

Pion Form Factor Measurements at EIC

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pQCD and the Pion Form Factor

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

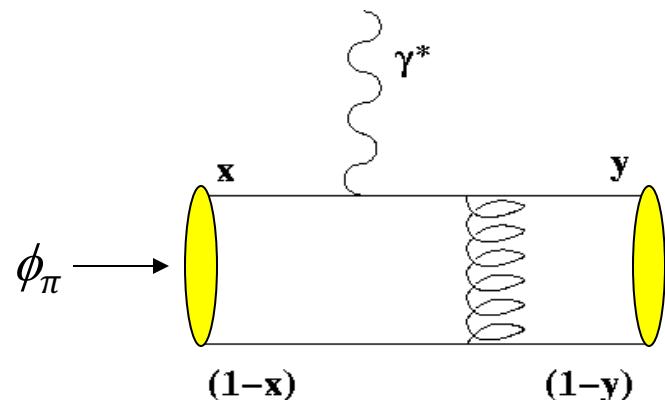
$$F_\pi(Q^2) = \frac{4}{3} \pi \alpha_s \int_0^1 dx dy \frac{2}{3} \frac{1}{xy Q^2} \phi(x) \phi(y)$$

at asymptotically large Q^2 ,
the pion wave function becomes

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

and F_π takes the simple form

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

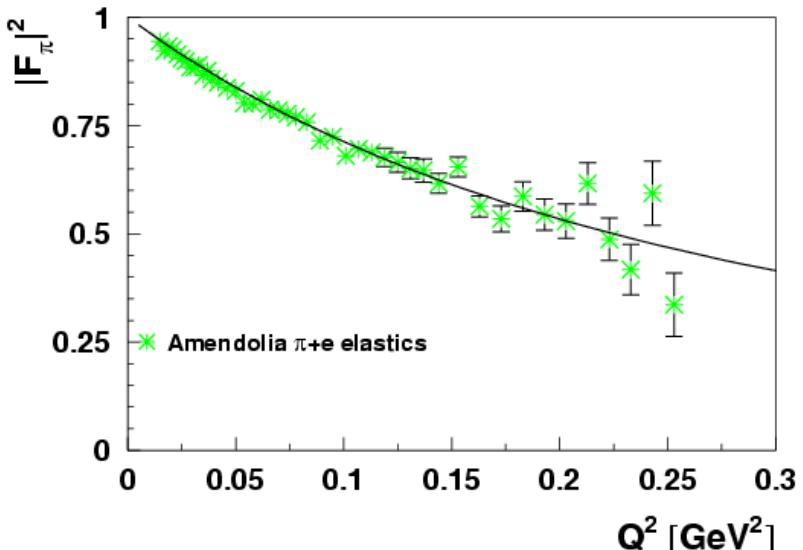


$f_\pi = 93$ MeV is the $\pi^+ \rightarrow \mu^+ \nu$ decay constant.

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

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

- At low Q^2 , F_π can be measured **directly** via high energy elastic π^- scattering from atomic electrons
 - CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25 \text{ GeV}^2$
[Amendolia et al, NPB277, 168 (1986)]
 - These data used to extract the pion charge radius
- $r_\pi = 0.657 \pm 0.012 \text{ fm}$
- Maximum accessible Q^2 roughly proportional to pion beam energy
 - $Q^2=1 \text{ GeV}^2$ requires 1000 GeV pion beam

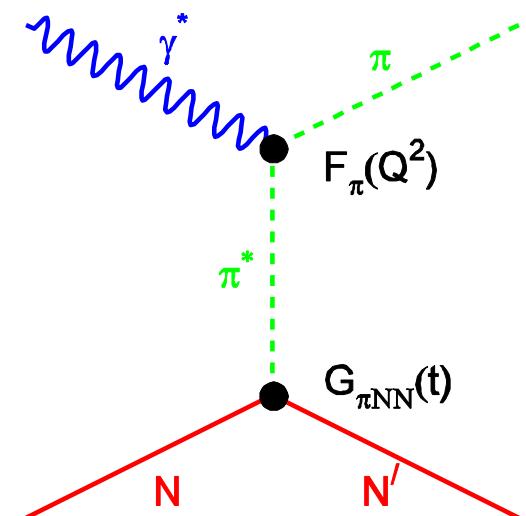


Measurement of π^+ Form Factor – Larger Q^2

- At larger Q^2 , F_π must be measured indirectly using the “pion cloud” of the proton via $p(e,e'\pi^+)n$
 - At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
 - In Born term model, F_π^2 appears as,

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

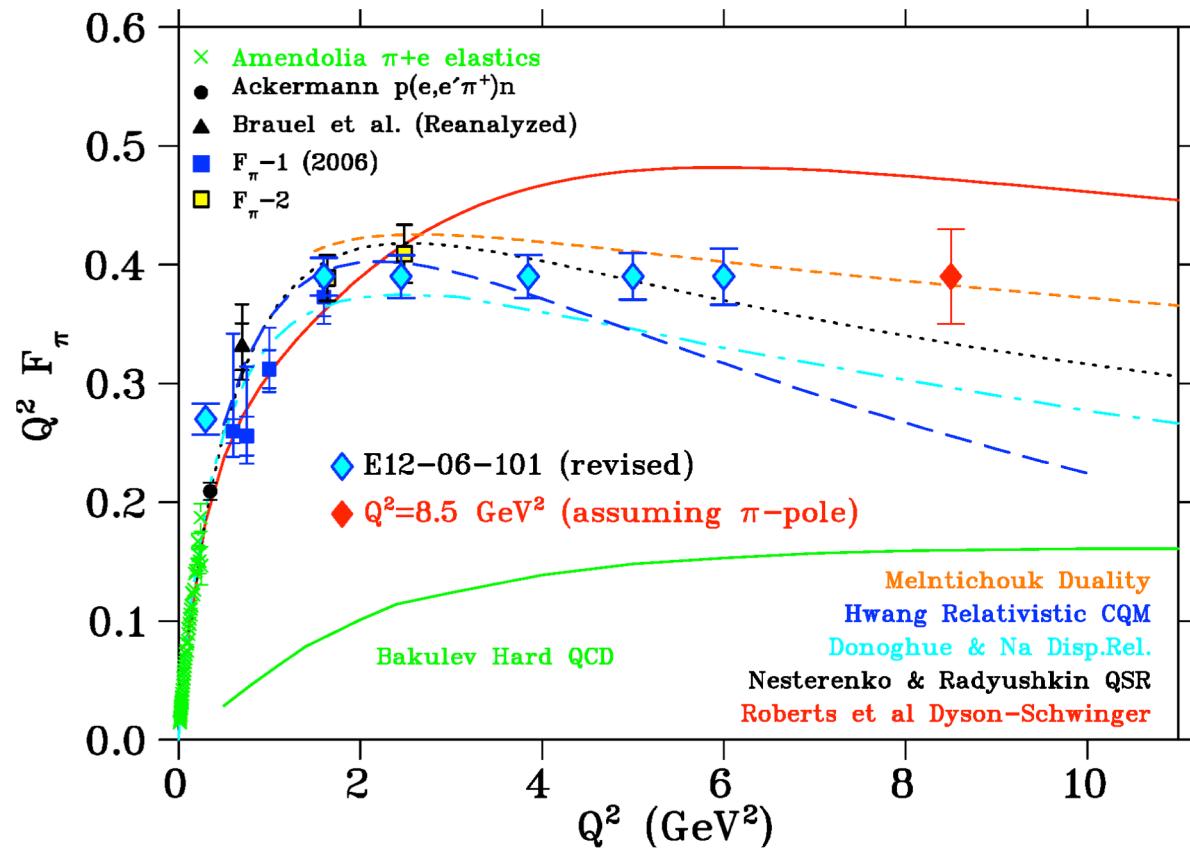
- Drawbacks of this technique
 - Isolating σ_L experimentally challenging
 - Theoretical uncertainty in form factor extraction



$F_\pi(Q^2)$ Kinematic Reach with 12 GeV JLab

JLab 12 GeV
upgrade +
HMS/SHMS will
allow
measurement up
to $Q^2=8.5 \text{ GeV}^2$

EIC can
potentially allow
measurement up
to significantly
larger Q^2



Two key challenges to extracting pion form factor at EIC:

1. Identification of **exclusive** final state
2. Demonstrating dominance of pole process in electroproduction reaction

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

In addition to tagging neutron, selective kinematic cuts can help reduce SIDIS background → more study required

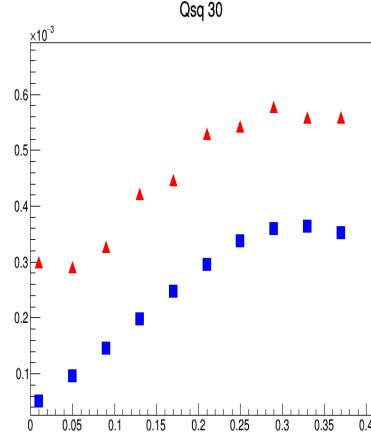
Rates as Cuts are Applied – $Q^2=30 \text{ GeV}^2$



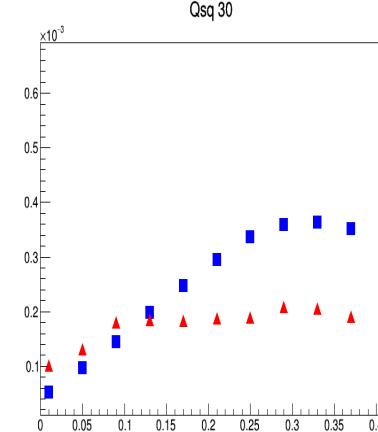
Rate (Hz) per $-t$ bin $<0.4 \text{ GeV}^2$

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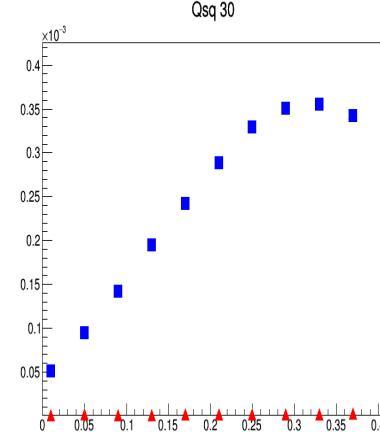
Only $-t < 0.4 \text{ GeV}^2$ cut



Add $\theta_n = 2.86^\circ \pm 0.7^\circ$ cut



Add $p_{\text{miss}} < 80 \text{ GeV}$ cut



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

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

Pole Dominance of $p(e,e'\pi^+)n$ Reaction

At JLab – L-T separation used to isolate pole-dominated σ_L
→ At EIC, will have to rely on model prediction that $\sigma_L \gg \sigma_T$

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

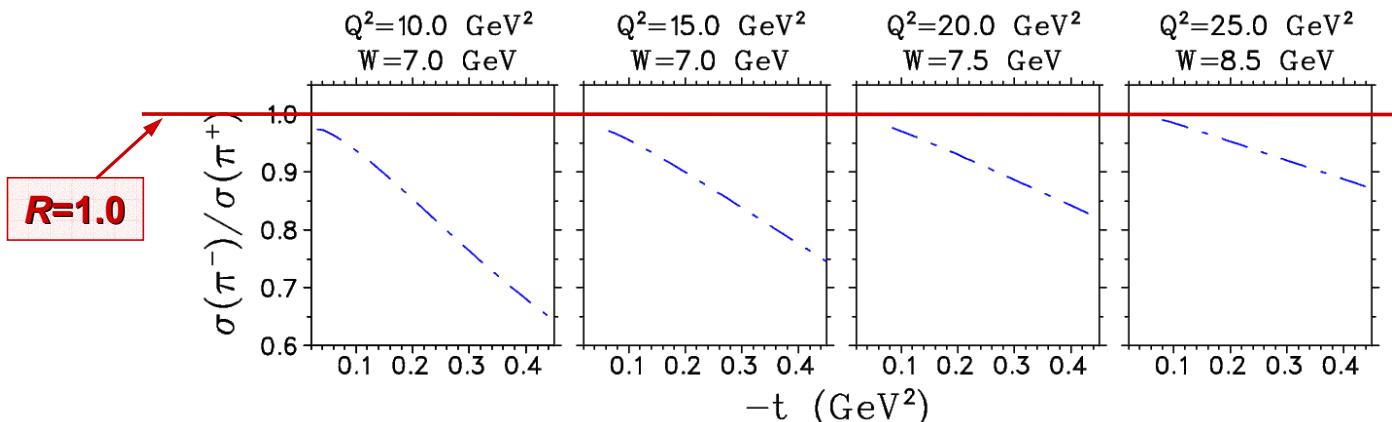


- Exclusive ${}^2\text{H}(e,e'\pi^+n)n$ and ${}^2\text{H}(e,e'\pi^-p)p$ in same kinematics as $p(e,e'\pi^+)n$
- π t -channel diagram is purely isovector (G-parity conservation).

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

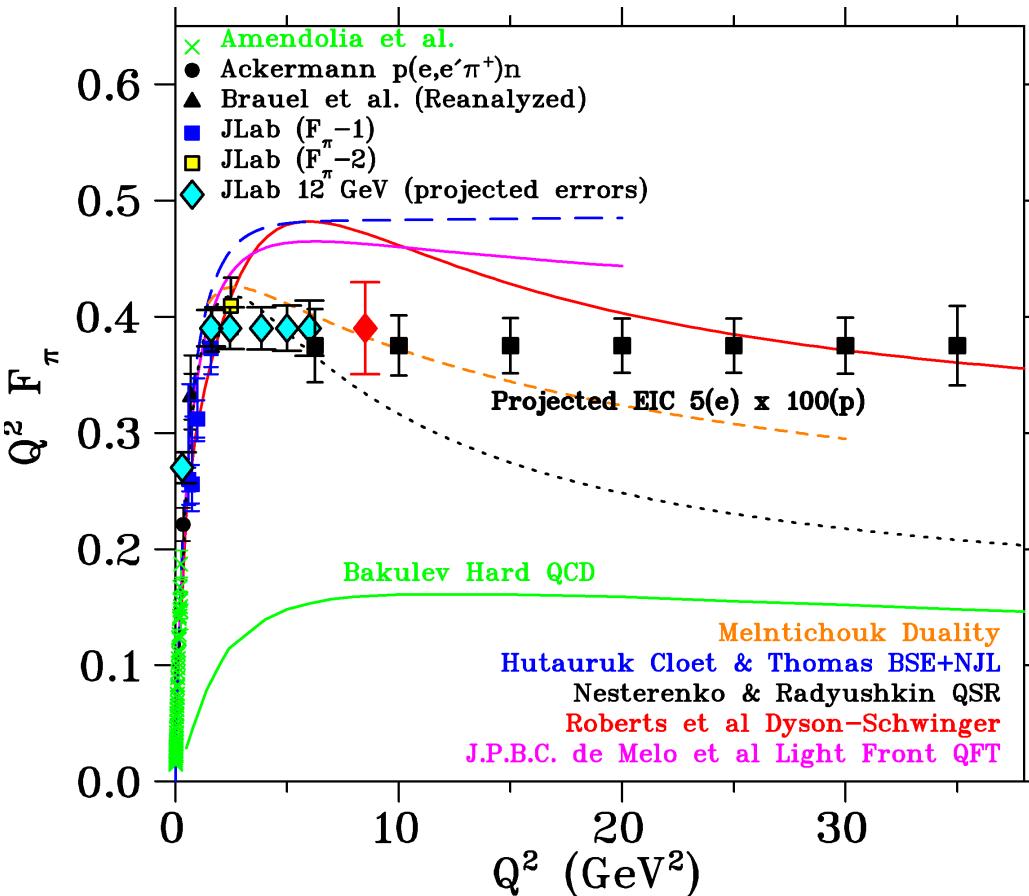
- The π^-/π^+ ratio will be diluted if σ_T is not small, or if there are significant non-pole contributions to σ_L .
- Compare measured π^-/π^+ ratio to model expectations.

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EIC Kinematic Reach (2018 update)

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Assumptions:

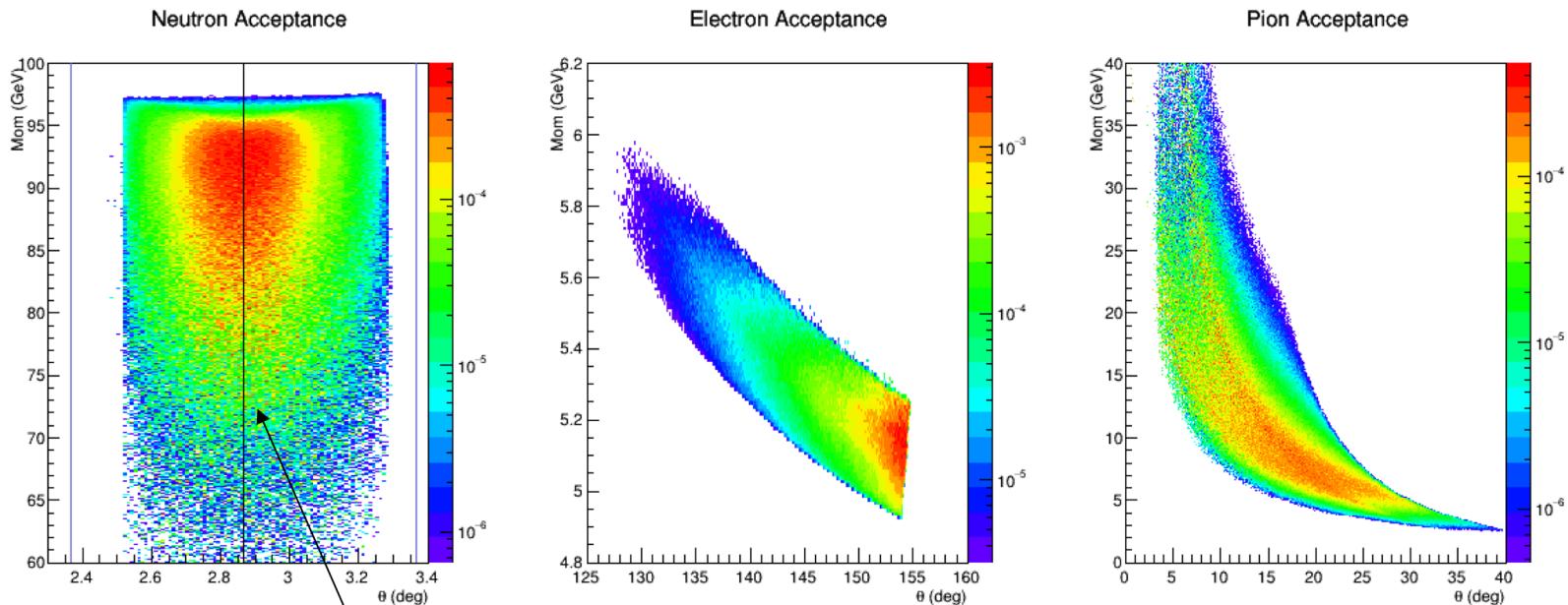
- $5(e^-) \times 100(p)$.
- Integrated $L=20 \text{ fb}^{-1}/\text{yr}$.
- Clean identification of exclusive $p(e, e'\pi^+ n)$ events.
- Syst. Unc: 2.5% pt-pt and 12% scale.
- $R = \sigma_L / \sigma_T = 0.013 - 0.14$ at lowest $-t$ from VR model, and $\delta R = R$ syst. unc. in model subtraction to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

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

EXTRA

DEMP π^+ , n, e' Acceptance for $-t < 0.5$ GeV²

5(e⁻) x 100(p) GeV Collisions $\rightarrow E_{cm} = 44.7$ GeV



Neutrons:
80–98 GeV/c
 $<0.2^\circ$ of outgoing
proton beam

Offset due to
50 mrad beam
crossing angle

Scattered electrons:
5–6 GeV/c,
 $25\text{--}45^\circ$ from outgoing
e beam

Pions:
5–12 GeV/c,
 $7\text{--}30^\circ$ from p beam

Assure exclusivity of $p(e,e'\pi^+n)$ reaction by detecting neutron

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

Separating σ_L from σ_T in e–p Collider

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

- 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 .**