Pion and Kaon Form Factors from Deep Exclusive Meson Production at Jefferson Lab and EIC

University of Regina

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(on behalf of the PionLT Collaboration)

Center for Frontiers in Nuclear Science
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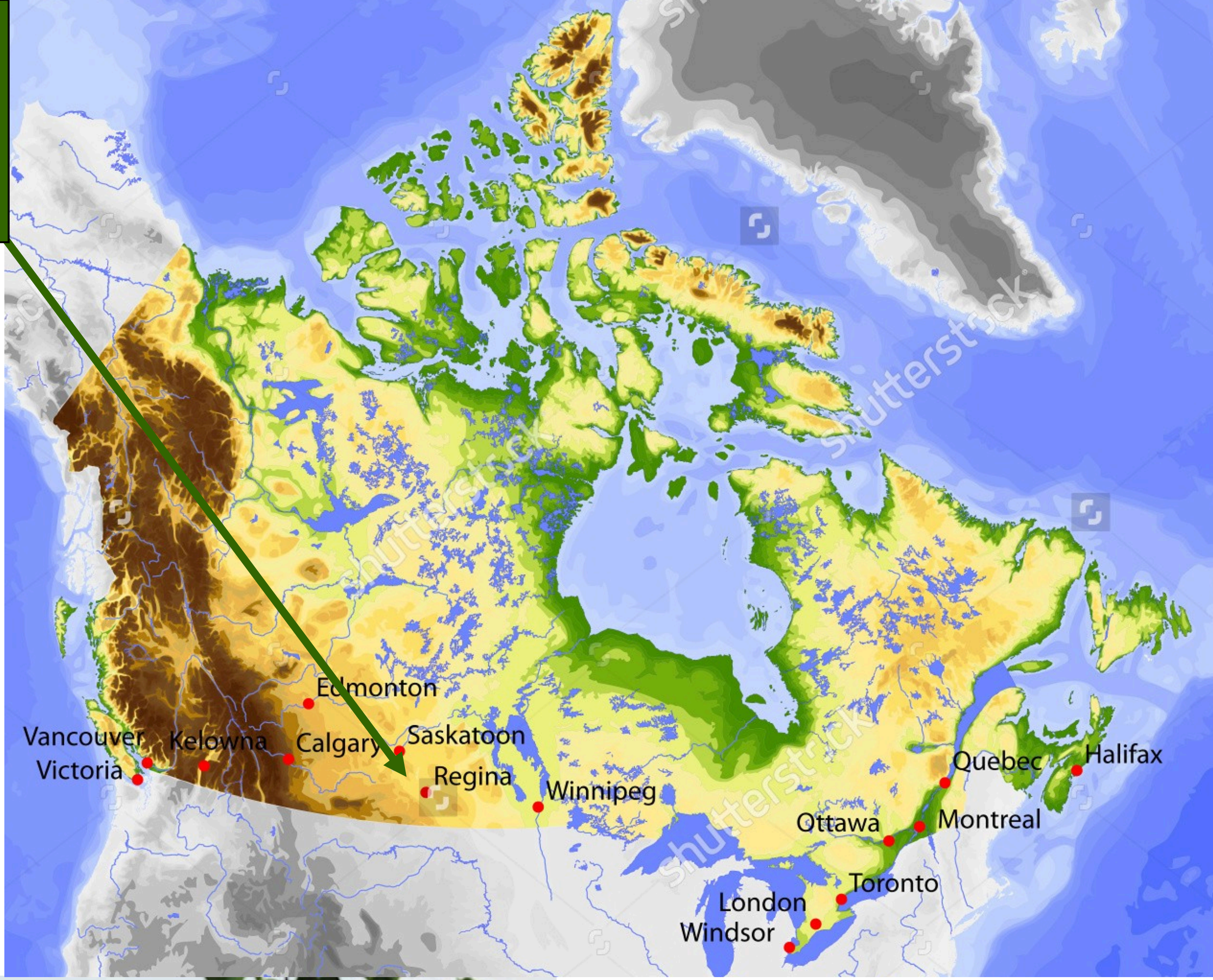
Regina, Saskatchewan CANADA



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Regina is named after Queen Victoria, and is capital of the province of Saskatchewan

Charged Meson Form Factors

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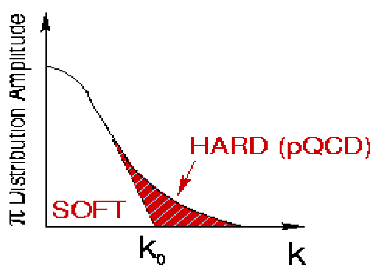
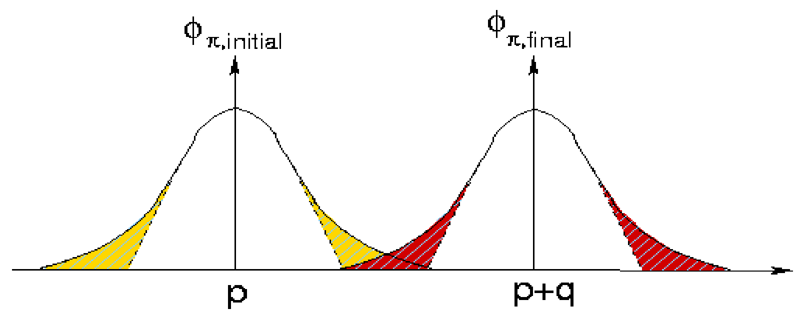
Simple $q\bar{q}$ valence structure of mesons presents the ideal testing ground for our understanding of bound quark systems.

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.

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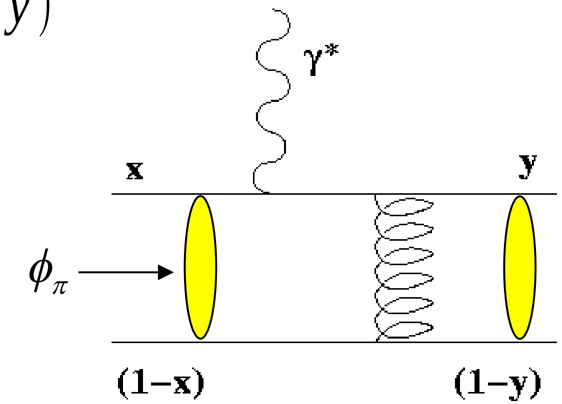
The Pion in perturbative QCD

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

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



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

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

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^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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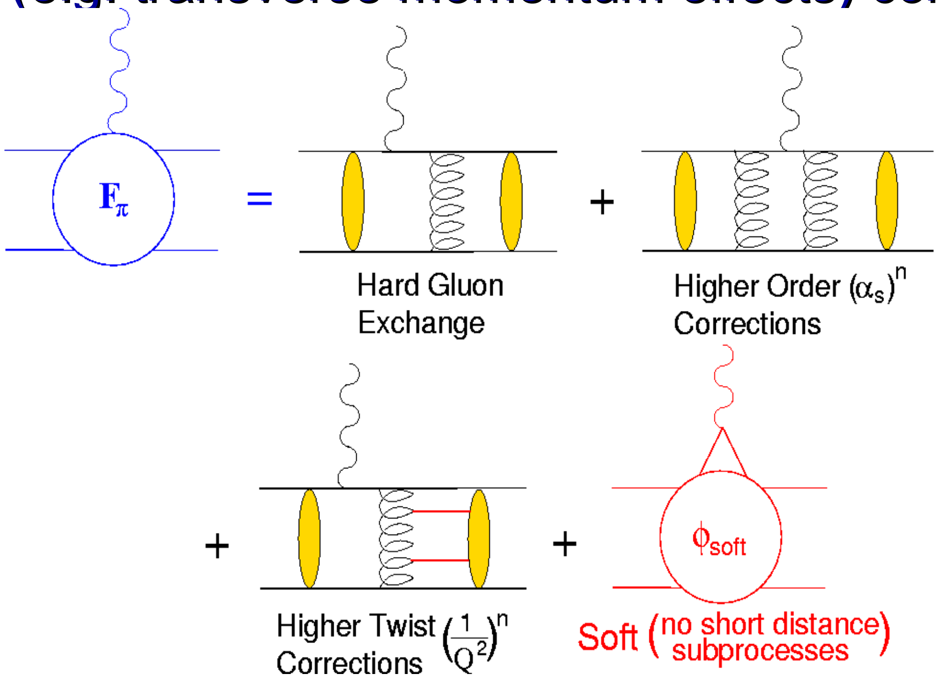
Pion Form Factor at Intermediate Q^2

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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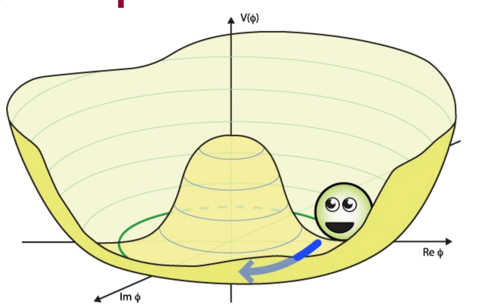
The Pion as a Goldstone Boson

- 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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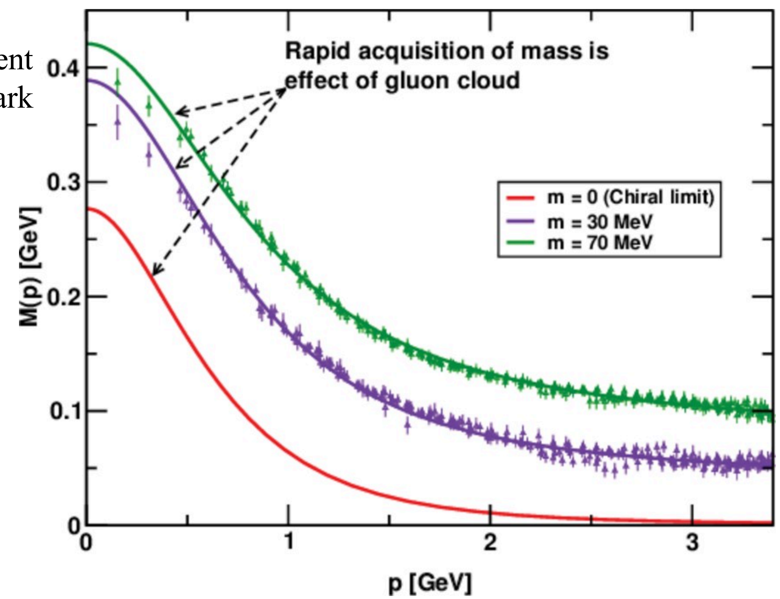
Recent Theoretical Advances

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.

Constituent quark



Current quark

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

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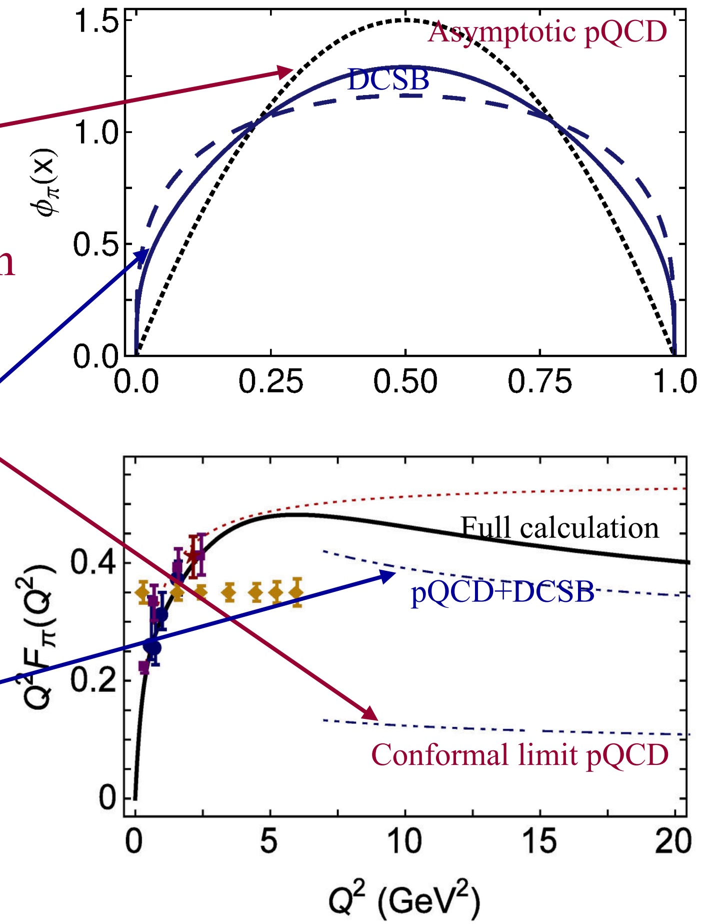
Implications for Pion Structure

Craig Roberts (2016): ***"No understanding of confinement within the Standard Model is practically relevant unless it also explains the connection between confinement and DCSB, and therefore the existence and role of pions."***

- For the pQCD derivation on slide #4, the normalization for F_π has been based on the conformal limit of the pion's twist–2 PDA.
$$\varphi_\pi^{cl}(x) = 6x(1-x)$$
- This leads to "too small" F_π values in comparison with present & projected JLab data.
- Recent works incorporating DCSB effects indicate that at experimentally accessible energy scales the actual pion PDA is broader, concave function, close to
$$\varphi_\pi(x) = (8/\pi)\sqrt{x(1-x)}$$
- Simply inputting this $\varphi_\pi(x)$ into the pQCD expression for F_π brings the calculation much closer to the data.
- **Underestimates full computation by ~15% for $Q^2 \geq 8$ GeV^2. Addresses issue raised in 1977.**



L. Chang, et al., PRL **110** (2013) 132001; **111** (2013) 141802.

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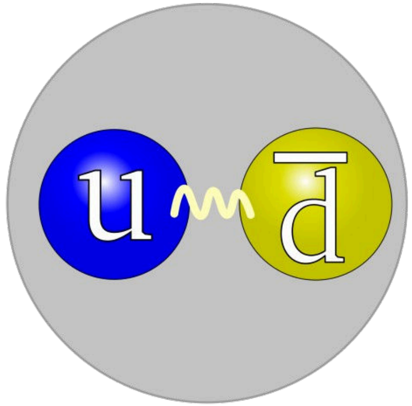
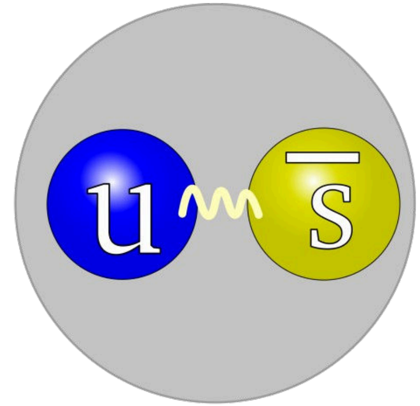
The Charged Kaon – a 2nd QCD test case



π^+



K^+

- In the hard scattering limit, pQCD predicts that the π^+ 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.

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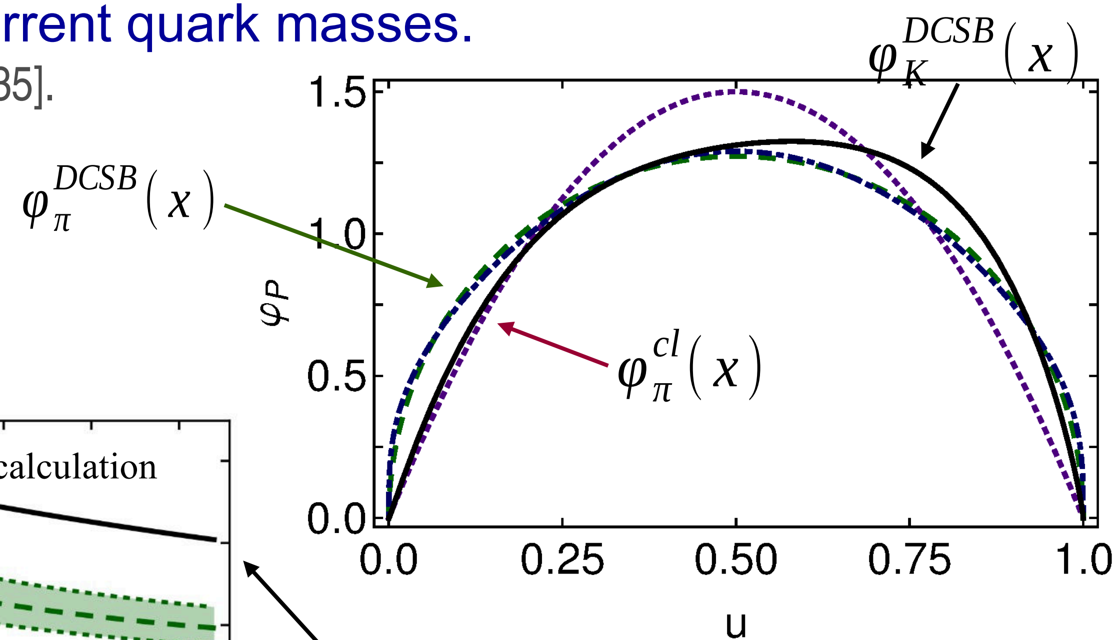
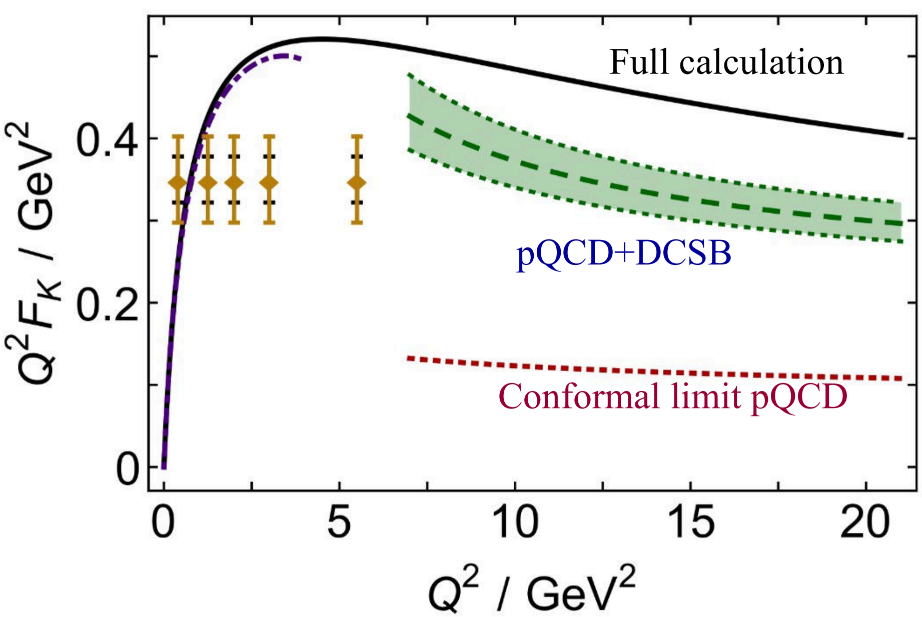
K^+ properties also strongly influenced by DCSB

- ***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].

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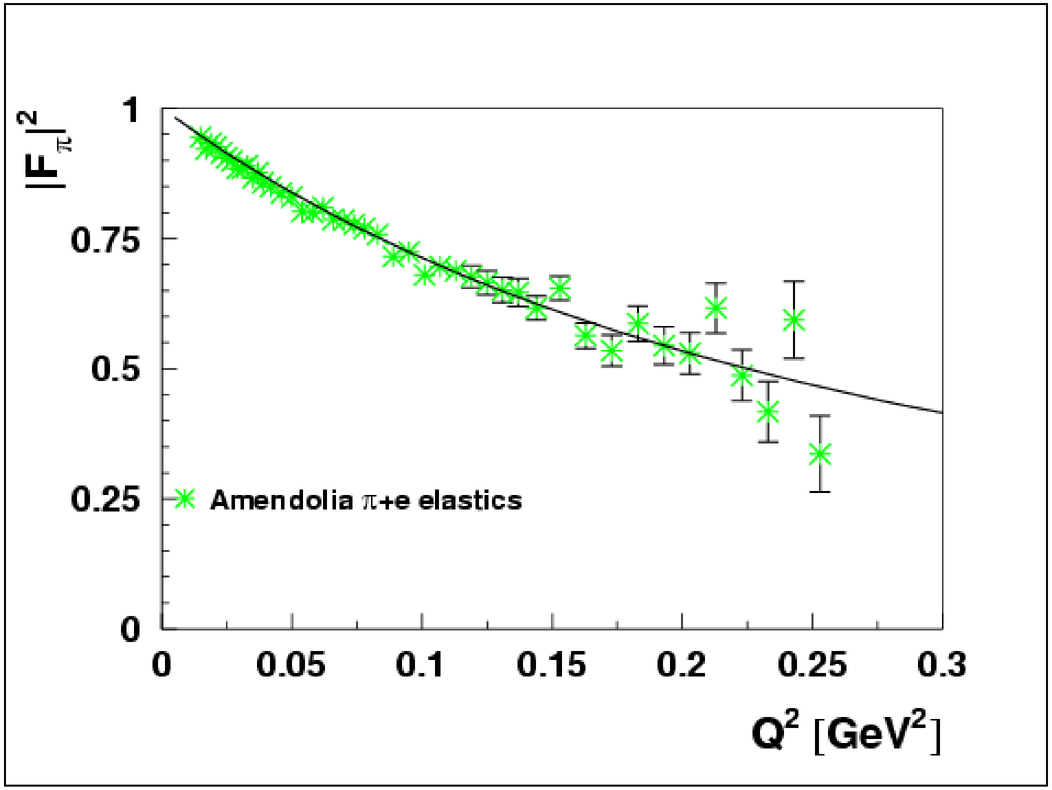
Measurement of π⁺ Form Factor – Low Q^2

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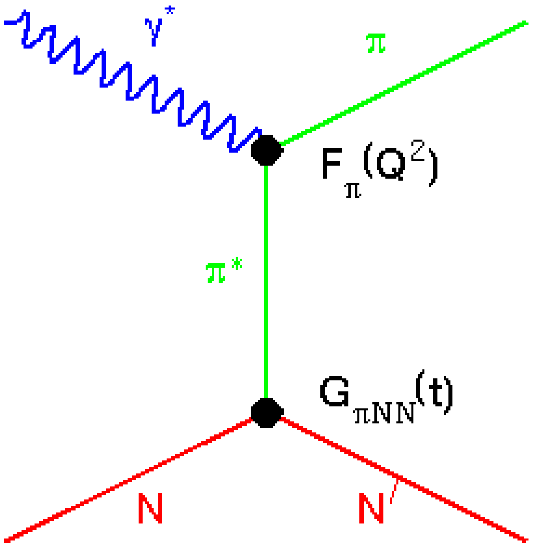
Above Q^2>0.3 GeV^2, F_π is measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

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

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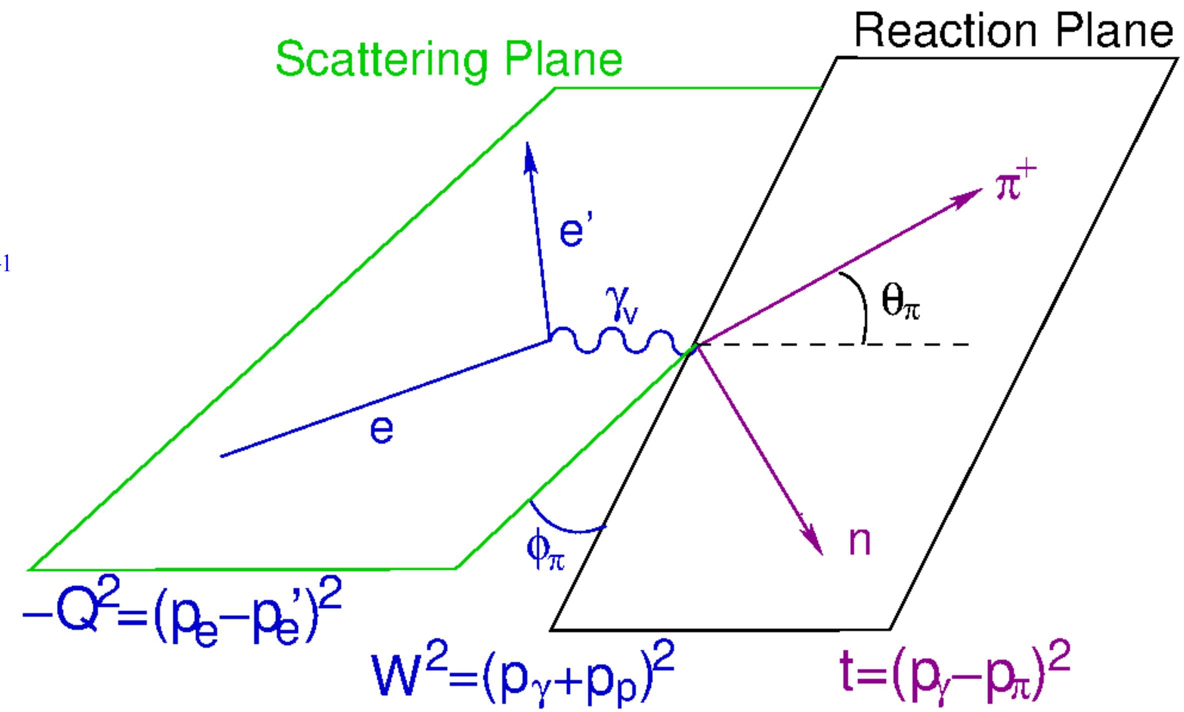
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$

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**
- **Need to measure t–dependence of σ_L at fixed Q^2,W**

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Chew–Low Method to determine Pion Form Factor

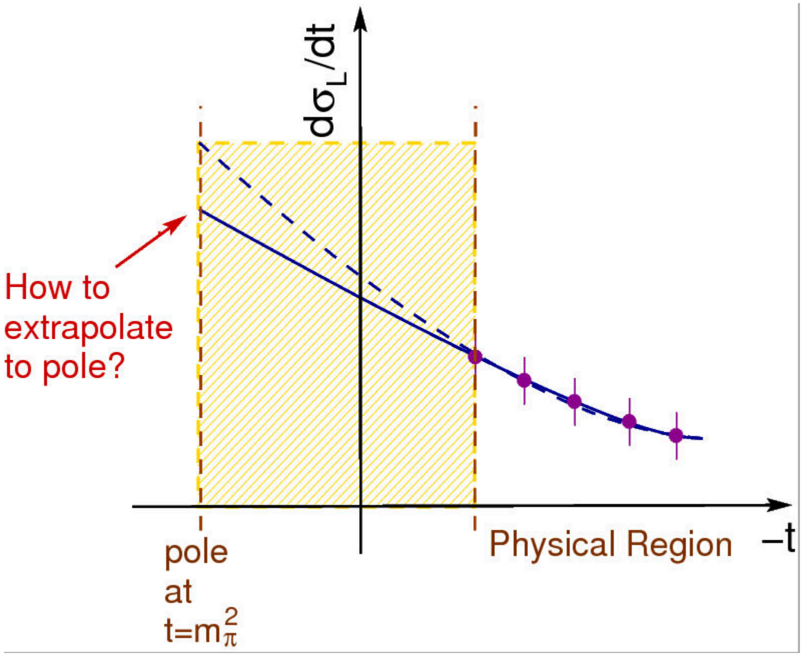
$p(e,e'\pi^+)n$ data are obtained some distance from the $t=m_\pi^2$ pole.

→ "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 use 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. There has been considerable recent interest:
  - *T.K. Choi, K.J. Kong, B.G. Yu, arXiv: 1508.00969.*
  - *T. Vrancx, J. Ryckebusch, PRC **89**(2014)025203.*
  - *M.M. Kaskulov, U. Mosel, PRD **81**(2010)045202.*
  - *S.V. Goloskokov, P. Kroll, Eur.Phys.J.C **65**(2010)137.*

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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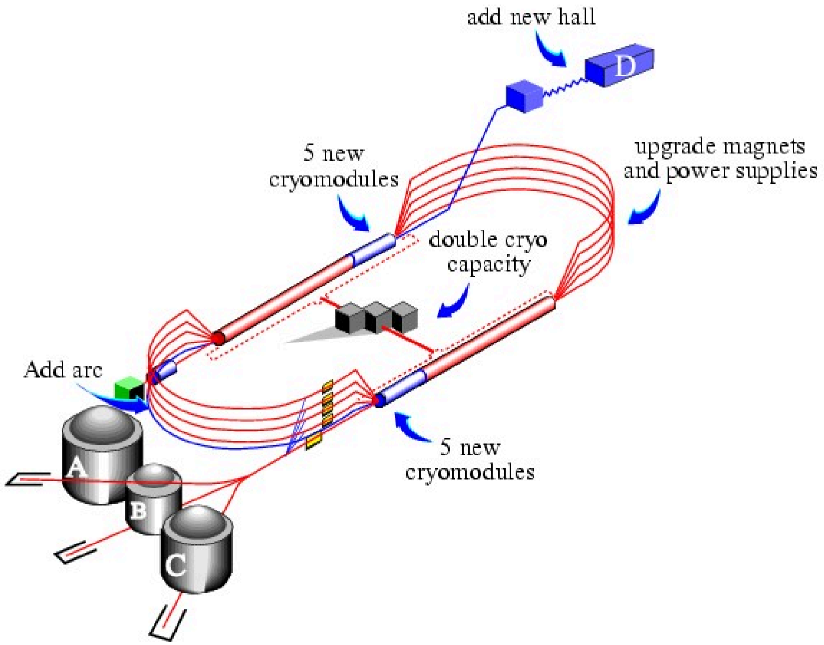
Jefferson Lab
Thomas Jefferson National Accelerator Facility



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**

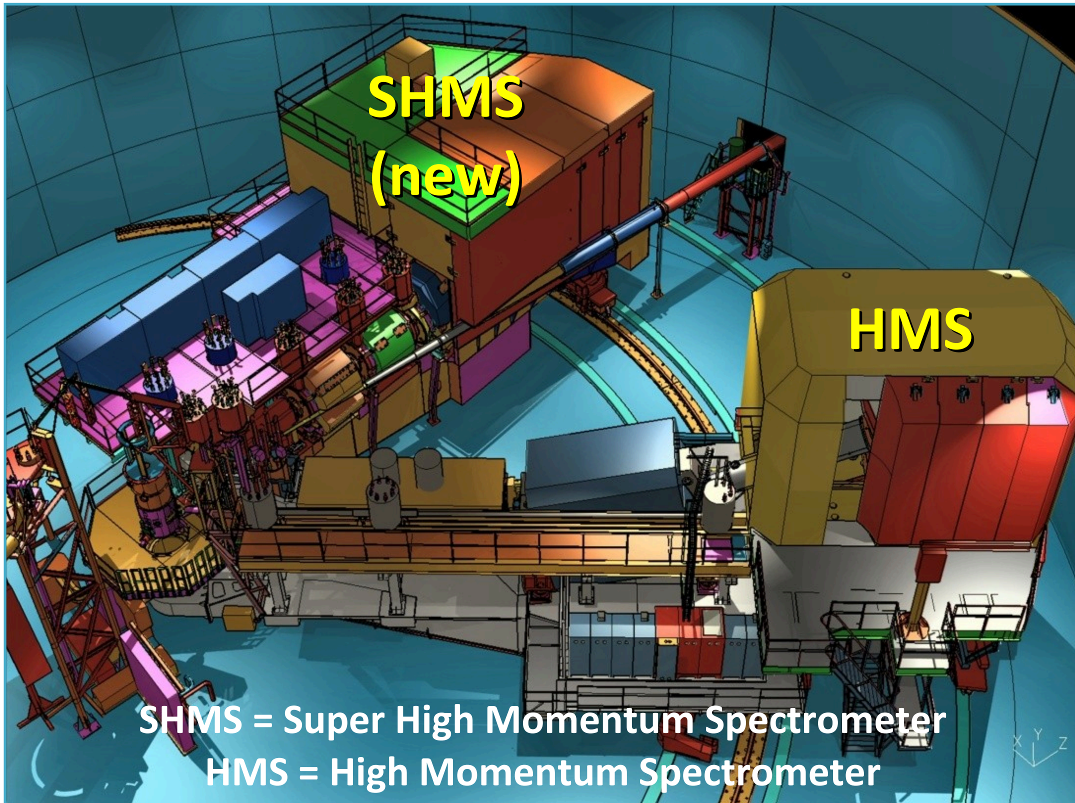
MAGNETIC OPTICS:
- Point-to Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

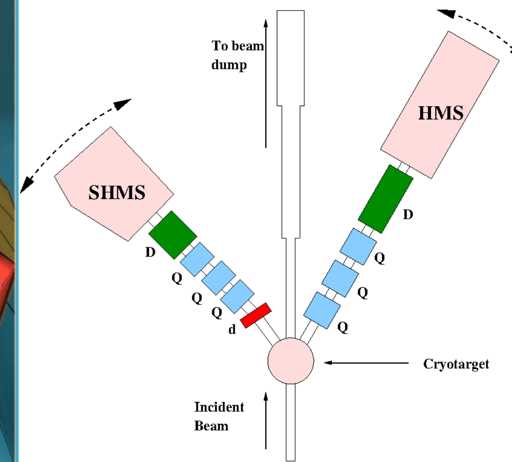
Detector Package:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter

Well-Shielded Detector Enclosure

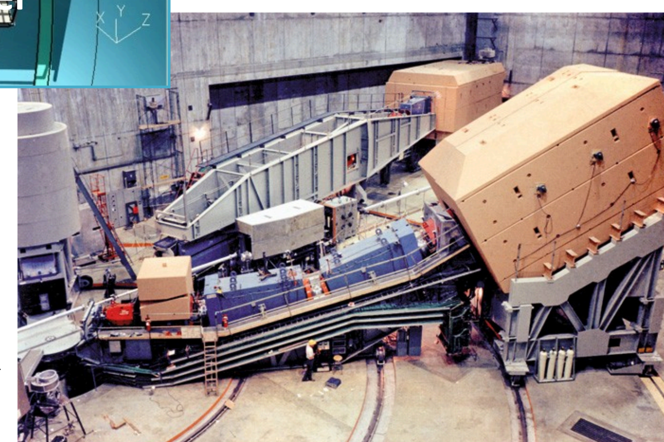
Rigid Support Structure
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS

Luminosity
- ~4x10^{38} cm^{-2} s^{-1}



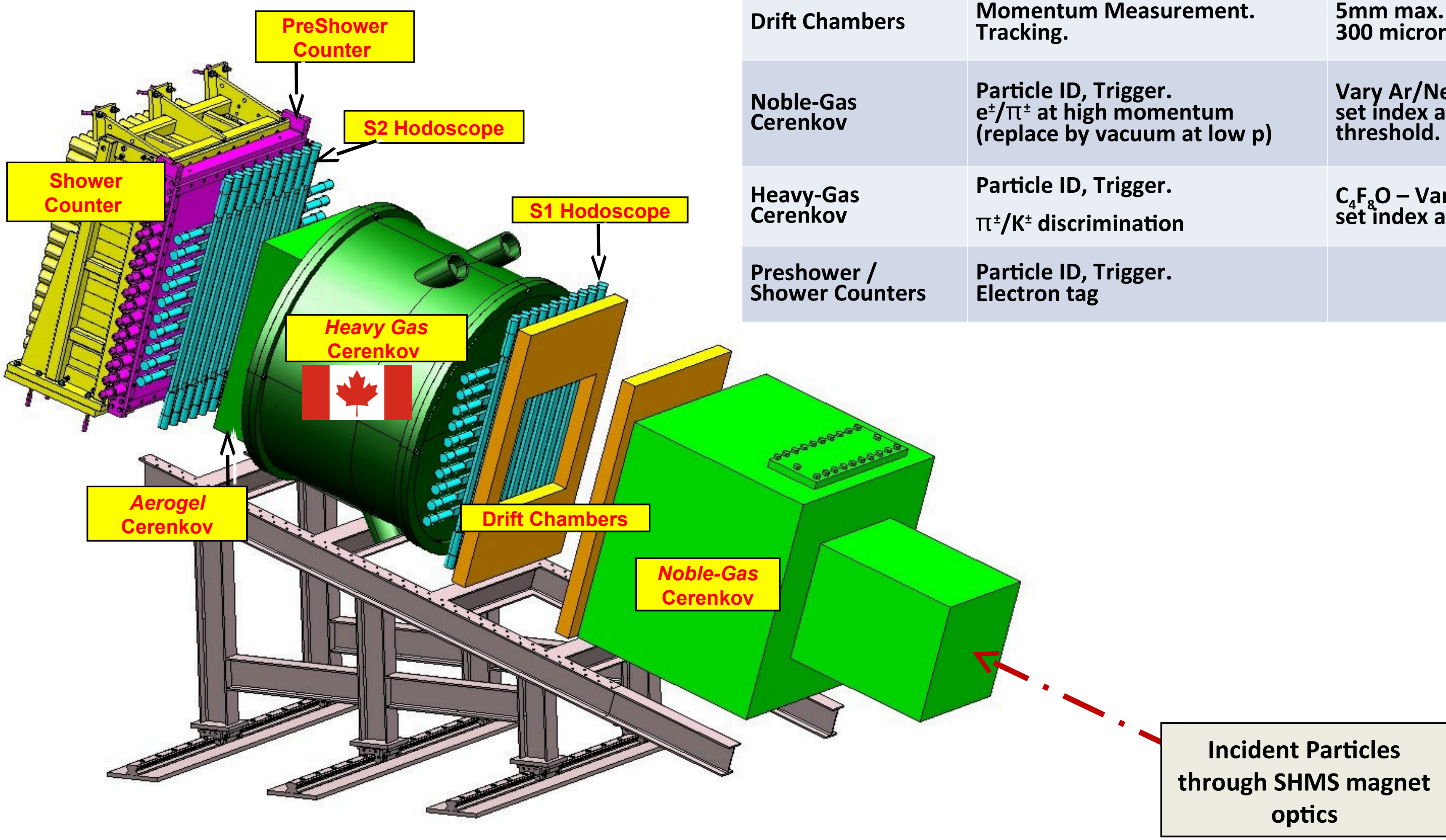


Upgraded Hall C has some similarity to SLAC End Station A, where the quark substructure of proton was discovered in 1968.



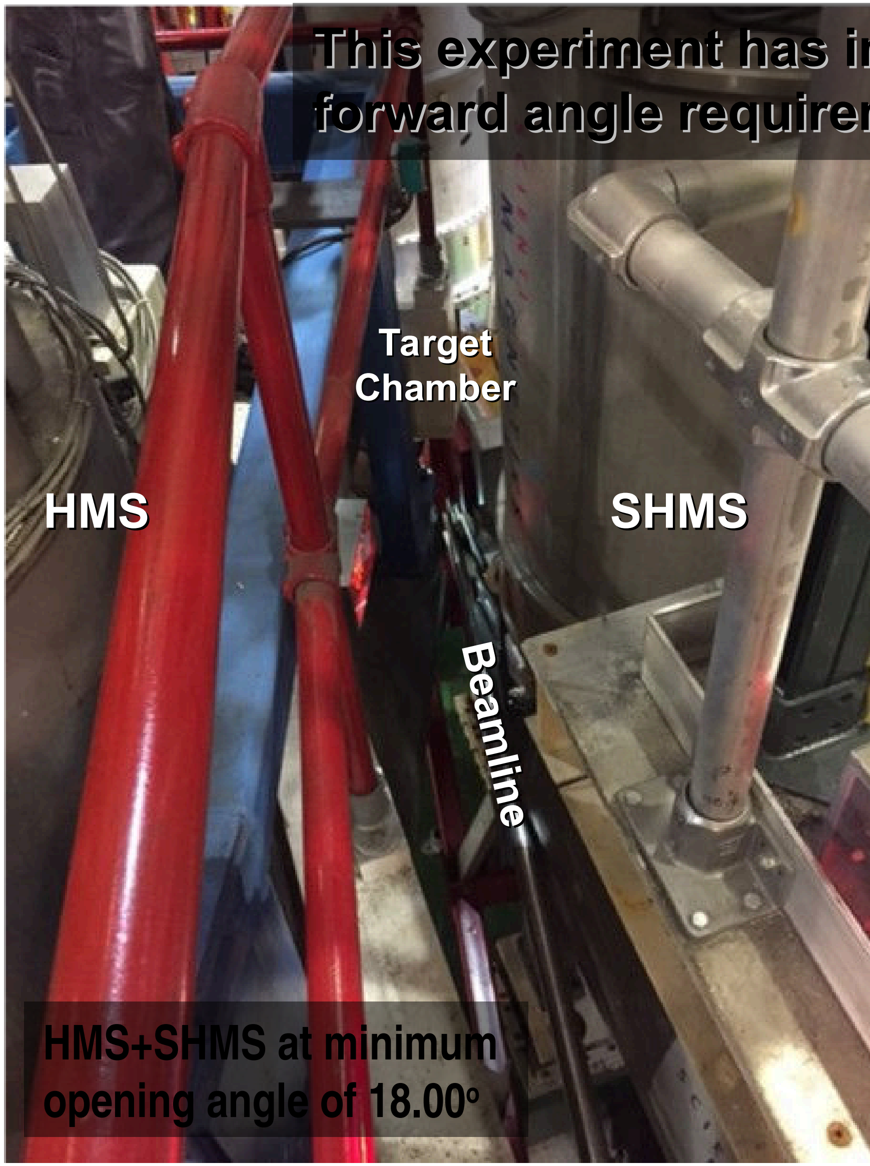
SHMS Focal Plane Detector System

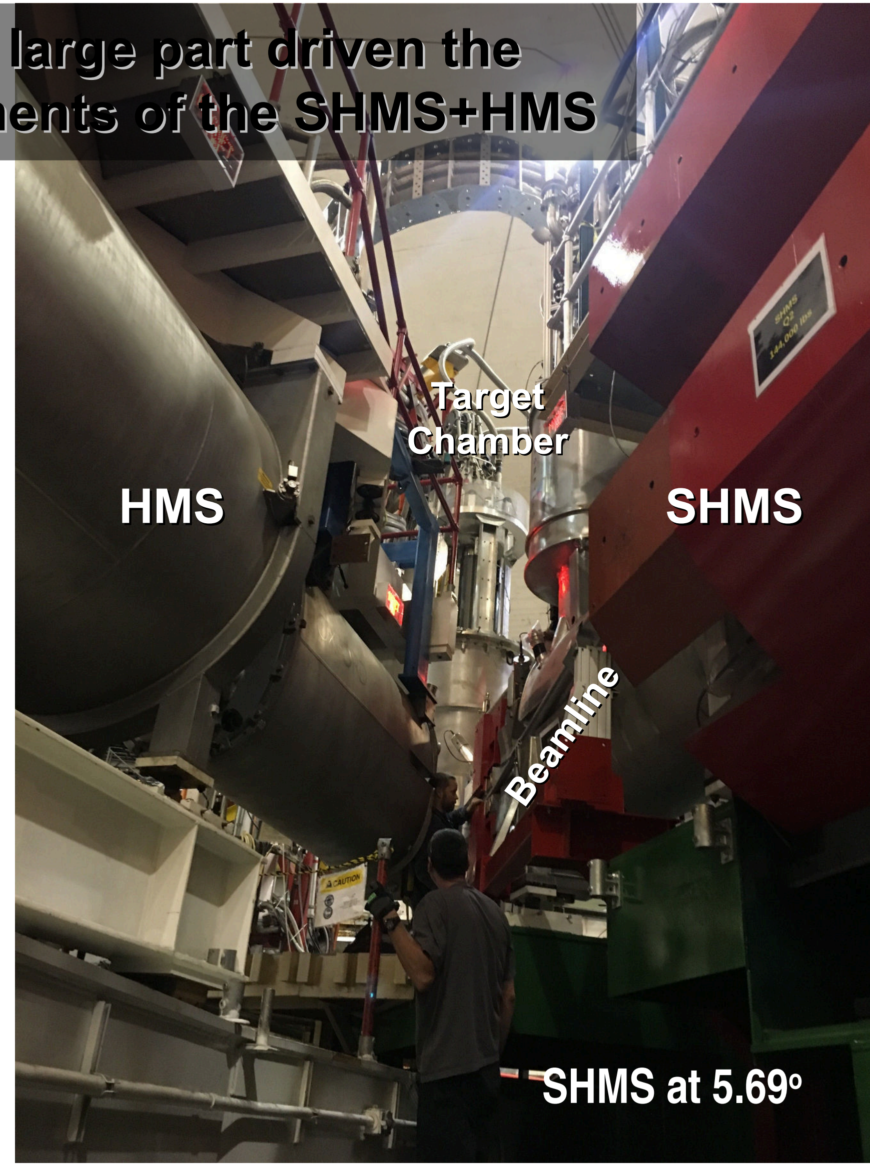
DETECTOR	PURPOSE	NOTES
S1XY, S2XY Hodoscopes	Lowest-level Trigger. Time reference	
Drift Chambers	Momentum Measurement. Tracking.	5mm max. drift 300 micron resolution
Noble-Gas Cerenkov	Particle ID, Trigger. $e^{\pm}/\pi^{\pm}$ at high momentum (replace by vacuum at low p)	Vary Ar/Ne mixture to set index 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	



HMS and SHMS during Data Taking

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





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

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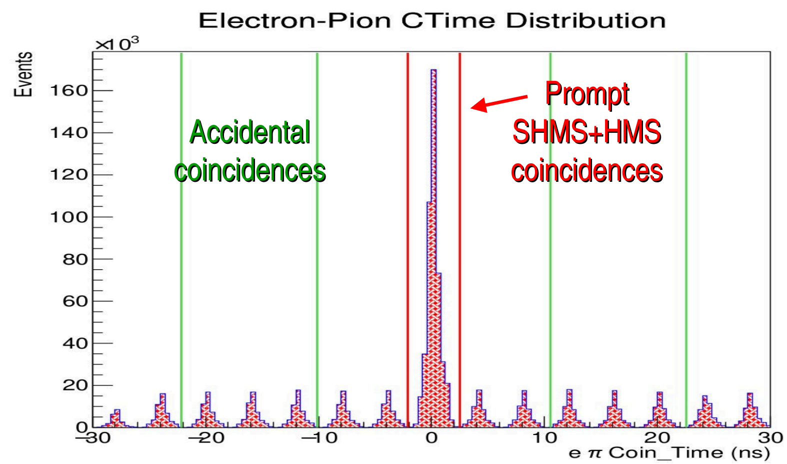
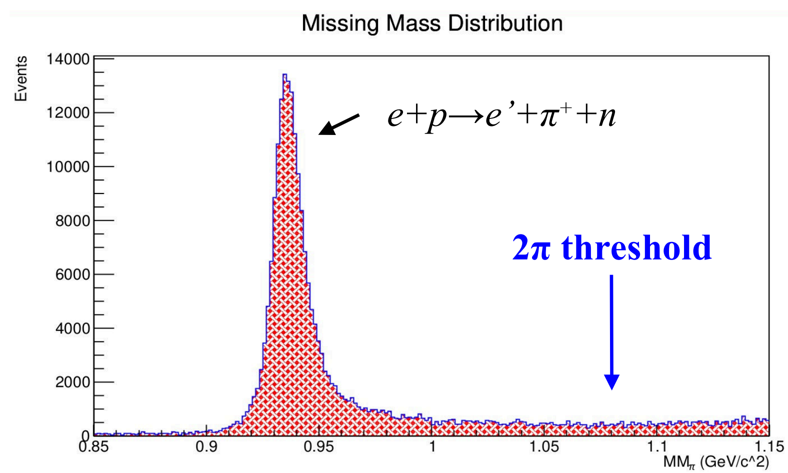
Coincidence measurement between charged pions in SHMS and electrons in HMS.

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

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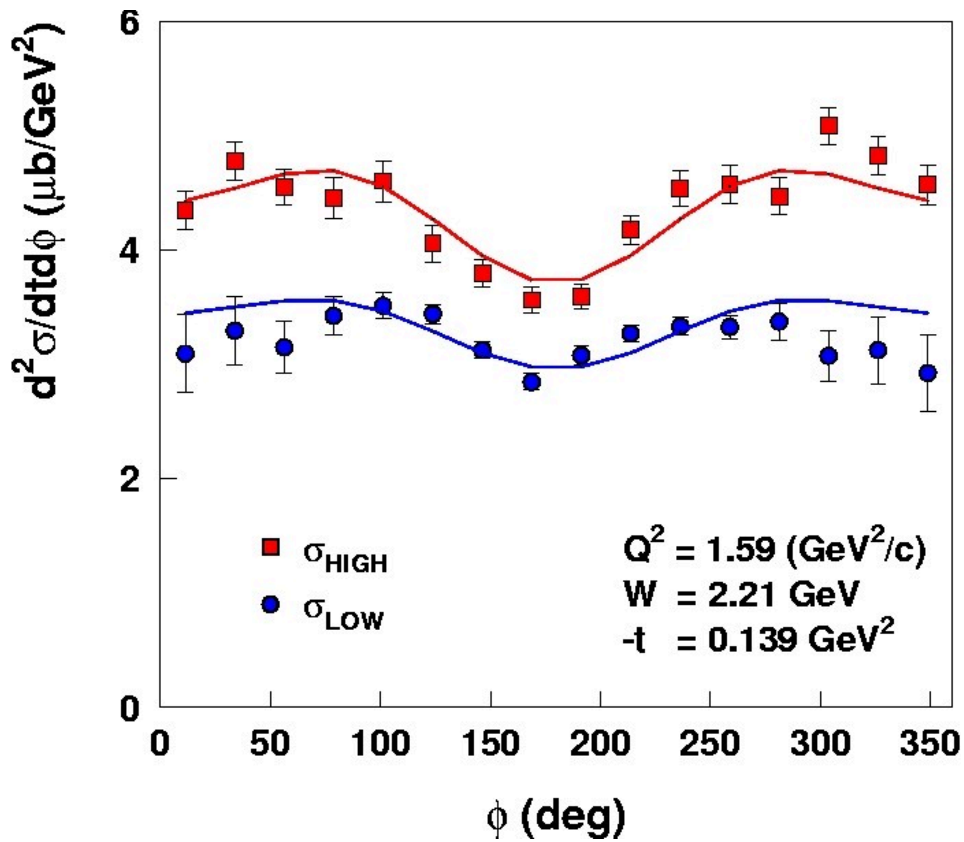
The different pion arm (SHMS) settings are combined to yield φ-distributions for each *t*-bin

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

- 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 $1/\Delta\varepsilon$ error amplification in σ_L**
  - Careful attention must be paid to spectrometer acceptance, kinematics, efficiencies, …



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

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L/T–separation error propagation

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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_π extraction are R and $\Delta\varepsilon$

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

Magnetic Spectrometer Calibrations

- **Similarly to Fπ–2, we 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.**
  - Fπ–2 beam energy and spectrometer momenta determined to <0.1%.
  - Spectrometer angles <0.5 mr.
  - Fπ–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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Extract $F_\pi(Q^2)$ from JLab σ_L data

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

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VGL Regge Model:

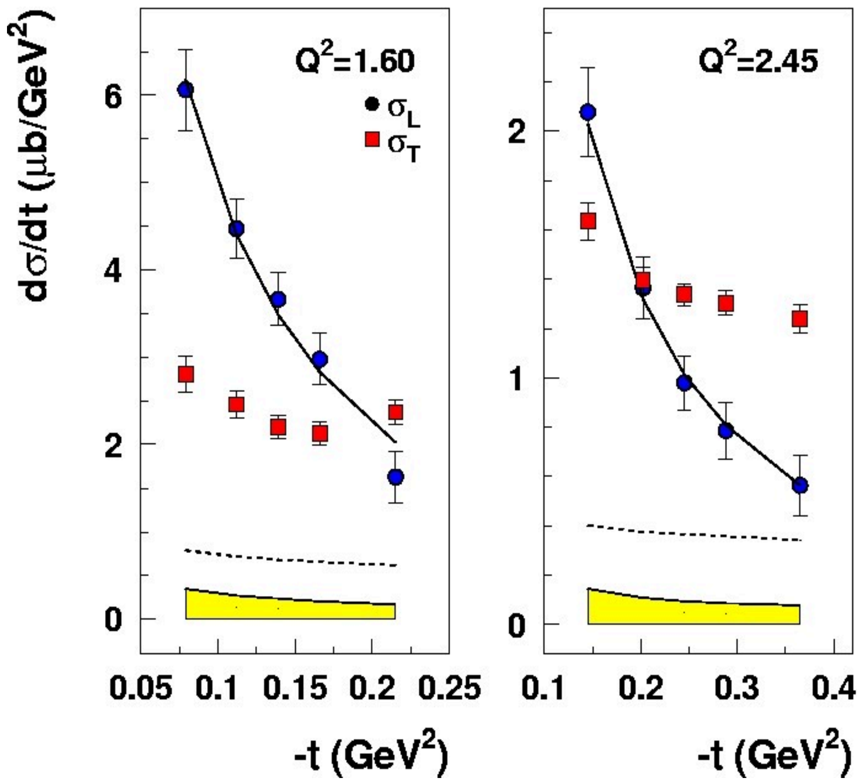
- Feynman propagator $\left(\frac{1}{t - m_\pi^2}\right)$

  replaced by π and ρ Regge propagators.
  - Represents the exchange of a <u>series</u> of particles, compared to a <u>single</u> 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**

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

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.

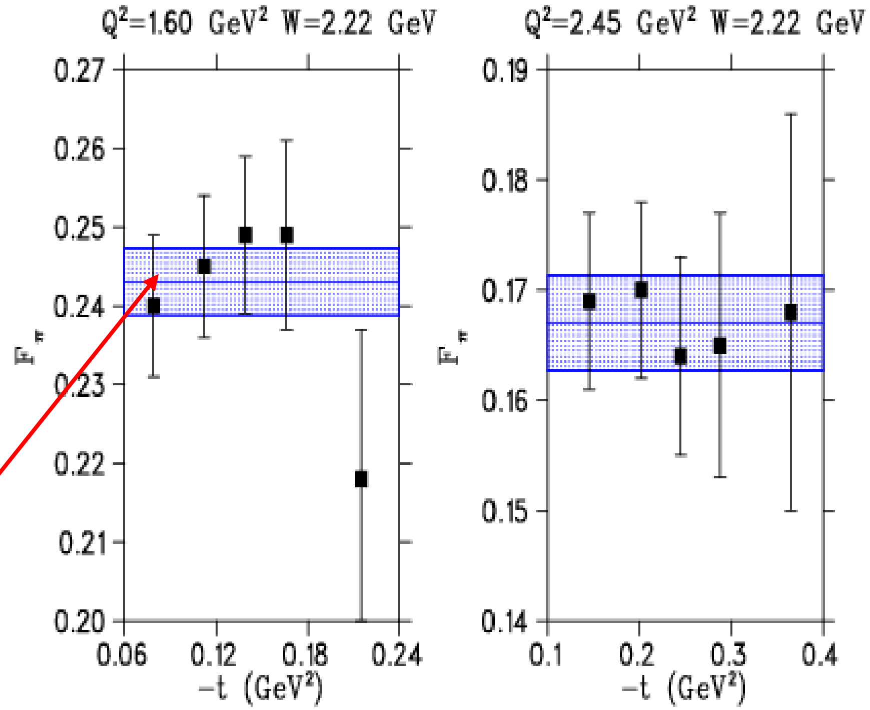
Λ_π^2=0.513, 0.491 GeV^2, Λ_ρ^2=1.7 GeV^2.

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.



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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π^-/π^+ data to check t–channel dominance

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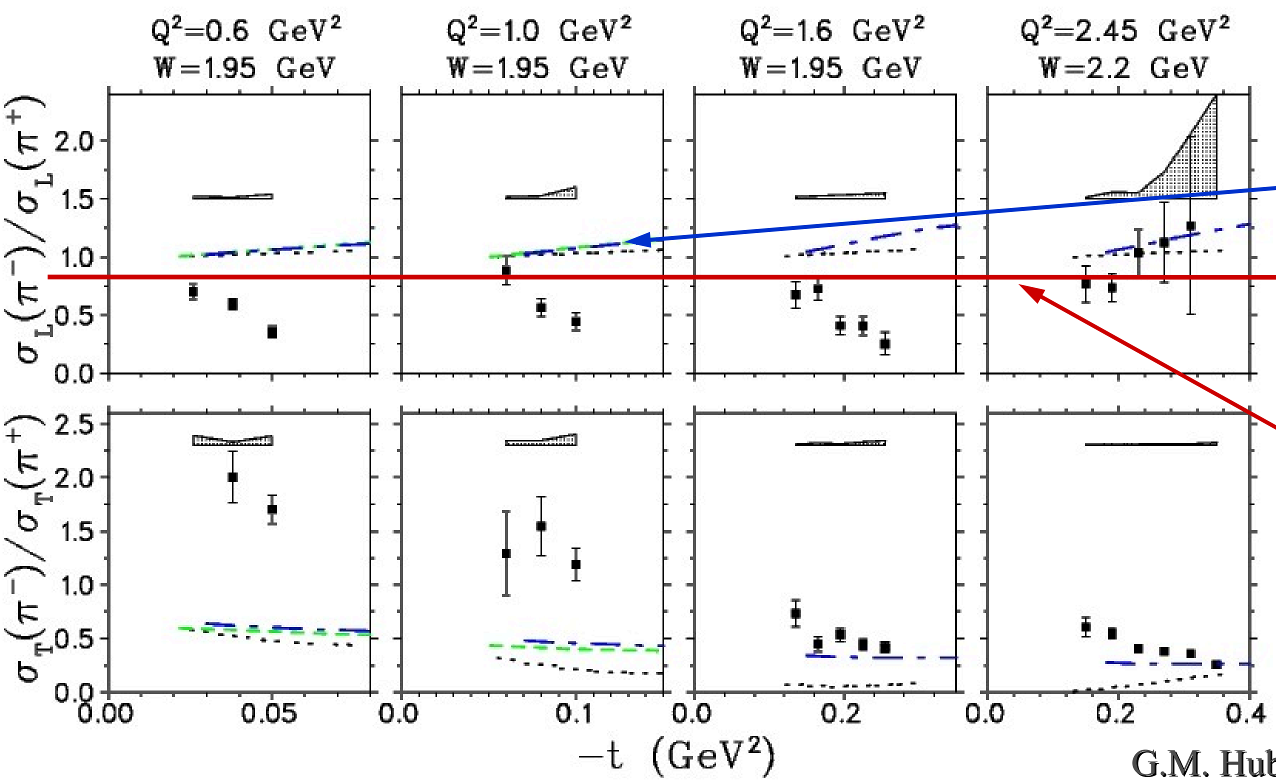
- π^+ t–channel diagram is purely isovector (G-parity conservation).

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

- Isoscalar backgrounds (such as $b_1(1235)$ contributions to t-channel) will dilute ratio.

- **Qualitatively in agreement with our analysis:**
  - We found evidence for small additional contribution to σ_L at W=1.95 GeV not taken into account by the VGL model.
- We found no evidence for this contribution at W=2.2 GeV.



Vrancx-Ryckebusch Model:

- VR extend VGL with hard DIS process of virtual photons off nucleons.

[PRC **89**(2014)025203]

R_L=0.8 consistent with $|A_S/A_V|$<6%.

G.M. Huber, et al., PRL **112**, 182501 (2014)

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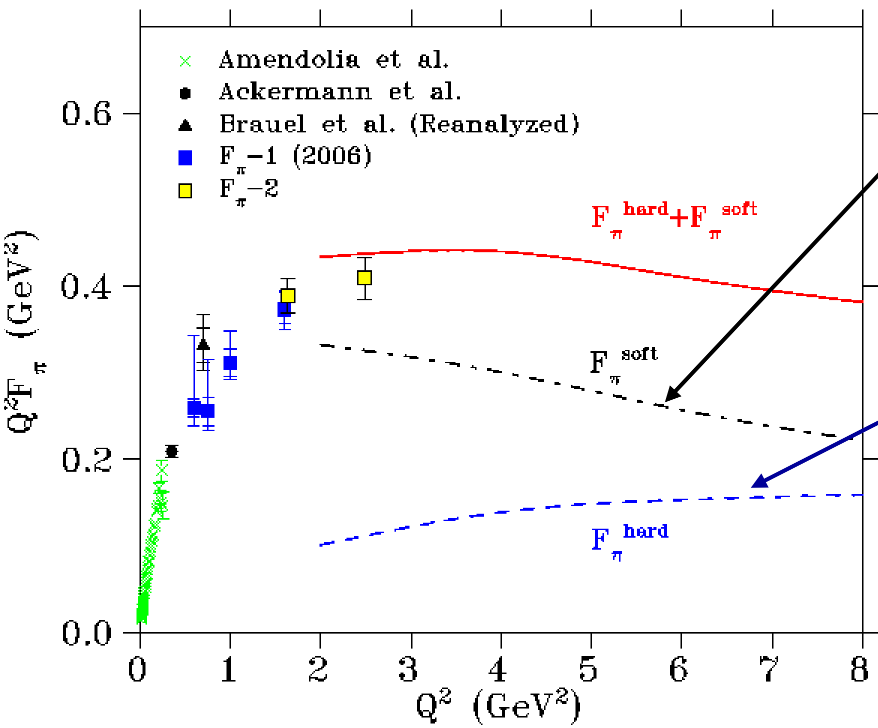
Current Experimental Status

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.

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Current and Projected F_π Data

University of Regina

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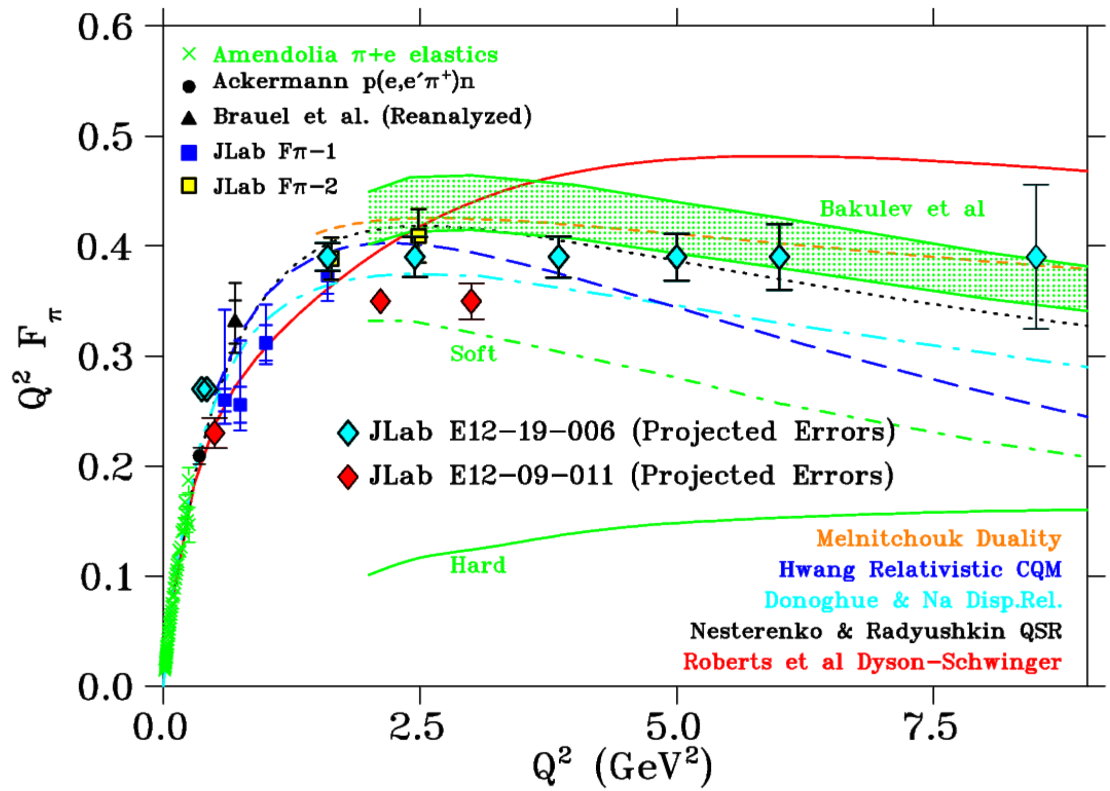
SHMS+HMS will allow measurement of F_π to much higher Q^2.

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.



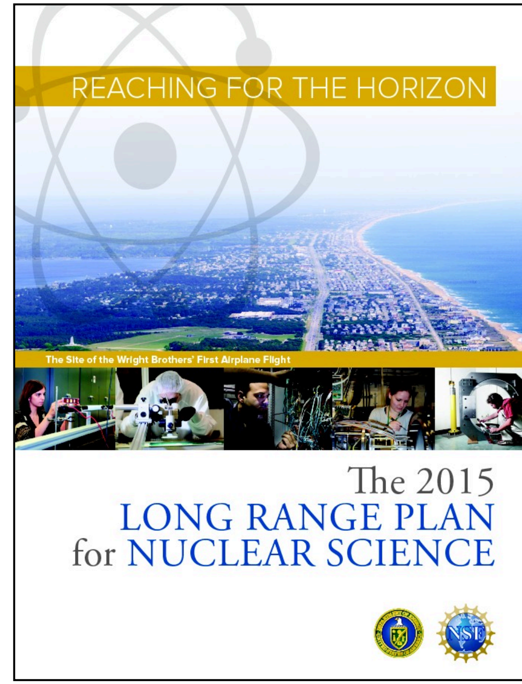
The ~10% measurement of F_π at Q^2=8.5 GeV^2 is at higher $-t_{min}$=0.45 GeV^2

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

Endorsement in USA Long Range Plan

Section 2.1.1: The Quark Structure of Hadrons

- The pion plays a unique role in nature. It is the lightest quark system… It is also the particle responsible for the long range character of the strong interaction that binds the atomic nucleus together.
- If [chiral symmetry] were completely true, the pion would have no mass.
- The pion is seen as key to confirm the mechanisms that dynamically generate nearly all of the mass of hadrons and central to the effort to understand hadron structure.



- **With such strong theoretical motivation, the study of the pion form factor is one of the flagship goals of the JLab 12–GeV Upgrade.**
- **The SHMS (in Hall C) will nearly quadruple the momentum transfer over which the pion form factor is known.**
- **These measurements will probe a broad regime in which the phenomenology of QCD begins to transition from large– to small–distance–scale behavior.**

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Measurement of K^+ Form Factor

- Similar to π^+ form factor, elastic K^+ scattering from electrons used to measure charged kaon form factor at low Q^2

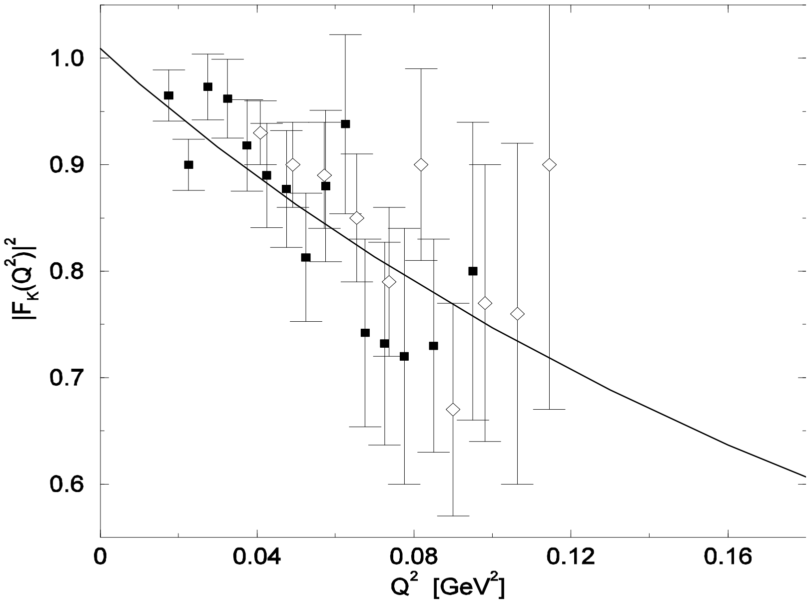
  [Amendolia, et al., PL **B178** (1986) 435]

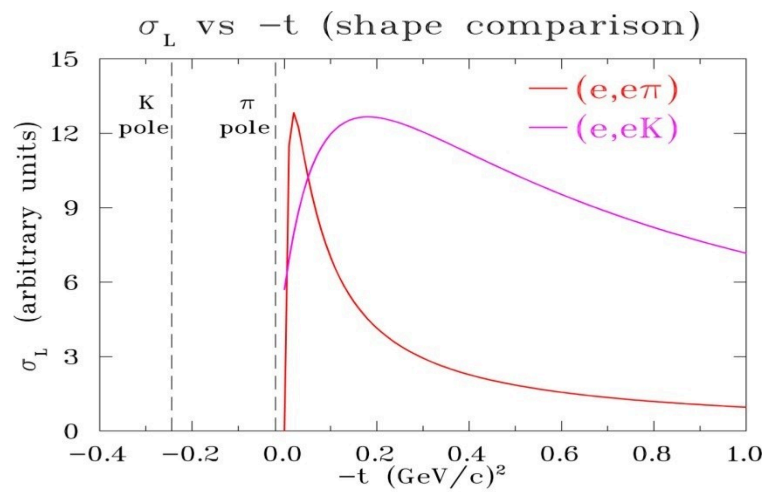
- Can "kaon cloud" of the proton be used in the same way as the pion to extract kaon form factor via ***p(e,e'K⁺)Λ*** ?

- Kaon pole further from kinematically allowed region

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{\left(t-m_K^2\right)} \, g_{K\Lambda N}^2(t) \, F_K^2(Q^2,t)$$

- Many of these issues are being explored in JLab E12–09–011





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$p(e,e'K^+)\Lambda(\Sigma^0)$ Experiment

University of Regina

Isolate Exclusive Final States via Missing Mass

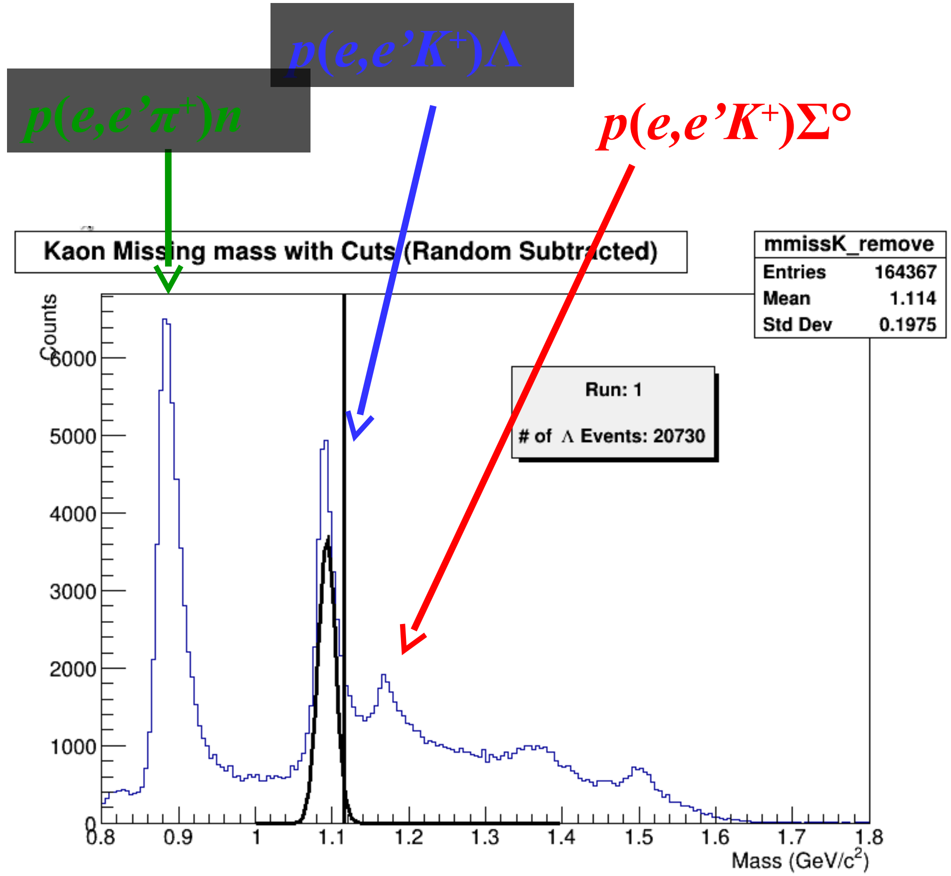
$$M_X = \sqrt{(E_{det} - E_{init})^2 - (p_{det} - p_{init})^2}$$

- Spectrometer coincidence acceptance allows for simultaneous studies of Λ and $\Sigma°$ channels.

- Kaon-pole dominance test through

$$\frac{\sigma_L(\gamma^* p \to K^+\Sigma^0)}{\sigma_L(\gamma^* p \to K^+\Lambda^0)}$$

- Should be similar to ratio of $g^2_{pK\Lambda}/g^2_{pK\Sigma}$ coupling constants if t-channel exchange dominates.



Online: Q^2=3.0 GeV^2 , W=2.32, high ε, θ_{Kq}=+3.0

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Kaon Form Factor Experiment Goals

- **Measure the –*t* dependence of the $p(e,e'K^+)\Lambda,\Sigma°$ cross section at fixed Q^2 and W>2.5 GeV to search for evidence of K^+ pole dominance in σ_L**
  - Separate the cross section components: L, T, LT, TT
  - First L/T measurement above the resonance region in K^+ production
- **<u>If warranted by the data</u>, extract the Q^2 dependence of the kaon form factor to shed new light on QCD's transition to quark–gluon degrees of freedom.**

- **<u>Even if we cannot extract the kaon form factor</u>, the measurements are important.**
  - $K^+\Lambda$ and $K^+\Sigma^\circ$ reaction mechanisms provide valuable information in our study of hadron structure
  - Flavor degrees of freedom provide important information for QCD model building and understanding of basic coupling constants

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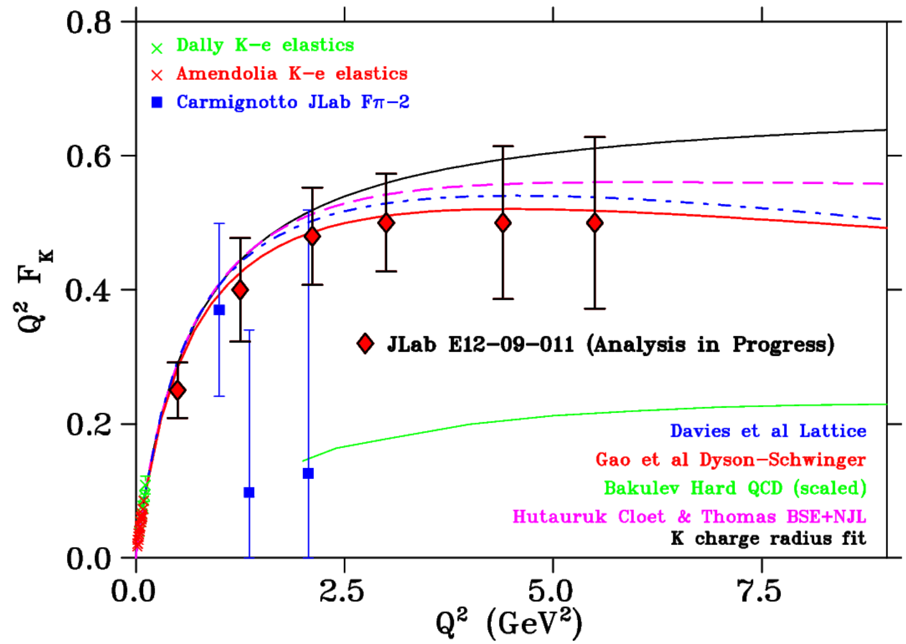
Projected Uncertainties for K^+ Form Factor

- 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.

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



Extraction of F_K from Q^2>4 GeV^2 data is more uncertain, due to higher $-t_{min}$

Partially completed as an early SHMS commissioning experiment: LT–separation. (E12–09–011: T. Horn, G. Huber and P. Markowitz, spokespersons)

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Extension of Studies to EIC

- **Physics Motivation:**
  - JLab measurements have led to a renewed recognition of importance of π^+ and K^+ structure studies for understanding QCD's transition from "weak" and "strong" domains, and understanding DCSB's role in generating hadron properties
  - Definite answers to these questions require high Q^2 data well beyond JLab's reach
  - The Electron–Ion Collider (EIC) may provide this reach
- **Experimental Issues:**
  - The DEMP cross section is small, can the exclusive $p(e,e'\pi^+)n$ channel be cleanly identified?
    - Count rates, Detector Acceptances?
  - Is the detector resolution sufficient to reliably reconstruct (Q^2,W,t)?
  - How to measure the longitudinal cross section $d\sigma_L/dt$ needed for form factor extraction?

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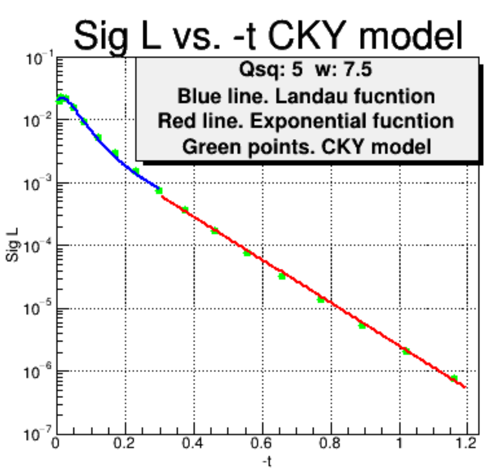
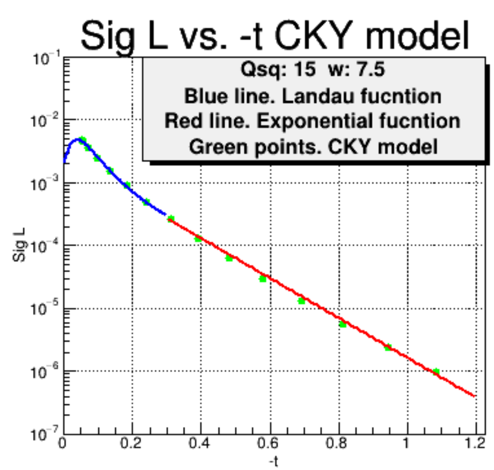
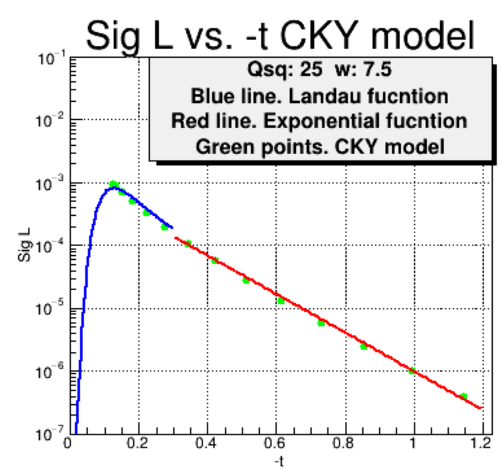
DEMP Event Generator

- We initially looked at the $p(e,e'\pi^+)n$ model by C. Weiss, V. Guzey (2008), which is an extrapolation of a soft model cross section to high Q^2, assuming QCD scaling behavior and $W^2 \gg Q^2$.
  - However, we need to generate many events with $W^2 \sim Q^2$, where this model is unreliable
- Regge-based $p(e,e'\pi^+)n$ model of *T.K. Choi, K.J. Kong, B.G. Yu (CKY) arXiv: 1508.00969* seemed better behaved over a wide kinematic range.
  - Created a MC event generator by parameterizing CKY σ_L, σ_T for $5<Q^2$ (GeV^2)<35 $2.0<W$ (GeV)<10 $0<-t$ (GeV^2)<1.2







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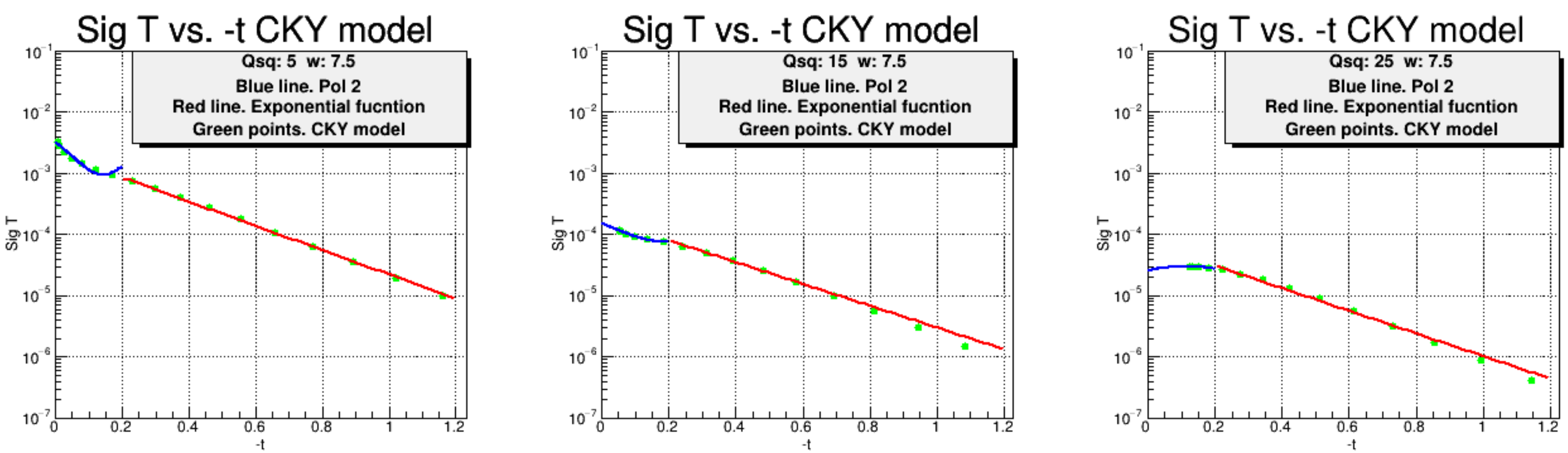

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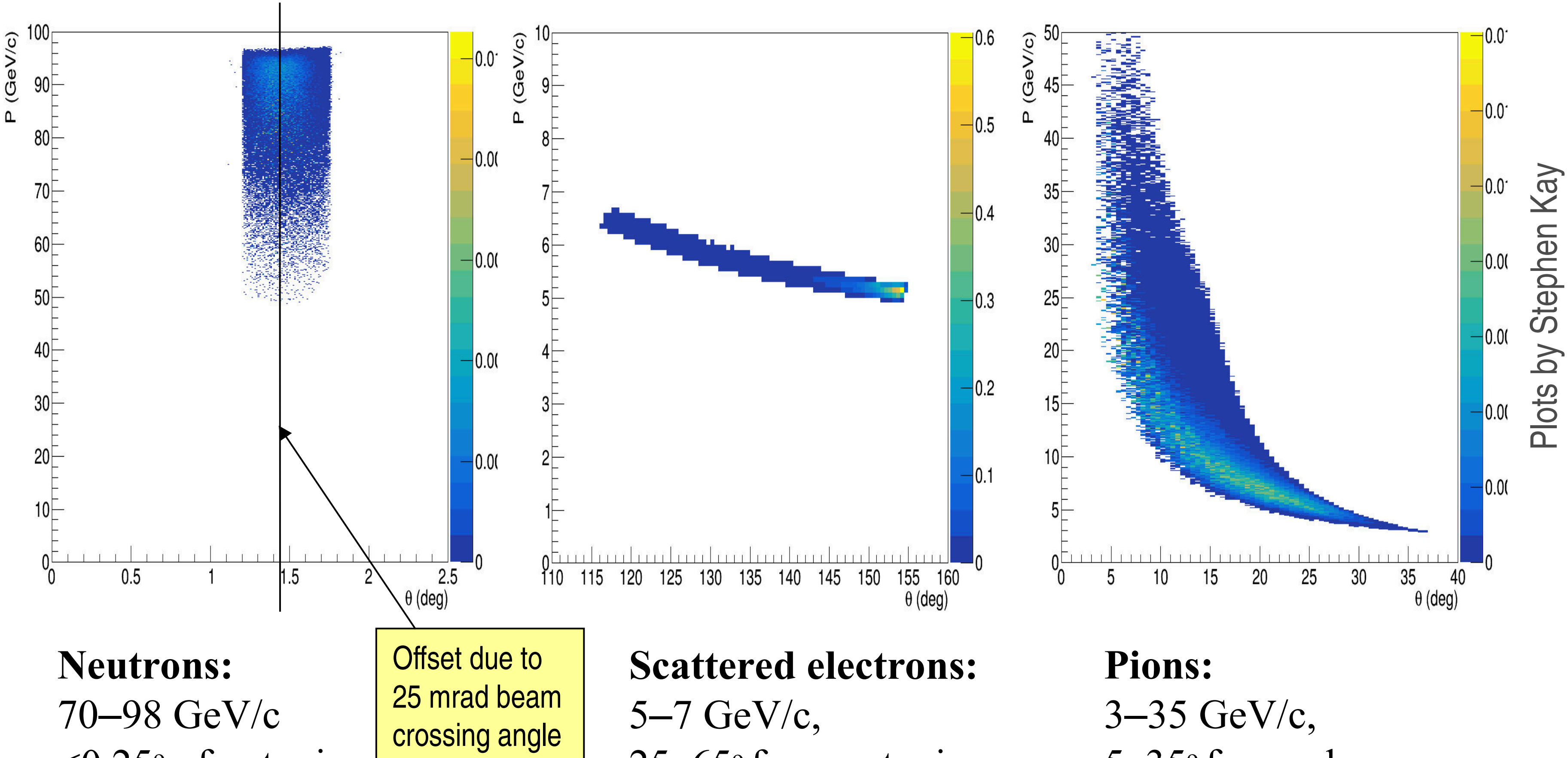
DEMP n, e', π^+ Acceptance for $-t$<0.5 GeV^2

5(e$^-$) x 100(p) GeV Collisions → E_{cm}=44.7 GeV



Neutrons:
70–98 GeV/c
<0.25^o of outgoing proton beam

Scattered electrons:
5–7 GeV/c,
25–65^o from outgoing e beam

Pions:
3–35 GeV/c,
5–35^o from p beam

Assure exclusivity of *p(e,e'π^+n)* reaction by detecting neutron

e–π–n triple coincidences, weighted by cross section, truth info

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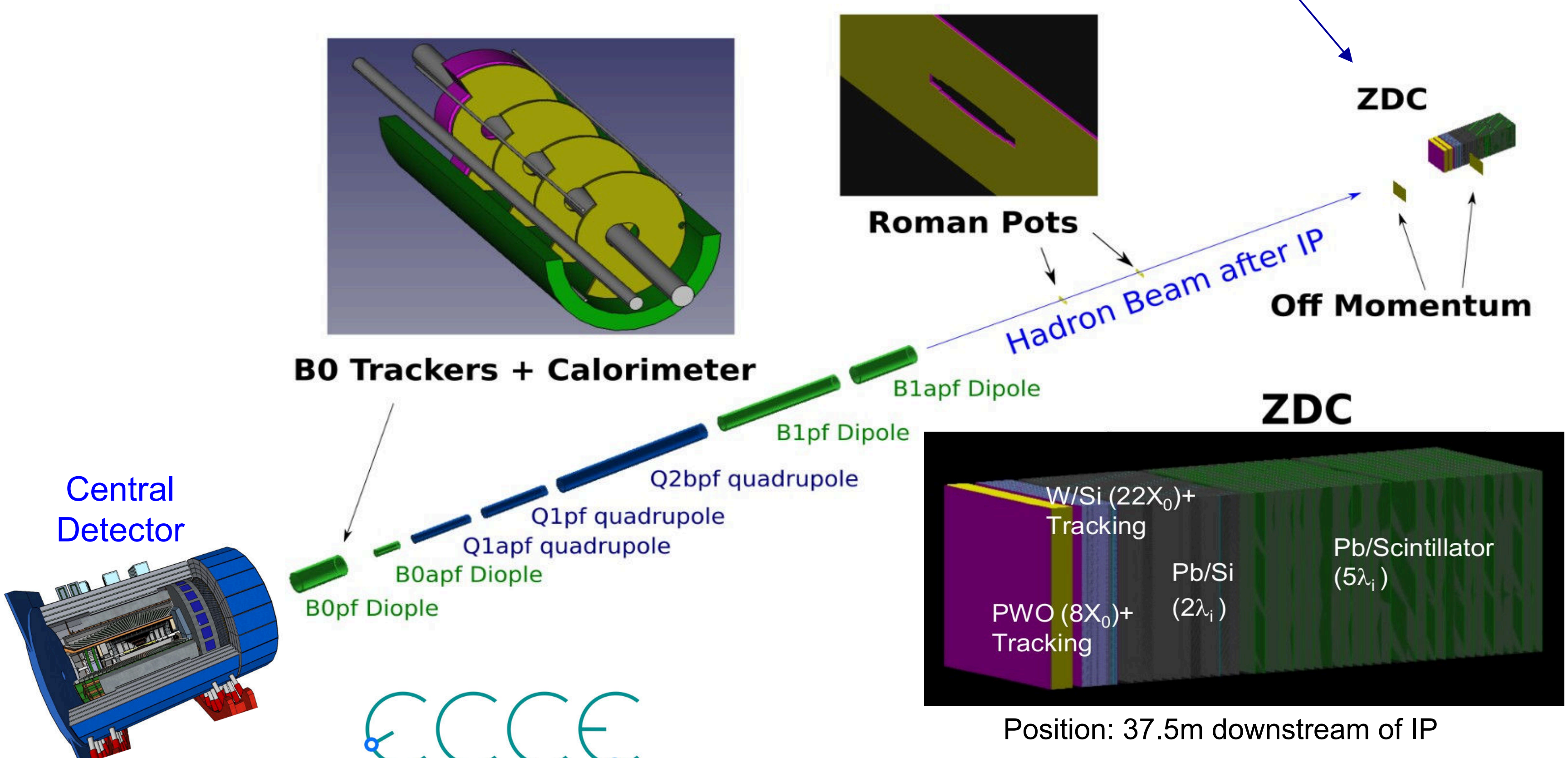
EIC Far Forward Detectors

- Crucial to cleanly separate exclusive $p(e,e'\pi^+n)$ process from competing inclusive reactions
- EIC measurement <u>impossible</u> unless recoil neutron (very high momentum, <1° from outgoing hadron beam) is efficiently detected
- **High quality Zero Degree Calorimeter (ZDC) essential**



Position: 37.5m downstream of IP

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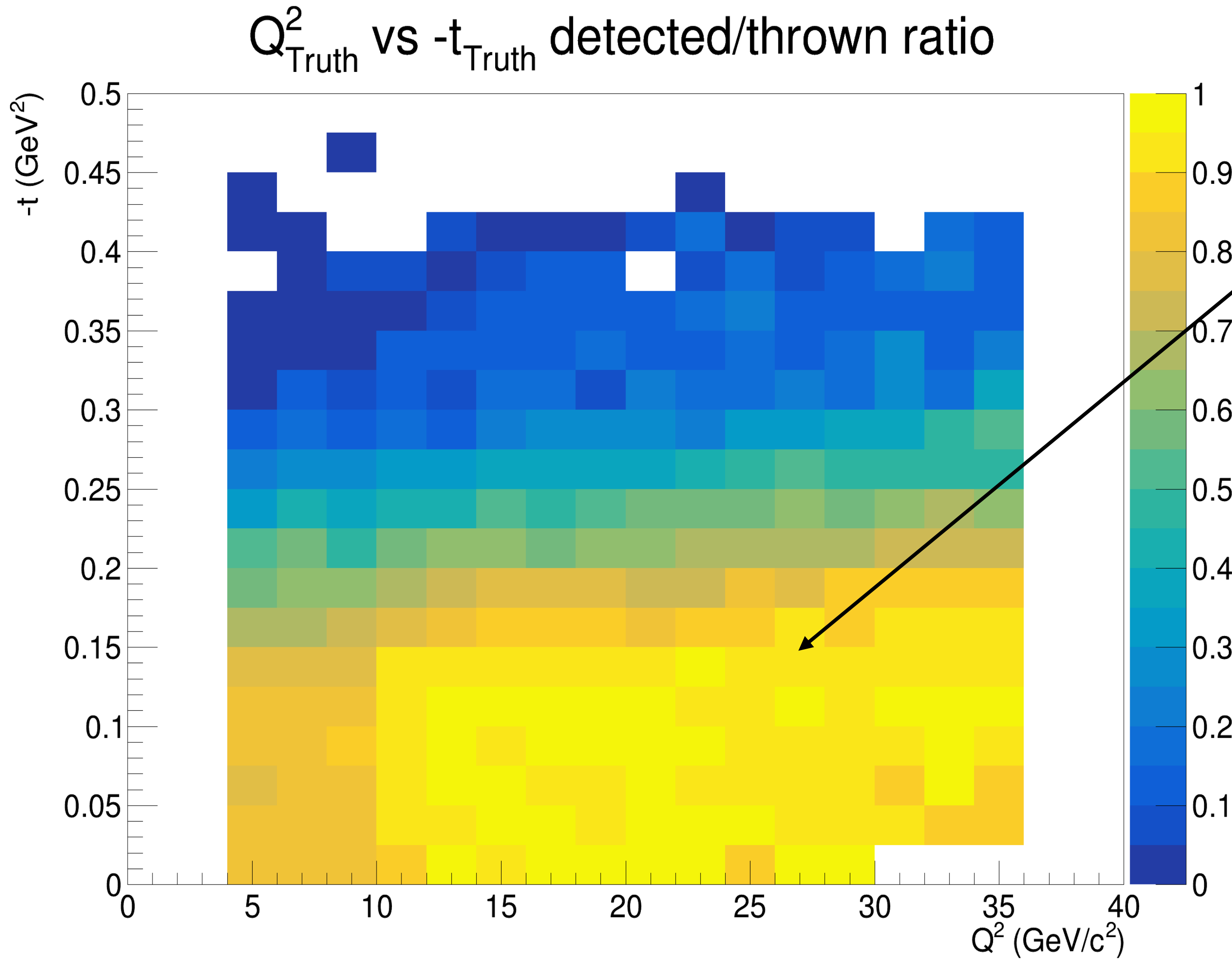
Detection efficiency per (Q^2,t) bin



Detection efficiency best in crucial low $-t$ region

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Plot by Stephen Kay

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

- **Can we isolate a clean sample of exclusive $p(e,e'\pi^+n)$ events by detecting the neutron, or are other requirements needed in addition?**
- For a source of background $p(e,e'\pi^+)X$ events we used the EIC SIDIS generator written by Tianbo
  - located on JLab farm at /work/eic/evgen/SIDIS_Duke/e5p100
- Since the generator does not output the neutron momentum, we use the missing momentum as a proxy

- The SIDIS and DEMP event generators are used to create LUND format files
- Generated events are fed into ECCE Geant4 simulation to study acceptance and resolution requirements

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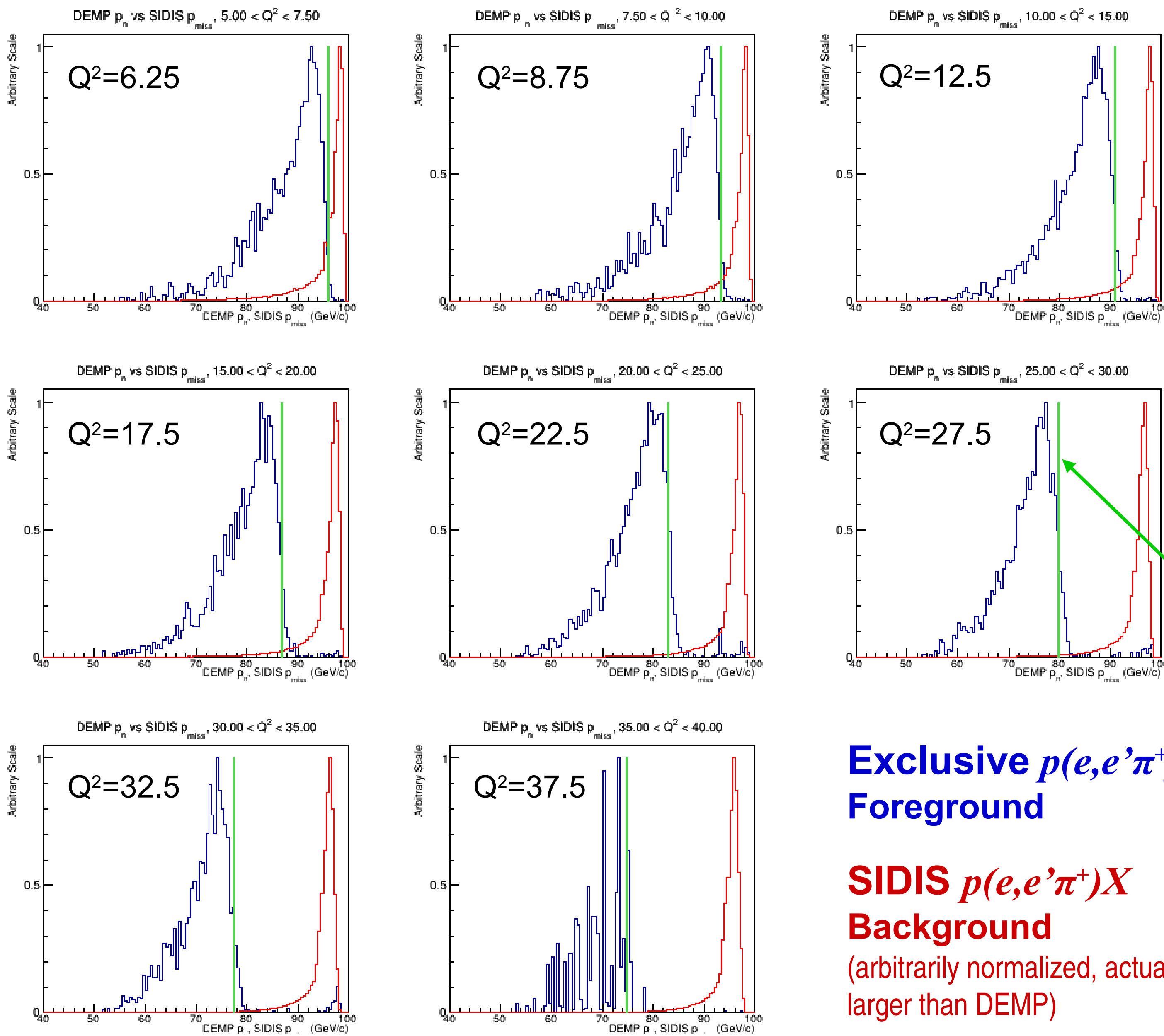
p_{miss} cut vs Q^2–bin

$$p_{miss} = \left| \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+} \right|$$



Plots by Stephen Kay

Cut value
(varies w/Q^2)

Exclusive *p(e,e'π⁺)n*
Foreground

SIDIS *p(e,e'π⁺)X*
Background
(arbitrarily normalized, actually much larger than DEMP)

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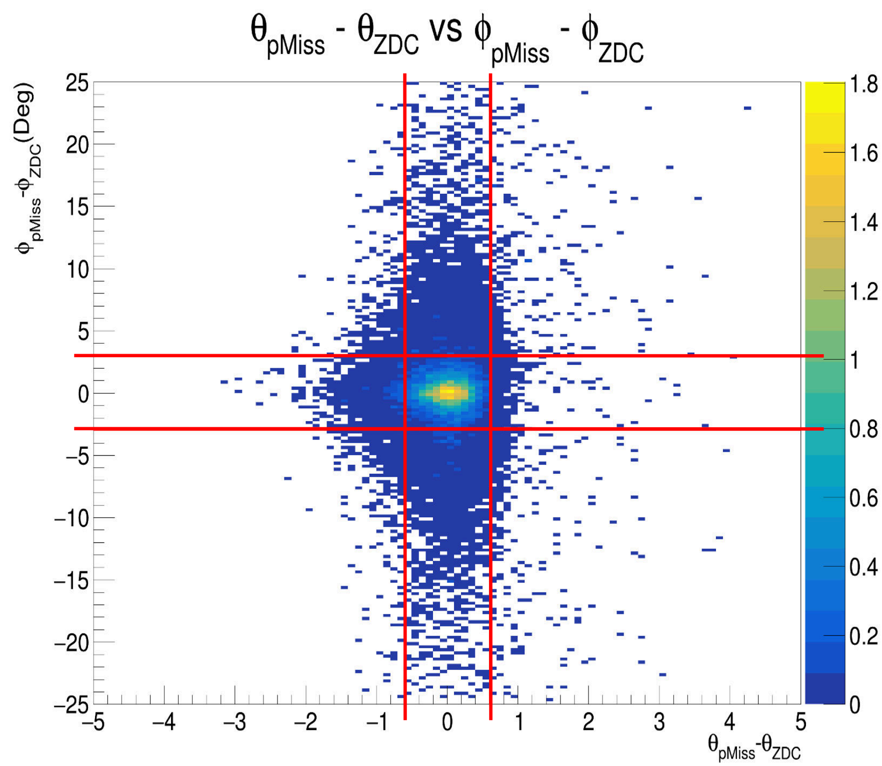
Another Cut to Remove Background

- **Make use of high angular resolution of Zero Degree Calorimeter (ZDC) to further reduce background events**
  - Compare hit (θ,φ) positions of energetic neutron on ZDC to calculated position from p_{miss}
  - If no other particles are produced (i.e. exclusive reaction) these quantities should be highly correlated
  - Energetic neutrons from inclusive background processes will be less correlated, since additional lower energy particles are produced



Differences between hit and calculated neutron positions on ZDC for DEMP events

Cuts applied: $|\Delta\theta|<0.6^o$ $|\Delta\varphi|<3.0^o$ in addition to triple coincidence cuts

Plot by Stephen Kay

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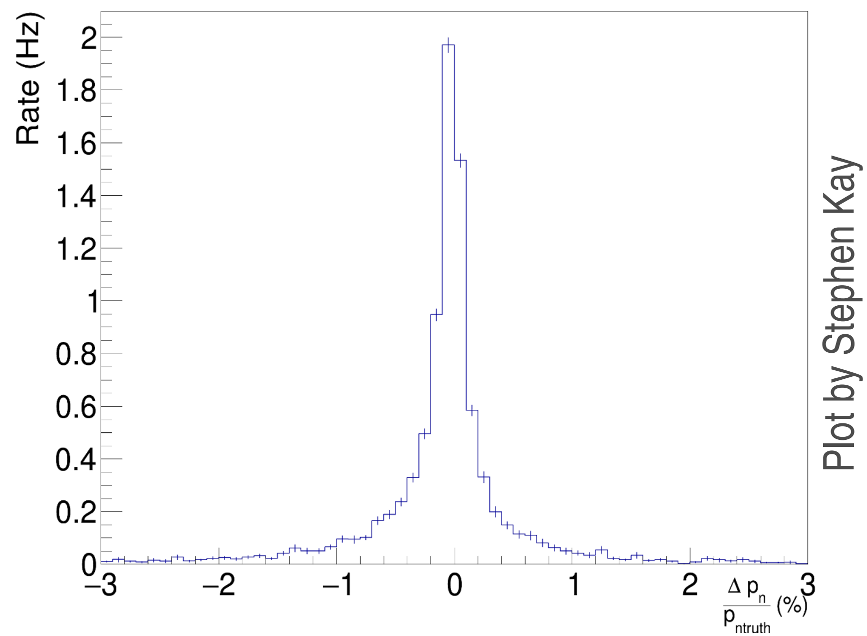
Improving *neutron* reconstruction resolution

- **Exclusive $p(e,e'\pi^+n)$ event selection requires exactly one high energy ZDC hit as a veto**
- Since the neutron hit position from ZDC is known to high accuracy, this information can be used to "correct" the missing momentum track $p_{miss} = \left|\vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}\right|$
- **Use ZDC hit positions θ_{ZDC}, φ_{ZDC} instead of calculated θ_{miss}, φ_{miss} angles**
- E_{miss} also adjusted to reproduce neutron mass
- After these adjustments, the neutron track momentum was reconstructed to <1% of "true" momentum



$\Delta p_n = (p_{n\ track} - p_{n\ truth}) / p_{n\ truth}$

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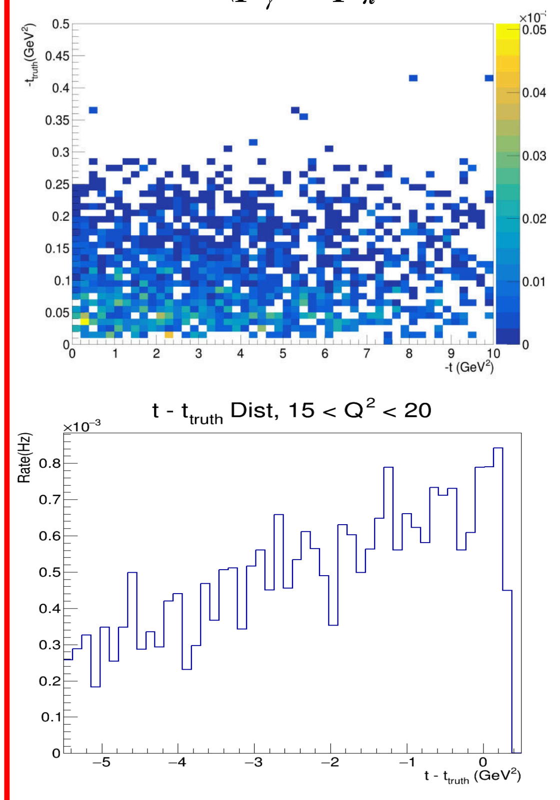
Reconstructing Mandelstam *t*

- Extraction of pion form factor from $p(e,e'\pi^+n)$ data requires *t* to be reconstructed accurately, as we need to verify dominance of the *t*–channel process from the dependence of $d\sigma/dt$ *upon t*

$t_{reconst}(x)$ vs $t_{truth}(y)$

$t_{reconstr} - t_{truth}$

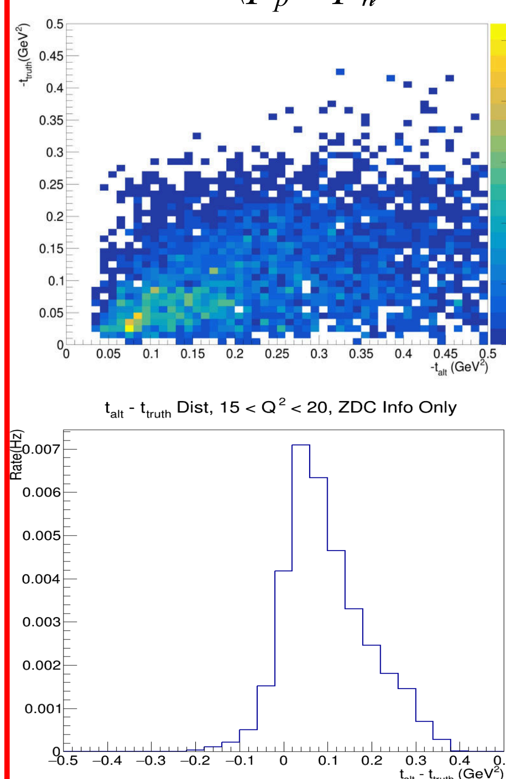
$t=(p_{\gamma*}-p_{\pi})^2$



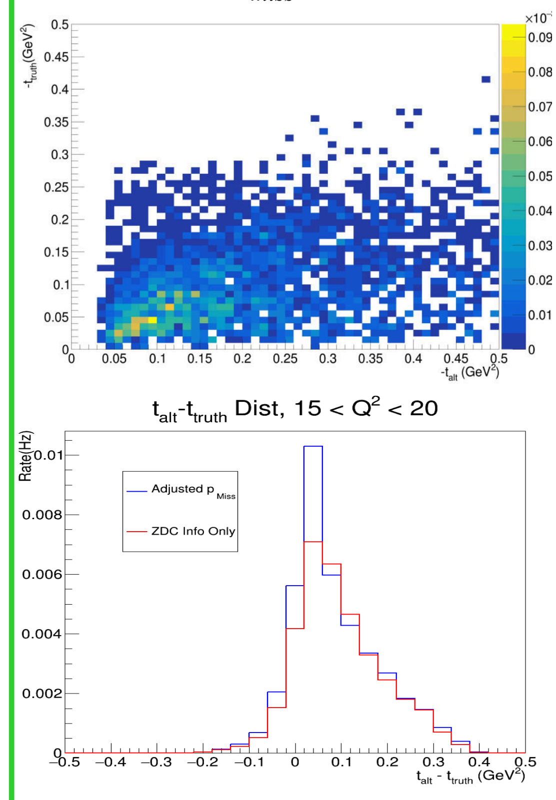
Unusable *t* reconstruction

$\sigma_{t\ reconstr}$=3.4 GeV²

$t=(p_p-p_n)^2$



Correct p_{miss} w/ ZDC(θ,φ)



Best *t* reconstruction

$\sigma_{t\ reconstr}$=0.073 GeV²

Plots by Stephen Kay

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Separating σ_L from σ_T in e–p Collider

$$\varepsilon = \frac{2(1-y)}{1+(1-y)^2} \quad \text{where the fractional energy loss} \quad y = \frac{Q^2}{x\left(s_{tot} - M_{N^2}\right)}$$

- **Systematic uncertainties in σ_L are magnified by $1/\Delta\varepsilon$.**
  - **Desire $\Delta\varepsilon > 0.2$.**
- **To access $\varepsilon < 0.8$, one needs $y > 0.5$.**
  - This can only be accessed with small s_{tot},

    i.e. low proton collider energies (5–15 GeV), where luminosities are too small for a practical measurement.
- **A conventional L–T separation is impractical, need some other way to identify σ_L.**

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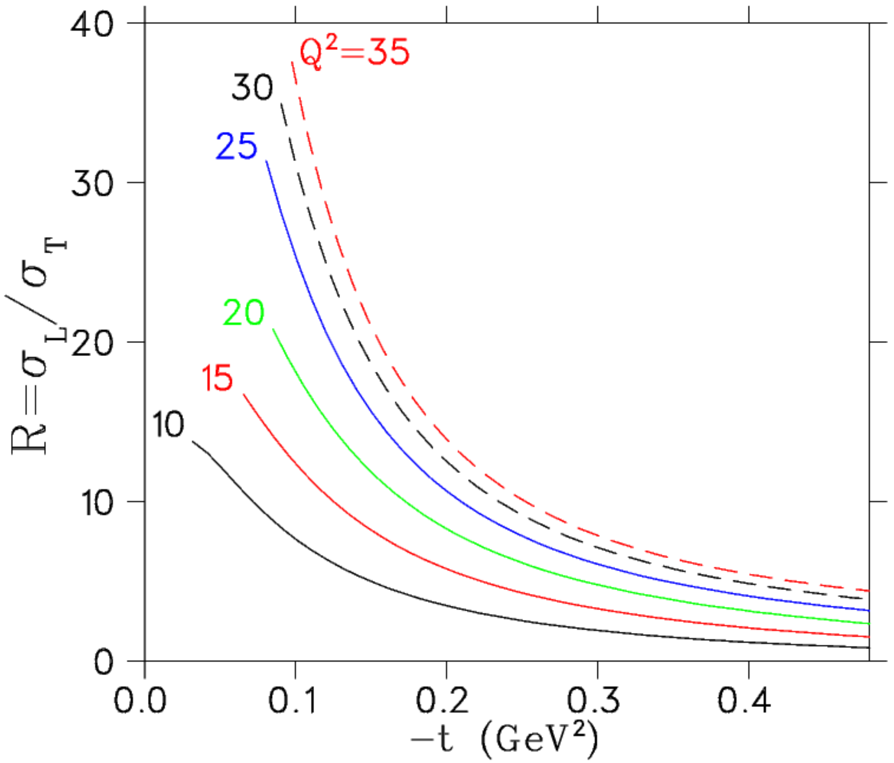
Isolate $d\sigma_L/dt$ using a Model

- In the hard scattering regime, QCD scaling predicts $\sigma_L \propto Q^{-6}$ and $\sigma_T \propto Q^{-8}$.
- At high Q^2, W accessible at EIC, phenomenological models predict $\sigma_L \gg \sigma_T$ at small $-t$.
- The most practical choice might be to use a model to isolate dominant $d\sigma_L/dt$ from measured $d\sigma_{UNS}/dt$.
- **In this case, it is very important to confirm the validity of the model used.**



- T. Vrancx, J. Ryckebusch, PRC **89**(2014)025203.
- Predictions are for ε>0.995 Q^2,W kinematics shown earlier.

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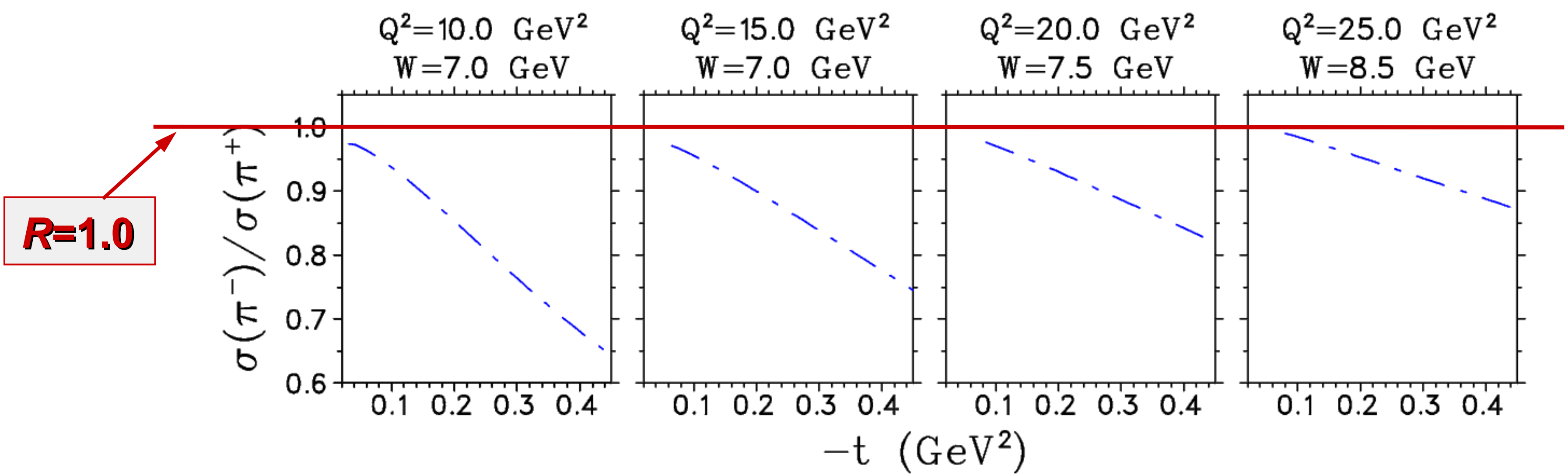
Using π^-/π^+ ratios to confirm $\sigma_L \gg \sigma_T$

- Exclusive $^2H(e,e'\pi^+n)n$ and $^2H(e,e'\pi^-p)p$ in same kinematics as $p(e,e'\pi^+n)$
- π *t*–channel diagram is purely isovector (G–parity conservation).

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

- **The π^-/π^+ ratio will be diluted if σ_T is not small, or if there are significant non-pole contributions to σ_L.**
- **Compare measured π^-/π^+ ratio to model expectations.**



T. Vrancx, J. Ryckebusch, PRC 89(2014)025203.

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EIC Kinematic Reach (Apr 2022 update)

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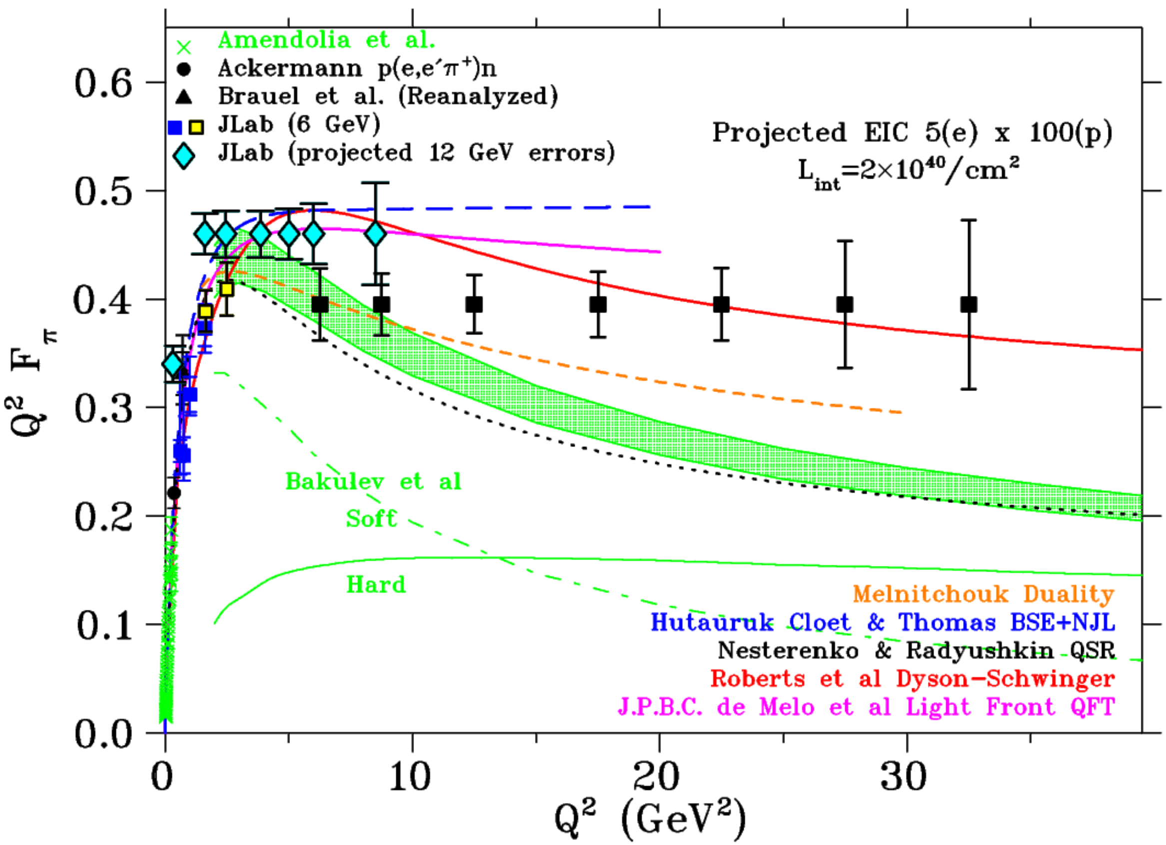

Assumptions:

- $5(e^-)$ x $100(p)$
- Integrated L=20 fb^{-1}/yr
- Clean identification of exclusive $p(e,e'\pi^+n)$ events
- t reconstruction resolution based on ECCE detector design
- Syst. Unc: 2.5% pt–pt and 12% scale
- $R=\sigma_L/\sigma_T$ =0.013–0.14 at lowest $-t$ from VR model, and $\delta R=R$ syst. unc. in model subtraction to isolate σ_L.
- π pole dominance at small $-t$ confirmed in ^{2}H π^-/π^+ ratios.

Summary

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- **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
- **Measurement of F_π at EIC involves significant challenges**
  - Need efficient identification of $p(e,e'\pi^+n)$ triple coincidences
  - Need good resolution t reconstruction to avoid excessive bin migration
  - Conventional L–T separation not possible due to low proton ring energies required to access $\varepsilon<0.8$
  - As $\sigma_L \gg \sigma_T$ expected, most likely possibility is to use model to extract σ_L from $d\sigma_{UNS}/dt$ → Used also for Q^2=10 GeV^2 Cornell expt (1978)
  - Best to use exclusive π^-/π^+ ratio in e+d collisions to validate model
  - **Feasibility studies look very encouraging for data to Q^2≈30 GeV^2**

PDF position available

- **Contribute to this program and more!**
- Excellent opportunity for those who are looking forward to a permanent academic position in the future, to strengthen their research and teaching resumes and gain valuable experience in the classroom.
- High priority experiments measuring the kaon and pion electric form factors at Jefferson Lab Hall C
- Feasibility studies to extend these measurements to higher energy at the EIC
- Cherenkov detector development for the Solenoidal Large Intensity Device (SoLID) in Jefferson Lab Hall A.
- Position is for a 3-year term. Upon mutual agreement, there is possibility of a further 2-year extension. Comprehensive benefits package is included.
- **Further information:** http://lichen.phys.uregina.ca
- **Position advertisement:** https://inspirehep.net/jobs/2610393
- **Contact me at** huberg@uregina.ca

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