Pion Form Factor and Factorization to High Q^2
E12–19–006

University of Regina

Garth Huber

Hall A/C Joint User's Meeting
July 9, 2021

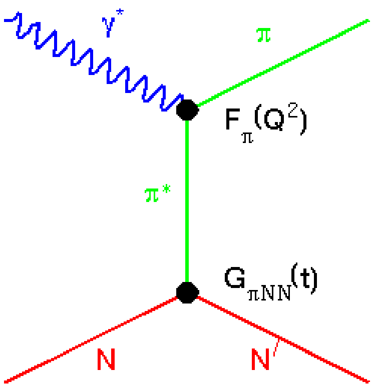
Supported by:
NSERC CRSNG
SAPIN-2021-00026

Motivations of the Experiment

1) Determine the Pion Form Factor to high Q^2:

- Indirectly measure F_π using the "pion cloud" of the proton via p(e,e'π^+)n

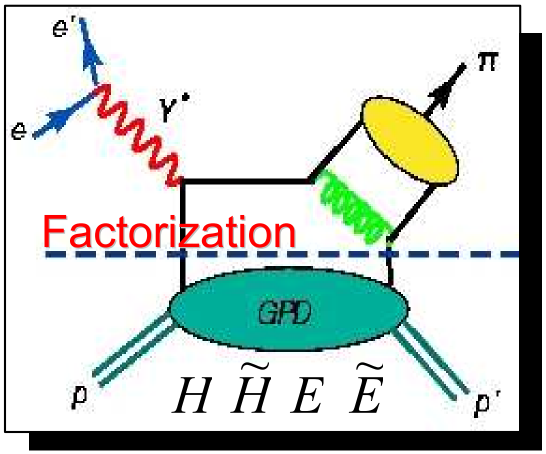
$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \ldots$$



- **The pion form factor is a key QCD observable.**
- The experiment should obtain high quality F_π over a broad Q^2 range. Rated "high impact" by PAC.

2) Study the Hard-Soft Factorization Regime:

- **Need to determine region of validity of hard-exclusive reaction meachanism, as GPDs can only be extracted where factorization applies.**
- Separated p(e,e'π^+)n cross sections vs. Q^2 at fixed x to investigate reaction mechanism towards 3D imaging studies.
- Perform exclusive π^-/π^+ ratios from ^{2}H, yielding insight to hard–soft factorization at modest Q^2.



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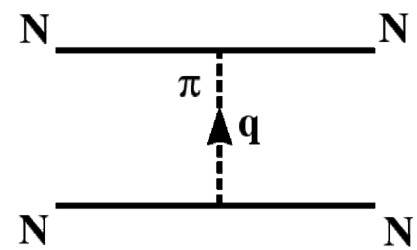
The Pion has Particular Importance

- The pion is responsible for the long–range part of the nuclear force, acting as the basis for meson exchange forces, and playing a critical role as an elementary field in nuclear structure Hamiltonians.



- As the lightest meson, it must be a valence $q\bar{q}$ bound state, but understanding its structure through QCD has been exceptionally challenging.
  - e.g. Constitutent Quark Models that describe a nucleon with m_N=940 MeV as a qqq bound state, are able to describe the ρ-meson under similar assumptions, yielding a constituent quark mass of about

$$m_Q \approx \frac{m_N}{3} \approx \frac{m_\rho}{2} \approx 350 \text{ MeV}$$

- The pion mass $m_\pi \approx$140 MeV seems "too light".

- **We exist because nature has supplied two light quarks and these quarks combine to form the pion, which is unnaturally light and hence very easily produced.**

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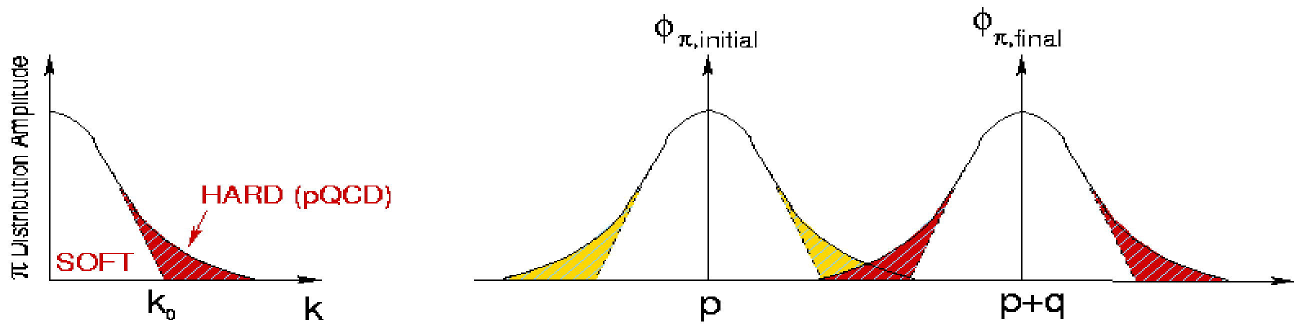
Charged Meson Form Factors

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 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.

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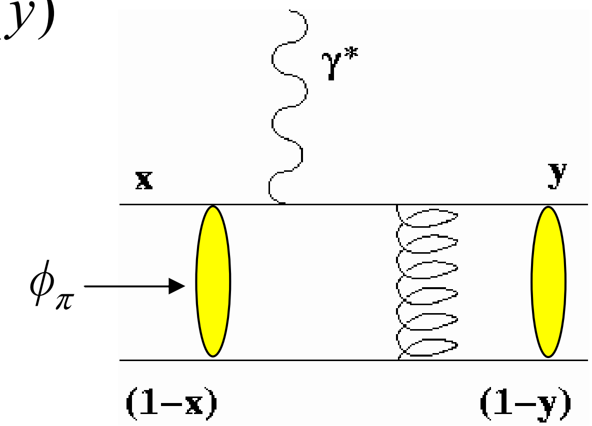
The Pion in perturbative QCD

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

$$F_\pi(Q^2) = \frac{4}{3}\pi\alpha_s \int_0^1 dxdy \frac{2}{3}\frac{1}{xyQ^2}\phi(x)\phi(y)$$



at asymptotically high Q^2, the pion distribution amplitude becomes

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

and F_π takes the very simple form

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

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^2F_π 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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The pion is the "positronium atom" of QCD, its form factor is a test case for most model calculations

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- **What is the structure of the π^+ at all Q^2?**
  - at what value of Q^2 will the pQCD contributions dominate?
- A difficult question to answer, as both "hard" and "soft" components (such as gluonic effects) must be taken into account.
  - non-perturbative hard components of higher twist strongly cancel soft components, even at modest Q^2.

    *[Braun et al., PRD **61**(2000)073004]*
  - the situation for nucleon form factors is even more complicated.
- **Many model calculations exist, but ultimately...**
  - **Reliable $F_\pi(Q^2)$ data are needed to delineate the role of hard versus soft contributions at intermediate Q^2.**
- **A program of study unique to Jefferson Lab** (until the completion of the EIC)

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Measurement of F_π via Electroproduction

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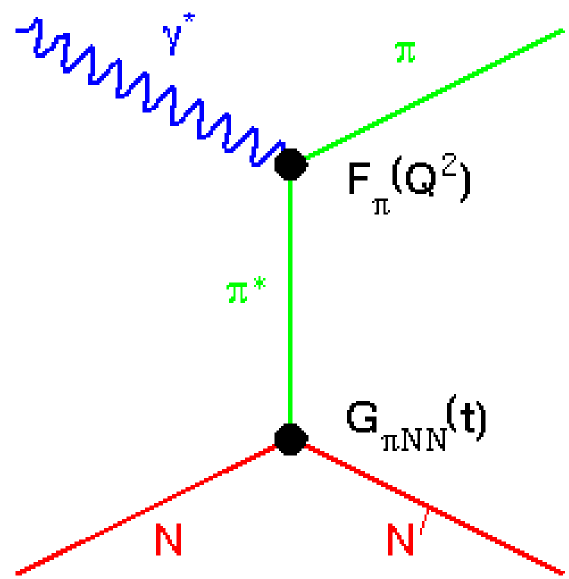
Above Q^2>0.3 GeV^2, F_π is measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

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

- At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
- In Born term model, F_π^2 appears as

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



Drawbacks of this technique:

1. Isolating σ_L experimentally challenging.
2. The F_π values are in principle dependent upon the model used, but this dependence is expected to be reduced at sufficiently small $-t$.

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Extraction of form factor from σ_L data

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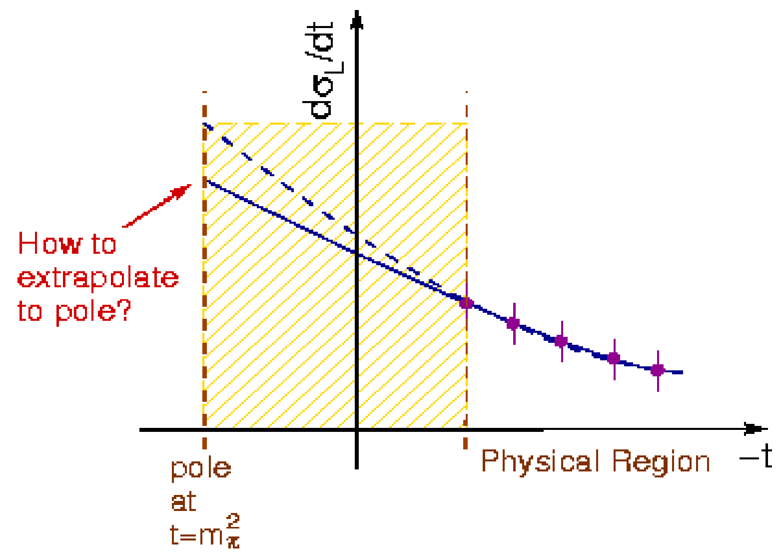
$p(e,e'\pi^+)n$ data are obtained some distance from the $t=m_\pi^2$ pole.

- No reliable phenomenological extrapolation possible.

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



Our philosophy is 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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E12–19–006 Forward Angle Requirements

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

Test of SHMS at 5.69° in Aug 2018

Requirements for Fall 2021 Run:

Setting	Beam Energy	θ_{SHMS}	θ_{HMS}	θ_{OPEN}
Q^2=1.60 W=3.08	9.20	6.28°	**12.34°**	**18.62°**
Q^2=3.85 W=3.07	8.00	**5.50°**	34.15°	39.65°
Q^2=5.00 W=2.95	8.00	6.35°	42.91°	49.26°
Q^2=6.00 W=3.19	9.20	**5.50°**	46.43°	51.93°
Q^2=8.50 W=2.79	9.20	**5.52°**	**57.70°**	63.22°

- Steve Lassiter has been working on θ_{SHMS}=5.50° requirement
- SHMS+HMS minimum opening angle has also been investigated

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p(e,e'π^+)n Event Selection

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

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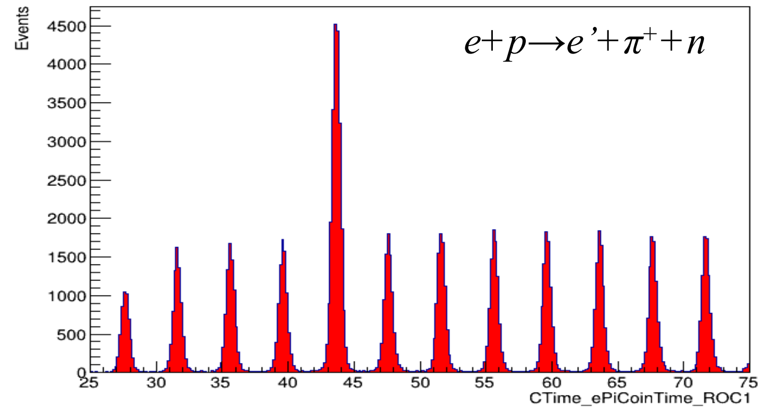
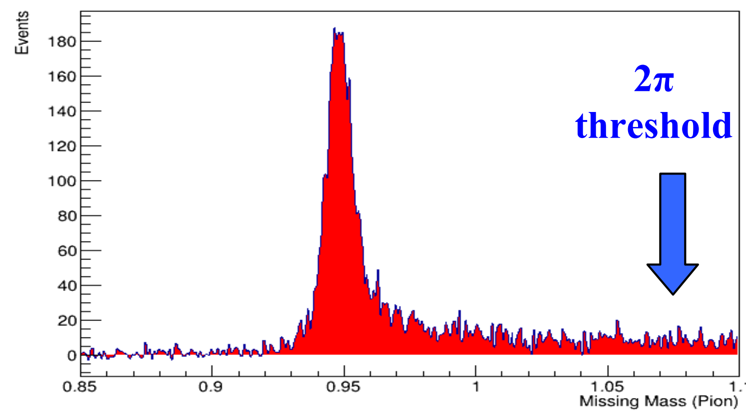
Easy to isolate exclusive channel

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





Sample data from Kaon–LT experiment E12–09–011

Q^2=3.0, W=3.14, x= 0.25, low ε Run: 8045

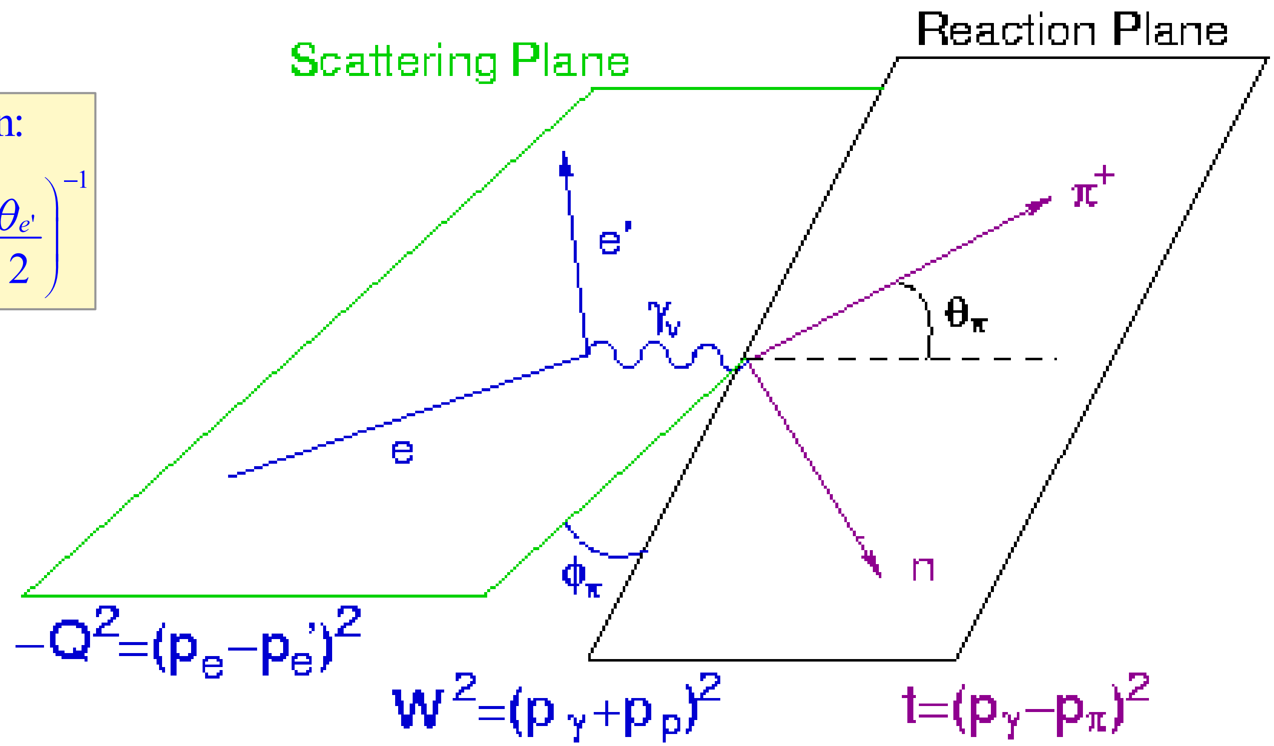
E_{beam}=8.186 GeV, P_{SHMS}=+6.0530 GeV/c, θ_{SHMS}= 6.910°

Plots by Vijay Kumar

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

Virtual-photon polarization:

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



Extraction of F_π requires t dependence of σ_L to be known.

- Only three of Q^2, W, t, θ_π are independent.
- Vary θ_π to measure t dependence.
- Since non-parallel data needed, LT and TT must also be determined.

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

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

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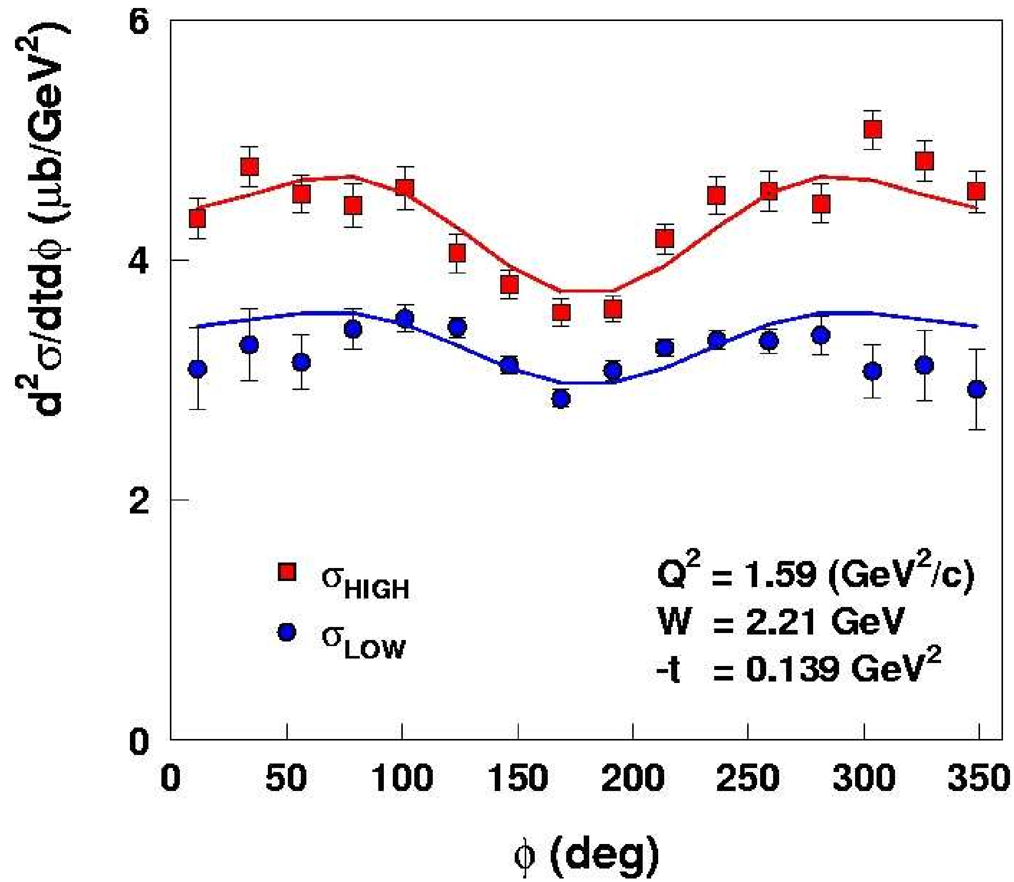
- Extract all four response functions via a simultaneous fit using measured azimuthal angle (φ_π) and knowledge of photon polarization (ε).
- **This technique demands good knowledge of the magnetic spectrometer acceptances.**
  - **Control of point-to-point systematic uncertainties crucial due to 1/Δε error amplification in σ_L**
  - Careful attention must be paid to spectrometer acceptance, kinematics, efficiencies, …



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

Magnetic Spectrometer Calibrations

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- Similarly to $F\pi$-2, we plan to use the over-constrained *p(e,e'p)* reaction and inelastic $e+^{12}C$ in the DIS region to calibrate spectrometer acceptances, momenta, offsets, etc.
  - $F\pi$-2 beam energy and spectrometer momenta determined to <0.1%.
  - Spectrometer angles <0.5 mr.
  - $F\pi$-2 agreement with published $p+e$ elastics cross sections <2%.

Uncertainties from F_π Proposal (E12–06–101)

Projected Systematic Uncertainty Source	Pt-Pt ε-random t-random	ε-uncorrelated common to all t-bins	Scale ε-global t-global
Spectrometer Acceptance	0.4%	0.4%	1.0%
Target Thickness		0.2%	0.8%
Beam Charge	-	0.2%	0.5%
HMS+SHMS Tracking	0.1%	0.4%	1.5%
Coincidence Blocking		0.2%	
PID		0.4%	
Pion Decay Correction	0.03%	-	0.5%
Pion Absorption Correction	-	0.1%	1.5%
MC Model Dependence	0.2%	1.0%	0.5%
Radiative Corrections	0.1%	0.4%	2.0%
Kinematic Offsets	0.4%	1.0%	-

- Uncorrelated uncertainties in σ_{UNS} are amplified by $1/\Delta\varepsilon$ in L/T separation.
- Scale uncertainty propagates directly into separated cross section.

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F_π Extraction from JLab data

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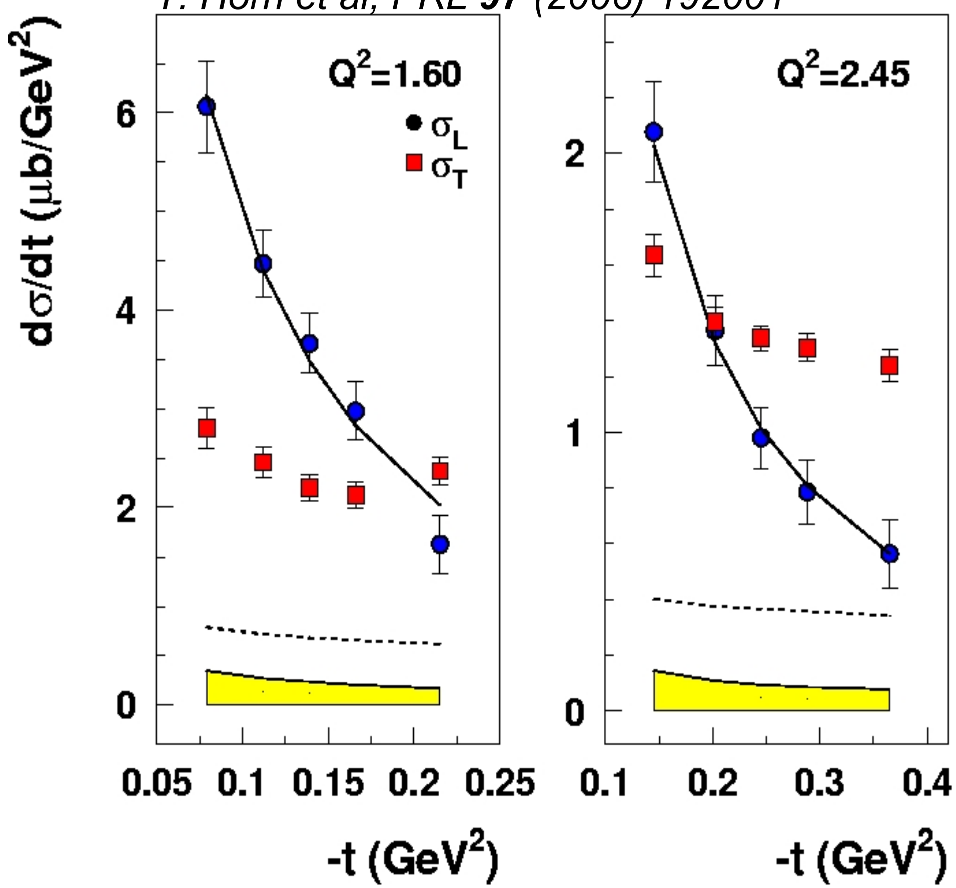
- Model is required to extract F_π from σ_L
- JLab F_π experiments used the VGL Regge model
  [Vanderhaeghen, Guidal, Laget, PRC 57 (1998) 1454]
  - Propagator replaced by π and ρ Regge trajectories
  - Most parameters fixed by photoproduction data
  - 2 free parameters: Λ_π, Λ_ρ
  - At small $-t$, σ_L only sensitive to Λ_π

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

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



New model by R. Perry, A. Kizilersu, A.W. Thomas [PLB 807 (2020) 135581] may allow a second way to extract F_π from σ_L data

Current and Projected F_π Data

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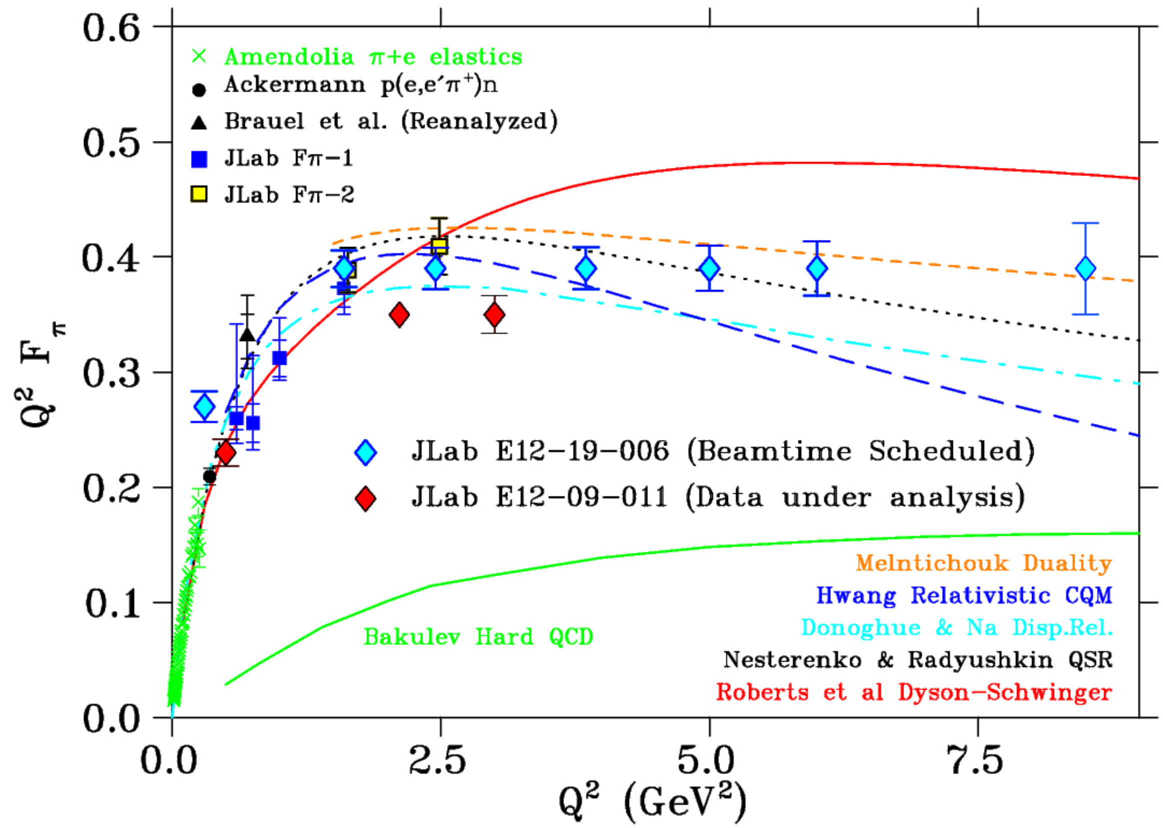
SHMS+HMS will allow measurement of F_π to much higher Q^2.

No other facility worldwide can perform this measurement.

New overlap points at $Q^2=1.6, 2.45$ will be closer to pole to constrain $-t_{min}$ dependence.

New low Q^2 point (data acquired in 2019) will provide comparison of the electroproduction extraction of F_π vs. elastic $\pi+e$ data.



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.

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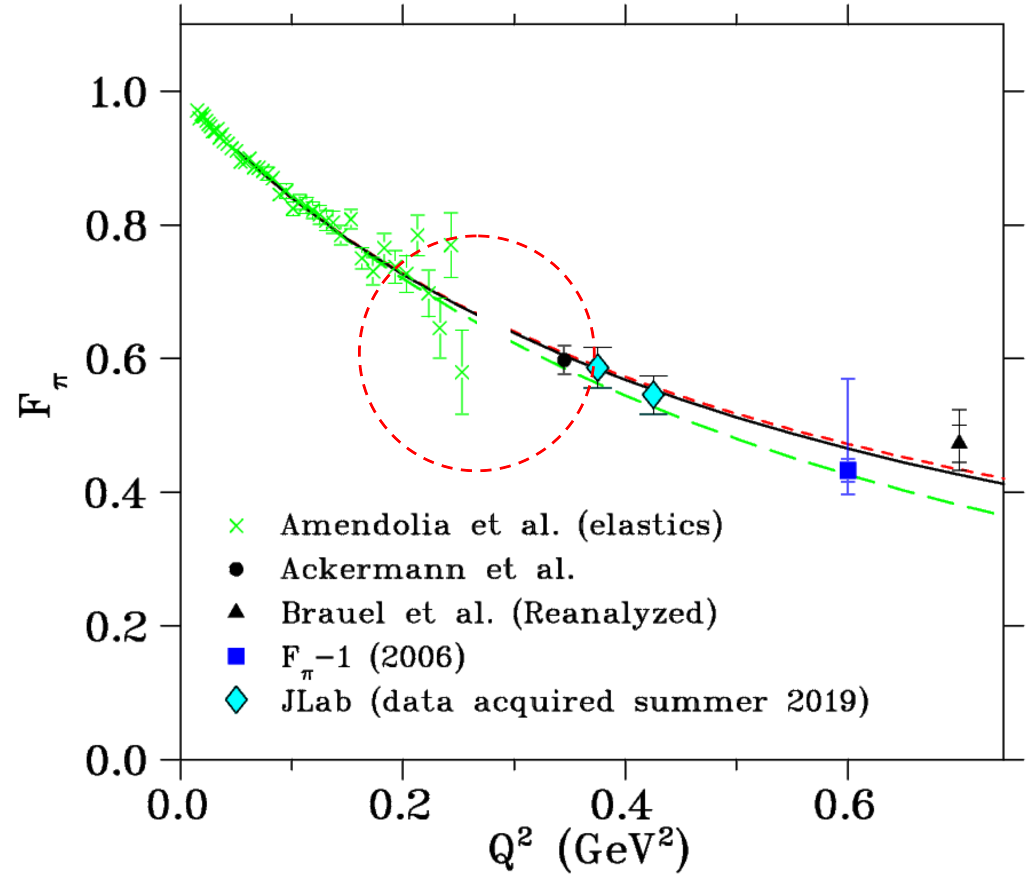
Check of Pion Electroproduction Technique

- 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

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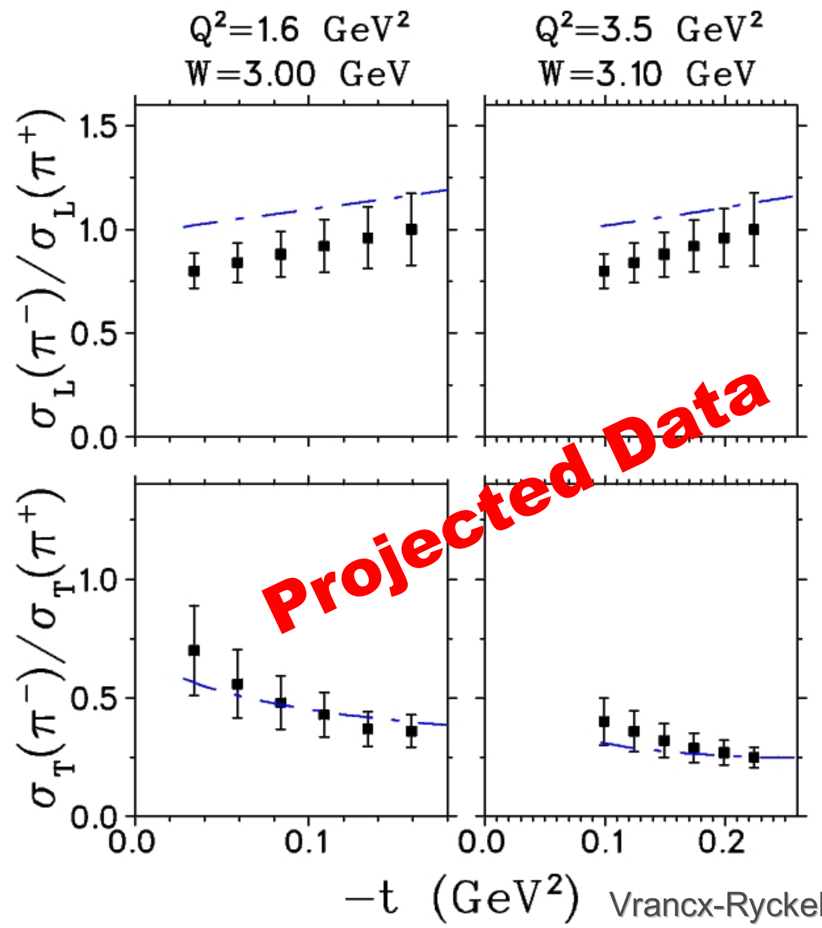
Verify that σ_L is dominated by *t*-channel process

- 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.

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$p(e,e'\pi^+)n$ Q^{-n} Hard–Soft Factorization Test

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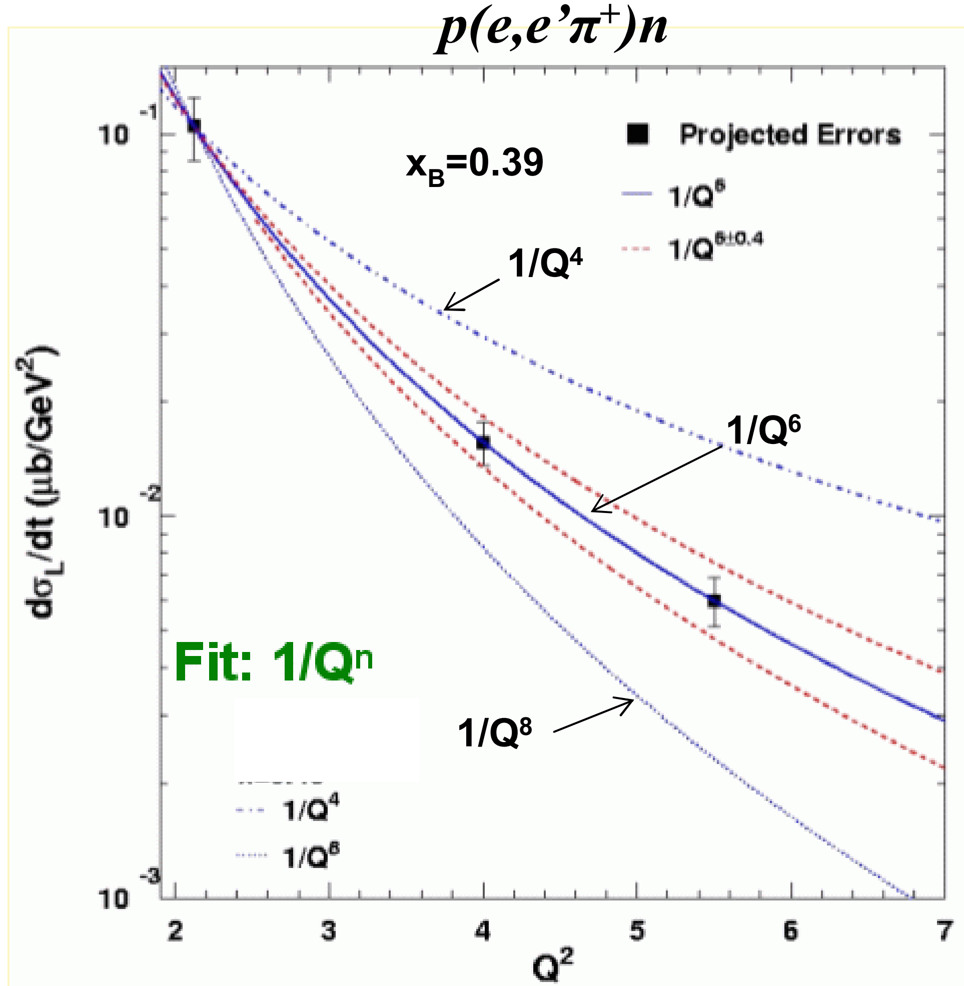
- QCD counting rules predict the Q^{-n} dependence of $p(e,e'\pi^+)n$ cross sections in Hard Scattering Regime:
  - σ_L scales to leading order as Q^{-6}.
  - σ_T scales as Q^{-8}.
  - As Q^2 becomes large: $\sigma_L >> \sigma_T$.

x	Q^2 (GeV²)	W (GeV)	$-t_{min}$ (GeV/c)²
0.31	1.45–3.65	2.02–3.07	0.12
0.39	2.12–6.0	2.05–3.19	0.21
0.55	3.85–8.5	2.02–2.79	0.55



- **Experimental validation of onset of hard scattering regime is essential for reliable interpretation of JLab GPD program results.**
  - If σ_L becomes large, it would allow leading twist GPDs to be studied.
  - If σ_T remains large, it could allow for transversity GPD studies.

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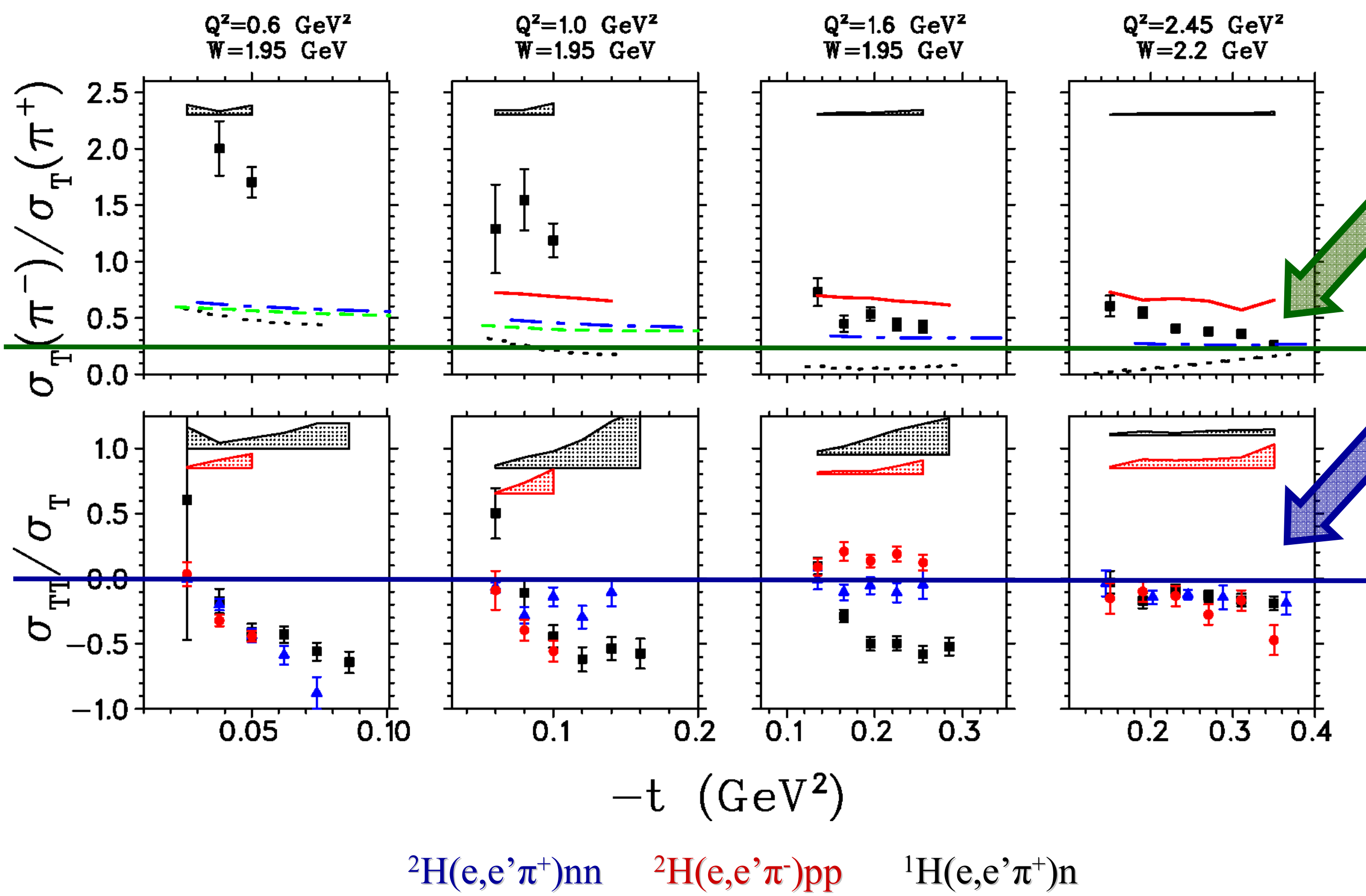
π^-/π^+ Hard–Soft Factorization Test

- **Transverse Ratios tend to ¼ as –*t* increases:**
  - **→ Is this an indication of Nachtmann's quark charge scaling?**
- **–*t*=0.3 GeV² seems too low for this to apply. Might indicate the partial cancellation of soft QCD contributions in the formation of the ratio.**

A. Nachtmann, Nucl.Phys.**B115** (1976) 61.



$$R_T \rightarrow \frac{2Q_d^2}{2Q_u^2} = \frac{1}{4}$$

- Another prediction of quark–parton mechanism is the suppression of σ_{TT}/σ_T due to *s*-channel helicity conservation.
- Data qualitatively consistent with this, since σ_{TT} decreases more rapidly than σ_T with increasing Q^2.

G.M. Huber, et al., PRC **92** (2015) 015202

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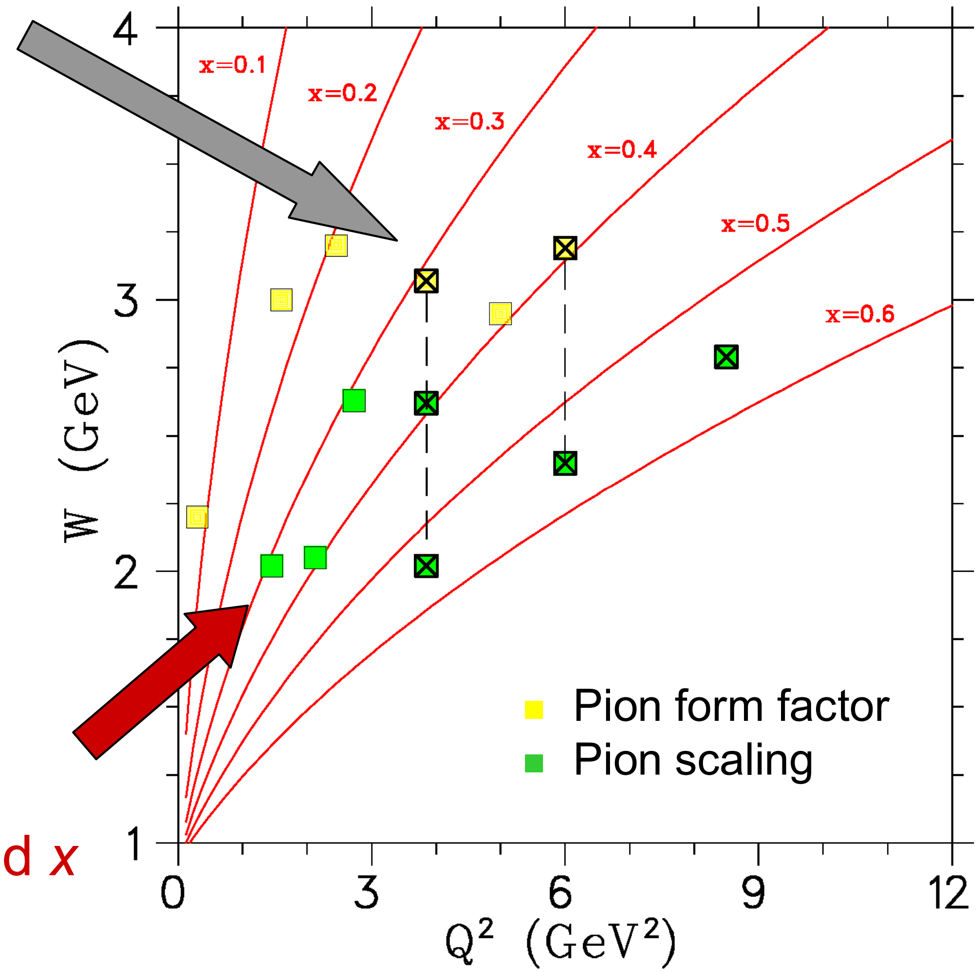
E12–19–006 Optimized Run Plan

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/

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Strong Endorsement in many Reviews

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Report to PAC18, 12 GeV Session:

Measuring F_π at Higher Q^2

G.M. Huber, H.P. Blok, D.J. Mack

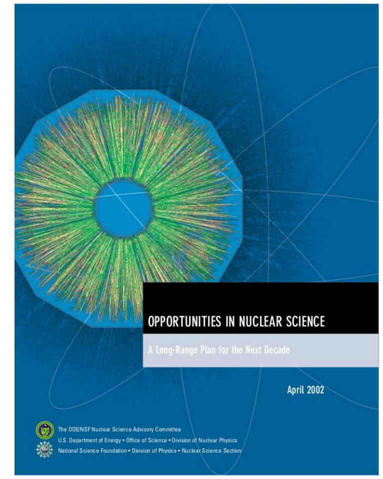
on behalf of the Exclusive Reactions Working Group

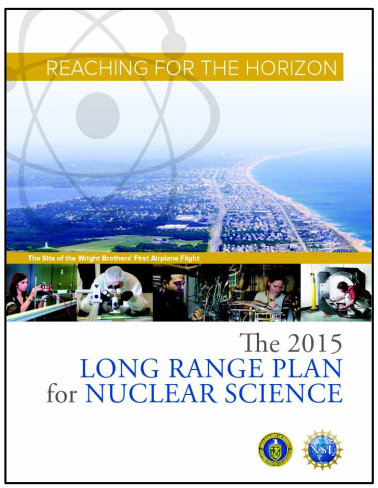
July 6, 2000

F_π first proposed to JLab PAC in 2000!

F_π Rated "Early High Impact" by PAC35 in 2010

F_π endorsed by NSAC in 2002, as one of the key motivations for the 12 GeV Upgrade.





F_π endorsed again by NSAC in 2015, *"as one of the flagship goals of the JLab 12 GeV Upgrade".*

PAC47 (2019) Theory Report:

"Since the proposals were originally reviewed, the physics motivations for BOTH studies have only increased."

"A" rating reaffirmed by PAC for BOTH studies.

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2021 Run Plan Outline

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- **Aug 23 – Oct 16: 9.2 GeV (5 pass @ 1.82 GeV/pass)**

Q^2	W	Target & SHMS polarity
1.6	3.08	LH+, LD+, LD-
6.0	3.19	LH+
8.5	2.79	LH+

- **Nov 28 – Dec 11: 9.9 GeV (5 pass @ 1.96 GeV/pass)**

Q^2	W	Target & SHMS polarity
3.85	3.07	LH+
5.0	2.95	LH+
6.0	3.19	LH+

- **Oct 20 – Nov 27: 8.0 GeV (4 pass @ 1.96 GeV/pass)**

Q^2	W	Target & SHMS polarity
6.0	2.40	LH+, LD+, LD-
2.45	3.20	LH+
3.85	3.07	LH+, LD+, LD-
5.0	2.95	LH+

- **Dec 12 – 14: 6.0 GeV (3 pass @ 1.96 GeV/pass)**

Q^2	W	Target & SHMS polarity
3.85	2.02	LH+

- **Dec 14 – 21: Schedule Contingency**

These are primarily the low ε settings
Additional 9 weeks of beam for high ε data scheduled in Fall 2022

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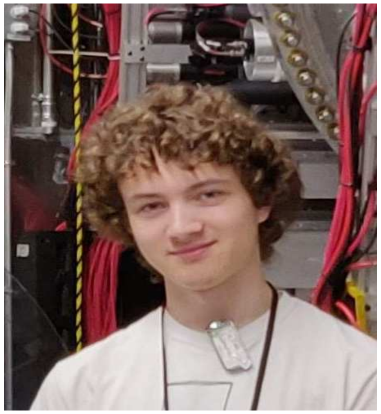
E12–19–006 Important Group Members

- Spokespersons: Dave Gaskell, Tanja Horn, GH
- Graduate Students on the Experiment:

Jacob Murphy
Ohio U.

Muhammad Junaid
U. Regina



Nathan Heinrich
U. Regina

- Run Coordinators (2021):
  - DG, Mark Jones, Simona Malace (2x), Stephen Kay, Douglas Higinbotham, Wenliang Li, Carlos Yero, Holly Szumilla-Vance, Arun Tadepalli, Gabriel Niculescu, Ciprian Gal, Dave Mack, Vladimir Berdnikov

- If interested in joining the team, please contact DG, TH, or GH

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A 12 GeV Flagship Experiment

- **E12–19–006 is expected to provide the definitive $p(e,e'\pi^+)n$ L/T–separation data set, and will remain important for decades to come**
- **F_π–1 and F_π–2 experiments were very productive, and are among JLab's top cited results (top 4 listed):**
  - Volmer et al, PRL 2001 (F_π–1) 333 citations
  - Horn et al, PRL 2006 (F_π–2) 273 citations
  - Tadevosyan et al, PRC 2007 (F_π–1) 224 citations
  - Huber et al, PRC 2007 (F_π–2) 217 citations
- **WE REALLY NEED YOUR ASSISTANCE TO MAKE THE EXPERIMENT A SUCCESS!!**
  - Fall 2021: 756 person shifts needed @ 2 workers/shift
  - We would like co-authors to take shifts in both 2021 and 2022 runs. 2021 requirement: 10 shifts. 2022: ~5 shifts.

    Otherwise, please contact DG, TH, GH for alternate arrangements
  - Shift sign up now open at: https://misportal.jlab.org/mis/apps/physics/shiftSchedule/index.cfm?experimentRunId=HALLC-PIONLT

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