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

University of Regina

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(on behalf of the PionLT Collaboration)

Hadron Physics Online Forum (HAPOF)
Institute of Theoretical Physics CAS, Beijing
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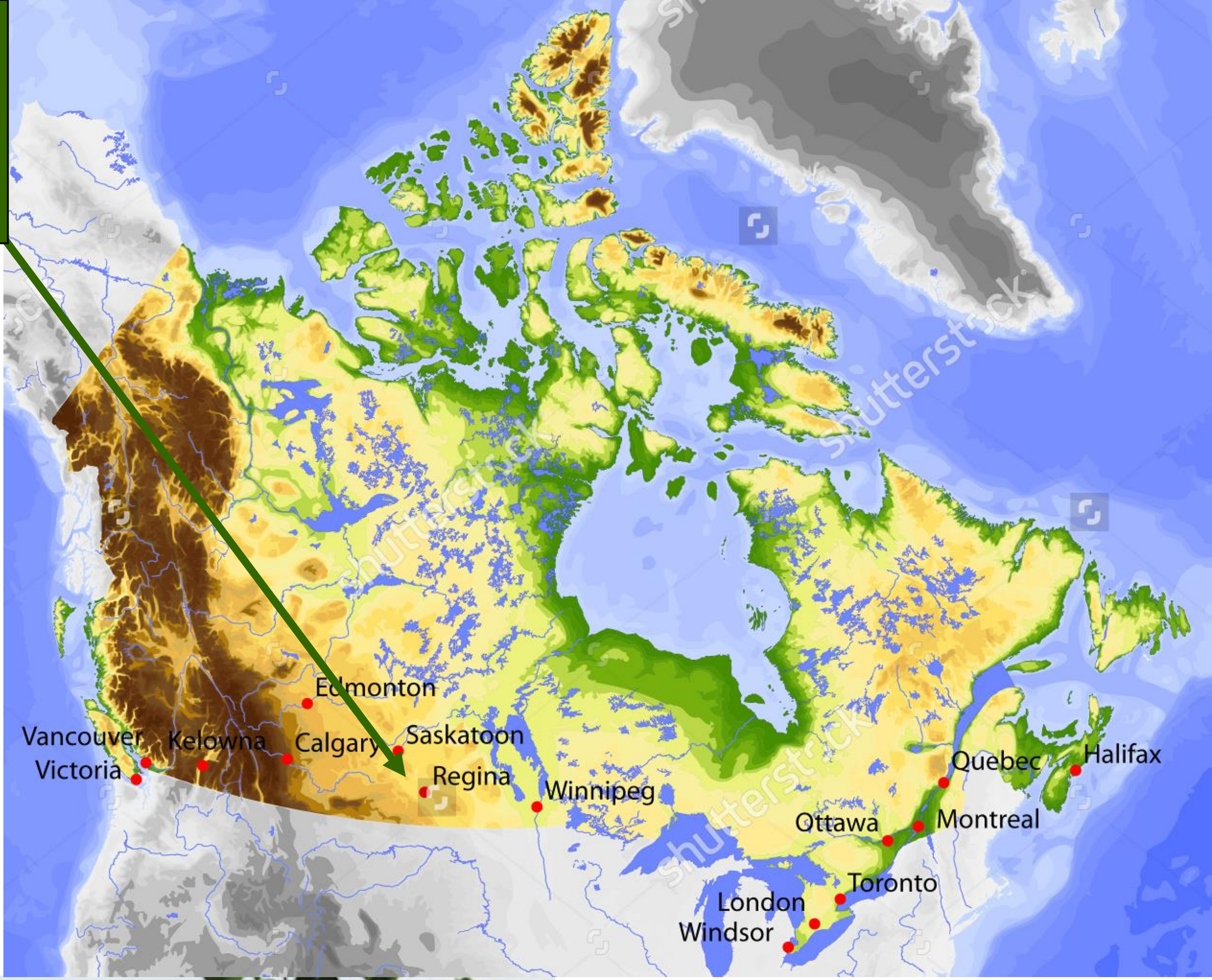
Regina, Saskatchewan CANADA



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

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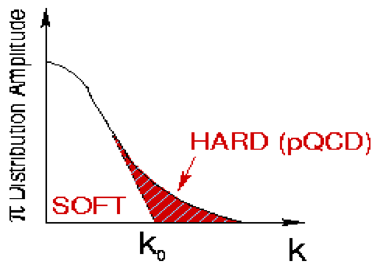
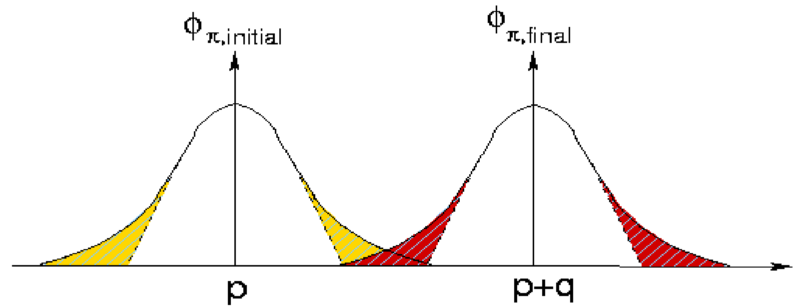
Charged Meson Form Factors

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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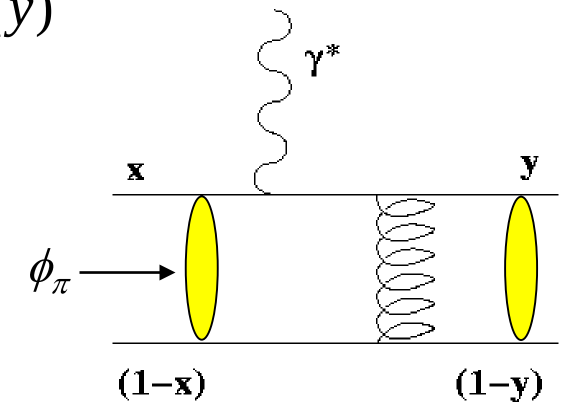
The Pion in perturbative QCD

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

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

and F_π takes the very simple form

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

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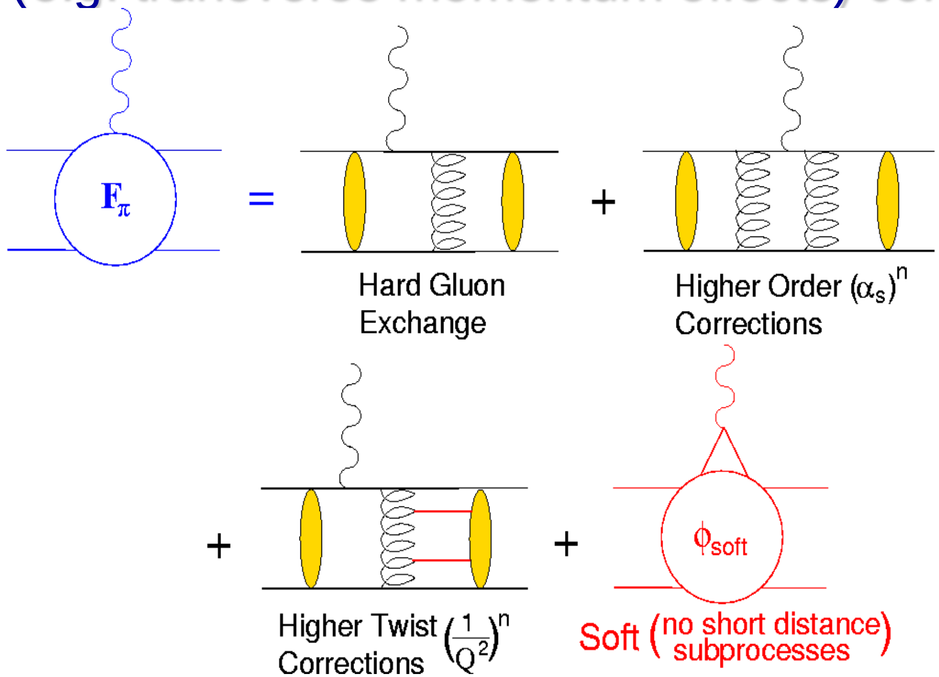
At experimentally-accessible Q^2, both the "hard" and "soft" components (e.g. transverse momentum effects) contribute.



- **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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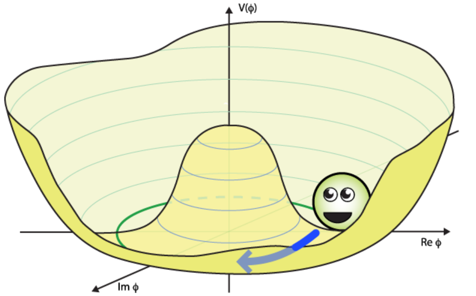
The Pion as a Goldstone Boson

- 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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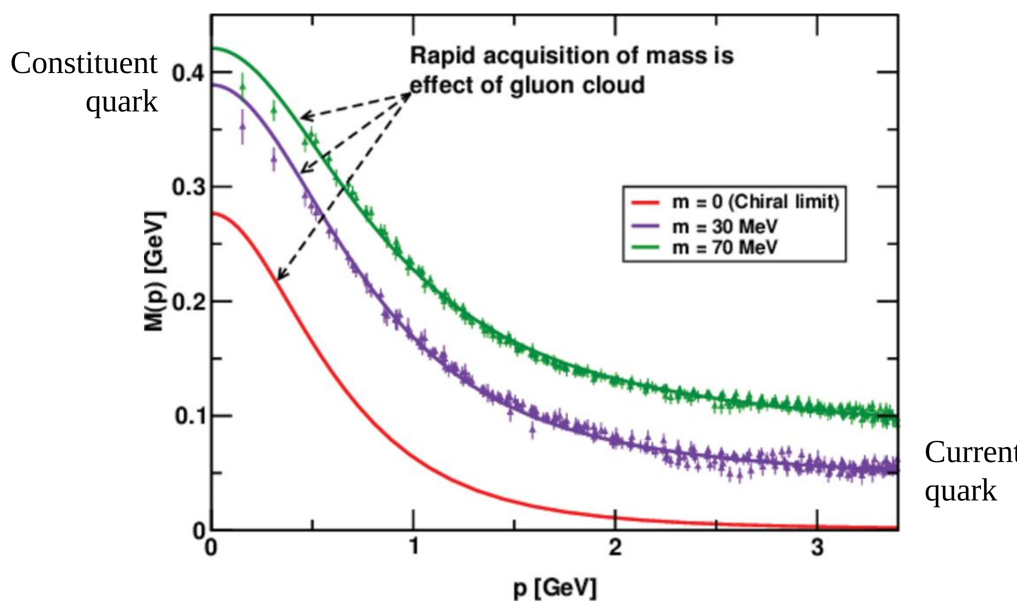
Recent Theoretical Advances

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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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 #13, the normalization for F_π has been based on the conformal limit of the pion's twist–2 PDA.

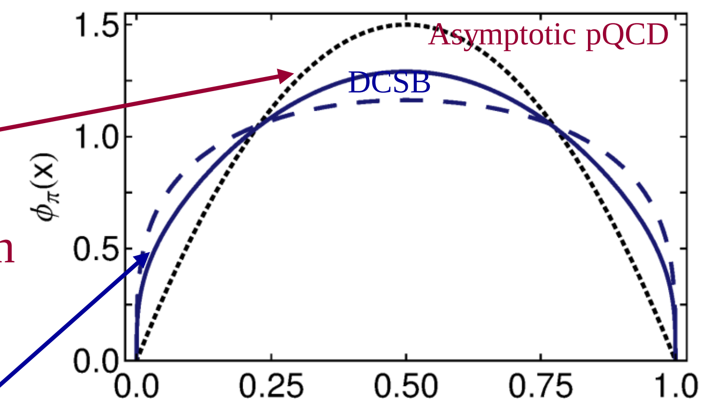
$$\phi_\pi^{cl}(x) = 6x(1-x)$$

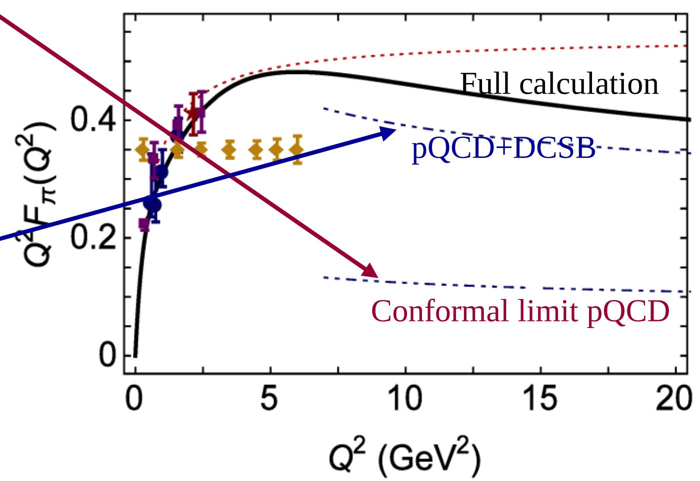
- This leads to "too small" F_π values in comparison with present & projected JLab data.

- Recent works incorporating DCSB effects indicate that at experimentally accessible energy scales the actual pion PDA is broader, concave function, close to

$$\phi_\pi(x) = (8/\pi)\sqrt{x(1-x)}$$

- 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 pion is the "positronium atom" of QCD, its form factor is a test case for most model calculations

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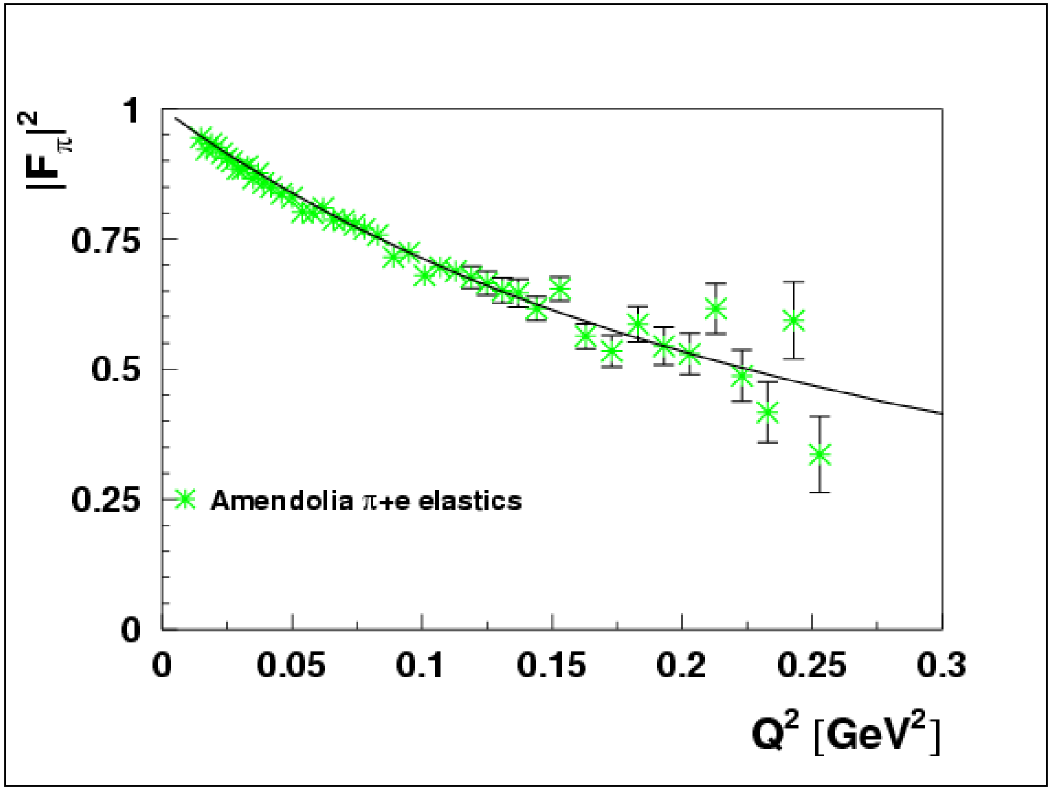
Measurement of π^+ Form Factor – Low Q^2

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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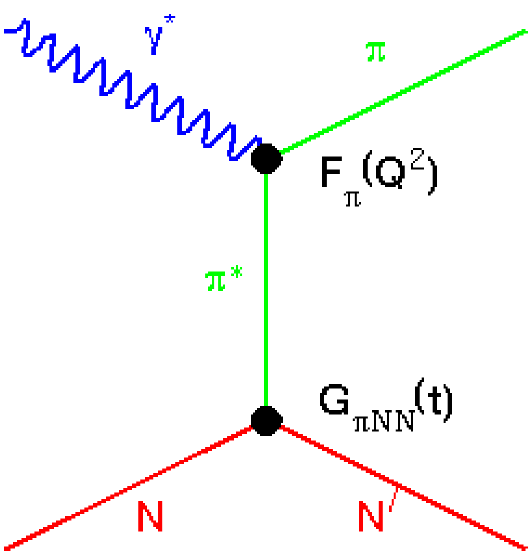
Measurement of π⁺ Form Factor – Higher Q^2

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,

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



Drawbacks of this technique

1. Isolating σ_L experimentally challenging
2. Theoretical uncertainty in form factor extraction.

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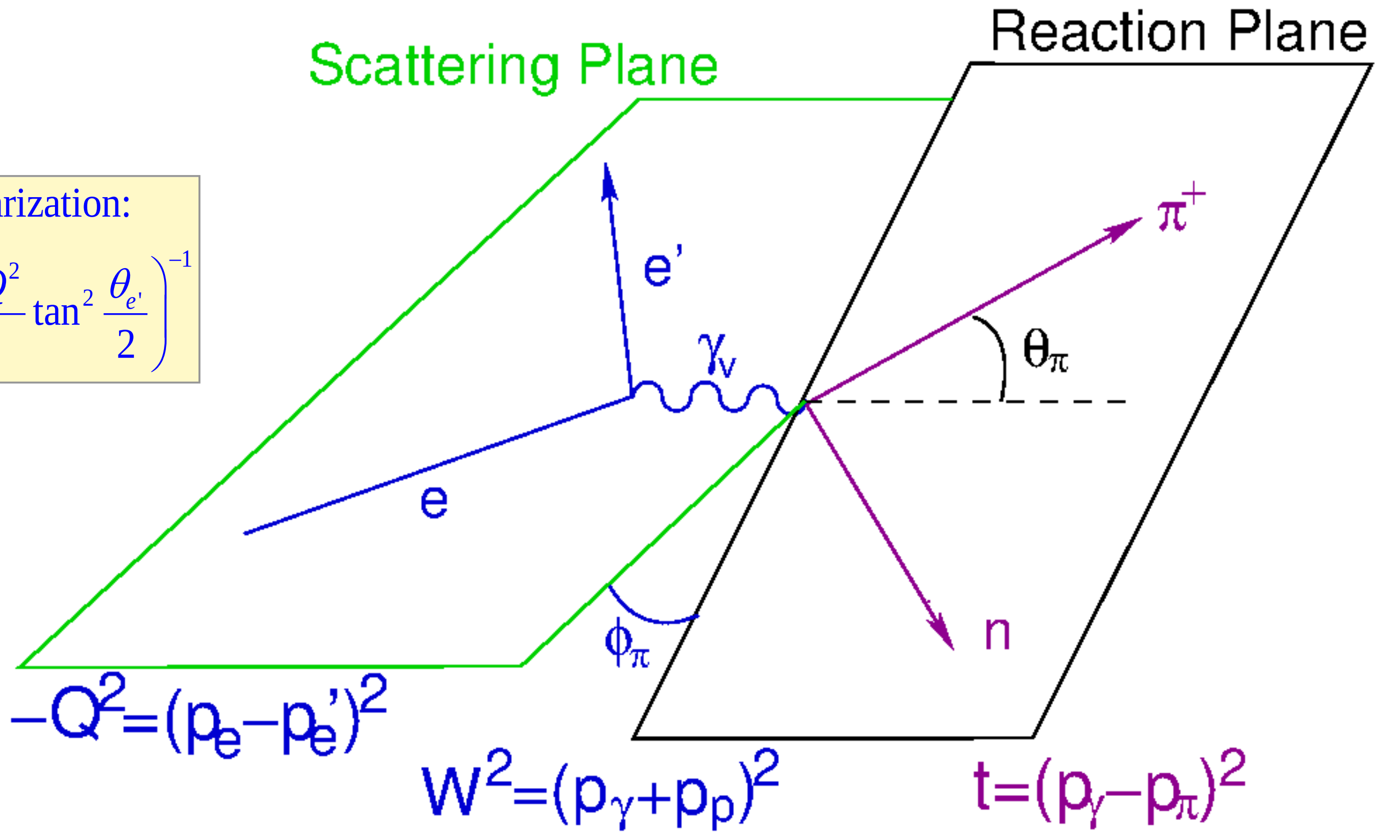
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$

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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Chew–Low Method to determine Pion Form Factor

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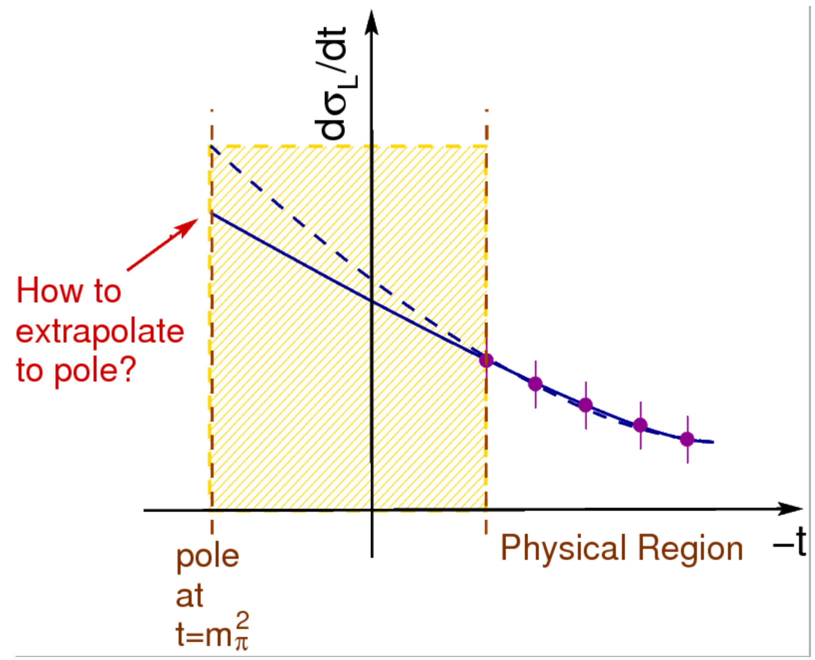
$p(e,e'\pi^+)n$ data are obtained some distance from the $t=m_\pi^2$ pole.

→ "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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Chew–Low Method Check with PseudoData

Plot $F^2 = \frac{N}{4\hbar c(eg_{\pi NN})^2} \frac{(t-m_\pi^2)^2}{-Q^2 m_\pi^2} \frac{d\sigma_L}{dt}$ **vs. –*t***

- Pure pole cross section gives straight line through origin, with value $F_\pi^2(Q^2)$ at pole.
- **Other contributions introduce non–linearities since don't contain $(t-m_\pi)^2$ factor, but don't influence F^2 value at pole**

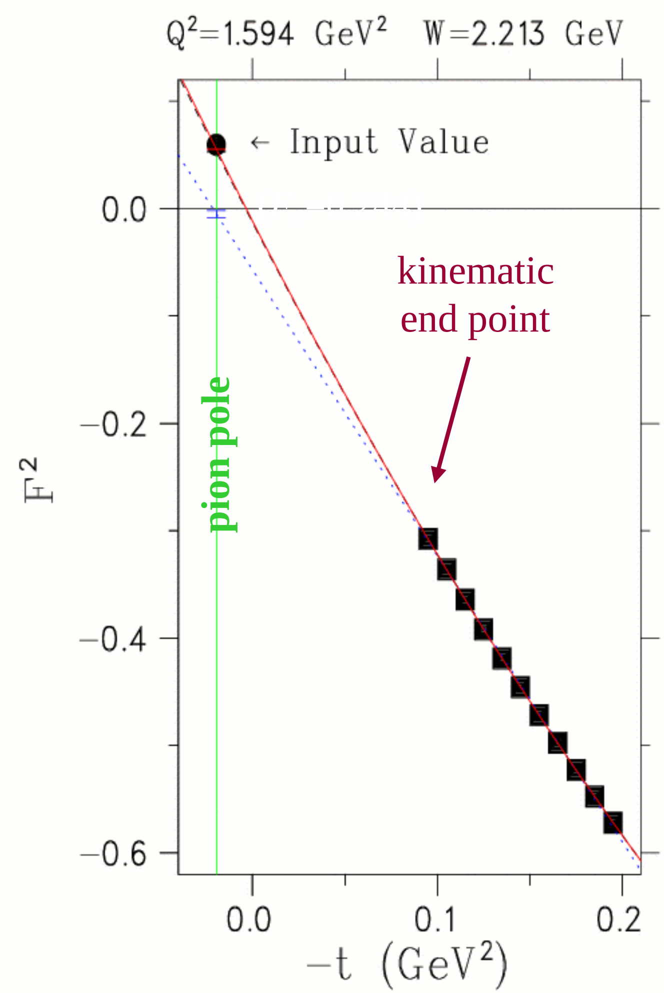
  → Do not know if behavior of F^2 with $-t$ is linear, quadratic, or higher order

All fits missed the input F_π

→ no consistent trend on order of polynomial best able to reproduce input value
(6-15% deviation, Q^2=0.6–2.45 GeV^2)

- Experimental data have only 4–6 *t*-bins and statistical and systematic uncertainties of 5–10%

  → Extrapolation with real data will be even more uncertain



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

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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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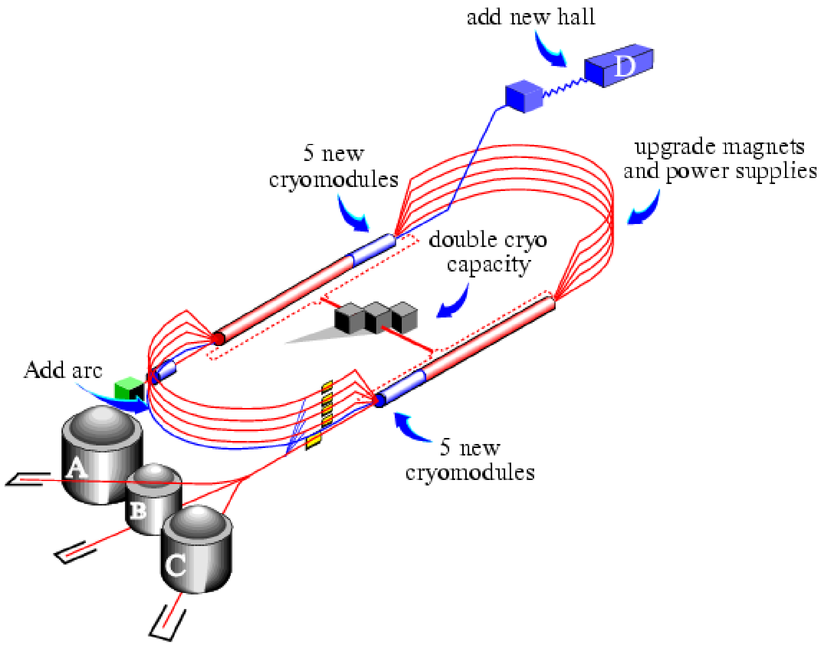


Two 1.5 GHz Superconducting Linear Accelerators provide electron beam for Nucleon & Nuclear structure studies.

- **Beam energy E $\rightarrow$ 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**

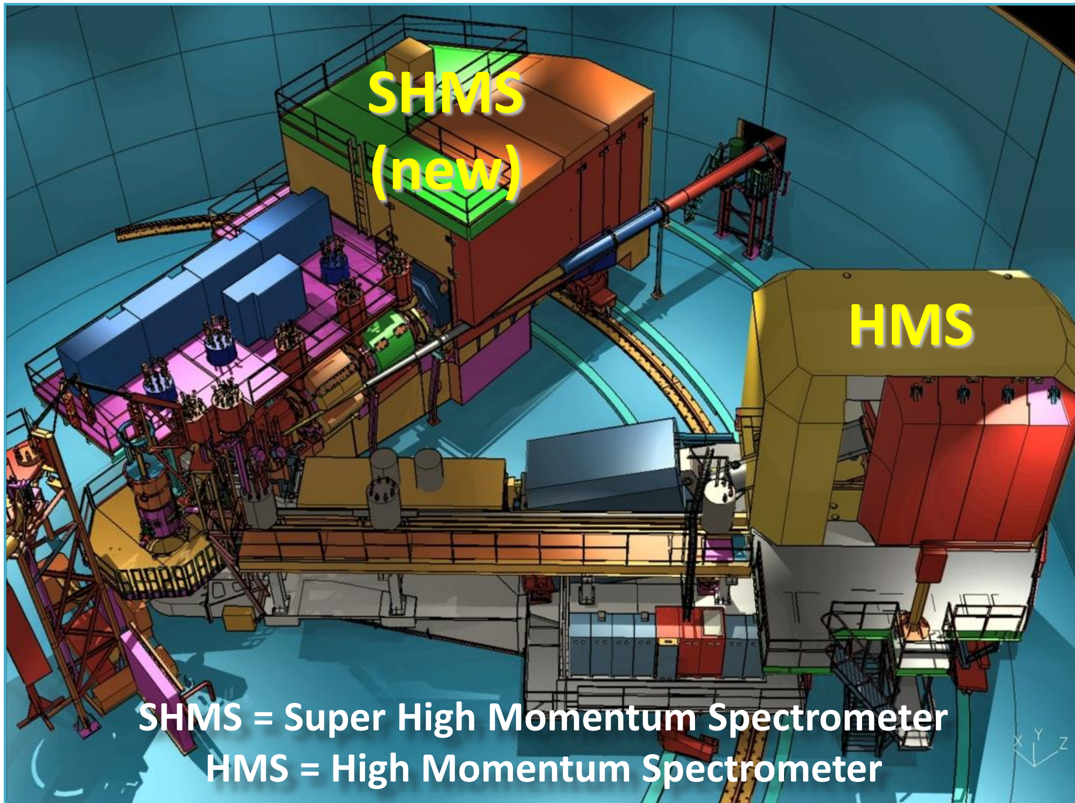
MAGNETIC OPTICS:
- Point-to Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

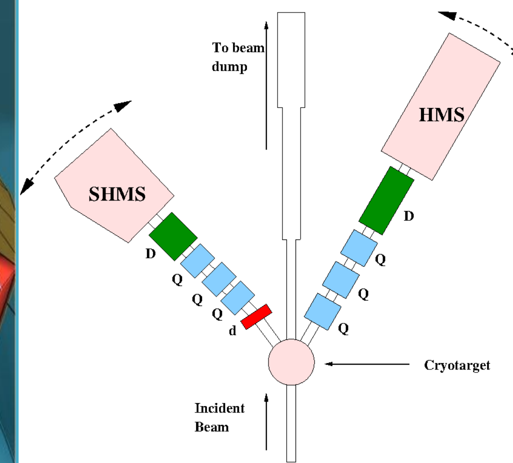
Detector Package:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter

Well-Shielded Detector Enclosure

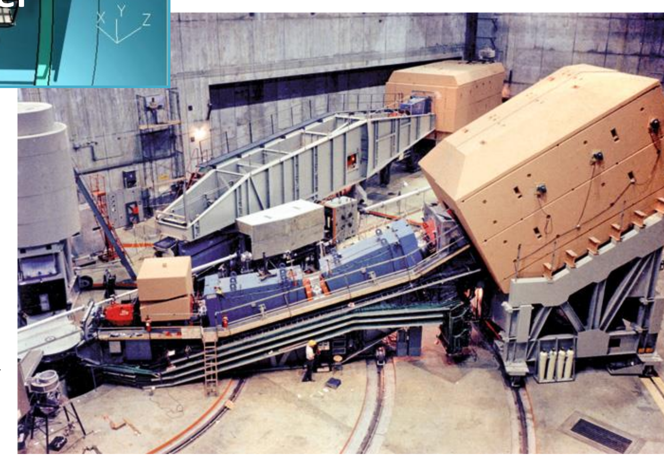
Rigid Support Structure
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS

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



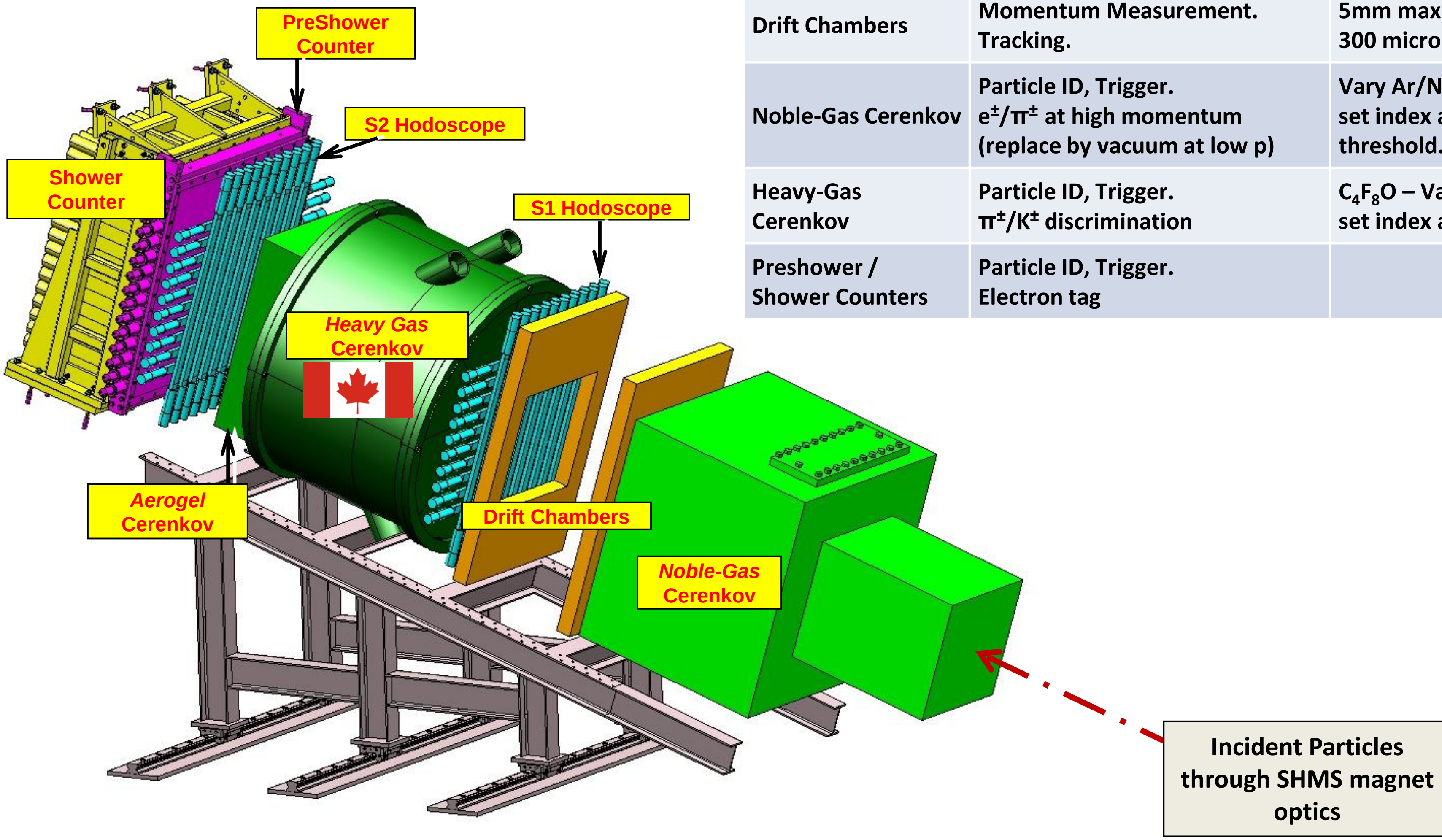


Upgraded Hall C has some similarity to SLAC End Station A, where the quark substructure of proton was discovered in 1968.



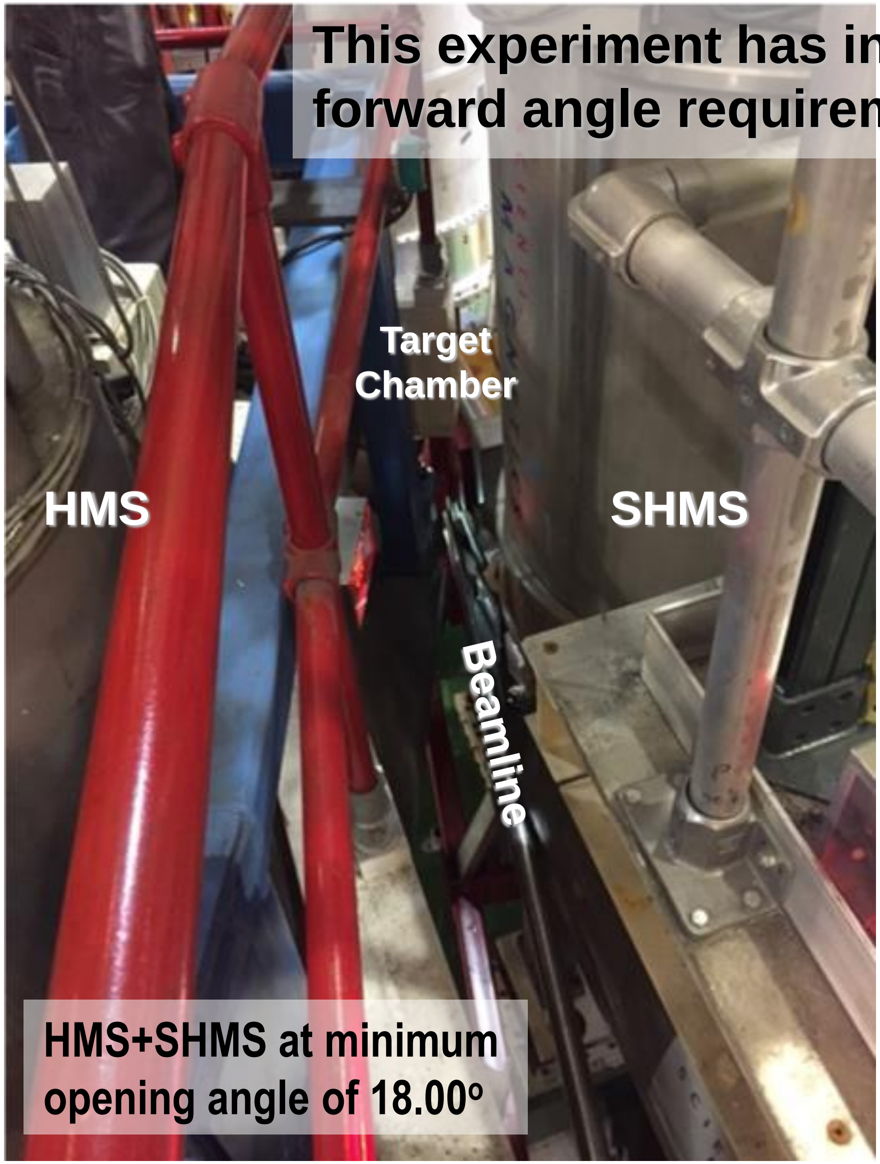
SHMS Focal Plane Detector System

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



HMS+SHMS at minimum opening angle of 18.00°

SHMS at 5.69°

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

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

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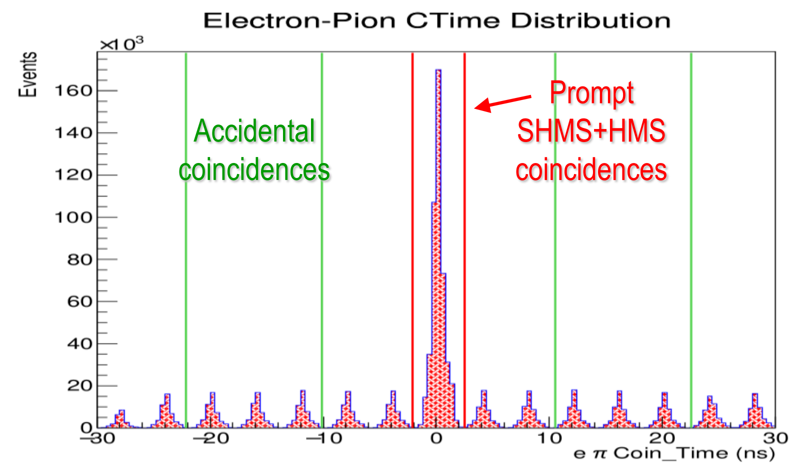
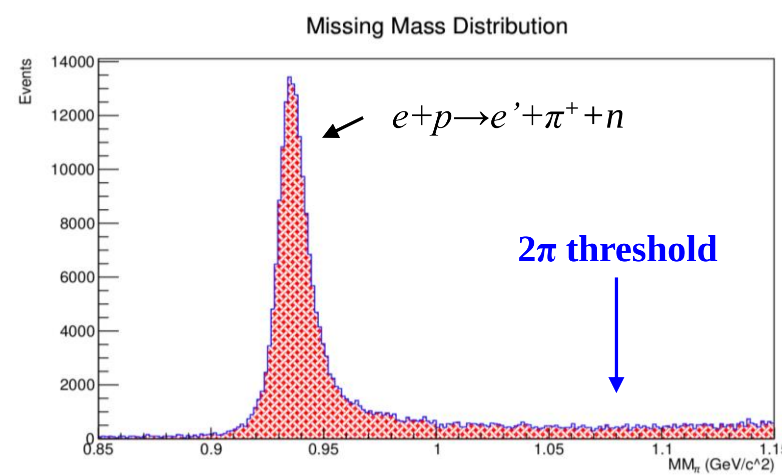
Easy to isolate exclusive channel

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





PionLT experiment E12–19–006 Data

Q^2=1.60, W=3.08, x= 0.157, ε=0.685

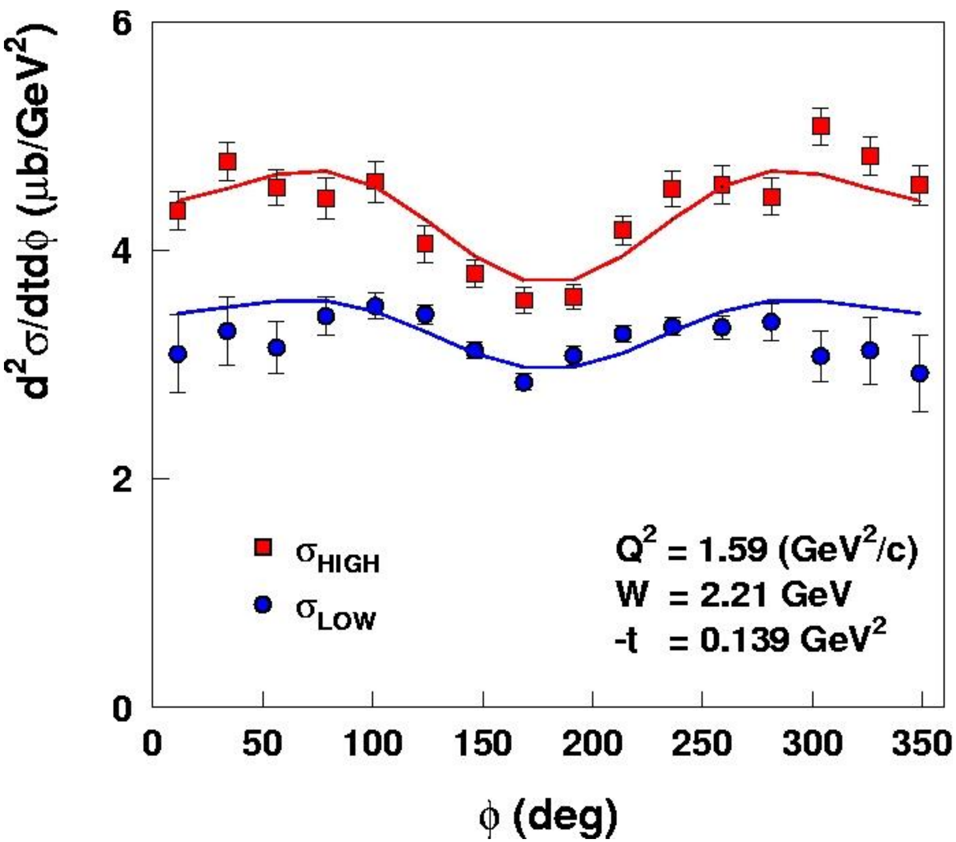
E_{beam}=9.177 GeV, P_{SHMS}=+5.422 GeV/c, θ_{SHMS}= 10.26° (left)

Plots by Muhammad Junaid

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

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 $\Delta\varepsilon$

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

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

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

VGL Regge Model:

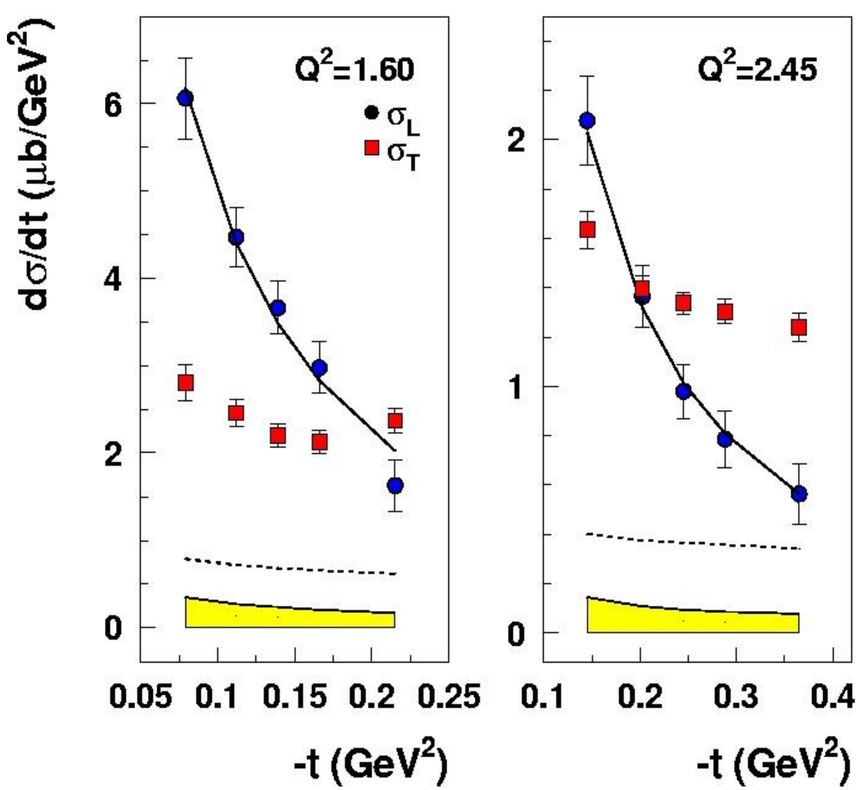
- Feynman propagator $\left(\frac{1}{t-m_\pi^2}\right)$

  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

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

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.

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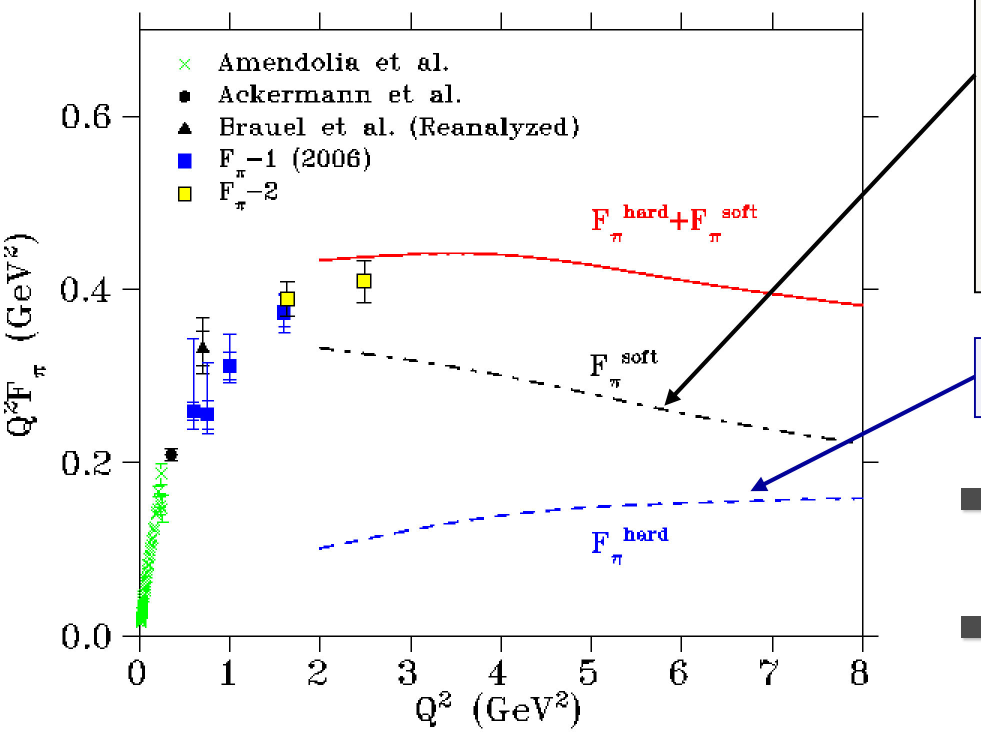
pQCD LO+NLO Calculation:

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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Model / Intepretation Issues

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- 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 and K-e elastic scattering at same Q^2.

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Check of Pion Electroproduction Technique

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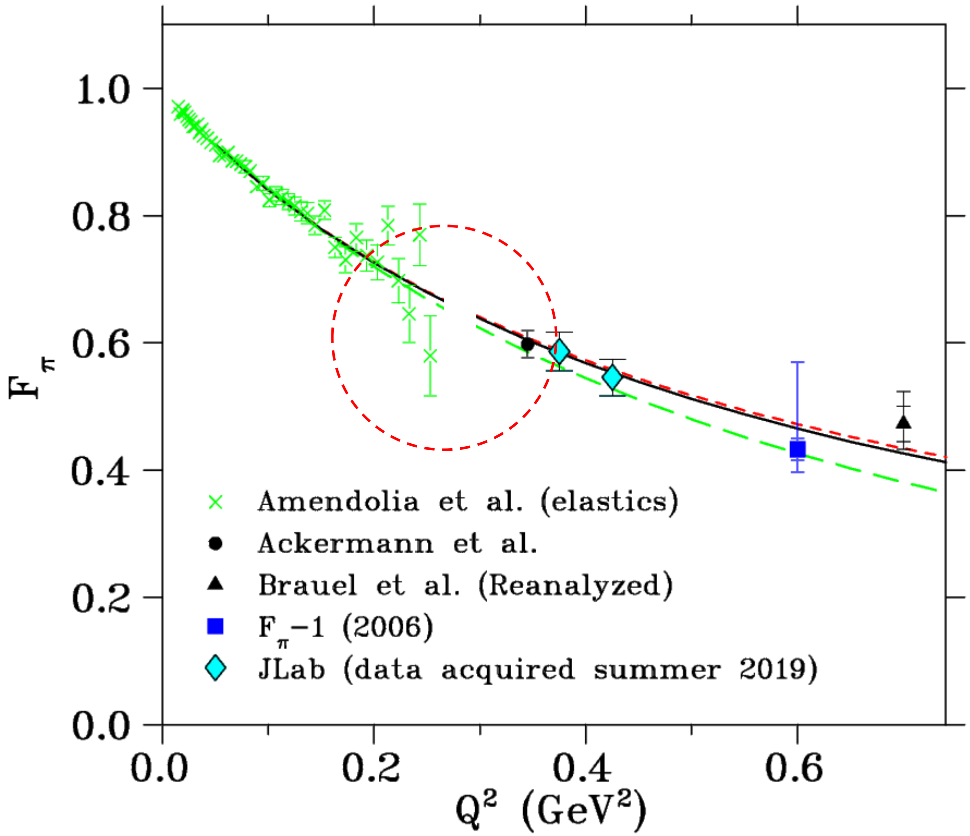
- Does electroproduction really measure the on–shell form–factor?
- Test by making *p(e,e'π⁺)n* measurements at same kinematics as *π⁺e* elastics.
- ***Can't quite reach the same Q^2, but electro–production appears consistent with extrapolated elastic data.***



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

Garth Huber, huberg@uregina.ca

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

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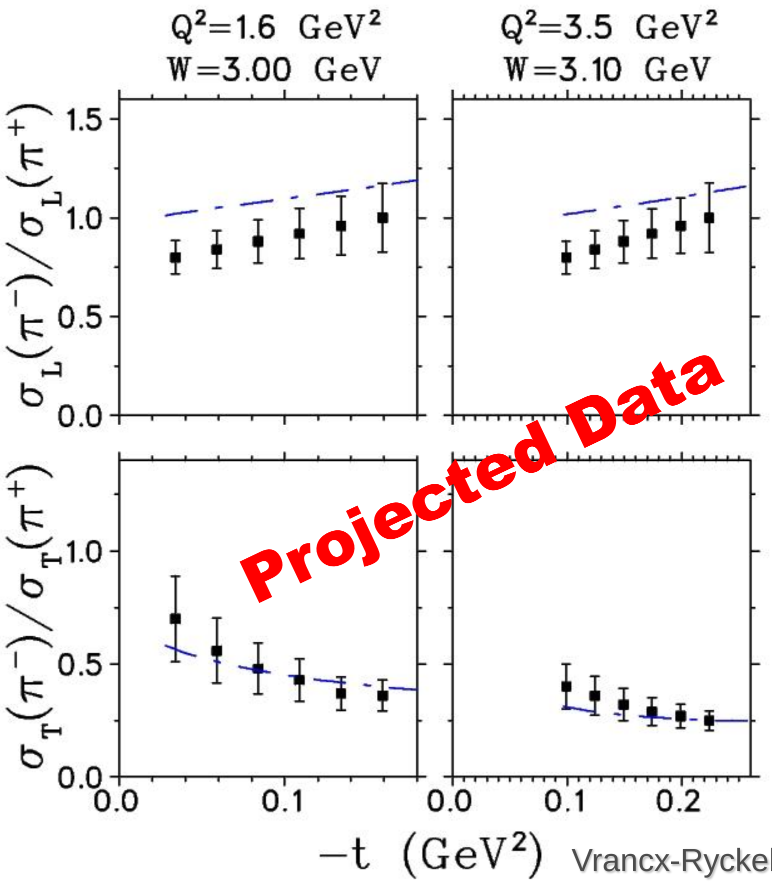
- π^+ *t*-channel diagram is purely isovector.
- Measure

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

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.

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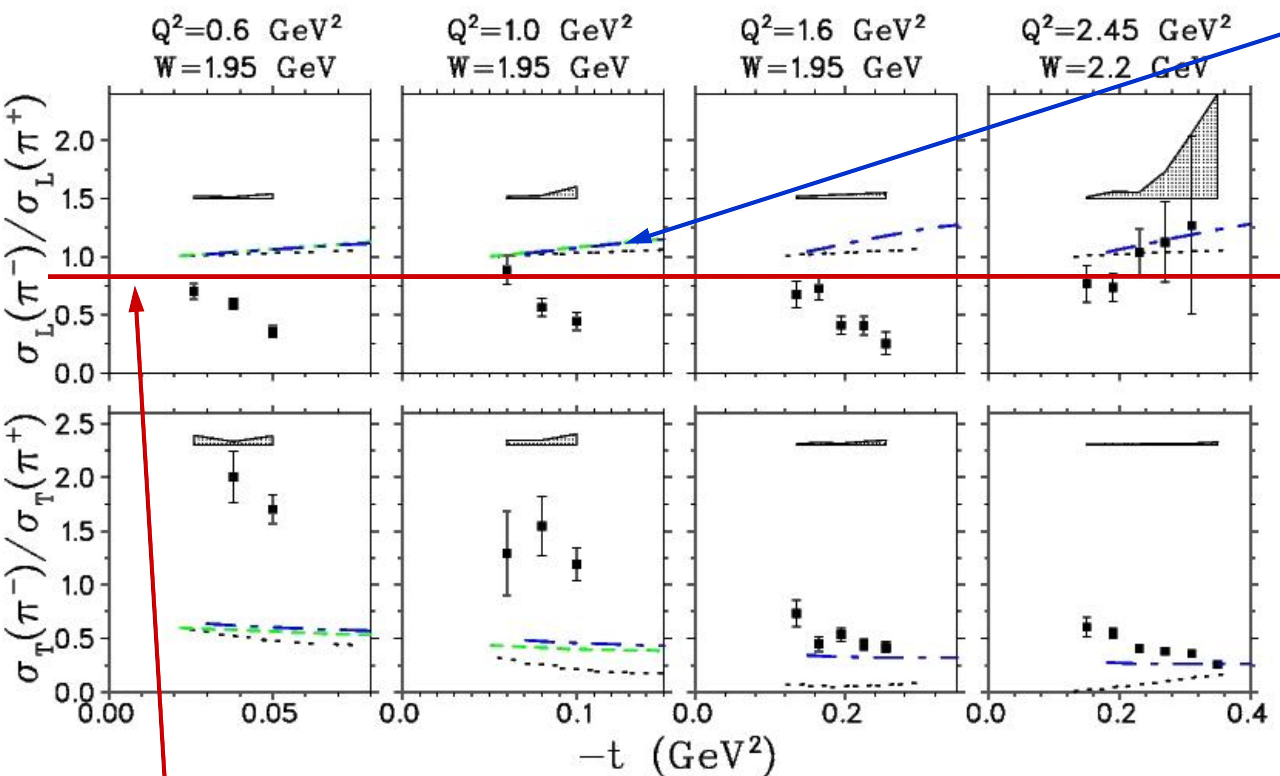
Relevance to Pion Form Factor Extraction



Vrancx-Ryckebusch Regge+DIS Model:

- VGL Regge Model underpredicts σ_T by large factor.
- VR extend Regge model with hard DIS process of virtual photons off nucleons.
- W=1.95 GeV, higher –t data described poorly.

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

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

- **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 little evidence for this contribution in data analysis at *W*=2.2 GeV.

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Fπ-2 VGL $p(e,e'\pi^+)n$ model check

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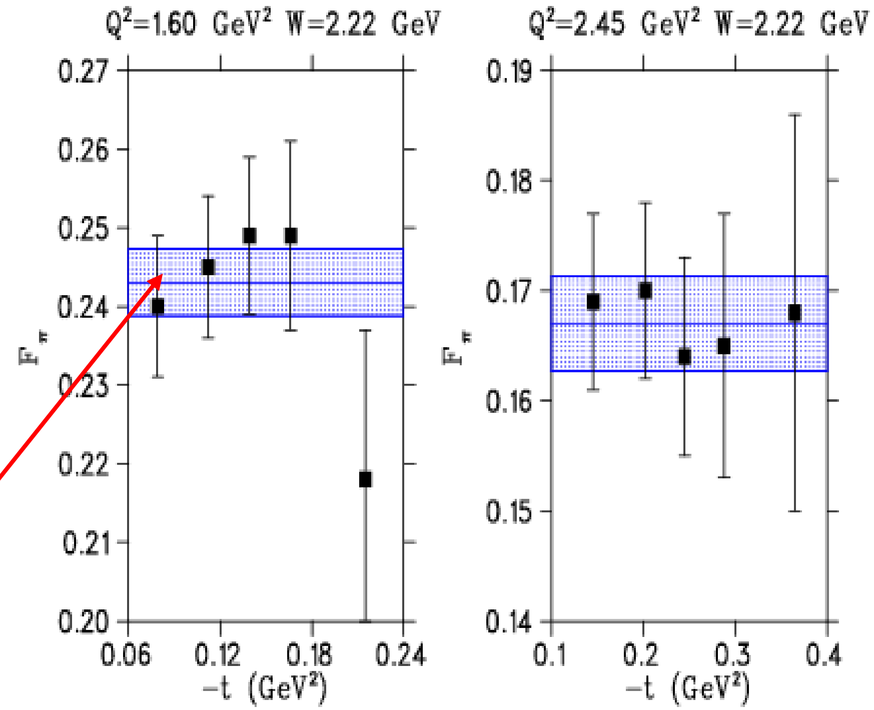
- To check whether VGL Regge model properly accounts for:
  - π^+ production mechanism.
  - spectator nucleon.
  - other off-shell (*t*-dependent) effects.

  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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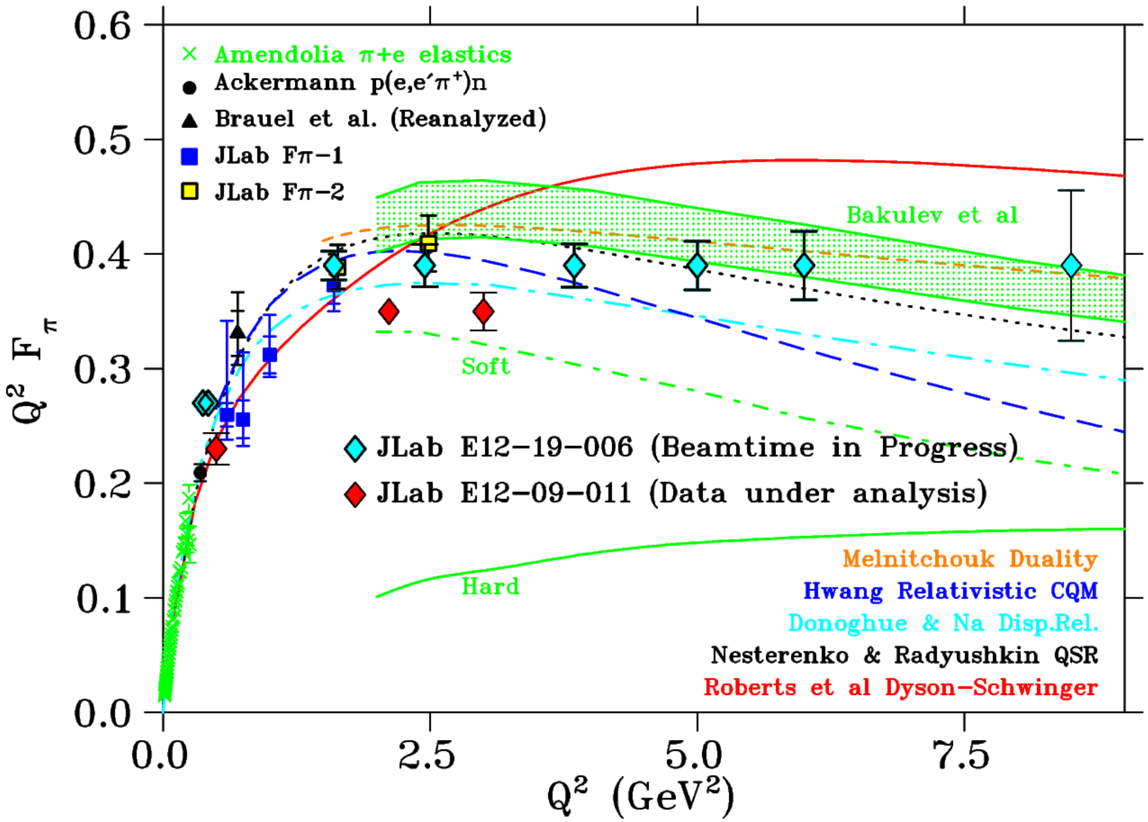
Current and Projected F_π Data

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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Strong Endorsement in many Reviews

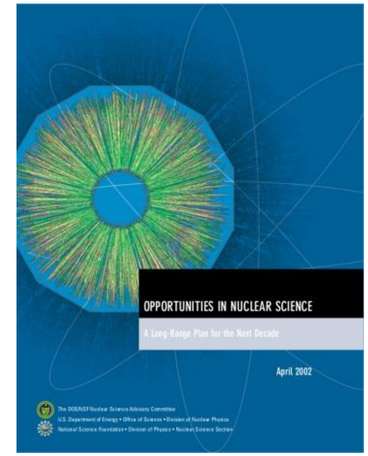
University of Regina

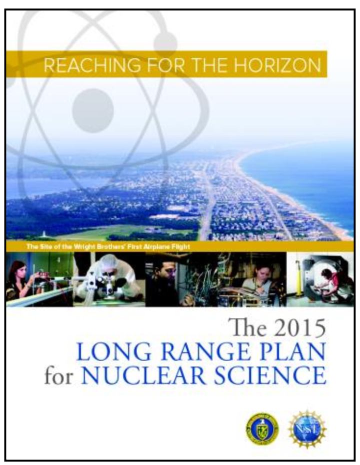
Report to PAC18, 12 GeV Session:
Measuring F_π at Higher Q^2
G.M. Huber, H.P. Blok, D.J. Mack
on behalf of the Exclusive Reactions Working Group
July 6, 2000

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 JLab 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 have only increased."
→ Top "A" rating reaffirmed by PAC

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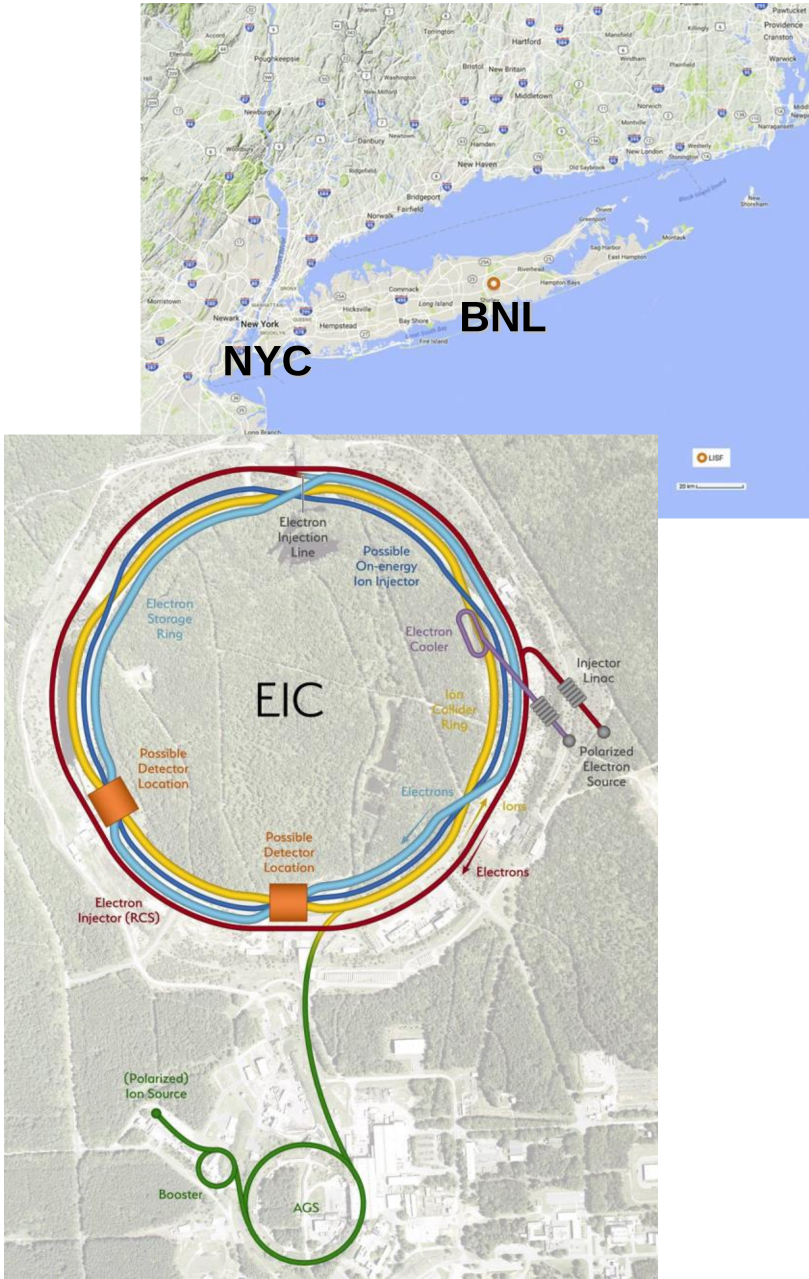
Electron–Ion Collider @ BNL

University of Regina

Use existing Relativistic Heavy Ion Collider (RHIC)

- Up to 275 GeV protons (polarized).
- Existing: tunnel, detector halls, hadron injector complex (AGS).
- Build new 18 GeV electron linac and add high intensity electron storage ring in same tunnel.
- Achieve high luminosity, high energy *e–p*/A collisions with full acceptance detectors.
- High luminosity achieved by extensions of state–of–the–art beam cooling techniques.



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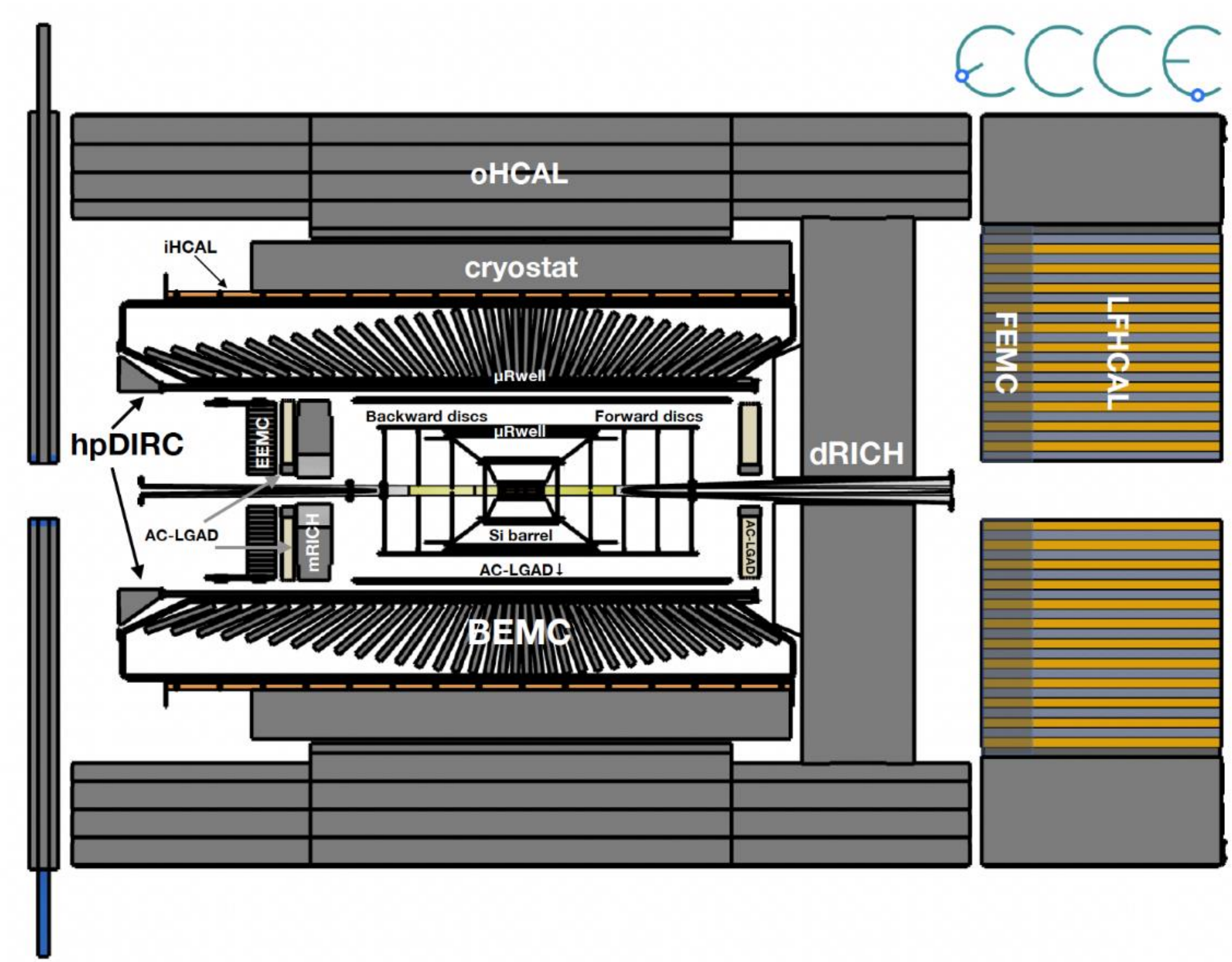
EIC Detector (Central Barrel)



41 – 275 GeV proton or ion beam

5 – 18 GeV electron beam

Solenoid: superconducting 1.5T 3.5m(length) x 1.5m(radius) from SLAC BaBar

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EIC Far Forward Detectors

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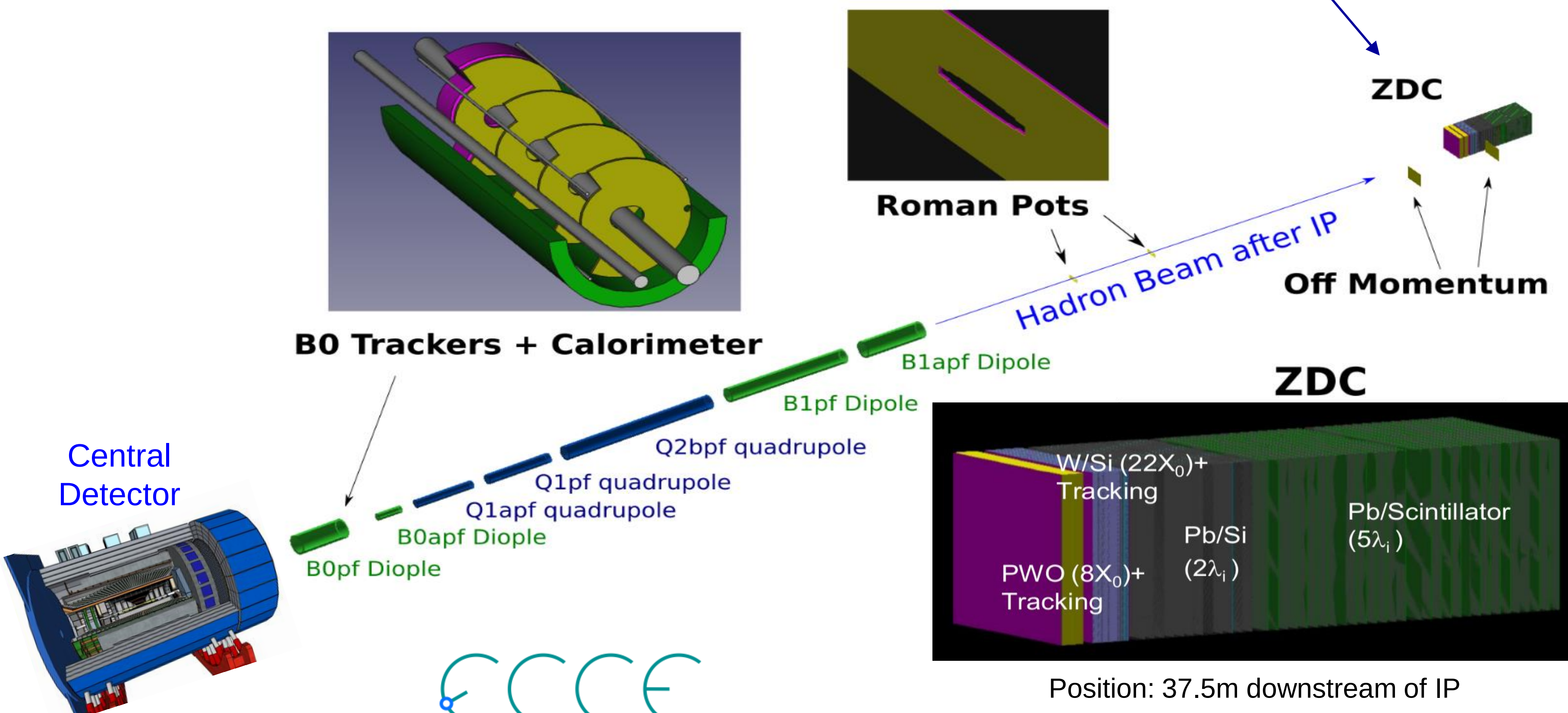
- Crucial to cleanly separate exclusive $p(e,e'\pi^+n)$ process from competing inclusive reactions
- EIC measurement <u>impossible</u> unless recoil neutron (very high momentum, <1^o from outgoing hadron beam) is efficiently detected
- **High quality Zero Degree Calorimeter (ZDC) essential**



Position: 37.5m downstream of IP

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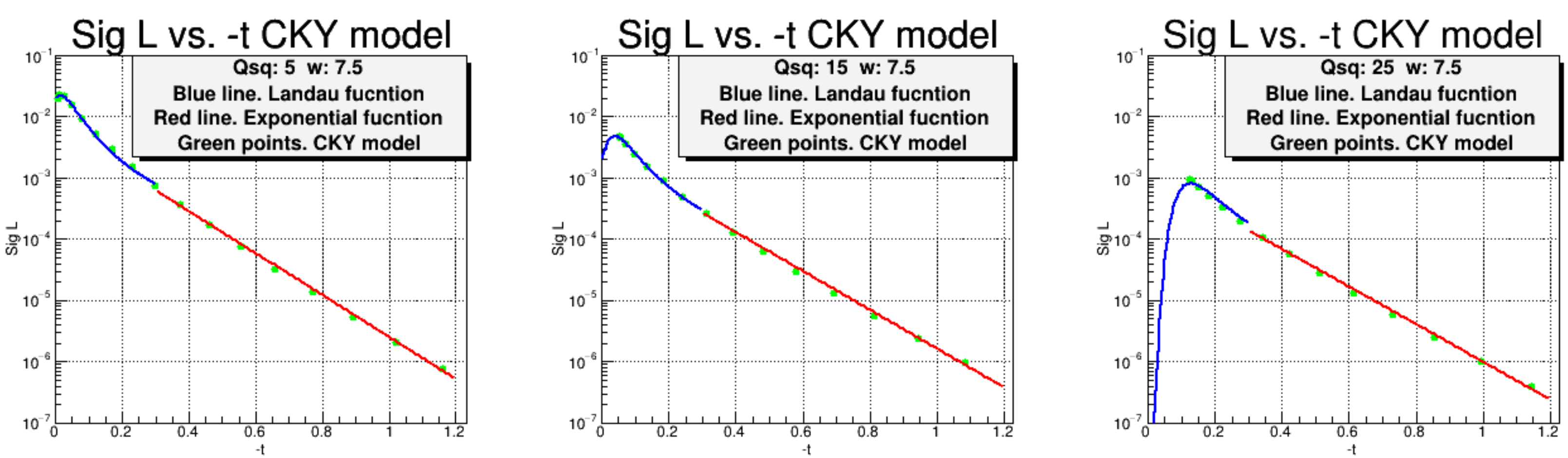
DEMP Event Generator

- 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 $W^2 >> Q^2$.
  - 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 the 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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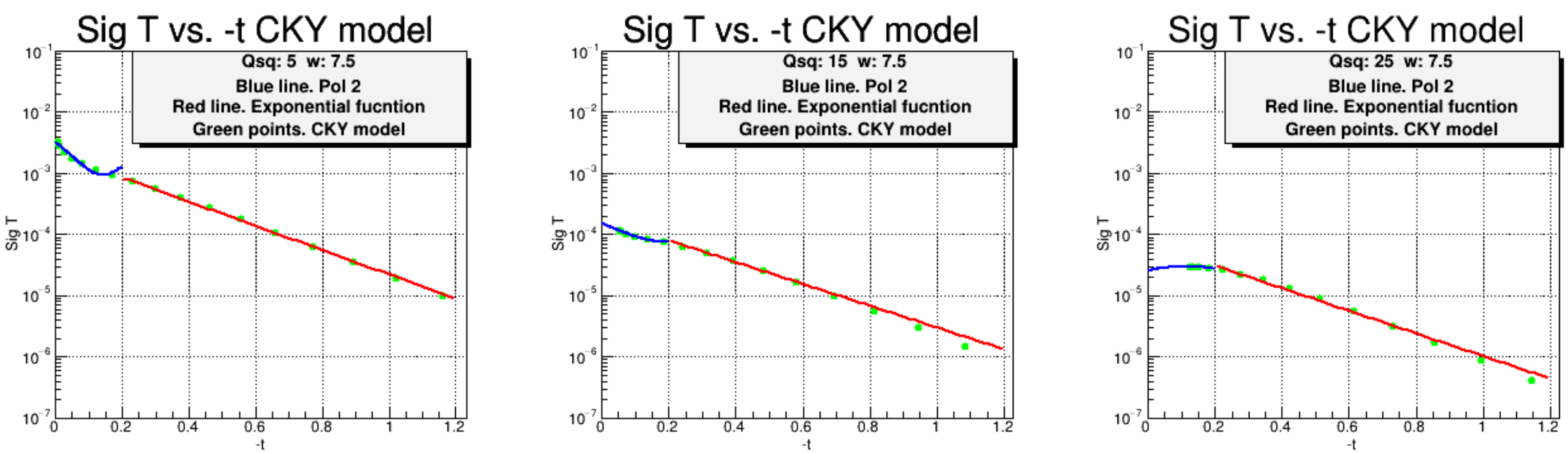

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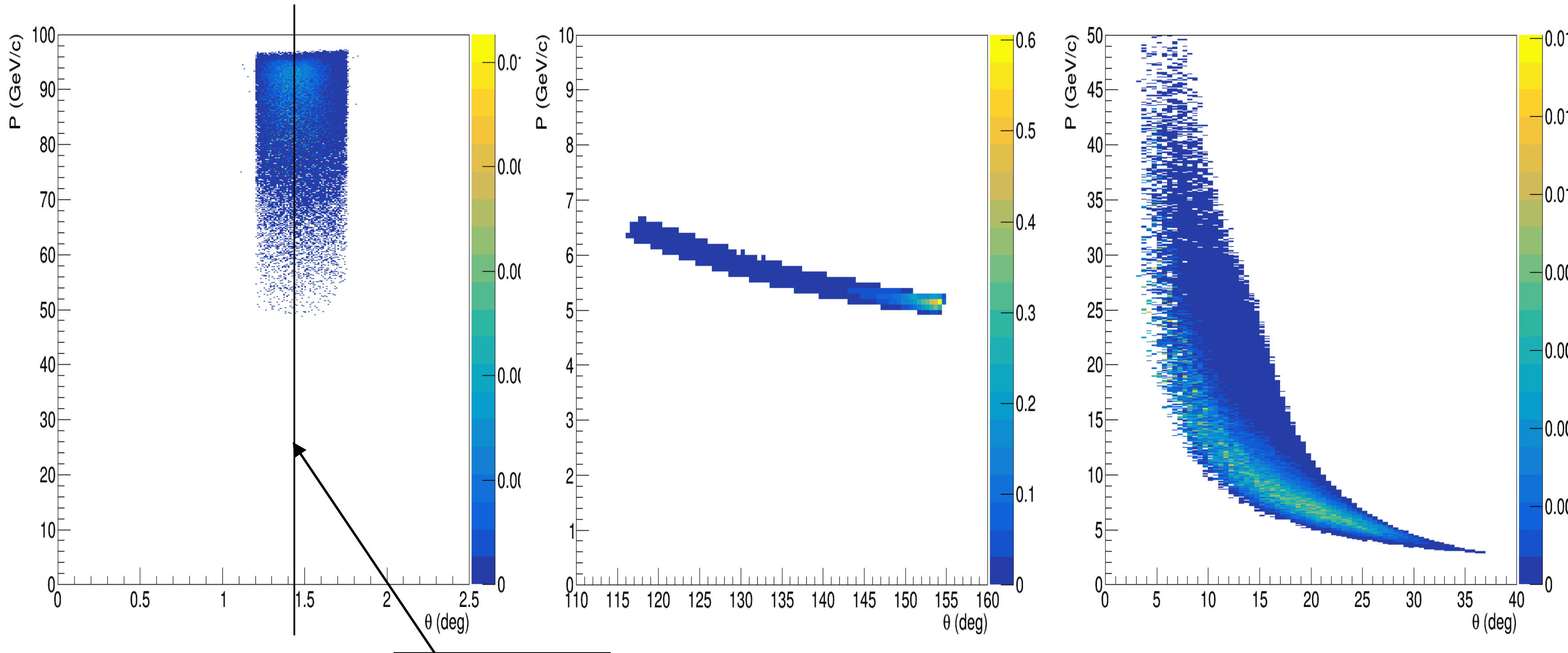
DEMP n, e', π^+ Acceptance for $-t$<0.5 GeV^2

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



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

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

Pions:
3–35 GeV/c,
5-35° 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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Isolating Exclusive $p(e,e'\pi^+)n$ Events

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- **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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Comparison of DEMP and SIDIS kinematics

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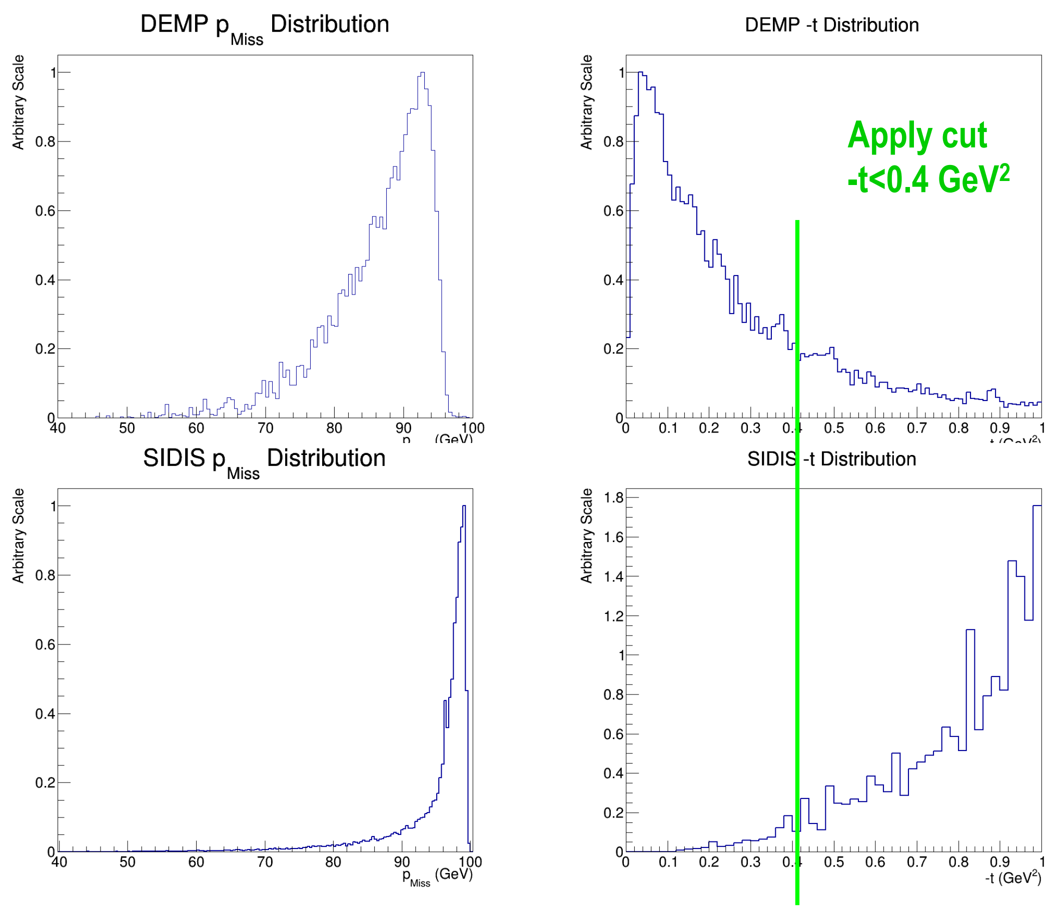
- SIDIS events are distributed over wider momentum range, and much larger $-t$ than foreground DEMP events.

Exclusive
p(e,e'π⁺)n
Foreground

SIDIS
p(e,e'π⁺)X
Background



Plots by Stephen Kay

DEMP events are e' π^+ n triple coincidence.
SIDIS events are e' π^+ double coincidence, and p_{miss} reconstructed.

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p_{miss} cut vs Q^2–bin

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

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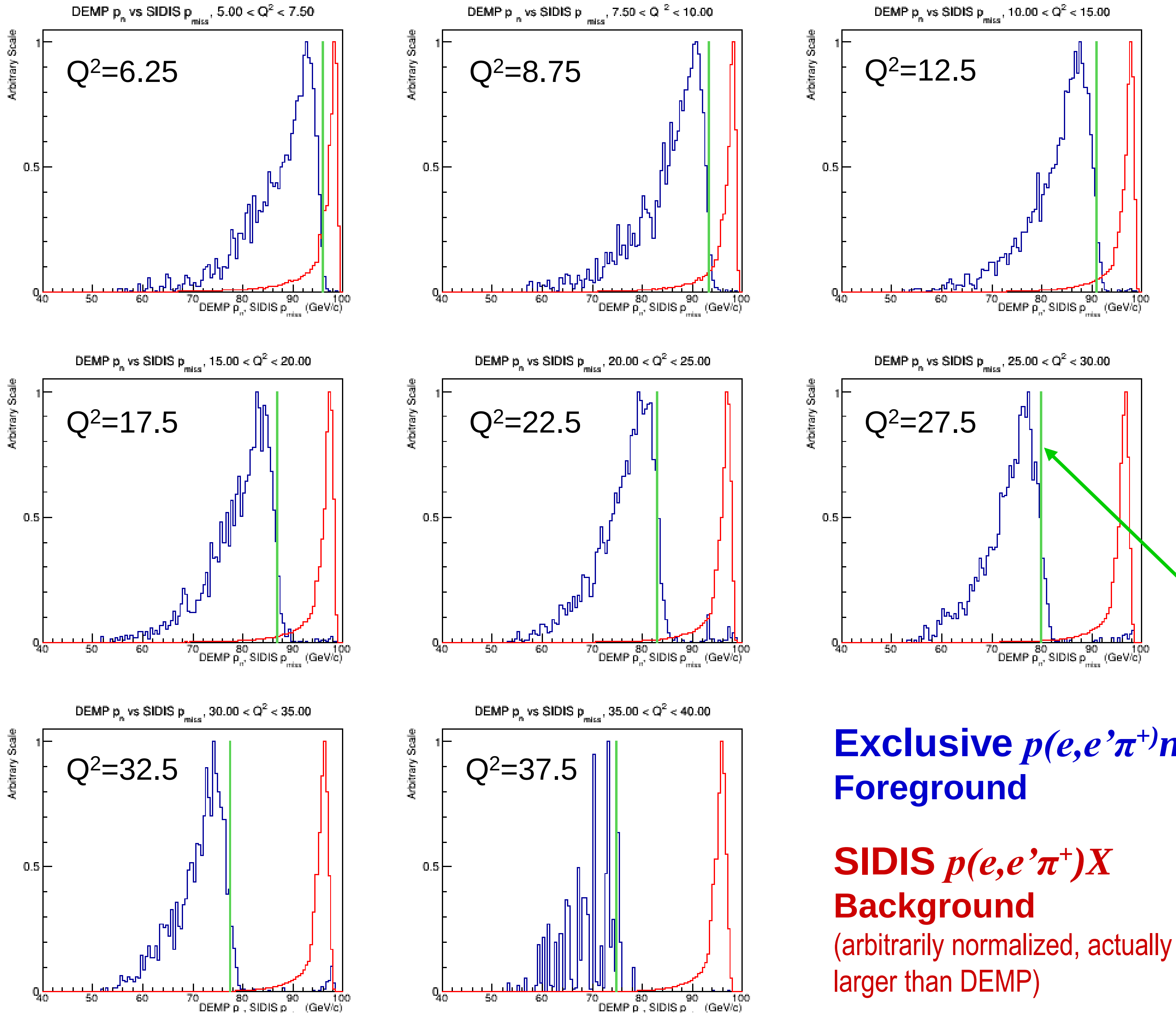

Plots by Stephen Kay

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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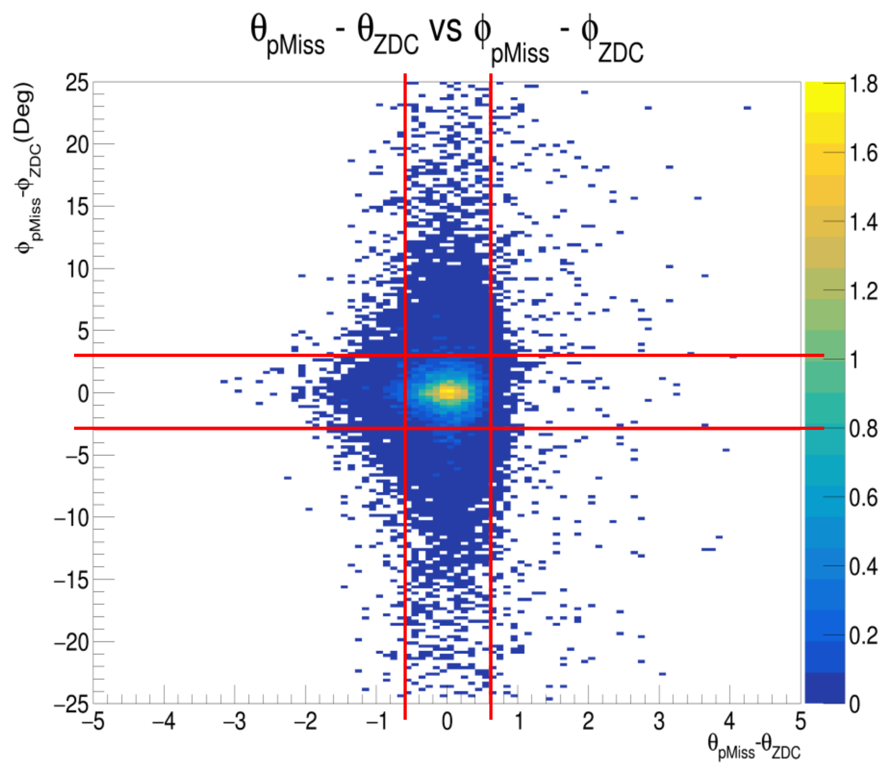
Another Cut to Remove Background

- **Make use of high angular resolution of 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

Garth Huber, huberg@uregina.ca

Improving *neutron* reconstruction resolution

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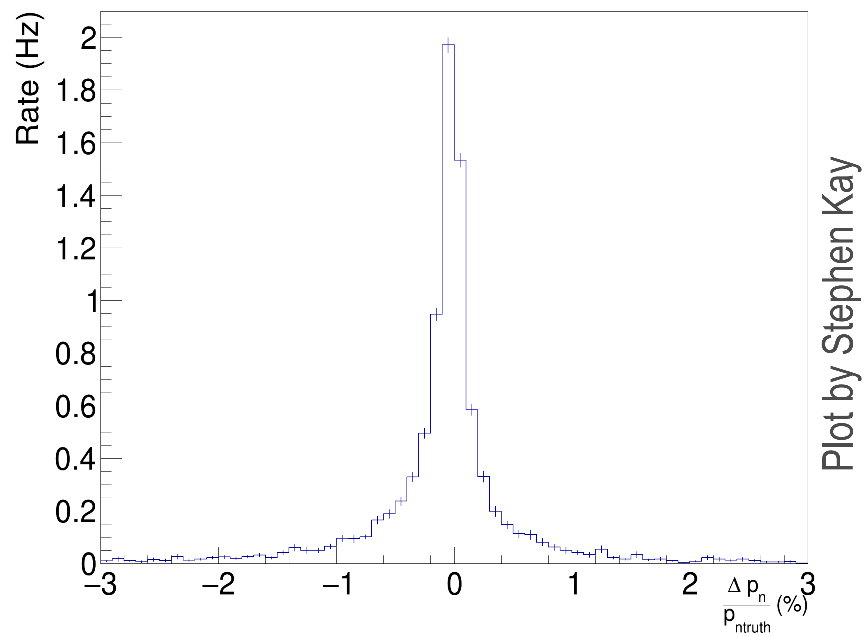
- **Exclusive $p(e,e'\pi^+n)$ event selection requires exactly one high energy ZDC hit as a veto**
- Since the neutron hit position from ZDC is known to high accuracy, this information can be used to "correct" the missing momentum track $p_{miss} = \left| \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+} \right|$
- **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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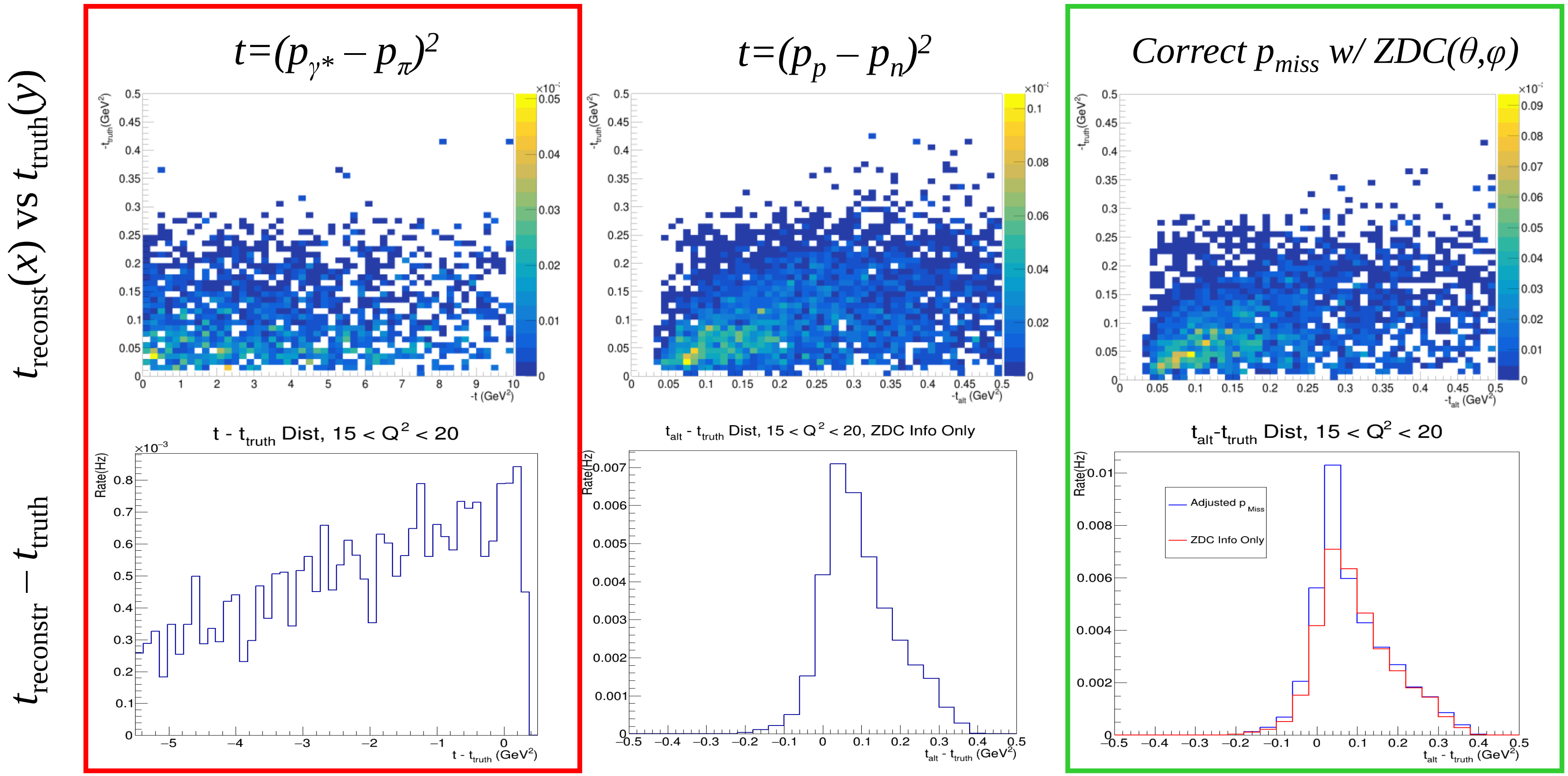
Reconstructing Mandelstam *t*

- 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*



Unusable *t* reconstruction
$\sigma_{t\ reconstr} = 3.4\ \mathrm{GeV}^2$

Plots by Stephen Kay

Best *t* reconstruction
$\sigma_{t\ reconstr} = 0.073\ \mathrm{GeV}^2$

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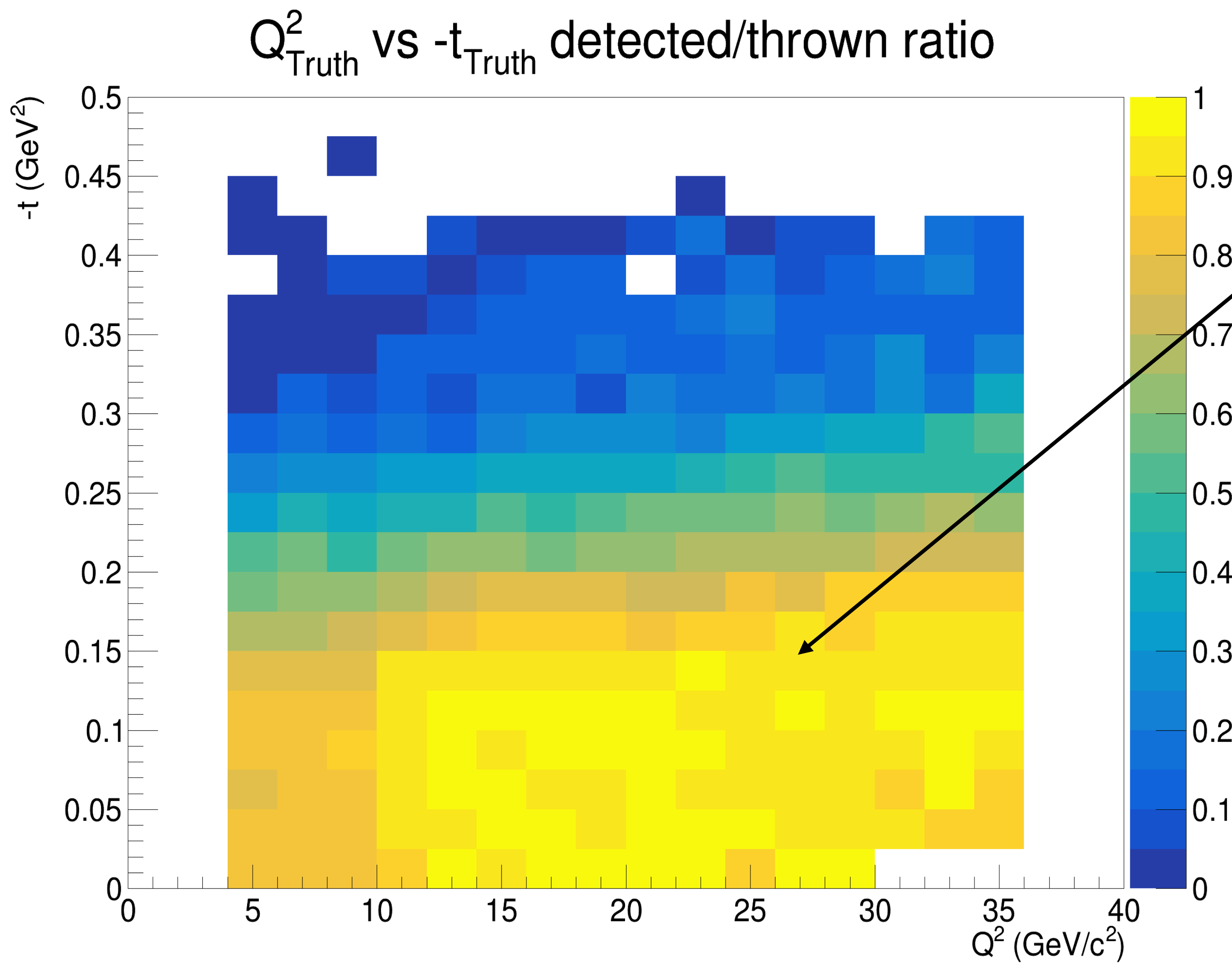
Detection efficiency per (Q^2,*t*) bin



Detection efficiency best in crucial low –*t* region

Plot by Stephen Kay

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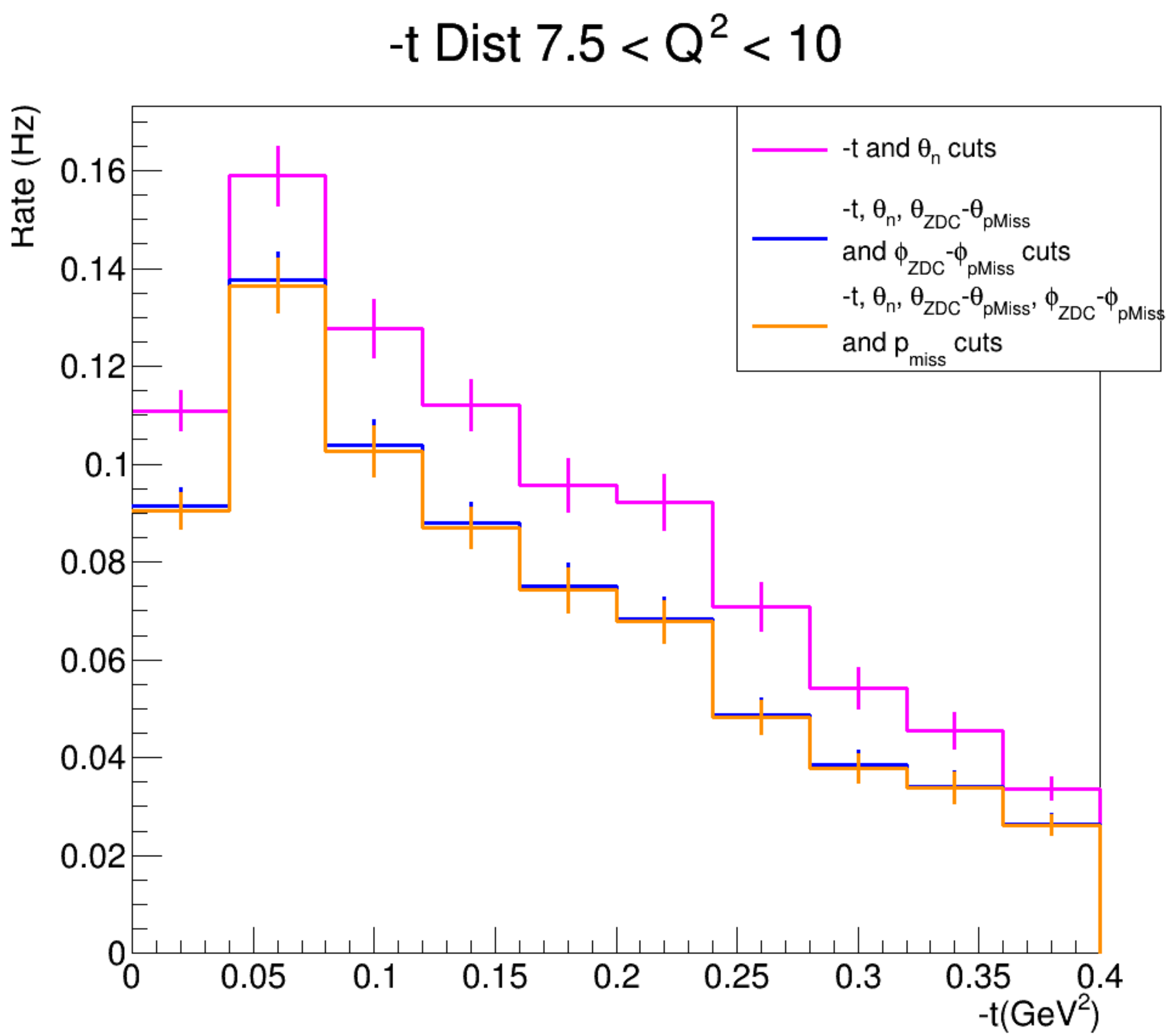
DEMP Rates as Cuts Applied – Q^2=8.75 GeV^2

Rate (Hz) per –*t* bin



Only –*t*<0.4 GeV^2 and triple coincidence cuts

Add ΔθΔφ ZDC cuts

Add p_{miss}<93 GeV cut (removes only SIDIS background)

Plot by Stephen Kay

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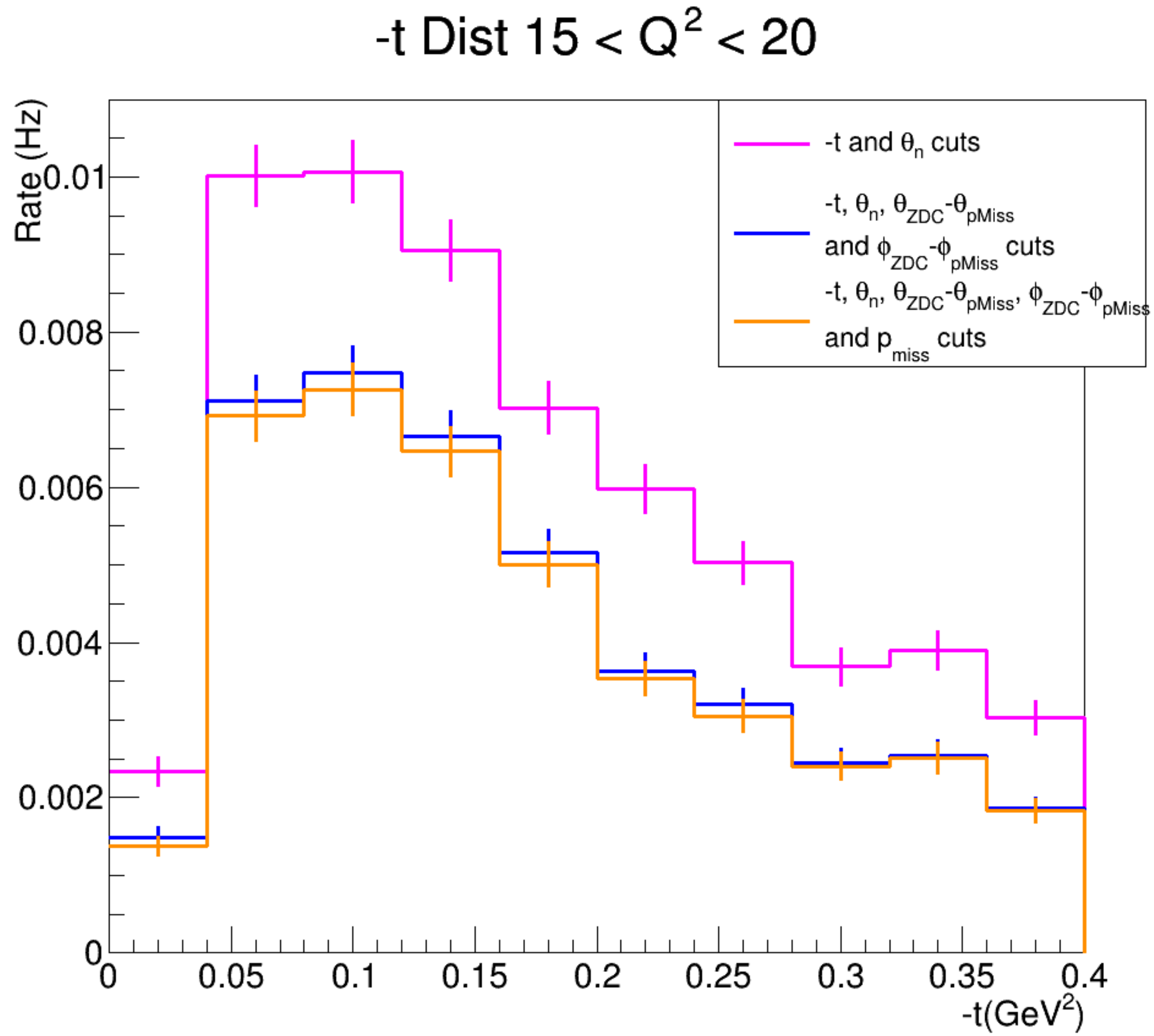
DEMP Rates as Cuts Applied – Q^2=17.5 GeV^2

Rate (Hz) per –*t* bin



Only –*t*<0.4 GeV^2 and triple coincidence cuts

Add ΔθΔφ ZDC cuts

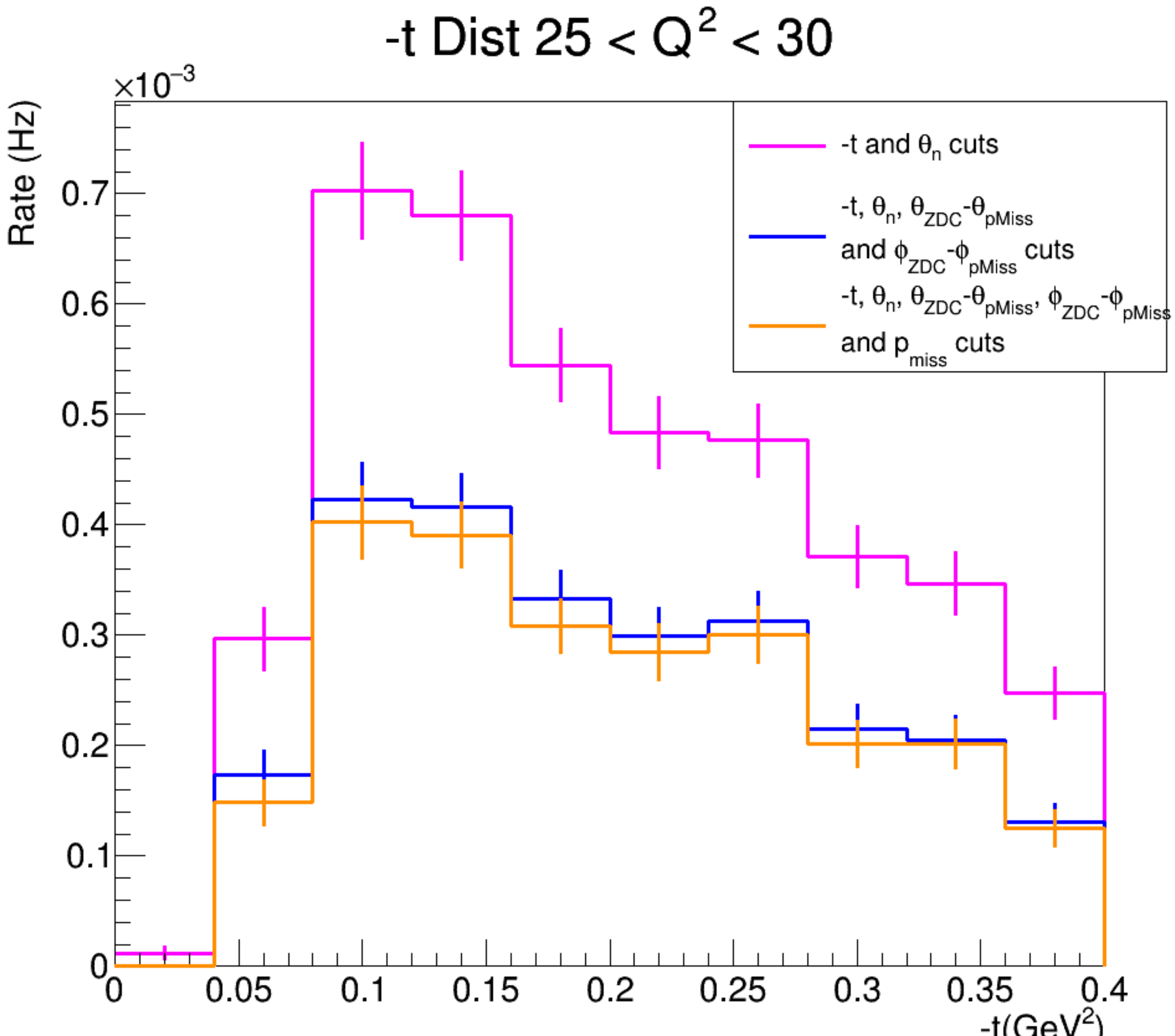
Add p_{miss}<87 GeV cut (removes only SIDIS background)

Plot by Stephen Kay

Garth Huber, huberg@uregina.ca

DEMP Rates as Cuts Applied – Q^2=27.5 GeV^2

Rate (Hz) per –*t* bin



Only –*t*<0.4 GeV^2 and triple coincidence cuts

Add ΔθΔφ ZDC cuts

Add p_{miss}<80 GeV cut
(removes only SIDIS background)

Plot by Stephen Kay

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Separating σ_L from σ_T in e–p Collider

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

- 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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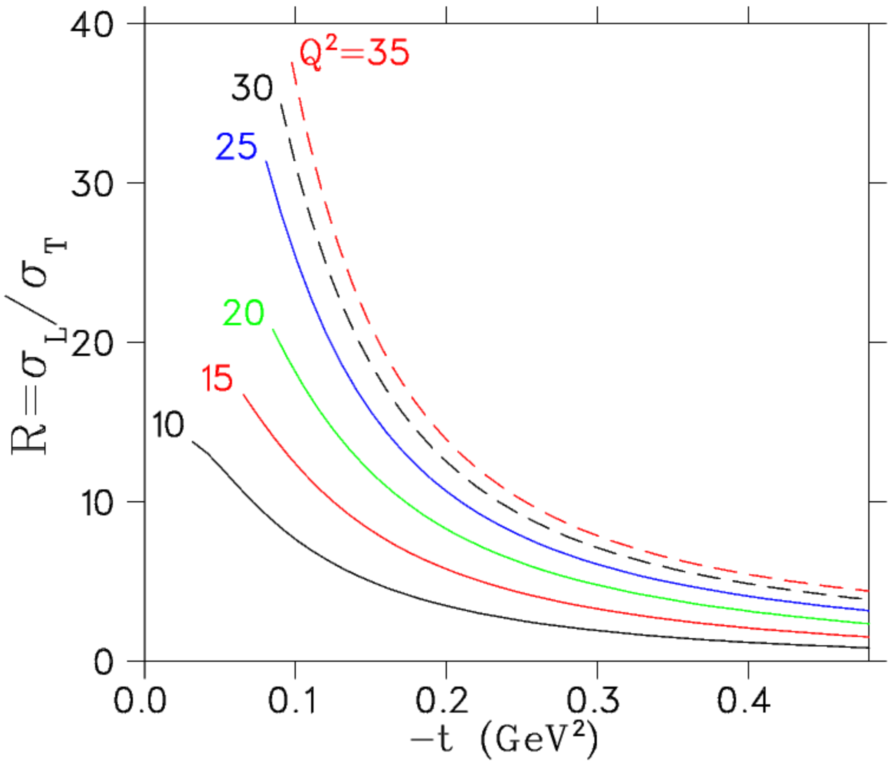
Isolate $d\sigma_L/dt$ using a Model

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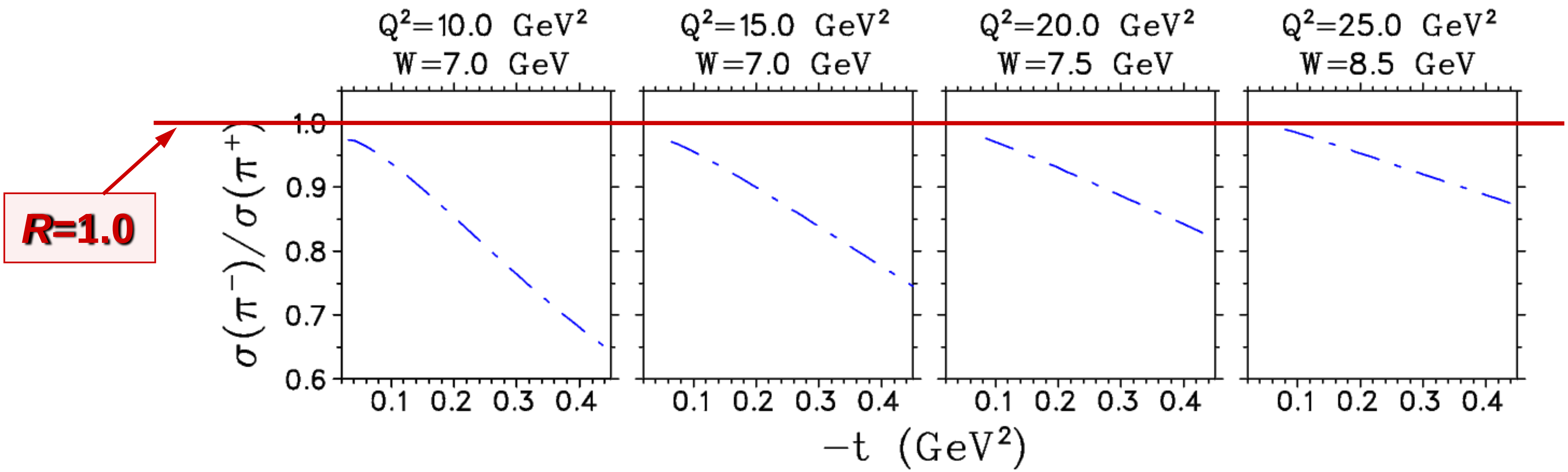
Using π^-/π^+ ratios to confirm $\sigma_L \gg \sigma_T$

- 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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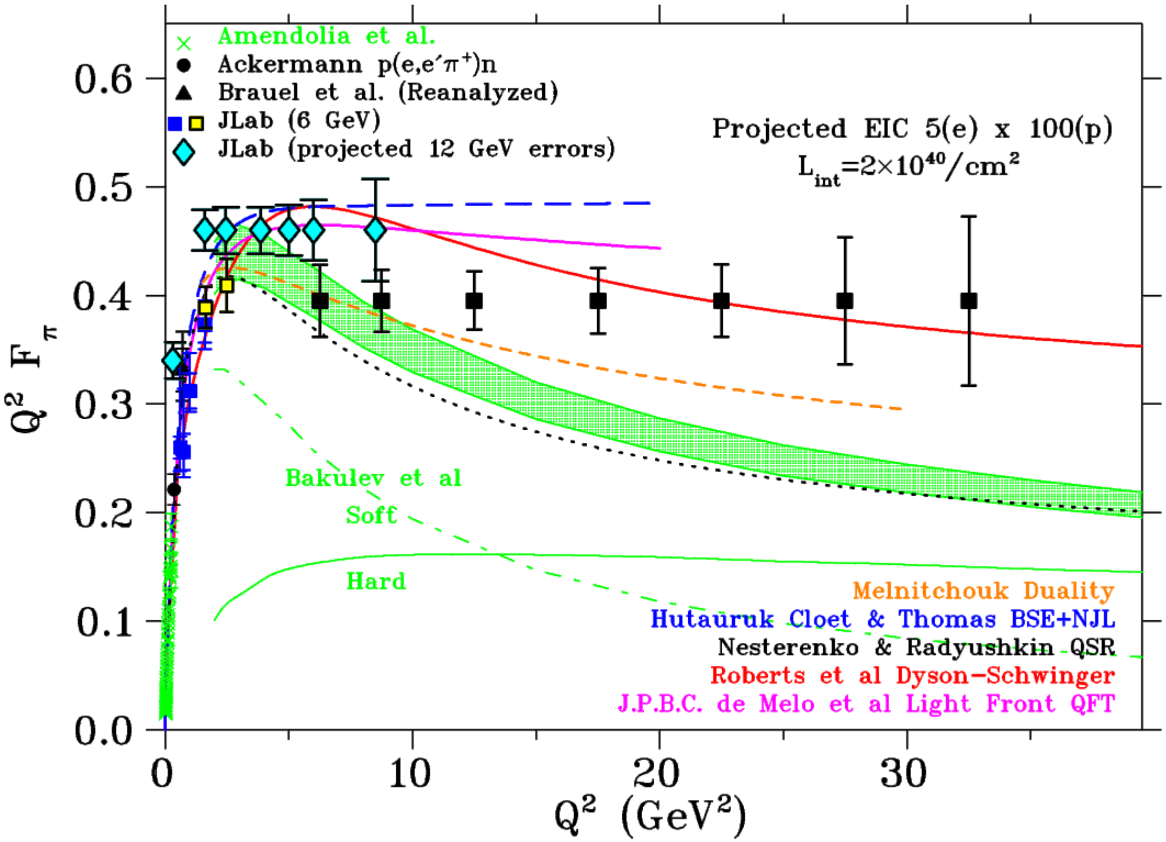
EIC Kinematic Reach (Apr 2022 update)

University of Regina



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 ^2H π^-/π^+ ratios.

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Similar issues to consider at EicC

- **F_π deserves to be an important part of EicC program**
- Experiment coverage should be better optimized for low Q^2 than EIC, the broader overlap with high quality JLab F_π data would be an important contribution
- However, high quality L/T–separations require ε<0.8
  - For Q^2=5 GeV^2 → implies 2(e-) x 5(p) beam energy combination
  - Such low proton ring energies are not planned for EicC
  - JLab will remain the only source of high quality L/T–separated $p(e,e'\pi^+)n$ data for decades to come
- At lower Q^2 and W of EicC, non-pole backgrounds could be larger, and the L/T ratio likely to be less favorable
  - Event generator cannot assume only π–pole process to σ_L, and has to include non–pole and σ_T contributions
  - For F_π extraction from σ_{UNS} data, it will be important to do model tests (such as π^-/π^+ ratio) to confirm the validity of model used for form factor extraction

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Summary

University of Regina

- 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 $Q^2 \approx 30$ GeV^2**

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