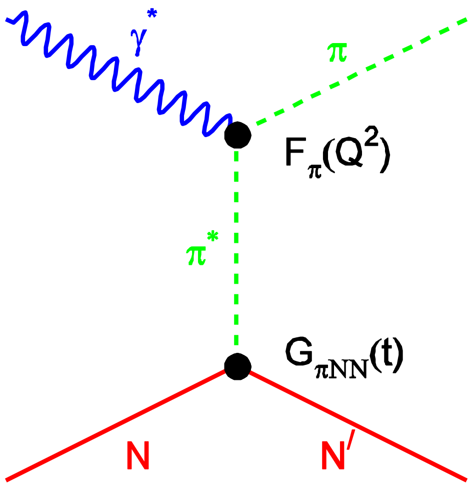
# Exploring Meson Structure at Jefferson Lab

- Meson structure, hadronic mass, and QCD
- Charged pion form factor via pion electroproduction
- Kaon form factor via kaon electroproduction
- Inelastic pion and kaon structure via recoil tagging

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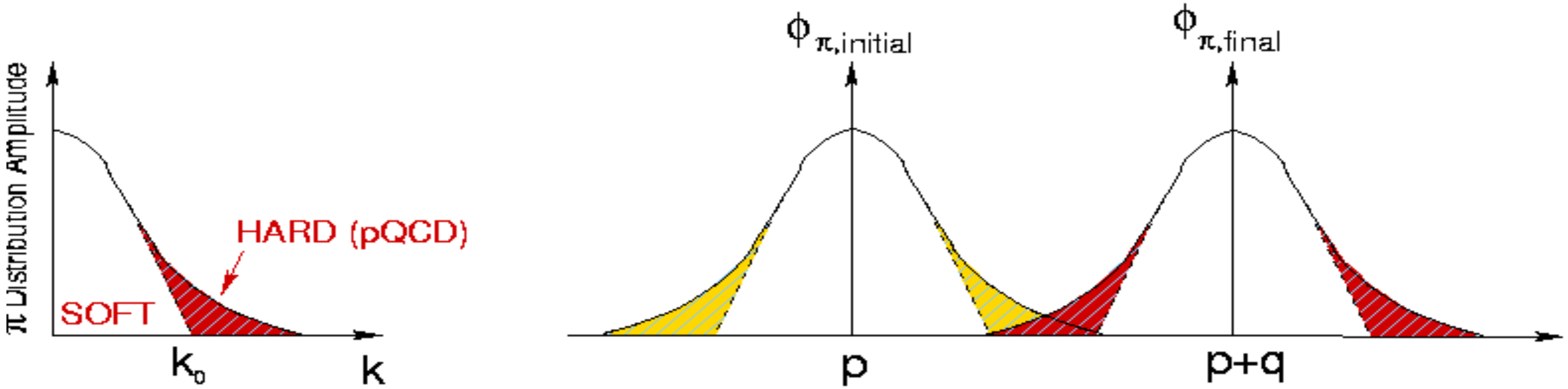
SPIN 2023

September 24-29, 2023

# Charged Meson Form Factors

Simple quark-antiquark structure of mesons ideal system for studying bound quarks

Quantum field theory → form factor is overlap integral $$F_\pi(Q^2) = \int \phi_\pi^*(p)\phi_\pi(p+q)dp$$




Meson wave function can be separated into soft and hard components

$\phi_\pi^{soft}$ → Low momentum contributions only

$\phi_\pi^{hard}$ → High momentum components can be treated in pQCD

$Q^2$ dependence of meson form factors allows us to study the soft and hard contributions to pion structure, and the transition between the two

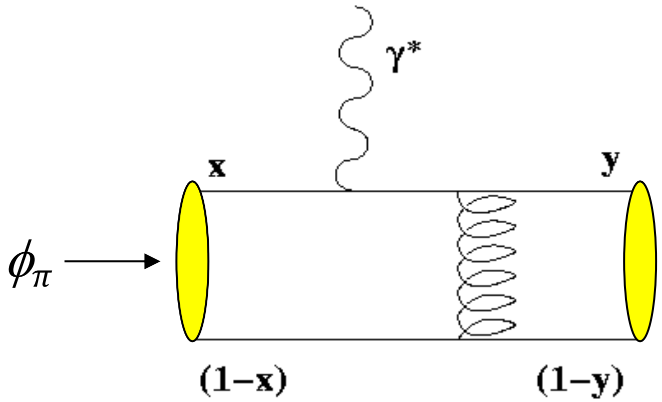
# The Pion Form Factor and the Interplay of Soft and Hard Physics

The pion form factor is unique in that its asymptotic form can be calculated exactly in pQCD

However, it is unclear at what $Q^2$ the pQCD expression is relevant – soft processes play an important role at moderate $Q^2$

Recent calculations suggest that the most significant soft physics is found in the pion distribution amplitude

→ Calculations of pion DA from lattice give pion DA similar to that from state of the art DSE calculations

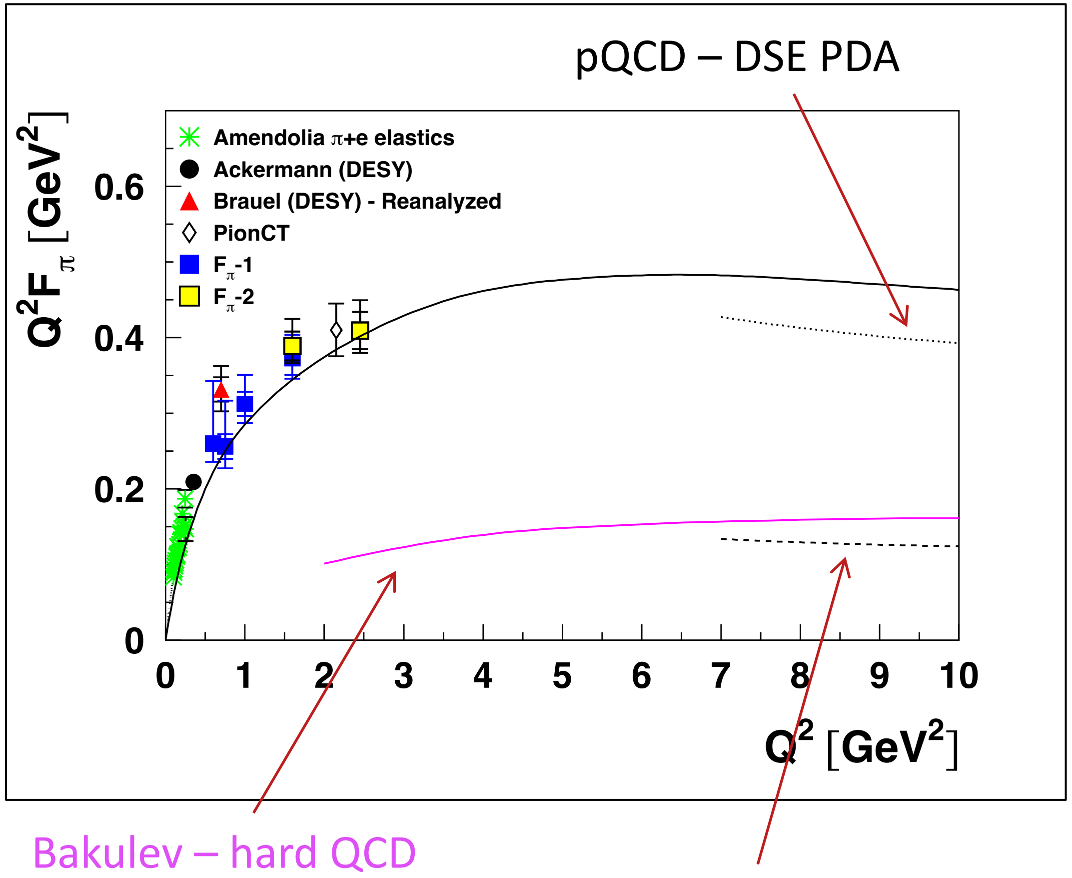



$f_\pi$=93 MeV is the $\pi^+ \rightarrow \mu^+ \nu$ decay constant.

$$\boxed{F_\pi(Q^2) \xrightarrow[Q^2\to\infty]{} \frac{16\pi\alpha_s(Q^2) f_\pi^2}{Q^2}}$$

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

# pQCD and the Pion Form Factor

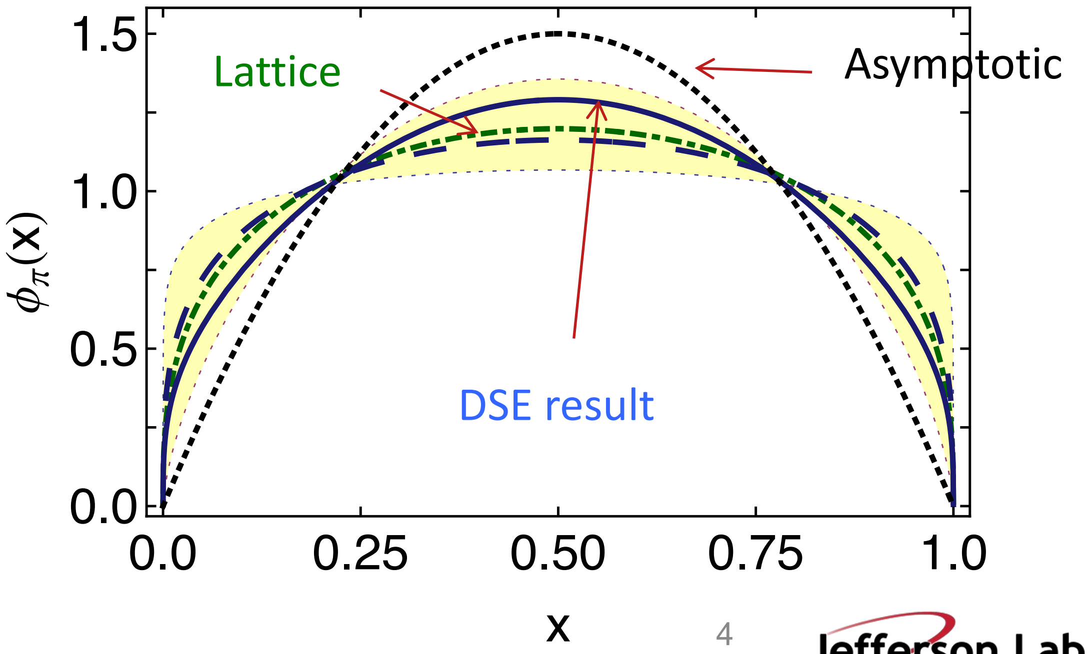



Is it possible to apply pQCD at experimentally accessible $Q^2$?

→ Use pion DA derived using DSE formalism instead of asymptotic form

→ DSE-based result consistent with DA derived using constraints from lattice

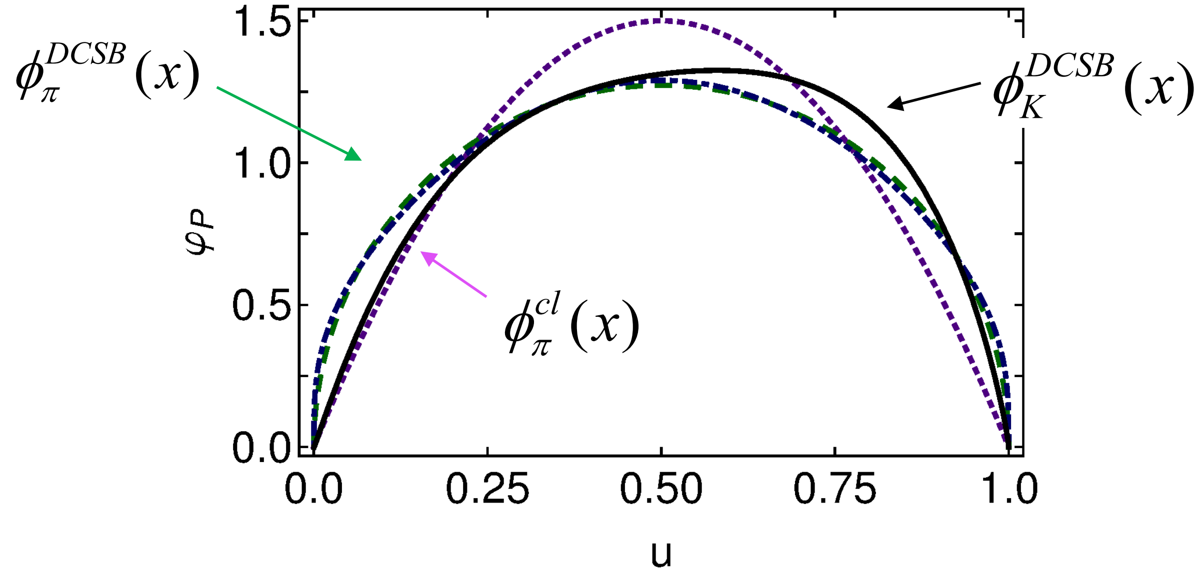
*L. Chang et al, Phys.Rev.Lett. 111 (2013) 14, 141802*
*I. Cloet et al, Phys.Rev.Lett. 111 (2013) 092001*
*L. Chang et al, Phys.Rev.Lett. 110 (2013) 13, 132001*



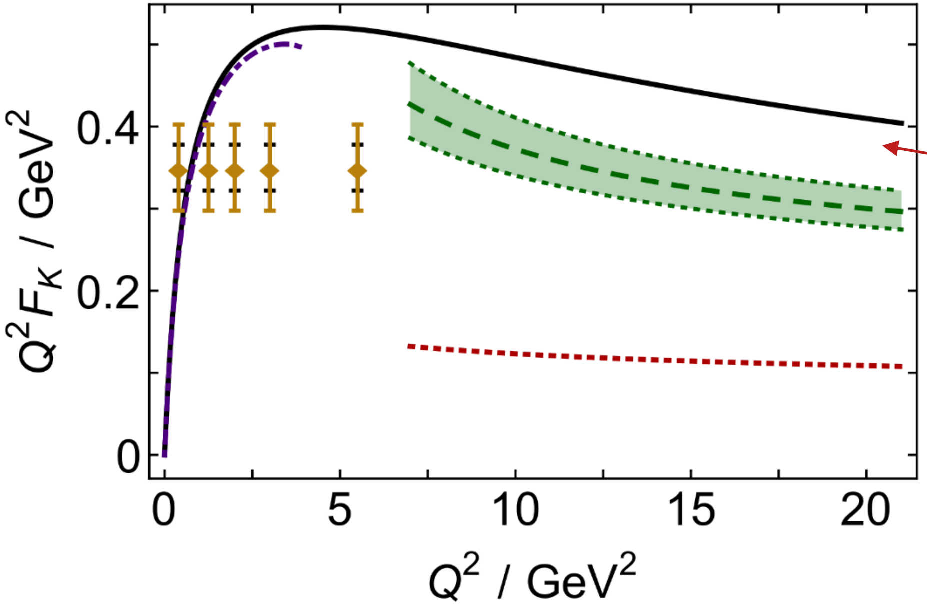
# Kaon Form Factor

Kaon similar to pion, but with heavier *s* quark
→ Similar behavior in asymptotic limit
→ Distribution amplitudes similar although not identical

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




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




$F_K$ DCSB model prediction for JLab kinematics [F. Guo, et al., arXiv: 1703.04875].

Does Kaon FF approach asymptotic limit in same way as pion?

Understanding $Q^2$ dependence of both pion and kaon provides important test of our understanding of QCD



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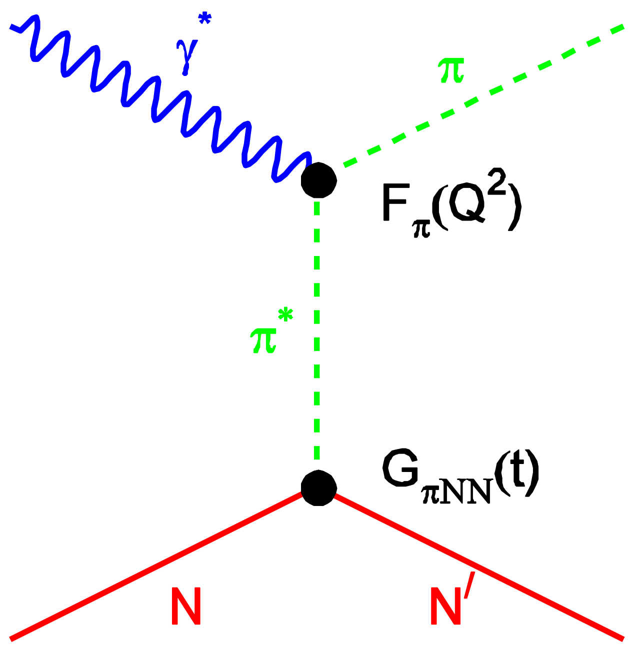
# Measurement of Pion (and Kaon) Form Factor at Large $Q^2$

- At small $Q^2$, pion and kaon form factors measured directly using pion/kaon scattering from atomic electrons
- At larger $Q^2$, $F_\pi$ must be measured indirectly using the "pion cloud" of the proton via *p(e,e'π⁺)n*
  - At small $-t$, the pion pole process dominates the longitudinal cross section, $\sigma_L$
  - In Born term model, $F_\pi^2$ appears as,

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

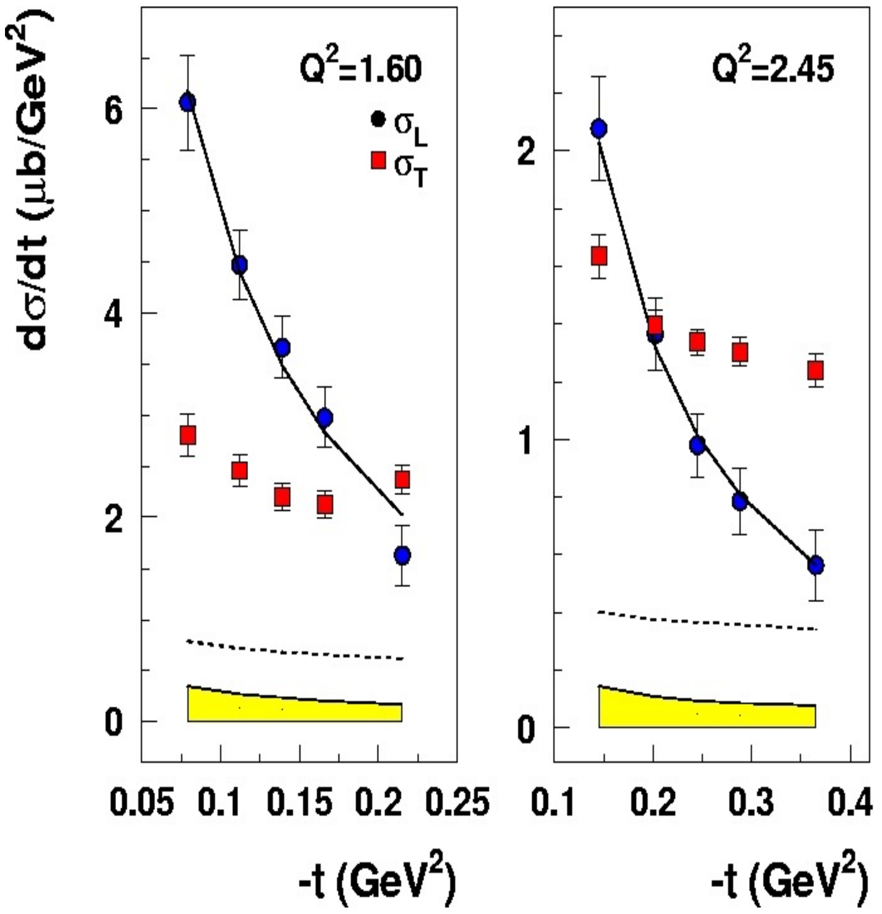
*(In practice more sophisticated model is used)*

- Requirements for this technique
  - Isolate $\sigma_L$ (L-T separation)
  - Model to extract form factor from data – model dependence should be small at small $-t$

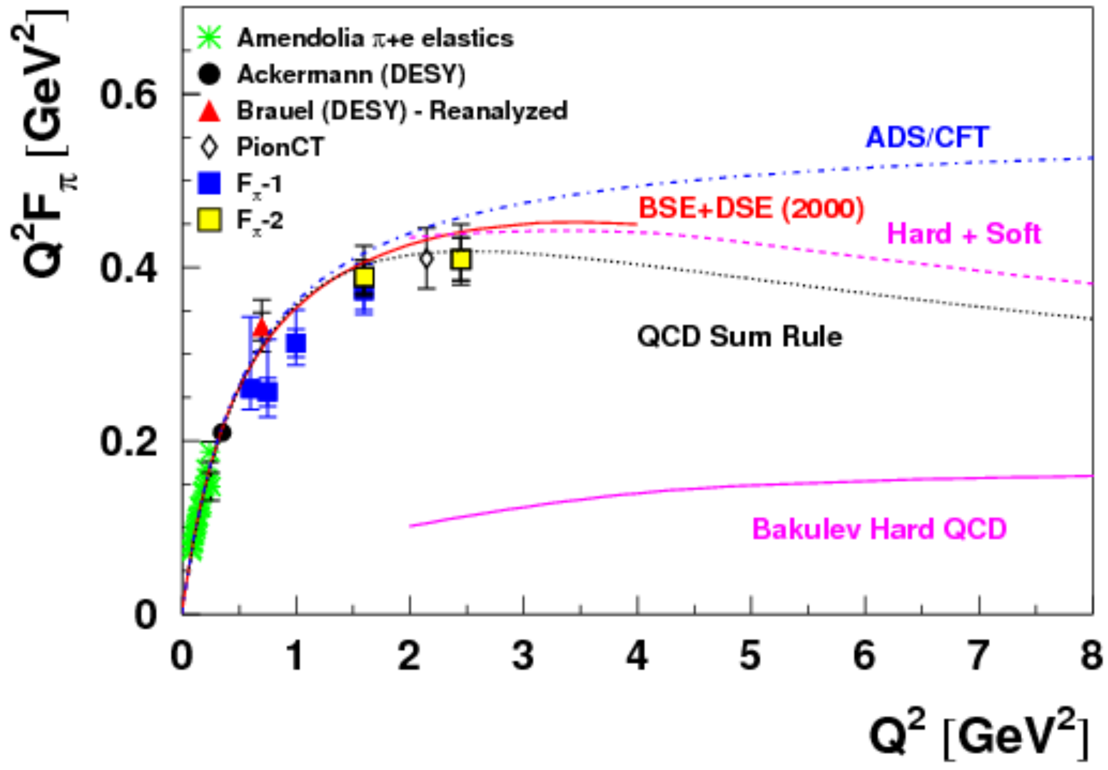



$t=(\gamma^*-\pi)^2$= (mass)² of struck virtual pion

# Measurement of Charged Pion Form Factor at 6 GeV JLab

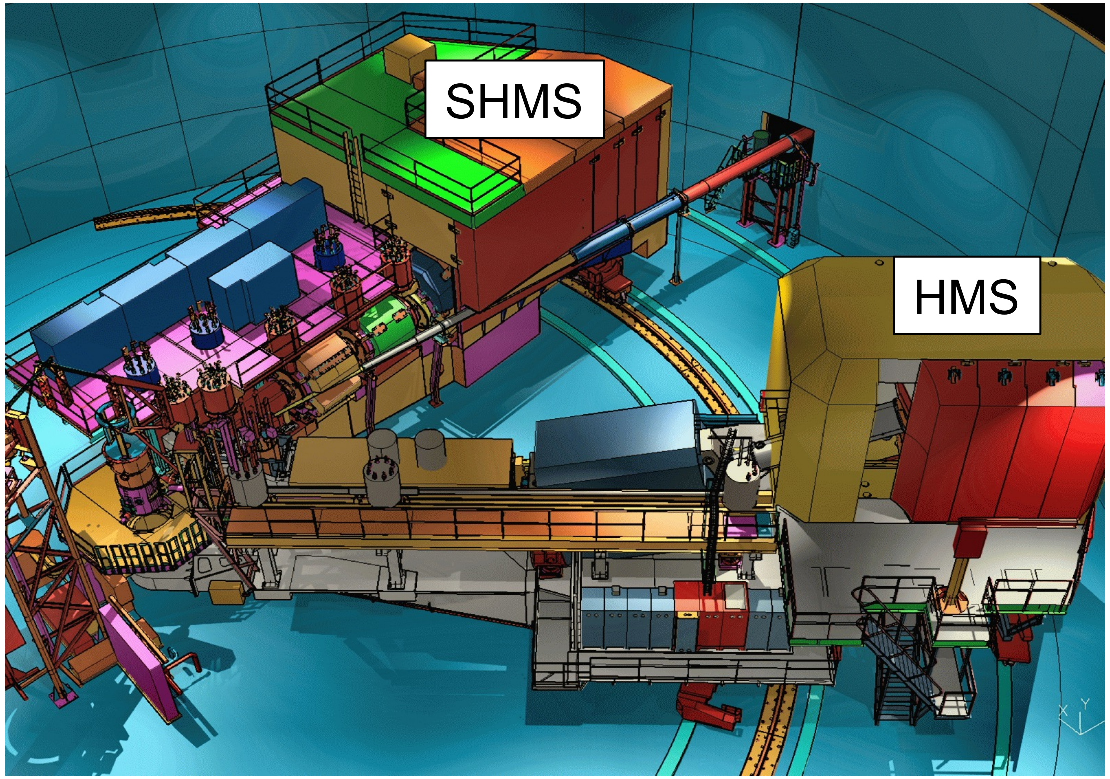



JLab-Hall C measurements: $F_\pi$-1, $F_\pi$-2
**L-T Separation** – extracted $F_\pi$ via fit to $\sigma_L$ using VGL Regge model




Measured $F_\pi$ up to $Q^2$=2.45 GeV$^2$
→ Still far from pQCD limit
→ Models start to diverge just above measured FF

# Pion and Kaon Production in Experimental Hall C at 12 GeV Jefferson Lab




Excellent control of point-to-point systematic uncertainties required for precise L-T separations
→ Ideally suited for focusing spectrometers
→ One of the drivers for SHMS design

## Spectrometer properties

**HMS:** Electron arm
Nominal capabilities:
d$\Omega$ ~ *6* msr, ***$P_0$= 0.5 – 7 GeV/c***
***$\theta_0$=10.5 to 80 degrees***
*e* ID via calorimeter and gas Cerenkov

**SHMS:** Pion arm → ***NEW!***
Nominal capabilities:
d$\Omega$ ~ *4* msr, ***$P_0$= 1 – 11 GeV/c***
***$\theta_0$=5.5 to 40 degrees***
*π:K:p* separation via heavy gas Cerenkov and aerogel detectors

# Hall C $\pi^+$ Program at JLab

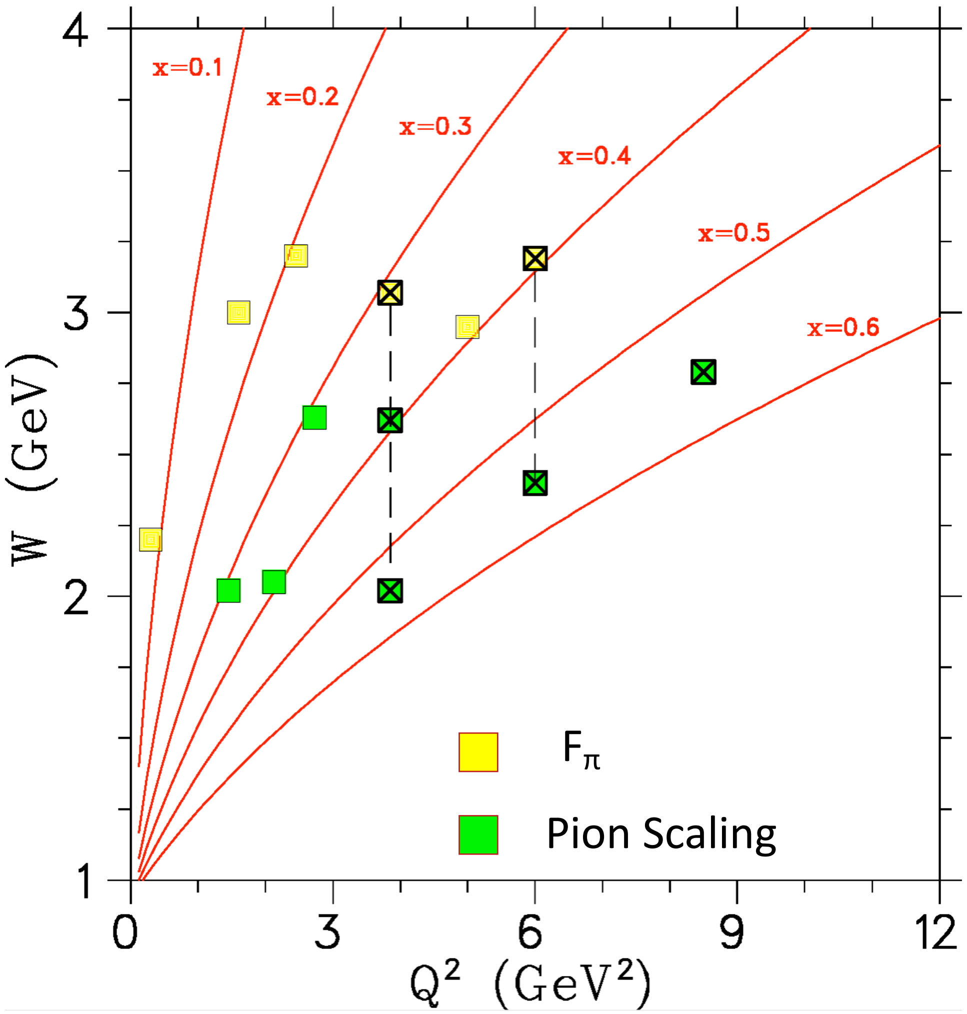
E12-19-006: Study of the L–T Separated Pion Electroproduction Cross Section at 11 GeV and Measurement of the Charged Pion Form Factor to High $Q^2$
Spokepersons: T. Horn, G. Huber, D. Gaskell

***Ran in 2019 (low $Q^2$) and 2021-2022***

<u>Program of L-T separated $\pi^+$ cross sections to measure:</u>

1. Pion form factor at low $-t$ up to $Q^2$=6 GeV$^2$
2. $Q^2$ dependence of $\sigma_L$ at fixed *x and -t*
3. Pion form factor up to $Q^2$=8.5 GeV$^2$

Additional data were taken to verify dominance of pole contribution and explore larger $-t_{min}$ for $F_\pi$ extraction



# Hall C $K^+$ Program at JLab

E12-09-011: Studies of the L-T Separated Kaon Electroproduction Cross Section from 5-11 GeV
Spokespersons: T. Horn, G. Huber, P. Markowitz

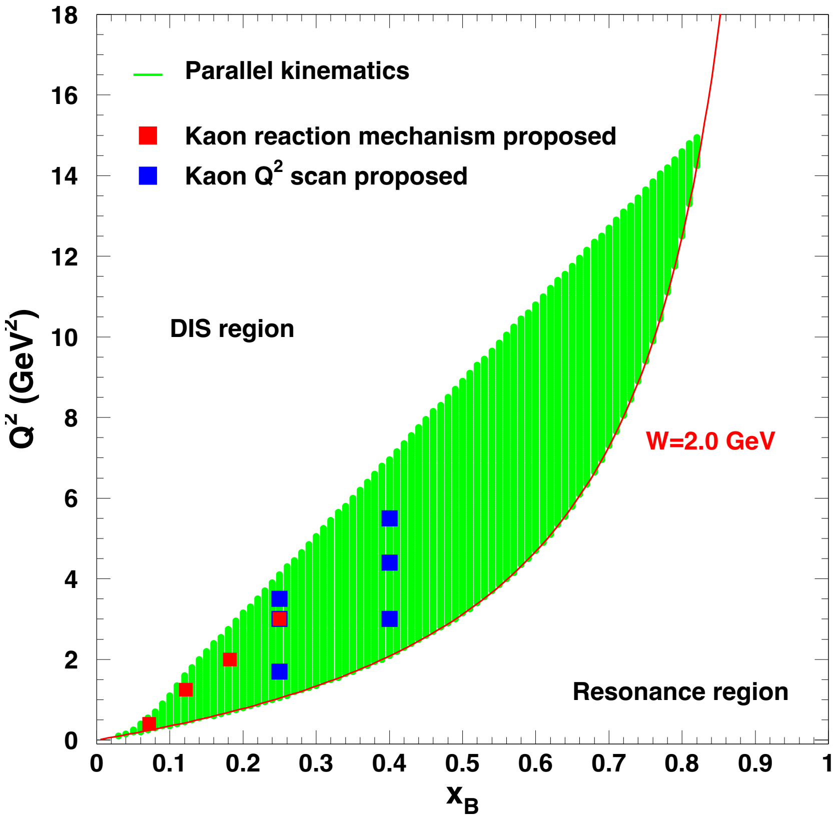
***Ran in Hall C in 2018-2019 (partially complete)***

Measure L-T separated $K^+$ cross sections
→ Fixed x and –t, varying $Q^2$ (scaling)
→ -t dependence measurements at fixed x/$Q^2$ (reaction mechanism/form factor)

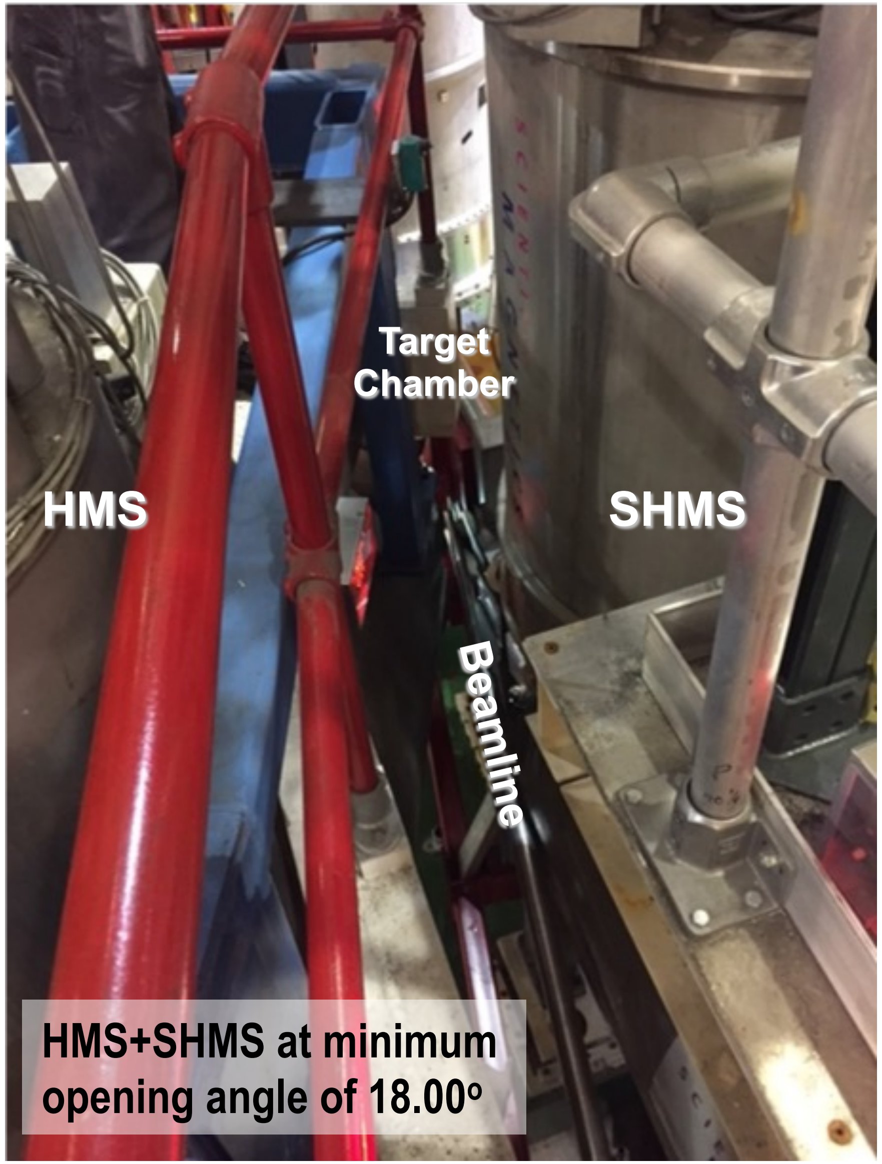
p(e,e'K+)$\Lambda/\Sigma^0$ channels both in acceptance

First L-T separated kaon cross sections above resonance region

| x | $Q^2$ ($GeV^2$) | W (GeV) | -t |
|---|---|---|---|
| 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 |

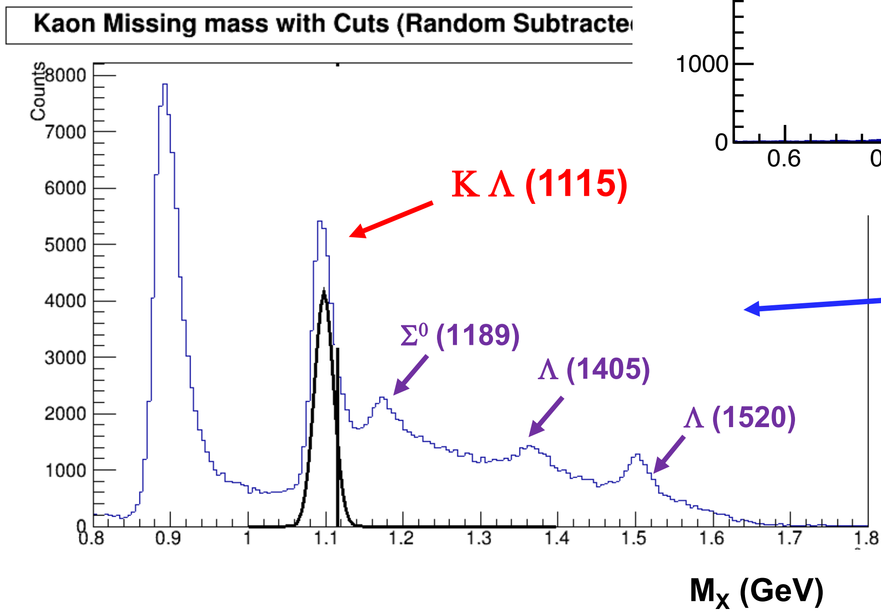


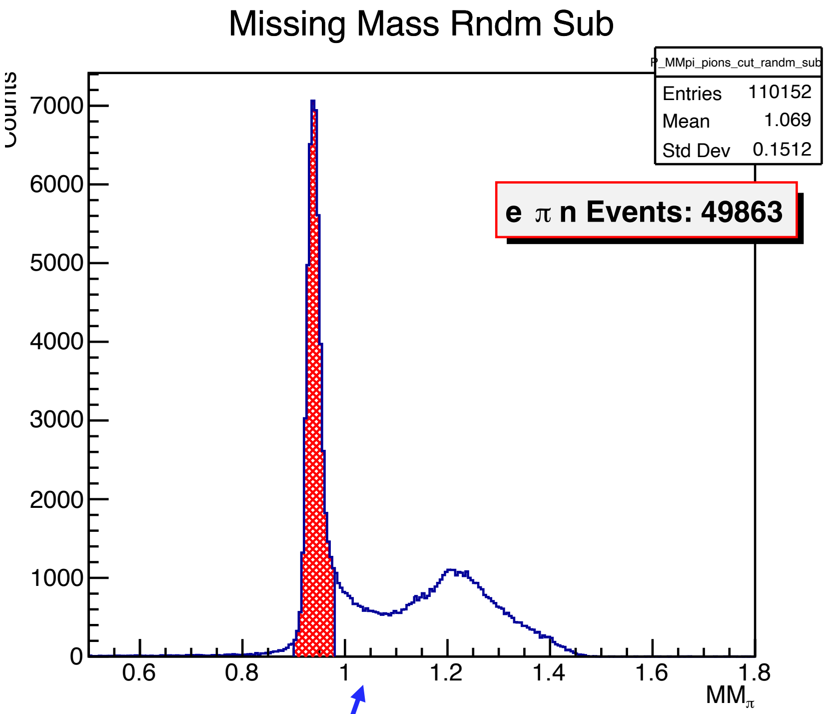
# Experimental Issues




Small spectrometer and opening angles between spectrometers required

Exclusive final states identified via missing-mass




*Online spectra*

Good p/$\pi$/$K^+$ separation required



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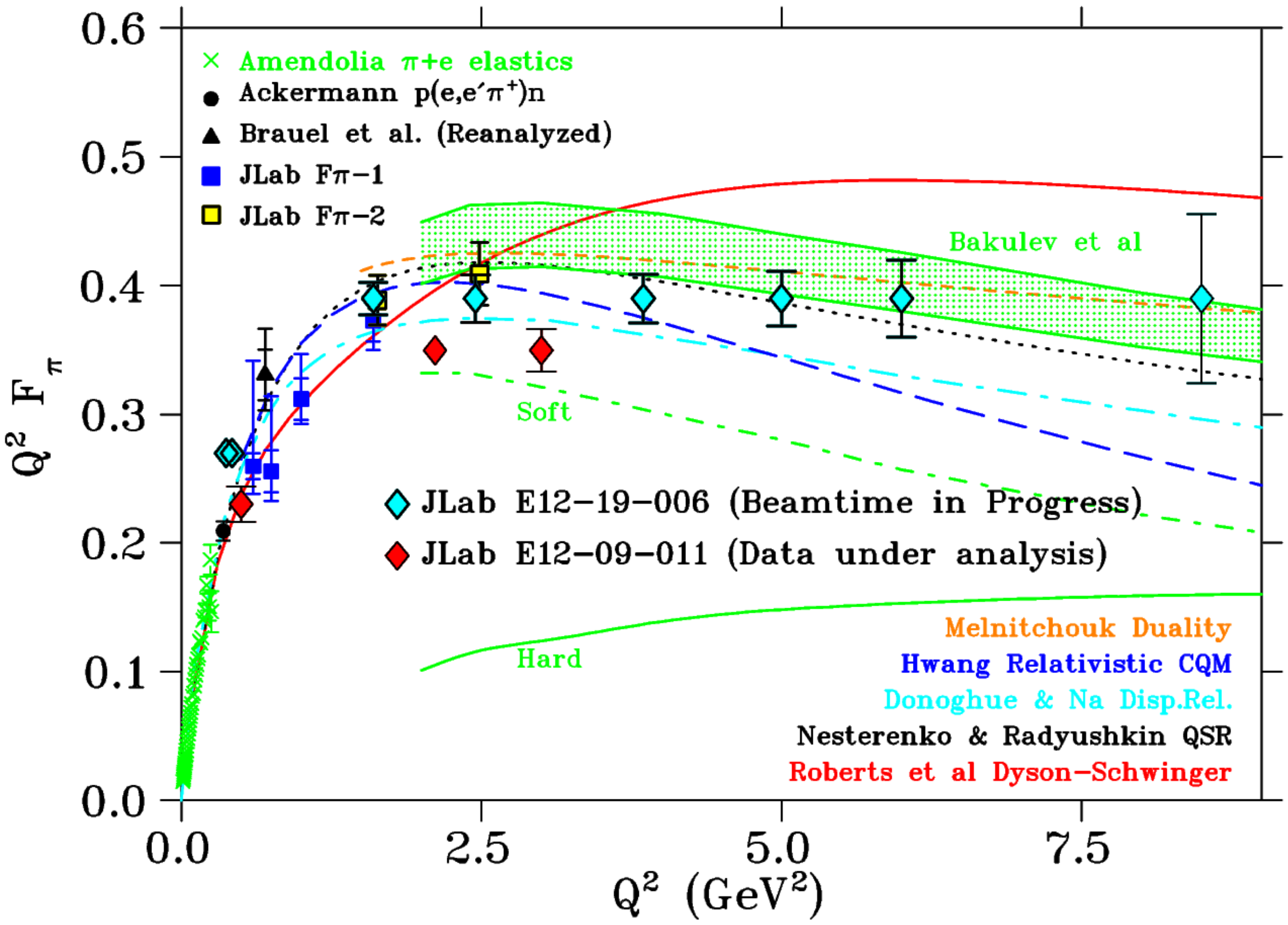
# $F_\pi$ Measurements at 12 GeV

JLab 12 GeV program will allow $F_\pi$ measurements up to $Q^2$=8.5 GeV$^2$

→ Largest $Q^2$ data at $-t_{min}$=0.55 so ultimate precision will in part depend on supplemental data

Require $\Delta\varepsilon$>0.2 to minimize error amplification in L-T separation




*E12–19–006: Run complete in 2022*



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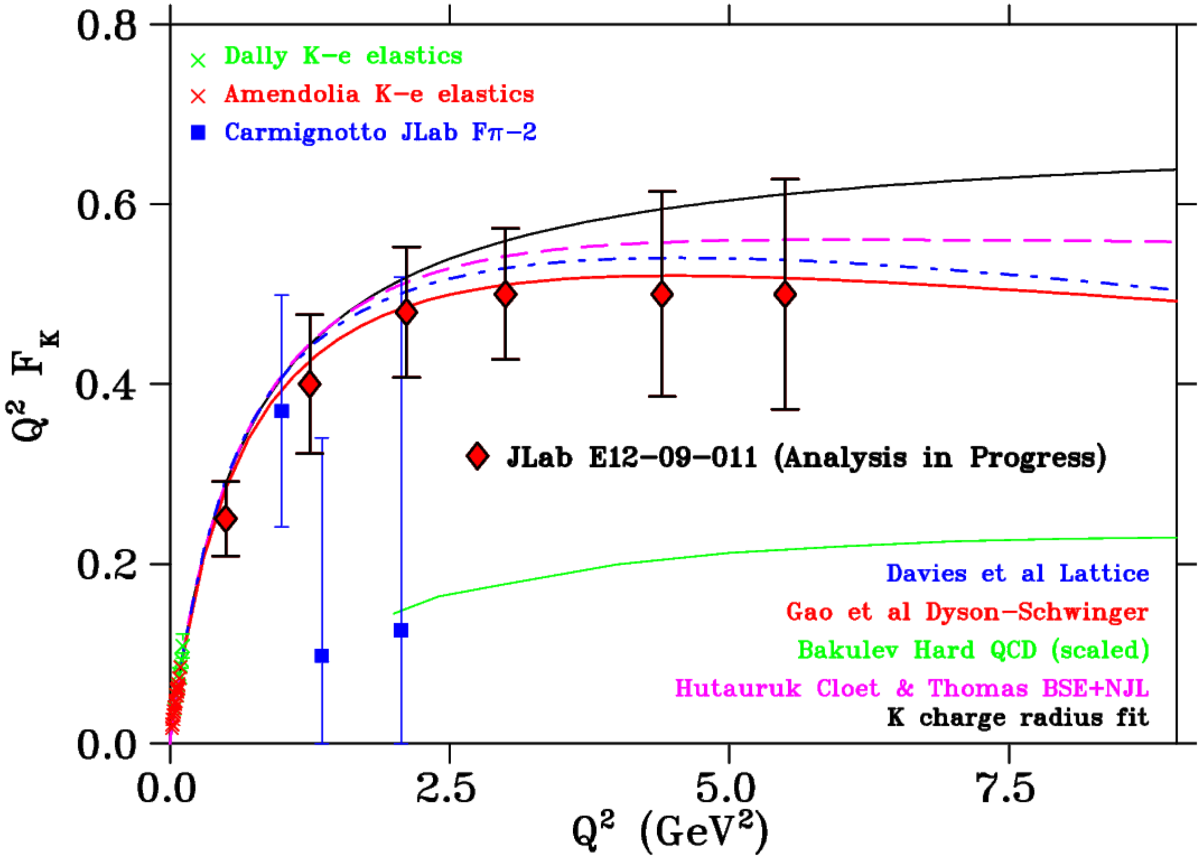
# $F_K$ Measurements at 12 GeV

- Kaon form factor can also be extracted in manner analogous to pion
- Data at low $Q^2$ to check consistency with elastic scattering data
- Extraction of form factor up to $Q^2$=3 → larger uncertainties at larger $Q^2$ due to larger $-t_{min}$

$p(e,e'K^+)\Lambda$ **W>2.5 GeV**




***E12–09-011: Run partially complete in 2019***

# $F_\pi$ at 22 GeV JLab

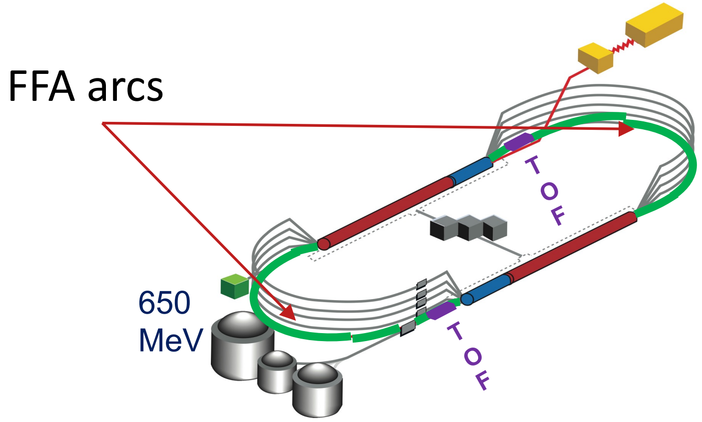
**JLab** is the ***only*** facility for the foreseeable future that will be able to make precise measurements of L-T separated cross sections

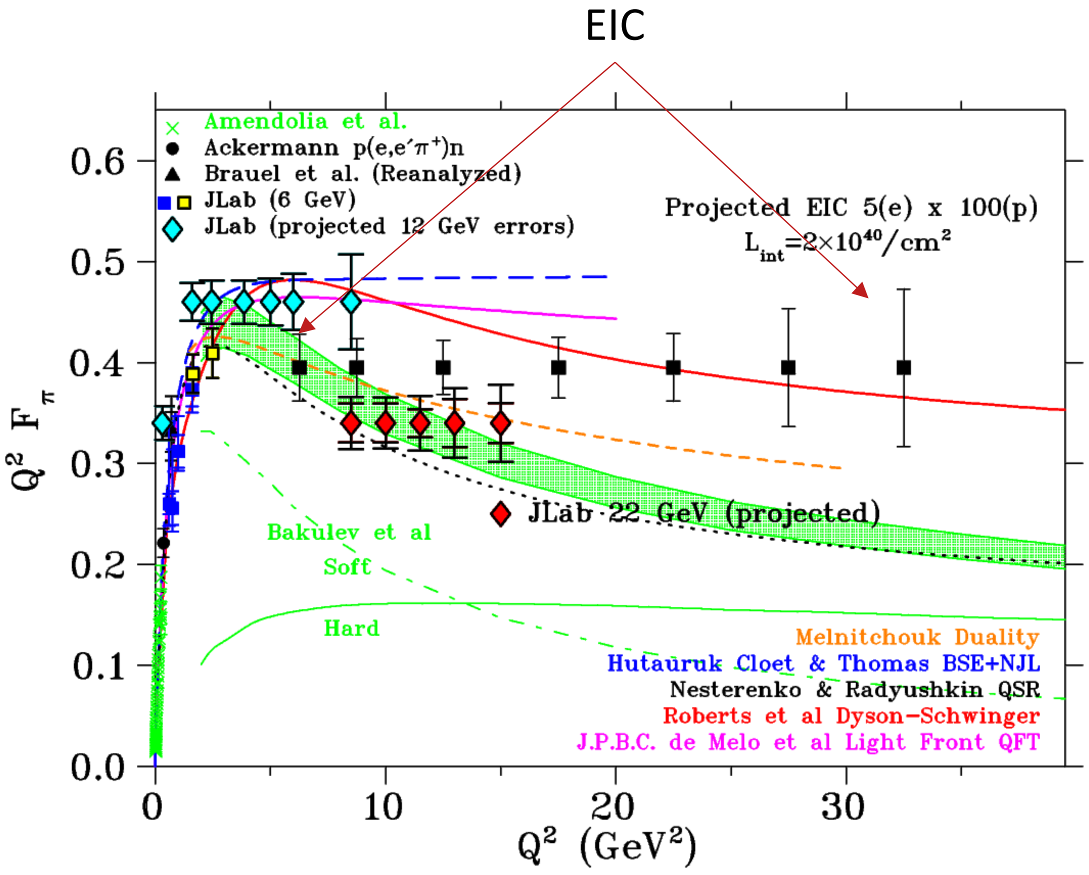
→ EIC will make $F_\pi$ measurements using model for $\sigma_T$ since L-T separations not possible

Upgraded JLab at 22 GeV will allow $F_\pi$ measurements up to $Q^2$=15 GeV$^2$

→ Will provide substantial overlap with EIC measurements from unseparated cross sections

→ Crucial cross-check of model-dependent EIC results



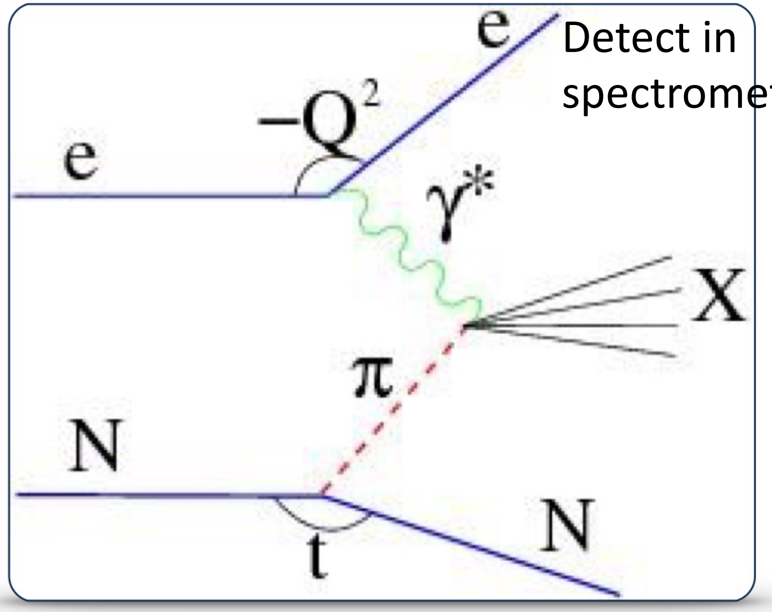

*More on 22 GeV upgrade in C. Keppel's talk Friday*

# Inelastic Pion Structure

Pion cloud of the nucleon can also be used to access inelastic pion structure → $F_2^{\pi}$

Experimentally, measure the semi-inclusive tagged structure function

→ Detect DIS electron ($Q^2$,W) and reconstruct Mx od recoiling hadronic system




Detect in spectrometer

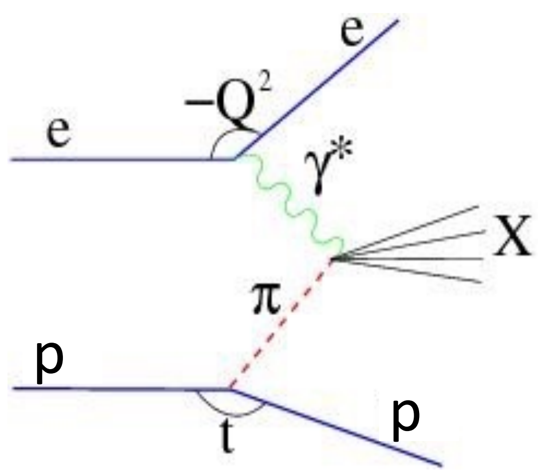
Detect in recoil detector

$$R^T = \frac{d^4\sigma(ep \to e'Xp')}{dxdQ^2dzdt} \Big/ \frac{d^2\sigma(ep \to e'X)}{dxdQ^2} \Delta z \Delta t \sim \frac{F_2^T(x,Q^2,z,t)}{F_2^p(x,Q^2)} \Delta z \Delta t.$$

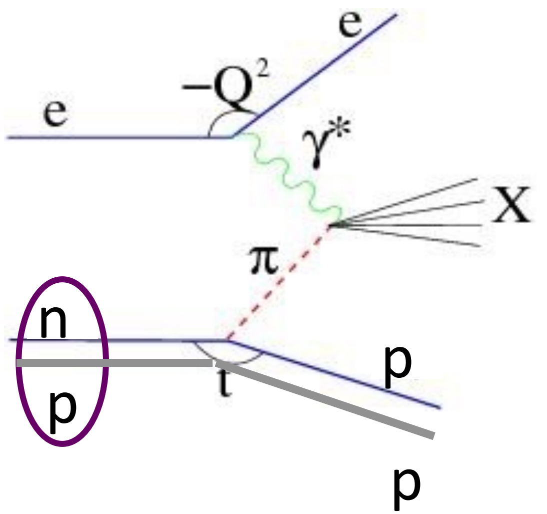
$$F_2^T(x,Q^2,z,t) = \frac{R^T}{\Delta z \Delta t} F_2^p(x,Q^2).$$

# C12-15-005: The Tagged Deep Inelastic Scattering Experiment

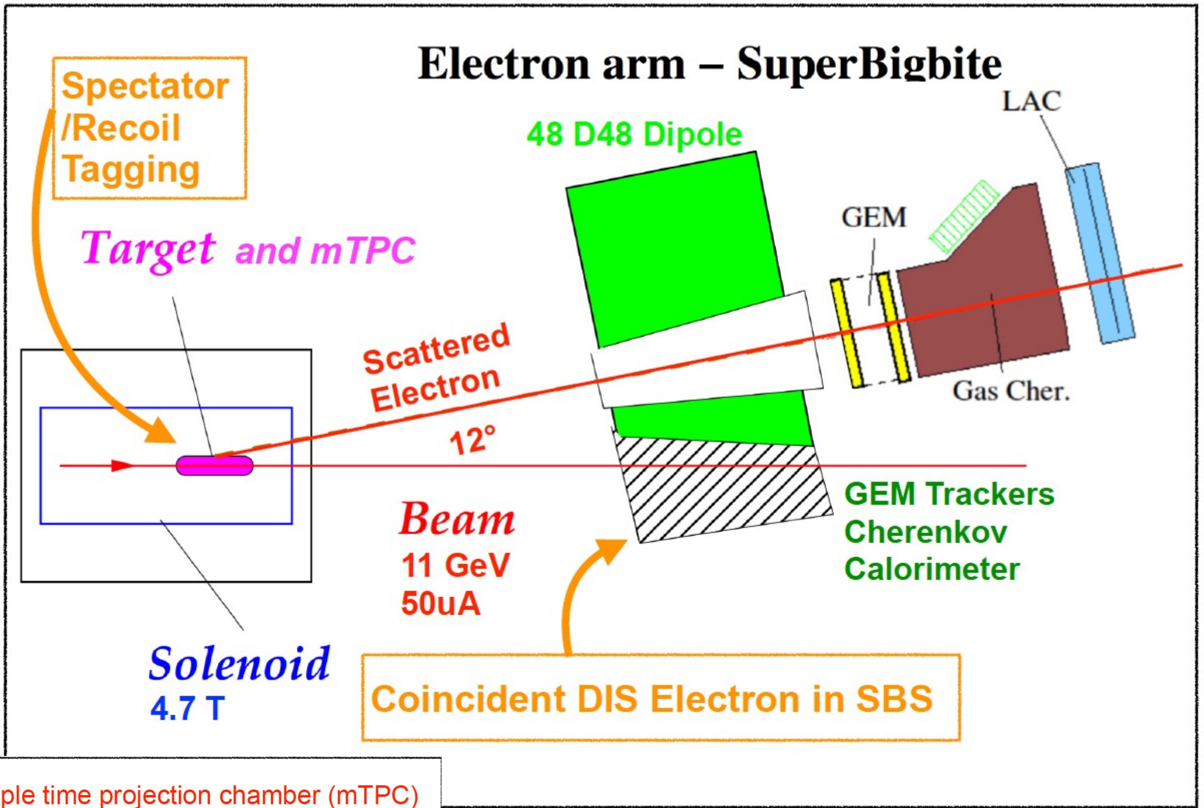
TDIS experiment will tag spectator proton(s) to access inelastic pion structure

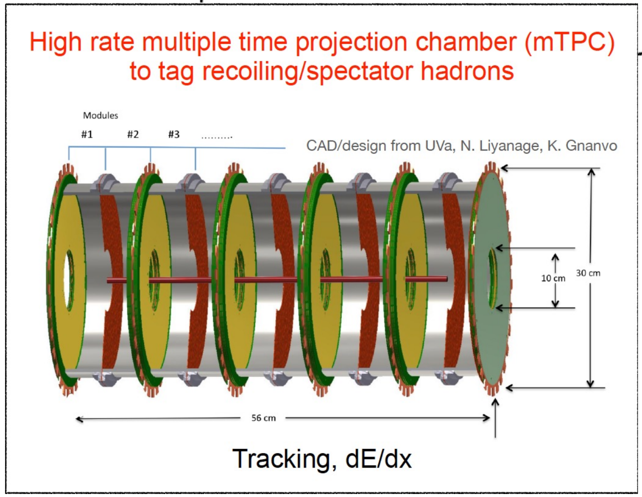



Hydrogen
→ Single spectator proton
→ Neutral pion structure




Deuterium
→ Two spectator protons
→ Charged pion structure




Spokespersons: D. Dutta, C. Keppel, P. King, N. Liyanage, R. Montgomery, B. Wojtsekhowski

# TDIS will provide a unique extraction of the pion structure function at large x

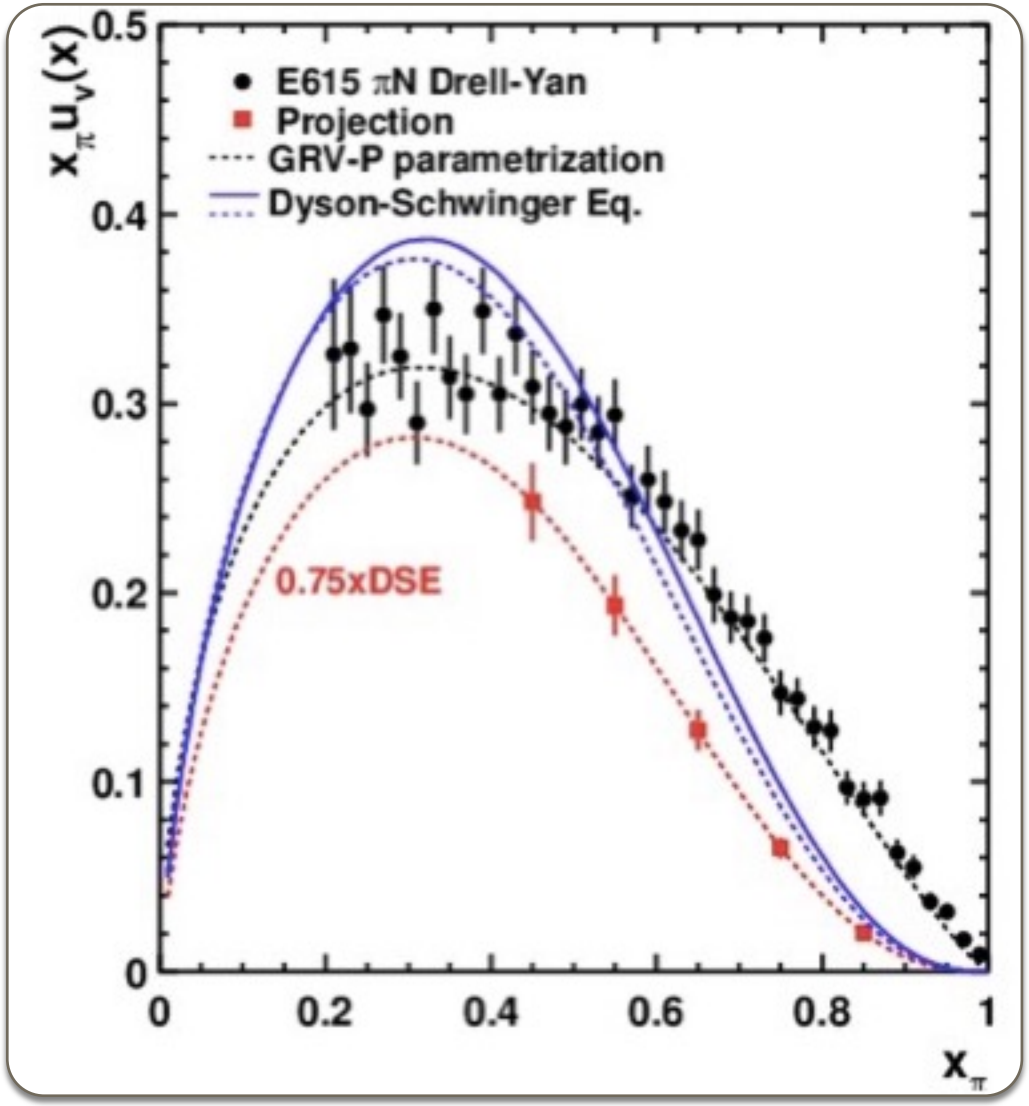
Large x behavior will help verify resummed Drell-Yan results;

Large *x*, low *Q* complementary to HERA low *x*, high *Q*

Will also measure ($\pi^-$, $\pi^0$) difference - look for isospin dependence

Experiment **C12-15-006A*** will use the same apparatus to access kaon inelastic structure

*Spokespersons: R. Montgomery, T. Horn, K. Park



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# Summary

- Elastic and inelastic meson structure provides a unique testing ground for our understanding of QCD
  - 2-quark structure → simplest bound QCD system
- Elastic pion and kaon form factors calculable exactly in pQCD at asymptotic QCD
  - $Q^2$ dependence allows studying transition from soft, non-perturbative regime to hard, perturbative limit
- Exciting program of pion form factor measurements has been carried out in Hall C at Jefferson Lab
  - Measurements up to $Q^2$=2.45 GeV$^2$ at 6 GeV
  - Recently completed experiment after JLab 12 GeV upgrade will extend up to $Q^2$=8 GeV$^2$
- Kaon-LT experiment in Hall C will explore similar form factor extractions for $K^+$
- Inelastic pion structure will be studyied using spectator tagging → TDIS experiment using SBS and new mTPC
- Possible 22 GeV upgrade at JLab would allow extending the phase space of all of the above
  - Example: $F_\pi$ → increase overlap between L-T separated measurements at JLab and model-dependent extractions at EIC

# EXTRA

# Measuring $\sigma_L$ and $\sigma_T$

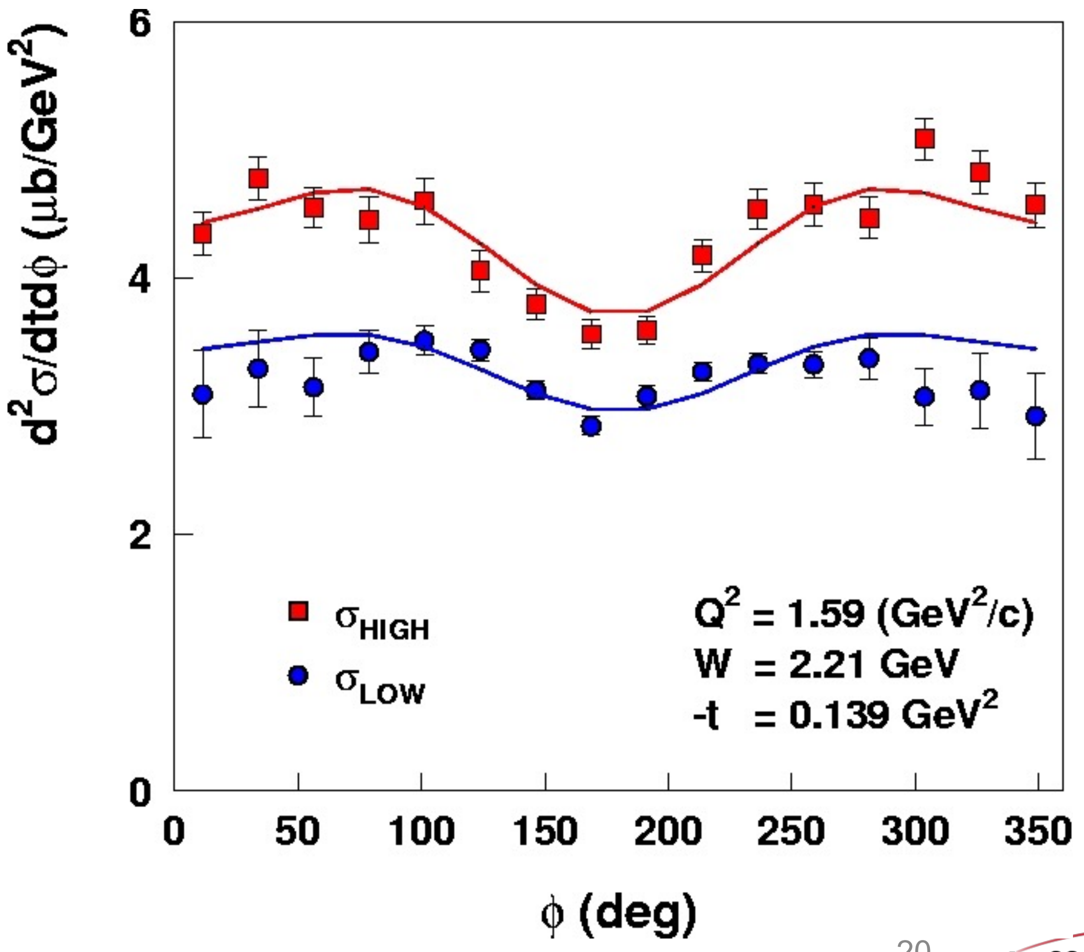
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \epsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Rosenbluth separation required to isolate $\sigma_L$

→Measure cross section at fixed ($W,Q2,-t$) at 2 beam energies
→Simultaneous fit at 2 $\varepsilon$ values to determine $\boldsymbol{\sigma_L}$, $\boldsymbol{\sigma_T}$, and interference terms

Control of point-to-point systematic uncertainties crucial due to ***1/ε*** error amplification in $\sigma_L$

Careful attention must be paid to spectrometer acceptance, kinematics, efficiencies, …



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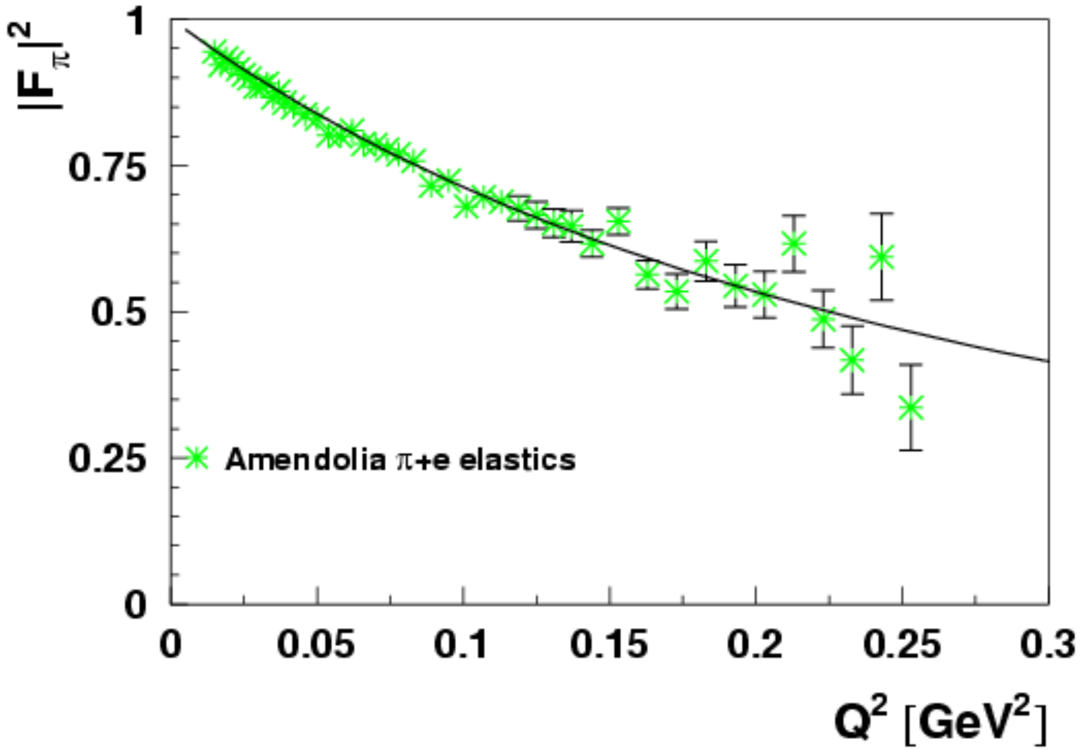
## Measurement of π⁺ Form Factor – Low $Q^2$

- At low $Q^2$, $F_\pi$ can be measured ***directly*** via high energy elastic $\pi^-$ scattering from atomic electrons
  - CERN SPS used 300 GeV pions to measure form factor up to $Q^2$ = 0.25 GeV$^2$

    *[Amendolia et al, NPB277, 168 (1986)]*
  - These data used to extract the pion charge radius

    $r_\pi$ = 0.657 ± 0.012 fm
- Maximum accessible $Q^2$ roughly proportional to pion beam energy
  - $Q^2$=1 GeV$^2$ requires 1000 GeV pion beam



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# Pole Dominance Tests via $\pi^-/\pi^+$

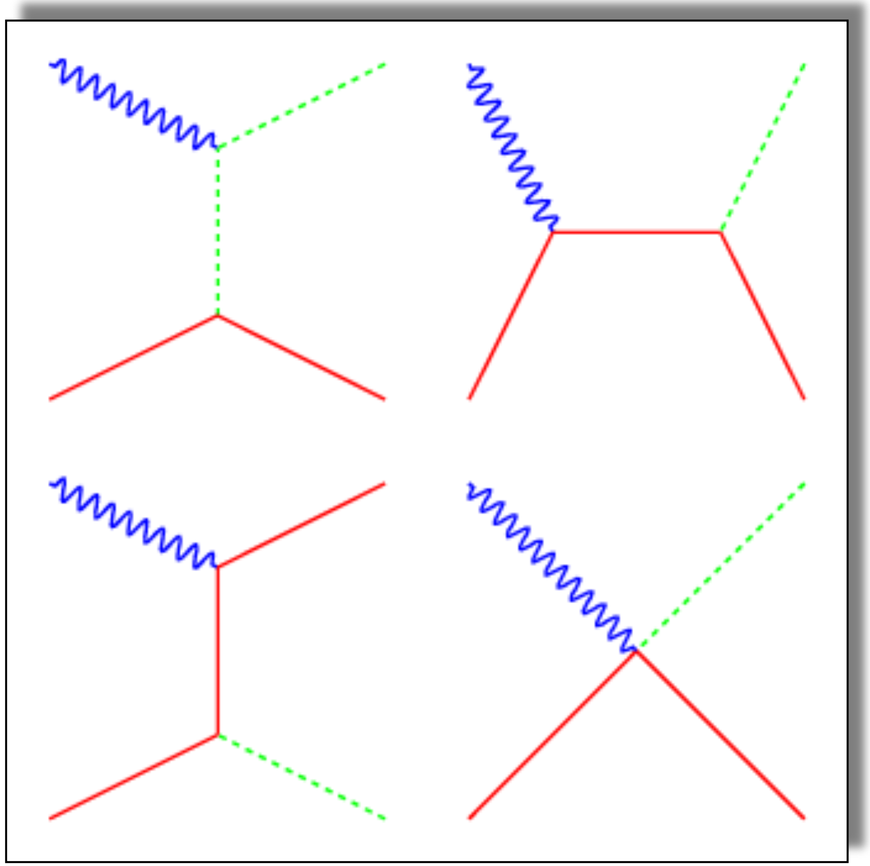
Extraction of $F_\pi$ relies on dominance of pole diagram

→t-channel diagram pure isovector

→Other Born diagrams both isovector and isoscalar

Measure (separated) $\pi^-/\pi^+$ ratios to test pole dominance

$$\frac{\sigma_L(\pi^-)}{\sigma_L(\pi^+)} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$



Ratio = 1 suggests no isoscalar backgrounds