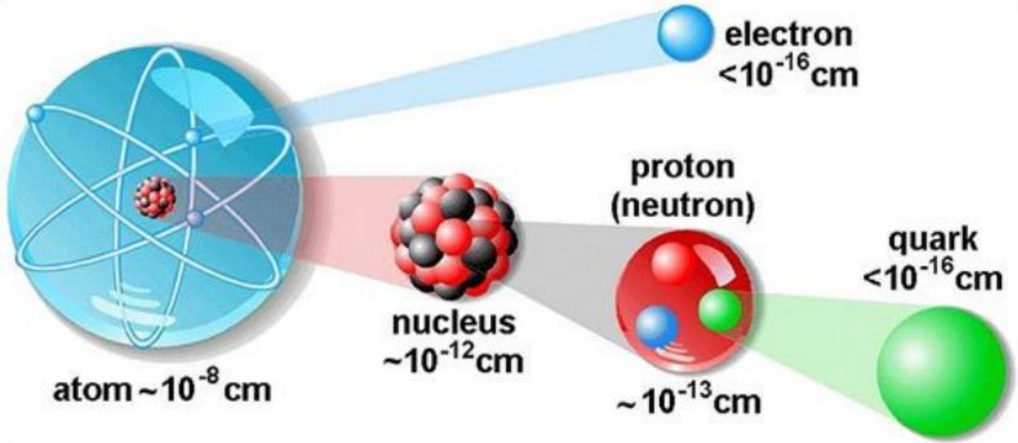
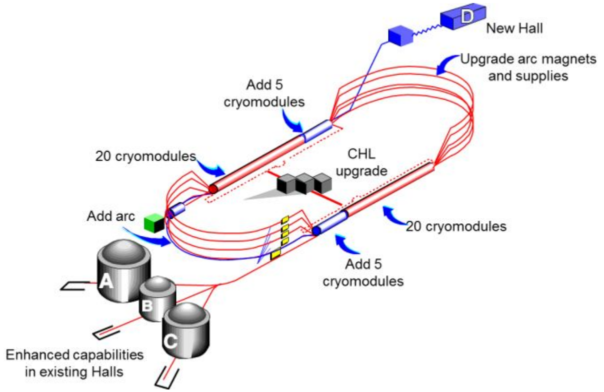




Studies of L-T Separated Kaon Electroproduction

Richard Trotta

Spokespeople: Tanja Horn, Garth Huber, Pete Markowitz

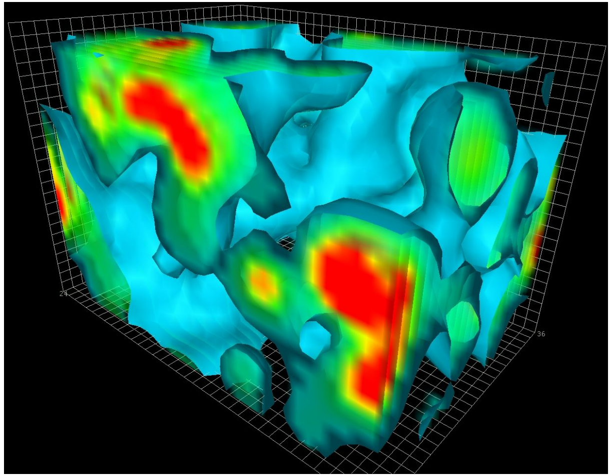
CUA

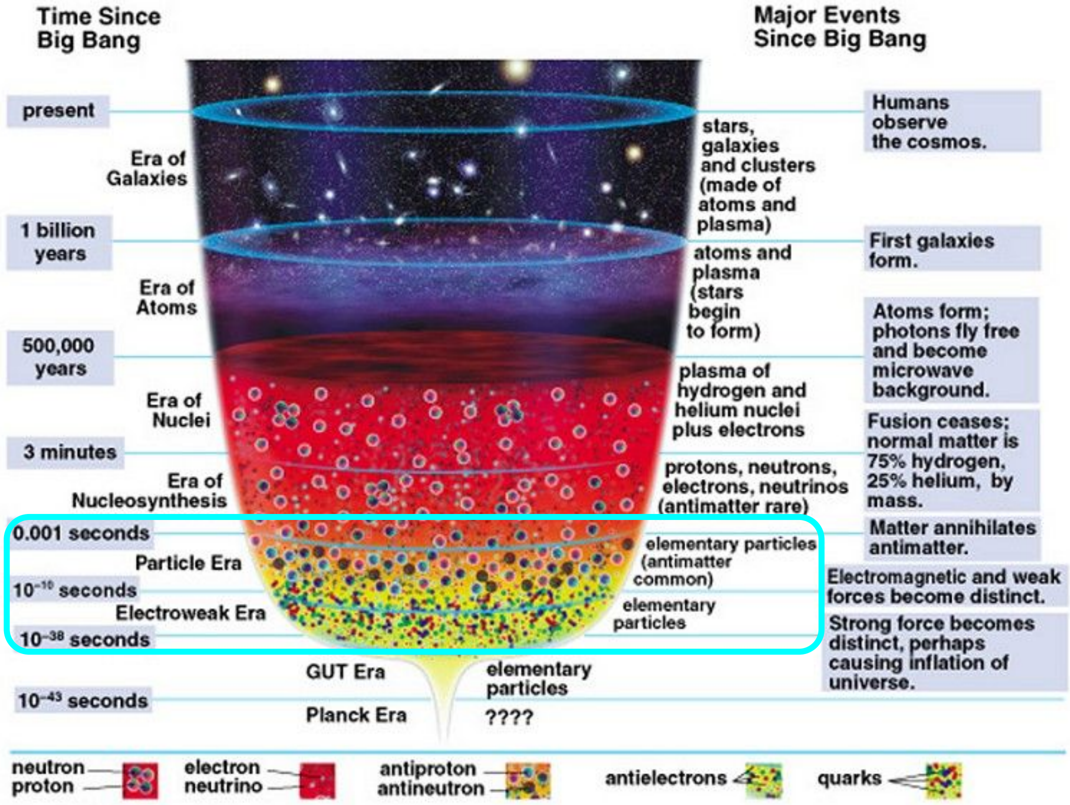
DEUS LUX MEA EST

Jefferson Lab

Particle and Nuclear Physics

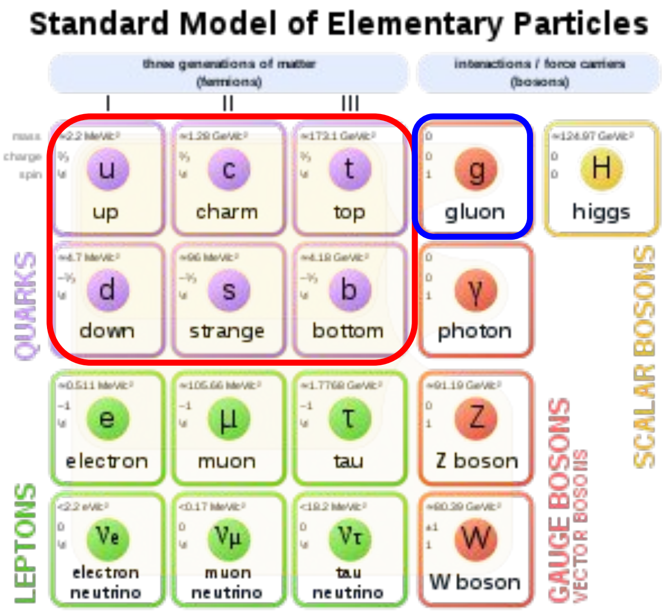
- Nuclear physics seeks to
    - Understand the fundamental structure of visible matter (i.e. quarks, gluons)
    - Understand how hadrons (i.e. mesons, nucleons) are formed





Try All Six Flavors!

- Quarks, similar to leptons, have six flavors
- Everyday matter is made of protons and neutrons, which are made of the light up and down quarks
- The strong force mediates massless gluons between quarks, like how photons are the mediating force carrier between charged particles
- These gluons interact with the up and down quarks, rapidly changing colors to make what we see as protons and neutrons
  - Hadrons are color-neutral bound states of quarks
    - three valence quarks (baryons)
    - valence quark-antiquark pair (mesons)

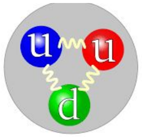


Is the Proton Pointlike?

- A microscope uses photons to see tiny objects, can we do something similar to view the proton?
  - Very very very high momentum photons would be needed

$$\Delta x \geq \frac{\hbar}{2\Delta p}$$

  - Why not use a similar probe with easier to access momenta?
  - Let's use the de Broglie Wavelength for motivation

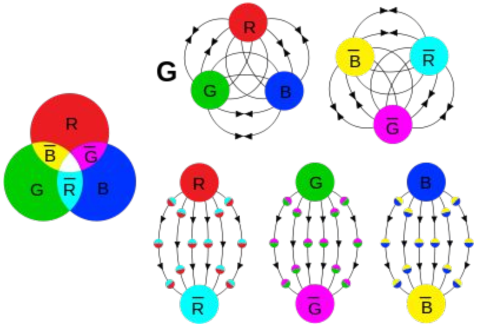


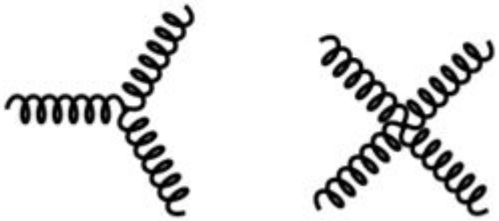
$$d_{probe} \propto \lambdabar = \frac{\hbar}{p}$$

- The proton interacts electromagnetically, so we use a lepton (e.g. electron) with a high momentum as a probe.

What is Quantum ChromoDynamics (QCD)?

- QCD is the theory describing strong force interactions through color-charged particles (quarks)
    - The strong force holds together protons and neutrons
    - Color is a quantum number
        - Quarks come in three colors; red, blue, green
        - Antiquarks come in three anticolors; antired, antiblue, antigreen

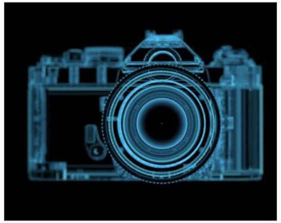




- Gluons generate a color change for quarks (for the more advanced $SU_c(3)$), but they also can self interact (unlike photons in E&M)

Coming to a finer resolution

- QCD and QED are both relativistic quantum gauge-field theories which have the property that nothing is constant
  - Beloved quantum mechanical cornerstones are now dynamic, including charge distribution, mass, and even the number of particles
- This means that what you see depends on the wavelength of the probe used
  - Think about the wavelength of light for a photo vs. a xray



$$\lambda \simeq \frac{1}{\sqrt{Q^2}}$$

Momentum transfer

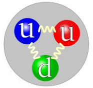
- This also means the strength of the force depends on the resolution, a so called mass-scale

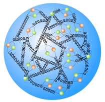
Dynamical Nature of QCD

- The dynamical nature of QCD also affects what we know as a “quark”
- The uncertainty principle can be viewed as an inequality of energy and time
  - Nearly infinite energies can exist as long as they disappear incredibly fast

$$\Delta x \Delta p \geq \frac{\hbar}{2} \Rightarrow \Delta E \Delta t \geq \frac{\hbar}{2}$$

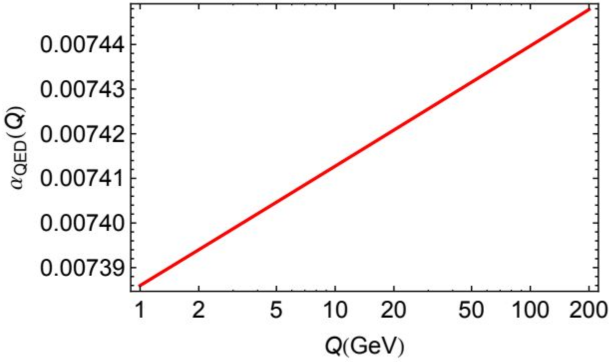
  - This is how virtual particles arise in quantum field theories
- But now in QCD these virtual particles (virtual quarks and gluons) interact with the valence quarks that make up a proton
- Probing at different scales we can see three distinct “quark” types
  - At ~30% the fractional longitudinal momentum of the proton (a variable called x) we see the valence quarks
  - At ~10% we see a cloud of pions where the valence quarks are hidden in. (Partons we call them)
  - At ~1% we see the singlet quarks and gluons

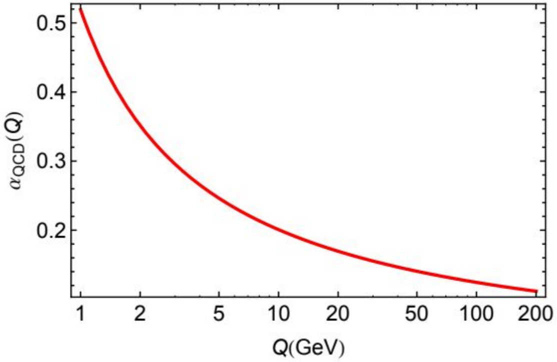




Asymptotic Freedom

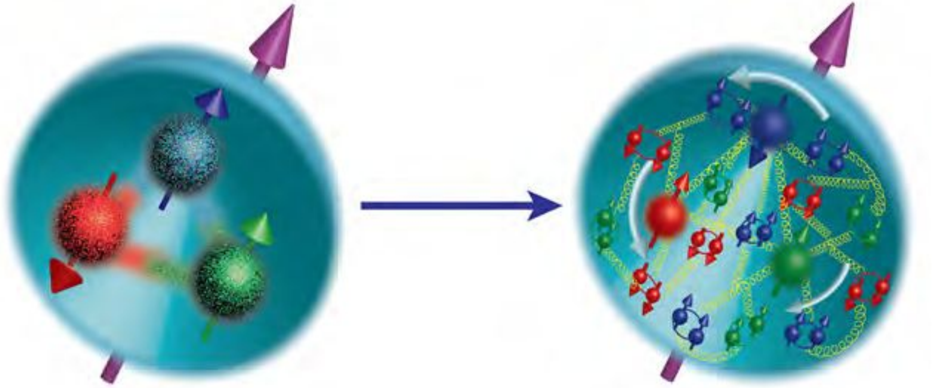
- At a higher mass-scale, the strong force asymptotically falls off. A feature known as asymptotic freedom.
- This allows QCD to be studied perturbatively at high energies
- Finding the onset of hard (perturbative QCD, pQCD) and soft (non-perturbative QCD) factorization is of critical importance in medium to high-energy physics
    - A scaling behavior in the parton model should show a dependence on transferred momentum (Q^2) at higher order corrections



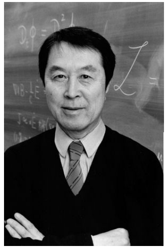


Summary of QCD

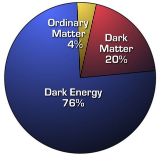
- QCD is characterized by two emergent phenomena:
  - confinement
  - dynamical chiral symmetry breaking (DCSB)
- The bound state degrees of freedom can be viewed through two lenses
  - Hadrons at large distance scales
  - Partons at small distance scales
- This transition from hadronic to partonic degrees of freedom is required to characterize hadrons ab initio
- Upgraded and new facilities, like Jlab and the EIC, will provide data to shed light on these transitions and guide theory models



Dynamical Chiral Symmetry Breaking



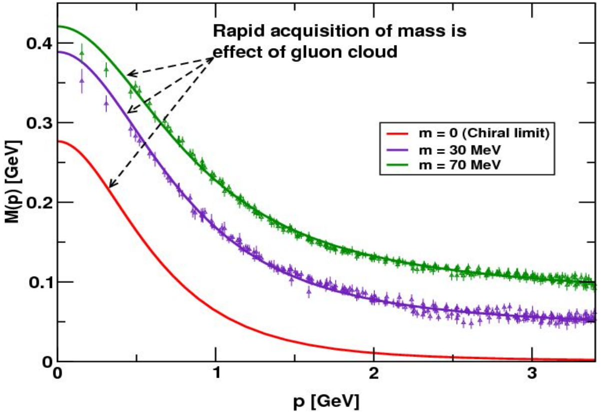
- But what is Dynamical Chiral Symmetry Breaking (DCSB)???
- Higgs boson gives valence quarks mass
  - This only contributes <1% the proton mass
  - Where does the rest of the mass come from? Well, DCSB!
  - This means that 98% of all visible matter comes from DCSB!



- This is because of a spontaneously broken symmetry, chirality (left and right "handedness")
- The best way to study DCSB is primarily through the pion (and as we will subsequently the kaon)
- Chiral symmetry requires the pion to be partnered with a scalar meson of equal mass
  - There is no evidence for the existence of such a particle
  - No other properties of chiral symmetry are apparent in nature so the symmetry must be broken

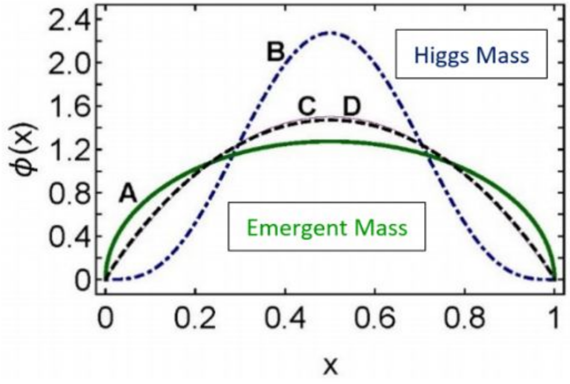
Pion Mysteries

- The pion consists of an up quark and down antiquark so it is the simplest system to study light quarks, but also has many other unique properties
- The pion's mass is just a fifth what is expected in quantum mechanics
  - This can be contributed to symmetry constraints imposed by DCSB
  - These constraints lead to cancellations by (negative) gluon binding effects
  - This makes the pion a pseudo Nambu-Goldstone boson
- All this means that finding the origin of the proton's mass is the same as asking why the pion is so light, which is the connection between confinement and DCSB



What a Strange World!

- What about heavier quark bound states?
- The data suggests that heavier flavor quark mass is primarily generated through the Higgs mechanism
- The kaon sits in a unique position because its quark composition is both light and heavy
  - The kaon consists of an up quark and a strange antiquark
  - A competition seems to arise between DCSB and the Higgs mechanism
- The kaon is also a pseudo Nambu-Goldstone boson which makes it a prime candidate for deeper DCSB studies

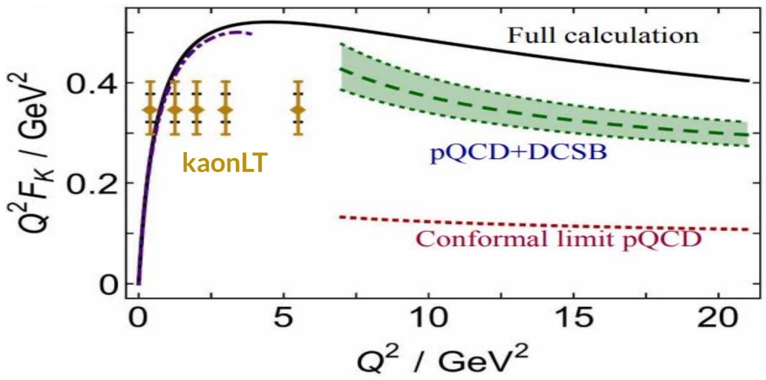


Meson Form Factors at Jlab

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

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

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



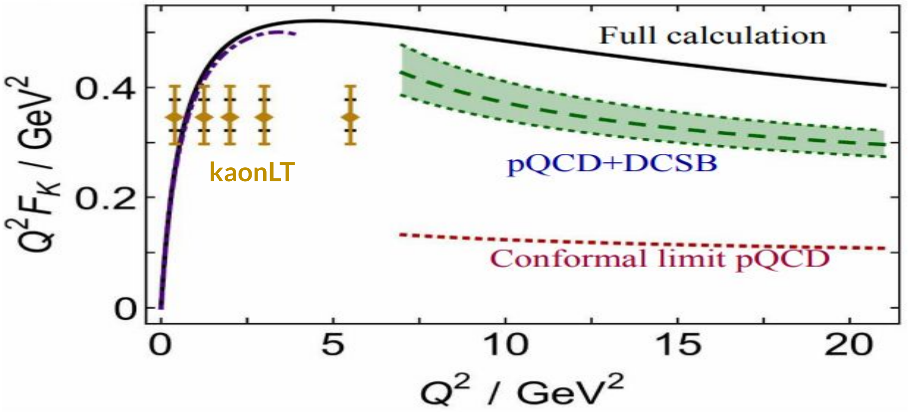
What is the Form Factor?

- We want a way to see how quarks are distributed in the pion/kaon
- QED is well understood so we exploit the charge of quarks
- There are two types of form factors used
  - Electric form factor (G_E), charge
  - Magnetic form factor (G_M), current
- The form factor is the fourier transform of the transverse spatial charge density
  - **1D function** dependent on the transferred momentum (Q^2)
- We can get the form factor from the cross-section

Point-like cross section

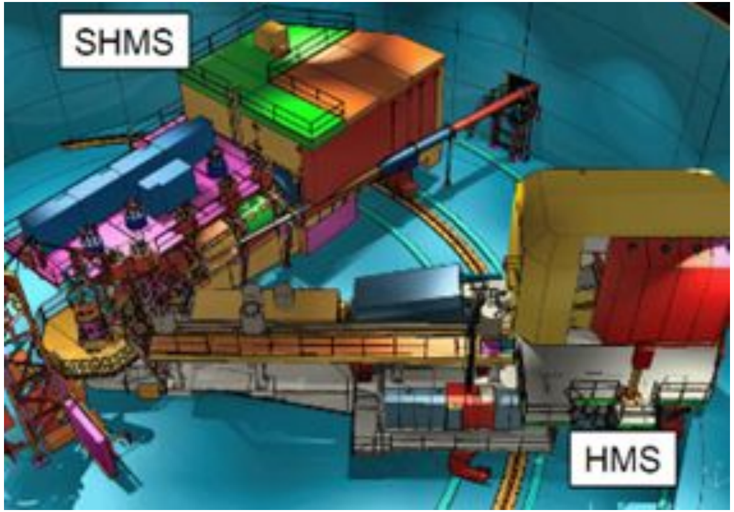
$$\frac{d\sigma}{d\Omega} = \boxed{\left(\frac{d\sigma}{d\Omega}\right)_{Mott}}\boxed{|F(Q^2)|^2}$$

Form Factor



Review E12-09-011 (KaonLT) Goals

- First kaon experiment at high enough energies for non-perturbative studies
  - Need very high precision, which only focusing spectrometers can do
  - SHMS in Hall C was built for this purpose
- Q^2 dependence will allow studying the scaling behavior of the separated cross sections
- t-dependence allows for detailed studies of the reaction mechanism
  - Contributes to understanding of the non-pole contributions, which should reduce the model dependence
  - If warranted by data, extract the kaon form factor

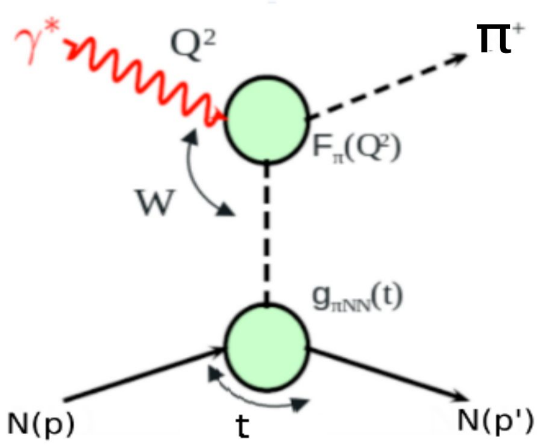


Experimental Determination of the π/K$^+$ Form Factor

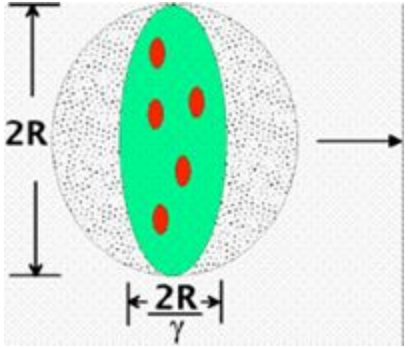
- At larger Q^2, $F_{\pi+}{}^2$ must be measured indirectly using the "pion cloud" of the proton via the p(e,e'π^+)n process
  - At small –t, the pion pole process dominates σ_L
  - In the Born term model, $F_{\pi+}{}^2$ appears as

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

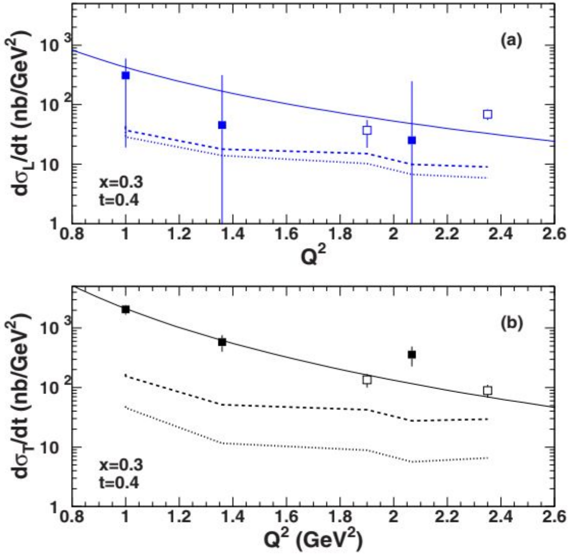
- Pole comes from the fact that π/K$^+$ are not real (i.e. pion cloud), but can be treated as real if the pole dominates σ_L at small t
  - This is needed for validation that the form factor can be extracted
- For the same Q^2 values, one can fit several σ_L values for different virtual photon polarizations (ε).



Hard-Soft Factorization



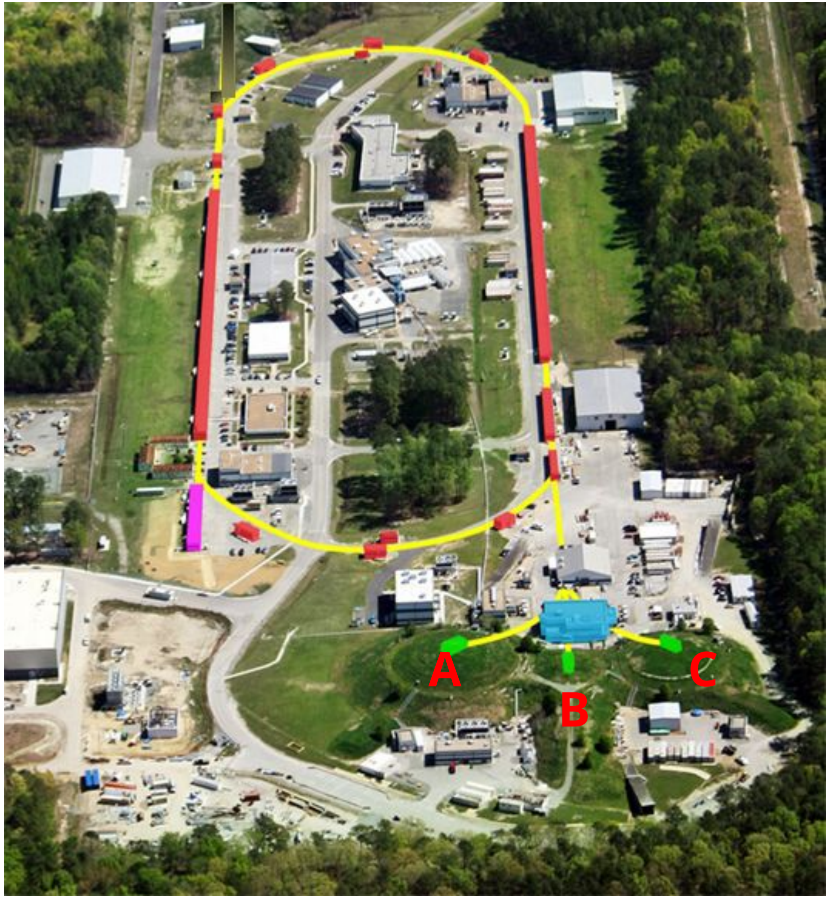
- The K^+ electroproduction cross section has a Q^2 dependence at fixed x and -t
  - Factorization of σ_L scales to leading order Q^{-6}
  - In that regime expect σ_T to go as Q^{-8} and consequently $\sigma_L \gg \sigma_T$
  - Important because partons are "frozen" transversely in the reference frame of pQCD (i.e. infinite momentum frame)
- 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*

Jefferson Lab Continuous Electron Beam Accelerator Facility (Jlab CEBAF)

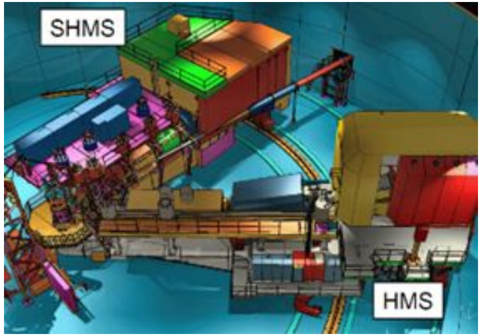
- 1995-2012:
  - Energies 0.4-6.0 GeV
  - 200 μA, 85% polarization
  - Simultaneous beam delivery to 3 halls

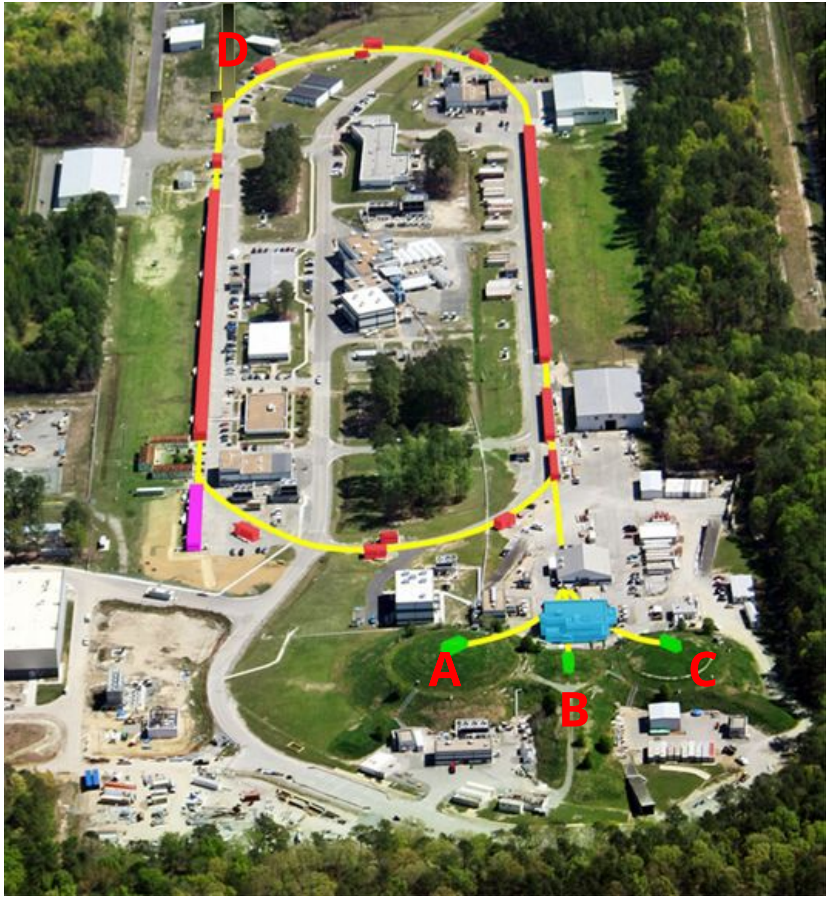


Jefferson Lab Continuous Electron Beam Accelerator Facility (Jlab CEBAF)

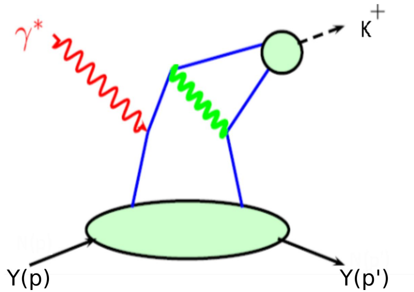
- 1995-2012:
  - Energies 0.4-6.0 GeV
  - 200 μA, 85% polarization
  - Simultaneous beam delivery to 3 halls
- 2016-:
  - Energies 0.4-12.0 GeV
  - 150 μA, 85% polarization
  - Simultaneous beam delivery to 4 halls

Hall C

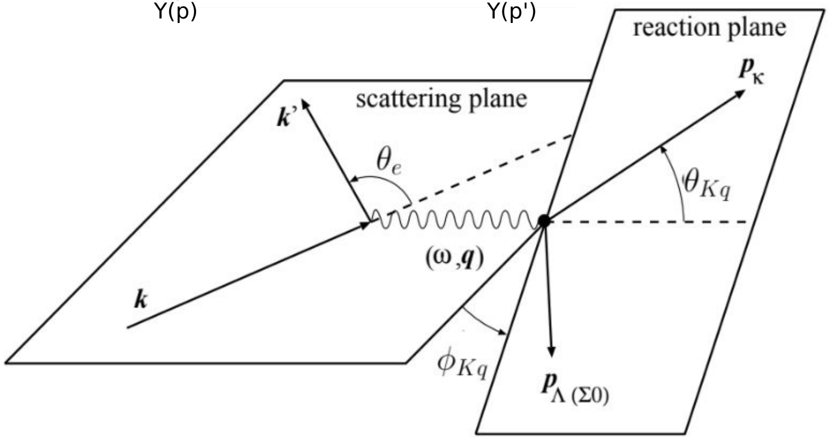




Exclusive K^+ Electroproduction



- $p(e, e'K^+)\Lambda(\Sigma^0)$
- Scattering Plane
  - Incident electron, k
  - Virtual photon, q
  - Scattered electron, k'
  - The incident electron scatters off the proton at an angle θ_e.
- Reaction Plane
  - Kaon, p_K
  - The kaon ejectile scatters at angle θ_{Kq}
  - The remaining proton energy (now a hyperon), $p_{\Lambda(\Sigma)}$
- ϕ_{Kq} is the azimuthal angle between the planes

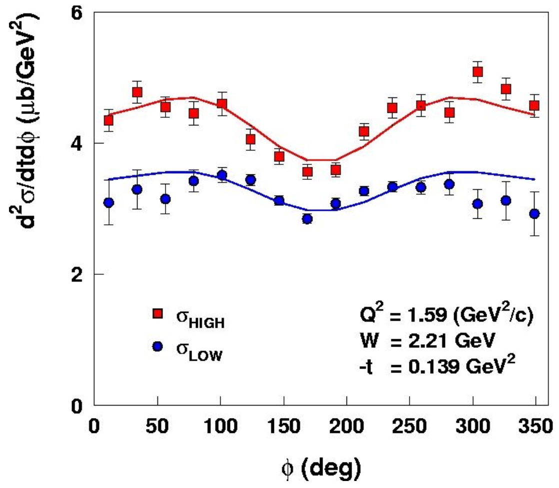


- The exclusive products are the scattered electron and Kaon, while the missing hyperon mass is calculated explicitly

L/T Separation Basics

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

σ_L will give us F^2_{K+}



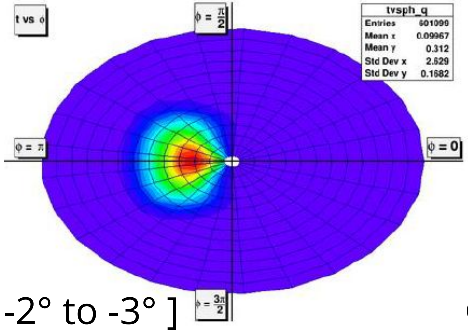
*T. Horn et al., PhysRevC **97**(2006)192001*

- σ_L is isolated using the Rosenbluth separation technique
- Measure the cross section at two beam energies and fixed W, Q^2, -t
  - A high and low ε value
- Full azimuthal coverage, ϕ, will eliminate the interference terms
- Simultaneous fit using measured azimuthal angle (ϕ) allows for extracting L, T, LT, and TT
  - σ_L -> slope
  - σ_T -> y-intercept

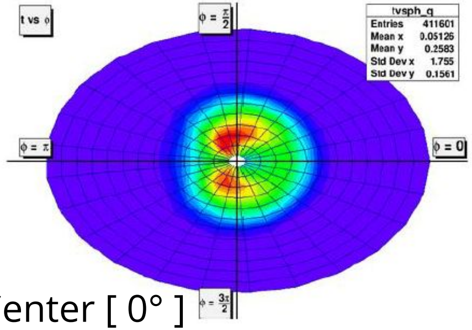
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt}$$

L/T Separation Example

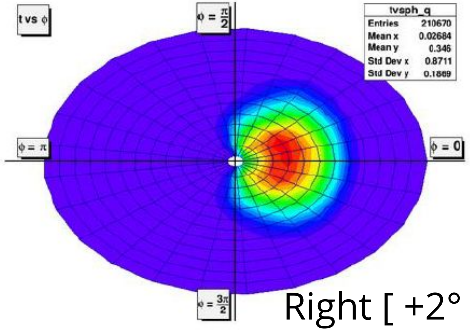
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$



Left [-2° to -3°]

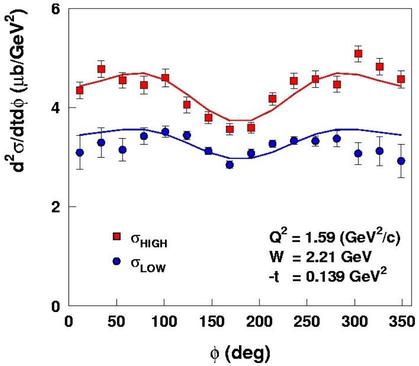


Center [0°]



Right [+2° to +3°]

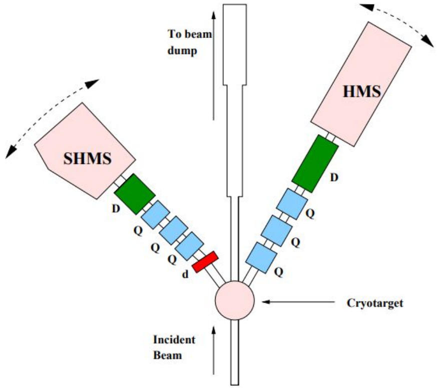
- Three SHMS angles for azimuthal (ϕ) coverage to determine the interference terms (LT, TT)
- Using the two beam energies (ε) to separate longitudinal (L) from transverse (T) cross section



Fit using measured ε and ϕ dependence

Kaon LT - Data Collected

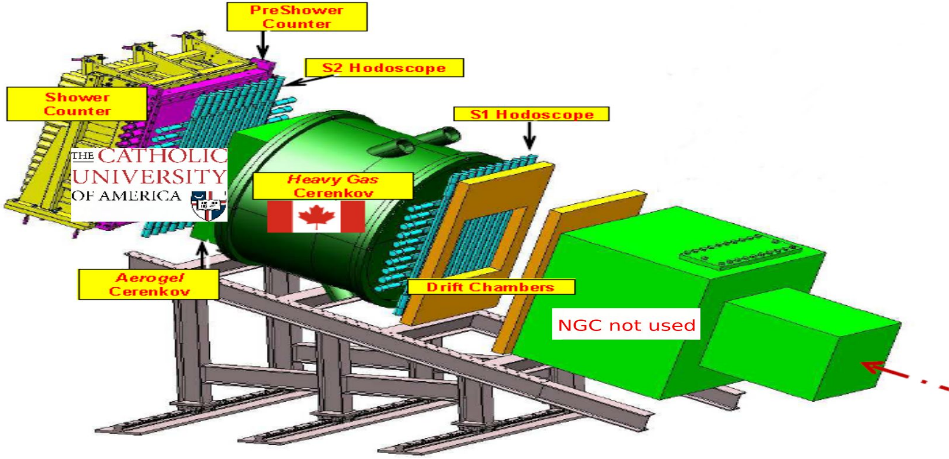
- The $p(e, e'K^+)\Lambda,\Sigma^0$ experiment ran in Hall C at Jefferson Lab over the fall and spring.

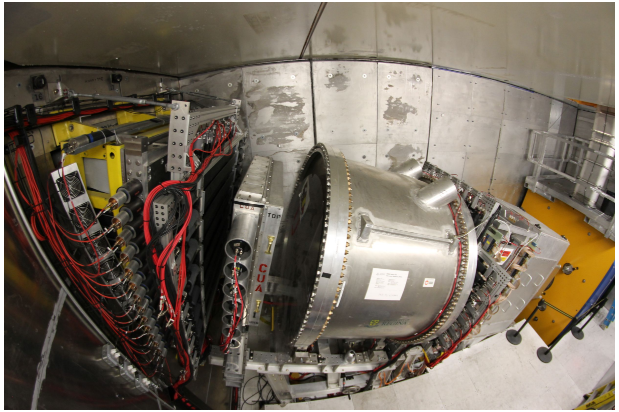


E (GeV)	Q^2 (GeV^2)	W (GeV)	x	$\varepsilon_{high}/\varepsilon_{low}$
10.6/8.2	5.5	3.02	0.40	0.53/0.18
10.6/8.2	4.4	2.74	0.40	0.72/0.48
10.6/8.2	3.0	3.14	0.25	0.67/0.39
10.6/6.2	3.0	2.32	0.40	0.88/0.57
10.6/6.2	2.115	2.95	0.21	0.79/0.25
4.9/3.8	0.5	2.40	0.09	0.70/0.45

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

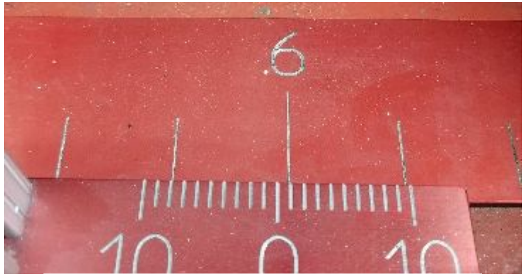


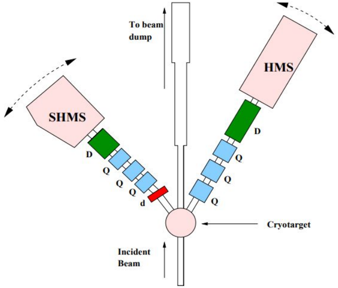


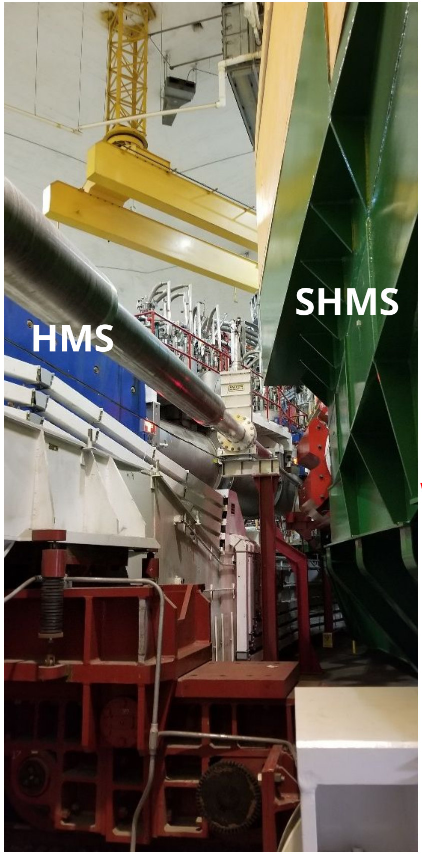
SHMS small angle operation

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

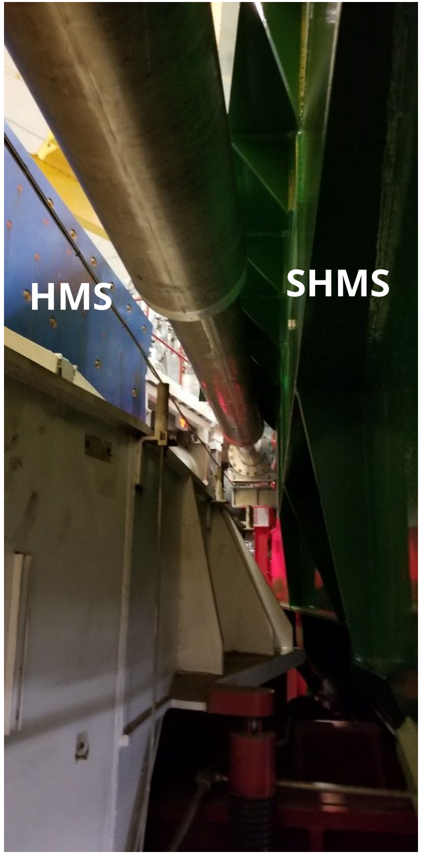
[12/17/18]







Work of many people ...



KaonLT Event Selection

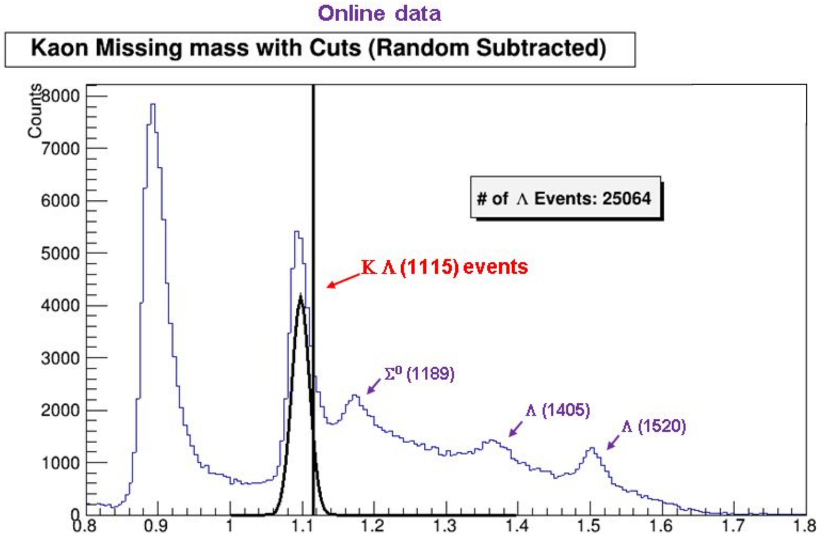
- Isolate exclusive final states through missing mass

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

- 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

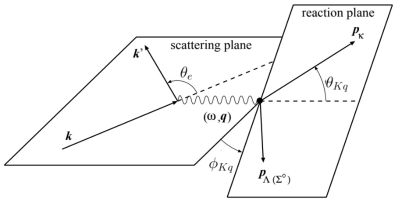
$$\frac{\sigma_L(\gamma^* p \to K^+\Sigma^0)}{\sigma_L(\gamma^* p \to K^+\Lambda)}$$

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



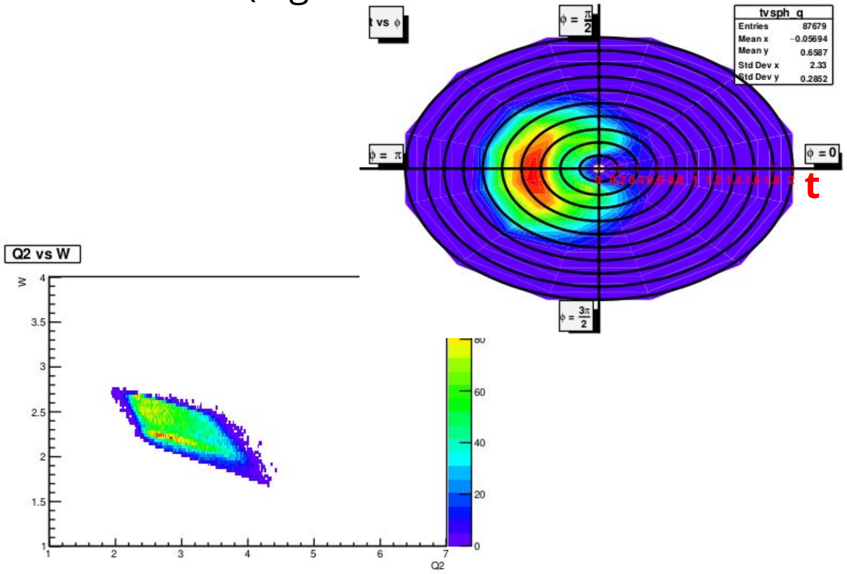
Plot by R. Ambrose, S. Kay, R. Trotta

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

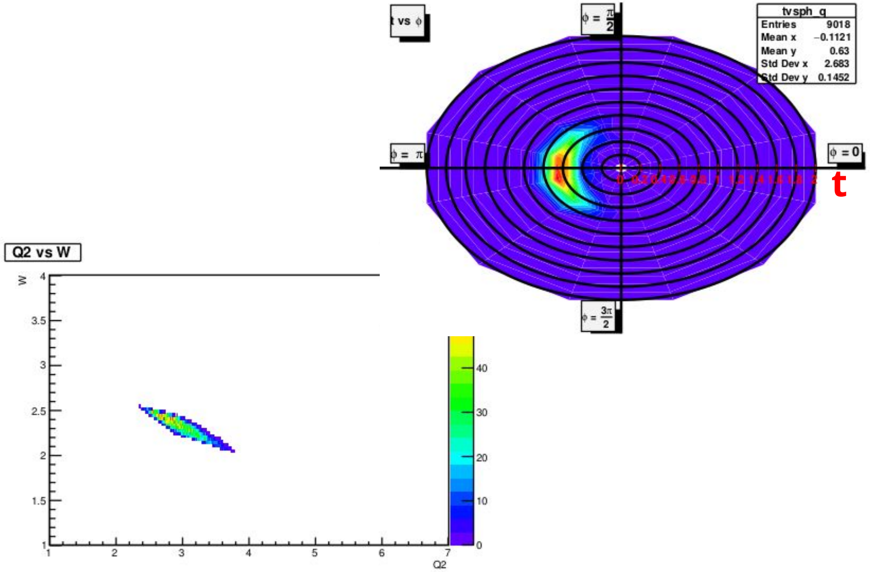


- [10.6 Gev (high ε), 6.2 Gev (low ε)]
- Left (θ_{high}=21.18,θ_{low}=16.28)

10.6 GeV (high ε)



6.2 GeV (low ε)



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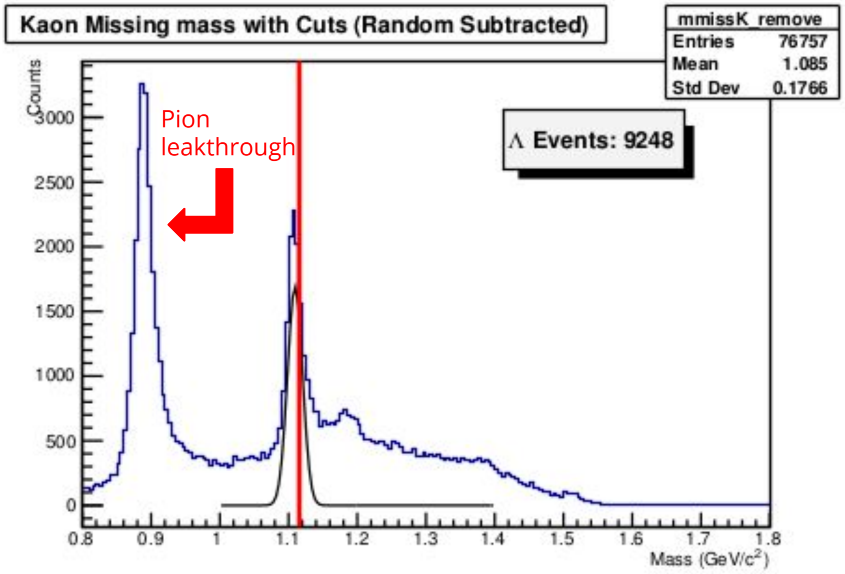
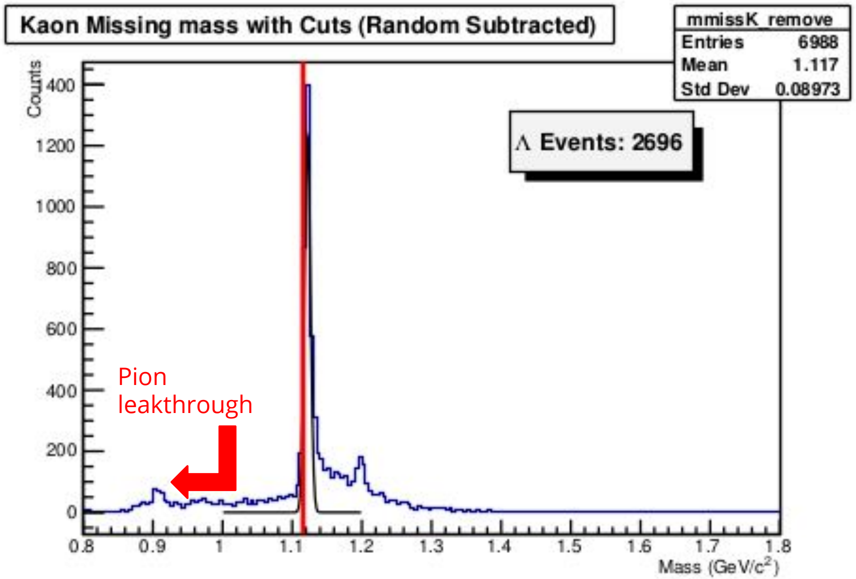


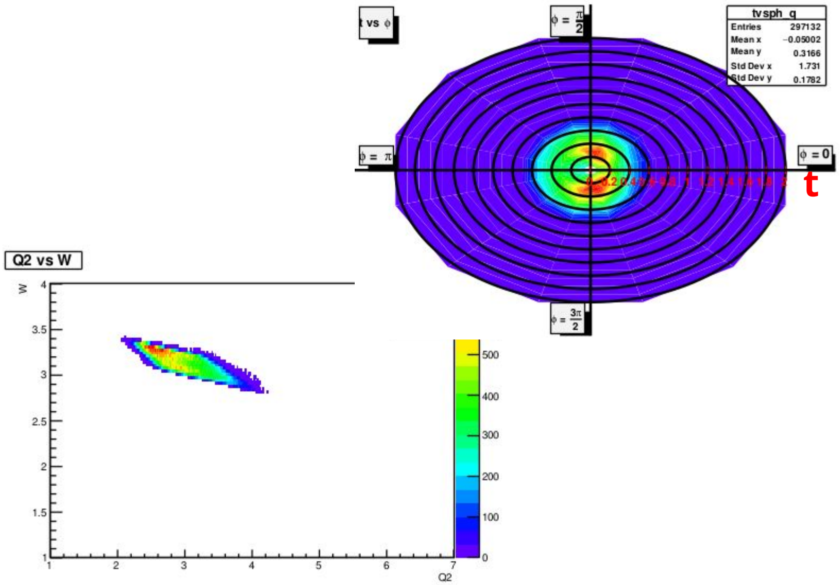
6.2 GeV (low ε)



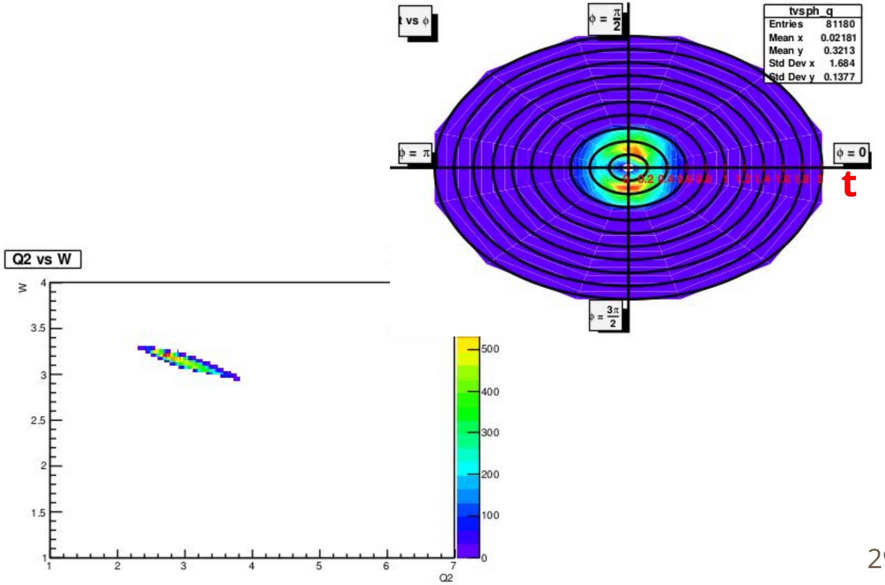
Comparison of high and low ε [Q^2=3.0, W=3.14, x=0.25]

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

10.6 GeV (high ε)



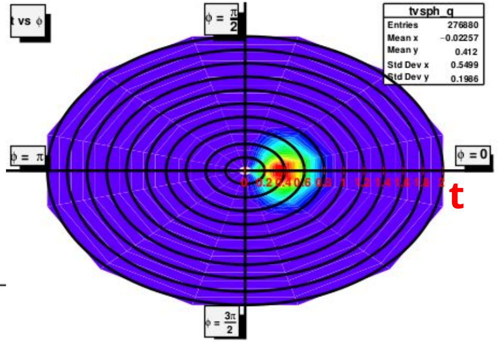
8.2 GeV (low ε)

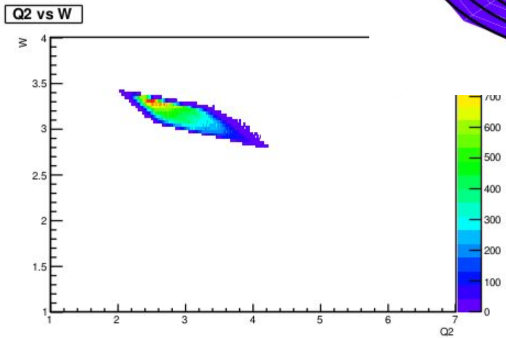


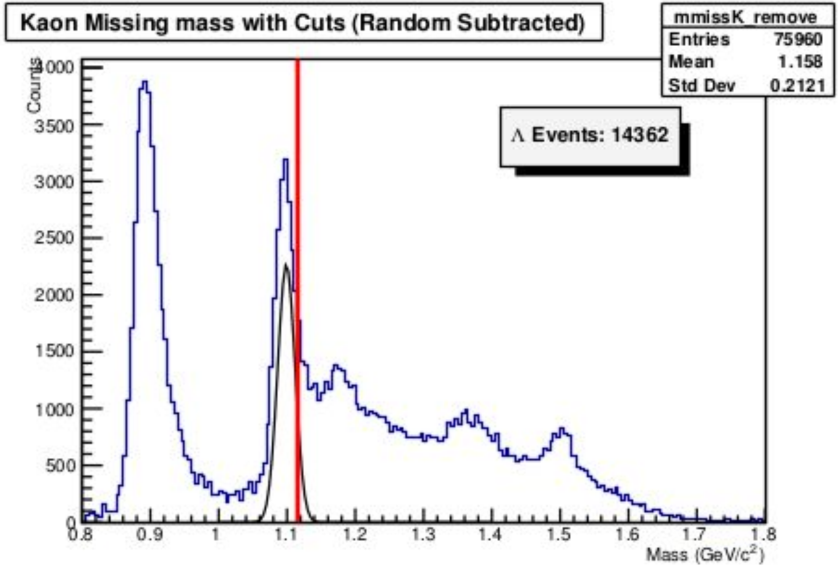
Comparison of high and low ε [Q^2=3.0, W=3.14, x=0.25]

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

10.6 GeV (high ε)







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 2.1: Previous luminosity/tracking analysis

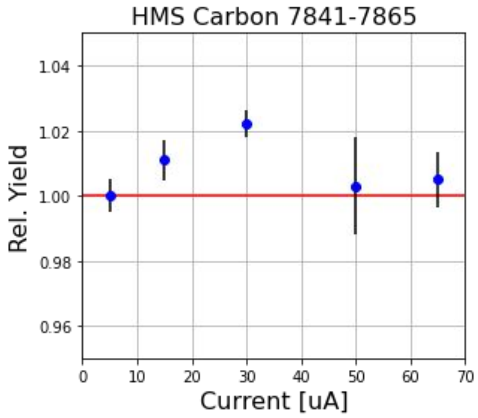
- Singles luminosity scans has been previously looked out with online data

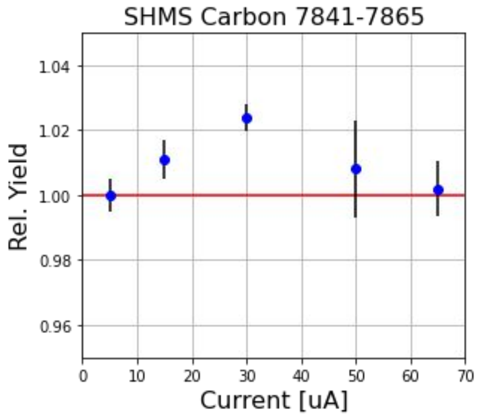
- Relative yield has been reduced to ~2% spread for carbon target

- Early on tracking efficiencies were 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

    - Many of these issues have been fixed after a in depth analysis of many groups

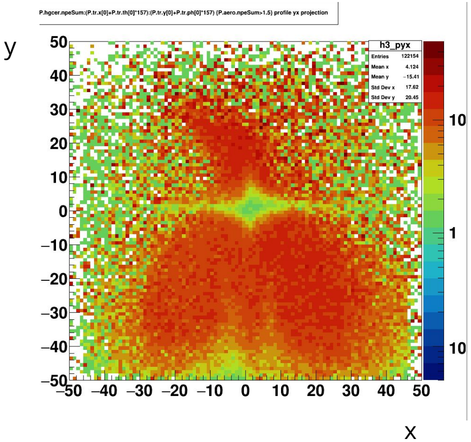




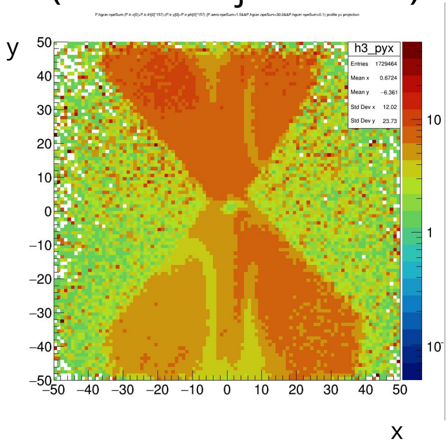
Phase 2.1: HGCer Challenges

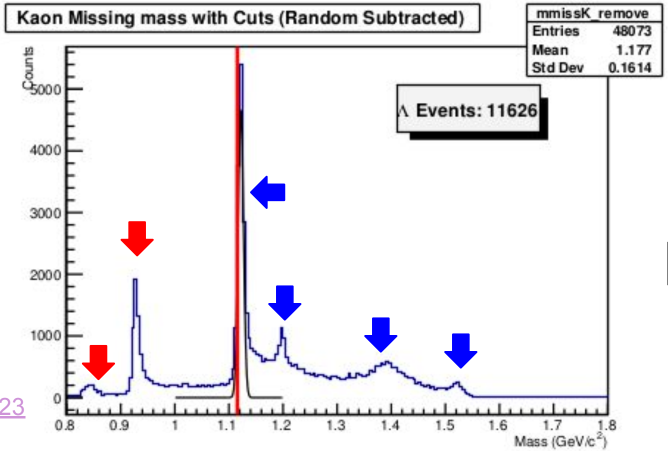
- A hole in the HGCer will allow unwanted pions and accidentals
- An in depth analysis will be required for proper efficiency determination
- This hole is already causing visible issues

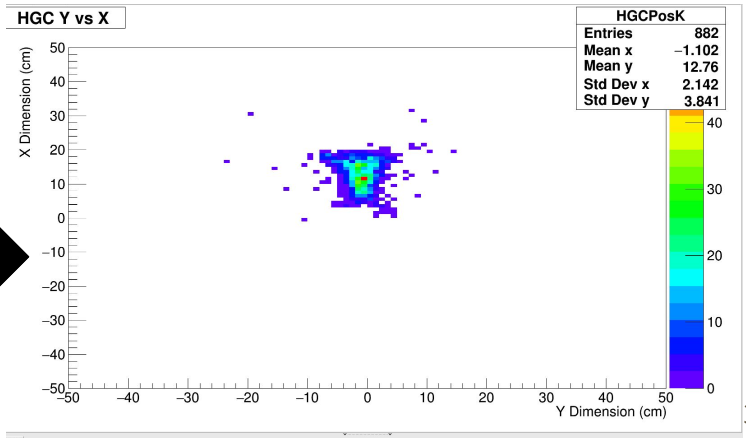
Fall



Spring
(After readjustments)







Stephen Kay analysis
https://logbooks.jlab.org/entry/3676623

Phase 2.2: Heep Runs

E (GeV)	$-P_{SHMS}$ (GeV)	$-P_{HMS}$ (GeV)	Type	Target	Current (uA)
10.6	6.30-8.04	5.32-6.59	Single+ COIN	LH2	10,15,30,35,40
8.2	4.35-5.75	4.35-5.75	Single+ COIN	LH2	65,70
6.2	3.28-3.94	2.94-3.71	Single+ COIN	LH2	25,50,65,70
4.9	2.58-4.64	2.58-4.37	Single+ COIN	LH2	10,35,70
3.9	2.48-3.01	2.03-3.01	Single+ COIN	LH2	50

Conclusion

- QCD is the theory describing the internal working of the proton and neutron
- Confinement and DCSB are the two emergent phenomena characterizing QCD
- The pion, being a pseudo Nambu-Goldstone boson, is the cleanest way to further studies of DCSB
- Kaon can provide an interesting way to expand previous data of charged pion form factor with access to the mechanism involving strangeness
- E12-09-011 has completed its 2018-19 run
- Potential to extract the Kaon form factor from the L/T separated cross sections to the highest Q^2 achievable at Jlab
- Potential to provide much needed data for Q^2 scaling at fixed x and -t in Kaon electroproduction to validate QCD factorization for hadron imaging studies
- Currently in the second phase of analysis

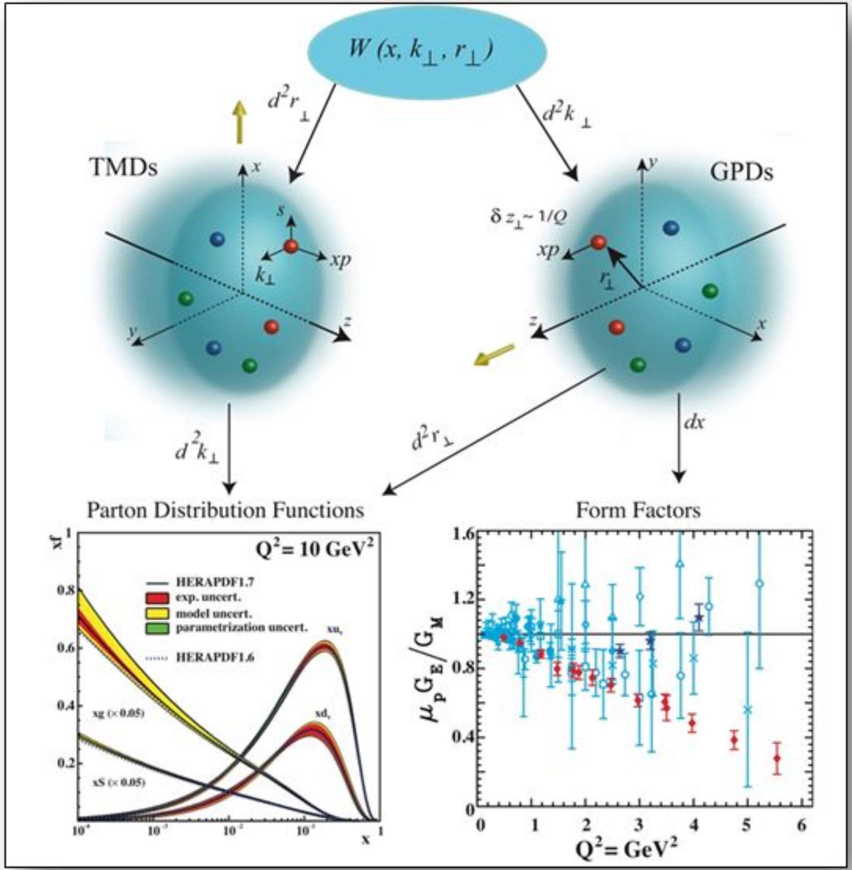
Extra Slides

Bringing it All Together

- ❑ We discovered that (nearly) massless quarks and gluons make up the nucleon and that QCD governs their interactions.
- ☐ We had hoped to find out how quarks and gluons and their interactions give rise to the characteristics of the nucleons.
  - Spin
  - Mass
- ☐ We also hoped that we would be able to find out how nucleon-nucleon interactions work in terms of QCD.
  - How nuclear forces arise?
  - How do nuclear characteristics come about?
- Need something beyond a 1D form factor description...

Meson Structure in 3D

- Form factors are vital in understanding internal hadronic structure and dynamics
- The 3D imaging of a nuclei uses Generalized Parton Distributions (GPDs) and Transverse Momentum-dependent parton Distributions (TMDs)
- TMDs: Confined motion in nucleon (semi-inclusive DIS)
- GPDs: Spatial imaging (exclusive DIS)
- Requires…
    - High luminosity
    - Polarized beams and targets



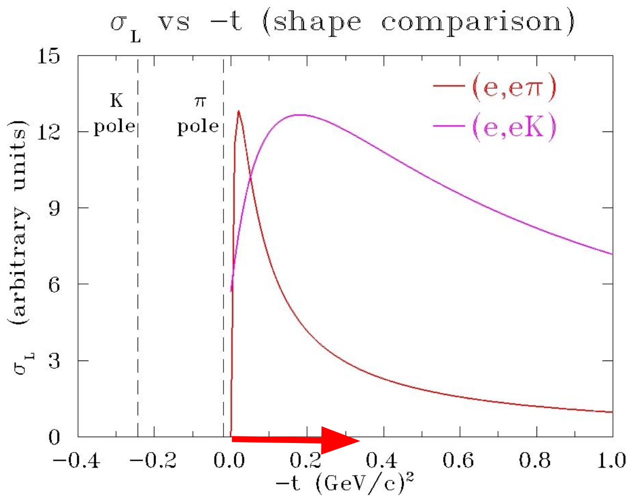
Comparing π and K⁺ Form Factor

- Large pion t data lies a similar distance from the pole as kaon data
  - The Born term model should be approximately valid for kaon form factor

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

- 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 pion pole process
  - Extraction of the form factor using a model
  - Validation of the technique - model dependent checks

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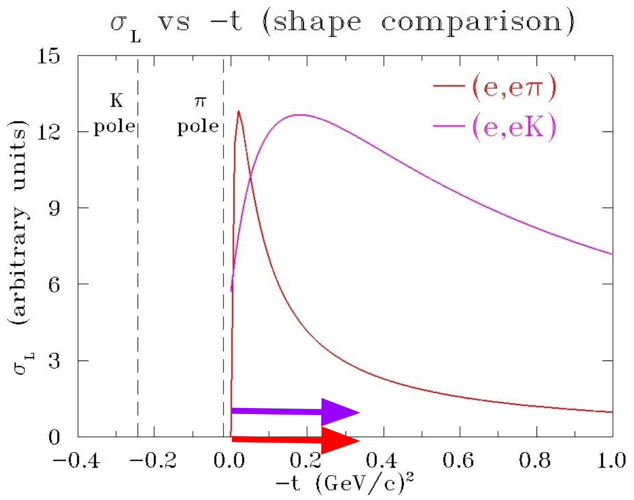

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  - Extraction of the form factor using a model
  - Validation of the technique - model dependent checks

Comparing π and K^+ Form Factor

- Large pion t data lies a similar distance from the pole as kaon data
  - The Born term model should be approximately valid for kaon form factor

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

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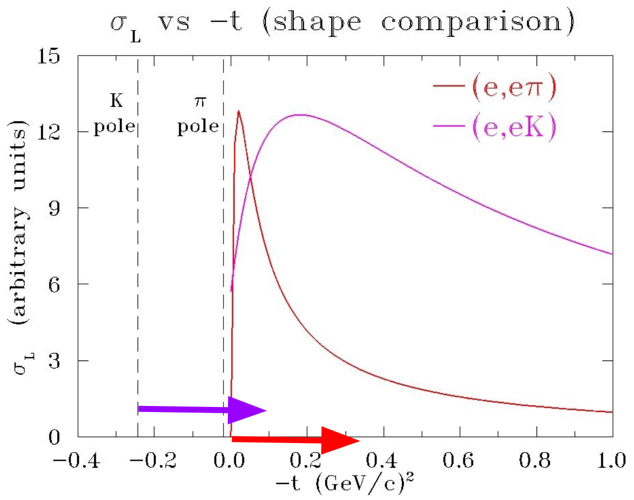

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