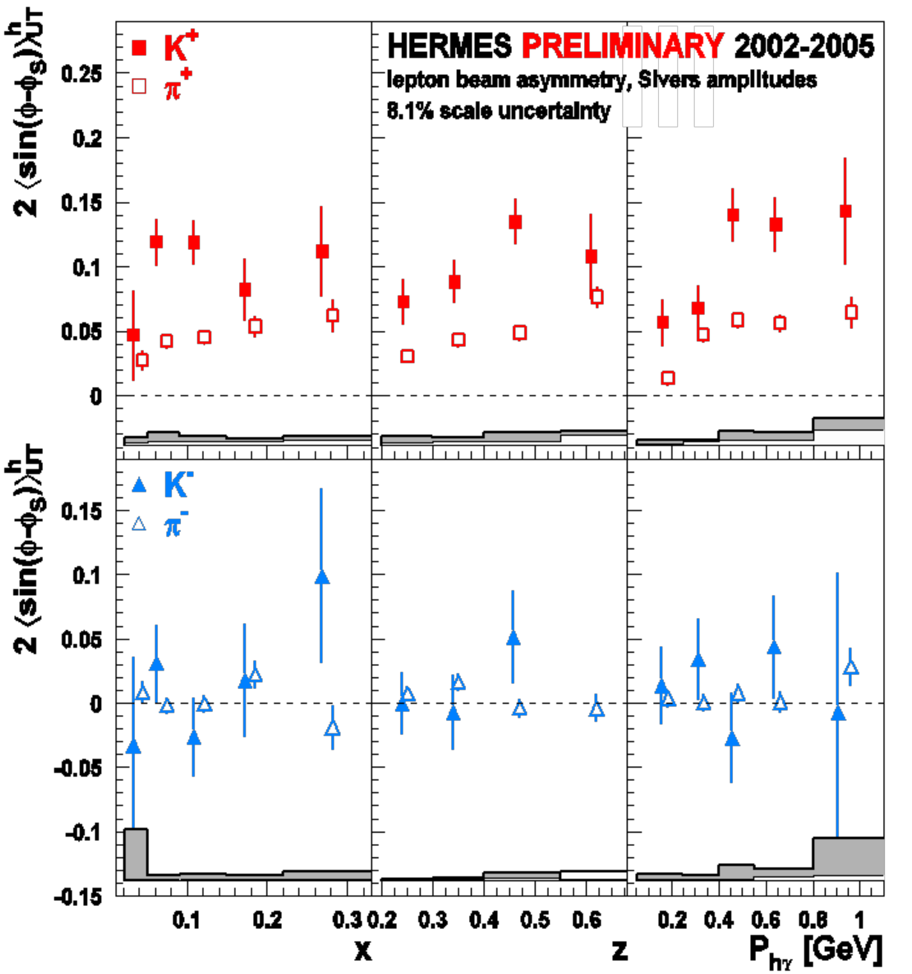
A global fit to the HERMES p, COMPASS d and BELLE e+e- data by the Torino group (Anselmino et al.).

PRD 75, 054032 (2007)



Collins/Sivers Moments for Kaon



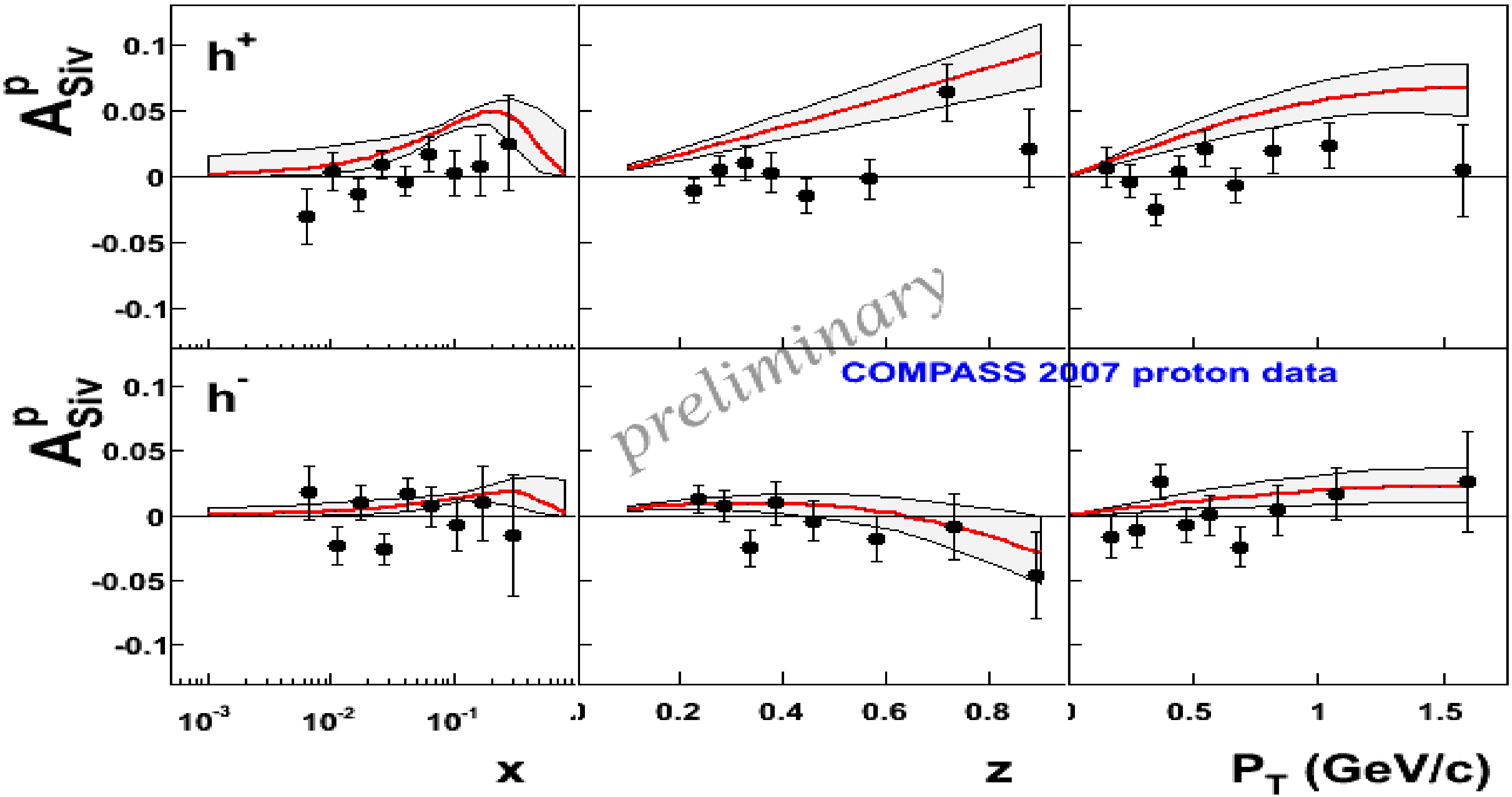


S. Gliske's talk at DNP09

Sivers asymmetry – proton data

comparison with the most recent predictions
from M. Anselmino et al. (arXiv 0805.2677)

Franco Bradamante
Transverse2008, Beijing



Summary of Current Status

- Large single spin asymmetry in *pp->πX*
- Collins Asymmetries

  - sizable for the *proton* (HERMES and COMPASS)

    large at high *x*, π and $\pi+$ has opposite sign

    unfavored Collins fragmentation as large as favored (opposite sign)?

  - consistent with 0 for the *deuteron* (COMPASS)

- Sivers Asymmetries

  - non-zero for π^+ from *proton* (HERMES), consistent with zero (COMPASS)?
  - consistent with zero for π from proton and for all channels from *deuteron*
  - large for K^+ ?

- Collins Fragmentation from Belle
- Global Fits/models by Anselmino *et al., Yuan et al.* and …
- Very active theoretical and experimental study

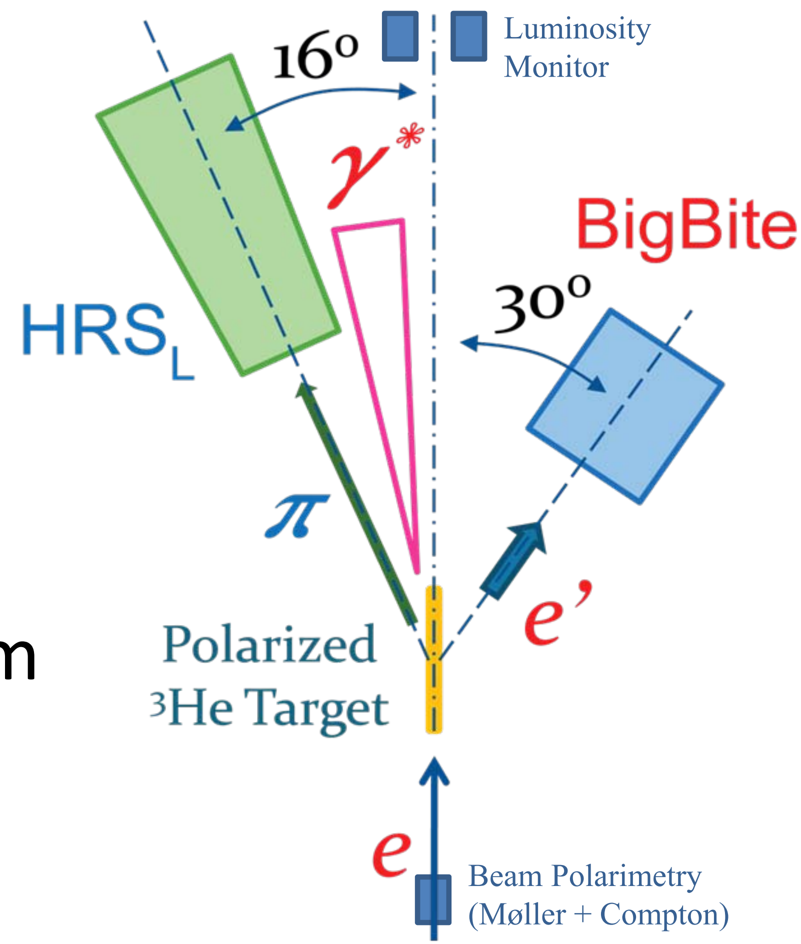
  RHIC-spin, JLab (6 GeV and 12 GeV), Belle, FAIR, J-PARC, … EIC

6 GeV Transversity Experiment: E06-010

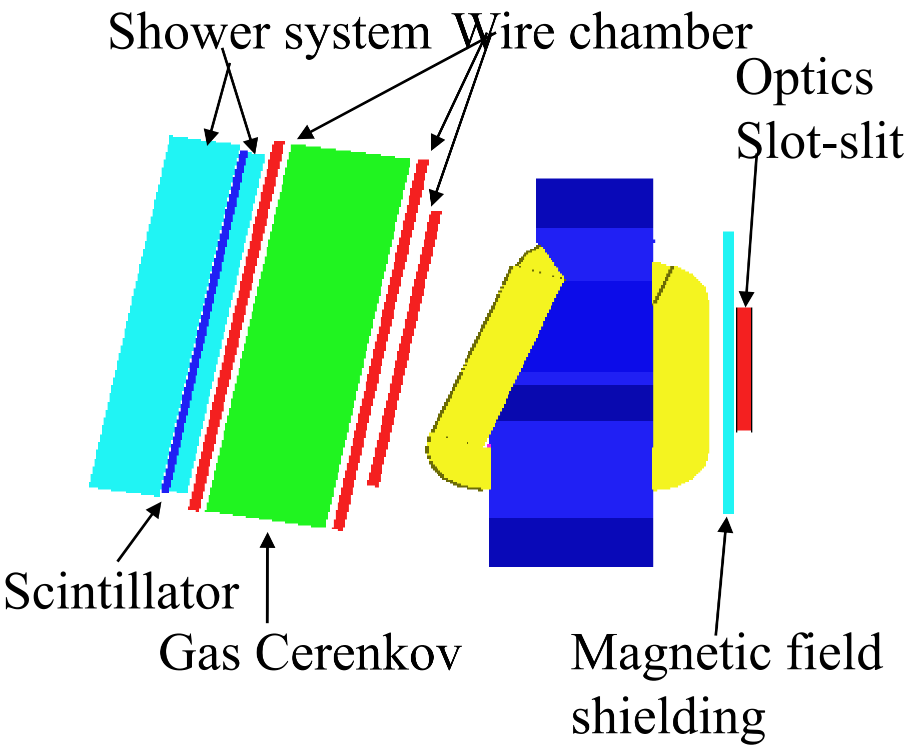
Preliminary Results

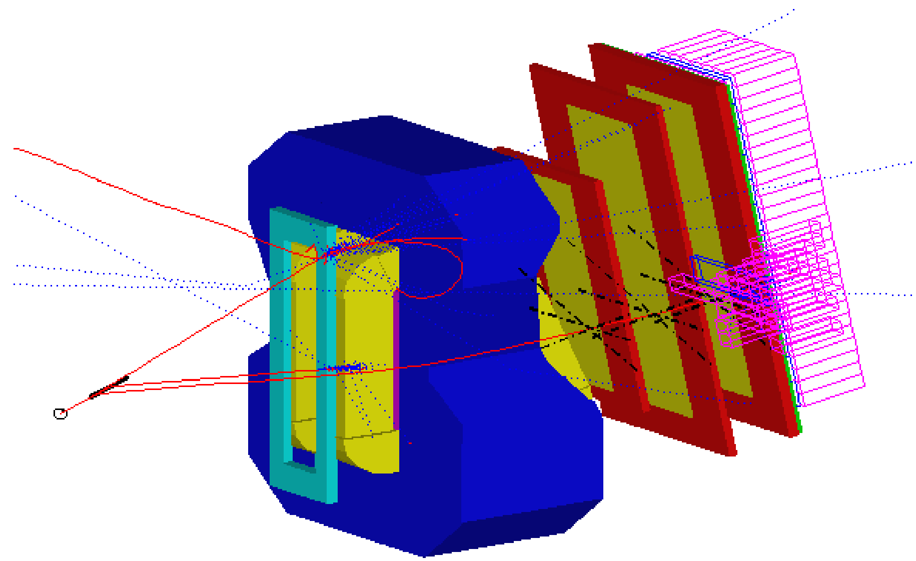
E06-010 Experiment Setup

- Polarized ^{3}He Target
- Polarized Electron Beam
  - ~80% Polarization
  - Fast Flipping at 30Hz
  - PPM Level Charge Asymmetry controlled by online feed back
- BigBite at 30º as Electron Arm
  - $P_e = 0.7 \sim 2.2$ GeV/c
- HRS$_L$ at 16º as Hadron Arm
  - $P_h = 2.35$ GeV/c



Electron Arm: BigBite



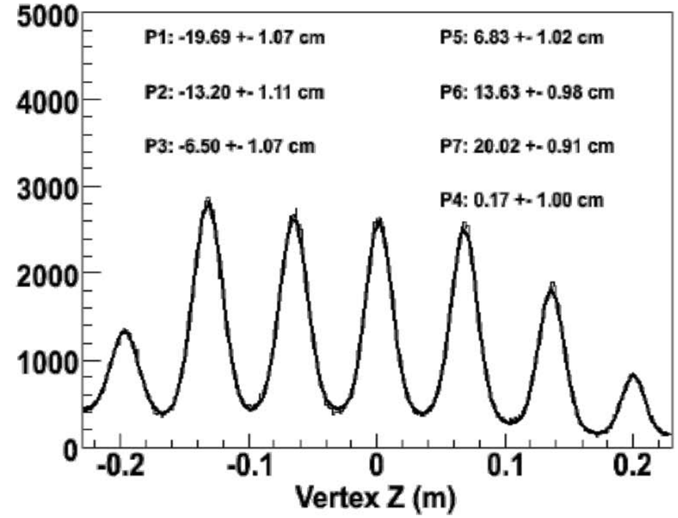


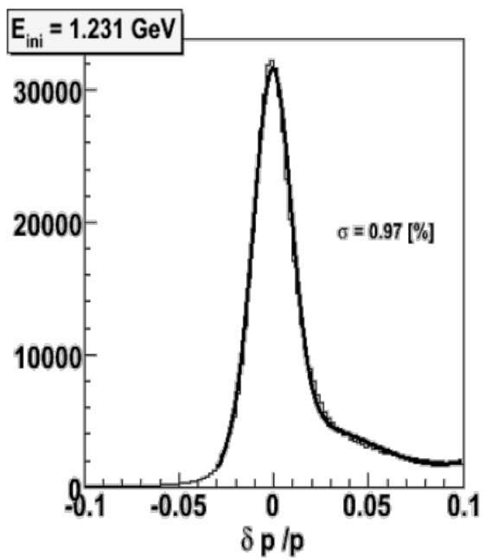
- 64 msr
- Large out-of-plane acceptance, essential for separating Collins/Sivers effect

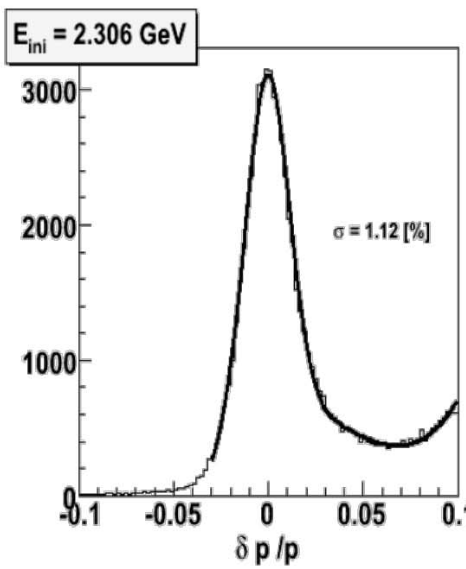
- Drift Chamber for Tracking
- Shower counter for electron PID.
- Scintillator for Timing

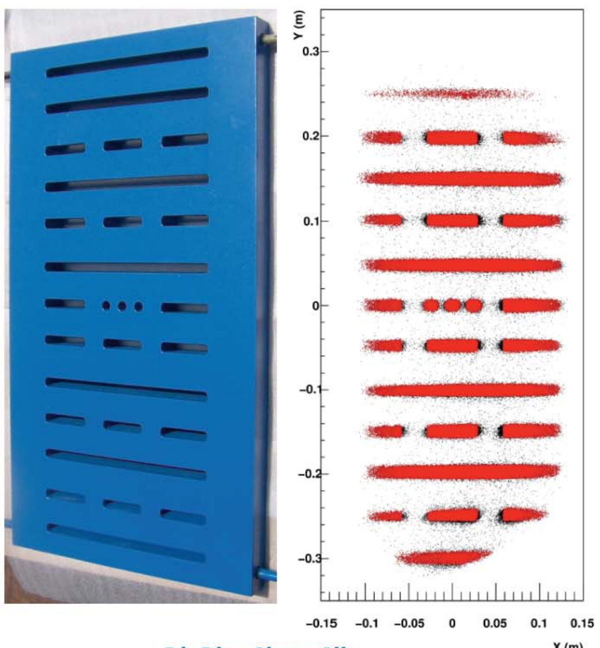
BigBite Optics Calibration

- Optics for both negative and positive charged particles have been done
- Wire Chamber Spatial Resolution: 180 μm
- Vertex Resolution: 1 cm
- Angular Resolution: ~ 10 mrad
- Momentum Resolution: 1%





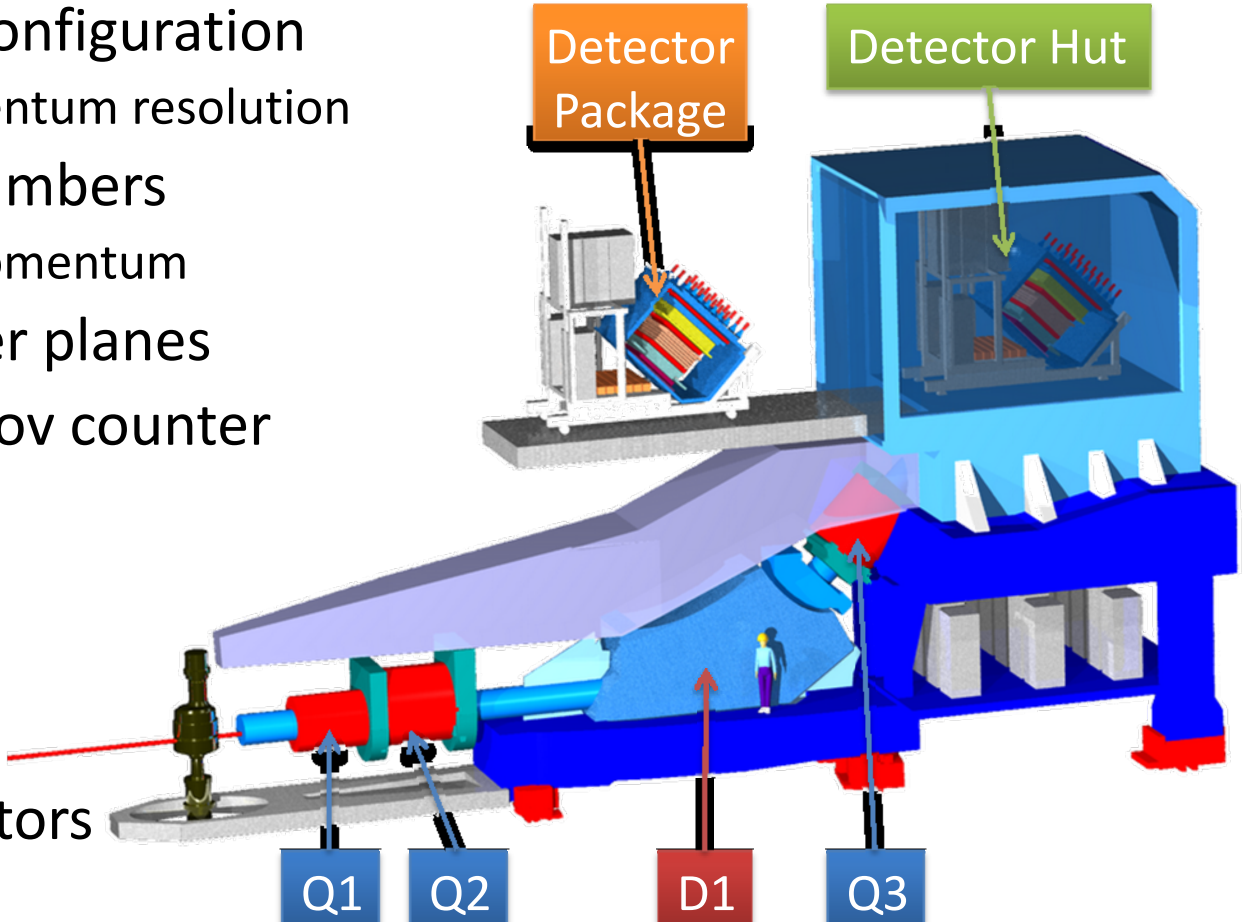




BigBite Sieve Slit

High Resolution Spectrometer

- Left HRS to detect hadrons of p_h = 2.35 GeV/c
- QQDQ magnet configuration
  - Very high momentum resolution
- Vertical Drift Chambers
  - Tracking and momentum
- Scintillator trigger planes
- Aerogel Cherenkov counter
  - n = 1.015
- RICH detector
  - n = 1.30
- Gas Cherenkov
- Lead-glass detectors

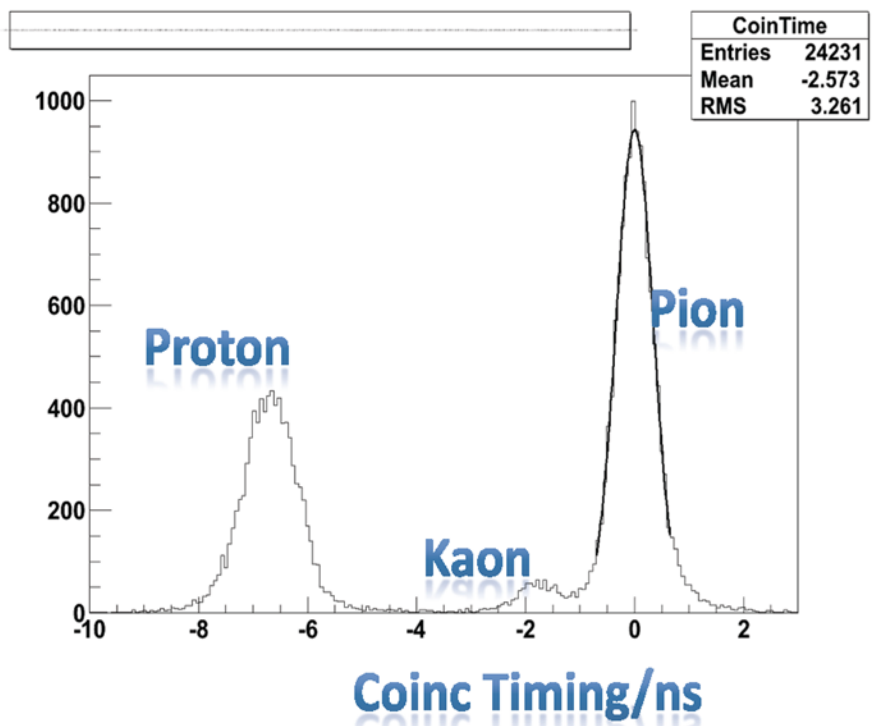


In addition to the HRS_L standard PID detectors ...

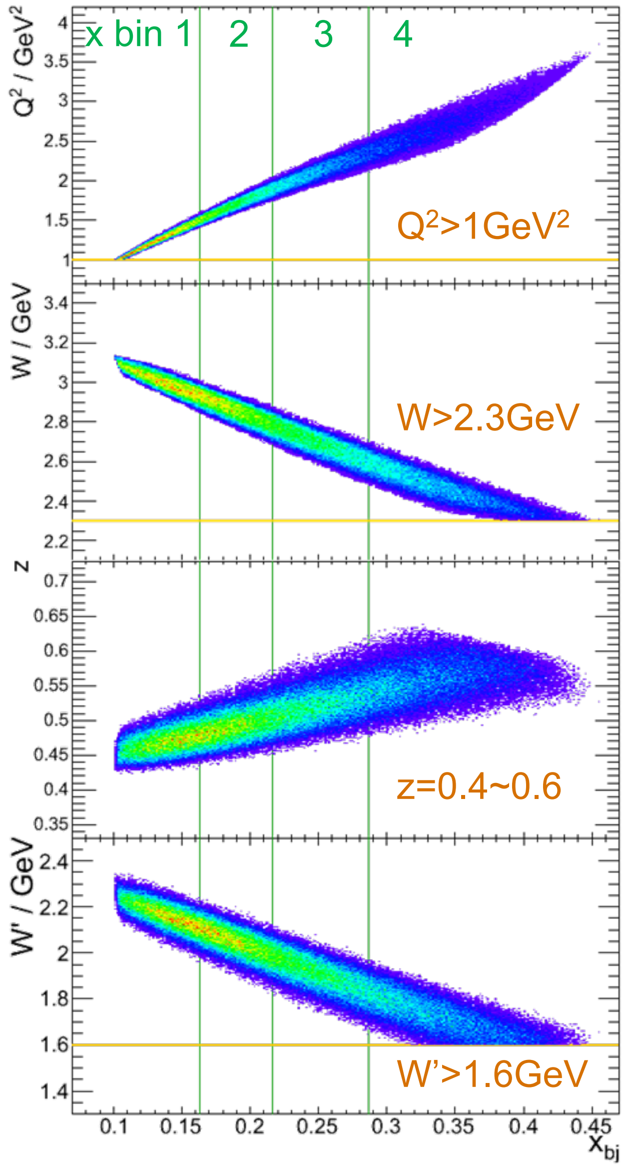
Coincidence time-of-flight as redundant particle identification

$$^{3}\mathrm{He}^{\uparrow}(e, e'h)$$

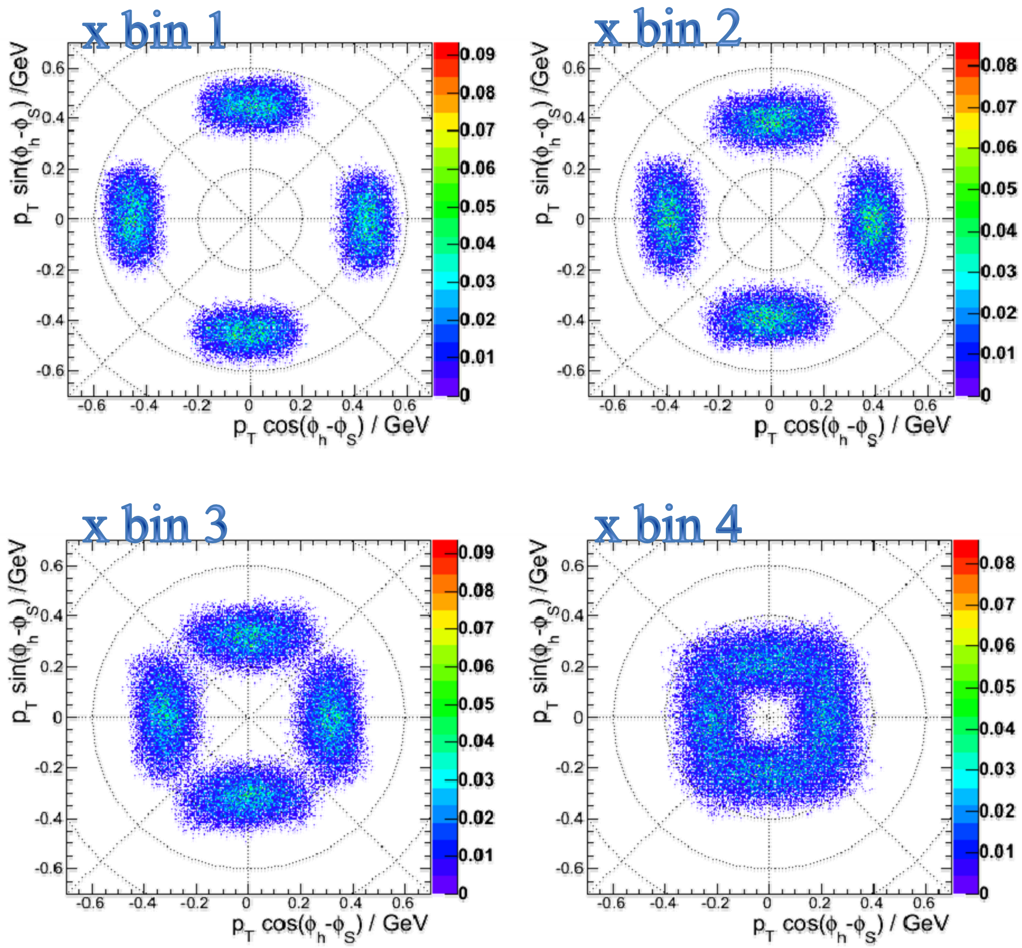
$$h = \pi^{+/-}, K^{+/-}$$



Data Coverage



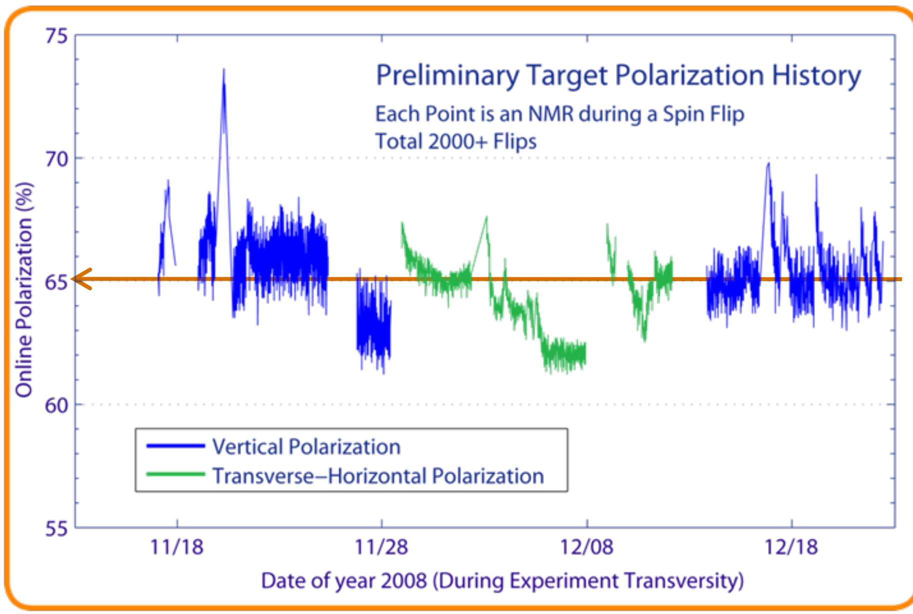
Kinematics Coverage

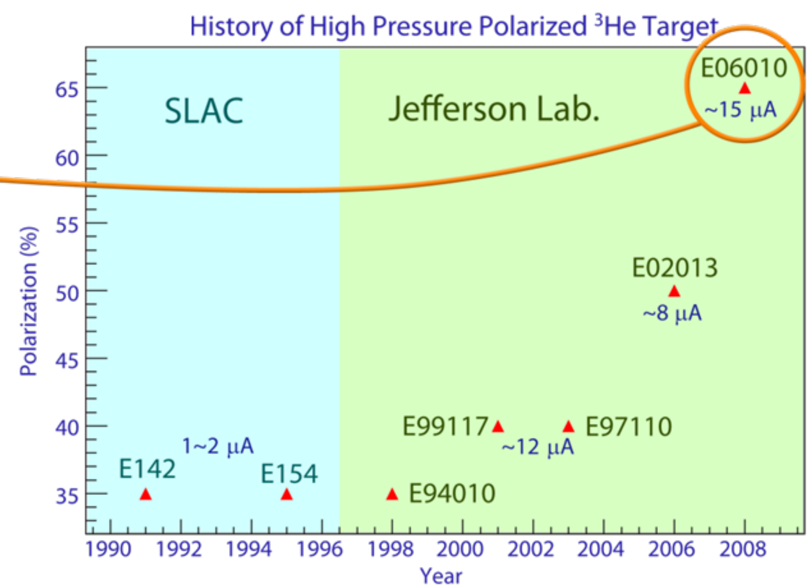


p_T & ϕ_h- ϕ_S Coverage

Performance of ^{3}He Target

- High luminosity: $L(n) = 10^{36}\ cm^{-2}\ s^{-1}$
- Record high 65% polarization (preliminary) in beam with automatic spin flip / 20min



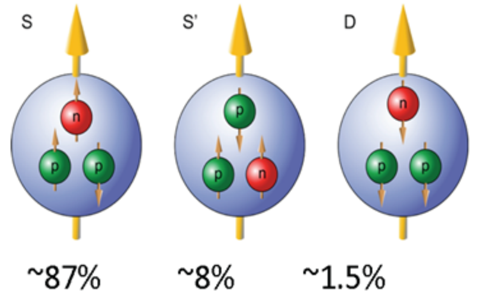


6 GeV Preliminary Results

^{3}He Target Single-Spin Asymmetry in SIDIS: JLab E06-010

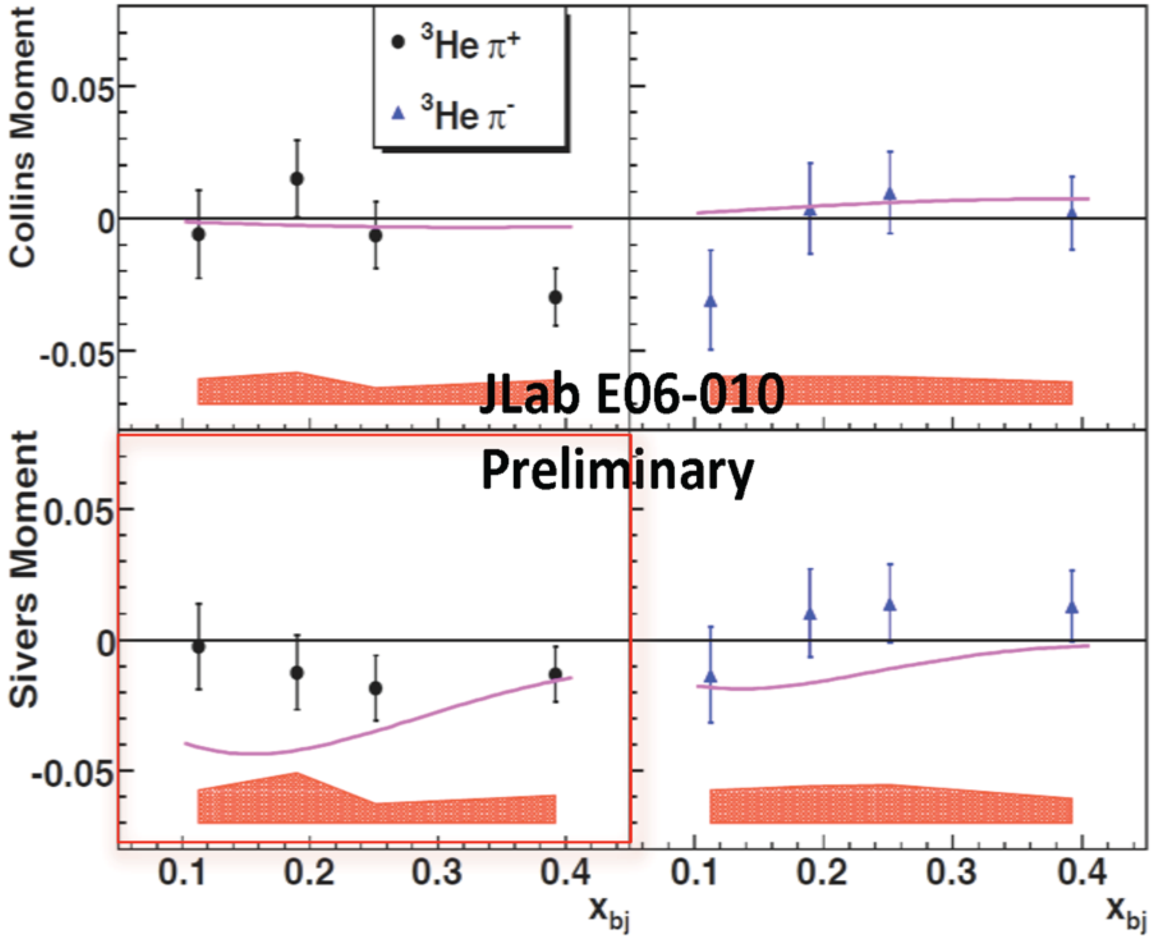
$$^3\mathrm{He}^{\uparrow}(e, e'h)$$

$$h = \pi^{+/-}, K^{+/-}$$



To extract information on neutron, one would assume:

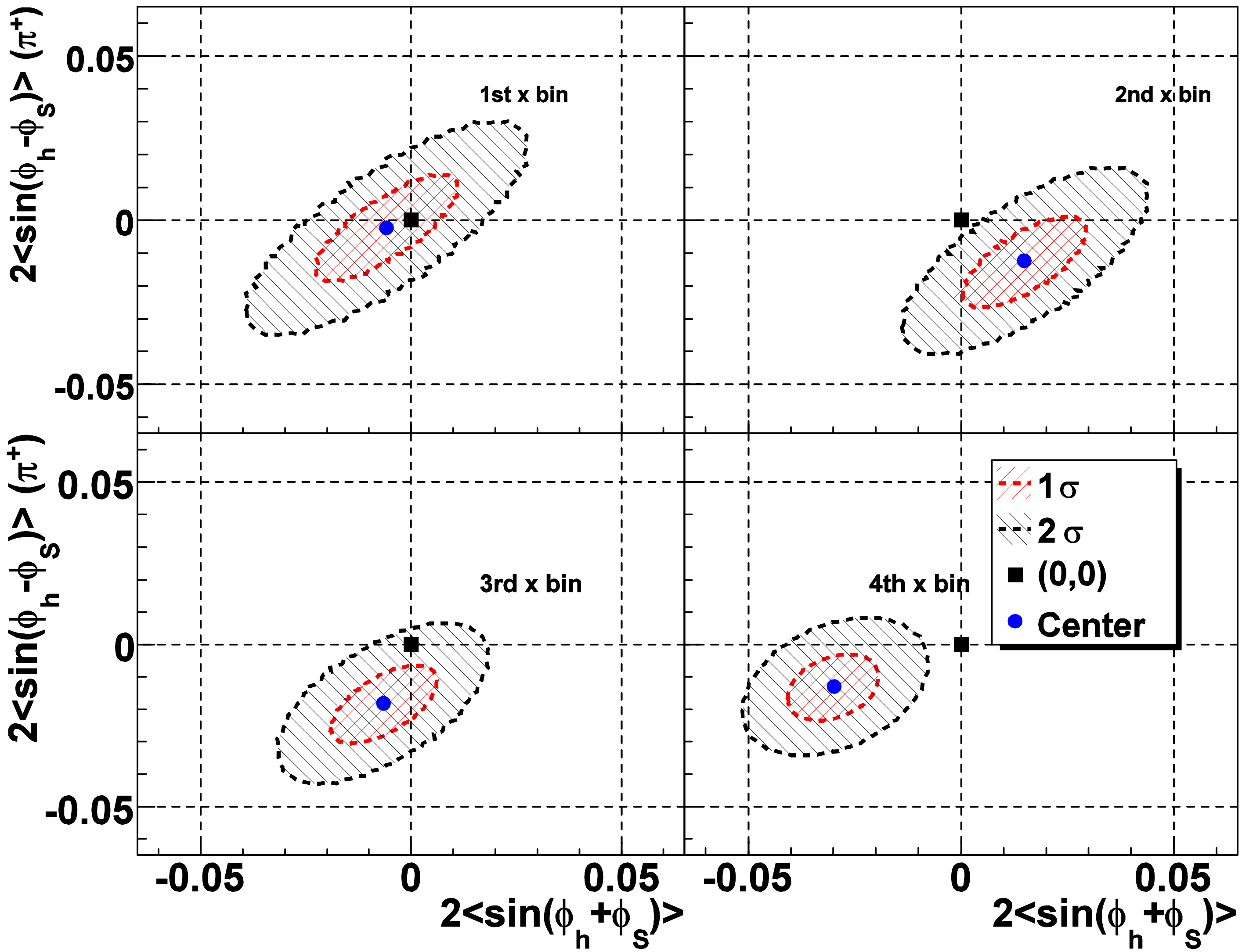
$$^3\mathrm{He}^{\uparrow} = 0.865 \cdot n^{\uparrow} - 2 \times 0.028 \cdot p^{\uparrow}$$



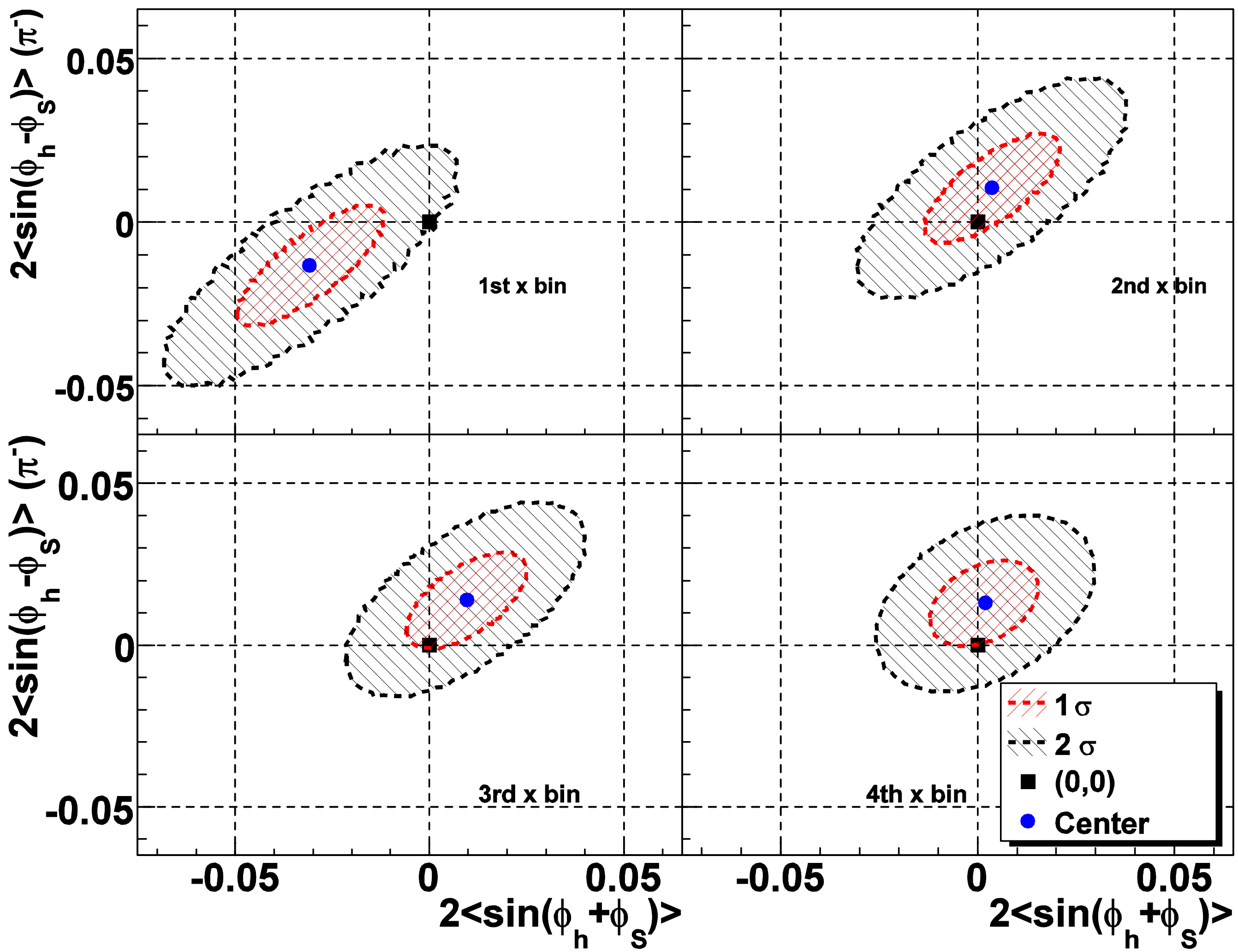
^{3}He Collins SSA are not large (as expected).

^{3}He Sivers SSA are smaller than expected (Vogelsong and Yuan 2006), follow the trend of Anselmino et al. 2009.

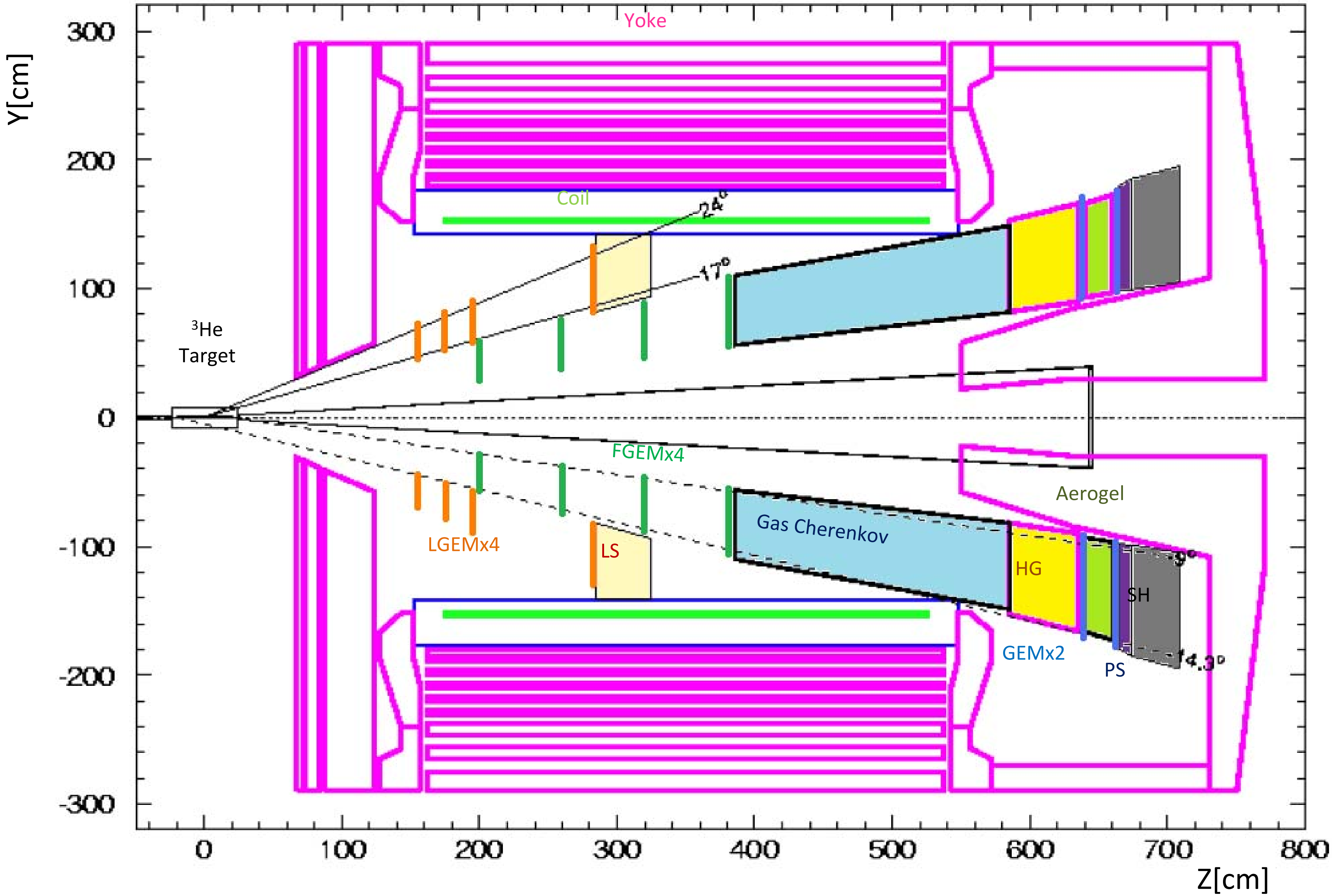
Results on ^3He (Clear Non-zero for π^+)



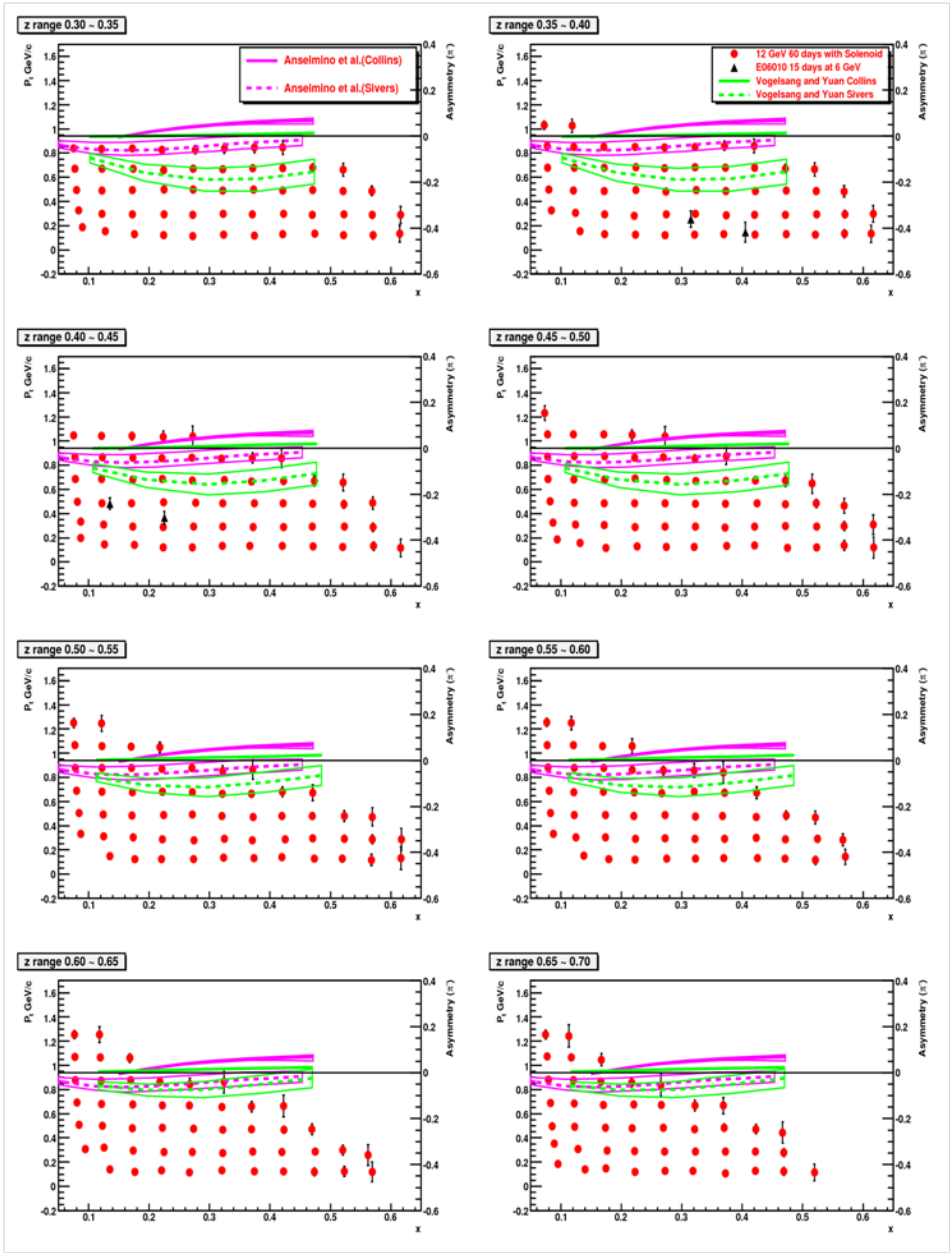
Results on ^{3}He (Consistent with zero for π^-)

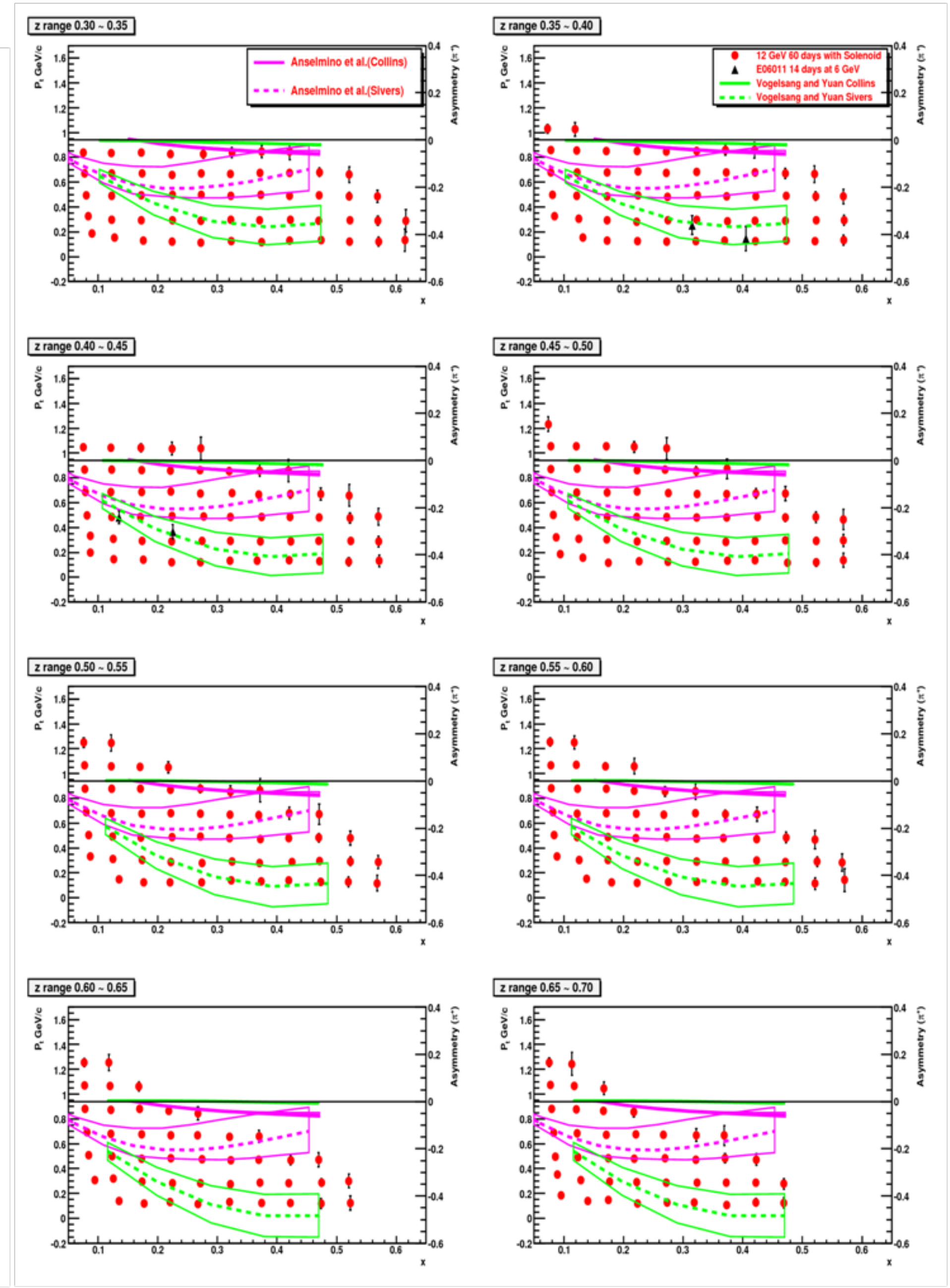


Solenoid detector for SIDIS at 11 GeV
(Approved by JLab PAC35)



Power of SOLID





Workshop on Partonic Transverse Momentum in Hadrons: Quark Spin-Orbit Correlations and Quark-Gluon Interactions March 12-13, 2010 Duke University

Menu

- Home
- Program
- Registration
- Participants List
- Workshop Photo
- Lodging & Travel
- Visiting Duke & TUNL
- Duke Campus Map
- Fine Restaurants in Durham
- Upload

Links

- Duke University
- Duke Physics Dept
- TUNL
- MEPG
- JLab

The workshop on "Partonic Transverse Momentum in Hadrons: Quark Spin-Orbit Correlations and Quark-Gluon Interactions", co-organized by Duke University, the Triangle Universities Nuclear Laboratory, and the Jefferson Lab Users Group Board of Directors, is one of the science workshops organized to investigate the physics potential that a high luminosity and moderate energy electron ion collider offers beyond the 12 GeV Upgrade of Jefferson Lab. The workshop aspires to articulate the importance of transverse hadronic structure of hadrons in the framework of Quantum Chromodynamics and to identify flagship measurements that can be uniquely carried out with such a machine. The workshop will take place on the campus of Duke University in Durham, NC on March 12 and 13th. We look forward to your participation in this workshop.

Organizing Committee:

- Haiyan Gao (Chair)
- Mauro Anselmino
- Harut Avagyan
- Matthias Burkardt
- Jian-Ping Chen
- Evaristo Cisbani
- Cynthia Keppel
- Jen-Chieh Peng
- Feng Yuan

Sponsors:

- Thomas Jefferson National Accelerator Facility
- Jefferson Science Associates, LLC Initiatives Fund
- Duke University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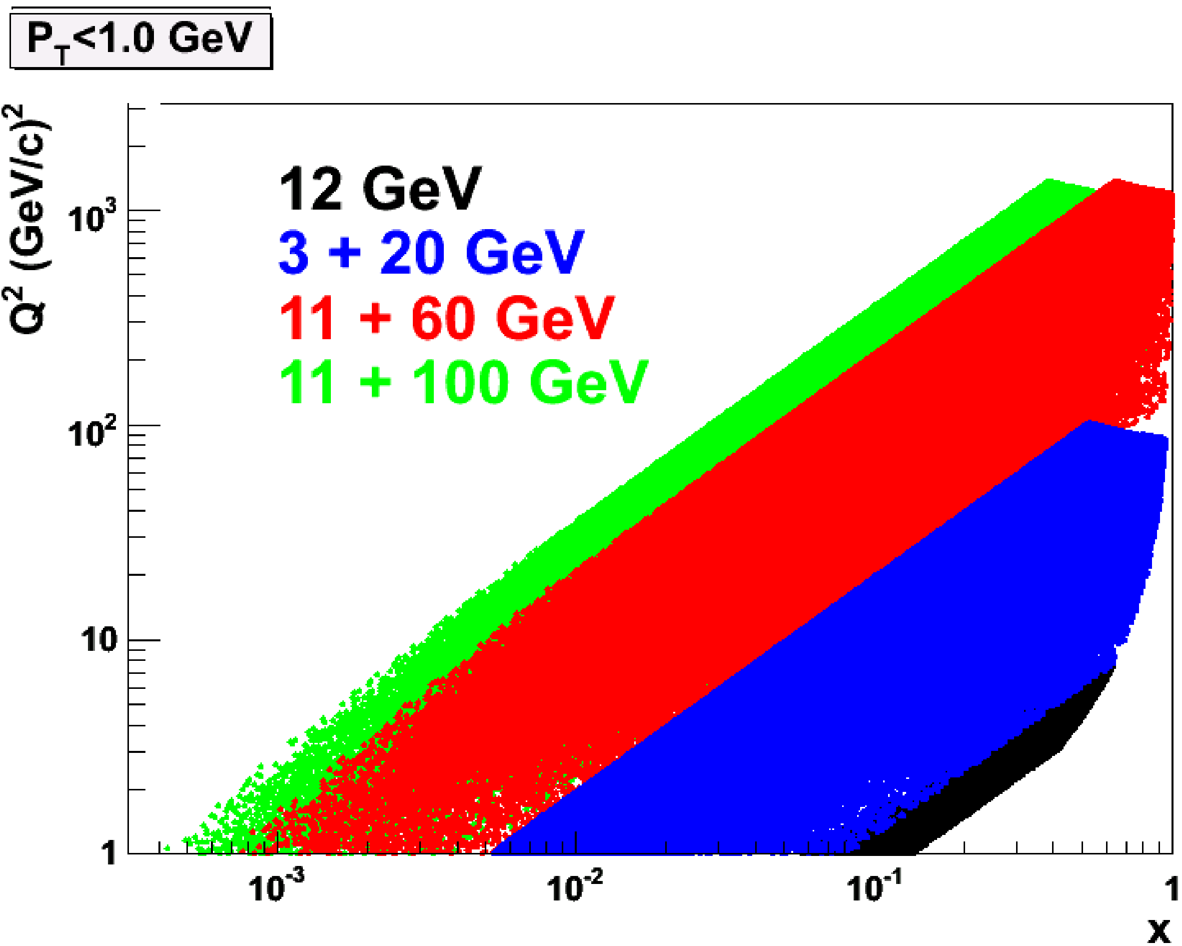
EIC phase space

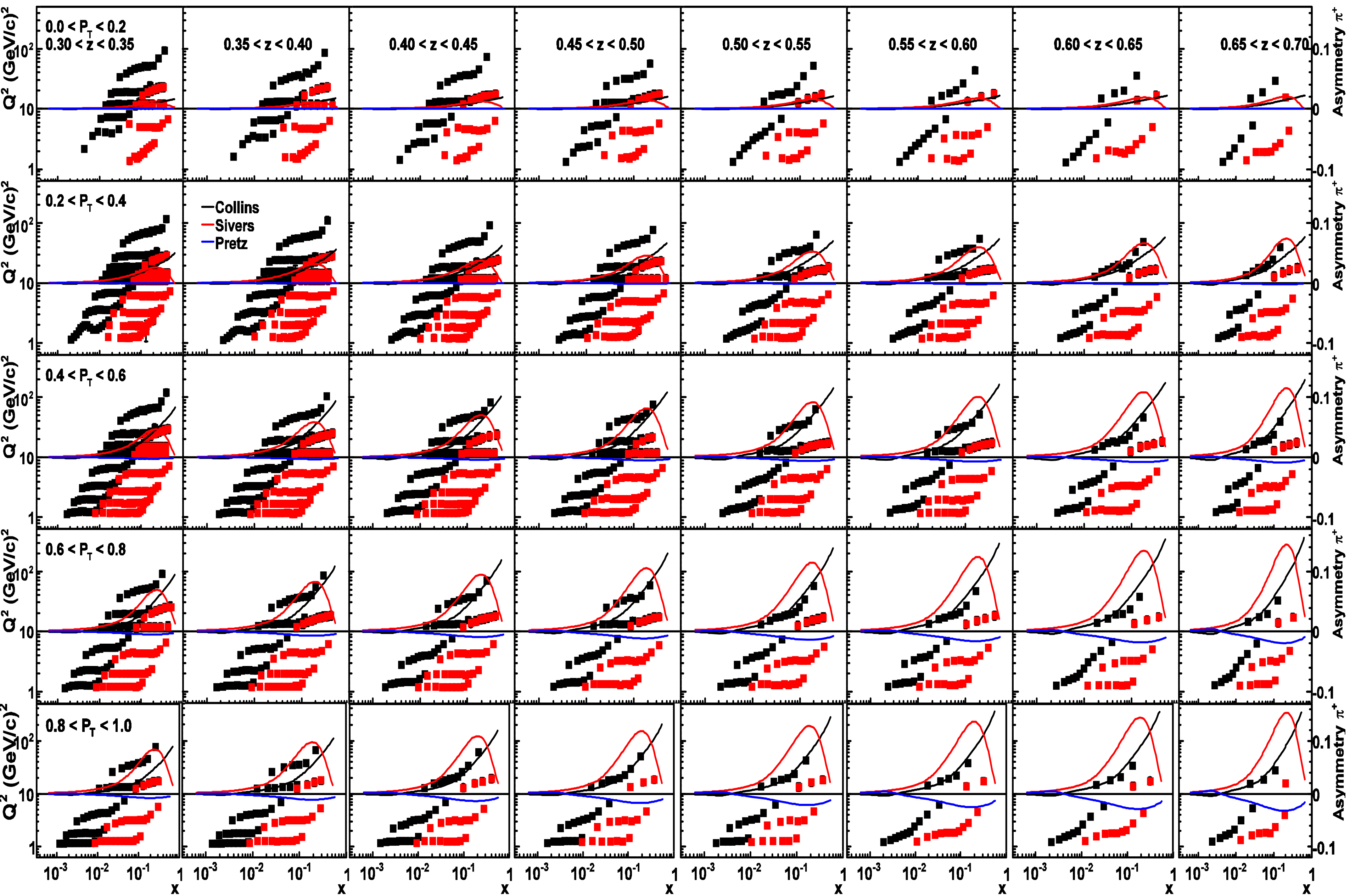


12 GeV: from approved SoLID SIDIS experiment

Lower y cut, more overlap with 12 GeV

$0.05 < y < 0.8$

EIC projection: Proton π^+ (z = 0.3-0.7)



Summary

TMDs: frontier in nucleon structure

- TMD physics active in both theory and experiment, ongoing and planned programs in all major laboratories in the world
- Beyond 1-d leading-twist distributions
- Direct link with orbital motion (orbital angular momentum)
- Transverse motion: spin-orbit correlations, multi-parton correlations, dynamics of confinement and QCD
- Transverse structure -> multi-dimension
- Valence, Sea and Gluon

Supported by U.S. Department of Energy under contract number

DE-FG02-03ER41231

Leading-Twist Transverse Momentum Dependent Parton Distributions

(Eight TMDs)