Update on the Pion and Kaon LT Experiments

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16/07/20

Outline

- Science overview
- Experiment specifics
- Current progress
- Future goals

Meson Form Factors

- E12-09-011 (Spokespeople: T. Horn, G Huber, P. Markowitz)
  - LT separated kaon cross section
  - Will attempt to extract F_K
- E12-19-006 (Spokespeople: D. Gaskell, T. Horn, G. Huber)
  - LT separated pion cross section
  - F_π to high Q^2 ($8.5\ GeV^2$)
  - Pion reaction mechanism studies
- Simple $q\bar{q}$ valence structure of mesons makes them an excellent testing ground
  - π - Lightest QCD system, vital to understand DCSB
  - K - Next simplest system, contains strangeness, larger Higgs contribution
- Clearest case for studying transition from perturbative to non perturbative QCD

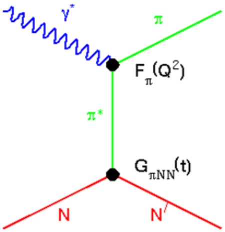
Measurement of F_π at High Q^2

- To access F_π at high Q^2, must measure F_π indirectly
  - Use the "pion cloud" of the proton via pion electroproduction $p(e, e'\pi^+)n$
- At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L

- In the Born term model, F_π^2 appears as -

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

- Drawbacks of this technique -
  - Isolating σ_L experimentally challenging
  - Theoretical uncertainty in F_π extraction
    $\rightarrow$ Model dependent



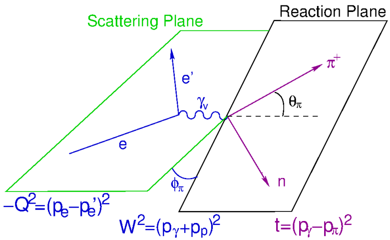
Measurement of F_π at JLab

- The physical cross section for the electroproduction process is given by -

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

$$\epsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$

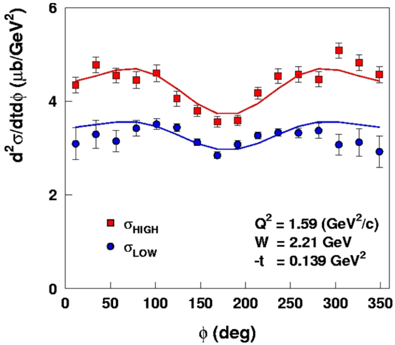
- $\epsilon \rightarrow$ Virtual photon polarisation
- L-T separation required to isolate σ_L from σ_T
- Need data at lowest $-t$ possible, σ_L has maximum pole contribution here



Measuring $\frac{d\sigma_L}{dt}$ at JLab

- Rosenbluth separation required to isolate σ_L
  - Fix W, Q^2 and $-t$, measure cross section at two beam energies
  - Carry out simultaneous fit at two different ϵ values to determine interference terms

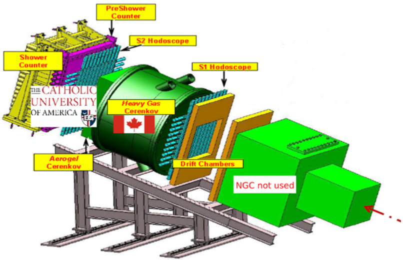
- Careful control of point-to-point systematics crucial, $1/\Delta\epsilon$ error amplification in σ_L
- Spectrometer acceptance, kinematics and efficiencies must all be carefully studied and understood



T. Horn, et al., PRL 97(2006) 192001

Detector Setup

- SHMS detects hadrons
- HMS detects electrons
- Wide angular and momentum range for each
- SHMS Aero and HGC used for PID
  - Aerogel $\rightarrow K/p$ separation
    - Four different n used
    - Lots of tray changes needed
    - V. Berdnikov oversaw all tray changes successfully
  - HGC $\rightarrow K/\pi$ separation



Physics Settings - Acquired

- All physics settings for the kaon (E12-09-011) and 3 PAC days worth of settings for the pion (E12-19-006) already acquired through various beamtime periods in 2018/2019

E_{Beam}/GeV	Q^2/GeV^2	W/GeV	x	ϵ
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
4.6, 3.7 & 2.8	0.38	2.20	0.087	0.781/0.629/0.286

Physics Settings - To Be Acquired Form Factor Points

- Many physics settings still need to be acquired for the pion
- Long and complex experimental run
  - **Angles as small as** $\theta_{HMS} = 10.62^\circ$ **and** $\theta_{SHMS} = 5.50^\circ$
  - Hard work and contribution of our collaborators is **vital** and much appreciated!
- LD2 runs as well

E_{Beam}/GeV	Q^2/GeV^2	W/GeV	x	ϵ
11.0/8.8/6.7	1.60	3.00	0.165	0.817/0.689/0.408
11.0/6.7	1.60	3.00	0.165	0.817/0.408
11.0/8.8/8.0	2.45	3.20	0.208	0.709/0.505/0.383
11/9.9/8.8/8.0	3.85	3.07	0.311	0.666/0.572/0.436/0.301
11.0/8.0	3.85	3.07	0.311	0.666/0.301
11.0/9.9/8.0	5.00	2.95	0.390	0.633/0.530/0.238
11.0/9.9/9.2	6.00	3.19	0.392	0.452/0.304/0.184

Analysis Phases

- 1. Calibrations ✓
  - Calorimeter, aerogel, HGC, HMS Cer, DC, Hodo
- 2. Efficiencies and offsets ← **current phase**
  - Luminosity scans, elastics, HEEP
- 3. First iteration of cross section
- 4. Fine tune
- 5. Repeat previous step
  - Repeat until acceptable and physical cross sections attained
- 6. Attempt extraction of form factor
  - Fit the data to model, iterate as needed
- See https://redmine.jlab.org/projects/kltexp/wiki/Analysis_Tasks for details on individual tasks in each phase

New Python Analysis Scripts

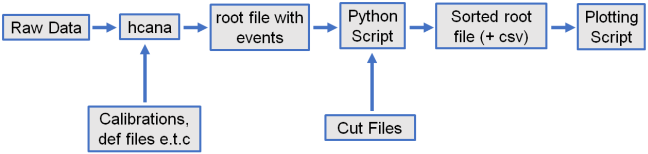
- Switching to python based analysis structure
- Aim for this to be clearer, more transportable and more accessible
- Lots of work on new scripts done by R. Trotta
- Need to be sure analysis is "working"
  - Compared new analysis code to previous TProof based scripts
- For more detail see
  - https://redmine.jlab.org/attachments/download/998/KaonLTMeeting_5_13_20.pdf
  - https://redmine.jlab.org/attachments/download/1000/Analysis_Meeting_14_05_20.pdf

Previous Script Issues

- Previously used a root macro to process replayed files and apply cuts, plot and save data
  - All in one script quickly bloats and becomes quite cumbersome
- Old scripts used root TProof to process data
  - TProof parallelises the processing of a chain
  - Fast, once it gets going
  - Very non-intuitive, debugging is not straightforward
  - Setup and initialisation of the analysis can be slow
- Previous scripts had hardcoded cuts and outputs in places
  - Not very flexible

General Data Flow

- Starting from raw data, process through hcana
- Get a resulting root file based on our defined def files etc.
- Run large root file through python analysis script, get a trimmed and sorted root file (and csv if desired) as output
  - Choice from the user as to which they use after that
  - Could use python based plotting/fitting if they want



Python Script

- Python analysis script takes a replayed root file and trims it down to a smaller, more manageable file
- Select out the branches you want, apply the cuts you want and save the output
  - Output saved as leaves in trees you can define
  - No longer all in one
  - New output can be as small or as complicated as you want
- Cuts are applied based on values that are read in from parameter files
  - No more hardcoded cuts
  - Just tweak the values for the run you are looking at in the parameter files
- An example use case $\rightarrow$ cutting using RF timing

RF Timing - Overview

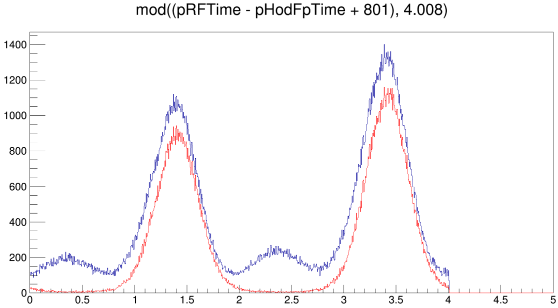
- Take difference between RF time and hodoscope start time
- Need to add an offset to this difference, then take modulo
  - Take mod 4.008 $\rightarrow$ from bunch spacing for the run set shown
  - Offset varies by run and by beam conditions, a value between 0 and 4.008
- Value plotted as time difference is -

$$\mathrm{fmod}(\mathrm{P.hod.fpHitsTime}[0] - \mathrm{T.coin.pRF\_tdcTime} + \textcolor{red}{\mathrm{offset}}, 4.008)$$

- The offset needed can shift quite a bit
  - For example, MCC switching the beam bucket we get causes a shift
- Applying the same offset value and not accounting for this leads to an odd double peaked plot

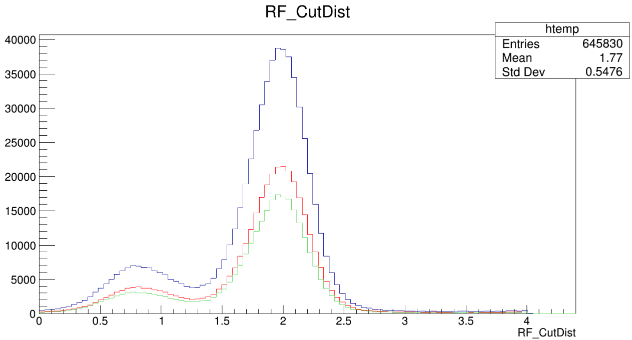
RF Timing Example

- RF time differences, after common cuts, shown in blue
- Events with pion PID cuts applied shown in red
- Without accounting for the change in beam bucket, clearly see the weird double peaking



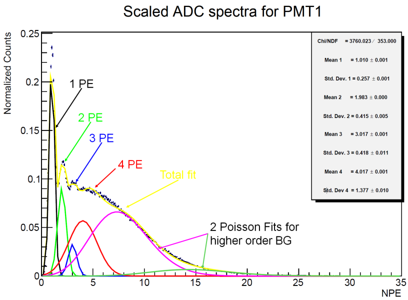
RF Timing Corrected

- New method of reading cut values means this can easily be accounted for
- Offset chosen to centre the distribution at ~ 2
- Combined events, events before the MCC change, events after the MCC change



HGC Calibration Script Updates

- Numerous improvements made to calibration script
  - More in-depth cross checks conducted
  - Calculation of calibration constants improved
  - Numerous algorithm improvements, corner cases resolved
  - New method to account for poissonian backgrounds



Plots and calibration script by V.Kumar, URegina, 2020

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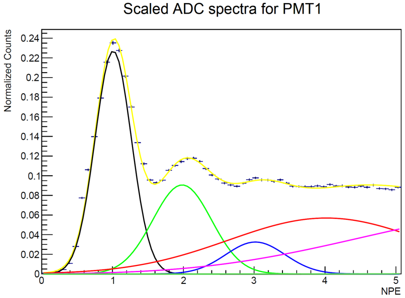
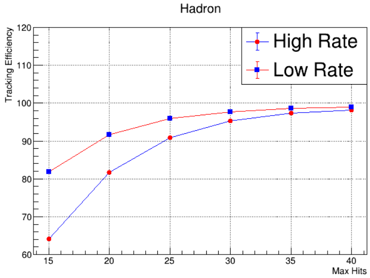


Plots and calibration script by V.Kumar, URegina, 2020

Current Work

- Work on checking efficiencies and doing luminosity scans in progress
- Optimisation of tracking efficiencies ongoing
- Interesting trends observed in tracking parameters

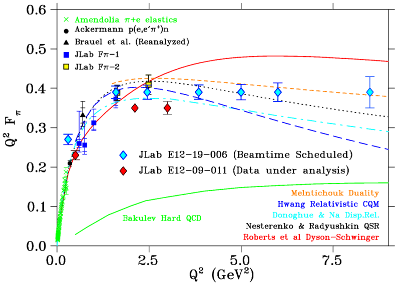
- MaxHits $\rightarrow$ max number of hits per drift chamber allowed in a track
- High Rate $= 706\ kHz$ (SHMS 3/4)
- Low Rate $= 76\ kHz$ (SHMS 3/4)



Plots and analysis by A. Usman, URegina, 2020
Info on setting - $Q^2 = 3.0$, $W = 3.14$, low ϵ setting. $E_b = 8.2\ GeV$, $P_{SHMS} = 6.05\ GeV/c$, $\theta_{SHMS} = 6.91^{\circ}$.
Runs 8038/8054

Current and Projected JLab F_π Data

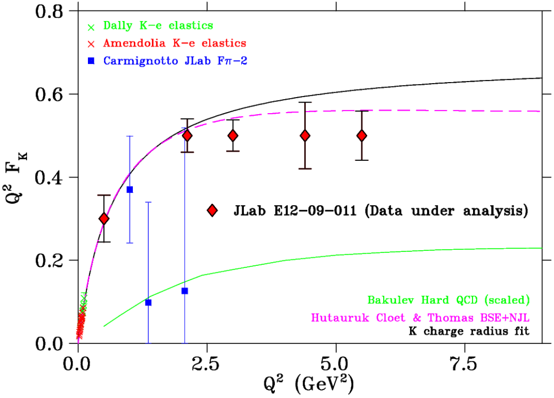
- JLab 12 *GeV* program includes measurements of F_π to higher Q^2
- No other facility worldwide can perform this measurement
- New overlap points at $Q^2 = 1.6, 2.45$ will be closer to pole to constrain $-t_{min}$ dependence
- Check π^+/π^- ratios at modest Q^2 to test t-channel dominance



- New low Q^2 point will provide best comparison of the electroproduction extraction of F_π vs elastic $\pi + e$ data

Current and Projected JLab F_K Data

- Points with projected errors shown below
- Data has all been acquired and analysis is in progress
- y positioning of points arbitrary



Upcoming Beamtime

- Many settings for E12-19-006 scheduled for Jun-Oct 2021
  - 4 months of beam! Lots of manpower will be needed

E_{Beam}/GeV	Q^2/GeV^2	W/GeV	x	ϵ	Note
8.0	2.45	3.20	0.208	0.383	
8.0	3.85	3.07	0.311	0.301	
9.9	3.85	3.07	0.311	0.572	
8.0	3.85	3.07	0.311	0.301	Deuterium
8.0	5.00	2.95	0.390	0.238	
9.9	5.00	2.95	0.390	0.5305	
9.2	6.00	3.19	0.392	0.184	
9.9	6.00	3.19	0.392	0.304	
6.0	3.85	2.02	0.546	0.582	Reaction mechanism
8.0	6.00	2.40	0.551	0.449	Reaction mechanism
8.0	6.00	2.40	0.551	0.449	Reat. Mech., Deut
9.2	8.5	2.79	0.552	0.156	Reaction mechanism

Bonus Data - Protons

- Hadron PID is done offline
  - Can also analyse "pion" and "kaon" data to look at protons
- Study backward angle meson production
  - "Knocking a proton out of the proton"

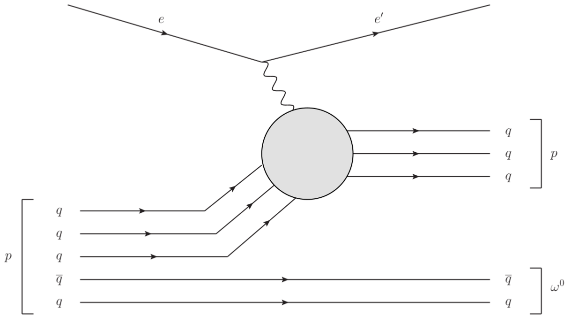
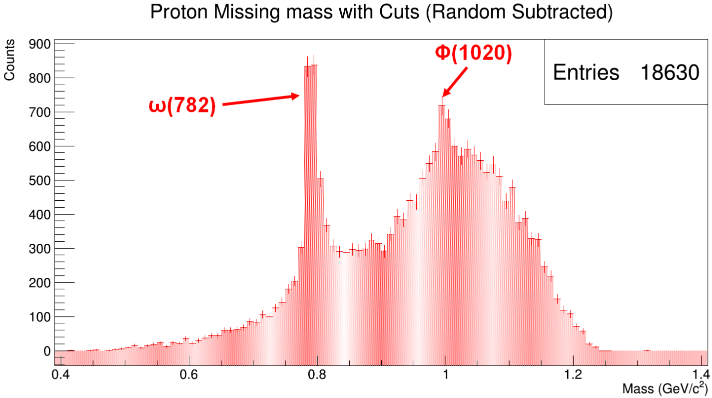


Figure - W.Li. PhD Thesis, University of Regina 2017

Bonus Data - Protons

- $Q^2 = 3,\ W = 2.32$ central setting, low ϵ
- Clear peaks visible in proton missing mass spectrum
  - $M_{Miss} = \sqrt{(E_b + m_t - E_{e'} - E_p)^2 - (\vec{p}_e - \vec{p}_{e'} - \vec{p}_p)^2}$



Summary

- Calibrations largely finalised
  - HGC calibration script improved and fixed
  - Expect a report and the updated script soon
- New python based analysis framework working and in use
- RF Timing being utilised for PID
- Work on checking efficiencies and offsets well under way
- Long and challenging pion beamtime on the horizon
  - Your help and hard work will be vital

Thanks for listening, any questions?

S.J.D. Kay, D. Gaskell, T. Horn, G.M. Huber, P. Markowitz, V. Berdnikov, V. Kumar , R. Trotta, A. Usman

This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), FRN: SAPIN-2016-00031, and the National Science Foundation (NSF), PHY1714133 and PHY2012430

Backup Zone

Physics Settings - To Be Acquired Reaction Mechanism Points

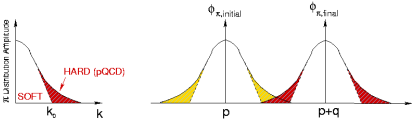
- As well as form factor points shown earlier, also have reaction mechanism data points
- LD2 runs as well

E_{Beam}/GeV	Q^2/GeV^2	W/GeV	x	ϵ
6.7	1.46	2.02	0.312	0.880
11.0/6.7	2.73	2.63	0.311	0.845/0.513
8.8	2.12	2.05	0.390	0.907
11.0/6.7	3.85	2.62	0.392	0.799/0.360
11.0/6.7	3.85	2.62	0.392	0.799/0.360
11.0/6.0	3.85	2.02	0.546	0.898/0.582
11.0/8.0	6.0	2.40	0.551	0.738/0.449
11.0/8.0	6.00	2.40	0.551	0.738/0.449
11.0/9.2	8.50	2.79	0.552	0.430/0.156

Charged Meson Form Factors

- Simple $q\bar{q}$ valence structure of mesons makes them an excellent testing ground
- Pion form factor , F_π, is the overlap integral -

$$F_\pi(Q^2) = \int \phi_\pi^*(p)\phi_\pi(p+q)dp$$

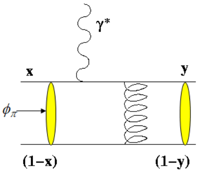


- Meson wave function can be split into ϕ_π^{soft} $(k < k_0)$ and ϕ_π^{hard}, the hard tail
  - Can treat ϕ_π^{hard} in pQCD, cannot with ϕ_π^{soft}
- Study of Q^2 dependence of form factor focuses on finding description of hard and soft contributions

The Pion in pQCD 1/2

- At very large Q^2, F_π can be calculated using pQCD via -

$$F_\pi(Q^2) = \frac{4_F\alpha_s(Q^2)}{Q^2}\left|\sum_{n=0}^{\infty} a_n \left(\log\left(\frac{Q^2}{\Lambda^2}\right)\right)^{-\gamma_n}\right|^2 \left[1 + O\left(\alpha_s(Q^2), \frac{m}{Q}\right)\right]$$



The Pion in pQCD 2/2

- At asymptotically high Q^2 ($Q^2 \rightarrow \infty$), the pion distribution amplitude becomes -
$$\phi_\pi(x) \rightarrow \frac{3f_\pi}{\sqrt{n_c}} x(1-x)$$
  - With $f_\pi = 93\ MeV$, the $\pi^+ \rightarrow \mu^+ \nu$ decay constant
- F_π takes the form -
$$Q^2 F_\pi \rightarrow 16\pi\alpha_s(Q^2) f_\pi^2$$
- This only relies on asymptotitc freedom in QCD, i.e. $(\partial\alpha_s/\partial\mu) < 0$ as $\mu \rightarrow \infty$
- $Q^2 F_\pi$ should behave as $\alpha_s(Q^2)$, even for moderately large Q^2
- Pion form factor seems to be the best tool for experimental study of the nature of the quark-gluon coupling constant renormalisation

Eqns - G.P. Lepage, S.J. Brodsky, PLB 87, p359, 1979 | Closing Statement - A.V. Efremov, A.V. Radyushkin PLB 94, p245, 1980

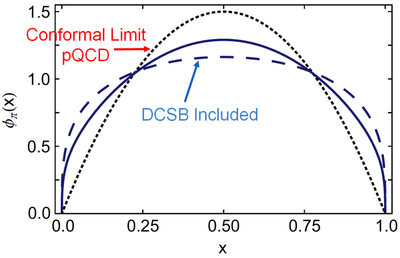
Implications for Pion Structure 1/2

- Previous pQCD derivation used normalisation of F_π based on the conformal limit of the pion's twist 2-PDA -

$$\phi_\pi^{cl}(x) = 6x(1-x)$$

- Gives F_π that are "too small"
- Incorporating the DCSB effects yields Pion PDA -

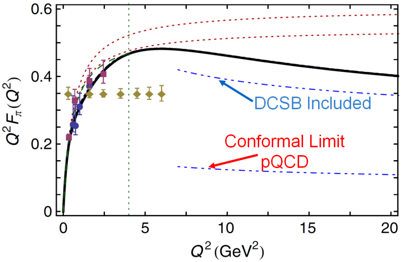
$$\phi_\pi(x) = \frac{8}{\pi}\sqrt{x(1-x)}$$



L. Chang, et al., PRL110(2013) 132001

Implications for Pion Structure 2/2

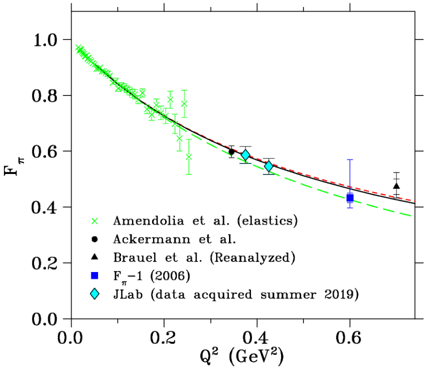
- Using this $\phi_\pi(x)$ in the pQCD expression brings the F_π calculation much closer to the data
- Underestimates the full computation by $\sim$ 15% for $Q^2 \geqslant 8\ GeV^2$



L. Chang, et al., PRL111(2013) 141802

Measurement of F_π - Low Q^2

- At low Q^2, F_π can be measured model independently
  - High energy elastic π^- scattering from atomic electrons in H
- CERN SPS used 300 GeV pions to measure F_π up to $Q^2 = 0.25\ GeV^2$
- Used data to extract pion charge radius - $r_\pi = 0.657 \pm 0.012\ fm$
- Maximum accessible Q^2 approximately proportional to pion beam energy
  - $Q^2 = 1\ GeV^2$ requires 1 TeV pion beam (!)

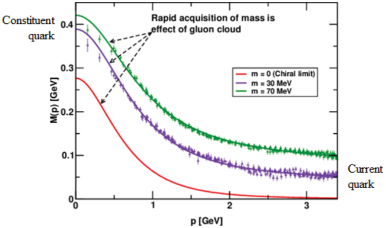


Amendolia, et al., NPB 277(1986) p168, P. Brauel, et al., ZPhysC (1979), p101, H. Ackerman, et al., NPB137 (1978), p294

Recent Theoretical Advances

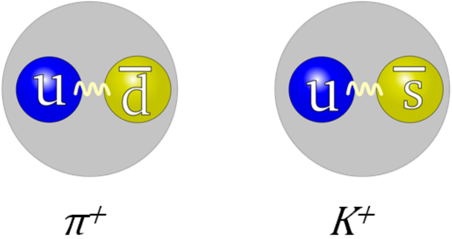
- Have a much better understanding of how **D**ynamical **C**hiral **S**ymmetry **B**reaking (**DCSB**) generates hadron mass
- Evolution of the current-quark of pQCD into constituent quark was observed as its momentum becomes smaller

- The constituent quark mass arises from a cloud of low momentum gluons attaching themselves to the current quark
- Non-perturbative effect that generates a quark mass from nothing, occurs in even in the chiral ($m = 0$) limit



M.S. Bhagwat, et al., PRC 68(2003) 015203, L. Chang, et al., Chin.J.Phys. 49(2011)955

A 2$^{\mathrm{nd}}$ Test Case - The Charged Kaon

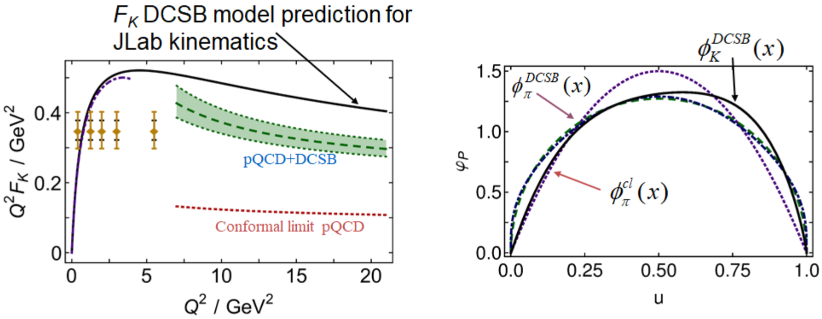


- In the hard scattering limit, pCQD predicts F_π and F_K will behave similarly -

$$\frac{F_K(Q^2)}{F_\pi(Q^2)} \rightarrow \frac{f_K^2}{f_\pi^2}$$

- Should compare the magnitude and Q^2 dependences of both form factors

- K^+ PDA is also broad, concave and asymmetric
- Heavier s quark carries more bound state momentum than the u quark, shift is less then one might expect based on the difference in current quark masses.



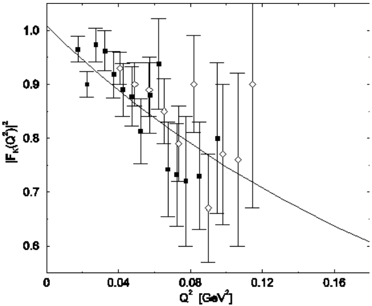
C. Shi, et al., PRD 92 (2015) 014035, F. Guo, et al., PRD 96(2017) 034024 (Full calculation)

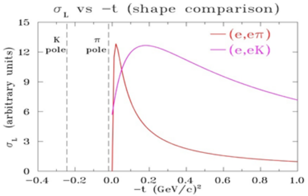
F_K Measurement at JLab

- Similar to F_π, elastic K^+ scattering from electrons used to determine F_K at low Q^2
- Can "kaon cloud" of the proton be used in the same way as the pion to extract F_k from electroproduction?
- Kaon pole further from kinematically allowed region

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_K^2)} g_K^2(T) F_K^2(Q^2,t)$$

- Issues are being explored and tested in JLab E12-09-011





Amendolia, et al., PLB178(1986)435

Chew-Low Method to determine F_π

- $p(e, e'\pi^+)n$ data obtained away from $t = m_\pi^2$ pole
- "Chew Low" extrapolation method - must know analytical dependence of $d\sigma_L/dt$ in unphysical region

- Extrapolation method last used in 1972 by Devenish and Lyth
- Very large systematic uncertainties
- Failed to produce a reliable result
- Different polynomial fits equally likely in physical region
  - Form factor values divergent when extrapolated

We do not use the Chew-Low method