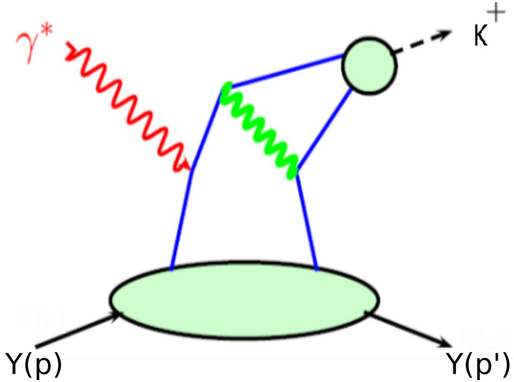
Update on KaonLT Experiment

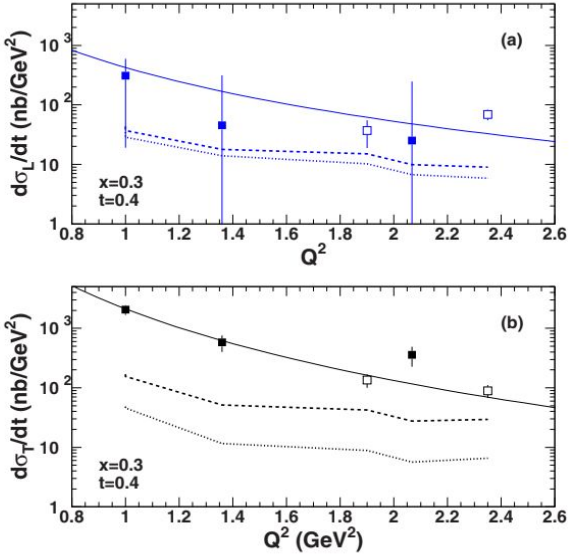
Richard Trotta, Tanja Horn, Garth Huber, Pete Markowitz,
Stephen Kay, Vijay Kumar, Vladimir Berdnikov, Ali Usman,
and the KaonLT collaboration

L/T separated data for verifying reaction mechanism

- Jlab 6 GeV data demonstrated the technique of measuring the Q^2 dependence of L/T separated cross sections at fixed x/t to test QCD Factorization
  - Consistent with expected scaling of σ_L to leading order Q^{-6} but with relatively large uncertainties

- Separated cross sections over a large range in Q^2 are essential for:
  - Testing factorization and understanding dynamical effects in both Q^2 and –t kinematics
  - Interpreting non-perturbative contributions in experimentally accessible kinematics





*M. Carmignotto et al., PhysRevC **97**(2018)025204*

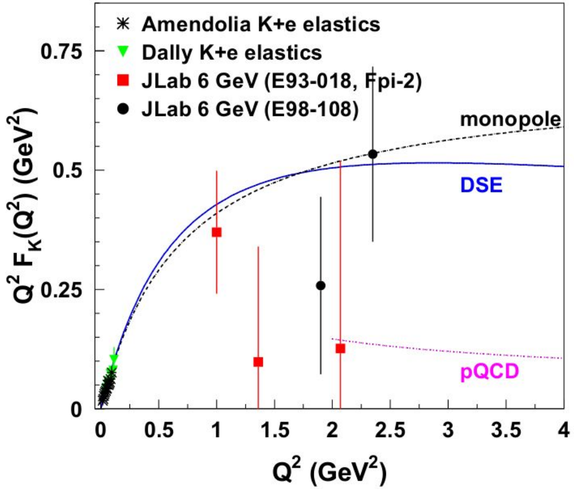
Meson Form Factors

- Pion and kaon form factors are of special interest in hadron structure studies
  - Pion - lightest QCD quark system and crucial in understanding dynamic generation of mass
  - Kaon - next simplest system containing strangeness

- Clearest case for studying transition from non-perturbative to perturbative regions

- Jlab 6 GeV data showed FF differs from hard QCD calculation
  - Evaluated with asymptotic valence-quark Distribution Amplitude (DA), but large uncertainties

- 12 GeV FF extraction data require:
  - measurements over a range of t, which allow for interpretation of kaon pole contribution

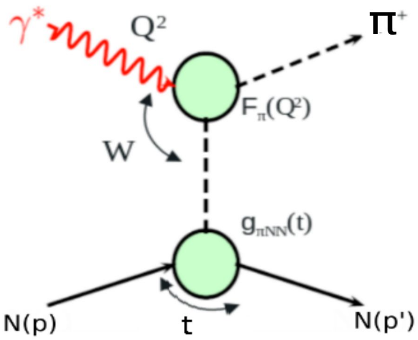


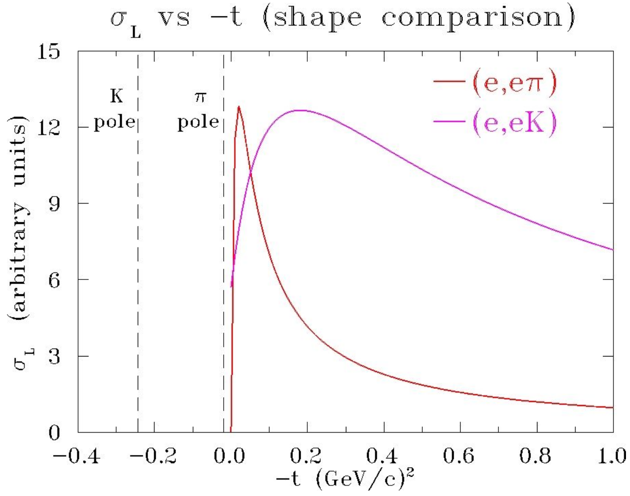
M. Carmignotto et al., PhysRevC ***97****(2018)025204*
F. Gao et al., Phys. Rev. D 96 (2017) no. 3, 034024

Experimental Determination of the π/K+ Form Factor

- At larger Q^2, $F_{\pi+}^{\ 2}$ must be measured indirectly using the "pion cloud" of the proton via the p(e,e'π^+)n process
  - At small –t, the pion pole process dominates σ_L
  - In the Born term model, $F_{\pi+}^{\ 2}$ appears as

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

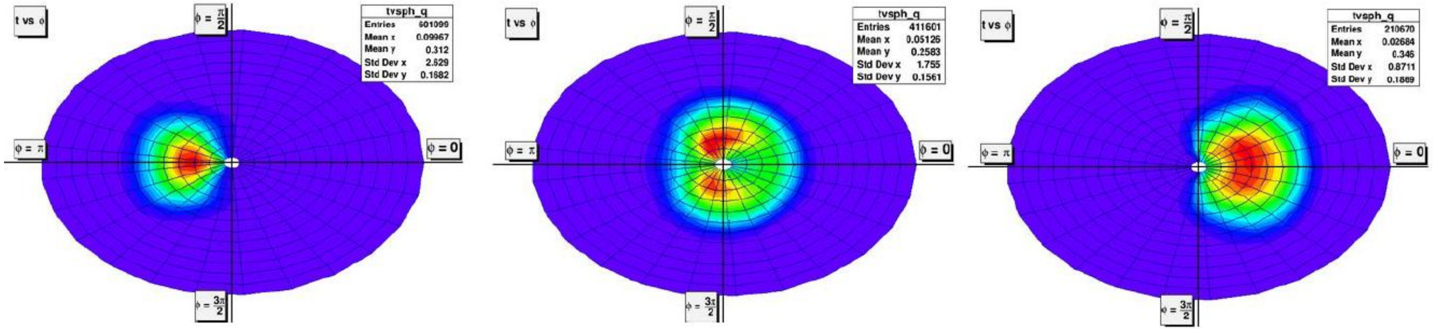




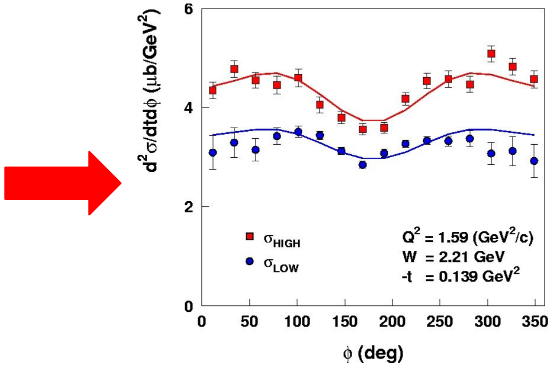
- Requirements:
  - Full L/T separation of the cross section – isolation of σ_L
  - Selection of the pion pole process
  - Extraction of the form factor using a model
  - Validation of the technique - model dependent checks

L/T Separation Example

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

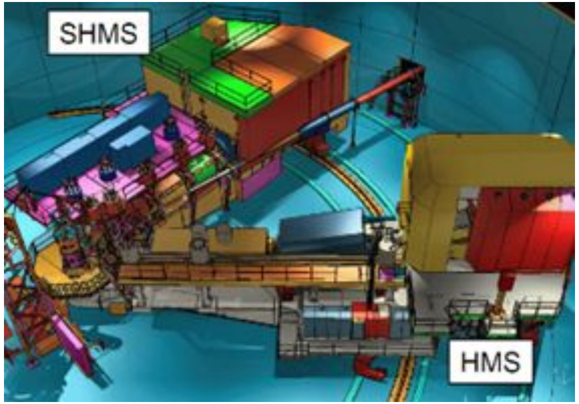


- Three SHMS angles for azimuthal (ϕ) coverage to determine the interference terms (LT, TT)
- Using the two beam energies (ε) to separate longitudinal (L) from transverse (T) cross section



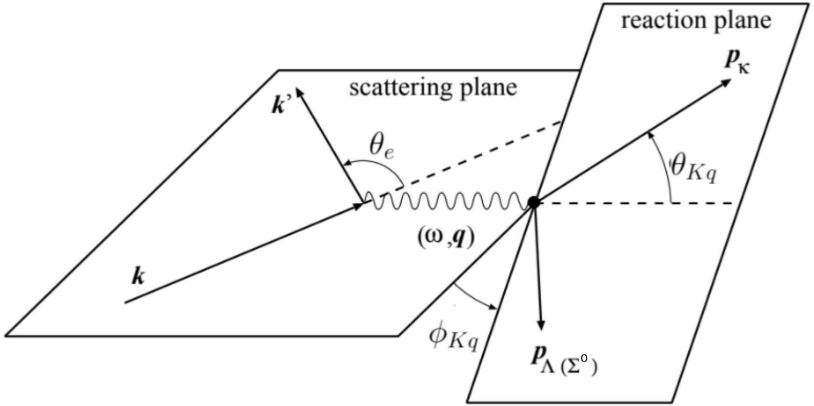
Fit using measured ε and ϕ dependence

Review E12-09-011 (KaonLT) Goals



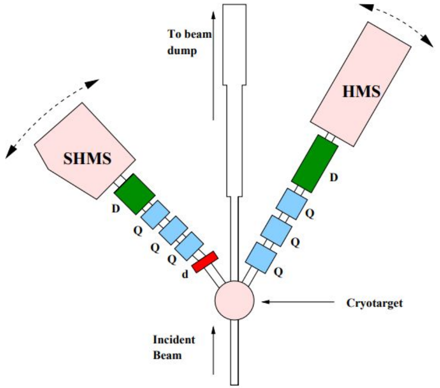
- Q^2 dependence will allow studying the scaling behavior of the separated cross sections
  - First cross section data for Q^2 scaling tests with kaons
  - Highest Q^2 for L/T separated kaon electroproduction cross section
  - First separated kaon cross section measurement above W=2.2 GeV

- t-dependence allows for detailed studies of the reaction mechanism
  - Contributes to understanding of the non-pole contributions, which should reduce the model dependence
  - Bonus: if warranted by data, extract the kaon form factor



Kaon LT - Data Collected

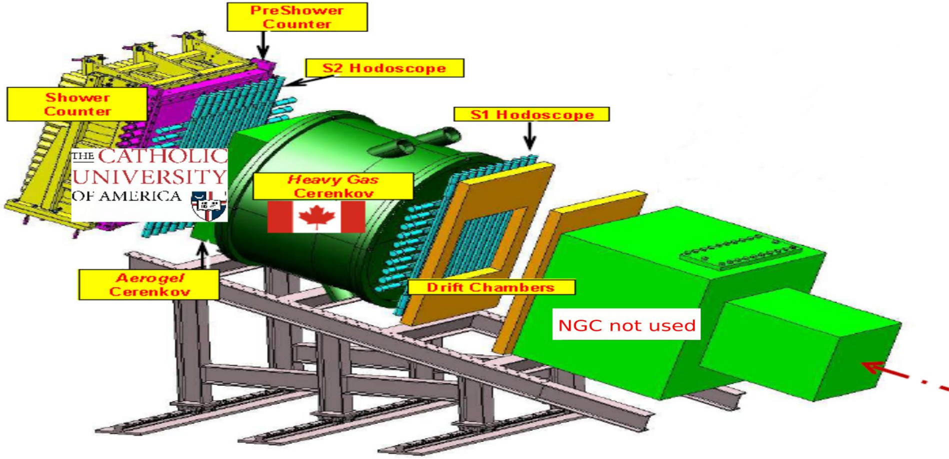
- The $p(e, e'K^+)\Lambda,\Sigma^0$ experiment ran in Hall C at Jefferson Lab over the fall and spring.



E (GeV)	Q^2 (GeV^2)	W (GeV)	x	$\varepsilon_{high}/\varepsilon_{low}$
10.6/8.2	5.5	3.02	0.40	0.53/0.18
10.6/8.2	4.4	2.74	0.40	0.72/0.48
10.6/8.2	3.0	3.14	0.25	0.67/0.39
10.6/6.2	3.0	2.32	0.40	0.88/0.57
10.6/6.2	2.115	2.95	0.21	0.79/0.25
4.9/3.8	0.5	2.40	0.09	0.70/0.45

Experimental Details

- Hall C: k_e=3.8, 4.9, 6.4, 8.5, 10.6 GeV
- SHMS for kaon detection :
  - angles, 6 – 30 deg
  - momenta, 2.7 – 6.8 GeV/c
- HMS for electron detection :
  - angles,10.7 – 31.7 deg
  - momenta, 0.86 – 5.1 GeV/c
- Particle identification:
  - Dedicated Aerogel Cherenkov detector for kaon/proton separation
    - Four refractive indices to cover the dynamic range required by experiments
  - Heavy gas Cherenkov detector for kaon/pion separation



n	π_{thr} (GeV/c)	K_{thr} (GeV/c)	P_{thr} (GeV/c)
1.030	0.57	2.00	3.80
1.020	0.67	2.46	4.67
1.015	0.81	2.84	5.40
1.011	0.94	3.32	6.31

Analysis Phases

1. Calibrations ✔
    - Calorimeter, aerogel, HG cer, HMS cer, DC, Quartz plan of hodo
    - Assure we are replaying to optimize our physics settings
2. Efficiencies and offsets ← Current Phase
    - Luminosity, elastics, heeps, etc.
3. First iteration of cross section
    - Bring everything together
4. Fine tune
    - Fine tune values to minimize systematics
5. Repeat previous step
    - Repeat until acceptable cross sections are reached
6. Possible attempt at form factor extraction
    - Fit the data to a model and iterate

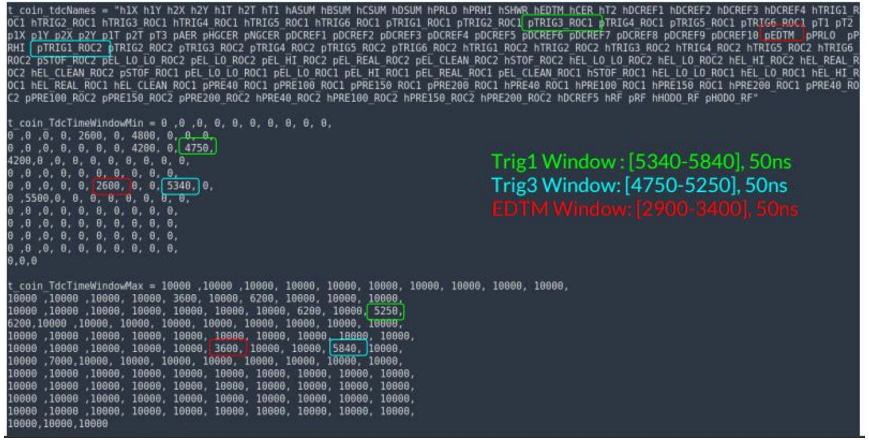
Phase 1: Timing Windows

- The TDC coincidence spectra are the outputs from the L1ACC pre-triggers. The cuts are applied to the raw TDC spectra first.

- The process of applying cuts to the coincidence time spectra should be done only once reference time cuts are properly chosen.

- Removal all cuts to the raw spectra to see the entire raw spectrum including background

- The final step is to subtract the background surrounding the peaks in order to clean the spectrum up a bit.
  - Applying cuts to the raw spectrum to subtract these backgrounds will clean up these peaks after another replay is run.



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OC1 hTRIG2_ROC1 hTRIG3_ROC1 hTRIG4_ROC1 hTRIG5_ROC1 hTRIG6_ROC1 pTRIG1_ROC1 pTRIG2_ROC1 pTRIG3_ROC1 pTRIG4_ROC1 pTRIG5_ROC1 pTRIG6_ROC1 pT1 pT2
p1X p1Y p2X p2Y p1T p2T pT3 pAER pHGCER pNGCER pDCREF1 pDCREF2 pDCREF3 pDCREF4 pDCREF5 pDCREF6 pDCREF7 pDCREF8 pDCREF9 pDCREF10 pEDTM  pPRLO  pP
RHI  pTRIG1_ROC2 pTRIG2_ROC2 pTRIG3_ROC2 pTRIG4_ROC2 pTRIG5_ROC2 pTRIG6_ROC2 hTRIG1_ROC2 hTRIG2_ROC2 hTRIG3_ROC2 hTRIG4_ROC2 hTRIG5_ROC2 hTRIG6
ROC2 pSTOF_ROC2 pEL_LO_LO_ROC2 pEL_LO_ROC2 pEL_HI_ROC2 pEL_REAL_ROC2 pEL_CLEAN_ROC2 hSTOF_ROC2 hEL_LO_LO_ROC2 hEL_LO_ROC2 hEL_HI_ROC2 hEL_REAL_R
OC2 hEL_CLEAN_ROC2 pSTOF_ROC1 pEL_LO_LO_ROC1 pEL_LO_ROC1 pEL_HI_ROC1 pEL_REAL_ROC1 pEL_CLEAN_ROC1 hSTOF_ROC1 hEL_LO_LO_ROC1 hEL_LO_ROC1 hEL_HI_R
OC1 hEL_REAL_ROC1 hEL_CLEAN_ROC1 pPRE40_ROC1 pPRE100_ROC1 pPRE150_ROC1 pPRE200_ROC1 hPRE40_ROC1 hPRE100_ROC1 hPRE150_ROC1 hPRE200_ROC1 pPRE40_RO
C2 pPRE100_ROC2 pPRE150_ROC2 pPRE200_ROC2 hPRE40_ROC2 hPRE100_ROC2 hPRE150_ROC2 hPRE200_ROC2 hDCREF5 hRF pRF hHODO_RF pHODO_RF"

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0 ,5500,0, 0, 0, 0, 0, 0, 0, 0,
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0 ,0 ,0, 0, 0, 0, 0, 0, 0, 0,
0 ,0 ,0, 0, 0, 0, 0, 0, 0, 0,
0 ,0 ,0, 0, 0, 0, 0, 0, 0, 0,
0,0,0

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10000 ,10000 ,10000, 10000, 10000, 10000, 10000, 10000, 10000, 10000,
10000 ,10000 ,10000, 10000, 10000, 10000, 10000, 10000, 10000, 10000,
10000 ,10000 ,10000, 10000, 10000, 10000, 10000, 10000, 10000, 10000,
10000 ,10000 ,10000, 10000, 10000, 10000, 10000, 10000, 10000, 10000,
10000,10000,10000
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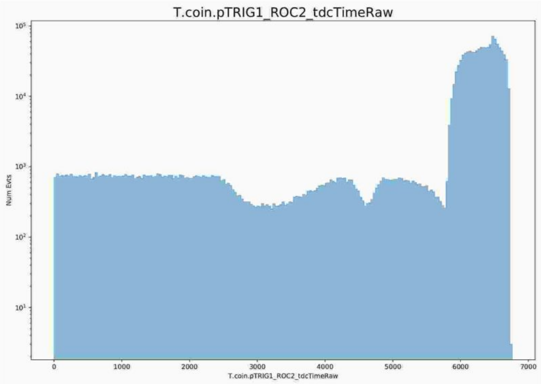
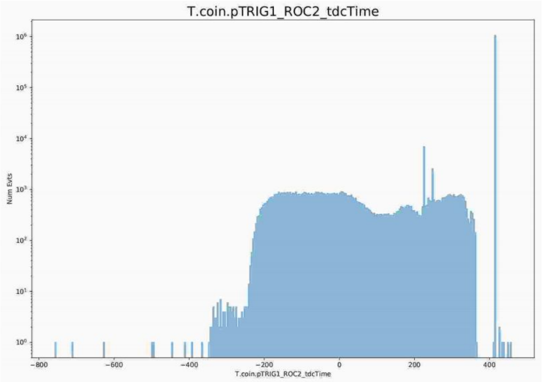
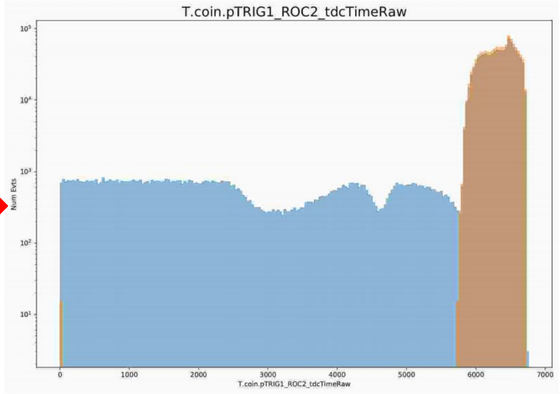
Phase 1: Timing Windows Example

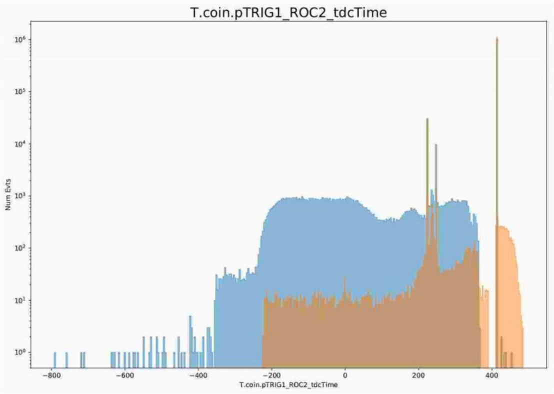
- SHMS ¾ spectra uncut
  - Left: Raw spectrum uncut
  - Right: Time spectrum uncut





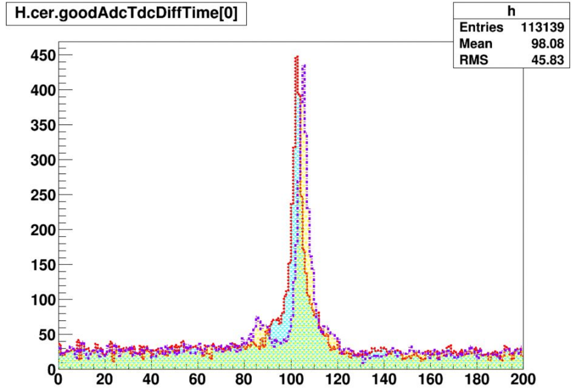
- SHMS ¾ spectra cut
  - Left: Raw spectrum cut (in orange)
  - Right: Time spectrum cut (in orange)

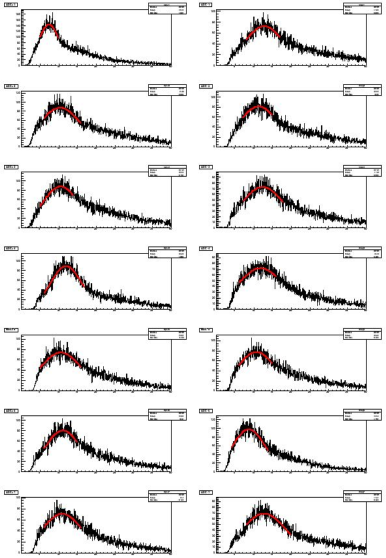


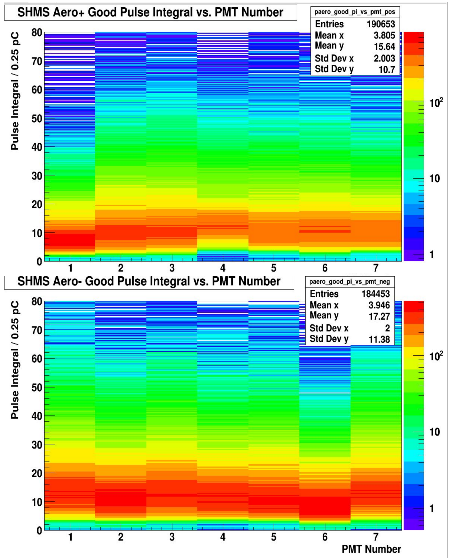


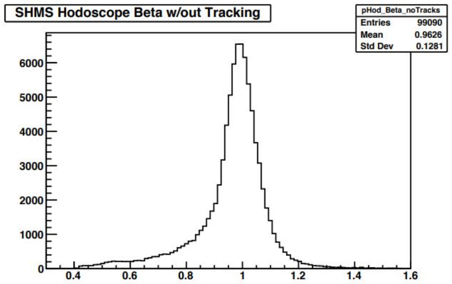
Phase 1: Detector Calibrations

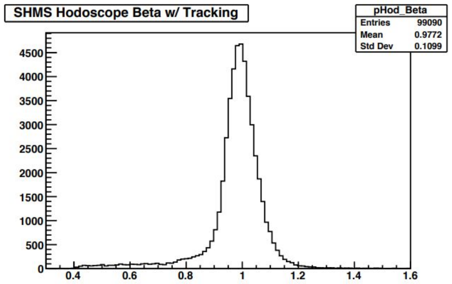
- The online calibrations of the HMS cherenkov, SHMS HGCer, aerogel, and the hodoscopes were determined to be satisfactory for our current analysis.
- Future calibrations will be completed on run by run basis





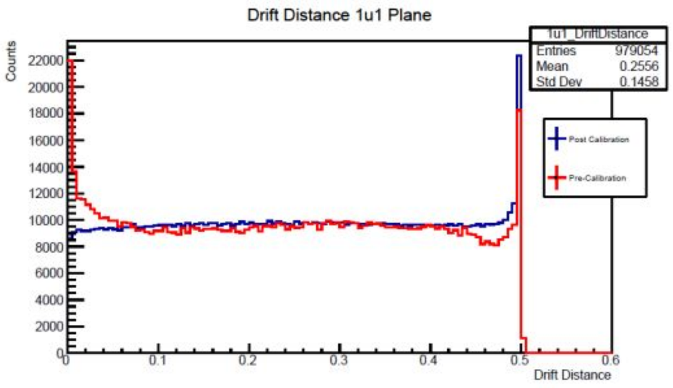


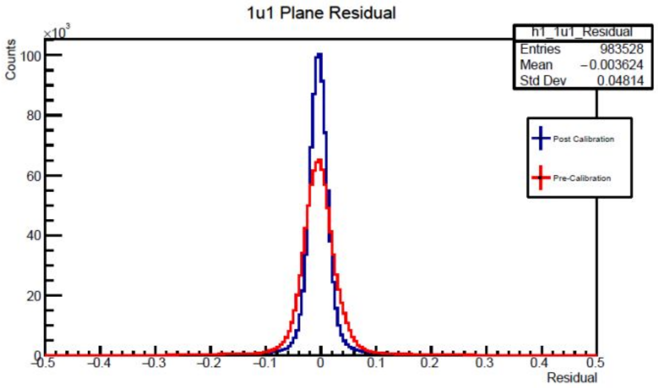




Phase 1: Drift Chamber Calibrations

- The file to be calibrated must be replayed with the parameter “h(p) using tzero per wire=0” set in the relevant h(p)dc cut.param file for the replay script.
  - The branches for the calorimeter and relevant cherenkovs for the spectrometer you are analysing should be included if you want to utilise PID in the calibration.
- Once the replay is complete, the calibration script must be executed on the replayed root file.
- Parameter files are created that can be utilised in future replays.
- A second replay that utilises the new parameters from the calibration should be carried out to verify performance.





Phase 1: Calorimeter Calibrations

- Before calibrating, a replay of the run to be calibrated must be carried out.
  - The calorimeter calibration script is designed to calibrate the detector using electrons, as such a run where the spectrometer was set to negative polarity must be used.
- The calibration script requires as an input file with several thresholds and ranges defined as well as the initial gain constants in utilised in the replay.
- Once the script runs, it should produce two files.
  - The parameter file is the new set of gain constants generated by the calibration script, these can be utilised in subsequent replays for performance verification

```
hcal_pos_gain_cor= 12.32,  5.47,  8.95,  9.24,  8.84, 11.86, 11.18, 11.03,  8.61, 13.80, 12.67, 11.32,  8.71,
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```
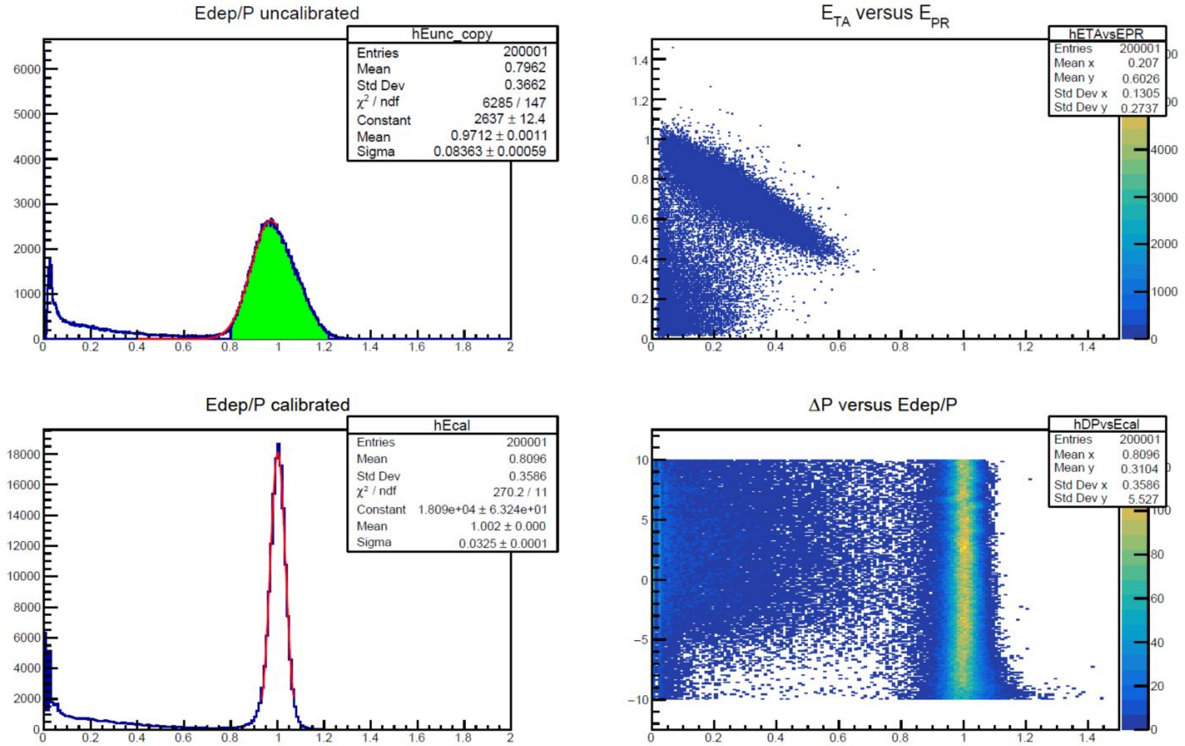

Phase 1: Calorimeter Calibrations

- Many iterations were performed for all adequate runs
- There were tiny wiggles that can be seen in most runs
    - Vardan is aware (and many other groups) this is an ongoing issue



Importance of Luminosity Runs

E (GeV)	Q^2 (GeV^2)	W (GeV)	x	Current (uA)	ε_{high}	ε_{low}
10.6	5.5	3.02	0.40	5,15,30,45,50,55,70	0.53	
8.2	5.5	3.02	0.40	10,25,40,45,60		0.18
8.2	4.4	2.74	0.40	5,15,30,45,50,65		0.48
10.6	3.0	3.14	0.25	50,70	0.67	
6.2	3.0	2.32	0.40	50,60,65,70		0.57

Careful evaluations of the systematic uncertainties is important due to the $1/\varepsilon$ amplification in the σ_L extraction

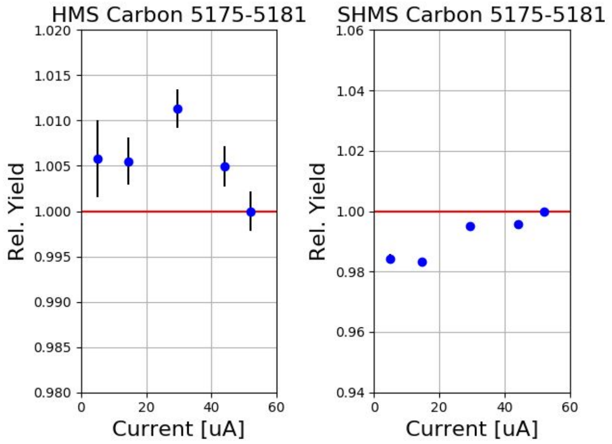
→ Spectrometer acceptance, kinematics , and efficiencies are the **primary contributors**

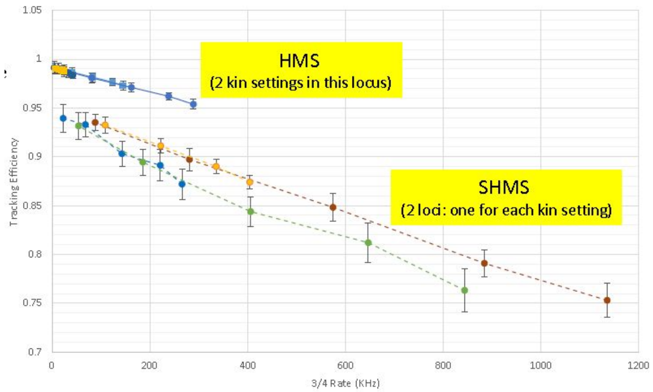
Previous luminosity/tracking analysis

- Understanding efficiencies from luminosity scans has been ongoing with only one run period having been looked at

- Relative yield has been reduced to ~2% spread for carbon target

- Tracking efficiencies are a big contributor
    - At a given ¾ rate, HMS tracking efficiency is ~4% higher than that of the SHMS
    - HMS tracking efficiency is mostly independent of kinematic setting – not the case for the SHMS
    - SHMS tracking efficiency extrapolates to ~95% at 0 KHz – hadron tracking efficiency low by 4-6%

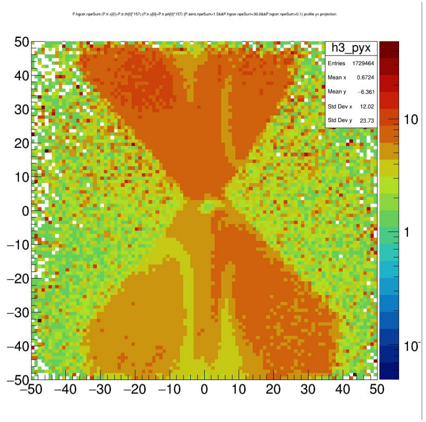


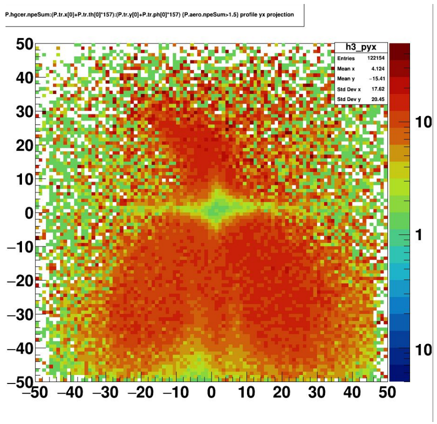


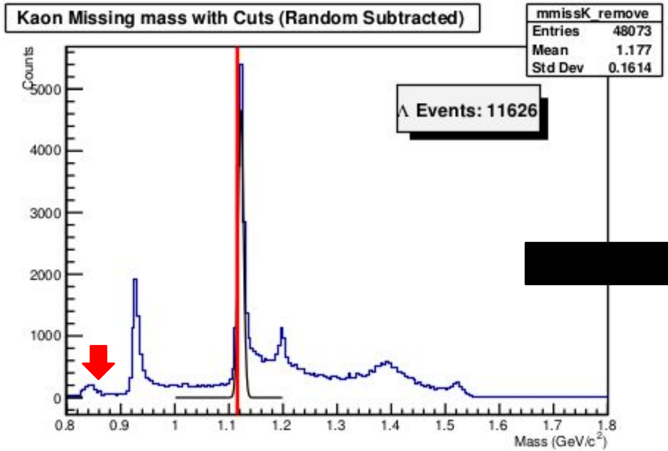
Analysis by D. Mack and R. Trotta

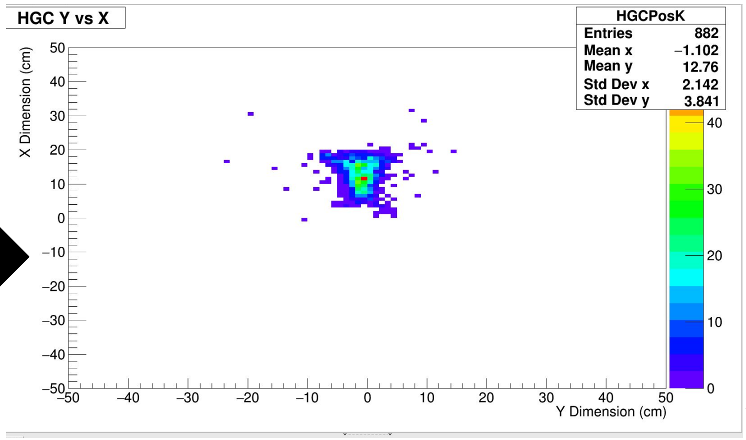
Phase 2: HGCer Challenges

- A hole in the HGCer will allow unwanted pions and accidentals
- An in depth analysis will be required for proper efficiency determination
- This hole is already causing visible issues









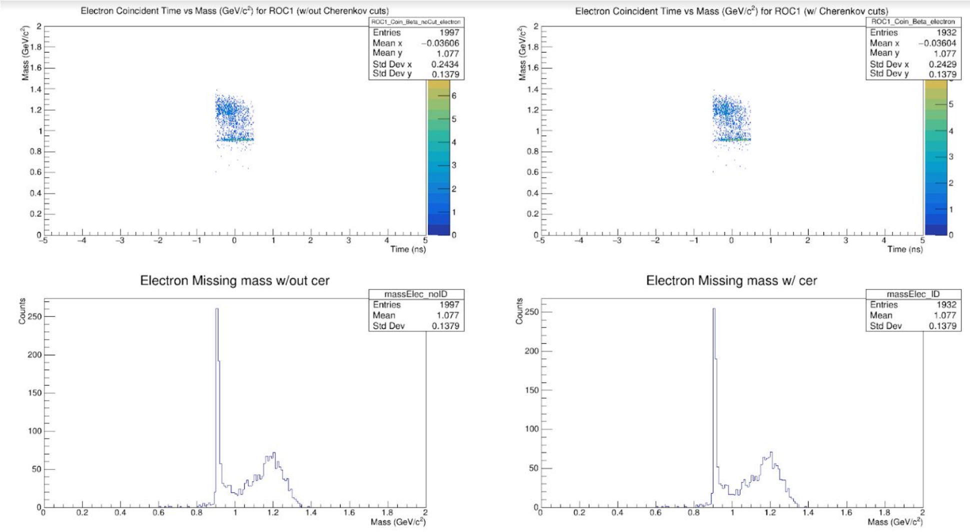
Conclusion

- E12-09-011 ran Fall 2018, Spring 2019
    - Also includes PionLT data from Summer 2019
- Currently in the second phase of analysis
- The calibrations are complete for all detectors
- Studies on tracking, efficiencies for luminosity for the immediate future
    - Nailing down our efficiencies is critical in diminishing our uncertainties for eventual cross section extraction
    - The hole in the HGCer will be a unique challenge for us to overcome which we look forward to figuring out.
- Acceptances and offsets will be the focus once this is complete

Extra Slides

Phase 2: PID Efficiencies

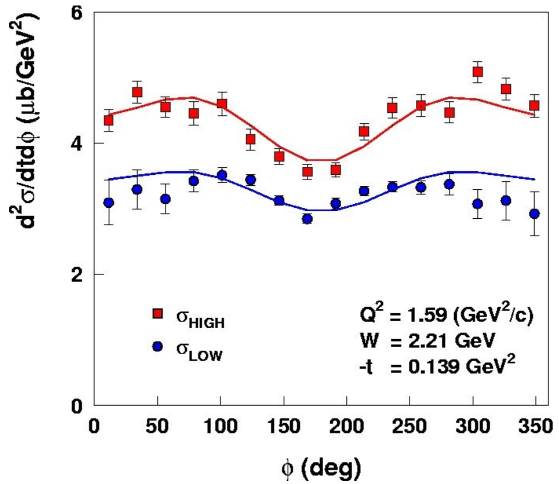
-



L/T Separation Example

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

σ_L will give us F^2_{K+}



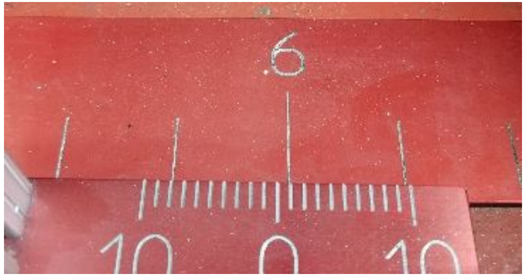
*T. Horn et al., PhysRevC **97**(2006)192001*

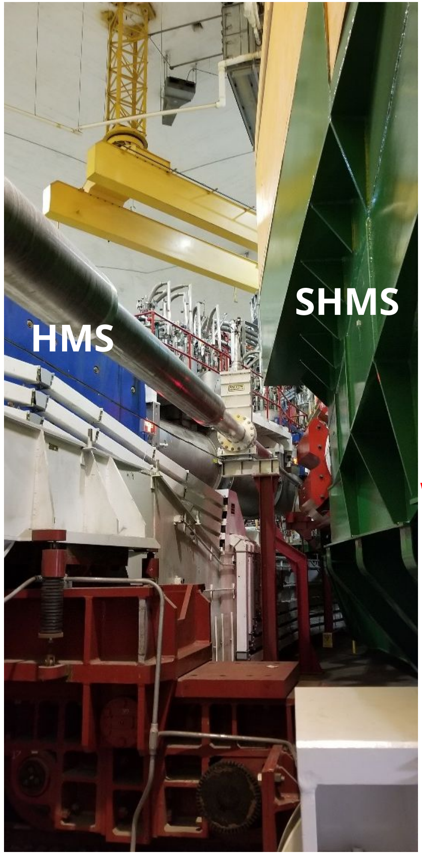
- σ_L is isolated using the Rosenbluth separation technique
- Measure the cross section at two beam energies and fixed W, Q^2, -t
- Simultaneous fit using measured azimuthal angle (ϕ) allows for extracting L, T, LT, and TT
  - Careful evaluation of the systematic uncertainties is important due to the 1/ε amplification in the σ_L extraction
- Must have magnetic spectrometers for such precision cross section measurements
  - This is only possible in Hall C at JLab

SHMS small angle operation

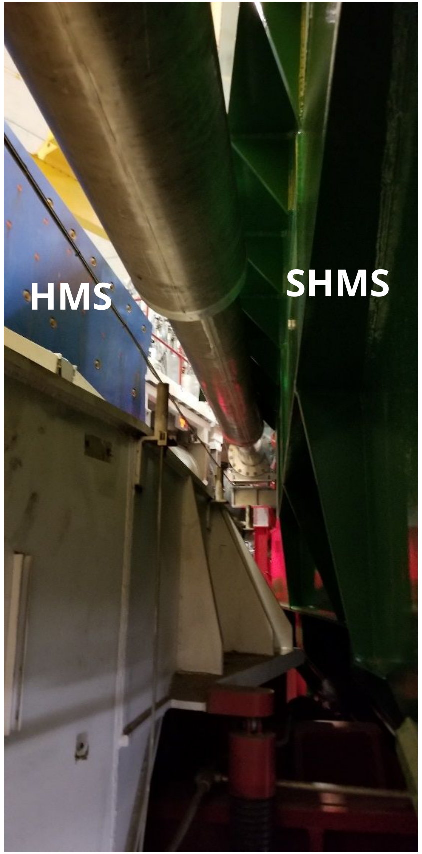
- Some issues with opening and small angle settings at beginning of run
  - SHMS at 6.01°
  - HMS at 12.7°

[12/17/18]



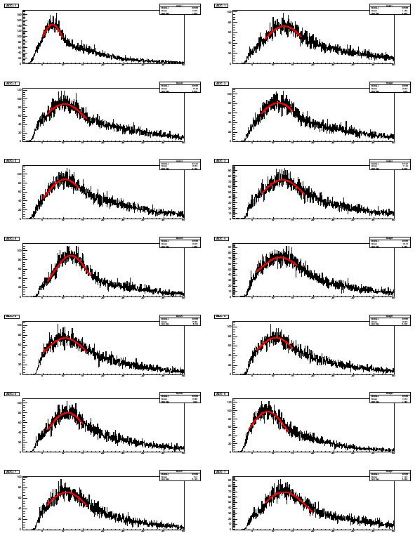


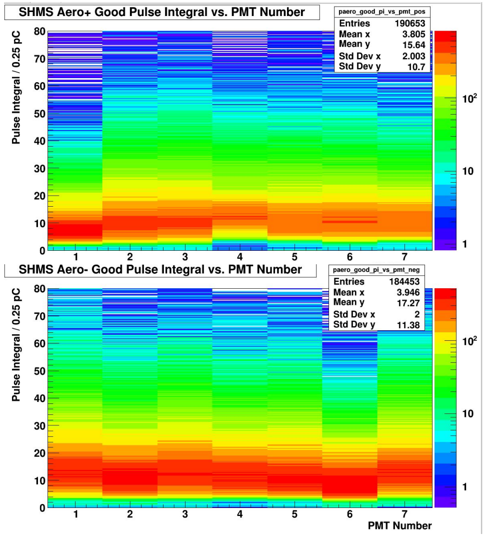
Work of many people ...

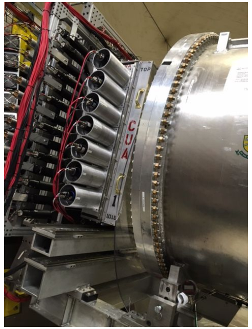


Aerogel Cherenkov detector in SHMS

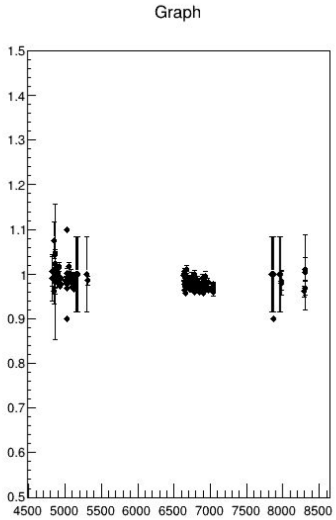
NSF MRI PHY-1039446

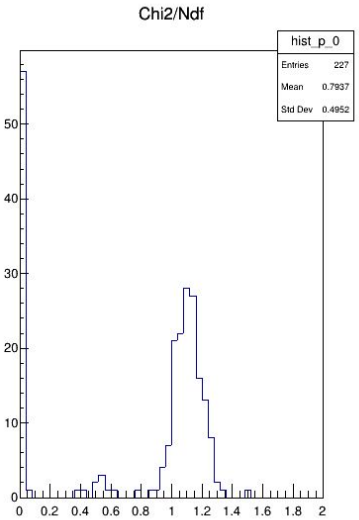






- ~15 successful tray exchanges since Fall 2018
- Aerogel performance as expected
- Trays require some optimization before next use - prevent damage from crane operation





Analysis by V. Berdnikov

KaonLT Event Selection

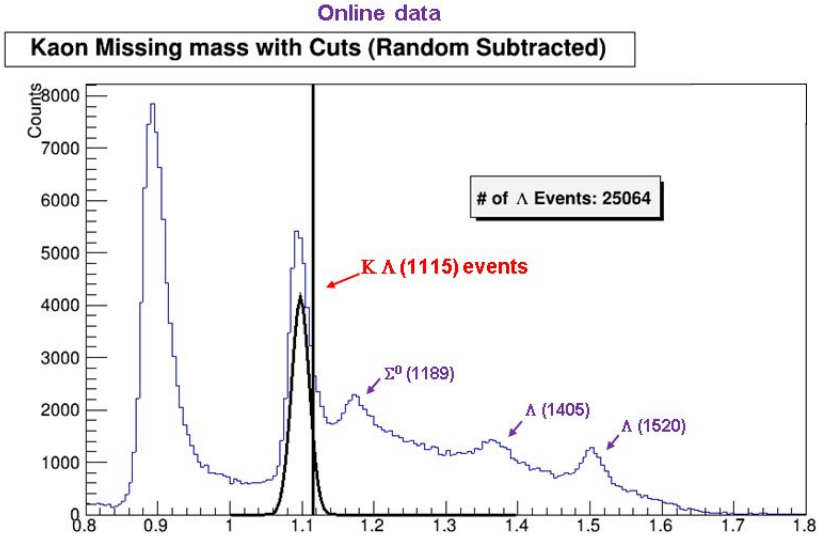
- Isolate Exclusive Final States through missing mass

$$M_x = \sqrt{(E_{det} - E_{init})^2 - (p_{det} - p_{init})^2}$$

- Coincidence measurement between kaons in SHMS and electrons in HMS
  - simultaneous studies of $K\Lambda$ and $K\Sigma^0$ channels…and a few others…
- Kaon pole dominance tests through

$$\frac{\sigma_L(\gamma^* p \rightarrow K^+\Sigma^0)}{\sigma_L(\gamma^* p \rightarrow K^+\Lambda)}$$

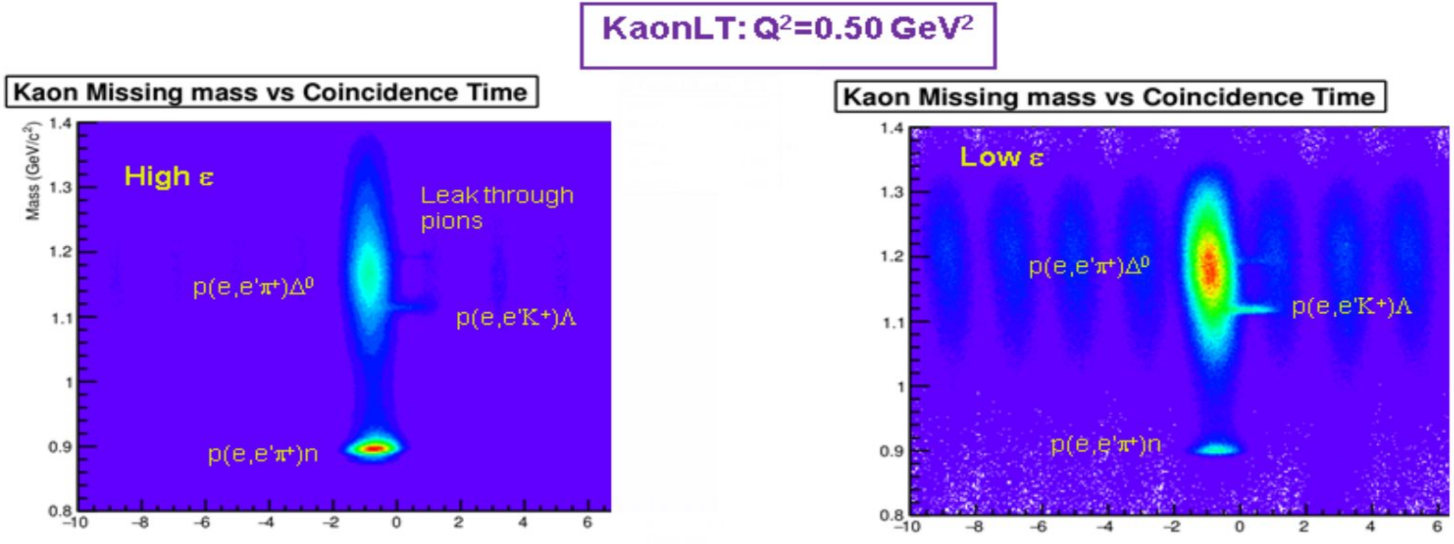
  - Should be similar to ratio of coupling constants $g^2_{pK\Sigma}/g^2_{pK\Lambda}$ in t-channel



Plot by R. Ambrose, S. Kay, R. Trotta

Interesting Physics in the other channels

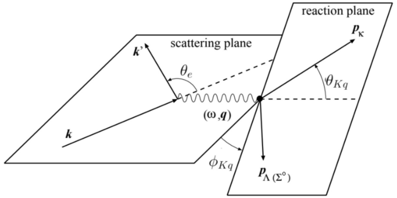
- Large difference in L/T ratio between p(e.e'π$^+$)n and p(e,e'π$^+$)Δ^0 final states – G. Huber hclog #3640187



Plots by R. Ambrose, S. Kay, R. Trotta

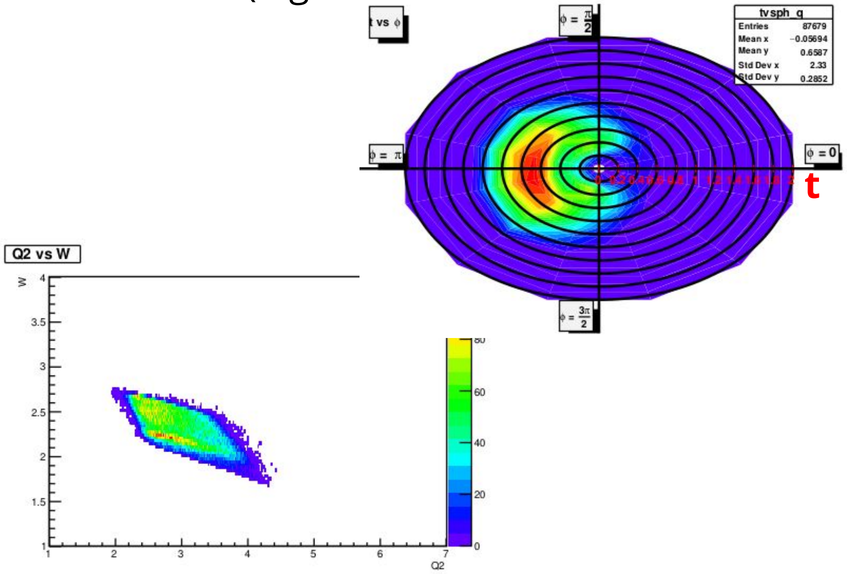
- Large increase in neutron missing mass peak at high epsilon is evidence of the pion-pole process at low Q^2 and small –t, which suggests $\sigma_L >> \sigma_T$
- Δ^0 exclusive longitudinal cross section expected to be at best $\sigma_L \sim \sigma_T$

Comparison of high and low ε [Q^2=3.0, W=2.32, x=0.40]

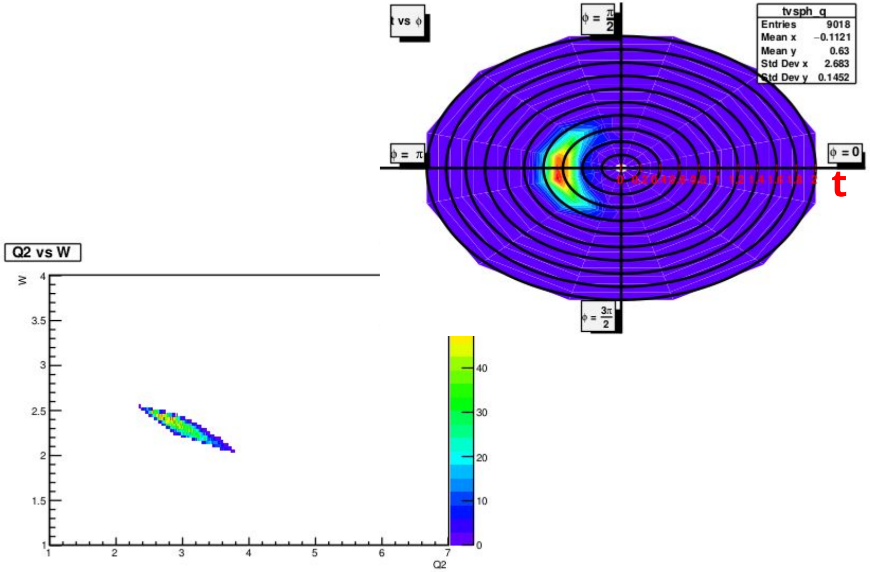


- [10.6 Gev (high ε), 6.2 Gev (low ε)]
- Left (θ_{high}=21.18,θ_{low}=16.28)

10.6 GeV (high ε)



6.2 GeV (low ε)



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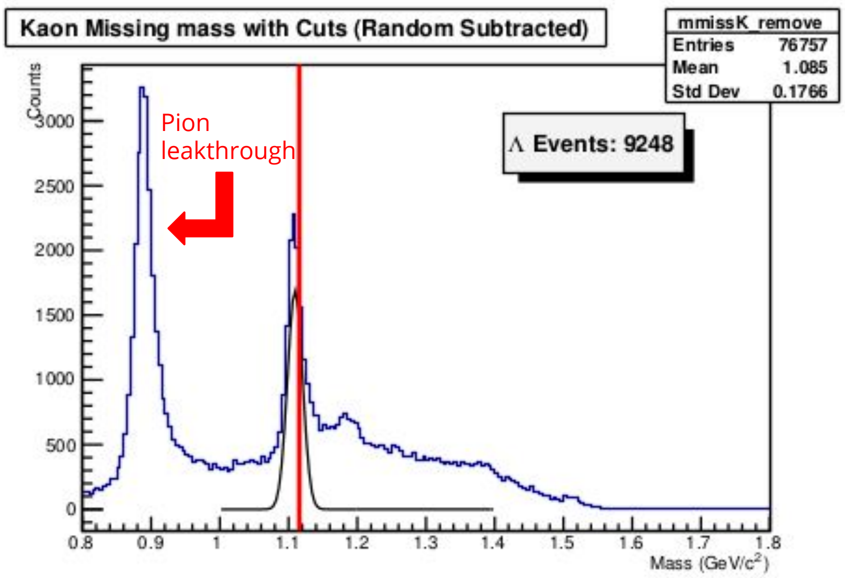
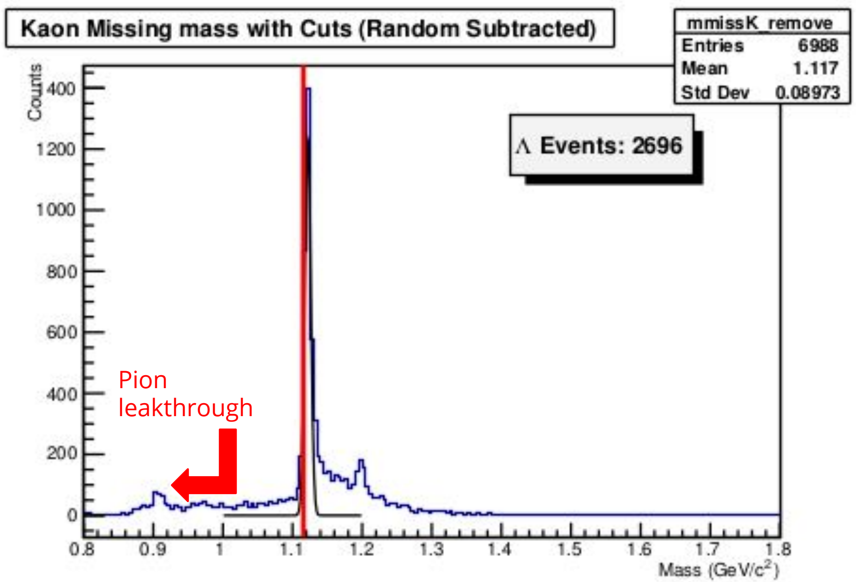


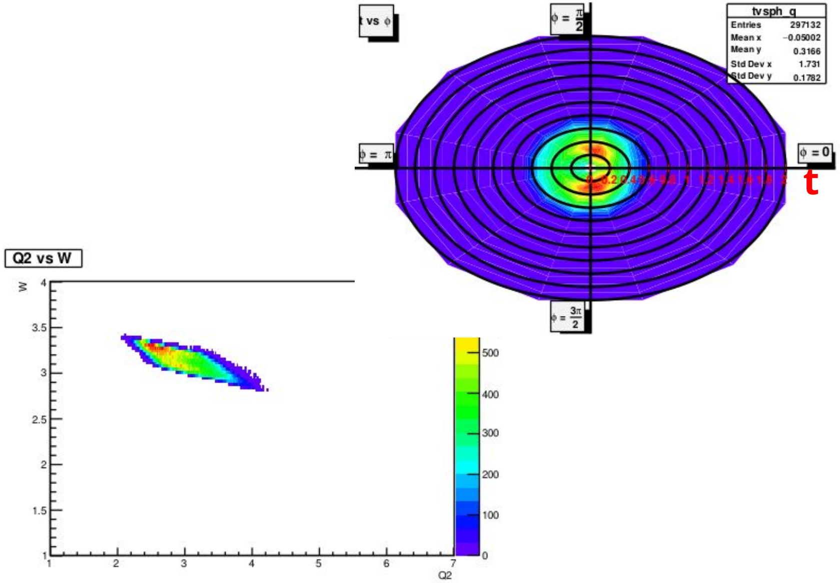
6.2 GeV (low ε)



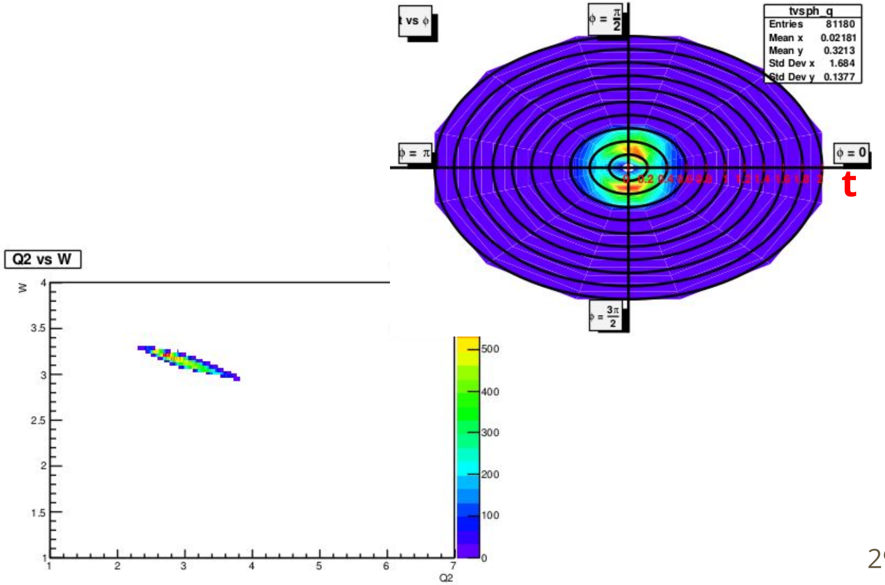
Comparison of high and low ε [Q^2=3.0, W=3.14, x=0.25]

- [10.6 Gev (high ε), 8.2 Gev (low ε)]
- Center (θ_{high}=9.42,θ_{low}=6.89)

10.6 GeV (high ε)



8.2 GeV (low ε)



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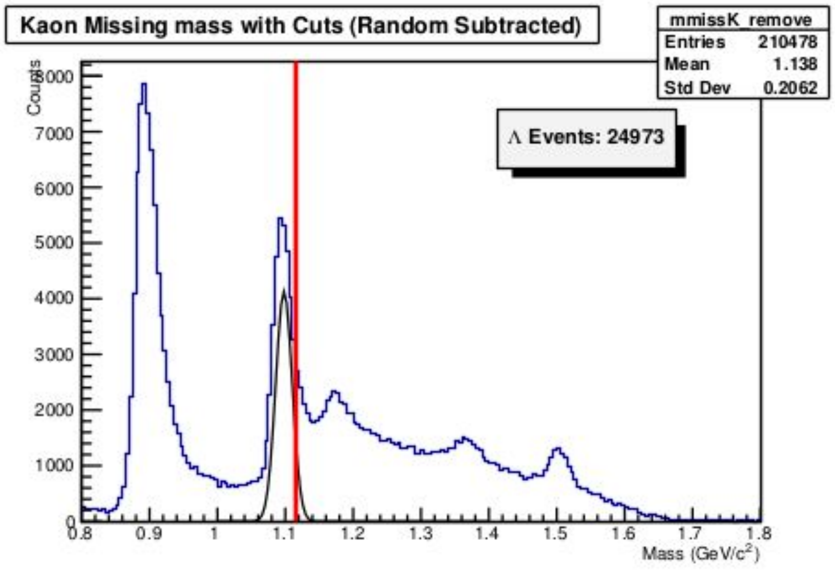
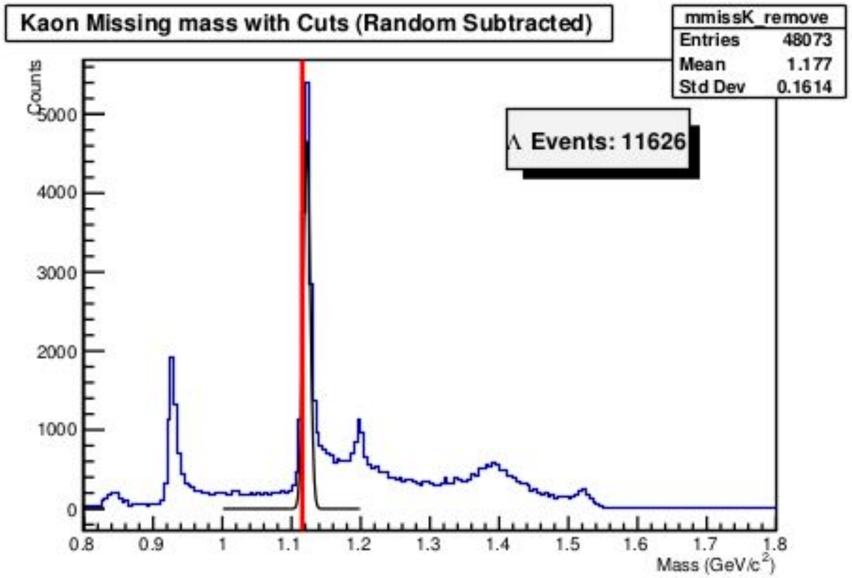
- [10.6 Gev (high ε), 8.2 Gev (low ε)]
- Center (θ_{high}=9.42,θ_{low}=6.89)

10.6 GeV (high ε)



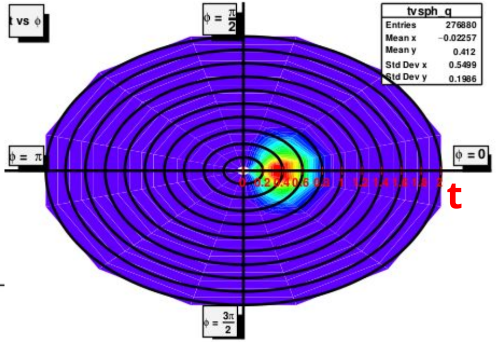
8.2 GeV (low ε)

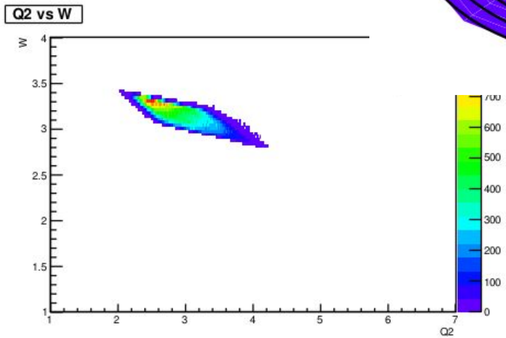


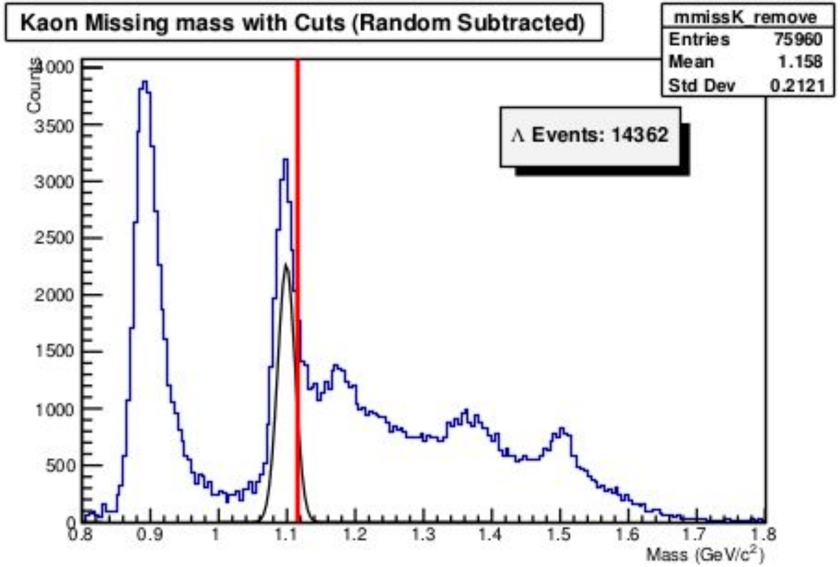
Comparison of high and low ε [Q^2=3.0, W=3.14, x=0.25]

- [10.6 Gev (high ε)]
- Right (θ_{high}=6.65)

10.6 GeV (high ε)



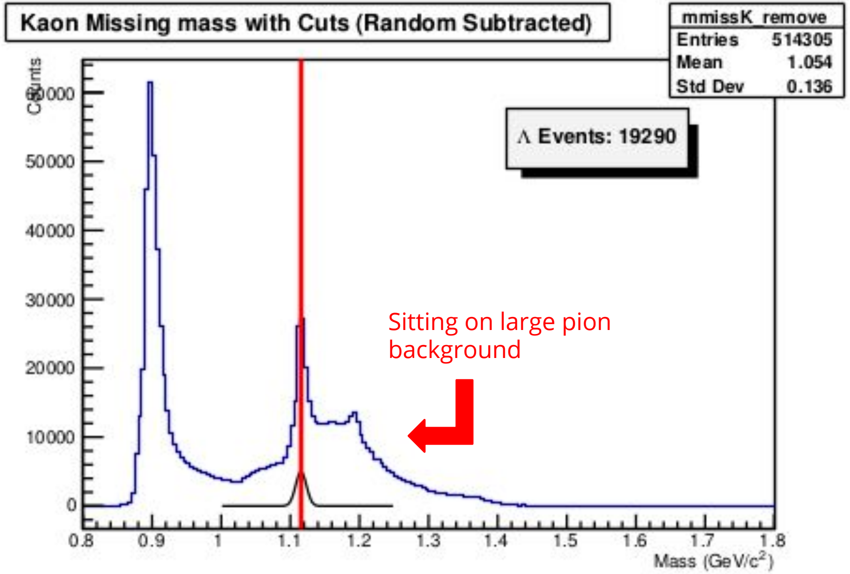




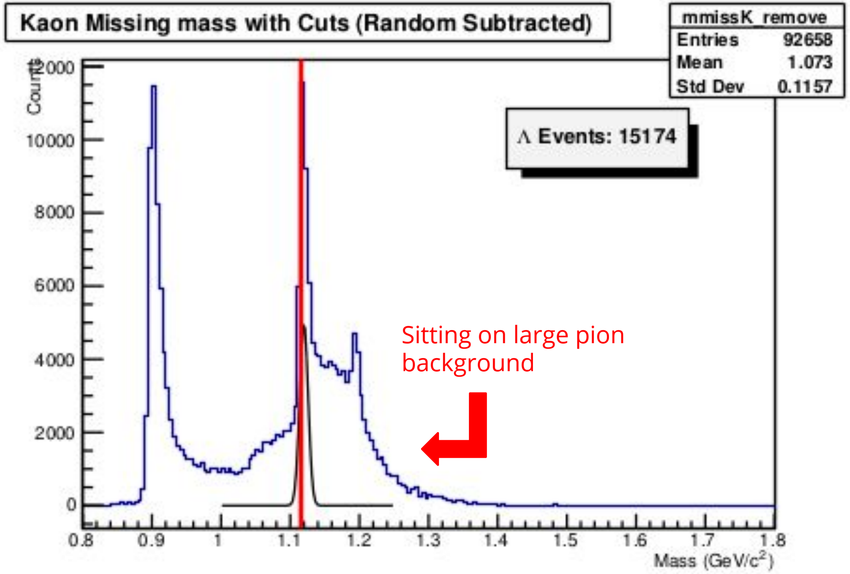
Comparison of high and low ε [Q^2=0.5, W=2.40, x=0.09]

- [4.9 Gev (high ε), 3.8 Gev (low ε)]
- Center (θ_{high}=8.86,θ_{low}=6.79)

4.9 GeV (high ε)



3.8 GeV (low ε)

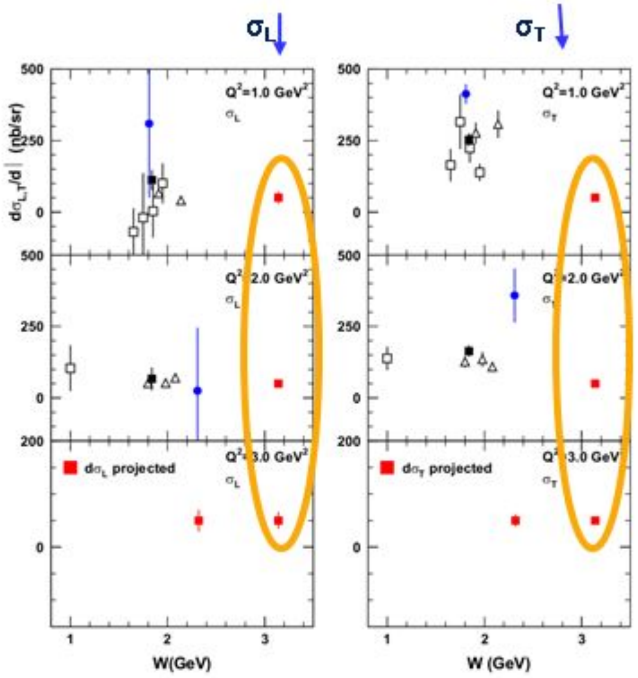


KaonLT Sample Projections

- E12-09-011: Separated L/T/LT/TT cross section over a wide range of Q^2 and t

E12-09-011 spokespersons: T. Horn, G. Huber, P. Markowitz

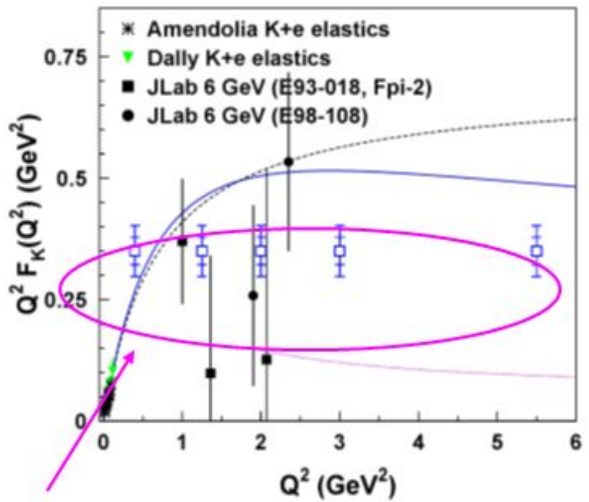
- JLab 12 GeV Kaon Program features:
  - First cross section data for Q^2 scaling tests with kaons
  - Highest Q^2 for L/T separated kaon electroproduction cross section
  - First separated kaon cross section measurement above W=2.2 GeV



blue points from M. Carmignotto, PhD thesis (2017)

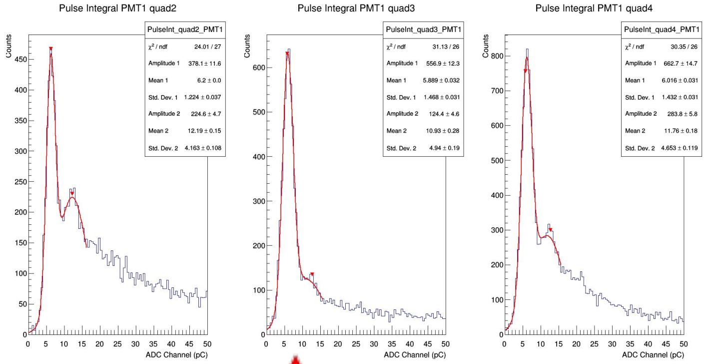
KaonLT: Projections for $F_{K+}(Q^2)$ Measurements

- E12-09-011: primary goal L/T separated kaon cross sections to investigate hard-soft factorization and non-pole contributions
- Possible K^+ form factor extraction to highest possible Q^2 achievable at JLab
  - Extraction like in the pion case by studying the model dependence at small t
  - Comparative extractions of F^2_π at small and larger t show only modest model dependence
    - larger t data lie at a similar distance from pole as kaon data

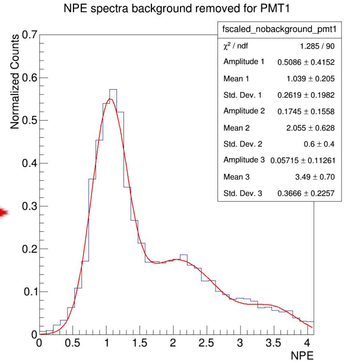


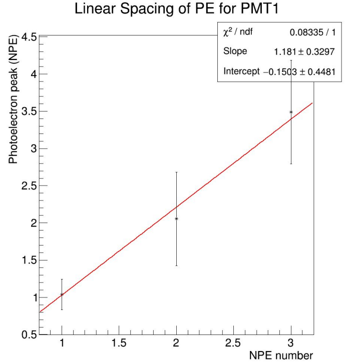
Possible extractions from 2018/19 run

P1: Calibration of HGC Detector (SHMS)

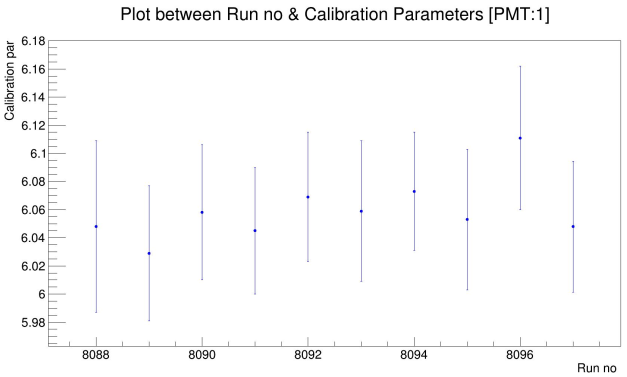


To see the second & third photo-electron, we fitted the scaled histogram with Poisson function and subtracted the higher photoelectron.





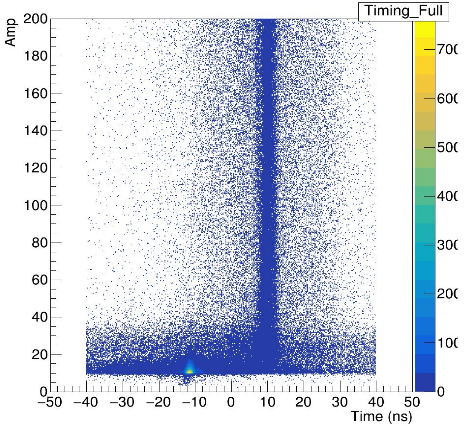
Showing the SPE in HGC for PMT1 FADC and fit it with a Gaussian function to get the mean of peaks.

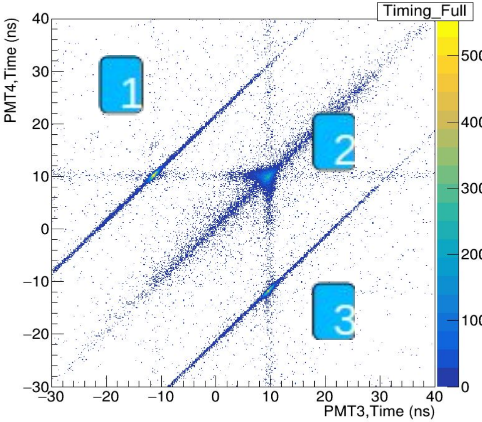


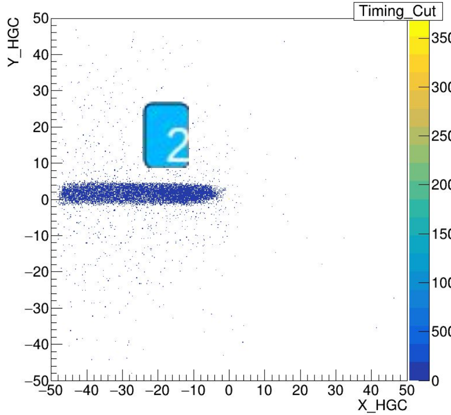
Run dependence of calibration parameters for the PMT1 to check the consistency of calibration.

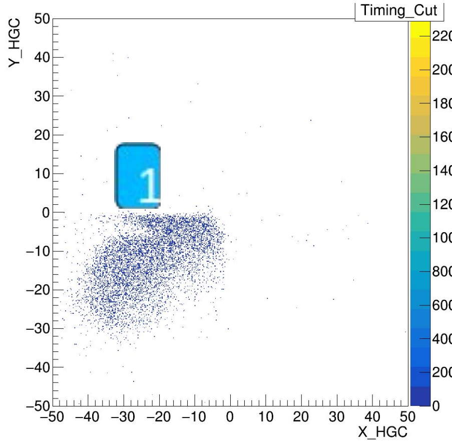
HGC Timing Study

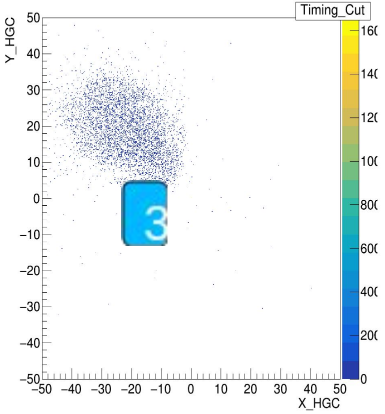
- In addition to main timing peak at +10ns, there is an unexpected second peak at -10ns.
- To better understand the origin of the unexpected peak, plot b/w Timing vs Amplitude.
    - 2nd peak corresponds to small pulses only.
- We also checked the tracking position in focal plane coordinates.
    - Interesting correlation between hit position and timing remains a mystery.











P1: SHMS Hodoscope Time Walk Calibration

In order to correct for time walk we:

- Plot ADC amplitude against TDC – ADC time
- Fit This Function: $f_{TW} = c_1 + \frac{1}{\left(\frac{a}{TDC_{Thrs.}}\right)^{c_2}}$
- Subtract second term
- Check parameter stability over run periods 6600 - 8000, stable within error
- Plots from PMT 2+ on 1x plane, similar for others