UPDATE ON PION-LT EXPERIMENT

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Hall A/C Summer Collaboration Meeting
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Contents

E12-19-006 Experiment Collaboration

- **Spokespersons**
  - Dave Gaskell (JLab), Tanja Horn (CUA), Garth Huber (URegina)
- **Graduate Students**
  - Nathan Heinrich (URegina), Muhammad Junaid (URegina), Jacob Murphy (Ohio U)
- **Key Members**
  - Vijay Kumar (URegina), Vladimir Berdnikov (CUA), Stephen Kay (URegina), Richard Trotta (CUA), Petr Stepanov (CUA), Julie Roche (Ohio U), Carlos Yero (JLab), Ali Usman (URegina)

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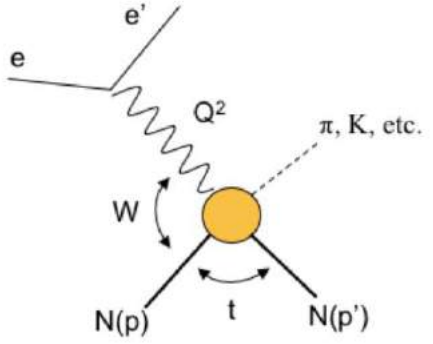
Experiment Goals

- ❑ Pion Form Factor extraction at low Q^2 and comparison with elastic data results from CERN
- ❑ Pion Form Factor extraction to high Q^2
- ❑ Study the Hard-Soft Factorization Regime
- ❑ Pion Scaling Study

Experiment Goals: Extraction of F_π

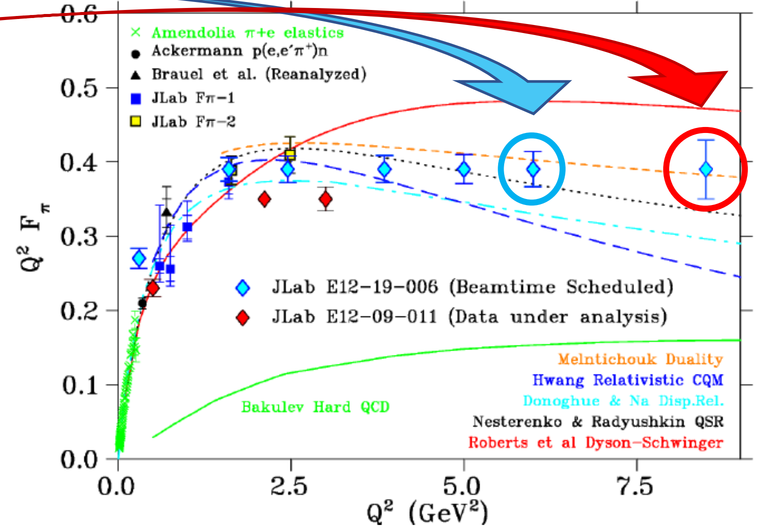
- Indirectly measure F_π using the "pion cloud" of proton via pion electroproduction $p(e, e'\pi^+)n$



t-channel process

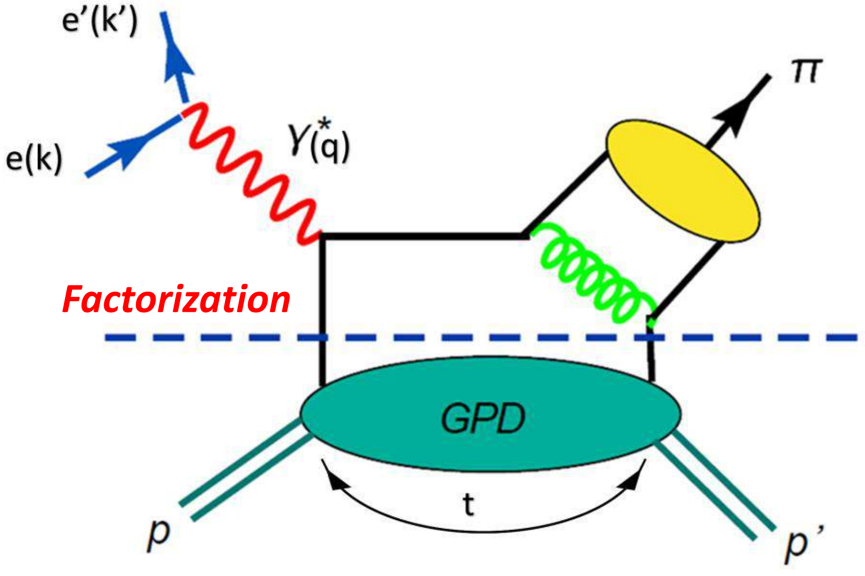
- Low Q^2 experimental data (Run period 1) already taken in 2019
  - Extract the F_π at $Q^2 = 0.38\ GeV^2$ & $0.42\ GeV^2$
  - Do comparison of results with already published CERN results.

- High Q^2 data includes;
  - Precise F_π extraction up to $Q^2 = 6\ GeV^2$
  - Highest possible F_π extraction at $Q^2 = 8.5\ GeV^2$
- High Q^2 experiment consists of two run periods;
  - Run period 2 (low epsilon) already completed (**05-Sep-2021 - 07-Feb-2022**)
  - Run period 3 (high epsilon) is in progress (**expected 06-June-2022 - 10-Aug-2022**)



Experiment Goals: Study the Hard-Soft Factorization Regime

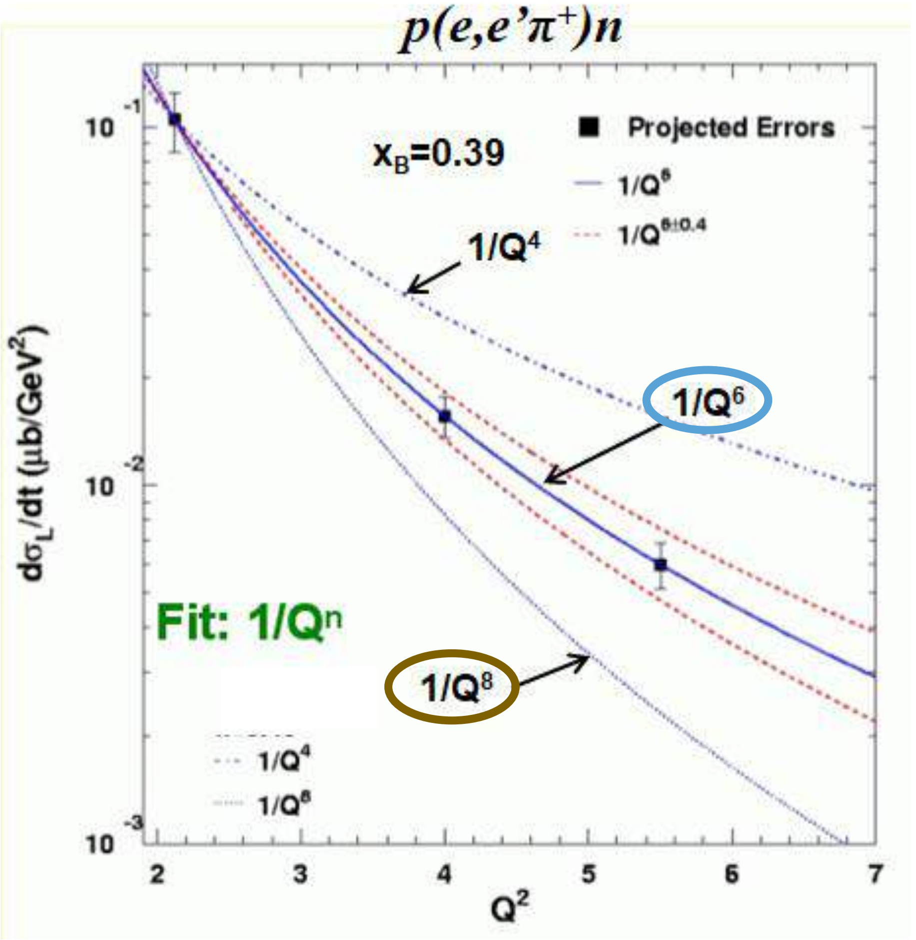
- Study the Hard-Soft Factorization Regime:
  - Non-perturbative (soft) physics is represented by **GPDs**
  - Factorized from perturbative QCD (hard) processes for longitudinal photons
  - Measurement of **GPDs** require confirmation of the applicability of hard-soft QCD factorization mechanism at intermediate Q^2
  - Need to determine region of validity of hard exclusive reaction mechanism, as **GPDs** can only be extracted where factorization applies
  - Separated $p(e, e'\pi^+)n$ cross sections vs Q^2 at fixed t to investigate reaction mechanism towards 3D imaging (**GPDs)** studies
  - Perform exclusive π^+/π^- ratios from ^2H, yielding insight to hard–soft factorization at modest Q^2



Experiment Goals: Pion Scaling Study

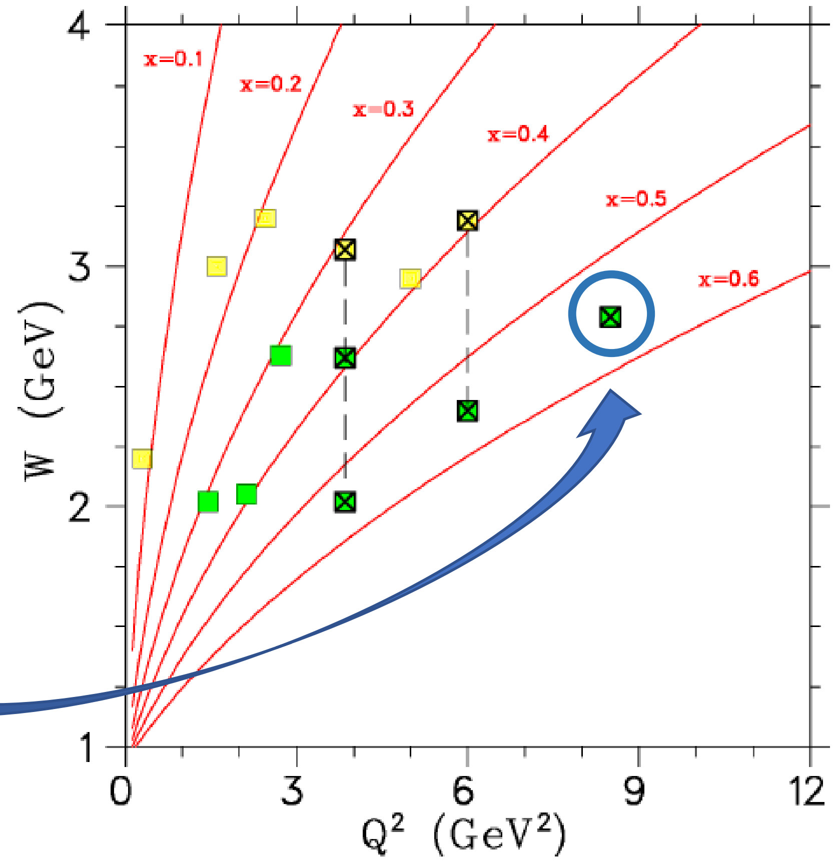
- **Scaling Study** at fixed x = 0.31, 0.39, 0.55 as a function of Q^2.
- QCD counting rules predict $1/Q^n$ dependence of $p(e,e'\pi^+)n$ cross sections in Hard Scattering Regime
- σ_L, to leading order, scales as $1/Q^6$
- σ_T scales as $1/Q^8$
- At large Q^2, $\sigma_L >> \sigma_T$

- Study hard-soft factorization for **GPD** extraction
  - If σ_L becomes large, would allow for leading twist **GPD** study
  - If σ_T becomes large, could allow for transversity **GPD** study



Optimized W vs Q^2 Settings for F_π Extraction and Pion Scaling Study

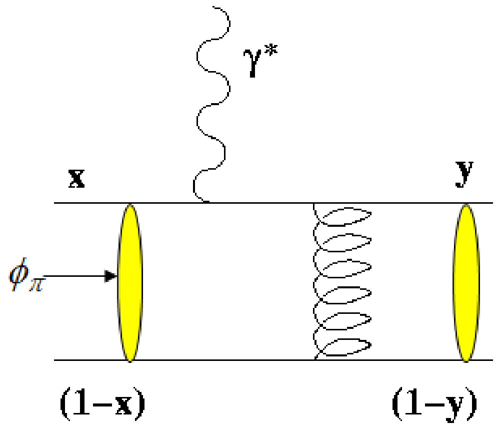
- Two separate experiments
  - Spokespersons managed to arrange both experiments into one
- Yellow points represents the Pion Scaling Study
- Green points represents the Pion Form Factor Study
- Vertical black dashed lines scan $-t_{min}$ at fixed Q^2
- Points marked with an '**x**' are instrumental in higher Q^2, F_π extraction
  - $Q^2 = 8.5\ GeV^2$ is highest achievable extraction at JLab
- Red lines allow for $1/Q^n$ scaling study at fixed x = 0.31, 0.39, 0.55



Pion Form Factor

- Form Factor describes transverse spatial position of partons within hadrons
- At very large Q^2, pion form factor (F_π) can be calculated using pQCD;

$$F_\pi(Q^2) = \frac{4}{3}\pi\alpha_s \int_0^1 dx\, dy \frac{2}{3}\frac{1}{xyQ^2}\phi(x)\phi(y)$$



- At asymptotically high Q^2, the pion distribution amplitude becomes;

$$\phi_\pi(x) \underset{Q^2\to\infty}{\rightarrow} \frac{3f_\pi}{\sqrt{n_c}} x(1-x)$$

- And F_π takes the very simple form;

$$Q^2 F_\pi(Q^2) \rightarrow 16\pi\alpha_s(Q^2) f_\pi^2 \qquad (Q^2 \rightarrow \infty)$$

[G.P. Lepage, S.J. Brodsky, Phys.Lett. 87B(1979)359].

- $Q^2 F_\pi$ should behave like $\alpha_s(Q^2)$ even for moderately large Q^2
- Pion form factor seems to be best tool for experimental study of nature of the quark-gluon coupling constant renormalization

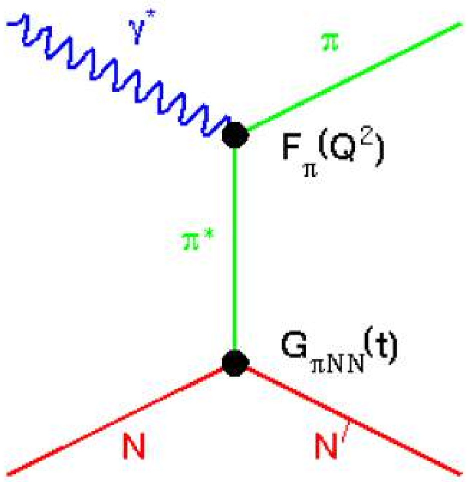
[A.V. Radyushkin, JINR 1977, arXiv:hep–ph/0410276]

Pion Form Factor Measurement

- Above $Q^2 > 0.3\text{GeV}^2$, F_π is measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$
- At small $-t$, the pion pole process dominates the longitudinal cross section σ_L
- Pion (π) targets not possible due to short lifetime
  - Scatter of virtual pion cloud of nucleon instead
- Indirect measurement – Form factor extraction requires a model
- As an illustration of how σ_L connects to $F_\pi^2(Q^2,t)$, we consider a simple Born Term Model;

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

- In reality, we use Regge Model such as VGL-model for $F_\pi^2(Q^2,t)$ extraction.
  - Critical to confirm the validity of the model used to extract the $F_\pi^2(Q^2,t)$!



Validation of F_π Extractions

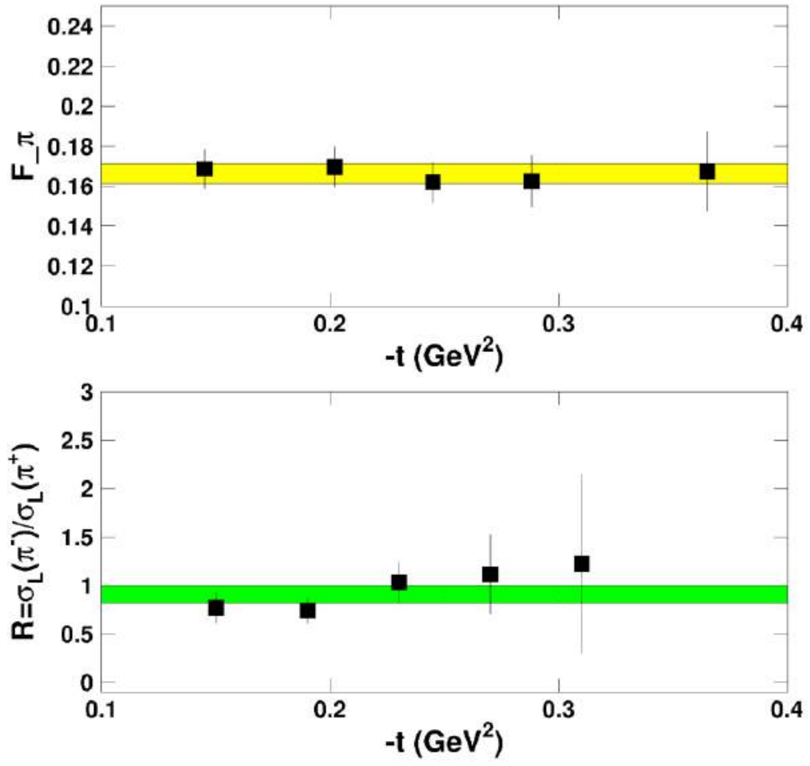
- Validation of F_π extractions at highest possible Q^2

- Extract F_π at fixed Q^2, scanning $-t$
  - F_π should be independent $-t$

- Check dominance of t-channel process
  - Examine ratio of σ_L for $d(e,e'\pi^-)pp_{sp}/d(e,e'\pi^+)nn_{sp}$
  - Tests to be repeated at $Q^2 = 1.60, 3.85, 6.0\ GeV^2$

- But determining σ_L is challenging

$Q^2 = 2.45, W = 2.22$
$(from\ Fpi2\ experiment)$



L/T Separated Pion Cross Sections

- Rosenbluth Separation technique is used to separate σ_L and σ_T terms
- In non-parallel kinematics (i.e., $\theta_\pi \neq 0$), the Physical cross section for the electroproduction process is given by;

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

- Where;

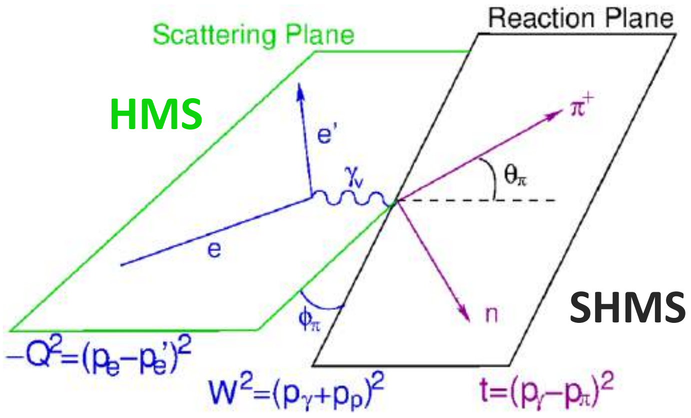
$$\epsilon = \left[1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2} . \tan^2\frac{\theta_{e'}}{2}\right]^{-1}$$

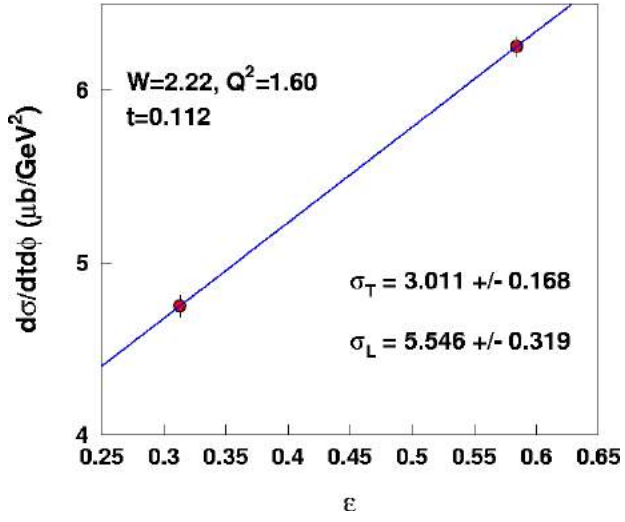
- $^1/_{\Delta\epsilon}$ error amplification in σ_L

$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{\epsilon_1 - \epsilon_2} \frac{1}{\sigma_L} \sqrt{\Delta\sigma_1^2 + \Delta\sigma_2^2}$$

Where "$\sigma_1 = \sigma_T + \epsilon_1\, \sigma_L$" and "$\sigma_2 = \sigma_T + \epsilon_2\, \sigma_L$"

- Careful attention must be paid to spectrometer acceptance, kinematics, efficiencies, …





Pion-LT Summer 2019 Run Period

- **Run period completed from June 2019 to August 2019**
- Data acquired for the three values of ϵ

- **Beam Energy : 2.8 GeV**

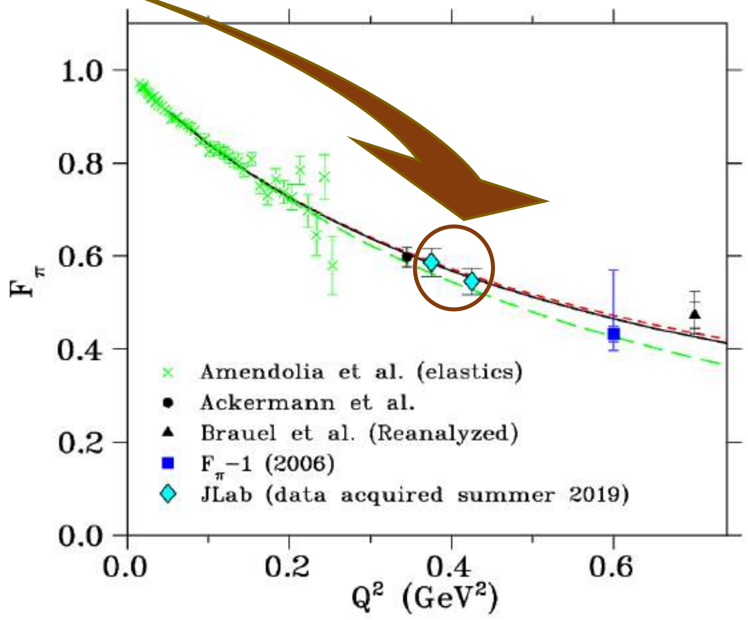
Q^2	W	Target & SHMS polarity
0.38	2.20	LH+
0.43	2.20	LH+

- **Beam Energy : 3.7 GeV**

Q^2	W	Target & SHMS polarity
0.38	2.20	LH+
0.43	2.20	LH+
1.45	2.20	LH+

- **Beam Energy : 4.6 GeV**

Q^2	W	Target & SHMS polarity
0.38	2.20	LH+
0.43	2.20	LH+
2.12	2.20	LH+



New data are at significantly closer to pion pole than Ackermann data

Pion-LT Fall 2021 Run Period

- **Beam Energy : 9.2 GeV (5 pass @ 1.82 GeV/pass)**

Q^2	W	Target & SHMS polarity
1.60	3.08	LH+, LD+, LD-
6.00	3.19	LH+
8.50	2.79	LH+

- **Beam Energy : 9.9 GeV (5 pass @ 1.92 GeV/pass)**

Q^2	W	Target & SHMS polarity
1.60	3.08	LH+
3.85	3.07	LH+
5.00	2.95	LH+
6.00	3.19	LH+

- **Beam Energy : 6.0 GeV (3 pass @ 1.96 GeV/pass)**

Q^2	W	Target & SHMS polarity
3.85	2.02	LH+

- **Beam Energy : 8.0 GeV (4 pass @ 1.96 GeV/pass)**

Q^2	W	Target & SHMS polarity
2.45	3.20	LH+
3.85	3.07	LH+, LD+, LD-
5.00	2.95	LH+
6.00	2.40	LH+, LD+, LD-

- **Run period completed from September 2021 to February 2022.**

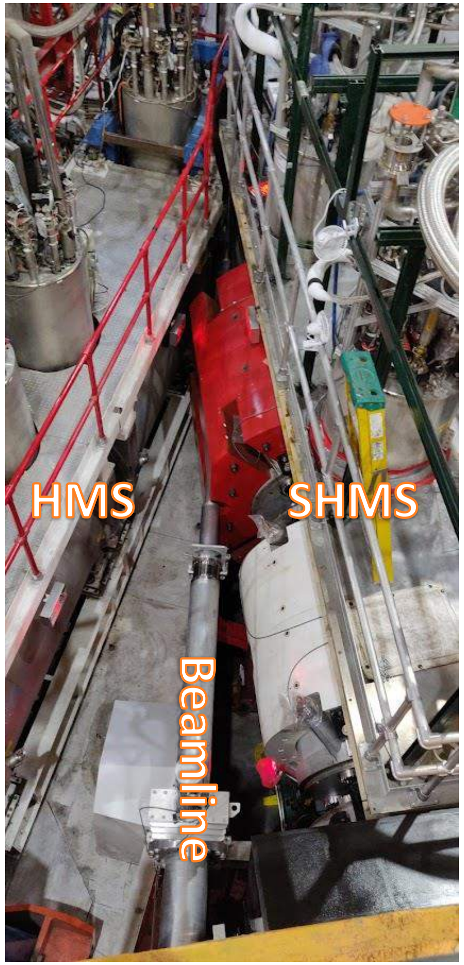
Pion-LT Fall 2021 Run Period

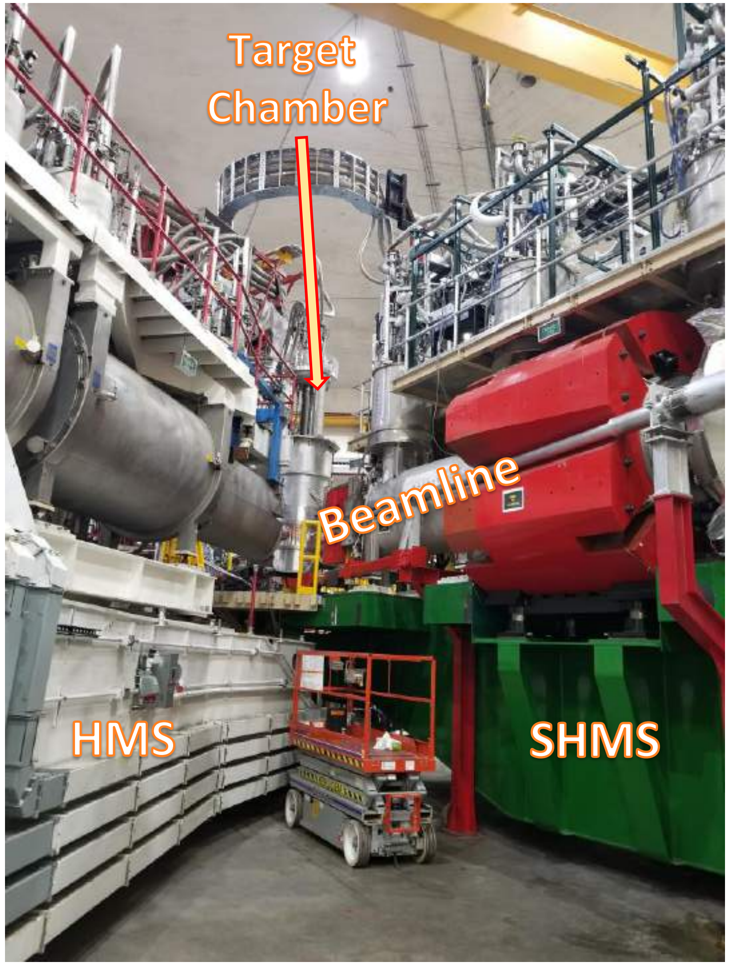
- **Fall 2021 Completed Kinematics;**
- $\theta_{\pi q}$ settings are limited;
  - Right-angle setting not always possible with hard limit of 5.50° for SHMS
  - $Q^2 = 8.50$ limited to central angle due to event rate
- Each setting is one part of the data needed for an L/T separation
  - Need AT LEAST two beam energies
  - Some settings have 3 ϵ points

Q^2	W	x	Run Type	θ_q	$\theta_{\pi q}$	ϵ	E_e
1.60	3.08	0.160	LH+, LD+, LD-	8.26	-2, 0, +2°	high	9.177
1.60	3.08	0.160	LH+	8.69	-2, 0, +2°	high-2	9.876
2.45	3.20	0.21	LH+	6.16	0, +2°	low	7.937
3.85	2.02	0.55	LH+	15.79	-2, 0, +2°	low	5.986
3.85	3.07	0.31	LH+	9.29	-2, 0, +2°	middle-2	9.876
3.85	3.07	0.31	LH+,LD+,LD-	6.39	-0.89, 0, +2°	low	7.937
5.00	2.95	0.39	LH+	9.73	-2, 0, +2°	middle	9.876
5.00	2.95	0.39	LH+	6.17	0, +2°	low	7.937
6.00	3.19	0.39	LH+	5.06	+0.44, +2°	low	9.177
6.00	3.19	0.39	LH+	6.6	0, +2°	middle	9.876
6.00	2.40	0.55	LH+,LD+,LD-	11.12	-2, 0, +2°	low	7.937
8.50	2.79	0.55	LH+	5.44	+0.06°	low	9.177

Hall C Extremes in this Experiment

- **This experiment has in large part driven the forward angle requirements of SHMS and HMS**
- The **minimum opening angle** between SHMS and HMS was, $18.00°$, was reached for this experiment.
  - HMS moved to $11.01°$ deg and SHMS moved $18.00°$ away at $6.99°$
- In this experiment, we pushed **SHMS to $5.50°$**.
  - Several kinematic settings used the SHMS at its minimum angle of $5.50°$
- **Thank you to the Hall C scientific and technical staff members who made all of this possible**





Pion-LT Fall 2021 Run Period

- $p(e, e'\pi^+)n$ **Event Selection;**
- Coincidence measurement between charged pions in SHMS and electrons in HMS

- Easy to isolate exclusive channel
- Excellent particle identification.

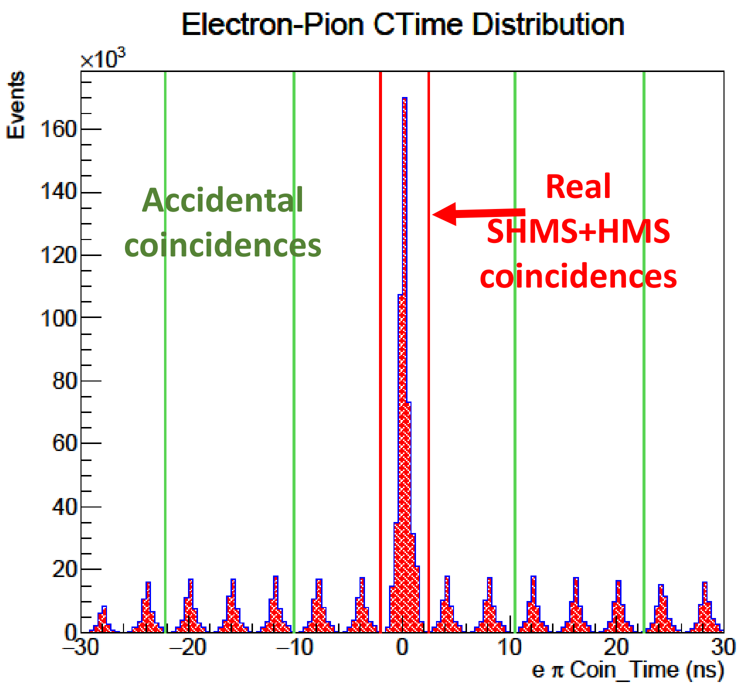
- Continuous beam minimizes accidental coincidences
- Missing mass resolution easily excludes 2–pion contributions

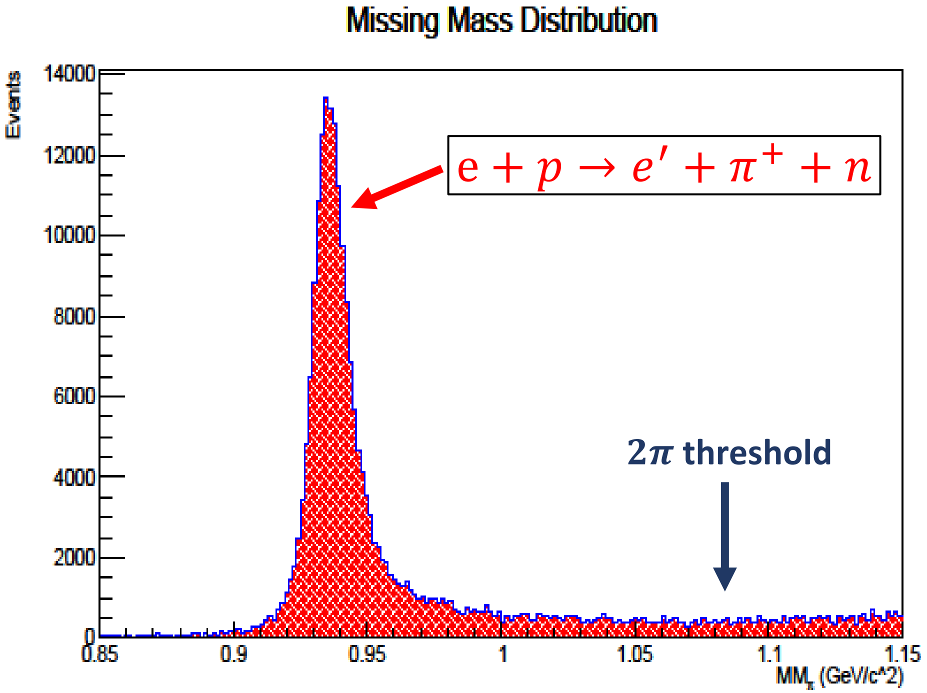
Pion-LT Experiment E12-19-006 Data

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

$E_{beam} = 9.177\ GeV, \quad P_{HMS} = -3.738\ GeV/c, \quad \theta_{HMS} = 12.40°$

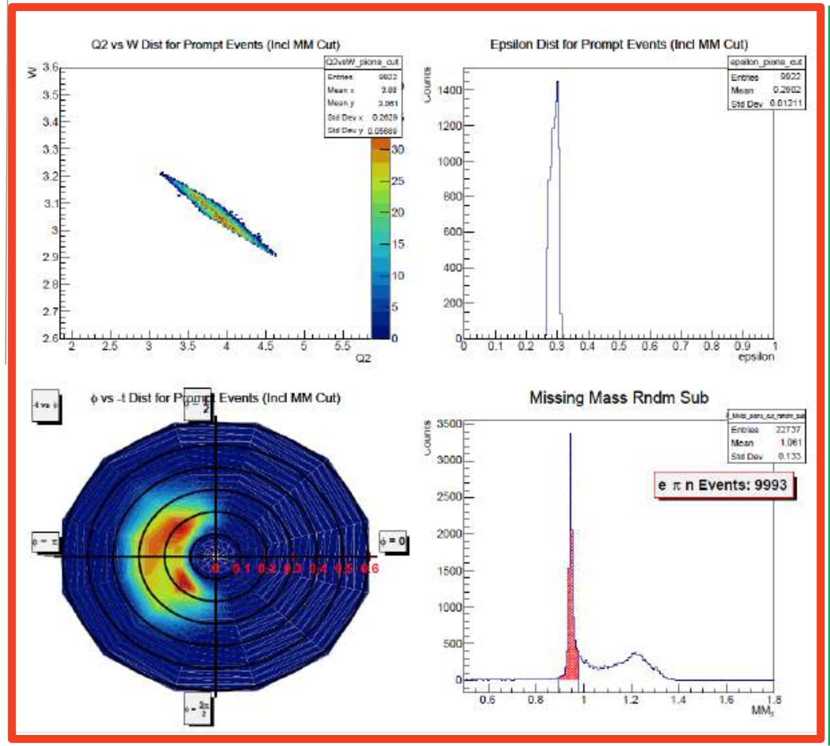
$P_{SHMS} = +5.422\ GeV/c, \quad \theta_{SHMS} = 10.26°(Left)$



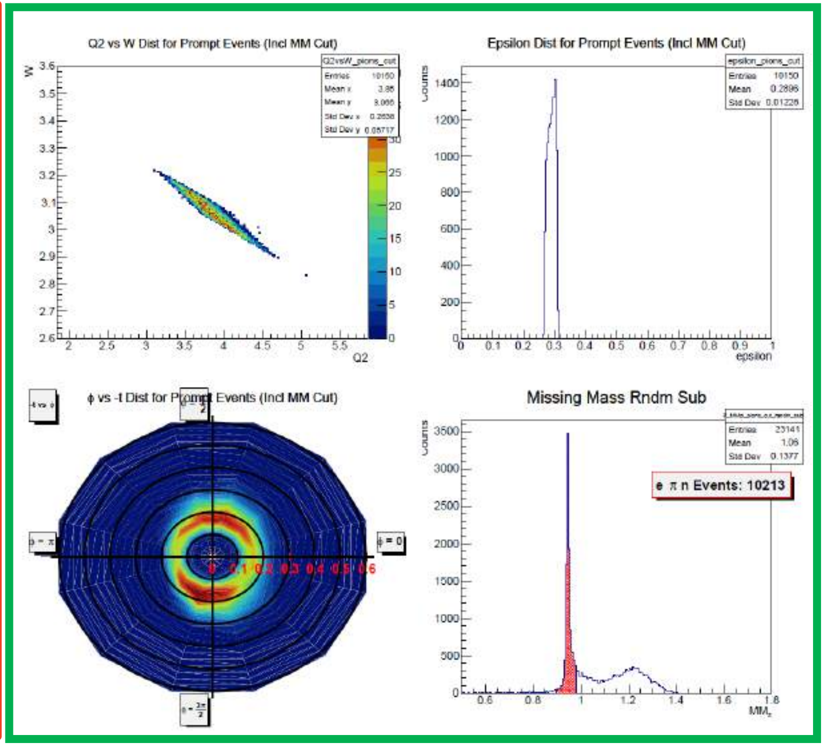


Pion-LT Fall 2021 Run Period

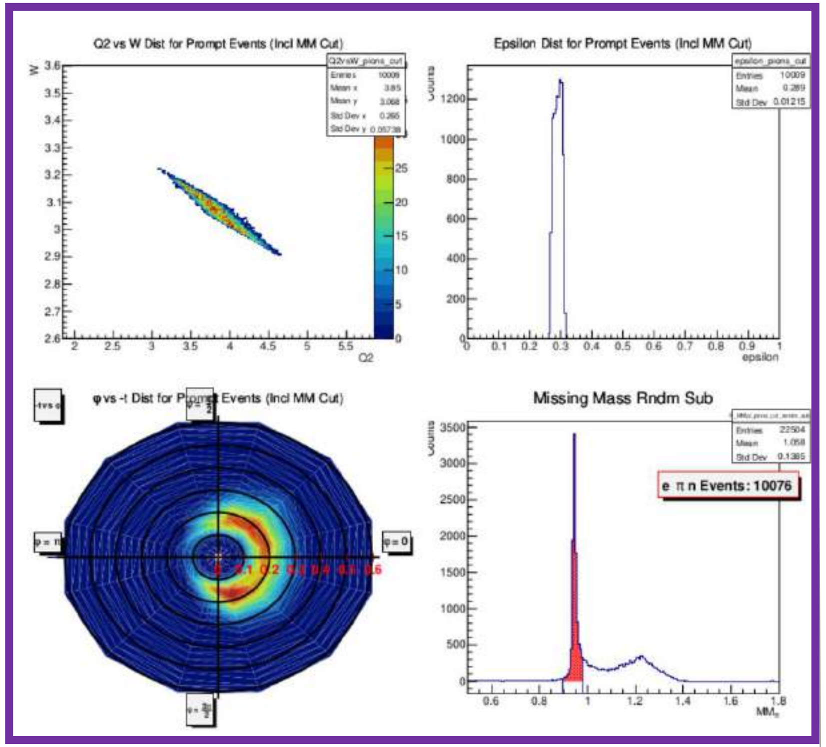
$$Q^2 = 3.85,\ \mathrm{W} = 3.07,\ \mathrm{x} = 0.31 \text{ for } p(e,e'\pi^+)n$$



$\theta_{SHMS} = 8.39°$ (Left)



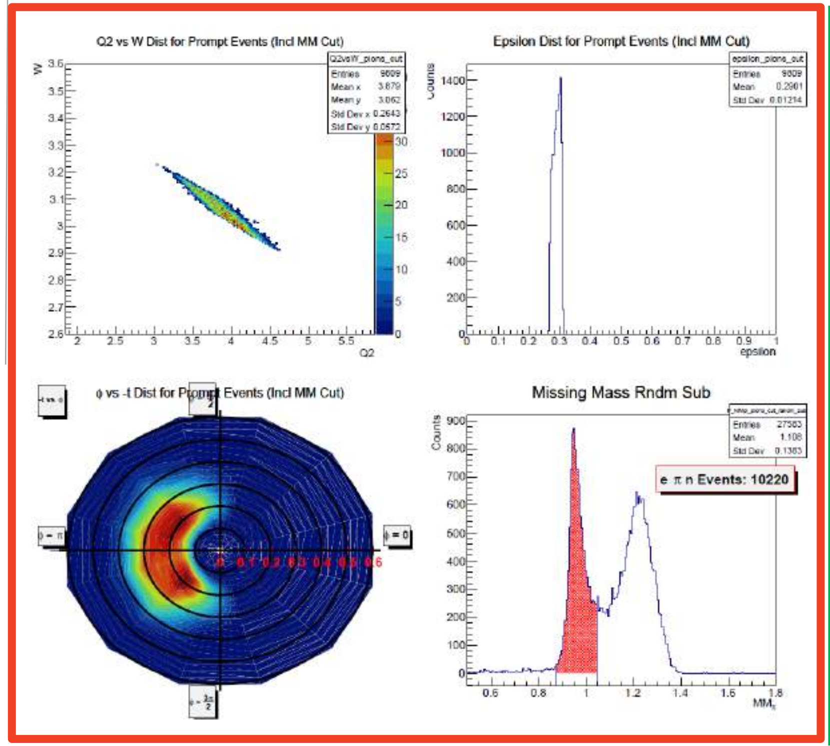
$\theta_{SHMS} = 6.39°$ (Center)

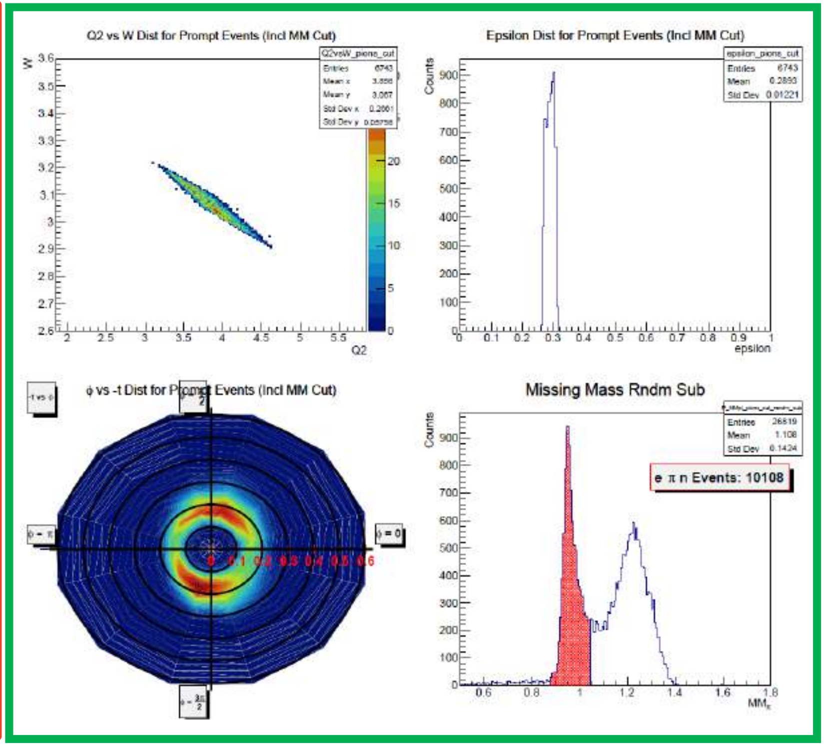


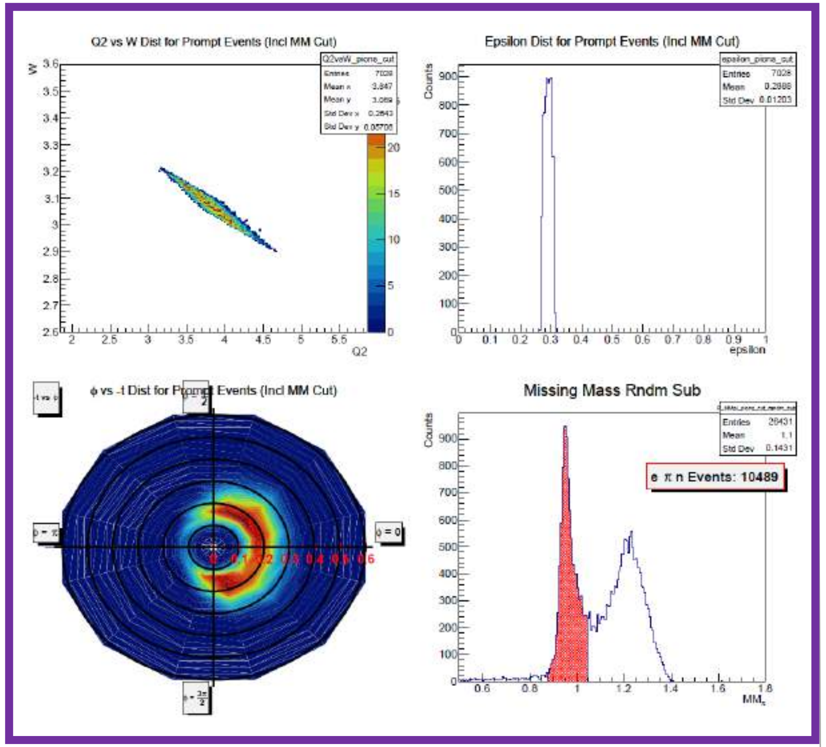
$\theta_{SHMS} = 5.50°\ (Right)$

Pion-LT Fall 2021 Run Period

$Q^2 = 3.85$, $W = 3.07$, $x = 0.31$ for $d(e, e'\pi^+)nn_{sp}$







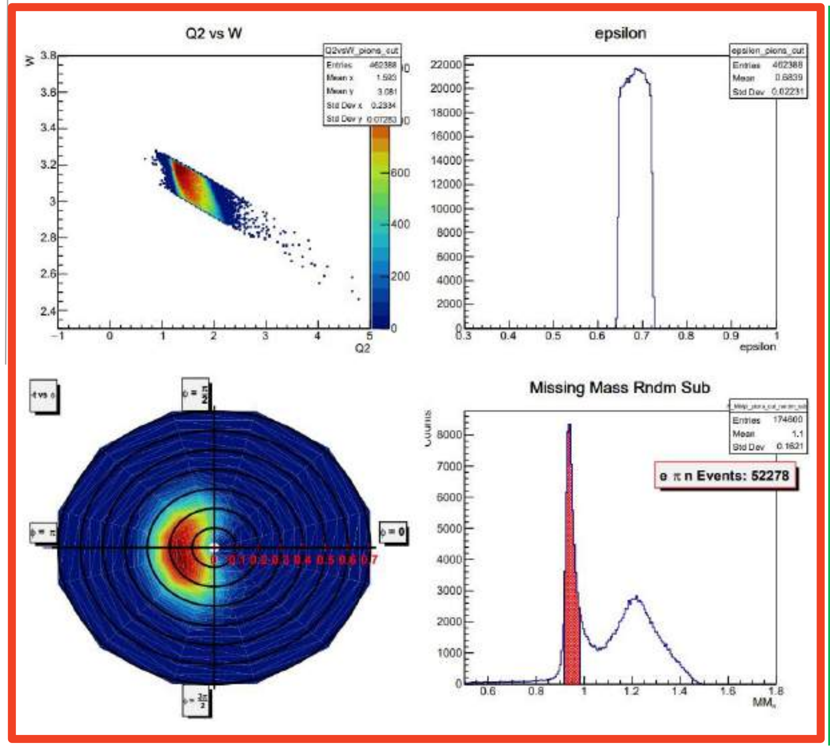
$\theta_{SHMS} = 8.39°$ (Left)

$\theta_{SHMS} = 6.39°$ (Center)

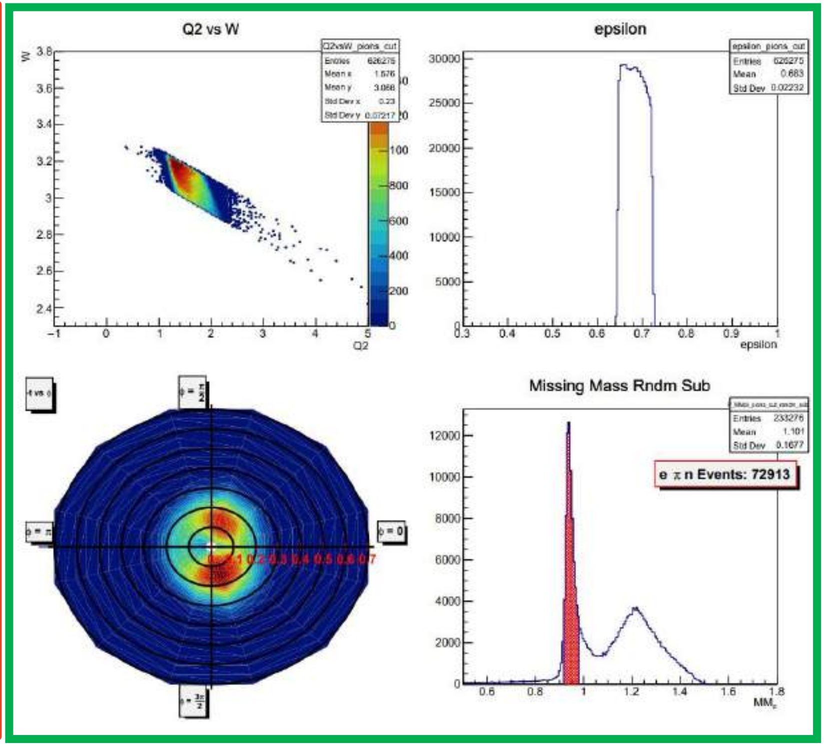
$\theta_{SHMS} = 5.50°$ (Right)

Pion-LT Fall 2021 Run Period

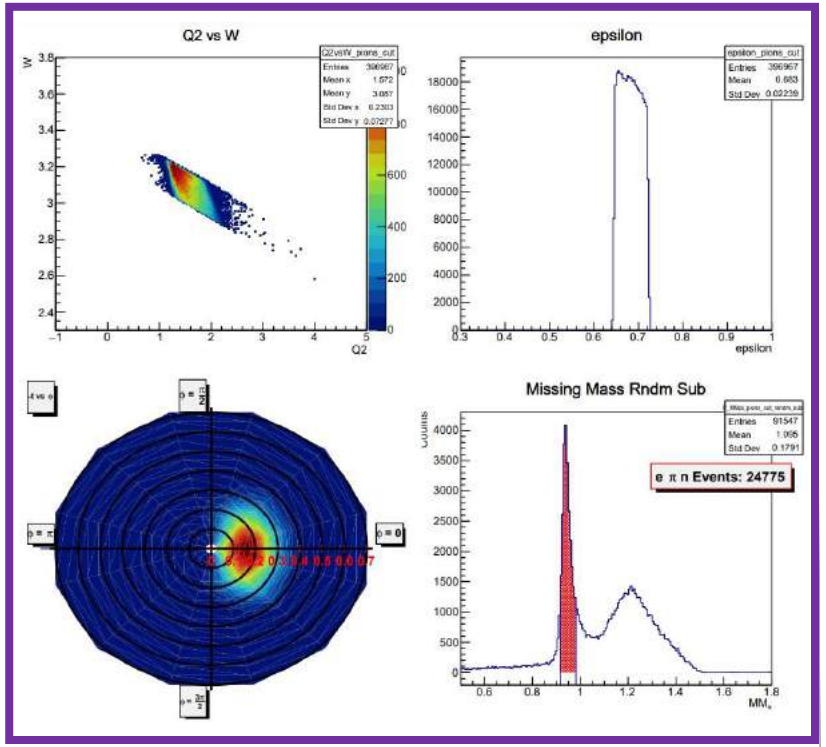
$$Q^2 = 1.60, \mathrm{W} = 3.08, \mathrm{x} = 0.16 \text{ for } d(e,e'\pi^-)pp_{sp}$$



$\theta_{SHMS} = 10.26°$ (Left)

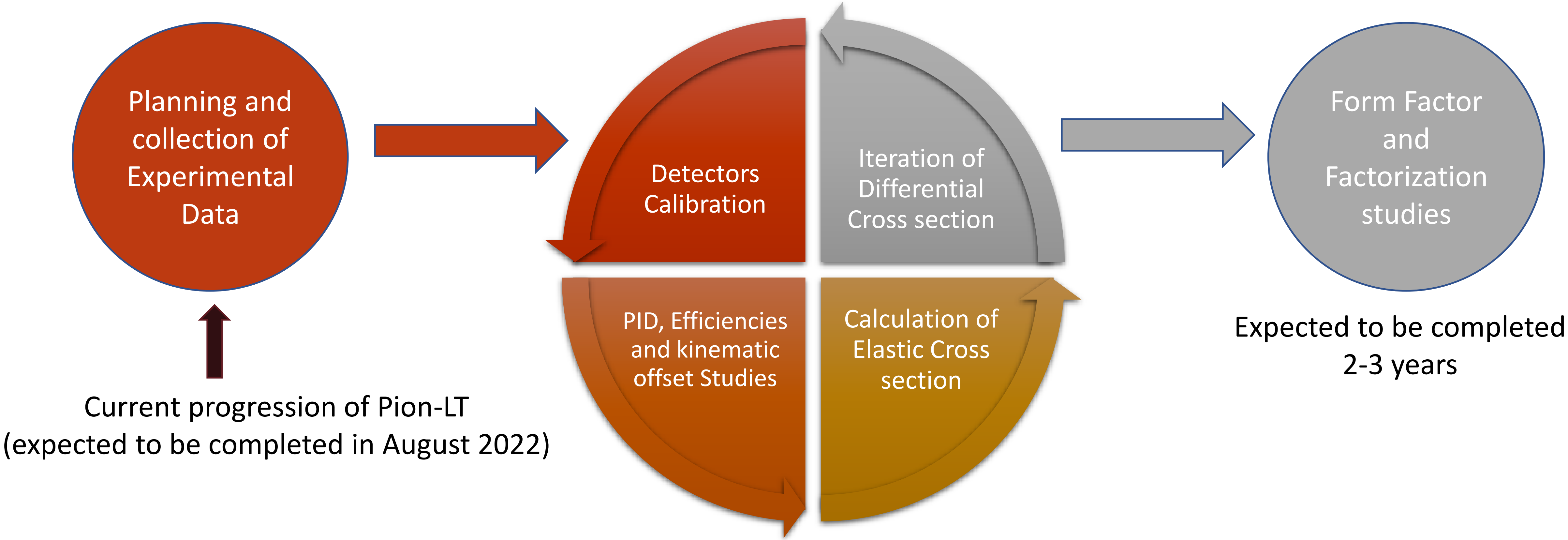


$\theta_{SHMS} = 8.26°$ (Center)



$\theta_{SHMS} = 6.26°$ (Right)

Analysis Flow Chart



Pion-LT Summer 2022 Run Period

- **Beam Energy : 10.6 GeV**

Q^2	W	Target & SHMS polarity
2.45	3.20	LH+
2.73	2.63	LH+
3.85	2.02	LH+
3.85	2.62	LH+, LD+, LD-
3.85	3.07	LH+, LD+, LD-
5.00	2.95	LH+
6.00	2.40	LH+, LD+, LD-
6.00	3.19	LH+
8.50	2.79	LH+

- **Beam Energy : 8.5 GeV**

Q^2	W	Target & SHMS polarity
2.12	2.05	LH+
2.45	3.20	LH+
3.85	3.07	LH+

- **Beam Energy : 6.4 GeV**

Q^2	W	Target & SHMS polarity
1.45	2.02	LH+
1.60	3.08	LH+, LD+, LD-
2.73	2.63	LH+
3.85	2.62	LH+, LD+, LD-

Pion-LT Summer 2022 Run Period

- Pion-LT Summer 2022 run period 3 (high epsilon) is in progress and will continue until August 2022
- High-ϵ data is necessary for L/T separation and for experiment goals to be met require high-ϵ

- Further data taken at same beam energies will not allow for an LT separation
- Higher beam energy allows for larger $\Delta\epsilon$
- Experiment results are very sensitive to $\Delta\epsilon$

- Range of $\Delta\epsilon$ is from 0.22 to 0.49

Q^2	W	x	Run Type	ϵ
1.45	2.02	0.312	LH+	High
1.60	3.08	0.160	LH+, LD+, LD-	Low
2.12	2.05	0.390	LH+	High
2.45	3.20	0.210	LH+	High
2.73	2.63	0.311	LH+	Low, high
3.85	2.02	0.550	LH+	High
3.85	2.62	0.392	LH+, LD+, LD-	Low, high
3.85	3.07	0.310	LH+	High
5.00	2.95	0.390	LH+	High
6.00	3.19	0.390	LH+	High
6.00	2.40	0.550	LH+, LD+, LD-	High
8.50	2.79	0.550	LH+	High

Summary

- E12–19–006 (12 GeV Flagship Experiment) is expected to provide the definitive $p(e,e'\pi^+)n$ L/T–separation data set and will remain important for decades to come
- $F_\pi - 1$ and $F_\pi - 2$ experiments were very productive, and are among JLab's top cited results (top 4 listed):
  - Volmer et al, PRL 2001 ($F_\pi - 1$) 232 citations
  - Horn et al, PRL 2006 ($F_\pi - 2$) 207 citations
  - Tadevosyan et al, PRC 2007 ($F_\pi - 1$) 234 citations
  - Huber et al, PRC 2008 ($F_\pi - 2$) 230 citations
- Data collection for fall 2021 was very successful
- **Thank you to the Hall C staff/users and our collaborators!**
- Pion-LT Summer 2022 run period 3 (high epsilon) is in progress and will continue until August 2022
- **WE REALLY NEED YOUR ASSISTANCE TO MAKE THE EXPERIMENT A SUCCESS!!**
- Summer 2022: 398 person shifts needed @ 2 workers/shift
- Shift sign up now open at: https://misportal.jlab.org/mis/apps/physics/shiftSchedule/index.cfm?experimentRunId=HALLC-PIONLT-2022

THANKS

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