# Probing the Onset of QCD's Hard-Soft Factorization via Deep Exclusive Meson Production

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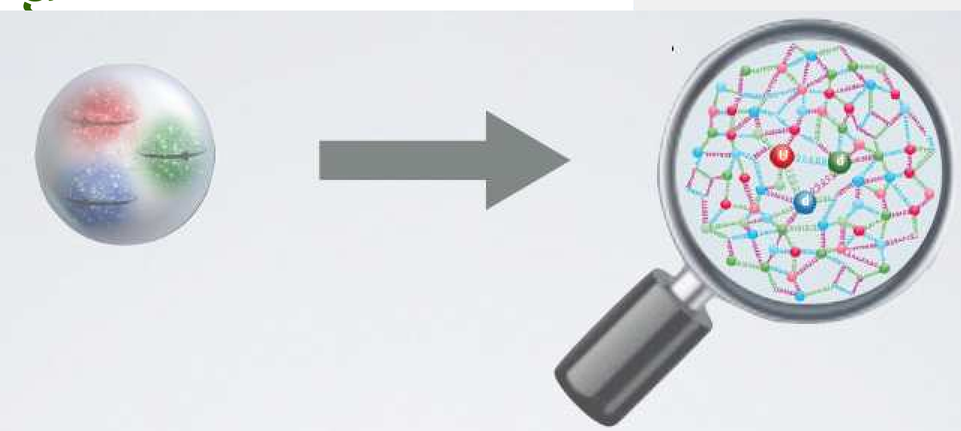
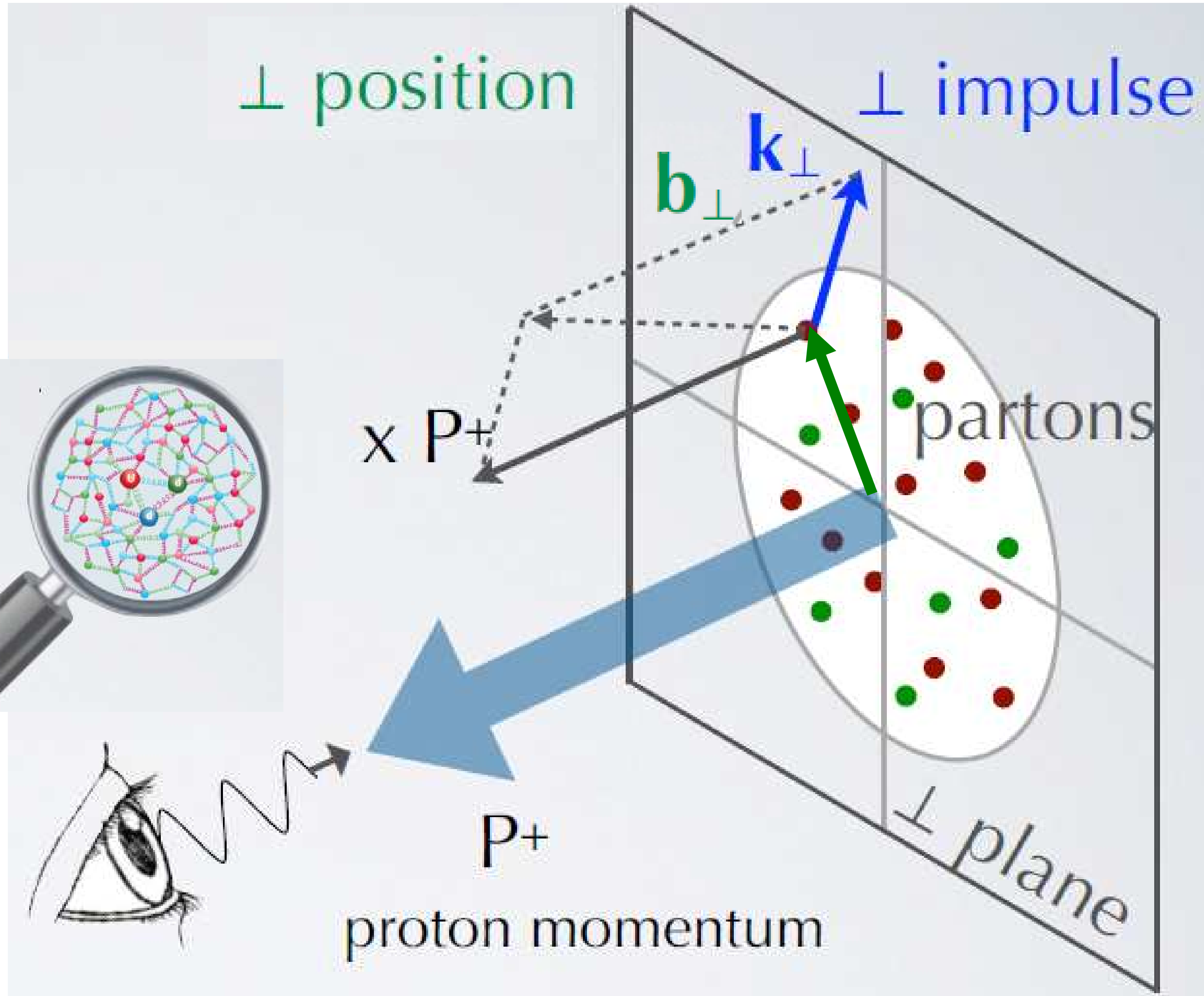
# Towards 3D Imaging of Hadrons

**Motivation:** in other sciences, imaging the physical systems under study has been key to gaining new understanding.

**Exclusive reactions have a key role!**

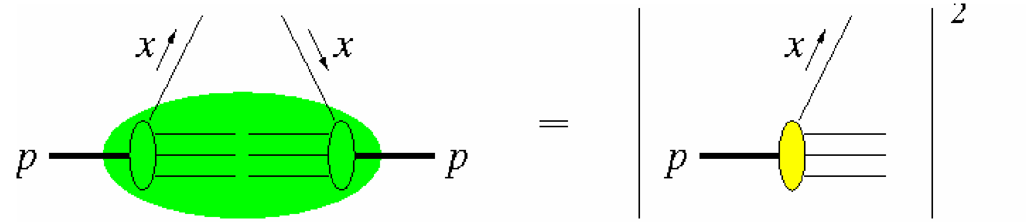




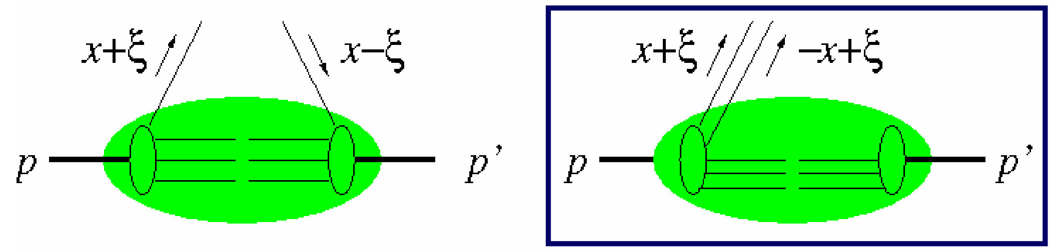

Structure mapped in terms of
**$b_T$** = transverse position
**$k_T$** = transverse momentum

# 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 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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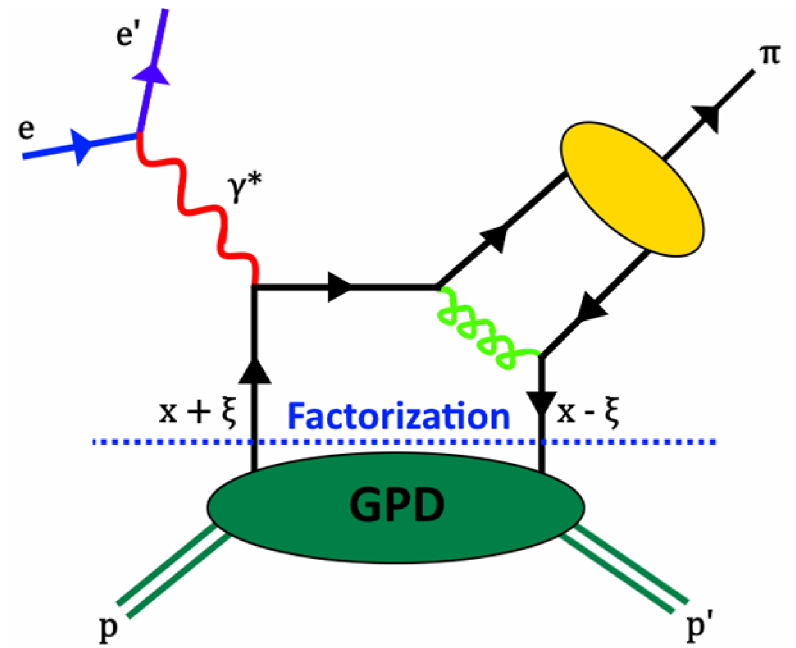
# Accessing GPD Information

- **At sufficiently high $Q^2$, the Hard–Soft Factorization Theorem separates the reaction amplitude into two parts:**
  - Hard scattering process, where perturbative QCD can be used
  - A non–perturbative (soft) part, where the response of the target nucleon to the virtual photon probe is encoded in GPDs

Collins, Frankfurt, Strikman PRD 56(1997)2982




$H \quad \widetilde{H} \quad E \quad \widetilde{E}$

- **To access physics contained in GPDs, one is limited to the kinematic regime where hard–soft factorization applies**
- No single criterion for applicability, but tests of necessary conditions can provide evidence that $Q^2$ scaling regime reached

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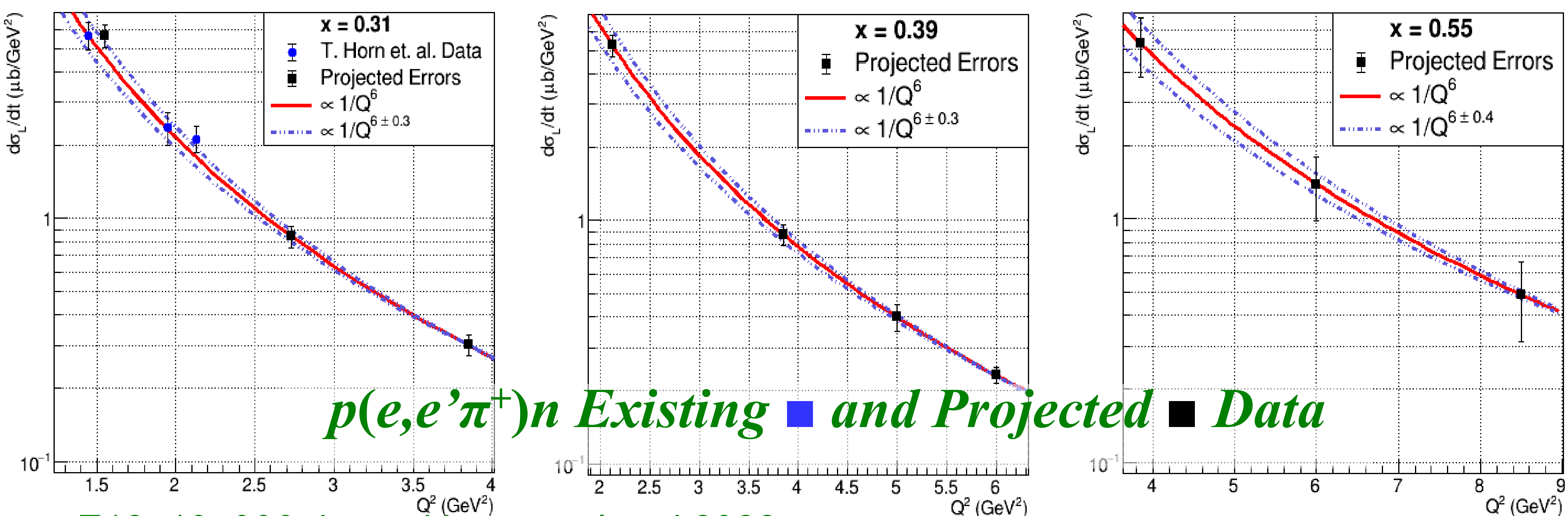
# Testing Factorization: *$p(e,e'\pi^+)n$*

- **One of most stringent tests of factorization is $Q^2$ dependence of π/K electroproduction cross sections**
  - $\sigma_L$ scales to leading order as $Q^{-6}$
  - As $Q^2$ becomes large: $\sigma_L \gg \sigma_T$
- **If we show factorization regime is not reached, it will have major implications for meson production GPD experiments in this $Q^2$ regime** (Some of these experiments are already taking data!)




*$p(e,e'\pi^+)n$ Existing ■ and Projected ■ Data*

- E12–19–006 data taking completed 2022
- PhD students: N. Heinrich, M. Junaid    Spokespersons: D. Gaskell, T. Horn, GMH

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# Important 2nd Test: $p(e,e'K^+)\Lambda$

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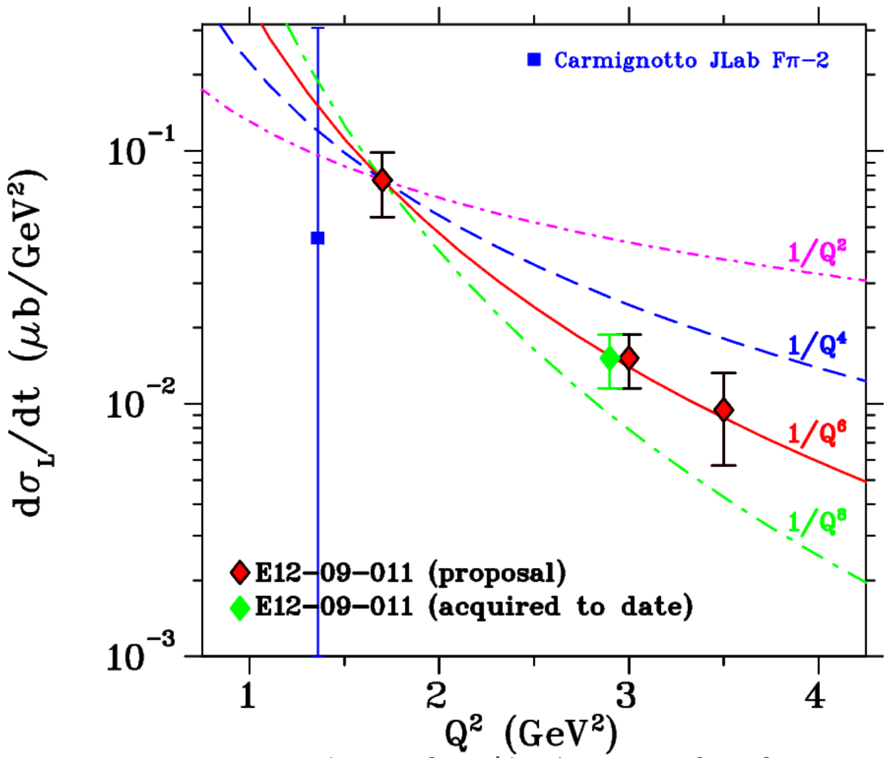
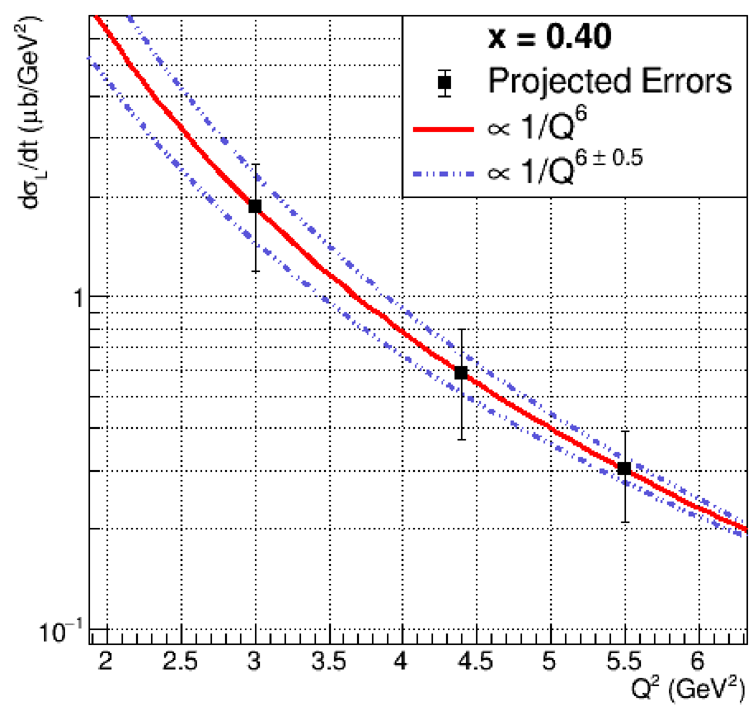
- Experimental validation of onset of hard scattering regime is essential for reliable interpretation of JLab GPD program results
- Is onset of scaling different for kaons than pions?
- $K^+$ and $\pi^+$ together provide quasi model-independent study




## *$p(e,e'K^+)\Lambda$ Existing ■ and Projected ♦♦■ Data*

- E12-09-011 data taking partially completed in 2019
- Data for $x_B$=0.40 scan in hand. Data for $x_B$=0.25 scan only partly acquired.
  - Spokespersons: T. Horn, P. Markowitz, GMH

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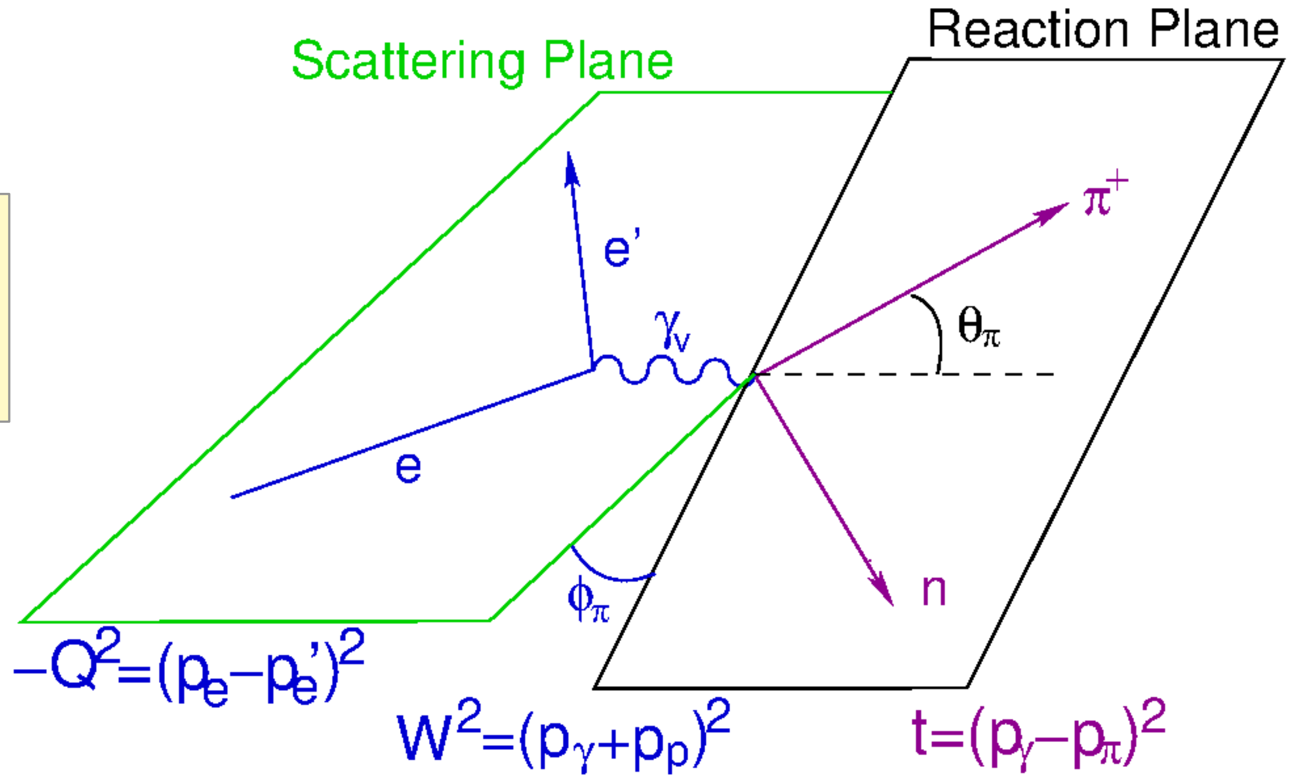
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Virtual-photon polarization:

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




- **For GPD factorization test, we need $\sigma_L$**
- **L-T separation required to separate $\sigma_L$ from $\sigma_T$**
- **For non–parallel kinematics, separation of $\sigma_{LT}$, $\sigma_{TT}$ also required, which requires full azimuthal coverage**

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# Jefferson Lab Hall C

**SHMS:**
- 11 GeV/c Spectrometer
- Partner of existing 7 GeV/c **HMS**

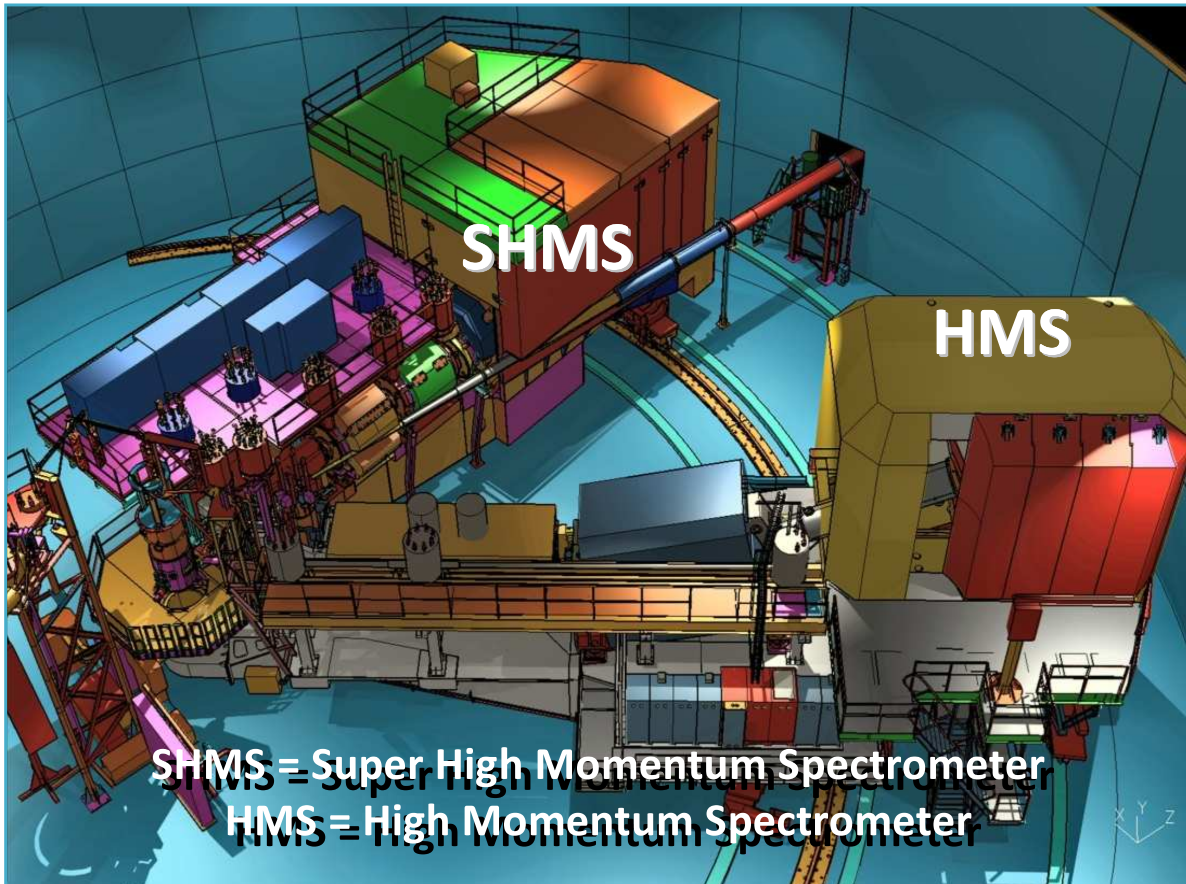
**MAGNETIC OPTICS:**
- Point-to Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

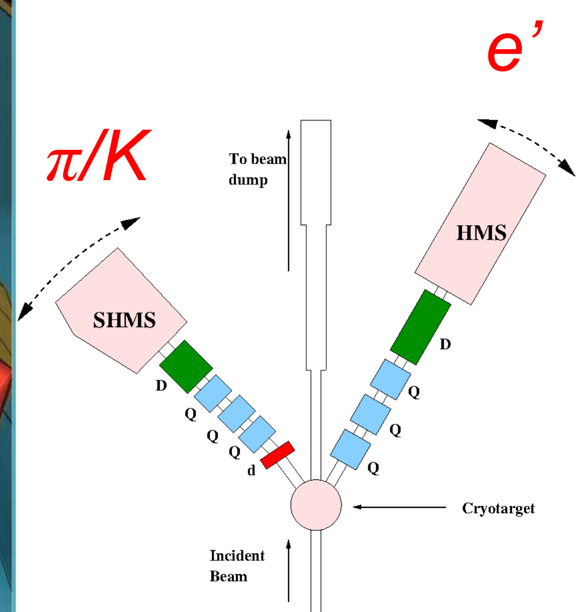
**Detector Package:**
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter

**Well-Shielded Detector Enclosure**

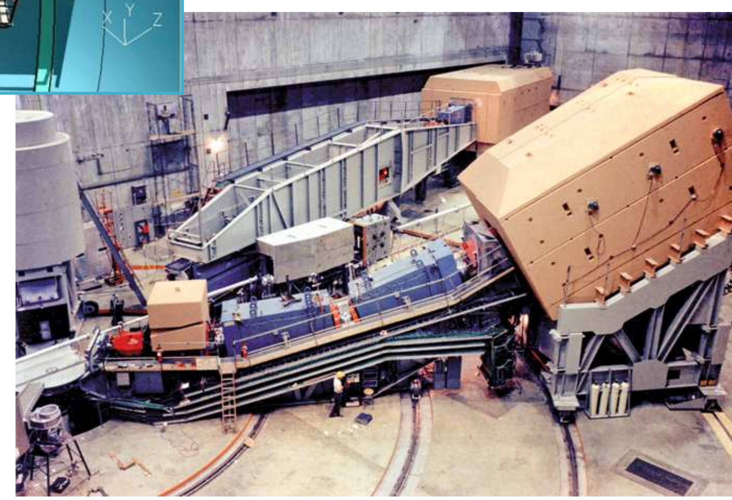
**Rigid Support Structure**
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS

**Luminosity**
- ~$4\times10^{38}$ $cm^{-2}$ $s^{-1}$




Upgraded Hall C has some similarity to SLAC End Station A, where the quark substructure of proton was discovered in 1968.



# PionLT (E12–19–006) t–φ Coverage

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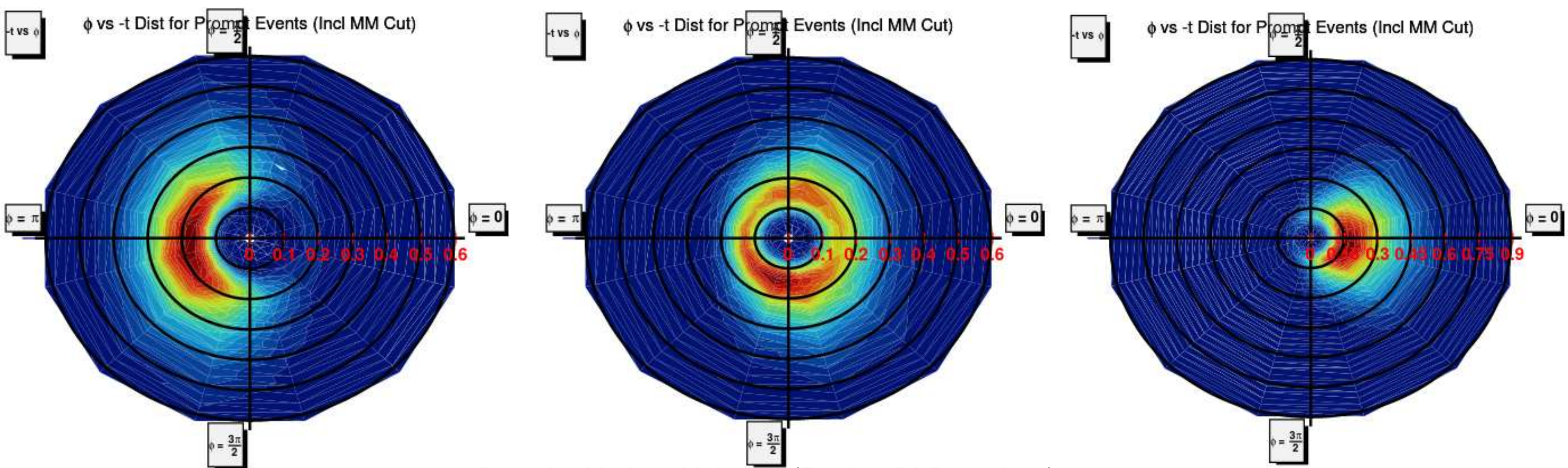
- Measure $\sigma_{LT}$, $\sigma_{TT}$ by taking data at three pion spectrometer (SHMS) angles, +2°, 0°, -2°, with respect to *q*–vector

Example t–φ plots from: $Q^2$=3.85, W=3.07, High ε

SHMS Left (+2°) | SHMS Center (0°) | SHMS Right (-2°)




Plots by Nathan Heinrich (Regina PhD student)

- To control systematics, an excellent understanding of spectrometer acceptances is required
  - Over–constrained *p(e,e'p)* reaction, and inelastic e+$^{12}$C, used to calibrated spectrometer acceptances, momenta, kinematic offsets, efficiencies.
  - Control of point–to–point systematic uncertainties crucial due to 1/Δε error amplification in $\sigma_L$

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# The different pion arm (SHMS) settings are combined to yield φ-distributions for each *t*-bin

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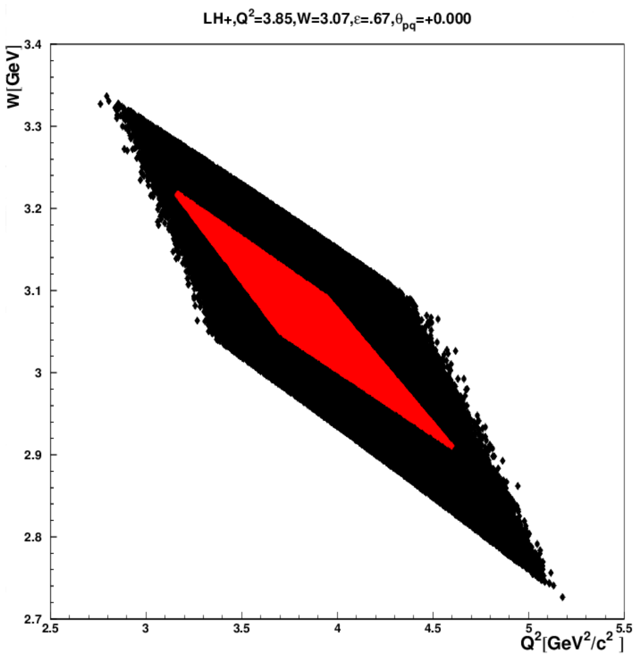
$$2\pi\frac{d^2\sigma}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

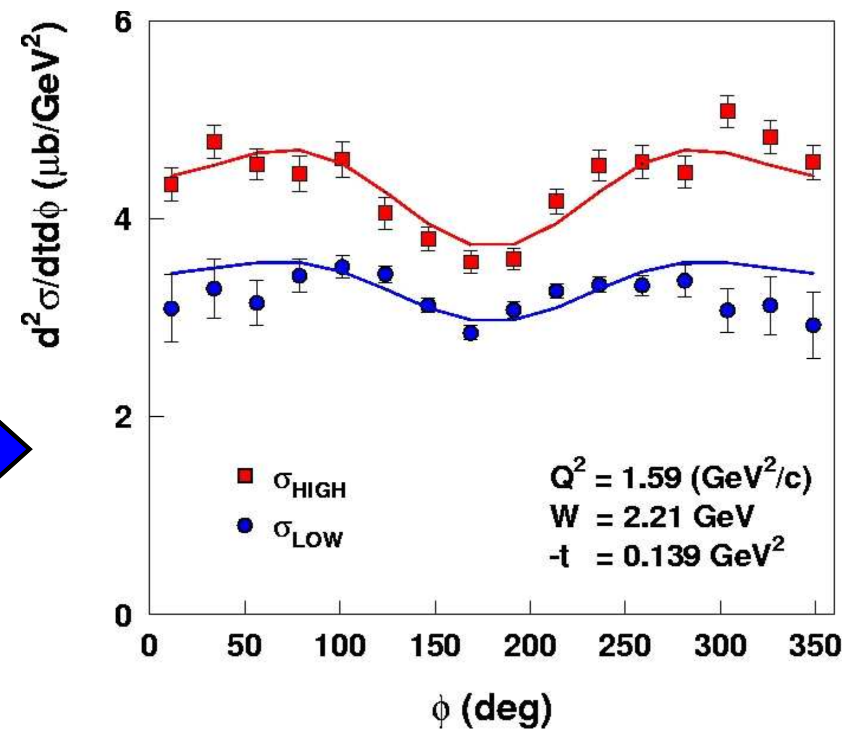



Diamond cuts define common ($W$,$Q^2$) coverage at both ε

Simulated SHMS+HMS acceptance at $Q^2$=3.85, W=3.07

■ High ε=0.67 ■ Low ε=0.30

- Extract $\sigma_L$ by simultaneous fit of L,T,LT,TT using measured azimuthal angle ($\varphi_\pi$) and knowledge of photon polarization (ε)

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# Opportunities with higher JLab $E_{beam}$

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- **JLab 22 GeV Upgrade White Paper:**

  A. Accardi, et al., ``Strong Interaction Physics at the Luminosity Frontier with 22 GeV electrons at Jefferson Lab", arXiv: 2306.09360, EPJA (in press)

- **Staged Hall C Upgrade Seems Logical**
- **Phase 1:** Upgrade Beam to 18 GeV, minor upgrades of SHMS, HMS PID, tracking and DAQ
- **Phase 2:** Upgrade Beam to 22 GeV, upgrade HMS' to 15 GeV/c
  - Would enable a significant increase in $Q^2$ reach of quality L–T separations for Deep Exclusive Meson Production

- **Hall C is world's only facility that can do L–T separations over wide kinematic range**
- **As the interpretation of some EIC data (e.g. GPD extraction) will depend on extrapolation of Hall C L–T separated data, maximizing overlap between Hall C and EIC data sets should be a high priority**

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# DEMP $Q^{-n}$ Hard–Soft Factorization Tests

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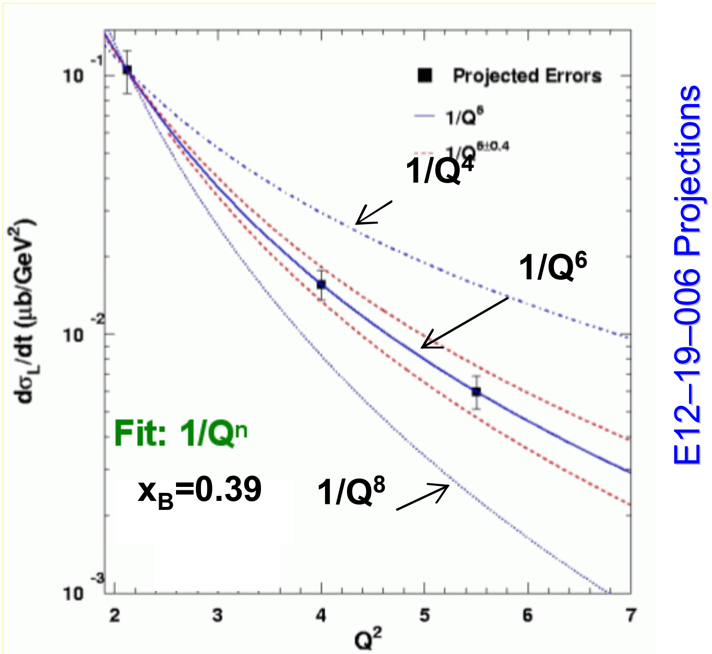
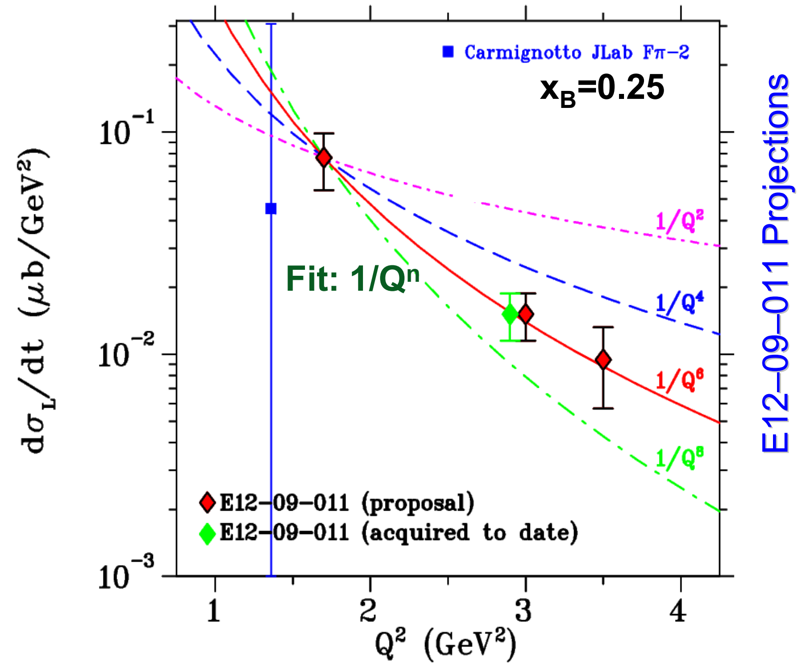
## $p(e,e'\pi^+)n$




| x | $Q^2$ (GeV$^2$) | W (GeV) | $-t_{min}$ (GeV$^2$) |
|---|---|---|---|
| 0.31 | 1.45–3.65 | 2.02–3.07 | 0.12 |
| | 1.45–6.5 | 2.02–3.89 | |
| 0.39 | 2.12–6.0 | 2.05–3.19 | 0.21 |
| | 2.12–8.2 | 2.05–3.67 | |
| 0.55 | 3.85–8.5 | 2.02–2.79 | 0.55 |
| | 3.85–11.5 | 2.02–3.23 | |

## $p(e,e'K^+)\Lambda$




| x | $Q^2$ (GeV$^2$) | W (GeV) | $-t_{min}$ (GeV$^2$) |
|---|---|---|---|
| 0.25 | 1.7–3.5 | 2.45-3.37 | 0.20 |
| | 1.7–5.5 | 2.45–4.05 | |
| 0.40 | 3.0–5.5 | 2.32–3.02 | 0.50 |
| | 3.0–8.7 | 2.32–3.70 | |

**PHASE 1 SCENARIO**

**$Q^{-n}$ scaling test range nearly doubles with 18 GeV beam and HMS+SHMS**

# Summary

- **GPDs are an important next step in our understanding of hadronic structure**
- **Factorization studies are crucial if the field is to fully utilize the information encoded in GPDs, as GPDs are only accessible experimentally in the hard–soft factorization regime**

- PionLT (E12–19–006) will measure LT–separated $p(e,e'\pi^+)n$ data for $Q^{-n}$ scans at $x_B$=0.31, 0.39, 0.55
- KaonLT (E12–09–011) has acquired $p(e,e'K^+)\Lambda$ data for a $Q^{-n}$ scan at $x_B$=0.40, and an eventual extension to $x_B$=0.25

- A further JLab upgrade to 18-22 GeV would double the $Q^2$ range covered in these tests, and allow the region of applicability of the factorization theorem to be probed with greater authority

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# Hadron Femtography via GPDs

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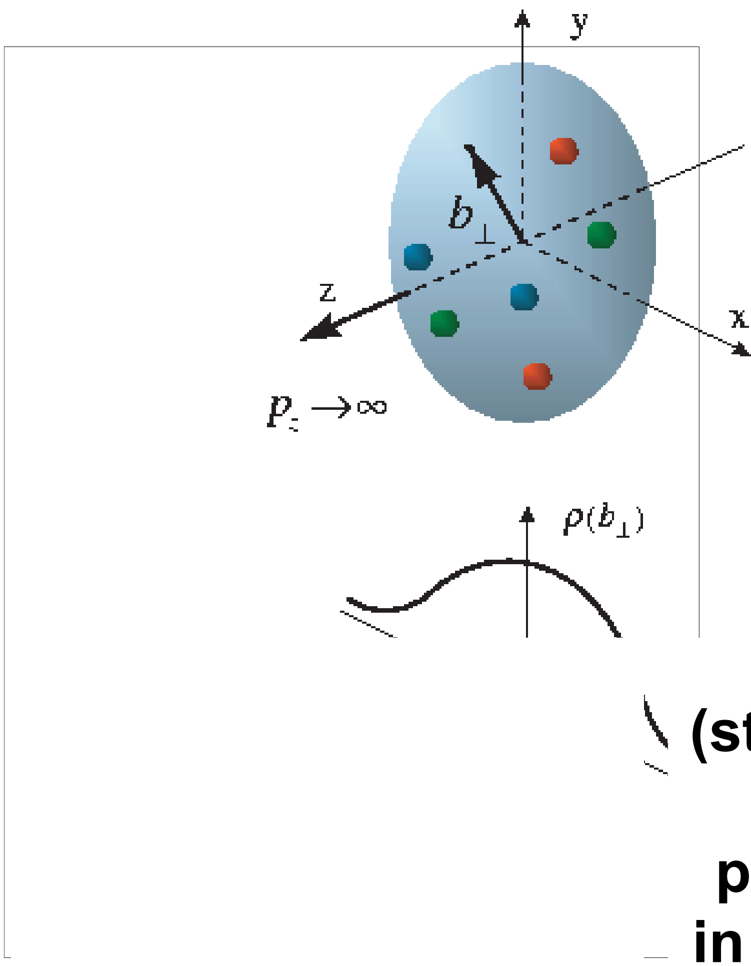



**DIS**
**(structure functions)**
**longitudinal**
**parton distribution**
**in momentum space**

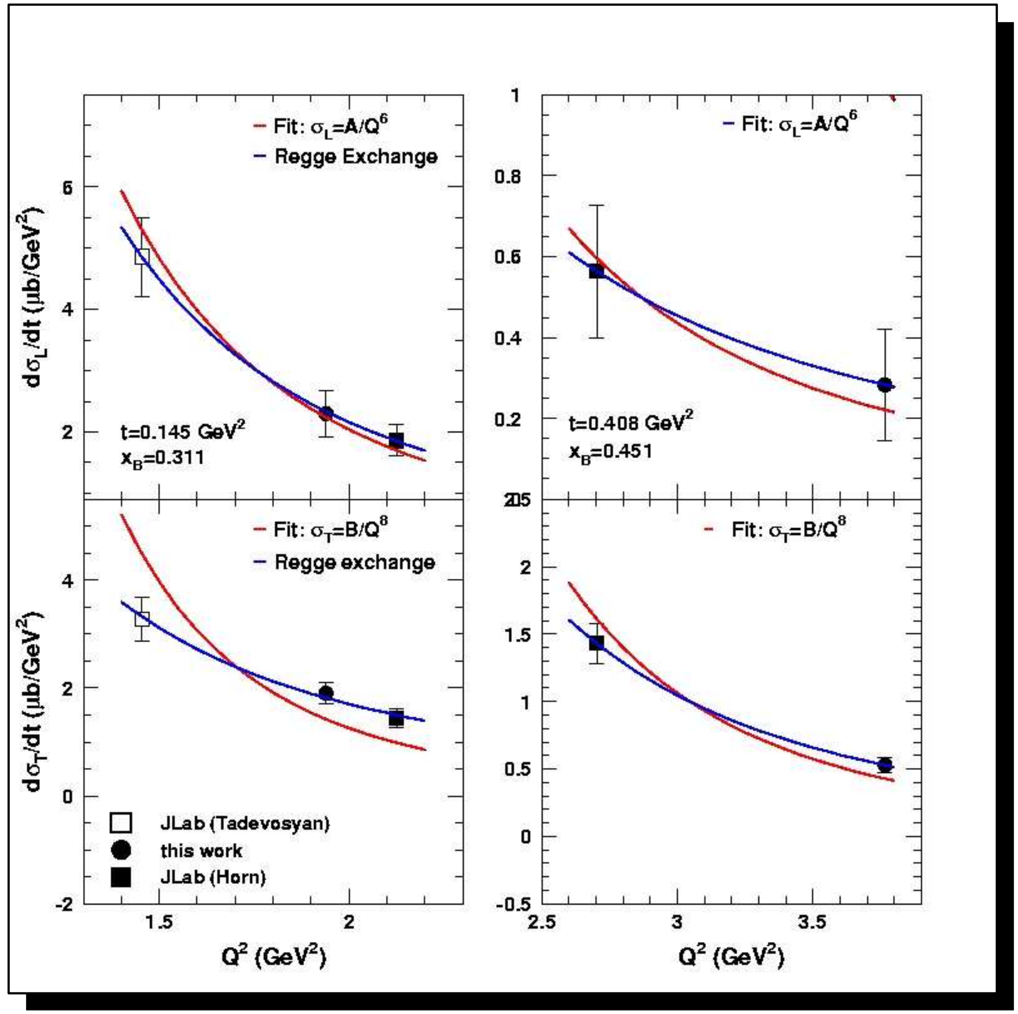
**DES (GPDs)**
**Fully-correlated**
**parton distribution in**
**both coordinate and**
**momentum space**

# Regge Exchange Contribution

- Calculation by *A.P. Szczepaniak et al. [arXiv:0707.1239v2]* suggest significant scaling violations at small –t and independent of $Q^2$
  - Expect $Q^2$ behavior characteristic for hadronic Regge amplitudes

$$\sigma_{L,T} \sim (Q^{-n})^{2\alpha(t)-1}$$

| x | $\alpha_L$ | $\alpha_T$ |
|---|---|---|
| 0.31 | 0.46 ± 0.50 | 1.90 ± 0.36 |
| 0.45 | 0.92 ± 2.00 | 0.99 ± 0.51 |




HERMES $\pi^+$ fit: $\alpha$=0.31 ± 0.2 (0.26 < $x_B$ < 0.80), BUT not separated

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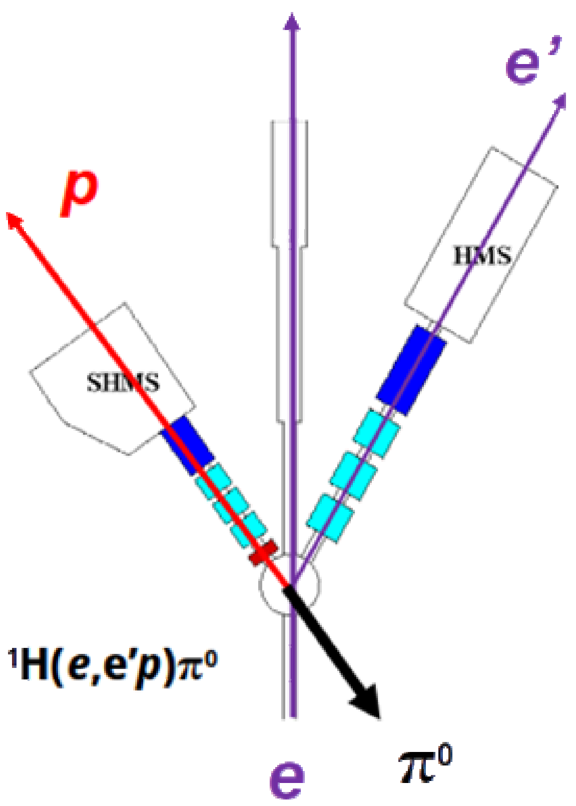
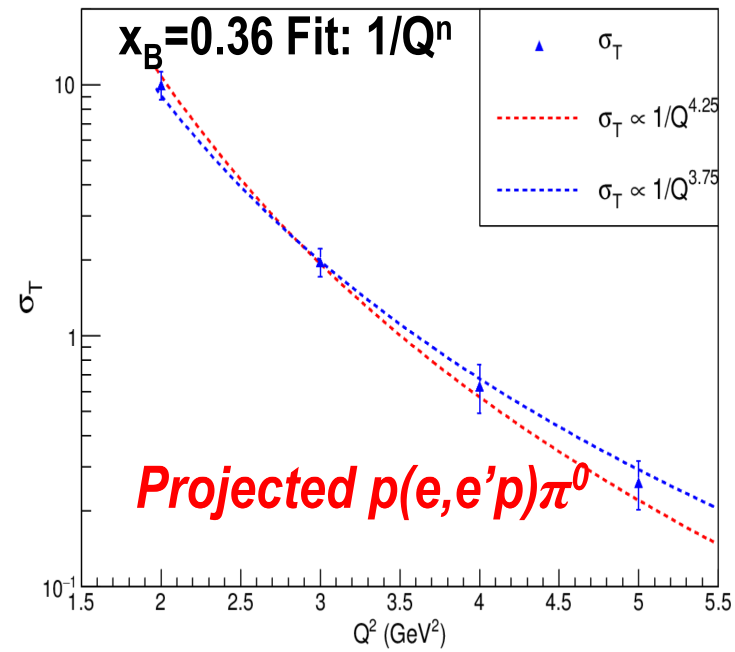
# Backward Angle Hard–Soft Factorization

## Extension of collinear factorization to u–channel

- Proposed by Frankfurt, Polykaov, Strikman, Zhalov, Zhalov [arXiv:hep-ph/0211263]
- Transition Distribution Amplitude (TDA) formalism by: B. Pire, K. Semenov–Tian–Shansky, L. Szymanowski, Phys. Rep. 920(2021)1




E12–20–007: W.B. Li, G.M. Huber, J. Stevens (spokespersons)




- **First *dedicated u*–channel electroproduction study above resonance region:**
  - Demonstrate existence of far backward u–channel cross section peak
  - $Q^{-n}$ scaling behavior of $d\sigma_T/dt$
  - u–dependence of L/T separated cross sections

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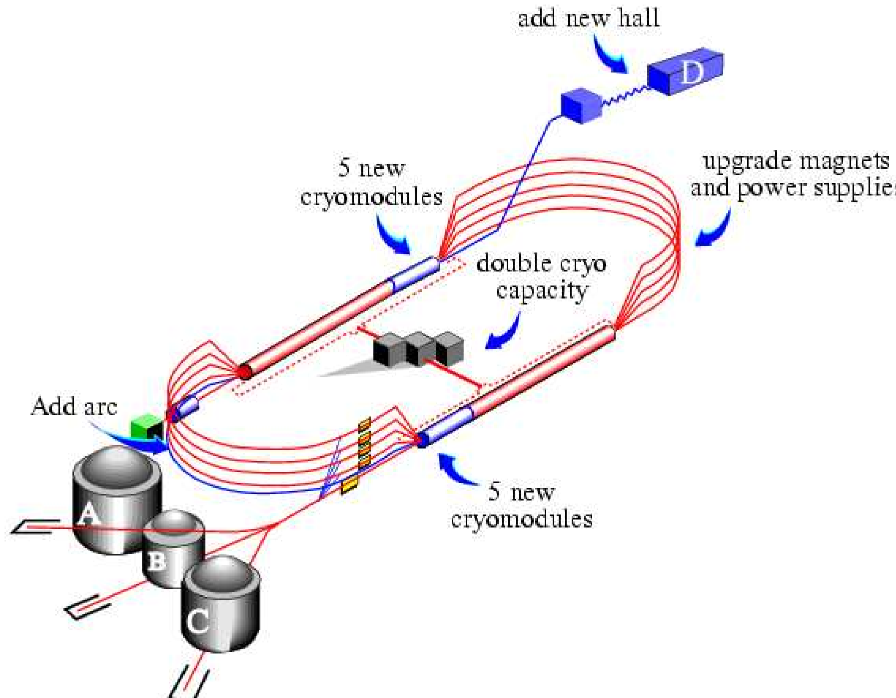
# Jefferson Lab
Thomas Jefferson National Accelerator Facility



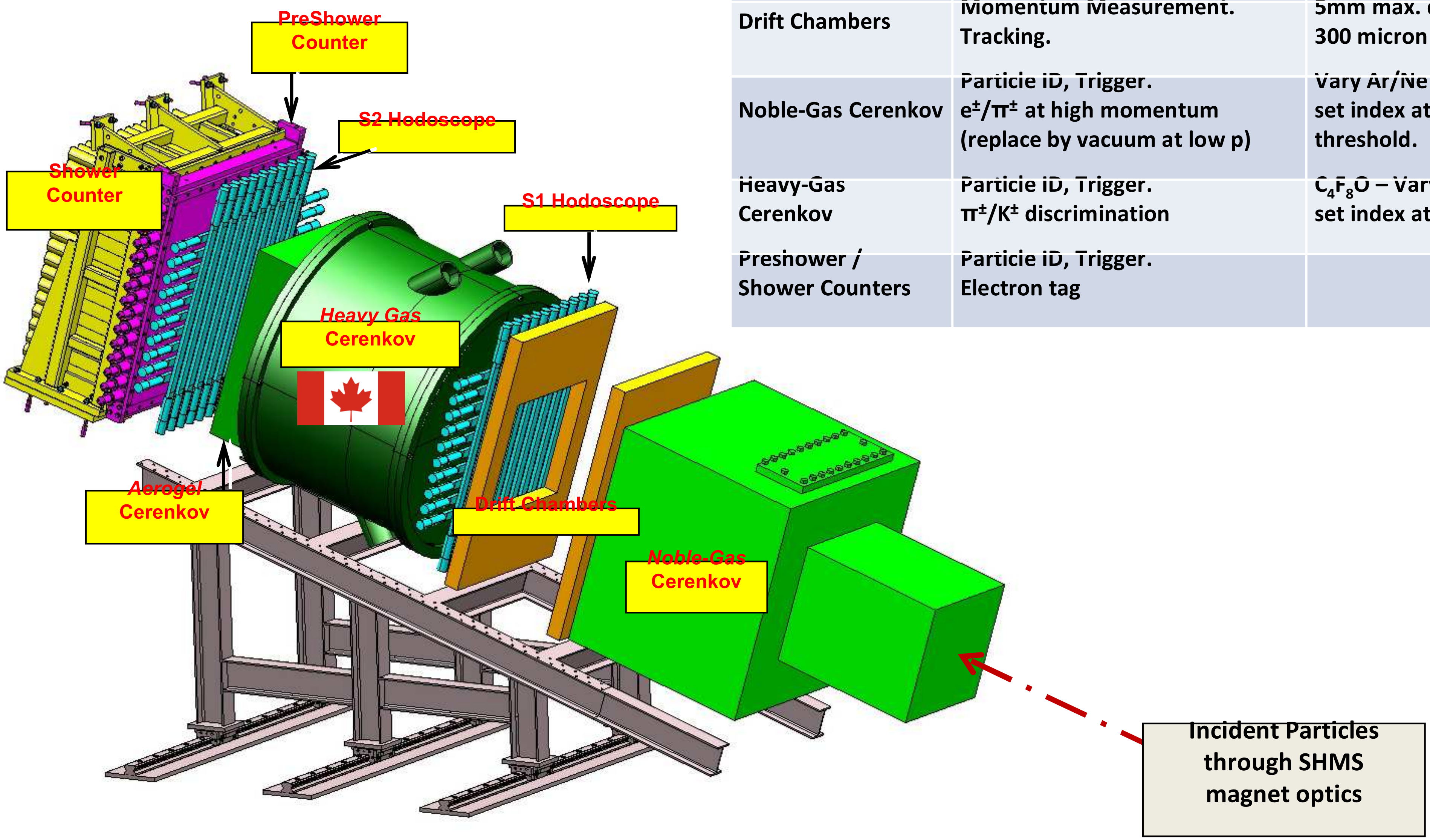



Two 1.5 GHz Superconducting Linear Accelerators provide electron beam for Nucleon & Nuclear structure studies.

- **Beam energy E → 12 GeV.**
- **Beam current >100 μA.**
- **Duty factor 100%, 85% polarization.**
- Experiments in all 4 Halls can receive beam simultaneously.

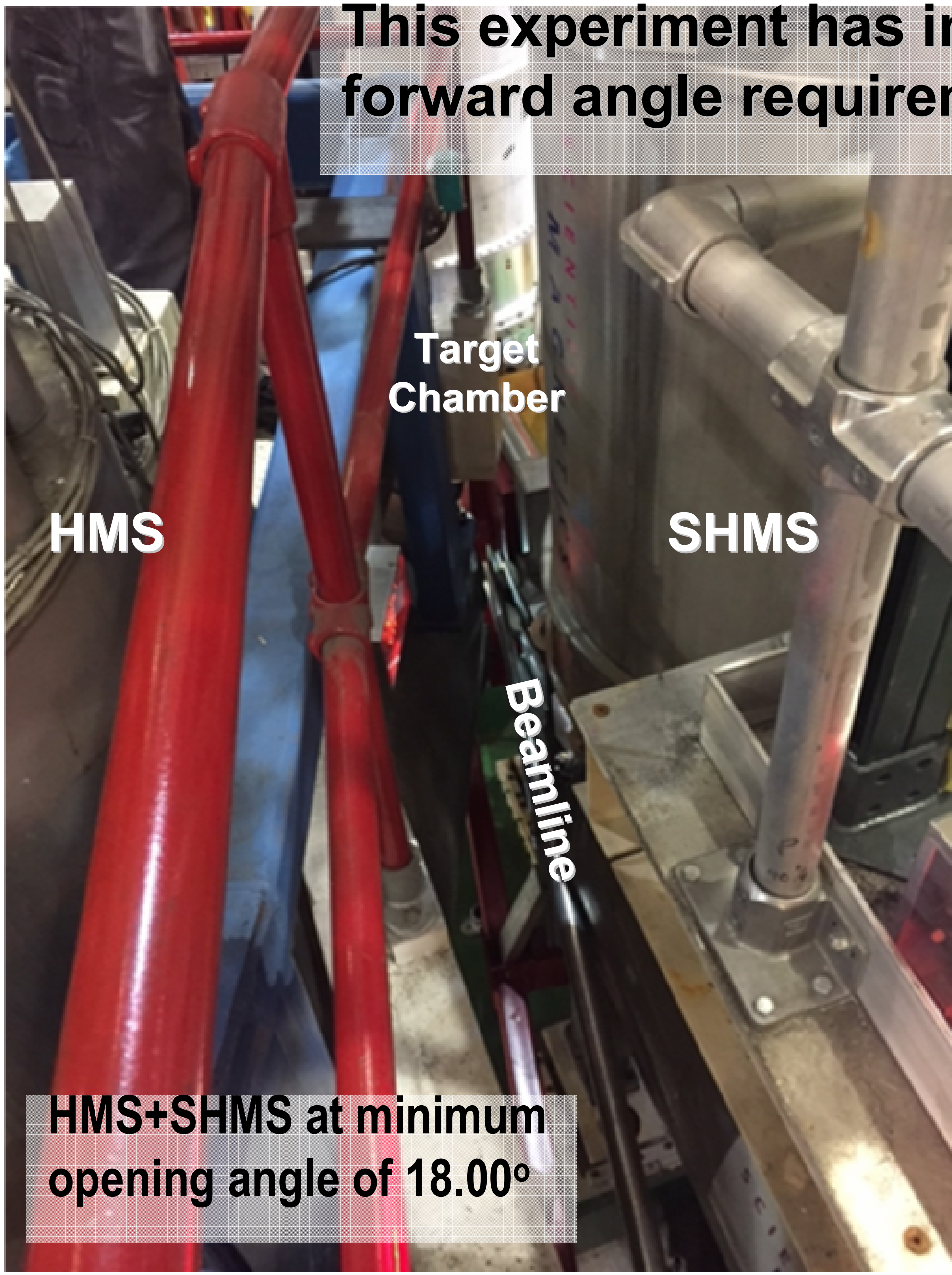
# SHMS Focal Plane Detector System

| DETECTOR | PURPOSE | NOTES |
|---|---|---|
| S1XY, S2XY Hodoscopes | Lowest-level Trigger. Time reference | |
| Drift Chambers | Momentum Measurement. Tracking. | 5mm max. drift 300 micron resolution |
| Noble-Gas Cerenkov | Particle ID, Trigger. $e^{\pm}/\pi^{\pm}$ at high momentum (replace by vacuum at low p) | Vary Ar/Ne mixture to set index at $\pi^{\pm}$ threshold. |
| Heavy-Gas Cerenkov | Particle ID, Trigger. $\pi^{\pm}/K^{\pm}$ discrimination | $C_4F_8O$ – Vary pressure to set index at $K^{\pm}$ threshold |
| Preshower / Shower Counters | Particle ID, Trigger. Electron tag | |



# HMS and SHMS during Data Taking

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




# $p(e,e'\pi^+)n$ Event Selection

## Coincidence measurement between charged pions in SHMS and electrons in HMS.

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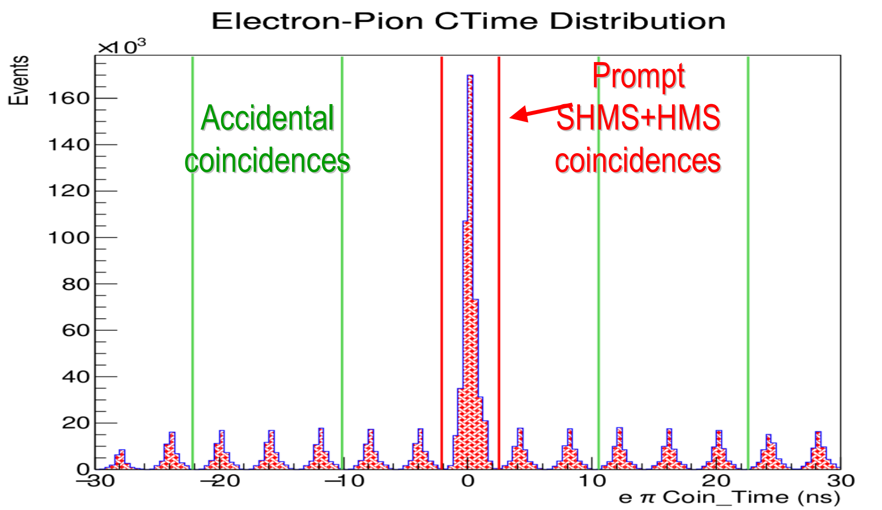
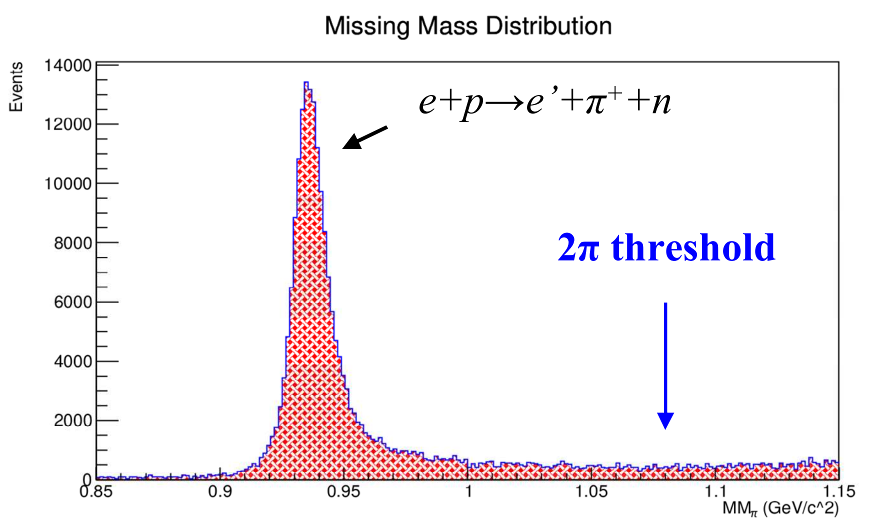
Easy to isolate exclusive channel

- Excellent particle identification
- CW beam minimizes "accidental" coincidences
- Missing mass resolution easily excludes 2–pion contributions




**PionLT experiment E12–19–006 Data**

$Q^2$=1.60, $W$=3.08, $x$= 0.157, $\varepsilon$=0.685

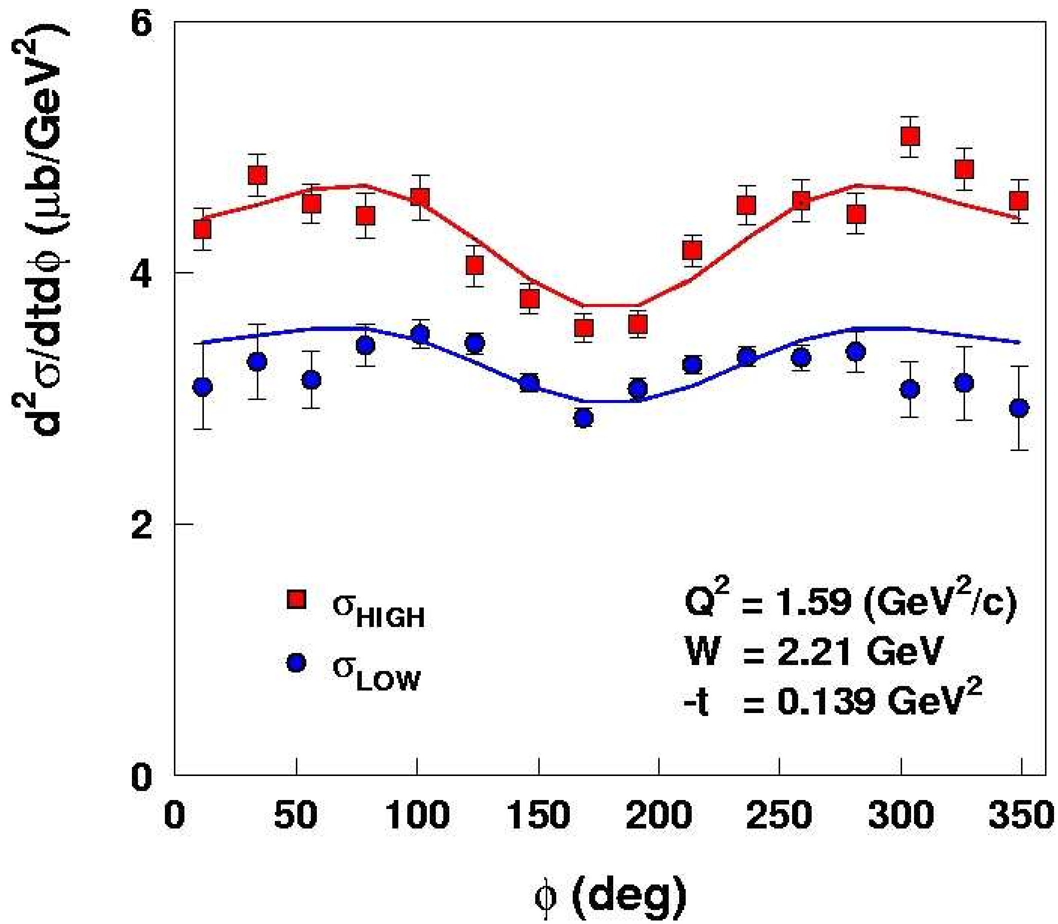
$E_{beam}$=9.177 GeV, $P_{SHMS}$=+5.422 GeV/c, $\theta_{SHMS}$= 10.26° (left)

Plots by Muhammad Junaid

# The different pion arm (SHMS) settings are combined to yield φ-distributions for each *t*-bin

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

- Extract all four response functions via a simultaneous fit using measured azimuthal angle ($\varphi_\pi$) and knowledge of photon polarization (ε).
- **This technique demands good knowledge of the magnetic spectrometer acceptances.**
  - **Control of point–to–point systematic uncertainties crucial due to 1/Δε error amplification in $\sigma_L$**
  - Careful attention must be paid to spectrometer acceptance, kinematics, efficiencies, …




*T. Horn, et al, PRL **97** (2006)192001*

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# L/T–separation error propagation

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

$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{(\varepsilon_1-\varepsilon_2)}\left(\frac{\Delta\sigma}{\sigma}\right)\sqrt{(R+\varepsilon_1)^2+(R+\varepsilon_2)^2} \qquad \text{where } R = \frac{\sigma_T}{\sigma_L}$$

$$\frac{\Delta\sigma_T}{\sigma_T} = \frac{1}{(\varepsilon_1-\varepsilon_2)}\left(\frac{\Delta\sigma}{\sigma}\right)\sqrt{\varepsilon_1^{\,2}\left(1+\frac{\varepsilon_2}{R}\right)^2+\varepsilon_2^{\,2}\left(1+\frac{\varepsilon_1}{R}\right)^2}$$

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

**Error in $d\sigma_L/dt$ is magnified by $1/\Delta\varepsilon$, where $\Delta\varepsilon=(\varepsilon_{Hi}-\varepsilon_{Low})$**

**→ To keep magnification factor <5x, need $\Delta\varepsilon$>0.2, preferably more!**

# Magnetic Spectrometer Calibrations

- **Similarly to Fπ–2, we use the over–constrained *p(e,e'p)* reaction and inelastic $e+^{12}C$ in the DIS region to calibrate spectrometer acceptances, spectrometer 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%.

Uncertainties from $F_\pi$ Proposal (E12–06–101)

| Projected Systematic Uncertainty Source | Pt-Pt ε-random t-random | ε-uncorrelated common to all t-bins | Scale ε-global t-global |
|---|---|---|---|
| Spectrometer Acceptance | 0.4% | 0.4% | 1.0% |
| Target Thickness | | 0.2% | 0.8% |
| Beam Charge | - | 0.2% | 0.5% |
| HMS+SHMS Tracking | 0.1% | 0.4% | 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 | 0.2% | 1.0% | 0.5% |
| Radiative Corrections | 0.1% | 0.4% | 2.0% |
| Kinematic Offsets | 0.4% | 1.0% | - |

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

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