Update on Pion-LT Experiment

JACOB MURPHY

OHIO UNIVERSITY (NSF AWARD #1913170)

HALL C COLLABORATION MEETING

E12-19-006

- Spokespersons:

Dave Gaskell (Jlab), Tanja Horn (CUA), Garth Huber (Regina)

- Graduate Students

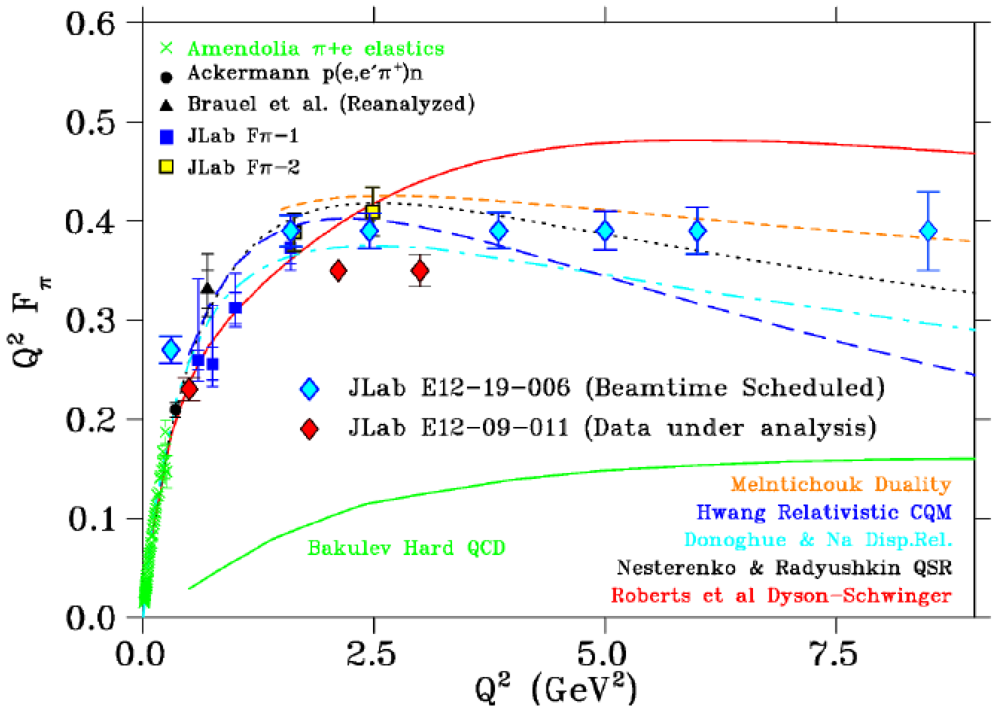
Nathan Heinrich (Regina), Muhammad Junaid (Regina), Jacob Murphy (Ohio U)

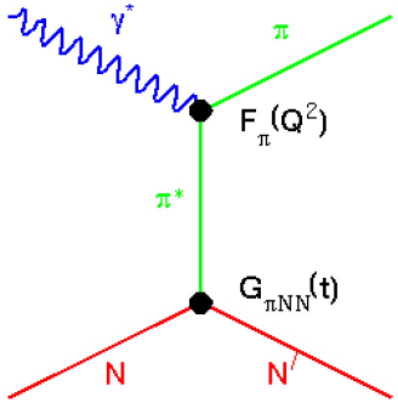
- Key Members:

Vladimir Berdnikov (CUA), Stephen Kay (Regina), Vijay Kumar (Regina), Julie Roche (Ohio U), Petr Stepanov (CUA), Richard Trotta (CUA), Ali Usman (Regina), Carlos Yero (Jlab)

Experiment Goals: Reliable F_π Extraction

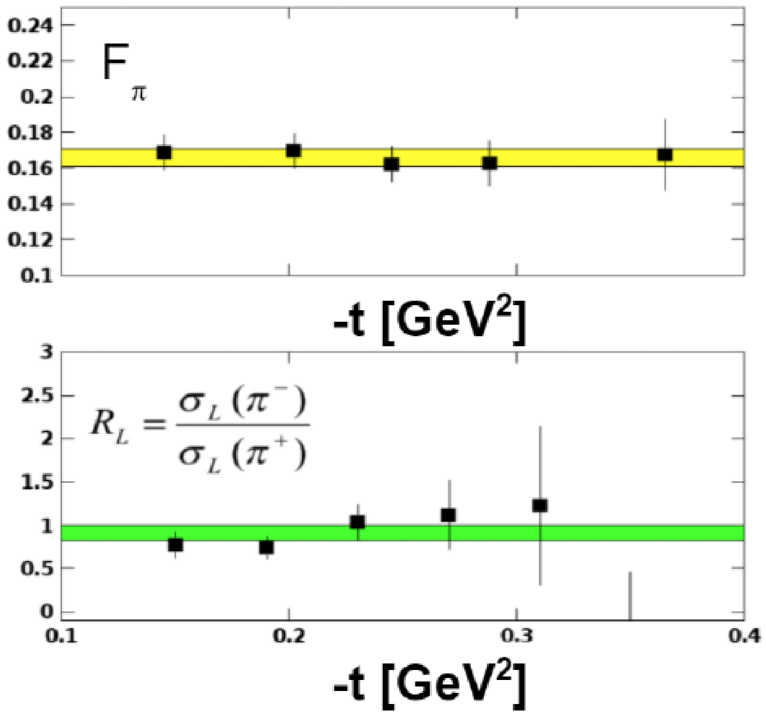
- Reliable Charged Pion Form Factor (F_π) extraction to highest possible Q^2
  - Using the proton's "pion cloud" and pion electroproduction $p(e,e'\pi^+)n$
  - At small –t, pion pole process dominates in σ_L
- Precise F_π extraction up to $Q^2 = 6\ GeV^2$
  - Highest possible F_π extraction at 8.5 GeV^2
- Low Q^2 data (taken in 2019) allows for testing if π^+electroproduction measures on-shell form factor
  - Compare $p(e,e'\pi^+)n$ F_π extraction with elastic eπ^+ at same Q^2





Experiment Goals: Validation of F_π Extraction

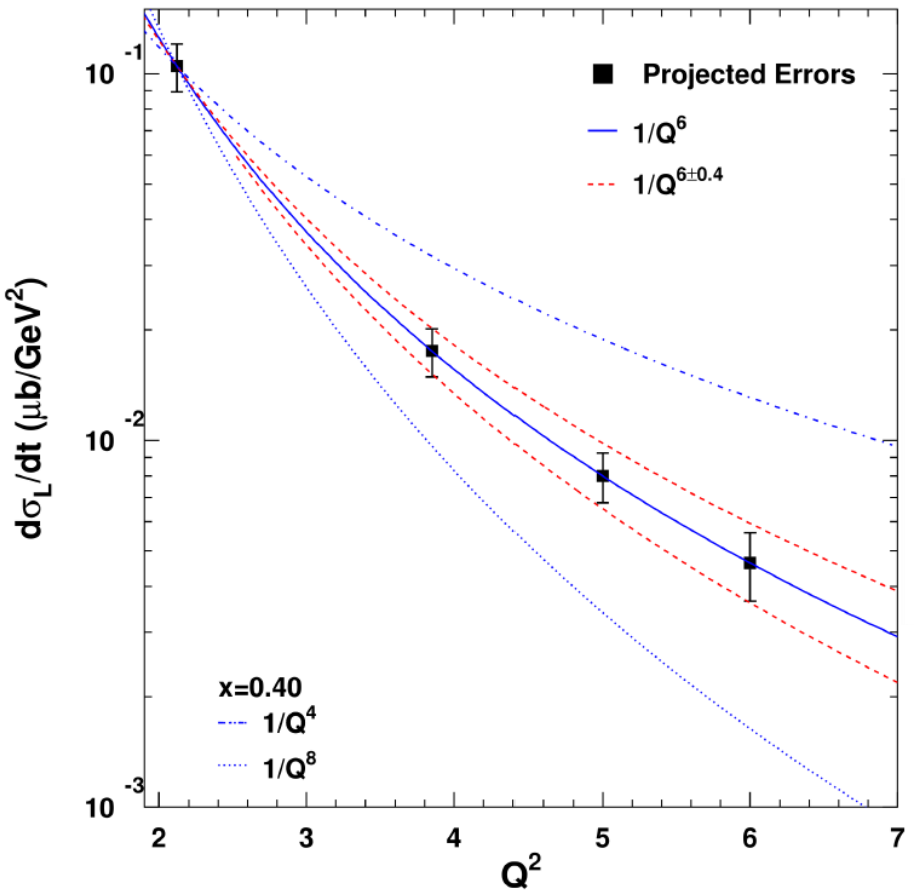
- Validation of F_π extractions at highest possible Q^2
- Extract F_π at fixed Q^2, scanning t
  - F_π should be independent of -t
- Check dominance of t-channel process
  - Examine ratio of σ_L for $d(e,e'\pi^-)pp_{sp}$ and $d(e,e'\pi^+)nn_{sp}$
  - Tests to be repeated at $Q^2 = 1.60, 3.85, 6.0\ GeV^2$

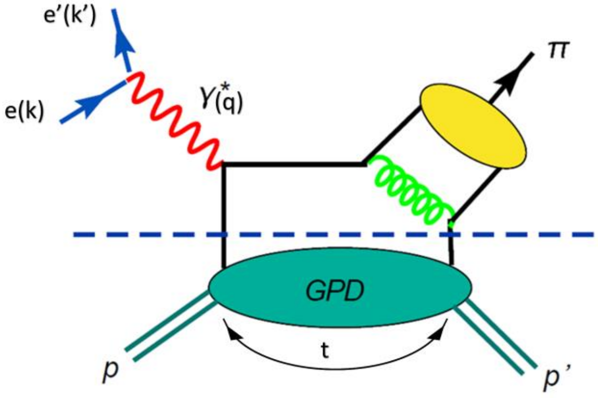


T. Horn, C.D. Roberts, J. Phys. G43 (2016) no.7, 073001
G. Huber et al, PRL112 (2014)182501
R. J. Perry et al., arXiV:1811.09356 (2019)

Experiment Goals: L/T Separated Pion Cross Sections

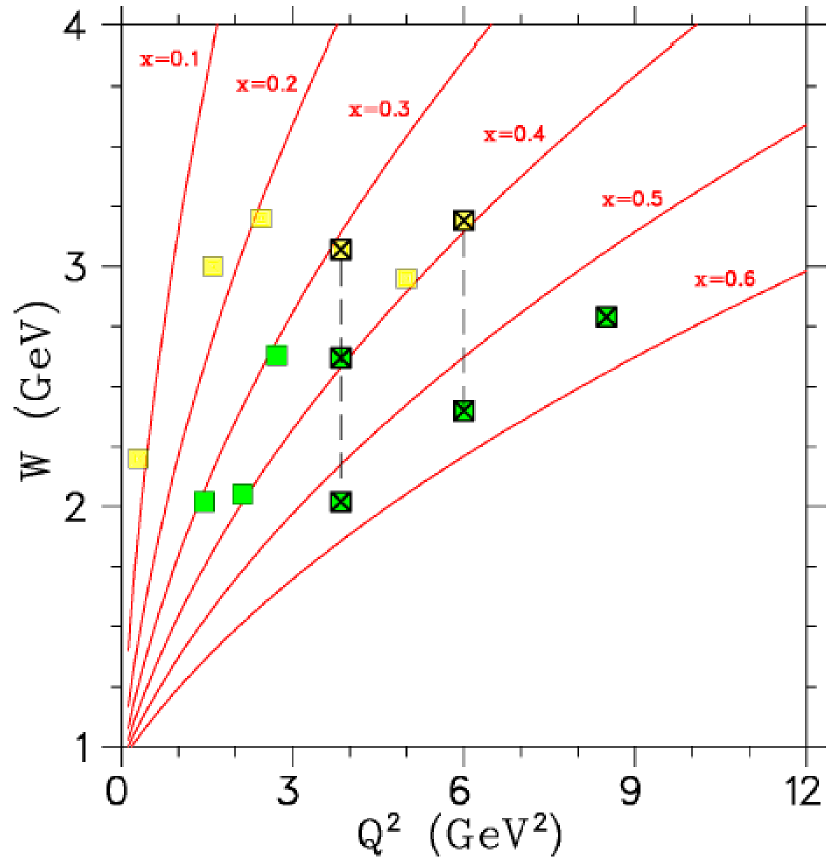
- Scaling Study at fixed x = 0.31, 0.39, 0.55 as a function of Q^2
- QCD counting rules predict $1/Q^n$ dependence of $p(e,e'\pi^+)n$ cross sections in Hard Scattering Regime:
  - σ_L, to leading order, scales as $1/Q^6$
  - σ_T scales as $1/Q^8$
  - At large Q^2, $\sigma_L >> \sigma_T$
- Study hard-soft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





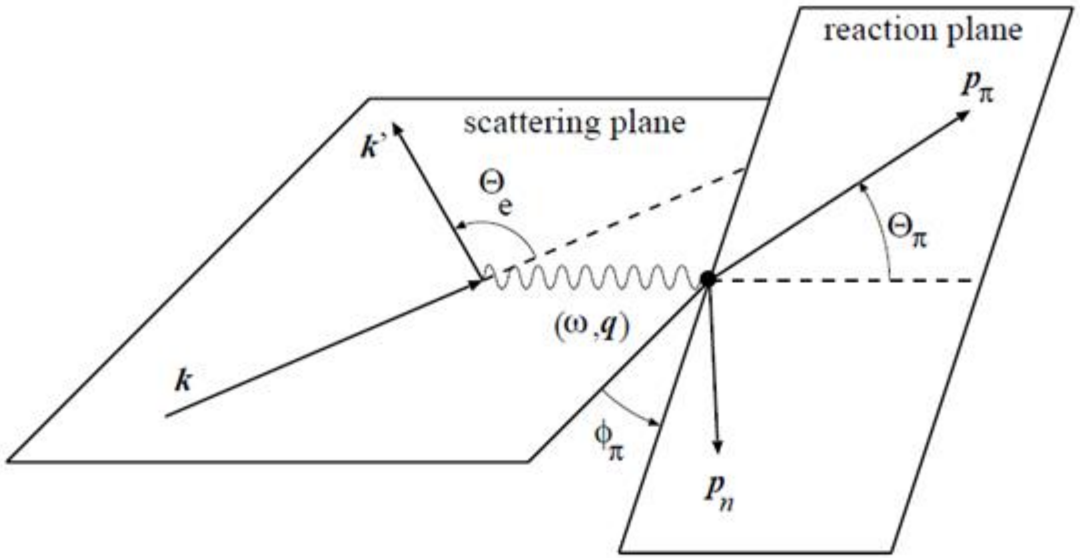
Optimized W vs Q^2 Settings for F_π Extraction and Pion Scaling Study

- Vertical dashed lines scan t at fixed Q^2
  - Allows for F_π extraction at varying distance from pion pole
  - Check that model accurately accounts for:
    - π^+ production mechanism
    - Spectator nucleon
    - Off-shell (t-dependent) effects
- 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



L/T Separation via Rosenbluth Technique

- Measure cross section at two beam energies with Q^2, W, and t fixed
  - Scan $\theta_{\pi q}$ across left and right of θ_π
- Carry out simultaneous fit at two different ϵ using the azimuthal angle ϕ_π
  - Allows for separation of σ_L, σ_T, σ_{LT}, and σ_{TT}
- See Richard Trotta's Kaon LT talk for more details



$$\frac{d^2\sigma}{dt d\phi_\pi} = \frac{1}{2\pi}\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dt}cos\phi_\pi + \epsilon\frac{d\sigma_{TT}}{dt}cos2\phi_\pi\right)$$

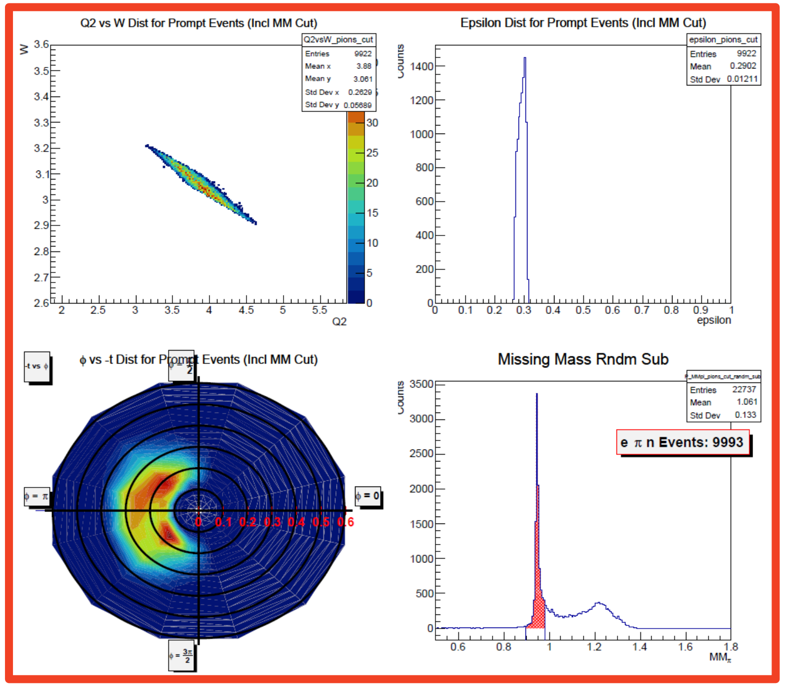
Fall 2021 Completed Kinematics

- Kinematic settings for data collection from September 2021 to February 2022
- $\theta_{\pi q}$ settings are limited
  - Right-angle setting not always possible with hard limit of 5.5° for SHMS
  - Q^2=8.50 limited to central angle due to event rate (388 hrs in PAC 47 proposal)
- 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 =1.60 setting requires low-ϵ data and rest require high-ϵ

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

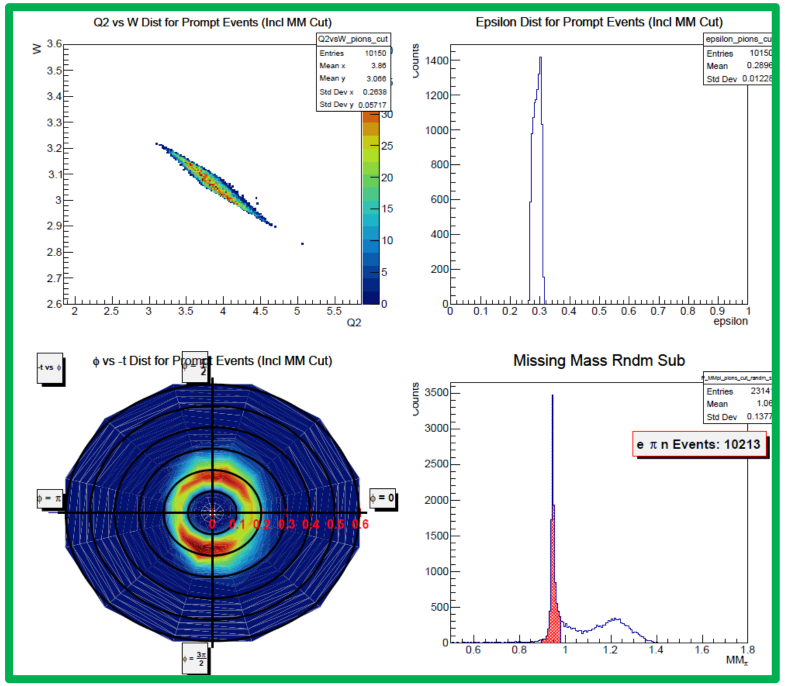
LH+: $p(e,e'\pi^+)n$ LD+: $d(e,e'\pi^+)nn_{sp}$ LD-: $d(e,e'\pi^-)pp_{sp}$

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



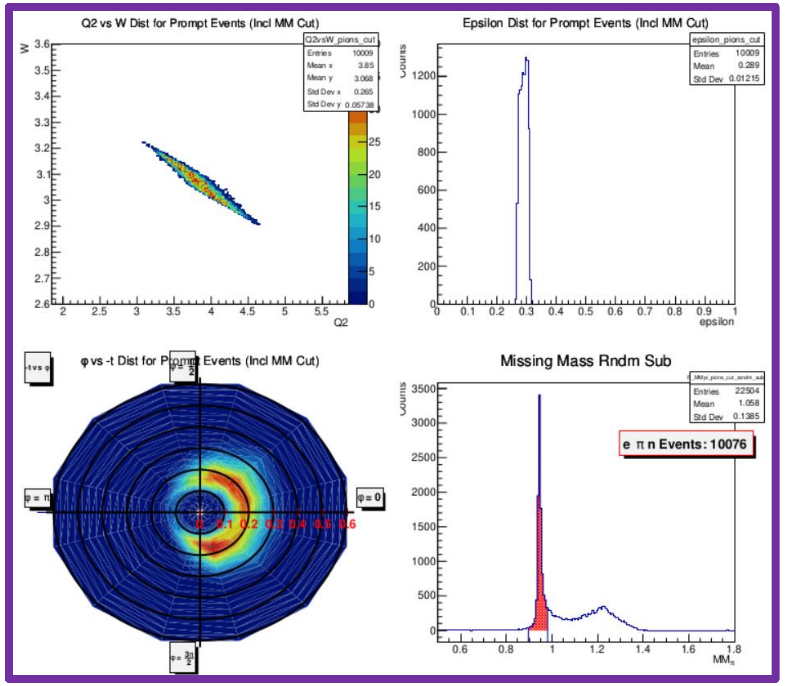
$\theta_{SHMS} = 8.39°$

LEFT



$\theta_{SHMS} = 6.39°$

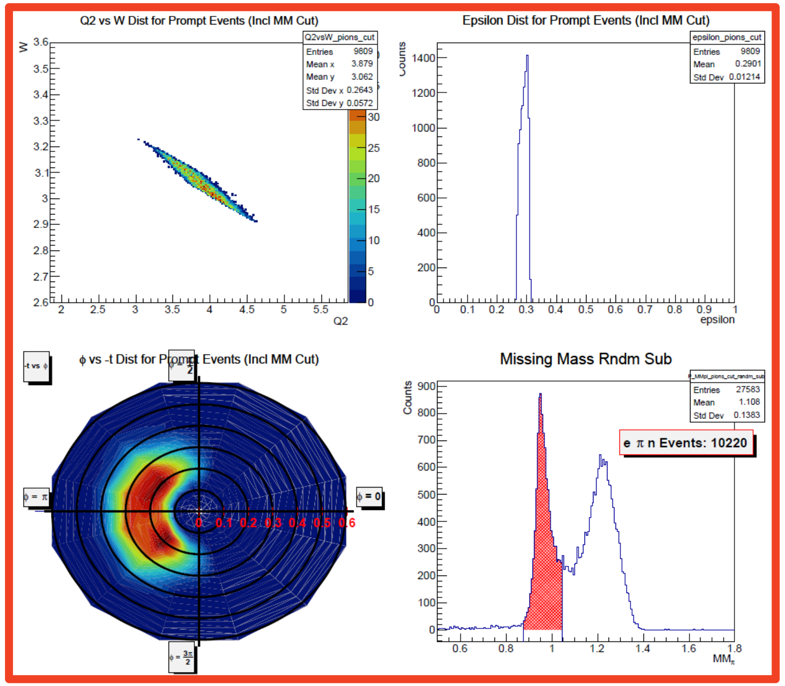
CENTER

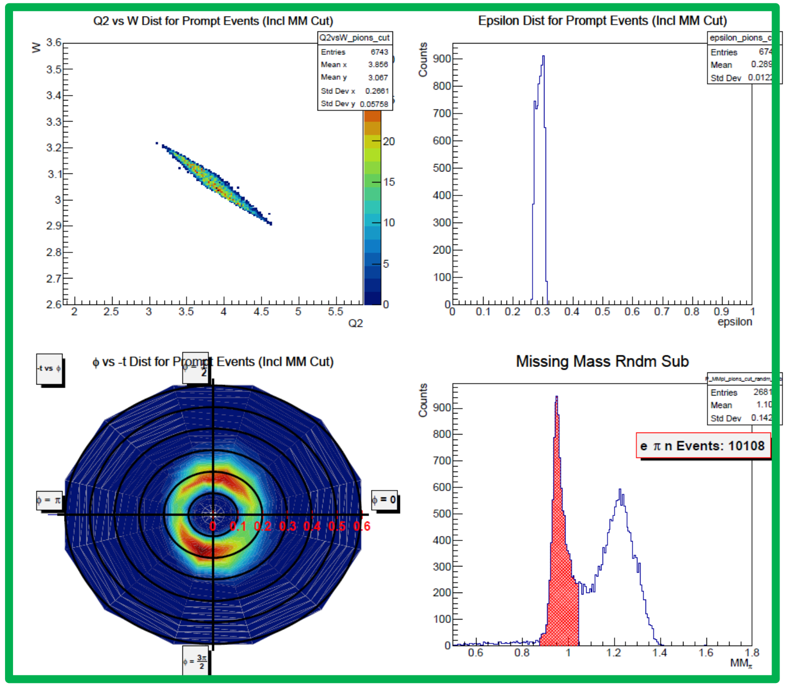


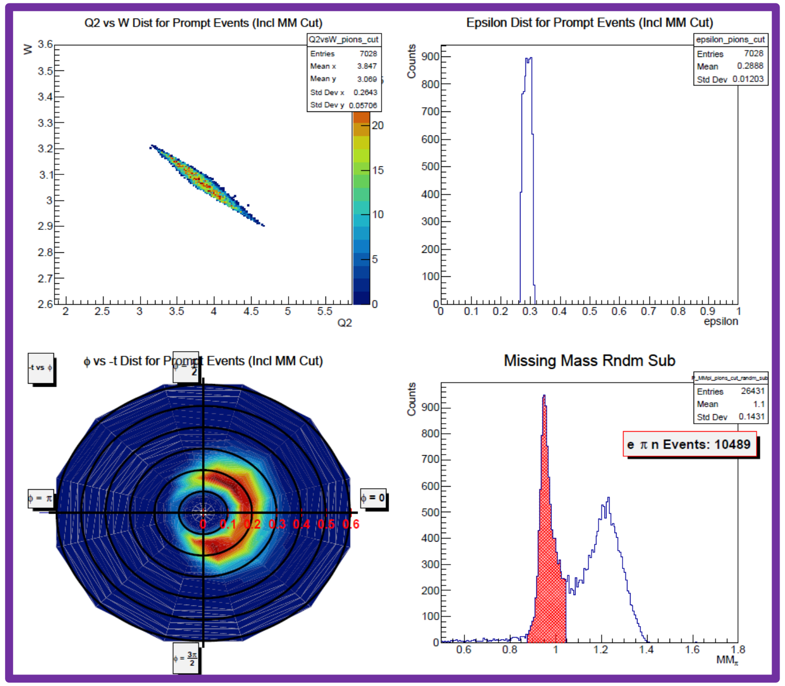
$\theta_{SHMS} = 5.5°$

RIGHT

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



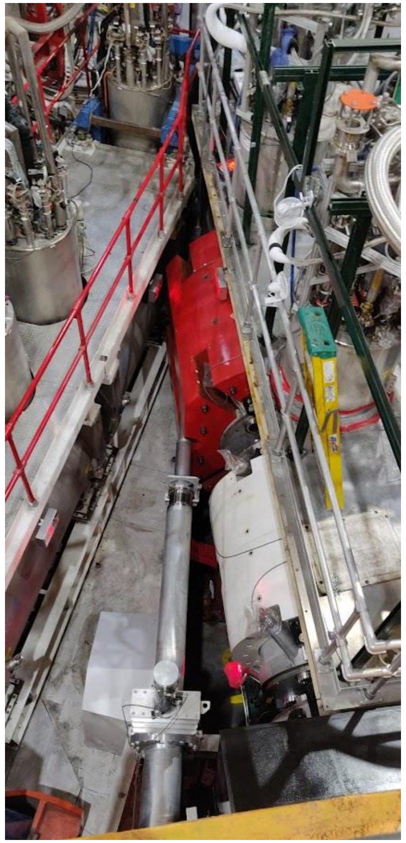




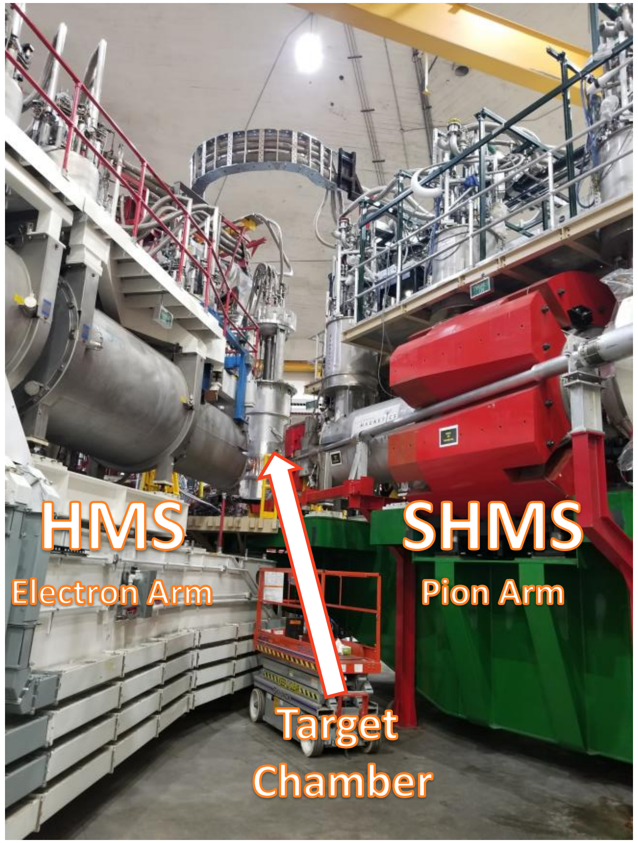
$\theta_{SHMS} = 8.39°$ | $\theta_{SHMS} = 6.39°$ | $\theta_{SHMS} = 5.5°$

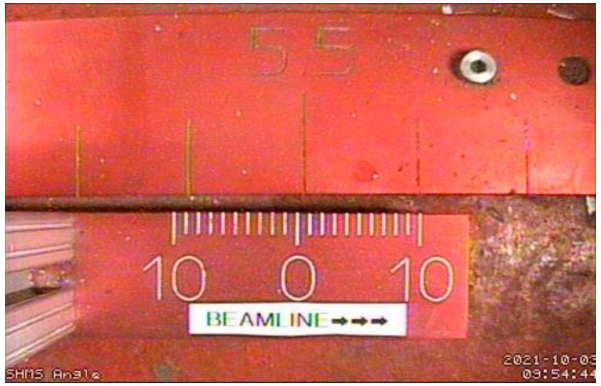
LEFT | CENTER | RIGHT

Hall C Extremes in this Experiment



- Several kinematic settings used the SHMS at its minimum angle of 5.5 deg
  - Ran continuously at this angle from October 3rd through November 5th, 2021
- Minimum opening angle between SHMS and HMS was reached for this experiment
  - HMS moved to 11.01 deg and SHMS moved 18 deg away at 6.99 deg
- Thank you to Hall C staff for making this possible!

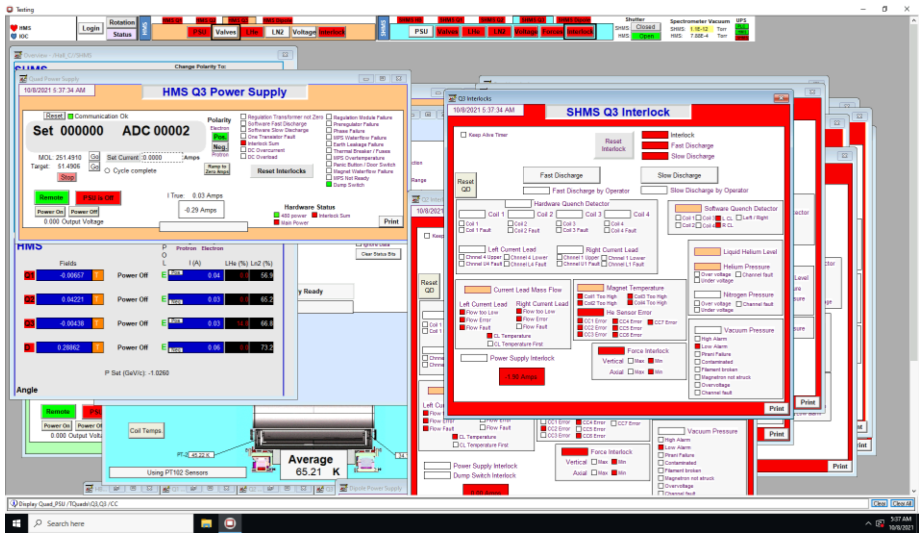




Spectrometer Issues While Running

- Radiation damage affected hall equipment and electronics
  - SHMS UPS dying caused ALL magnets to interlock

- SHMS Q1 interlocked at increased frequency near end-of-run
  - Burns are visible from experiment running



June, 2021

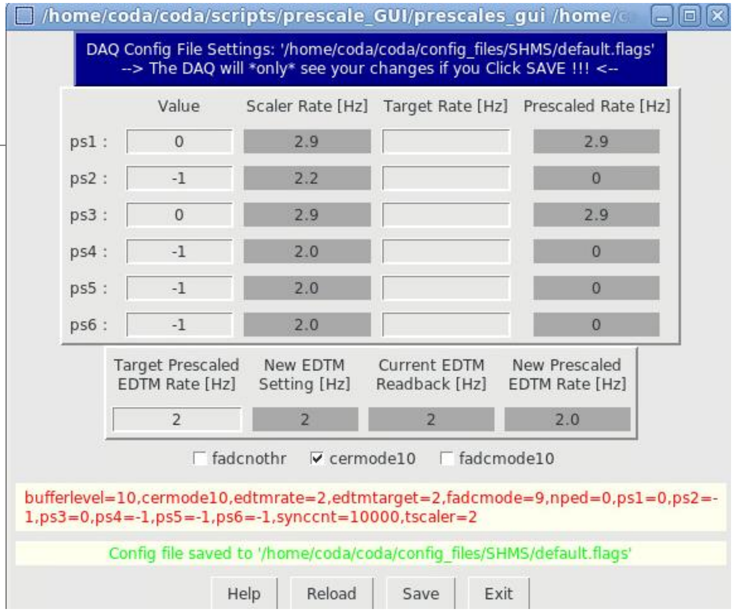
Nov 13, 2021

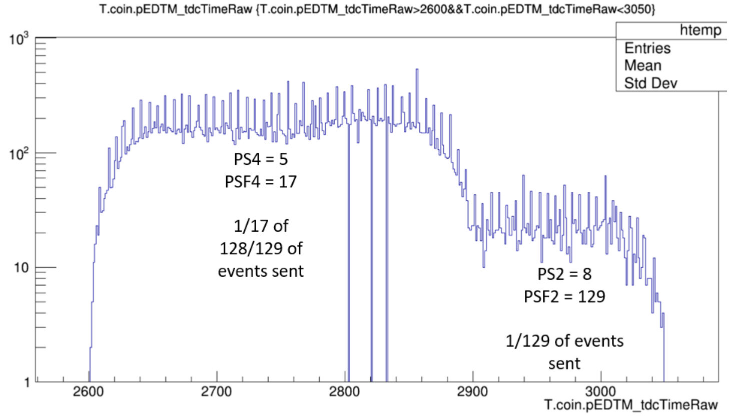
Jan 21, 2021

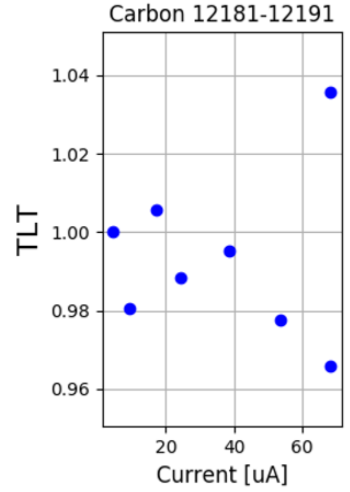
Thanks to the efforts off the hall staff, our run coordinators, and shift workers, these challenges did not hamper our data collection in this very successful run

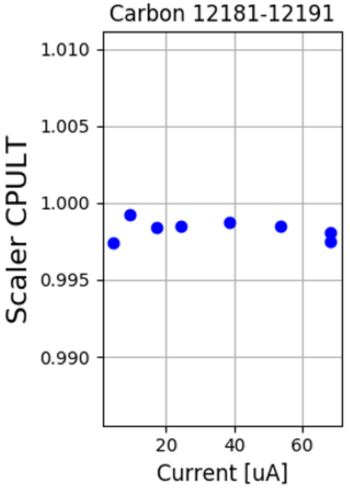
New EDTM GUI and EDTM Studies for TLT

- Brad Sawatzky's GUI sets EDTM clock by desired EDTM rate:
  - $EDTM_{acc} = \dfrac{EDTM_{sent}}{PSF_{min}}$
- $EDTM_{acc}$ measured by event count in EDMT tdc Time Raw
- Examining prescaled non-coin data, determined that equation is closer to:
  - $EDTM_{acc} = \dfrac{EDTM_{sent}}{PSF_1} + \dfrac{EDTM_{sent}}{PSF_2} - \dfrac{EDTM_{sent}}{PSF_1 * PSF_2}$
- Prescale correction improves TLT calculation, but still have runs with TLT>1
  - Richard Trotta and Jacob Murphy looking into this









Pion LT 2021 Running Complete!

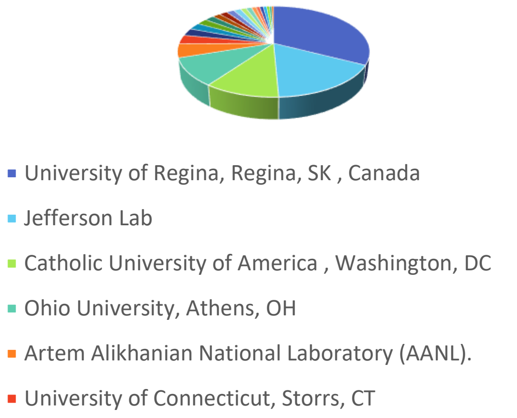
- Completion of a very successful data run
- COVID restrictions limited international collaboration
- With pandemic border restrictions improving, we are optimistic that international collaborators will have more opportunities to be involved this fall!

Ranking of most weighted shifts, combining institutions and individuals →

Note Owl was weighted as 1.5 shifts

Rank	Institution/ Individual Name	Number of Shifts	Number of Shifts with Weight
1	University of Regina, Regina, SK , Canada	419	487.5
2	Jefferson Lab	244	250
3	Catholic University of America , Washington, DC	131	159.5
4	Ohio University, Athens, OH	123	148.5
5	Jacob Murphy	94	117.5
6	Muhammad Junaid	95	111.5
7	Nathan Heinrich	79	104
8	Ali Usman	68	91
9	Stephen Kay	84	88
10	Richard Trotta	61	83
11	Artem Alikhanian National Laboratory (AANL).	49	73.5
12	Dave Gaskell	62	62
13	Garth Huber	60	60
14	Petr Stepanov	52	58.5
15	University of Connecticut, Storrs, CT	40	48
16	Hamlet Mkrtchyan	28	42
17	The College of William and Mary	29	39.5
18	Virginia Tech	33	36.5
19	Temple University, Philadelphia, PA	30	31.5
20	Vardan Tadevosyan	21	31.5
21	Vijay Kumar	31	31
22	A.I. Alikhanian National Science Laboratory	19	28.5
23	Arthur Mkrtchyan	19	28.5
24	Carlos Yero	25	26
25	University of Colorado, Boulder, CO	24	24

π-Chart of Participating Institutions



π-Chart of Participating Institutions' Countries

Fall 2022 Planned Kinematics

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	3.2	0.21	LH+	high
2.73	2.63	0.311	LH+	low, high
3.85	2.02	0.55	LH+	high
3.85	2.62	0.392	LH+,LD+,LD-	low,high
3.85	3.07	0.31	LH+	high
5	2.95	0.39	LH+	high
6	3.19	0.39	LH+	high
6	2.4	0.55	LH+,LD+,LD-	high
8.5	2.79	0.55	LH+	high

- Complementary of data taken in 2019 and 2021
  - Kinematics are fixed by data already taken
- High-ϵ data is necessary for L/T separation and for experiment goals to be met
  - 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 this gradient
  - Large impact on data quality

LH+: $p(e,e'\pi^+)n$ LD+: $d(e,e'\pi^+)nn_{sp}$ LD-: $d(e,e'\pi^-)pp_{sp}$

Call for Collaborators

- Data collection for fall 2021 was very successful
  - **Thank you** to the Hall C staff/users and our collaborators!
  - We need your continued support to complete this experiment!!
- The high-ϵ kinematics are an absolute necessity for L/T separation and our experimental goals
- E12-19-006 is currently scheduled to run October 1st 2022 through December 4th 2022

WE REALLY NEED YOUR CONTINUED ASSISTANCE TO MAKE THIS EXPERIMENT A SUCCESS!!!

Extra Slides

PAC 47 E12-19-006 Proposed Kinematics

- Kinematics for the pion form factor study (left) and pion scaling study (right)
- Blue settings are used in both studies
- Red kinematics taken in 2019
- Angles and beam energies NOT final for black and blue settings

Q^2	W	x	$-t_{min}$	Type	E_e	ϵ	θ_q	$\theta_{\pi q}$	Hrs
0.38	2.20	0.087	0.008	LH+	2.8	0.286	5.70	0, +2, +4^o	11.1
					3.7	0.629	8.87	-2, 0, +2, +4^o	14.8
					4.6	0.781	10.33	-4, -2, 0, +2, +4^o	18.5
1.60	3.00	0.165	0.029	LH+	6.7	0.408	6.36	0, +2^o	9.9
					8.8	0.689	8.70	-2, 0, +2^o	12.8
					11.0	0.817	9.91	-2, 0, +2^o	12.8
1.60	3.00	0.165	0.029	LD+	6.7	0.408	6.36	0, +2^o	9.9
					11.0	0.817	9.91	-2, 0, +2^o	12.8
1.60	3.00	0.165	0.029	LD-	6.7	0.408	6.36	0, +2^o	18.7
					11.0	0.817	9.91	-2, 0, +2^o	12.8
2.45	3.20	0.208	0.048	LH+	8.0	0.383	6.26	0, +2^o	9.9
					8.8	0.505	7.30	-1.8, 0, +2^o	12.8
					11.0	0.709	9.03	-2, 0, +2^o	12.8
3.85	3.07	0.311	0.120	LH+	8.0	0.301	6.53	-1.03, 0, +2^o	33.5
					8.8	0.436	7.97	-2, 0, +2^o	18.2
					9.9	0.572	9.31	-2, 0, +2^o	13.3
					11.0	0.666	10.27	-2, 0, +2^o	12.8
3.85	3.07	0.311	0.120	LD+	8.0	0.301	6.53	-1.03, 0, +2^o	33.5
					11.0	0.666	10.27	-2, 0, +2^o	12.8
3.85	3.07	0.311	0.120	LD-	8.0	0.301	6.53	0, +2^o	118.8
					11.0	0.666	10.27	-2, 0, +2^o	12.8
5.00	2.95	0.390	0.209	LH+	8.0	0.238	6.35	0, +2^o	74.5
					9.9	0.530	9.76	-2, 0, +2^o	41.1
					11.0	0.633	10.88	-2, 0, +2^o	27.0
6.00	3.19	0.392	0.214	LH+	9.2	0.184	5.13	0.37, +2^o	182.2
					9.9	0.304	6.64	0, +2^o	80.6
					11.0	0.452	8.22	-2, 0, +2^o	71.9
Calibrations									80.0
Beam Energy Changes									72.0
Total Hours (100% efficiency)									1054.6
PAC35 Approved Hours (100% efficiency)									1248.0
Time Saved: 1248-1054.6 hrs (100% efficiency)									-193.4

Q^2	W	x	$-t_{min}$	Type	E_e	ϵ	θ_q	$\theta_{\pi q}$	Hrs
1.45	2.02	0.312	0.114	LH+	3.7	0.511	13.76	-2, 0, +2^o	11.1
					6.7	0.880	20.17	-2, 0, +2^o	10.0
2.73	2.63	0.311	0.118	LH+	6.7	0.513	10.30	-2, 0, +2^o	13.8
					11.0	0.845	14.58	-2, 0, +2^o	9.3
2.12	2.05	0.390	0.195	LH+	4.6	0.573	15.14	-2, 0, +2^o	11.1
					8.8	0.907	21.44	-2, 0, +2^o	12.8
3.85	2.62	0.392	0.208	LH+	6.7	0.360	8.94	-2, 0, +2^o	22.5
					11.0	0.799	14.58	-2, 0, +2^o	9.6
3.85	2.62	0.392	0.208	LD+	6.7	0.360	8.94	-2, 0, +2^o	22.5
					11.0	0.799	14.58	-2, 0, +2^o	9.6
3.85	2.62	0.392	0.208	LD-	6.7	0.360	8.94	-2, 0, +2^o	74.9
					11.0	0.799	14.58	-2, 0, +2^o	9.6
3.85	2.02	0.546	0.487	LH+	6.0	0.582	17.41	-2, 0, +2^o	9.6
					11.0	0.898	21.92	-2, 0, +2^o	9.6
6.00	2.40	0.551	0.530	LH+	8.0	0.449	11.26	-2, 0, +2^o	48.5
					11.0	0.738	15.31	-2, 0, +2^o	18.4
6.00	2.40	0.551	0.530	LD+	8.0	0.449	11.26	-2, 0, +2^o	48.5
					11.0	0.738	15.31	-2, 0, +2^o	18.4
6.00	2.40	0.551	0.530	LD-	8.0	0.449	11.26	-2, 0, +2^o	48.5
					11.0	0.738	15.21	-2, 0, +2^o	18.4
8.50	**2.79**	**0.552**	**0.550**	**LH+**	**9.2**	**0.156**	**5.52**	**0^o**	**388.0**
					11.0	**0.430**	**9.36**	**0^o**	**108.5**
Calibrations									48.0
Extra calibrations needed for large angle *ytar*									8.0
Beam energy changes									72.0
Total Hours (100% efficiency)									1057.3
PAC38 Approved Hours (100% efficiency)									864.0
Extra time: 1035.3-864.0 (Table I) hrs (100% efficiency)									+193.5

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- Reliable Charged Pion Form Factor (F_π) extraction to highest possible Q^2
- Using the proton's "pion cloud" and pion electroproduction $p(e,e'\pi^+)n$
- At small –t, pion pole process dominates in σ_L
- Precise F_π extraction up to $Q^2 = 6\ GeV^2$
  - Highest possible F_π extraction at 8.5 GeV^2
- Low Q^2 data (taken in 2019) allows for testing if π^+electroproduction measures on-shell form factor
  - Compare $p(e,e'\pi^+)n$ F_π extraction with elastic $e\pi^+$ at same kinematic