Opportunities for Deep Exclusive Meson Production with Higher Energy JLab beam

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JLab 20+ Discussion
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GPDs in Deep Exclusive Meson Production

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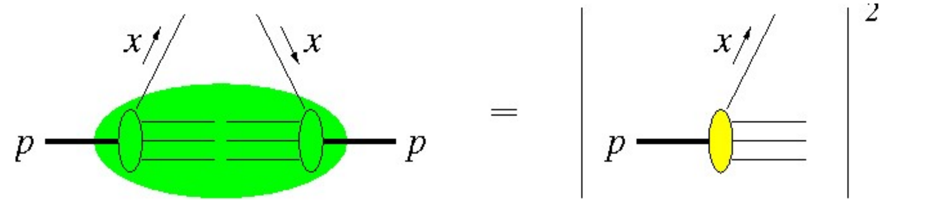
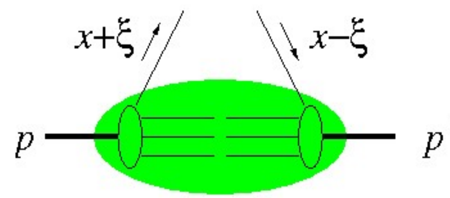
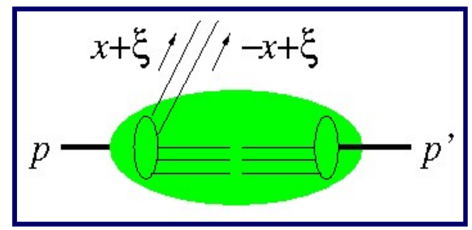
PDFs : probability of finding a parton with longitudinal momentum fraction x and specified polarization in fast moving hadron.



GPDs : interference between partons with $x+\xi$ and $x-\xi$, interrelating longitudinal momentum & transverse spatial 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.

- GPDs determined in this regime carry information about $q\bar{q}$ and gg-components in the hadron wavefunction.
- Because quark helicity is conserved in the hard scattering regime, the produced meson acts as helicity filter.
  - Pseudoscalar mesons → $\tilde{H}$ $\tilde{E}$
  - Vector mesons → H E

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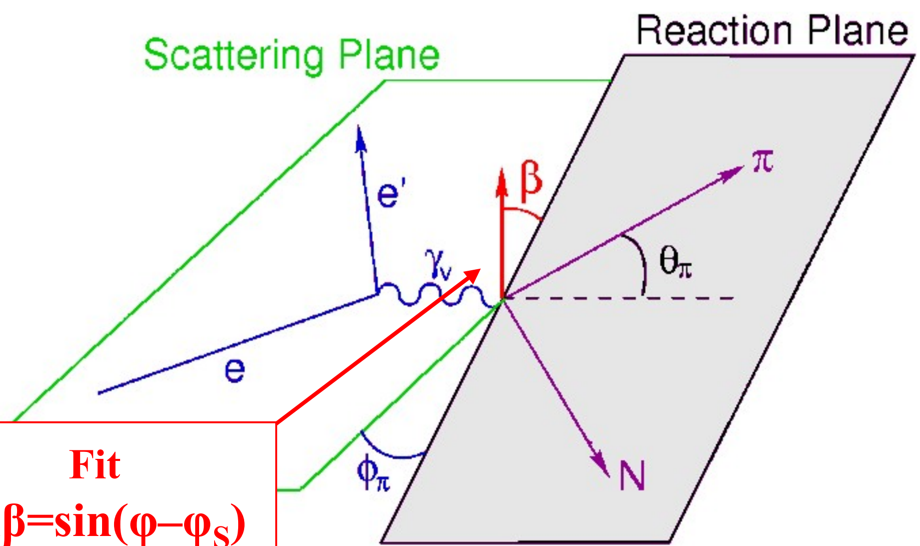
Exclusive π^- from Transversely Polarized Neutron

The most sensitive observable to probe $\tilde{E}$ is the transverse target single-spin asymmetry in exclusive π production:

$$A_L^{\perp} = \frac{\sqrt{-t'}}{m_p} \frac{\xi\sqrt{1-\xi^2}\,\mathrm{Im}(\tilde{E}^*\tilde{H})}{(1-\xi^2)\tilde{H}^2 - \frac{t\xi^2}{4m_p}\tilde{E}^2 - 2\xi^2\mathrm{Re}(\tilde{E}^*\tilde{H})}.$$



Fit $\sin\beta=\sin(\varphi-\varphi_S)$ dependence.

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

$d\sigma^\pi{}_L$ → exclusive cross section for longitudinal γ^*

$\beta=\varphi-\varphi_S$ → angle between polarized target and reaction plane

These experimental measurements can provide new nucleon structure information unlikely to be available from any other source.

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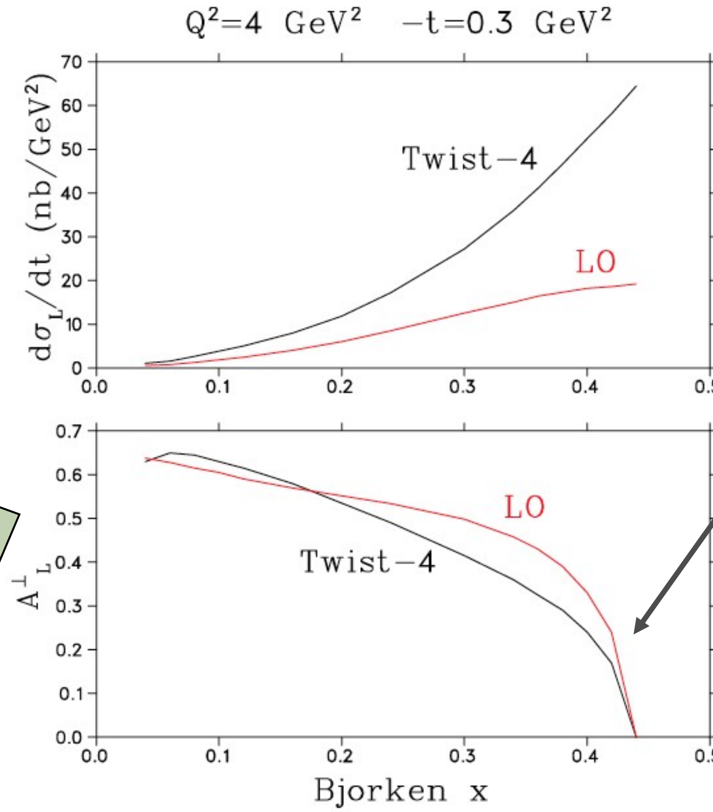
GPD information in $A_L^{\perp}$ may be particularly clean

- **$A_L^{\perp}$ is expected to display precocious factorization at only Q^2~2–4 GeV^2:**
  - At Q^2=10 GeV^2, Twist–4 effects can be large, but cancel in $A_L^{\perp}$ (Belitsky & Műller PLB 513(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 $\varphi - \varphi_s$ 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.

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Transverse Target Single Spin Asymmetry in DEMP

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Unpolarized Cross section

$$2\pi\frac{d^2\sigma_{UU}}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Transversely polarized cross section has additional components

$$\frac{d^3\sigma_{UT}}{dt\,d\phi\,d\phi_s}=-\frac{P_\perp\cos\theta_q}{\sqrt{1-\sin^2\theta_q\sin^2\phi_s}}\left(\begin{array}{l}\sin\beta\,\mathrm{Im}(d\sigma_{++}^{+-}+\varepsilon d\sigma_{00}^{+-})\\+\sin\phi\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}(d\sigma_{+0}^{+-})\\+\sin(\phi+\phi_s)\frac{\varepsilon}{2}\mathrm{Im}(d\sigma_{+-}^{+-})\\+\sin(2\phi-\phi_s)\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}(d\sigma_{+0}^{-+})\\+\sin(3\phi-\phi_s)\frac{\varepsilon}{2}\mathrm{Im}(d\sigma_{+-}^{-+})\end{array}\right)$$

$\sigma_{mn}^{ij}\rightarrow$ nucleon polarizations $ij=(+1/2,-1/2)$

photon polarizations $mn=(-1,0,+1)$

Note: Trento convention used for rest of talk

Gives rise to Asymmetry Moments

$$A(\phi,\phi_s)=\frac{d^3\sigma_{UT}(\phi,\phi_s)}{d^2\sigma_{UU}(\phi)}=-\sum_k A_{UT}^{\sin(\mu\phi+\lambda\phi_s)_k}\sin(\mu\phi+\lambda\phi_s)_k$$

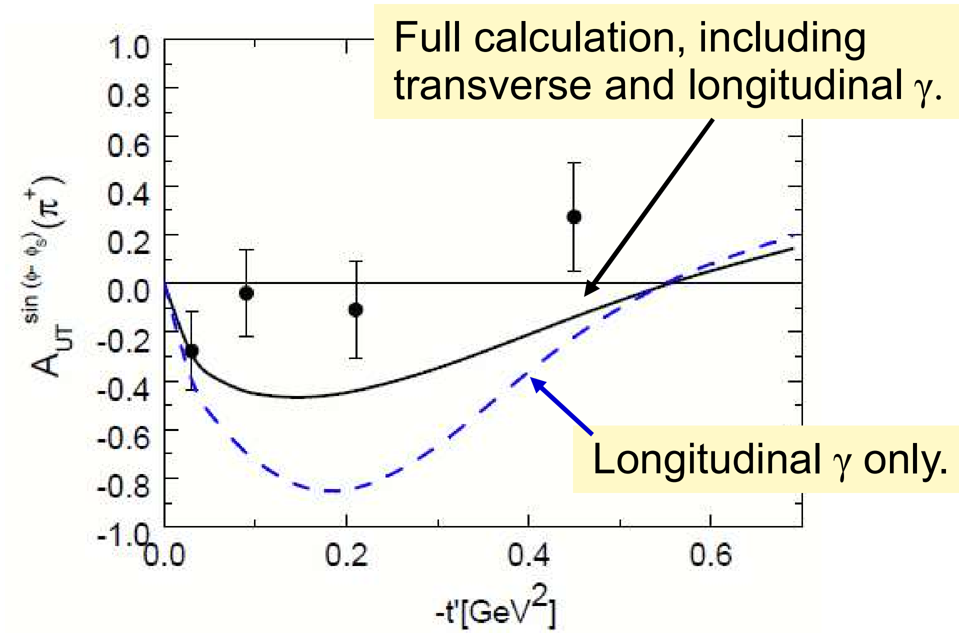
Unseparated sinβ=sin(φ-φ$_s$) Asymmetry Moment

$$A_{UT}^{\sin(\phi-\phi_s)}\sim\frac{d\sigma_{00}^{+-}}{d\sigma_L\binom{++}{00}}\sim\frac{\mathrm{Im}(\tilde{E}^*\tilde{H})}{|\tilde{E}|^2}\text{ where }\tilde{E}\gg\tilde{H}$$

Ref: M. Diehl, S. Sapeta, Eur.Phys.J. C**41**(2005)515.

HERMES $\sin(\varphi - \varphi_S)$ Asymmetry Moment

- Exclusive π^+ production by scattering 27.6 GeV positrons or electrons from transverse polarized ^{1}H [PL **B682**(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.



- **Since there is no L/T separation, $A_{UT}^{\sin(\varphi-\varphi s)}$ is diluted by the ratio of the longitudinal cross section to the unseparated cross section.**
- 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 trivially interpreted in terms of GPDs.

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HERMES sin(φ_s) Asymmetry Moment

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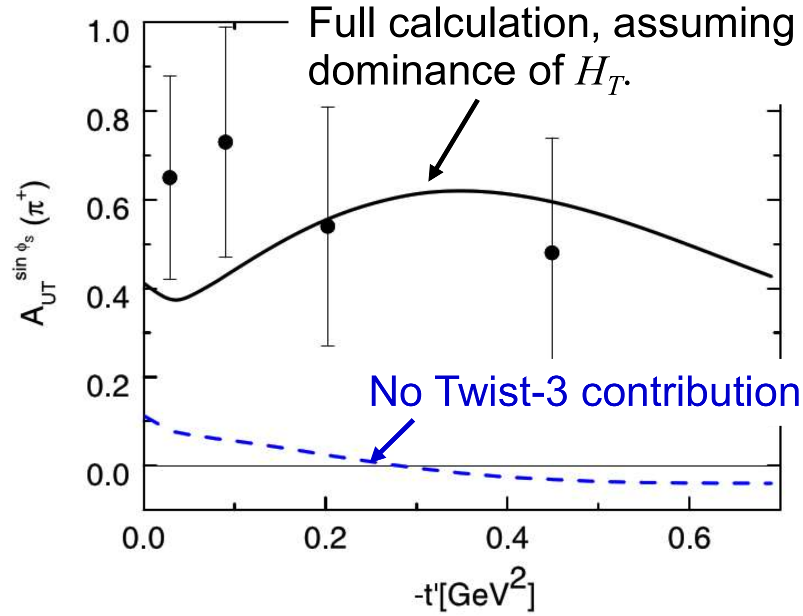
- While most of the theoretical interest and the primary motivation of our experiment is the sin(φ–φ_s) asymmetry moment, there is growing interest in the sin(φ_s) moment, which may be interpretable in terms of the transversity GPDs.



- In contrast to the sin(φ-φ_s) modulation, which has contributions from LL and TT interferences, the sin(φ_S) modulation measures only the LT interference.
- **The HERMES sin(φ_S) modulation is large and nonzero at –*t'*=0, giving the first clear signal for strong contributions from transversely polarized photons at rather large values of *W* and Q^2.**
- **Goloskokov and Kroll calculation** [Eur.Phys.J. **C65**(2010)137] **assumes the transversity GPD H_T dominates and that the other three can be neglected.**

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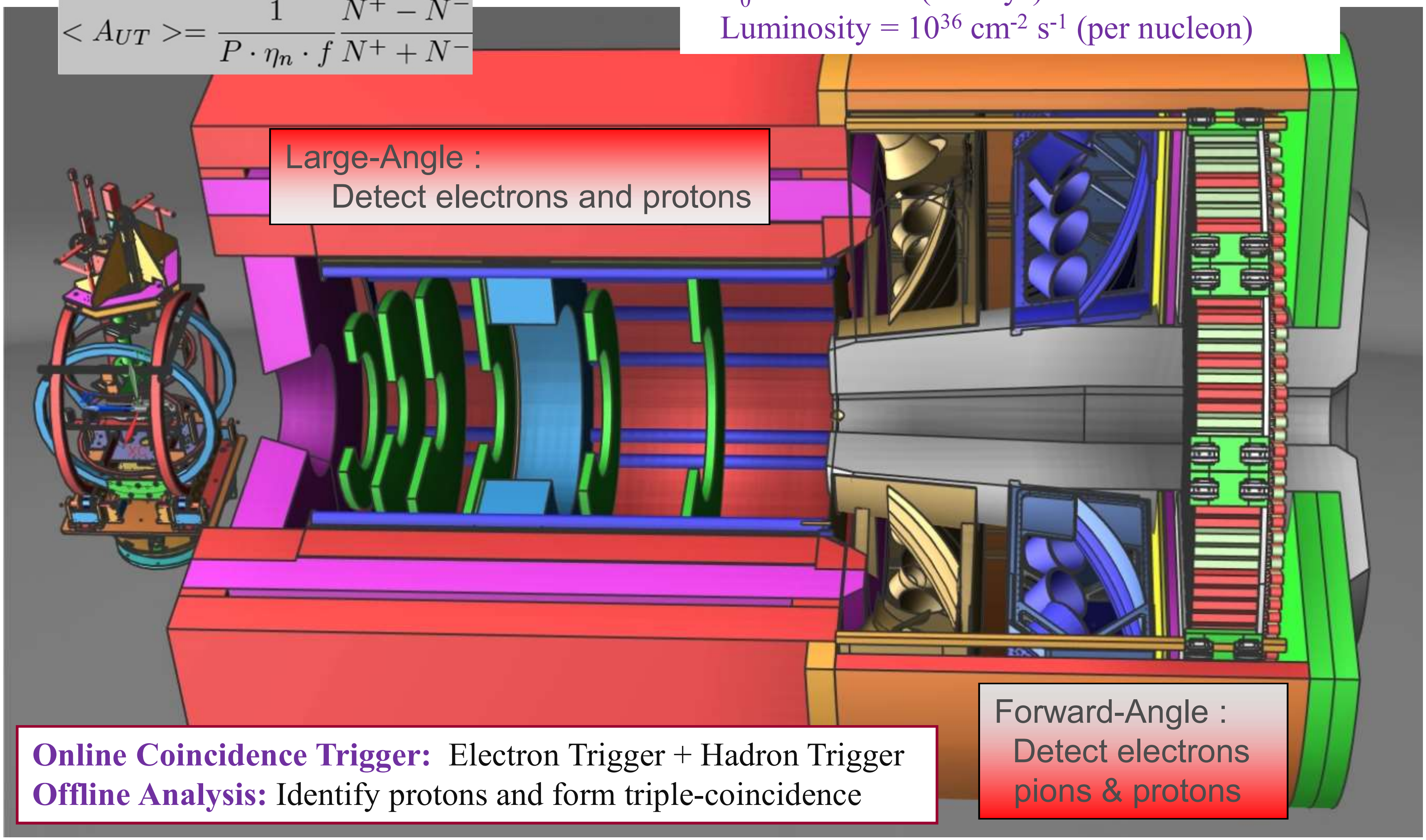
Measure DEMP with SoLID – Polarized ^{3}He

$\vec{n}(e,e'\pi^-)p$: with transversely polarized ^{3}He

$$< A_{UT} >= \frac{1}{P \cdot \eta_n \cdot f} \frac{N^+ - N^-}{N^+ + N^-}$$

Run in parallel with E12-10-006:
- E_0 = 11.0 GeV (48 days)
- Luminosity = 10^{36} cm^{-2} s^{-1} (per nucleon)



Online Coincidence Trigger: Electron Trigger + Hadron Trigger
Offline Analysis: Identify protons and form triple-coincidence

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E12–10–006B Kinematic Coverage and Binning

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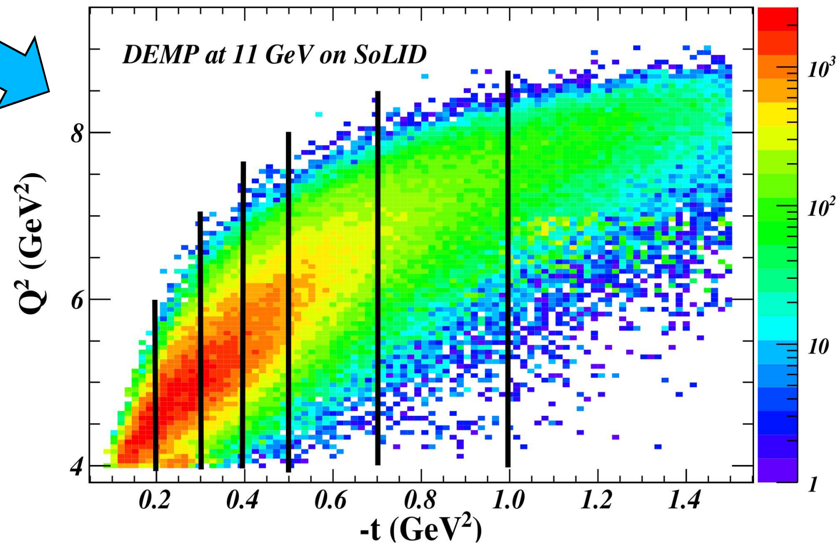
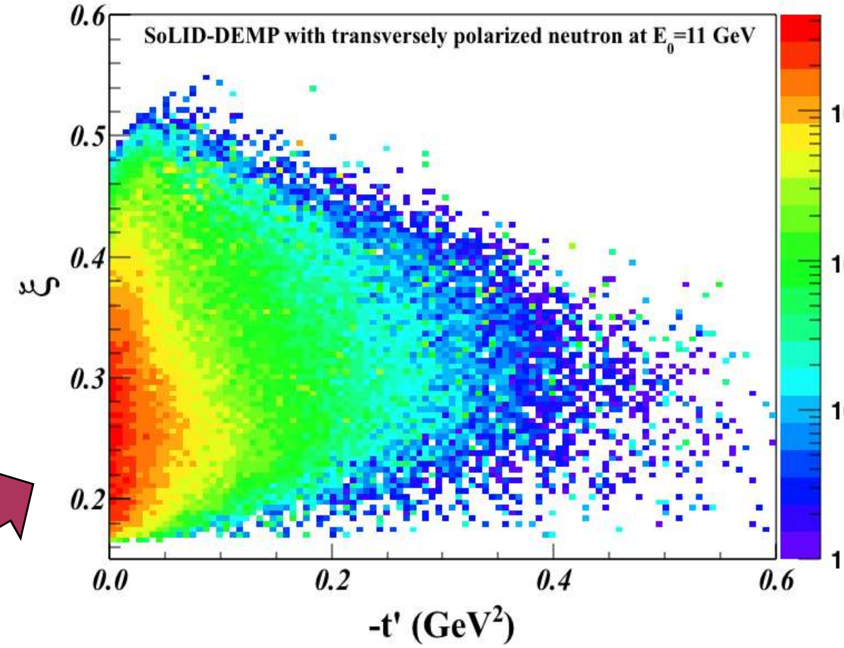
- **We binned the simulated data in 7 *t*–bins.**
- **In actual data analysis, we will consider alternate binning.**
- All JLab data cover a range of Q^2, x_{Bj} values.
  - x_{Bj} fixes the skewness (ξ).
  - Q^2 and x_{Bj} are correlated. In fact, we have an almost linear dependence of Q^2 on x_{Bj}.
- HERMES and COMPASS experiments are restricted kinematically to very small skewness (ξ<0.1).
- **With SoLID, we can measure the skewness dependence of the relevant GPDs over a fairly large range of ξ.**





Opportunities with higher E_{beam} & SoLID

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- Investigated some kinematics to see effect of a higher beam energy on the SoLID experiment
- For good $\pi^{\pm}/K^{\pm}$ separation, current design (with MRPC timing resolution of 20 ps) will work to 7 GeV/c
  - SoLID would need further-improved timing resolution or other method to allow good PID at higher momenta
- Restricting to 7 GeV/c, n(e,e'π^-)p count rate with 15 GeV beam at Q^2=6.0, W=3.0, $-t_{min}$=0.32, x=0.42, would increase by roughly an order of magnitude, due to larger available virtual photon flux
  - Dramatic effect: allow finer binning of data, enabling the skewness–dependence of the single spin asymmetries to be studied in much greater detail
- If can achieve good PID to ~9 GeV/c, then Q^2=10, W=2.8, x=0.59, $-t_{min}$=0.67 data can be acquired at 17 GeV

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DEMP Opportunities in Hall C

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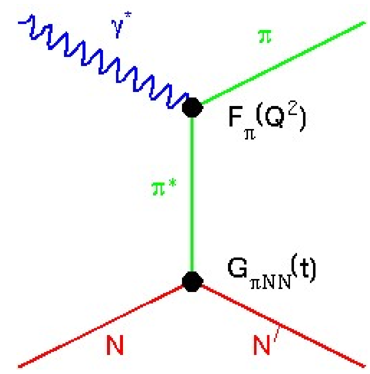
1) Determine the Pion Form Factor to high Q^2:

- Indirectly measure F_π using the "pion cloud" of the proton via p(e,e'π^+)n

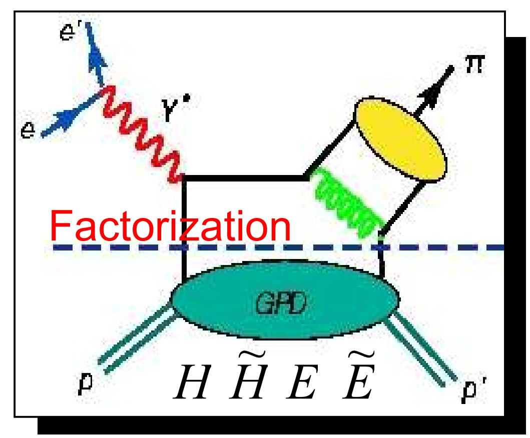
$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \ldots$$



- **The pion form factor is a key QCD observable.**
- The experiment should obtain high quality F_π over a broad Q^2 range. Rated "high impact" by PAC.

2) Study the Hard-Soft Factorization Regime:

- **Need to determine region of validity of hard-exclusive reaction meachanism, as GPDs can only be extracted where factorization applies.**
- Separated p(e,e'π^+)n cross sections vs. Q^2 at fixed x to investigate reaction mechanism towards 3D imaging studies.
- Perform exclusive π^-/π^+ ratios from ^{2}H, yielding insight to hard–soft factorization at modest Q^2.



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Charged Pion Form Factor

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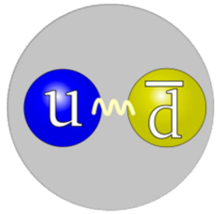
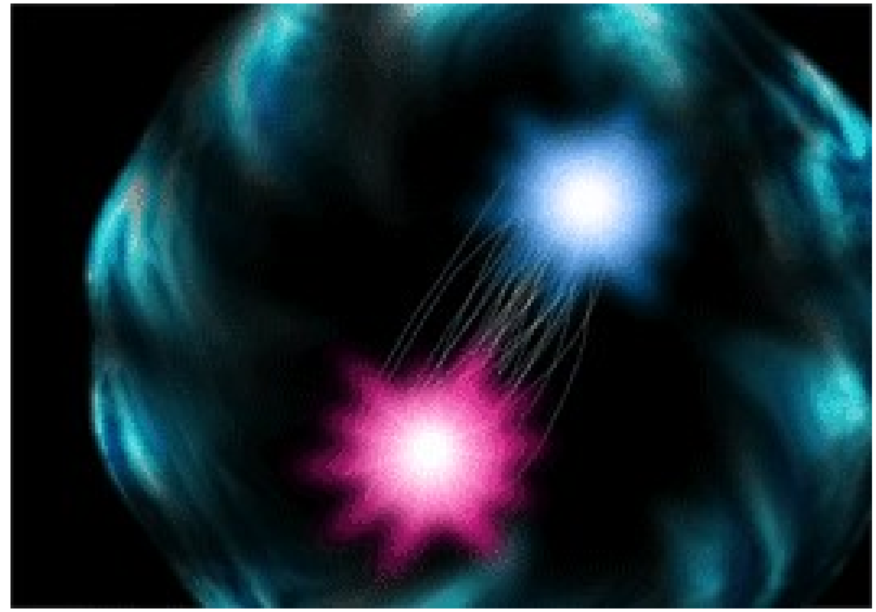
- **The pion is attractive as a QCD laboratory:**
  - Simple, 2 quark system



- **The pion is the "positronium atom" of QCD, its form factor is a test case for most model calculations**
- **The important question to answer is: What is the structure of the π^+ at all Q^2?**



Pion's structure is determined by two valence quarks, and the quark-gluon sea.

- **A program of study unique to Jefferson Lab Hall C** (until the completion of the EIC)

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Measurement of π^+ Form Factor – Larger Q^2

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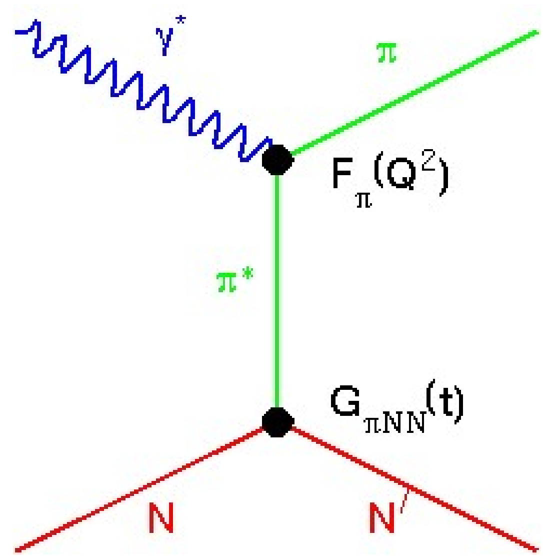
At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

$$\left|p\right\rangle = \left|p\right\rangle_0 + \left|n\pi^+\right\rangle + \ldots$$

- At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
- In Born term model, F_π^2 appears as,

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)}\, g_{\pi NN}^2(t)\, F_\pi^2(Q^2,t)$$

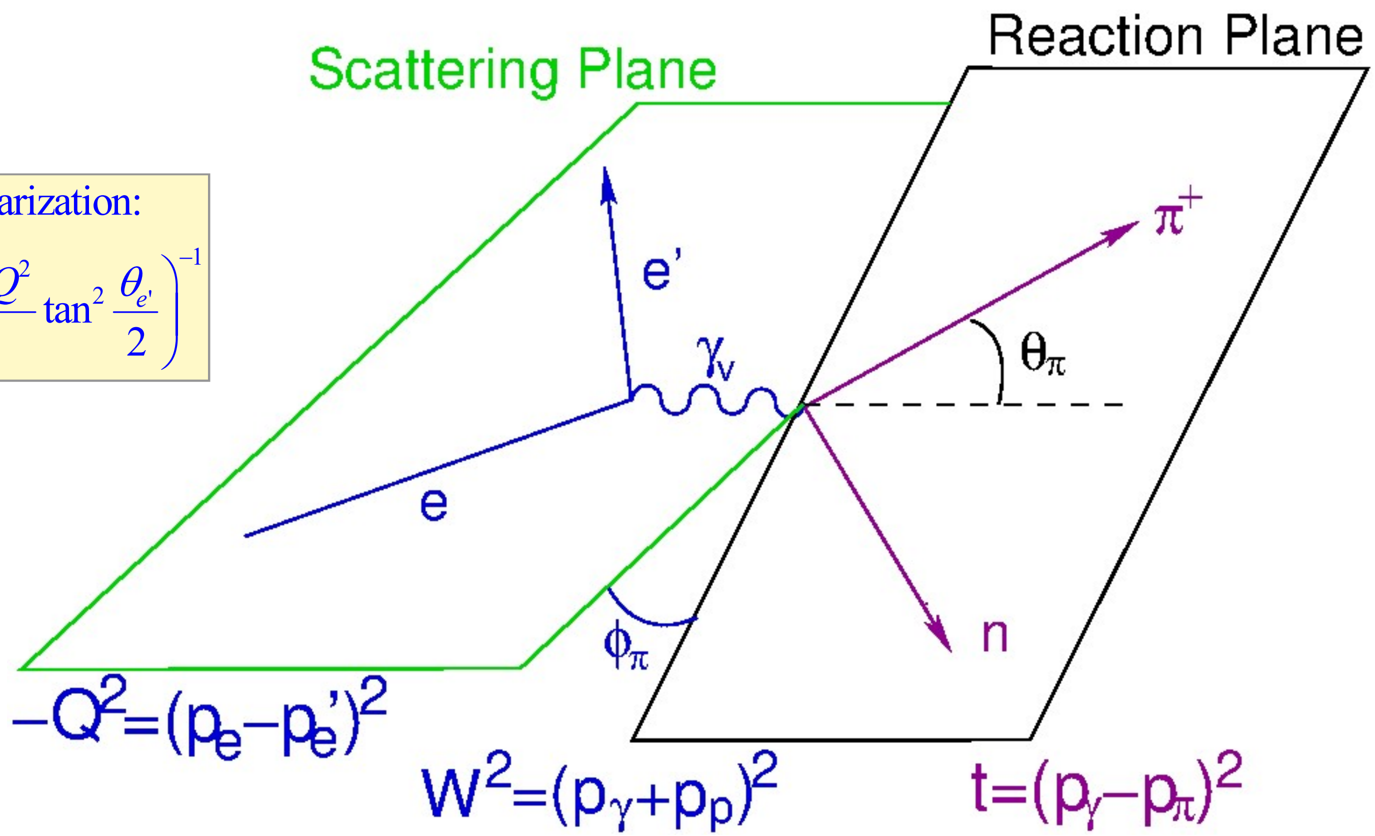


Drawbacks of this technique
1. Isolating σ_L experimentally challenging
2. Theoretical uncertainty in form factor extraction.

$$2\pi\frac{d^2\sigma}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Virtual-photon polarization:

$$\varepsilon=\left(1+2\frac{(E_e-E_{e'})^2+Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$



- **L-T separation required to separate σ_L from σ_T.**
- **Need to take data at smallest available $-t$, so σ_L has maximum contribution from the π^+ pole.**

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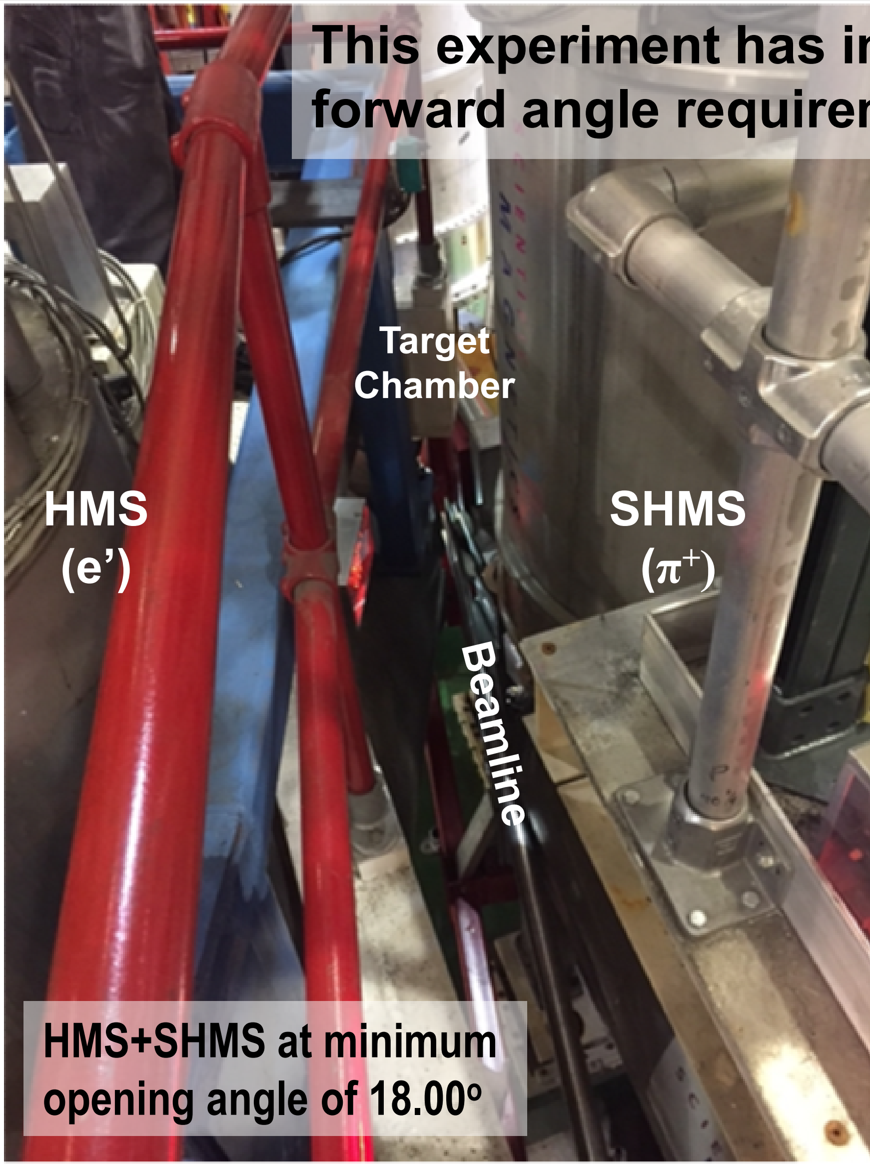
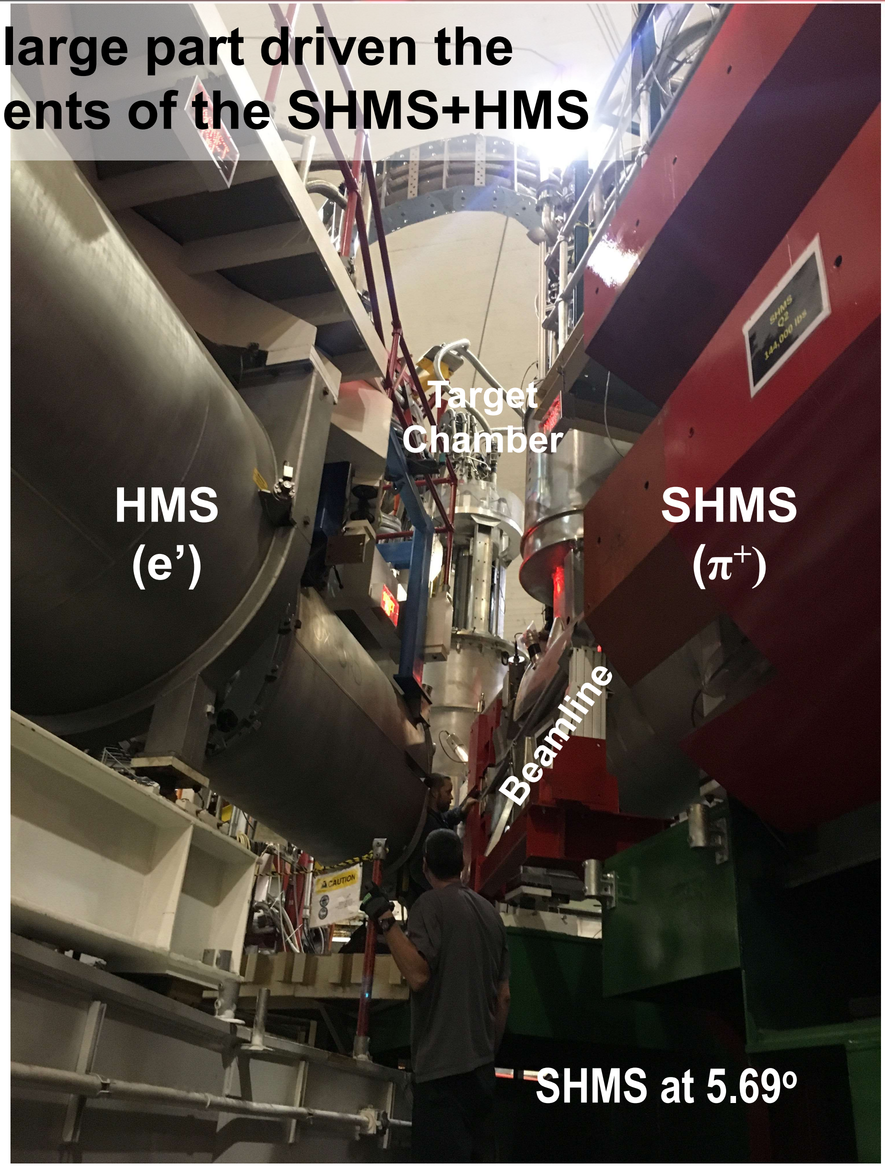
HMS and SHMS during Data Taking

This experiment has in large part driven the forward angle requirements of the SHMS+HMS





Extract $F_\pi(Q^2)$ from JLab σ_L data

Model incorporates π^+ production mechanism and spectator neutron effects:

VGL Regge Model:

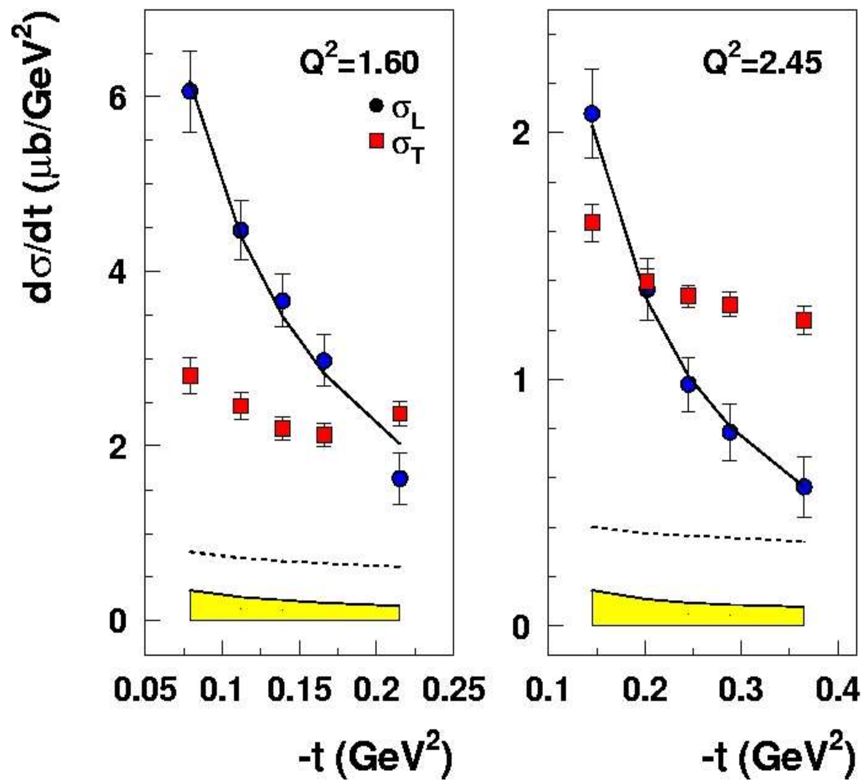
- Feynman propagator $\left(\frac{1}{t - m_\pi^2}\right)$ replaced by π and ρ Regge propagators.
  - Represents the exchange of a series of particles, compared to a single particle.
- Free parameters: Λ_π, Λ_ρ (trajectory cutoff).

[Vanderhaeghen, Guidal, Laget, PRC **57**(1998)1454]

- At small $-t$, σ_L only sensitive to F_π

$$F_\pi = \frac{1}{1 + Q^2 / \Lambda_\pi^2}$$

Fit to σ_L to model gives F_π at each Q^2



Fπ-2 data: T. Horn et al., PRL **97**(2006)192001.

Error bars indicate statistical and random (pt-pt) systematic uncertainties in quadrature.
Yellow band indicates the correlated (scale) and partly correlated (t-corr) systematic uncertainties.

Λ_π^2=0.513, 0.491 GeV^2, Λ_ρ^2=1.7 GeV^2.

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Current and Projected F_π Data

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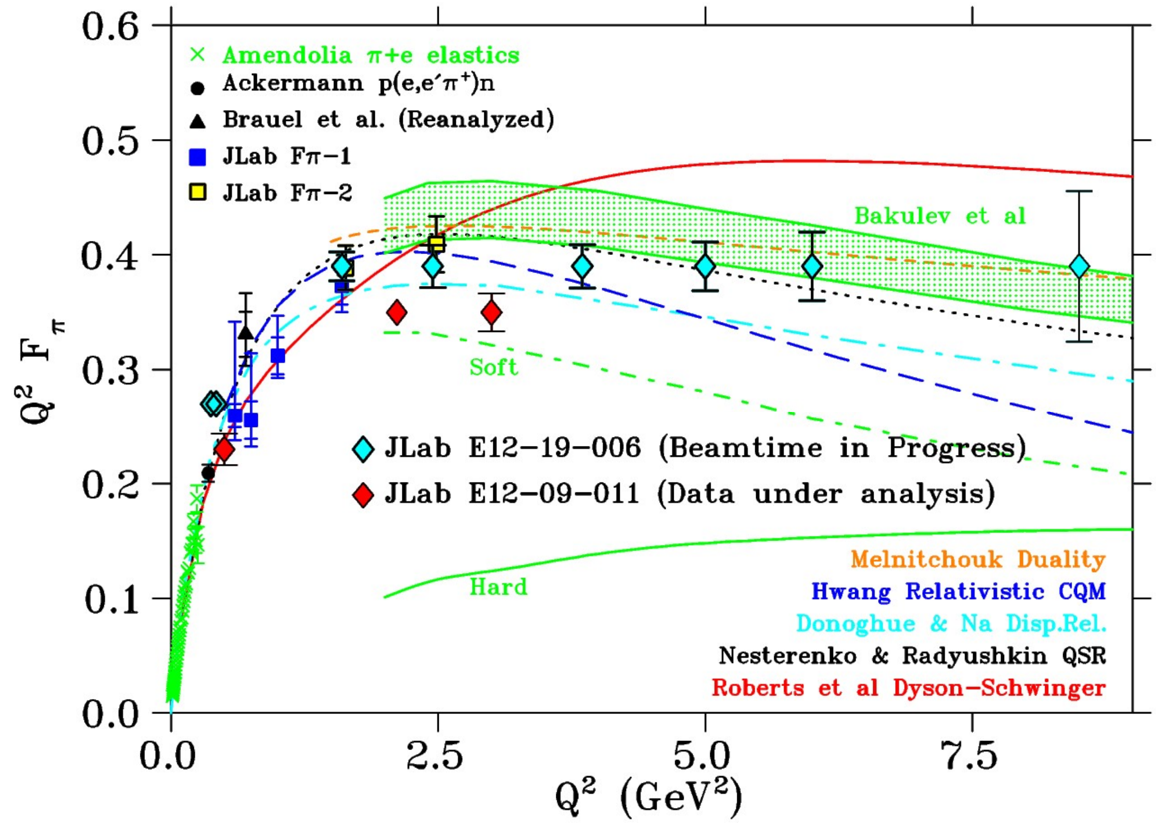
SHMS+HMS will allow measurement of F_π to much higher Q^2.

No other facility worldwide can perform this measurement.

The pion form factor is the clearest test case for studies of QCD's transition from non–perturbative to perturbative regions.



The ~17% measurement of F_π at Q^2=8.5 GeV^2 is at higher $-t_{min}$=0.45 GeV^2

E12–19–006: D. Gaskell, T. Horn and G. Huber, spokespersons

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$p(e,e'\pi^+)n$ Q^{-n} Hard–Soft Factorization Test

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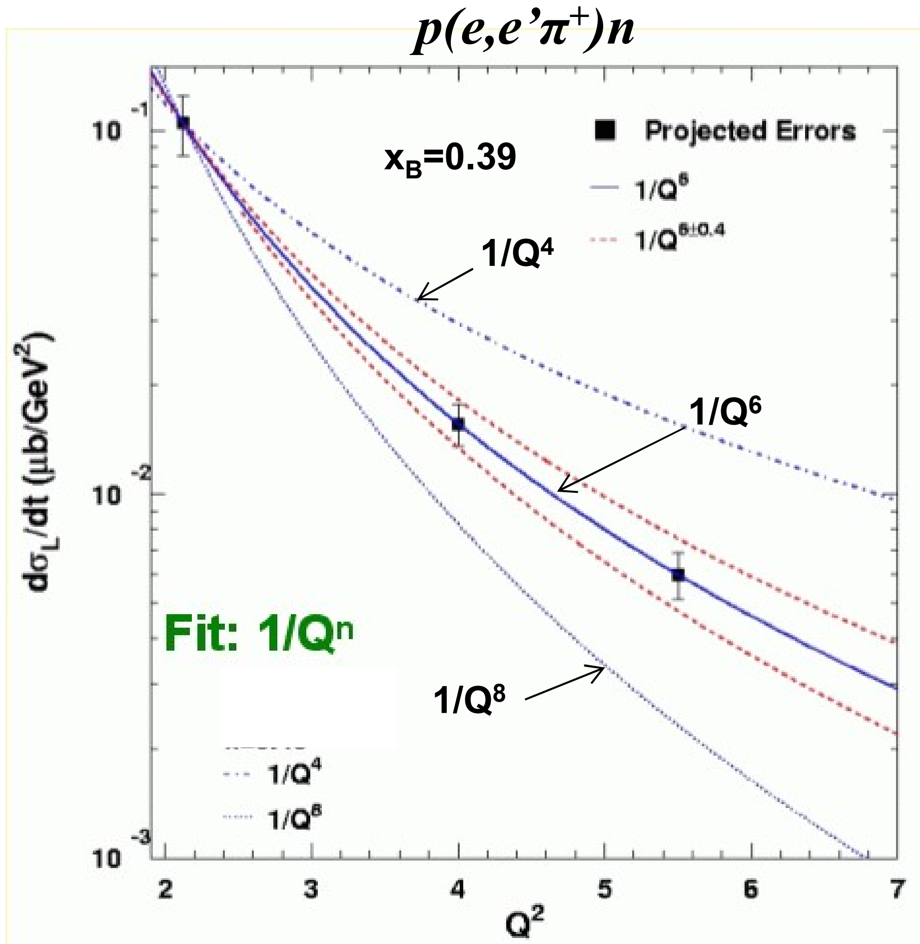
- QCD counting rules predict the Q^{-n} dependence of $p(e,e'\pi^+)n$ cross sections in Hard Scattering Regime:
  - σ_L scales to leading order as Q^{-6}.
  - σ_T scales as Q^{-8}.
  - As Q^2 becomes large: $\sigma_L >> \sigma_T$.

x	Q^2 (GeV^2)	W (GeV)	$-t_{min}$ (GeV/c)^2
0.31	1.45–3.65	2.02–3.07	0.12
0.39	2.12–6.0	2.05–3.19	0.21
0.55	3.85–8.5	2.02–2.79	0.55



- **Experimental validation of onset of hard scattering regime is essential for reliable interpretation of JLab GPD program results.**
  - If σ_L becomes large, it would allow leading twist GPDs to be studied.
  - If σ_T remains large, it could allow for transversity GPD studies.

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The Charged Kaon – a 2nd QCD test case

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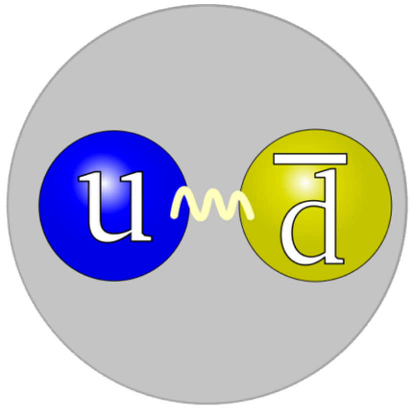
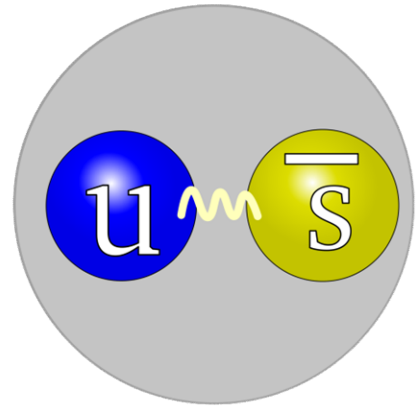


π^+



K^+

- In the hard scattering limit, pQCD predicts that the π^+ and K^+ form factors will behave similarly

$$\frac{F_K(Q^2)}{F_\pi(Q^2)} \xrightarrow[Q^2\to\infty]{} \frac{f_K^2}{f_\pi^{\,2}}$$

- It is important to compare the magnitudes and Q^2–dependences of both form factors.

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Projected Uncertainties for K^+ Form Factor

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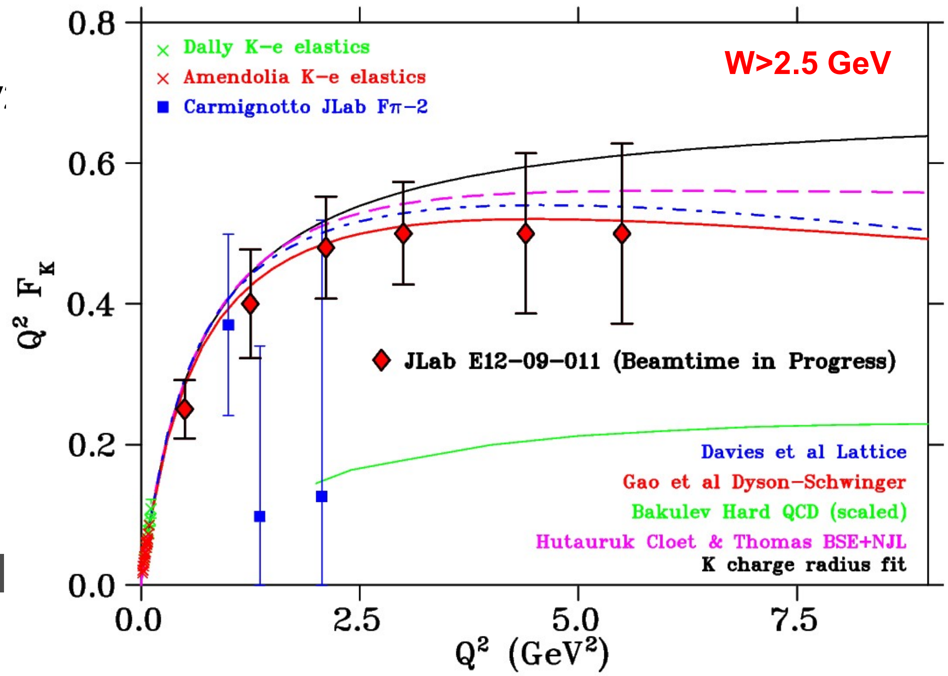
- First measurement of F_K well above the resonance region.
- Measure form factor to Q^2=3 GeV^2 with good overlap with elastic scattering data.
  - Limited by –t<0.2 GeV^2 requirement to minimize non–pole contributions.
- Data will provide an important second $q\bar{q}$ system for theoretical models, this time involving a strange quark.

p(e,e'K+)Λ



E12–09–011: T. Horn, G. Huber and P. Markowitz, spokespersons

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Opportunities with higher E_{beam} & Hall C

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- 7.2 GeV/c HMS & 11.0 GeV/c SHMS allow a lot of kinematic flexibility, **with no upgrades**
  - Maximum beam energy constrained by sum of HMS+SHMS maximum momenta
- L/T-separations with good $\Delta\varepsilon>0.4$ extend region of high quality σ_L measurements to $Q^2=10$, and data at larger $-t_{min}$ (larger F_π extraction uncertainties) to $Q^2=11.5$
- Since quality L/T-separations are impossible at the EIC (can't access $\varepsilon<0.95$) this extension of L/T-separated data would considerably increase the overlap in F_π data sets between JLab and EIC

$p(e,e'\pi^+)n$ Kinematics					
E_{beam}	θ_{HMS} (e')	P_{HMS} (e')	θ_{SHMS} (π^+)	P_{SHMS} (π^+)	Time FOM
$Q^2=8.5$ $W=3.64$ $-t_{min}=0.24$ $\Delta\varepsilon=0.49$					
13.0	34.30	1.88	5.29	10.99	64.7
18.0	15.05	6.88	8.94	10.99	2.2
$Q^2=10.0$ $W=3.44$ $-t_{min}=0.37$ $\Delta\varepsilon=0.40$					
13.0	37.78	1.83	5.56	10.97	122.7
18.0	16.39	6.83	9.57	10.97	4.5
$Q^2=11.5$ $W=3.23$ $-t_{min}=0.55$ $\Delta\varepsilon=0.29$					
14.0	31.53	2.78	7.13	10.93	79.6
18.0	17.66	6.78	10.11	10.93	8.7

$p(e,e'K^+)\Lambda$ kinematic reach would depend on good K^+/π^+ separation in SHMS at high momenta, and likely require some detector upgrades

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