The Longitudinal Photon, Transverse Nucleon, Single-Spin Asymmetry in Exclusive Pion Production

Dipangkar Dutta, *Mississippi State*
Dave Gaskell, *Jefferson Lab*
Bill Hersman, *University of New Hampshire*
Garth Huber, *University of Regina*

Hall C Summer Workshop, Jefferson Lab, June 22, 2012.

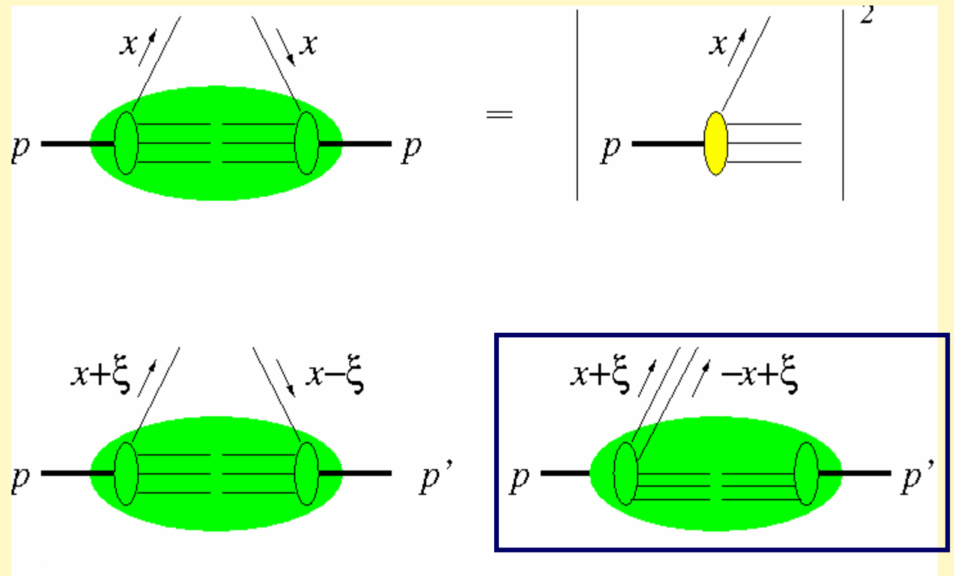
Jefferson Lab A_T^{pi} Collaboration

K. Allada, A. Camsonne, S. Covrig, H.C. Fenker, D. Gaskell, M.K. Jones, D.J. Mack, B. Sawtzky, P. Solvignon, S.A. Wood
Jefferson Lab, Newport News, VA , USA
J. Dunne, D. Dutta, A. Narayan, L. Ndukum, M. Shabestari, A. Subedi, Li Ye
Mississippi State University, Mississippi State, MS, USA
G.M. Huber, W. Li, Z. Papandreou, A. Semenov
University of Regina, Regina, SK, Canada
M. Mihovilovic, S. Sirca
Josef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
A. Ahmidouch, S. Danagoulian
North Carolina A&T State University, Greensoro, NC, USA
P.M. King, J. Roche
Ohio University, Athens, OH, USA
H. Baghdasaryan, M. Dalton
University of Virginia, Charlottesville, VA, USA
F. W. Hersman
University of New Hampshire, Durham, NH, USA
K. Hafidi
Argonne National Laboratory, Argonne, IL, USA
K. Aniol
California State University, Los Angeles, CA, USA
P. Markowitz
Florida International University, FL, USA
A.K. Opper
George Washington University, Washington, DC, USA
Xin Qian
California Institute of Technology, Pasadena, CA, USA
D.L. Hornidge
Mount Allison University, Sackville, NB, Canada
E. Korkmaz
University of Northern British Columbia, Prince George, BC, Canada
A.J. Sarty
St. Mary's University, Halifax, NS, Canada
F.R. Wesselmann
Xavier University of Louisiana, New Orleans, LA, USA

GPDs in Deep Exclusive Meson Production

PDFs : **probability of finding a parton with longitudinal momentum fraction x and specified polarization in fast moving hadron.**

GPDs : **interference between partons with $x+\xi$ and $x-\xi$, interrelating longitudinal and transverse momentum structure of partons within fast moving hadron.**



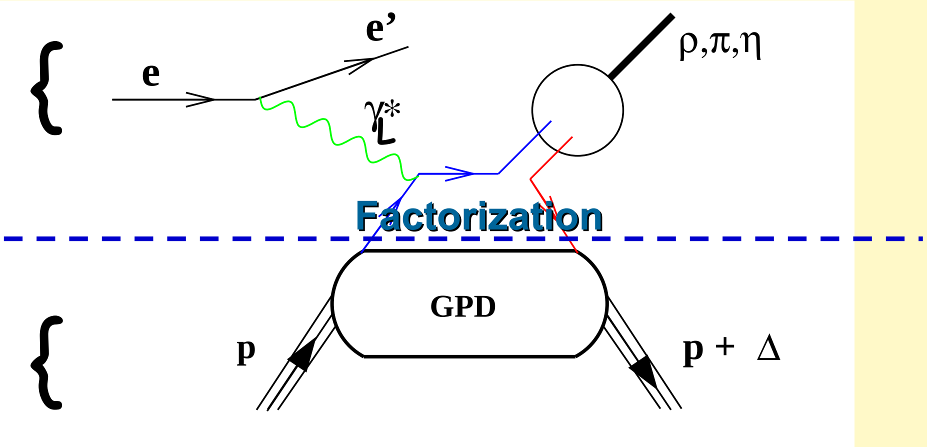
A special kinematic regime is probed in Deep Exclusive Meson Production, where the initial hadron emits $q\bar{q}$ or *gg* pair.

- No counterpart in usual PDFs.
- GPDs determined in this regime carry information about $q\bar{q}$ and gg-components in the hadron wavefunction.

GPDs require Hard Exclusive Reactions

- **In order to access the physics contained in GPDs, one is restricted to the hard scattering regime.**

- **Factorization property of hard reactions:**
  - **Hard probe creates a small size $q\overline{q}$ and gluon configuration,**
    - **interactions can be described by pQCD.**
  - **Non-perturbative part describes how hadron reacts to this configuration, or how the probe is transformed into hadrons (parameterized by GPDs).**

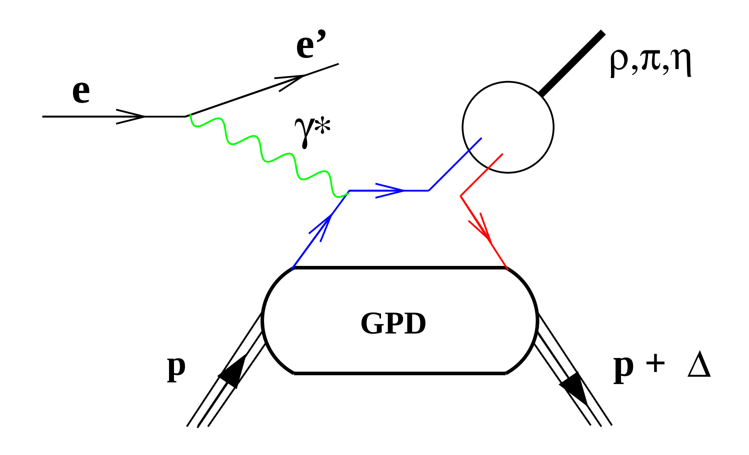


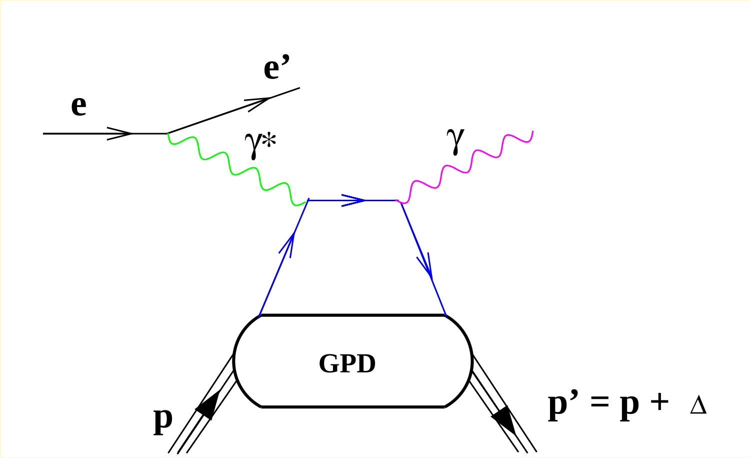
- Hard Exclusive Meson Electroproduction first shown to be factorizable by Collins, Frankfurt & Strikman [PRD **56**(1997)2982].
- Factorization applies when the γ^* is longitudinally polarized.
  - more favorable to produce a small size configuration than transversely polarized γ^*.

Complementarity of Different Reactions

Deep Exclusive Meson Production:

- Vector mesons sensitive to spin-average H, E.
- Pseudoscalar mesons sensitive to spin-difference $\tilde{H}$, $\tilde{E}$.





Deeply Virtual Compton Scattering:

- Sensitive to all four GPDs.

- **Need a variety of Hard Exclusive Measurements to disentangle the different GPDs.**

Links to other nucleon structure quantities

- First moments of GPDs are related to nucleon elastic form factors through model-independent sum rules:

$$\sum_q e_q \int_{-1}^{+1} dx\, H^q(x,\xi,t) = F_1(t)$$

$$\sum_q e_q \int_{-1}^{+1} dx\, E^q(x,\xi,t) = F_2(t)$$

Dirac and Pauli elastic nucleon form factors. *t* -dependence fairly well known.

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

Isovector axial form factor. *t* –dep. poorly known.

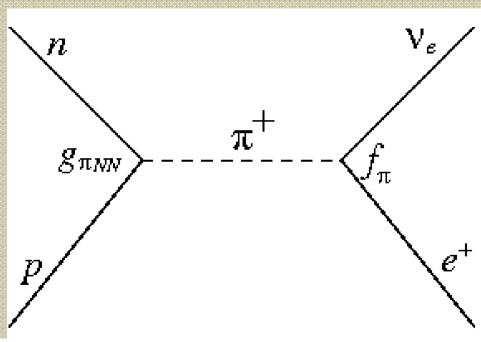
$$\sum_q e_q \int_{-1}^{+1} dx\, \tilde{E}^q(x,\xi,t) = G_P(t)$$

Pseudoscalar form factor. Very poorly known.

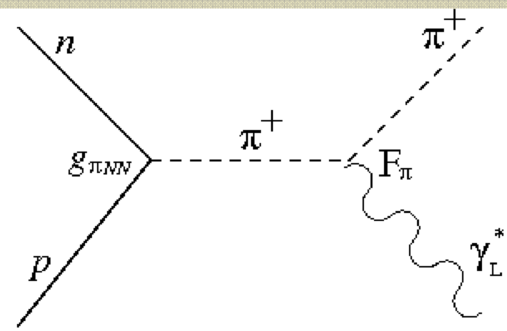
Spin-flip GPD $\tilde{E}$

$$\sum_q e_q \int_{-1}^{+1} dx\ \tilde{E}^q(x,\xi,t) = G_P(t)$$

- $G_P(t)$ is highly uncertain because it is negligible at the momentum transfer of β-decay.
- **Because of PCAC, $G_P(t)$ alone receives contributions from $J^{PG}=0^{--}$ states.**
  - **These are the quantum numbers of the pion, so $\tilde{E}$ contains an important pion pole contribution.**



Pion pole contribution to $G_P(t)$



Pion pole contribution to meson electroproduction at low –t.

For this reason, a pion pole-dominated ansatz is typically assumed:

$$\tilde{E}^{u,d}(x,\xi,t) = F_\pi(t)\frac{\theta(\xi > |x|)}{2\xi}\phi_\pi\left(\frac{x+\xi}{2\xi}\right)$$

where F_π is the pion FF and φ_π the pion PDF.

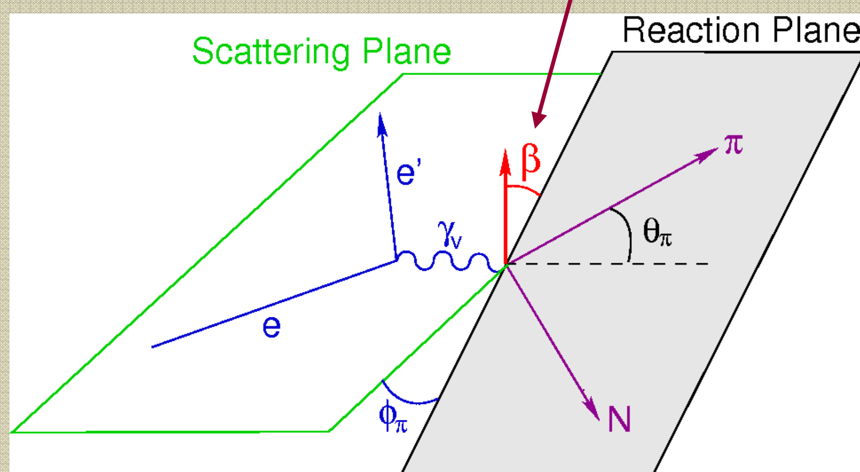
How to determine $\tilde{E}$

- **GPD $\tilde{E}$ not related to an already known parton distribution.**
- Experimental information on $\tilde{E}$ can provide new nucleon structure info unlikely to be available from any other source.
- **The most sensitive observable to probe $\tilde{E}$ is the transverse single-spin asymmetry in exclusive π production:**

$$A_{\perp} = \frac{\int_0^{\pi} d\beta \frac{d\sigma_L^{\pi^-}}{d\beta} - \int_{\pi}^{2\pi} d\beta \frac{d\sigma_L^{\pi^-}}{d\beta}}{\int_0^{2\pi} d\beta \frac{d\sigma_L^{\pi^-}}{d\beta}}$$

$d\sigma_{\pi}^{L}$ = exclusive π cross section for longitudinal γ^*

β =angle between transversely polarized target vector and the reaction plane.



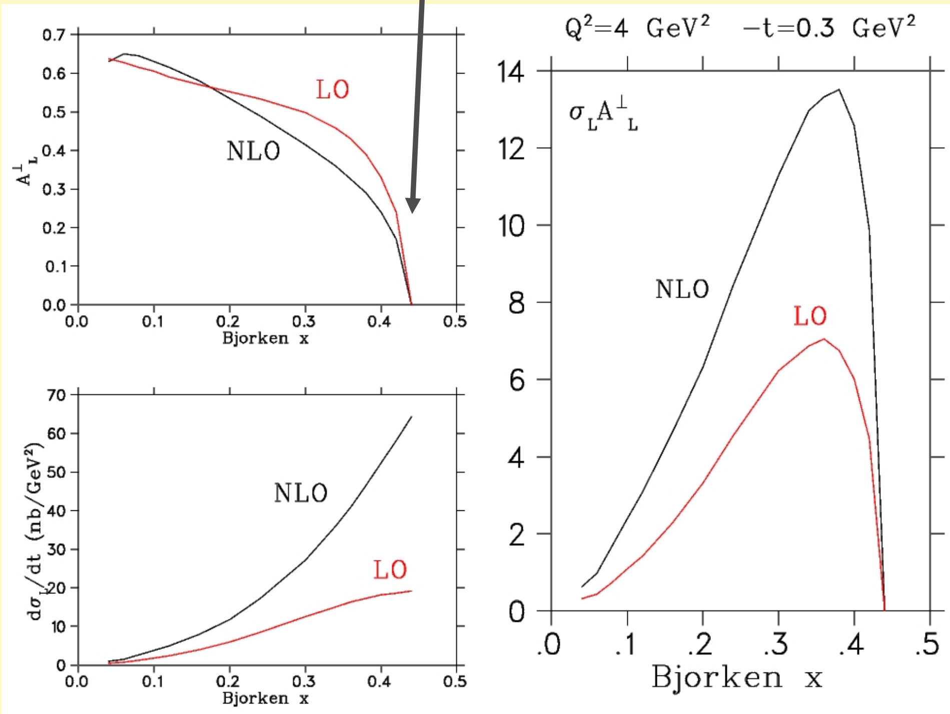
Single Spin Asymmetry in Exclusive π Production

- **Frankfurt et al. have shown $A_L^{\perp}$ vanishes if $\tilde{E}$ is zero** [PRD 60(1999)014010].
  - **If $\tilde{E}\neq 0$, the asymmetry will display a *sinβ* dependence.**
- They also argue that precocious factorization of the π production amplitude into three blocks is likely:
  1. overlap integral between γ, π wave functions.
  2. the hard interaction.
  3. the GPD.
  - **Higher order corrections, which may be significant at low Q^2 for σ_L, likely cancel in $A_L^{\perp}$.**
- **$A_L^{\perp}$ expected to display precocious factorization at moderate Q^2~2-4 GeV^2.**

Cancellation of Higher Twist Corrections in $A_L^{\perp}$

- **Belitsky and Müller GPD based calc. reinforces this expectation:**
  - At Q^2=10 GeV^2, NLO effects can be large, but cancel in $A_L^{\perp}$ (PL **B513**(2001)349).
  - At Q^2=4 GeV^2, higher twist effects even larger in σ_L, but still cancel in the asymmetry (CIPANP 2003).

$A_L^{\perp}$=0 at parallel kinematic limit, where P_y is not well defined.



This relatively low value of Q^2 for the expected onset of precocious scaling is important, because it is experimentally accessible at JLab 12 GeV.

Implications for Pion Form Factor Experiments

- **The study of $A_L^{\perp}$ is also important for the reliable extraction of F_π from $p(e,e'\pi^+)n$ data at high Q^2**
  [Frankfurt, Polyakov, Strikman, Vanderhaeghen PRL **84**(2000)2589].
  - Non-pion pole contributions need to be accounted for in some manner in order to reliably extract F_π from σ_L data at low -t.
  - "A-rated" 12 GeV Pion Form Factor experiment restricted to Q^2=6 GeV^2 by need to keep non-pole contributions to an acceptable level ($-t_{min}$<0.2 GeV^2).

- **$A_L^{\perp}$ is an interference between pseudoscalar and pseudovector contributions.**
  - **Help constrain the non-pole contribution to $p(e,e'\pi^+)n$.**
  - **Assist the more reliable extraction of the pion form factor.**
  - **Possibly extend the kinematic region for F_π measurements.**

Measurement of $A_L^{\perp}$

$$A_L^{\perp} = \frac{1}{P_{\perp}} \frac{2}{\pi} \frac{2\sigma_L^y}{\sigma_L}$$

- At very high Q^2, σ_T suppressed by $1/Q^2$ compared to σ_L.
- At JLab energies, can't ignore contributions from transverse photons.
  - Require two Rosenbluth separations and ratio of longitudinal cross sections:

$$\sigma_A = \sigma_T^{\perp} + \varepsilon\sigma_L^{\perp} \qquad \text{where } \sigma(\varepsilon)=\sigma_U + \sigma_A \sin\beta + \ldots$$

$$\sigma_U = \sigma_T + \varepsilon\sigma_L$$

To cleanly extract $A_{\perp}$, we need:

- Target polarized transverse to γ^* direction.
- Large acceptance in π azimuthal angle (i.e. φ, β).
- Measurements at multiple beam energies and electron scattering angles.

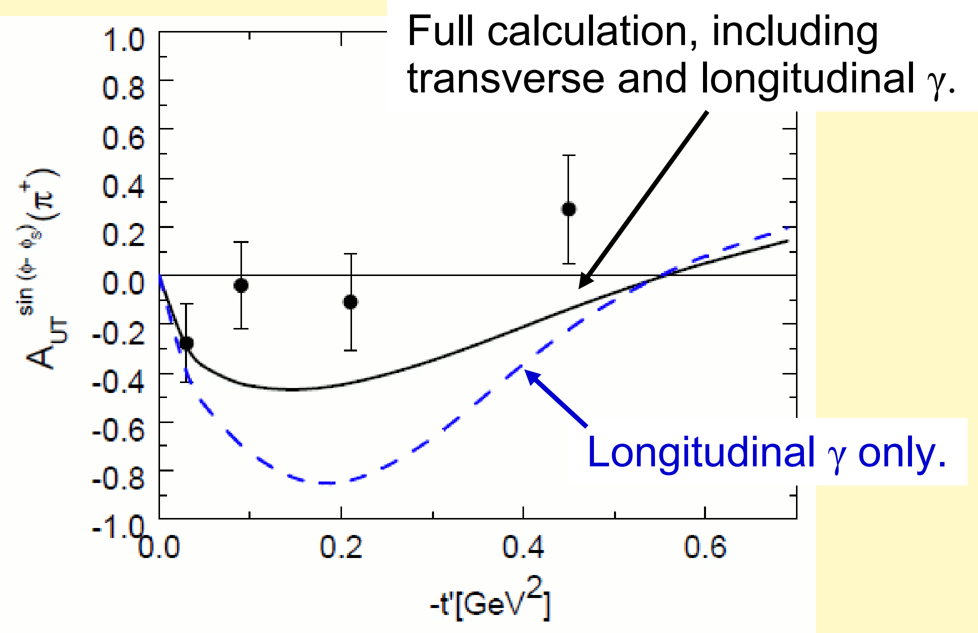
  → ε dependence (L/T separation)

  (advantage of focusing spectrometers in Hall C)

- **Need $\Delta\varepsilon$ as large as possible.**

HERMES Transverse Spin Asymmetry

- Exclusive π+ production by scattering 27.6 GeV positrons or electrons from transverse polarized [1]H **without L/T separation.**
  [PLB **682**(2010)345].
- Analyzed in terms of 6 Fourier amplitudes for φ_π, φ_s.
- $\langle x_B \rangle = 0.13$, $\langle Q^2 \rangle = 2.38$ GeV^2, $\langle -t \rangle = 0.46$ GeV^2.



- **Goloskokov and Kroll indicate the HERMES results have significant contributions from transverse photons, as well as from L and T interferences** [Eur Phys.J. **C65**(2010)137].
- **Because no factorization theorems exist for exclusive π production by transverse photons, these data cannot be simply interpreted in terms of GPDs.**
- Without L/T separation, at JLab the asymmetry dilution is also expected to be substantial [-0.13 vs. -0.32].

$A_L^{\perp}$ a Key GPD Measurement in Meson Sector

- In Deep Exclusive Meson Electroproduction, factorization can only be applied to **longitudinal photons**.
- JLab's unique contribution to this field is in:
  - ability to take measurements at multiple beam energies.
  - unambiguous isolation of $A_L^{\perp}$ using Rosenbluth separation.
- **A JLab $A_L^{\perp}$ measurement could thus establish the applicability of the GPD formalism, and precocious scaling expectations, for other $A^{\perp}$ experiments,**

$A_L^{\perp}$ is the ratio of two purely longitudinal quantities.
If the predicted precocious scaling is shown to not occur, then it may never be possible to experimentally determine GPDs via Deep Exclusive Meson Production.

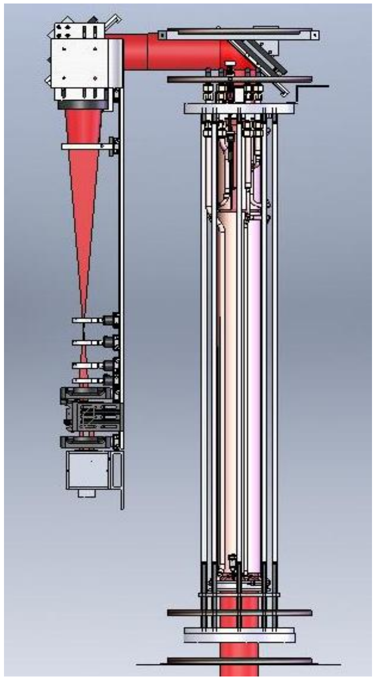
High Luminosity Essential

- **Physics case for a measurement of $A_L^{\perp}$ is compelling.**
- **High luminosity required:**
  - σ_L is largest in parallel kinematics, where $A_L^{\perp}=0$.
  - σ_L is small where $A_L^{\perp}$ is maximal.
- **New polarized ^3He target technology developed by Bill Hersman's group at UNH could allow the measurement to proceed via the $n(e,e'\pi^-)p$ reaction.**
  - Expected to achieve $L=5\times10^{37}$ $cm^{-2}s^{-1}$ needed for feasible measurement.
  - **Not intended to replace target for upcoming A_1^n d_2^n measurements, but should be seen as the development of a next generation ^3He target.**

UNH/Xemed Target Loop Concept

- Compress polarized ^3He and deliver to aluminum target cell
- Non-ferrous diaphragm compressor achieves 3000 psi (~200 bar)
- Returns through a pressure-reducing orifice

External polarizer



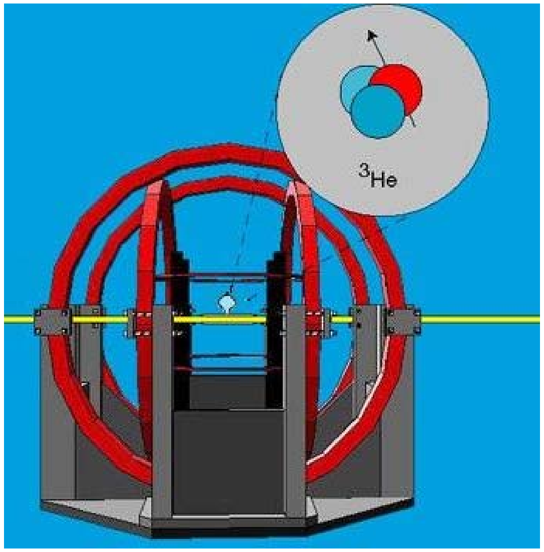
K:Rb Hybrid Spin Exchange Optical Pumping

20 Bar

Non-ferrous diaphragm compressor

200 Bar

Nuclear physics target



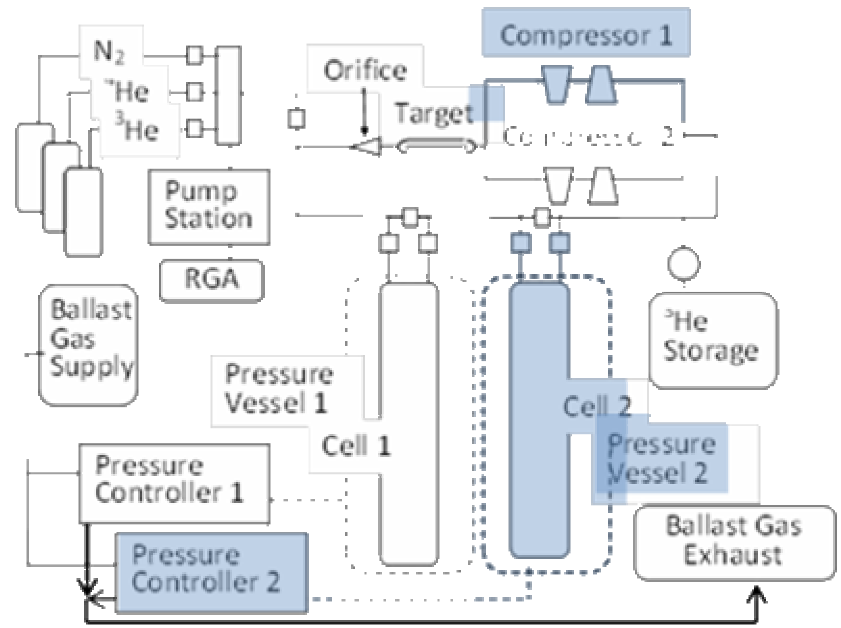
9 cm aluminum target cell
Cooled with LN_2 to 77K
Thickness of 0.5 g/cm^2

Expansion through an orifice

Recirculates at 25 SLPM

^{3}He Polarized Target Rationale

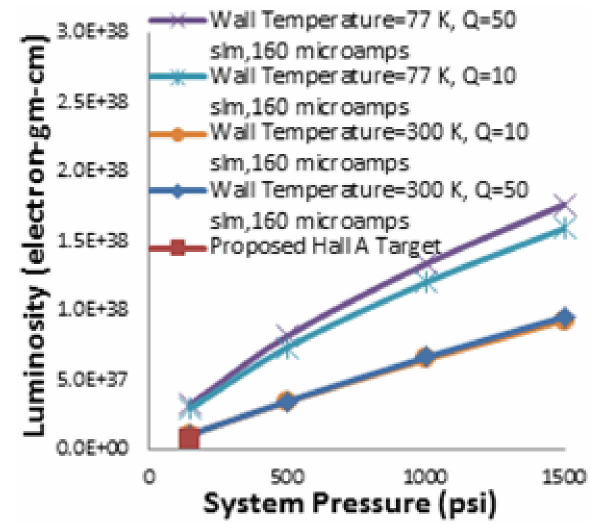
- By providing optical pumping repolarization rates that keep ahead of beam depolarization rates, we propose development of a scalable polarized ^{3}He target system that:
  - provides a ^{3}He target thickness as high as 0.5 g/cm^2 in 10 cm
  - accepts the full 80μA polarized beam current at Jefferson Laboratory, and
  - maintains 65% polarization at luminosity of 10^{38} e-nucleons/cm^2.



- By relocating critical components of the polarizer system in a loop outside the beam enclosure, we can incorporate redundancy and eliminate single points-of-failure.

Target Performance Goals

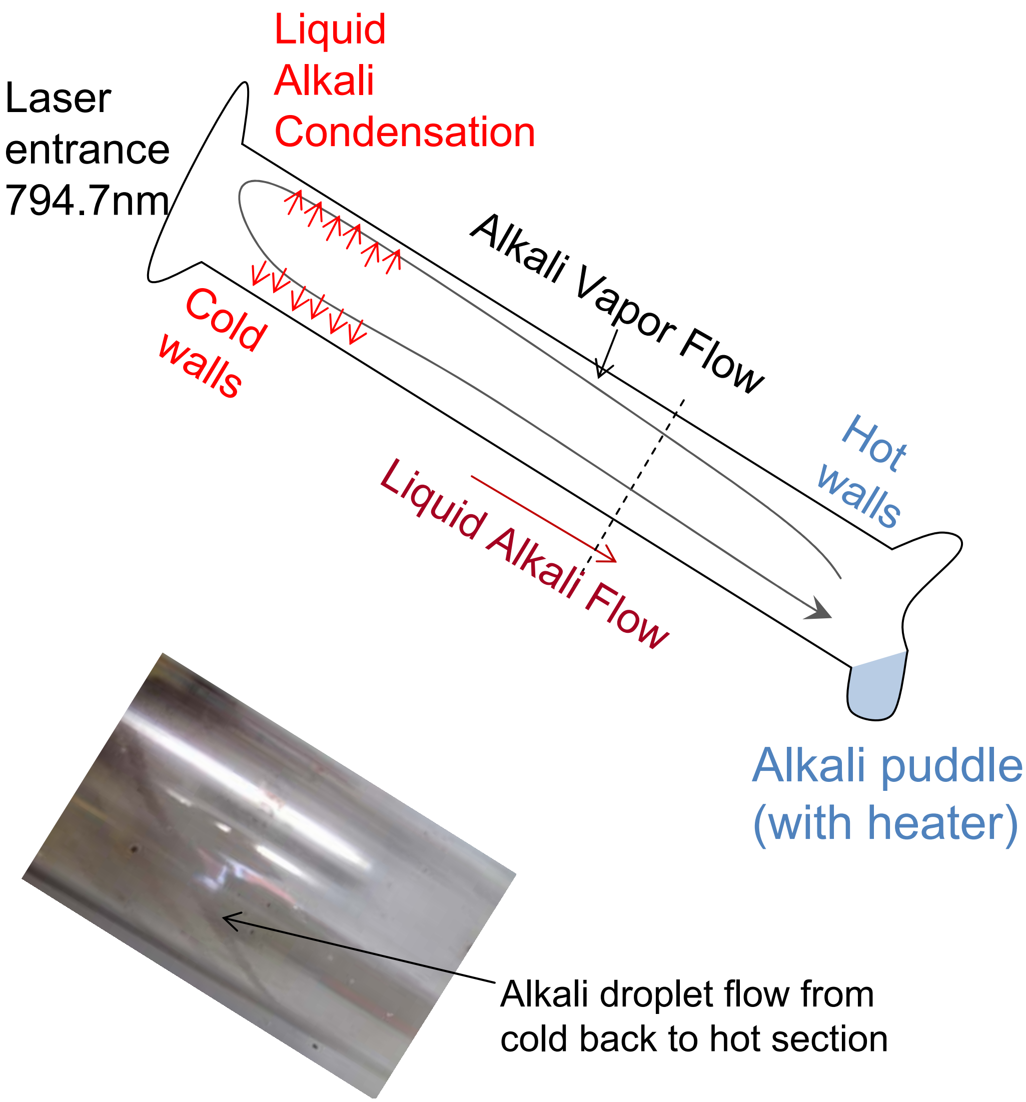
- Spin-up rate of one mole per hour (25% per hour with four moles of ^{3}He gas)
- Beam depolarization constant 10^{-39} per e-nucleon/cm^{2} per hour per atom
  - for rate, multiply times luminosity divide by dilution



Calculated for 160uA beam current on 40cm target

- Assuming beam depolarization dominates losses, peak figure-of-merit occurs at luminosity 10^{39} with half polarization, ~35%
- Maintains ~65% polarization at luminosity 10^{38} e-nucleons/cm^{2}

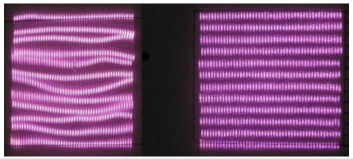
Polarizer Schematic

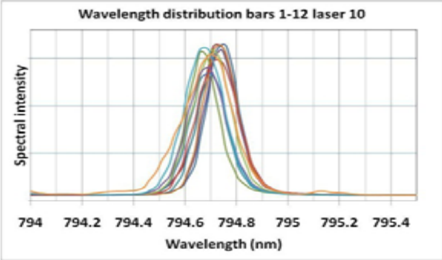


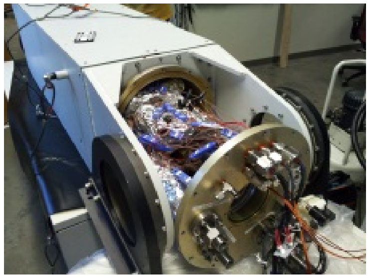
- K-He spin exchange less "lossy" than Rb-He, requiring fewer replacement photons.
- Can reach higher efficiencies by using high alkali densities at higher temperatures, reducing "spin-up time" to just a few hours.
- 8.5L cylindrical glass vessel with thin optical window at top.
- Enclosed in pressure vessel to neutralize pressure differential across glassware.
- Lower part of cell maintained at 250^{o}C, to achieve desired alkali density for hybrid SEOP.

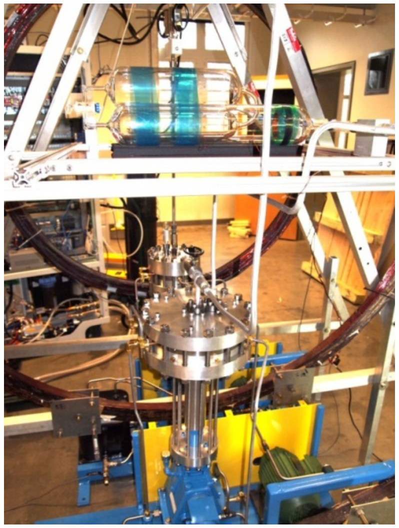
SEOP polarizer test station

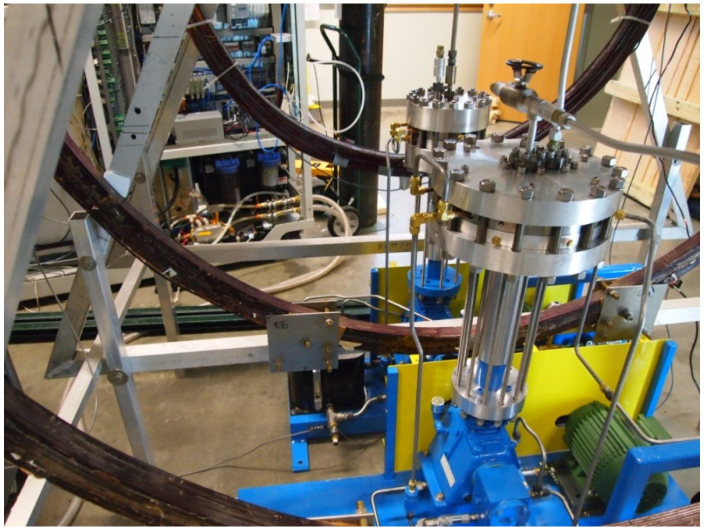
- 2.5kW spectrally-narrowed smile-corrected laser has demonstrated polarization spin-up of ~20%/hr
- 8.5L polarizer cell inside a 10atm pressure vessel (6 amagat) polarize 50L. Final design will be 20atm (12 amagat) to polarize 100L
- Titanium/bronze/PEEK pump for compression to 1000psi in test station. Final design is 3000psi.
- NMR measures polarization in loop







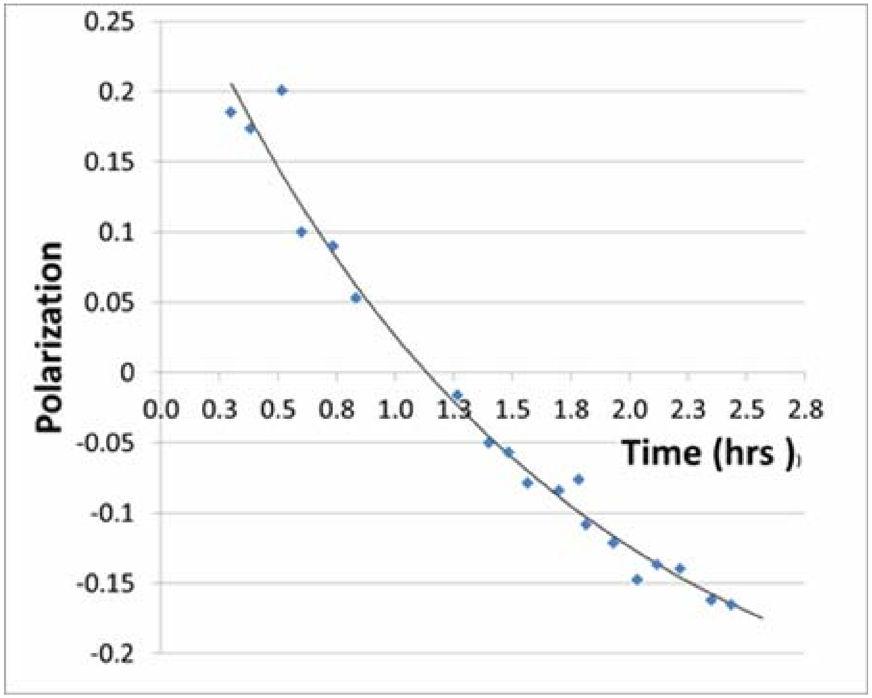




Working Large-Scale ^{3}He Polarizer Prototype

Assembled, Operating ^{3}He Polarizer

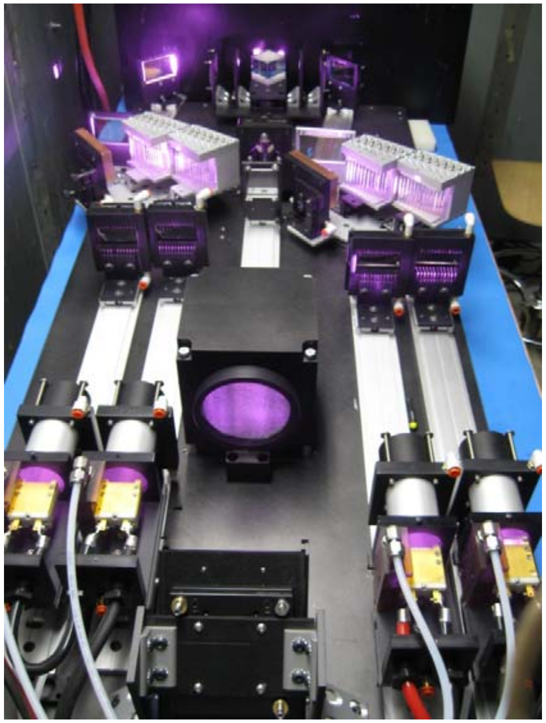
- 8.5L aluminosilicate glass cell.
- Pressure-vessel enclosure.
- Operation up to 20 atm.
- Hybrid pumping with K:Rb.
- Spectrally narrowed 2.5kW laser.



- Spin-up curve measured by laser-polarization-inversion.
- Spin-up rate ~15%/hr.

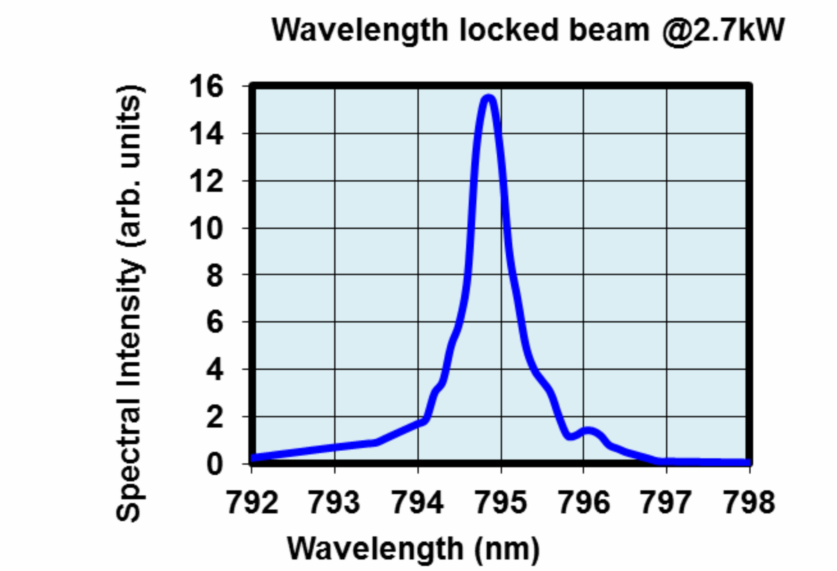
21

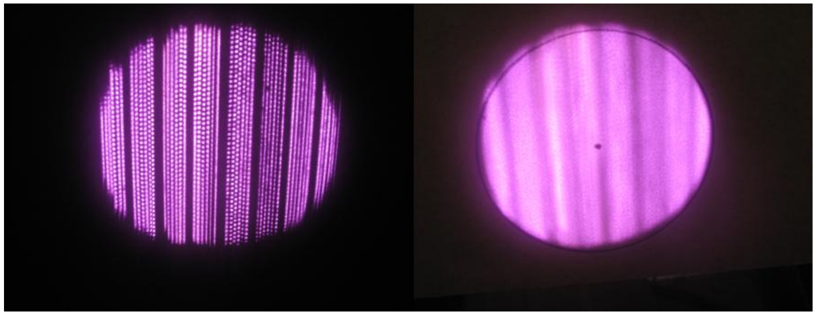
2700 Watt narrowed laser performance



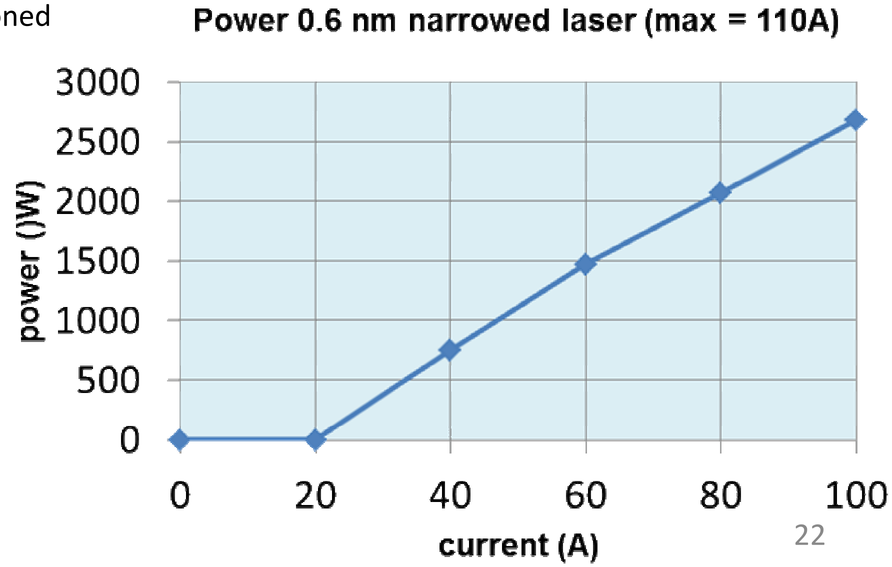
Four 12 bar lasers (foreground) combining their outputs into a single 10 cm diameter beam (center).

Less-than-optimal components decommissioned from other projects cause beam inhomogeneities

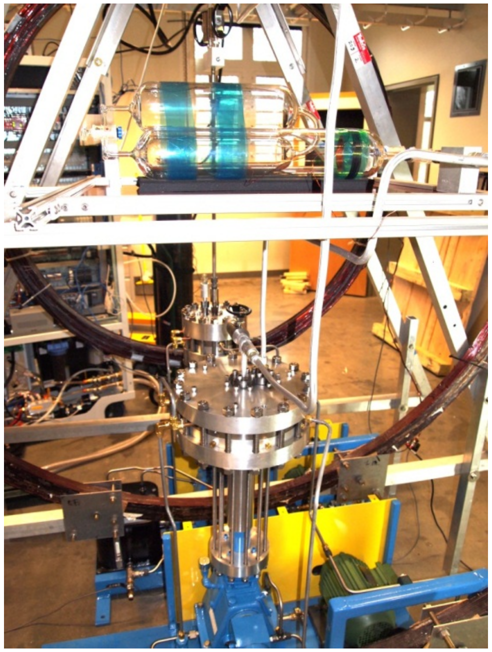


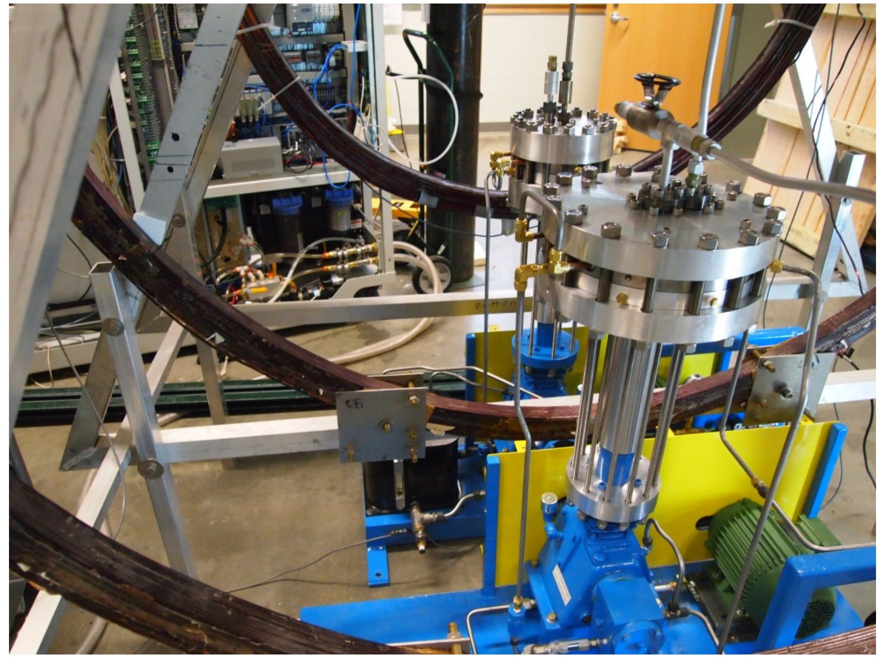


48 Bar exit beam, and 1m downstream with diffuser.
Divergence ~3x6 mrad (hor x vert.)



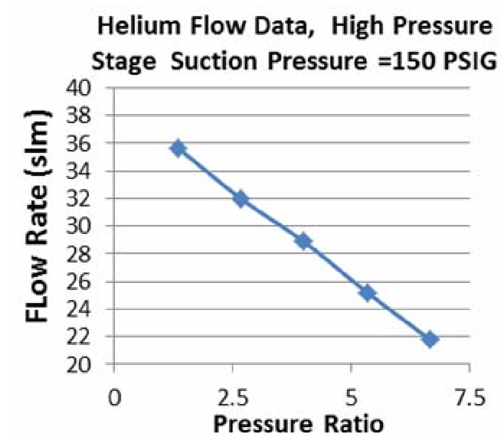
Status :Non-ferrous Diaphragm Pump





- Piston-driven hydraulic compression
- Nominal 30 cps
- Compression ratio ~6.5
- Two pumps ordered
- Low pressure: 50 torr to 150 psi
- 150psi to 1000 psi @ 22 SLM

- PEEK valves
- Titanium head 6AL4V
- Three-layer diaphragm
- Phosphor-bronze wetted
- Delivered February, 2012



High Luminosity Polarized ^{3}He Target Status

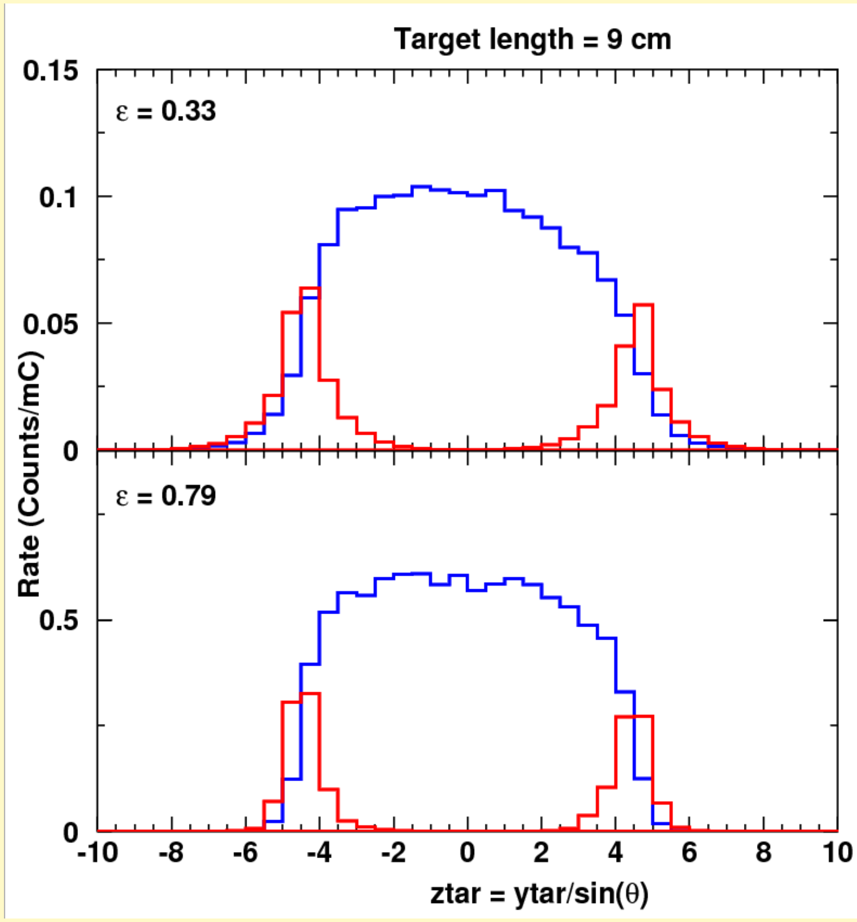
Many of the hardest technological hurdles have been demonstrated through working prototypes.

1. Large-scale ^{3}He polarizer can operate at temperatures, pressures and laser-beam intensities that replace spins (much) faster than they will be destroyed by the beam at L=5x10^{37} cm^{-2}s^{-1}.
2. Capability to develop and produce industrial-quality compressor pumps from non-ferrous materials.

Next phase of development:

1. Need to demonstrate high polarization (inadvertent contamination has limited asymptotic polarization <50%).
2. Need to make a cell with inlet and exit ports.
3. Need to measure ^{3}He depolarization in a loop that includes pump and orifice.

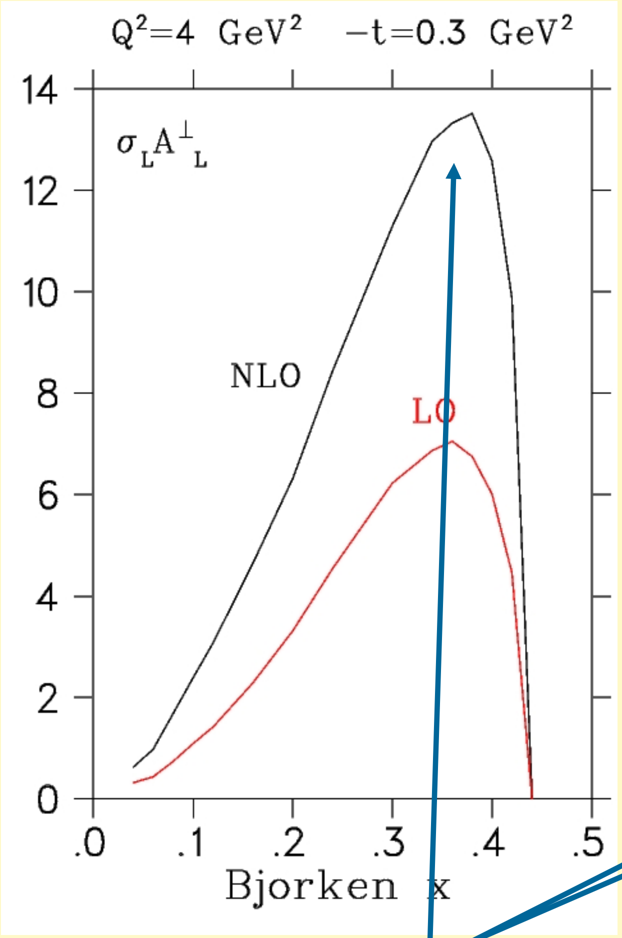
Reliable L/T Separations require short target cells



Q^2=4.0 GeV^2, W=2.6 GeV.
Acceptance matching "diamond cut" applied.

- Shorter target cell needed so full cell is within coincidence acceptance at high, low ε.
  - 9.5cm target is fully within acceptance, but will use 9.0cm to provide extra safety margin.
- To achieve $\mathcal{L}$=5x10^{37}cm^{-1}s^{-1} require 200atm ^{3}He gas at 130K.
  - Cool entrance and exit lines of cell with LN_2.
  - Initial design assumes 500μm Al walls. Final design will depend on JLab technical reviews, etc.
- Target wall contributions will be subtracted via dedicated Al dummy target runs.

SHMS+HMS Kinematics



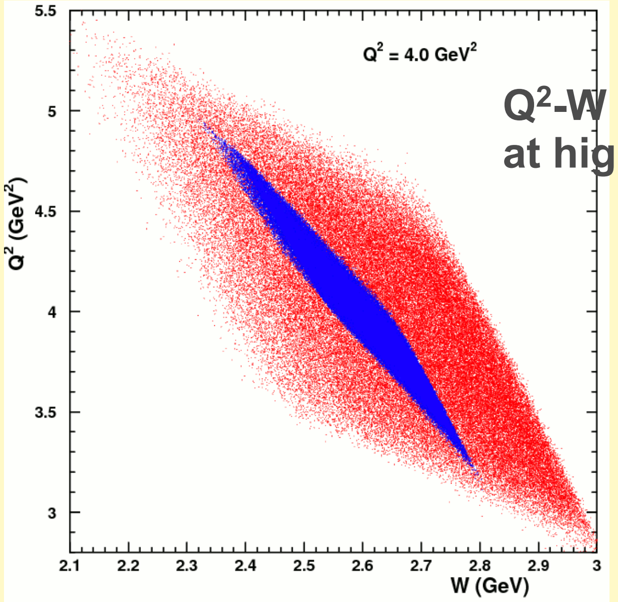
Near peak of Figure of Merit in Belitsky's calculation

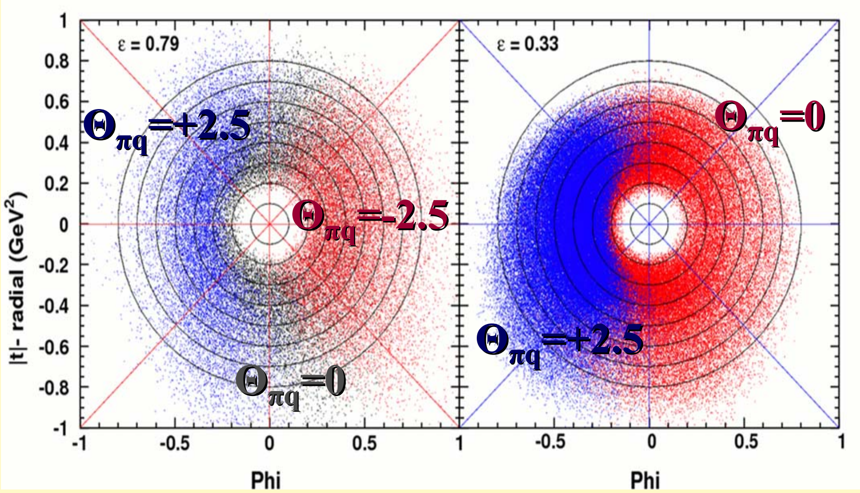
n(e,e'π-)p Kinematics						
E_{beam}	$E_{e'}$	$\theta_{e'}$	ε	θ_q	p_π	$\Theta_{\pi q}$
MAIN Q^2=4.0 W=2.6 x=0.40 $-t_{min}$=0.22						
6.60	1.34	39.2	0.33	-8.7	5.14	0, +2.5
10.92	5.66	14.6	0.79	-14.7	5.14	0, ±2.5
SCALING Q^2=3.0 W=2.3 x=0.40 $-t_{min}$=0.22						
6.60	2.66	23.9	0.64	-14.5	3.82	0, ±2.5
10.92	6.98	11.4	0.89	-18.7	3.82	0, ±2.5
NON-POLE Q^2=4.0 W=2.25 x=0.50 $-t_{min}$=0.39						
6.60	2.66	29.3	0.57	-14.3	4.03	0, ±2.5
10.9	6.69	13.4	0.87	-19.4	4.03	0, ±2.5

Simulated SHMS+HMS Acceptance

$^3He(e,e'\pi^-)p(pp)_{SP}$

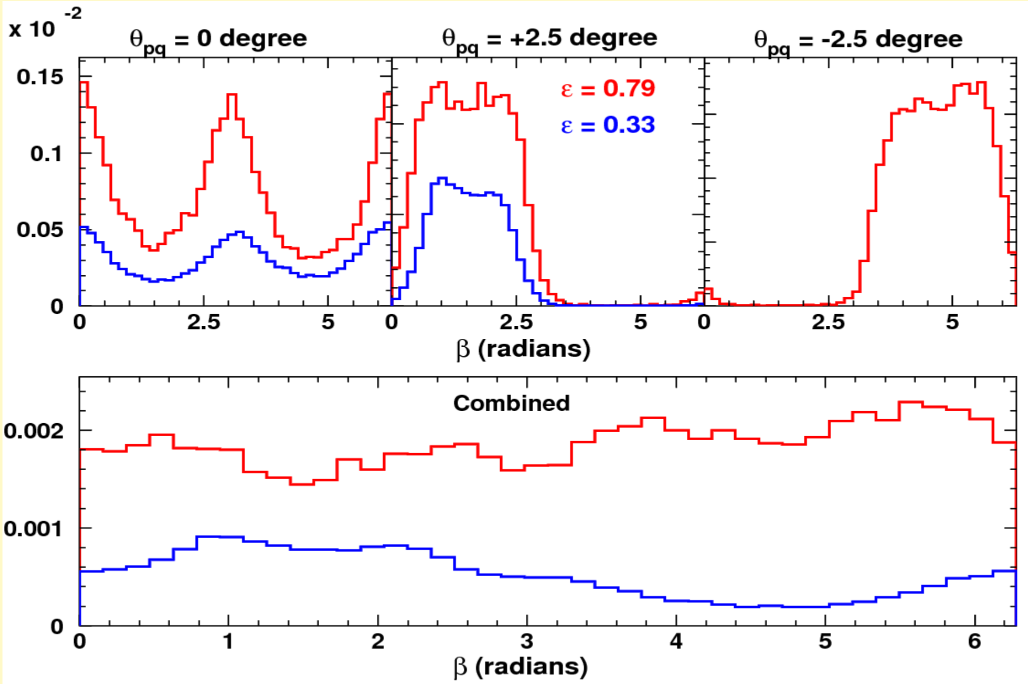
Q^2=4.0 W=2.6 low ε high ε Δε = 0.46





Q^2-W acceptance at high and low ε.

Azimuthal angle of (transversely) polarized target wrt hadron reaction plane.



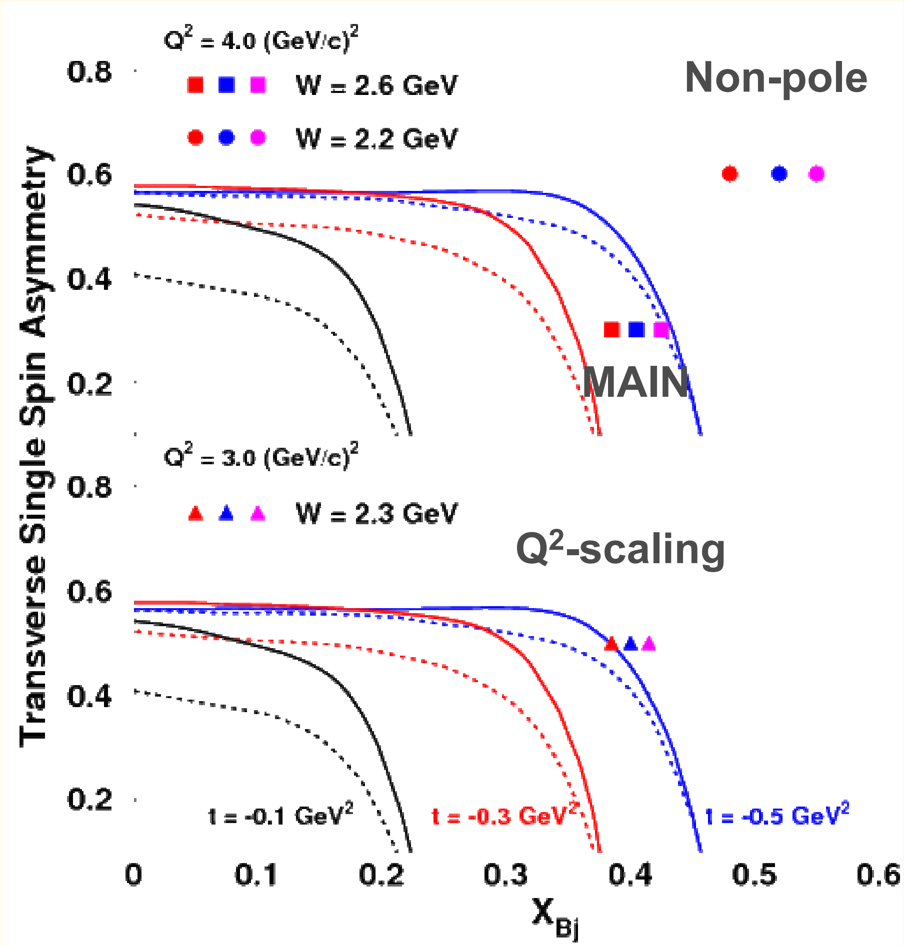
Magnetic Spectrometer Calibrations

- Similarly to Fπ-2, we propose to use the over-constrained *p(e,e'p)* reaction and inelastic $e+^{12}$C in the DIS region to calibrate spectrometer acceptances, momenta, offsets, etc.
  - Fπ-2 beam energy and spectrometer momenta determined to <0.1%.
  - Spectrometer angles <0.5 mr.
  - Fπ-2 agreement with published $p+e$ elastics cross sections <2%.
- **Some partial cancellation of uncorrelated uncertainties will occur when forming ratio of two longitudinal cross sections ($A_L^{\perp}$).**

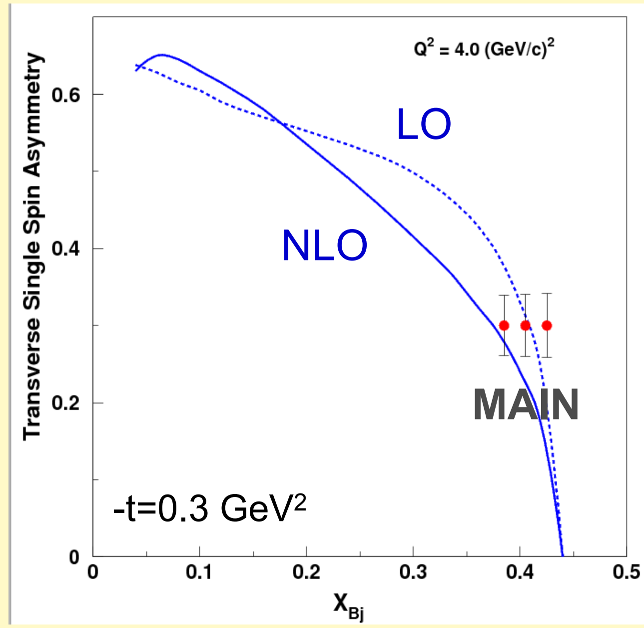
Projected Systematic Uncertainty Source	Pt-Pt ε-random t-random	ε-uncorrelated common to all t-bins	Scale ε-global t-global
Spectrometer Acceptance	0.7% (0.4%)	0.4% (0.2%)	1.0%
Target Thickness		0.2%	0.8%
Beam Charge	-	0.2%	0.5%
HMS+SHMS Tracking	0.1%	0.1%	1.5%
Coincidence Blocking		0.2%	
PID		0.4%	
Pion Decay Correction	0.03%	-	0.5%
Pion Absorption Correction	-	0.1%	1.5%
MC Model Dependence	0.4% (0.2%)	1.0% (0.5%)	0.5%
Radiative Corrections	0.1%	0.4%	2.0%
Kinematic Offsets	0.4% (0.2%)	1.0% (0.5%)	-
TOTAL	**0.8% (0.5%)**	**1.6% (1.0%)**	**3.3%**

- Uncorrelated uncertainties in σ_{UNS} are amplified by $1/\Delta\varepsilon$ in L-T separation.
- Scale uncertainty propagates directly into separated cross section.

Projected $A_L^{\perp}$ Uncertainties



Solid: asymptotic pion distribution amp.
Dashed: CZ pion dist. amp.



- **Example t-binning only.** Finer binning will depend on actual experimental factors.
- Errors include statistical and uncorrelated systematic uncertainties (including partial cancellation of uncorrelated systematic errors when forming the ratio).
- Assumes $\sigma_{L/}\sigma_T$=1 and ^{3}He target polarization of 65%.