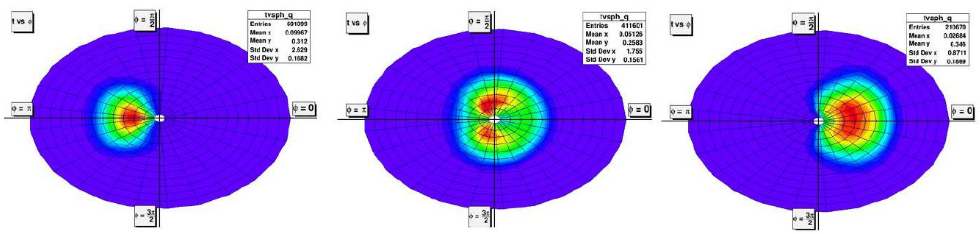
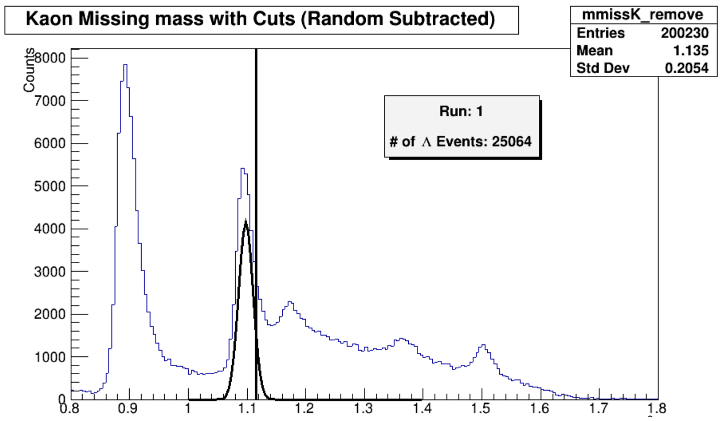
KaonLT: LT Separated Kaon Production Cross Sections and Form Factor

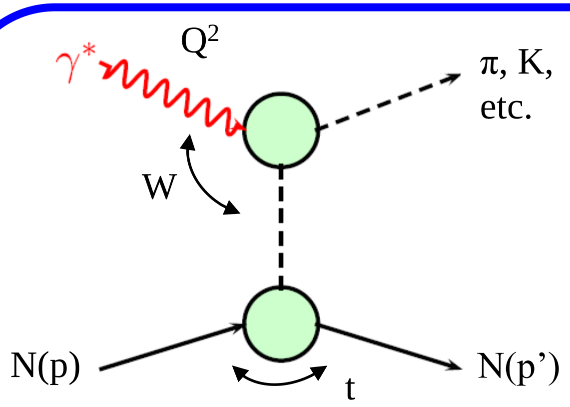
Spokespersons: Tanja Horn (CUA), Garth Huber (U. Regina), Pete Markowitz (FIU)

Graduate Students: Ryan Ambrose (U. Regina, M.Sc. 2018), Vijay Kumar (U. Regina), Mireille Muhoza (CUA), Richard Trotta (CUA)



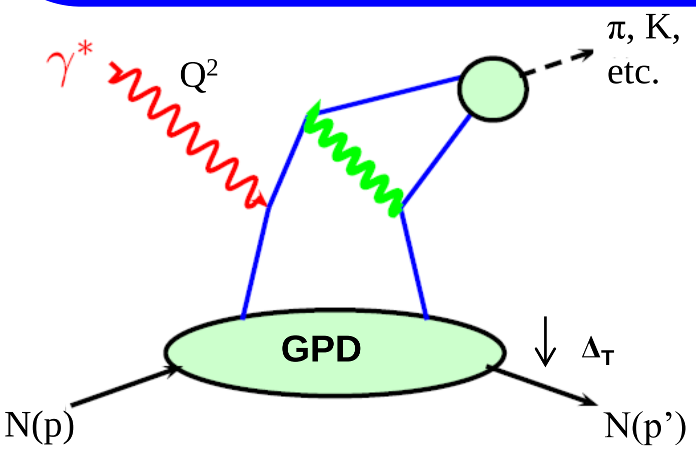


Deep Exclusive Meson Electroproduction



t-channel process

- In the limit of small –*t*, meson production can be described by the *t*-channel meson exchange (pole term)
  - Spatial distribution described by form factor



Handbag diagram

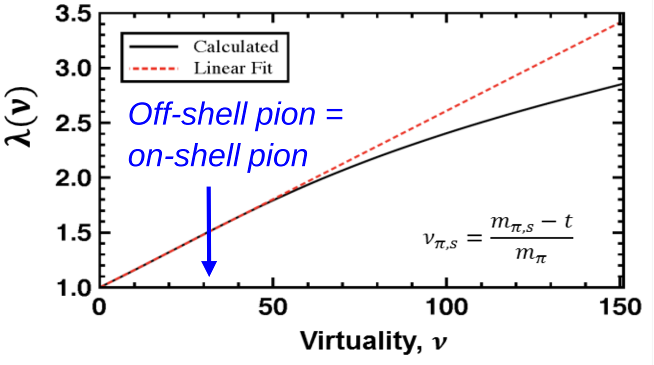
- At sufficiently high Q^2, the process should be understandable in terms of the "handbag" diagram – can be verified experimentally
  - The non-perturbative (soft) physics is represented by the GPDs
    - Shown to factorize from QCD perturbative processes for longitudinal photons *[Collins, Frankfurt, Strikman, 1997]*

Meson Form Factors

- **Pion and kaon form factors** are of special interest in hadron structure studies
  - The *pion* is the lightest QCD quark system and also has a central role in our understanding of the dynamic generation of mass - *kaon* is the next simplest system containing strangeness
    - ***Clearest test case for studies of the transition from non-perturbative to perturbative regions***

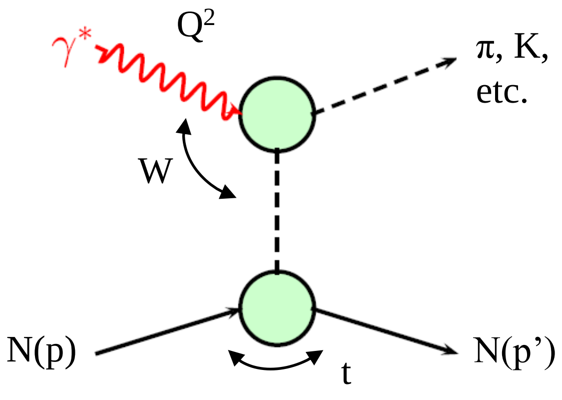
- Recent advances and future prospects in experiments
  - Dramatically improved precision in F_π measurements
    - ***12 GeV JLab data have the potential to quantitatively reveal hard QCD's signatures***
    - ***EIC data have the potential to quantitatively reveal DCSB emergent mass generation***

S-X Qin, C.Chen, C. Mezrag, C.D. Roberts, Phys. Rev. C97 (2018), no. 1, 015203



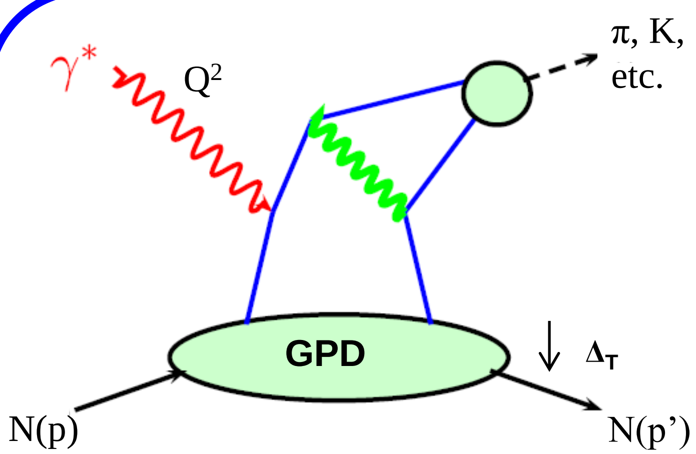
Off-shell meson = On-shell meson for t<0.6 GeV^2 (ν =30) for pions and t<0.9 GeV^2(ν_s~3) for kaons

Deep Exclusive Meson Electroproduction



t-channel process

- ❑ In the limit of small $-t$, meson production can be described by the t-channel meson exchange (pole term)
  - – Spatial distribution described by form factor

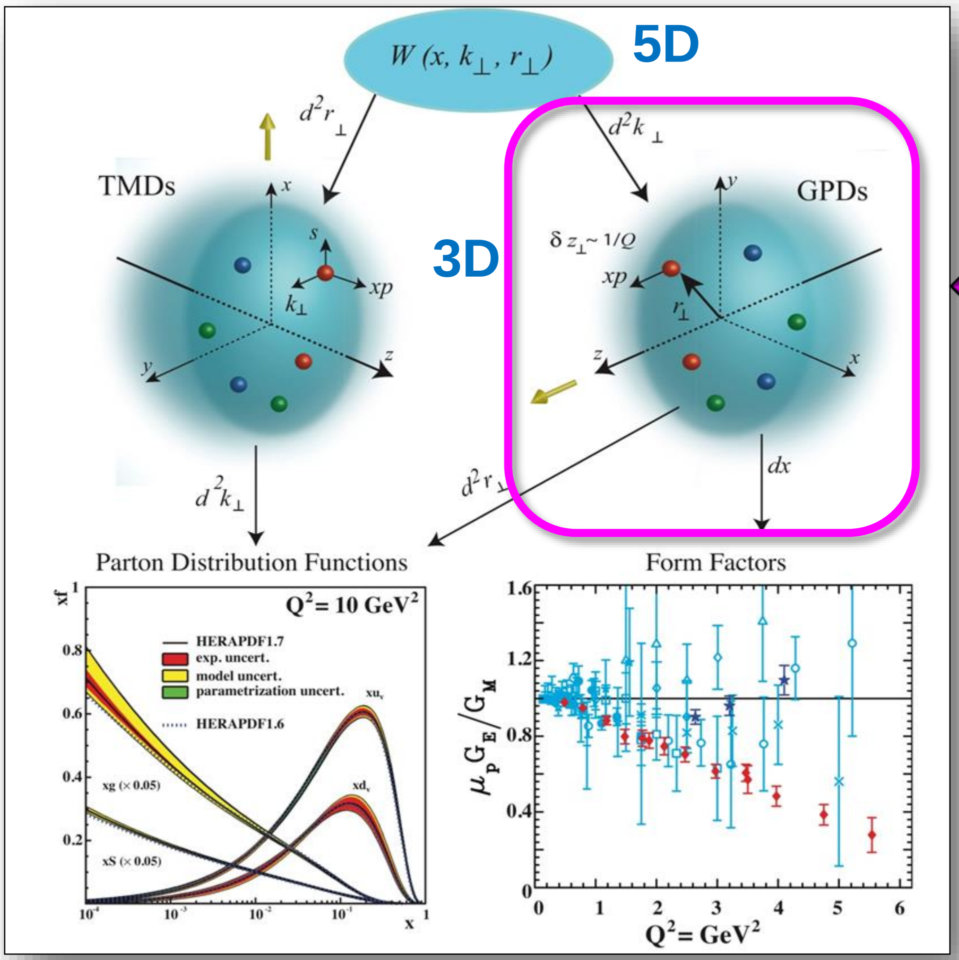


Handbag diagram

- ❑ At sufficiently high Q^2, the process should be understandable in terms of the "handbag" diagram – can be verified experimentally
  - – The non-perturbative (soft) physics is represented by the GPDs
    - ○ Shown to factorize from QCD perturbative processes for longitudinal photons *[Collins, Frankfurt, Strikman, 1997]*

The 3D Nucleon Structure

Generalized Parton and Transverse Momentum Distributions are essential for our understanding of internal hadron structure and the dynamics that bind the most basic elements of Nuclear Physics



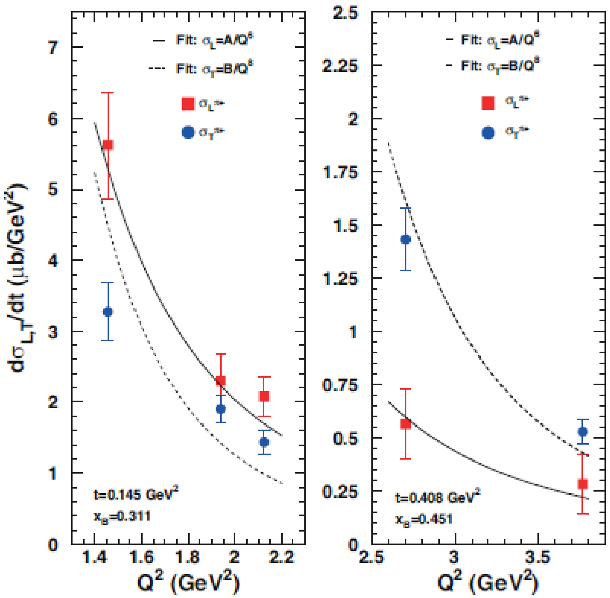
- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)
- GPDs
  - Spatial imaging (exclusive DIS)
- Requires
  - High luminosity
  - Polarized beams and targets

Major new capability with JLab12

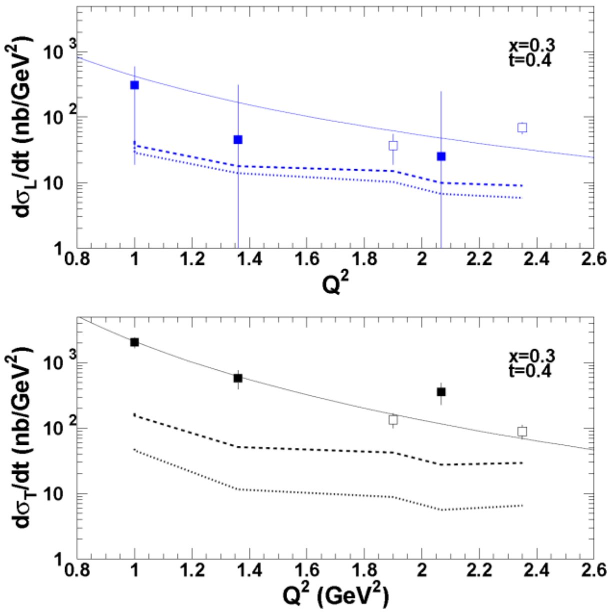
QCD Factorization - Results from 6 GeV JLab

- Data demonstrate the technique of measuring the Q^2 dependence of L/T separated cross sections at fixed x/t to test QCD Factorization (or perhaps, a precocious description)
    - Consistent with expected factorization, but small lever arm and relatively large uncertainties

π^+ *[T. Horn et al., Phys. Rev. C **78**, 058201 **(2008)**]*



K^+ *[M. Carmignotto et al., Phys. Rev. C**97** (2018) no.2, 025204]*

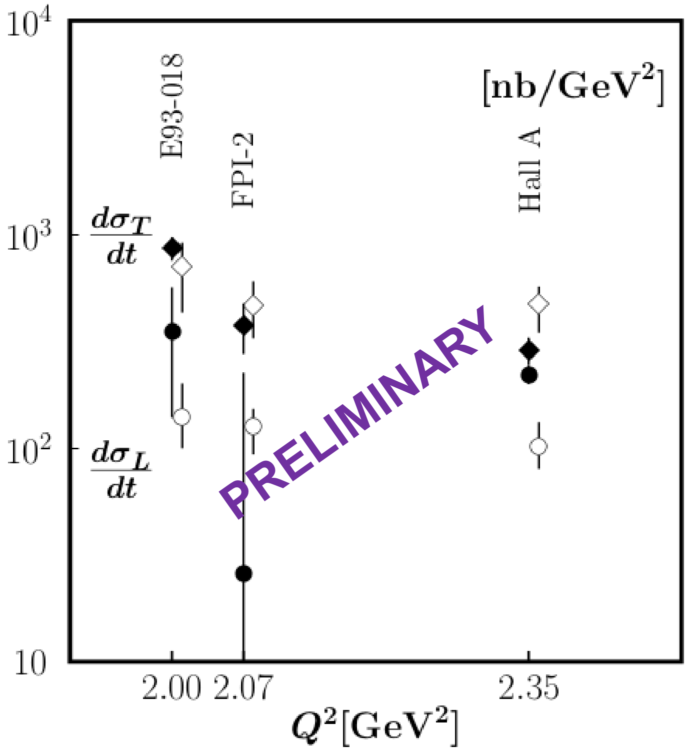


[L. Favart, M. Guidal, T. Horn, P. Kroll, Eur. Phys. J A 52 (2016) no.6, 158]

- 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
    - Interpretation of non-perturbative contributions in experimentally accessible kinematics

QCD Factorization - Results from 6 GeV JLab

Here, compare with P. Kroll's GPD model (circles=σ_L, diamonds=σ_T)

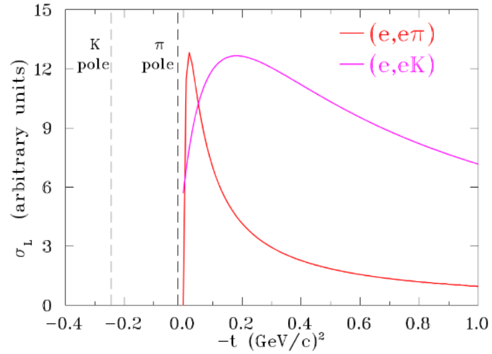


- Solid symbols are data
  - σ_L is comparable to σ_T at Q^2=2.4 GeV^2
- Open symbols model calculations
  - Model overpredicts σ_T
  - Model underpredicts σ_L

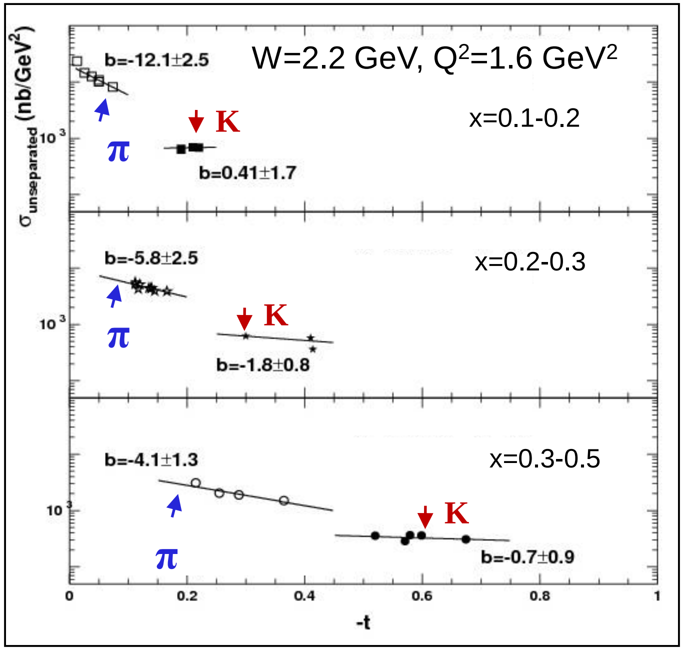
- Separated cross section data over a large range in Q^2 are essential for:
  - Testing factorization and understanding dynamical effects in both Q^2 and –t kinematics
  - Interpretation of non-perturbative contributions in experimentally accessible kinematics

Reaction mechanism in systems containing strangeness: the K^{+} Form Factor

- Similar to π^{+} form factor, elastic K^{+} scattering from electrons used to measure charged kaon for factor at low Q^2 *[Amendolia et al, PLB 178, 435 (1986)]*



- Can "kaon cloud" of the proton be used in the same way as the pion to extract kaon form factor via ***p(e,e'K⁺)Λ*** ? – *need to quantify the role of the kaon pole*



- Unseparated data: pion t-dependence is steeper *at* low *t* than for kaons

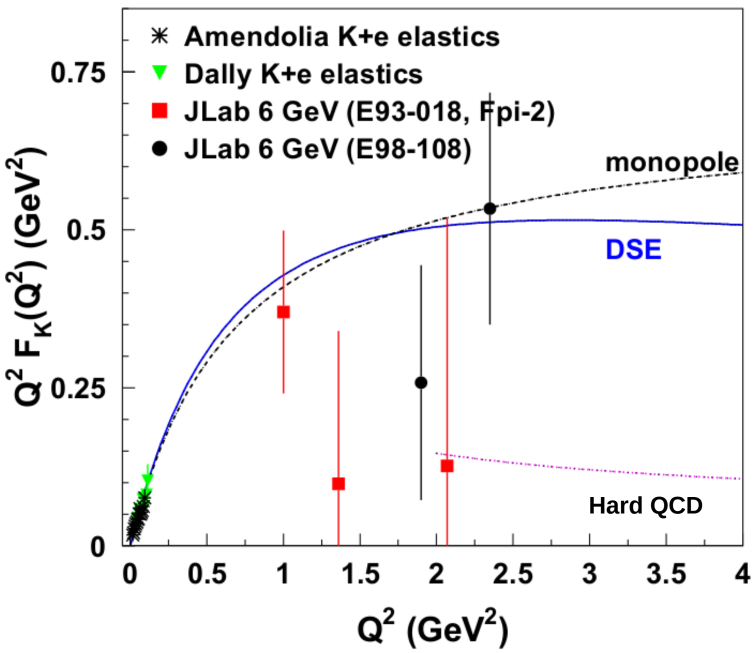
*[T. Horn, Phys. Rev. C **85 (2012)** 018202]*

- However, the kaon pole is expected to be strong enough to produce a maximum in σ_L

[Kroll/Goloskokov EPJ A47 (2011), 112]

JLab12 GeV essential for measurements at low *t*, which would allow for interpretation of the kaon pole contribution

$F_{K+}(Q^2)$ in 2018



- ❑ Differs from hard QCD calculation evaluated with asymptotic valence-quark Distribution Amplitude (DA)

  *[L. Chang, et al., PRL **111** (2013) 141802; PRL **110** (**2013**) 1322001]*

  – Trend consistent with time like meson form factor data up to Q^2=18 GeV^2 *[Seth et al, PRL **110** (2013) 022002]*

*[M. Carmignotto et al., Phys. Rev. C**97** (**2018**) no.2, 025204]*

*[F. Gao et al., Phys. Rev. D 96 (**2017**) no. 3, 034024]*

- ❑ Recent developments: when comparing the hard QCD prediction with a valence-quark DA of a form appropriate to the scale accessible in experiments, magnitude is in better agreement with the data

*[I. Cloet, et al., PRL **111** (2013) 092001]*

E12-09-011 (KaonLT) Goals

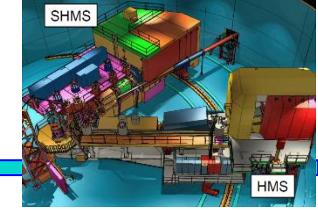
Measure the separated cross section of K^+ production above the resonance region

- Separated cross sections: L, T, LT, TT over a wide range of Q^2, t-dependence

- *The 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

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

KaonLT Sample Projections



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

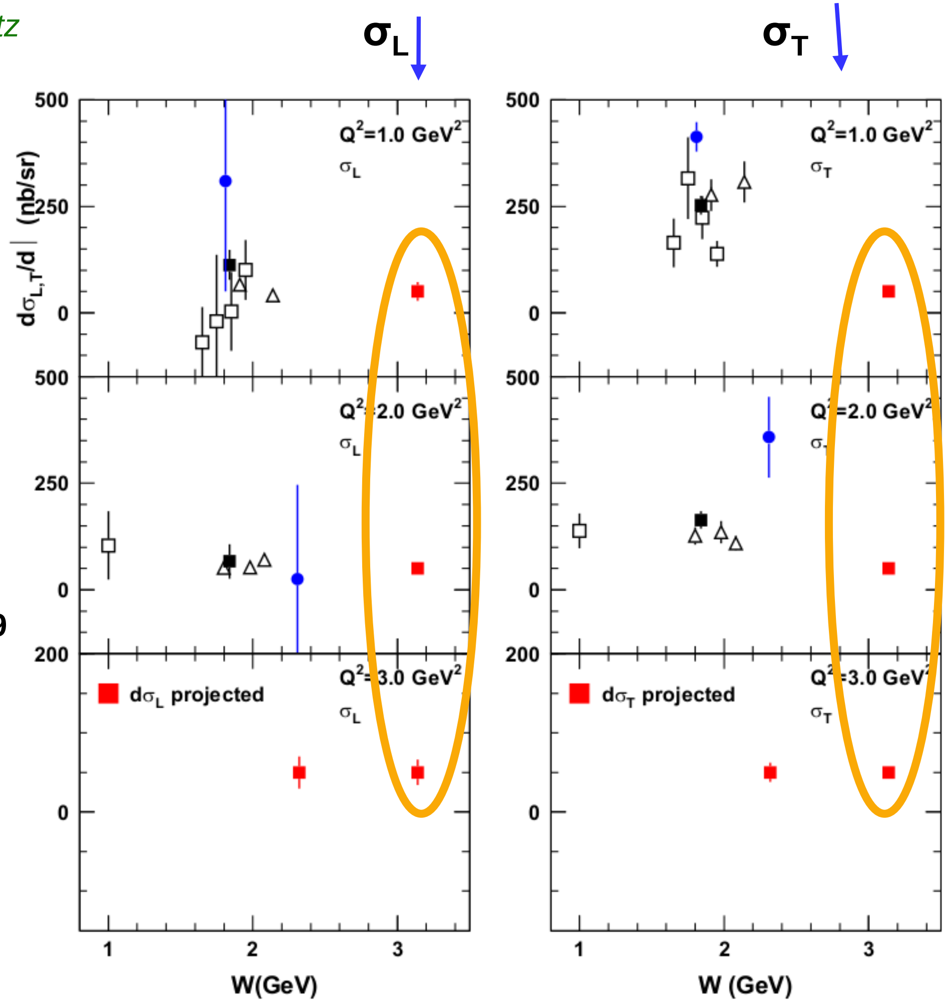
*E12-**09**-011 spokespersons: T. Horn, G. Huber, P. Markowitz*

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

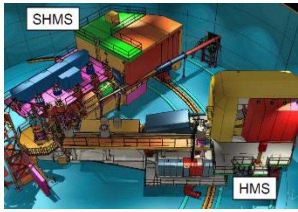
approved for 40 PAC days and **scheduled to run in 2018/19**

x	Q^2 (GeV^2)	W (GeV)	-t $(GeV/c)^2$
0.1-0.2	0.5-3.0	2.5-3.1	0.06-0.2
0.25	1.7-3.5	2.5-3.4	0.2
0.40	3.0-5.5	2.3-3.0	0.5



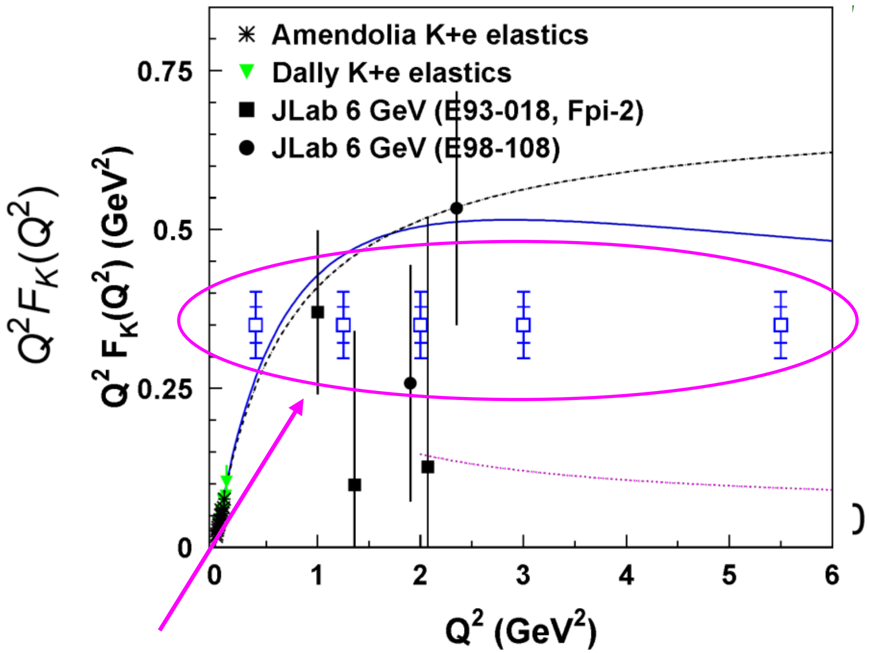
*[blue points from M. Carmignotto, PhD thesis **(2017)**]*

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

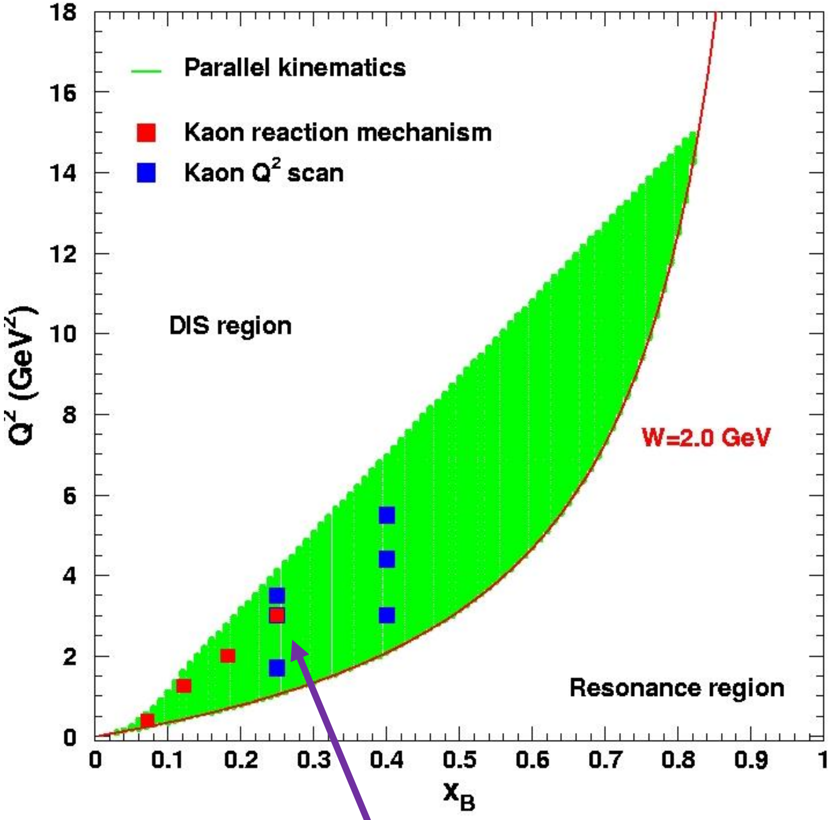
- Possible K^+ form factor extraction to highest possible Q^2 achievable at JLab
  - Extraction like in the pion case by studying the model dependence at small t
  - Comparative extractions of F_π at small and larger t show only modest model dependence
    - larger t data lie at a similar distance from pole as kaon data



Possible extractions from 2018/19 run

Kinematic Coverage

- Measure the separated cross sections at varying –t and x_B
- Measure separated cross sections for the p(e,e'K^+)$\Lambda(\Sigma^\circ)$ reaction at two fixed values of –t and x_B
  - Q^2 coverage is a factor of 2-3 larger compared to 6 GeV at much smaller –t



x	Q^2 (GeV^2)	W (GeV)	-t $(GeV/c)^2$
0.1-0.2	0.4-3.0	2.5-3.1	0.06-0.2
0.25	1.7-3.5	2.5-3.4	0.2
0.40	3.0-5.5	2.3-3.0	0.5

Q^2=3.0 GeV^2 was optimized to be used for both t-channel and Q^{-n} scaling tests

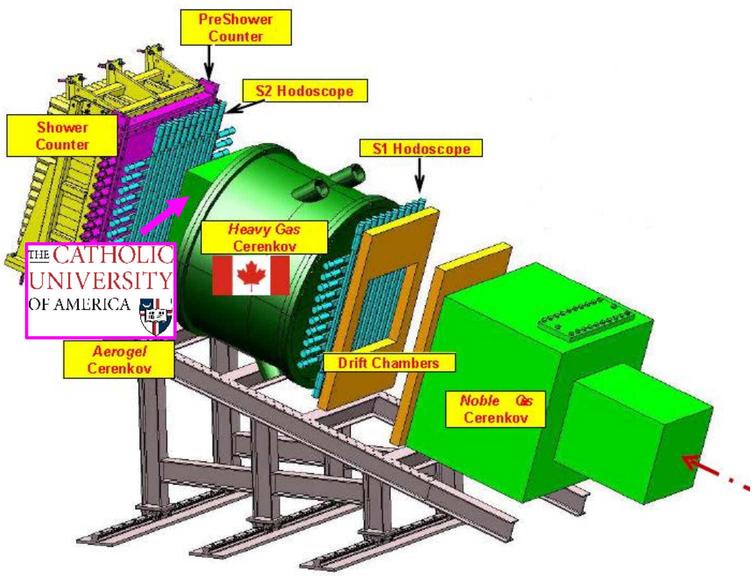
Experimental Constraints

- Hall C: k_e=3.8, 4.9, 6.4, 8.5, 9.4, 10.6 GeV

  Moved point to 8.5 GeV

- SHMS for kaon detection :
  - Kaon angles between **6** – 30 deg
  - Kaon momenta between 2.7 – 6.8 GeV/c

- HMS for electron detection :
  - angles between 10.7 – 31.7 deg
  - momenta between 0.86 – 5.1 GeV/c



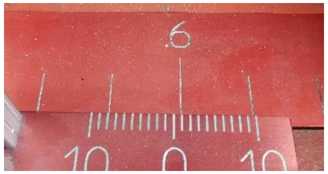
- Particle identification:
  - Dedicated Aerogel Cherenkov detector for kaon/proton separation
    - Four refractive indices to cover the dynamic range required by experiments
  - Heavy gas Cherenkov detector for kaon/pion separation

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

SHMS small angle operation

Both spectrometers at 15 degrees here - go to even smaller angles for KaonLT…

SHMS small angle operation



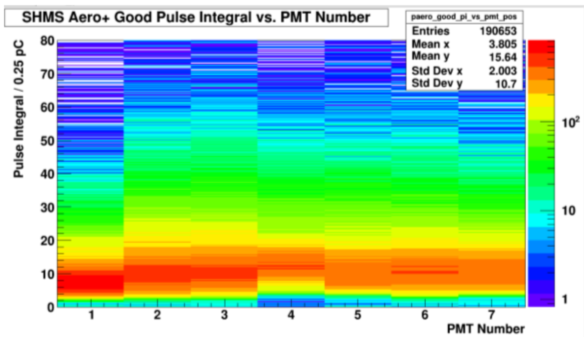
Some issues with opening and small angle settings at beginning of run, but SHMS at 6.01° and HMS at 12.7° on 12/17/18

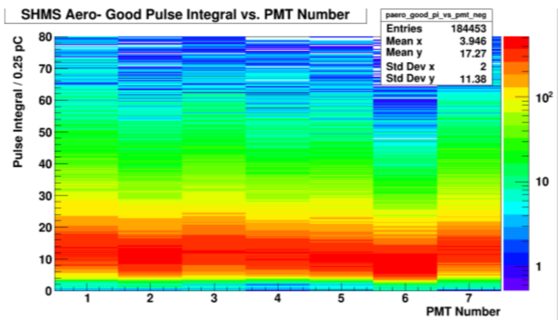
Work of many people…

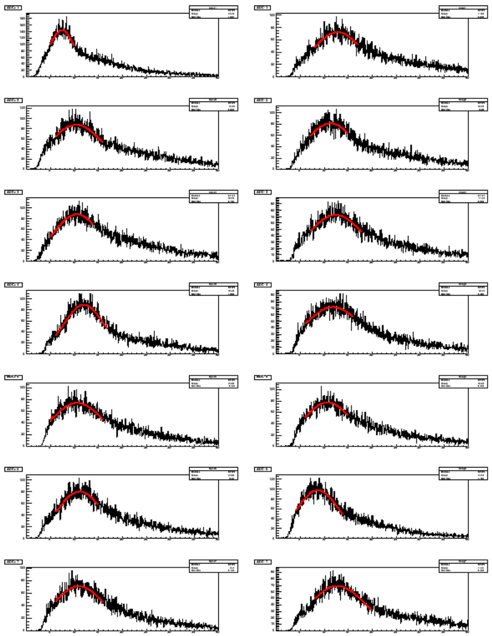
Dedicated equipment: Aerogel Cherenkov detector in SHMS

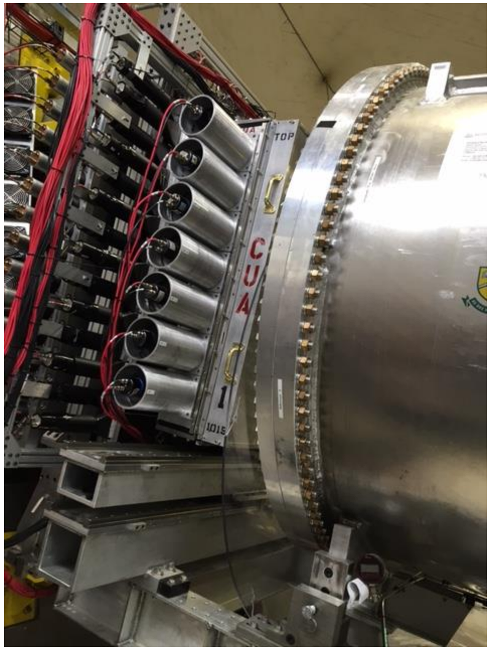
NSF MRI PHY-1039446

Analysis by V. Berdnikov

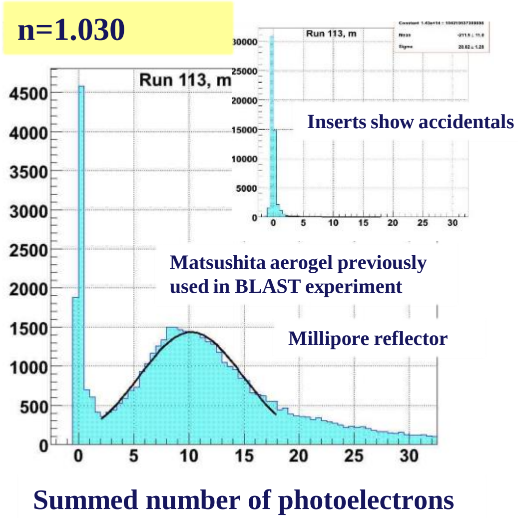


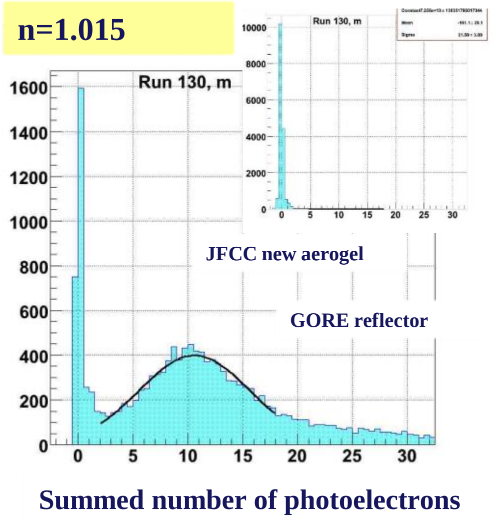






- ❑ 5 successful tray exchanges since Fall 2018
- ❑ Aerogel performance as expected
- ❑ SP-15 tray requires some fixing before next use





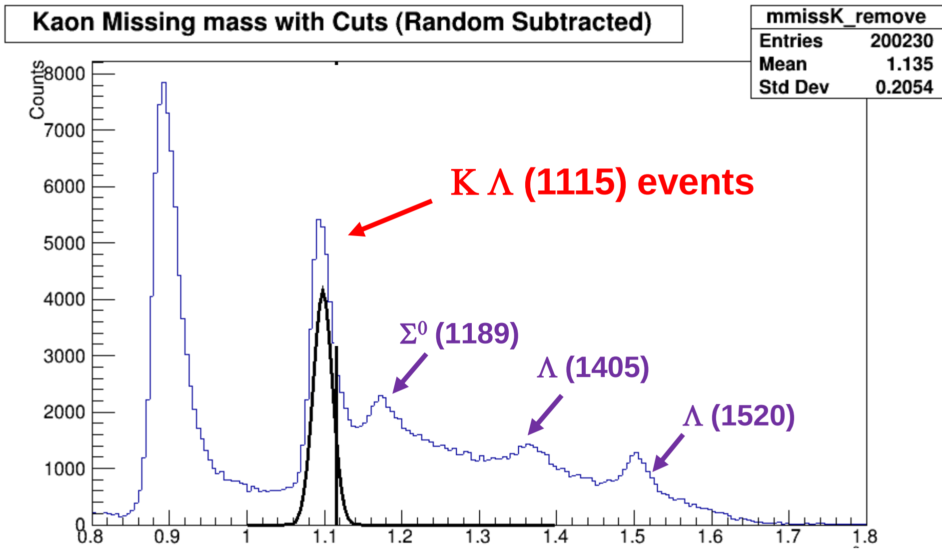
KaonLT Event Selection

Plots from: R. Ambrose, S. Kay, R. Trotta

- Isolate Exclusive Final States through missing mass

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

Online data



M_X (GeV)

- Coincidence measurement between kaons in SHMS and electrons in HMS
  - simultaneous studies of KΛ and KΣ^0 channels…and a few others…

- Kaon pole dominance tests through

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

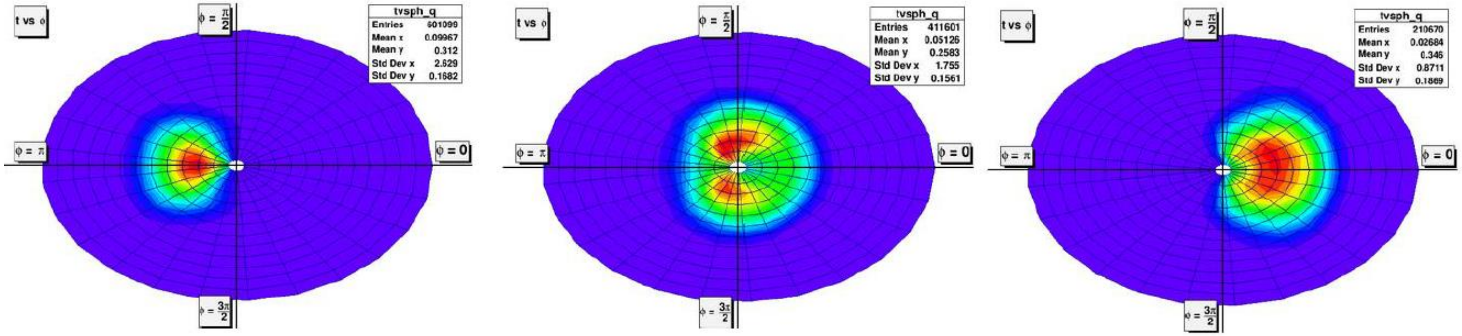
  - Should be similar to ratio of coupling constants $g^2_{pK\Lambda}/g^2_{pK\Sigma}$ if t-channel exchange dominates

L/T Separation Example

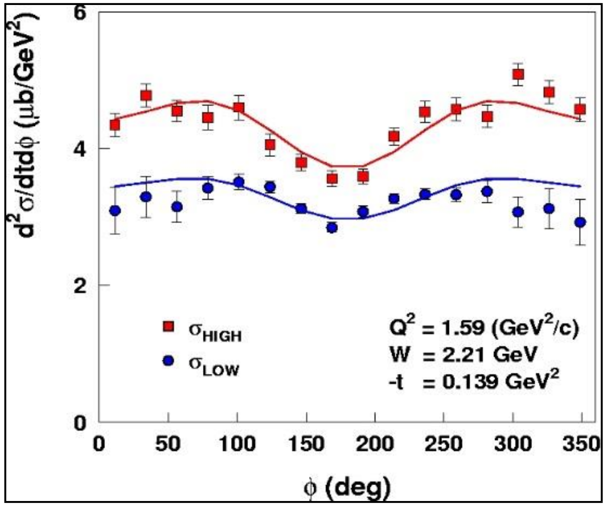
Plots from: R. Ambrose, S. Kay, R. Trotta

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

Physics cross section



- ❑ Three SHMS angles for azimuthal (ϕ) coverage to determine the interference terms (LT, TT)
- ❑ Two beam energies (ε) to separate longitudinal (L) from transverse (T) cross section
- ❑ Careful evaluation of the systematic uncertainties is important due to the 1/ε amplification in the σ_L extraction
  - ➢ spectrometer acceptance, kinematics, efficiencies…



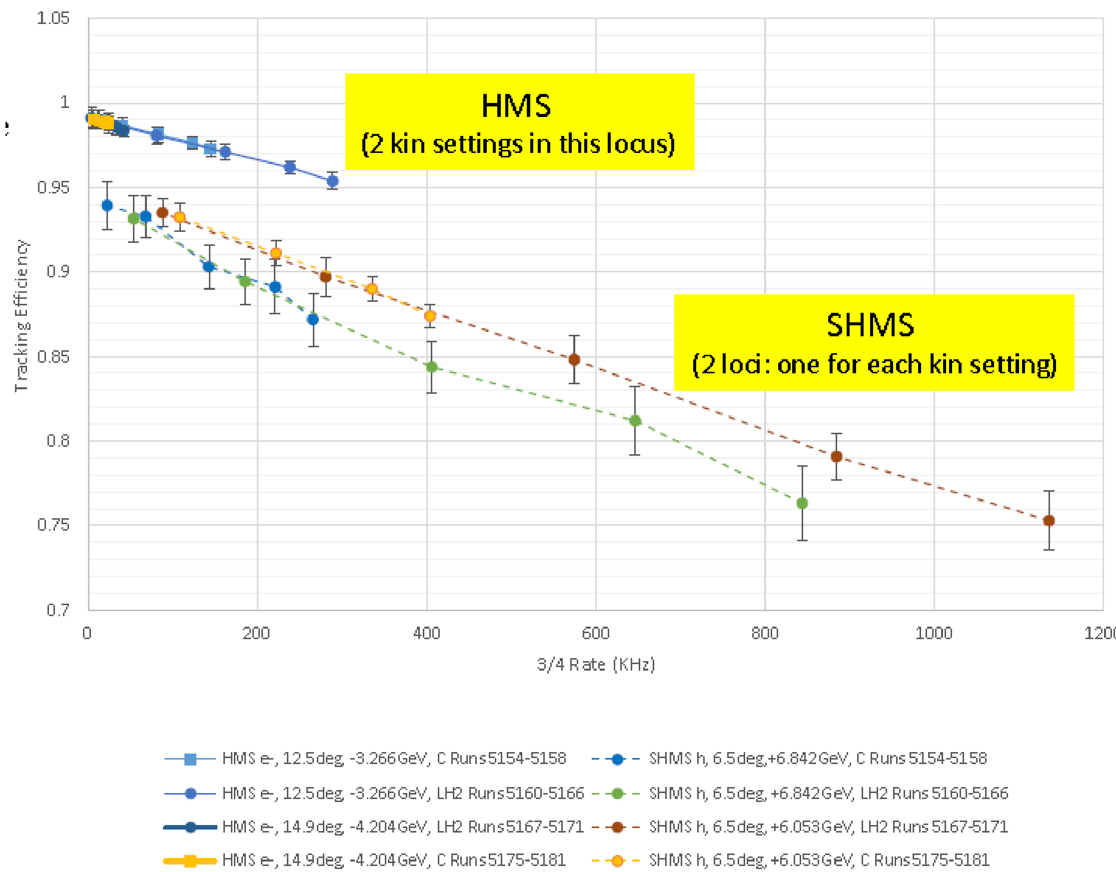
Fit using measured ε and ϕ dependence

Data Analysis - tracking

Analysis by D. Mack, R. Trotta

- ❑ Results are largely independent of target
- ❑ At a given ¾ rate, the 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%

From hclog 3625806 – analysis based on tracking efficiencies in KaonLT report files



Data Analysis – Luminosity scans

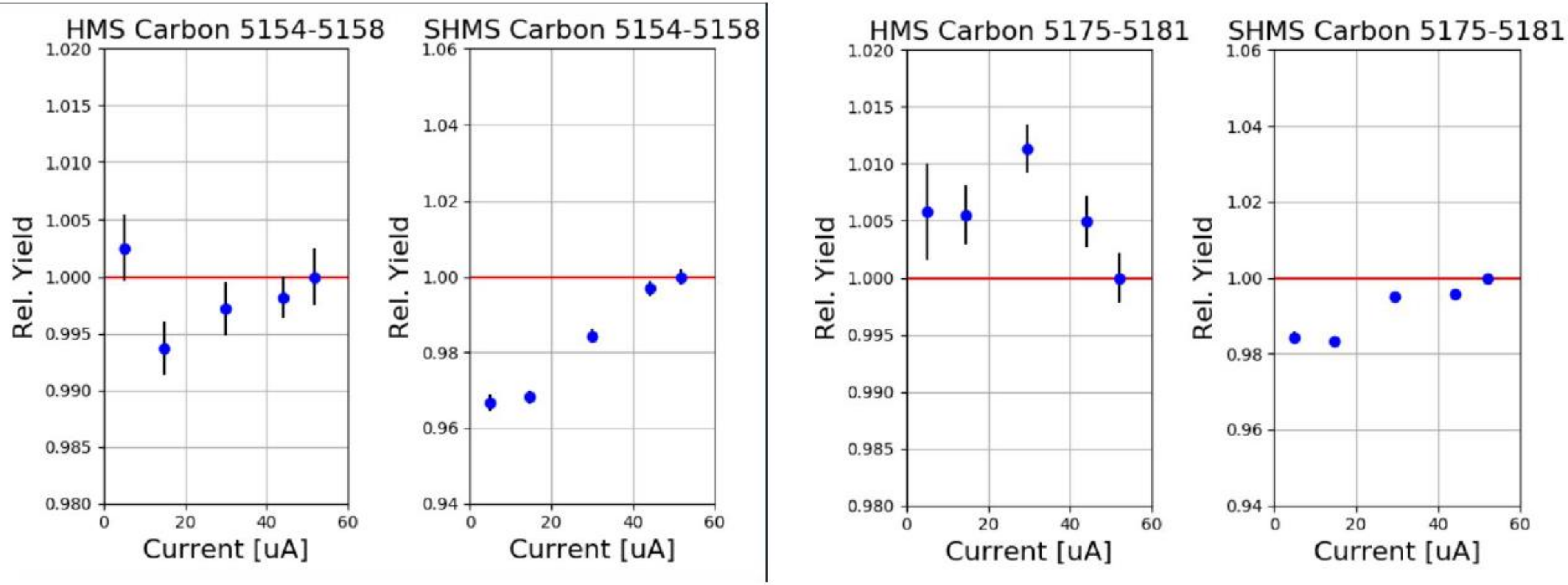
From Kaon_LT log 3645294 and 3645391

Analysis by R. Trotta, D. Mack

Most up to date plots (Carbon)

P_{HMS}=-3.266, Θ_{HMS}=12.50 P_{SHMS}=+6.842, Θ_{SHMS}=6.55

P_{HMS}=-4.204, Θ_{HMS}=14.51 P_{SHMS}=+6.053, Θ_{SHMS}=6.55



$$Y = \frac{N * PS}{Q * \varepsilon * cpuLT}$$

N= number of reconstructed events passing cuts on calo, cer, and SHMS aerogel

PS= prescale

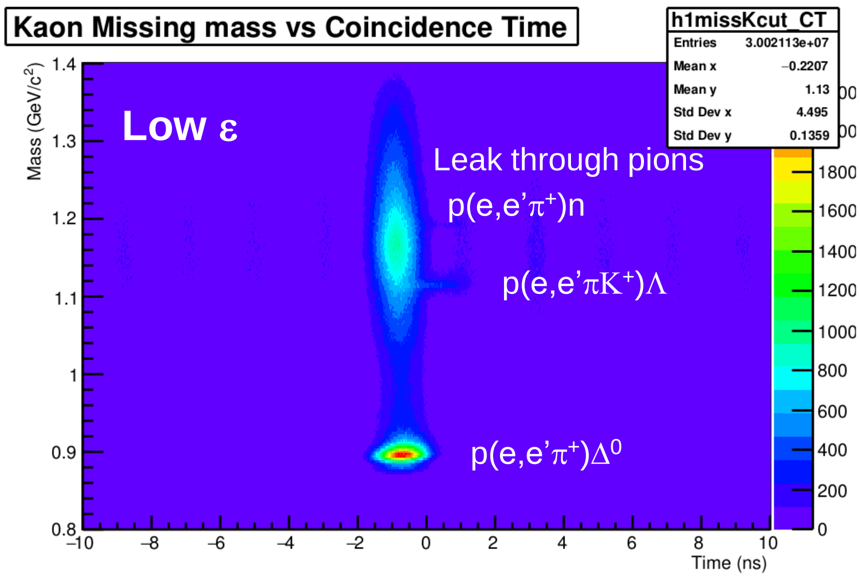
cpuLT calculated separately for HMS and SHMS

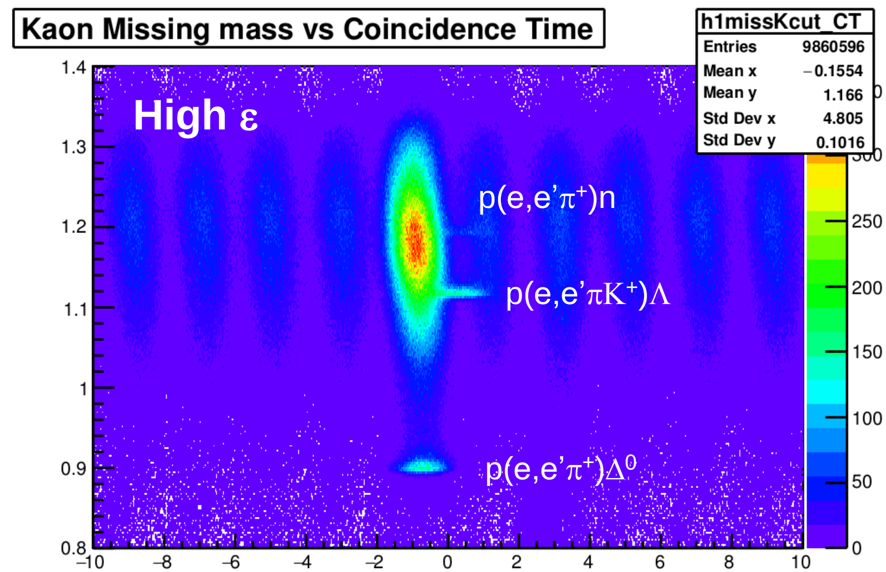
ε = tracking efficiency (HMS=electron, SHMS=hadron)

Interesting Physics in the other channels

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

KaonLT: Q^2=0.50 GeV^2





- Large increase in neutron missing mass at high epsilon is evidence of the pion-pole process at low Q^2 and small –t – suggests $\sigma_L >> \sigma_T$

- Δ^0 exclusive longitudinal cross section expected to be at best $\sigma_L \sim \sigma_T$

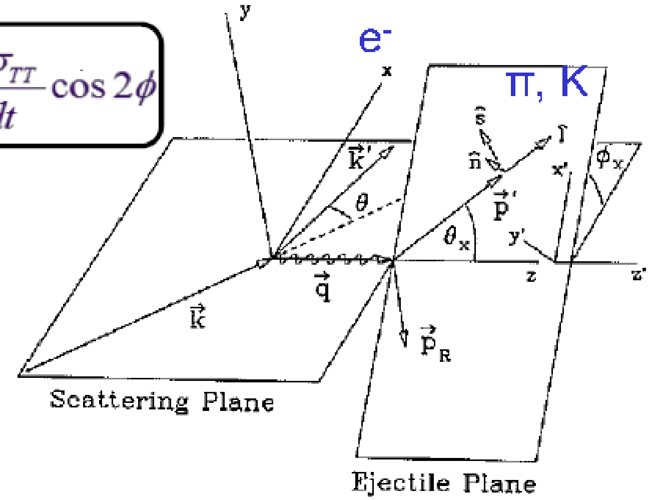
Physics Insight: Beam Single Spin Asymmetry

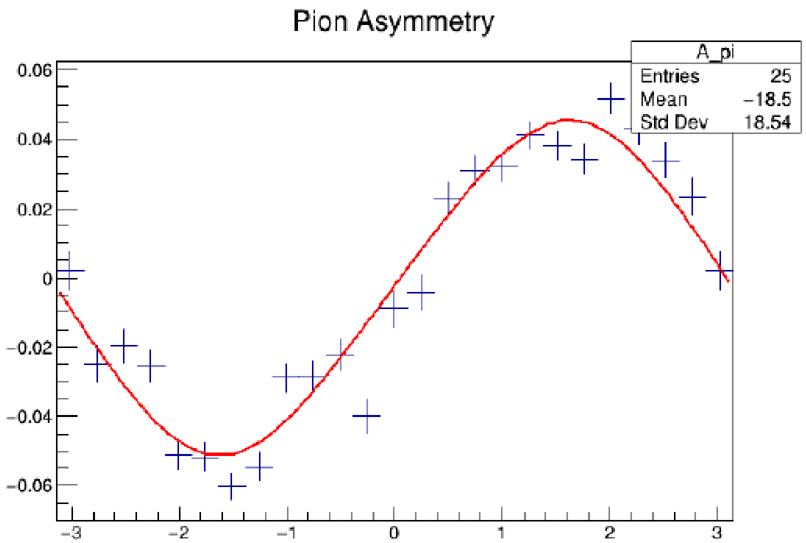
Analysis by S. Wood – see also his talk in the Monday session

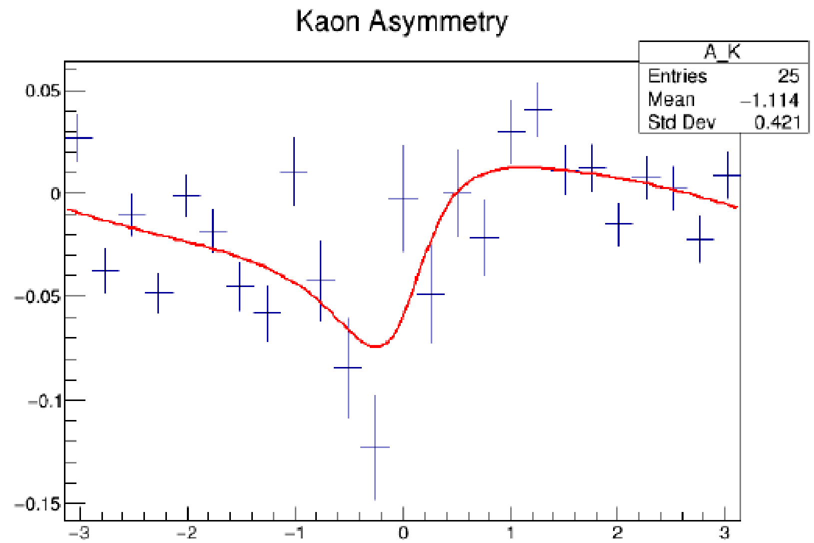
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Additional term if beam polarized $h \frac{d\sigma_{LT'}}{dt} \sin\phi$

Measure $A(\phi) = \frac{\sigma^+(\phi) - \sigma^-(\phi)}{\sigma^+(\phi) + \sigma^-(\phi)}$







KaonLT Current Status

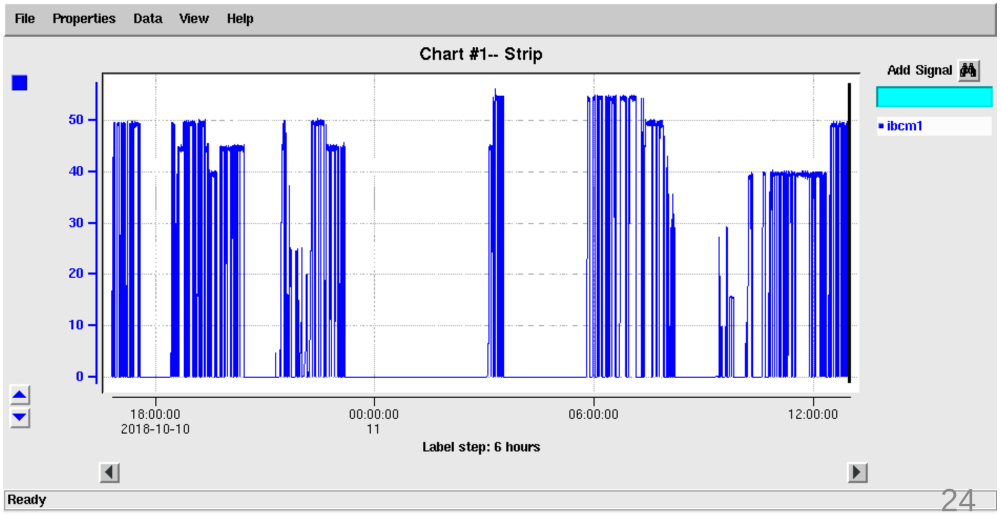
KaonLT experiment – status of completion

Setting	Low ε data	High ε data
Q^2=0.50 W=2.40	✓	✓
Q^2=2.1 W=2.95	✗	✓
Q^2=3.0 W=2.32	✗	✓
Q^2=3.0 W=3.14	✗	✓
Q^2=4.4 W=2.74	✗	✓
Q^2=5.5 W=3.02	✗	✓

- Experiment is ~60% done
  - Accelerator difficulties delayed the start of the experiment by ~5 weeks - most low ε settings had to be cancelled and are now rescheduled for March/April 2019
  - Additional difficulties with reaching desired beam currents and stability, in particular during Sept-Oct part of the run

- Some KaonLT requirements for March/April Run:
  - Small angle beam pipe
  - Aerogel n=1.011 tray
  - Prefer no NGC installed

From RC report 11 Oct. 2018 – beam current



Summary and Outlook

- **E12-09-011**: primary goal L/T separated kaon cross sections to investigate hard-soft factorization and non-pole contributions

- About 60% of data were taken in fall 2018 – almost all at high epsilon
  - For physics goal (L/T separations) require both, low and high ε data

- Remaining kinematic settings scheduled to run in March/April 2019 – standard beam energies: 6.4 and 8.5 GeV
  - Requires small angle beam pipe and has all the other challenges from last fall

- Initial data analysis ongoing

Thanks to the Hall A/C team for excellent support!