12 GeV Neutron/3He Transversity/TMDs with SoLID

- Brief review on nucleon longitudinal spin structure
- Experimental access to TMDs
- **12 GeV SoLID Experiment**
- Summary

Second Workshop on
Hadron Physics in China and Opportunities with 12 GeV JLab
July 27- July 31, 2010, Beijing， China

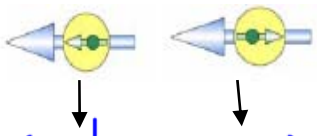
Haiyan Gao
Duke University
Durham, NC, U.S.A.

Nucleon Spin Structure

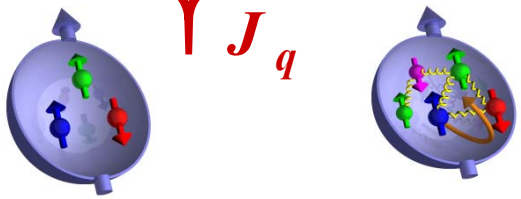
- Understand Nucleon Spin in terms of quarks and gluons (QCD).
  - **Nucleon spin is ½ at all energies.**

Nucleon's spin
Ji's Sum Rule

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



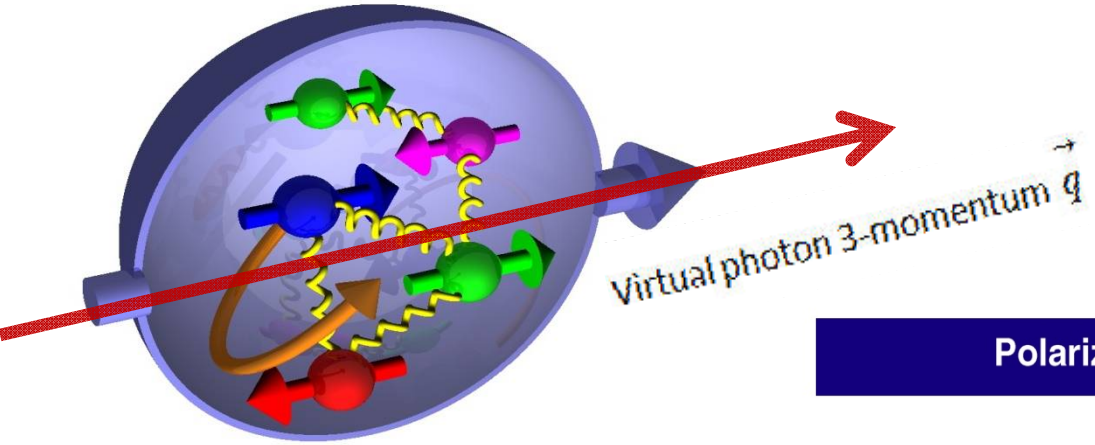
J_q



~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.**

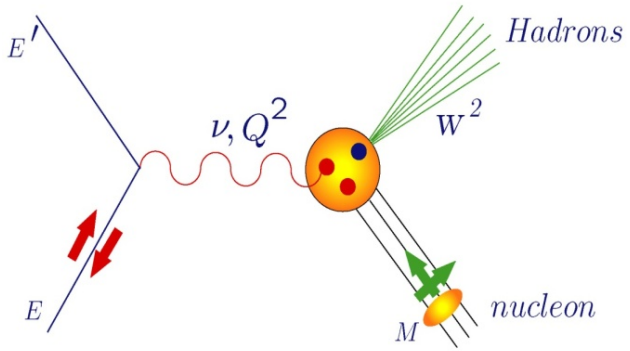
Longitudinal Spin Structure



g_{1L}

Probability for quark polarized in the nucleon spin direction

Polarized Deep Inelastic Electron Scattering



$x = \frac{Q^2}{2M\nu}$ 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

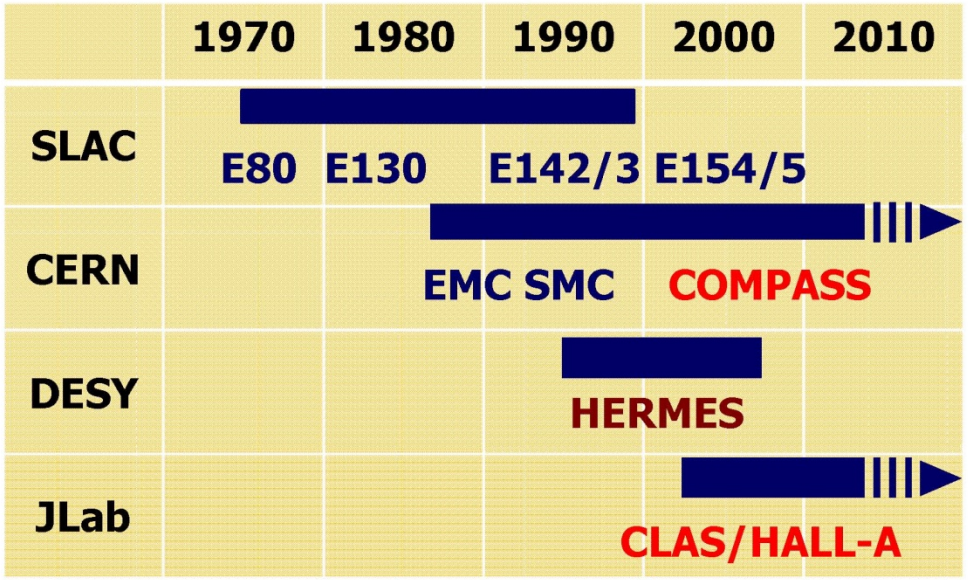
F_2 and F_1 the unpolarized (spin averaged) structure functions,

and

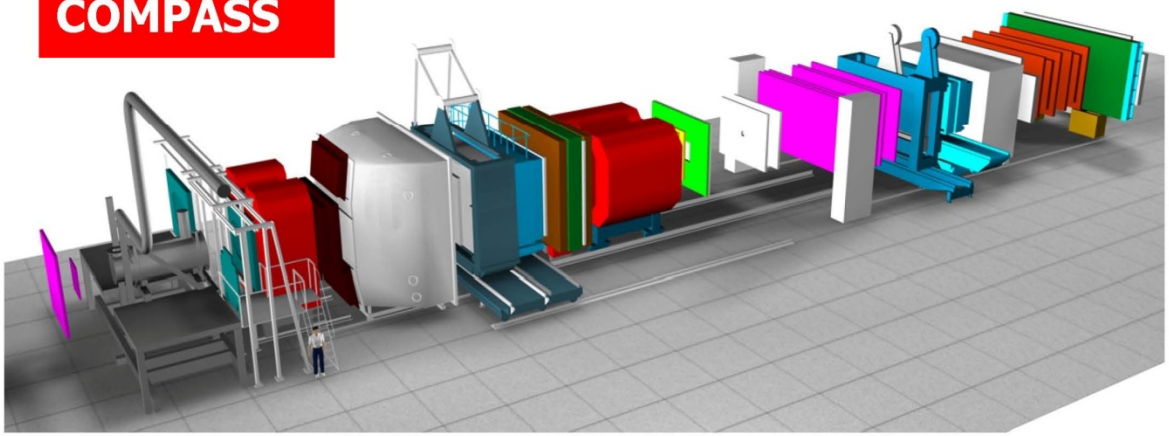
g_1 and g_2 the spin dependent structure functions

Experiments @Lepton facilities

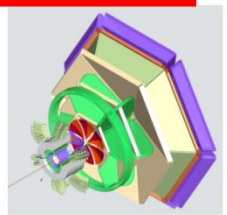
E80, E130	$\vec{e}\,\vec{p}$	≤ 20 GeV
EMC	$\vec{\mu}\,\vec{p}$	100–200 GeV
E142, 143	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	≤ 28 GeV
SMC	$\vec{\mu}\,\vec{p},\vec{d}$	100, 190 GeV
E154, 155	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	≤ 50 GeV
HERMES	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	27.5 GeV
COMPASS	$\vec{\mu}\,\vec{p},\vec{d}$	160 GeV
HALL A	$\vec{e}\,\vec{n}$	6 GeV
CLAS	$\vec{e}\,\vec{p},\vec{d}$	6 GeV

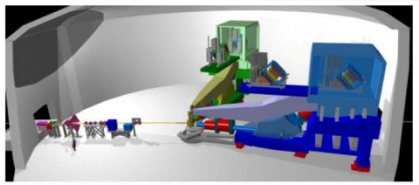


COMPASS



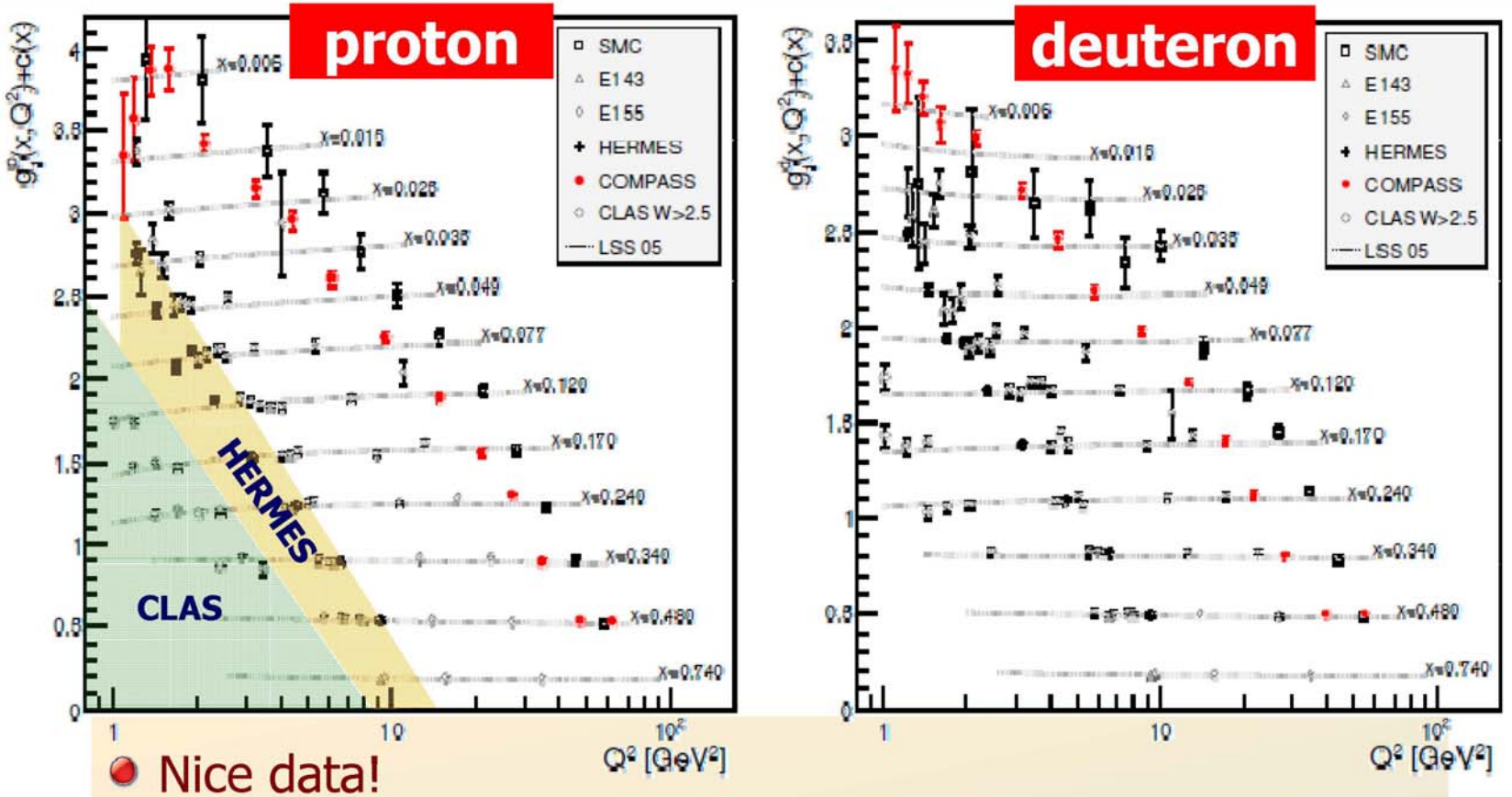
Jlab - CLAS, Hall A





Horst Fischer DIS2010

Global NLO QCD Analysis



- Nice data!
- Q^2 dependence of g_1 data described in QCD
- Limited kinematic range (c.f. Collider)

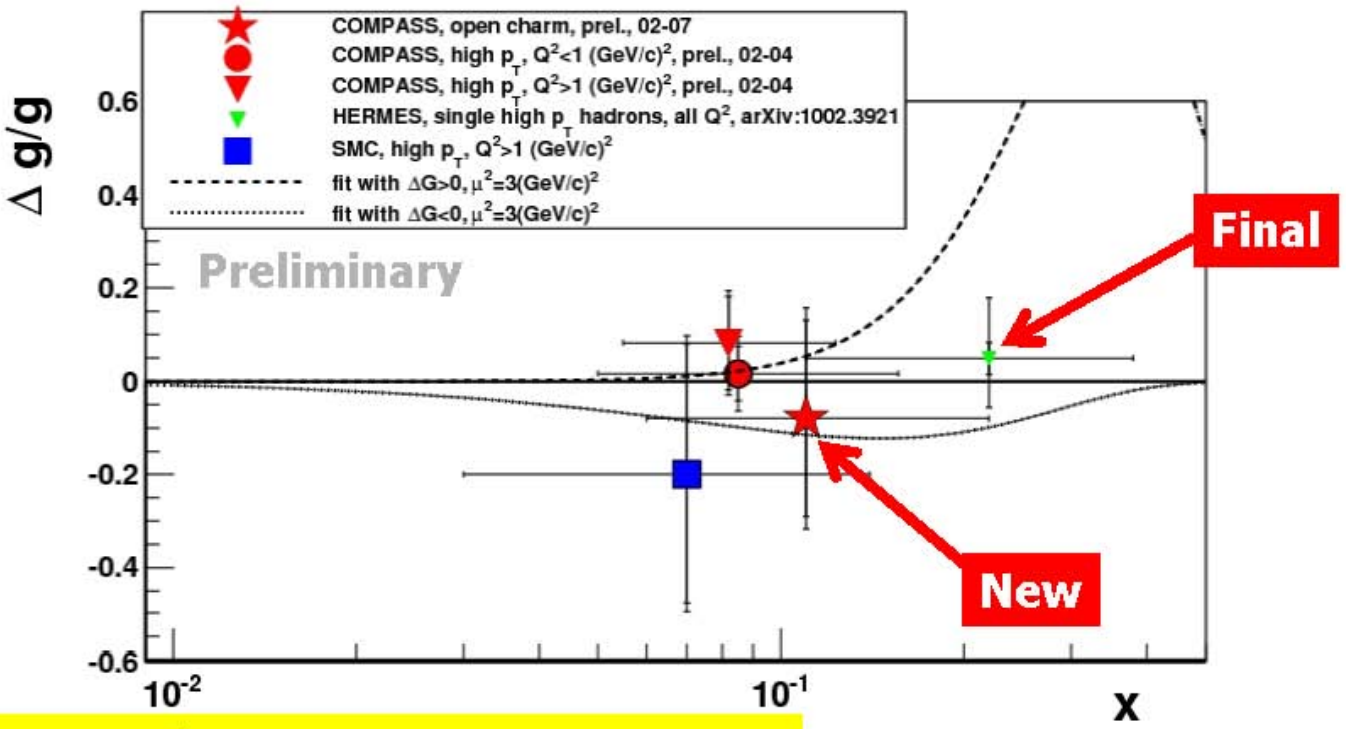
Horst Fischer DIS2010

SLAC and JLab ^{3}He data not shown

See Talk 1193 by F. Kunne

Summary Gluon Polarization

Presently all Analysis in LO only



COMPASS Open Charm:

ΔG/G=-0.08+- 0.21(stat) +- 0.11(sys.)
(Systematic error still under investigations)

(Value supersedes previous publication)

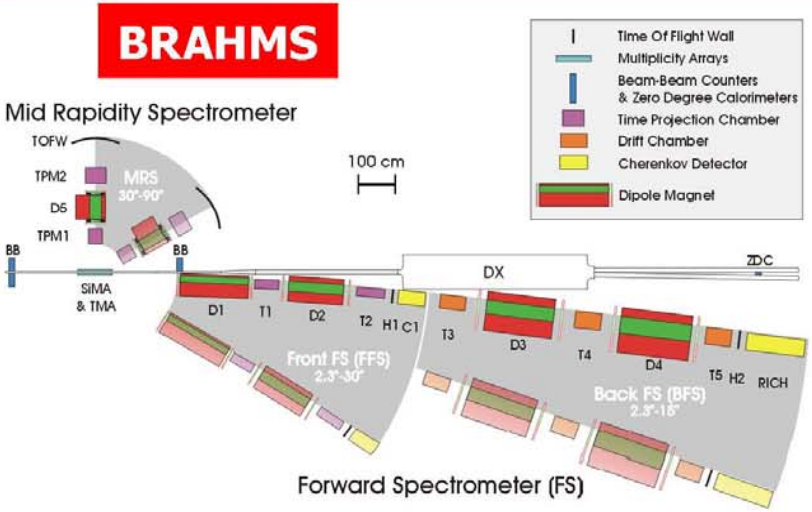
C.Franco

See Talk 1193 by F. Kunne

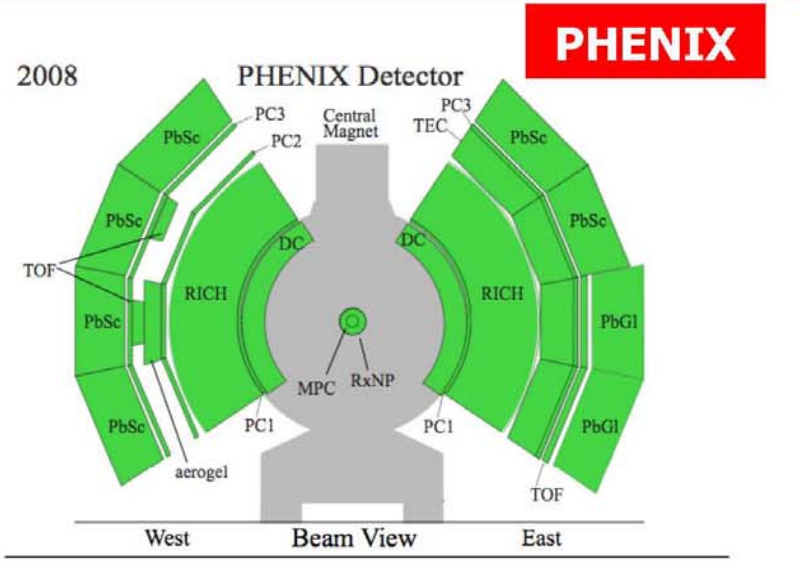
Horst Fischer DIS2010

Proton-Proton Scattering Experiments

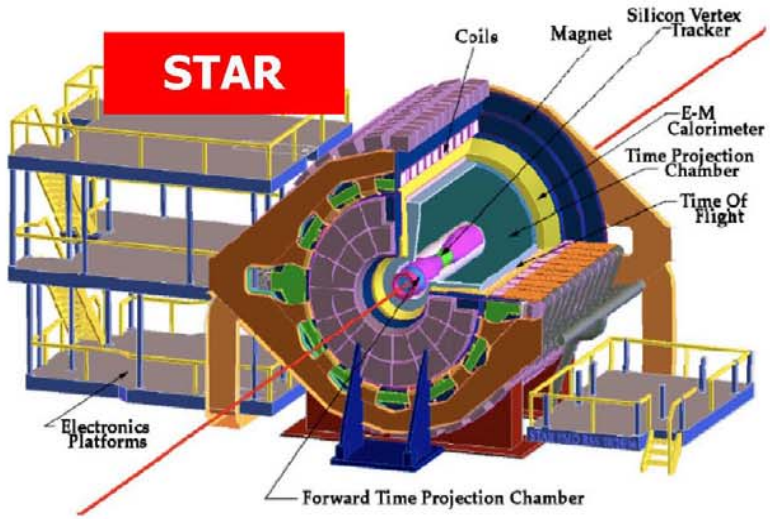
BRAHMS



PHENIX



STAR



RHIC @ BNL: Proton-Proton

√s=200 /500 GeV

~50% polarization

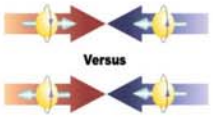
Lumi: L/T 48/18 pb^{-1}

Horst Fischer DIS2010

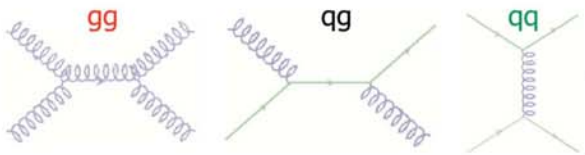
Talks by Surrow 636, Haggerty 1013

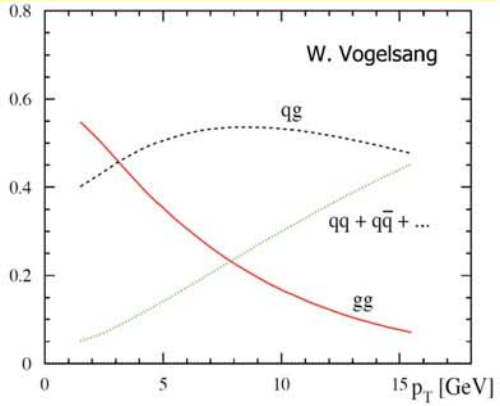
Gluon Polarization from RHIC

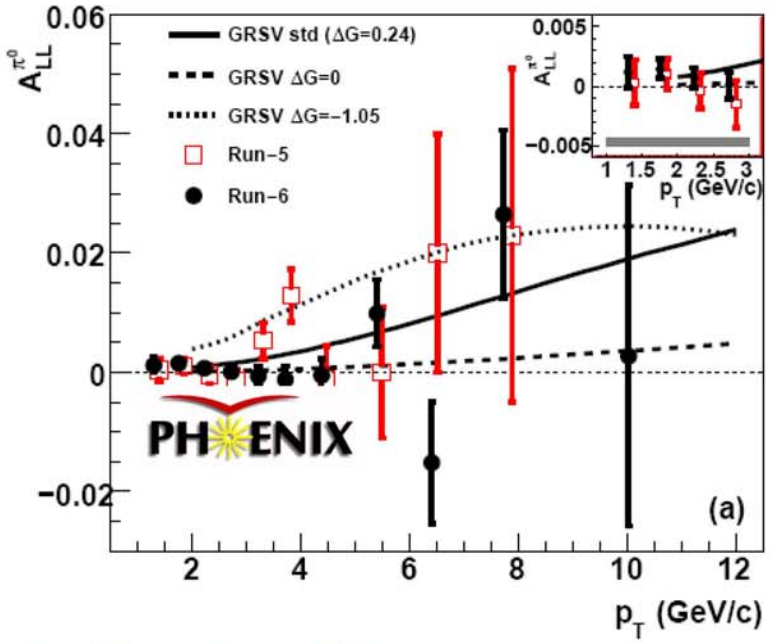
One example from PHENIX & STAR:

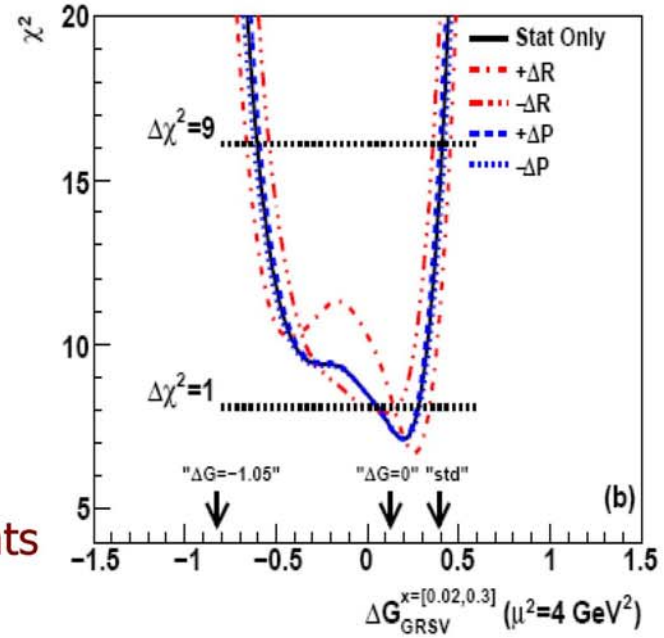


$$p^{\uparrow}p^{\uparrow} \rightarrow \pi^0 X$$









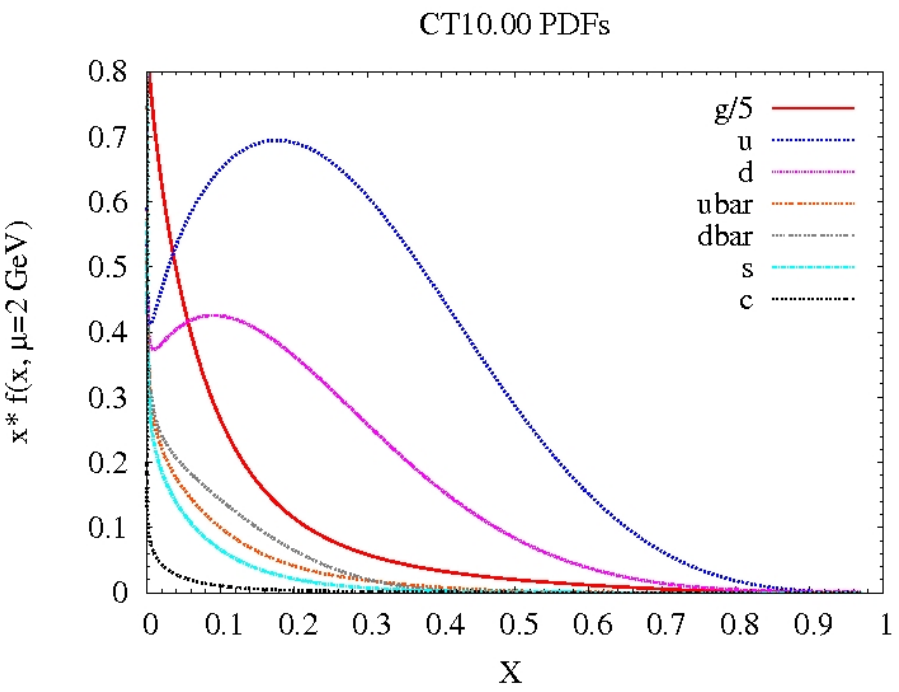
- Confirmation of lepton scattering experiments
- Impact on extraction of Δg(x) in QCD-fits

STAR PV SSA results from W production (B. Surrow, Talk 636)

Horst Fischer DIS2010

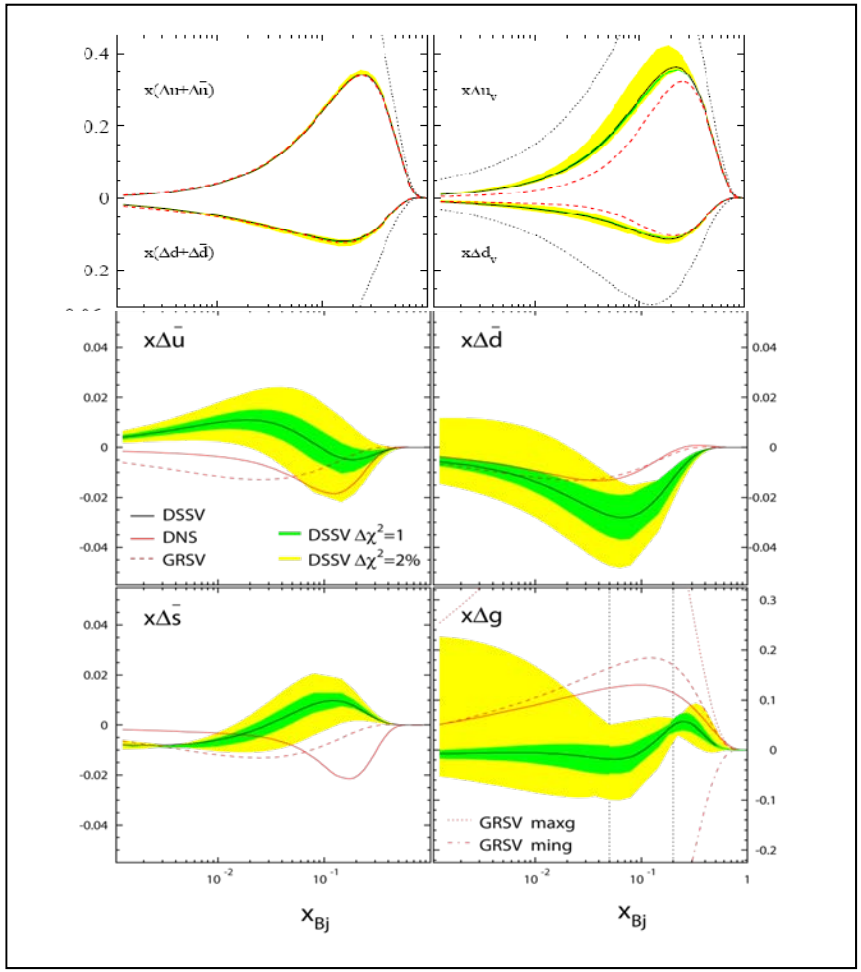
Parton Distributions (CTEQ and DSSV)

Unpolarized PDFs



CTEQ-TEA, H.L. Lai et al, arXiv:1007.2241

Polarized PDFs



DSSV, PRL101, 072001 (2008)

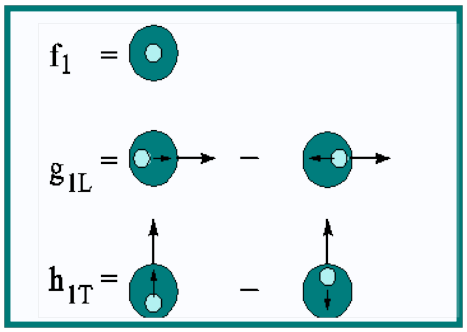
Stefano Forte Talk 509

Q: how about quark transverse momentum ?

3-D description in momentum space?

Transverse Momentum-dependent parton distributions (TMDs)

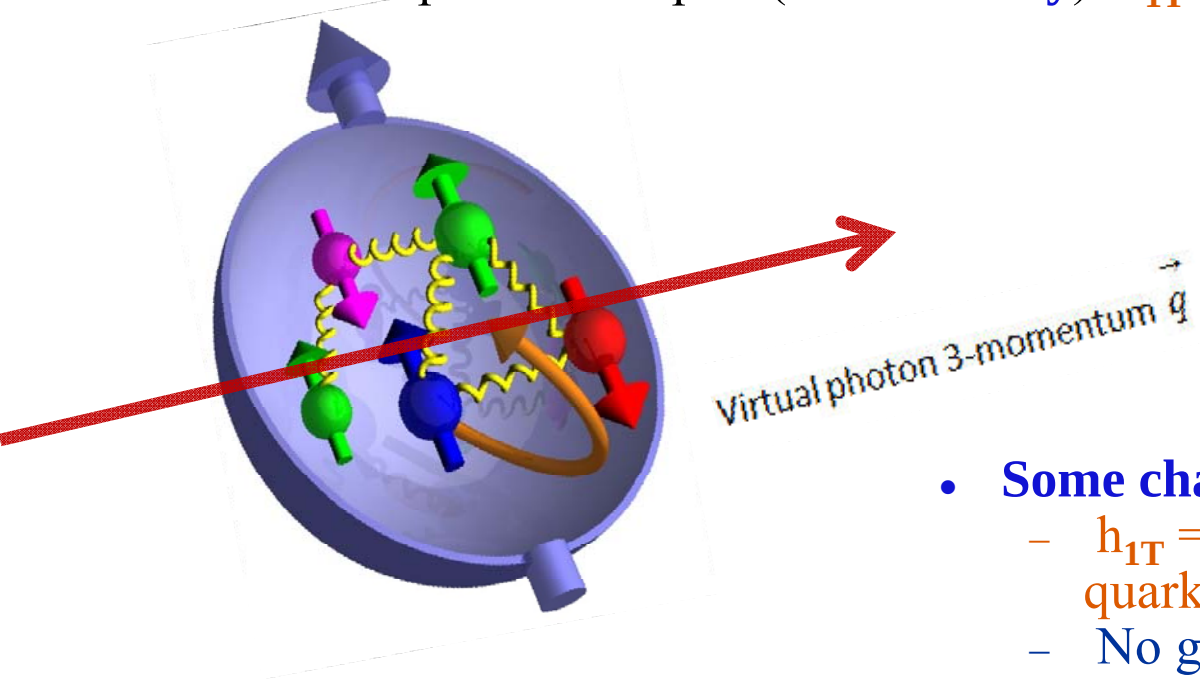
At leading twist 8 total, only 3 TMDs non vanishing upon integrating over transverse momentum of the quark

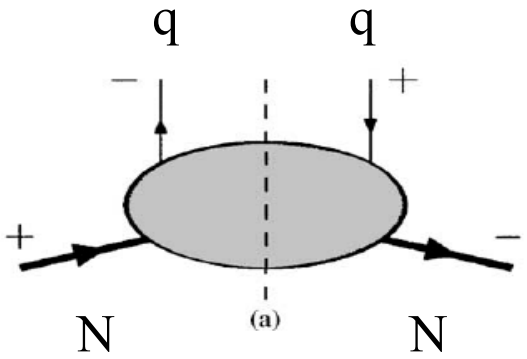


So how to study transversity and other TMDs experimentally?

Transverse Spin Structure

Longitudinal Spin structure function: g_{1L}
Its transverse spin counter part (**Transversity**): h_{1T}



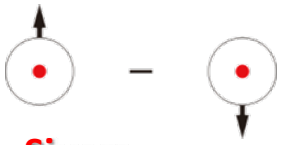


Nucleon tensor charge = $\int_{-1}^{1} h_{1T}\,dx$

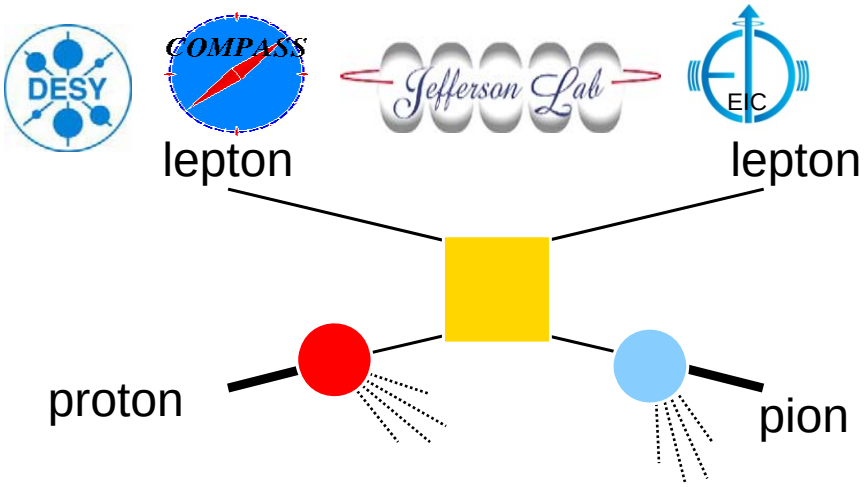
- **Some characteristics of transversity**
  - $h_{1T} = g_{1L}$ for non-relativistic quarks
  - No gluon transversity in nucleon
  - Chiral-odd → difficult to access in inclusive DIS
  - Soffer's bound
    - $|h_{1T}| <= (f_1+g_{1L})/2$

All Leading Twist TMDs

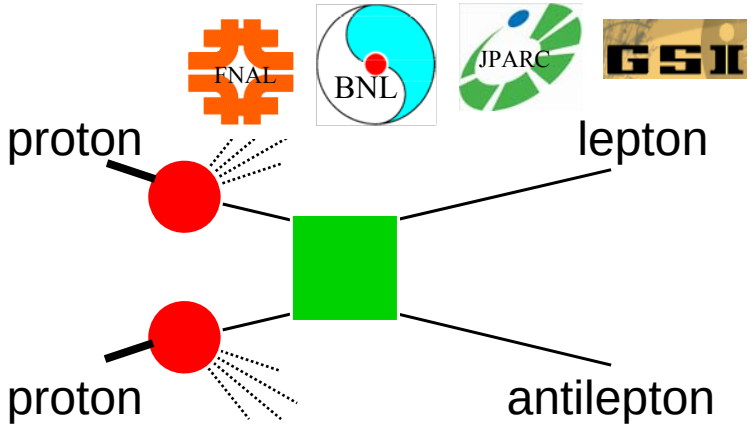
Nucleon
Quark Spin

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

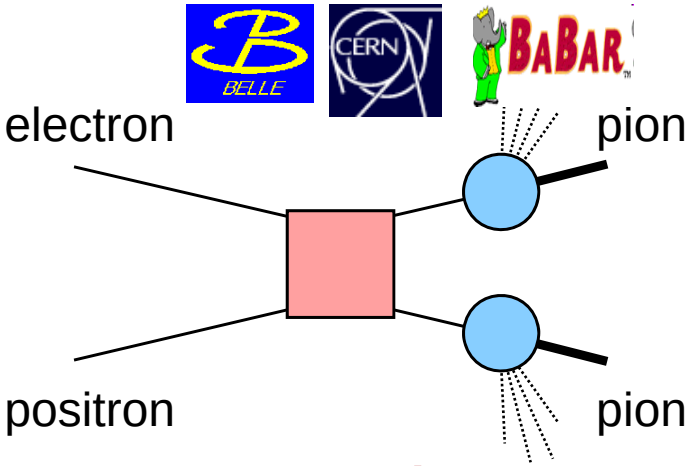
Access TMDs through Hard Processes



SIDIS



Drell-Yan



e^-e^+ to pions

Partonic scattering amplitude

Fragmentation amplitude

Distribution amplitude

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

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

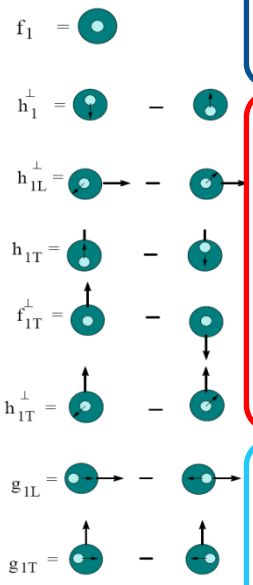
Access Parton Distributions through Semi-Inclusive DIS

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

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

Unpolarized

Boer-Mulder



Transversity

Sivers

Pretzelosity

$$+ S_L[\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$$
$$+ S_T[\varepsilon\sin(\phi_h+\phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+ \sin(\phi_h-\phi_S)\cdot(F_{UL}^{\sin(\phi_h-\phi_S)} + \ldots)$$
$$+ \varepsilon\sin(3\phi_h-\phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]$$

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

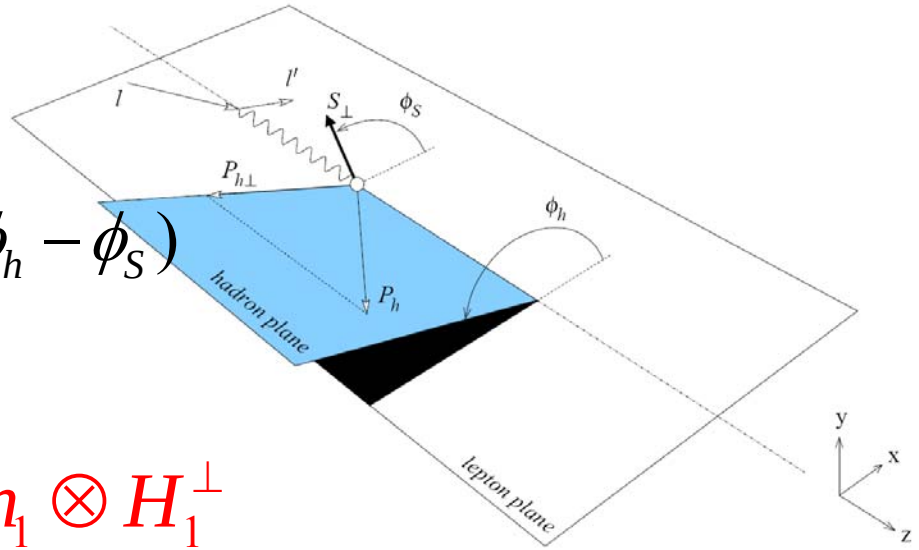
S_L, S_T: Target Polarization; λ_e: Beam Polarization

Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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



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

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

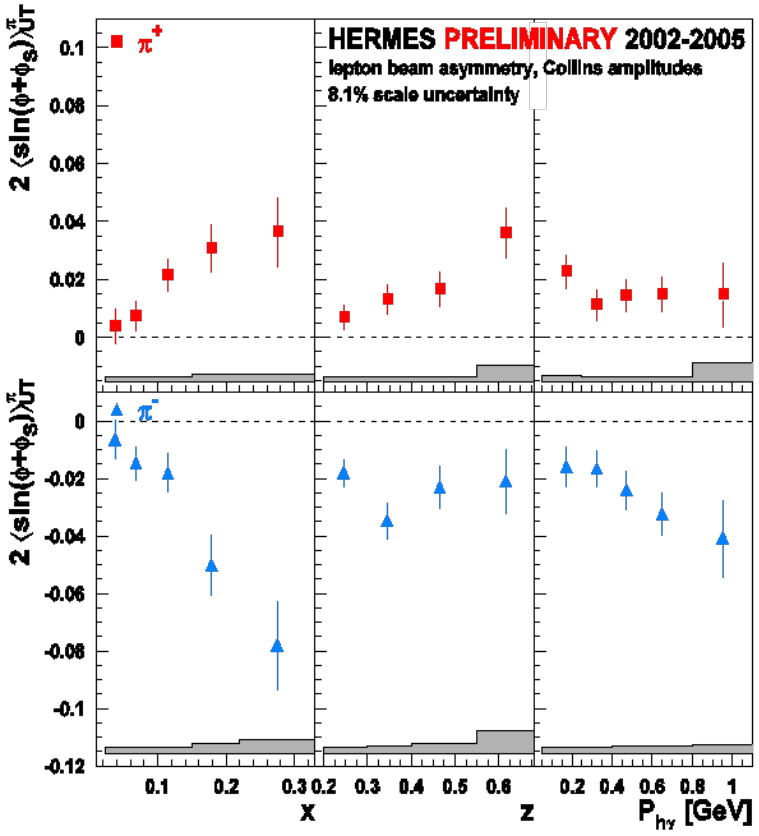
$$A_{UT}^{Pretzelosity} \propto \left\langle \sin(3\phi_h - \phi_S) \right\rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)

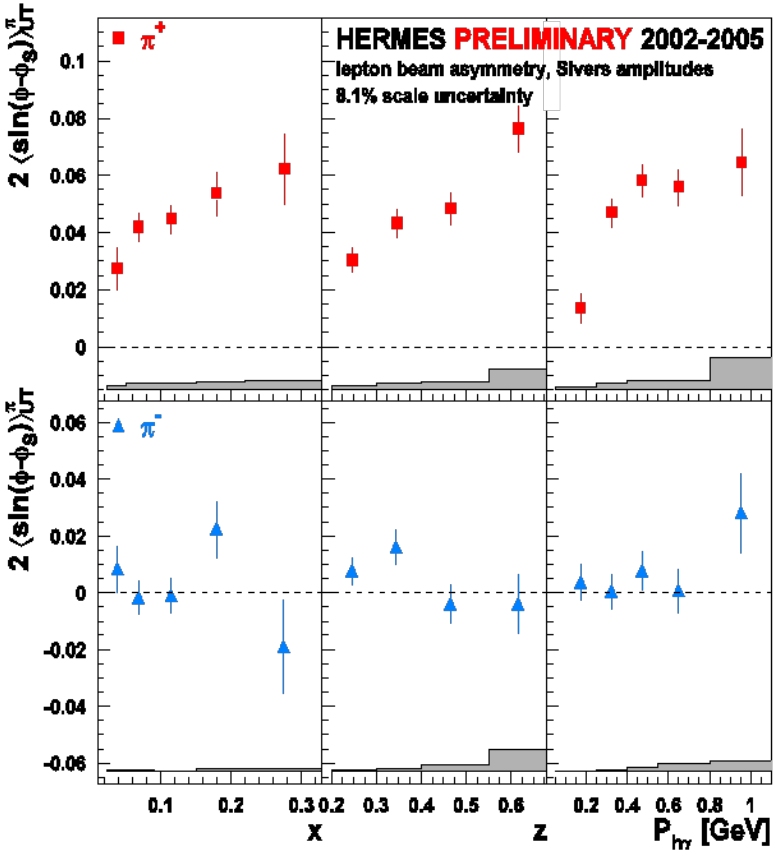
Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.

$A_{UT}^{\sin(\phi)}$ 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

Klaus Rith , Talk 1194

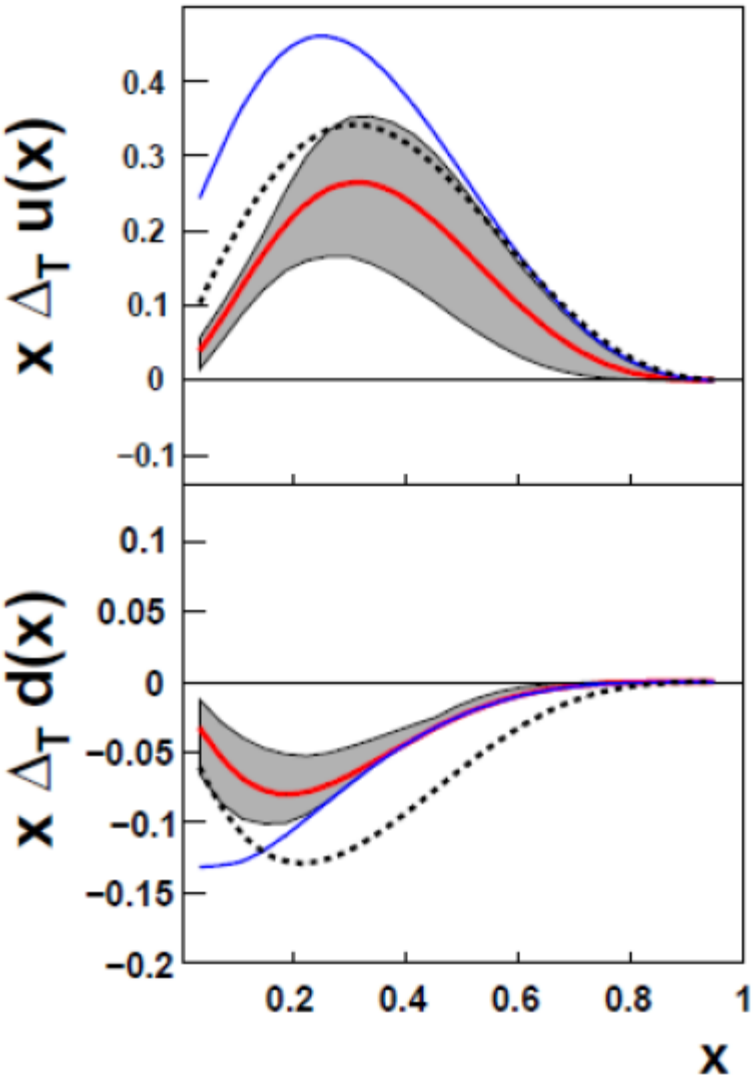
Transversity Distributions

A global fit to the HERMES p, COMPASS d and BELLE e+e- data by the Torino group, Anselmino et al., arXiv:0812.4366

Solid red line : transversity distribution, analysis at $Q^2=2.4\ (GeV/c)^2$

Solid blue line: Soffer bound
$|h_{1T}| <= (f_1+g_{1L})/2$
GRV98LO + GRSV98LO

Dashed line: helicity distribution g_{1L}, GRSV98LO



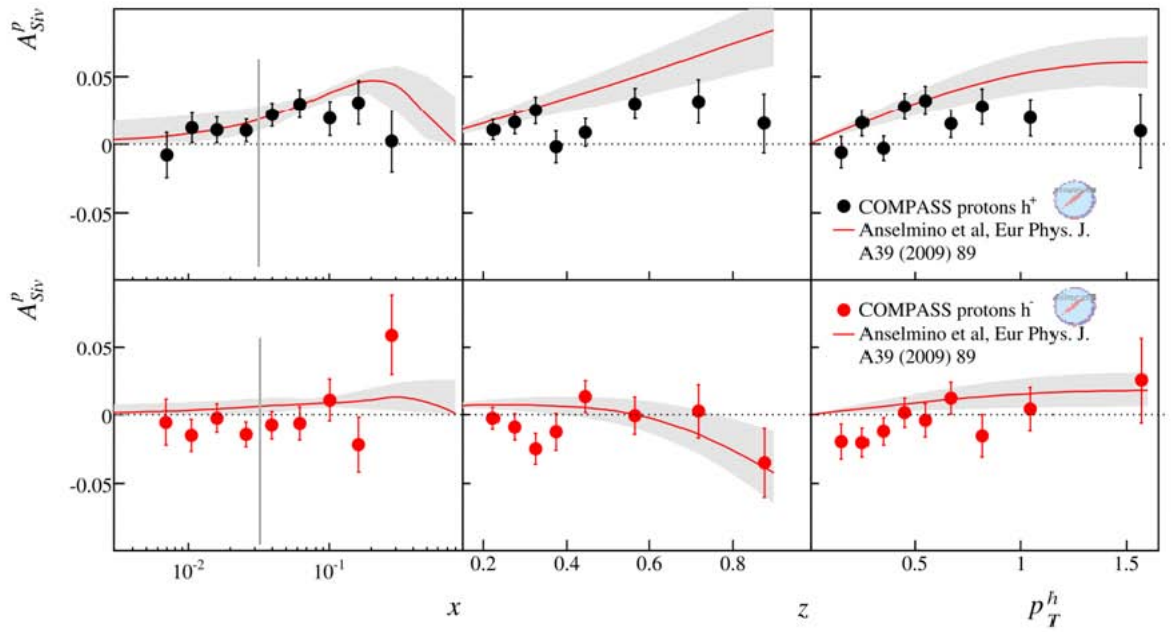
$$\Delta_T = h_{1T}$$

A. Prokudin, Talk 1059

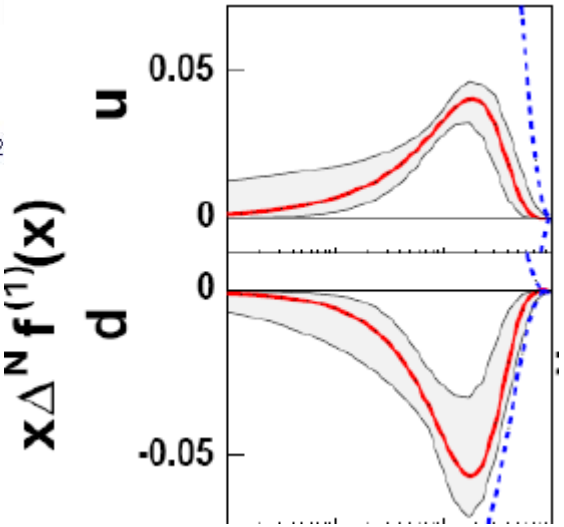
Sivers asymmetry - proton

comparison with theory

… most recent predictions from *M. Anselmino et al.*
based on the fit of HERMES proton and COMPASS deuteron data



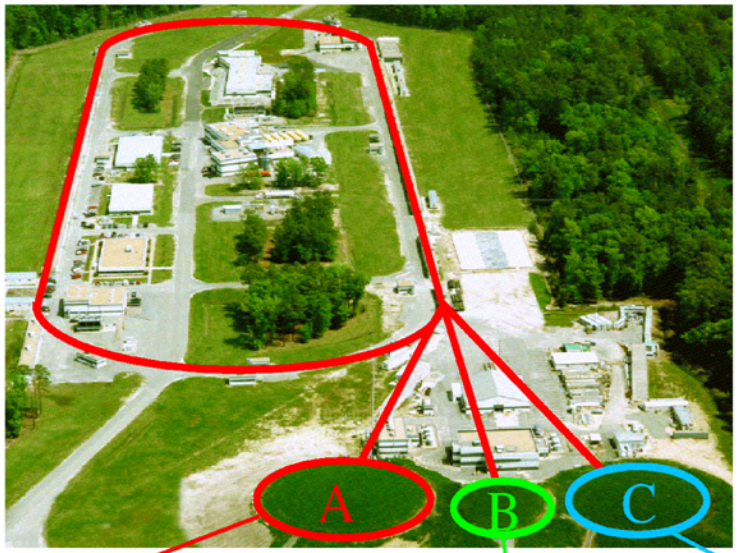
Extraction of Sivers fcn (HERMES p, COMPASS d)



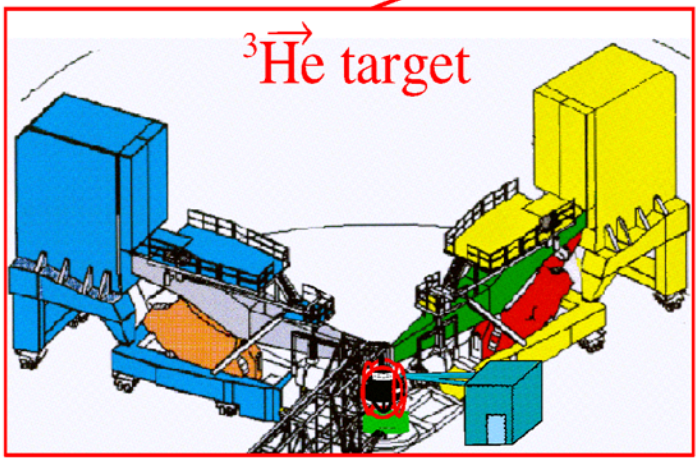
Ext: M. Anselmino *et al.*, arXiv:0812.4366

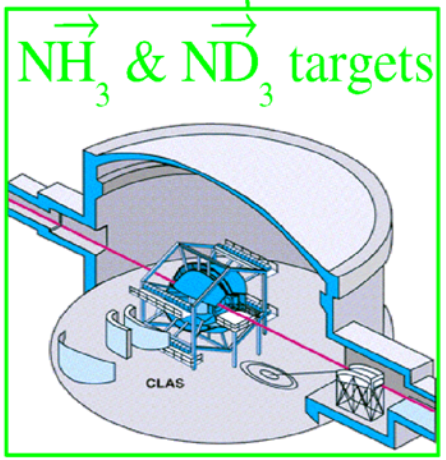
Jefferson Lab Experimental Halls

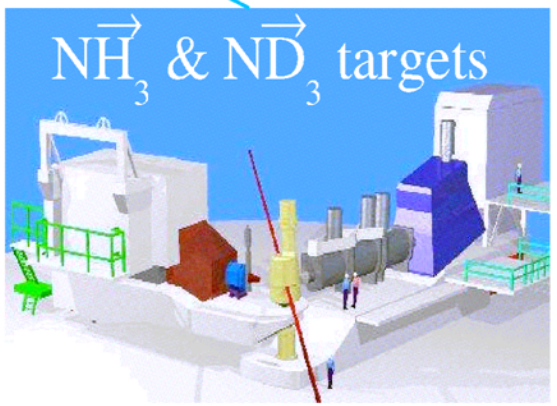
6 GeV polarized
CW electron beam
Pol=85%, 180μA



Will be upgraded to 12 GeV by ~2014 with a new Hall D







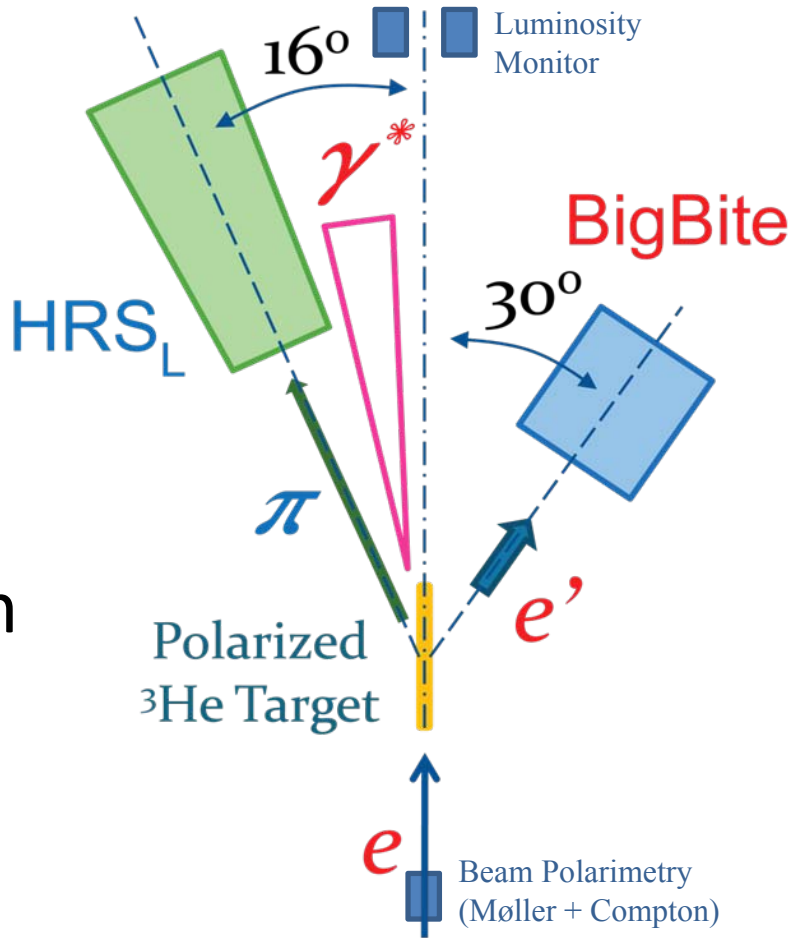
HallA: two HRS'

Hall B:CLAS

Hall C: HMS+SOS

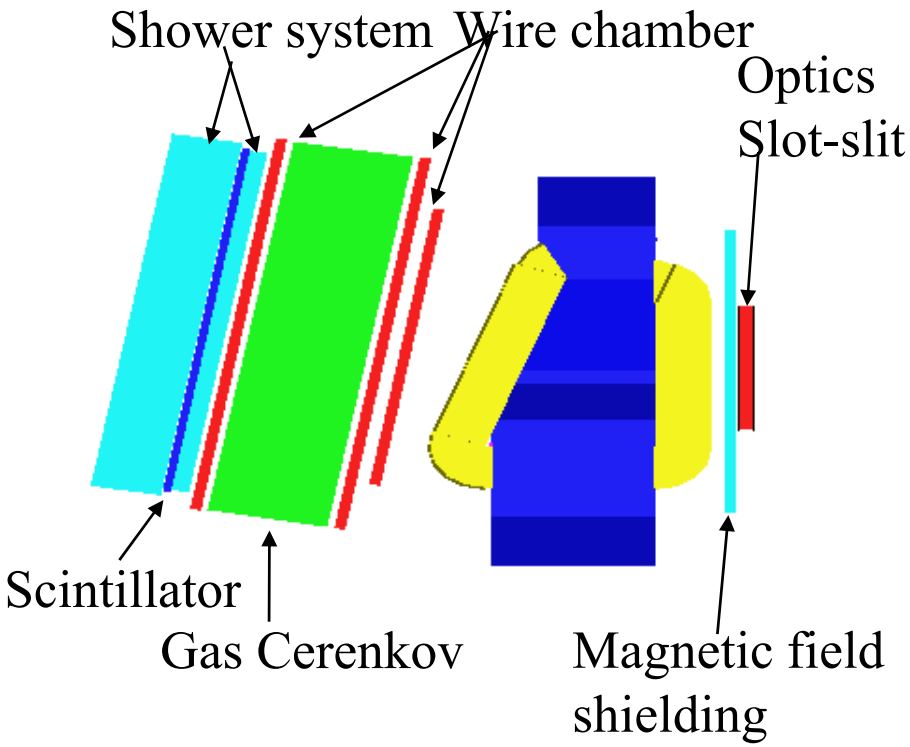
JLab E06-010 Experiment

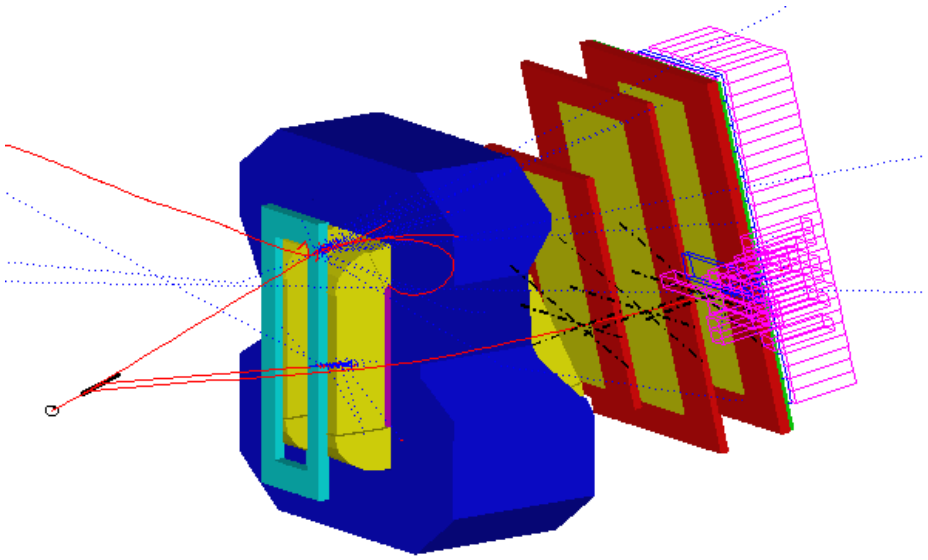
- Polarized ^{3}He Target, > 60% with beam, world record
- Polarized Electron Beam
  - ~80% Polarization
  - Fast Flipping at 30Hz
  - PPM Level Charge Asymmetry controlled by online feed back
- BigBite at 30º as Electron Arm
  - P_e = 0.7 ~ 2.2 GeV/c
- HRS_L at 16º as Hadron Arm
  - P_h = 2.35 GeV/c



Jian-Ping Chen July 29

Electron Arm: BigBite



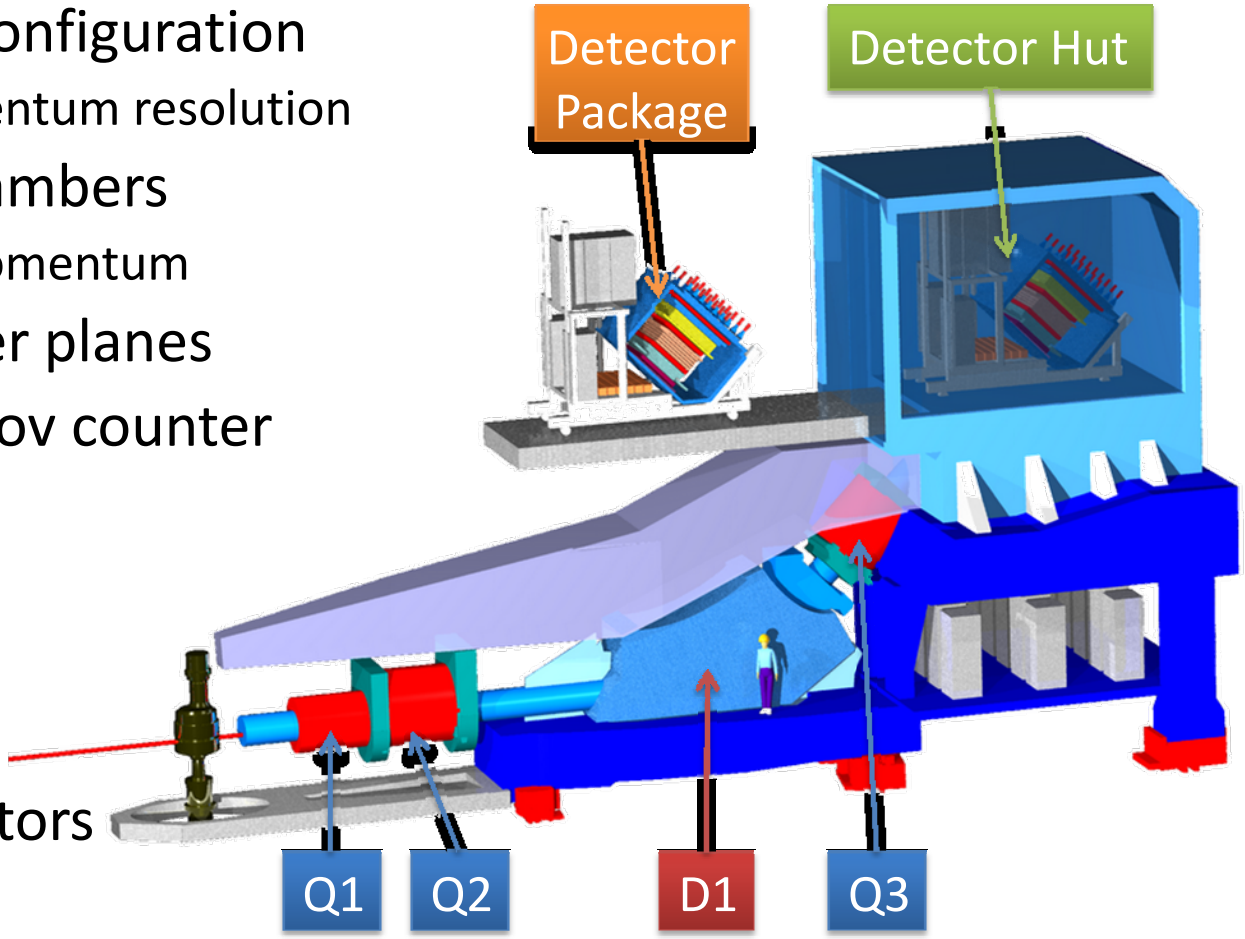


- 64 msr
- Large out-of-plane acceptance, essential for separating Collins/Sivers effect

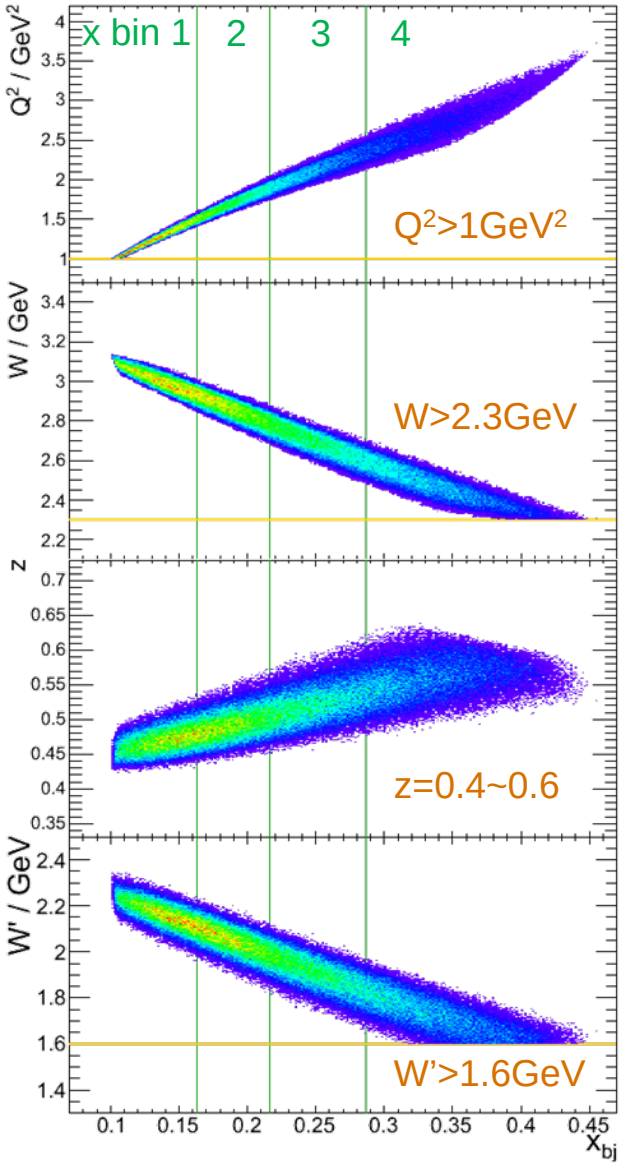
- Drift Chamber for Tracking
- Shower counter for electron PID.
- Scintillator for Timing

High Resolution Spectrometer

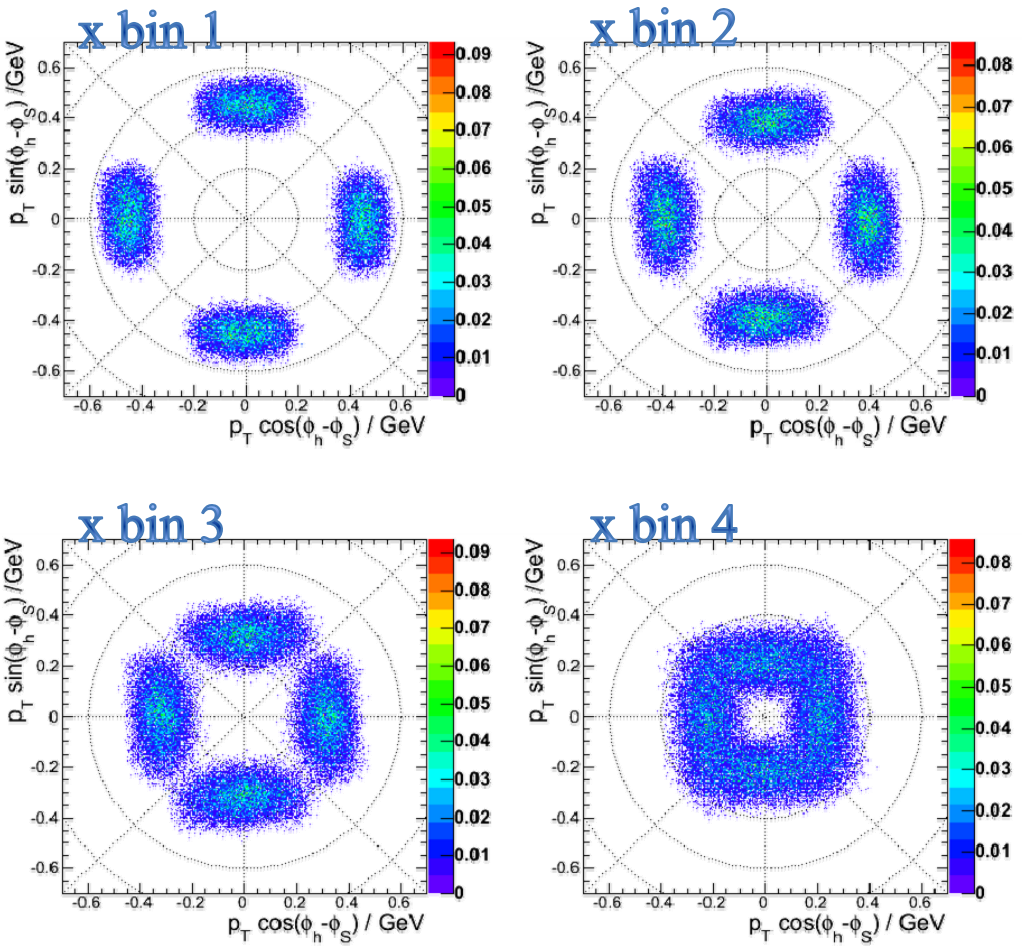
- Left HRS to detect hadrons of p_h = 2.35 GeV/c
- QQDQ magnet configuration
  - Very high momentum resolution
- Vertical Drift Chambers
  - Tracking and momentum
- Scintillator trigger planes
- Aerogel Cherenkov counter
  - n = 1.015
- RICH detector
  - n = 1.30
- Gas Cherenkov
- Lead-glass detectors



Data Coverage



Kinematics Coverage



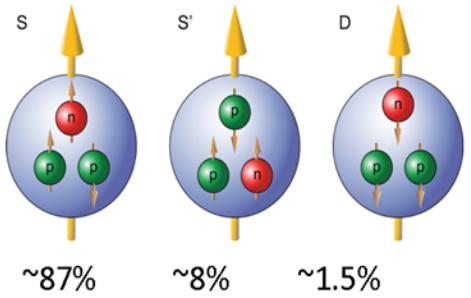
p_T & ϕ_h- ϕ_S Coverage

6 GeV Preliminary Results

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

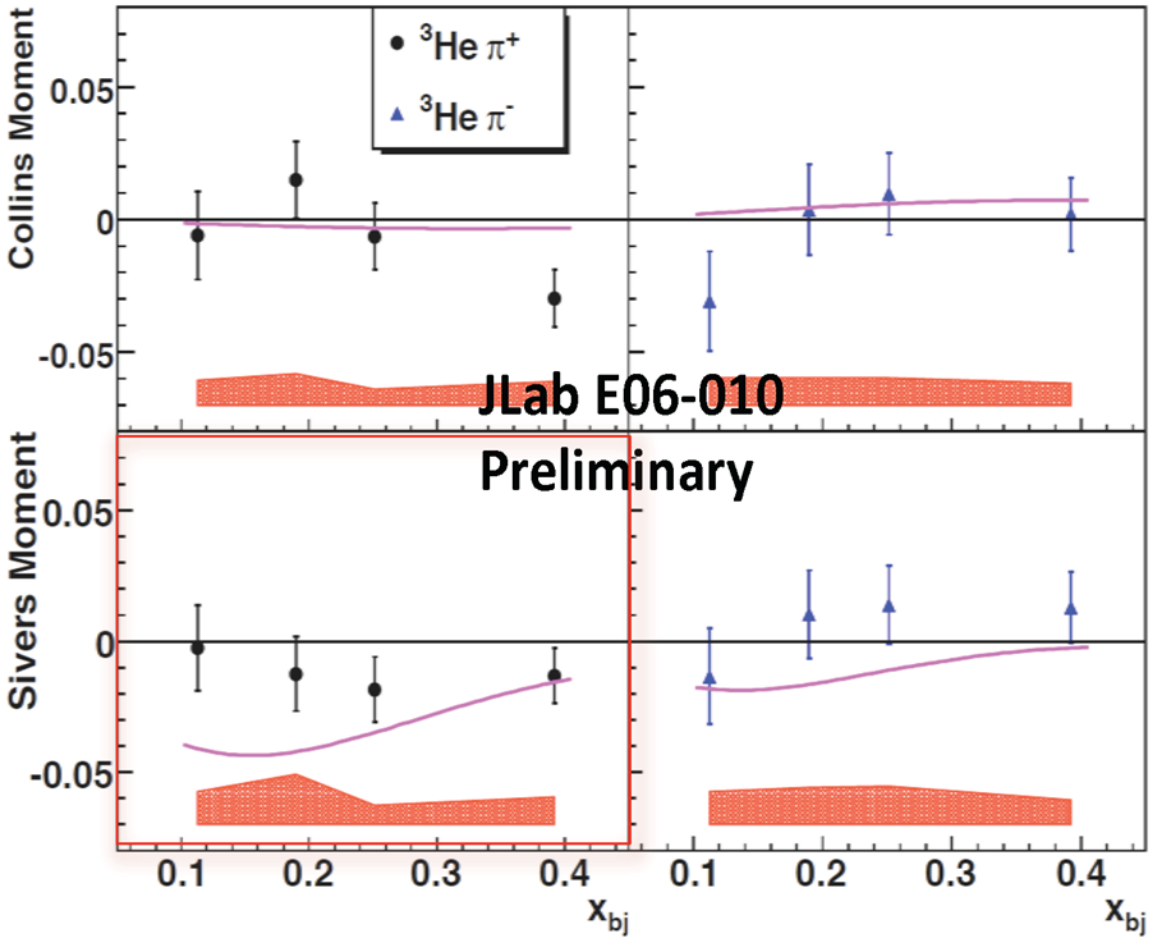
$$^3\mathrm{He}^{\uparrow}(e,e'h)$$

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



To extract information on neutron, one would assume:

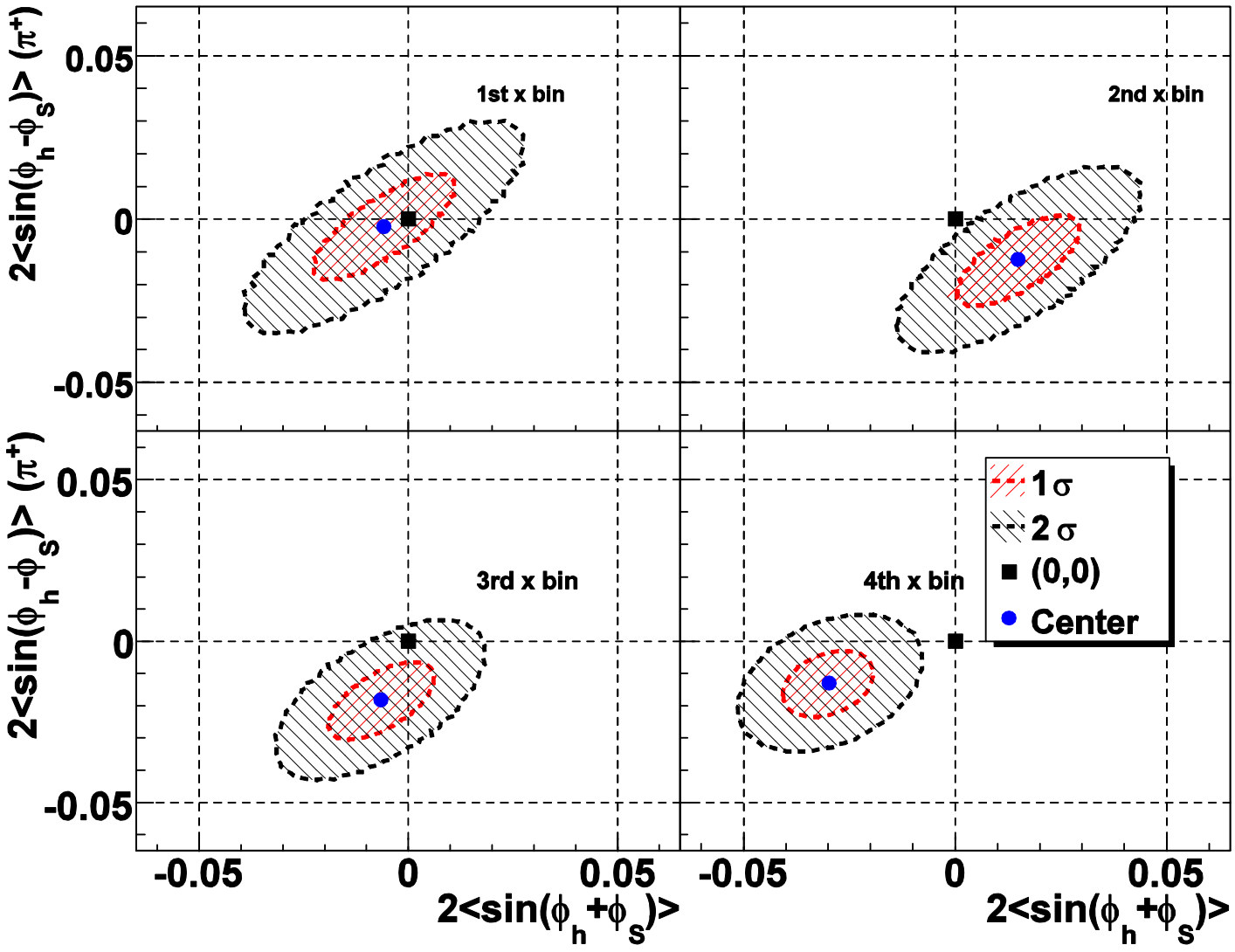
$$^3\mathrm{He}^{\uparrow} = 0.865 \cdot \mathrm{n}^{\uparrow} - 2 \times 0.028 \cdot \mathrm{p}^{\uparrow}$$



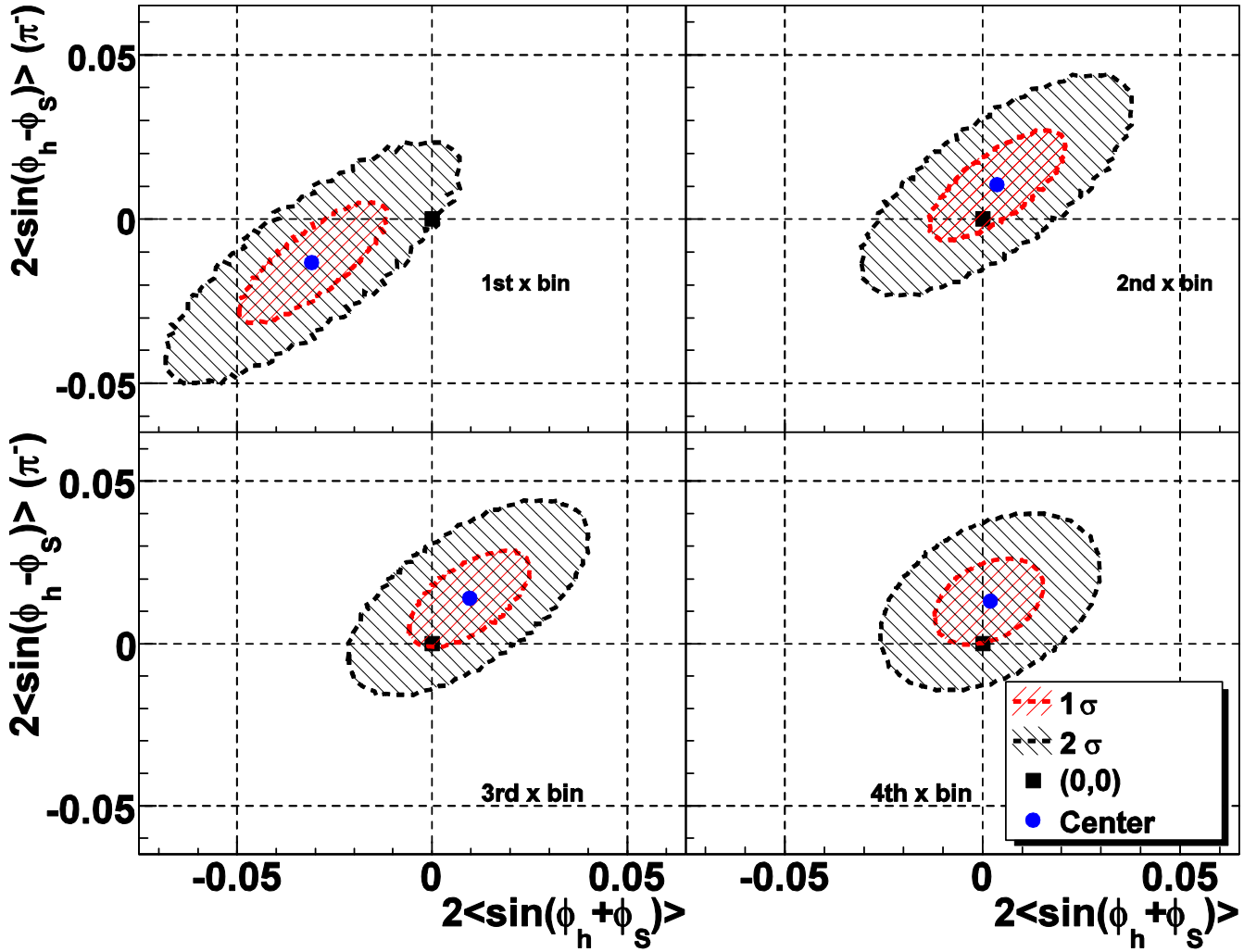
^{3}He Collins SSA are not large (as expected).

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

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



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



PR-10-006: Update to PR-09-014

Nucleon Transversity at 11 GeV Using a Polarized ^{3}He Target and SOLid in Hall A

Beijing U., CalState-LA, CIAE, W&M, Duke, FIU, Hampton, Huangshan U., Cagliari U. and INFN, INFN-Bari and U. of Bari, INFN-Frascati, INFN-Pavia, Torino U. and INFN, JLab, JSI (Slovenia), Lanzhou U, LBNL, Longwood U, LANL, MIT, Miss. State, New Mexico, ODU, Penn State at Berks, Rutgers, Seoul Nat. U., St. Mary's, Syracuse, Tel aviv, Temple, Tsinghua U, UConn, Glasgow, UIUC, Kentucky, Maryland, UMass, New Hampshire, USTC, UVa

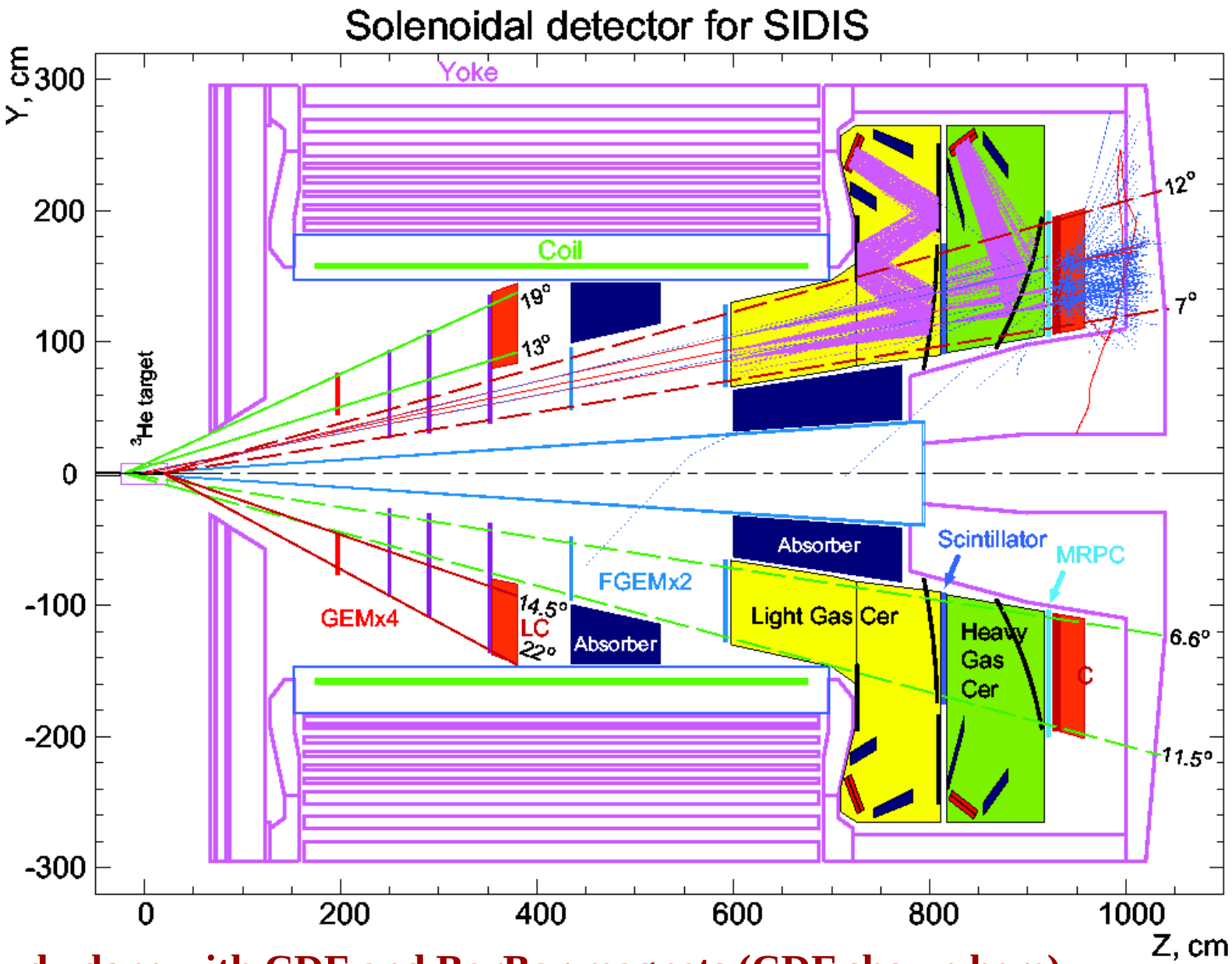
and the Hall A Collaboration

Strong theory support, Over 130 collaborators, 40 institutions, 8 countries, strong overlap with PVDIS Collaboration

Approved by JLab PAC35

E12-10-006

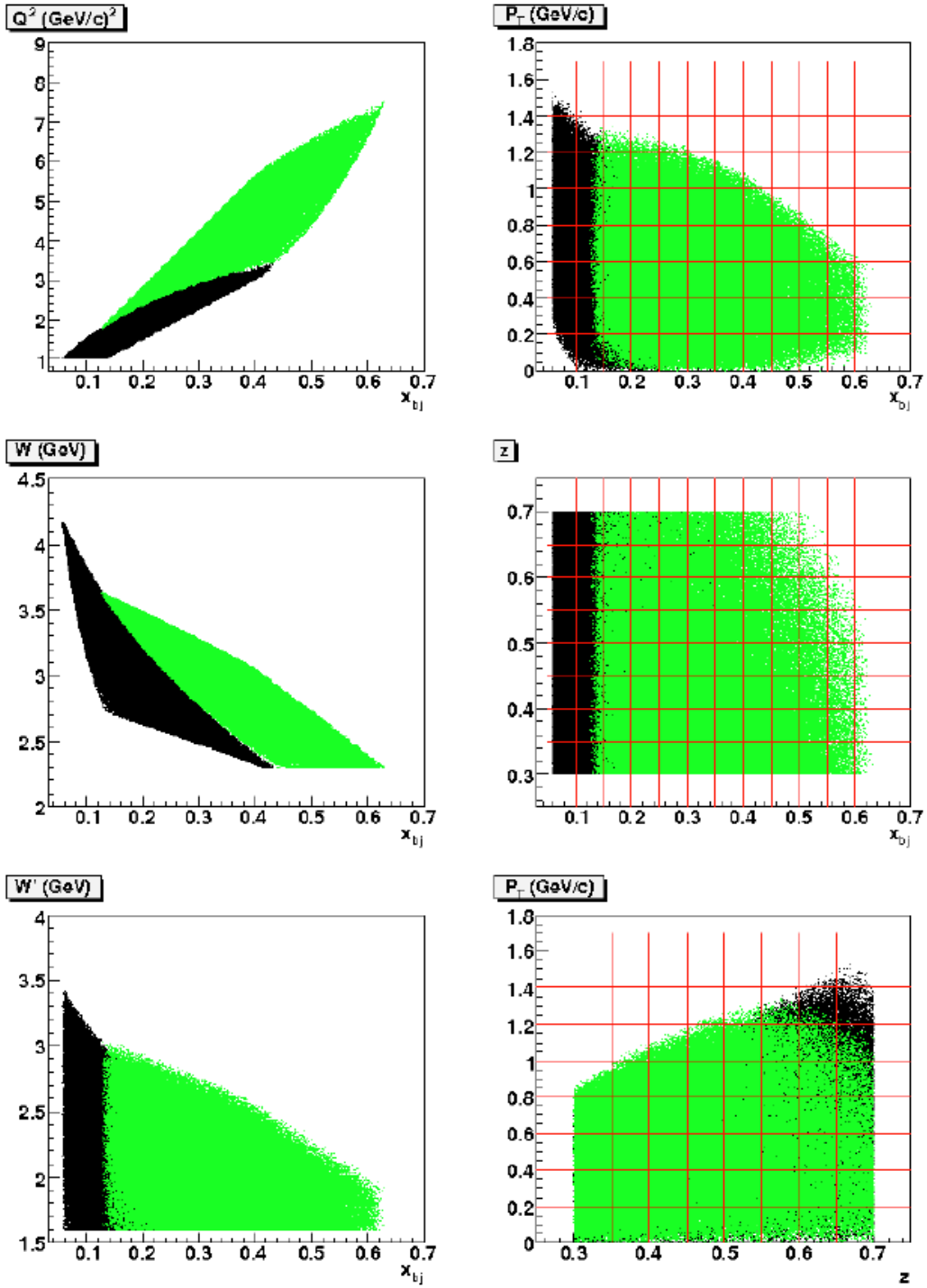
Experiment E12-10-006



Study done with CDF and BarBar magnets (CDF shown here)

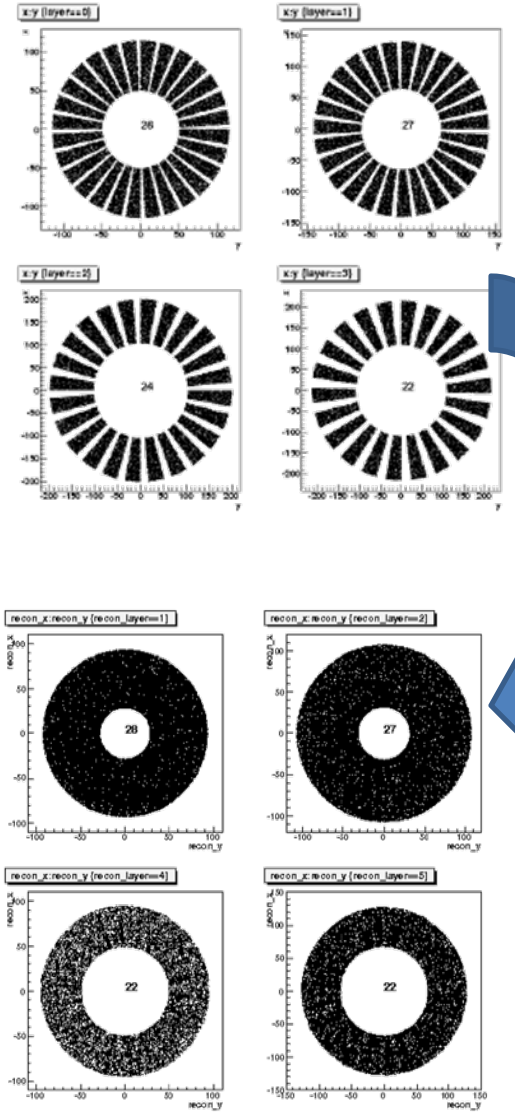
Kinematic Coverage

- Precision 4-D (x, Q^2, p_T and z) mapping of Collins, Sivers and pretzelosity.
- **Coverage with 11 GeV beam shown here**
  - Black: forward angle
  - **Green: large angle**
- x_B: 0.1 ~ 0.6
- P_T: 0 ~ 1.5 GeV/c
- W: 2.3 ~ 4 GeV
- z: 0.3 ~ 0.7
- M_m: 1.6~ 3.3 GeV



Tracking with GEM detectors

- 5 planes reconfigured from PVDIS GEM detectors (23 m^2)
- Total surface for this experiment ~ 18 m^2
- Need to build the first plane 1.15 m^2
- Electronics will be shared



	R_{min} (cm)	R_{max} (cm)	z (cm)	Status	PVDIS configuration (cm)
Chamber1	46	76	197	New	N/A
Chamber2	28	93	250	PVDIS C1	50-115
Chamber3	31.5	107.5	290	PVDIS C2	64-140
Chamber4	39	135	352	PVDIS C3	104-200
Chamber5	49	95	435	PVDIS C4	109-215
Chamber6	67	127	592	PVDIS C4	109-215

PAC 34 report

Particle Identification

- **Large angle side: 14.5^o – 22^o (Electron only)**
  - Momentum: 3.5 – 6.0 GeV/*c*
  - π/e < 1.5
  - Shashlyk calorimeter: (Pre-shower/Shower)
- **Forward angle side: 6.6^o – 12^o (Electron and Pion)**
  - Momentum: 0.9 – 7.0 GeV/*c*
  - Calorimeter: Pre-shower/Shower splitting
  - Light Gas Cherenkov for electron identification
  - Heavy Gas Cherenkov and TOF detectors for hadron identification

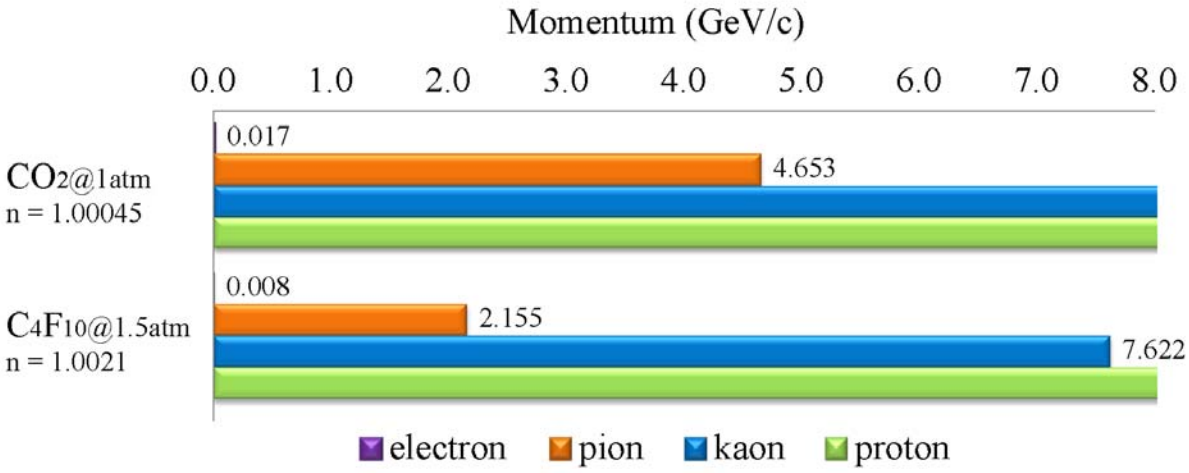
Hadron Identification

- **Momentum range: 0.9 – 7.0 GeV/*c***
- **Configuration for only pion identification**

Gas Cherenkov: CO_2@ 1 atm

n = 1.000585, 210 cm

N.P.E. ~ 17 (80:1 pion rejection)



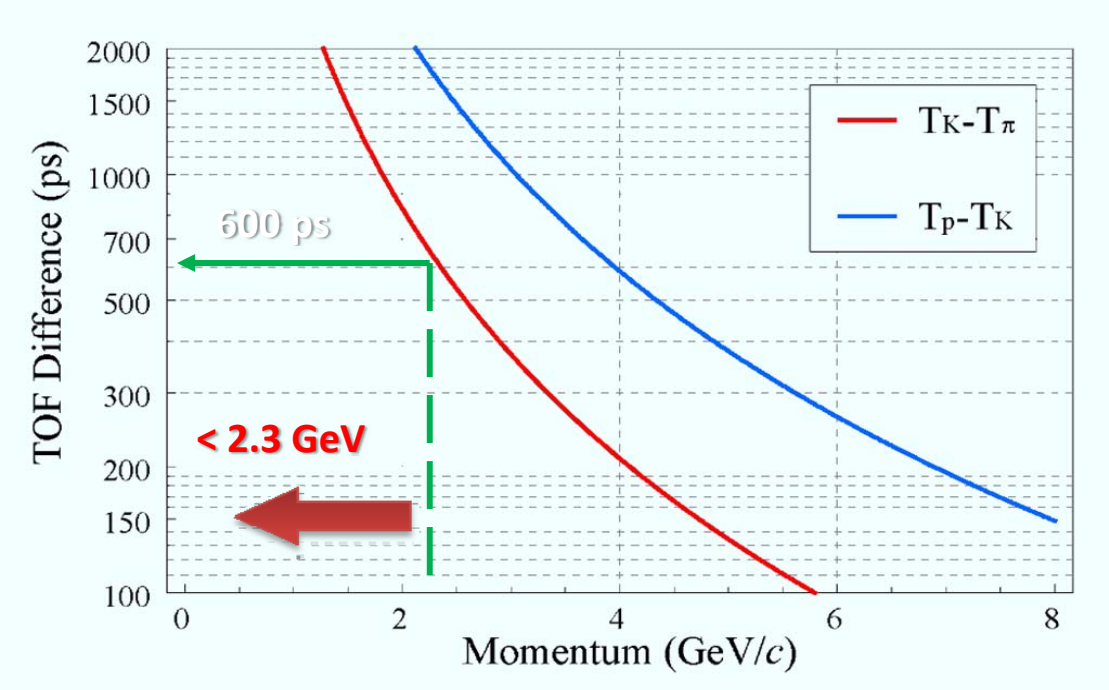
Heavy Gas Cherenkov: C_4F_{10}@1.5 atm

n = 1.0021, 80 cm

N.P.E ~ 25 (50:1 kaon rejection)

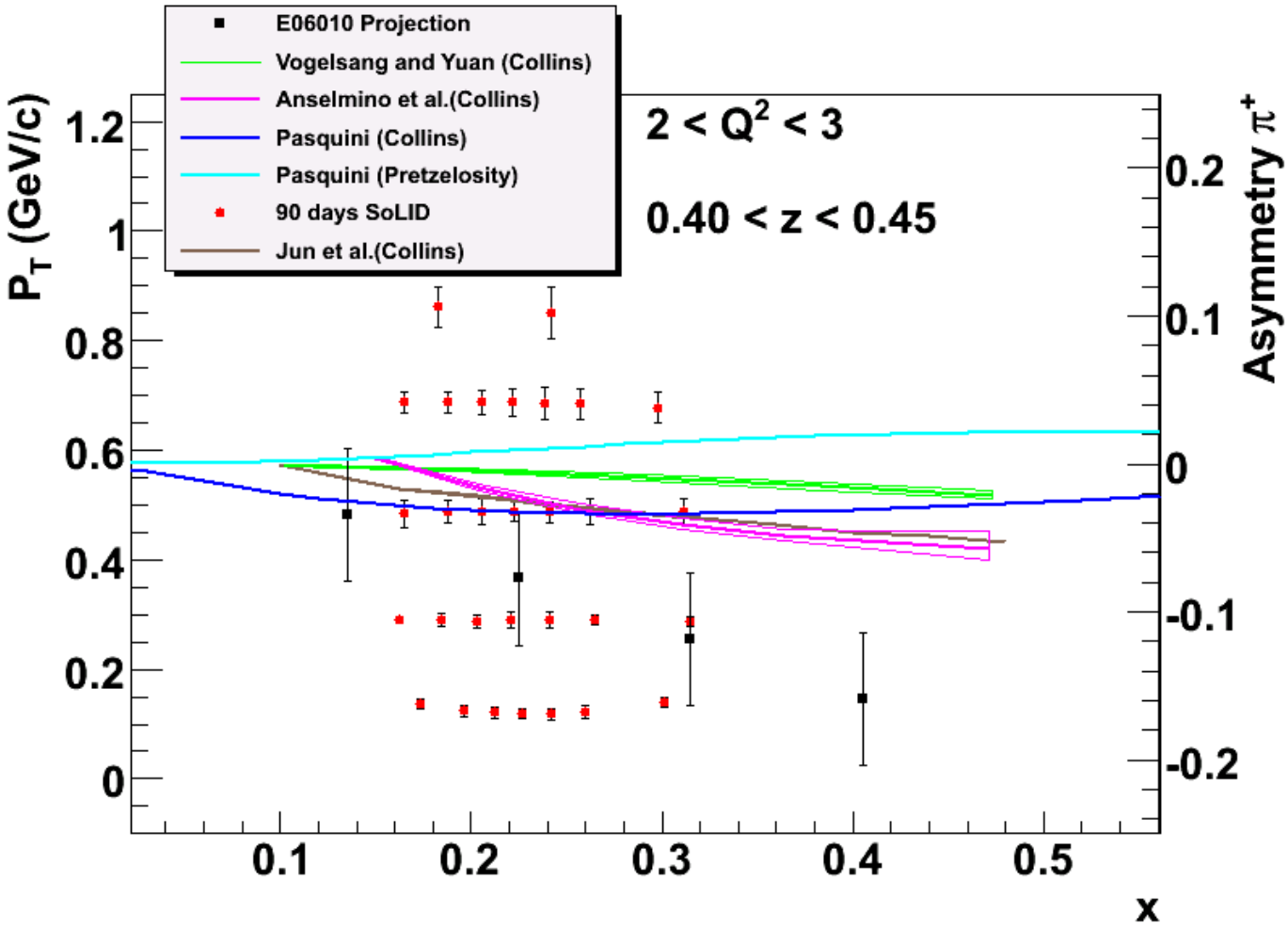
Time-of-Flight (MRPC)

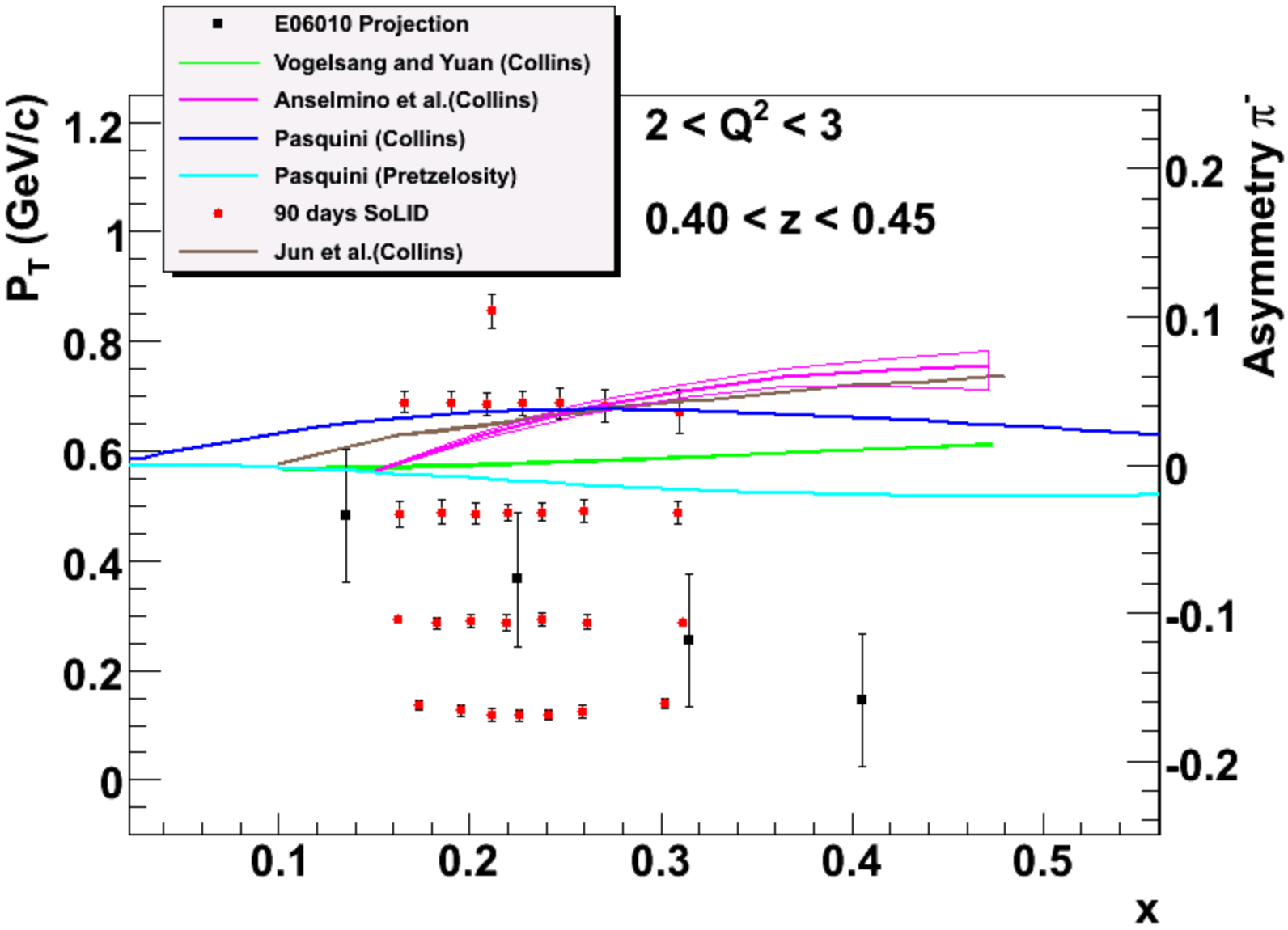
- **π/K separation up to 2.5 GeV/c**
  - assume 9 meter path-length: (20:1 kaon rejection at 2.5 GeV/c)
- **Can also help to suppress photon events**
  - **Multi-Resistive Plate Chamber**
  - **σ < 80ps**
  - **Rates > 0.28 kHz/mm²**
  - **Estimated rates: 0.1 kHz/mm²**



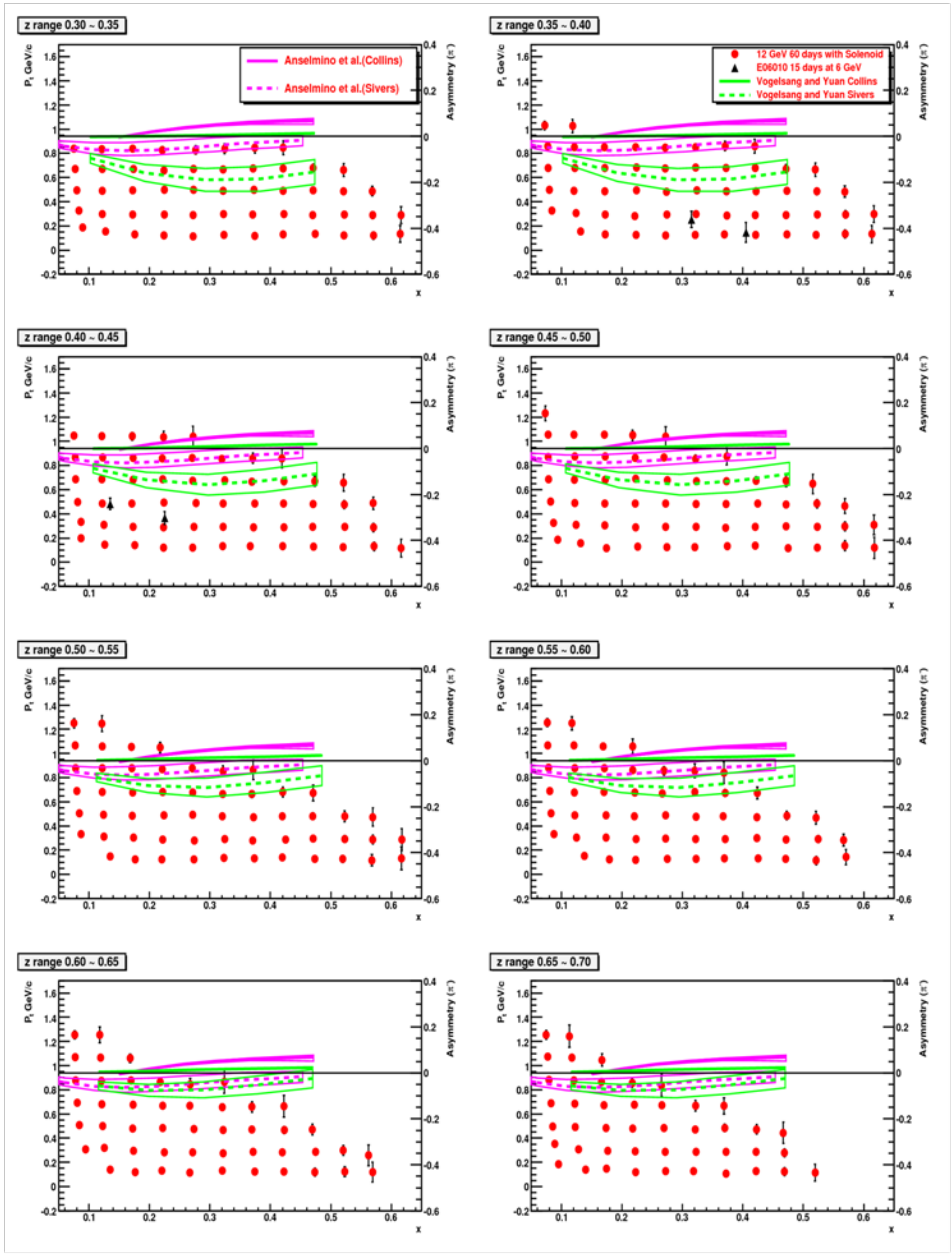
Projected Data

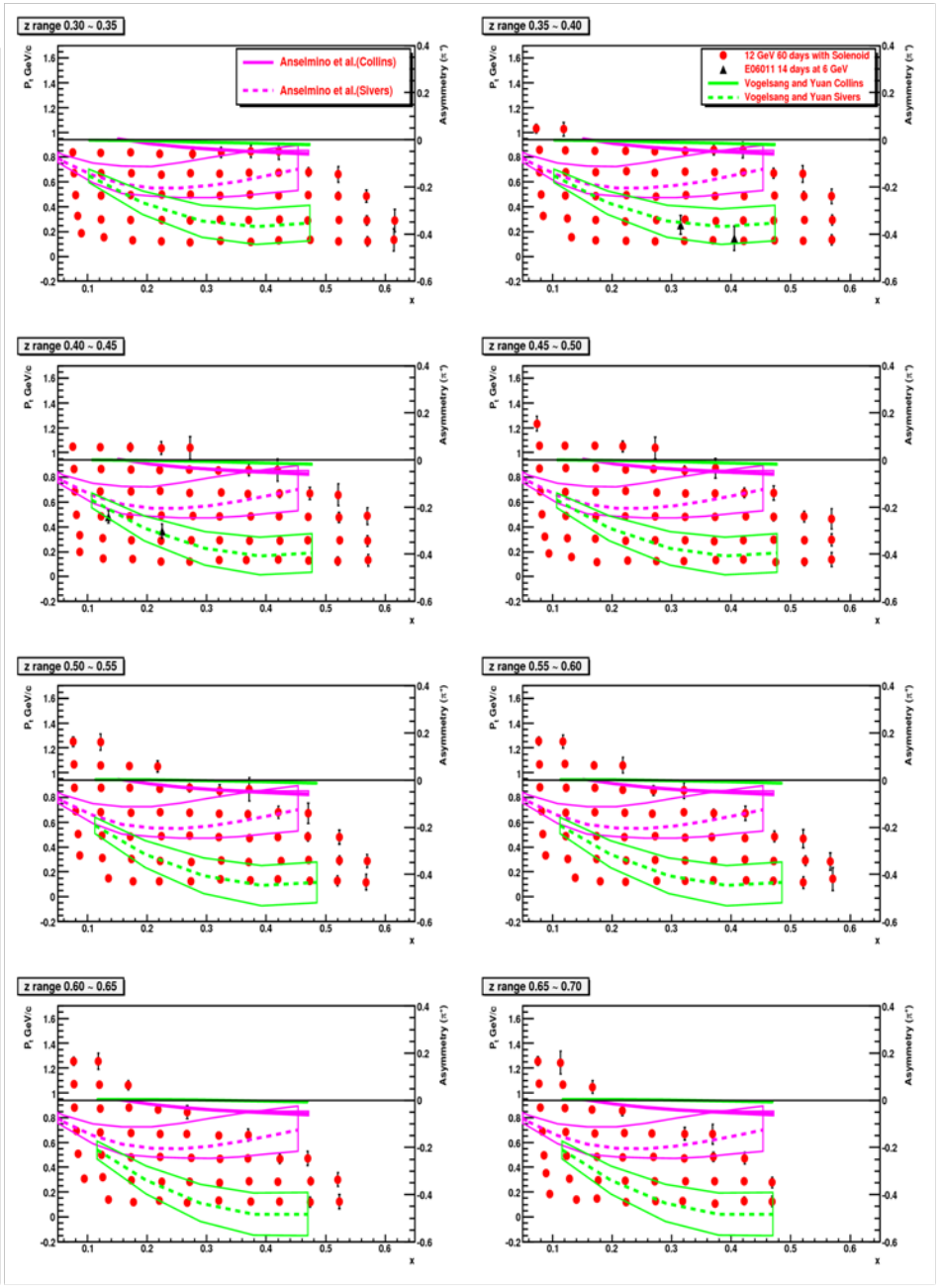
- Total 1400 bins in x, Pt and z for 11/8.8 GeV beam.
- z ranges from 0.3 ~ 0.7, only a sub-range of 11/8.8 GeV shown here.




E06010 Projection
Vogelsang and Yuan (Collins)
Anselmino et al.(Collins)
Pasquini (Collins)
Pasquini (Pretzelosity)
90 days SoLID
Jun et al.(Collins)
2 < Q2 < 3
0.40 < z < 0.45
PT (GeV/c)
Asymmetry π-
x
1.2
1
0.8
0.6
0.4
0.2
0
0.2
0.1
0
-0.1
-0.2
0.1
0.2
0.3
0.4
0.5

Power of SOLID





Responsibilities

- CO_2 gas Cerenkov detector: Temple U.
- Heavy Gas Cerenkov: Temple U.
- ECal: W&M, UMass, JLab, Rutgers, Syracuse
- GEM detectors:UVa, Miss State, W&M, Chinese Collaboration (CIAE, Huangshan U, PKU, LZU, Tsinghua, USTC), UKY, Korean Collaboration (Seoul National U)
- Scintillator: Chinese Cobllaboration, Duke
- MRPC: Tsinghua Univ., Duke
- Electronics: JLab
- DAQ: LANL, UVa and JLab
- Magnet: JLab and UMass
- Simulation: JLab and Duke

Blue: common with PVDIS

Black: part in common with PVDIS

Red: This experiment only

Large overlap between this collaboration and PVDIS:
Collaboration has extensive experience with various detectors

Summary

- ***The study of chiral-odd quark distribution (transversity, Sivers function, …) and fragmentation function (Collins function): an exciting, rapidly developing frontier, worldwide effort***
  - *JLab is becoming a major player, more so with 12 GeV upgrade and the approval of the SoLID experiment*

- ***11 GeV with Solenoid and polarized ^{3}He target allows for***
  - *Precision 4-d mapping of neutron Collins, Sivers, and pretzelocity asymmetries, and the extraction of transversity, Sivers and pretzlocity distribution functions*

- ***Together with world proton results provides determination of tensor charge of d quark***
  - *Provide benchmark test of Lattice QCD calculations*

Supported in part by U.S. Department of Energy under contract number DE-FG02-03ER41231