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

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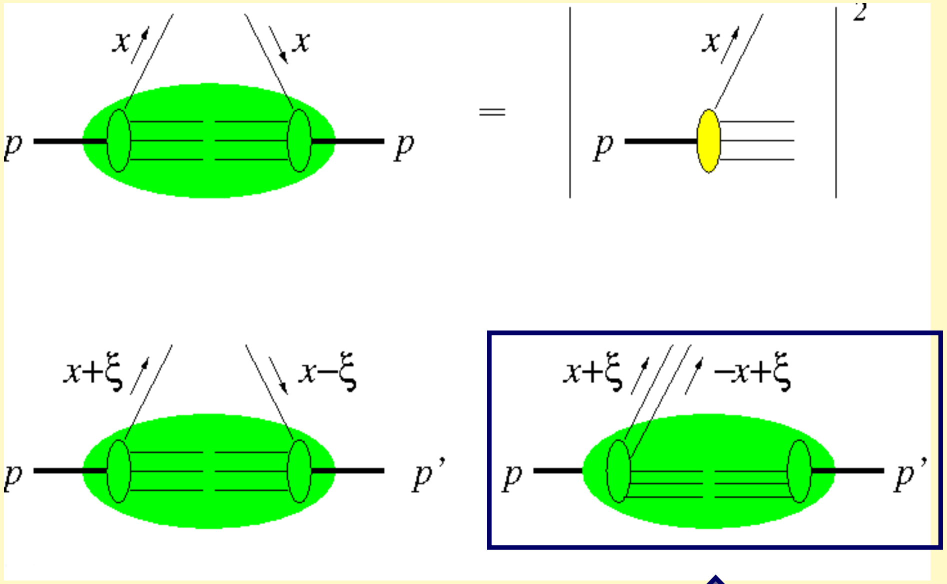
GPDs in Deep Exclusive Meson Production

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.**



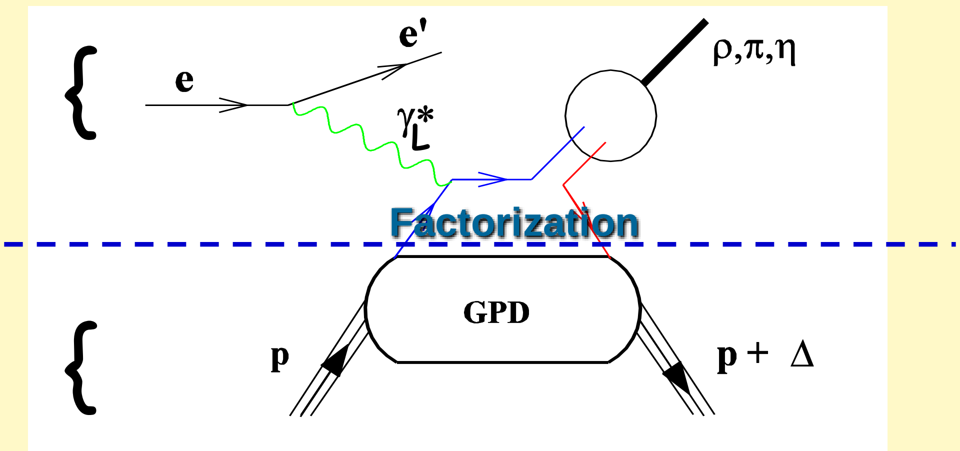
A special kinematic regime is probed in Deep Exclusive Meson Production, where the initial hadron emits $q\bar{q}$ or gg pair.

- 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 $q\bar{q}$ 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).

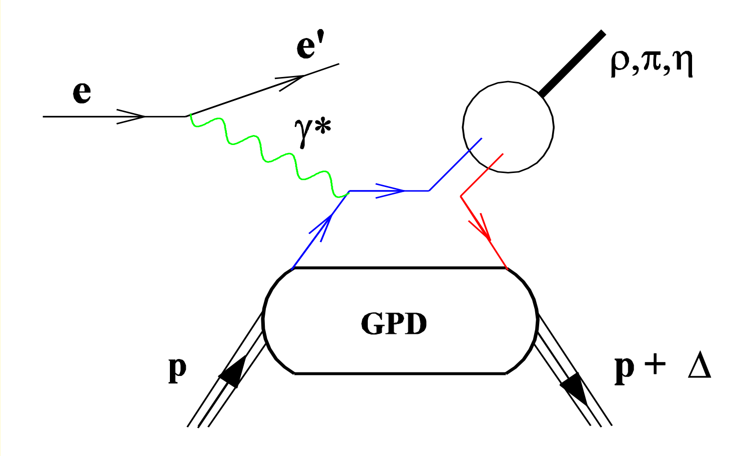


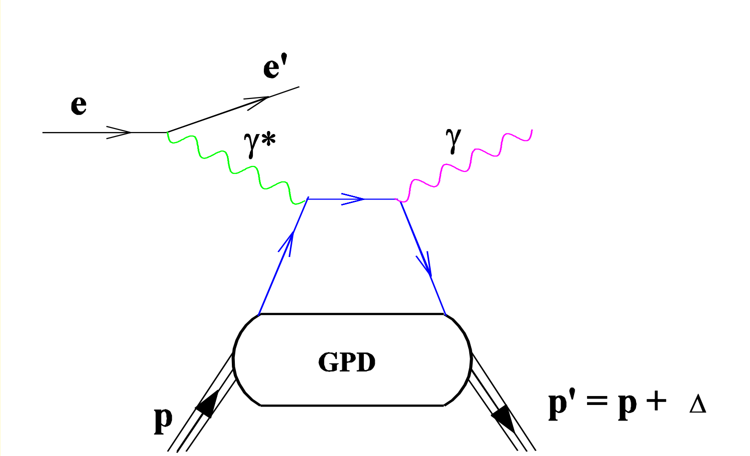
- Hard Exclusive Meson Electroproduction first shown to be factorizable by Collins, Frankfurt & Strikman [PRD **56**(1997)2982].
- Factorization applies when the γ^* is longitudinally polarized.
  - more favorable to produce a small size configuration than transversely polarized γ^*.

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.

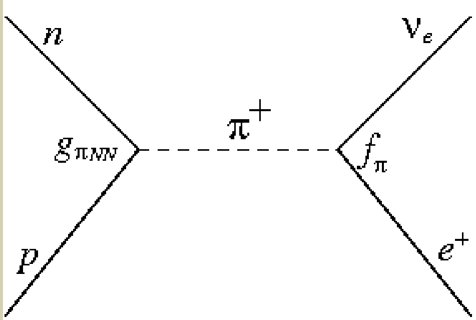
$$\sum_q e_q \int_{-1}^{+1} dx\ \tilde{E}^q(x,\xi,t) = G_P(t)$$

Pseudoscalar form factor. Very poorly known.

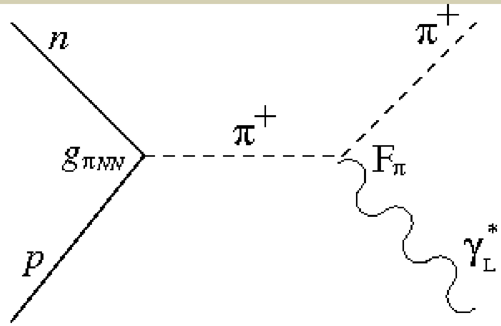
Spin-flip GPD $\tilde{E}$

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

- $G_P(t)$ 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.

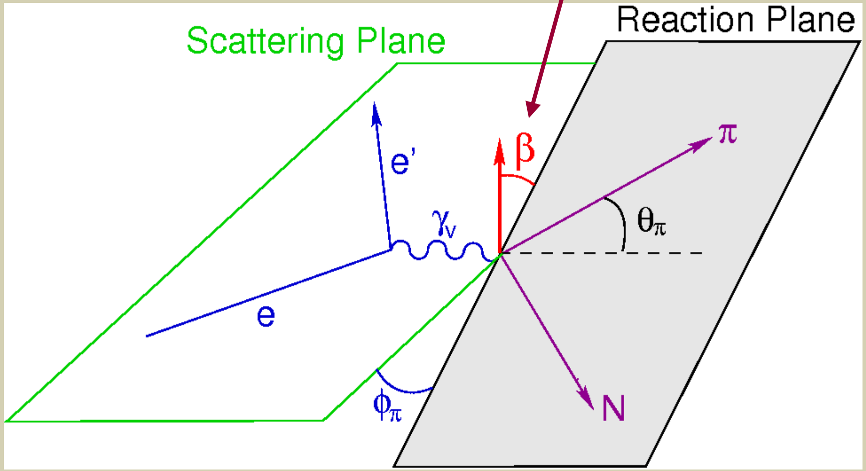
How to determine $\tilde{E}$

- **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.



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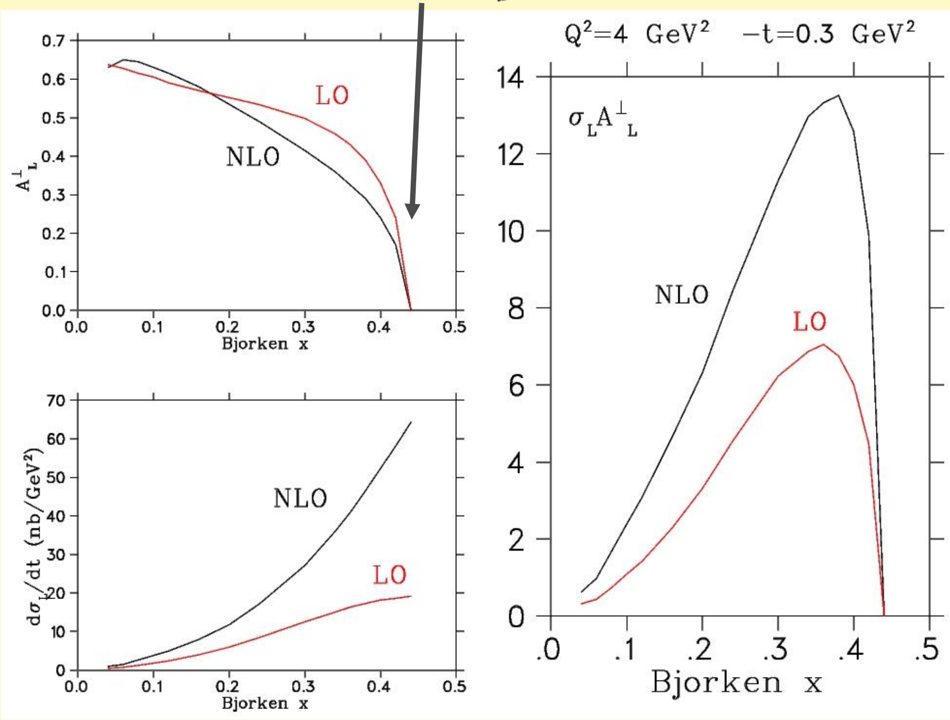
Single Spin Asymmetry in Exclusive π Production

- **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)

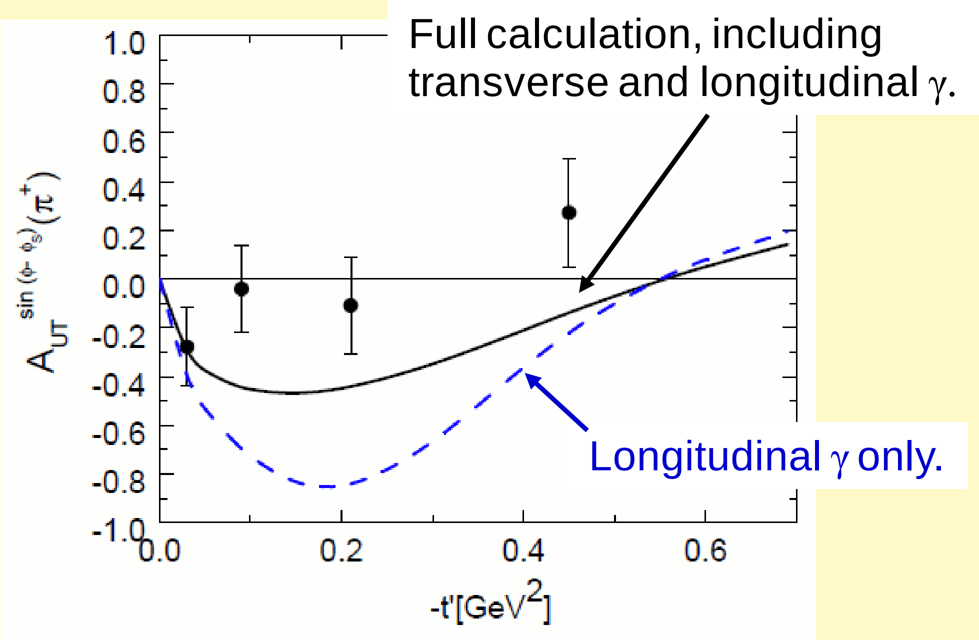
  (advantage of focusing spectrometers in Hall C)

- **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.

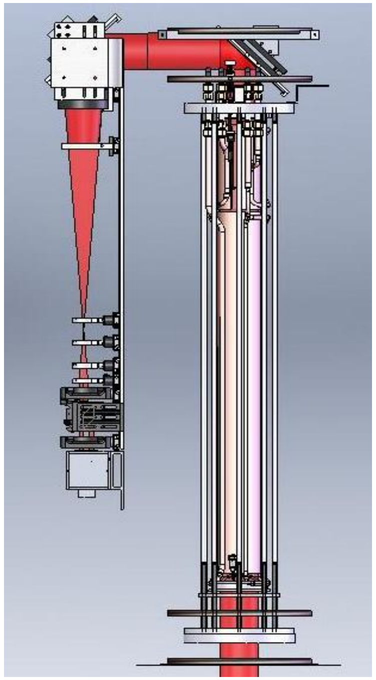
High Luminosity Essential

- **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 ^{3}He 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=5x10^{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 ^{3}He 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



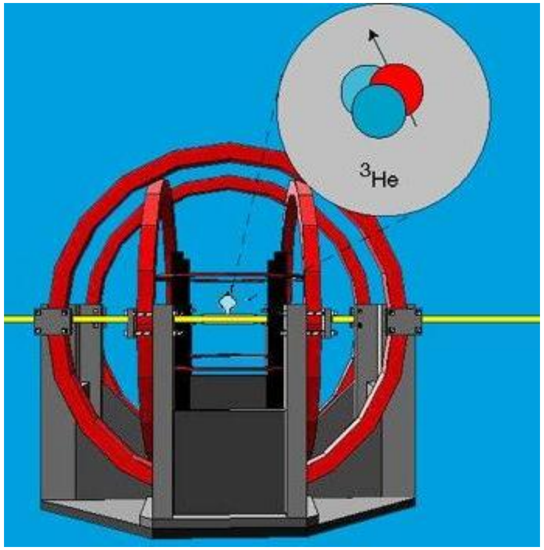
K:Rb Hybrid Spin Exchange Optical Pumping

20 Bar

Non-ferrous diaphragm compressor

200 Bar

Nuclear physics target



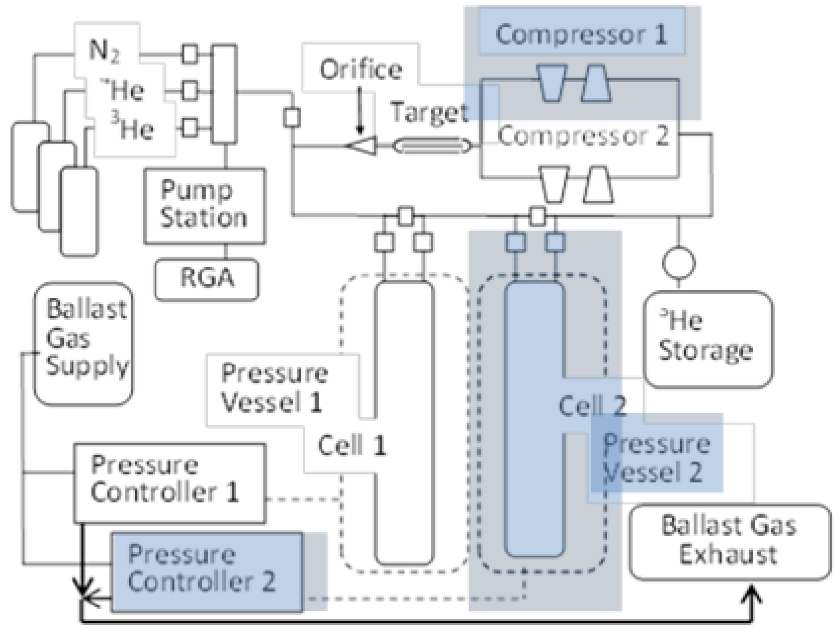
9 cm aluminum target cell
Cooled with LN_2 to 77K
Thickness of 0.5 g/cm²

Expansion through an orifice

Recirculates at 25 SLPM

^{3}He Polarized Target Rationale

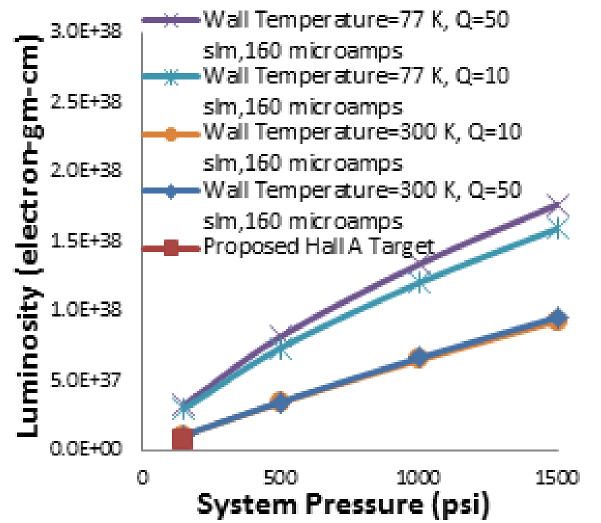
- By providing optical pumping repolarization rates that keep ahead of beam depolarization rates, we propose development of a scalable polarized ^{3}He target system that:
  - provides a ^{3}He target thickness as high as 0.5 g/cm^2 in 10 cm
  - accepts the full 80μA polarized beam current at Jefferson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

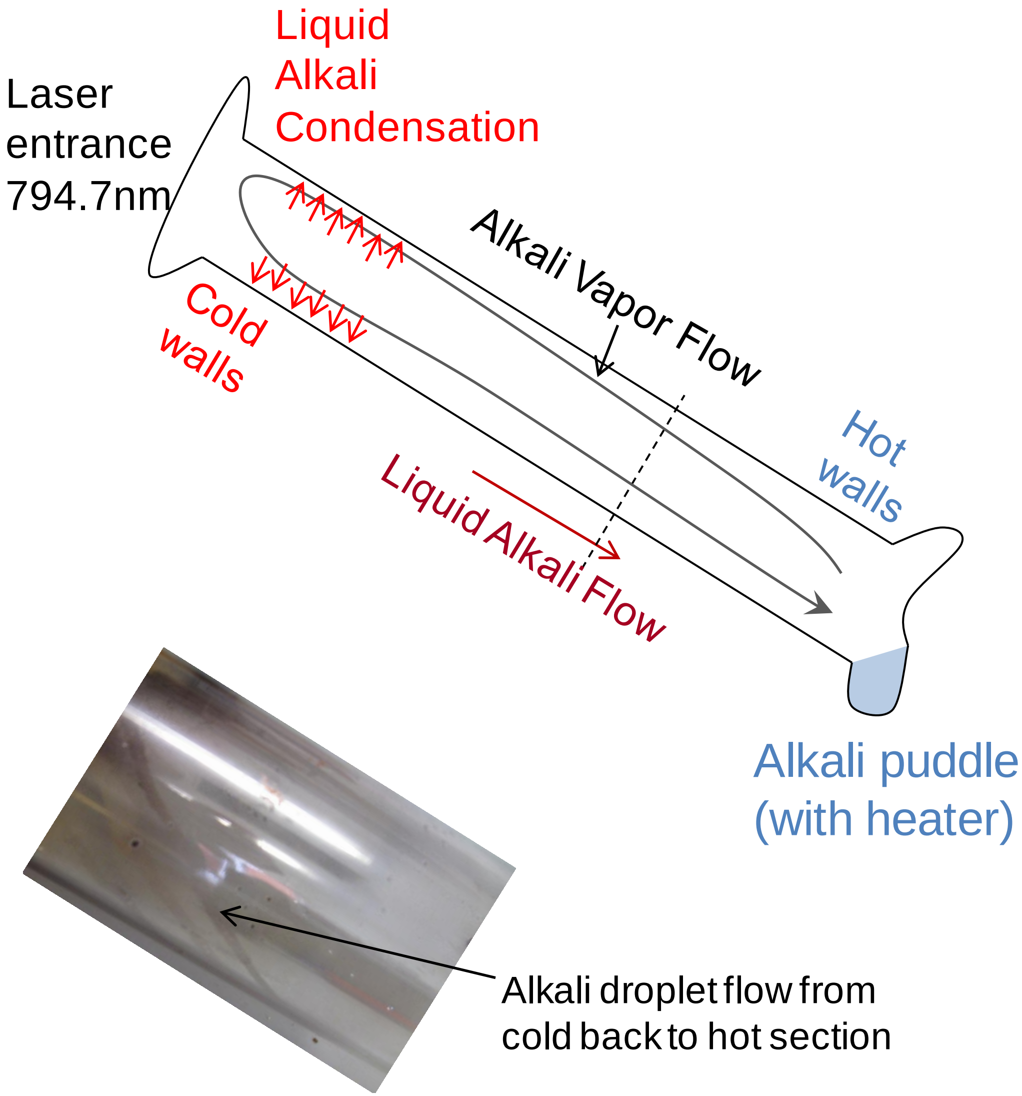
- Spin-up rate of one mole per hour (25% per hour with four moles of ^3He gas)
- Beam depolarization constant 10^{-39} per e-nucleon/cm^2 per hour per atom
  - for rate, multiply times luminosity divide by dilution



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

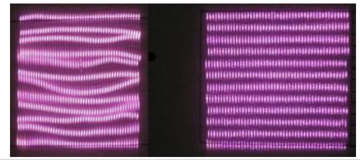
Polarizer Schematic

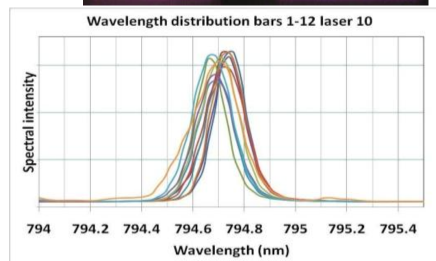


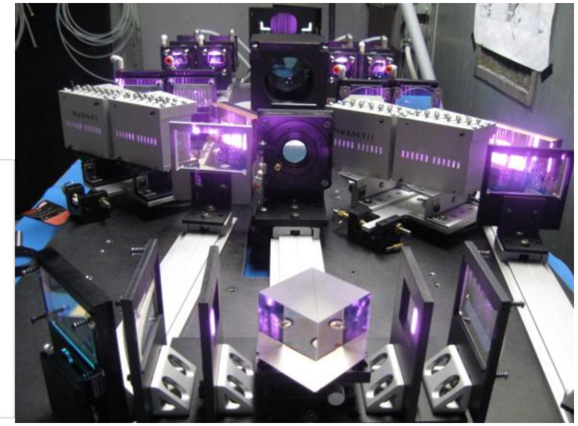
- K-He spin exchange less "lossy" than Rb-He, requiring fewer replacement photons.
- Can reach higher efficiencies by using high alkali densities at higher temperatures, reducing "spin-up time" to just a few hours.
- 8.5L cylindrical glass vessel with thin optical window at top.
- Enclosed in pressure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

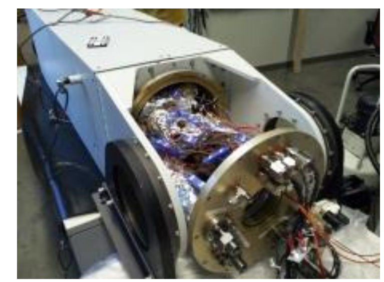
SEOP polarizer test station

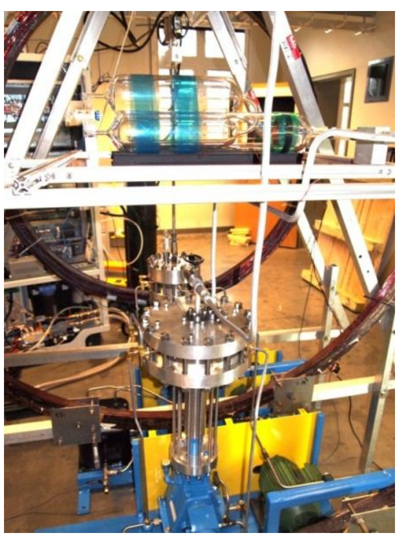
- 2.5kW spectrally-narrowed smile-corrected laser has demonstrated polarization spin-up of ~20%/hr
- 8.5L polarizer cell inside a 10atm pressure vessel (6 amagat) polarize 50L. Final design will be 20atm (12 amagat) to polarize 100L
- Titanium/bronze/PEEK pump for compression to 1000psi in test station.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

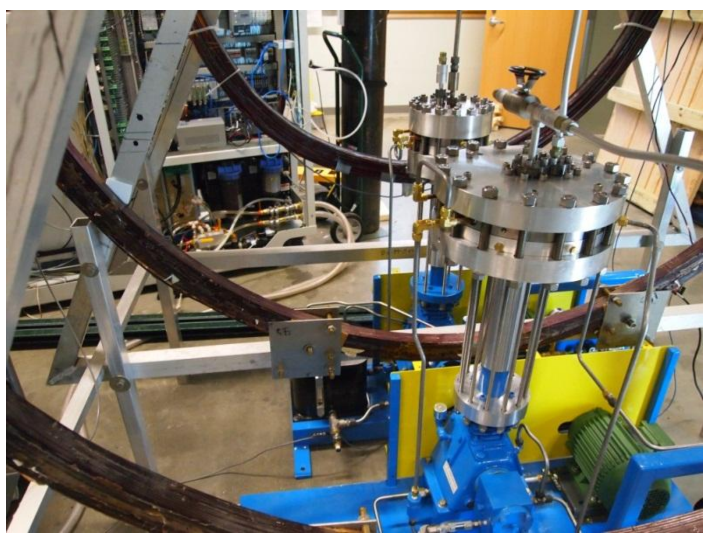








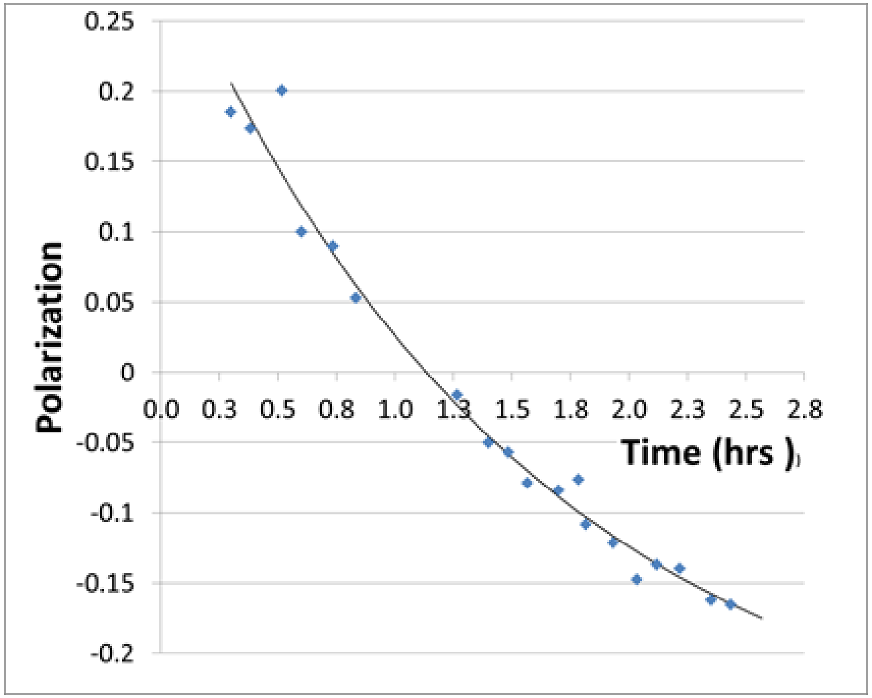




Working Large-Scale ^{3}He Polarizer Prototype

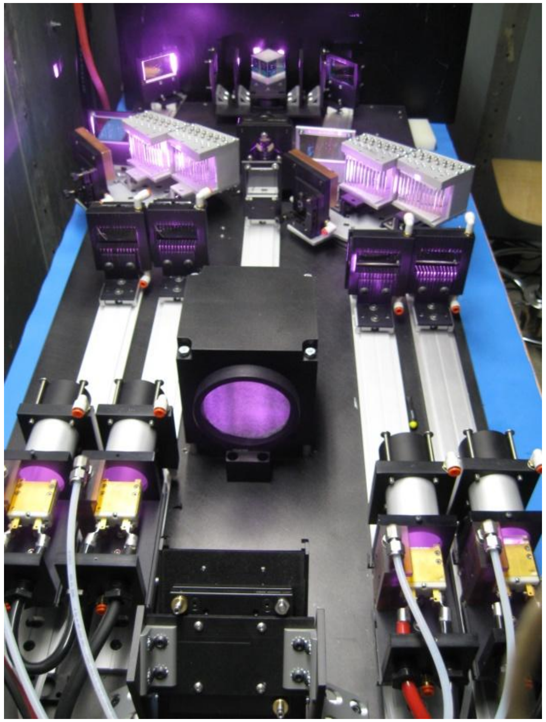
Assembled, Operating ^{3}He Polarizer

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



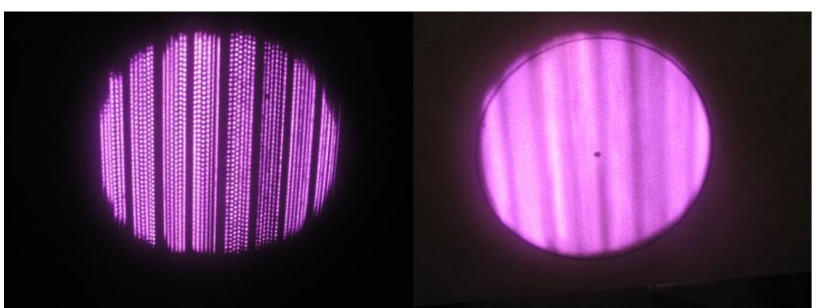
- Spin-up curve measured by laser-polarization-inversion.
- Spin-up rate ~15%/hr.

2700 Watt narrowed laser performance

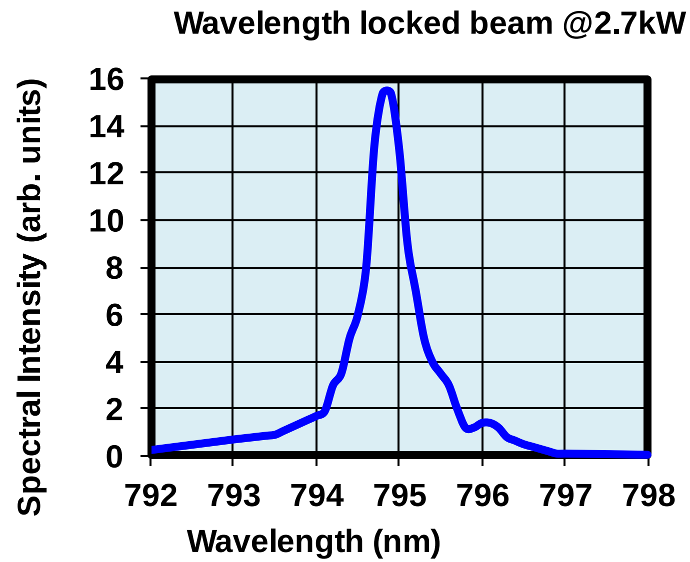


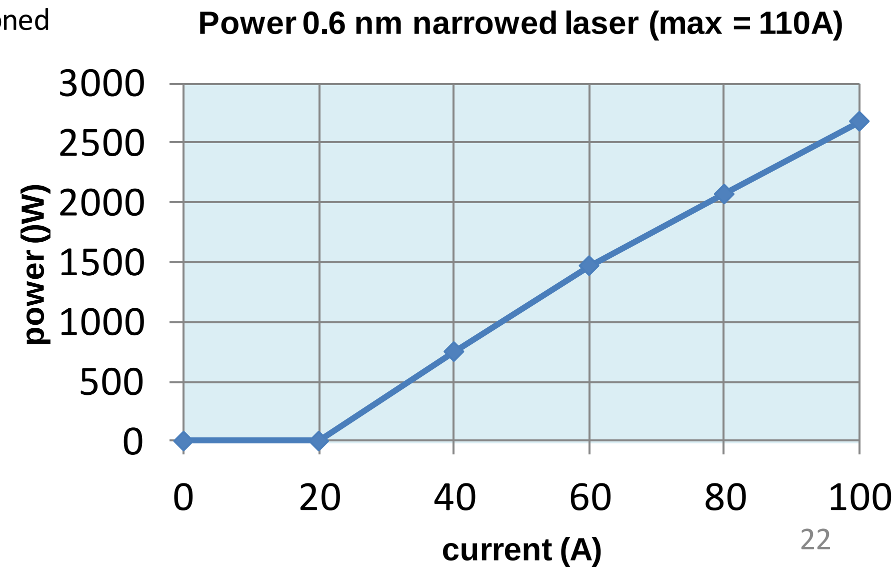
Four 12 bar lasers (foreground) combining their outputs into a single 10 cm diameter beam (center).

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

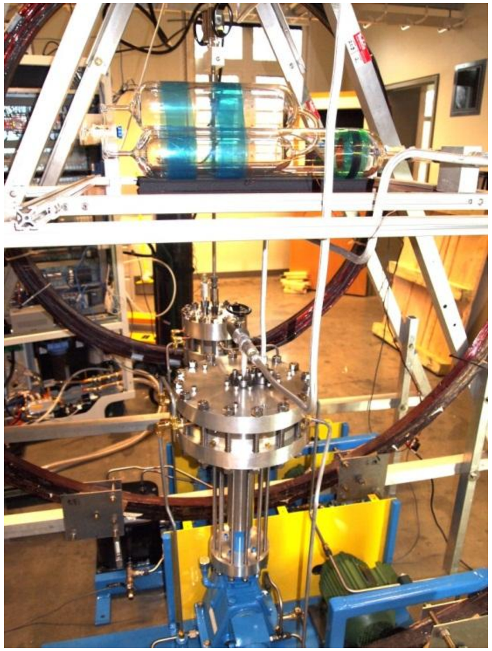


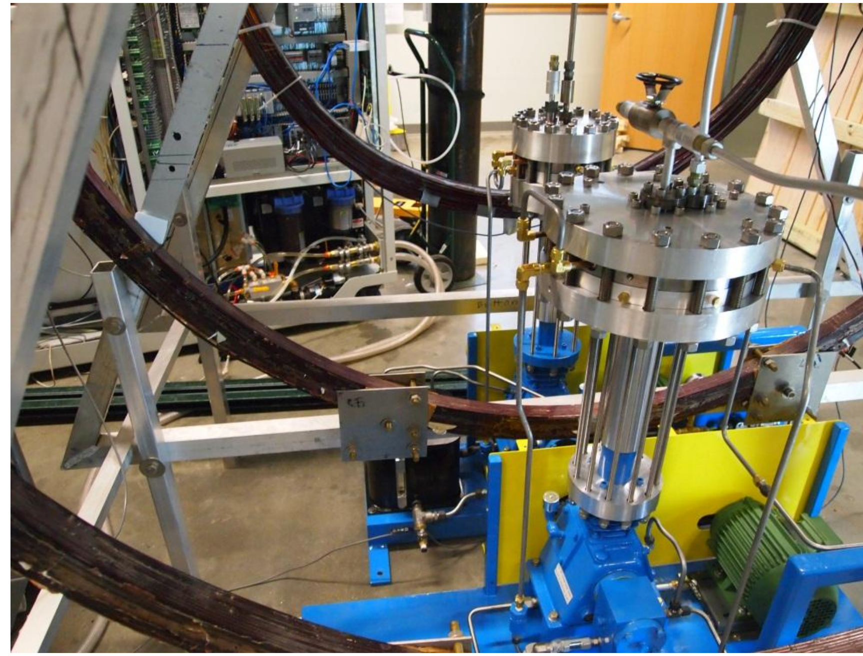
48 Bar exit beam, and 1m downstream with diffuser.
Divergence ~3x6 mrad (hor x vert.)





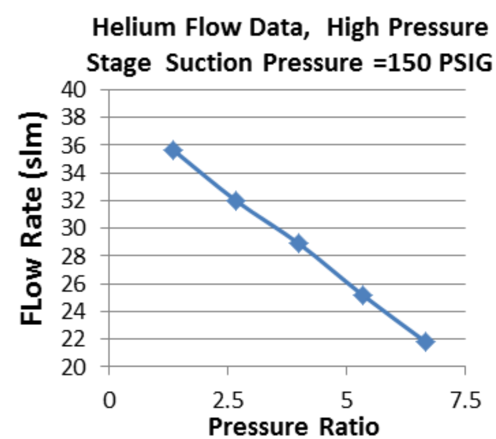
Status :Non-ferrous Diaphragm Pump





- 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

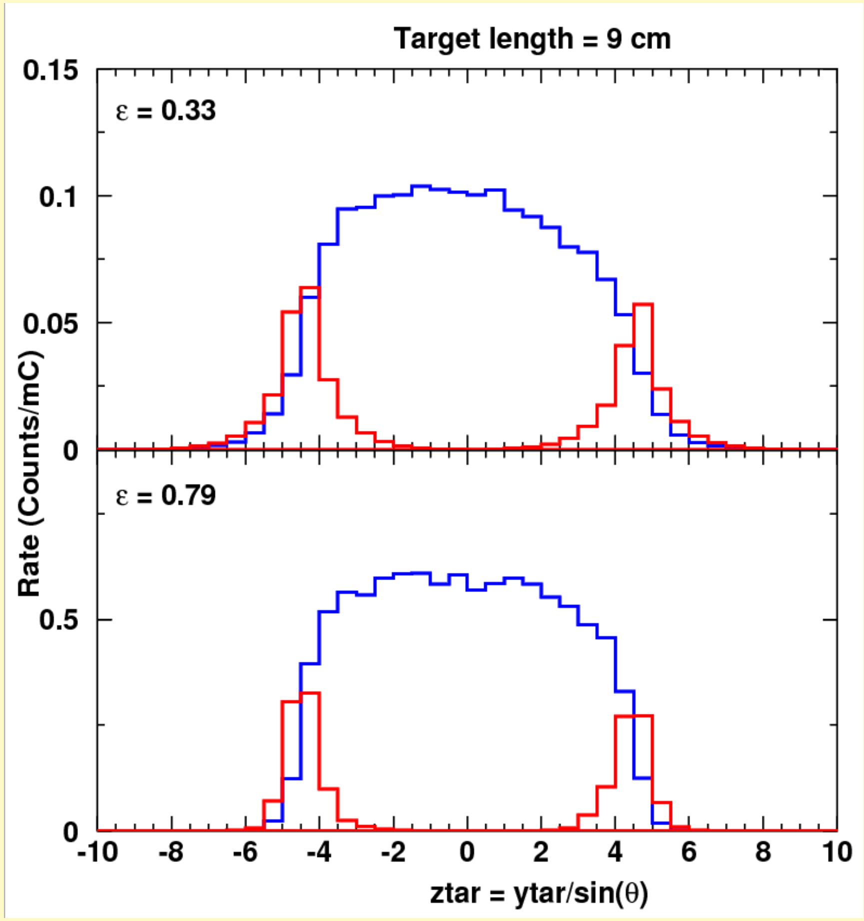
Many of the hardest technological hurdles have been demonstrated through working prototypes.

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.

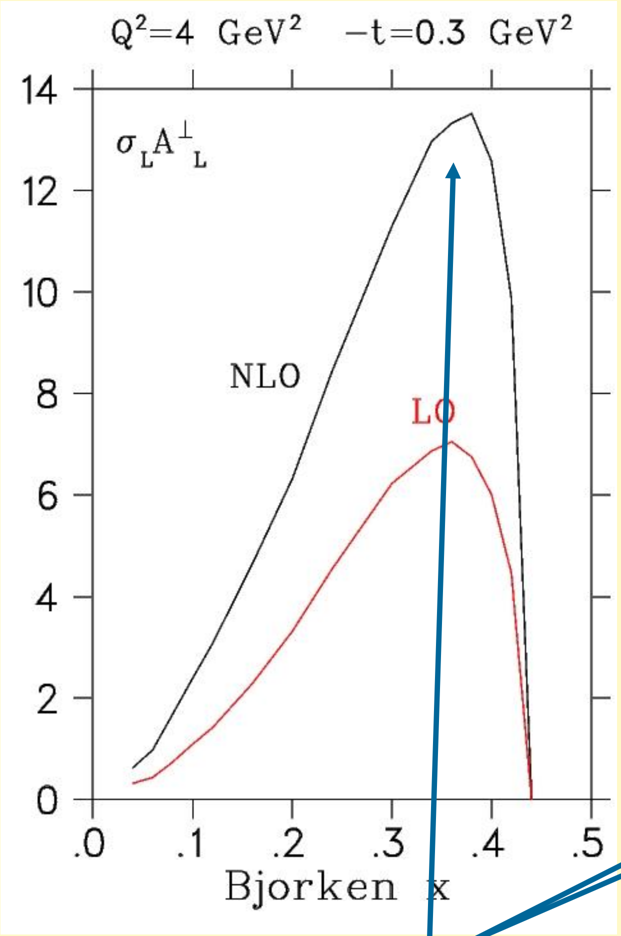
Reliable L/T Separations require short target cells



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 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



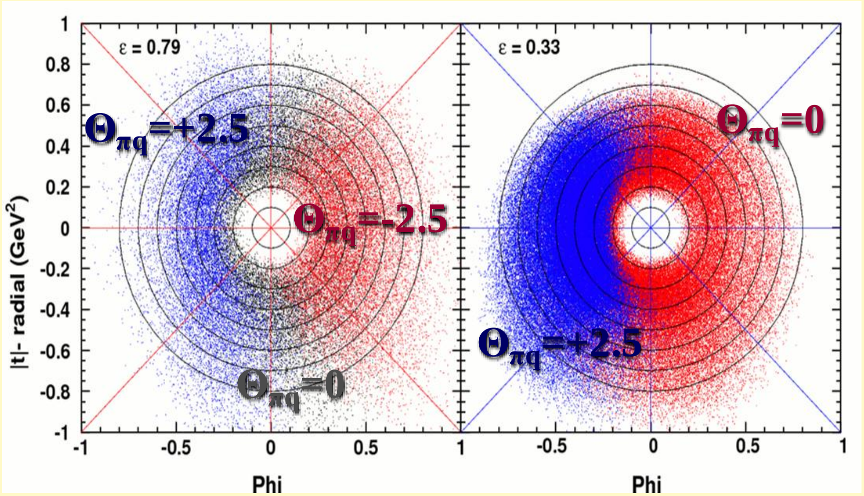
Near peak of Figure of Merit in Belitsky's calculation

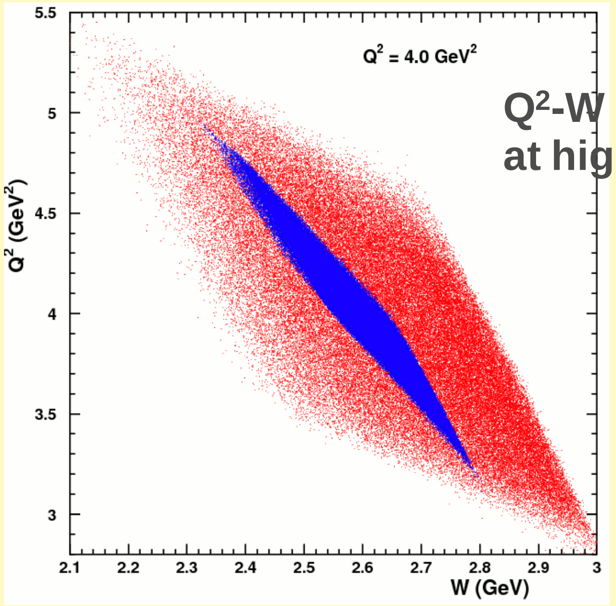
n(e,e'π-)p Kinematics						
E_{beam}	$E_{e'}$	$\theta_{e'}$	ε	θ_q	p_π	$\Theta_{\pi q}$
MAIN Q^2=4.0 W=2.6 x=0.40 -t_{min}=0.22						
6.60	1.34	39.2	0.33	-8.7	5.14	0, +2.5
10.92	5.66	14.6	0.79	-14.7	5.14	0, ±2.5
SCALING Q^2=3.0 W=2.3 x=0.40 –t_{min}=0.22						
6.60	2.66	23.9	0.64	-14.5	3.82	0, ±2.5
10.92	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

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

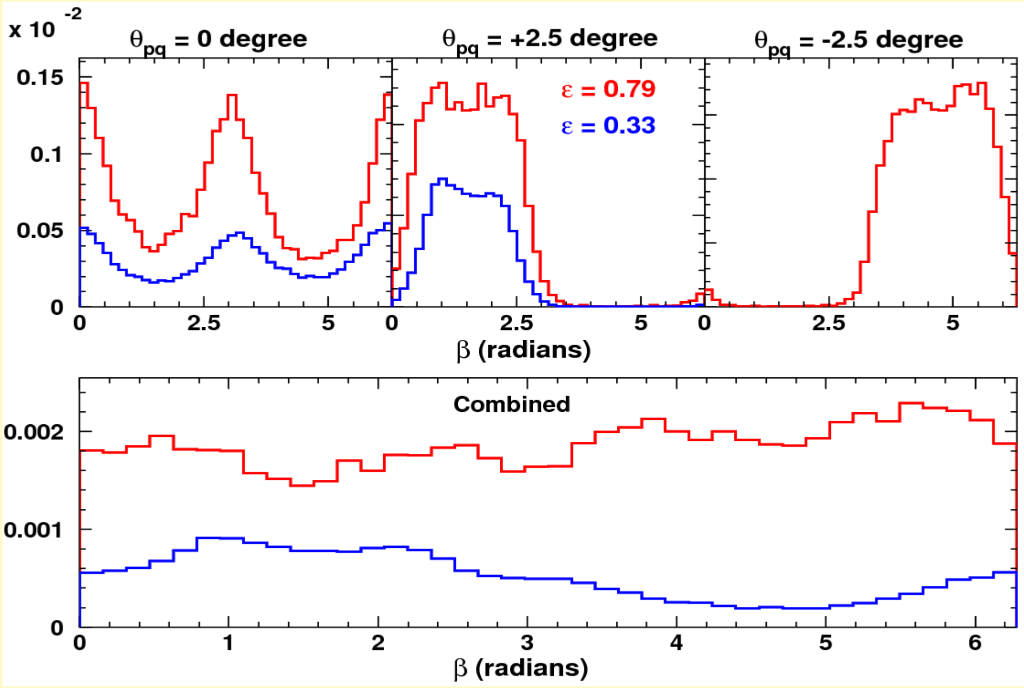
Q^2=4.0 W=2.6 low ε high ε Δε = 0.46





Q^2-W acceptance at high and low ε.

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



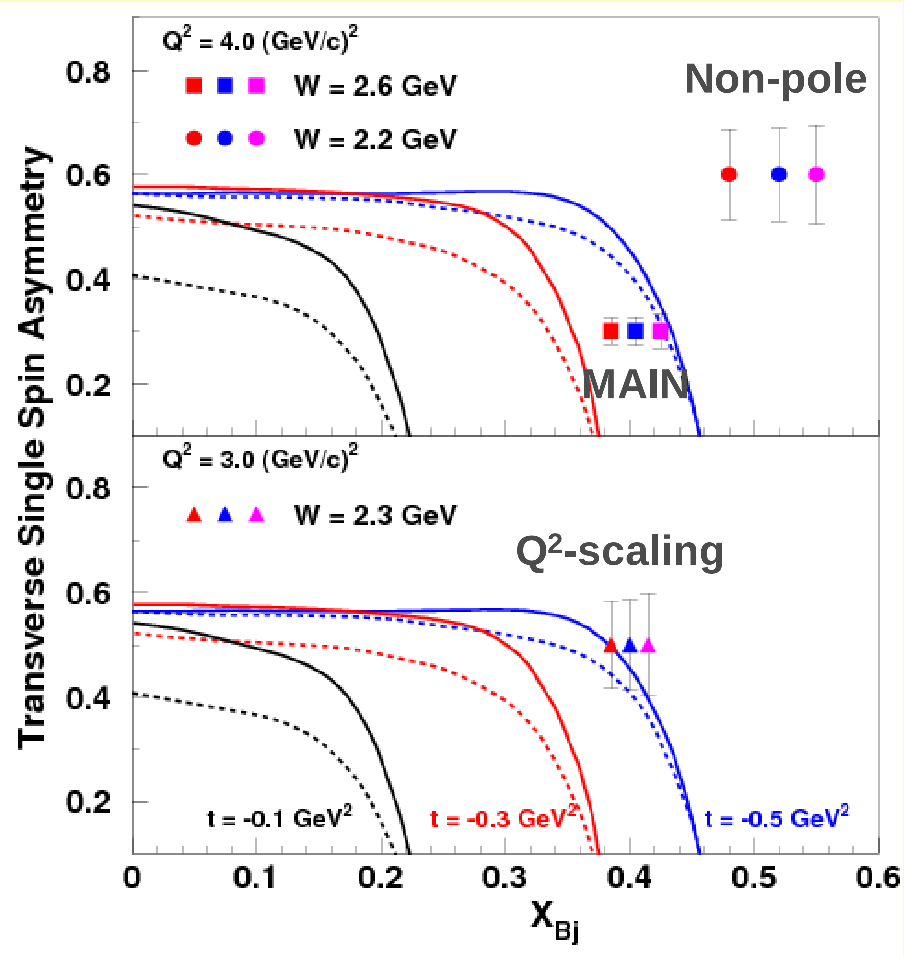
Magnetic Spectrometer Calibrations

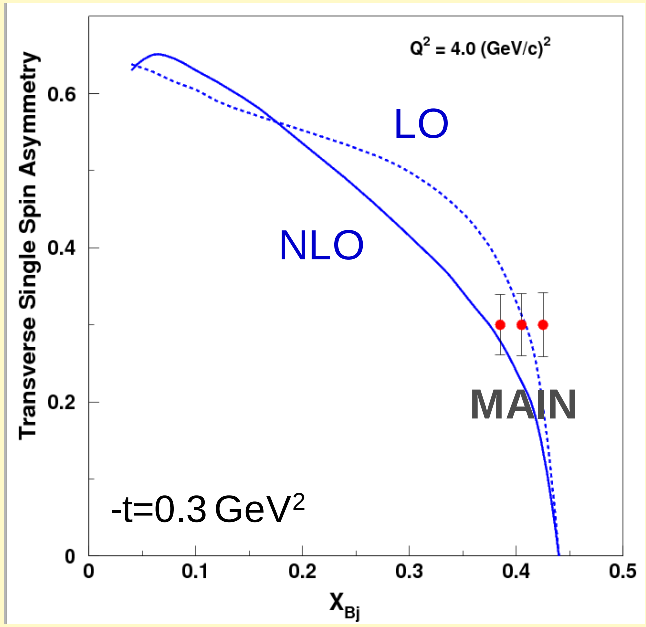
- Similarly to Fπ-2, we propose to use the over-constrained *p(e,e'p)* reaction and inelastic $e+^{12}C$ in the DIS region to calibrate spectrometer acceptances, momenta, offsets, etc.
  - Fπ-2 beam energy and spectrometer momenta determined to <0.1%.
  - Spectrometer angles <0.5 mr.
  - Fπ-2 agreement 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 ^3He target polarization of 65%.

Effect of β acceptance on $A_L^{\perp}$ extraction

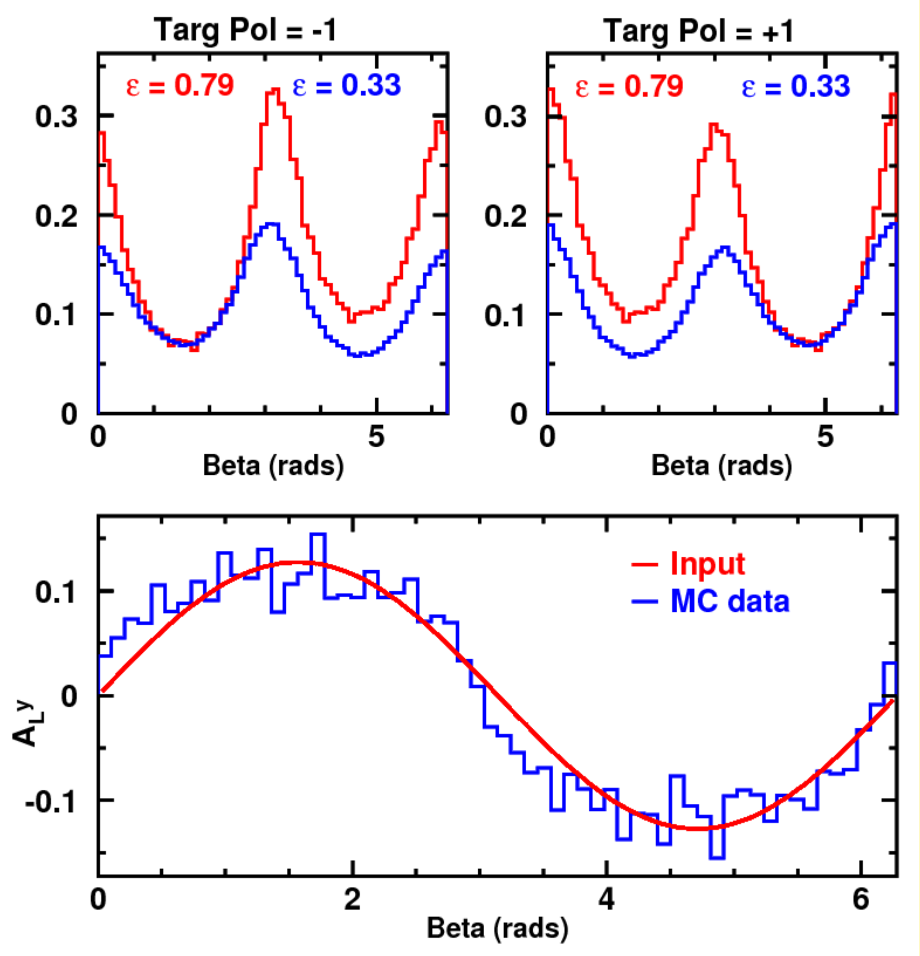
Simple MC exercise:

- Generate data with 10% asymmetry:
  - Q^2=4.0, W=2.6 at ε=0.79, 0.33.
  - Two different target polarization orientations.
  - Diamond cuts to equalize high, low ε acceptances.

- For each target polarization setting, perform L/T separation separately for each β bin.

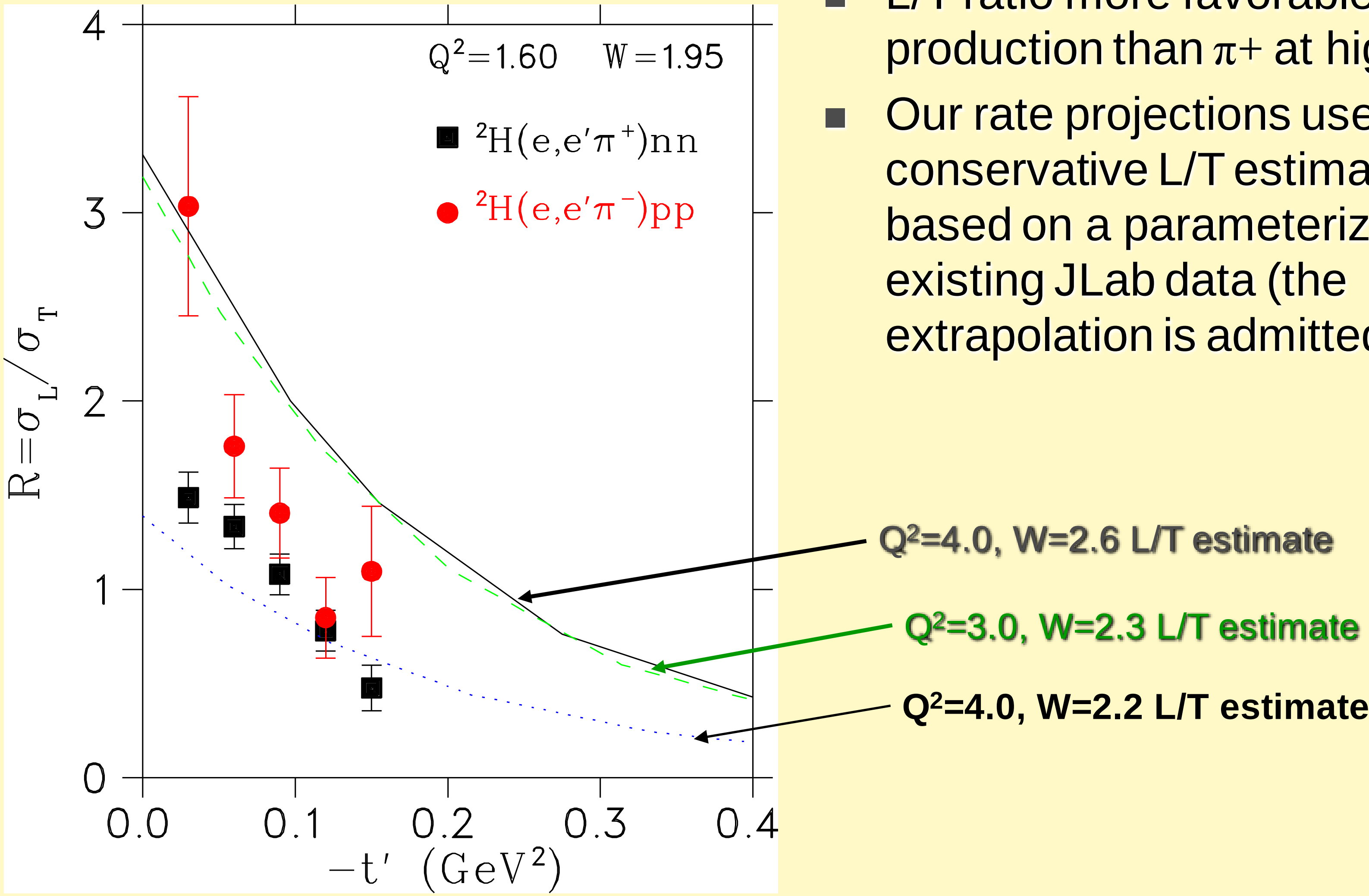
$$A_L^y = \frac{\sigma_{L\uparrow} - \sigma_{L\downarrow}}{\sigma_{L\uparrow} + \sigma_{L\downarrow}}$$

shows clear β-dependence, consistent with the injected asymmetry.



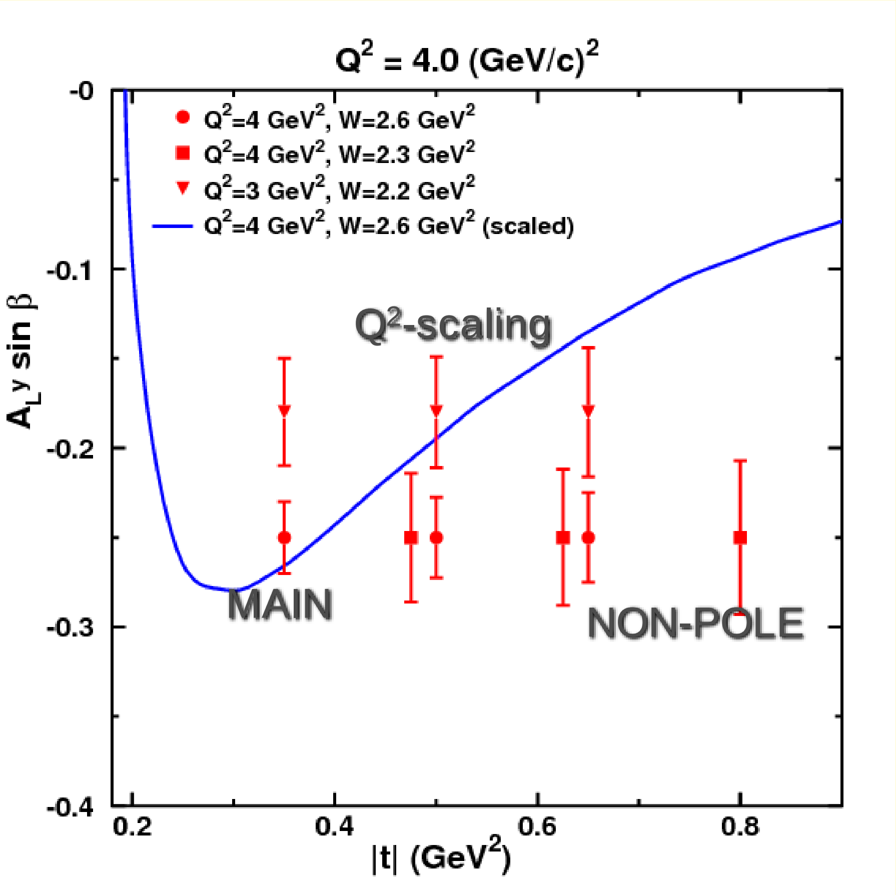
Actual experimental analysis will be considerably more sophisticated, involving multiple SHMS settings to equalize the azimuthal acceptance for each *t*-bin.

σ_L/σ_T Ratios from 2H(e,e'π-)NN



- L/T ratio more favorable for π- production than π+ at higher Q^2.
- Our rate projections use conservative L/T estimates, based on a parameterization of existing JLab data (the extrapolation is admittedly large).

Projected $A_L^{\perp}$ uncertainties vs. –t



- Curve is very approximate:
  - Goloskokov & Kroll calculation for the *unseparated* asymmetry at Q^2=4.0 GeV^2, scaled by the ratio of their calculations for HERMES kinematics.

Polarizer Schematic Design

- 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.