



UPDATE ON PION-LT EXPERIMENT

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Hall A/C Summer Collaboration Meeting
June 16 – 17, 2022

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E12-19-006 Experiment Collaboration

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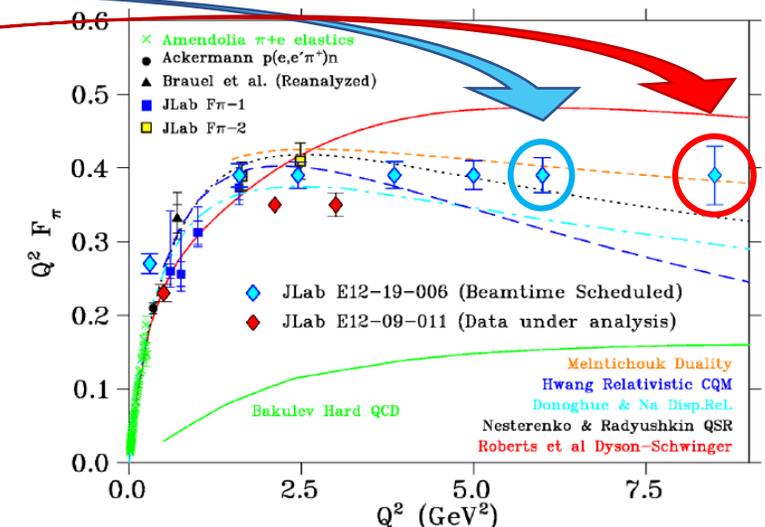
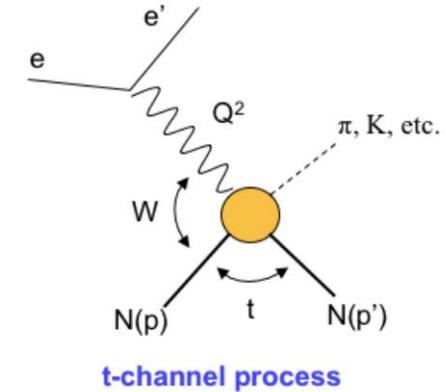


Experiment Goals

- 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

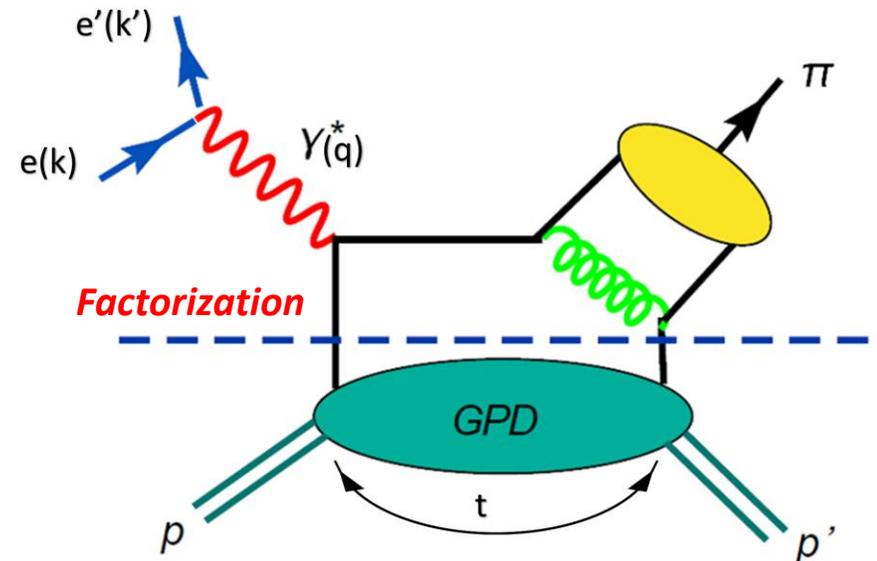
Experiment Goals: Extraction of F_π

- ❑ Indirectly measure F_π using the “pion cloud” of proton via pion electroproduction $p(e, e'\pi^+)n$
- ❑ Low Q^2 experimental data (Run period 1) already taken in 2019
 - Extract the F_π at $Q^2 = 0.38 \text{ GeV}^2$ & 0.42 GeV^2
 - Do comparison of results with already published CERN results.
- ❑ High Q^2 data includes;
 - Precise F_π extraction up to $Q^2 = 6 \text{ GeV}^2$
 - Highest possible F_π extraction at $Q^2 = 8.5 \text{ GeV}^2$
- ❑ 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

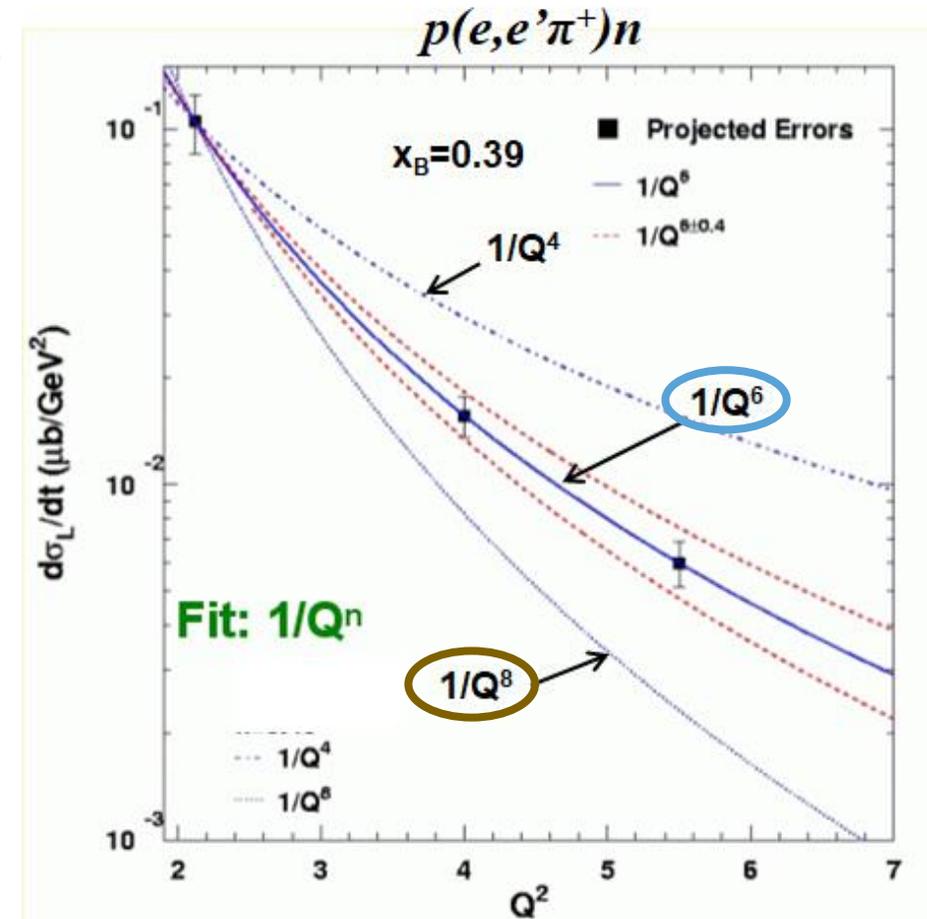
- ❑ Study the **Hard-Soft Factorization Regime**:
 - Non-perturbative (soft) physics is represented by **GPDs**
 - Factorized from perturbative QCD (hard) processes for longitudinal photons
 - Measurement of **GPDs** require confirmation of the applicability of **hard-soft QCD factorization** mechanism 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

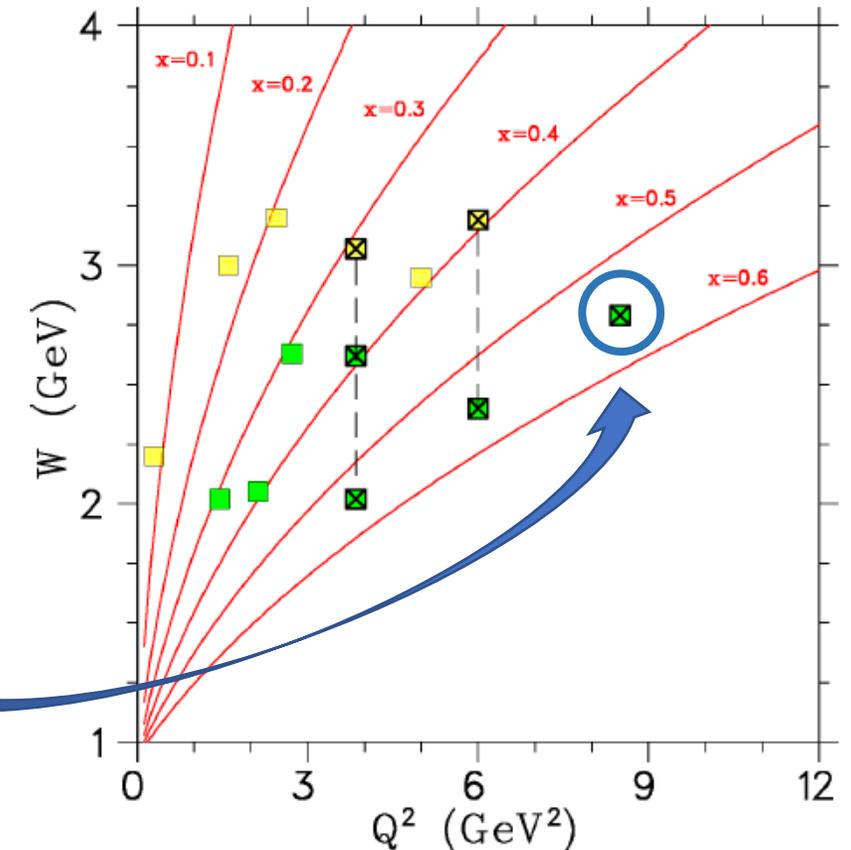
- **Scaling Study** at fixed $x = 0.31, 0.39, 0.55$ as a function of Q^2 .
 - QCD counting rules predict $1/Q^n$ dependence of $p(e, e'\pi^+)n$ cross sections in Hard Scattering Regime
 - σ_L , to leading order, scales as $1/Q^6$
 - σ_T scales as $1/Q^8$
 - At large Q^2 , $\sigma_L \gg \sigma_T$

- 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
 - $Q^2 = 8.5 \text{ GeV}^2$ 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;

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

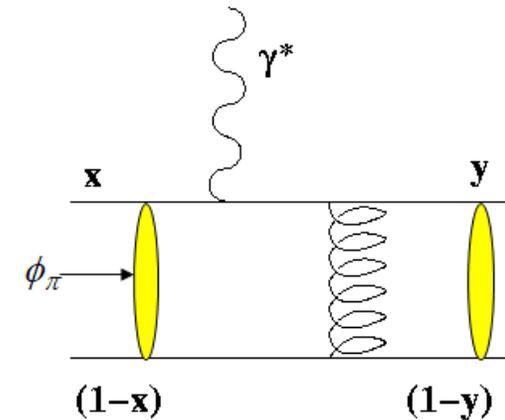
- And F_π takes the very simple form;

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

[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]

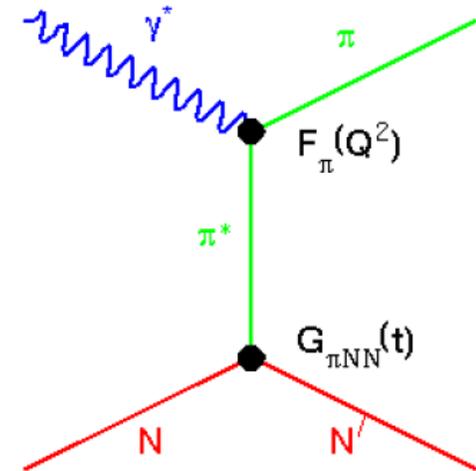


Pion Form Factor Measurement

- 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

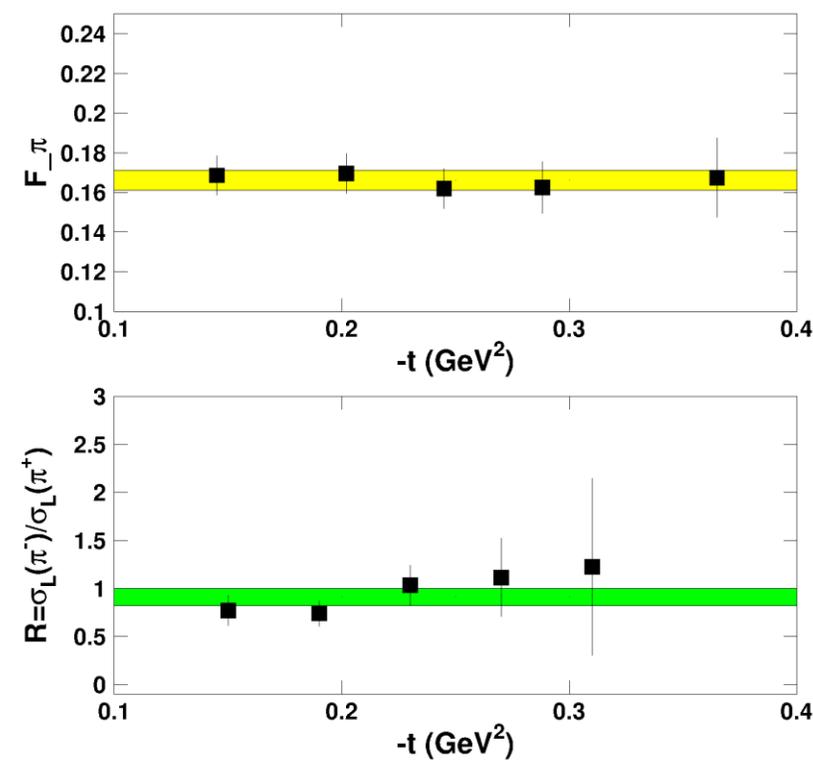
- Extract F_π at fixed Q^2 , scanning $-t$
 - F_π should be independent $-t$

- 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 $Q^2 = 1.60, 3.85, 6.0 \text{ GeV}^2$

- 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;

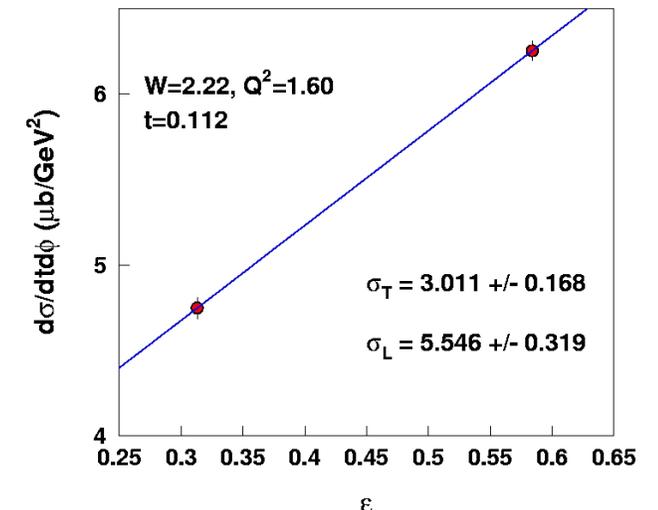
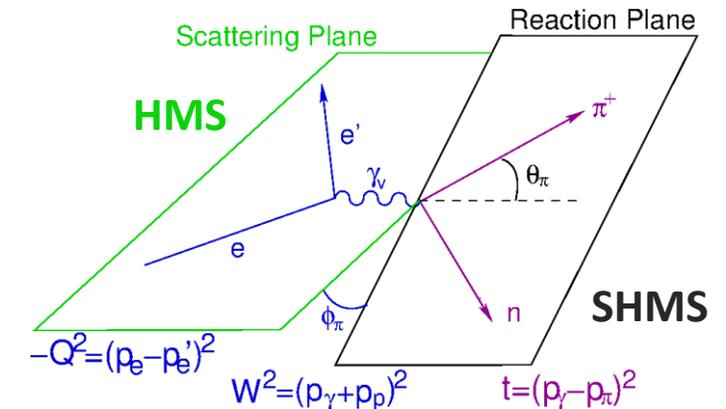
$$\epsilon = \left[1 + 2 \frac{(E_e - E_{e'})^2 + Q^2}{Q^2} \cdot \tan^2 \frac{\theta_{e'}}{2} \right]^{-1}$$

- $1/\Delta\epsilon$ 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

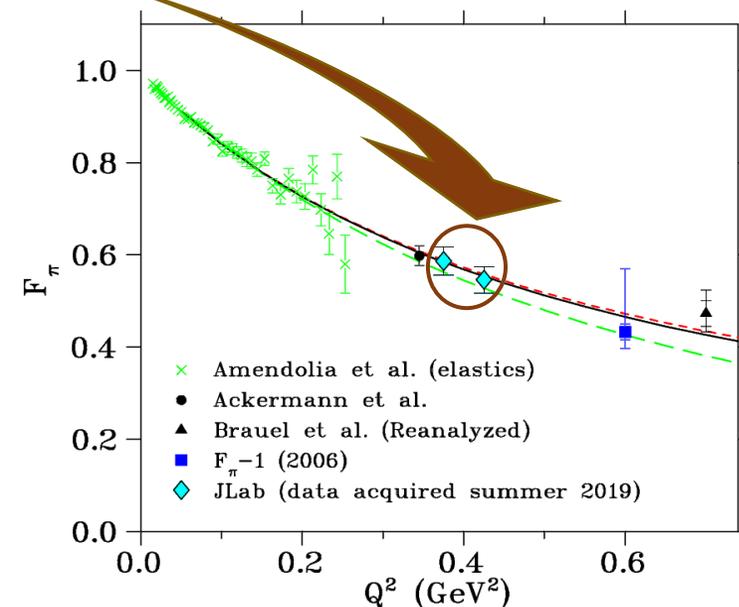
Q^2	W	Target & SHMS polarity
0.38	2.20	LH+
0.43	2.20	LH+

- Beam Energy : 4.6 GeV

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



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.

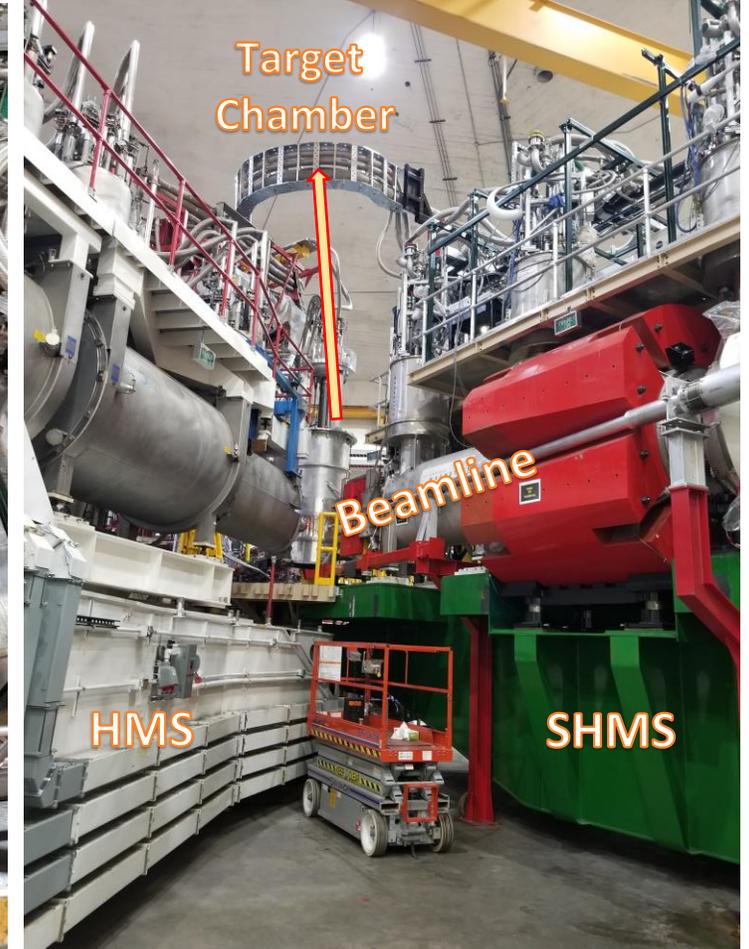
Pion-LT Fall 2021 Run Period

- **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, $+2^\circ$	high	9.177
1.60	3.08	0.160	LH+	8.69	-2, 0, $+2^\circ$	high-2	9.876
2.45	3.20	0.21	LH+	6.16	0, $+2^\circ$	low	7.937
3.85	2.02	0.55	LH+	15.79	-2, 0, $+2^\circ$	low	5.986
3.85	3.07	0.31	LH+	9.29	-2, 0, $+2^\circ$	middle-2	9.876
3.85	3.07	0.31	LH+,LD+,LD-	6.39	-0.89, 0, $+2^\circ$	low	7.937
5.00	2.95	0.39	LH+	9.73	-2, 0, $+2^\circ$	middle	9.876
5.00	2.95	0.39	LH+	6.17	0, $+2^\circ$	low	7.937
6.00	3.19	0.39	LH+	5.06	+0.44, $+2^\circ$	low	9.177
6.00	3.19	0.39	LH+	6.6	0, $+2^\circ$	middle	9.876
6.00	2.40	0.55	LH+,LD+,LD-	11.12	-2, 0, $+2^\circ$	low	7.937
8.50	2.79	0.55	LH+	5.44	+0.06 $^\circ$	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

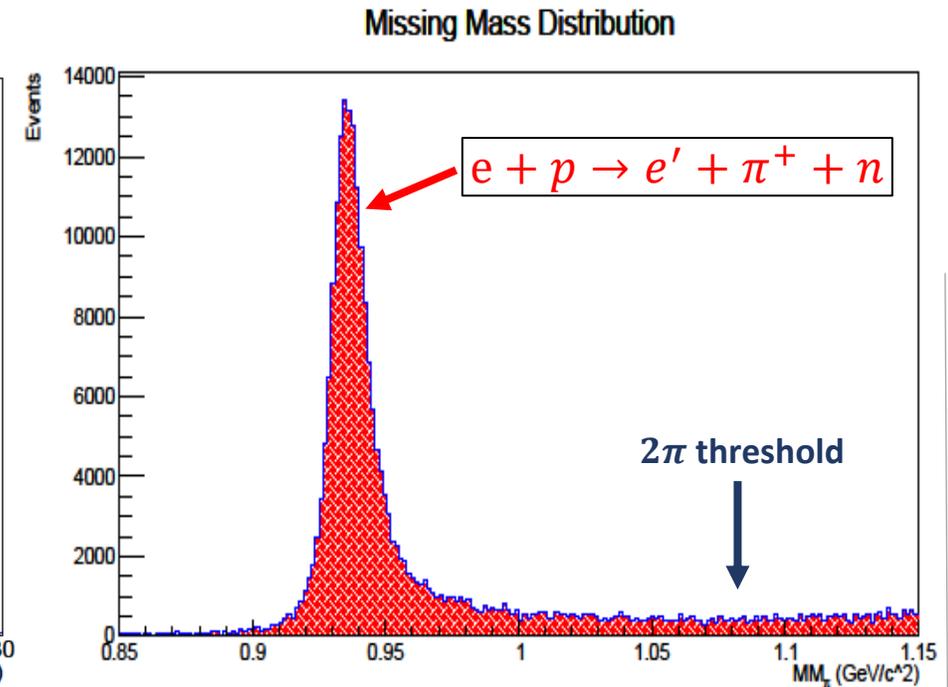
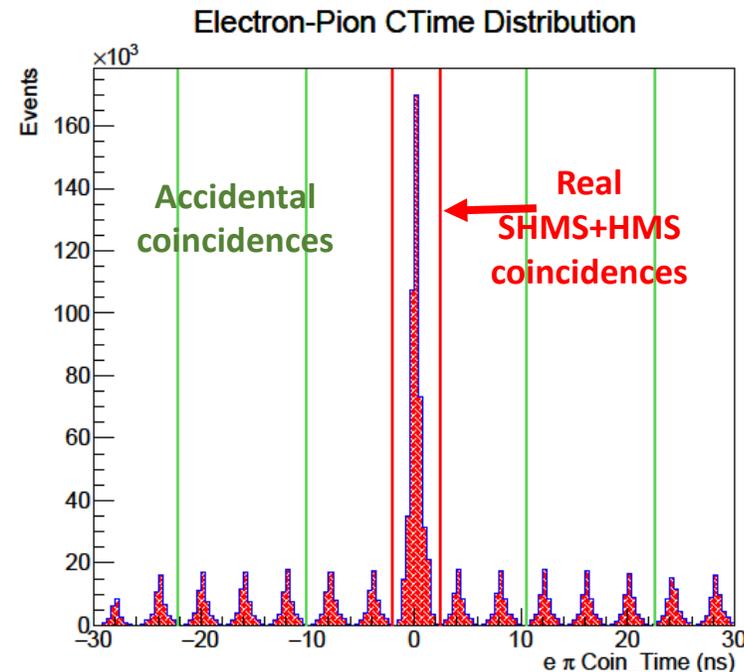
- $p(e, e'\pi^+)n$ Event Selection;
- Coincidence measurement between charged pions in SHMS and electrons in HMS
- Easy to isolate exclusive channel
- Excellent particle identification.
- Continuous beam minimizes accidental coincidences
- Missing mass resolution easily excludes 2-pion contributions

Pion-LT Experiment E12-19-006 Data

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

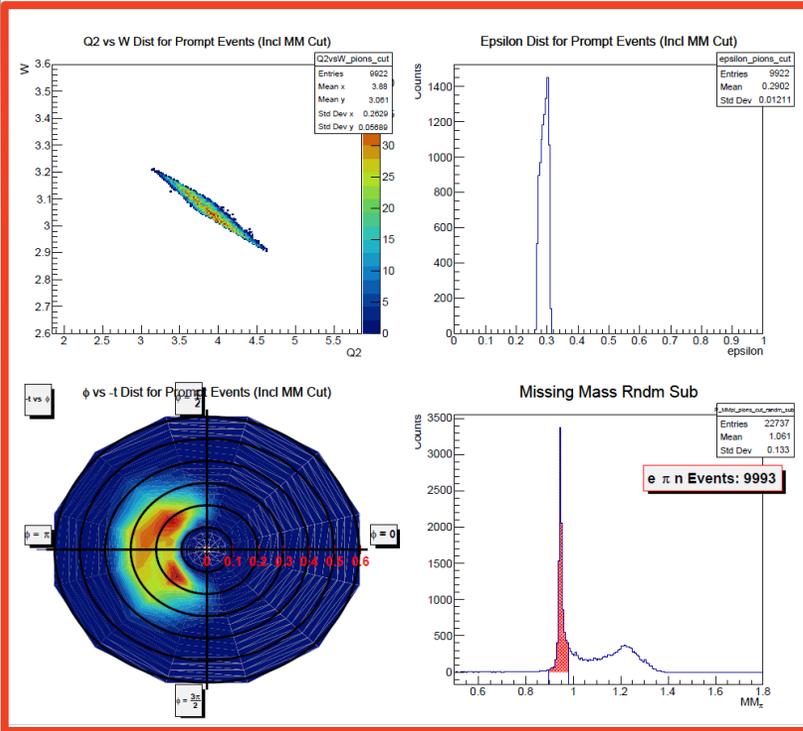
$$E_{beam} = 9.177 \text{ GeV}, \quad P_{HMS} = -3.738 \text{ GeV}/c, \quad \theta_{HMS} = 12.40^\circ$$

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

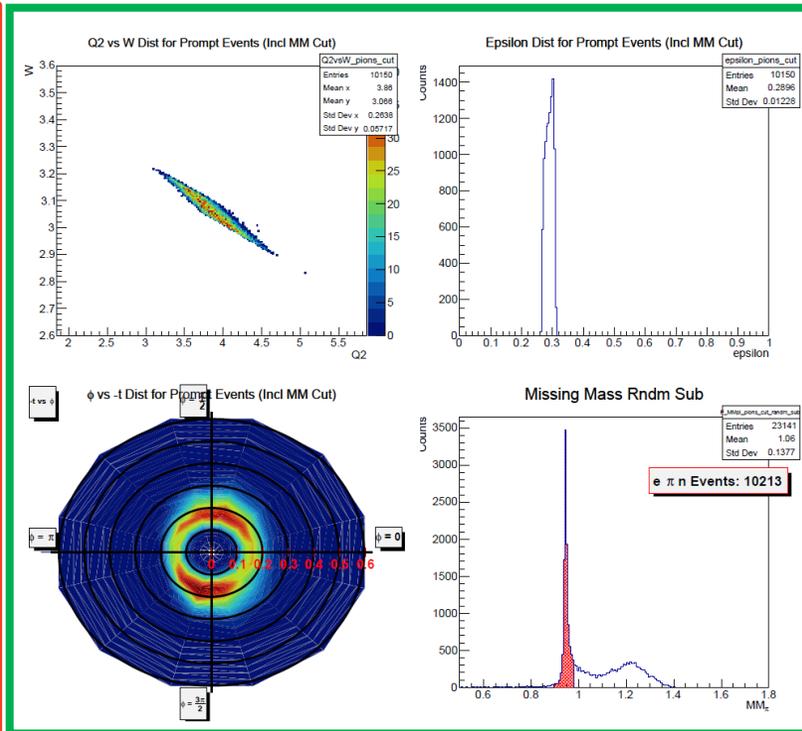


Pion-LT Fall 2021 Run Period

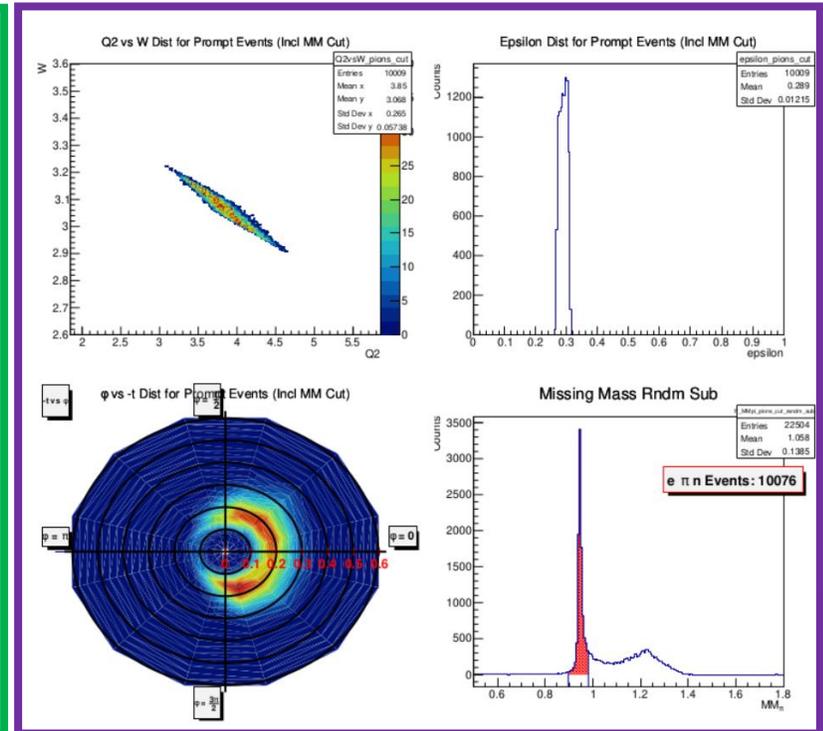
$$Q^2 = 3.85, W = 3.07, x = 0.31 \text{ for } p(e, e'\pi^+)n$$



$$\theta_{SHMS} = 8.39^\circ \text{ (Left)}$$



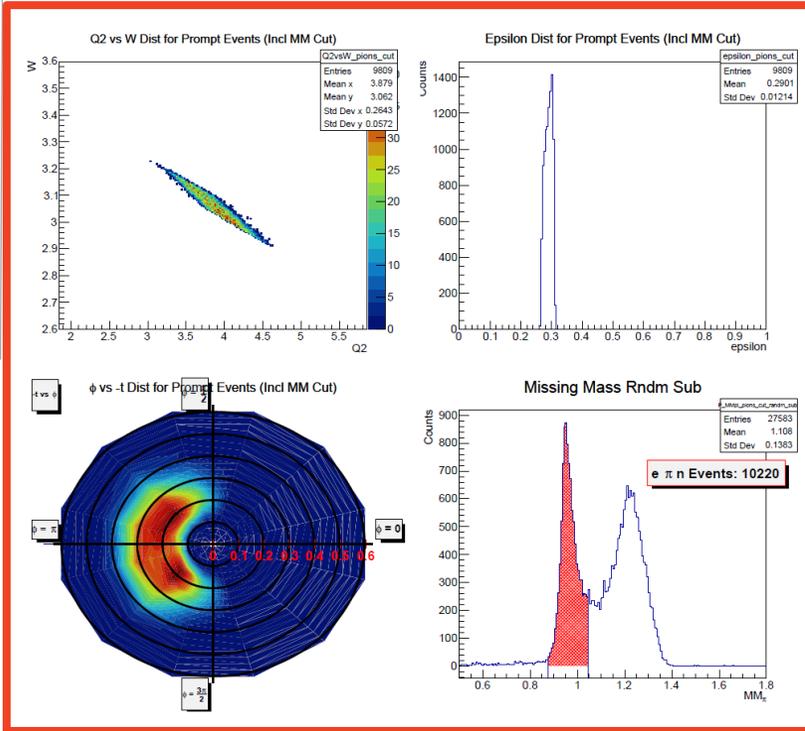
$$\theta_{SHMS} = 6.39^\circ \text{ (Center)}$$



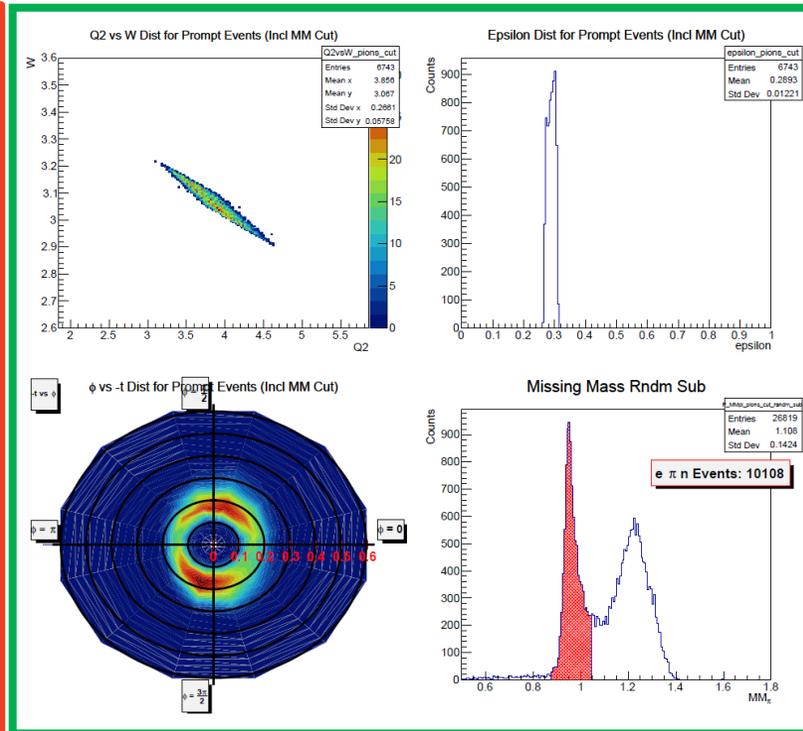
$$\theta_{SHMS} = 5.50^\circ \text{ (Right)}$$

Pion-LT Fall 2021 Run Period

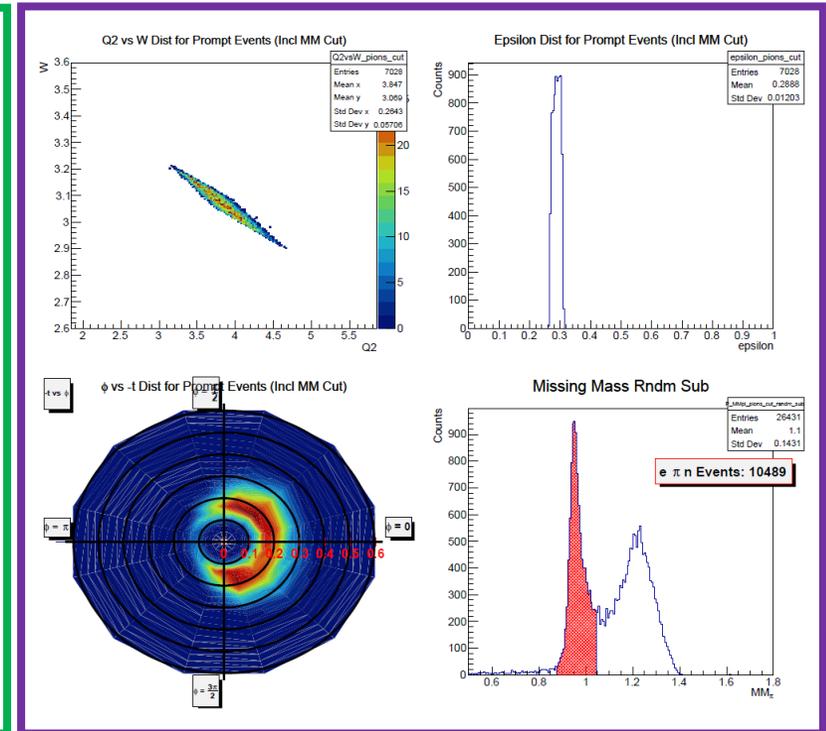
$$Q^2 = 3.85, W = 3.07, x = 0.31 \text{ for } d(e, e' \pi^+) n n_{sp}$$



$$\theta_{SHMS} = 8.39^\circ \text{ (Left)}$$



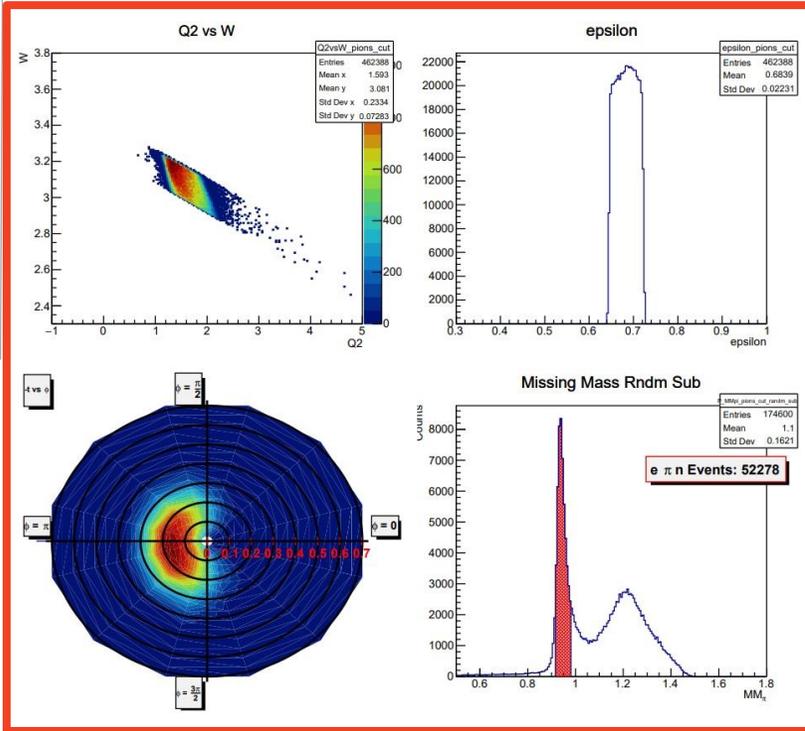
$$\theta_{SHMS} = 6.39^\circ \text{ (Center)}$$



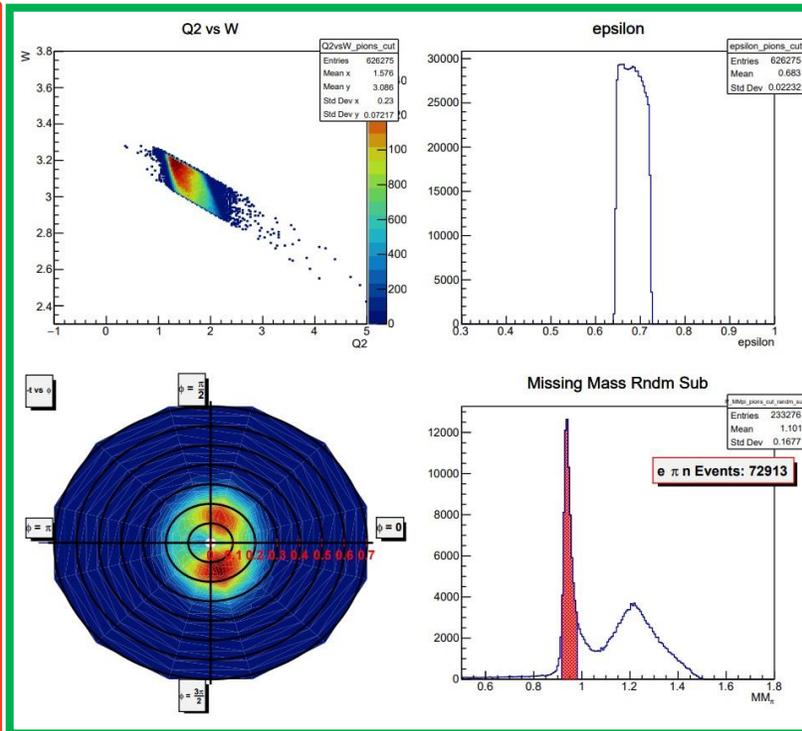
$$\theta_{SHMS} = 5.50^\circ \text{ (Right)}$$

Pion-LT Fall 2021 Run Period

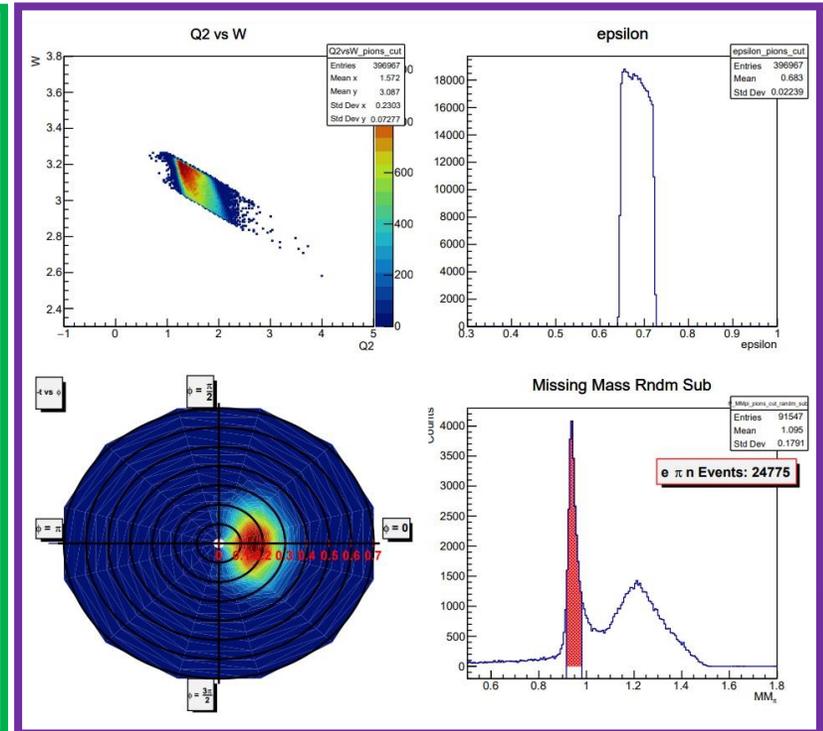
$Q^2 = 1.60, W = 3.08, x = 0.16$ for $d(e, e' \pi^-)pp_{sp}$



$\theta_{SHMS} = 10.26^\circ$ (Left)

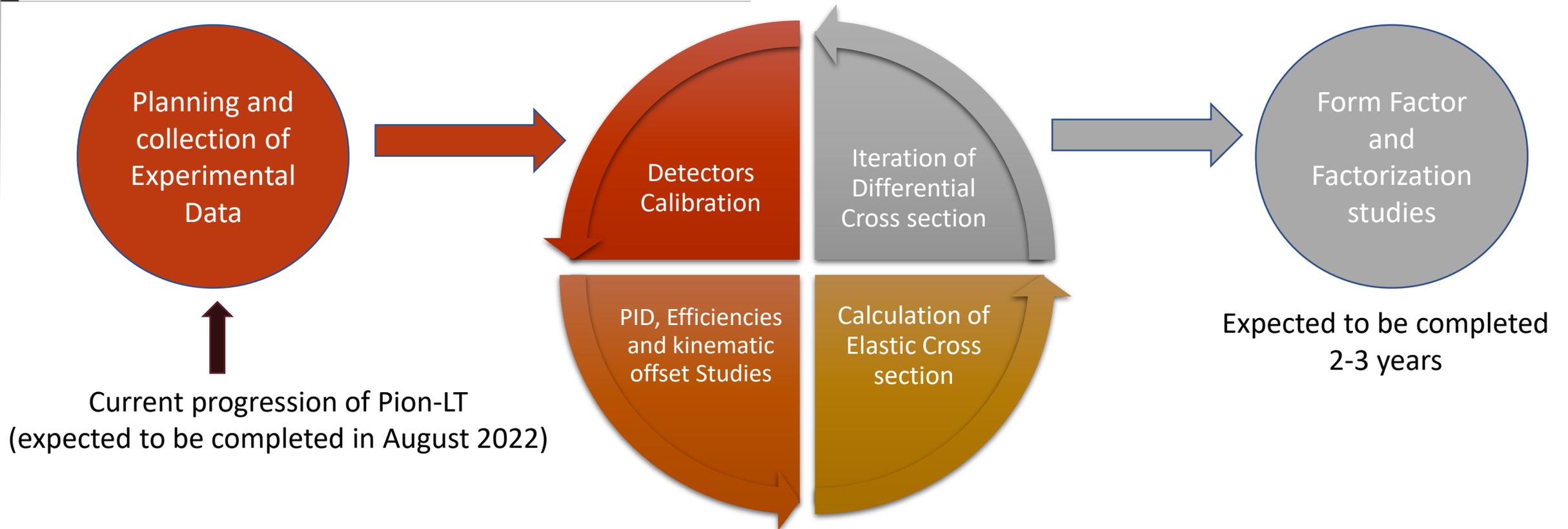


$\theta_{SHMS} = 8.26^\circ$ (Center)



$\theta_{SHMS} = 6.26^\circ$ (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



This research is funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) FRN: SAPIN-2021-00026