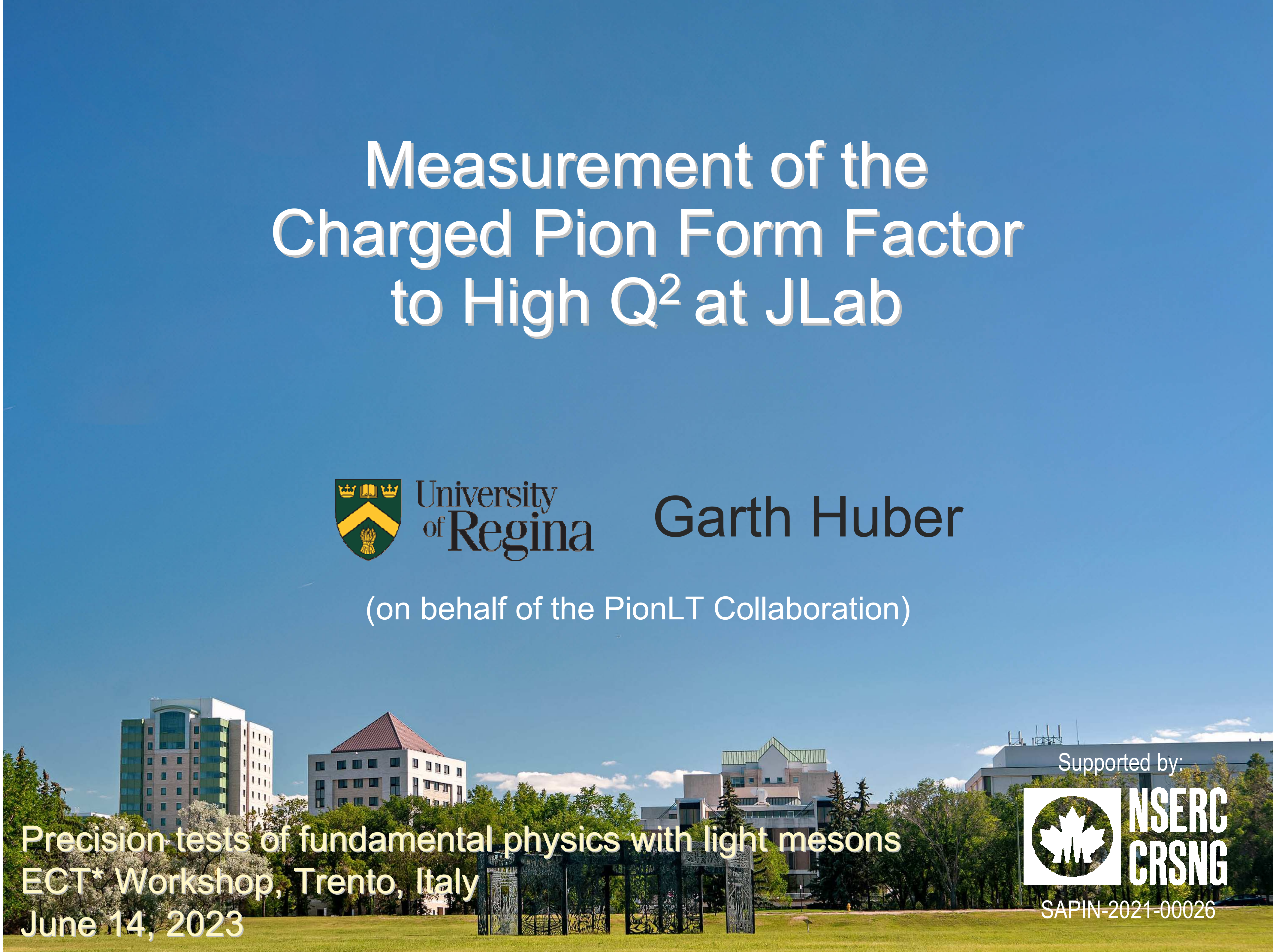

Measurement of the Charged Pion Form Factor to High Q^2 at JLab

University of Regina

Garth Huber

(on behalf of the PionLT Collaboration)

Precision tests of fundamental physics with light mesons
ECT* Workshop, Trento, Italy
June 14, 2023

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Charged Meson Form Factors

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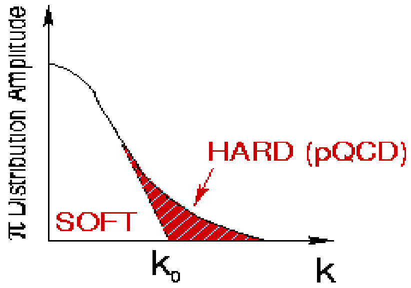
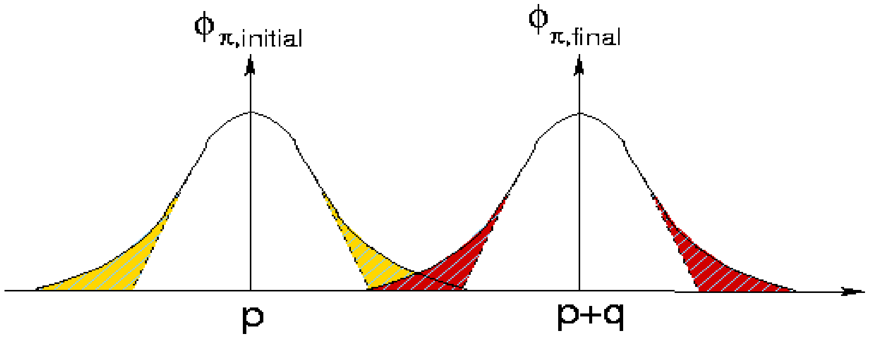
Simple $q\bar{q}$ valence structure of mesons presents the ideal testing ground for our understanding of bound quark systems.

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 φ_π^{soft} with only low momentum contributions ($k<k_0$) and a hard tail φ_π^{hard}.

While φ_π^{hard} can be treated in pQCD, φ_π^{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.

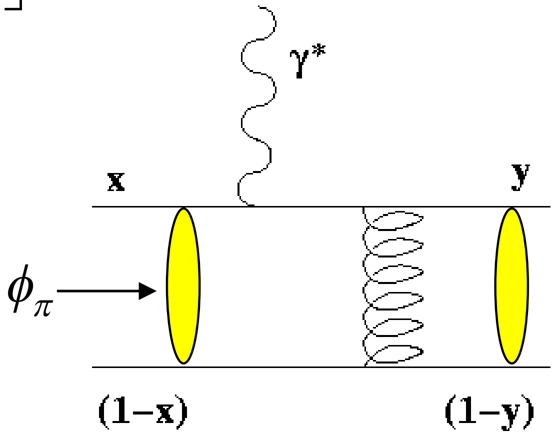
The Pion in perturbative QCD

At very large Q^2, pion form factor (F_π) can be calculated using pQCD

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

At asymptotically high Q^2, only hardest portion of pion distribution amplitude contributes

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



and F_π takes the very simple form

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

f_π=93 MeV is the $\pi^+ \to \mu^+ \nu$ decay constant

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

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

$Q^2 F_\pi$ 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]

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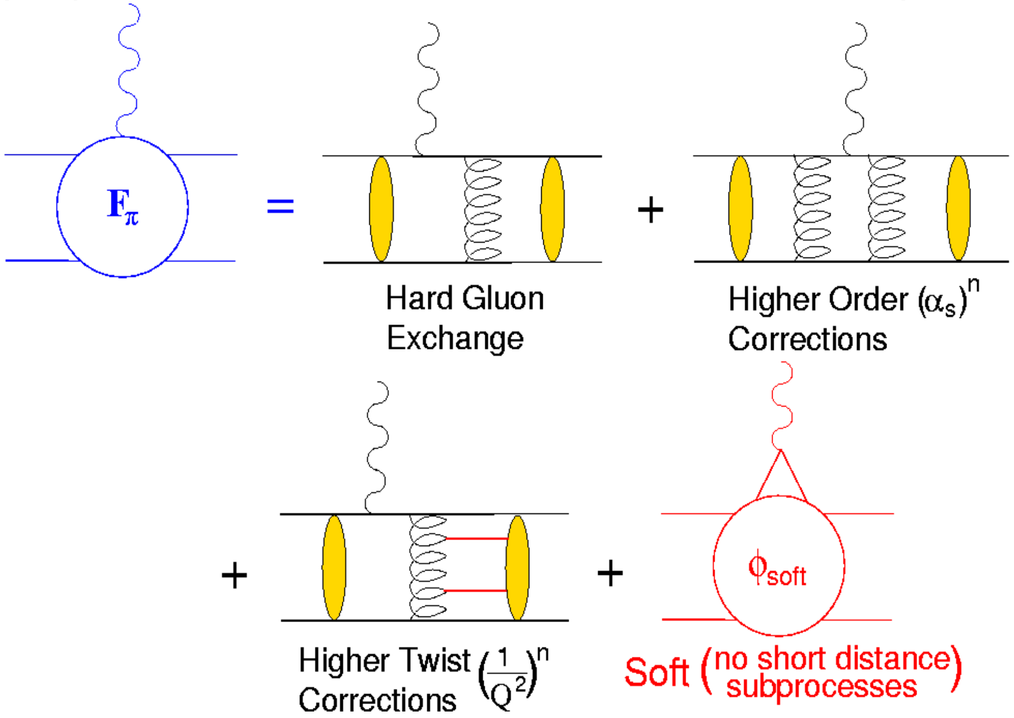
Pion Form Factor at Intermediate Q^2

At experimentally–accessible Q^2, both the "hard" and "soft" components (e.g. transverse momentum effects) contribute.



- **The interplay of hard and soft contributions is poorly understood.**

  → Different theoretical viewpoints on whether higher–twist mechanisms dominate until very large momentum transfer or not.

- **The pion elastic and transition form factors experimentally accessible over a wide kinematic range.**

  → A laboratory to study the **transition** from the soft to hard regime.

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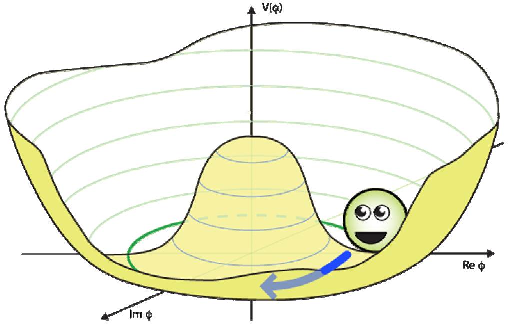
The Pion as a Goldstone Boson

- A remarkable feature of QCD is Dynamical Chiral Symmetry Breaking (DCSB) because it cannot be derived directly from the Lagrangian and is related to nontrivial nature of QCD vacuum.
  - Explicit symmetry breaking, which is put in “by hand” through finite quark masses, is quite different.
- DCSB is now understood to be one of the most important emergent phenomena in the Standard Model, responsible for generation of >98% baryonic mass.



- **Two important consequences of DCSB:**
  1. Valence quarks acquire a dynamical or constituent quark mass through their interactions with the QCD vacuum.
  2. The pion is the spin-0 boson that arises when Chiral Symmetry is broken, similar to how Higgs boson arises from Electroweak Symmetry Breaking.

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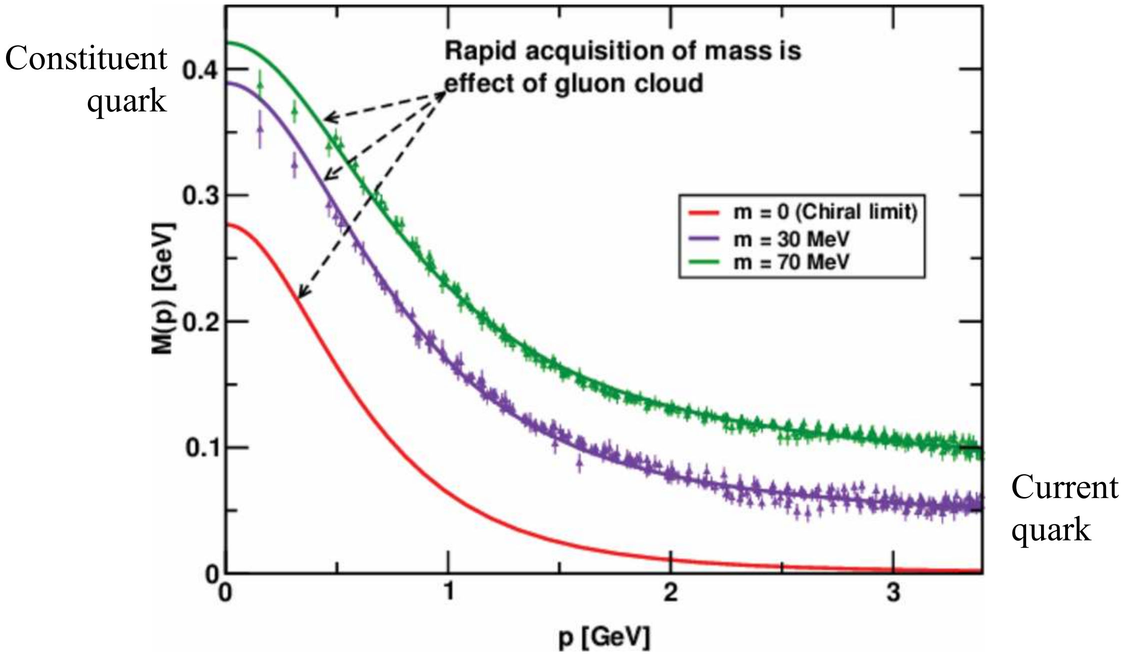
Recent Theoretical Advances

Amazing progress in the last few years.

- **We now have a much better understanding how Dynamical Chiral Symmetry Breaking (DCSB) generates hadron mass.**
- Quenched lattice–QCD data on the dressed–quark wave function were analyzed in a Bethe–Salpeter Equation framework by Bhagwat, et al.
- For the first time, the 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.
- **This is DCSB:** an essentially non-perturbative effect that generates a quark *mass from nothing*: namely, it occurs 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.

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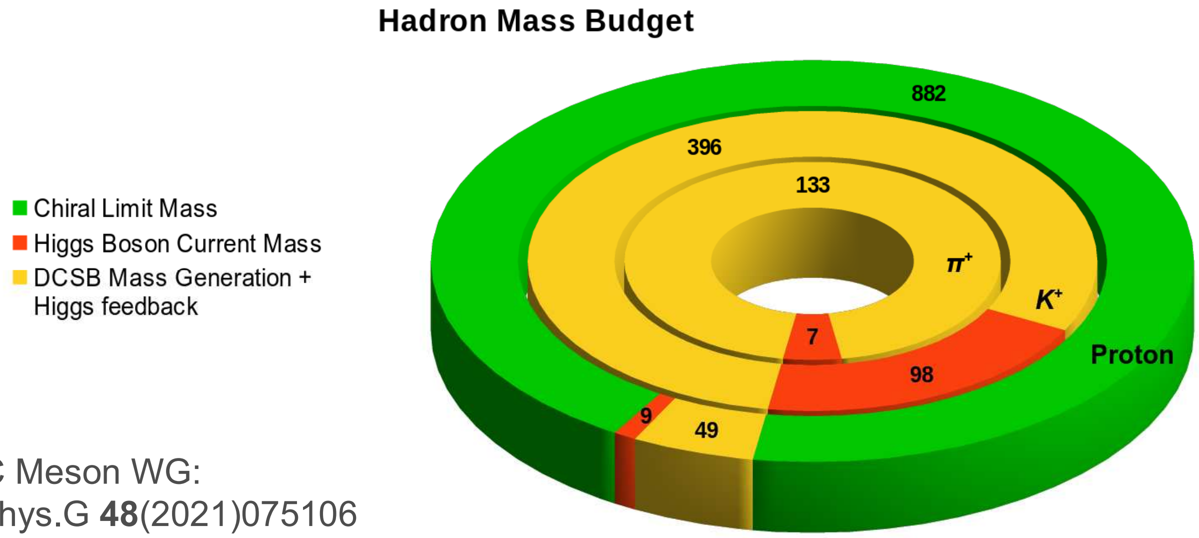
Contrasts in Hadron Mass Budgets



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

Stark Differences between proton, K$^+$, π^+ mass budgets

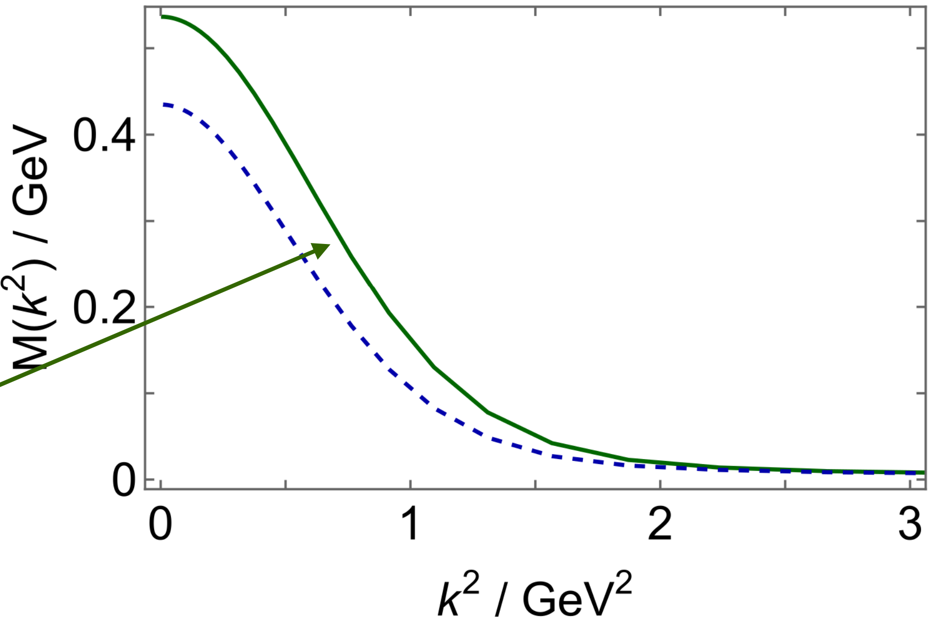
- Due to Emergent Hadronic Mass (EHM), Proton mass large in absence of quark couplings to Higgs boson (chiral limit).
- Conversely, and yet still due to EHM and DCSB, *K* and π are massless in chiral limit (i.e. they are Goldstone bosons).
- The mass budgets of these crucially important particles demand 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 π and *K*.

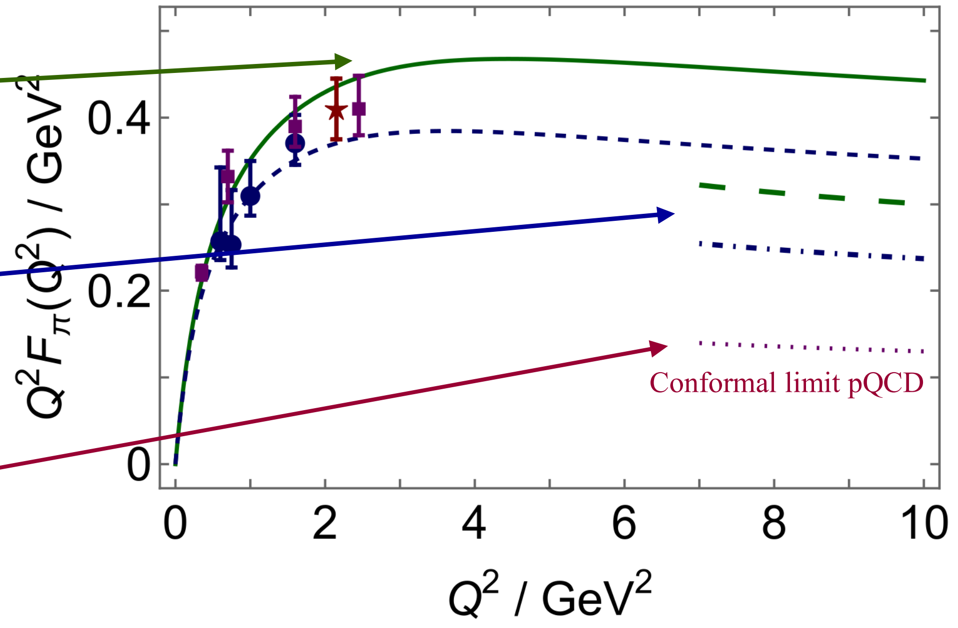
Synergy: Emergent Mass and π^+ Form Factor

At empirically accessible energy scales, π^+ 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_π=0.66 fm with solid green curve
  - r_π=0.73 fm with solid dashed blue curve
- **$F_\pi(Q^2)$ predictions from QCD hard scattering formula (slide #3), 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

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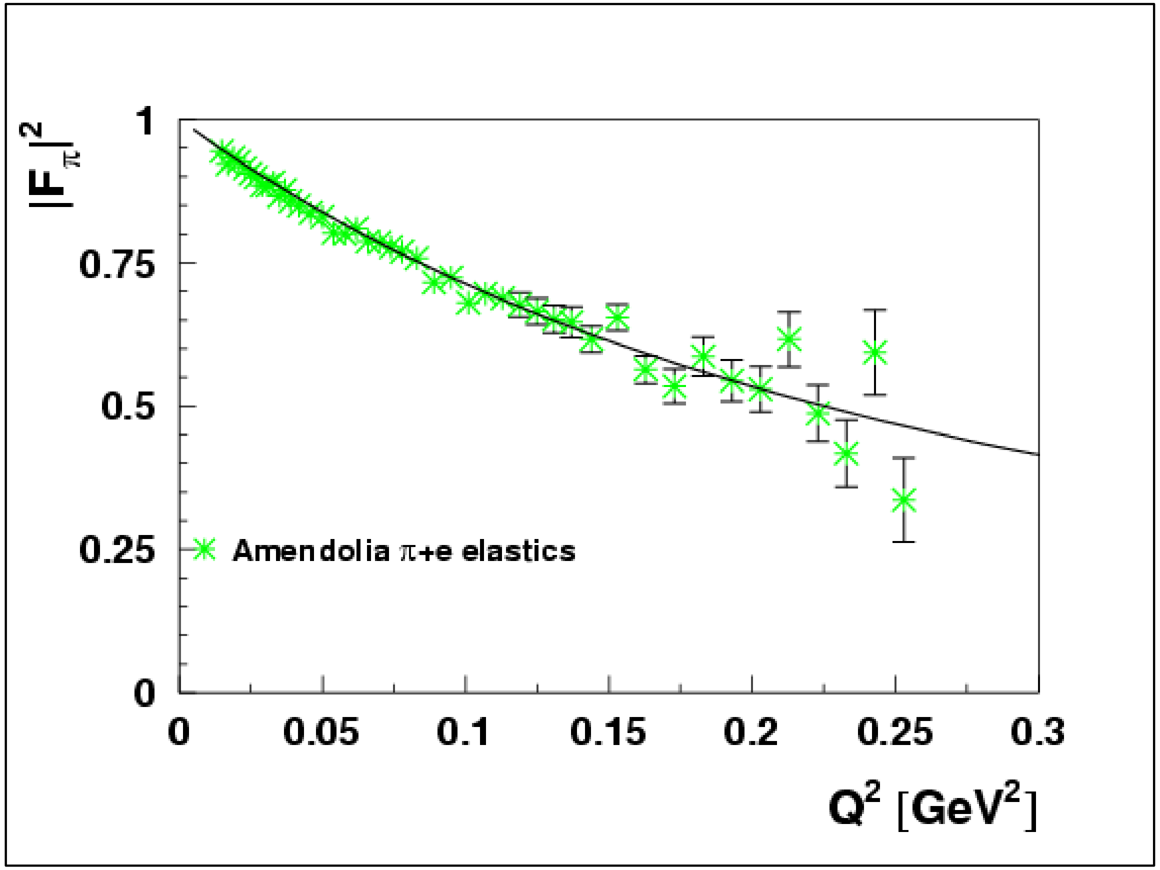
Measurement of π^+ Form Factor – Low Q^2

At low Q^2, F_π can be measured model–independently via high energy elastic π^- scattering from atomic electrons in Hydrogen

- CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2 *[Amendolia, et al., NPB **277**(1986)168]*

- Data used to extract pion charge radius

  $r_\pi = 0.657 \pm 0.012$ fm



Maximum accessible Q^2 roughly proportional to pion beam energy

Q^2=1 GeV^2 requires 1 TeV pion beam

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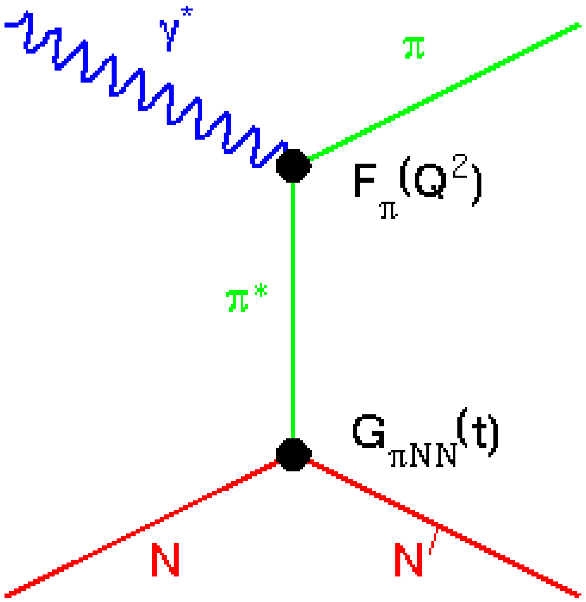
Measurement of π^+ Form Factor – Higher Q^2

At larger Q^2, F_π 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, σ_L
- In Born term model, F_π^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 σ_L experimentally challenging
2. Theoretical uncertainty in form factor extraction.

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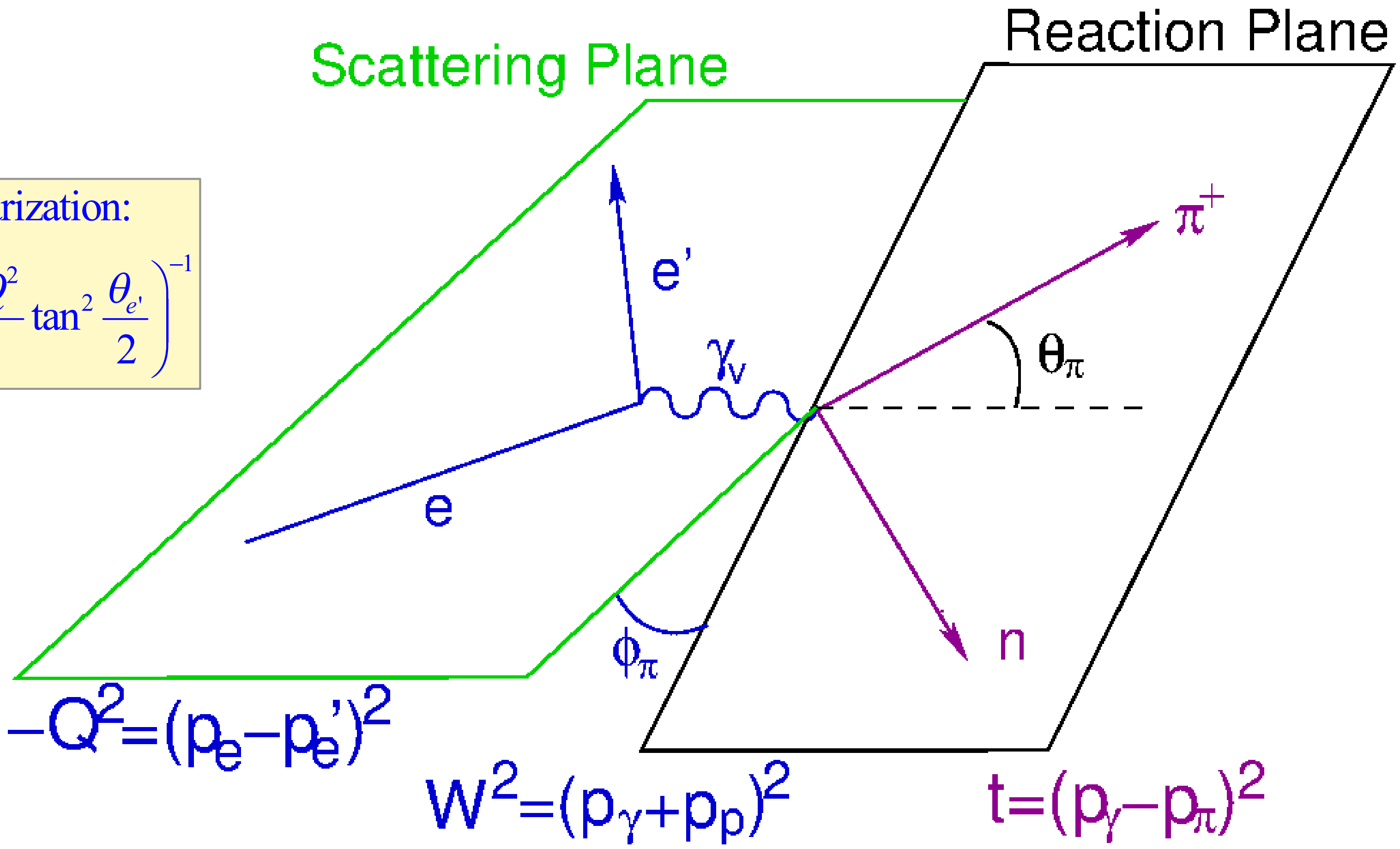
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$

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 σ_L from σ_T.
- Need to take data at smallest available $-t$, so σ_L has maximum contribution from the π^+ pole.

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L/T–separation error propagation

Error in $d\sigma_L/dt$ is magnified by $1/\Delta\varepsilon$

→ **To keep magnification factor <5x, need Δε>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_π extraction are R and Δε

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

Chew–Low Method to determine Pion Form Factor

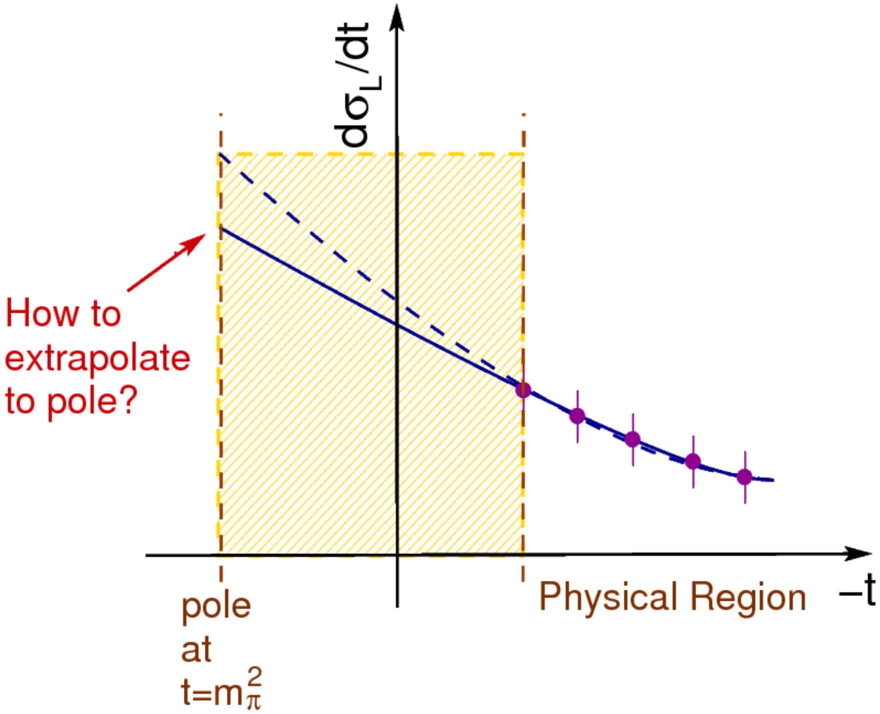
$p(e,e'\pi^+)n$ data are obtained some distance from the $t=m_\pi^2$ pole.

→ "Chew Low" extrapolation method requires knowing the analytic dependence of $d\sigma_L/dt$ through the unphysical region.

Extrapolation method last used in 1972 by Devenish & Lyth

- Very large systematic uncertainties.
- Failed to produce reliable result.

→ Different polynomial fits equally likely in physical region gave divergent form factor values when extrapolated to $t=m_\pi^2$



The Chew–Low Method was subsequently abandoned

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Only reliable approach is to use a model incorporating the π^+ production mechanism and the `spectator' nucleon to **extract** F_π from σ_L

- JLab F_π experiments have used the Vanderhaeghen-Guidal-Laget (VGL) Regge model, as it has proven to give a reliable description of σ_L across a wide kinematic domain
  *[Vanderhaeghen, Guidal, Laget, PRC **57**(1998)1454]*

- **More models would allow a better understanding of the model dependence of the F_π result.**

- Some recent model developments, more are welcome!
  - *R.J. Perry, A. Kizilersu, A.W. Thomas, PLB **807**(2020)135581*
  - *T.K. Choi, K.J. Kong, B.G. Yu, J.Kor.Phy.Soc. **67**(2015) L1089; arXiv: 1508.00969*
  - *T. Vrancx, J. Ryckebusch, PRC **89**(2014)025203*

Our philosophy remains to publish our experimentally measured $d\sigma_L/dt$, so that updated values of $F_\pi(Q^2)$ can be extracted as better models become available.

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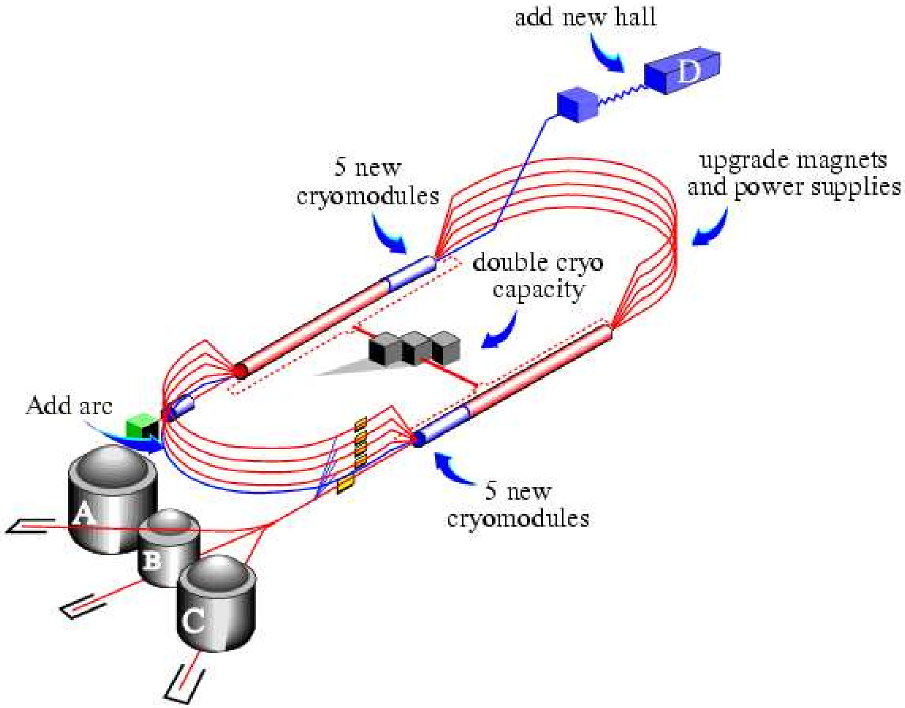


Two 1.5 GHz Superconducting Linear Accelerators provide electron beam for Nucleon & Nuclear structure studies.

- **Beam energy E → 12 GeV.**
- **Beam current >100 μA.**
- **Duty factor 100%, 85% polarization.**
- Experiments in all 4 Halls can receive beam simultaneously.

JLab Hall C – 12 GeV Upgrade

SHMS:
- 11 GeV/c Spectrometer
- Partner of existing 7 GeV/c **HMS**

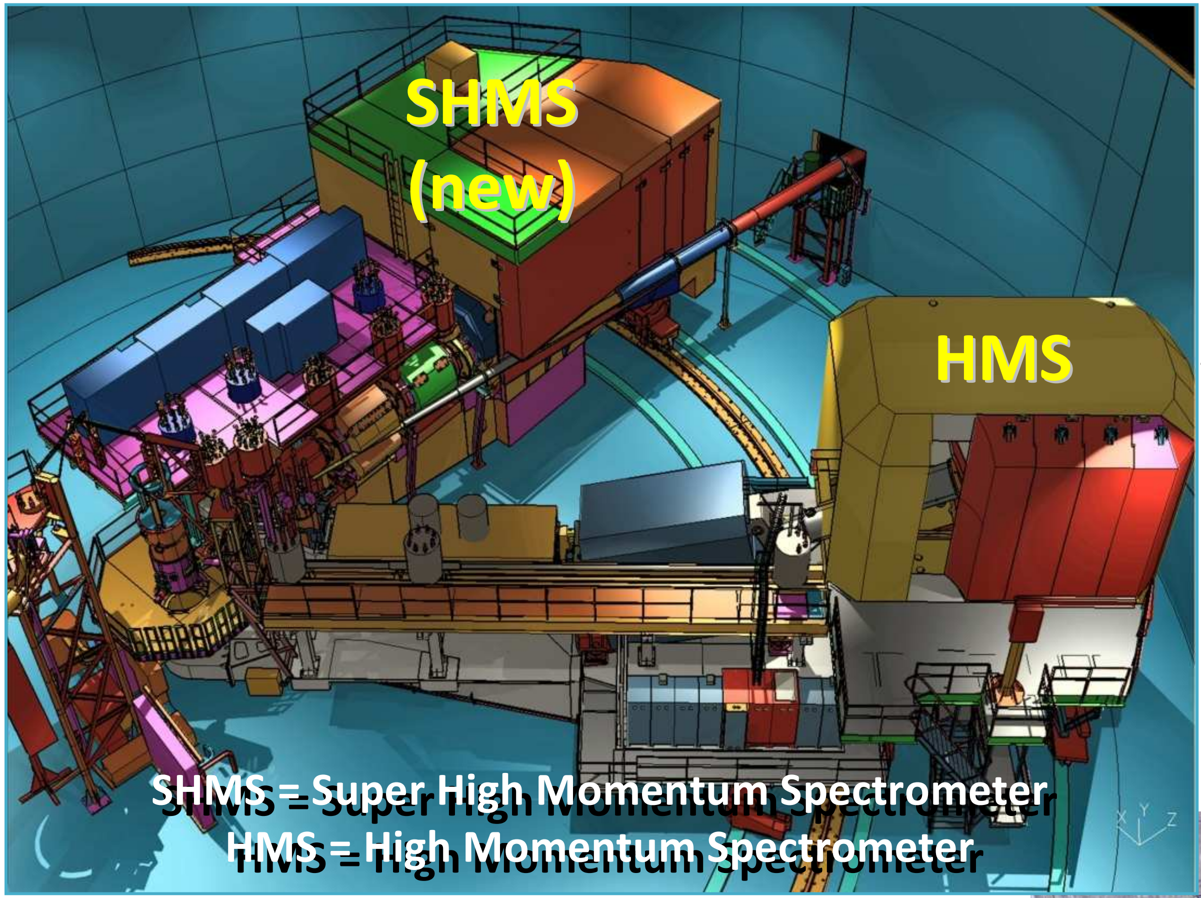
MAGNETIC OPTICS:
- Point-to Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

Detector Package:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter

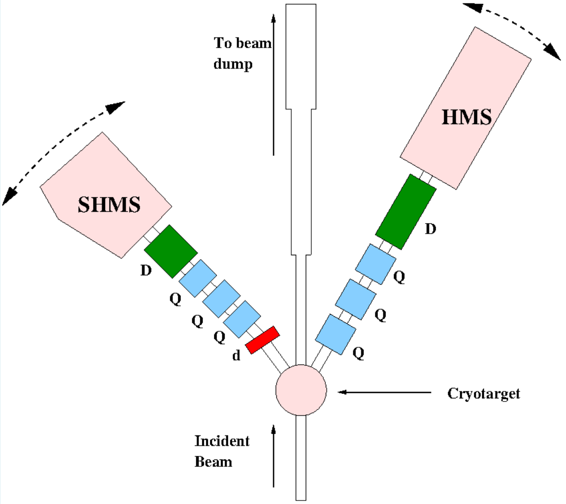
Well-Shielded Detector Enclosure

Rigid Support Structure
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS

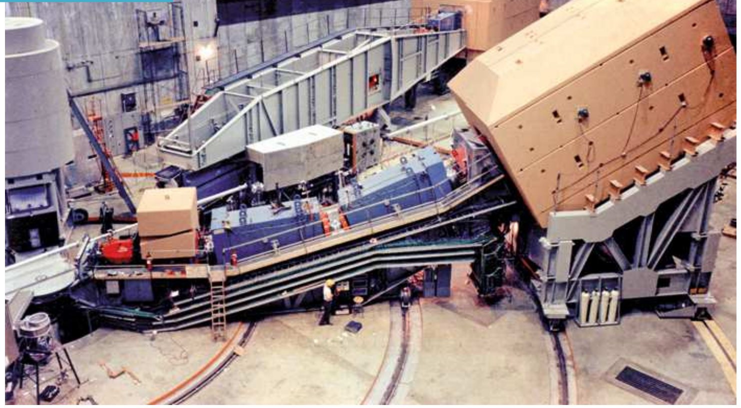
Luminosity
- $\sim 4\times10^{38}$ cm^{-2} s^{-1}



SHMS = Super High Momentum Spectrometer
HMS = High Momentum Spectrometer

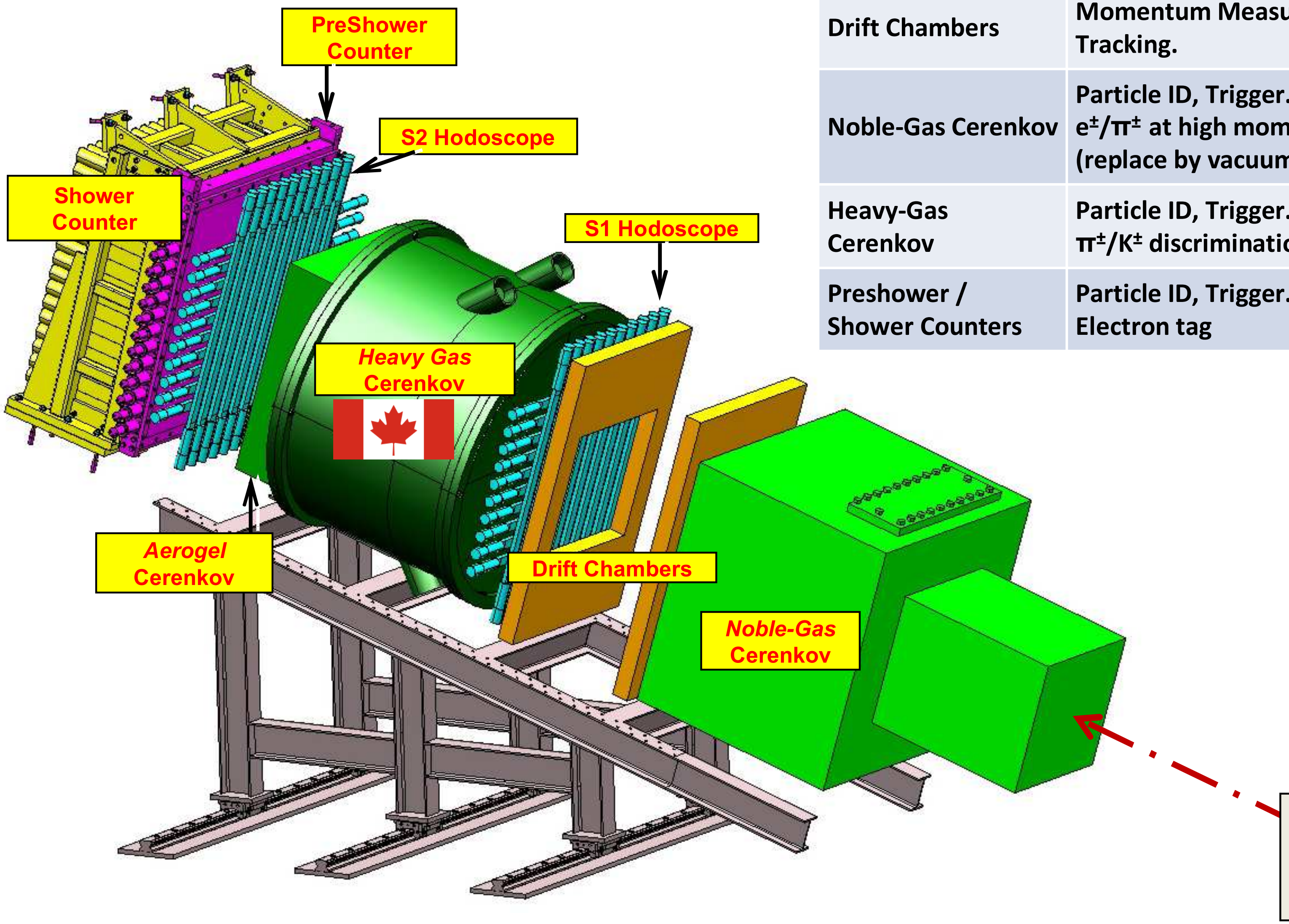


Upgraded Hall C has some similarity to SLAC End Station A, where the quark substructure of proton was discovered in 1968.



SHMS Focal Plane Detector System

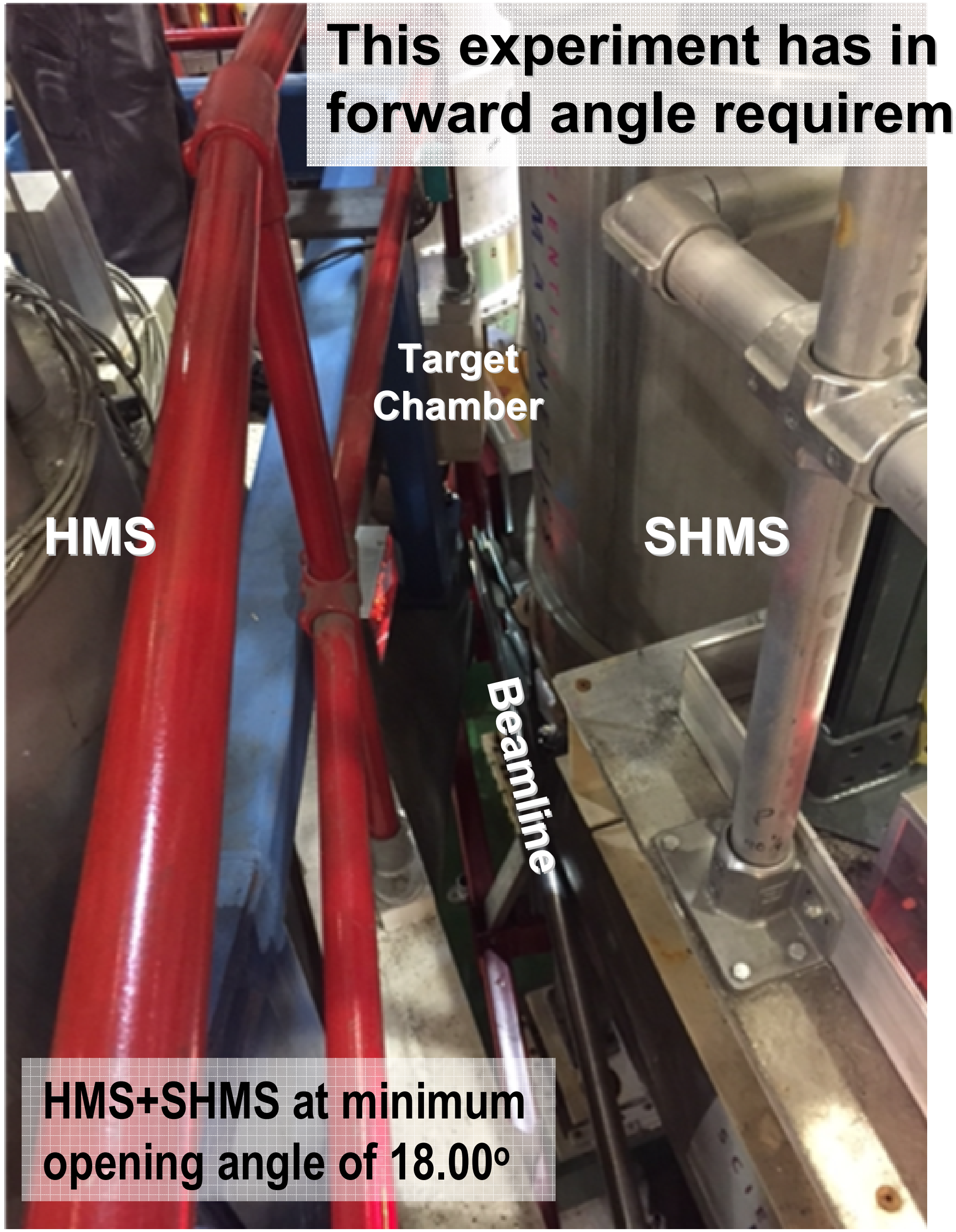
DETECTOR	PURPOSE	NOTES
S1XY, S2XY Hodoscopes	Lowest-level Trigger. Time reference	
Drift Chambers	Momentum Measurement. Tracking.	5mm max. drift 300 micron resolution
Noble-Gas Cerenkov	Particle ID, Trigger. $e^\pm/\pi^\pm$ at high momentum (replace by vacuum at low p)	Vary Ar/Ne mixture to set index at $\pi^\pm$ threshold.
Heavy-Gas Cerenkov	Particle ID, Trigger. $\pi^\pm/K^\pm$ discrimination	C_4F_8O – Vary pressure to set index at $K^\pm$ threshold
Preshower / Shower Counters	Particle ID, Trigger. Electron tag	



Incident Particles through SHMS magnet optics

HMS and SHMS during Data Taking

This experiment has in large part driven the forward angle requirements of the SHMS+HMS



HMS+SHMS at minimum opening angle of 18.00°

SHMS at 5.69°

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

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

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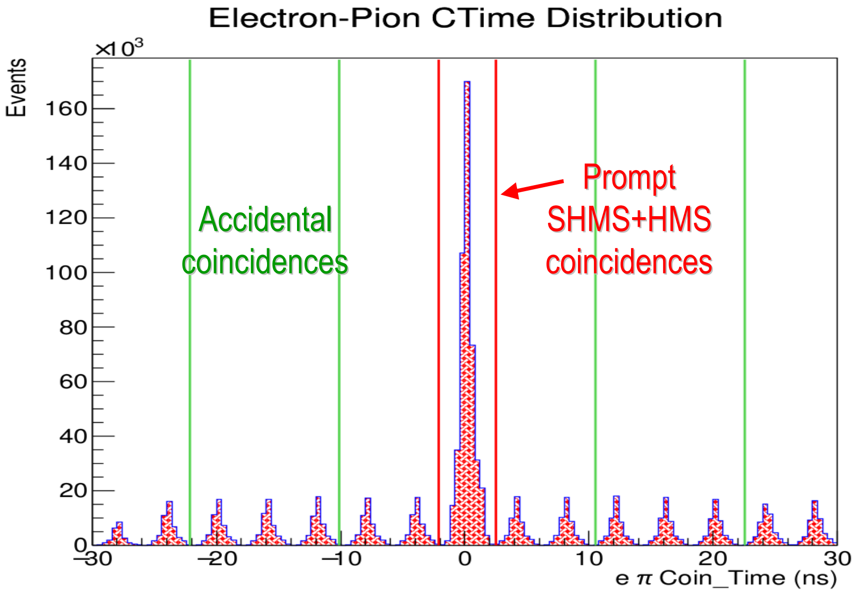
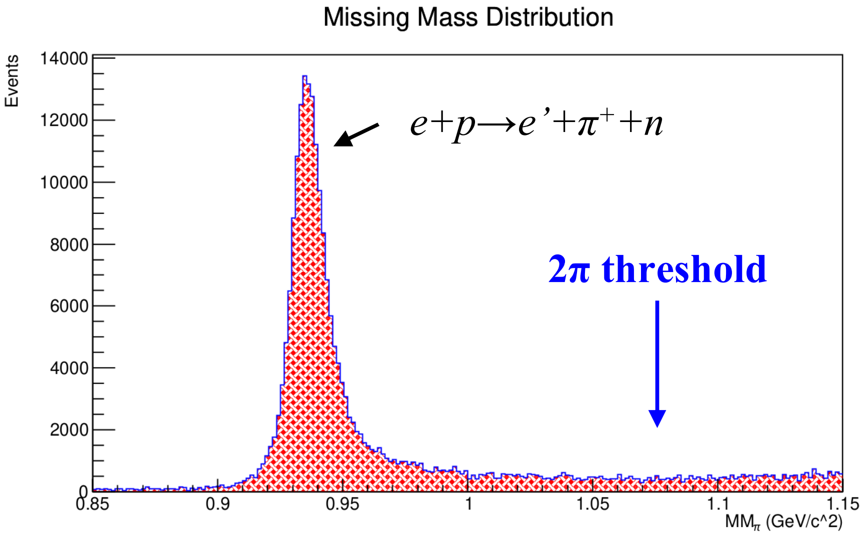
Easy to isolate exclusive channel

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





PionLT experiment E12–19–006 Data

Q^2=1.60, W=3.08, x= 0.157, ε=0.685

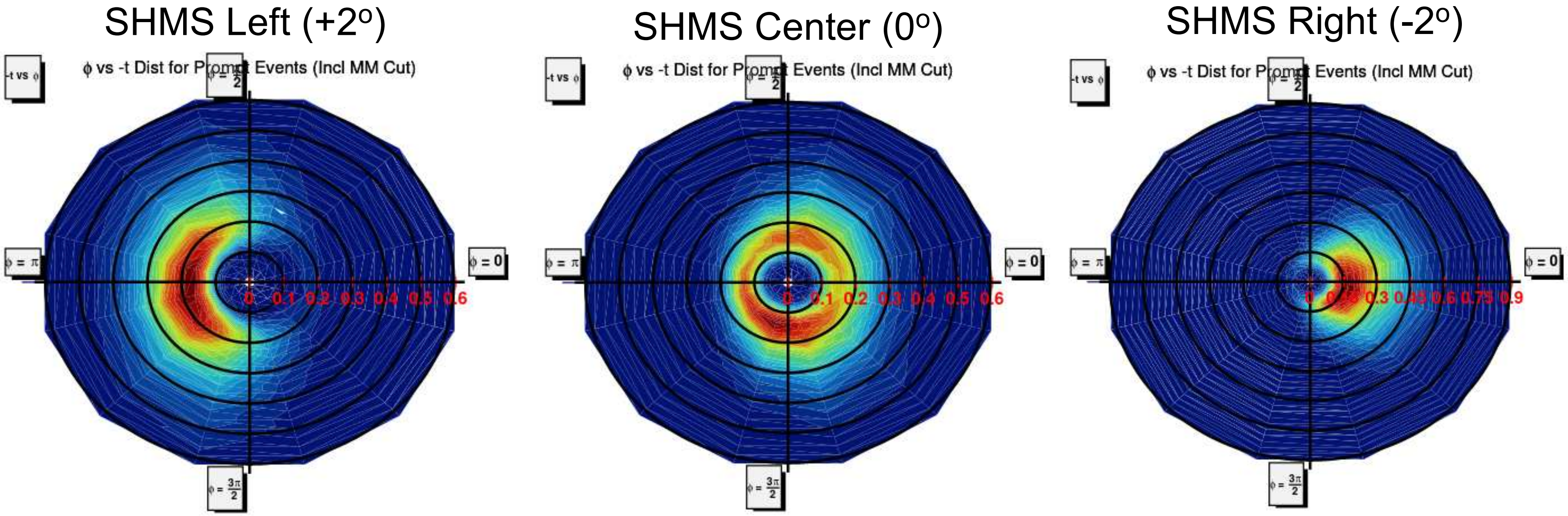
E_{beam}=9.177 GeV, P_{SHMS}=+5.422 GeV/c, θ_{SHMS}= 10.26° (left)

Plots by Muhammad Junaid (Regina PhD student)

PionLT (E12–19–006) t–φ Coverage

- Measure σ_{LT}, σ_{TT} by taking data at three pion spectrometer (SHMS) angles, +2^o, 0^o, -2^o, with respect to *q*–vector

Example t–φ plots from: Q^2=3.85, W=3.07, High ε

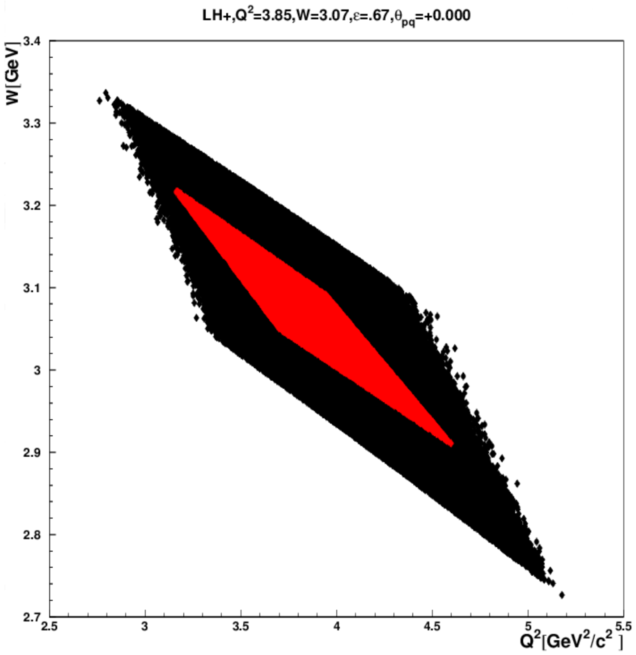

SHMS Left (+2^o)
SHMS Center (0^o)
SHMS Right (-2^o)

Plots by Nathan Heinrich (Regina PhD student)

- To control systematics, an excellent understanding of spectrometer acceptances is required
  - Over–constrained *p(e,e’p)* reaction, and inelastic e+^{12}C, used to calibrated spectrometer acceptances, momenta, kinematic offsets, efficiencies.
  - Control of point–to–point systematic uncertainties crucial due to 1/Δε error amplification in σ_L

The different pion arm (SHMS) settings are combined to yield φ-distributions for each *t*-bin

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

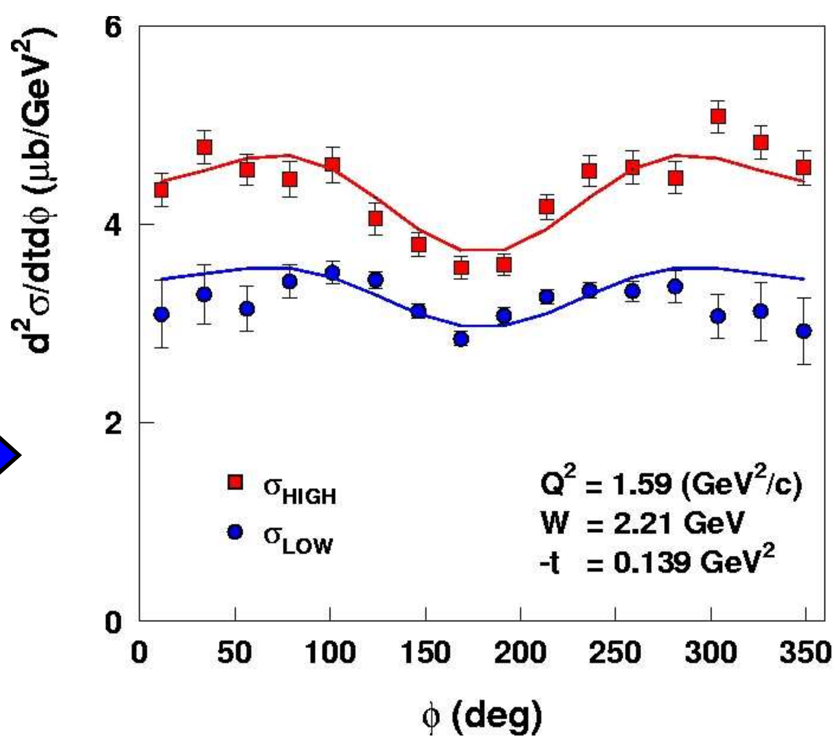


Diamond cuts define common (*W*,*Q*^{2}) coverage at both ε

Simulated SHMS+HMS acceptance at Q^2=3.85, W=3.07

⬛ High ε=0.67 🟥 Low ε=0.30

- Extract σ_L by simultaneous fit of L,T,LT,TT using measured azimuthal angle (φ_π) and knowledge of photon polarization (ε)



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

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

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Model incorporates π^+ production mechanism and spectator neutron effects:

VGL Regge Model:

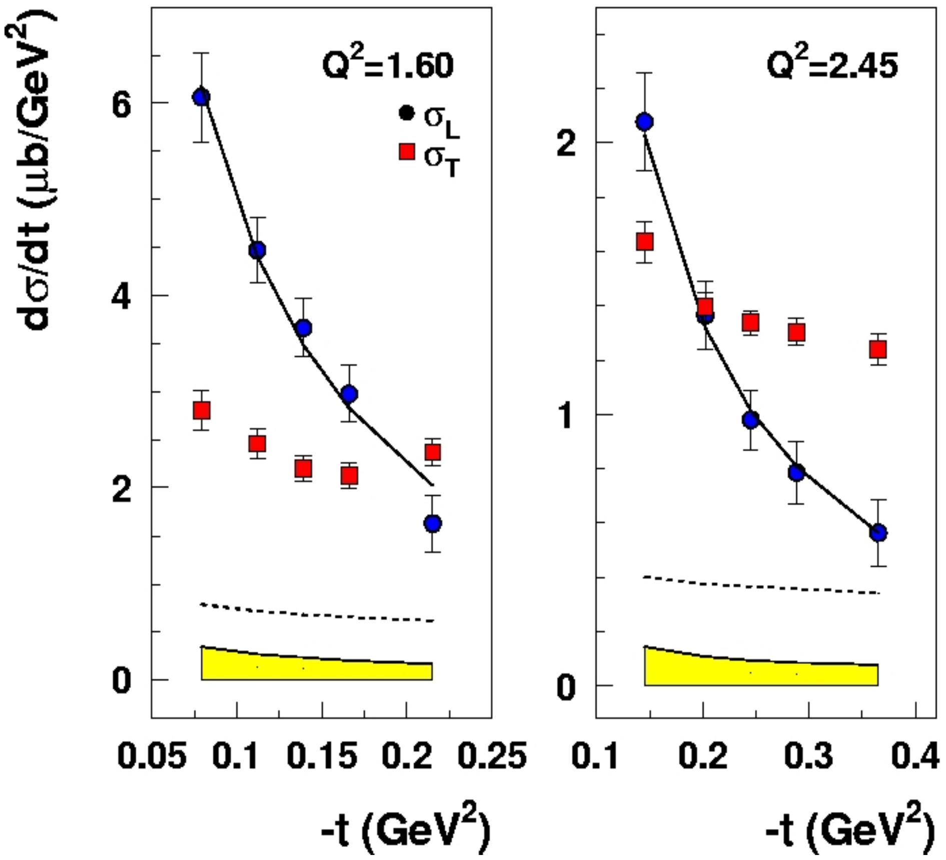
- Feynman propagator $\left(\frac{1}{t - m_\pi^2}\right)$

  replaced by π and ρ Regge propagators.
  - Represents the exchange of a series of particles, compared to a single particle.
- Free parameters: Λ_π, Λ_ρ (trajectory cutoff).

  [Vanderhaeghen, Guidal, Laget, PRC **57**(1998)1454]
- At small $-t$, σ_L only sensitive to F_π

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

Fit to σ_L to model gives F_π 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.

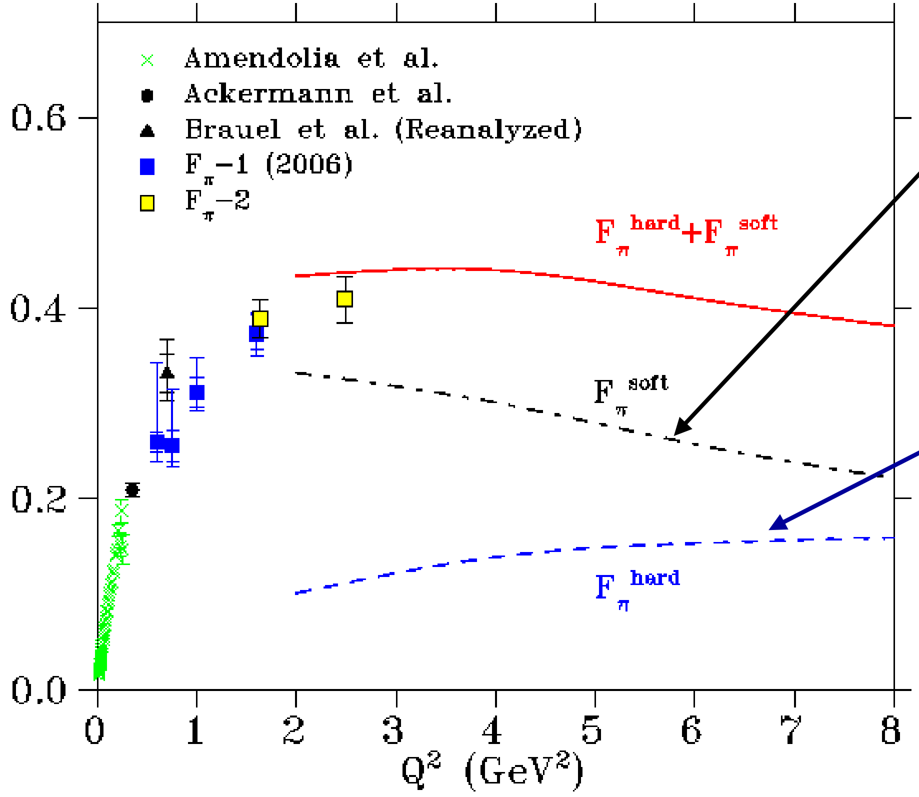
Λ_π^2=0.513, 0.491 GeV², Λ_ρ^2=1.7 GeV².

Current Experimental Status

pQCD LO+NLO Calculation:

Analytic perturbation theory at the parton amplitude level.

*A.P. Bakulev, K. Passek-Kumericki, W. Schroers, & N.G. Stefanis, PRD **70** (2004) 033014.*



For details: G.M. Huber et al., PRC **78** (2008) 045203.

SOFT QCD:

- Extra piece needed to describe data.
- Estimated from local quark-hadron duality model.
- Consistent with DCSB expectations.

HARD QCD: pQCD LO+NLO

- JLab 6 GeV F_π results are far from the values predicted by pQCD.
- At the distance scales probed by the experiment (0.15<r<0.30 fm), the π^+ structure is not governed by the two valence quarks.
- Virtual quarks and gluons dominate.

Model / Intepretation Issues

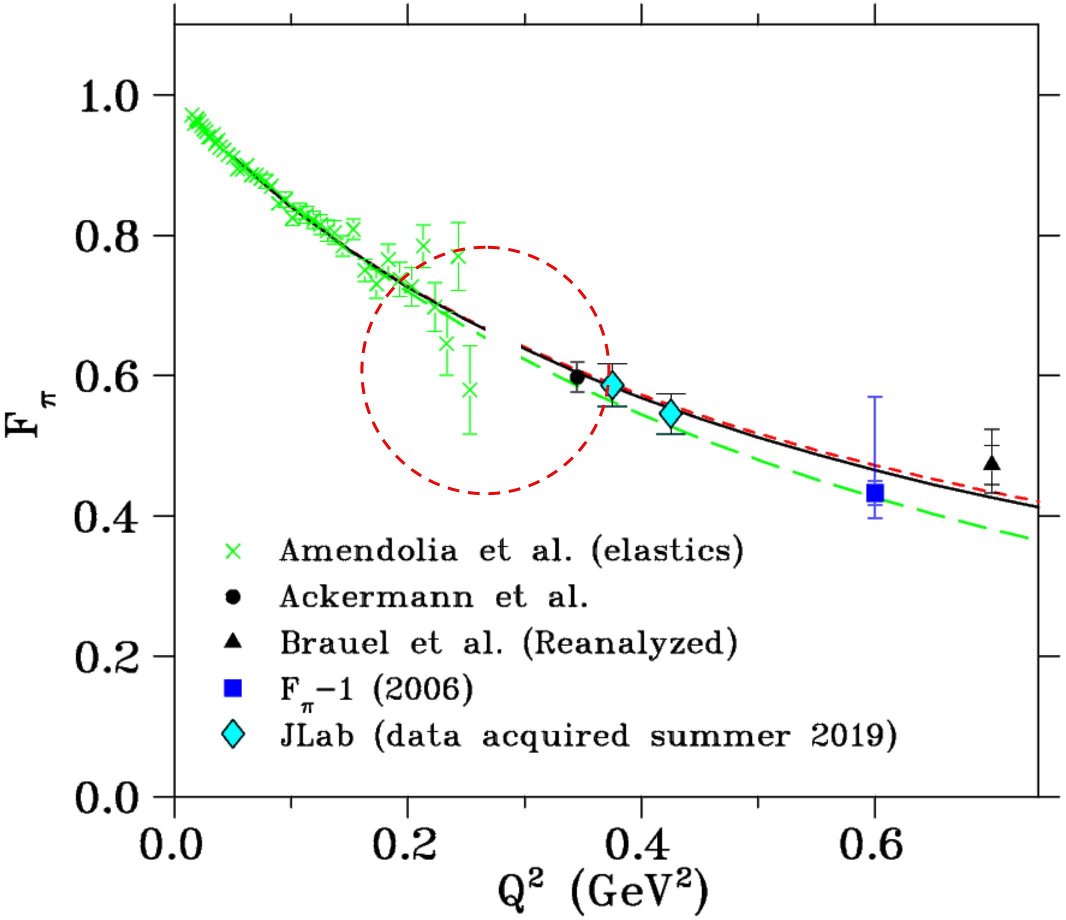
- A common criticism of the electroproduction technique is the difficulty to be certain one is measuring the “physical” form factor.

> “What is at best measured in electroproduction is the transition amplitude between a mesonic state with an effective space-like mass $m^2=t<0$ and the physical pion. It is theoretically possible that the off-shell form factor $F_\pi(Q^2,t)$ is significantly larger than the physical form factor because of its bias towards more point-like $q\bar{q}$ valence configurations within its Fock state structure.” --S.J. Brodsky, Handbook of QCD, 2001.

- What tests/studies can we do to give confidence in the result?
  - Check consistency of model with data.
  - Extract form factor at several values of $-t_{min}$ for fixed Q^2.
  - Test that the pole diagram is really the dominant contribution to the reaction mechanism.
  - Verify that electroproduction technique yields results consistent with π^+e elastic scattering at same Q^2.

Check of Pion Electroproduction Technique

- Does electroproduction really measure the on–shell form–factor?
- Test by making $p(e,e'\pi^+)n$ measurements at same kinematics as π^+e elastics.
- ***Can't quite reach the same Q^2, but electro–production appears consistent with extrapolated elastic data.***



Data for new test acquired in Summer 2019:

- small Q^2 (0.375, 0.425) competitive with DESY Q^2=0.35
- $-t$ closer to pole (=*0.008* GeV^2) vs. DESY 0.013

A similar test for K^+ form factor is part of Kaon–LT

Verify that σ_L is dominated by *t*-channel process

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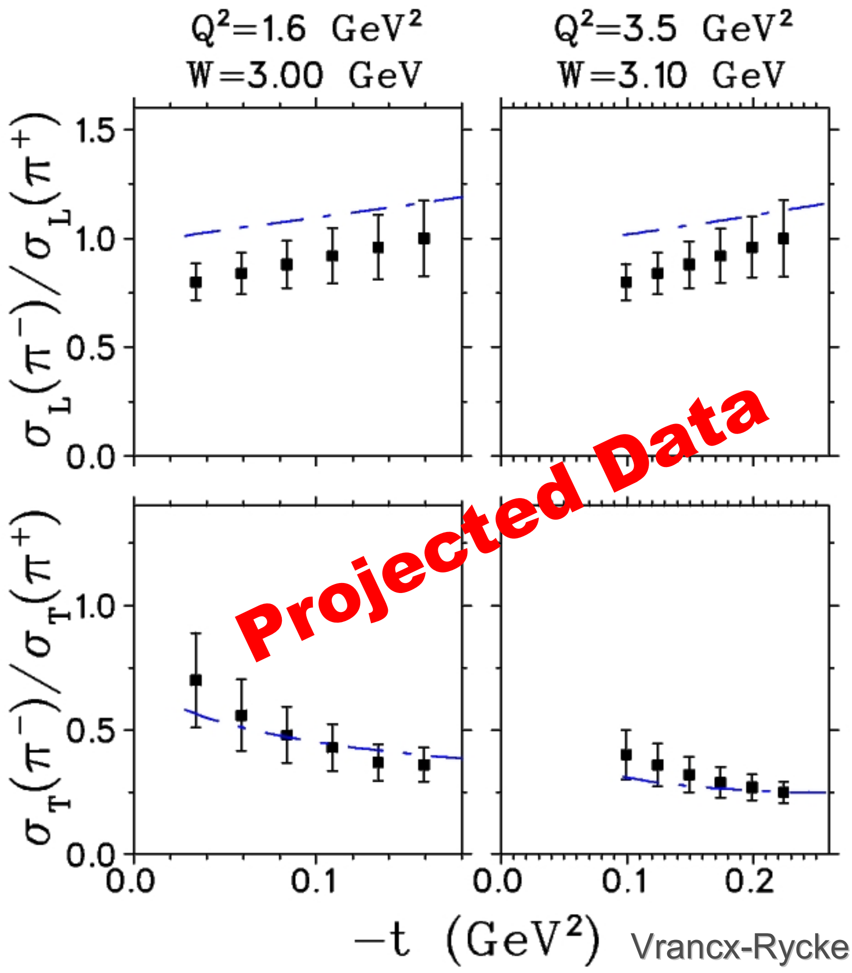
- π^+ *t*-channel diagram is purely isovector.
- Measure

$$R_L = \frac{\sigma_L[n(e,e'\pi^-)p]}{\sigma_L[p(e,e'\pi^+)n]} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

using a deuterium target.

- Isoscalar backgrounds (such as $b_1(1235)$ contributions to the *t*-channel) will dilute the ratio.
- We will do the same tests at Q^2=1.60, 3.85, 6.0 GeV^2.



Vrancx-Ryckebusch Regge+DIS Model [PRC **89**(2014)025203]

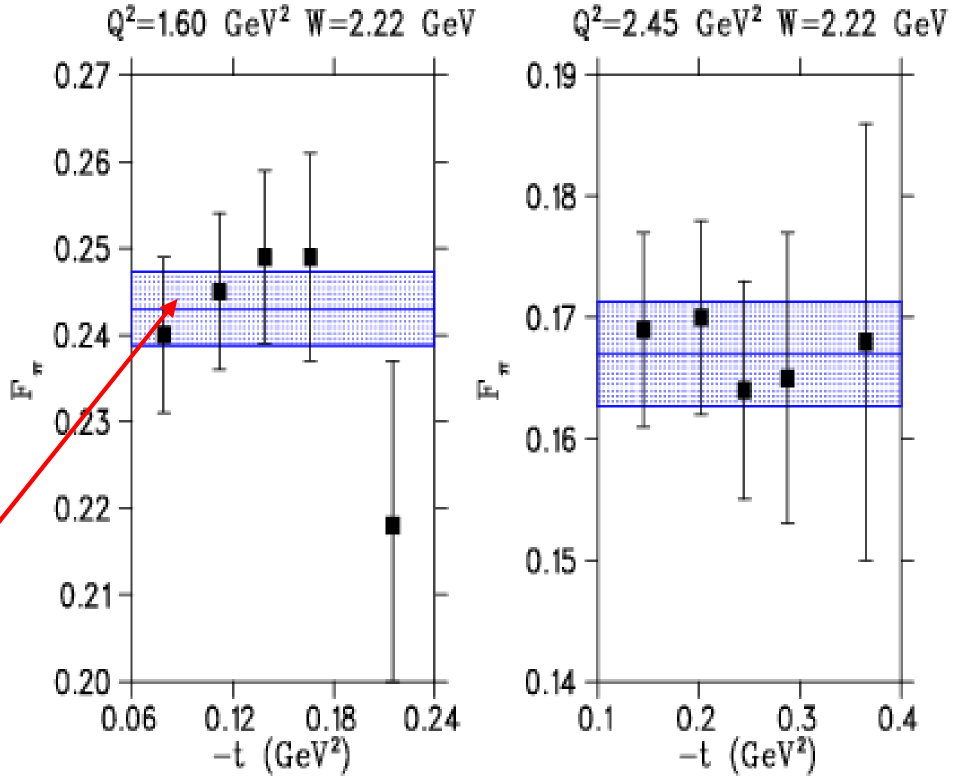
Because one of the many problems encountered by the historical data was isoscalar contamination, this test will increase the confidence in the extraction of $F_\pi(Q^2)$ from our σ_L data.

Fπ–2 VGL $p(e,e'\pi^+)n$ model check

- To check whether VGL Regge model properly accounts for:
  - π^+ production mechanism.
  - spectator nucleon.
  - other off–shell (*t*–dependent) effects.

  extract F_π values for each *t*–bin separately, instead of one value from fit to all *t*–bins.

Error band based on fit to all *t*-bins.



Fπ-2 data: G.M. Huber, et al., PRC **78** (2008) 045203

Only statistical and t–uncorrelated systematic uncertainties shown

- Deficiencies in model may show up as *t*–dependence in extracted $F_\pi(Q^2)$ values.
- Resulting F_π values are insensitive (<2%) to *t*–bin used.
- Lends confidence in applicability of VGL model to the kinematical regime of the JLab data, and the validity of the extracted $F_\pi(Q^2)$ values.

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E12–19–006 Optimized Run Plan

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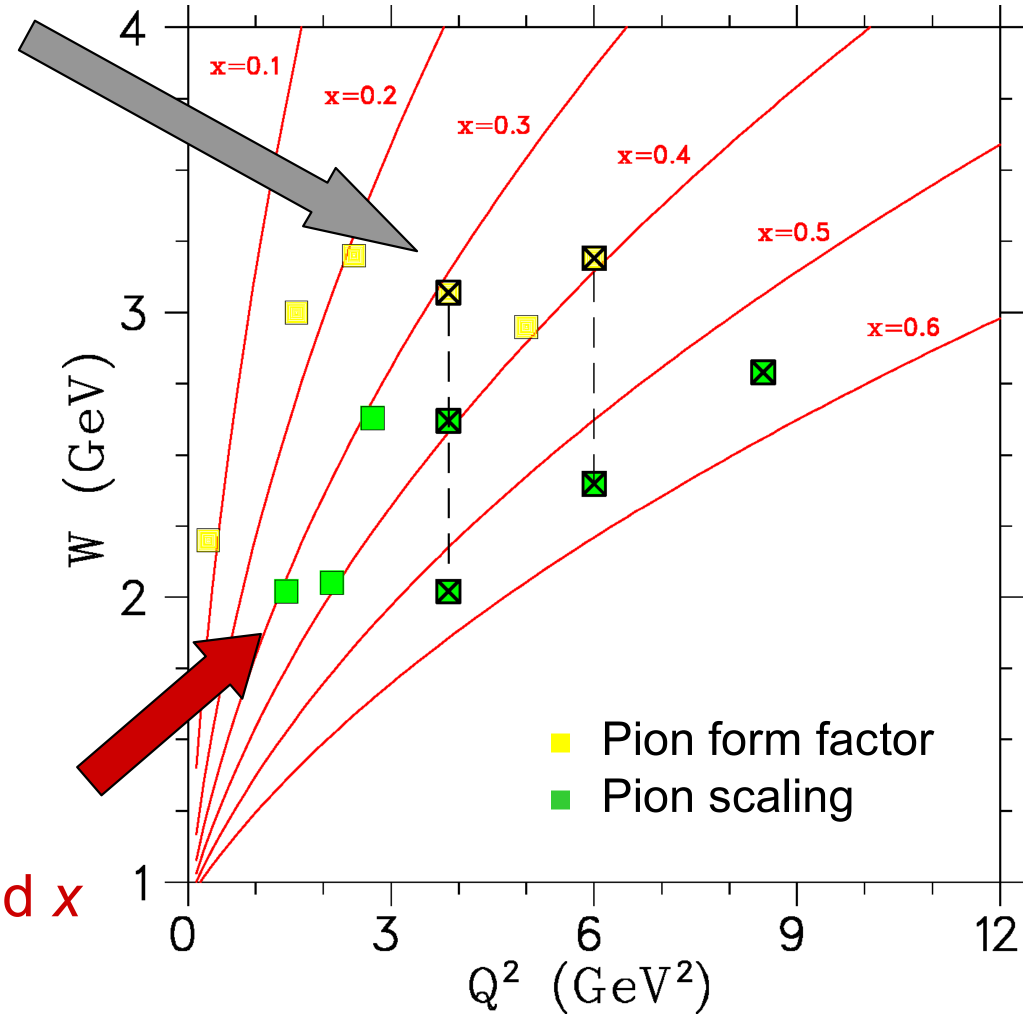
Points along vertical lines allow F_π values at different distances from pion pole, to check the model properly accounts for:

- π^+ production mechanism
- spectator nucleon
- off-shell (*t*–dependent) effects.



Points along red curves allow $1/Q^n$ scaling tests at fixed *x*

For more details, visit Pion-LT RedMine: https://redmine.jlab.org/projects/hall-c/wiki/

Current and Projected F_π Data

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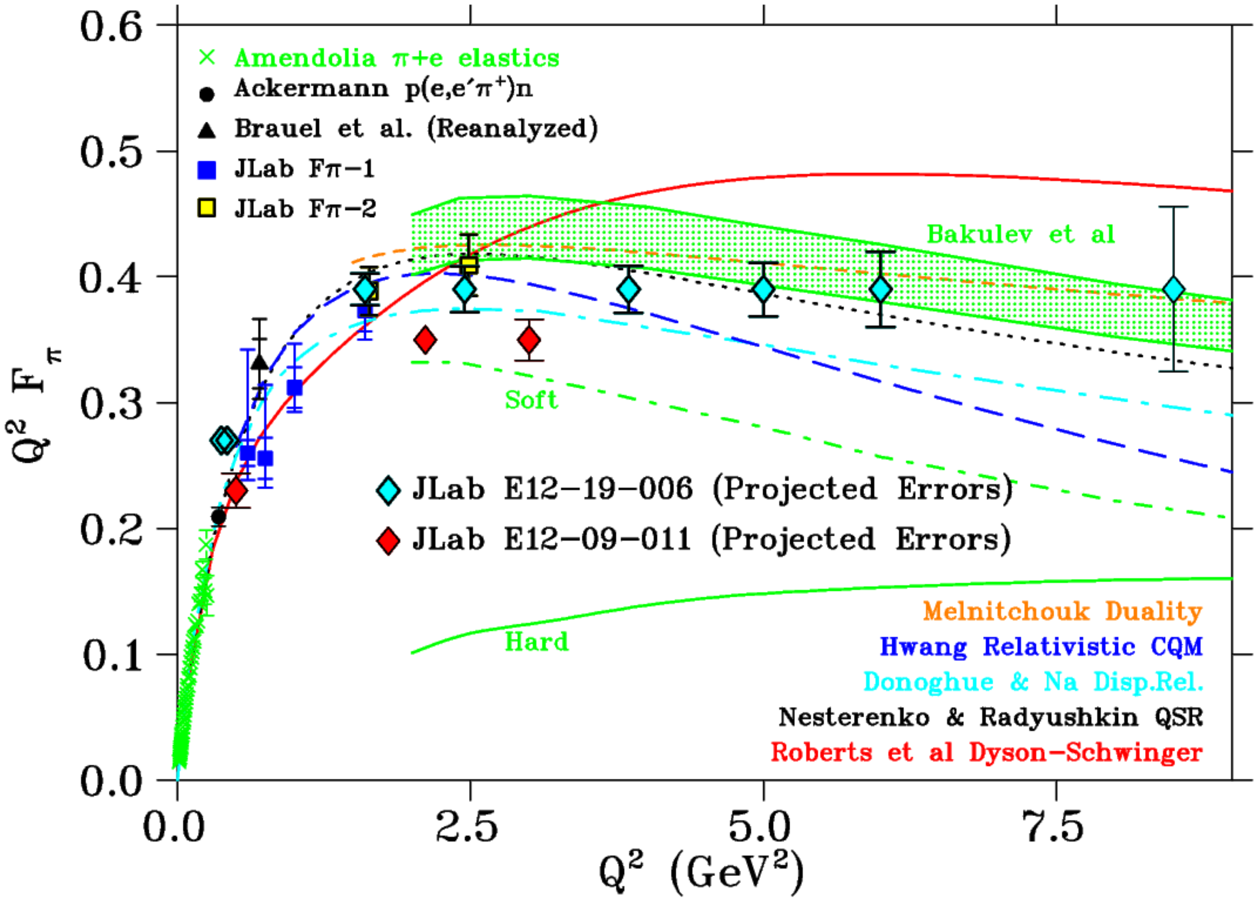
SHMS+HMS will allow measurement of F_π to much higher Q^2

No other facility worldwide can perform this measurement

Data taking completed September 2022 (E12–19–006: G. Huber, D. Gaskell and T. Horn, spokespersons)

y–positions of projected points are arbitrary

Error bars are calculated from obtained statistics and projected systematic uncertainties



The ~10% measurement of F_π at Q^2=8.5 GeV^2 is at higher $-t_{min}$=0.45 GeV^2

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

Summary

- Higher Q^2 data on the pion form factor are vital to our better understanding of hadronic physics
  - Pion properties are intimately connected with dynamical chiral symmetry breaking (DCSB), which explains the origin of more than 98% of the mass of visible matter in the universe
  - F_π is our best hope to directly observe QCD's transition from confinement-dominated physics at large length–scales to perturbative QCD at short length-scales
- New experimental capabilities:
  - PionLT (E19–12–006) has for the first time, since the pioneering measurements at Cornell in 1970's, acquired the high quality data needed to test these theoretical developments with authority
  - Expect first results in ~2 years