PR12-20-002

A Program of Spin-Dependent Electron Scattering from a Polarized ^{3}He Target in CLAS12

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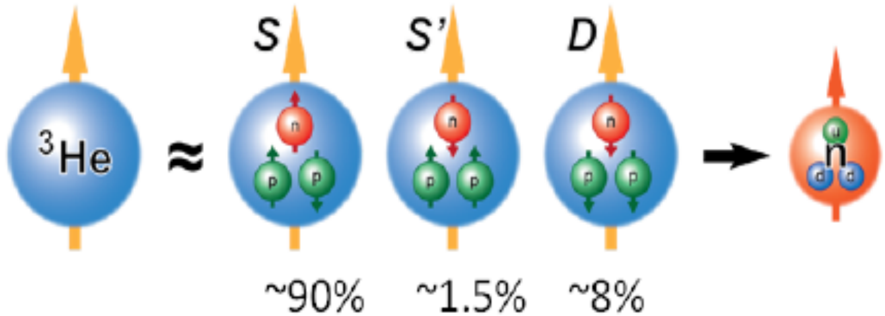
for the
CLAS12 Collaboration

- Context
- Target
- Proposed Measurements
- Beamtime Request

Context

- This proposal seeks to leverage a recent technical advance in high field MEOP arising from R&D by a BNL-MIT collaboration since 2012 to realize a polarized ^{3}He ion source for RHIC/EIC.
- It employs an established target technology: cryogenically cooled target cell in diffusive contact with the pumping cell – used successfully at MIT-Bates in 1989-91 with 25 µA e-beam: Ph.D. theses of Haiyan Gao and Ole Hansen.
- The target will be located directly in the 5 T central solenoid of CLAS12 and will take advantage of the existing and upgraded capabilities of CLAS12.
- With the 10.6 GeV polarized electron beam at an intensity of 0.5 µA in Hall B, we can reach the luminosity of 2.7 x 10^{34} nucleons/cm^2/s in CLAS12.
- Our initial proposal requesting 30 PAC days focuses on spin-dependent DIS and SIDIS on a longitudinally polarized He-3 target with two main physics goals:
  - P_T -dependence of the neutron longitudinal spin structure
  - Nuclear corrections to SIDIS
- We believe that the measurements we propose complement the approved CLAS12 program on ND_3 , are also complementary to ongoing and planned SEOP experiments and can strengthen the science case for the proposed SoLID spectrometer, i.e. will add value to the JLab scientific agenda and will not diminish in any way the approved and planned program.

Why Polarized ^{3}He ?



Neutron polarization: 87%

Proton polarization: 2.7%

- Polarized ^{3}He is an effective polarized neutron target
- Crucial for direct study of neutron spin structure
- Calculable light nuclear system, including nuclear effects
- Complementary to deuteron
- Electron scattering experiments since late 1980s all with **low magnetic field**

Polarized ^{3}He Targets

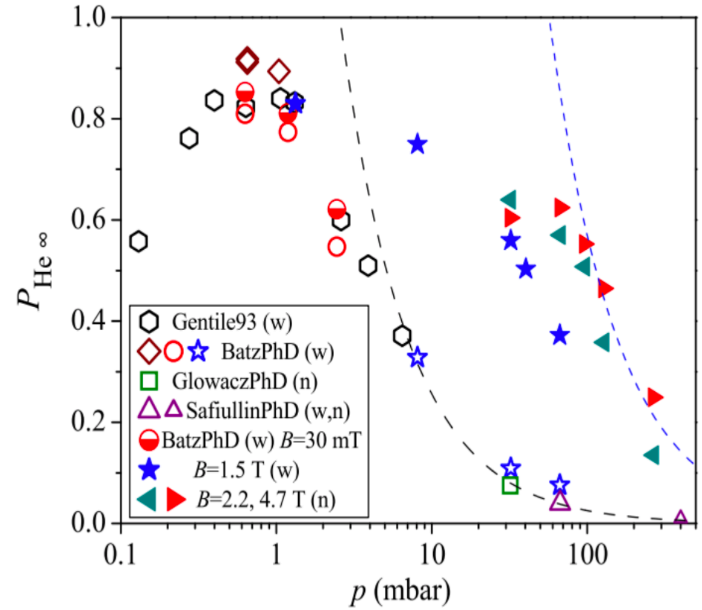
- **Spin Exchange Optical Pumping** (SEOP) of ^{3}He has been an integral tool for spin physics since SLAC
  - JLab 6 GeV era: 13 experiments in Hall A
  - JLab 12 GeV era: already 7 approved experiments
- Polarized ^{3}He targets have never been used in Hall B
  - SEOP ^{3}He is not available within CLAS12 5T solenoid due to increasing wall relaxation at high magnetic field.

- **Metastability Exchange Optical Pumping** (MEOP) of ^{3}He operates at much lower pressures
  - Used in medical imaging, neutron scattering
  - MIT-Bates 88-02 polarized ^{3}He target used double cell cryotarget (17 K) to increase density
- New development: High Magnetic Field MEOP

MEOP at High Magnetic Fields and Pressures

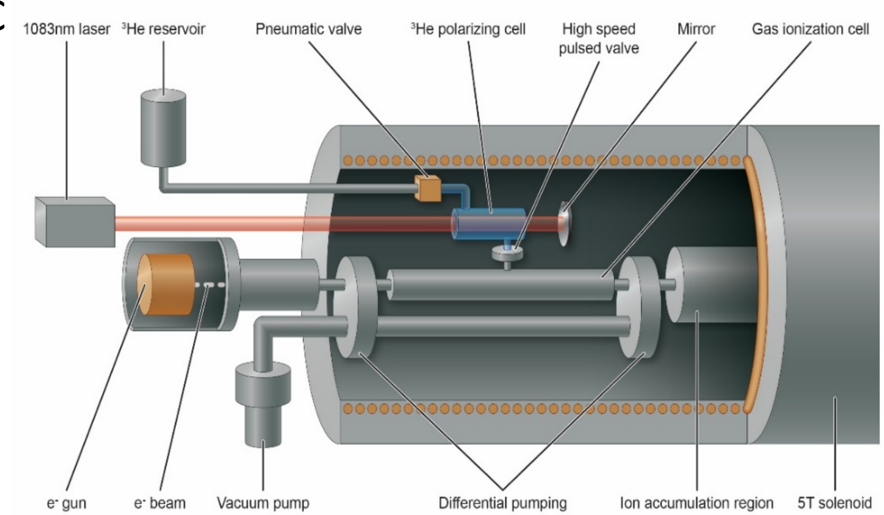
- Development at ENS, Paris: Nikiel *et al.*, EPJD **67**, (2013).
- Higher fields allowed higher polarization at higher pressures
- Ameliorates an important disadvantage of MEOP: low pressure
- Allows operation in high fields

T.R. Gentile *et al.,* RMP **89**, 045004 (2017).



- Polarized ^{3}He Ion Source: High field MEOP design by BNL-MIT collaboration for RHIC/EIC
- "Must do" in 2017 Jones review
- Highlighted in 2018 NAS assessment of EIC science

J.D. Maxwell *et. al.*, NIM A **959**, 161892 (2020).



Reach > 50% polarization at 4.7 T and 100 mbar

Target Concept for CLAS12

High Field MEOP

- High Polarization (~60%)
- High Magnetic Field (5 T)
- Pressure Increase 100x

Nikiel-Osuchowska, *et al*.
EPJ D **67.9**, 200 (2013).

+

Double-Cell Cryo Target

- Polarize at 300 K
- Transfer to 5 K Target Cell
- Density Increase 60x

Milner, McKeown, and Woodward
NIM A **274** 56-63, (1989).

- By combining technologies, increase MEOP target density 6,000x
- Achieves 5.4 amg, roughly half JLab SEOP target gas density
- Polarize *within* 5 T solenoid: CLAS12 standard configuration
- 20 cm long Al target cell, H_2 coating: 14.4 mg/cm^2
- Conceptual Design Report on **arXiv:1911.06650**

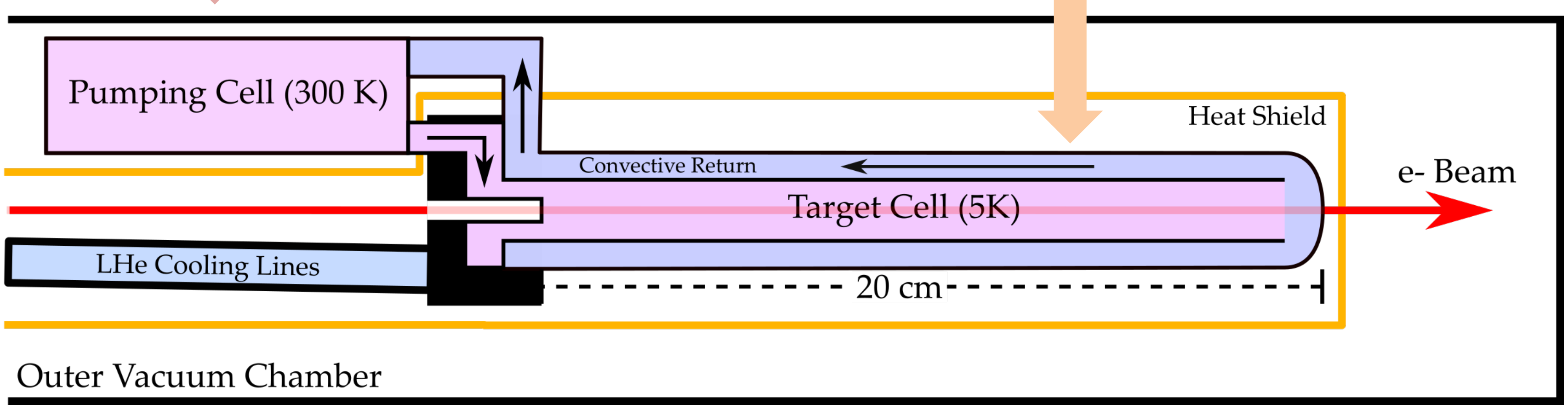
Proposed Target Design

Glass Pumping Cell

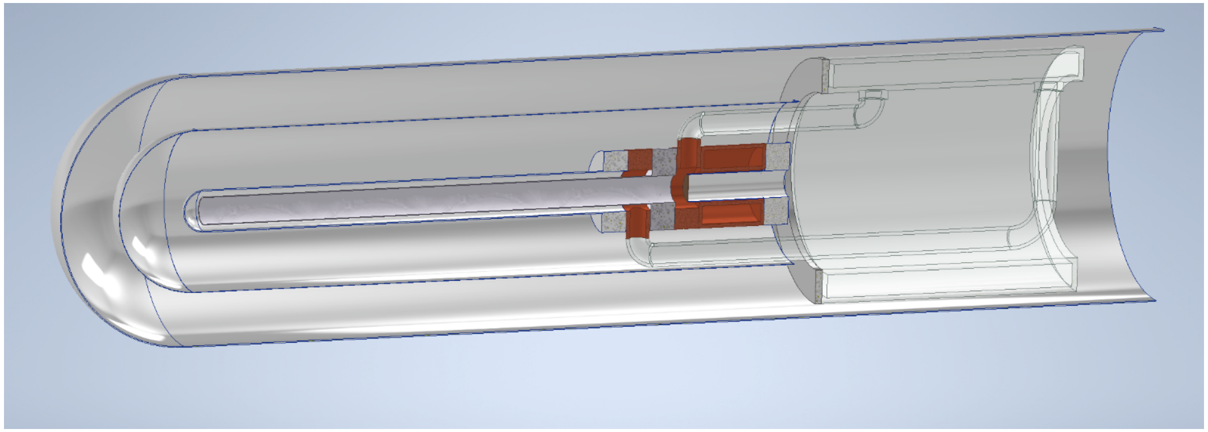
- Temperature: 300k
- Pressure: 100 mbar
- Optical pumping: 60%
- Convective transfer

Aluminum Target Cell

- Temperature: 5K
- Heat exchange: Liquid He supply
- H_2 coating avoids wall relaxation
- 25 μm foil Al beam window

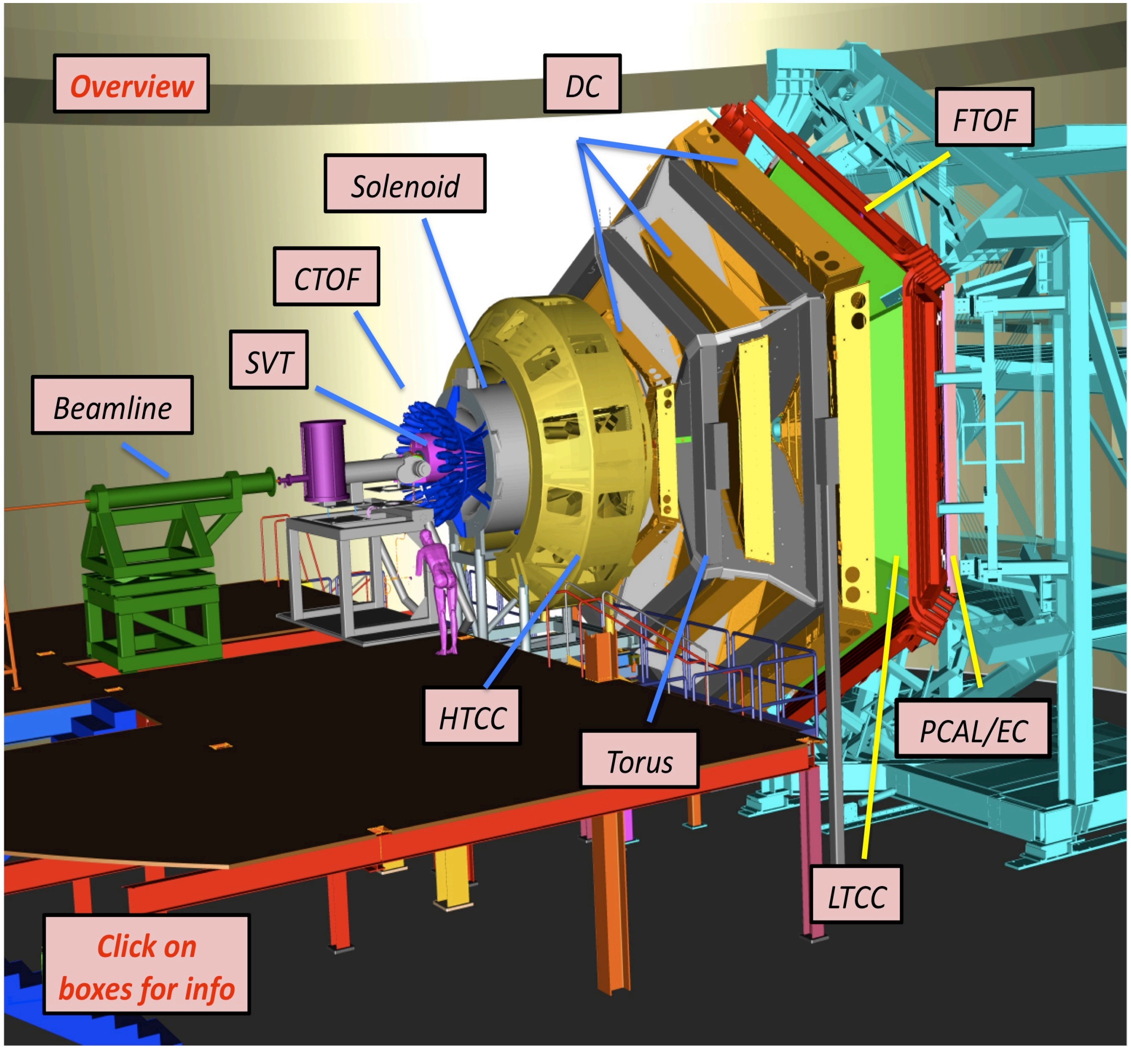


Path to Target Realization



- Development at JLab (J. Maxwell) with support from JLab Target Group, Hall B, and R. Milner's MIT Group.
  - Major equipment: 5 T magnet, pulse-tube cryocooler, pump and probe laser systems, cryostat, pumps
  - Lab space: accommodate class IV lasers and cryogens
- Prototype used to confirm polarization, pressure and field performance, test convective transfer
  - Relaxation due to molecular $^3He_2^+$ expected to be low at high fields, confirm with in-beam tests at UITF

Locate Polarized ^{3}He Gas Target in CLAS12 Central Solenoid (5T)

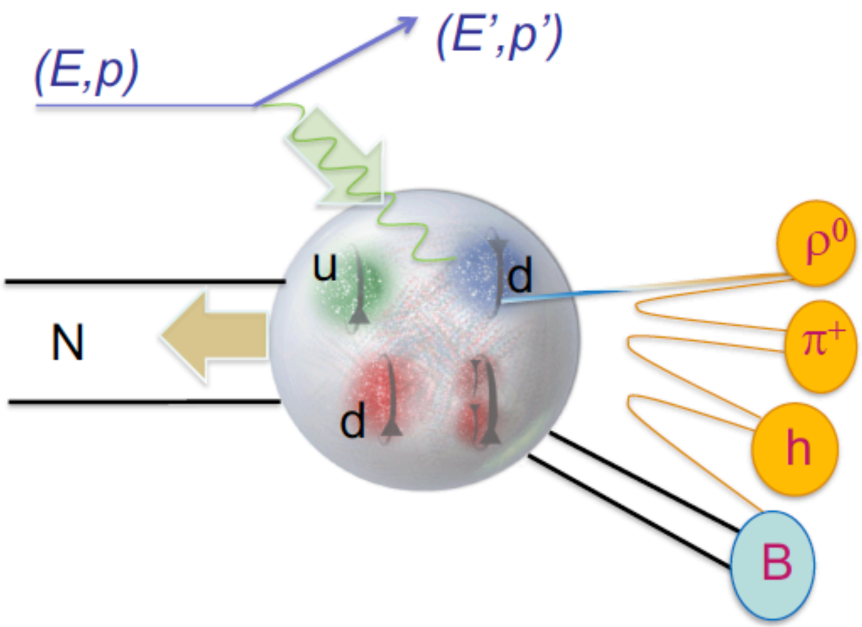


Running Assumptions

- Incident electron beam
  - Energy = 10.6 GeV
  - Current = 0.5 μA
  - Polarization = 80%
- Target: MEOP
  - Thickness = 3×10^{21} $^{3}He/cm^{2}/s$
  - Polarization = 50%
- Luminosity: 0.9×10^{34} $^{3}He/cm^{2}/s$
- 30 PAC days, CLAS standard configuration

Precision measurements to study
Transverse Momentum Dependent (TMD) parton distributions

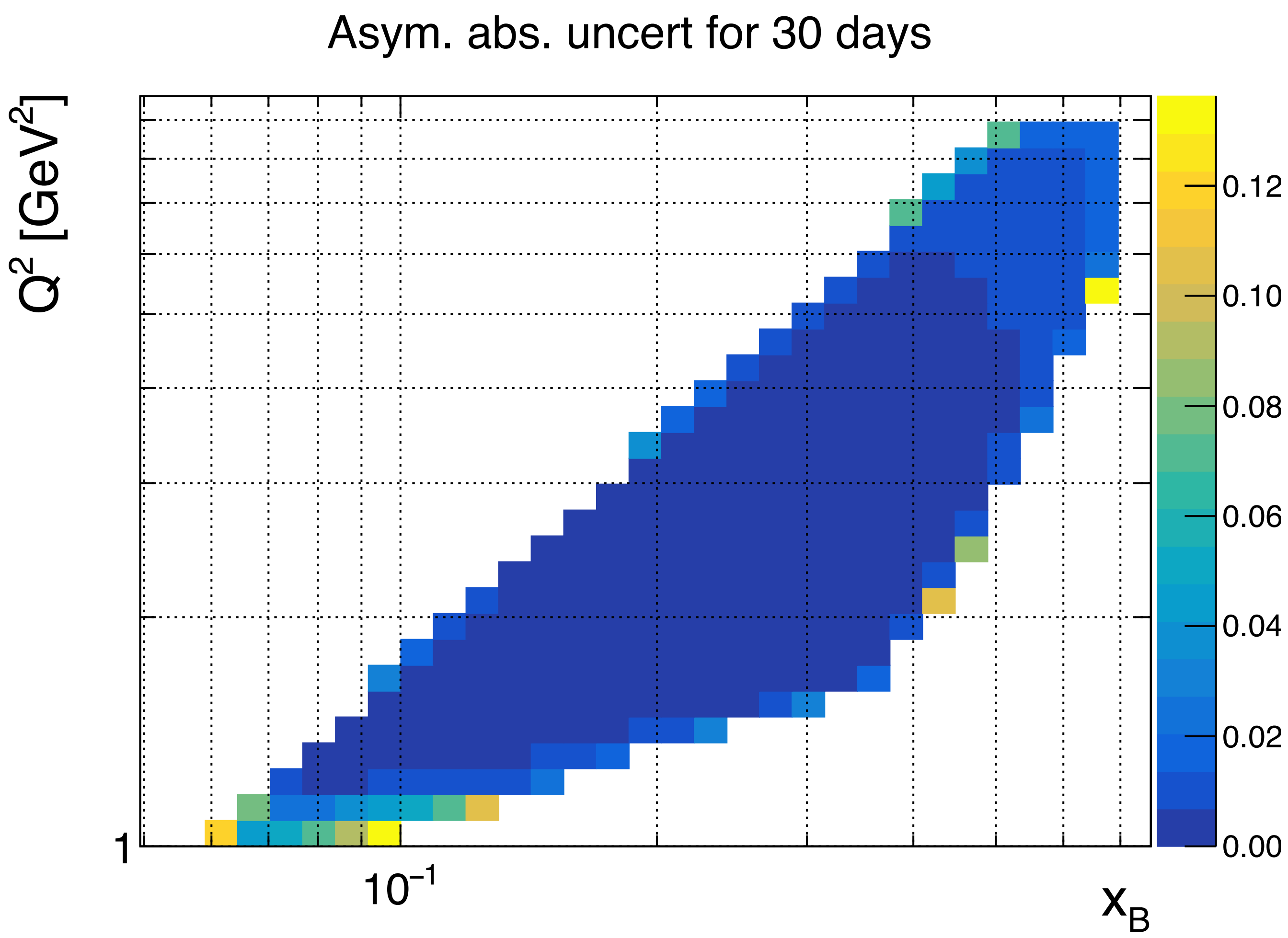
High Energy Electron Scattering



- Fundamental process to understand and image nucleon and nuclear structure.
- While there are currently major uncertainties with existing theoretical description at JLab energies (see theory review), most JLab data are in good agreement for different multiplicities of single and di-hadron production with LUND-MC(LEPTO,PYTHIA), developed for much higher beam energies.

- New measurements are **ESSENTIAL** to make progress.

High precision: DIS

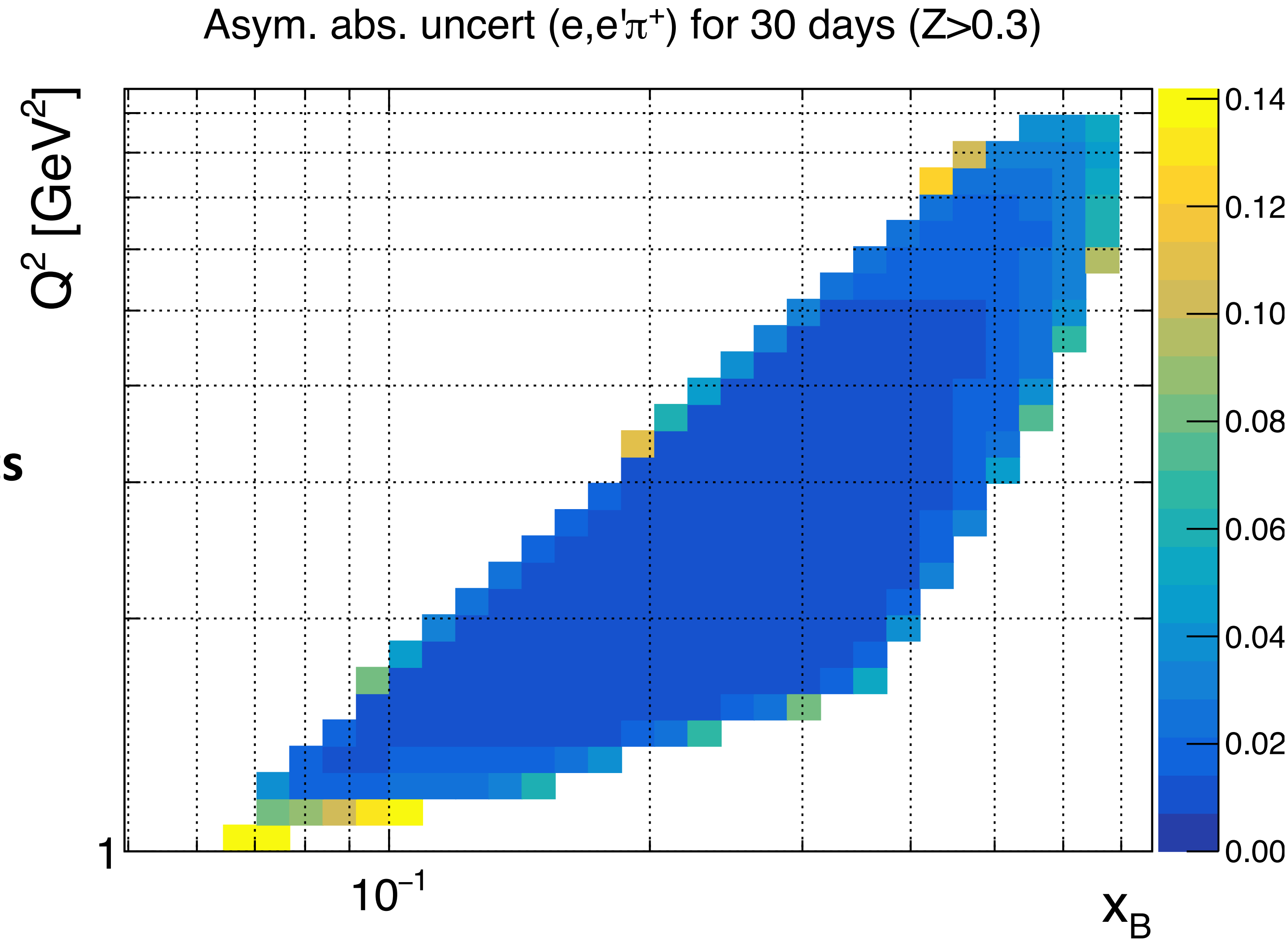


Logarithmic binning 28 x 28 in *x* and Q^2

780 M events

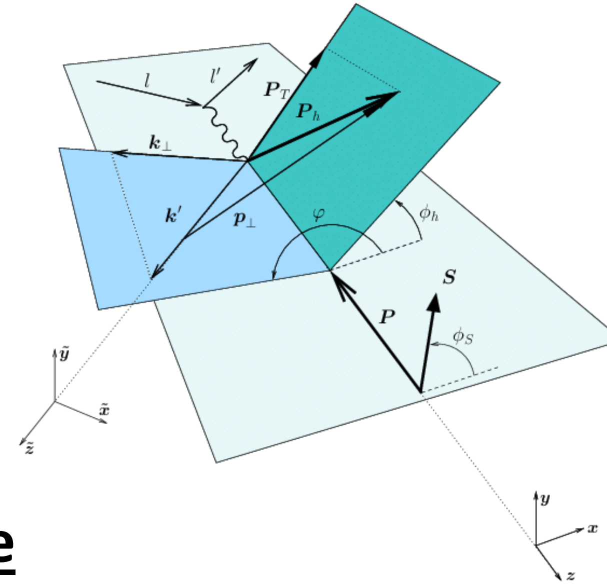
High precision: SIDIS

114 M events



SIDIS Measurements ($\pi^{\pm}$, $K^{\pm}$)

High precision 5D (x, z, P_T, Q^2, ϕ_h) on neutron



$Q^2 = -(k-k')^2$ $x = Q^2/(2q \bullet P)$ $z = (P \bullet P_h)(P \bullet q)$

P_T : hadron transverse momentum
ϕ_h: angle between lepton and hadron planes
k_T : quark transverse momentum

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 $h_{1T}^{\perp}$

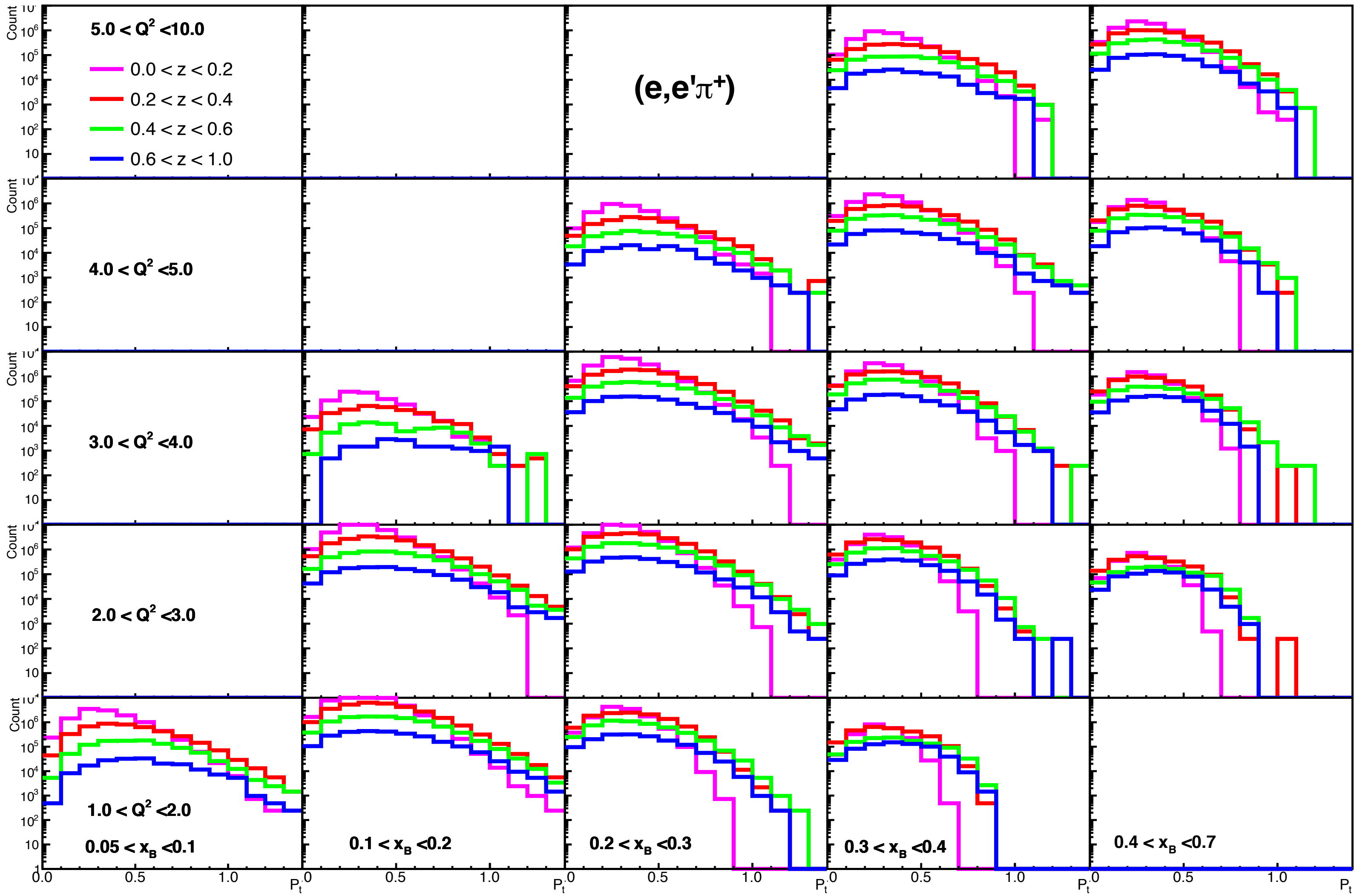
Kinematic coverage of this proposal:

$0.05 < x < 0.7$ $1 < Q^2 < 9$
$0.2 < z < 0.9$ $0 < P_T < 1.3$

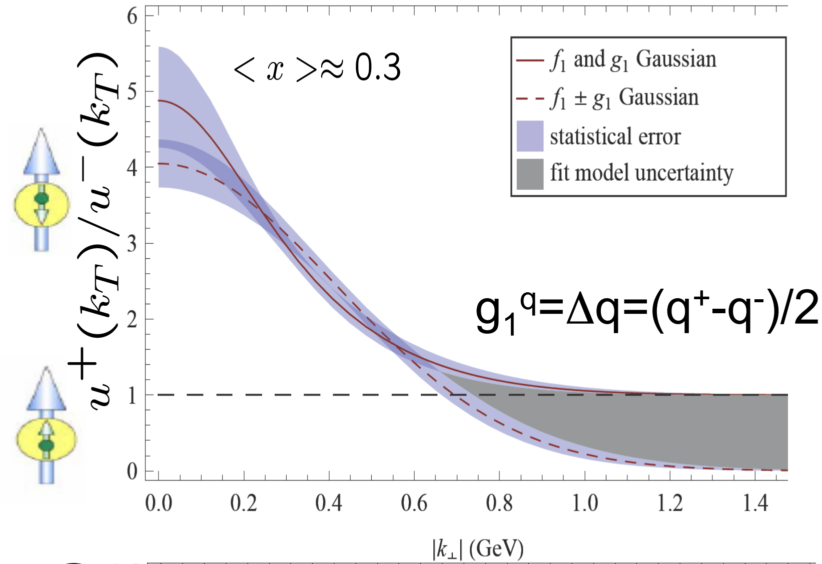
$$\sigma = F_{UU} + P_t P_b F_{LL} + P_t F_{UL}^{\sin 2\phi} \sin 2\phi + P_t F_{UL}^{\sin \phi} \sin \phi + \ldots$$

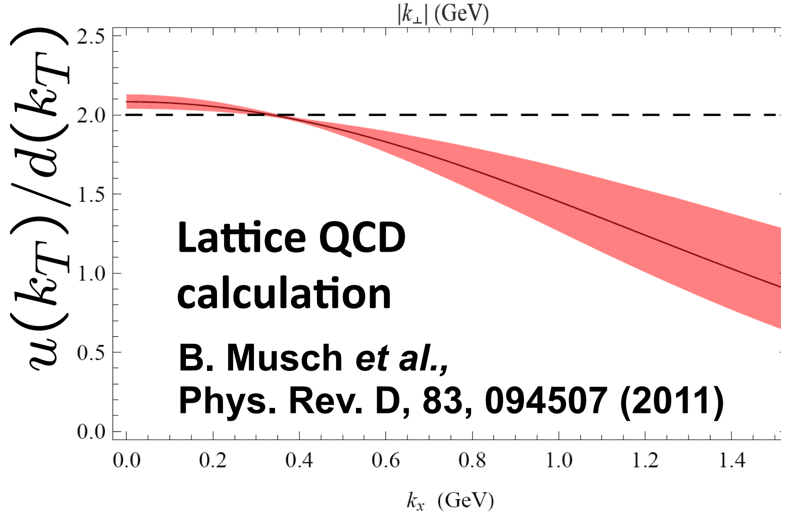
P_T in SIDIS provides access to orbital motion of quarks.

(e,e'π^+) events binning in x, Q^2, z, P_T



Spin and flavor dependence of k_T distribution





M. Anselmino *et al.*
Phys. Rev. D, 74, 074015 (2006)

$$f_1^q(x, k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

$$g_1^q(x, k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

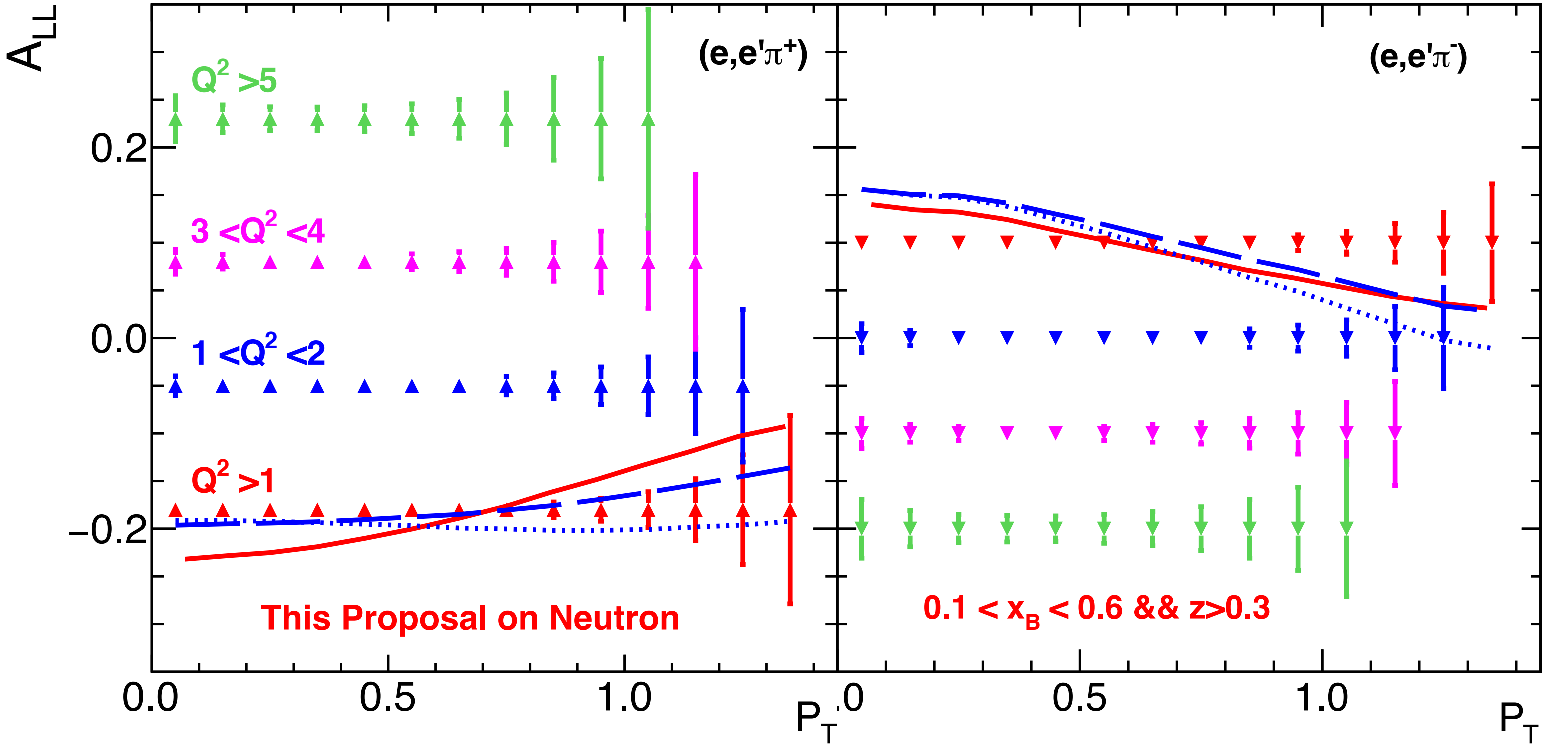
$$D_1^q(z, p_T) = D_1(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_T^2}{\mu_D^2}\right)$$

$F_{LL} \sim g_1 * D_1$
$F_{UU} \sim f_1 * D_1$
$F_{UL} \sim h_{1L} * H_1 * \sin(2\phi)$
$A_{LL} = F_{LL}/F_{UU}$
$A_{UL} = F_{UL}/F_{UU}$

P_T-dependence of the double spin asymmetry provides access to the k_T-dependence of polarized quarks.

Charged Pion P_T Projections

P_T-dependent projection for different bins in Q^2 using Musch *et al.*



- ❑ Measure P_T dependence: providing access to spin and flavor dependence of k_T distribution of valence quarks.
- ❑ Measure in different Q^2 bins: test the validity of underlying theory (P_T << Q).

Sensitivity to *d*-quark Structure

Assumptions:

- LO parton model
- k_T distributions are Gaussian, in the valence region
- known widths for unpolarized distributions
- the double spin asymmetries vs k_T-widths of Δu and Δd depend on a linear combination of A_{LL} asymmetries for π+ and π-.

Uncertainties:

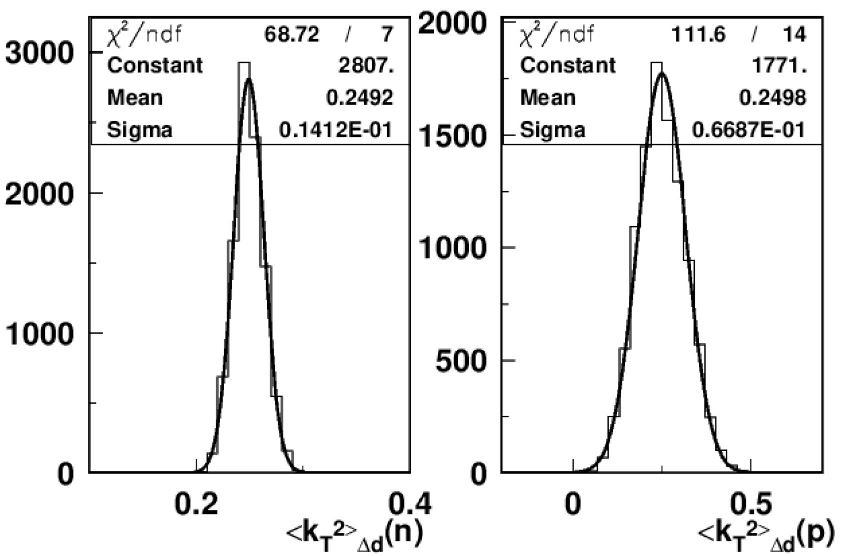
- unpolarized widths for *u* and *d* known to ±20%
- Δ*d*, Δu at large *x* known to ±20%

$$P_{\Delta u} = \frac{e^{\frac{-P_T^2}{\langle k_\perp^2\rangle_{\Delta u} z^2 + \langle p_\perp^2\rangle}}}{\pi(\langle k_\perp^2\rangle_{\Delta u} z^2 + \langle p_\perp^2\rangle)}$$

$$P_{\Delta d} = \frac{e^{\frac{-P_T^2}{\langle k_\perp^2\rangle_{\Delta d} z^2 + \langle p_\perp^2\rangle}}}{\pi(\langle k_\perp^2\rangle_{\Delta d} z^2 + \langle p_\perp^2\rangle)}$$

$$P_{\Delta u} = \theta A_{LL,p}^{\pi^+} + \epsilon A_{LL,n}^{\pi^-}$$

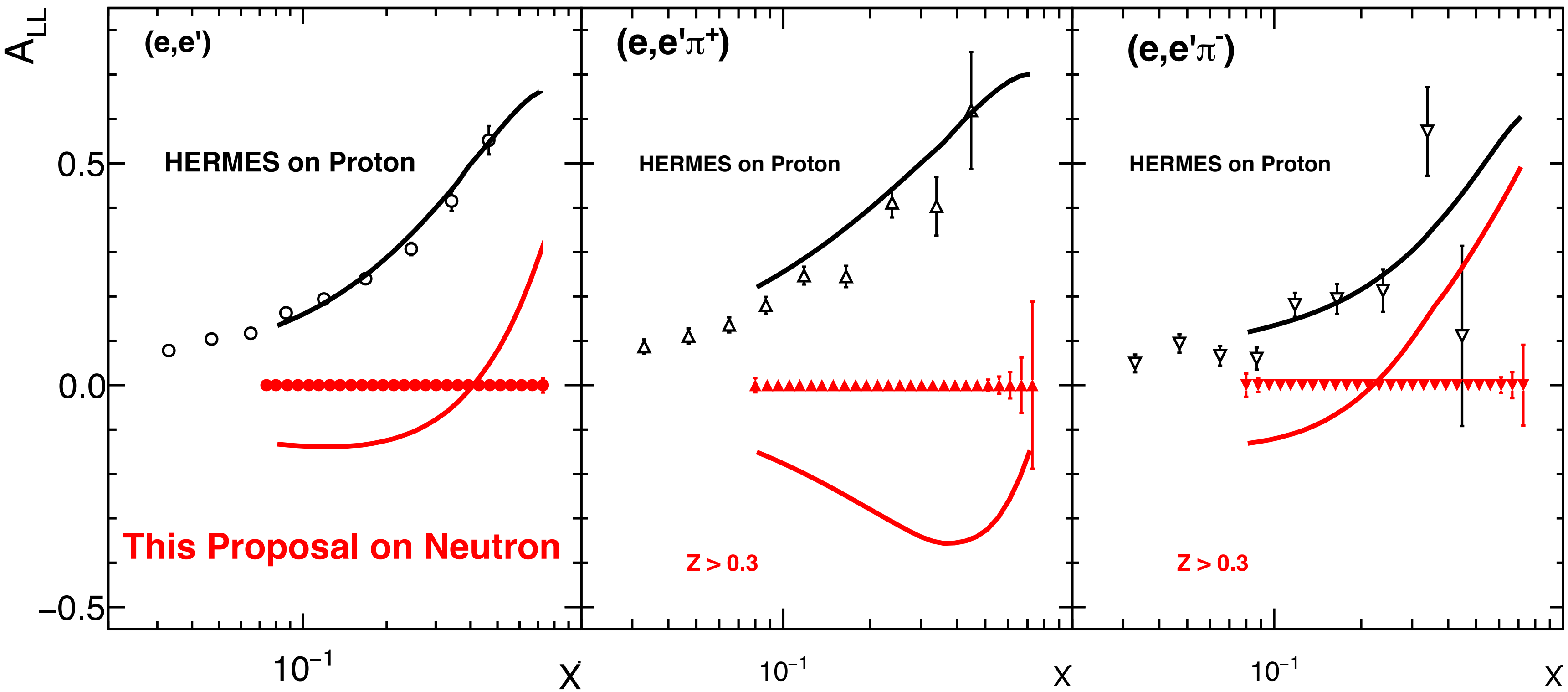
$$P_{\Delta d} = \mu A_{LL,p}^{\pi^+} + \nu A_{LL,n}^{\pi^-}$$



Conclusion:
The k_T-dependent width of the polarized d-quark distribution has a significantly smaller uncertainty from the neutron data compared to the determination from the proton data.

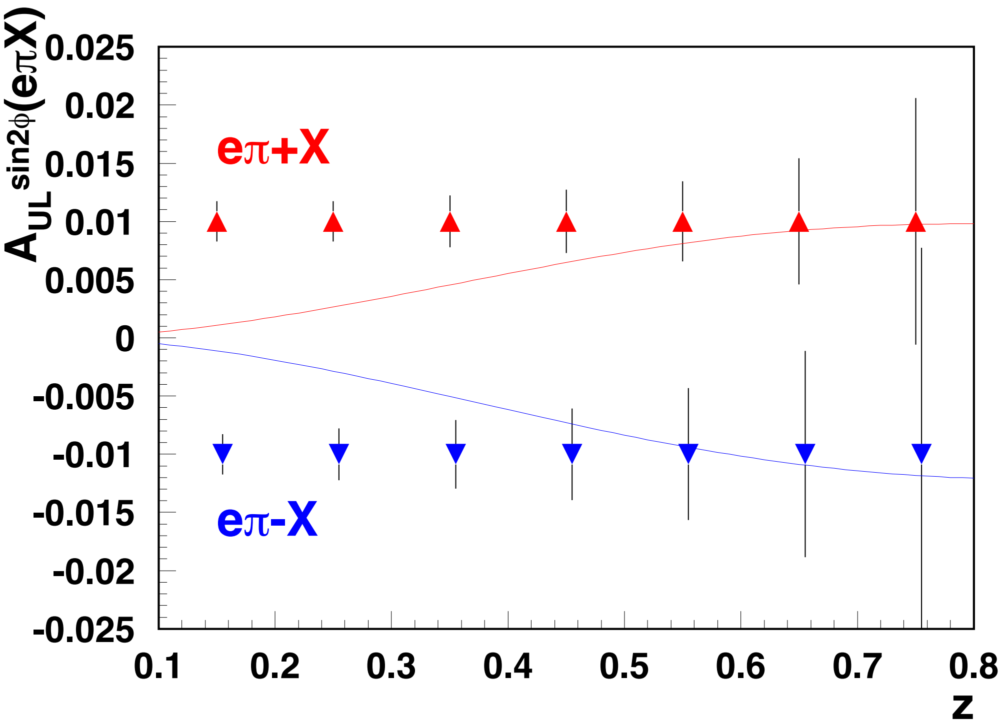
Proposal Projection Measurements

x-dependent projection using GRV and DSS

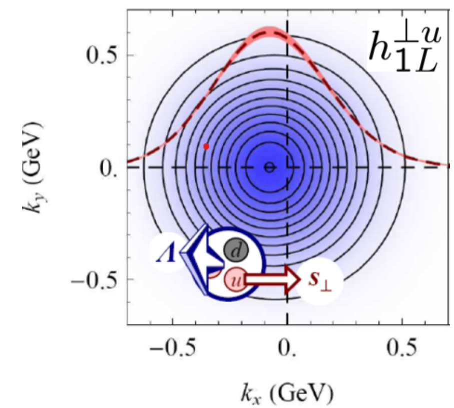


- To study x dependence of $g_1(x, k_T)$ integration over full P_T and ϕ range
- Data on A_{LL} provides important input in global analysis of polarized PDF
- First direct data from neutron
- Statistical precision is significant to determine different dependence

Collins fragmentation: Long. polarized target



Kotzinian-Mulders asym.
Phys. Lett. B406, 373 (1997)



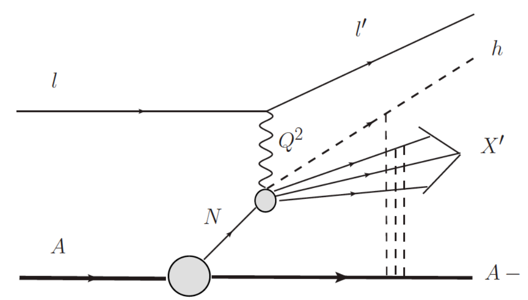
Ph. Hägler *et al.*, Eur. Lett. 88, 61001 (2009)

A_{UL} $h_{1L}^{\perp} H_1^{\perp}$ $\sin 2\phi$

- ❑ Provide access to trans. pol'd quark in long. pol'd neutron.
- ❑ Provide access to Collins fragmentation function.

Nuclear Corrections to the SIDIS Process

- The SIDIS process is fundamental to the scientific agenda of JLab 12 Gev and EIC.
- It is typically (naively) described in terms of PWIA and a convolution of nucleon and sub-nucleon d.o.f.
- However, known processes violate this simplistic picture, e.g. FSI.
- Spin-dependent precision SIDIS on calculable light nuclei (^{2}H, ^{3}He) is an excellent starting point to develop understanding of SIDIS in nuclei.
- ND_3 and polarized ^{3}He in CLAS12 offer the ideal experimental configuration to pursue this.



FSI: Generalized Eikonal Approx.

Kaptari *et al.*, Phys. Rev. C **89**, 035206 (2014)

Systematic Uncertainties

- Beam polarization:

  uncertainty of ±3% and reversal at 30 Hz
- Target polarization:

  uncertainty of ±5% and reversal every 6 hours
- Nuclear corrections in neutron asymmetry extraction: ±6%
- Total systematic uncertainty of ±8%

TABLE I: Budget for systematic uncertainties.

Source	Type	A_{LL}
Raw asymmetries	absolute	negligible
Random coincidences	relative	1%
Polarimetry	relative	6%
Nuclear corrections	relative	4%
Radiative corrections	relative	3%
Total	absolute	negligible
	relative	8%

Møller Scattering

- TAC requested a Geant4 calculation of Møller scattering from the target.
- This has been carried out by Sangbaek Lee using GEMC with full reconstruction of events.
- Under the proposed running conditions, the drift chamber occupancy is less than 3% for all sectors.
- Longitudinally polarized ^{3}He with 0.5 μA has comparable background to running with the LH2 target at 80 nA.

Proposed Beam Current

- Assumed maximum electron beam intensity of 0.5 μA available with current Hall B capabilities.
- With same beamtime request of 30 PAC days, this increases statistical uncertainties over original proposal by x 2.24.
- The proposed experiment still has unprecedented statistical precision.
- Major effect is in high z and P_T bins.
- However, theoretical prediction of asymmetries has uncertainty which may be reduced with further theory and measurements as we develop polarized ^{3}He target.
- May be more informed in 2-3 years when proposed experiment gets underway.
- Further, reducing the beam current has the effect of both reducing beam depolarization and backgrounds in CLAS12.
- After careful consideration believe that 0.5 μA is optimal at this time.

Request

- We request 30 PAC days of polarized electron beam at an energy of 10.6 GeV, intensity of 0.5 μA and polarization 0.8 in Hall B.
- The CLAS12 spectrometer will be operated in the standard configuration.

Summary

- The polarized ^{3}He nucleus, sitting at the interface of the nucleon and calculable light nuclear systems, will be a rich mine of insight into hadron structure for the coming decades.
- The proposed target, together with the CLAS12 spectrometer and upgraded CEBAF beam, offers an unprecedented ability to precisely and comprehensively study this unique nucleus .
- Our initial proposal requesting 30 PAC days focuses on spin-dependent DIS and SIDIS on a longitudinally polarized ^{3}He target with two main physics goals:
  - P_T -dependence of the neutron longitudinal spin structure
  - Nuclear corrections to SIDIS
- Our proposed measurements are complementary and synergistic with previously approved and planned experiments.
- Once the target is realized, other scientific opportunities will be pursued.
- We request scientific approval to allow us to proceed with the development of the target.