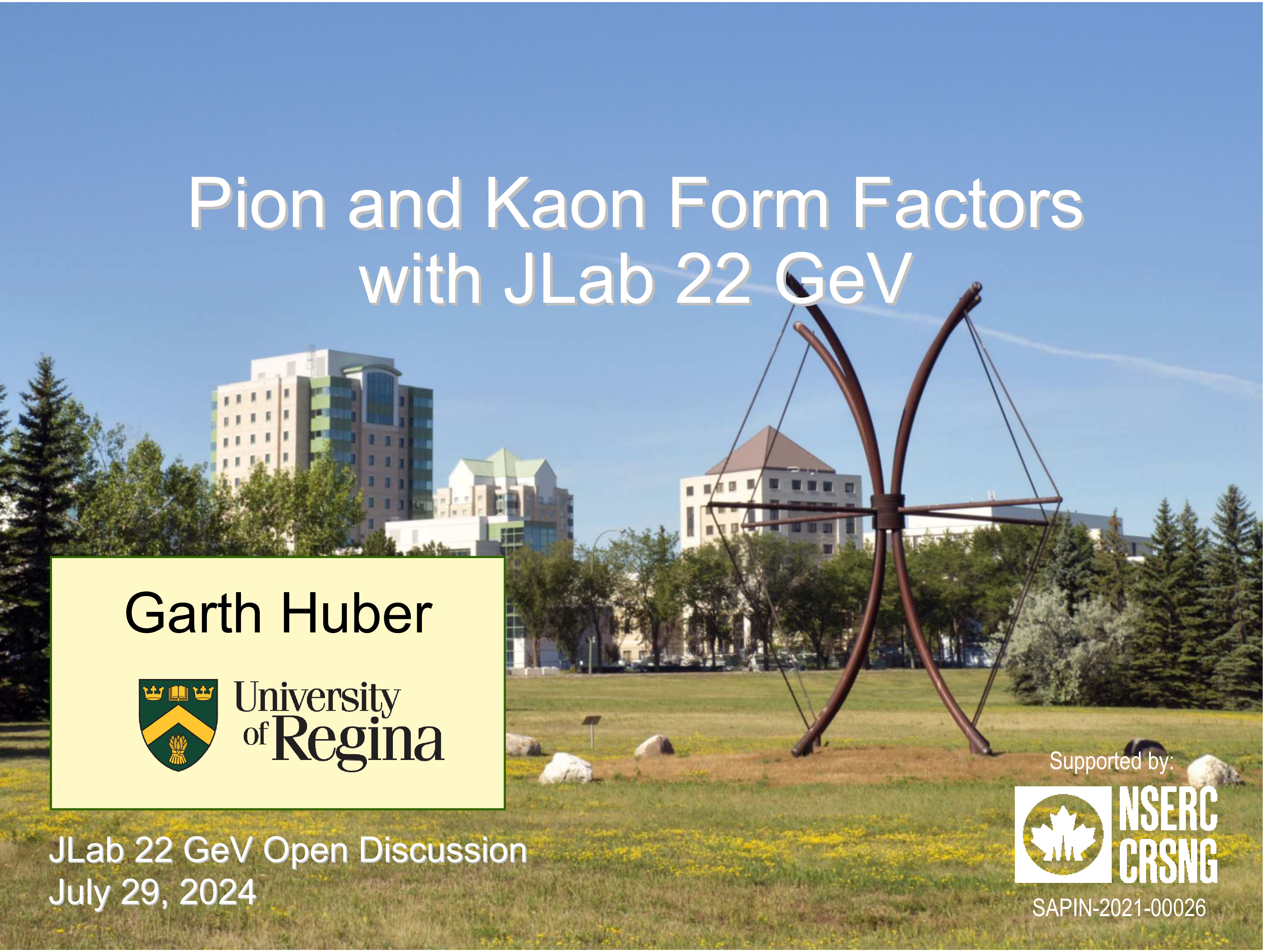

# Pion and Kaon Form Factors with JLab 22 GeV

**Garth Huber**

University of Regina

JLab 22 GeV Open Discussion
July 29, 2024

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# Why do we care?

- **The $\pi^+$ form factor is our best hope of observing experimentally QCD's transition from soft QCD to hard QCD**
  - This transition is expected to occur at a much lower $Q^2$ than for the proton
- **$K^+$ form factor:**
  - How does meson structure change when *s* quark is substituted for *d* quark?
  - At what $Q^2$ will the $K^+$ to $\pi^+$ form factor ratio converge to the value predicted by QCD?
- **The normalization of $\pi^+$ and $K^+$ form factors at high $Q^2$ is sensitive to quark and gluon energy contributions to emergent hadronic mass**
  - A comparison of $\pi^+$ and $K^+$ form factors over a wide range of $Q^2$ will provide unique information relevant to our understanding of hadronic mass generation

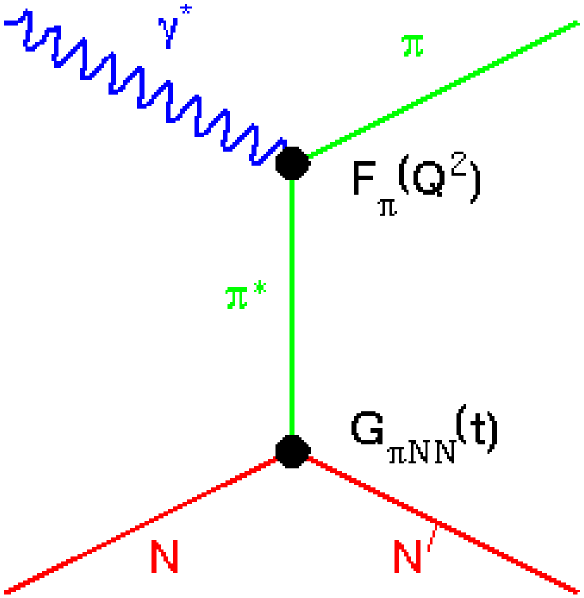
# Measurement of $\pi^+$ Form Factor – Larger $Q^2$

**At larger $Q^2$**, $F_\pi$ must be measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \ldots$$

- At small $-t$, the pion pole process dominates the longitudinal cross section, $\sigma_L$
- In Born term model, $F_\pi^2$ appears as,

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



Drawbacks of this technique

1. Isolating $\sigma_L$ experimentally challenging
2. Theoretical uncertainty in form factor extraction.

***$K^+$ pole is further in the unphysical region, uncertainties will be larger***

Garth Huber, huberg@uregina.ca

# Experimental Issues

## What is being measured?

- Scattered electron and $\pi^+/K^+$ in coincidence with the two high performance spectrometers in Hall C
  - High momentum, forward angle (5.5°) meson detection is required, with good Particle ID to separate $\pi^+$, $K^+$, p
  - Good momentum resolution required to reconstruct crucial kinematics, such as $M_{miss}$, $Q^2$, W, t
  - Need to measure the longitudinal cross section $d\sigma_L/dt$ needed for form factor extraction

## The role of 22 GeV electrons?

- Allows access to higher $Q^2$
- Expanded range of virtual photon polarization $\Delta\varepsilon=(\varepsilon_{HI}-\varepsilon_{LO})$, leading to reduced errors in the extraction of $d\sigma_L/dt$
  - Uncertainty in $\sigma_L \sim 1/\Delta\varepsilon$, desire $\Delta\varepsilon>0.2$, preferably larger

# Upgrade Scenarios Considered

**Phase 1:** higher energy beam, keep HMS+SHMS largely as is, with relatively small DAQ and PID upgrades

- See what can be accomplished in “cost effective approach”
- Goal: to extend kinematic range of L/T–separated measurements beyond what is possible with JLab 11 GeV beam

**Phase 2:** Replace HMS with a new Very High Momentum Spectrometer (VHMS) to enable measurements utilizing full 22 GeV beam energy

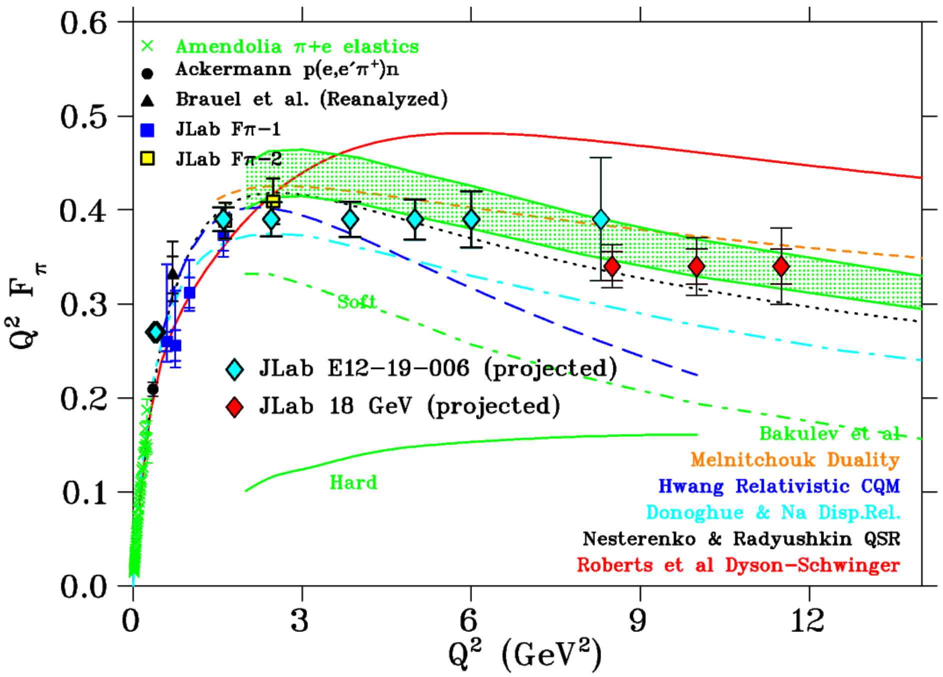
- See what extra physics can be obtained for significantly larger investment

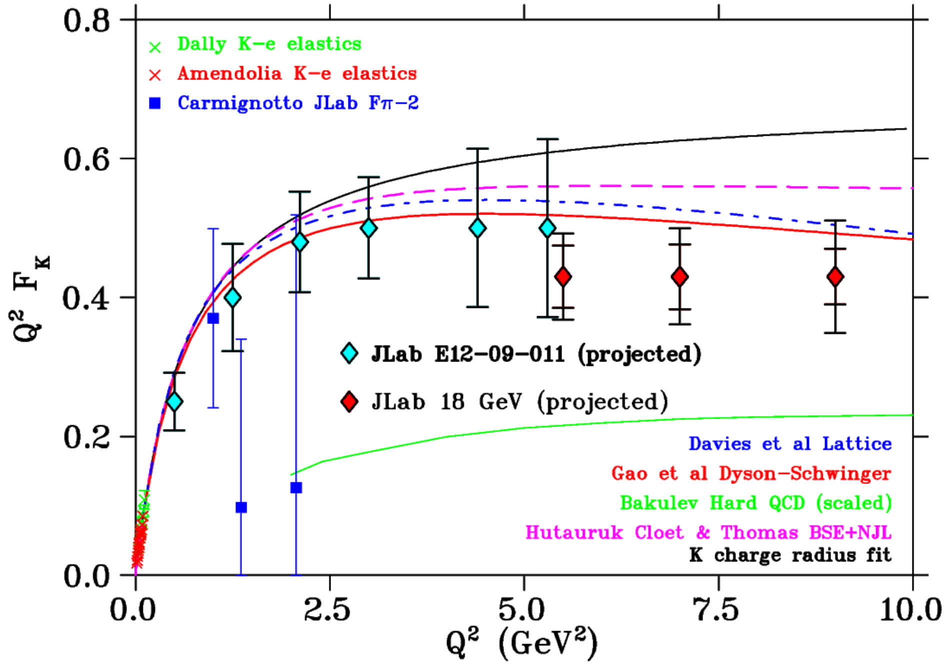
# Phase 1: Form Factor Projections

Garth Huber, huberg@uregina.ca

- 7.2 GeV/c HMS & 11.0 GeV/c SHMS allow a lot of kinematic flexibility, **with no major upgrades**
  - Success depends on good $K^+/\pi^+$ separation in SHMS at high momenta, likely requires a modest aerogel detector upgrade
  - Experiment could be done as soon as beam energy is available!
  - Maximum beam energy and higher $Q^2$ reach constrained by sum of HMS+SHMS maximum momenta

- $F_\pi$ assumes same statistics as acquired in PionLT experiment
- Inner error bar is projected statistical and systematic error
- Outer error bar also includes a model uncertainty in the form factor extraction, added in quadrature



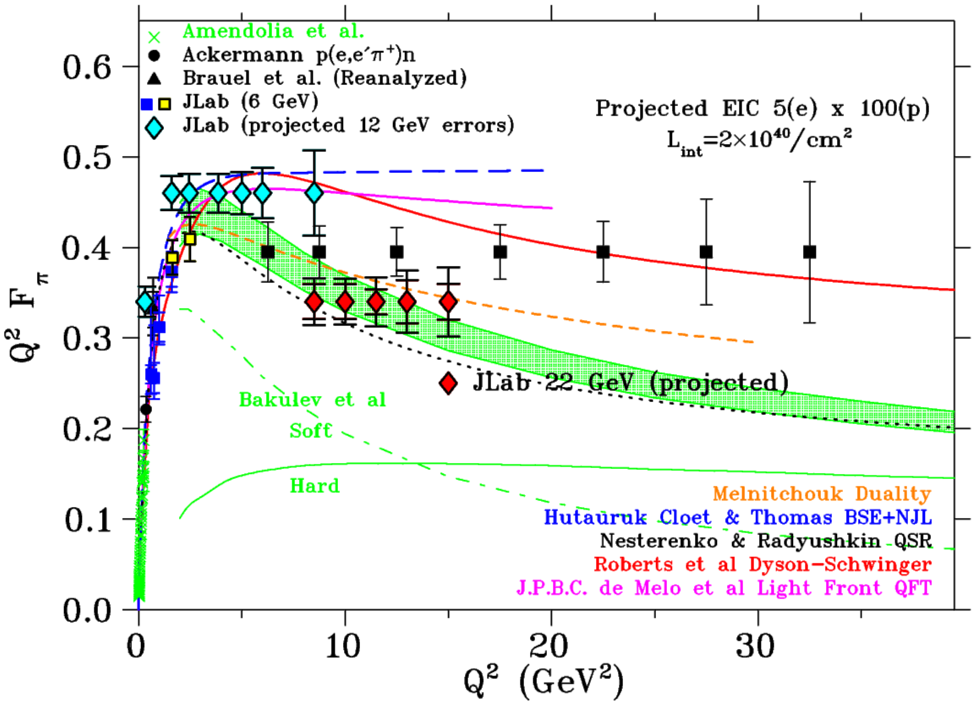


# Phase 2 Scenario: $\pi^+$ Form Factor

Garth Huber, huberg@uregina.ca

- **Replace HMS with VHMS for $\pi^+$, use SHMS for e’**
  - Assume $\theta_{min}$=5.5°, $\theta_{open}$=15.0°
  - VHMS: ΔΩ, ΔP/P similar SHMS
- $P_{VHMS}$=15.0 GeV/c is sufficient, constrained by max beam energy
- $\theta_{VHMS}$~5.5° allows improved Δε, but does not affect maximum $Q^2$ reach

- Dramatic increase in upper $Q^2$ 11.5 → 15.0 GeV$^2$
- Error bars for $Q^2$=8.5–11.5 GeV$^2$ substantially decrease due to smaller $-t_{min}$ (better $R=\sigma_T/\sigma_L$) and shorter running times
- Highest $Q^2$ running time is “expensive” but would have very high scientific priority.



- Extends region of high quality $F_\pi$ values to $Q^2$=13 GeV$^2$
- Somewhat larger errors to $Q^2$=15 GeV$^2$
- Provides MUCH improved overlap of $F_\pi$ data set between JLab and EIC

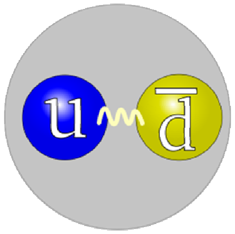
# JLab L–T Separations in the EIC Era

- **Hall C is world's only facility that can do L–T separations over a wide kinematic range**
- The error magnification in L–T separations depends crucially on the achievable difference in the virtual photon polarization parameter, ε.
  - Errors magnify as 1/Δε, where $\Delta\varepsilon = \varepsilon_{High} - \varepsilon_{Low}$
  - To keep the magnification <500%, one desires Δε>0.2
  - This is not feasible at the EIC, as the high ion ring energy constrains ε>0.98
- **As the interpretation of some EIC data (e.g. GPD extraction) will depend on extrapolation of Hall C L–T separated data, maximizing overlap between Hall C and EIC data sets should be a high priority**
  - An important motivation for extending reach of Hall C data using 22 GeV beam

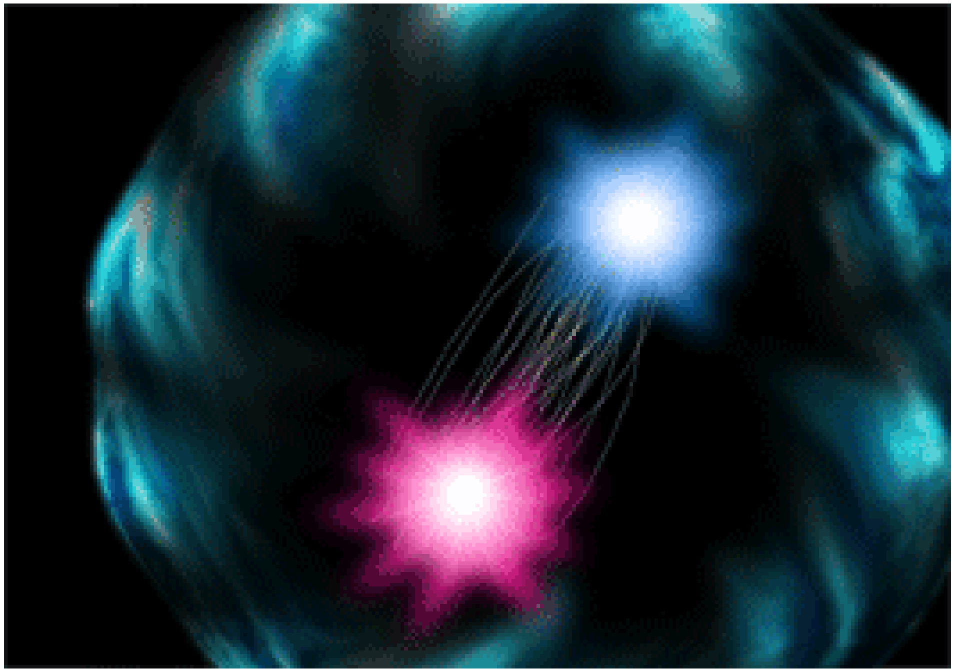
Garth Huber, huberg@uregina.ca

# Charged Pion Form Factor

- **The pion is attractive as a QCD laboratory:**
  - Simple, 2 quark system



- **The pion is the "positronium atom" of QCD, its form factor is a test case for most model calculations**
- **The important question to answer is: What is the structure of the $\pi^+$ at all $Q^2$?**



**Pion's structure is determined by two valence quarks, and the quark-gluon sea.**

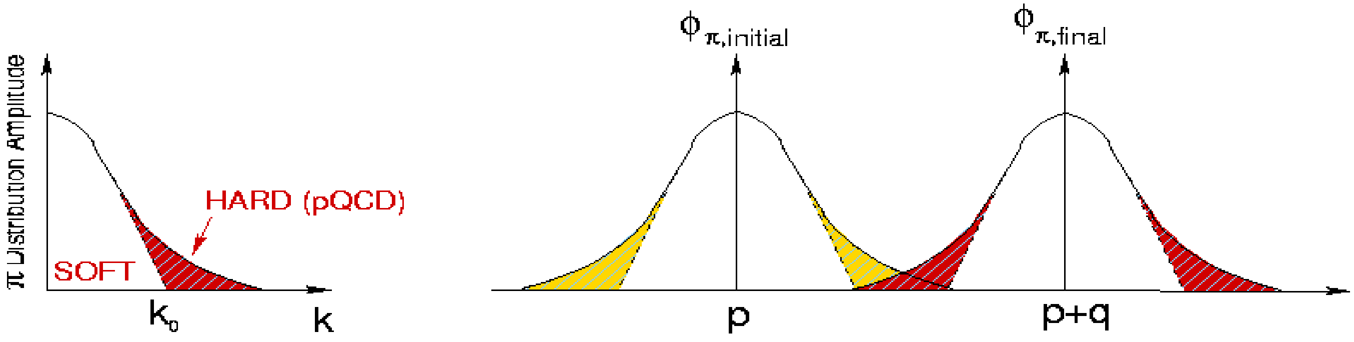
- **A program of study unique to Jefferson Lab Hall C** (until the completion of the EIC)

# Meson Form Factors

Simple $q\bar{q}$ valence structure of mesons presents the ideal testing ground for our understanding of bound quark systems.

In quantum field theory, the form factor is the overlap integral:

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



The meson wave function can be separated into $\varphi_\pi^{soft}$ with only low momentum contributions ($k<k_0$) and a hard tail $\varphi_\pi^{hard}$.

While $\varphi_\pi^{hard}$ can be treated in pQCD, $\varphi_\pi^{soft}$ cannot.

**From a theoretical standpoint, the study of the $Q^2$-dependence of the form factor focuses on finding a description for the hard and soft contributions of the meson wave-function.**

**A program of study unique to Hall C** (until completion of EIC)

# pQCD and the Charged Pion Form Factor

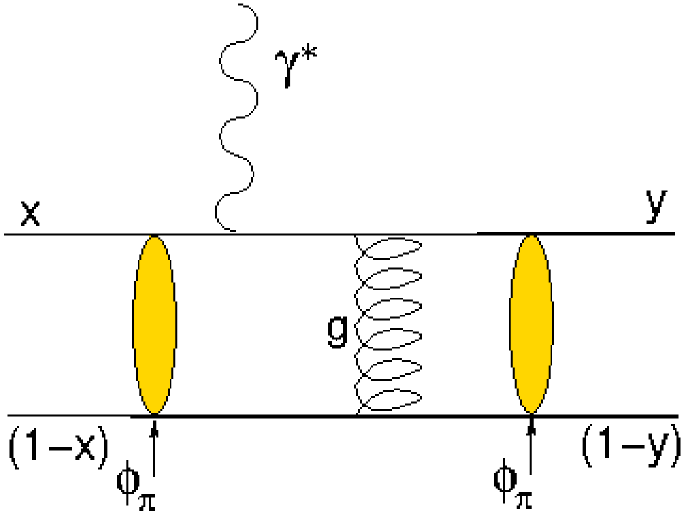
Garth Huber, huberg@uregina.ca

At large $Q^2$, perturbative QCD (pQCD) can be used

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

at asymptotically high $Q^2$, only the hardest portion of the wave function remains

$$\phi_\pi(x) \underset{Q^2\to\infty}{\to} \frac{3 f_\pi}{\sqrt{n_c}} x(1-x)$$



and $F_\pi$ takes the very simple form

$$F_\pi(Q^2) \underset{Q^2\to\infty}{\to} \frac{16\pi\alpha_s(Q^2) f_\pi^2}{Q^2}$$

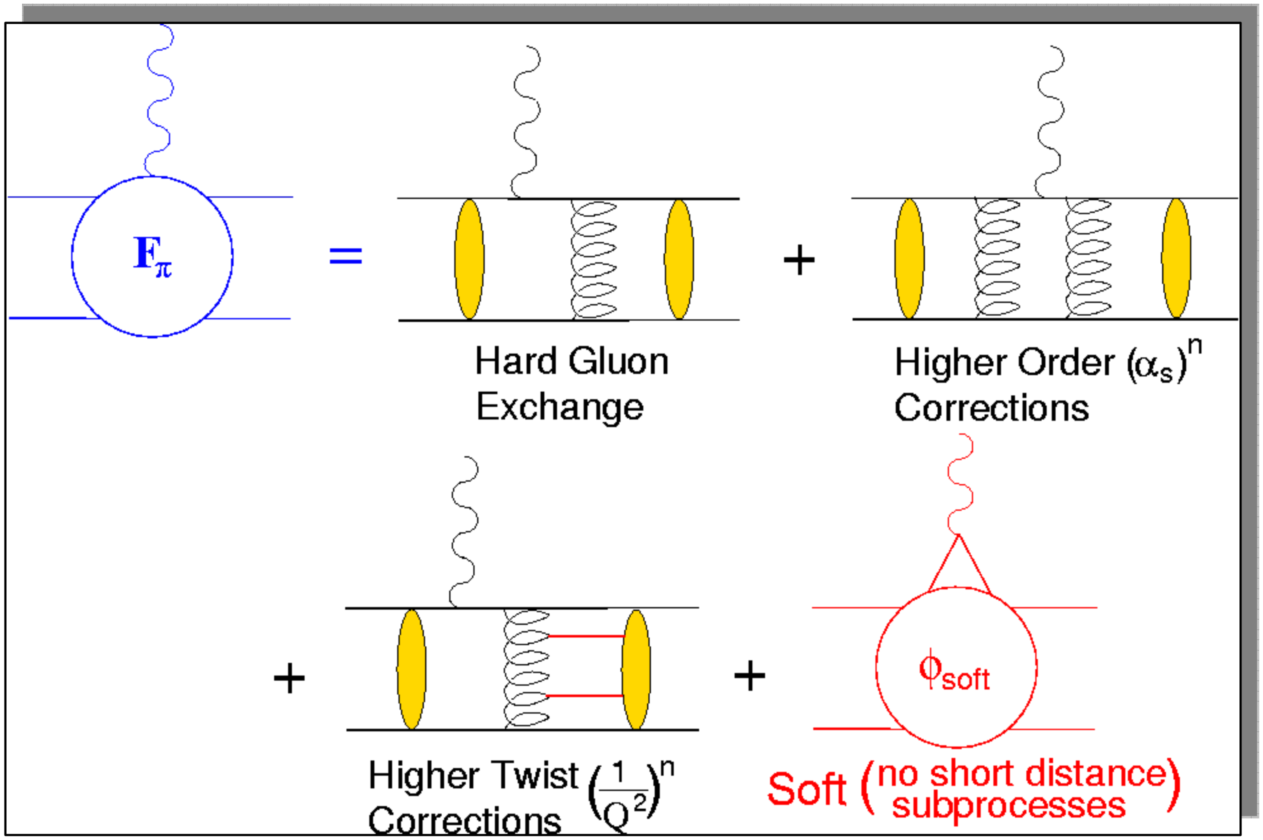
where $f_\pi$=92.4 MeV is the $\pi^+ \to \mu^+ \nu$ decay constant.

G.P. Lepage, S.J. Brodsky, Phys.Lett. **87B**(1979)359

This prediction only relies on asymptotic freedom in QCD, *i.e.* $(\partial\alpha_S/\partial\mu)<0$ as $\mu\to\infty$

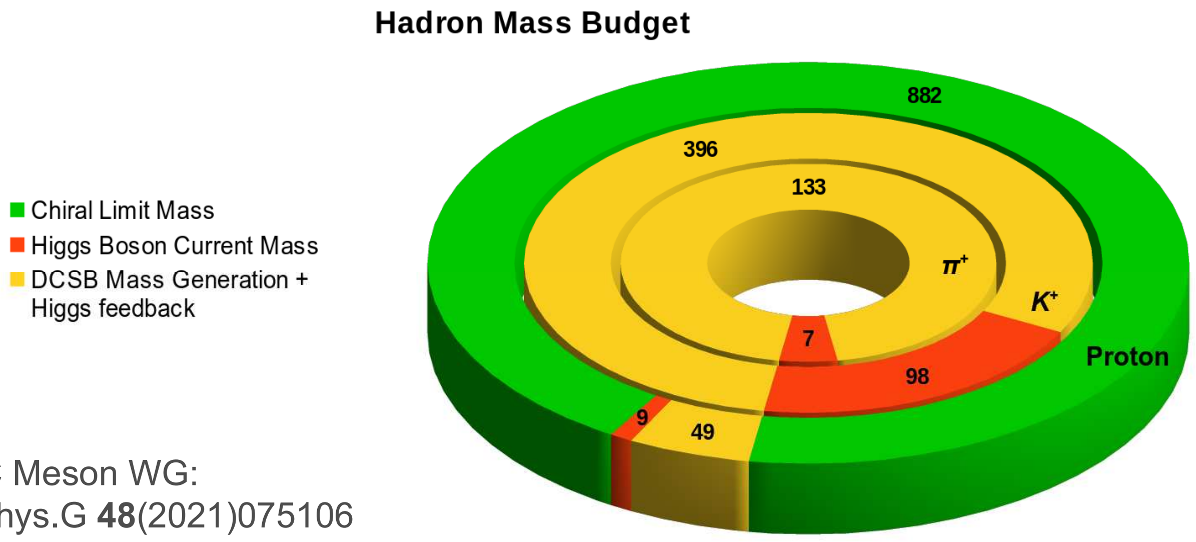
# Pion Form Factor at Finite $Q^2$

- At finite momentum transfer, higher order terms contribute.
- Calculation of higher order, “hard” (short distance) processes difficult, but tractable.



**$Q^2F_\pi$ should behave like $\alpha_s(Q^2)$ even for moderately large $Q^2$.**
→ Pion form factor seems to be best tool for experimental study of nature of the quark-gluon coupling constant renormalization.
[A.V. Radyushkin, JINR 1977, arXiv:hep–ph/0410276]

# Contrasts in Hadron Mass Budgets



EIC Meson WG:
J.Phys.G **48**(2021)075106

## Stark Differences between proton, $K^+$, $\pi^+$ mass budgets

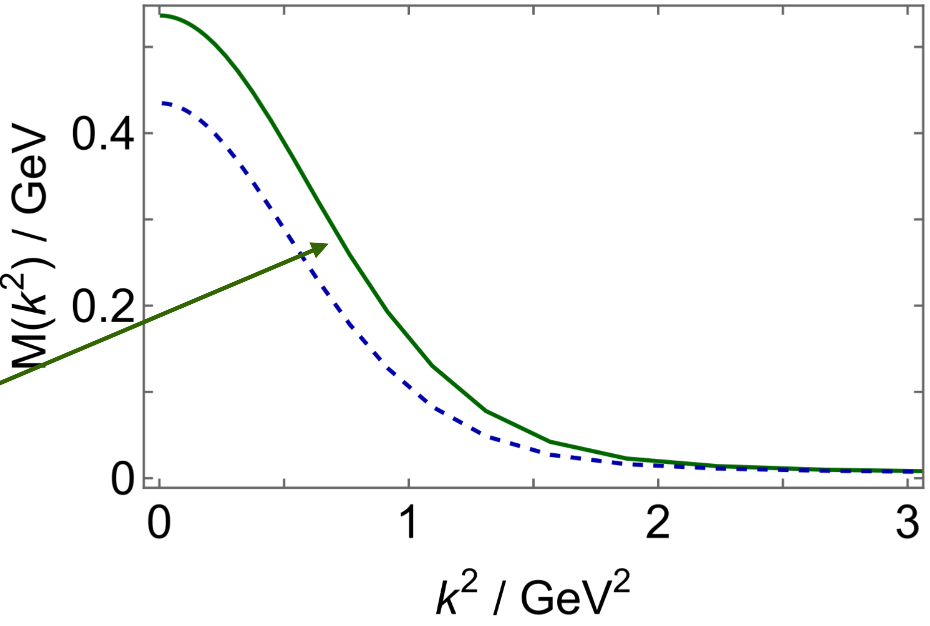
- Due to Emergent Hadronic Mass (EHM), Proton mass large in absence of quark couplings to Higgs boson (chiral limit).
- Conversely, and yet still due to EHM and DCSB, *K* and $\pi$ are massless in chiral limit (i.e. they are Goldstone bosons of QCD).
- The mass budgets of these crucially important particles demand interpretation.
- Equations of QCD stress that any explanation of the proton's mass is incomplete, unless it simultaneously explains the light masses of QCD's Goldstone bosons, the $\pi$ and *K*.

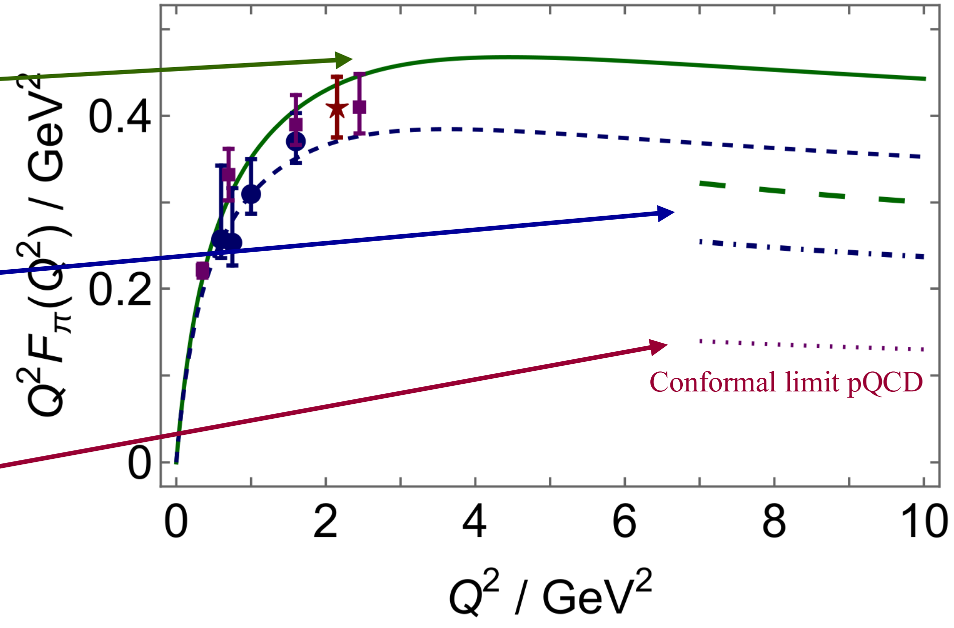
# Synergy: Emergent Mass and $\pi^+$ Form Factor

**At empirically accessible energy scales, $\pi^+$ form factor is sensitive to emergent mass scale in QCD**

- **Two dressed–quark mass functions distinguished by amount of DCSB**
  - DCSB emergent mass generation is 20% stronger in system characterized by solid green curve, which is more realistic case
- **$F_\pi(Q^2)$ obtained with these mass functions**
  - $r_\pi$=0.66 fm with solid green curve
  - $r_\pi$=0.73 fm with solid dashed blue curve
- **$F_\pi(Q^2)$ predictions from QCD hard scattering formula, obtained with related, computed pion PDAs**
- **QCD hard scattering formula, using conformal limit of pion's twist–2 PDA**

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

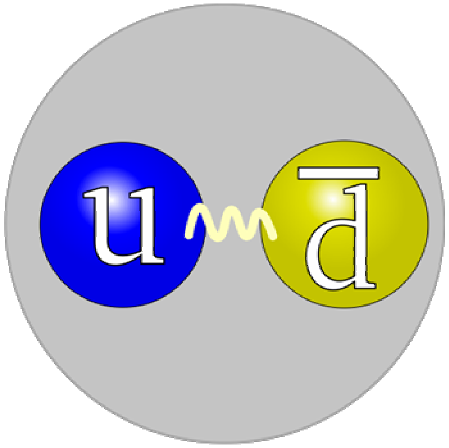




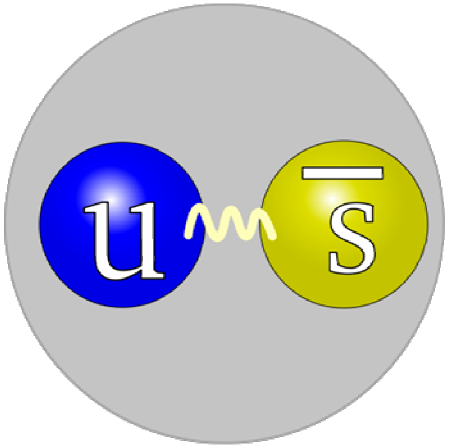
Chen, et al., PRD **98**(2018)091505(R); Aguilar et al, EPJA **55**(2019)190

Garth Huber, huberg@uregina.ca

# The Charged Kaon – a 2nd QCD test case



$\pi^+$



$K^+$

- In the hard scattering limit, pQCD predicts that the $\pi^+$ and $K^+$ form factors will behave similarly

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

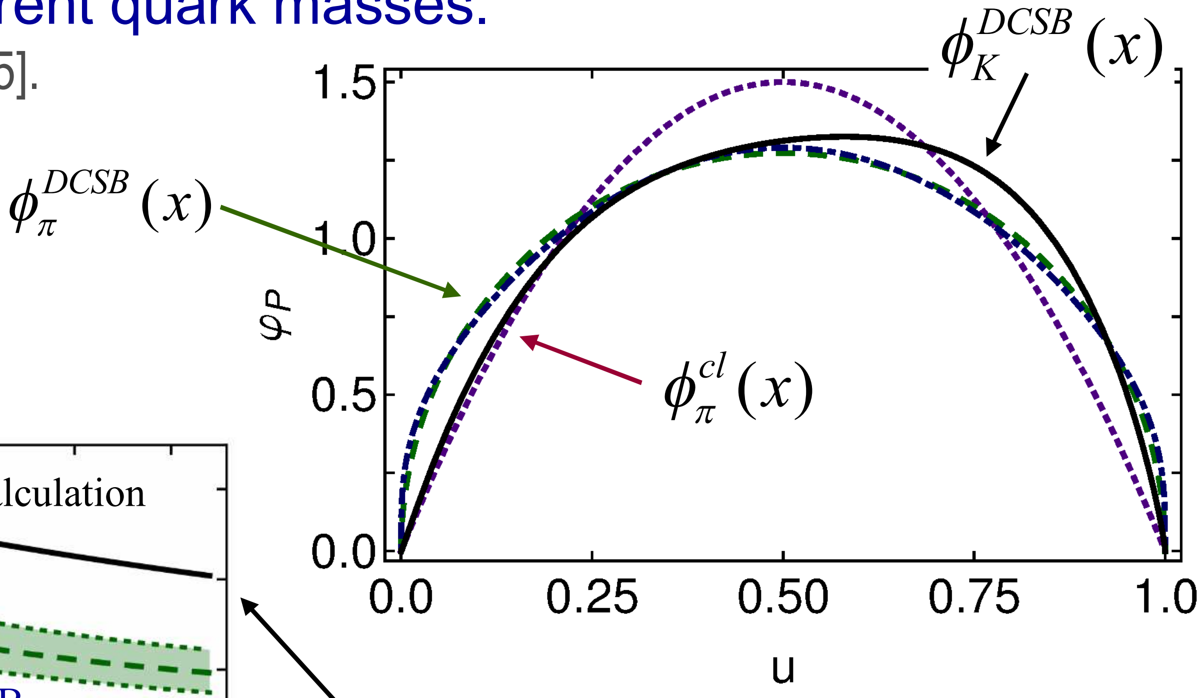
- It is important to compare the magnitudes and $Q^2$–dependences of both form factors.

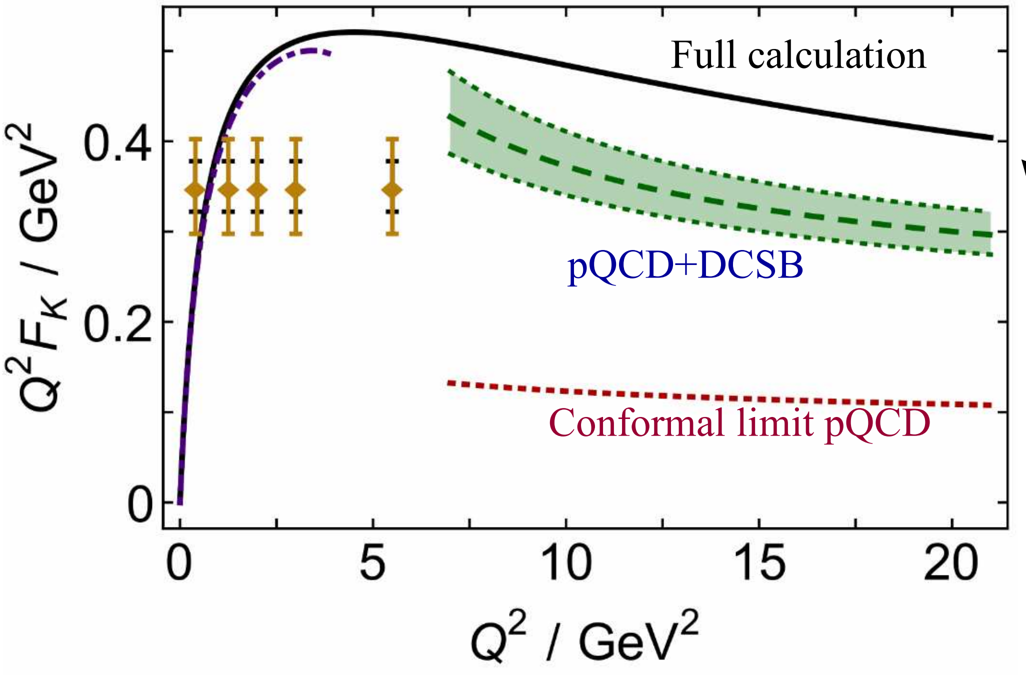
Garth Huber, huberg@uregina.ca

# $K^+$ properties also strongly influenced by EHM

- ***$K^+$* PDA also is broad, concave and asymmetric.**
- While the heavier $s$ quark carries more bound state momentum than the $u$ quark, the shift is markedly less than one might naively expect based on the difference of $u$, $s$ current quark masses.

  [C. Shi, et al., PRD **92** (2015) 014035].





- ***$F_K$* DCSB model prediction for JLab kinematics**

  [F. Guo, et al., arXiv: 1703.04875].

# Experimental Issues

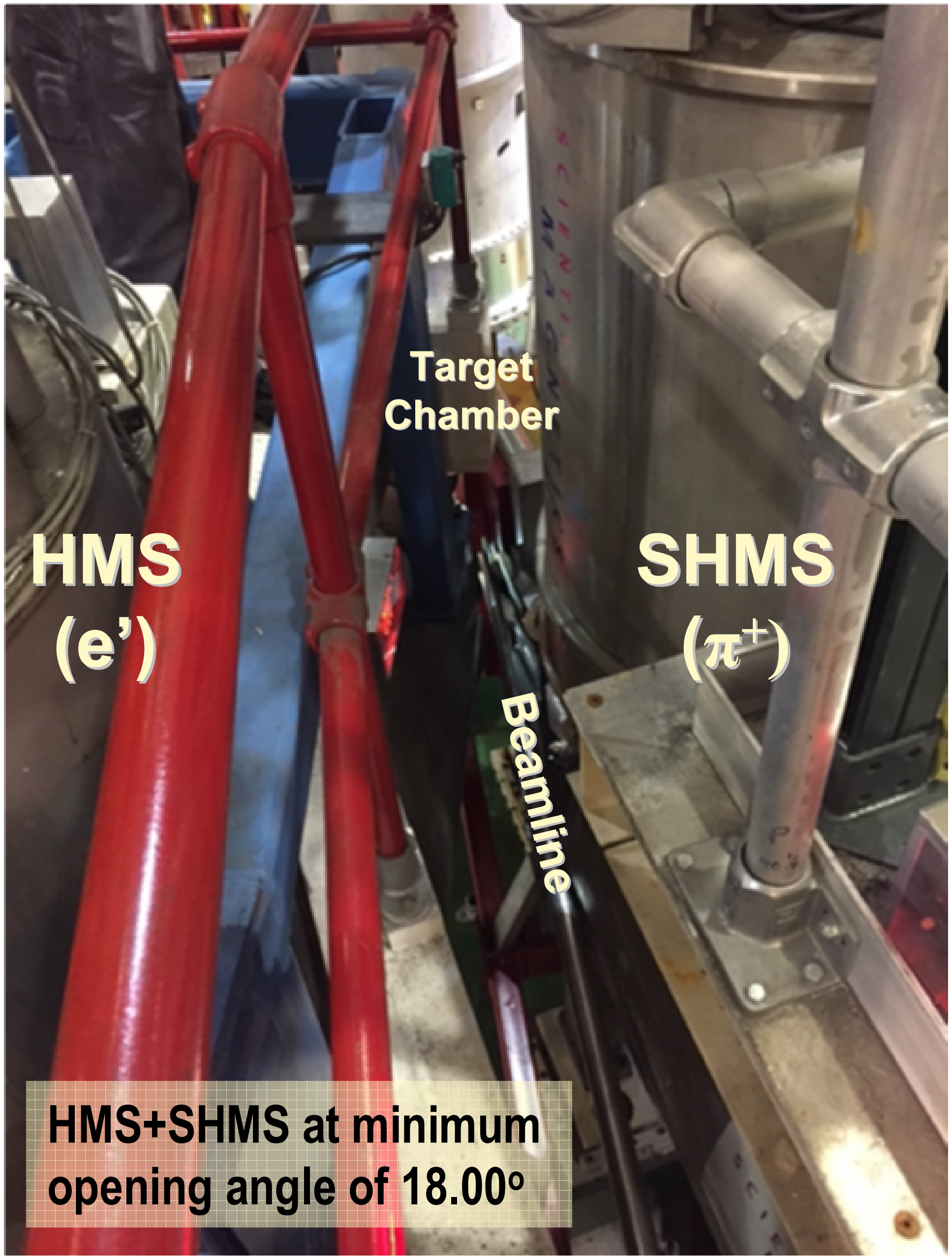
- Deep Exclusive Meson Production (DEMP) cross section is small, can exclusive $p(e,e'\pi^+)n$ and $p(e,e'K^+)\Lambda$ channels be cleanly identified?
  - High momentum, forward angle (5.5°) meson detection is required, with good Particle ID to separate $\pi^+$, $K^+$, p
  - Good momentum resolution required to reconstruct crucial kinematics, such as $M_{miss}$, $Q^2$, $W$, $t$
- Need to measure the longitudinal cross section $d\sigma_L/dt$ needed for form factor extraction

**Hall C of Jefferson Lab has been optimized for specifically such studies**

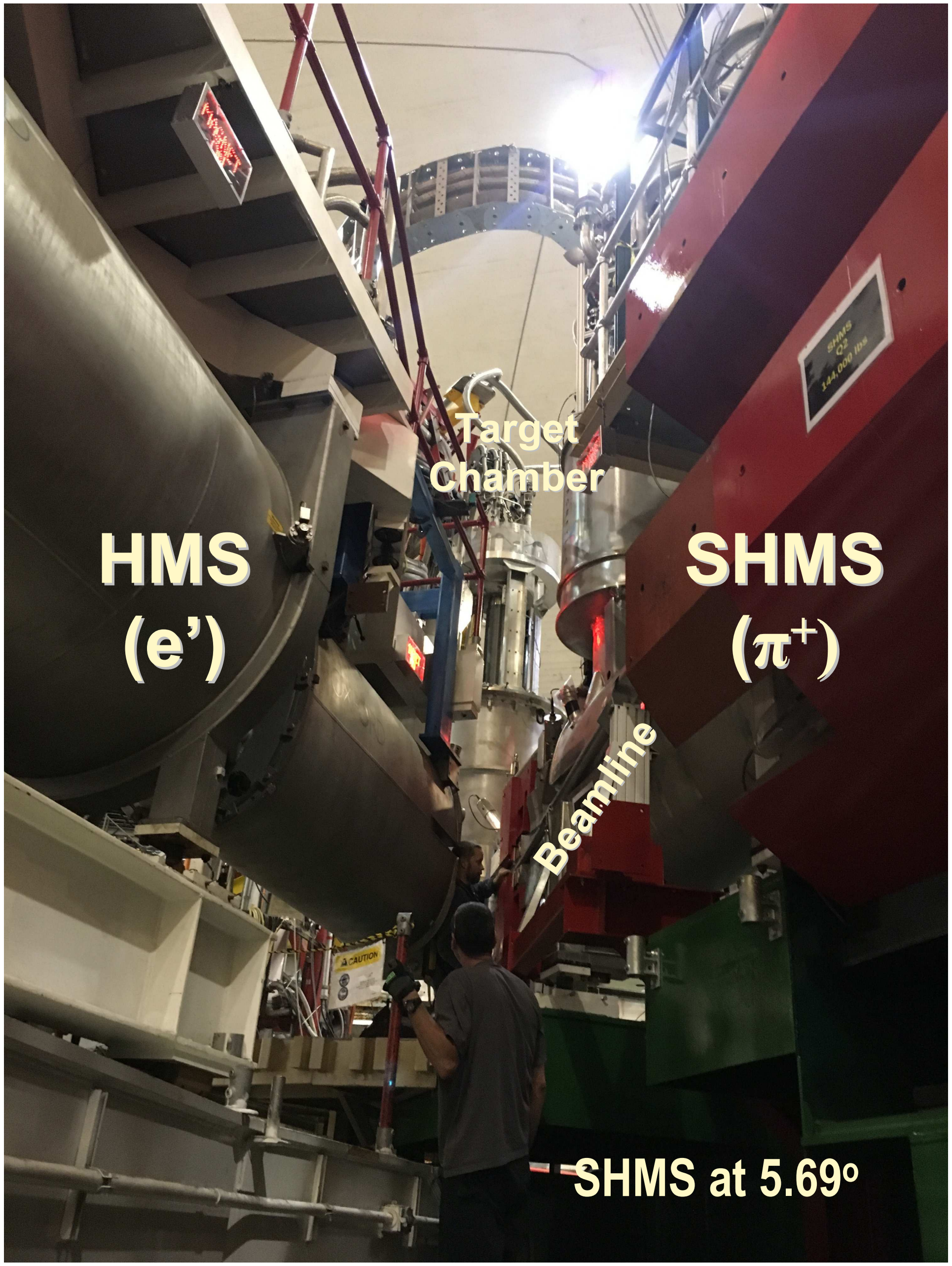
Garth Huber, huberg@uregina.ca

# Hall C during Data Taking

**$\pi^+/K^+$ FF experiments have challenging forward angle requirements**



HMS+SHMS at minimum opening angle of 18.00°



SHMS at 5.69°

Garth Huber, huberg@uregina.ca

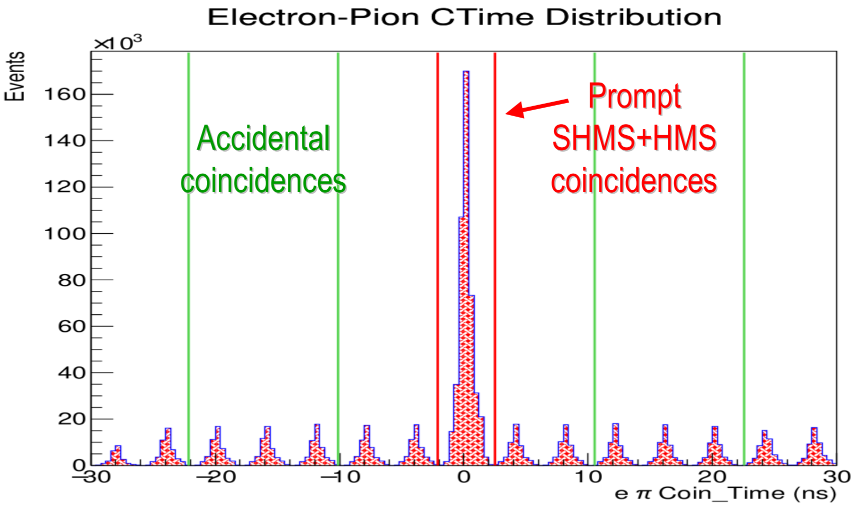
# $p(e,e'\pi^+)n$ Event Selection

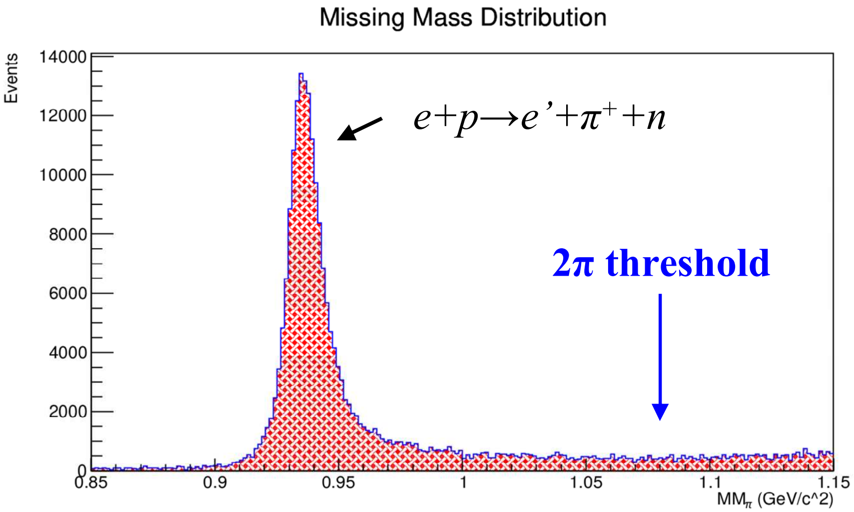
## Coincidence measurement between charged pions in SHMS and electrons in HMS

Garth Huber, huberg@uregina.ca

Easy to isolate exclusive channel

- Excellent particle identification
- CW beam minimizes "accidental" coincidences
- Missing mass resolution easily excludes 2–pion contributions


Electron-Pion CTime Distribution


Missing Mass Distribution

**PionLT experiment E12–19–006 Data**

$Q^2$=1.60, $W$=3.08, $x$= 0.157, $\varepsilon$=0.685

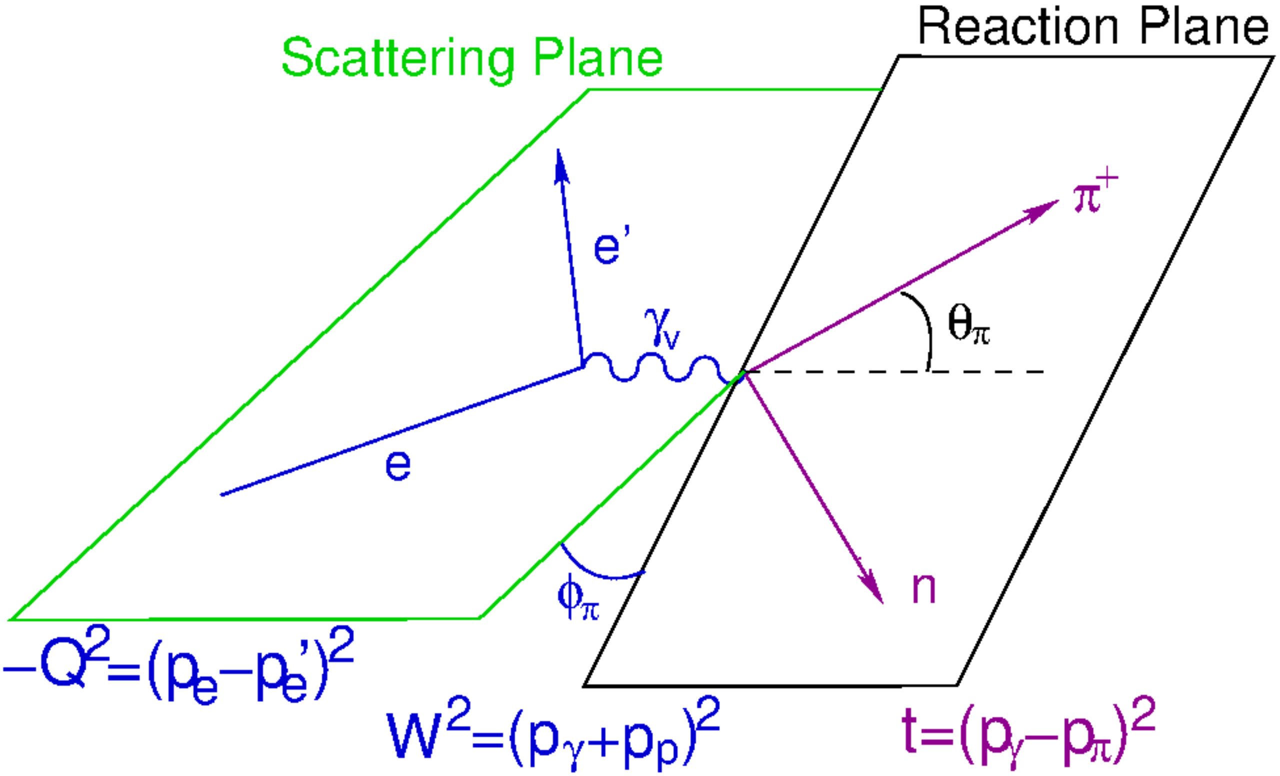
$E_{beam}$=9.177 GeV, $P_{SHMS}$=+5.422 GeV/c, $\theta_{SHMS}$= 10.26° (left)

Plots by Muhammad Junaid

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

Virtual-photon polarization:

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



- **L-T separation required to separate $\sigma_L$ from $\sigma_T$**
- **Need to take data at smallest available $-t$, so $\sigma_L$ has maximum contribution from the $\pi^+$ pole**
- **Need to measure $t$–dependence of $\sigma_L$ at fixed $Q^2$,W**

**Garth Huber, huberg@uregina.ca**

# L/T–separation error propagation

Garth Huber, huberg@uregina.ca

**Error in $d\sigma_L/dt$ is magnified by $1/\Delta\varepsilon$, where $\Delta\varepsilon=(\varepsilon_{Hi}-\varepsilon_{Low})$**

**→ To keep magnification factor <5x, need $\Delta\varepsilon>0.2$, preferably more!**

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

$$\frac{\Delta\sigma_L}{\sigma_L}=\frac{1}{(\varepsilon_1-\varepsilon_2)}\left(\frac{\Delta\sigma}{\sigma}\right)\sqrt{(R+\varepsilon_1)^2+(R+\varepsilon_2)^2}\qquad \text{where } R=\frac{\sigma_T}{\sigma_L}$$

$$\frac{\Delta\sigma_T}{\sigma_T}=\frac{1}{(\varepsilon_1-\varepsilon_2)}\left(\frac{\Delta\sigma}{\sigma}\right)\sqrt{\varepsilon_1^2\left(1+\frac{\varepsilon_2}{R}\right)^2+\varepsilon_2^2\left(1+\frac{\varepsilon_1}{R}\right)^2}$$

**The relevant quantities for $F_\pi$ extraction are $R$ and $\Delta\varepsilon$**

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

# Extract $F_\pi(Q^2)$ from JLab $\sigma_L$ data

Model incorporates $\pi^+$ production mechanism and spectator neutron effects:

## VGL Regge Model:

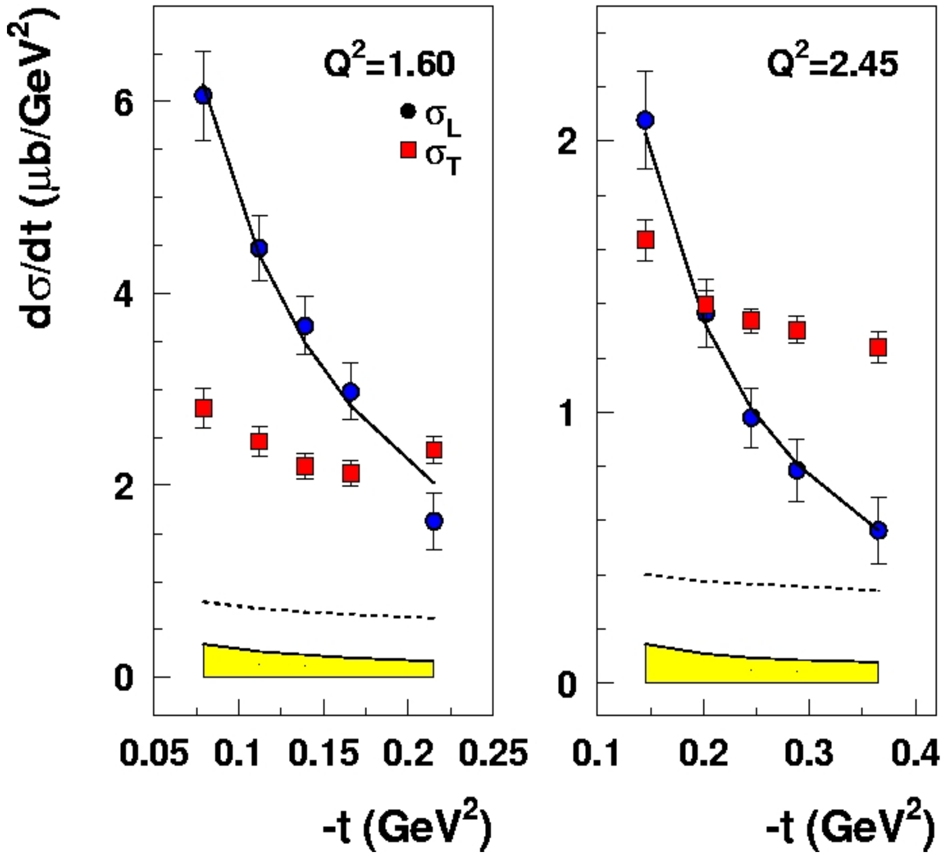
- Feynman propagator $\left(\frac{1}{t-m_\pi^2}\right)$ replaced by π and ρ Regge propagators.
  - Represents the exchange of a series of particles, compared to a single particle.
- Free parameters: $\Lambda_\pi$, $\Lambda_\rho$ (trajectory cutoff).

[Vanderhaeghen, Guidal, Laget, PRC **57**(1998)1454]

- At small $-t$, $\sigma_L$ only sensitive to $F_\pi$

$$\boxed{F_\pi = \frac{1}{1+Q^2/\Lambda_\pi^2}}$$

Fit to $\sigma_L$ to model gives $F_\pi$ at each $Q^2$



Fπ-2 data: T. Horn et al., PRL **97**(2006)192001.

Error bars indicate statistical and random (pt-pt) systematic uncertainties in quadrature.

Yellow band indicates the correlated (scale) and partly correlated (t-corr) systematic uncertainties.

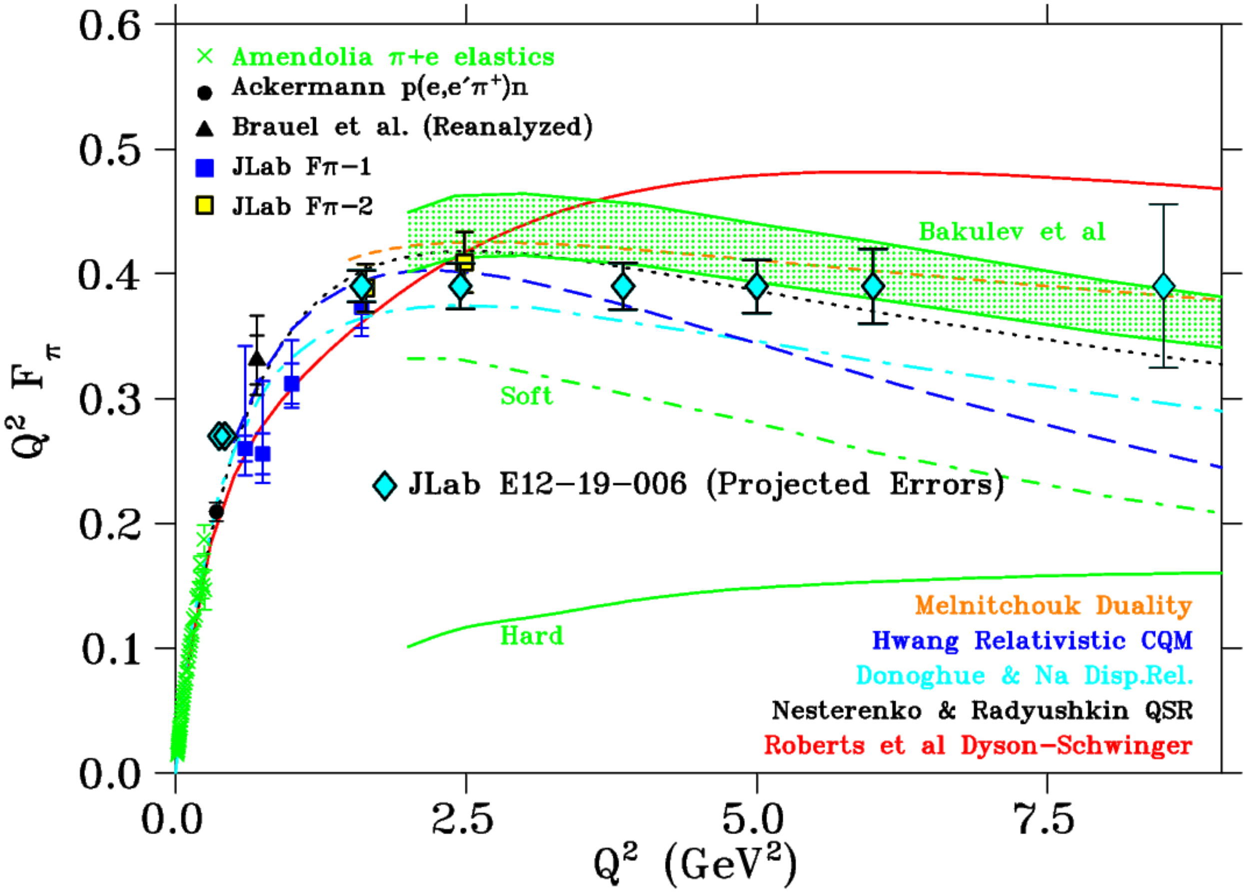
$\Lambda_\pi^2$=0.513, 0.491 GeV², $\Lambda_\rho^2$=1.7 GeV².

# Current and Projected $F_\pi$ Data

SHMS+HMS will allow measurement of $F_\pi$ to much higher $Q^2$.

**No other facility worldwide can perform this measurement.**

**The pion form factor is the clearest test case for studies of QCD's transition from non–perturbative to perturbative regions.**



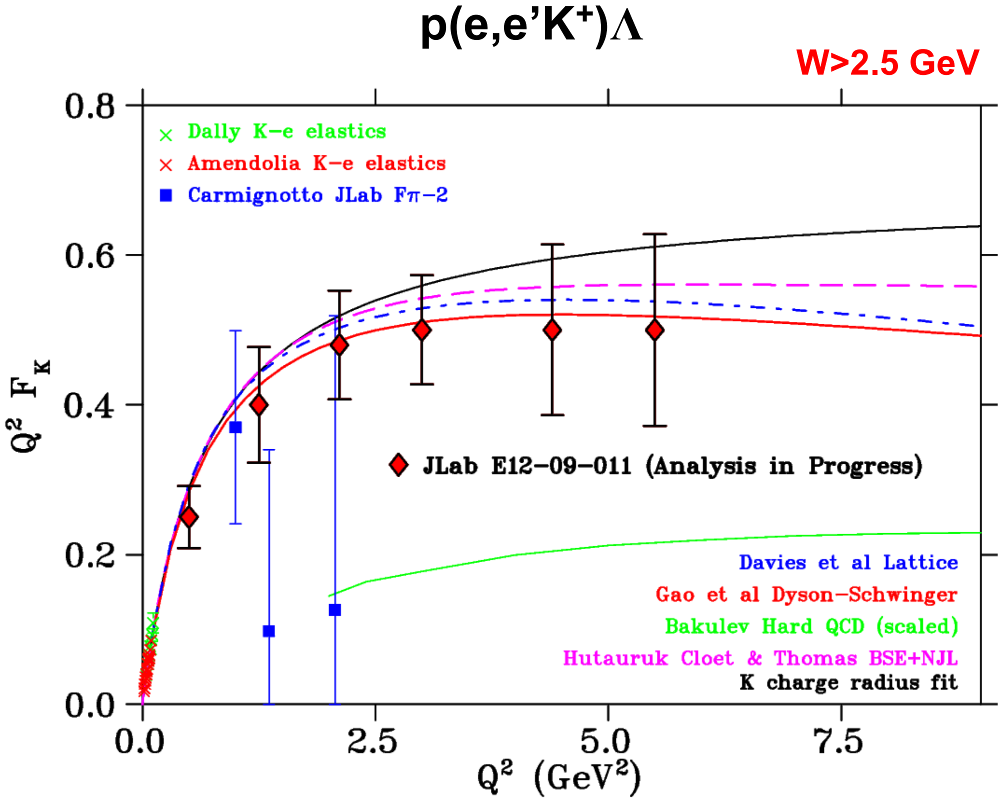
The ~17% measurement of $F_\pi$ at $Q^2$=8.5 GeV$^2$ is at higher $-t_{min}$=0.45 GeV$^2$

*E12–19–006: D. Gaskell, T. Horn and G. Huber, spokespersons*

**Garth Huber, huberg@uregina.ca**

# Projected Uncertainties for $K^+$ Form Factor

- First measurement of $F_K$ well above the resonance region.
- Measure form factor to $Q^2$=3 GeV$^2$ with good overlap with elastic scattering data.
  - Limited by $-t$<0.2 GeV$^2$ requirement to minimize non–pole contributions.
- Data will provide an important second $q\bar{q}$ system for theoretical models, this time involving a strange quark.



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

# Phase 1 Scenario: $\pi^+$ Form Factor

- 7.2 GeV/c HMS & 11.0 GeV/c SHMS allow a lot of kinematic flexibility, **with no major upgrades**
  - Experiment could be done as soon as beam energy is available!
  - Maximum beam energy and higher $Q^2$ reach constrained by sum of HMS+SHMS maximum momenta
  - $Q^2$=8.5 and 11.5 Time FOM similar to PionLT $Q^2$=6.0 and 8.5 points

**p(e,e'$\pi^+$)n Kinematics**

| $E_{beam}$ | $\theta_{HMS}$ (e') | $P_{HMS}$ (e') | $\theta_{q(SHMS)}$ ($\pi^+$) | $P_{SHMS}$ ($\pi^+$) | Time FOM |
|---|---|---|---|---|---|
| $Q^2$=8.5 $W$=3.64 $-t_{min}$=0.24 $\Delta\varepsilon$=0.40 | | | | | |
| 13.0 | 34.30 | 1.88 | 5.29 | 10.99 | 64.7 |
| 18.0 | 15.05 | 6.88 | 8.94 | 10.99 | 2.2 |
| $Q^2$=10.0 $W$=3.44 $-t_{min}$=0.37 $\Delta\varepsilon$=0.40 | | | | | |
| 13.0 | 37.78 | 1.83 | 5.56 | 10.97 | 122.7 |
| 18.0 | 16.39 | 6.83 | 9.57 | 10.97 | 4.5 |
| $Q^2$=11.5 $W$=3.24 $-t_{min}$=0.54 $\Delta\varepsilon$=0.29 | | | | | |
| 14.0 | 31.73 | 2.75 | 7.06 | 10.96 | 82.4 |
| 18.0 | 17.70 | 6.75 | 10.05 | 10.96 | 8.8 |

| | 10.6 GeV | 18.0 GeV | Improvement in $\delta F_\pi/F_\pi$ |
|---|---|---|---|
| $Q^2$=8.5 | $\Delta\varepsilon$=0.22 | $\Delta\varepsilon$=0.40 | 16.8%→8.0% |
| $Q^2$=10.0 | New high quality $F_\pi$ data | | |
| $Q^2$=11.5 | Larger $F_\pi$ extraction uncertainty due to higher $-t_{min}$ | | |

- **Since quality L–T separations are impossible at EIC (can't access $\varepsilon$<0.95) this extension of L–T separated data considerably increases $F_\pi$ data set overlap between JLab and EIC**

Garth Huber, huberg@uregina.ca

# Phase 1 Scenario: $K^+$ Form Factor

- 7.2 GeV/c HMS & 11.0 GeV/c SHMS allow a lot of kinematic flexibility
- Maximum beam energy and higher $Q^2$ reach constrained by sum of HMS+SHMS maximum momenta
- Success depends on good $K^+/\pi^+$ separation in SHMS at high momenta, likely requires a modest aerogel detector upgrade
- Counting rates are roughly 10x lower than pion form factor measurement

|  | 10.6 GeV | 16.0 GeV | Improvement in $\delta F_K/F_K$ |
|---|---|---|---|
| $Q^2$=5.5 | $\Delta\varepsilon$=0.33 | $\Delta\varepsilon$=0.40 | 17.9%→10.7% |
| $Q^2$=7.0 | New high quality $F_K$ data |  |  |
| $Q^2$=9.0 | Larger $F_K$ extraction uncertainty due to higher $-t_{min}$ |  |  |

**$p(e,e'K^+)\Lambda$ Kinematics**

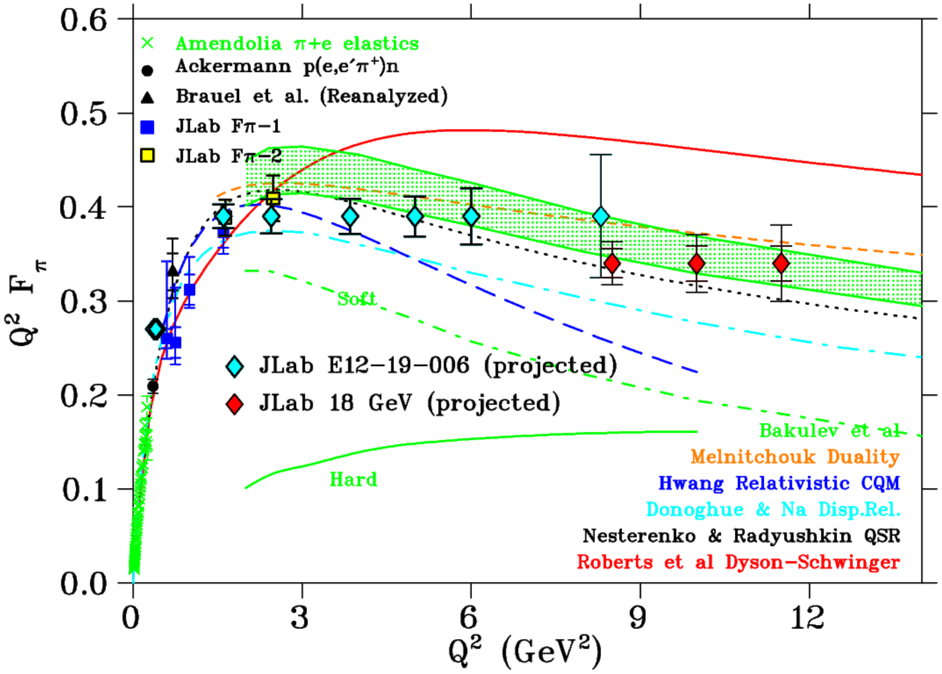
| $E_{beam}$ | $\theta_{HMS}$ (e') | $P_{HMS}$ (e') | $\theta_{q(SHMS)}$ ($\pi^+$) | $P_{SHMS}$ ($\pi^+$) | Time FOM |
|---|---|---|---|---|---|
| $Q^2$=5.5 $W$=3.56 $-t_{min}$=0.32 $\Delta\varepsilon$=0.40 |  |  |  |  |  |
| 11.0 | 30.69 | 1.79 | 5.50 | 8.84 | 746 |
| 16.0 | 12.92 | 6.79 | 9.18 | 8.84 | 150 |
| $Q^2$=7.0 $W$=3.90 $-t_{min}$=0.33 $\Delta\varepsilon$=0.29 |  |  |  |  |  |
| 14.0 | 25.16 | 2.64 | 5.51 | 10.98 | 620 |
| 18.0 | 13.91 | 6.64 | 7.85 | 10.98 | 192 |
| $Q^2$=9.0 $W$=3.66 $-t_{min}$=0.54 $\Delta\varepsilon$=0.30 |  |  |  |  |  |
| 14.0 | 29.17 | 2.54 | 5.98 | 10.97 | 964 |
| 18.0 | 15.90 | 6.54 | 8.69 | 10.97 | 350 |

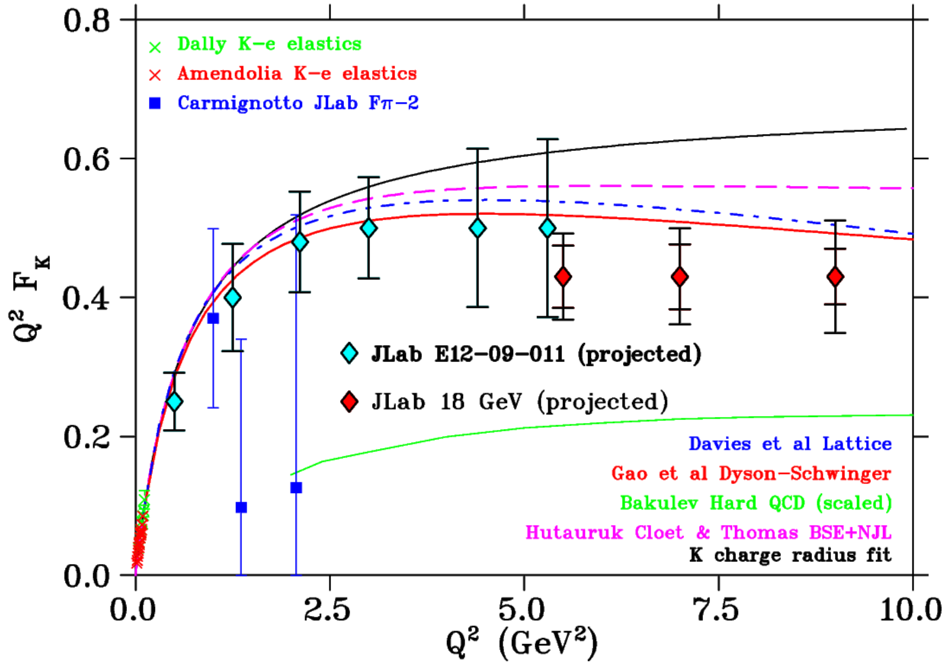
- **$F_K$ feasibility studies at EIC are ongoing, but we already know that such measurements there are exceptionally complex.**
- **JLab measurements likely a complement to those at EicC.**

Garth Huber, huberg@uregina.ca

# Phase 1: Form Factor Projections

- $Y$-axis values of projected data are arbitrary
- The errors are projected, based on Δε from beam energies on earlier slides, and T/L ratio calculated with Vrancx Ryckebusch model
- Assumes same statistics as acquired in PionLT experiment
- Inner error bar is projected statistical and systematic error
- Outer error bar also includes a model uncertainty in the form factor extraction, added in quadrature
- $F_\pi$ errors based on Fπ–2 and E12–19–006 experience
- $F_K$ errors more uncertain, as E12–09–011 analysis not yet completed, projected running times extremely long





Garth Huber, huberg@uregina.ca

# Phase 2 Scenario: $\pi^+$ Form Factor

- **Replace HMS with VHMS for $\pi^+$, use SHMS for e’**
  - Assume $\theta_{min}$=5.5°, $\theta_{open}$=15.0°
  - VHMS: ΔΩ, ΔP/P similar SHMS
- $P_{VHMS}$=15.0 GeV/c is sufficient, constrained by max beam energy
- $\theta_{VHMS}$~5.5° allows improved Δε, but does not affect maximum $Q^2$ reach
- $\theta_{SHMS}$<12.0°, $P_{SHMS}$>9.0 not used
- Dramatic increase in upper $Q^2$ 11.5 → 15.0 GeV²
- Error bars for $Q^2$=8.5–11.5 GeV² substantially decrease due to smaller $-t_{min}$ (better $R=\sigma_T/\sigma_L$) and shorter running times
- $Q^2$=15.0 GeV² point would be very “expensive” in terms of running time, but it would likely have very high scientific priority

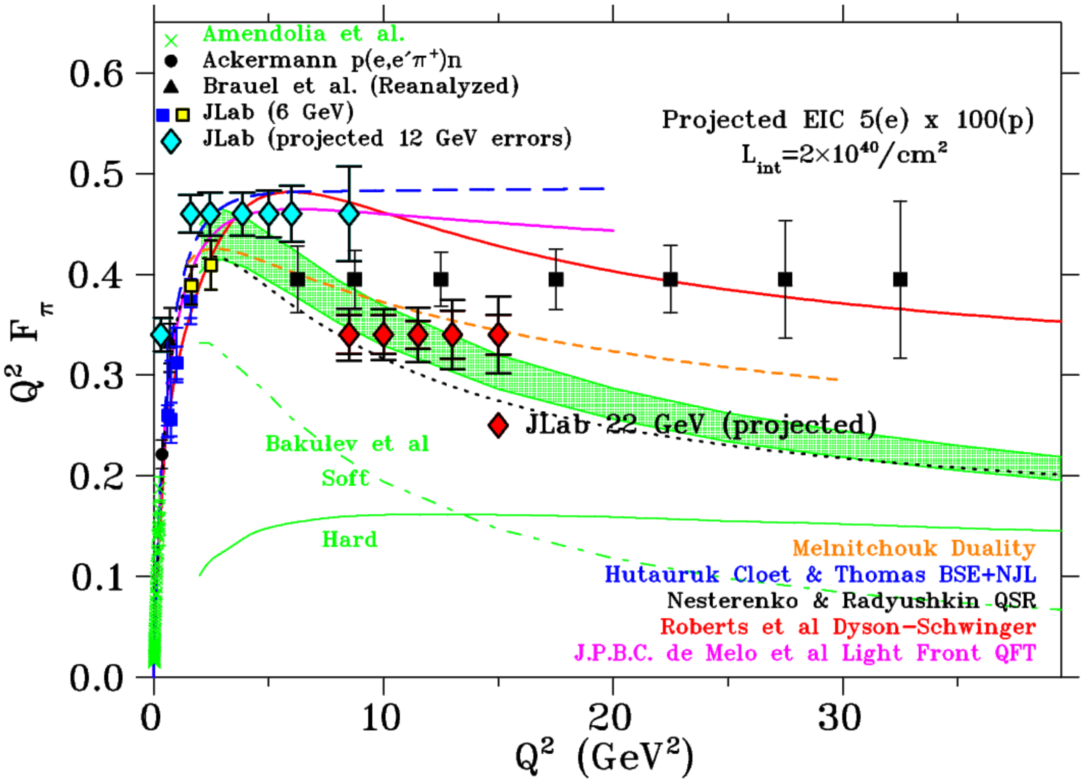
- **Feasible scenario for Phase 2 Upgrade**

**$p(e,e'\pi^+)n$ Kinematics**

| $E_{beam}$ | $\theta_{SHMS}$ (e’) | $P_{SHMS}$ (e’) | $\theta_{q(VHMS)}$ ($\pi^+$) | $P_{VHMS}$ ($\pi^+$) | Time FOM |
|---|---|---|---|---|---|
| $Q^2$=8.5 $W$=4.18 $-t_{min}$=0.15 Δε=0.28 | | | | | |
| 17.0 | 21.39 | 3.63 | 5.55 | 13.29 | 20.5 |
| 22.0 | 12.15 | 8.63 | 7.62 | 13.29 | 1.8 |
| $Q^2$=10.0 $W$=4.08 $-t_{min}$=0.21 Δε=0.30 | | | | | |
| 17.0 | 24.49 | 3.27 | 5.52 | 13.62 | 53.3 |
| 22.0 | 13.46 | 8.27 | 7.85 | 13.62 | 4.3 |
| $Q^2$=11.5 $W$=3.95 $-t_{min}$=0.29 Δε=0.31 | | | | | |
| 17.0 | 27.34 | 3.03 | 5.55 | 13.82 | 124.8 |
| 22.0 | 14.66 | 8.03 | 8.12 | 13.82 | 9.3 |
| $Q^2$=13.0 $W$=3.96 $-t_{min}$=0.35 Δε=0.25 | | | | | |
| 18.0 | 27.55 | 3.18 | 5.54 | 14.63 | 209.5 |
| 22.0 | 16.49 | 7.18 | 7.69 | 14.63 | 24.4 |
| $Q^2$=15.0 $W$=3.73 $-t_{min}$=0.52 Δε=0.26 | | | | | |
| 18.0 | 30.24 | 3.06 | 5.73 | 14.66 | 560 |
| 22.0 | 17.88 | 7.06 | 8.07 | 14.66 | 65.7 |

Garth Huber, huberg@uregina.ca

# Importance of JLab $F_\pi$ in EIC Era



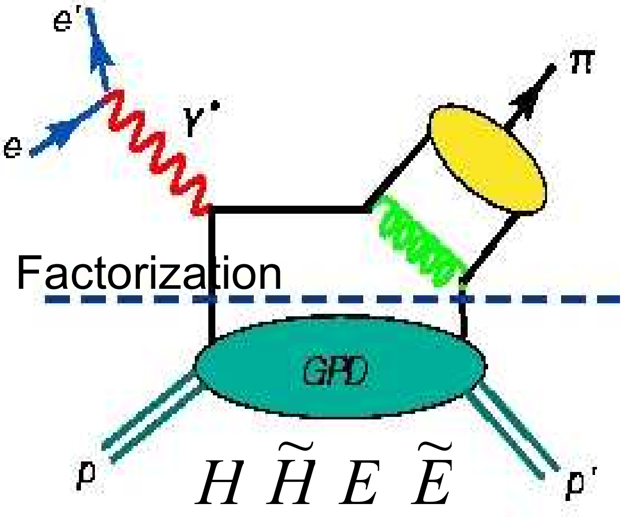
- Quality L/T-separations impossible at EIC (can't access ε<0.95)
- JLab will remain ONLY source of quality L–T separated data!
- **Phase 2: 22 GeV beam with upgraded VHMS**
  - Extends region of high quality $F_\pi$ values to $Q^2$=13 GeV$^2$
  - Somewhat larger errors to $Q^2$=15 GeV$^2$
- Provides MUCH improved overlap of $F_\pi$ data set between JLab and EIC!

Garth Huber, huberg@uregina.ca

# Hard–Soft Factorization in DEMP

- **To access physics contained in GPDs, one is limited to the kinematic regime where hard-soft factorization applies**
  - No single criterion for the applicability, but tests of necessary conditions can provide evidence that the $Q^2$ scaling regime has been reached

- **One of the most stringent tests of factorization is the $Q^2$ dependence of the $\pi/K$ electroproduction cross sections**
  - $\sigma_L$ scales to leading order as $Q^{-6}$
  - $\sigma_T$ does not, expectation of $Q^{-8}$
  - As $Q^2$ becomes large: $\sigma_L >> \sigma_T$

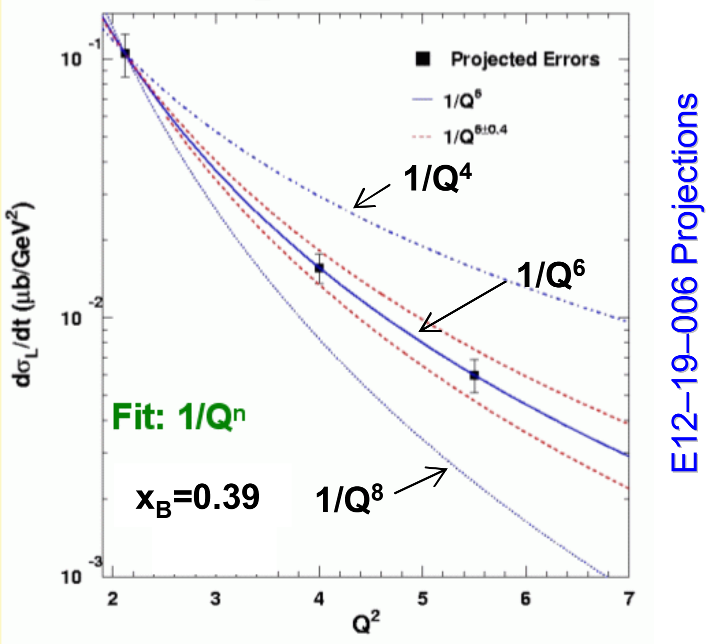


- **Experimental validation of onset of hard scattering regime is essential for reliable interpretation of JLab GPD program results**
  - Is onset of scaling different for kaons than pions?
  - $K^+$ and $\pi^+$ together provide quasi model-independent study

# DEMP $Q^{-n}$ Hard–Soft Factorization Tests

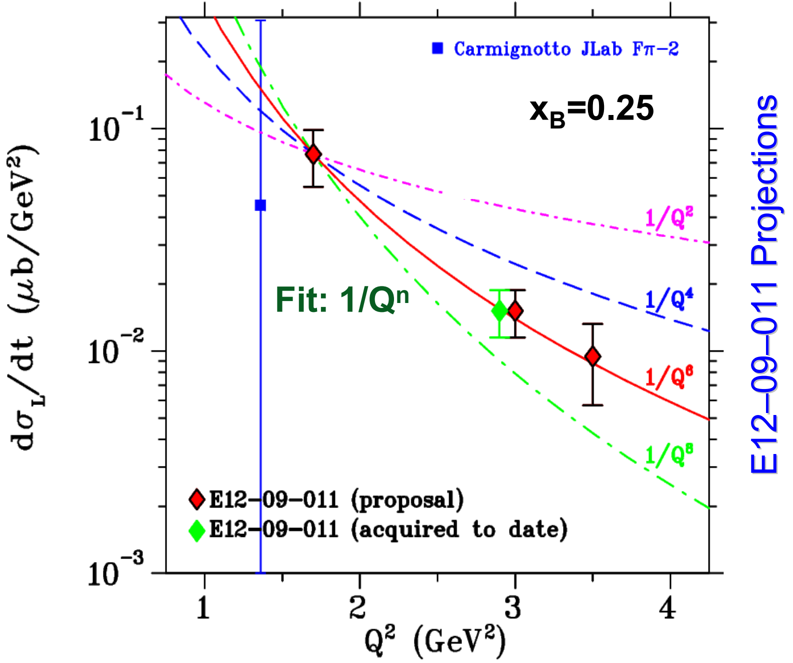
Garth Huber, huberg@uregina.ca

$p(e,e'\pi^+)n$



| $x$ | $Q^2$ (GeV$^2$) | $W$ (GeV) | $-t_{min}$ (GeV$^2$) |
|---|---|---|---|
| 0.31 | 1.45–3.65 | 2.02–3.07 | 0.12 |
| | 1.45–6.5 | 2.02–3.89 | |
| 0.39 | 2.12–6.0 | 2.05–3.19 | 0.21 |
| | 2.12–8.2 | 2.05–3.67 | |
| 0.55 | 3.85–8.5 | 2.02–2.79 | 0.55 |
| | 3.85–11.5 | 2.02–3.23 | |

$p(e,e'K^+)\Lambda$



| $x$ | $Q^2$ (GeV$^2$) | $W$ (GeV) | $-t_{min}$ (GeV$^2$) |
|---|---|---|---|
| 0.25 | 1.7–3.5 | 2.45-3.37 | 0.20 |
| | 1.7–5.5 | 2.45–4.05 | |
| 0.40 | 3.0–5.5 | 2.32–3.02 | 0.50 |
| | 3.0–8.7 | 2.32–3.70 | |

**PHASE 1 SCENARIO**

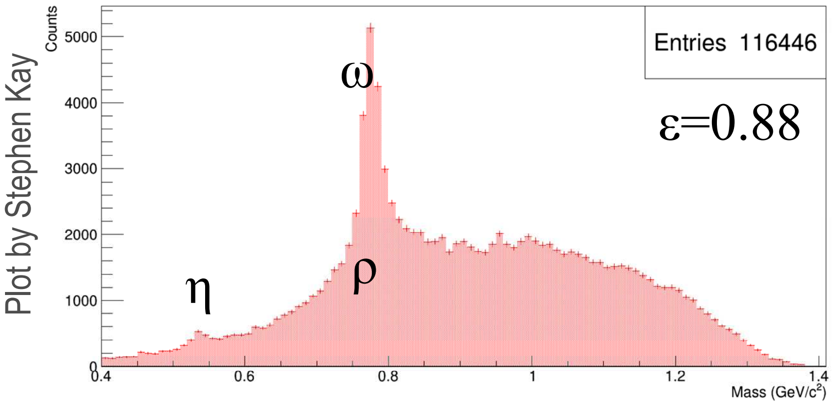
**$Q^{-n}$ scaling test range nearly doubles with 18 GeV beam and HMS+SHMS**

# Hard–Soft Factorization in Backward Exclusive $\pi^0$

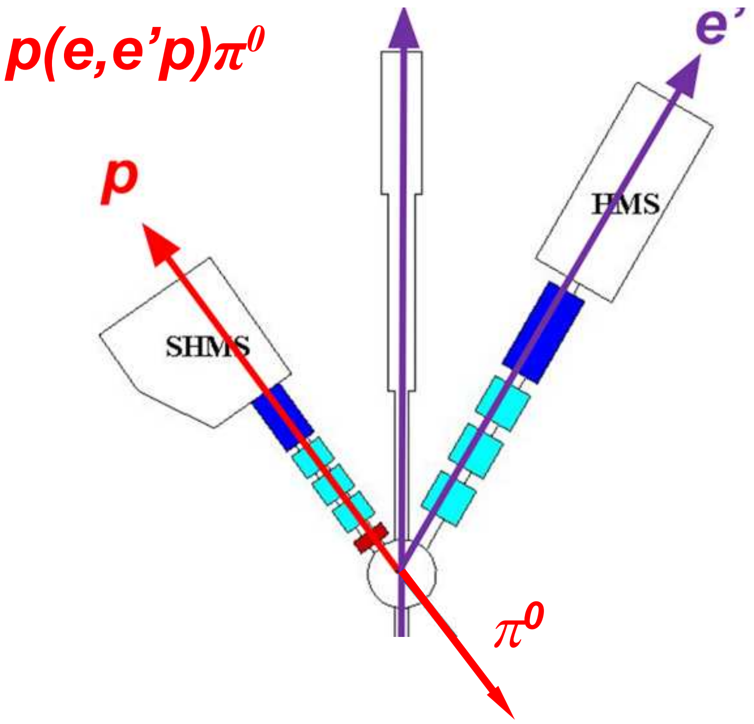
Garth Huber, huberg@uregina.ca

***p(e ,e'p)X*** KaonLT Data Analysis

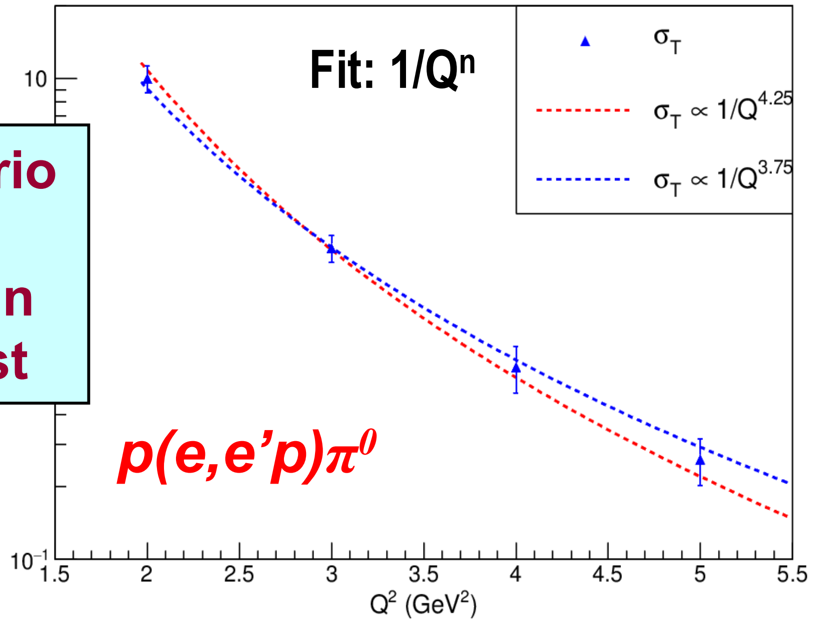
$Q^2$=3.00 $W$=2.32 $\theta_{pq}$=+3.0° $-u$=0.15 $\xi_u$=0.15



- **Fortuitous discovery of substantial backward angle meson production during meson form factor experiments**
- Can be described by extension of collinear factorization to backward angle (u–channel)
- Backward angle factorization first suggested by Frankfurt, Polykaov, Strikman, Zhalov, Zhalov [arXiv:hep-ph/0211263]



**Phase 1 Scenario will enable improvement in *Q⁻ⁿ* scaling test**



**E12–20–007: First dedicated u–channel experiment**

Spokespersons: W.B. Li, G.M. Huber, J. Stevens

**Purpose:** test applicability of TDA formalism for $\pi^0$ production

# Staged Upgrade Seems Logical

- **Phase 1:** Upgrade Beam to 18 GeV, minor upgrades of SHMS, HMS PID, tracking and DAQ
  - Example Measurements:
  - Pion form factor to $Q^2$=10 GeV$^2$ with small errors, and to 11.5 with larger uncertainties
  - Kaon form factor requires very long running times, but could allow $Q^2$=7.0 GeV$^2$ with small errors, and to 9.0 with larger uncertainties
  - Hard–Soft $Q^{-n}$ factorization tests with $p(e,e'\pi^+)n$ and $p(e,e'K^+)\Lambda$
  - Studies of backward angle $Q^{-n}$ factorization via u–channel $p(e,e'p)\pi^0$ and $p(e,e'p)\omega$
- **Phase 2:** Upgrade Beam to 22 GeV, upgrade VHMS to 15 GeV/c
  - Would enable a significant increase in $Q^2$ reach of quality L–T separations for Deep Exclusive Meson Production
    - e.g. Pion Form factor up to $Q^2$=15 GeV$^2$