Pion Form Factor from Exclusive π^+ Production at EIC

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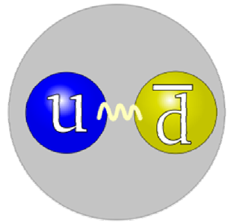
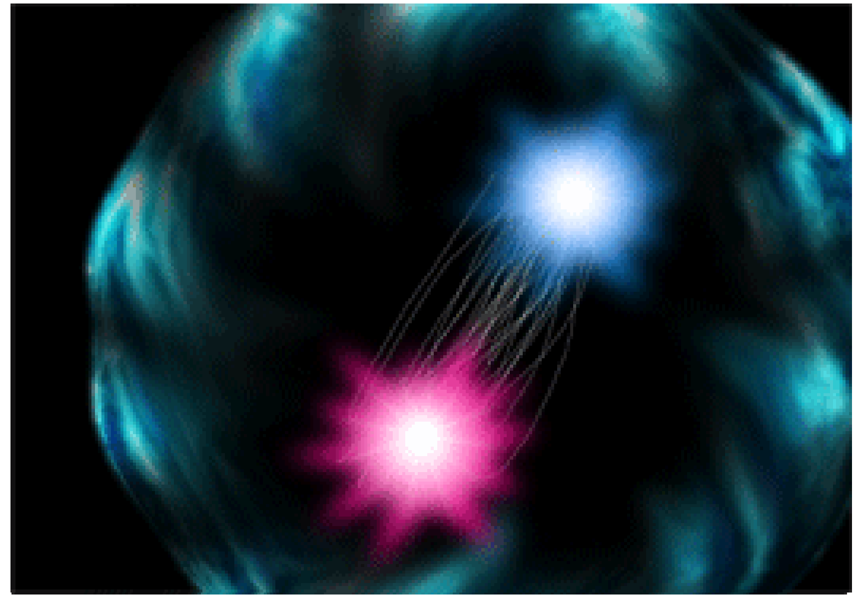
Charged Pion Form Factor

- **The pion is attractive as a QCD laboratory:**
  - Simple, 2 quark system





Pion's structure is determined by two valence quarks, and the quark-gluon sea.

  - Electromagnetic form factor can be calculated exactly at very large momentum transfer (small distances).
  - For moderate Q^2, it remains a theoretical challenge.
    - "the positronium atom of QCD"

Downside for experimentalists:

- No "free" pion targets.
- Measurements at large momentum transfer difficult.

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Measurement of F_π via Electroproduction

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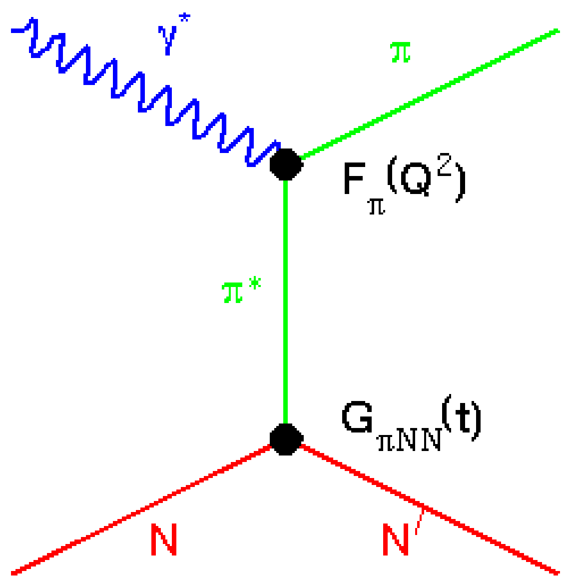
Above Q^2>0.3 GeV^2, F_π is measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

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

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

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



Drawbacks of this technique:

1. Isolating σ_L experimentally challenging.
2. 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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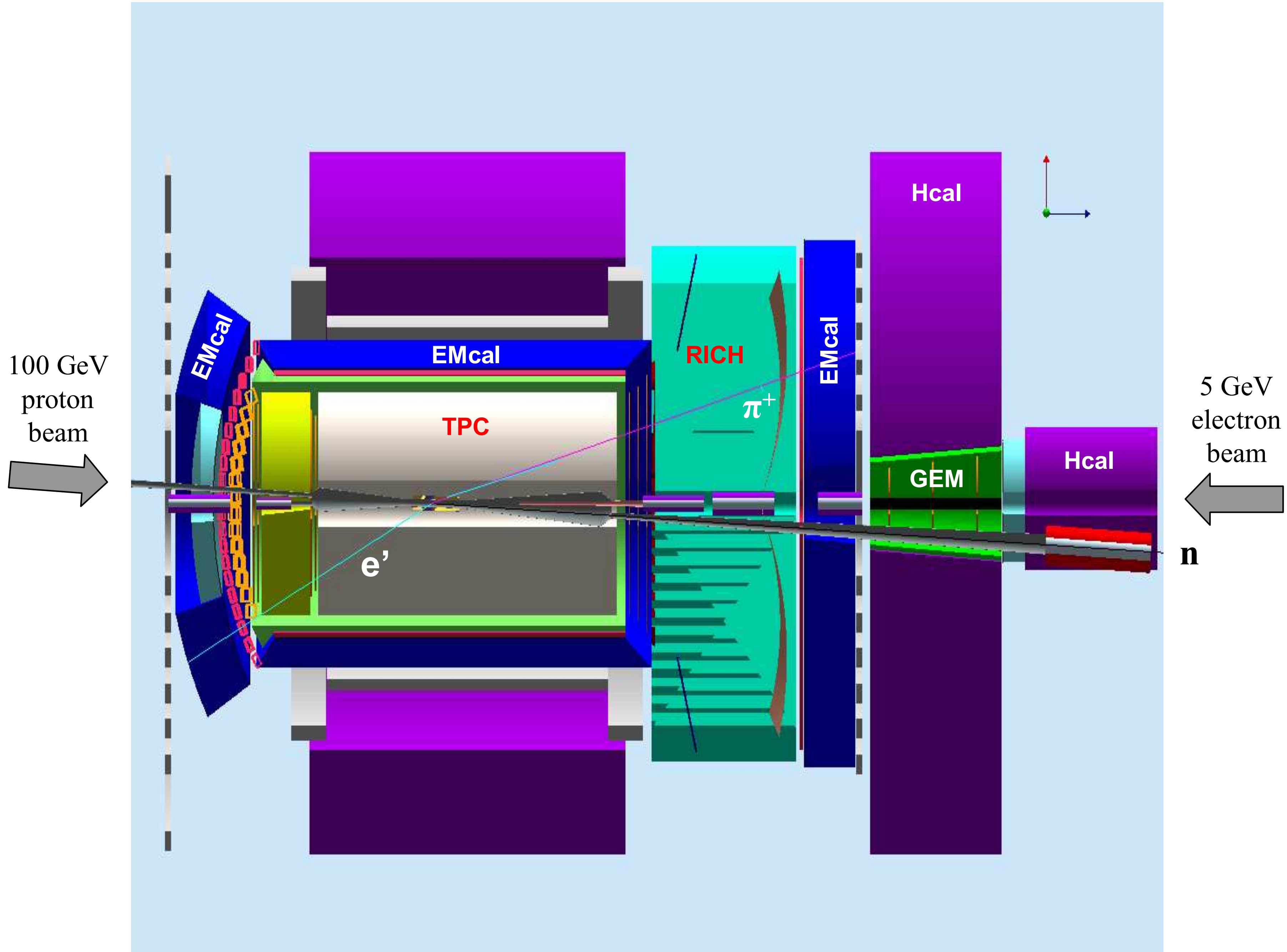
GEMC study of Exclusive $p(e,e'\pi^+)n$



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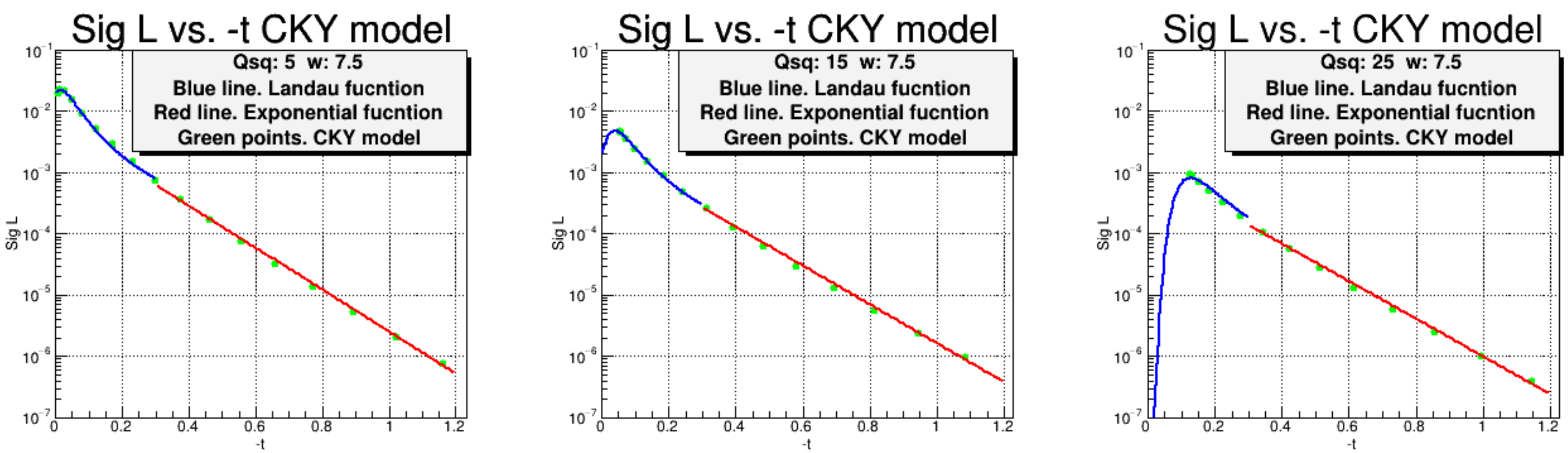
DEMP Event Generator

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

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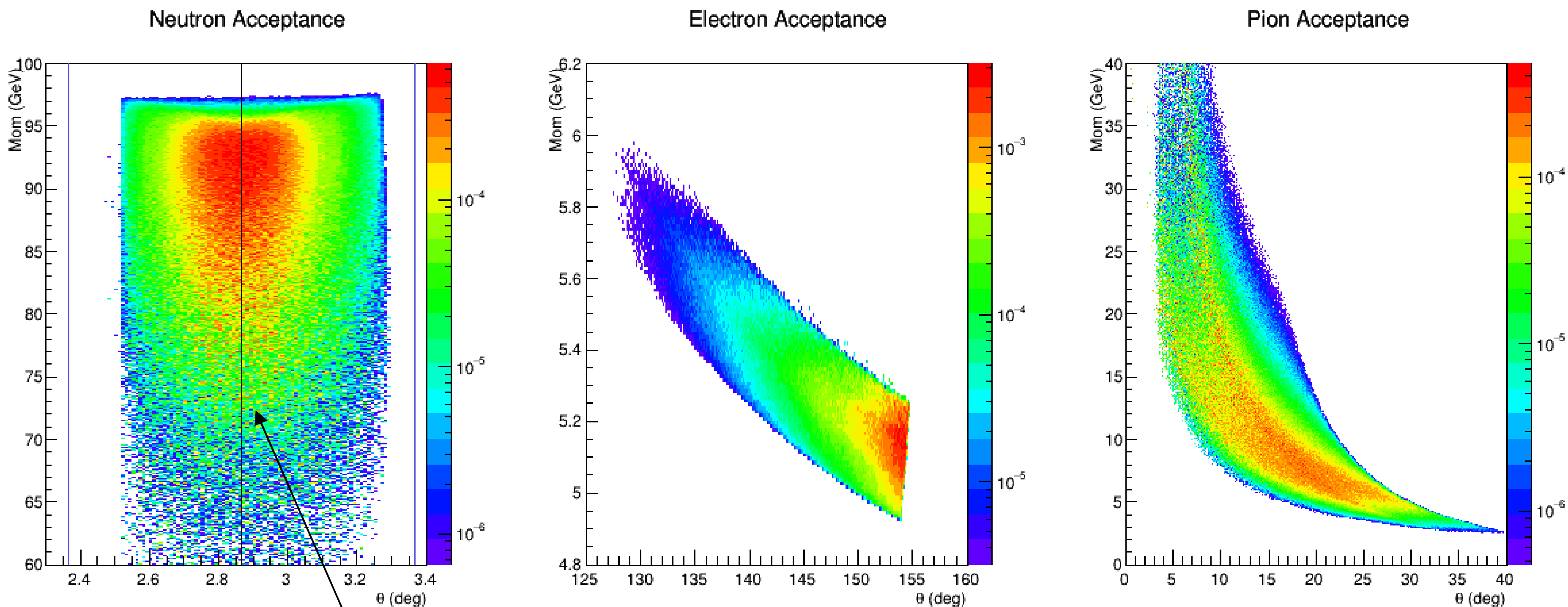
5(e$^-$) x 100(p) GeV Collisions → E_{cm}=44.7 GeV



Offset due to 50 mrad beam crossing angle

Neutrons:
80–98 GeV/c
<0.2° of outgoing proton beam

Scattered electrons:
5–6 GeV/c,
25-45° from outgoing e beam

Pions:
5–12 GeV/c,
7-30° from p beam

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

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

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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 for GEMC (Geant4 based framework originally developed for JLab Hall B)
• GEMC is used to study acceptance and resolution requirements
• GEMC generate files are analyzed by ROOT to make acceptance and missing momentum graphs

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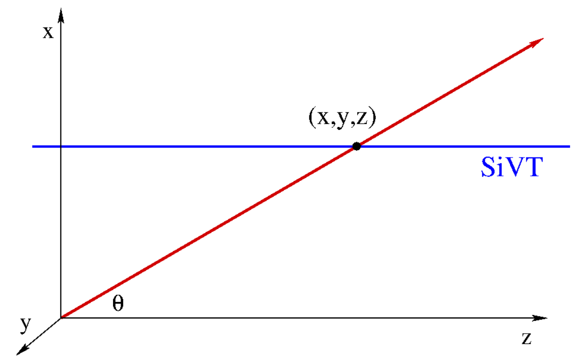
Estimated Detector Resolution

Angular Resolution:

- Simple propagation of error from Cartesian (x,y,z) of SiVT to polar coordinate (θ,φ).
- Assume 10 µm resolution (comparable to ZEUS).

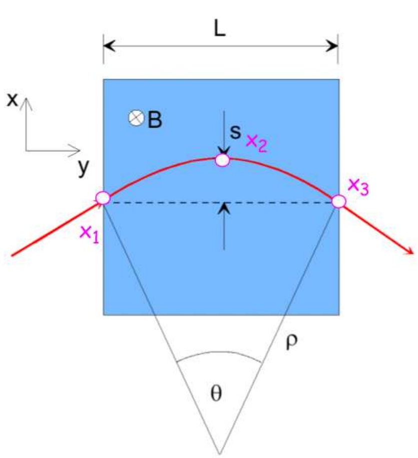
For y=const $(\phi=0^{\circ})$:

$$\delta\theta = \frac{1}{\sqrt{x^2+y^2+z^2}\,(x^2+z^2)}\left[(x^2+y^2)\delta z - zx\delta x\right]$$



- **To simplify MC study, we conservatively assume δp=250µrad for all angles, for both pion and electron, which is an over estimate.**

Momentum Resolution:



- Intrinsic momentum resolution from n equidistant measurements [R.L. Gluckstern NIM **24**(1963)381]

$$\left(\frac{\delta p}{p}\right) = \frac{p}{0.3B}\frac{\sigma_{r\phi}}{L'^2}\sqrt{\frac{720}{n+4}}$$

- B=central field (T)
- $\sigma_{r\varphi}$=position resolution (m)
- L'=length of transverse path through field (m)
- N=number of measurements

n=5, B=3T assumed

- **To simplify study, we conservatively assume δp/p=2% for all angles, for both pion and electron, which is an over estimate**
  - Typical π^+ angles: 7–30°
  - Typical e^- angles: 25–45°

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Comparison of DEMP and SIDIS kinematics

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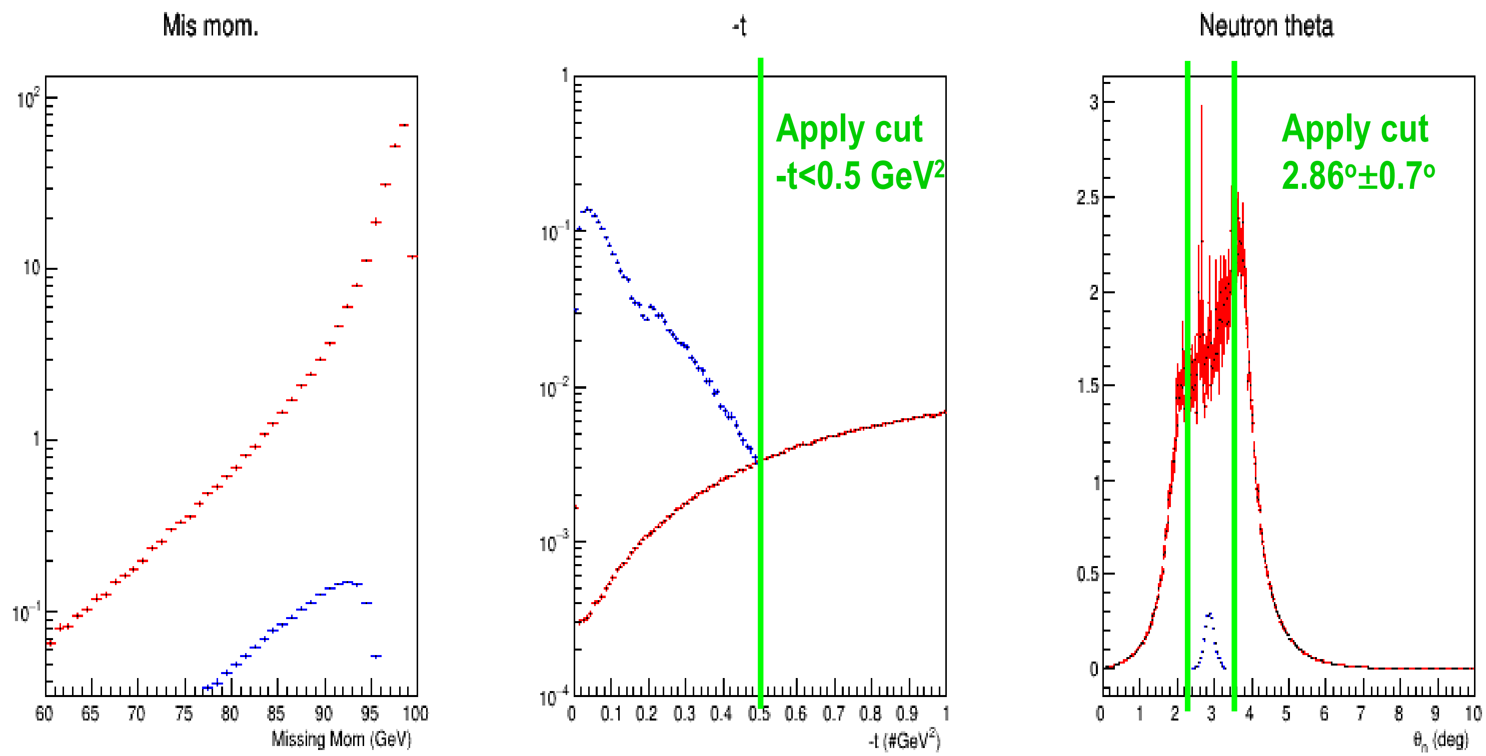
DEMP events are e' π^+ n triple coincidence.
SIDIS events are e' π^+ double coincidence, and p_{miss} reconstructed.

Exclusive
p(e,e'π⁺)n
Foreground

SIDIS
p(e,e'π⁺)X
Background



- As expected, the SIDIS events overwhelm the foreground exclusive events. But they are distributed over a much wider momentum range, and are primarily at larger –*t* than the DEMP events.

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p_{miss} cut vs Q^2–bin

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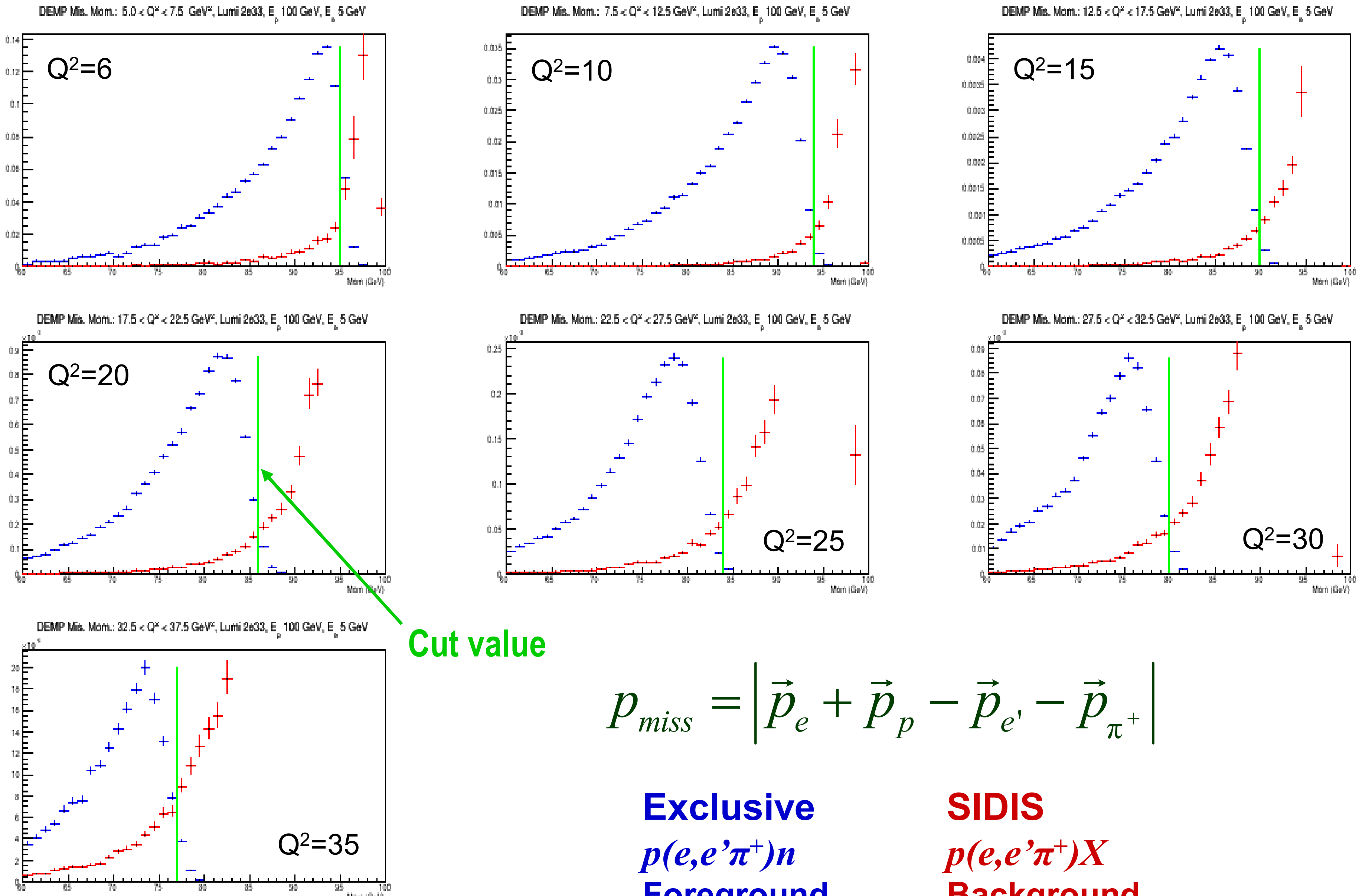

$$p_{miss} = \left| \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+} \right|$$

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

SIDIS
$p(e,e'\pi^+)X$
Background

Rates as Cuts are Applied – Q^2=30 GeV^2

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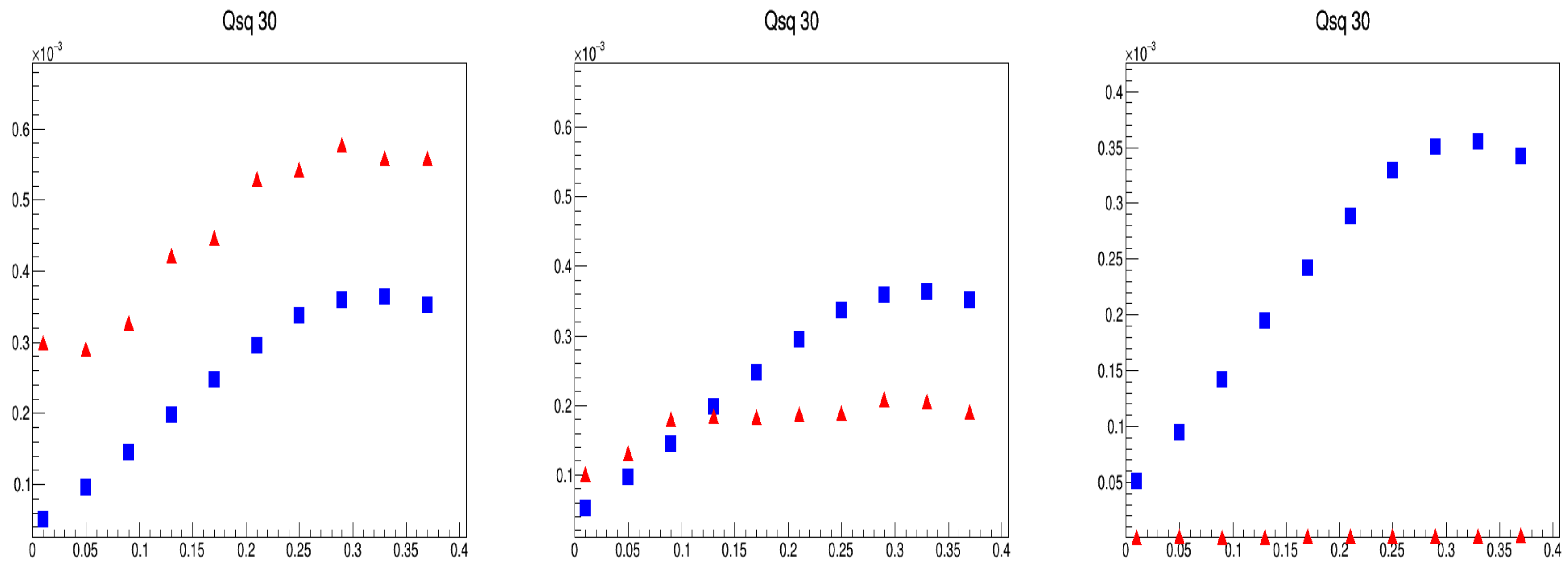
Rate (Hz) per $-t$ bin <0.4 GeV^2

Only $-t$<0.4 GeV^2 cut | Add θ_n=2.86°±0.7° cut | Add p_{miss}<80 GeV cut



Exclusive
p(e,e'π$^+$)n
Foreground

SIDIS
p(e,e'π$^+$)X
Background

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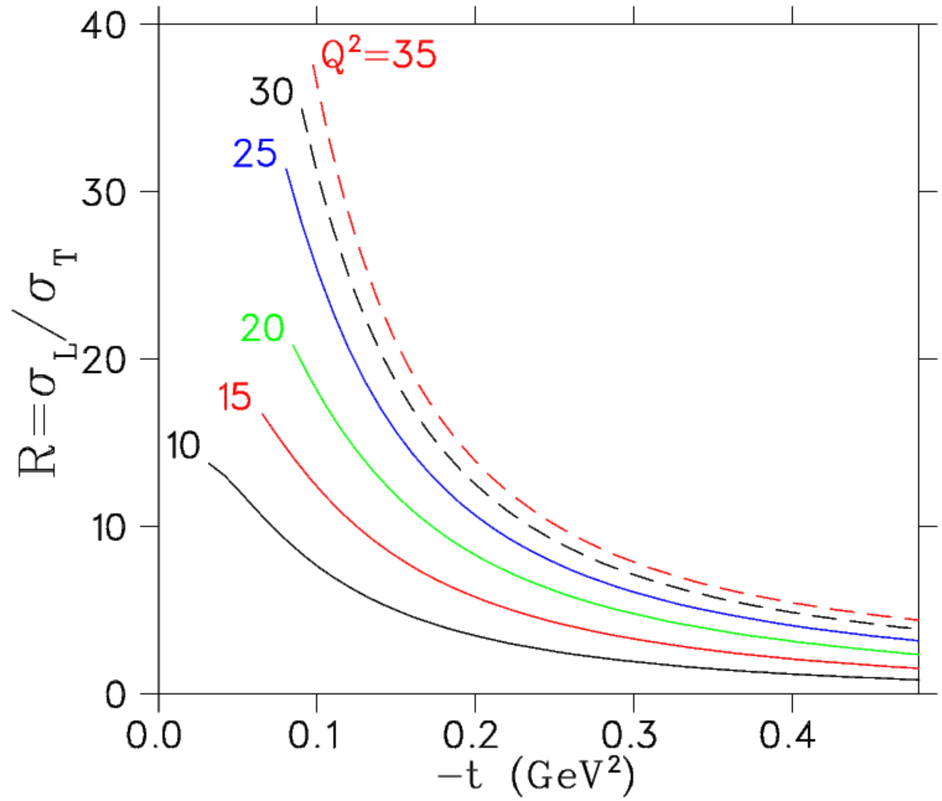
Isolate $d\sigma_L/dt$ using a Model

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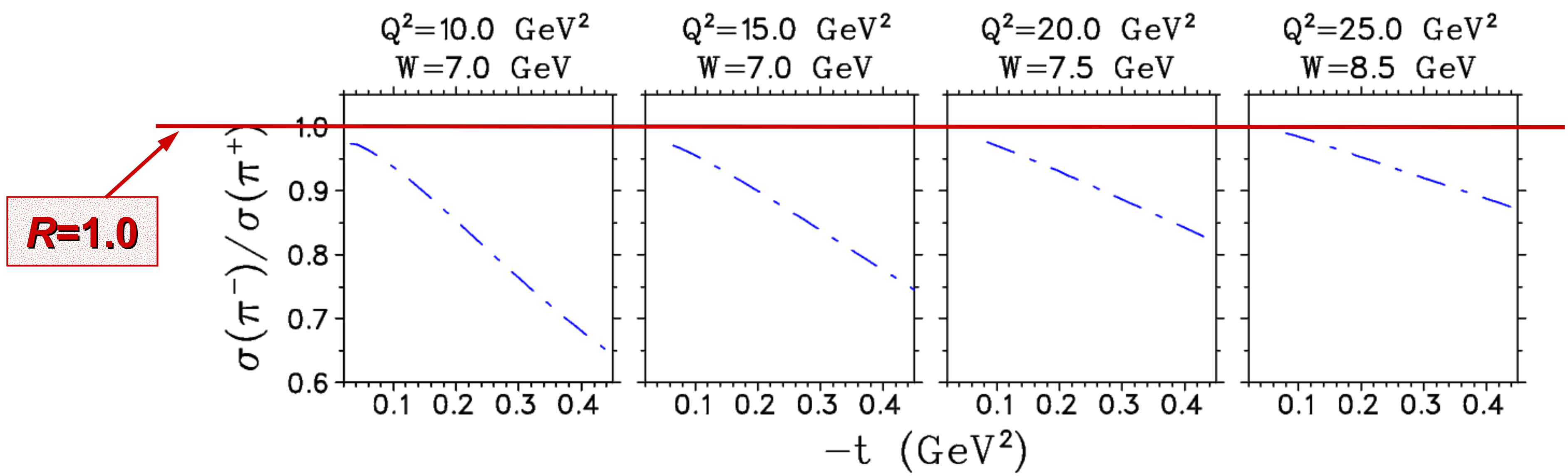
Using π^-/π^+ ratios to confirm $\sigma_L \gg \sigma_T$

- 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.**



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EIC Kinematic Reach (estimate)

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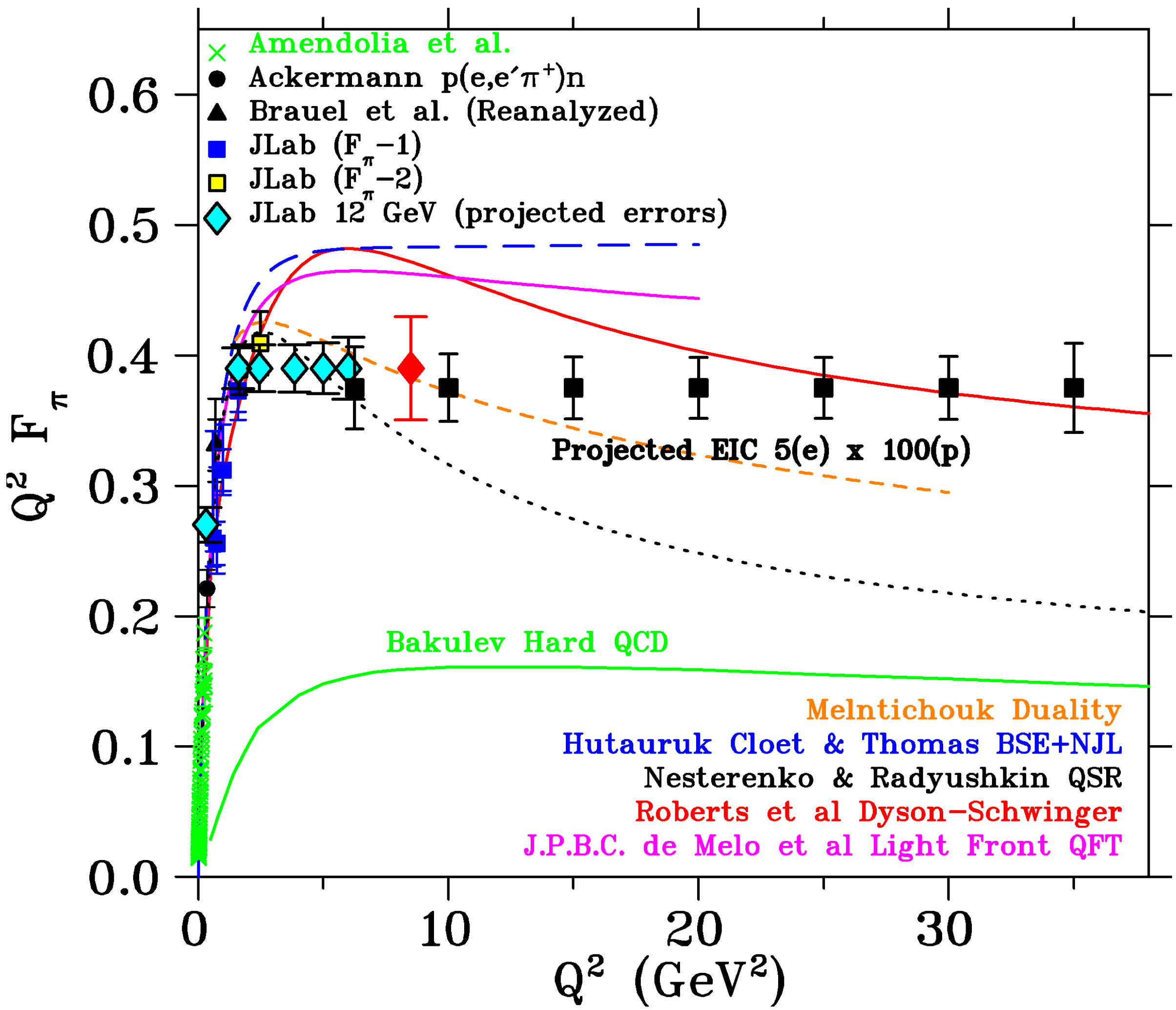

Assumptions:

- 5(e^-) x 100(p).
- Integrated L=20 fb^{-1}/yr.
- Clean identification of exclusive $p(e,e'\pi^+n)$ events.
- 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.

Results look very promising, but more study needed to confirm assumptions.

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