# E12-06-101 and E12-07-105

S. Ali, D. Androic, K. Aniol, J. Arrington, A. Asaturyan, F. Benmokthar, V. Berdnikov, D. Biswas, W. Boeglin, P. Bosted, E.J. Brash, W. Boeglin, A. Camsonne, M. Carmignotto, J.-P. Chen, E.Christy, S. Covrig-Dusa, D. Day, D. Crabb, W. Deconinck, M. Diefenthaler, D. Dutta, M.Elaasar, R. Ent, **D. Gaskell**, H. Fenker, E. Fuchey, D. Hamilton, O. Hansen, F. Hauenstein, D.Higinbotham, **T. Horn**, **G.M. Huber**, C.E. Hyde, M. Jones, S. Joosten, S. Kay, D. Keller, C.Keppel, P. King, E. Kinney, M. Kohl, V. Kumar, W. Li, A. Liyanage, D. Mack, S. Malace, P.Markowitz, R. Michaels, A. Mkrtchyan, H. Mkrtchyan, M. Muhoza, C. Munoz-Camacho, A.Puckett, G. Niculescu, I. Niculescu, Z. Papandreou, J. Roche, B. Sawatzky, S. Sirca, G.R.Smith, H. Szumila, V. Tadevosyan, R. Trotta, A. Teymurzyan, A. Usman, B. Wojtsekhowski, S. Wood, C. Yero

*A.I. Alikhanyan National Science Laboratory/Yerevan, Catholic University of America, Institut de Physique Nucleaire d'Orsay/France, Jefferson Laboratory, Florida International Univ., Argonne National Laboratory, Hampton Univ. Mississippi State Univ., Univ. of Regina, Univ. of Virginia, Jozef Stefan Institute and Univ. of Ljubljana, James Madison Univ., Univ. of Zagreb, California State Univ., Duquesne Univ., Christopher Newport Univ., Univ. of Glasgow, Southern Univ., College of W&M, Old Dominion Univ., Univ. of Colorado, Ohio Univ.*

# Overview E12-06-101/E12-07-105 (PionLT)

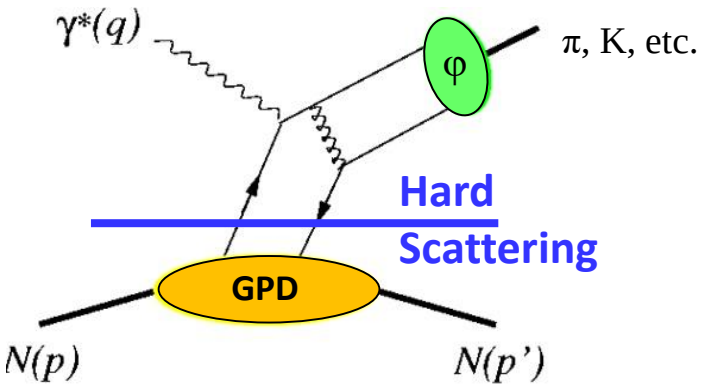
## Goals

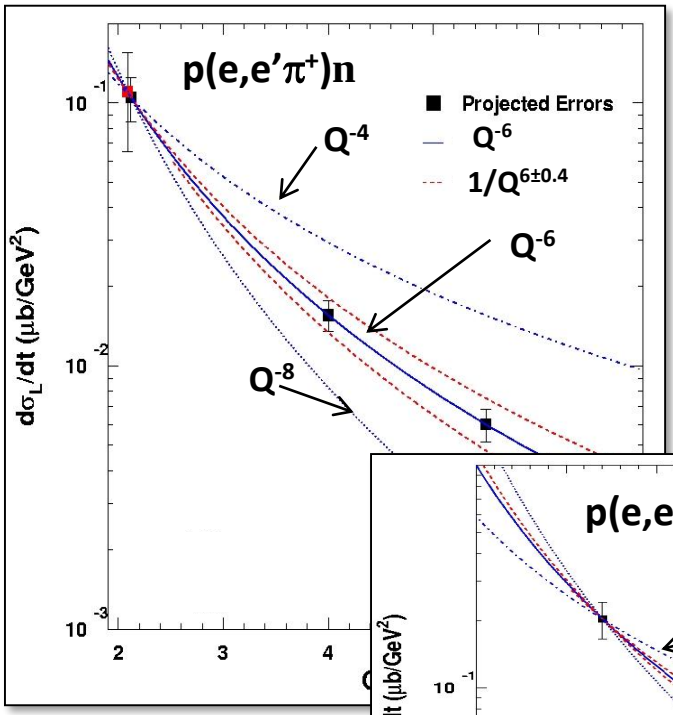
- Separated cross sections as a function of $Q^2$ at fixed x=0.3, 0.4, 0.55 to investigate the reaction mechanism towards 3D imaging studies
- Reliable pion form factor extractions up to the largest $Q^2$ accessible until the EIC
  - Combine two separately PAC-approved experiments to achieve more physics output from the same beam time (88 days)

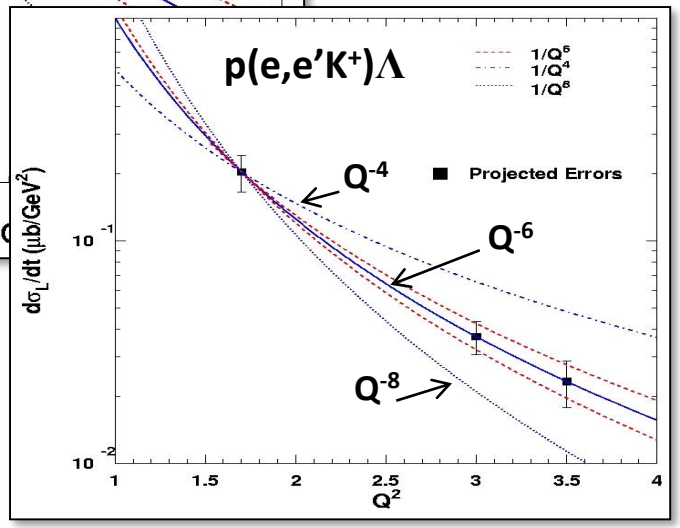
## Motivation

- Pion structure is the clearest test case for studies of the transition from the nonperturbative to perturbative region
- Need to validate the hard-exclusive reaction mechanism – key are precision longitudinal-transverse (L/T) separated data over a range of $Q^2$ at fixed x/t
- L/T separated pion electroproduction is the clearest test case for studies of the transition from the nonperturbative to perturbative region beyond DVCS
- Pion electroproduction could allow access to transversity and regular GPDs

# Review Scientific Motivation: Reaction Mechanism




$\pi^+$: to $Q^2$~9 GeV$^2$
$K^+$: to $Q^2$~6 GeV$^2$

Fit: $1/Q^n$

- One of the most stringent tests of the reaction mechanism is the $Q^2$ dependence of the $\pi$ and K electroproduction cross section
  - $\sigma_L$ scales to leading order as $Q^{-6}$
  - $\sigma_T$ does not
- Experimental validation of reaction mechanism is essential for reliable interpretation of results from the JLab GPD program at 12 GeV for meson electroproduction
  - **If $\sigma_T$ is confirmed to be large, it could allow for detailed investigations of transversity GPDs. If, on the other hand, $\sigma_L$ is measured to be large, this would allow for probing the usual GPDs**

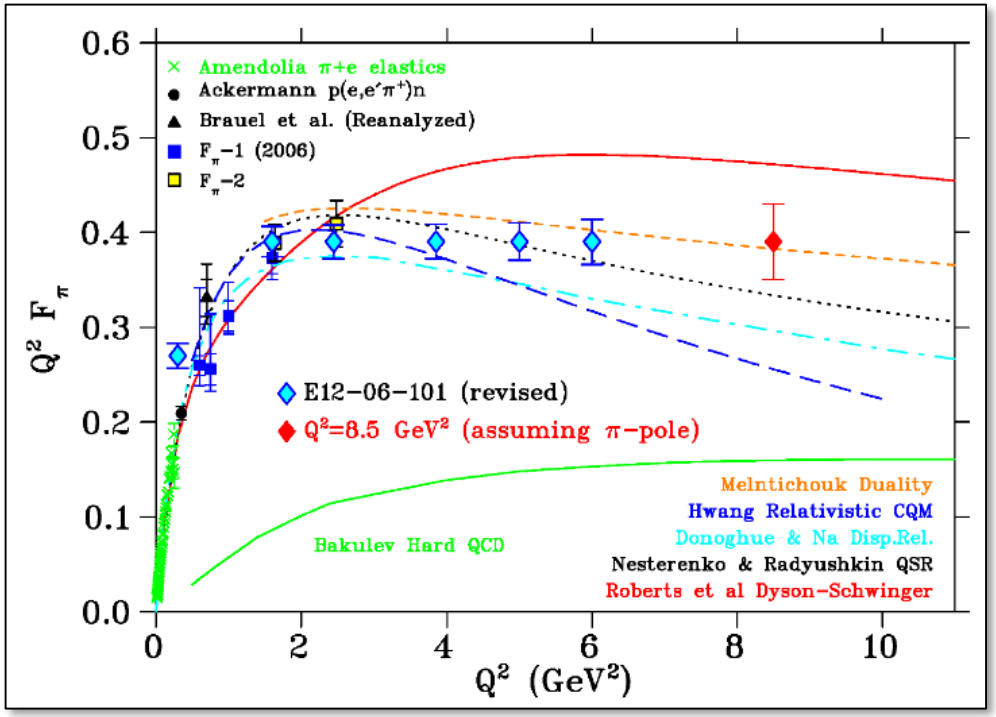
# Review Scientific Motivation: Form Factors

- ***Pion and kaon form factors*** are of special interest in hadron structure studies
  - The *pion* is the lightest QCD quark system and also has a central role in our understanding of the dynamic generation of mass

***Clearest test case for studies of the transition from non-perturbative to perturbative regions***

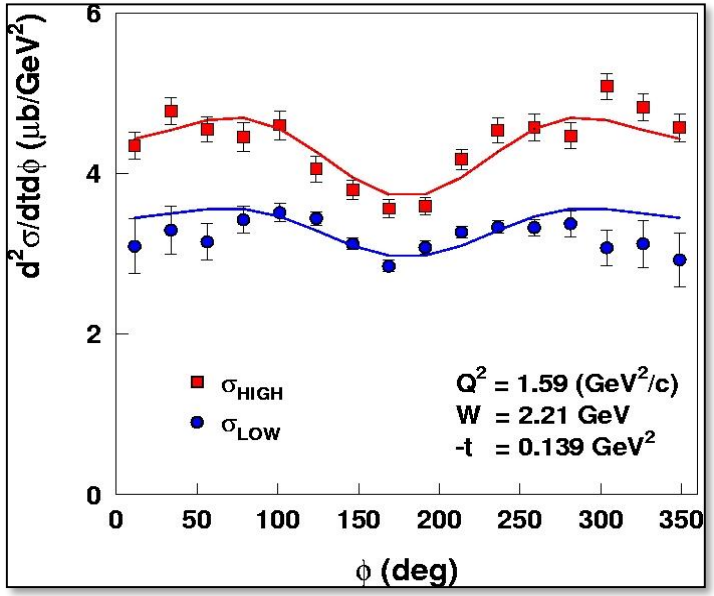
- Completed Hall C experiments have established JLab's capability for reliable $F_\pi$ measurements and are among the top-cited works from JLab

- New higher $Q^2$ data would challenge QCD-based models in the most rigorous way and provide a real advance in our understanding of light quark systems



# L/T Separation Example

- $\sigma_L$ is isolated using the Rosenbluth separation technique
  - Measure the cross section at two beam energies and fixed W, $Q^2$, -t
  - Simultaneous fit using the measured azimuthal angle ($\phi_\pi$) allows for extracting L, T, LT, and TT
- Careful evaluation of the systematic uncertainties is important due to the 1/ε amplification in the $\sigma_L$ extraction
  - Spectrometer acceptance, kinematics, and efficiencies




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

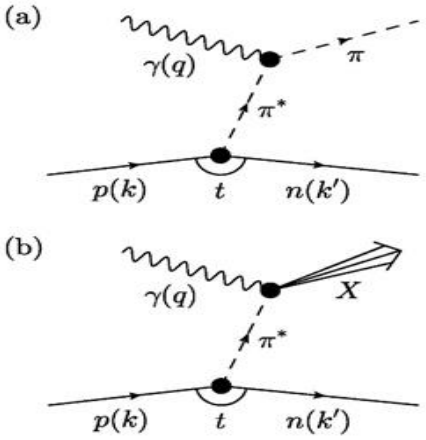
$\sigma_L$ will give us $F_\pi$

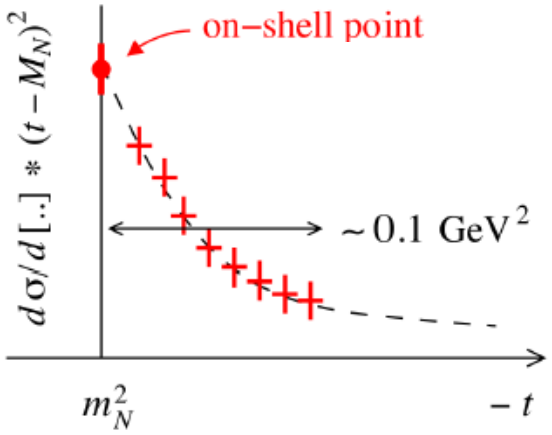
Magnetic spectrometers a must for such precision cross section measurements

- This is only possible in Hall C at JLab
- SHMS was built to meet these exp. req.

# Accessing pion structure through the Sullivan Process

- The **Sullivan process can provide reliable access to a meson target** as *t* becomes space-like if the pole associated with the ground-state meson remains the dominant feature of the process and the structure of the related correlation evolves slowly and smoothly with virtuality.




- To **check these conditions** are satisfied empirically, one can **take data covering a range in *t*** and compare with phenomenological and theoretical expectations.

- Recent **theoretical calculations found that for -t ≤ 0.6 GeV², all changes in pion structure are modest** so that a well-constrained experimental analysis should be reliable The Sullivan processes can provide a valid pion target for -t ≤ 0.6 GeV²

*[S.-X. Qin, C. Chen, C. Mezrag and C. D. Roberts, Phys. Rev. C 97 (2018) 015203.]*

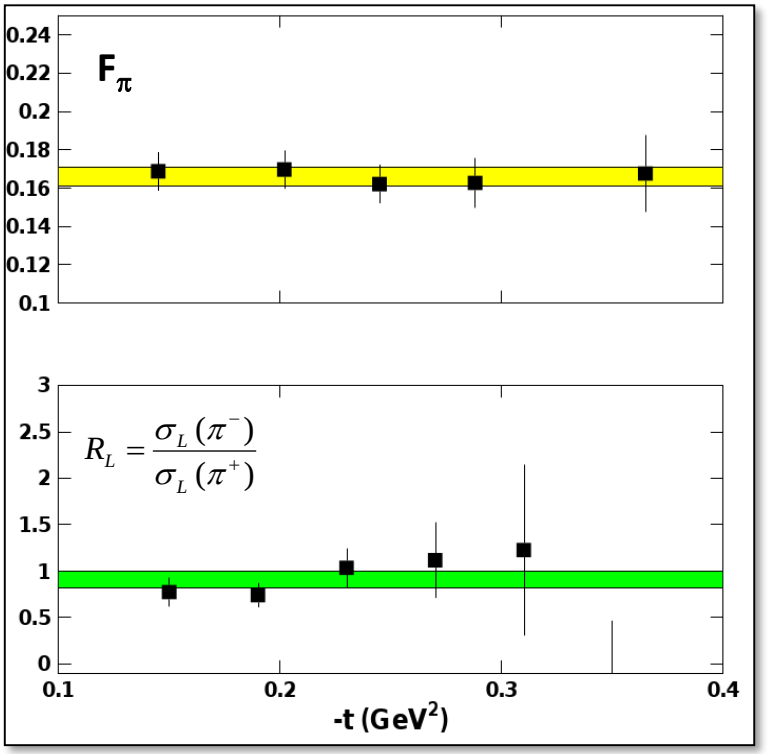
# Experimental Validation (Pion Form Factor example)

Experimental studies over the last decade have given more *confidence* in the electroproduction method yielding the physical pion form factor

Experimental studies include:

- Check consistency of model with data
  - $F_\pi$ values seem robust at larger -t (>0.2) – increased confidence in applicability of model to the kinematic regime of the data
- Verify that the pion pole diagram is the dominant contribution in the reaction mechanism
  - $R_L$ (= $\sigma_L(\pi^-)/\sigma_L(\pi^+)$) approaches the pion charge ratio, consistent with pion pole dominance
- Extract $F_\pi$ at several values of $t_{min}$ for fixed $Q^2$ (not shown here)

$Q^2$=2.45 GeV$^2$, W=2.22 GeV




$$R_L = \frac{\sigma(n(e,e'\pi^-)p)}{\sigma(p(e,e'\pi^+)n))} = \frac{|A_v - A_s|^2}{|A_v + A_s|^2}$$

# Using a model to extract of $F_\pi$ from $\sigma_L$ JLab data

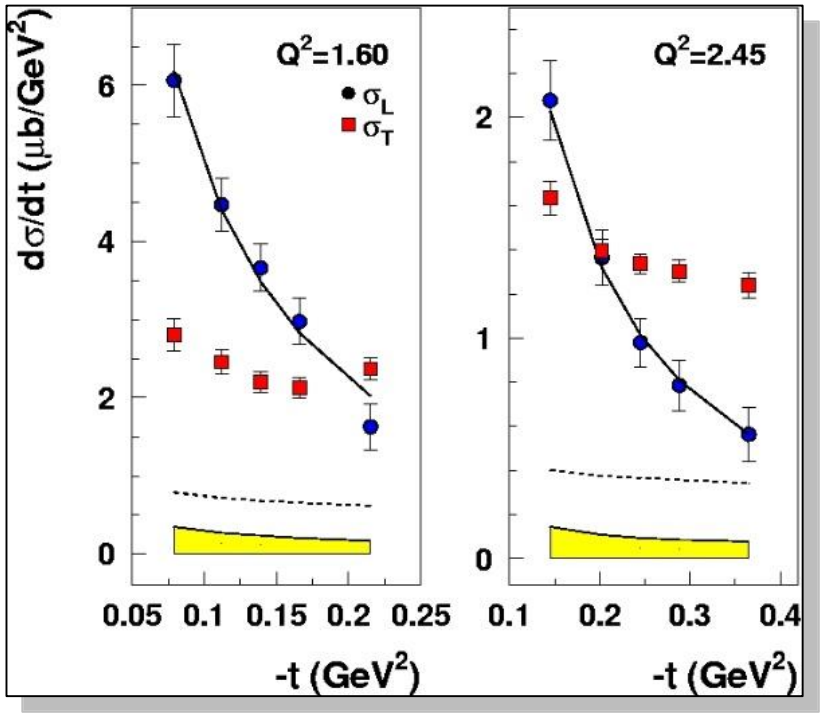
- JLab 6 GeV $F_\pi$ experiments used the VGL/Regge model as it has proven to give a reliable description of $\sigma_L$ across a wide kinematic domain

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

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

**Fit of $\sigma_L$ to model gives $F_\pi$ at each $Q^2$**

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




- Separated L/T cross sections will be published, so $F_\pi$ can be extracted using other models as they become available, e.g. *R. J. Perry et al., arXiv:1811.09356 (2018)*

$$\Lambda_\pi^2 = 0.513,\ 0.491\ GeV^2$$

$$\Lambda_\rho^2 = 1.7\ GeV^2$$

# PionLT Publications – based on two 6 GeV pion experiments

~2000

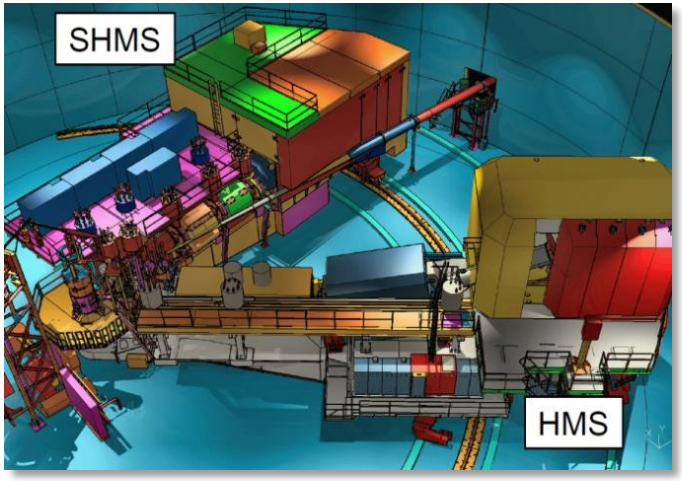
6 GeV Pion Experiments:
1997 (phase 1)
2003 (phase 2)

- J. Volmer, et al., Phys. Rev. Lett. **86** (2001) 1713 – **305 citations**
  - Precision $F_\pi$ results between $Q^2$=0.60 and 1.60 GeV$^2$
- T. Horn, D. Gaskell, G. Huber, et al., Phys. Rev. Lett. **97** (2006) 192001 – **236 citations**
  - Precision $F_\pi$ results at $Q^2$=1.60 and 2.45 GeV$^2$
- V. Tadevosyan, et al., Phys. Rev. C**75** (2007) 055205 – **200 citations**
- G. Huber, T. Horn, D. Gaskell, et al., Phys. Rev. C**78** (2008) 045203 – **175 citations**
  - Archival paper of precision $F_\pi$ measurements at JLab 6 GeV
- H. P. Blok, T. Horn, G. Huber, et al., Phys. Rev. C**78** (2008) 045202 – **101 citations**
  - Archival paper of precision LT separated pion cross sections at JLab 6 GeV
- T. Horn, D. Gaskell, G. Huber, et al., Phys. Rev. C**78** (2008) 058201 – **62 citations**
  - L/T cross sections and $F_\pi$ at $Q^2$=2.15 GeV$^2$ ,exploratory at $Q^2$~4.0 GeV$^2$
- Plus several spin-off papers on, e.g. L/T separations in $\pi^-$ and $\omega$ production, high-t, transverse charge density (2012-present)

**2019**

# Exclusive Pion Experiments in Hall C @ 12 GeV

- The pion experiments L/T separation requirements greatly influenced design specs of the new SHMS
  - Small forward-angle capabilities
  - Good angular reproducibilty
  - Missing mass resolution

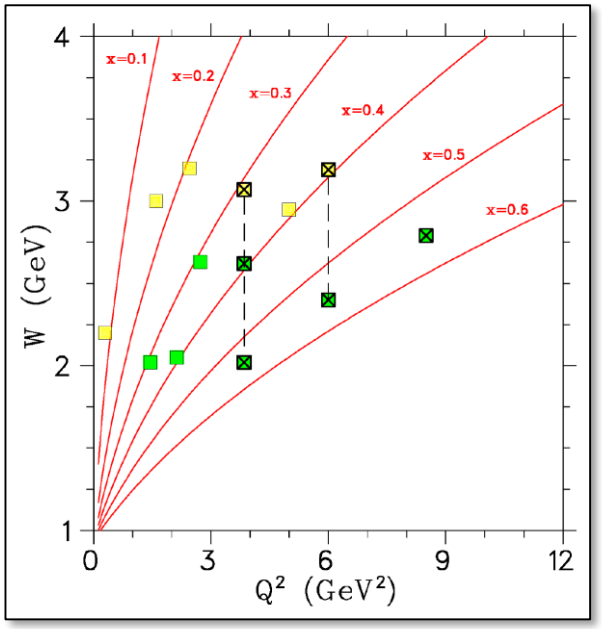



- The pion experiment proponents built (and are maintaining) key SHMS detectors for the experiments
  - Aerogel Cherenkov – funded by NSF MRI (CUA)
  - Heavy gas Cherenkov – partially funded by NSERC (U Regina)

# Optimization of two experiments into one program

- Combined the kinematics of E12-06-101 and E12-07-105 to get more physics output from the same (approved) beam time:
  - L/T separated cross sections at fixed x=0.3, 0.4, 0.55 up to $Q^2$=8.5 $GeV^2$
  - Pion form factor at $Q^2$ values up to 6 $GeV^2$
  - Combining kinematics enables (within approved PAC days) pion form factor extraction at $Q^2$ =8.5 $GeV^2$, highest achievable at 12 GeV JLab

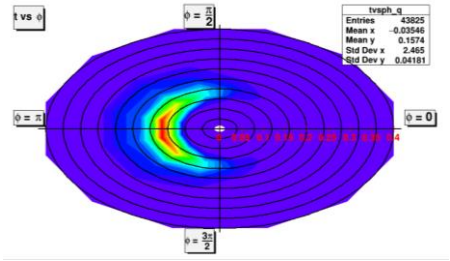
**Consistent with PAC44 recommendation:** "*The PAC confirms the high-impact status of the measurements of $F_\pi$ to $Q^2$=6 $GeV^2$ and encourages the Lab to schedule the E12-06-101 component of this proposal accordingly. We recommend that the emphasis for the remaining beam time approved for E12-06-101 and E12-07-105 be further measurements of separated pion cross sections over a range of $Q^2$, x and, -t.*"

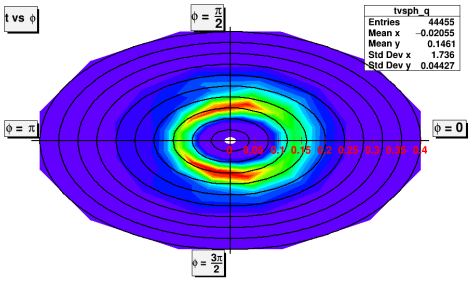


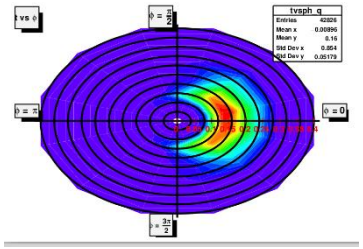

- Completed 3 PAC days out of 88 total in summer 2019 (at low energies) with this combined kinematics runplan

# Low energy kinematic run summer 2019

With combined and optimized run plan completed 2 L/T separations at low $Q^2$ and took data for the low epsilon points for two more settings, which also required these beam energies







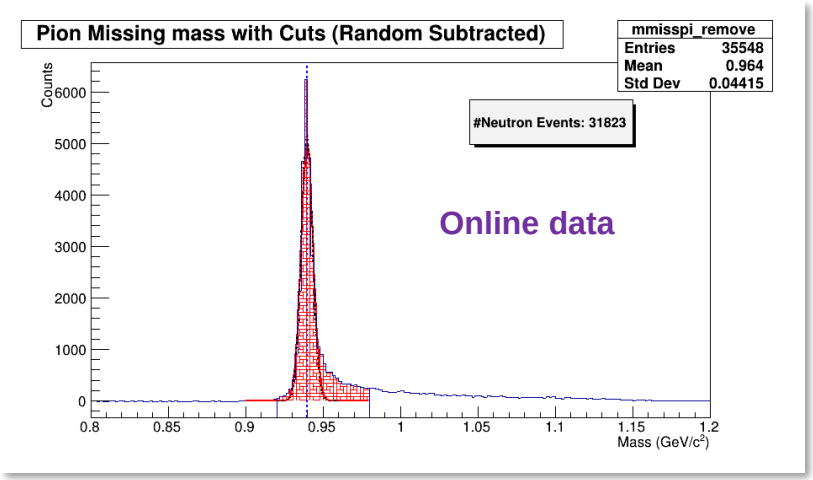
Three SHMS angles

Physics cross section

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

Two/three beam energies

| $Q^2$ ($GeV^2$) | $x_B$ | L/T complete | Purpose |
|---|---|---|---|
| 0.375 | 0.09 | Yes ✓ | Form Factor |
| 0.425 | 0.1 | Yes ✓ | Form Factor |
| 1.45 | 0.3 | No | Reaction mechanism |
| 2.12 | 0.4 | No | Reaction mechanism |



# Theory Report PAC47 (2019)

***"Since the proposals were originally reviewed, the physics motivations for both studies have only increased"***

- Calculations of the FF to highest values of $Q^2$ subject of ongoing activities in lattice community and calculations through, e.g. the DSE approach
  - Lattice: recent calculations have achieved ~6 $GeV^2$ (arxiv:1902.03808)
  - New methods to compute first principles calculation of the quark distribution amplitude (Braun et al.)
- Different approaches and calculational methods show significant differences as $Q^2$ increases, the emphasis in the combined run plan in attaining the highest possible $Q^2$ is particularly important

# Selection of efforts benefitting from *new* L/T cross sections

2019

- P. Kroll, "Hard exclusive processes involving kaons", Eur. Phys. J. A**55** (2019) no. 5, 76
- *M. Carmignotto et al., "Separated Kaon Electroproduction cross section and the kaon form factor from 6 GeV Jlab data", Phys. Rev. C**97** (2018) no. 2, 025204*
- S.X. Qin, C. Chen, C. Mezrag, C.D. Roberts, "Off-shell persistence of [illegible]pions and kaons", Phys. Rev. C**97** (2018) no. 1, 0152203
- T. Horn, C.D. Roberts, "The pion: an enigma within the Stand[illegible]nys. G**43** (2016) no.7, 073001
- L. Favart, M. Guidal, T. Horn, P. Kroll, "Deeply Virtual M[illegible]n on the nucleon", Eur. Phys. J. A**52** (2016) no. 6, 158
- *M. Defurne et al., "Rosenbluth separation of th[illegible]duction cross section", Phys. Rev. Lett.**117** (2016) no. 26, 262001*
- G.R. Goldstein, J. Osvaldo Hernande[illegible]ie Parm. of GPDs: The Chiral Odd Sector", Phys. Rev. D**91** (2015) no.11, 114013
- T.K. Choi, K.J. Kong, B.G. Yu[illegible]. Soc. **67** (2015), L1089, arXiv:1508.00969
- T. Vrancx, J. Ryckebusch[illegible]*production above the resonance region*", Phys. Rev. C**89** (2014), 025203
- S.V. Goloskokov, P. Kroll, "[illegible]pole in hard exclusive VM leptoproduction", Eur. Phys. J. A**50** (2014) no. 9, 146
- S.V. Goloskokov, P. Kroll, "Transversity in exclusive vector-meson leptoproduction", Eur. Phys. J. C**74** (2014) 2725
- M. Carmignotto, T. Horn, G.Miller, "Pion transverse charge density and the edge of hadrons", Phys. Rev.. C**90** (2014)
- S. Liuti, G.R. Goldstein, J. Osvaldo Hernandez, K. Kathuria, "Chiral odd GPDs from exclusive p0 electroproduction", Nuovo Cim. C**036** (2013) no.05, 121
- P. Kroll, H. Moutarde, F. Sabatie, "From hard exclusive electroproduction to deeply virtual Compton Scattering", Eur. Phys. J. C**73** (2013) no. 1, 2278

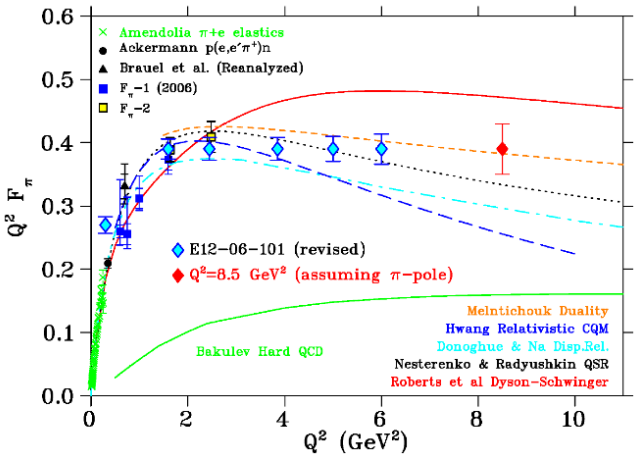
~2011 (PAC38)

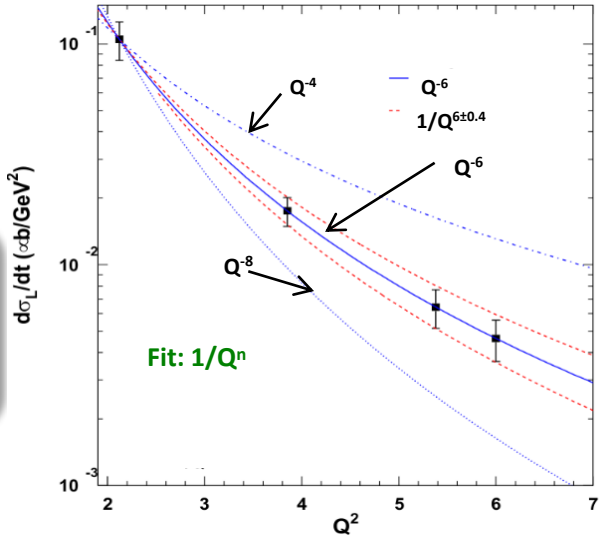
- S.V. Goloskokov, P. Kroll, "Transversity in hard exclusive electroproduction of pseudoscalar mesons", Eur. Phys. J. A**47** (2011) 112

Much progress in theory – need new data now to make further progress

# Summary PionLT Program at 12 GeV

- Low-$Q^2$ data for E12-06-101/E12-07-105 (combined) completed this summer – equivalent to 3 PAC days
- Enables measurements of the separated $\pi^+$ cross sections as function of $Q^2$ at x=0.3, 0.4, 0.55
- Enables measurements of pion form factor at low t up to $Q^2$ = 6 GeV$^2$
- Combined allows for pion form factor extraction to the very largest $Q^2$ accessible at 12 GeV JLab, 8.5 GeV$^2$




A comprehensive and coherent program of charged pion electroproduction, L/T-separated cross section measurements

$F_\pi$ measurement up to $Q^2$=8.5 GeV$^2$ will contribute greatly to our understanding of QCD