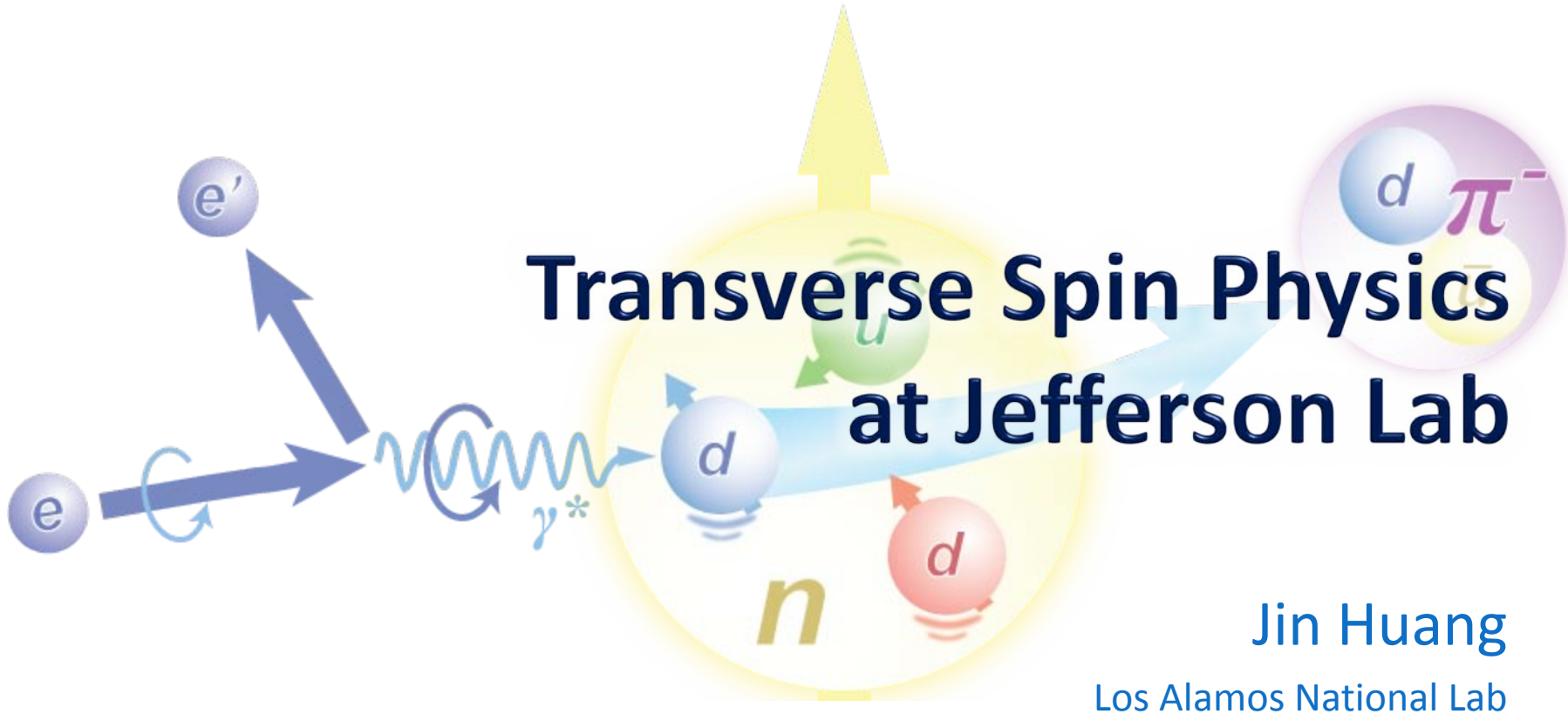


Transverse Spin Physics at Jefferson Lab

Jin Huang

Los Alamos National Lab

RBRC Forward Physics Workshop

Los Alamos NATIONAL LABORATORY EST. 1943

Jefferson Lab

Transverse Momentum Dependent (TMD) Parton Distributions

- TMD PDFs link
  - Intrinsic motion of partons
  - Parton spin
  - Spin of the nucleon
- Multi-Dimension structure
  - Imaging the 3D motion of the quark
  - Probes orbital motion of quarks
- A new phase of study, fast developing field
  - Great advance in theories (factorization, models, Lattice ...)
  - Experimentally, not systematically studied until recent years
  - Complementary study between CEBAF and RHIC

Leading-Twist TMD PDFs

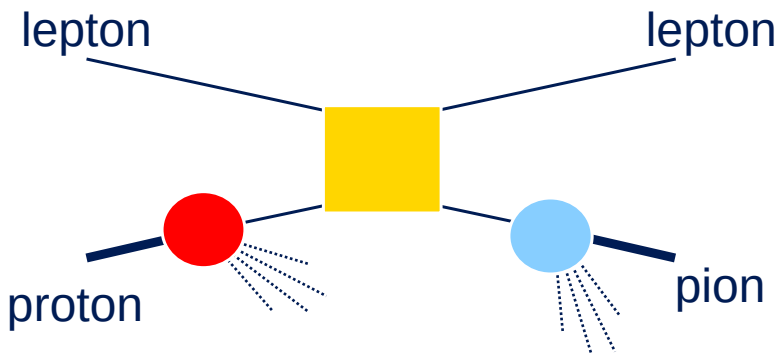
Nucleon Spin

Quark Spin

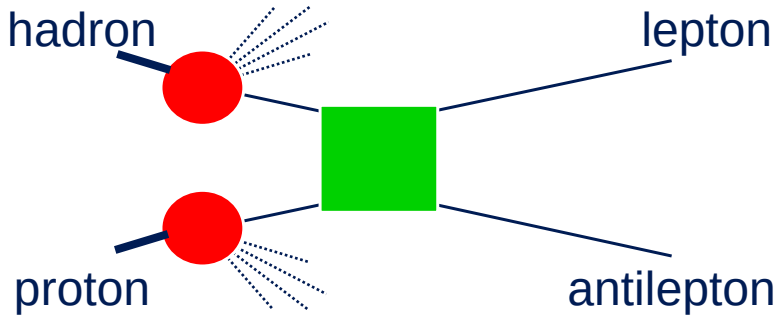
Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	f_1 =		$h_1^{\perp}$ = – Boer-Mulders
L		g_1 = – Helicity	$h_{1L}^{\perp}$ = – Worm Gear (Kotzinian-Mulders)
T	$f_{1T}^{\perp}$ = – Sivers	g_{1T}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

: Survive trans. momentum integration

Access TMDs through Hard Processes



SIDIS

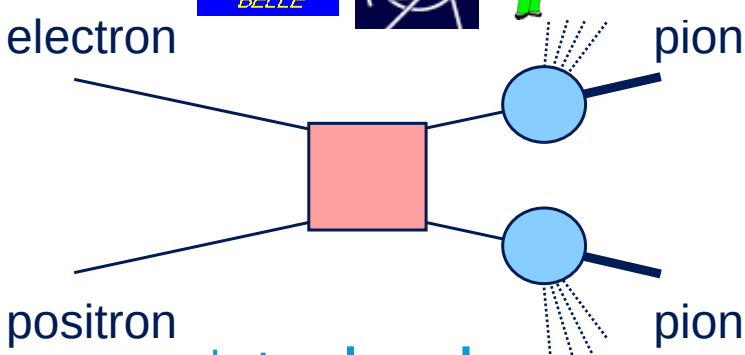


Drell-Yan, …

Partonic scattering amplitude

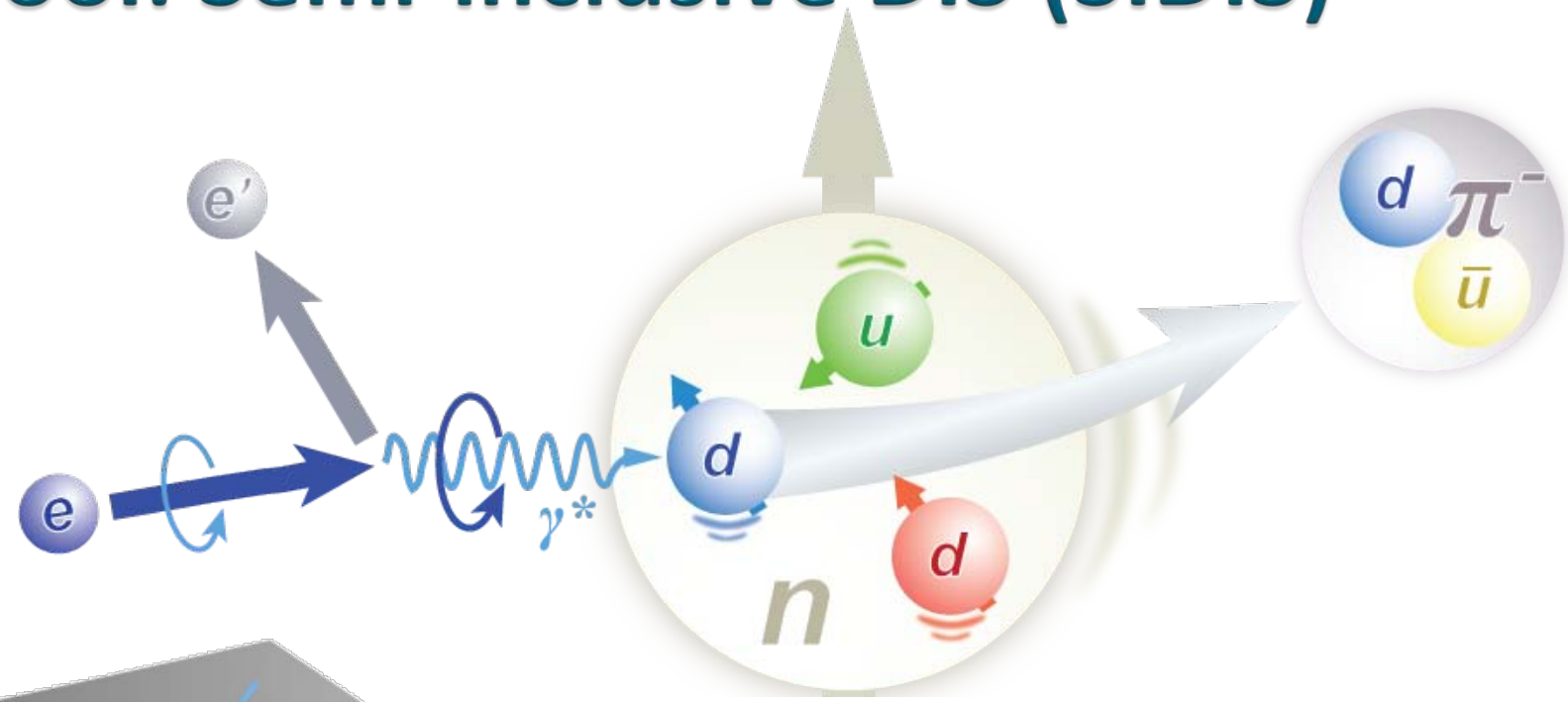
Fragmentation amplitude

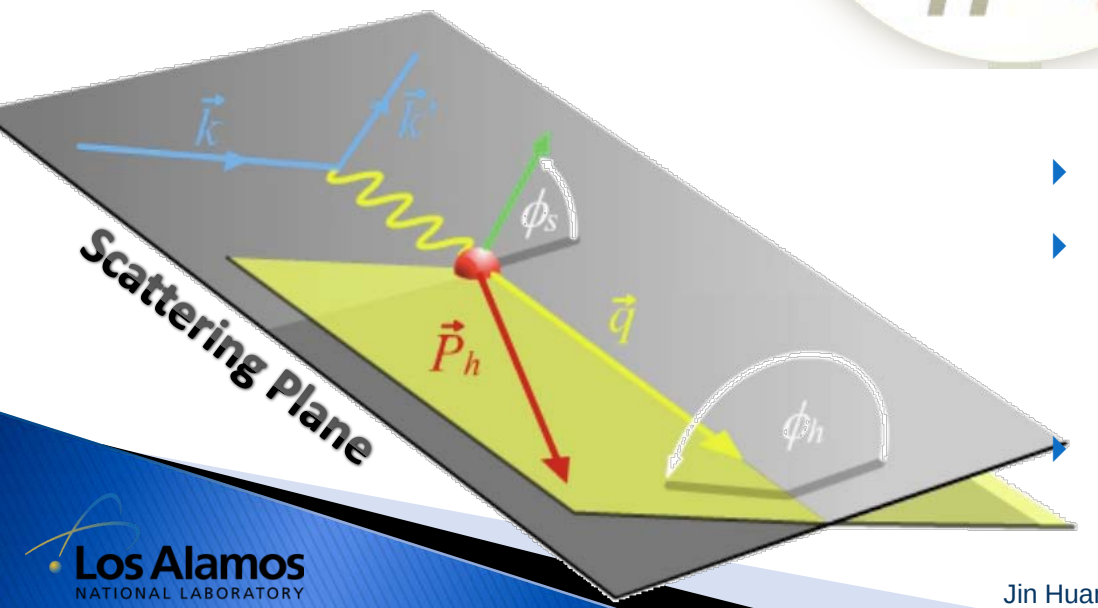
Distribution amplitude



e^-e^+ to hadrons

Tool: Semi-inclusive DIS (SIDIS)





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

TMDs in SIDIS Cross Section

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

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

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

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

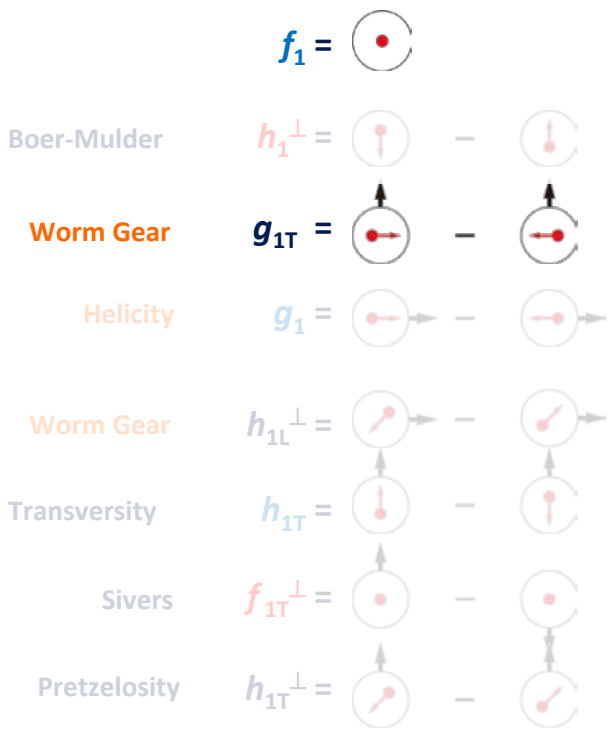
$$+ S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$

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

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

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

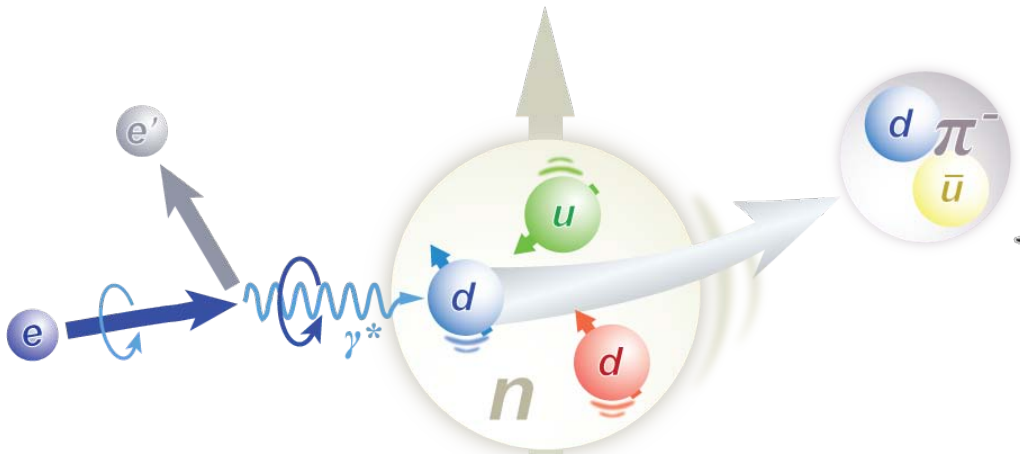
$$+\varepsilon\sin(3\phi_h-\phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]\}$$

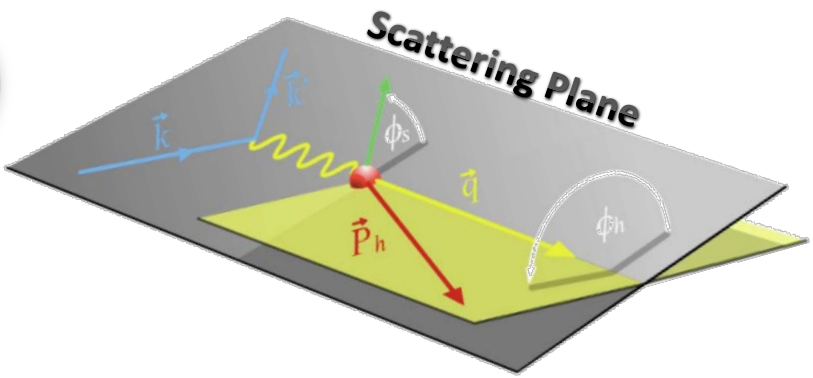


S_L, S_T: Target Polarization; λ_e: Beam Polarization

Accessing TMD through SIDIS e.g. experimental study of g_{1T}

- Double Beam-Target Spin Asymmetry (DSA) in SIDIS with transversely polarized target: A_{LT}





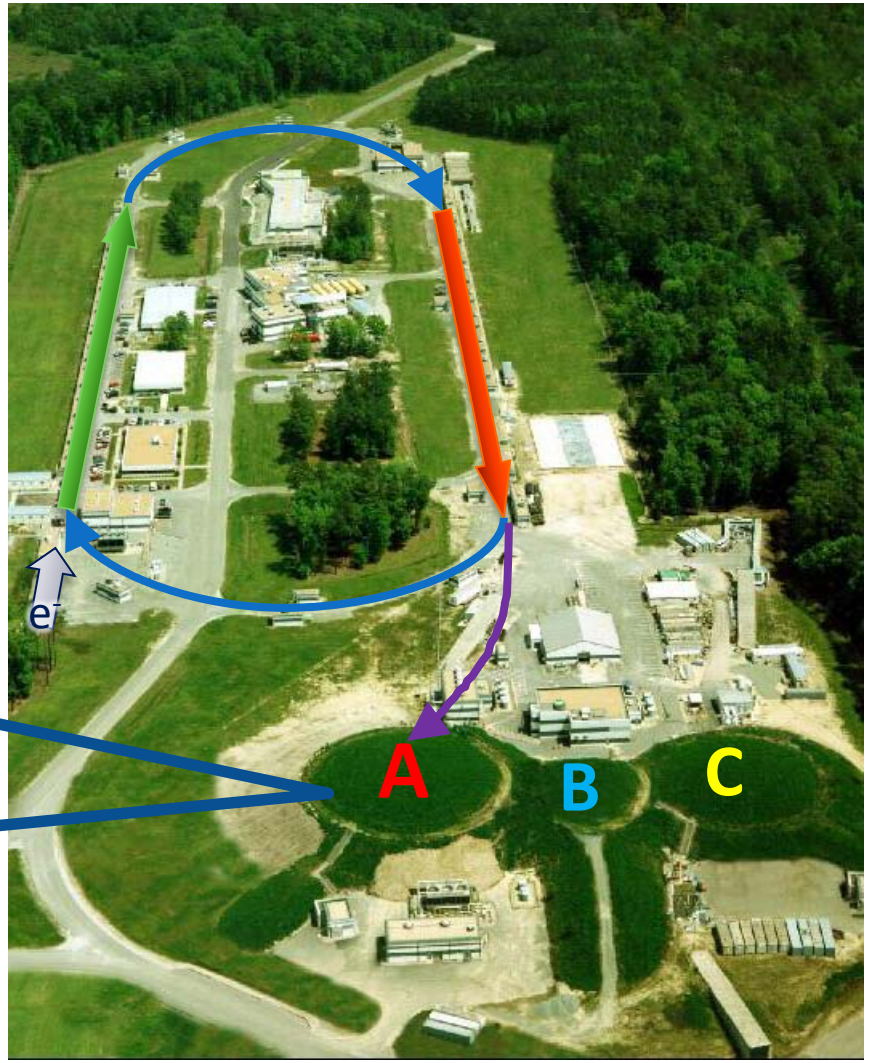
$$A_{LT}^{\cos(\phi_h-\phi_s)} \equiv 2\frac{\int d\phi_s^h\left(d\vec{\sigma}-d\overleftarrow{\sigma}\right)\cos(\phi_h-\phi_s)}{\int d\phi_s^h\left(d\vec{\sigma}+d\overleftarrow{\sigma}\right)}$$

$$\propto g_{1T}^q \otimes D_{1q}^h$$

- Technically, azimuthal amplitude in asymmetry extracted through methods considering acceptance and luminosity corrections, including
  - azimuthal asymmetry fits
  - Maximum likelihood analysis

Jefferson Lab Overview

- Newport News, Virginia
- Linear accelerator provides continuous polarized electron beam
  - $E_{\text{beam}} = 6\ \text{GeV}$
  - $P_{\text{beam}} = 85\%$
- 3 experimental halls A, B and C



CEBAF @ JLab Today

- Superconducting recirculating electron accelerator
  - maximum energy 6 GeV
  - maximum current 200 uA
  - electron polarization 85%
- Equipment in 3 halls (simultaneous operation)

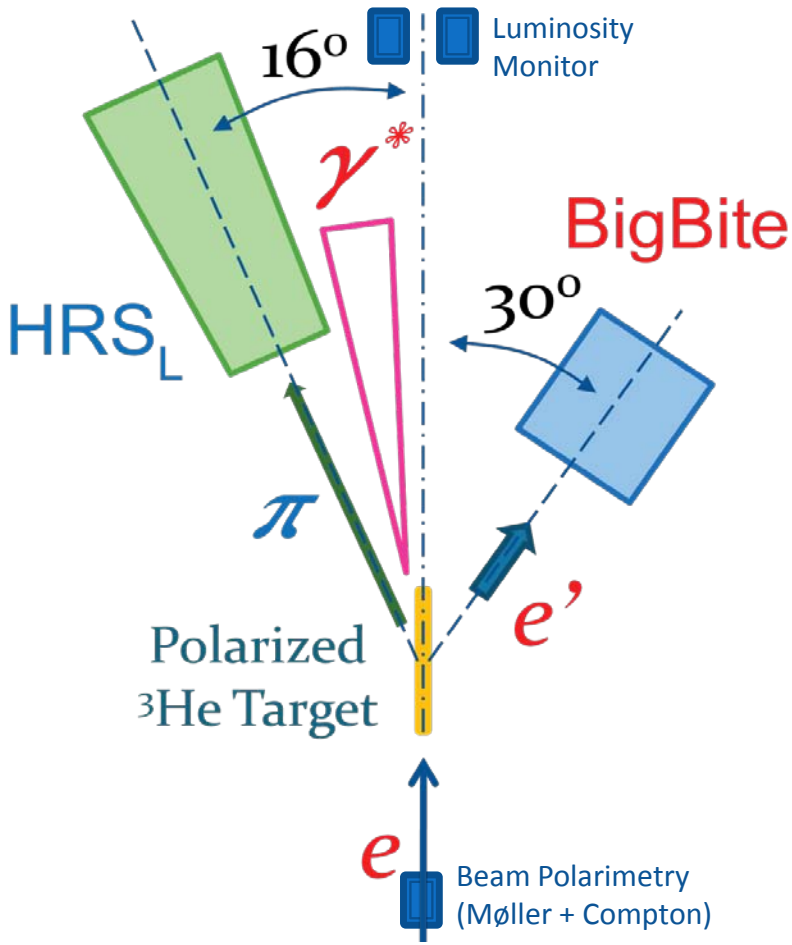
	L[$cm^{-2}s^{-1}$]	(pol.)
A: 2 High Resolution Spectrometers	10^{39}	(10^{36})
B: Large Acceptance Spectrometer	10^{34}	(10^{34})
C: 2 spectrometers and dedicated devices	10^{39}	(10^{35})

- JLab and User Community
  - ~600 JLab employees
  - ~2000 users from ~300 institutions, ~40 countries
  - ~ 1/4-1/3 of the nuclear physics PhDs in US
- Experiment scale: ~100 collaborators (10-20 core), ~run for few months

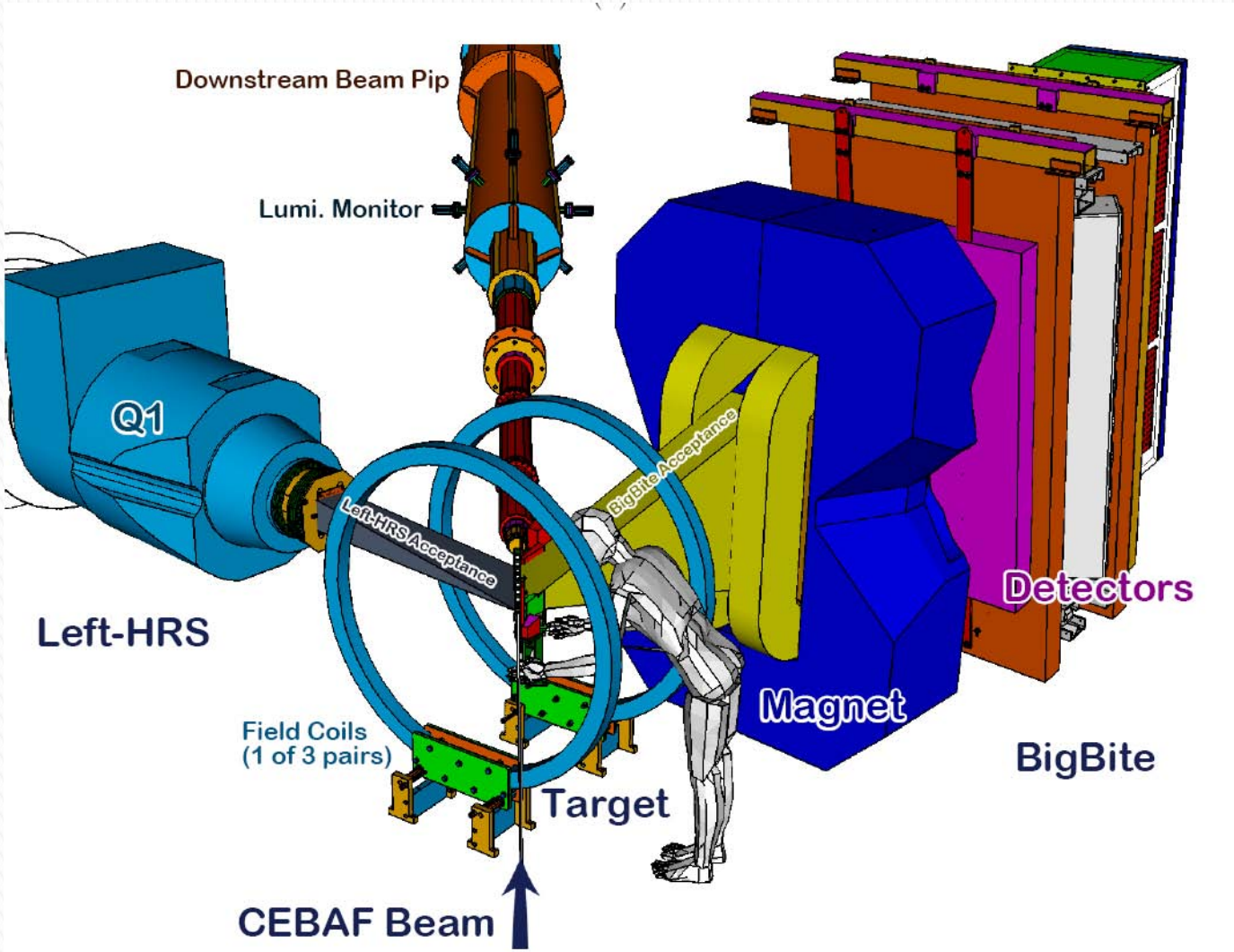
First exploring of TMD using polarized He3 Target

E06-010 6-GeV Transversity Experiment

- Successful data taking 2008-09
- Polarized electron beam
  - With 30 Hz helicity reversal
- Polarized ^{3}He target
- BigBite at 30º detect electron
  - Dipole magnet, P_e = 0.6 ~ 2.2 GeV/c
  - MWDC/shower-preshow/scitillator
- HRS_L at 16º detect hadron
  - QQDQ config, P_h = 2.35 GeV/c
  - Scintillator/drift chamber/Cherenkov



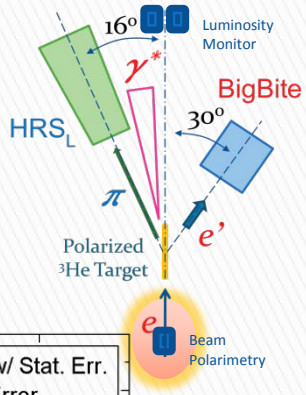
Rest of Left-HRS ~25 m



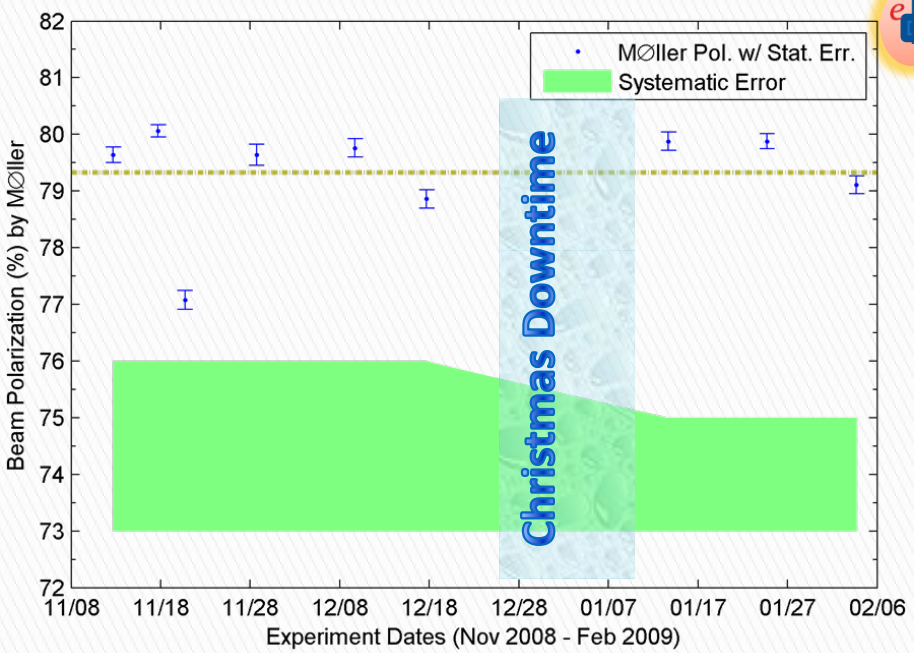
Experiment Setup

Only Small Part of Left-HRS and He-3 Target is Shown

Polarized Electron Beam



- Overall polarization
  <P>=76.8 +- 3.5%
- Fast beam helicity reversal at 30 Hz
- Beam charge balance between two helicity states

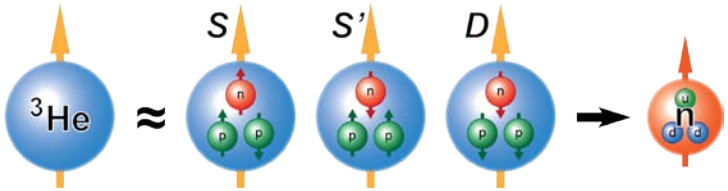


- Two method cross check
  - Moller polarimetry
  - Compton polarimetry

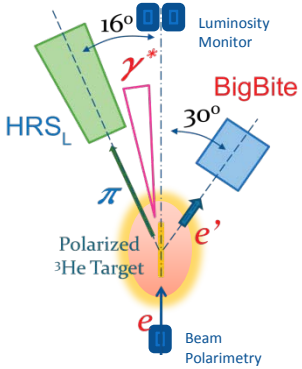
Polarized beam at Jefferson Lab is crucial

Polarimetery

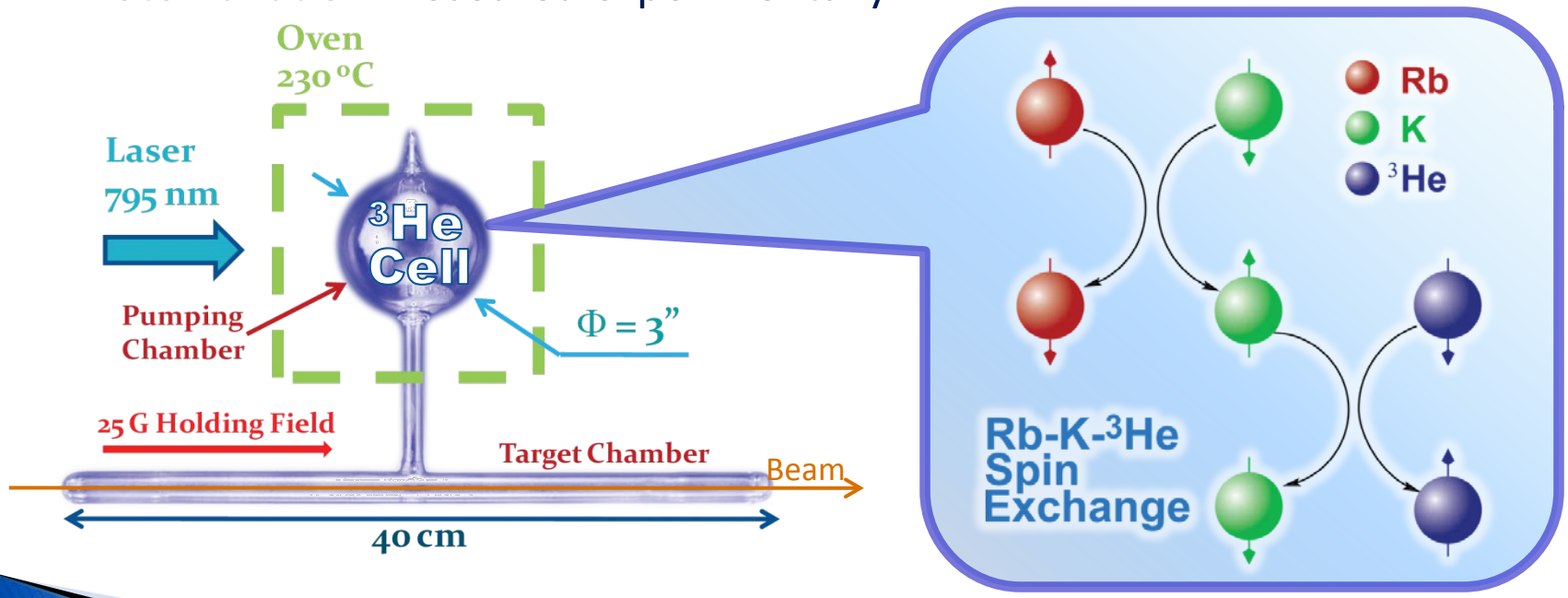
Polarized ^{3}He Target



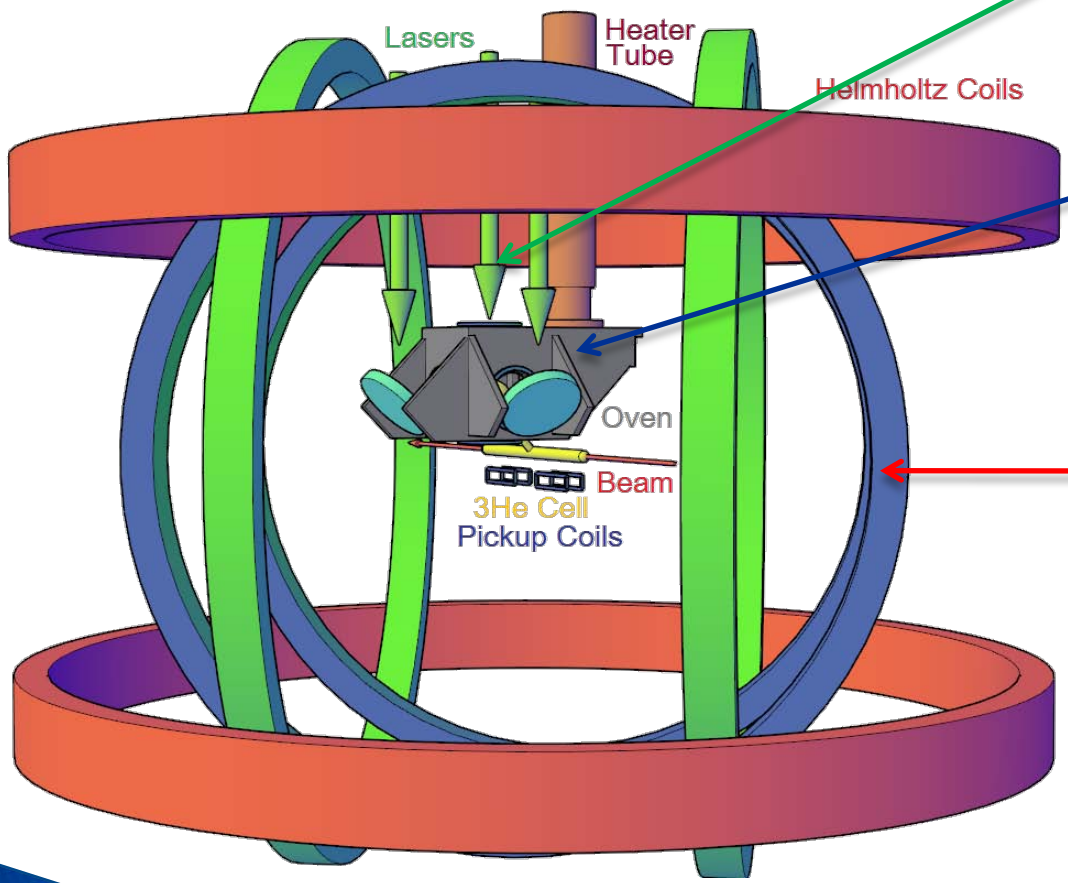
~90% ~1.5% ~8%

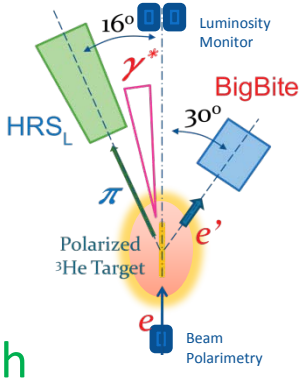


- High Luminosity polarize target: $L(n) = 10^{36}$ cm^{-2} s^{-1}(achieved), 10^{37} cm^{-2} s^{-1} (R&D)
- Compact size: No cryogenic support needed
- Proton dilution measured experimentally



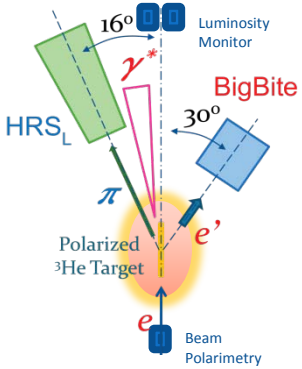
Highlights of Target Setup



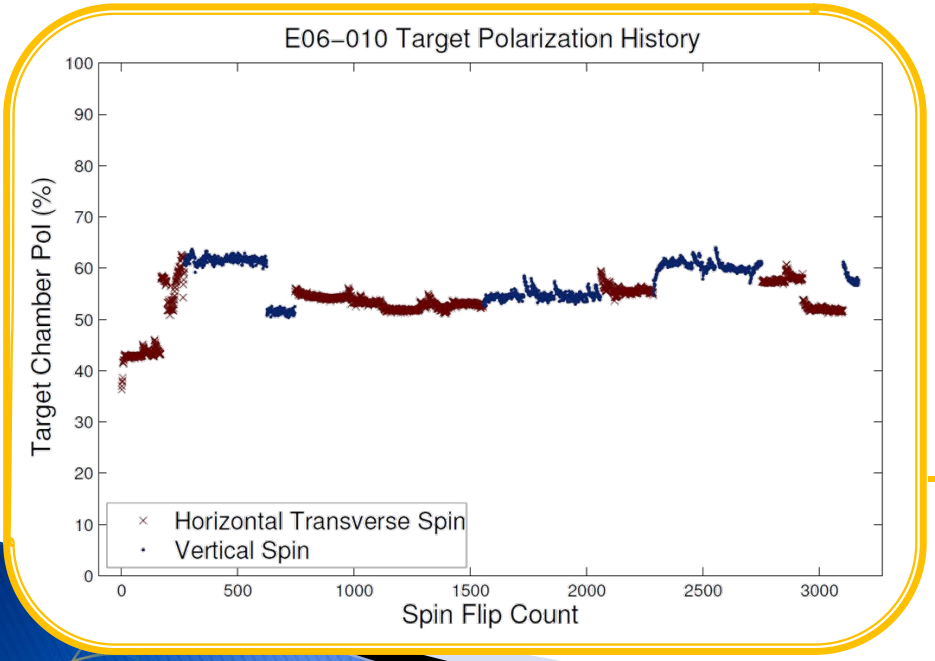


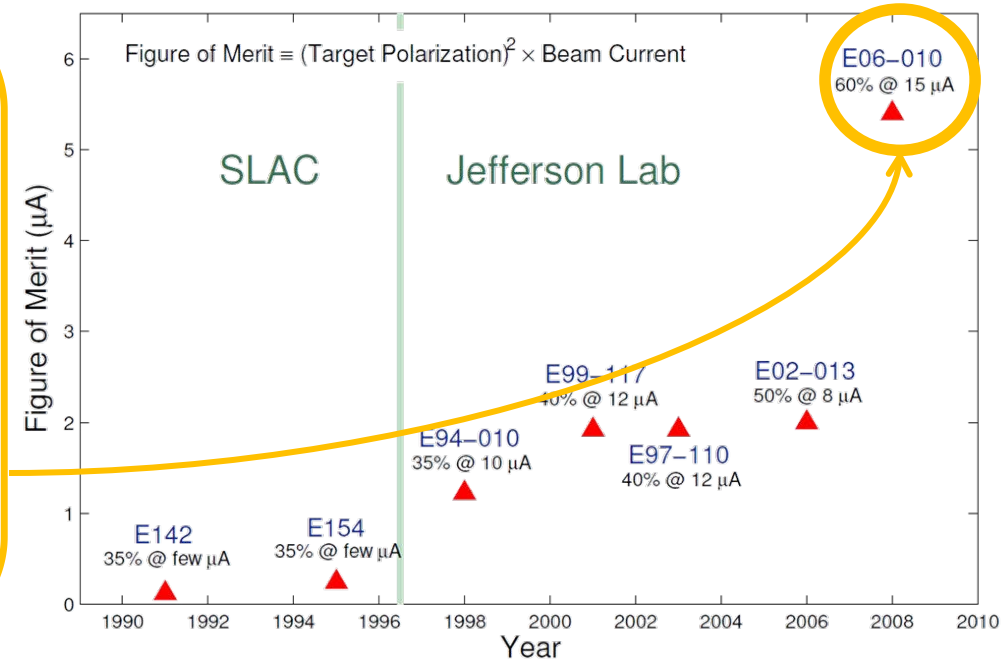
- New laser
  - Narrow line width
  - ^{3}He ↑P/P ~30%
- New optics and oven
  - Polarizing and polarimetery at 3 directions
- Holding magnet field
  - 3D field hold spin to any direction
- A smart target
  - Flip ^{3}He spin every 20min
  - $<10^{-3}$ failure rate
  - Auto analysis, log and early warnings

Performance of ^{3}He Target

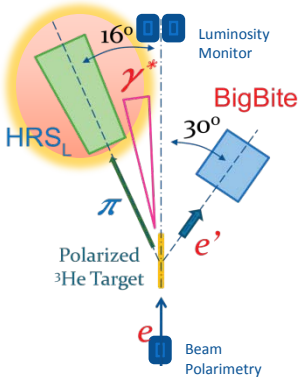


- High luminosity: $L(n) = 10^{36}$ cm^{-2} s^{-1}
- Record high 50-65% polarization in beam with automatic spin flip / 20min
- <P> = 55.4% ± 0.4% (stat. per spin state) ± 2.7 % (sys.)

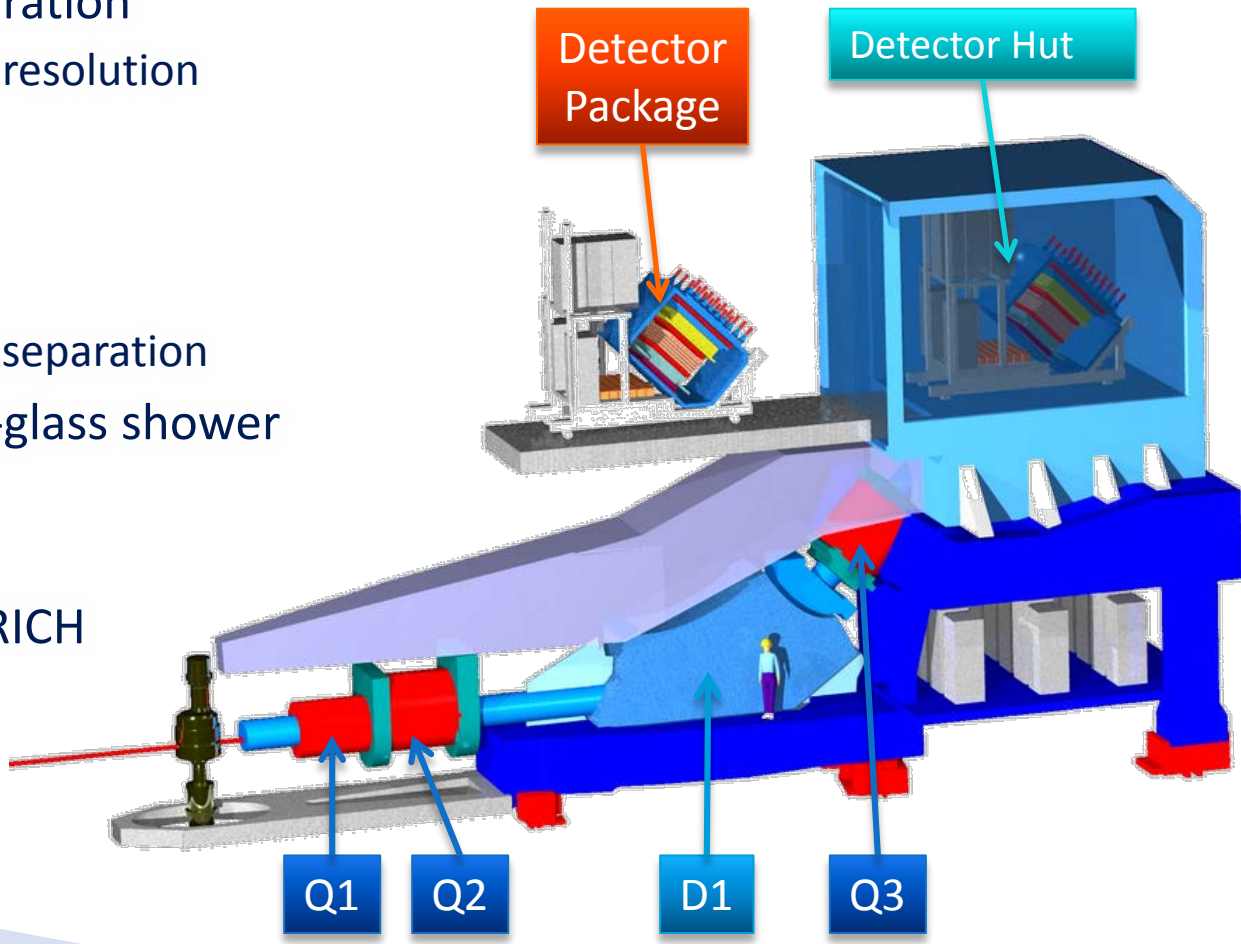




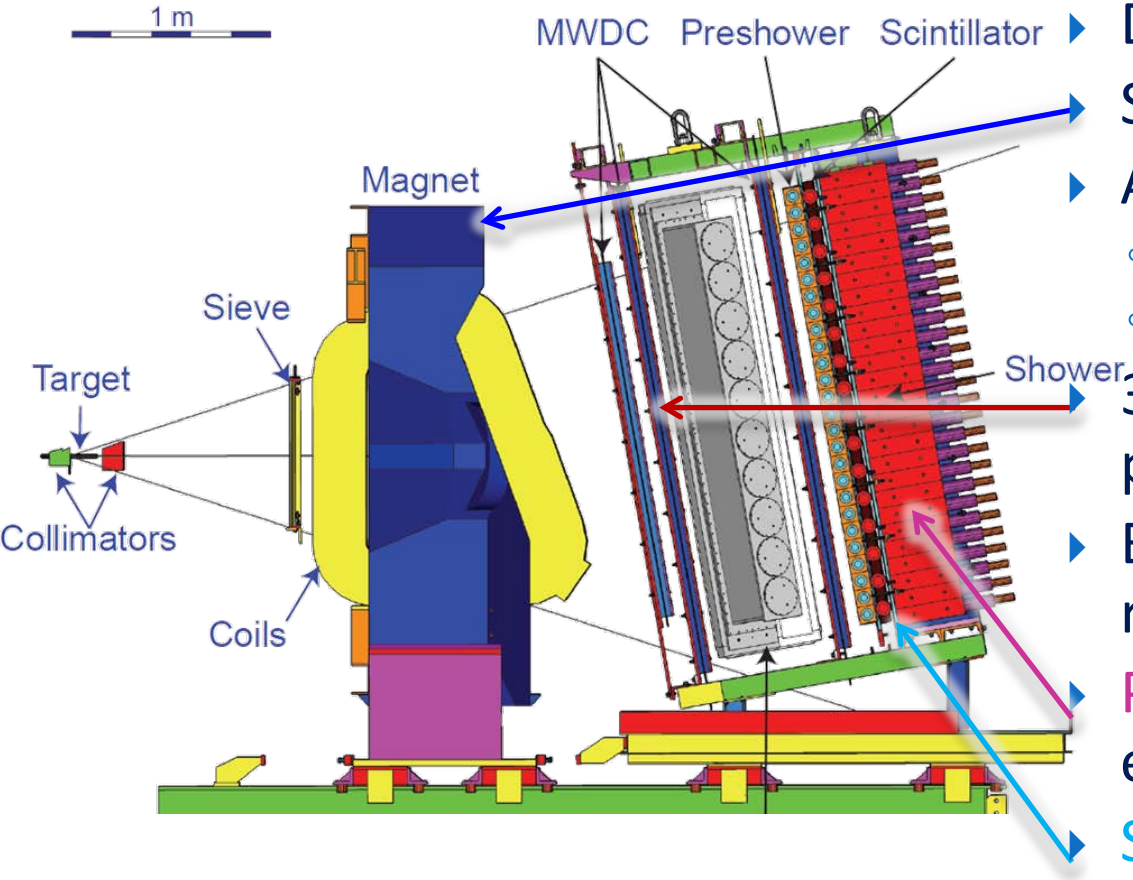
High Resolution Spectrometer (HRS)

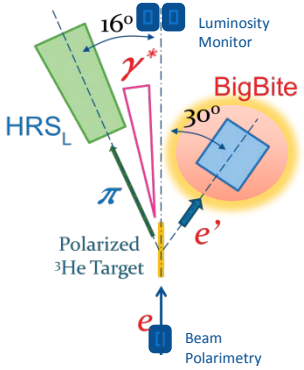


- HRS$_L$ to detect hadrons of p_h = 2.35 GeV
- QQDQ magnet configuration
  - Very high momentum resolution
- Drift chambers
  - Tracking
- Scintillator planes
  - Trigger & Timing, pi/p separation
- Gas Cherenkov & lead-glass shower detectors
  - e/hadron separation
- Aerogel Cherenkov & RICH
  - π/K separation

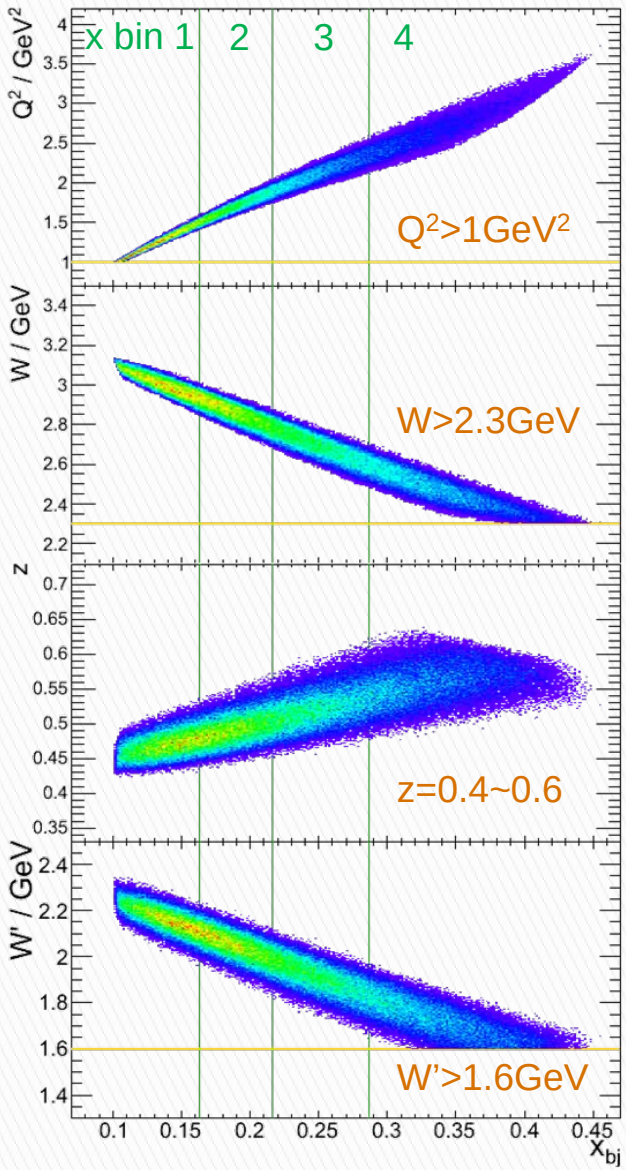


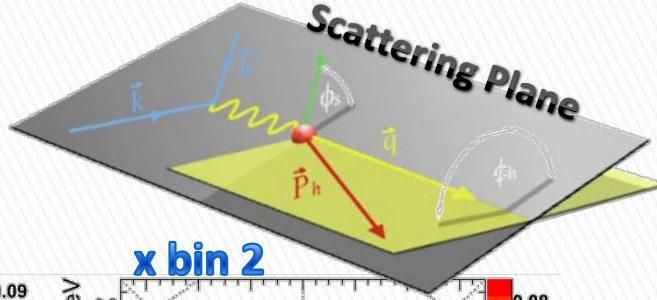
BigBite Spectrometer

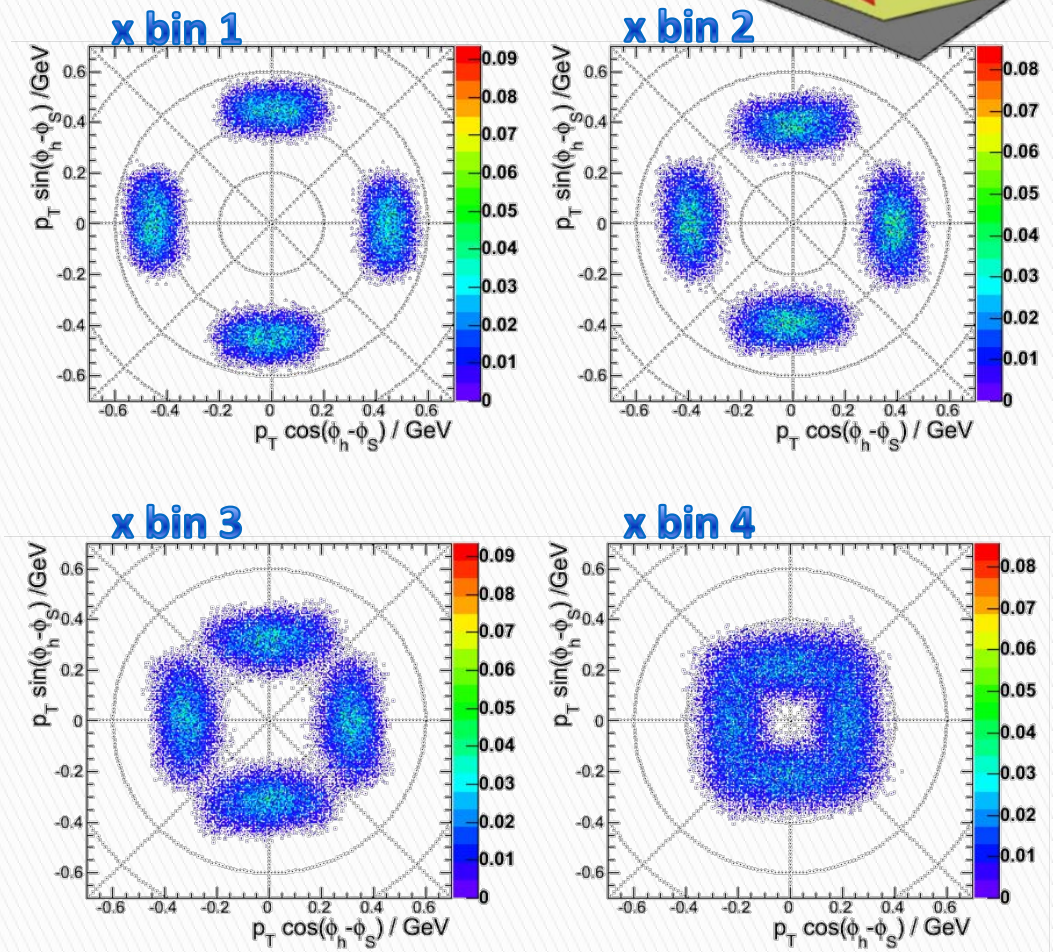




- Detects electrons
- Single dipole magnet
- A "big bite" of acceptance
  - $\Delta\Omega = 64$ msr
  - P : 0.6 ~ 2.2 GeV/c
- 3 wire chambers: 18 planes for precise tracking
- Bipolar momentum reconstruction
- Pre-shower and shower for electron PID
- Scintillator for coincidence with left HRS



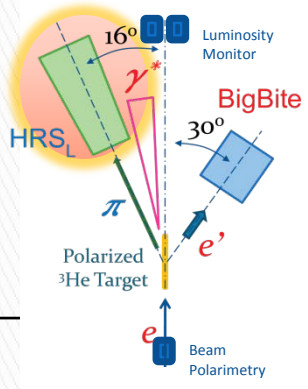


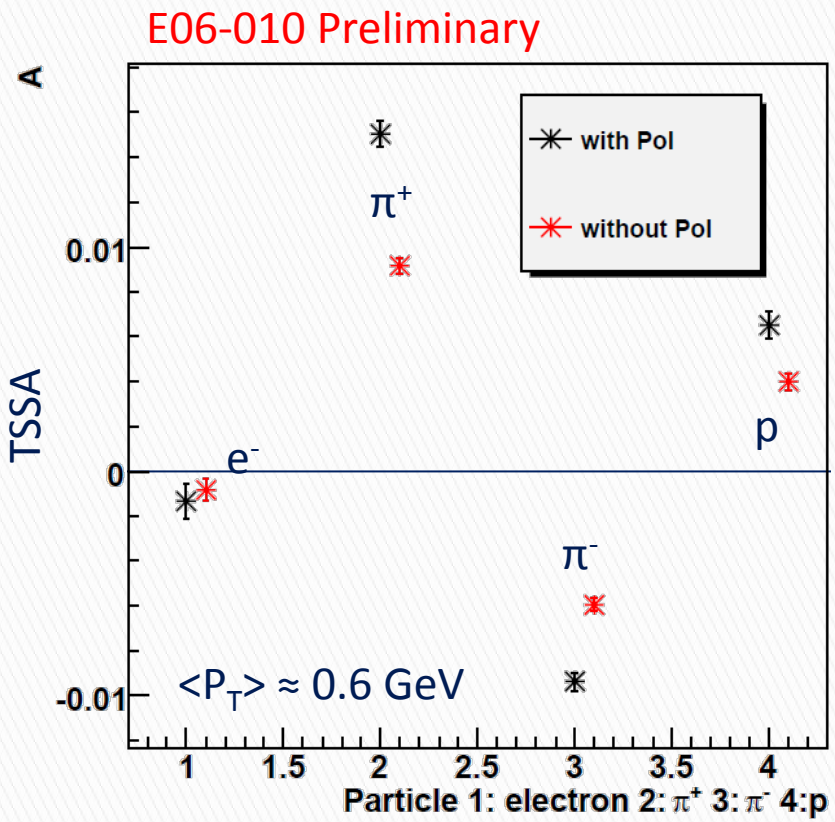


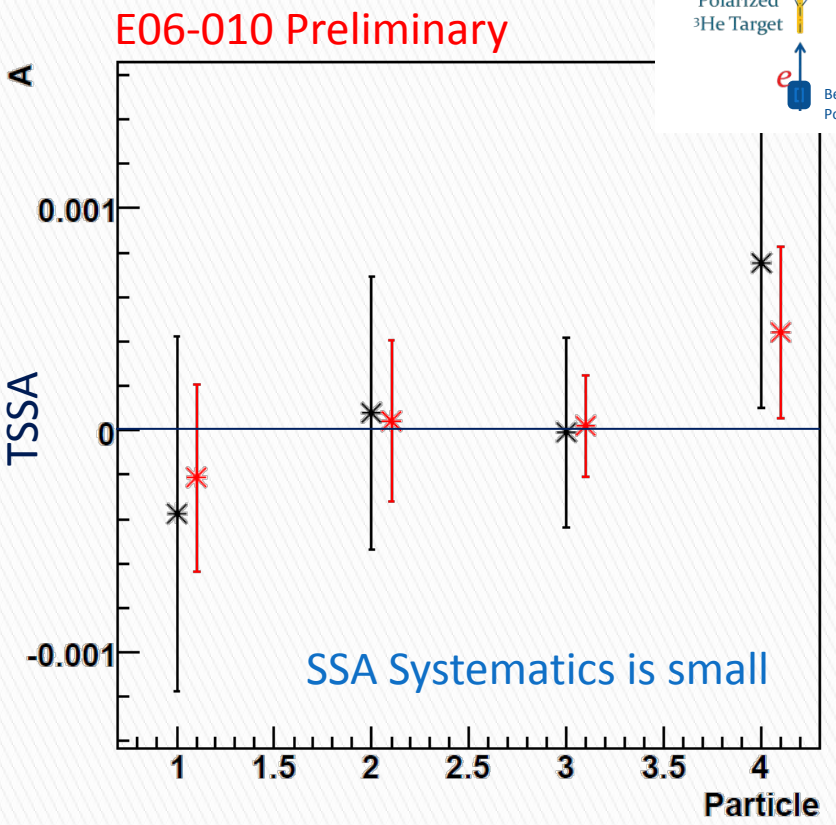
Kinematics coverage

p_T & ϕ_h- ϕ_S coverage

e ^{3}He → h X, Target SSA



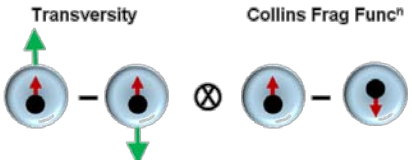




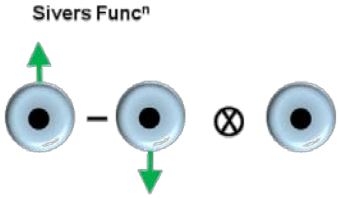
Left-right asymmetry

Spin parallel to P_h
(Sys. check, $A=S_T \times P_h=0$)

SSA Results on Neutron

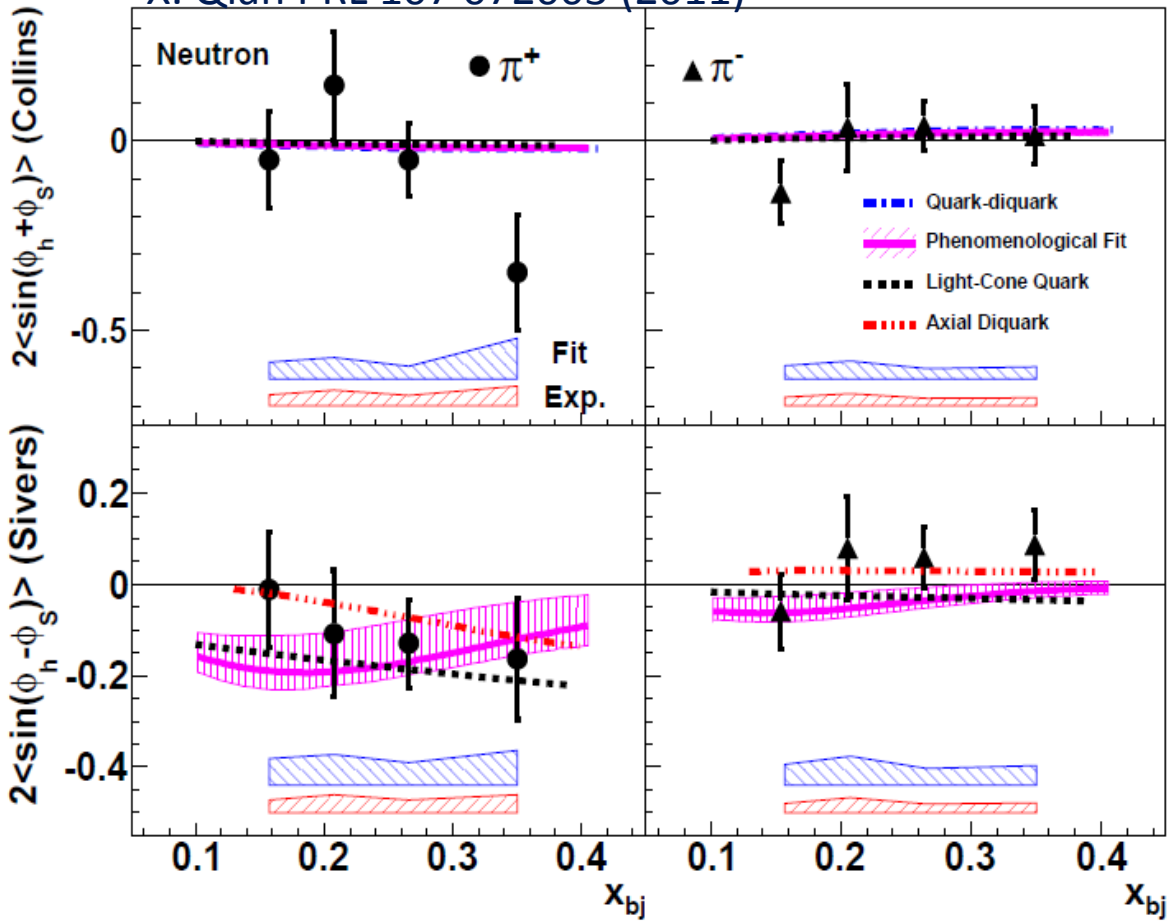
- 

  Sizable Collins π^+ asymmetries at x=0.34?
  - Sign of violation of Soffer's inequality?
  - **Data are limited by stat. Needs more precise data!**

- 

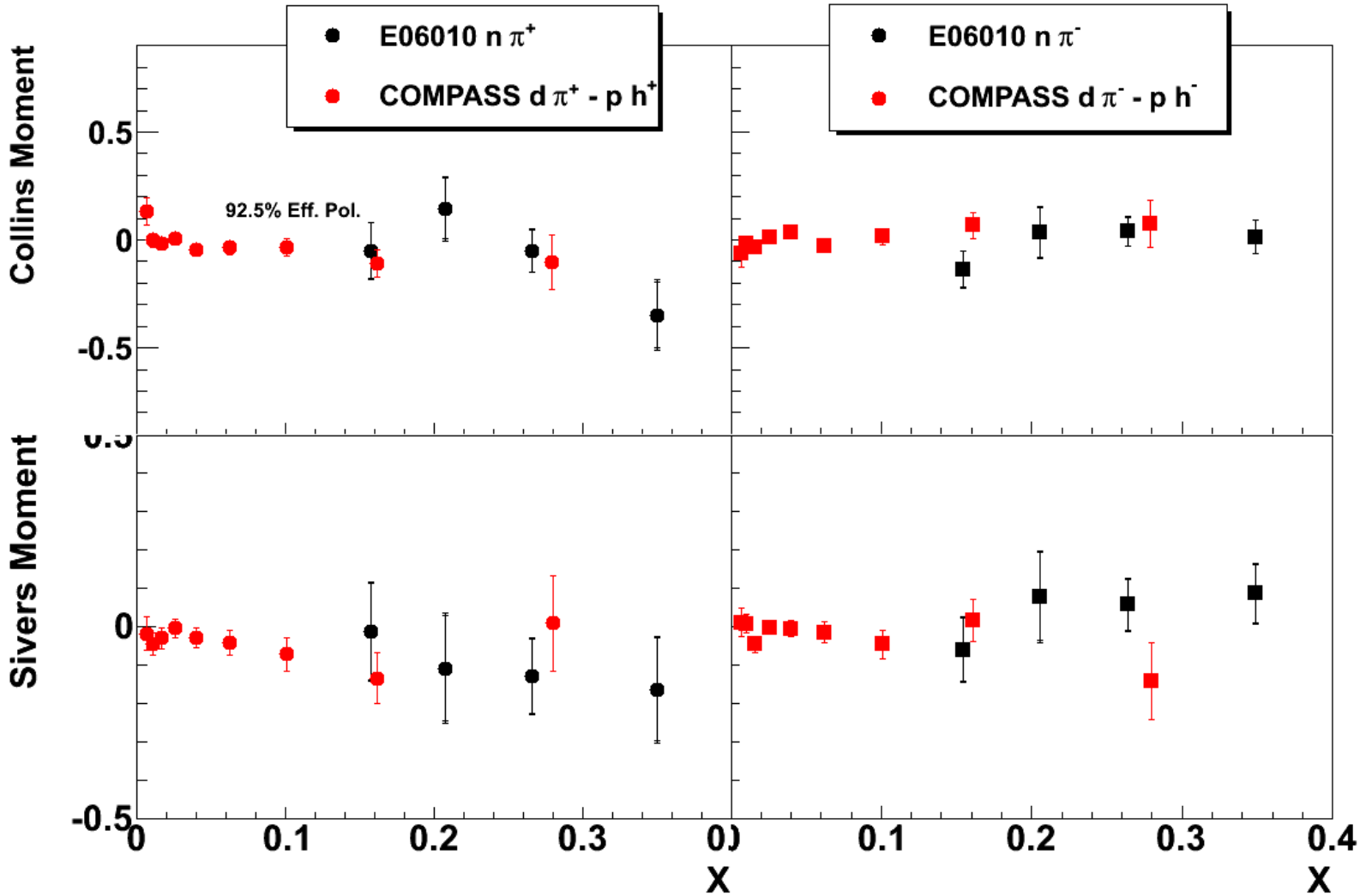
  Negative Sivers π^+ Asymmetry
  - Consistent with HERMES/COMPASS
  - **Independent demonstration of negative d quark Sivers function.**

X. Qian PRL 107 072003 (2011)



Model (fitting) uncertainties shown in blue band.

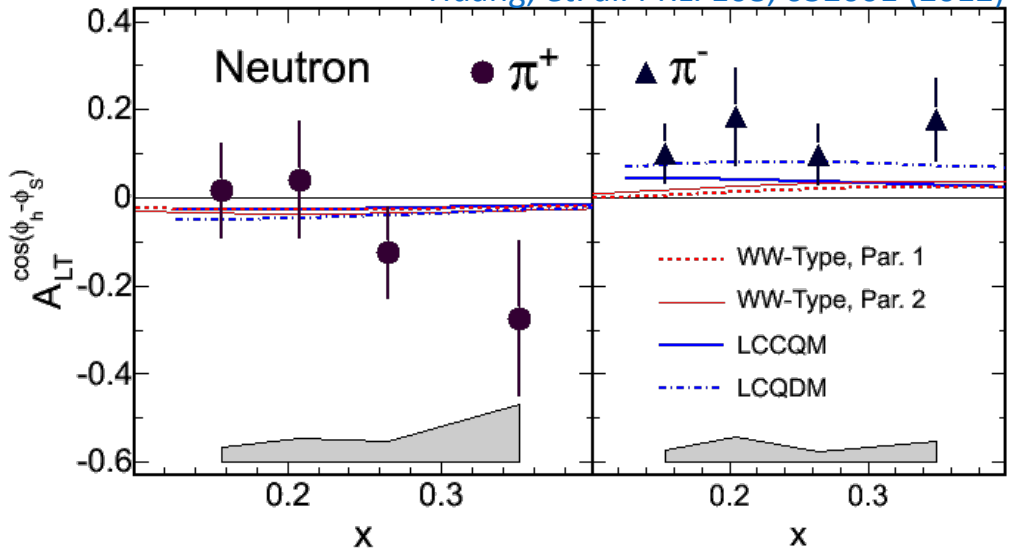
Best Measurements on Neutron at High x



Neutron A_{LT}

- Access g_{1T} =
- Dominated by real part of interference between L=0 (S) and L=1 (P) states
  - Imaginary part -> Sivers effect
- No GPD correspondence

Huang, et. al. PRL. 108, 052001 (2012)



- Consistent with models in signs
- Suggest larger asymmetry, possible interpretations:
  - Larger quark spin-orbital interference
  - different P_T dependence
  - larger subleading-twist effects

JLab Polarized Proton/Deuteron Target

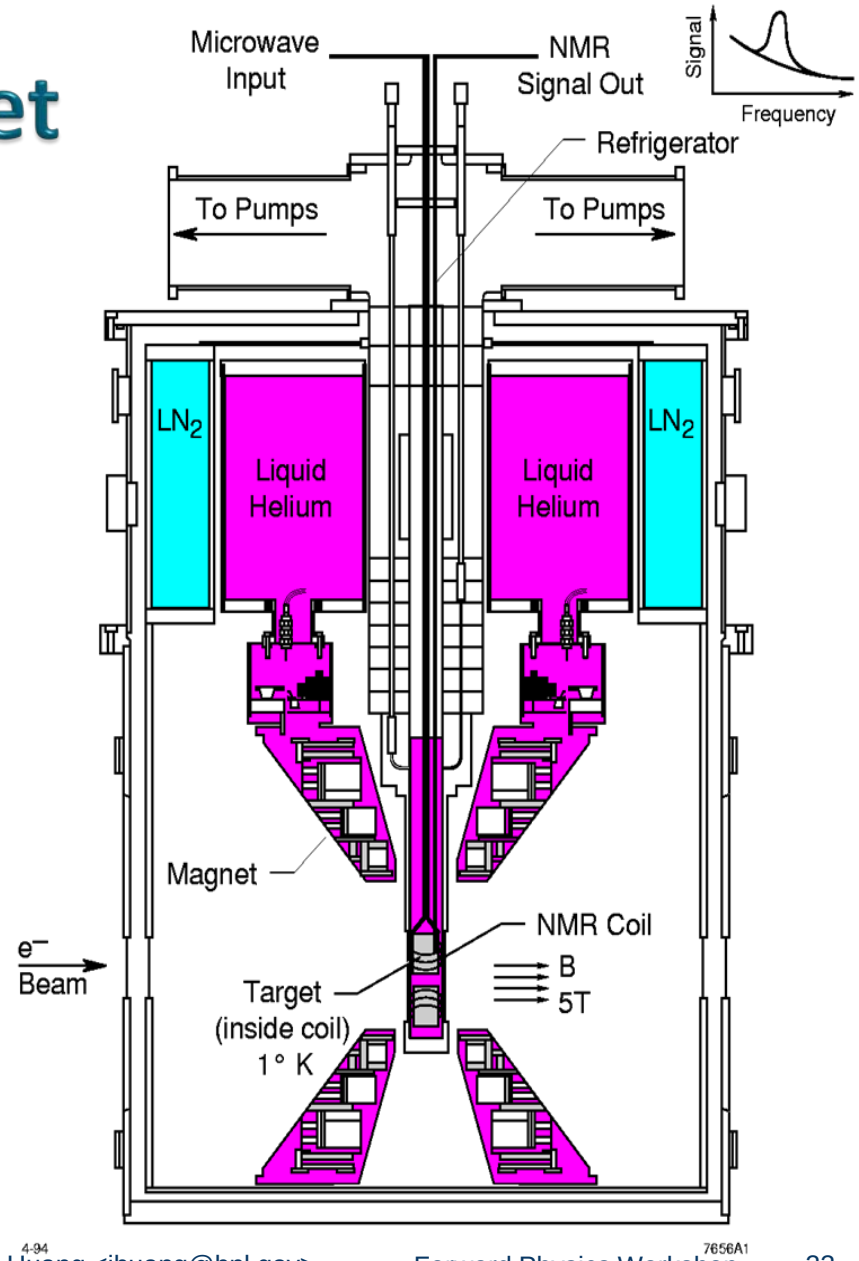
- Polarized NH_3/ND_3 targets also available at Jefferson Lab
  - Used in Hall B/CLAS SIDIS experiment
- New magnet with transverse opening (>25°) in design
  - Proposal approved for 12 GeV Era

- Dynamical Nuclear Polarization
- In-beam average polarization

  70-90% for p

  30-40% for d
- Luminosity up to
  - ~ 10^{35} (Hall C/A)
  - ~ 10^{34} (Hall B)

Hall C/A polarized p/D target



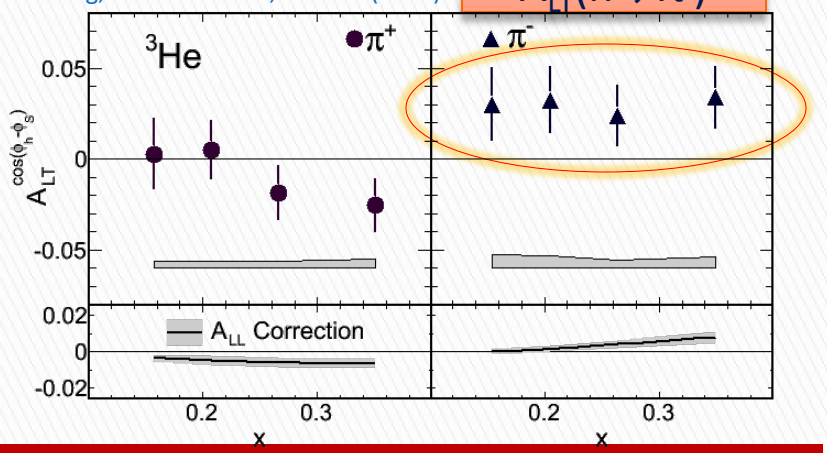
The other worm-gear function $h_{1L}^{\perp}$ studied in Hall B

$h_{1L}^{\perp} = -g_{1T}$ favored (naively)

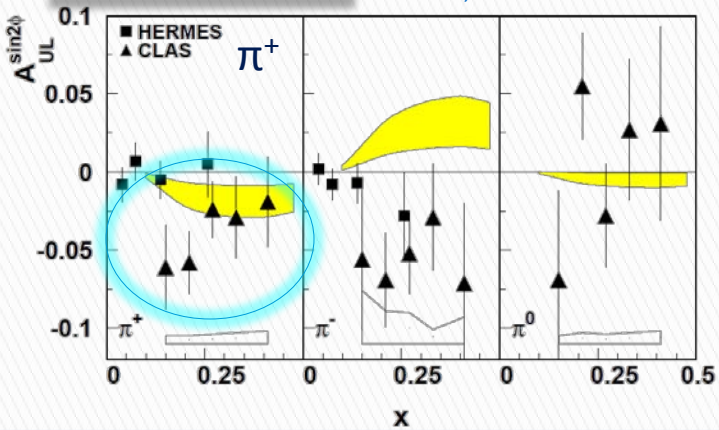
d quark in neutron dominant $A_{LT}(n \to \pi^-)$

u in proton dominant $A_{LT}(n \to \pi^-)$

Huang, et. al. PRL. 108, 052001 (2012)



Avakian, et. al. PRL. 105.262002 (2010)

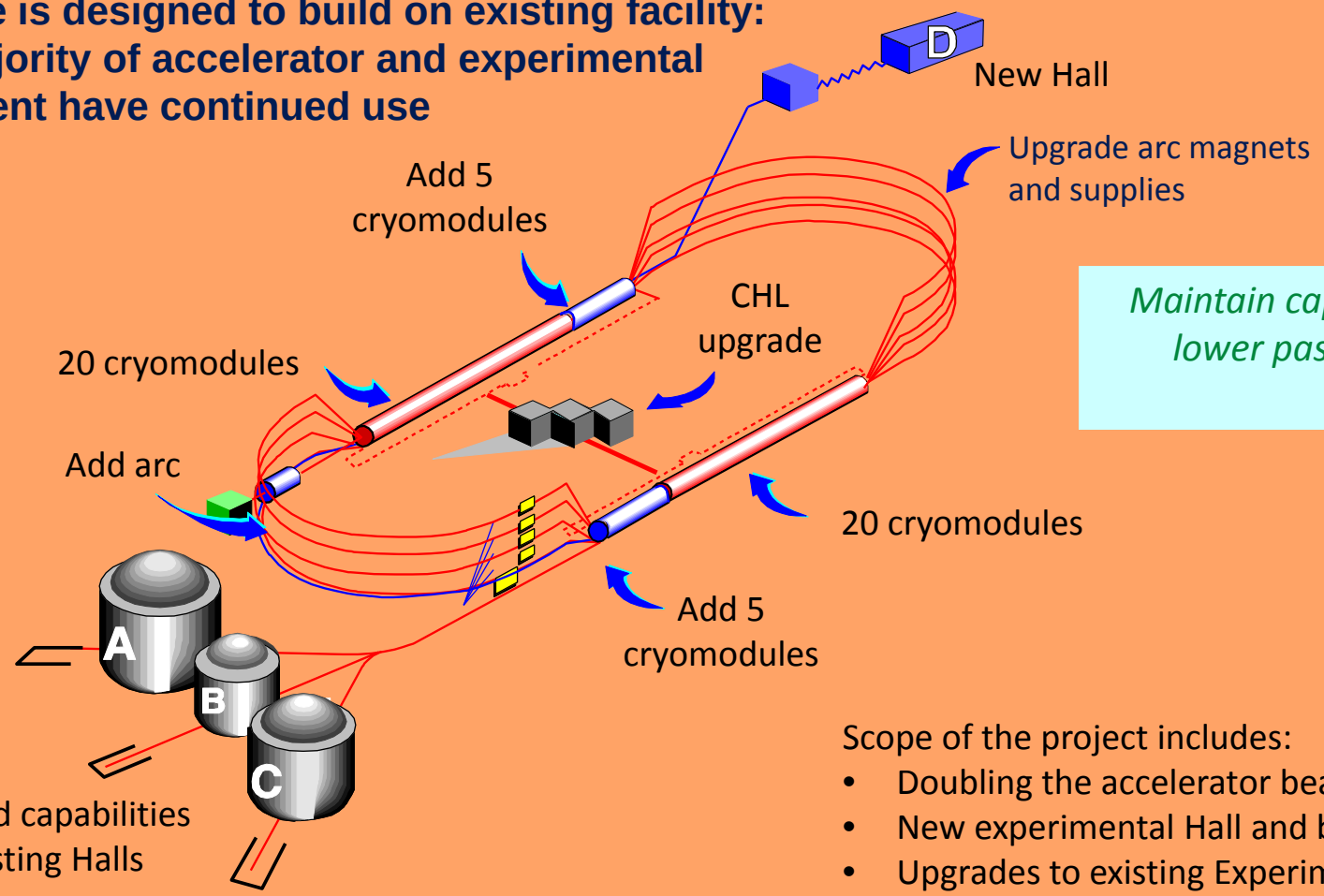


E06-010 A_{LT} on ^{3}He

CLAS A_{UL} on proton

Future is coming : 12 GeV Upgrade Project

Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use



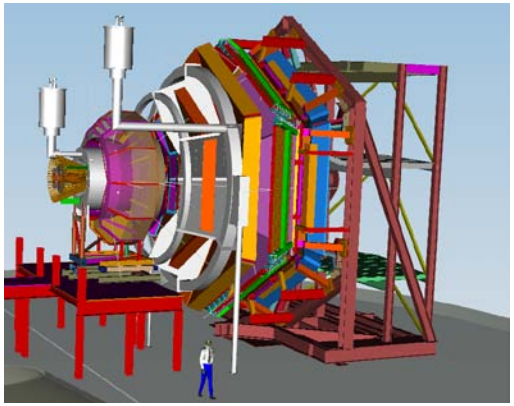
Maintain capability to deliver lower pass beam energies: 2.2, 4.4, 6.6….

Scope of the project includes:

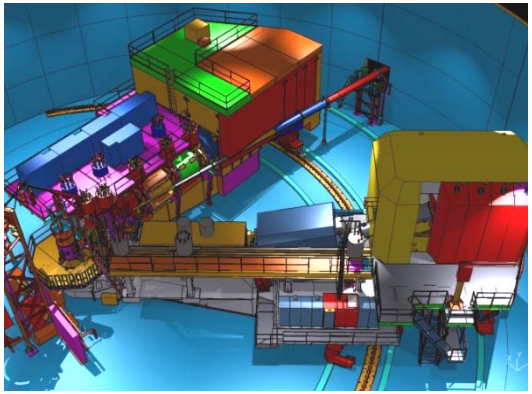
- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

12 GeV Spin Physics Capabilities

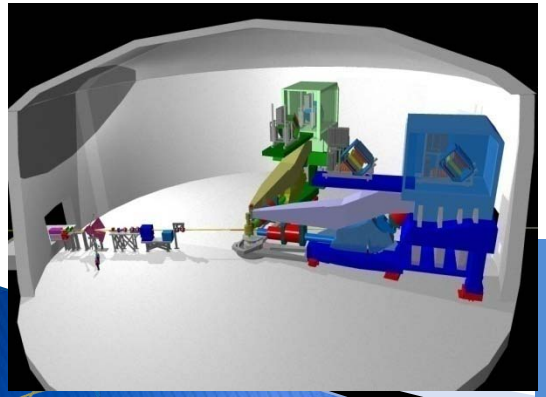
Coherent programs on SIDIS / TMD physics planned



Hall B – understanding nucleon structure via GPDs and TMDs



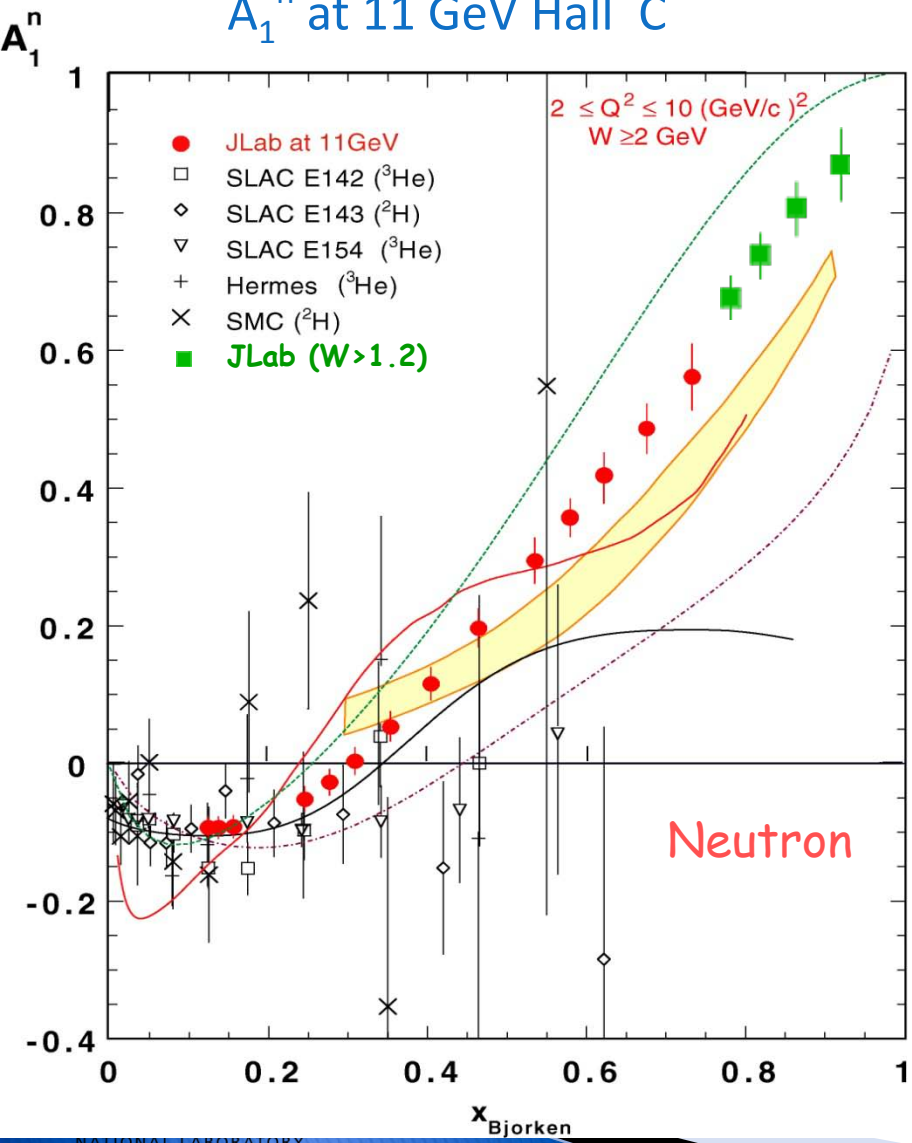
Hall C – precision determination of valence quark properties in nucleons and nuclei



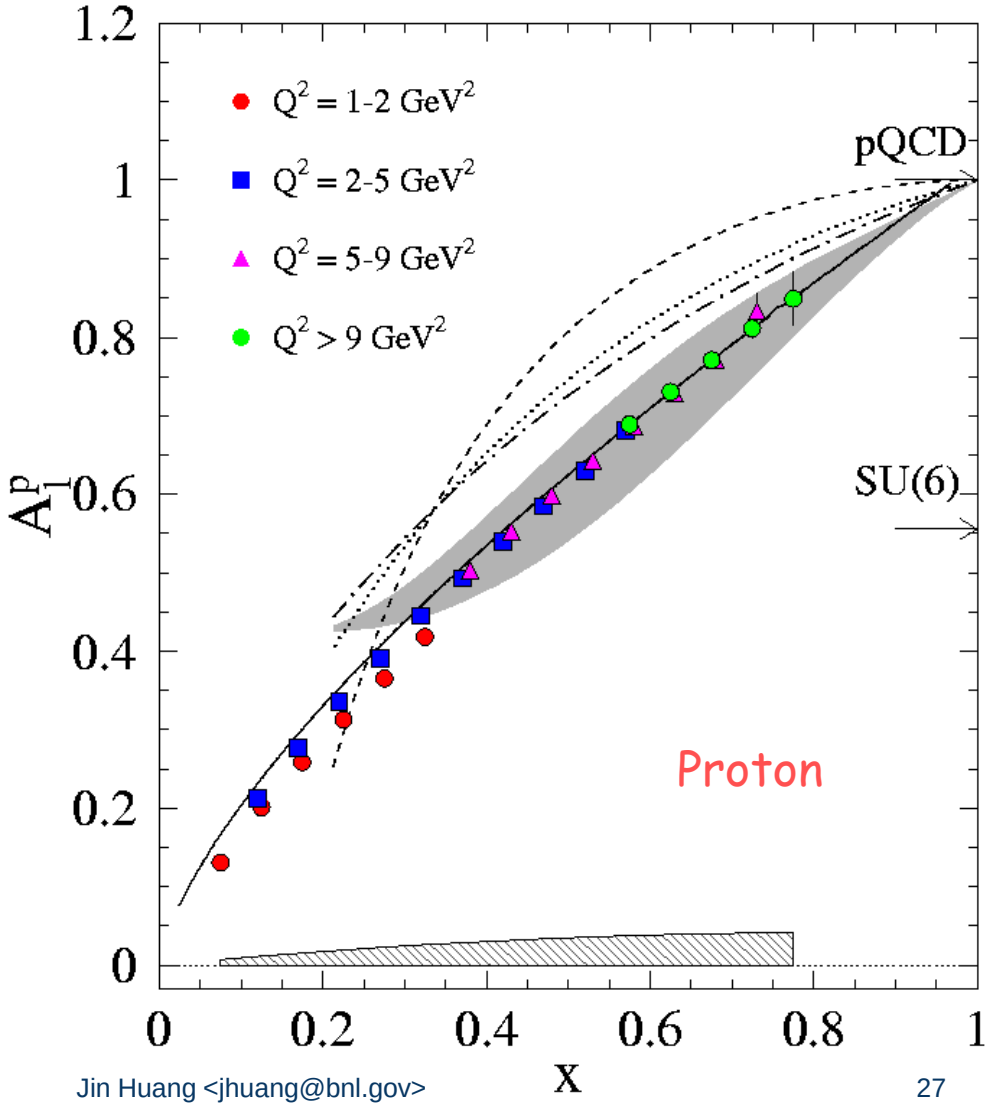
Hall A – future new experiments (e.g. SIDIS/PVDIS with SOLID, Super BigBite and Moller)

Rich spin programs, e.g.
Inclusive double spin asymmetries using 12 GeV

A_1^n at 11 GeV Hall C



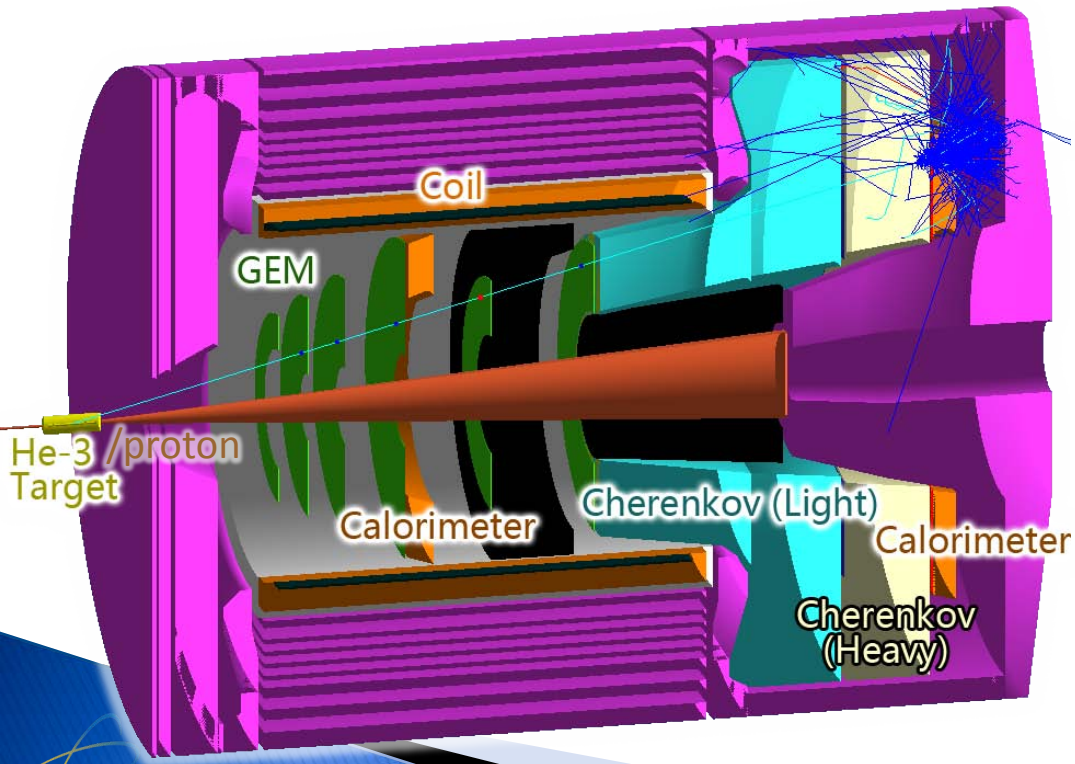
Hall B - CLAS 12

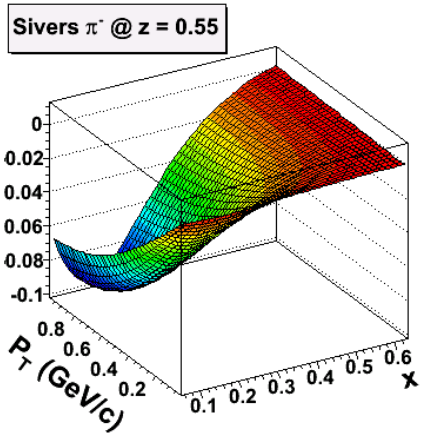


Key Device for High-Precision SIDIS measurement

The SoLID Spectrometer proposed for Hall A

- Key device to achieve high-precision mapping and minimizing systematics
- High Luminosity target and upgraded beam energy -> 12 GeV
- Large acceptance: enable 4D-mapping of asymmetries
- Full/symmetric azimuthal angular coverage: minimize systematics
- Device shared by three SIDIS experiment and a parity-violation DIS exp.
  - Budget: ~20M; early design stage; detector prototyping





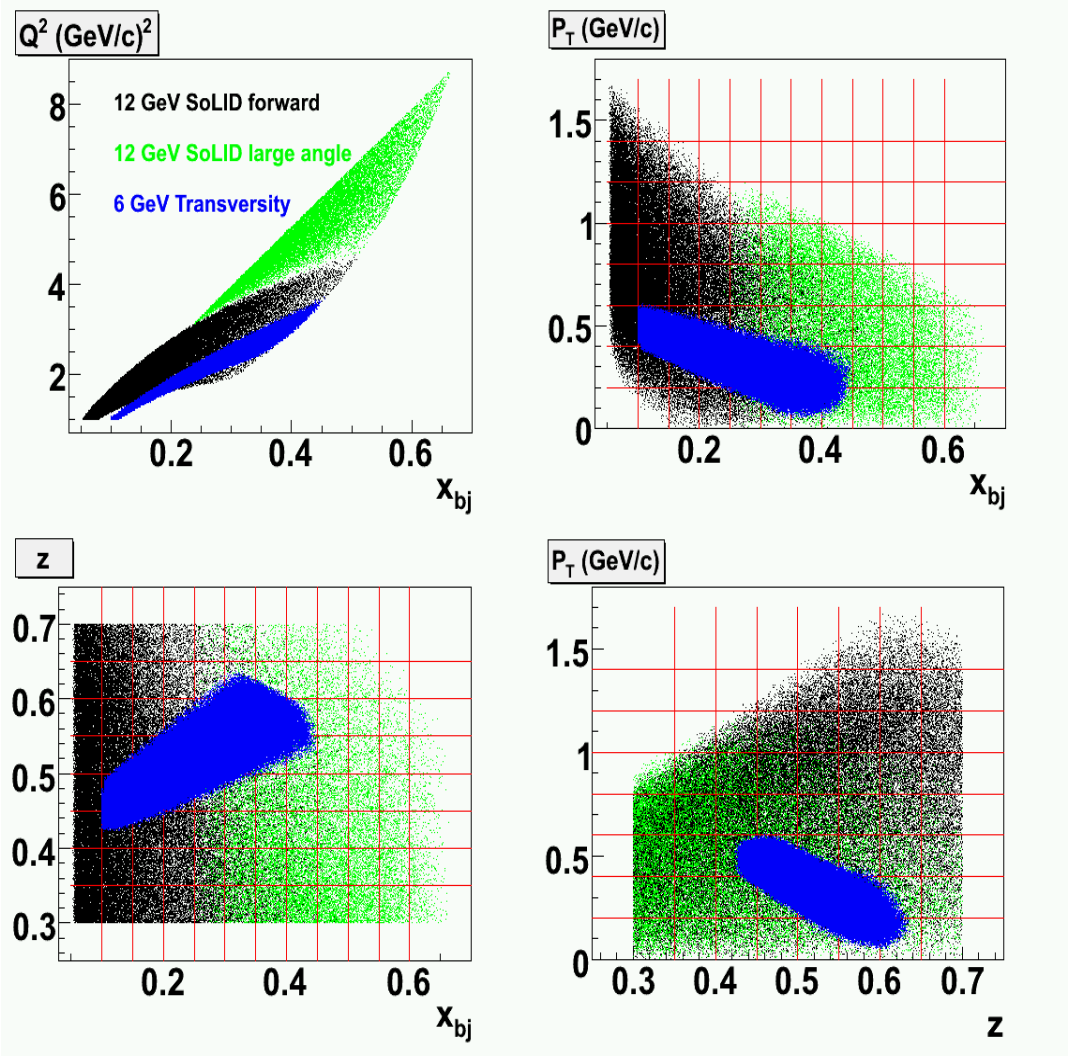
E12-10-006: 90 day
Single Spin Asymmetry on Transverse ^{3}He

E12-11-007: 30 day
Single and Double Spin Asymmetry on ^{3}He

E12-11-108: 120 day
Single and Double Spin Asymmetries on Transverse Proton

Phase space coverage

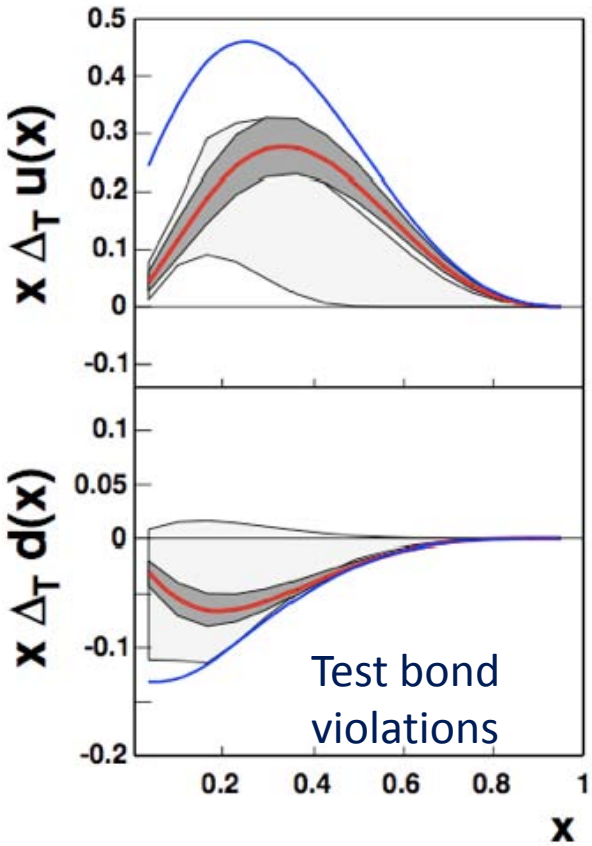
- Natural Extension of E06-010
- Much wider phase space
  - Also data at low and high z value to access target frag. and exclusive channels.
- Both transverse and longitudinal polarized target: 6/7 polarized leading twist TMDs Studied



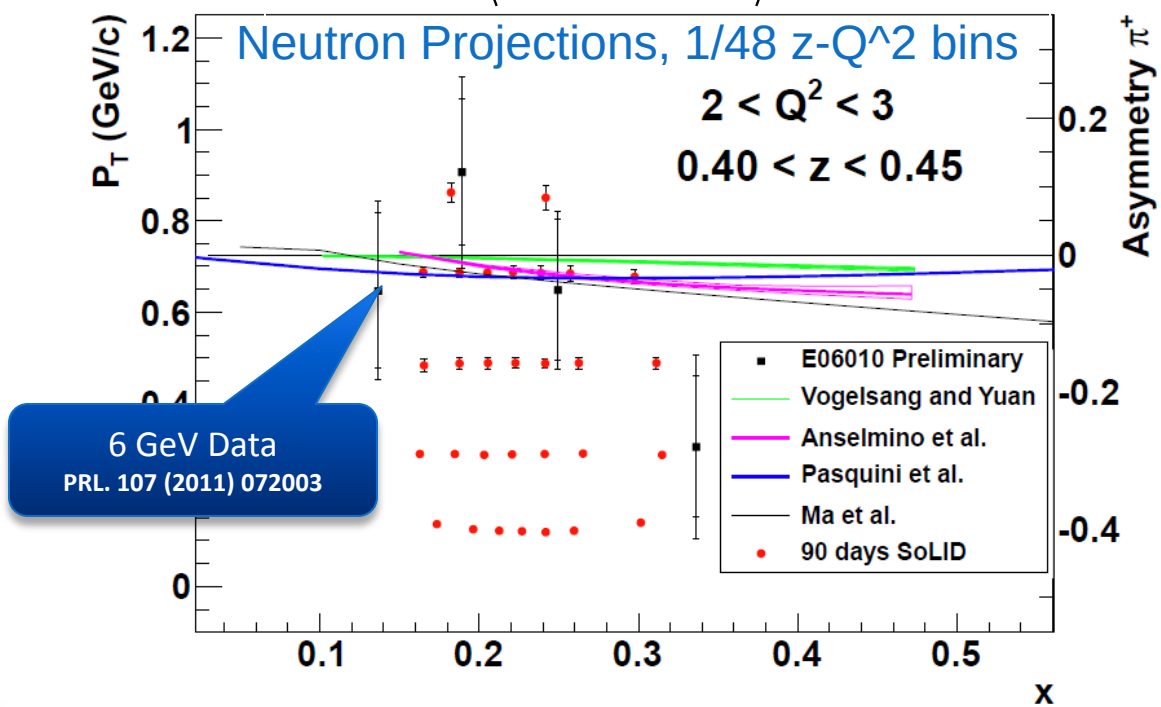
Transversity

h_{1T} =

- The third PDFs in addition to f_1 and g_{1L}
- 10% quark tensor charge (both u and d!) from both SSA data
  - Fundamental property, benchmark test of Lattice QCD



$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_s) \rangle \propto h_{1T} \otimes H_1^{\perp}$$

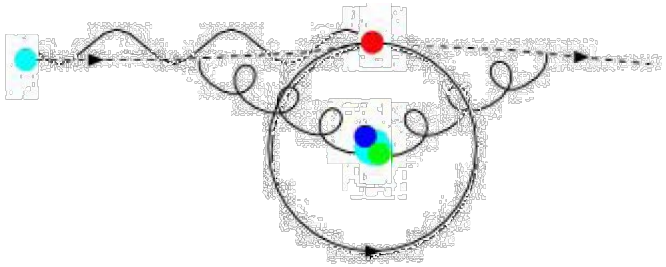


Proton data also planned

Sivers Effect

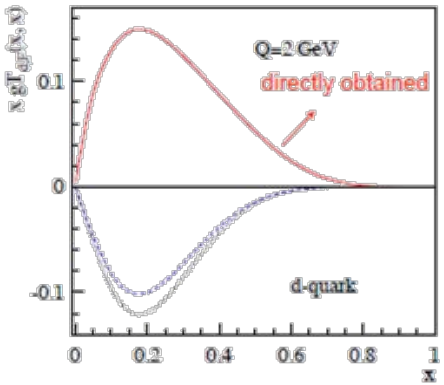
$$f_{1T}^{\perp q} =$$

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



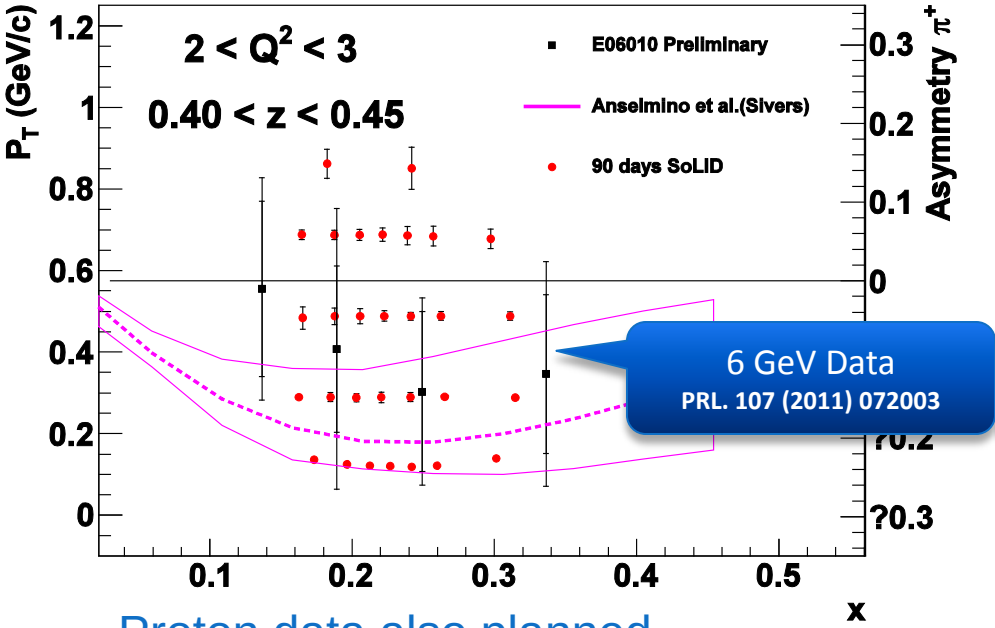
- Correlation between nucleon spin with quark angular momentum
- Important test for TMD factorization
- Relation with twist-3 quark-gluon corr. and RHIC measurements
- T-odd final state interaction -> Target SSA

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS}$$



Neutron Projection , 1/48 z-Q^2 bins

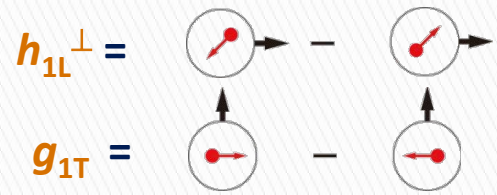
$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_s) \rangle \propto f_{1T}^{\perp} \otimes D_1$$

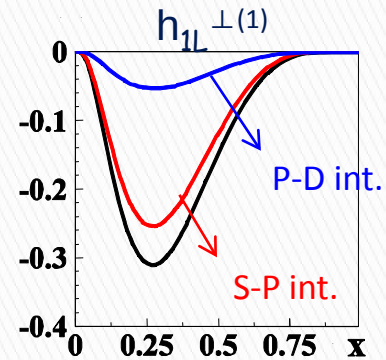


6 GeV Data
PRL. 107 (2011) 072003

Proton data also planned

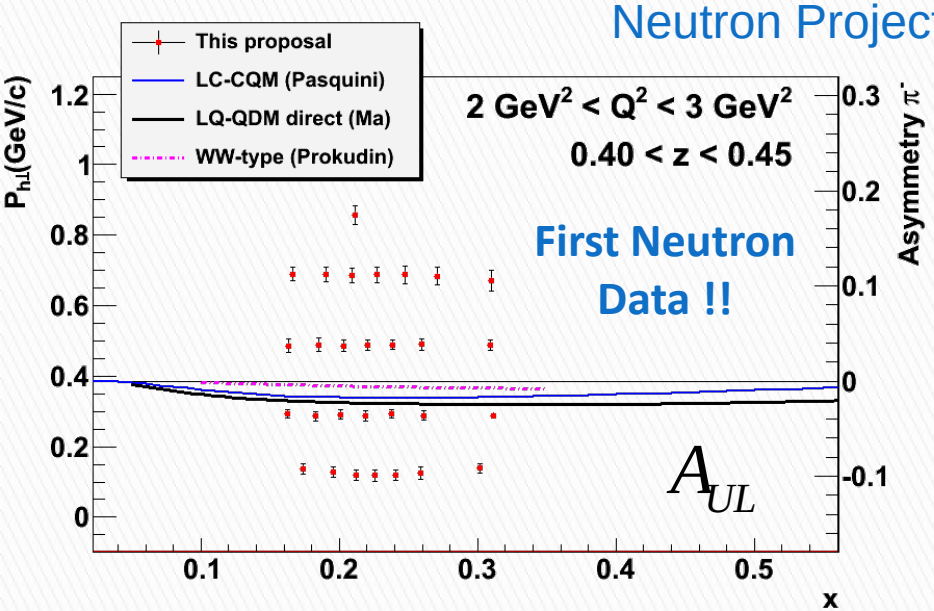
Worm-gear functions

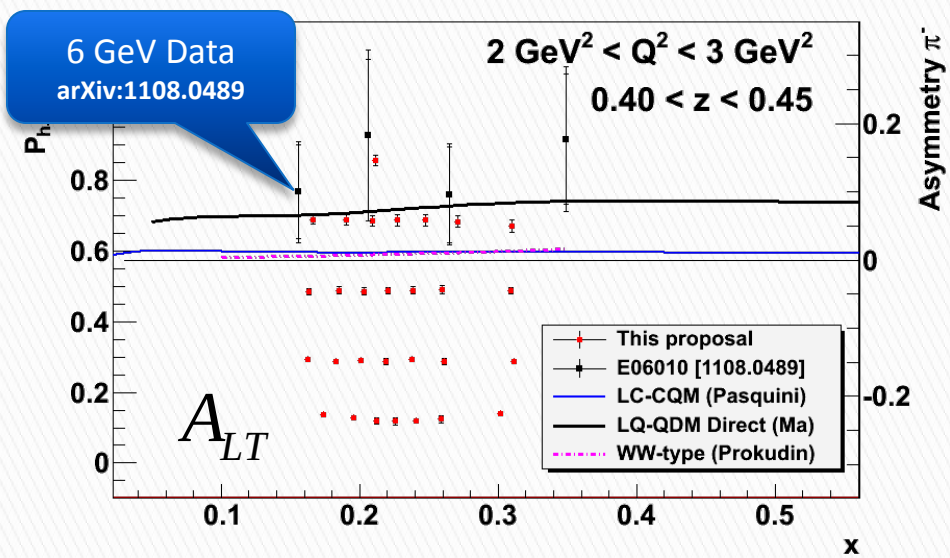




- Dominated by real part of interference between L=0 (S) and L=1 (P) states
- No GPD correspondence
- Lattice QCD -> Moments of worm-gear TMDs
- Model Calculations -> $h_{1L}^{\perp}$ =? $-g_{1T}$
- Connections with Collinear PDFs through WW approx. and LIR.

Neutron Projections, 1/48 z-Q^2 bins



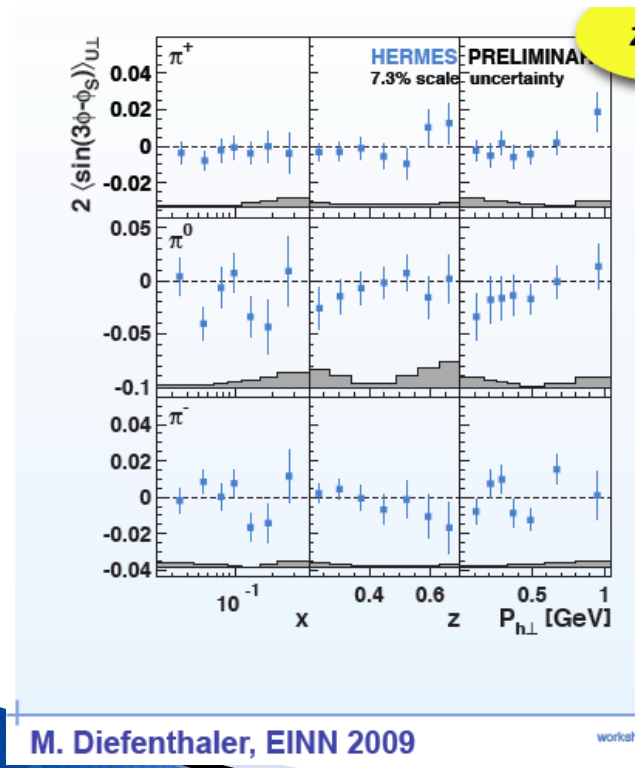


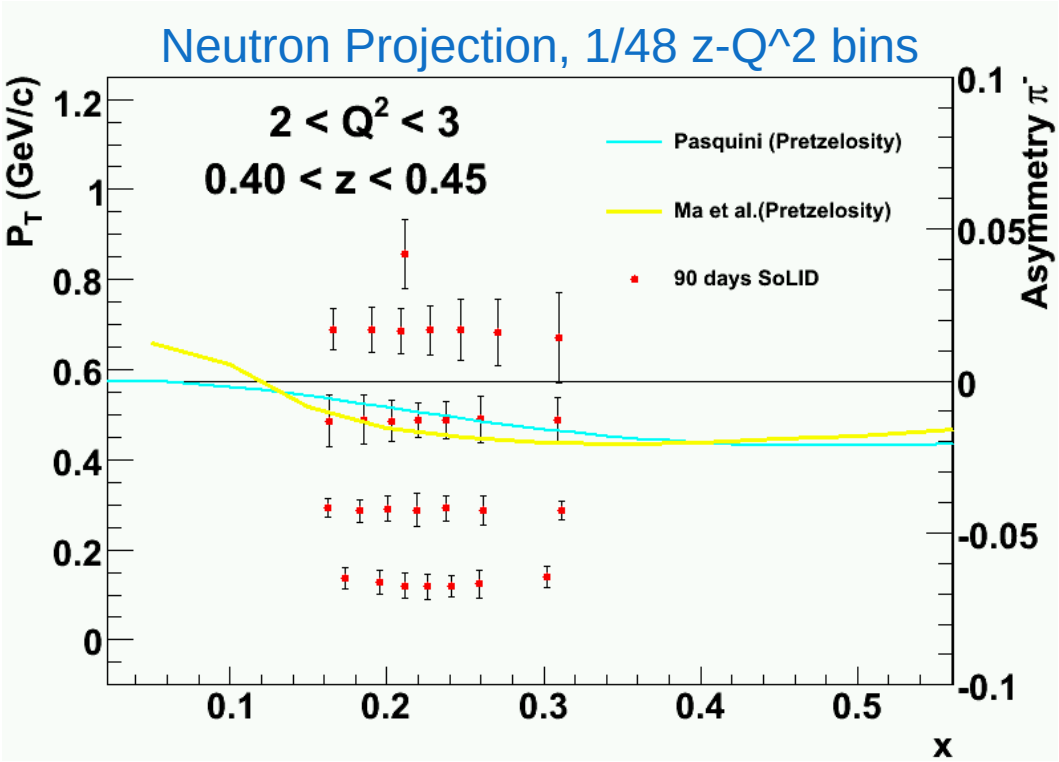
$$A_{UL} \sim h_{1L}^{\perp}(x) \otimes H^{\perp}{}_{1}(z)$$

$$A_{LT} \sim g_{1T}(x) \otimes D_1(z)$$

Pretzlosity: $h_{1T}^{\perp}$ =

- Relativistic effect of quark , PRD 78, 114024 (2008)
- (in models) direct measurement of OAM, PRD 58, 096008 (1998)
- Expect first non-zero Pretzelosity asymmetries





Proton data also planned

E12-11-007 Full projection, neutron A_{LT}

Satisfying the multi-D natural of this study

z= 0.3~0.7

x_{bj}

data point: Projection for neutron A_{LT} of π^-

Q^2 = 1~8 GeV^2

$P_{h\perp}$ (GeV/c)

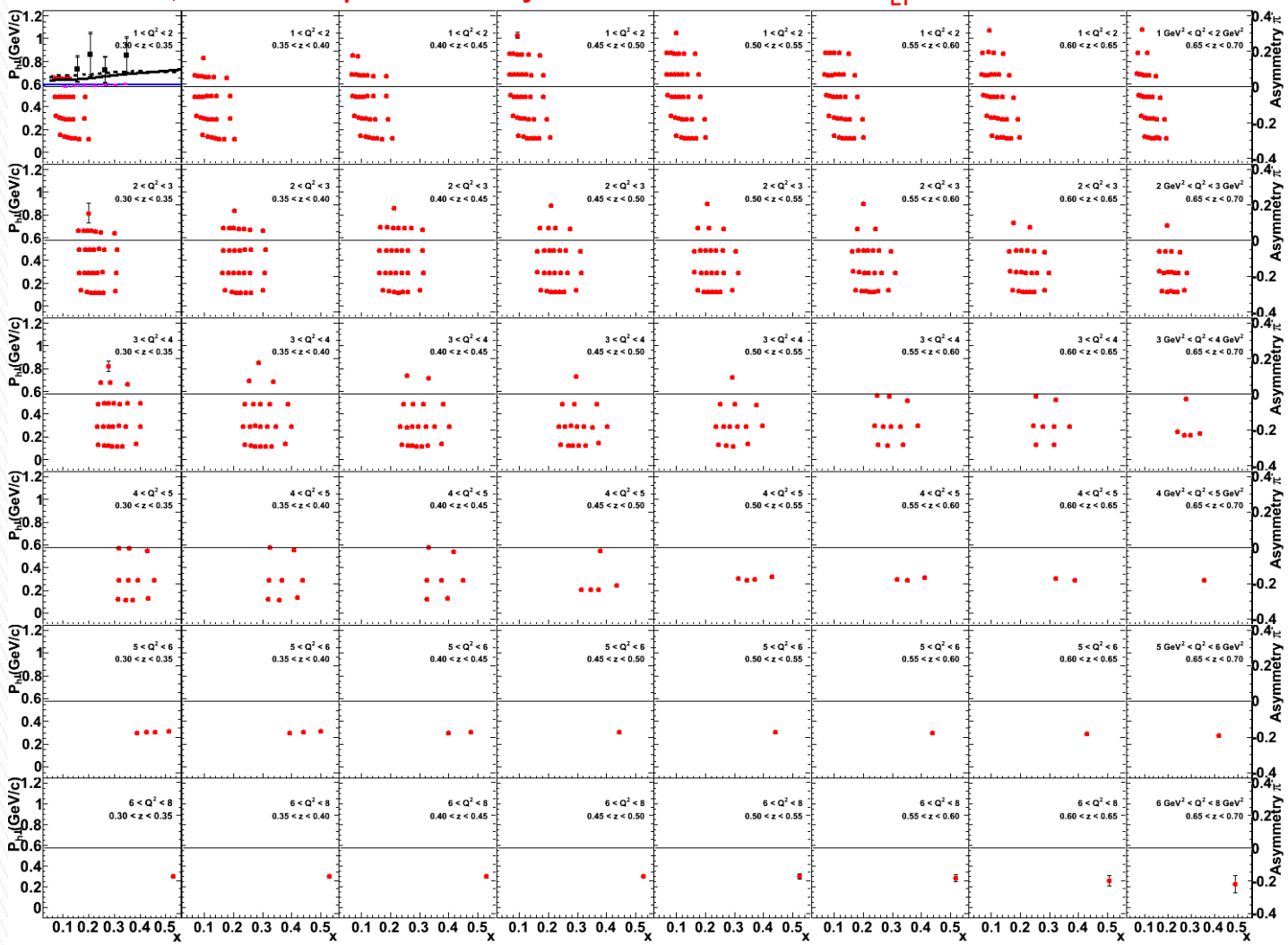
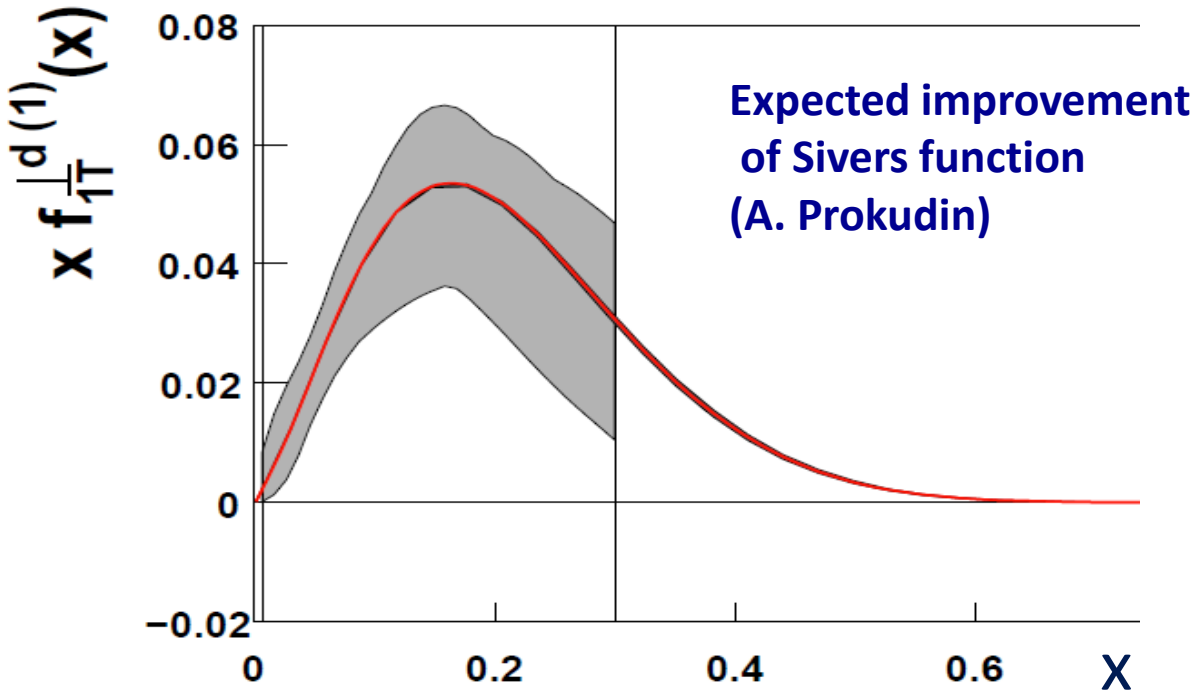


Illustration of precision: projection in 1-D (x)

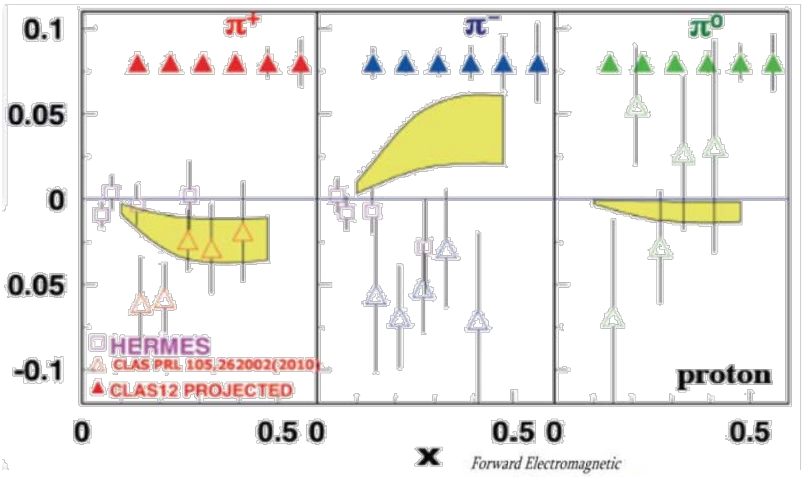


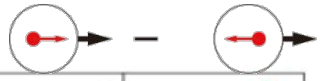
Assumption: We know the k_T dependence, Q^2 evolution of TMDs. Also knowledge on TMFF → project onto 1-D in x to illustrate the power of SoLID-^{3}He.

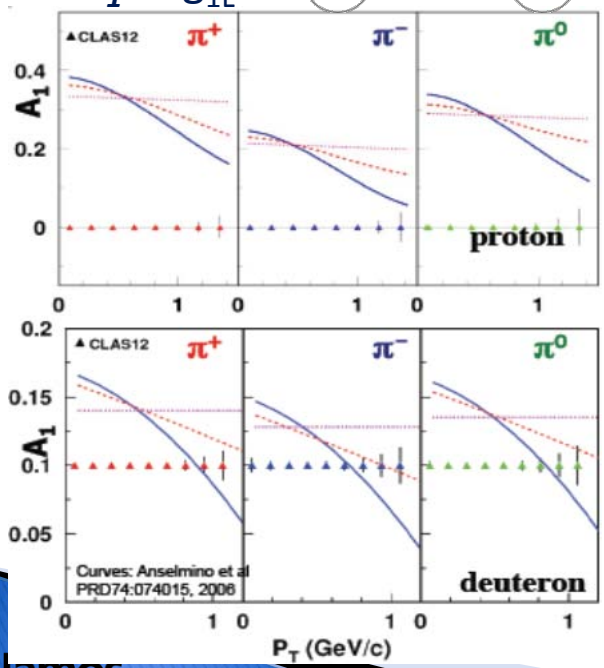
Polarized SIDIS programs in Hall B/CLAS12

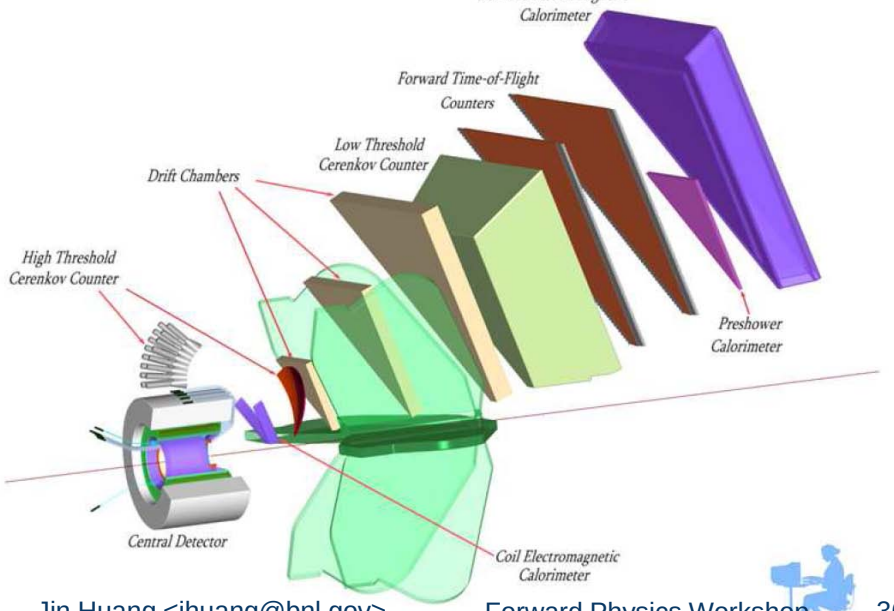
- Toroidal spectrometer with ~2π azimuthal coverage
- Long. polarized p/D targets
- Transversely polarized HD ice target in tests

$A_{UL} \propto h_{1L}^{\perp} =$



$A_1 \propto g_{1L} =$ 





Summary

- Jefferson Lab probed TMD through SIDIS process
  - Hall A : transversely polarized ^{3}He target, first measurement on neutron SIDIS SSA and DSA
  - Hall B : SIDIS w/ long. polarized proton/deuteron target
  - Hall C : studied unpolarized SIDIS cross section using LH/LD targets

- Bright future for 12 GeV upgrade
  - Proposals to study all 8 leading-twist TMD functions
  - New instruments to map the SIDIS asymmetries in high precision
    - Hall A : polarized 3He/proton target with SoLID and Super BigBite spectrometer
    - Hall B : polarized proton/deuteron target with CLAS12
    - Hall C : study unpolarized SIDIS cross section