Preliminary look at KaonLT Cross Sections

January 18th, 2023

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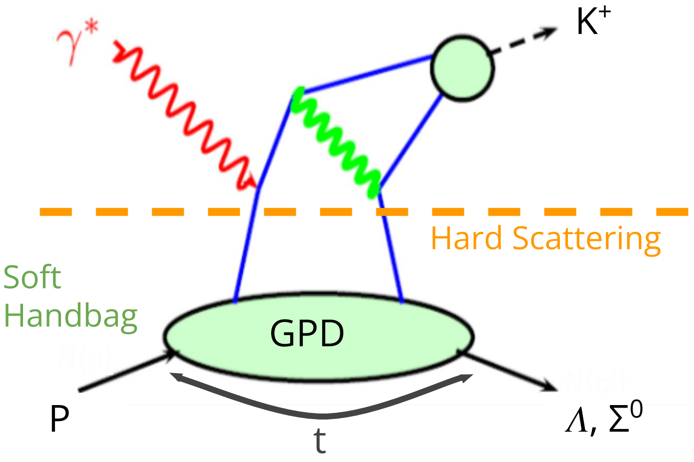
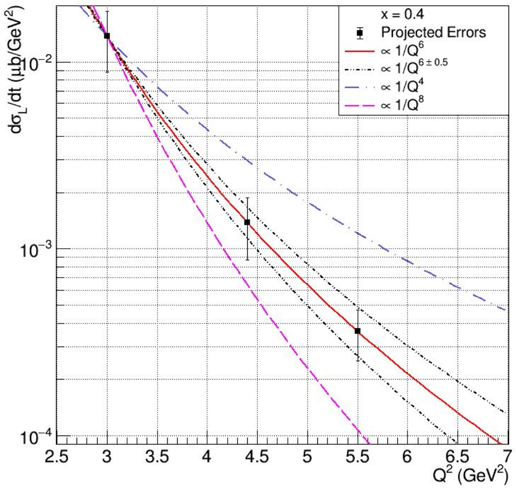
Jefferson Lab

THE CATHOLIC UNIVERSITY OF AMERICA

Hard-Soft Factorization

- Hard-soft factorization is prerequisite for three-dimensional hadron structure studies
- This can be tested experimentally by measuring the L-T separated cross sections ($p(e, e'K^+)\Lambda,\Sigma^0$)
- The K^+ electroproduction cross section has a Q^2 dependence at fixed x and -t
  - Provides important insight into hard-soft factorization for systems including strangeness
  - Factorization of σ_L scales to leading order Q^{-6}
  - In that regime expect σ_T to go as Q^{-8} and consequently $\sigma_L >> \sigma_T$
  - Important because partons are "frozen" transversely in the reference frame of pQCD (i.e. infinite momentum frame)

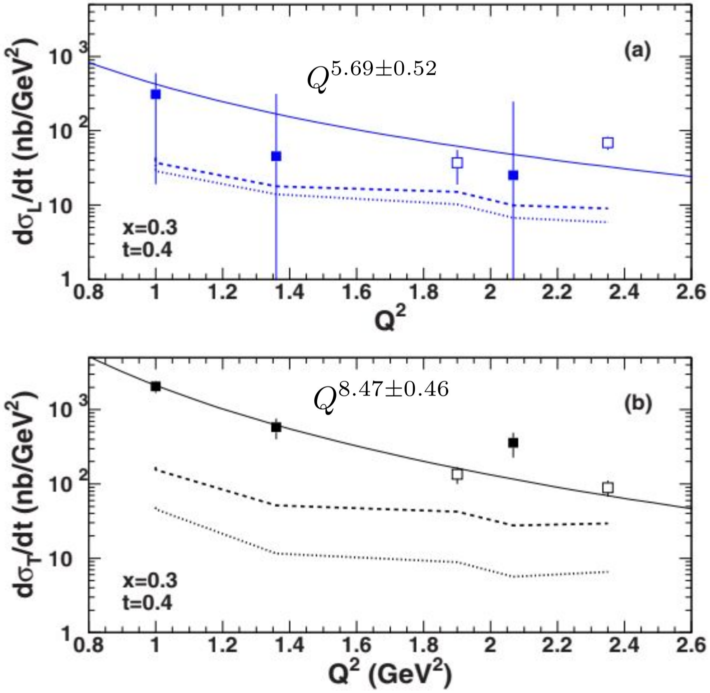




L-T Separated K^+ Data for Verifying Reaction Mechanism

- Jlab 6 GeV K^+ 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 hard-soft factorization and understanding dynamical effects in both Q^2 and –t kinematics
  - Interpreting non-perturbative QCD contributions in experimentally accessible kinematics
- Hall C at JLab 12 GeV provides the facilities for such measurements

Results from JLab 6 GeV data

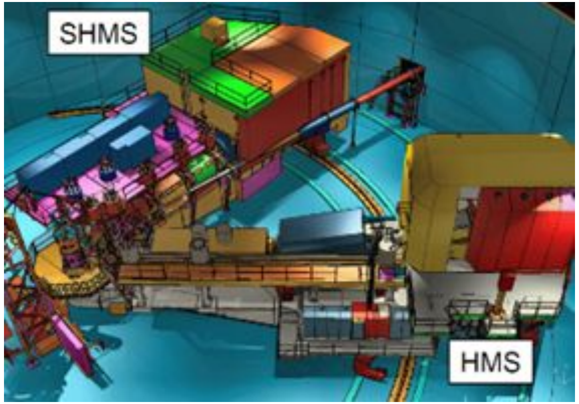


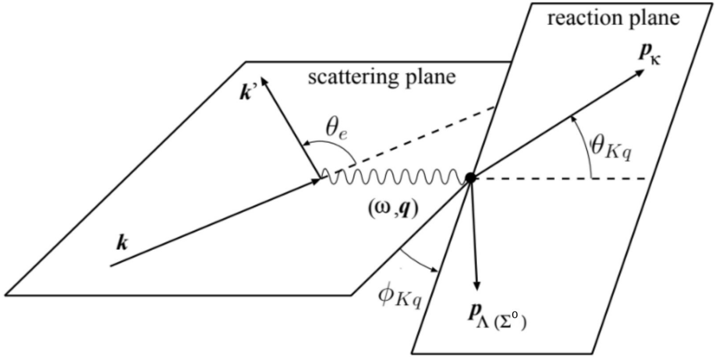
*M. Carmignotto et al., PhysRevC **97**(2018)025204*

Review E12-09-011 (KaonLT) Goals

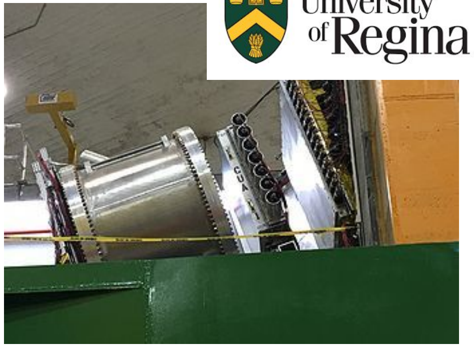
- Q^2 dependence will allow studying the scaling behavior of the separated cross sections
  - First cross section data for Q^2 scaling tests (x=0.25, 0.4) with kaons
  - Highest Q^2 (Q^2=5.5 GeV^2) for L-T separated kaon electroproduction cross section
  - First separated kaon cross section measurement above W=2.2 GeV
- $p(e,e'K^+)\Lambda,\Sigma^0$ t-dependence allows for detailed studies of the reaction mechanism
  - Contributes to understanding of the non-pole QCD contributions, which should reduce the model dependence
  - Bonus: if warranted by data, extract the kaon form factor from Λ data

Overview Hall C at 12 GeV





KaonLT Experimental Details



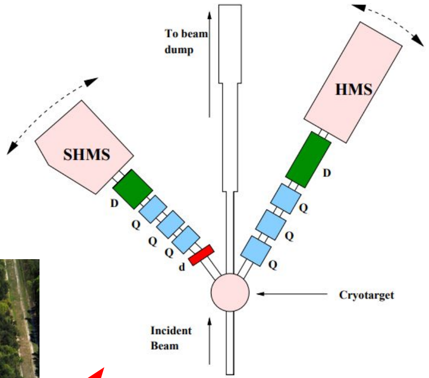
- Hall C: k_e=3.8, 4.9, 6.4, 8.5, 10.6 GeV
- SHMS for kaon detection :
  - angles, 6 – 30 deg
  - momenta, 2.7 – 6.8 GeV/c
- HMS for electron detection :
  - angles, 10.7 – 31.7 deg
  - momenta, 0.86 – 5.1 GeV/c
- Particle identification:
  - Dedicated Aerogel Cherenkov detector for kaon/proton separation
    - 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**

KaonLT - Data Collected

~70% of proposal data taken

- The $p(e, e'K^+)\Lambda,\Sigma^0$ experiment ran in Hall C at Jefferson Lab over the fall 2018 and spring 2019.

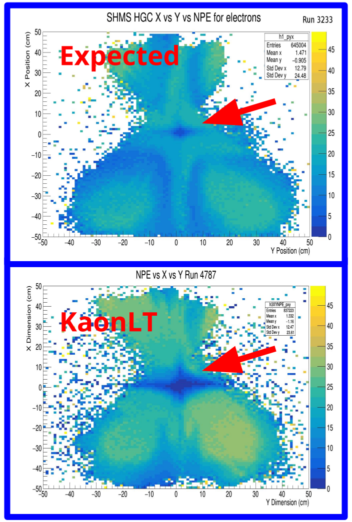


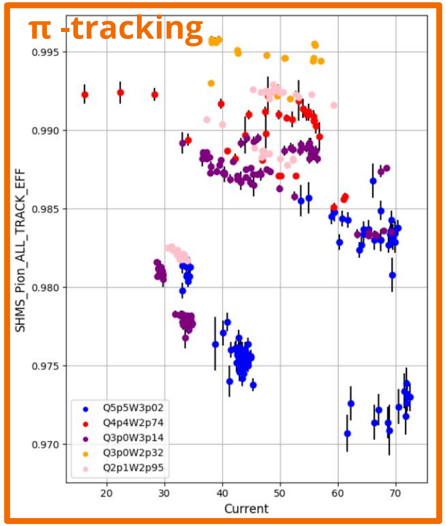
E (GeV)	Q^2 (GeV^2)	W (GeV)	x	$\varepsilon_{high}/\varepsilon_{low}$	$\Delta\varepsilon$	Study Type
10.6/8.2	5.5	3.02	0.40	0.53/0.18	0.35	scaling
10.6/8.2	4.4	2.74	0.40	0.72/0.48	0.24	scaling
10.6/6.2	3.0	2.32	0.40	0.88/0.57	0.31	both
10.6/8.2	3.0	3.14	0.25	0.67/0.39	0.28	scaling
10.6/6.2	2.115	2.95	0.21	0.79/0.25	0.54	both
4.9/3.8	0.5	2.40	0.09	0.70/0.45	0.25	FF

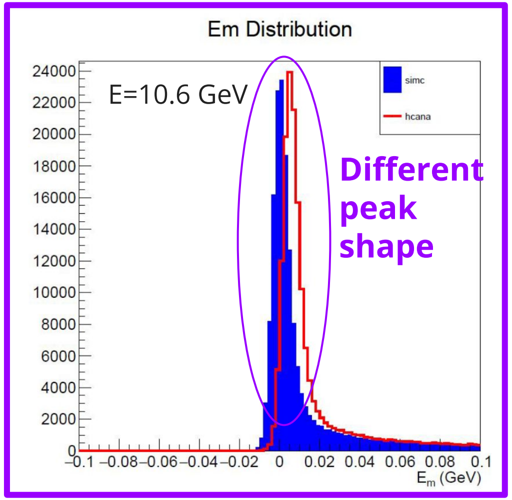
Notable Challenges

***First commissioning L-T separation for the HMS+SHMS setup**

- **SHMS Heavy Gas Cerenkov Hole**
  - Improperly aligned mirrors resulted in a larger hole at the center of the HGCer than expected
  - HGLOG (2/28/2019)
- **Tracking**
  - Tracking algorithm was initially insufficient for the high precision hadron tracking required
  - Commissioning meeting (1/4/2021, 5/18/2021)
- **Luminosity Analysis**
  - EDTM calculation is made complex when prescaling is involved
  - Hall C Quarterly Meeting I (10/20/2022)
- **HCANA vs SIMC calculations**
  - The kinematic variable calculations in HCANA and SIMC differ, which resulted in differing distribution for high level physics variables
  - Hall C Quarterly Meeting III (4/27/2023)
- KaonLT Weekly Meetings

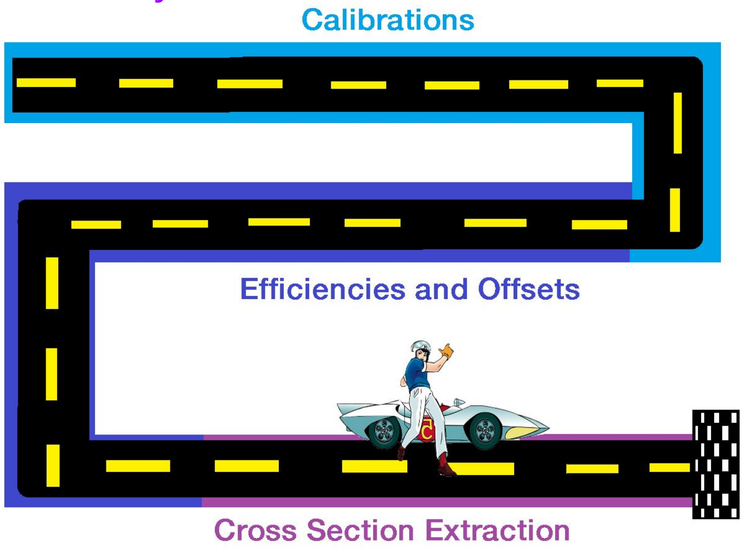




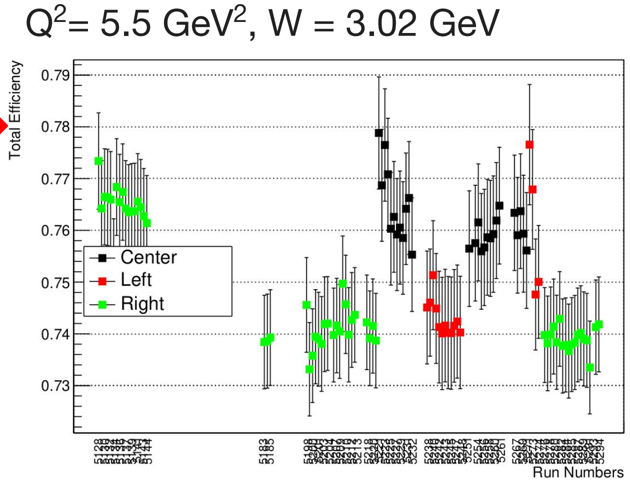


KaonLT Analysis Phases

- Optimize calibrations
  - Poorly done calibrations can lead to backtracking
- Thorough understanding of efficiencies and offsets
  - Critically important for understanding systematics

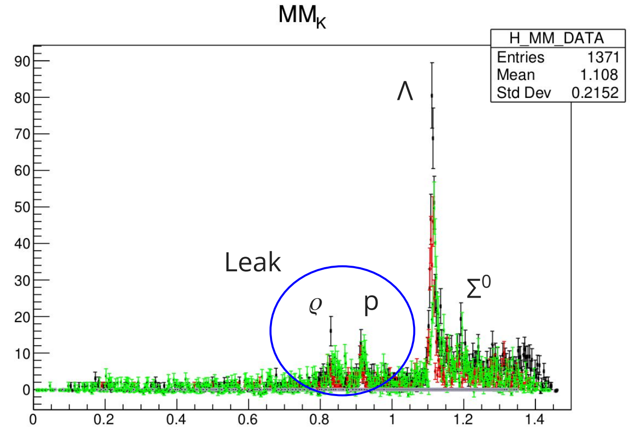


$$\epsilon_{Total} = \epsilon_{tracking} * \epsilon_{detectors} * \epsilon_{livetime} * \epsilon_{boiling}$$



π^- contamination found in HMS calorimeter and Cerenkov driving lower efficiency

Ali U. Studies
Jan 19, 2024
Feb 09, 2023
Feb 23, 2023



Uncertainy Considerations

- This is perhaps the most important step in the entire analysis.
- These studies are so critical because of a 1/Δε amplification and possibly small $R=\sigma_L/\sigma_T$ in the systematic uncertainty of the σ_L

$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{\epsilon_1 - \epsilon_2}\frac{\Delta\sigma}{\sigma}\sqrt{(1/R+\epsilon_1)^2 + (1/R+\epsilon_2)^2}$$

- Careful analysis will allow the required precision cross section measurements for extracting form factors.
- Two main tools: luminosity scans and elastic analysis

1/Δε

Source	pt-to-pt	t-correlated	scale
Acceptance	0.4	0.4	1.0
PID		0.4	0.5
Coincidence Blocking		0.2	
Tracking efficiency	0.1	0.1	1.5
Charge		0.2	0.5
Target thickness		0.2	0.8
Kinematics	0.4	1.0	
Kaon Absorption		0.5	0.5
Kaon Decay		1.0	3.0
Radiative Corrections	0.1	0.4	2.0
Monte Carlo Model	0.2	1.0	0.5
Total	0.6	2.0	4.2

Altered from KaonLT Proposal, PAC 34

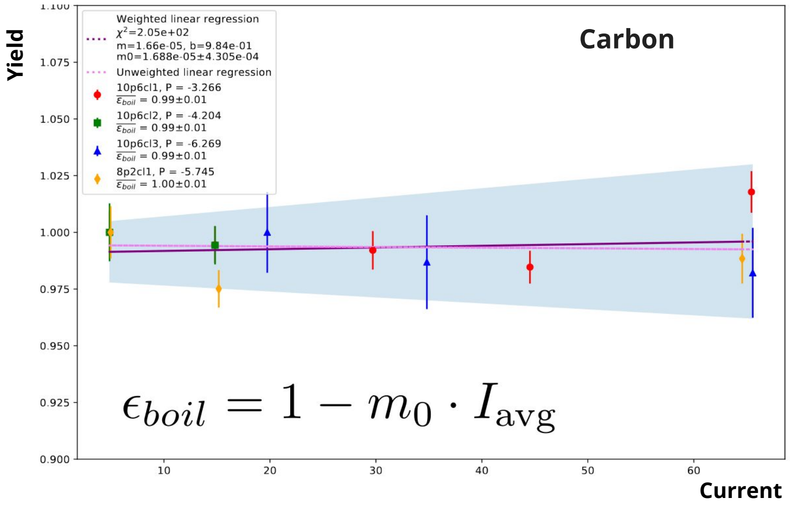
Luminosity

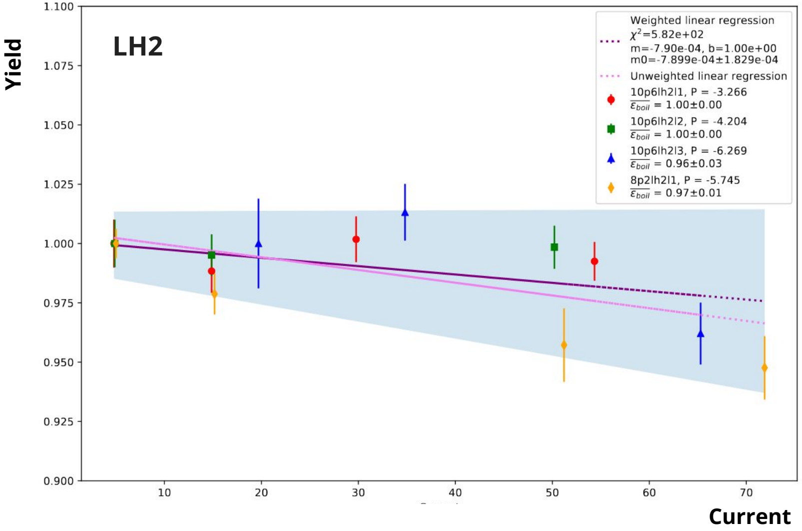
$$Y_{track} = \frac{N_{track}}{Q_{tot}\epsilon_{track}\epsilon_{cpuLT}}$$

- For KaonLT, the luminosity scans provide a means to understand the accuracy of various efficiencies
- Limited good data because…
  - Some SHMS data taken at positive polarity
  - EDTM not yet integrated into CODA
- Ended up extrapolating a slope using a weighted linear regression
- **Final Luminosity Results (Carbon, LH2)**

Carbon is flat (m0=1.688e-05±4.305e-04)

LH2 has a slope of ~8%+/-2% (m0=-7.899e-04±1.829e-04)





Elastic Analysis

- Comprehensive understanding of the offsets to the kinematics and spectrometer acceptances.
- Able to use one set of momenta and angle offsets for all beam energies
  - Small energy offsets per beam setting
- **Final Offset Results (v3)**

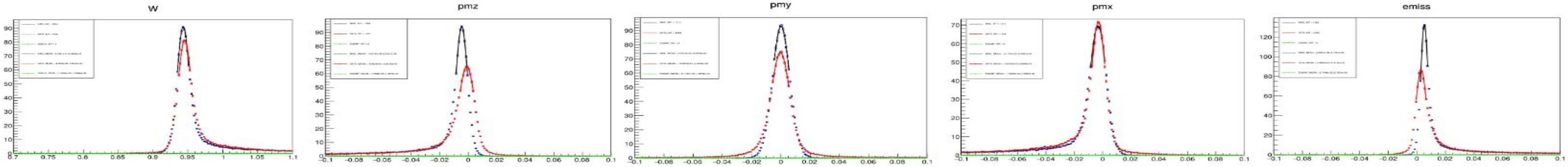
Final KaonLT Offsets

E: 3834.9 | 4932.0 | 6190.3 | 8208.8 | 10585.4 MeV
dE: -0.3000 | -0.7000 | -0.2000 | +0.5000 | +0.5000

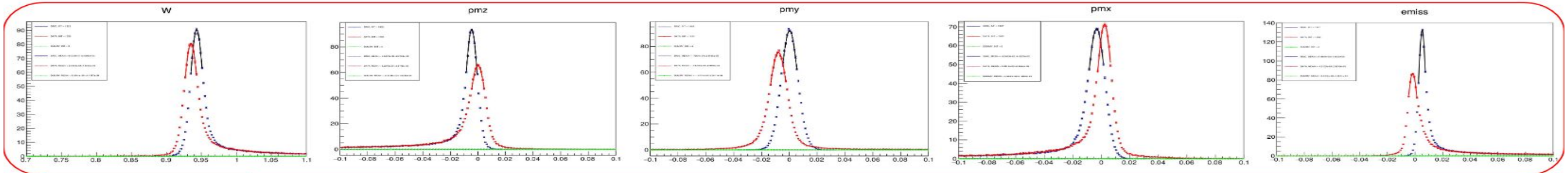
All energies...
dthe 1.0000 dthp 1.1000 dphe 2.5100 dphp -0.1100
dpe -1.0000 dpp -2.0000

All offsets are in units...
0.1% for momenta/energy, 1 mrad for angles

E=4.9 GeV



W Pmz Pmy Pmx Em

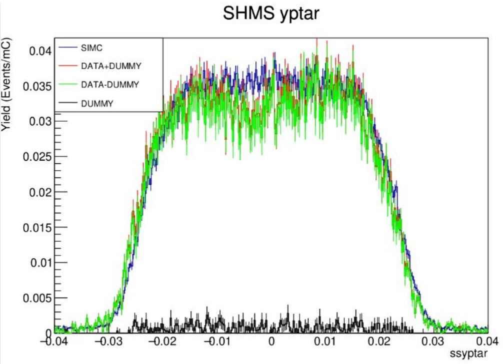


No Offsets

Extract the Kaon Electroproduction Cross Section

E=10.6 GeV

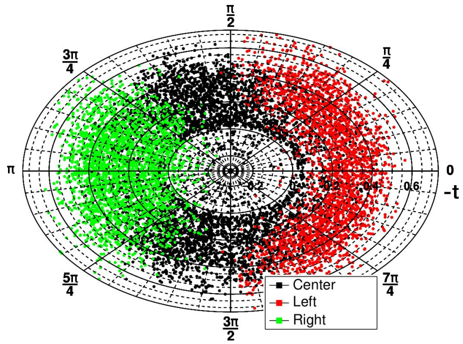
Q^2=0.5, W=2.40, x=0.09, ε_{low}=0.45



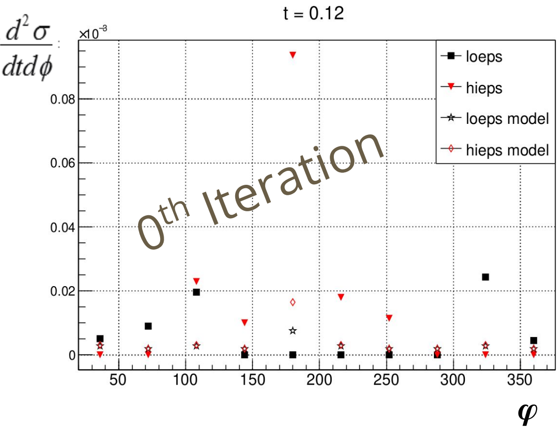
- SIMC, including a model of the experimental setup, is used to simulate a variety of effects.
- A model for the kaon electroproduction cross section is developed, including a $\chi 2$ minimization to achieve the best agreement between data and SIMC.
- This is achieved by iterating the model input cross section.
- The experimental cross section can then be extracted as long as the model input cross section properly describes the dependence on all kinematic variables.

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

L-T Separation



- σ_L is isolated using the Rosenbluth separation technique
- Measure the cross section at two beam energies and fixed W, Q^2, -t

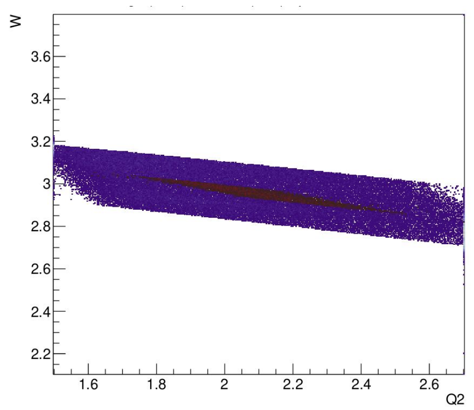


1. Phase space matching to constrain the kinematic region for the two differing beam energies
2. Extract cross section in -t and ϕ bins

$$\left(\frac{d\sigma^2_{exp}}{dtd\phi}\right)\Bigg|_{Q^2=\bar{Q^2},t=\bar{t}} = \frac{Y_{exp}}{Y_{SIMC}}\left(\frac{d\sigma^2_{model}}{dtd\phi}\right)\Bigg|_{Q^2=\bar{Q^2},t=\bar{t}}$$

3. This allows for the simultaneous extraction of L, T, LT, and TT

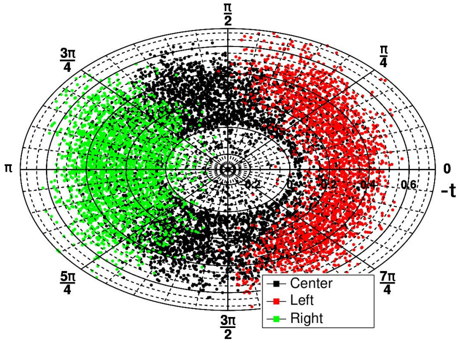
Q^2= 2.115 GeV^2, W = 2.95GeV



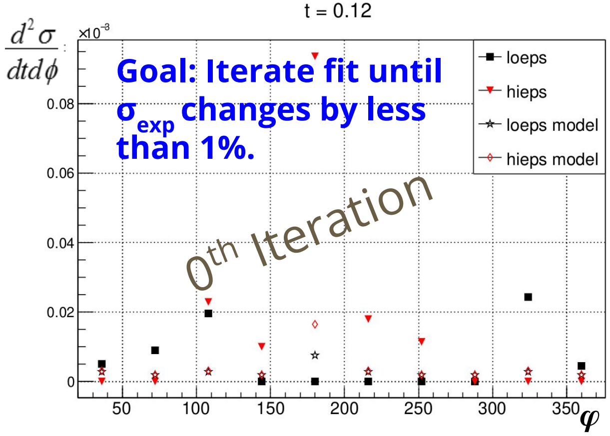
$$2\pi\frac{d^2\sigma}{dtd\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Iteration Procedure Summary

Good φ coverage across 3 settings



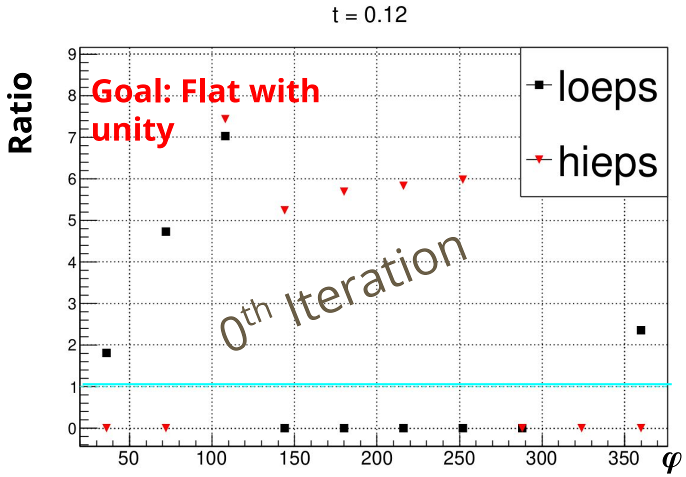
Q^2= 2.115 GeV^2, W = 2.95GeV



For each K$^+$ SHMS setting, form ratio:

$$R = \frac{Y_{Data}}{Y_{SIMC}}$$

Combine ratios for K$^+$ settings together, Propagating errors accordingly.



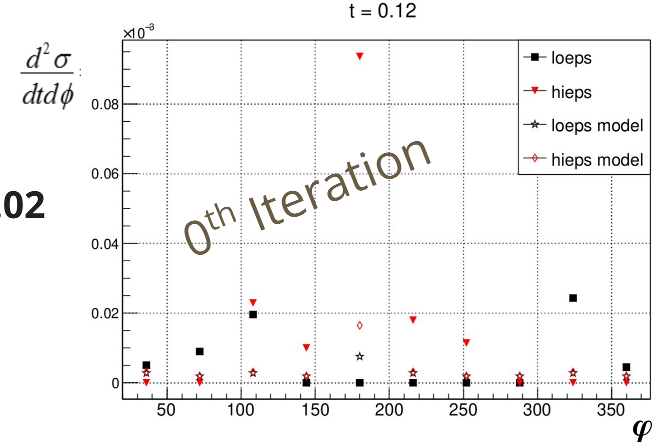
Extract via simultaneous fit of L,T,LT,TT

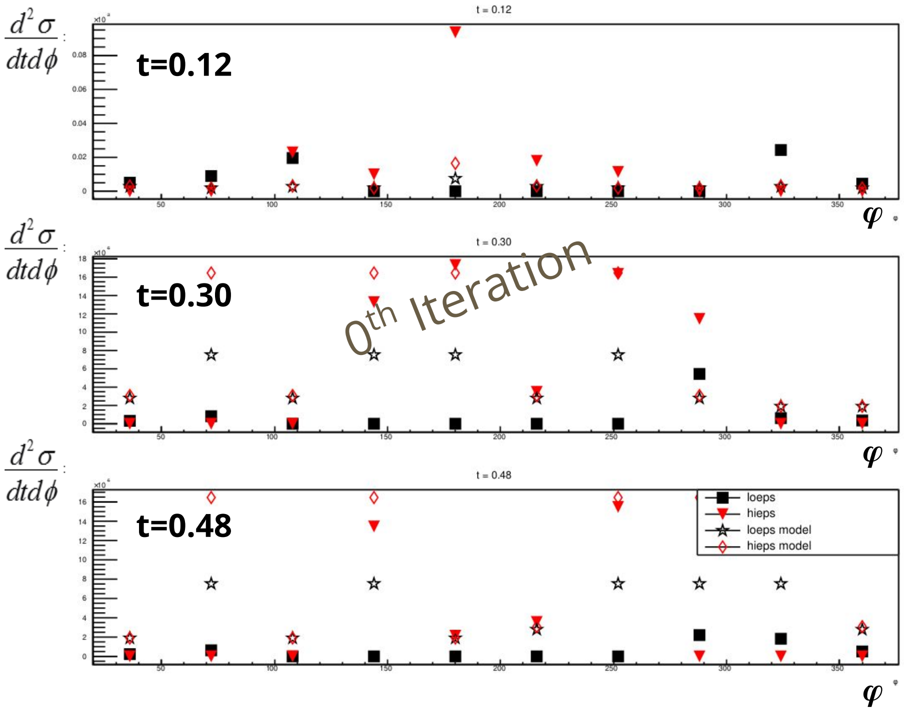
$$\left(\frac{d\sigma^2_{exp}}{dtd\phi}\right)\Bigg|_{Q^2=\bar{Q^2},t=\bar{t}} = \frac{Y_{exp}}{Y_{SIMC}}\left(\frac{d\sigma^2_{model}}{dtd\phi}\right)\Bigg|_{Q^2=\bar{Q^2},t=\bar{t}}$$

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

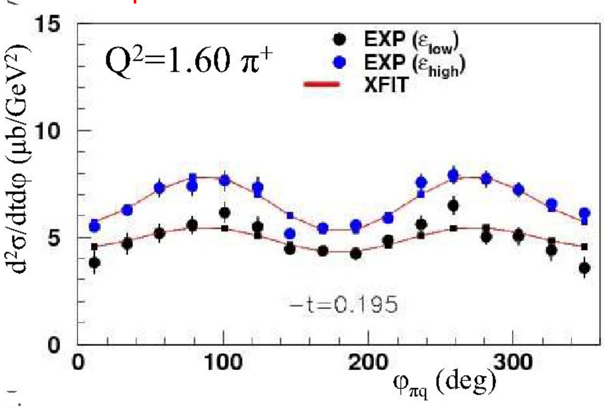
Comparison to Model

Q^2=2.115, W=3.02





Comparison: 11th iteration from Fπ2



- Comparing even the 0th iteration to Fπ2 for a similar Q^2 and t-bin shows good initial agreement

t-range = (0.001-0.600)
t_bins = 3
phi_bins = 10

Outlook and Conclusion

- E12-09-011 ran Fall 2018, Spring 2019
  - PionLT from Summer 2019, Fall 2021, Winter 2022, and Summer 2022
- In the process of extracting the kaon electroproduction cross section for Λ channel
  - This is achieved by iterating the model input cross section
  - The experimental cross section can then be extracted as long as the model input cross section properly describes the dependence on all kinematic variables.
  - Using the model from Fπ2 as a starting point shows good agreement for similar Q^2, even at 0th iteration
- Publication expected **this year!**

KaonLT collaboration

NSF PHY2012430 and PHY2309976

Salina Ali, Ryan Ambrose, Darko Androic, Whitney Armstrong, Carlos Ayerbe Gayoso, Samip Basnet, Vladimir Berdnikov, Hem Bhatt, Deepak Bhetuwal, Debaditya Biswa, Peter Bosted, Ed Brash, Alexandre Camsonne, Jian-Ping Chen, Junhao Chen, Mingyu Chen, Michael Christy, Silviu Covrig, Wouter Deconinck, Markus Diefenthaler, Burcu Duran, Dipangkar Dutta, Mostafa Elaasar, Rolf Ent, Howard Fenker, Eric Fuchey, Dave Gaskell, David Hamilton, Ole Hansen, Florian Hauenstein, Nathan Heinrich, Tanja Horn, Garth Huber, Shuo Jia, Mark Jones, Sylvester Joosten, Muhammad Junaid, Md Latiful Kabir, Stephen Kay, Vijay Kumar, Nathaniel Lashley-Colthirst, Bill Li, Dave Mack, Simona Malace, Pete Markowitz, Mike McCaughan, Robert Michaels, Rachel Montgomery, Jacob Murphy, Gabriel Niculescu, Maria Niculescu, Zisis Papandreou, Sanghwa Park, Eric Pooser, Love Preet, Julie Roche, Greg Smith, Petr Stepanov, Holly Szumila-Vance, Vardan Tadevosyan, Aram Teymurazyan, Richard Trotta, Hakob Voskanyan, Carlos Yero, Ali Usman

(Proposal to Jefferson Lab PAC 34)

Studies of the L-T Separated Kaon Electroproduction Cross Section from 5-11 GeV

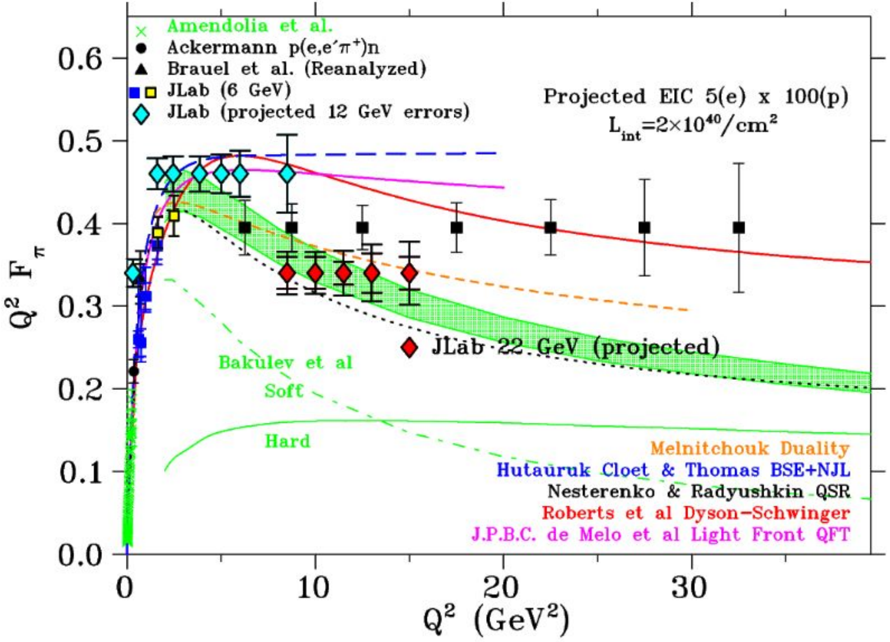
December 15, 2008

Thank You for Your Time!

EXTRA

Meson Form Factors

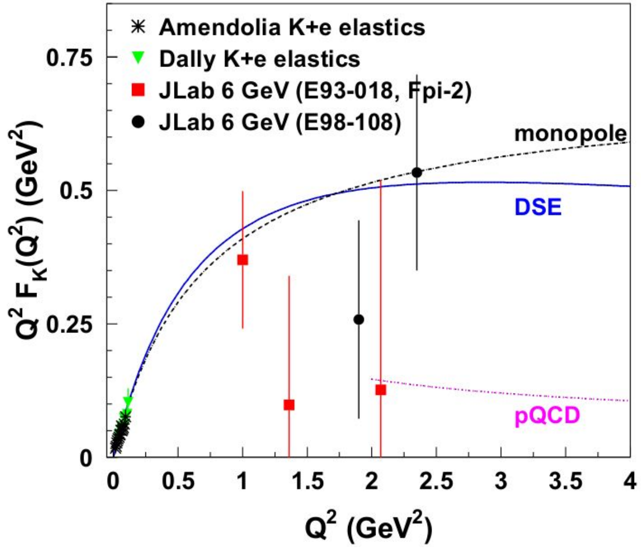
- π^+ and K^+ form factors are of special interest in hadron structure studies
- Clearest case for studying transition from non-perturbative to perturbative regions
- π^+ form factor has data covering a wide rang of Q^2 (up to 8.5 GeV^2)
  - Fπ1/Fπ2: 2006, 2008
  - PionLT: E12-09-011 which covers KaonLT data plus Summer 2019
  - PionLT: E12-19-006 ran Fall 2021, Winter 2022, Summer 2022 and Fall 2022
- Meanwhile, the K^+ form factor data is very limited...



L-T Separated K+ Data for Form Factor

- Jlab 6 GeV data showed the K^+ form factor differs from hard QCD calculation
  - Evaluated with asymptotic valence-quark Distribution Amplitude (DA), but large uncertainties
- 12 GeV K^+ form factor extraction data require:
  - Measurements over a range of -t, which allow for interpretation of kaon pole contribution

Results from JLab 6 GeV data



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

Experimental Considerations: Comparing π^+ and K^+ FF

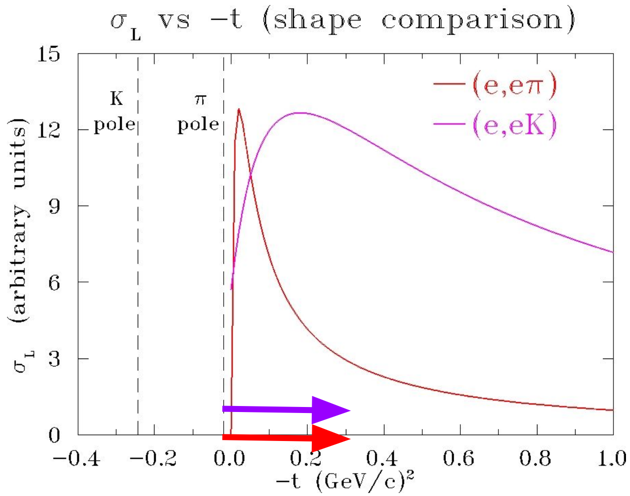
- At large -t, pion data lies a similar distance from the pole as kaon data
- The hard scattering limit in pQCD predicts a similar result

$$\frac{F_K(Q^2)}{F_\pi(Q^2)} \xrightarrow[Q^2\to\infty]{} \frac{f_K^2}{f_\pi^2}$$

- Requirements:
  - Full L/T separation of the cross section – isolation of σ_L (which requires $\sigma_L >> \sigma_T$)
  - Selection of the kaon pole process
  - Extraction of the form factor using a model
  - Validation of the technique - model dependent checks

$$\sigma_L \approx \frac{-tQ^2}{(t-m_K^2)^2} g_{KNN}^2(t) F_K^2(Q^2,t)$$

We **do not** use the Born term model!



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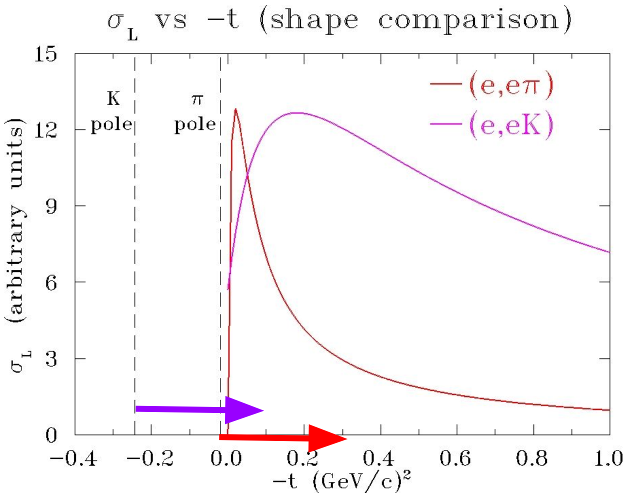
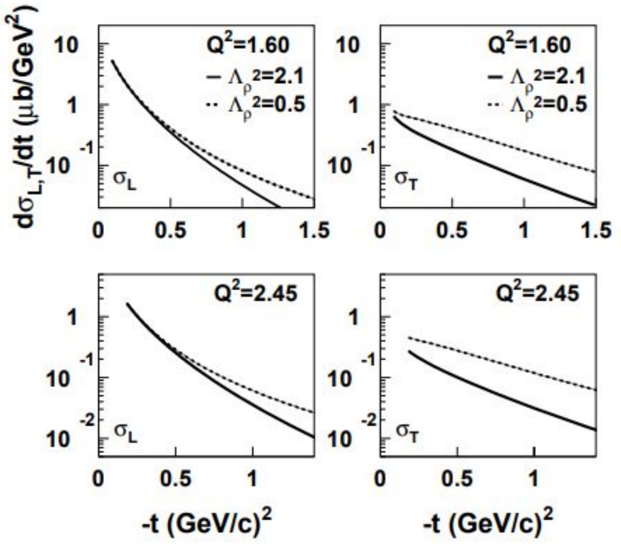


- Hall C magnetic spectrometers can provide the facilities for this measurement

Form Factor Extraction



T. Horn's Thesis

- The product of the kaon form factor is related to σ_L through the probability of the virtual photon interacting with a kaon
- If σ_L shows an exponential fall off with t this is a sign of the point-like behavior warranting the form factor extraction
- The extraction of the kaon form factor is done by fitting the longitudinal cross section calculated by the VGL Regge model to the experimental data.
- The model is evaluated for different values of Λ^2_{K+}

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

$$\sigma_L \approx \frac{-tQ^2}{(t-m_K^2)^2} g^2_{KNN}(t) F_K^2(Q^2,t)$$

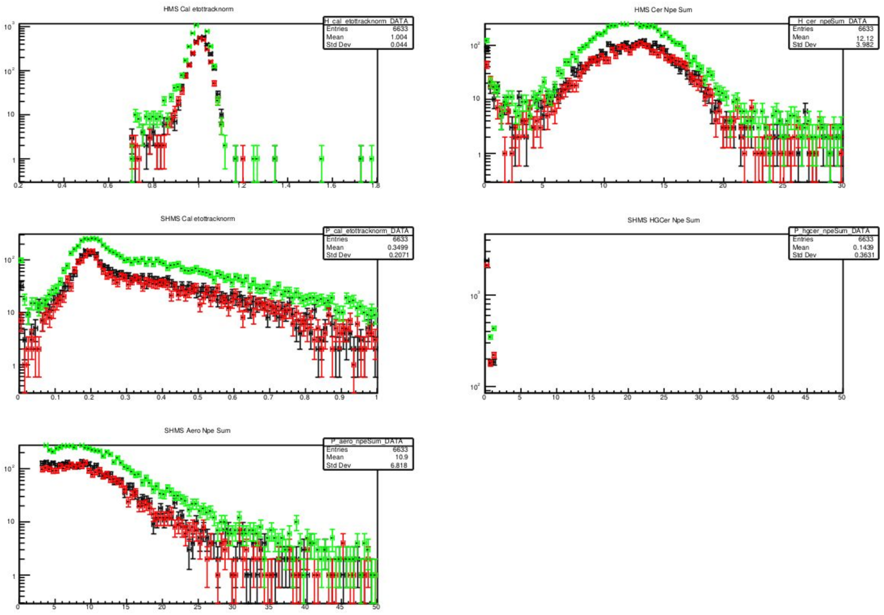
$$F_K(Q^2,t) = (1 + Q^2/\Lambda_K^2)^{-1}$$

$$\frac{\chi^2}{\text{dof}} = \frac{1}{\text{dof}}\sum_{\text{t bins}}\frac{(\sigma_L^{VGL} - \sigma_L^{exp})^2}{\Delta\sigma_L^2}$$

M. Vanderhaeghen, M. Guidal, and J.-M. Laget, Phys. Rev. C 57, 1454

Applied Cuts

- CTime_eKCoinTime_ROC1" : (CTime_eKCoinTime_ROC1 > ((0)-((4.008)/2.0)-(0.25))) & (CTime_eKCoinTime_ROC1 < ((0)+((4.008)/2.0)+(0.25)))
- (P_RF_Dist > (0.75)) & (P_RF_Dist < (1.75))
- (P_hod_goodstarttime == 1.0) & (H_hod_goodstarttime == 1.0)
- (P_dc_InsideDipoleExit == 1) & (H_dc_InsideDipoleExit == 1)
- (ssdelta>=-10.0) & (ssdelta<=20.0) & (ssxptar>=-0.06) & (ssxptar<=0.06) & (ssyptar>=-0.04) & (ssyptar<=0.04)
- (hsdelta>=-8.0) & (hsdelta<=8.0) & (hsxptar>=-0.08) & (hsxptar<=0.08) & (hsyptar>=-0.045) & (hsyptar<=0.045)
- ((abs(P_gtr_beta-1)) < 0.3)
- (P_aero_npeSum > 3) & (P_hgcer_npeSum < 1.5) & (P_cal_etottracknorm >= 0.0)
- (H_cal_etottracknorm > 0.7)



SIMC vs HCANA General Calculations

- Inputs
  - Initial energy
  - Scattered (S)HMS momentum and theta angle
- In SIMC, (S)HMS delta, xptar, yptar, z are produced from phase space these initial inputs produce
- In HCANA, (S)HMS delta, xptar, yptar, z are produced from detectors (e.g. xptar is from tracking info)
- (S)HMS delta, xptar, yptar, z, P, E, theta, and phi, along with Ein, are used to calculate the rest of the kinematic variables

Comparison to Model

- Initially starting with model from Fpi-2, which were at nearly constant W.
- Since we have more than one W setting for fixed Q^2 (i.e. Q^2=3.0), simple adjustments are being implemented.

$$\sigma_L = (a + b \cdot \log(Q^2)) \cdot \exp\left((c + d \cdot \log(Q^2)) \cdot |\, t \,|\right)$$

$$\sigma_T = e + f \cdot \log(Q^2) + (g + h \cdot \log(Q^2)) \cdot \frac{|t| - \text{tav}}{\text{tav}}$$

$$\sigma_{LT} = \left(i \cdot \exp\left(j \cdot |t|\right) + \frac{k}{|t|}\right) \cdot \sin(\theta_{\text{cm}})$$

$$\sigma_{TT} = l \cdot Q^2 \cdot \exp\left(-Q^2\right) \cdot \frac{|t|}{(|t| + m_{K+}^2)^2} \cdot \sin^2(\theta_{\text{cm}})$$

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