Exclusive Charged Pion Electroproduction with Nucleon Tagging

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Exploring Hadron Structure with Tagged Structure Functions

January 18, 2014

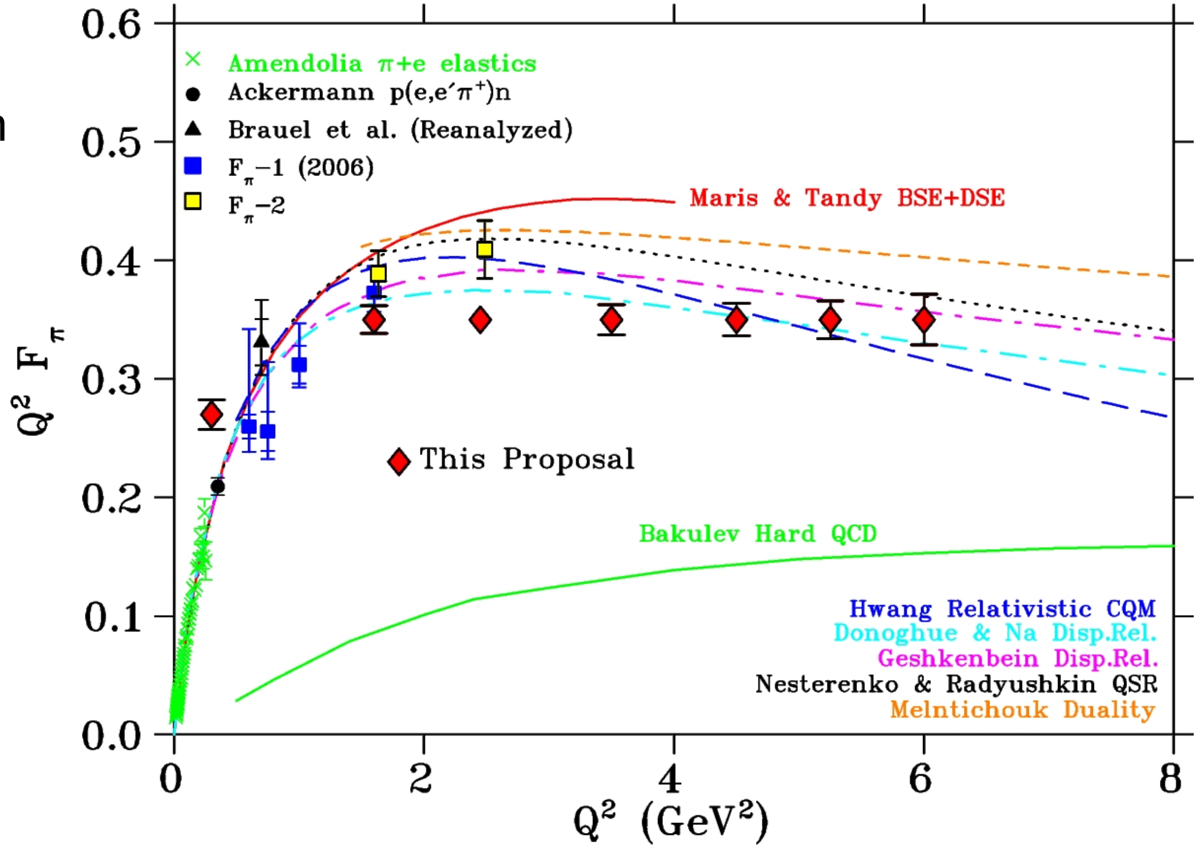
JLAB F_π Program – 6 and 12 GeV

JLab 6 GeV – 2 experiments extracted the elastic pion form factor

F_π-1: $Q^2 = 0.6, 0.75\ 1.6$ GeV^2
F_π-2: $Q^2 = 1.6, 2.5$ GeV^2

JLab 12 GeV upgrade will allow measurement of F_π up to Q^2=6 GeV^2

Primary constraint on maximum value of Q^2 accessible is the need to measure the cross section close to the pole



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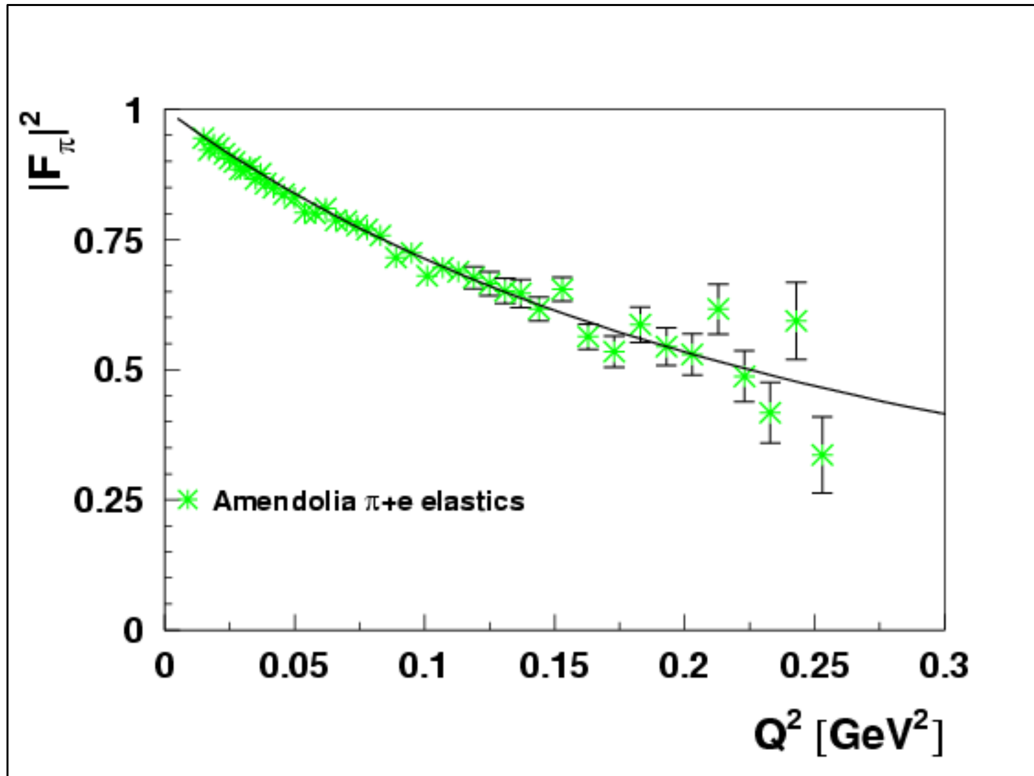
Measurement of π^+ Form Factor – Low Q^2

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 $Q^2 = 0.25$ GeV^2 *[Amendolia et al, NPB277, 168 (1986)]*

→ 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 1000 GeV pion beam

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

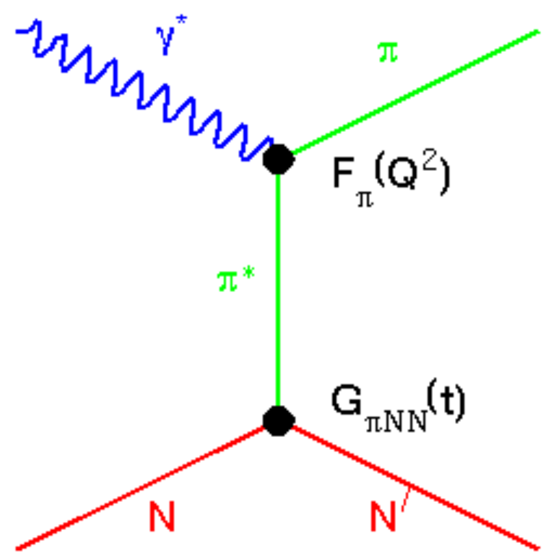
At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via pion $p(e,e'\pi^+)n$

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

→At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L

→In Born term model, F_π^2 appears as,

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

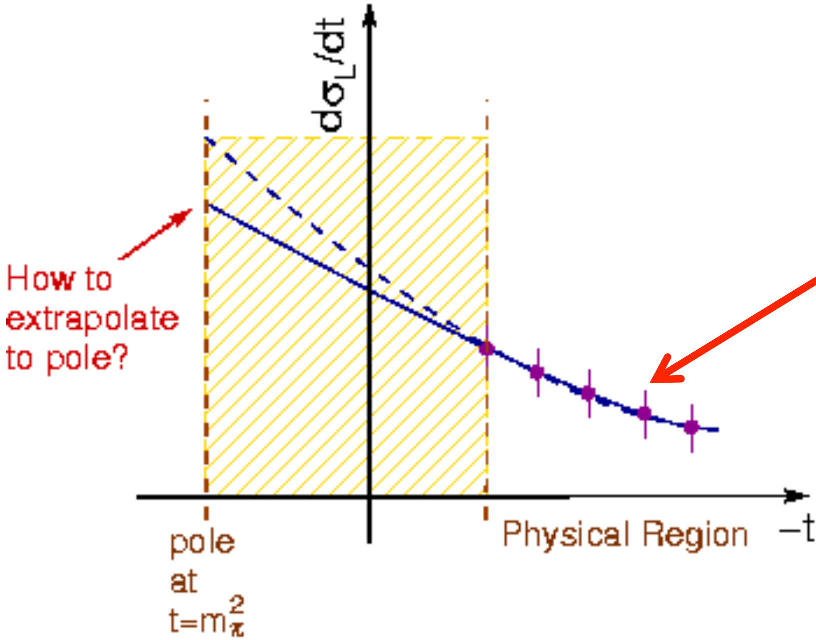


Drawbacks of this technique

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

Extraction of π^+ Form Factor in $p(e,e'\pi^+)n$

π^+ electroproduction can only access $t<0$ (away from pole)



Early experiments used "Chew-Low" technique
1. Measured $-t$ dependence
2. Extrapolated to physical pole

Chew-Low extrapolation unreliable[1] – FF depends on fit form

Fitting/constraining a ***model*** incorporating FF is a more robust technique
→ *t-pole* "extrapolation" is implicit, but one is only fitting data in physical region

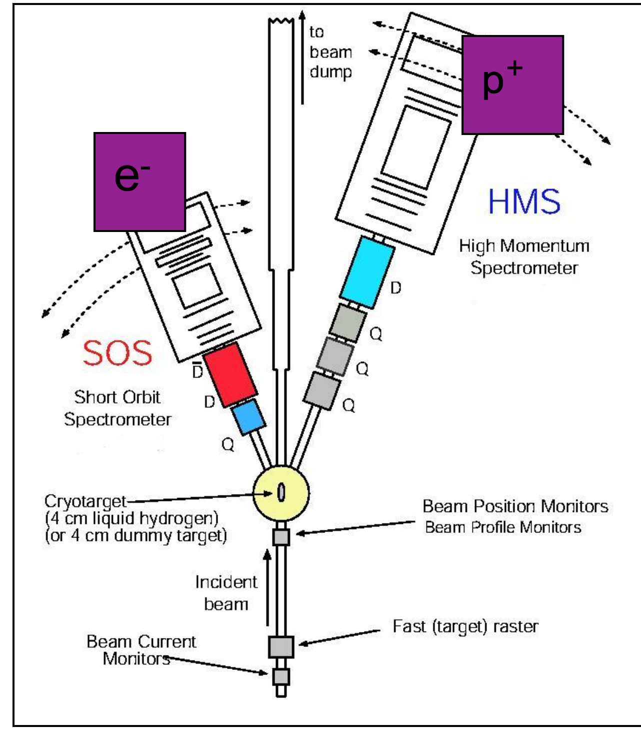
[1]see PRC 78, 045203 (2008) for more details on this

JLab F_π Experiment Details

Reaction:

$$e + p \rightarrow e' + \pi^+ + n$$

beam SOS HMS undetected



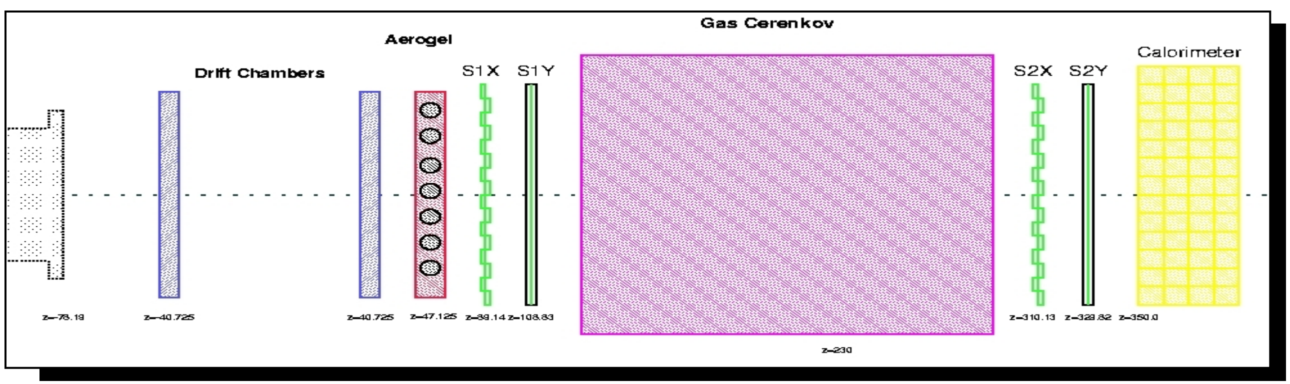
Electron ID in SOS:

→Threshold gas Cerenkov detector

→Lead-glass detector ($E/p_{reconstructed}$)

Pion ID in HMS:

→Aerogel Cerenkov detector

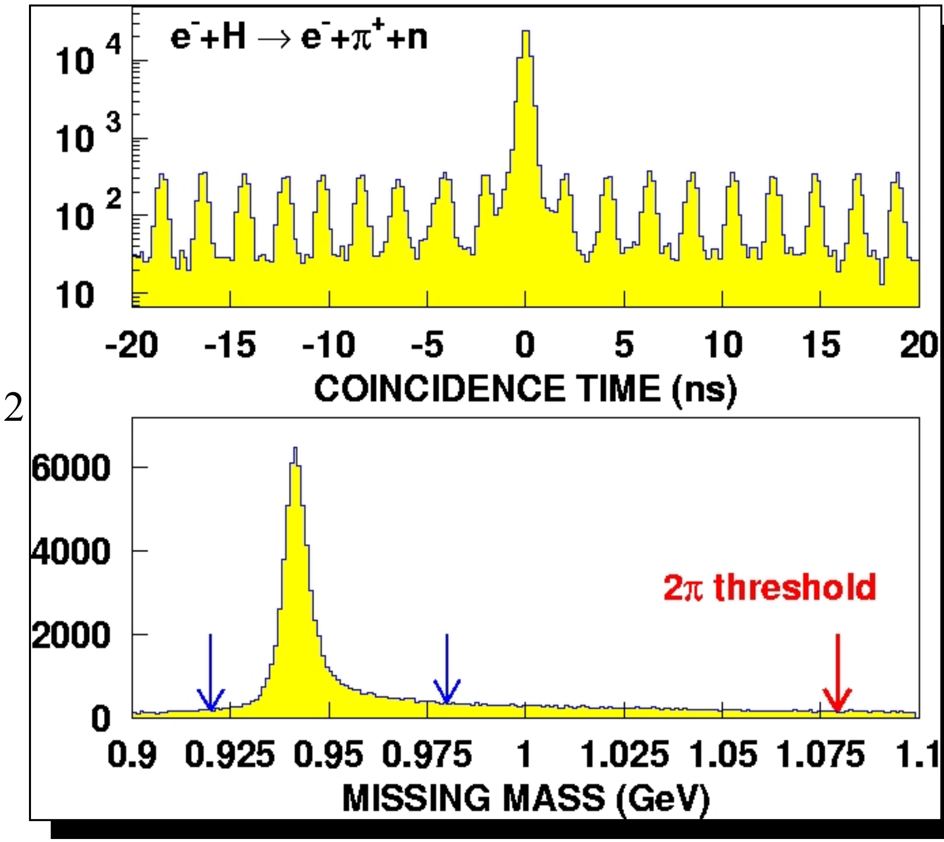


p(e,e'π⁺)n Event Selection

1. Select electrons in SOS and pions in HMS
2. Reconstruct undetected neutron mass

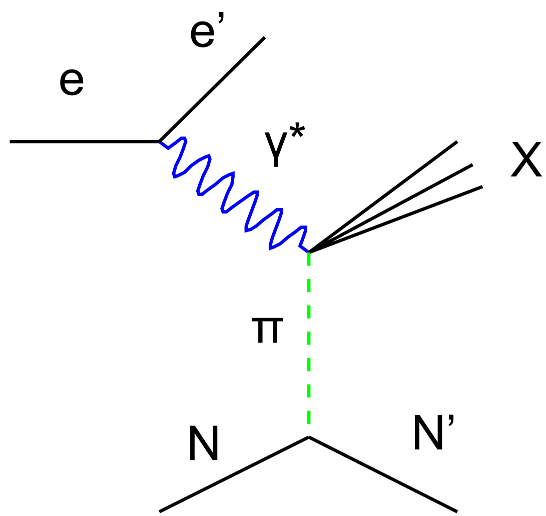
$$M_n^2 = (P^{\mu}_{e-beam} + P^{\mu}_{p} - P^{\mu}_{e'} - P^{\mu}_{\pi})^2$$

3. Identify events that arrived simultaneously in HMS and SOS



Pion Structure Function vs. Pion Form Factor

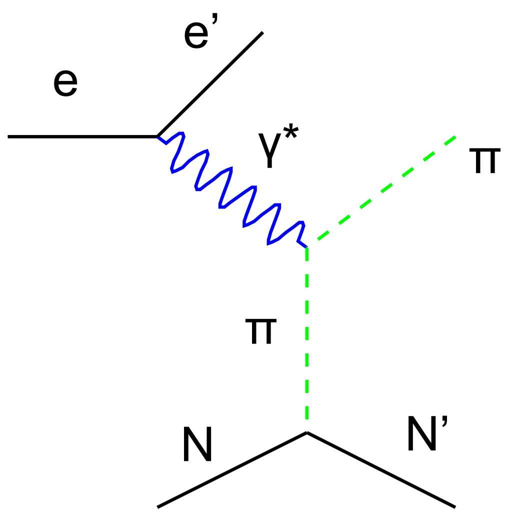
Both $F_2^{\pi}(x)$ and $F_{\pi}(Q^2)$ measurements use pion cloud of nucleon to provide “virtual pion” target



Pion structure function – “inclusive” final state

→ Hadron detection needed to “tag” virtual pion

→ Kinematic constraint: $-t > x_{\pi}^2 M_N^2/(1-x_{\pi})$



Pion form factor – real pion in final state tags the virtual pion

→ Similar constraint for $-t_{min}$

→ Hadron tagging not useful for getting closer to pole

$$t = (p_{N'} - p_N)^2 = m_N^2 + m_{N'}^2 - 2m_N E_{N'}$$

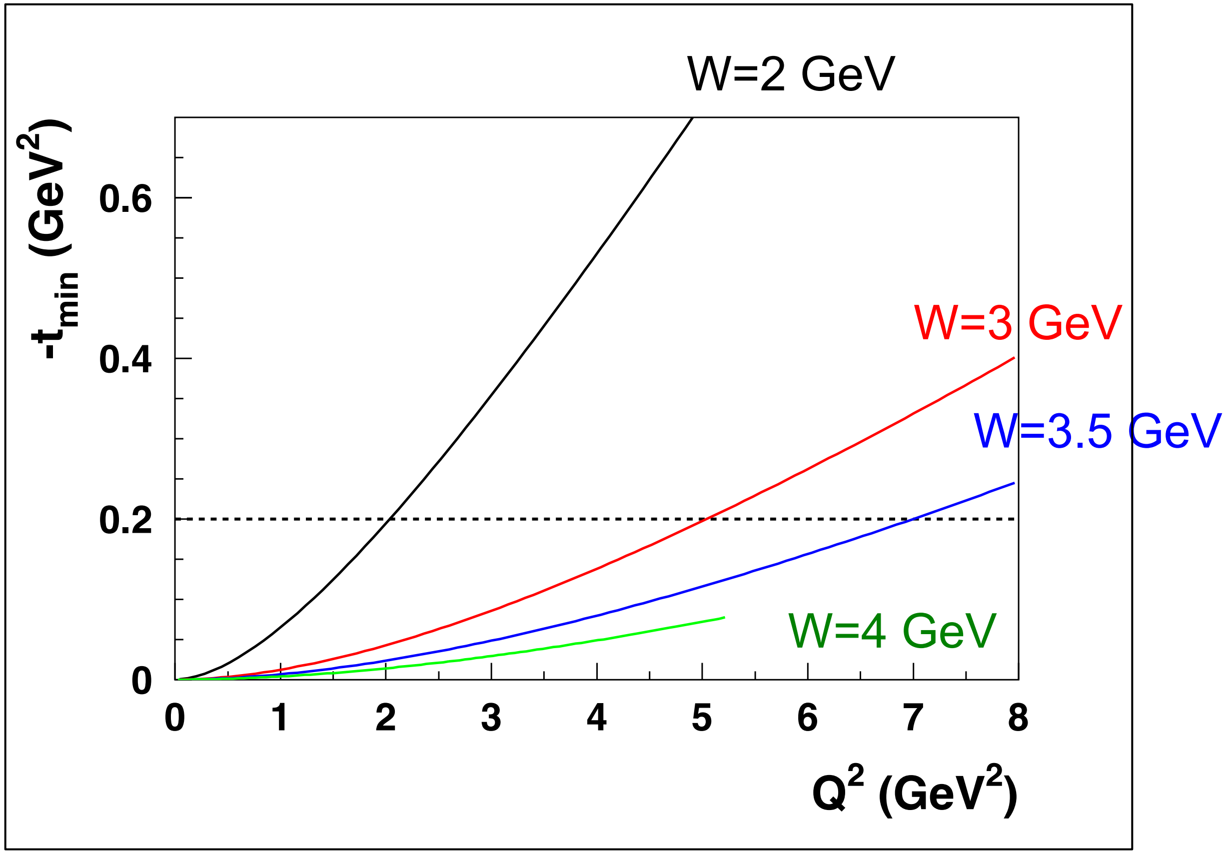
Kinematic Constraints on $-t_{min}$

Beam energy = 11 GeV

Minimum value of –t reached when pion emitted in direction of virtual photon

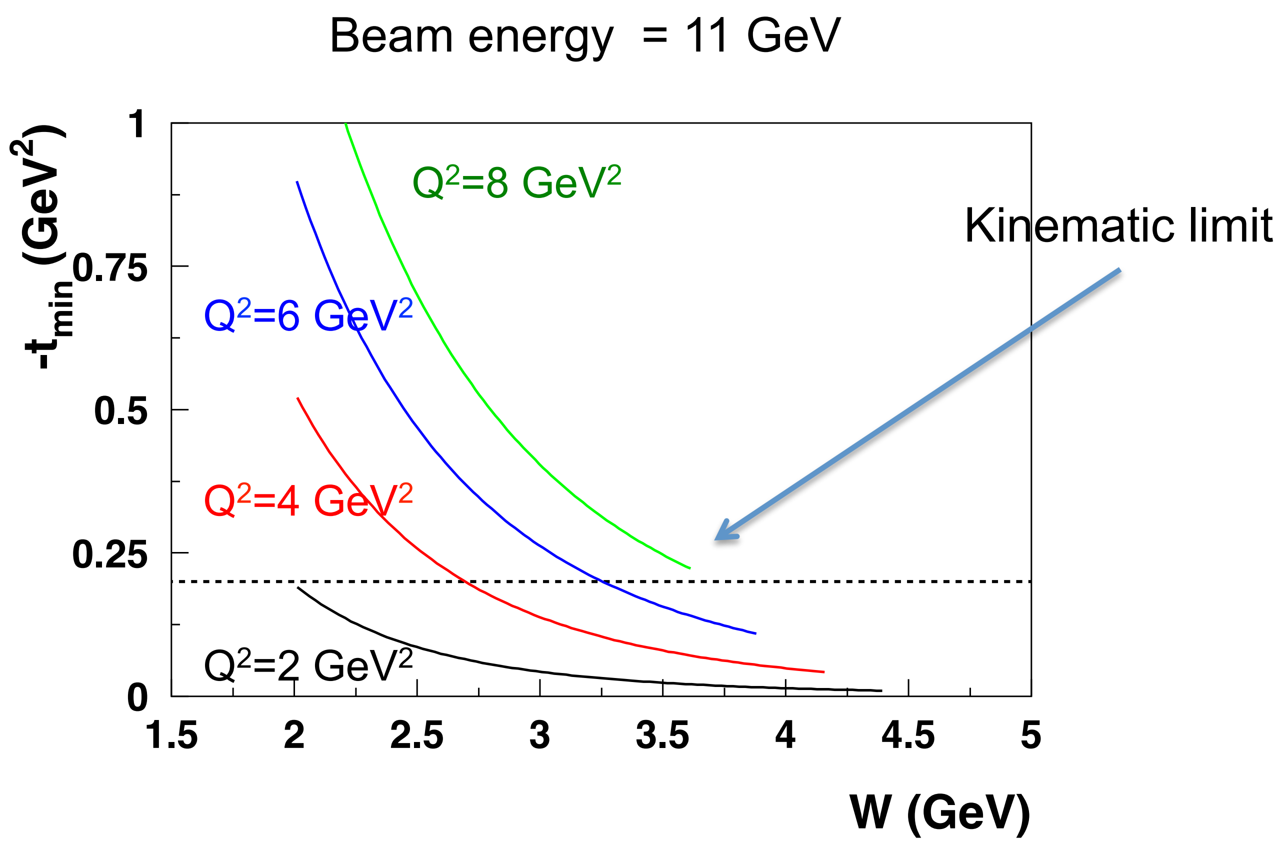
Require $-t_{min}$<0.2 for form factor extraction

F_{π}-12 will reach Q^2=6 GeV^2 detecting scattered electron and pion



Note: F_{π}-12 reach also constrained by requirements to detect forward pion

Kinematic Constraints on $-t_{min}$



Ultimate Q^2 reach of pion form factor program at JLab dictated by beam energy, and minimum accessible pion angle.

Separated π-/π+ Ratios

- F_π-1 and F_π-2 measured π-/π+ cross sections and ratios in the *D(e,e'π+)nn* and D*(e, e'π-)pp* reactions
- Longitudinal ratios:
  - Pole dominance implies $\sigma_L(\pi-)/\sigma_L(\pi+) \sim 1$
  - Deviation from 1 suggests non-pole backgrounds → complications for pion form factor extraction
- Transverse ratios
  - As –*t* increases, $\sigma_T(\pi-)/\sigma_T(\pi+)$ approaches ¼ → implies scattering from quarks in nucleon
- Extraction of ratios from deuterium → assumes that nuclear effects are either small or largely cancel in the ratio
  - Example: proton-proton, neutron-neutron final state interactions known not to exactly cancel at very small relative momentum
  - Any issues due to nucleon virtuality?

Separated π-/π+ Ratios

π-/π+ ratios from F_π-1 and F_π-2

$R_L \sim 1 \rightarrow$ pion pole dominance

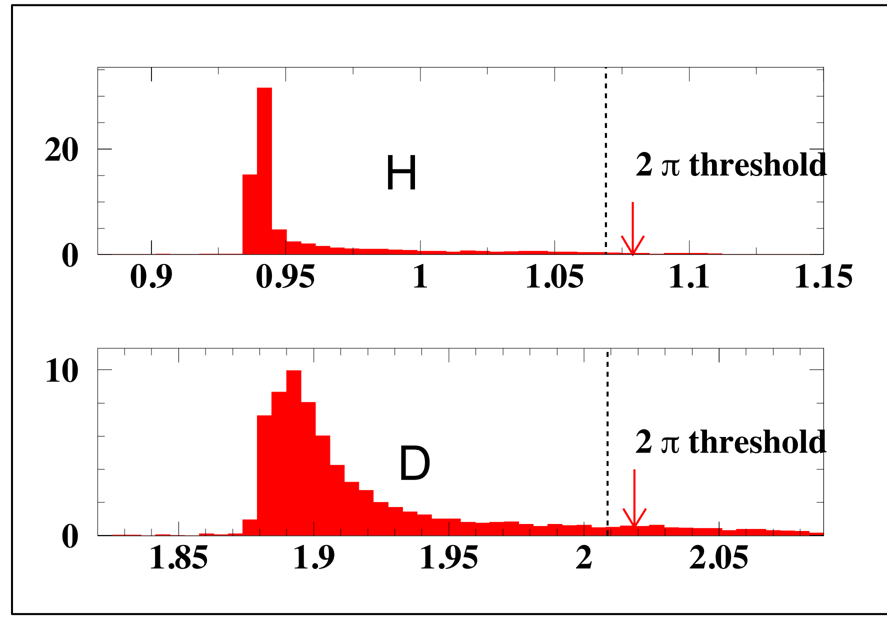
To appear soon.

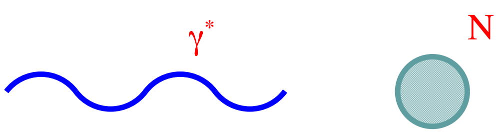
$R_T \rightarrow 1/4$ at large $-t$, scattering from quarks (?)

Quasifree D(e,e'π)

Missing mass not fixed to one value for pion production from deuterium – nucleon momentum distribution broadens distribution

Momentum distribution can also impact effective kinematics at the virtual photon-nucleon vertex

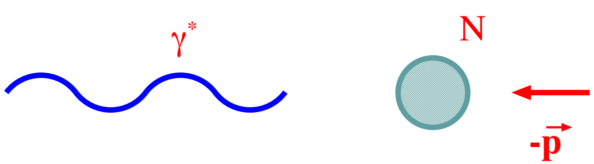




W = total center of mass energy

= $W_{stationary}$

$W < W_{stationary}$



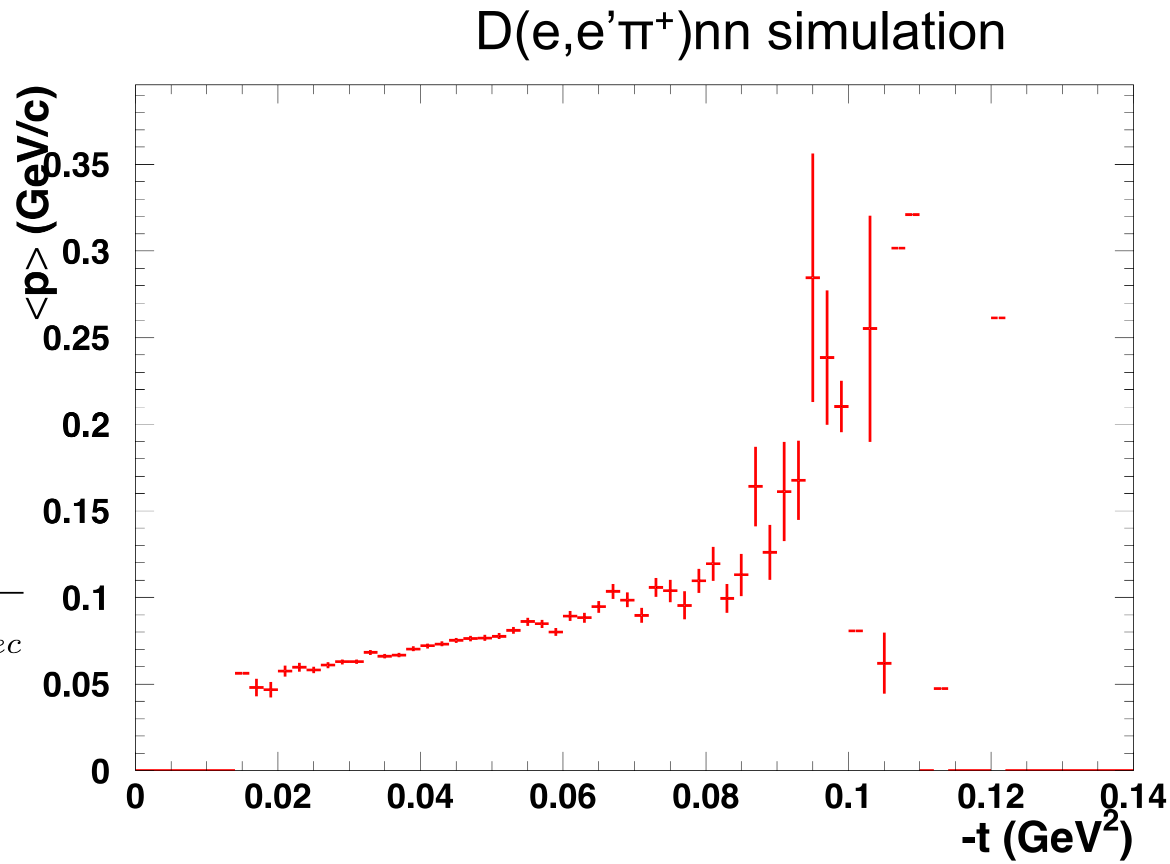
$W > W_{stationary}$

$P_{nucleon}$ vs. $-t$

Event generation uses deuteron momentum distribution

→ Pion kinematics from "struck" nucleon energy assuming spectator on-shell

$$E_{struck} = M_D - \sqrt{m_{spec}^2 + p_{spec}^2}$$



As $-t$ increases, so does average value of struck nucleon momentum

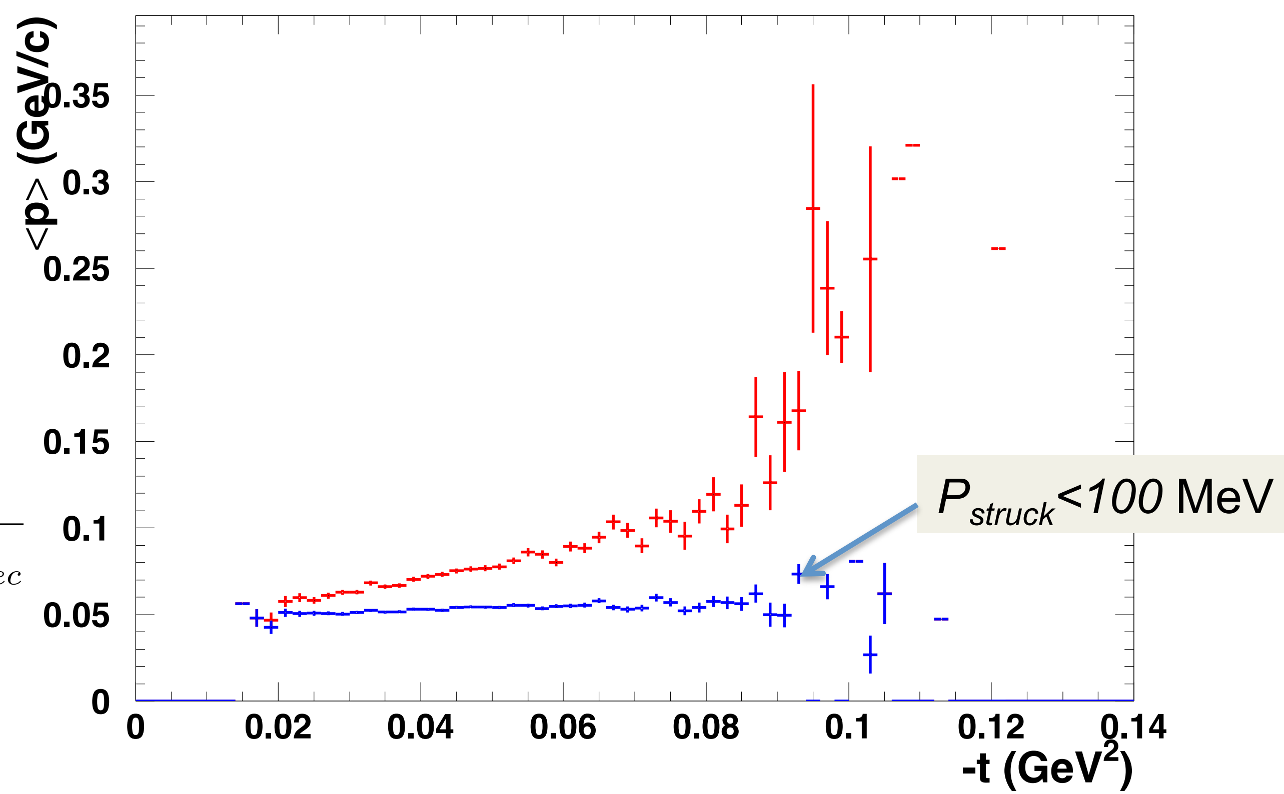
$P_{nucleon}$ vs. -t

Event generation uses deuteron momentum distribution

→ Pion kinematics from "struck" nucleon energy assuming spectator on-shell

$$E_{struck} = M_D - \sqrt{m^2_{spec} + p^2_{spec}}$$

D(e,e'π⁺)nn simulation



As –*t* increases, so does average value of struck nucleon momentum

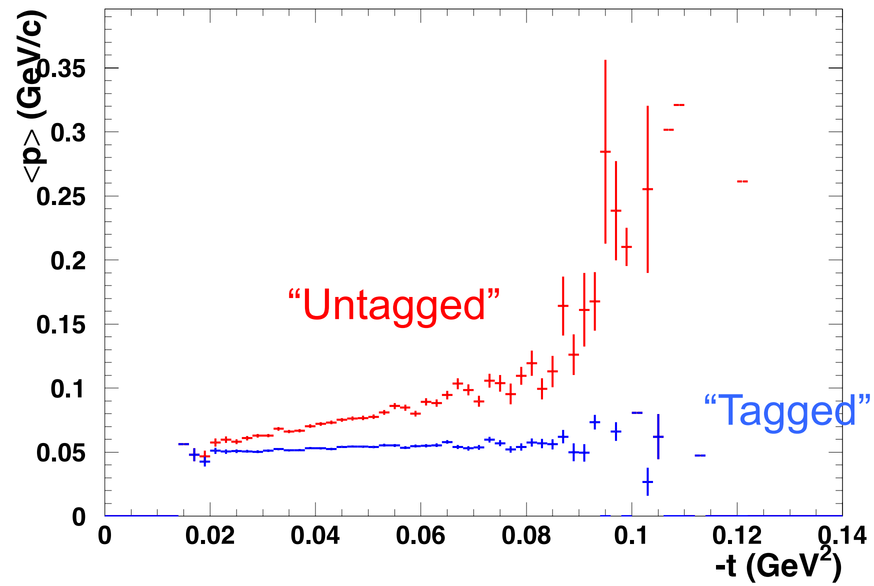
→ Tagging the low momentum nucleon removes this correlation

Tagged D(e,e'π±)

Test for nuclear effects in exclusive pion production in deuterium

$$\boxed{\frac{D(e,e'\pi^- p_s p)}{D(e,e'\pi^-)}}$$

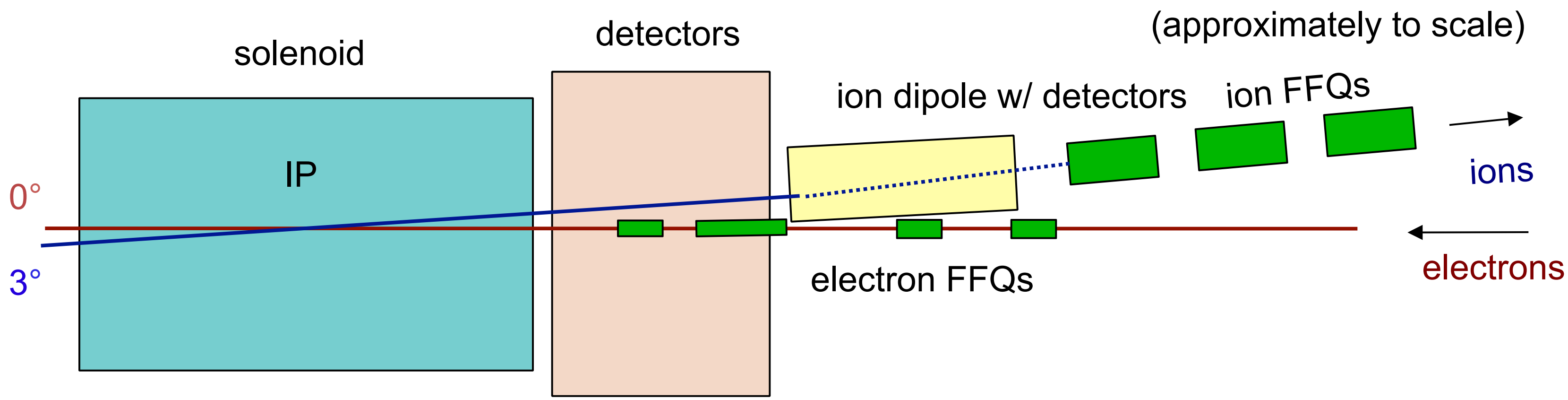
1. Examine tagged cross section integrated up to p_s=100 MeV
2. Bin in p_s up to largest accessible momentum



$$\boxed{\frac{D(e,e'\pi^- p_s p)}{D(e,e'\pi^+ n_s n)}}$$

Comparison of tagged protons to tagged neutrons would be most directly applicable to F-π program, but technically challenging

F_π at an Electron-Ion Collider



(Note: this detector concept figure out of date – see Pawel's talk)

At an electron-ion collider (EIC), tagging of recoil hadron crucial
→ Higher energies, detector resolutions mean missing mass technique can't be used to guarantee exclusivity

H(e,e' π^+n) → detect recoil neutron at small angles

D(e,e'π^-pp) → detect recoil and spectator proton?

Extracting F_π at an EIC

<u>Three potential approaches to extracting the pion form-factor at EIC</u>

1. Use the “fact” that as Q^2 gets very large, σ_L should dominate the unseparated cross section
→ Rely on measurements at JLab 12 GeV to proves whether this assumption is validated (may not be)
→ Form-factor has more model dependence

2. Perform explicit L-T separation similar JLab fixed target program
→ Requires low energies protons (5-15 GeV) to get sufficient epsilon lever arm

3. Use polarization degrees of freedom

Extract σ_L with no L-T separation?

In principle possible to extract $R=\sigma_L/\sigma_T$ using polarization degrees of freedom

In parallel kinematics
(outgoing meson along $\vec{q}$)

$$\longrightarrow \frac{R_L}{R_T} = \frac{1}{\epsilon}\left(\frac{1}{\chi_z} - 1\right)$$

$$\chi_z = \frac{1}{P_e\sqrt{1-\epsilon^2}} P_z$$

χ_z = z-component of proton "reduced" recoil polarization in *H(e,e'p)*π^0

Schmieden and Titator [Eur. Phys. J. A ***8****, 15-17 (2000)]*

A similar relation holds for pion production from a polarized target if we re-define χ_z

$$\chi_z = \frac{1}{2P_eP_T\sqrt{1-\epsilon^2}} A_z$$

A_z = target double-spin asymmetry

Isolating σ_L with Polarization D.O.F

$$\boxed{\sigma_{pol} \sim P_e P_p \sqrt{(1-\epsilon^2)} A_z}$$

Nominal, high energies, ε very close to 1.0 → destroys figure of merit for this technique

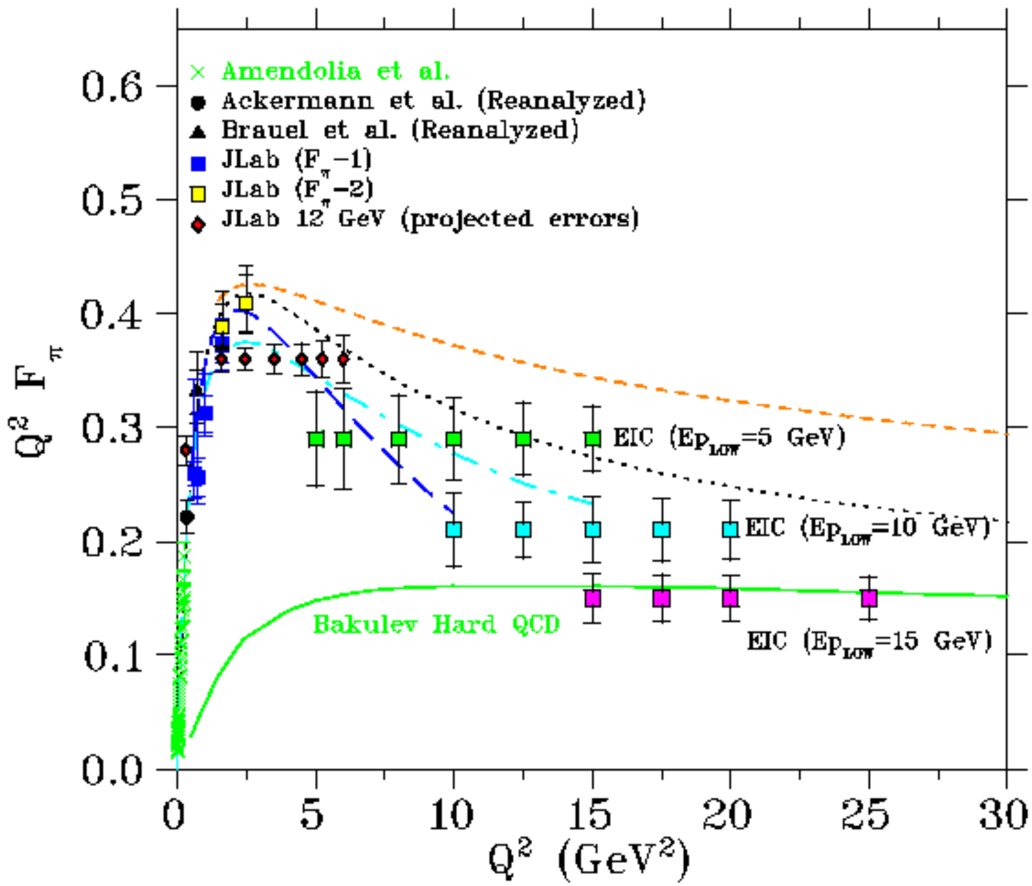
→If we can adjust ε to 0.9 then $\sqrt{(1-\epsilon^2)} \rightarrow 0.44$

→ *ε= 0.95* $\sqrt{(1-\epsilon^2)} \rightarrow 0.31$

Example: At Q^2 = *5*, lowest *s* of 3 GeV *e*- on 20 GeV *p* results in the smallest ε=0.947 (for which neutron is still easily detectable)

Additional issue: A_z = component of *p* polarization parallel to q → proton polarization direction ideally tunable at IP

Pion Form Factor at EIC – LT separation



Assumptions:

- High ε: 5(e^-) on 50(p).
- Low ε proton energies as noted.
- Δε~0.22.
- Scattered electron detection over 4π.
- Recoil neutrons detected at θ<0.35° with high efficiency.
- Statistical unc: $\Delta\sigma_L/\sigma_L$~5%
- Systematic unc: 6%/Δε.
- Approximately one year at $L=10^{34}$.

Excellent potential to study the **QCD transition** nearly over the whole range from the strong QCD regime to the hard QCD regime.

Summary

- Tagging not helpful for extraction of the pion form factor for JLab fixed target program
  - Missing mass can cleanly identify exclusive final state
  - Cannot get any closer to the pion pole → detecting produced pion is already sufficient for reaching $-t_{min}$
- Spectator tagging may be helpful for $D(e,e'\pi^-)pp$
  - $-t$ at the vertex correlated with momentum of struck nucleon → off-shellness introduces odd effects in charge ratios?
  - $D(e,e' e'\pi^- p_s p)$ could allow constraints on these effects
- Pion form factor (and all exclusive charged pion measurements) will require some kind of hadron tagging for measurements at EIC

Extra

F_π Extraction from JLab data

VGL Regge Model

Feynman propagator replaced by p and r Regge propagators

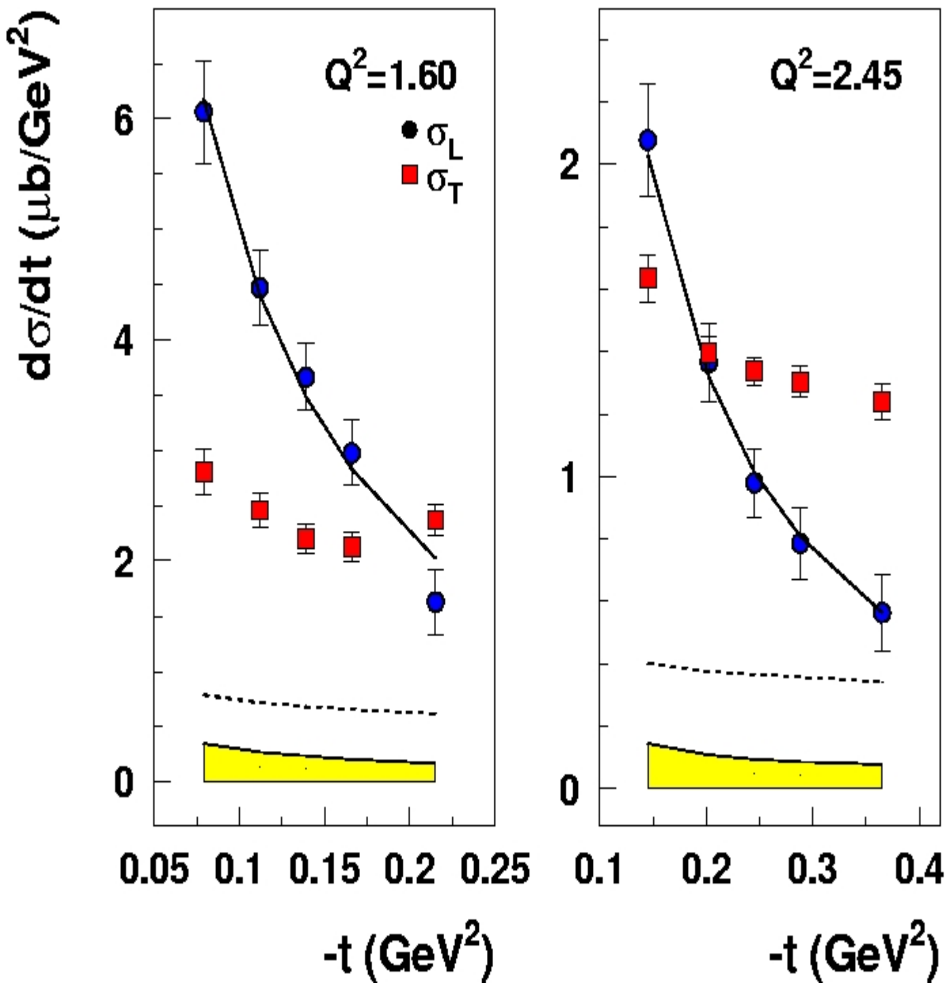
→Represents the exchange of a <u>series</u> of particles, compared to a <u>single</u> particle

Model parameters fixed from pion photoproduction

Free parameters: Λ_π , Λ_ρ *(trajectory cutoff)*

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

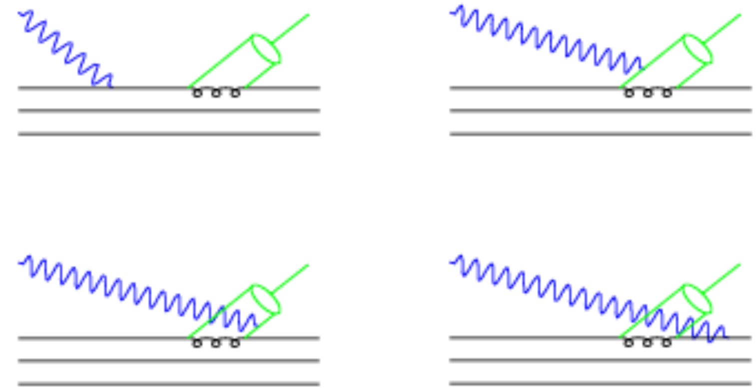
Horn et al, PRL97, 192001,2006



Λ_π^2=0.513, 0.491 GeV², Λ_ρ^2=1.7 GeV²

pQCD Contributions to *H(e,e'π^+)*

In addition to Born terms, pQCD processes can also contribute to π^+ production



Carlson and Milana ***[PRL 65, 1717 (1990)]*** calculated these contributions for Cornell kinematics
→ Asymptotic form for F_π→ King-Sachrajda nucleon distribution

For $-t>0.2$ GeV^2, pQCD contributions grow rapidly
→This helps set the constraint on maximum accessible Q^2
(fixed W, $-t_{min}$ grows w/Q^2)

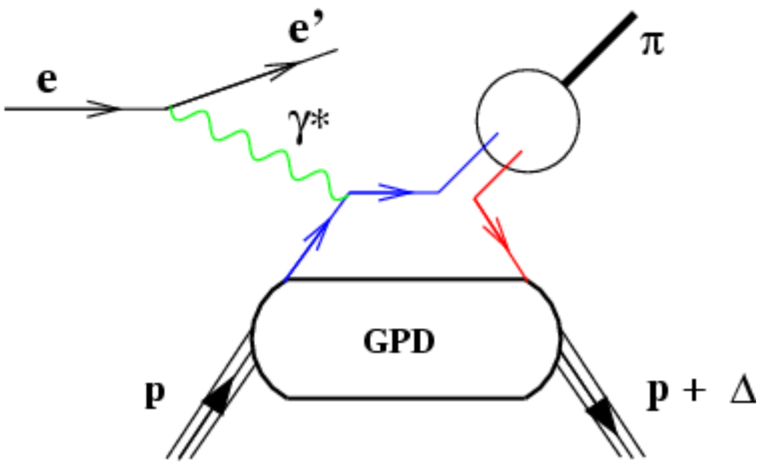
Q^2 (GeV^2)	W(GeV)	**-t (GeV^2)**	**M_{pQCD}/M_{pole}**
1.94	2.67	**0.07**	**0.12**
3.33	2.63	**0.17**	**0.18**
6.30	2.66	**0.43**	**0.81**
9.77	2.63	**0.87**	**2.82**

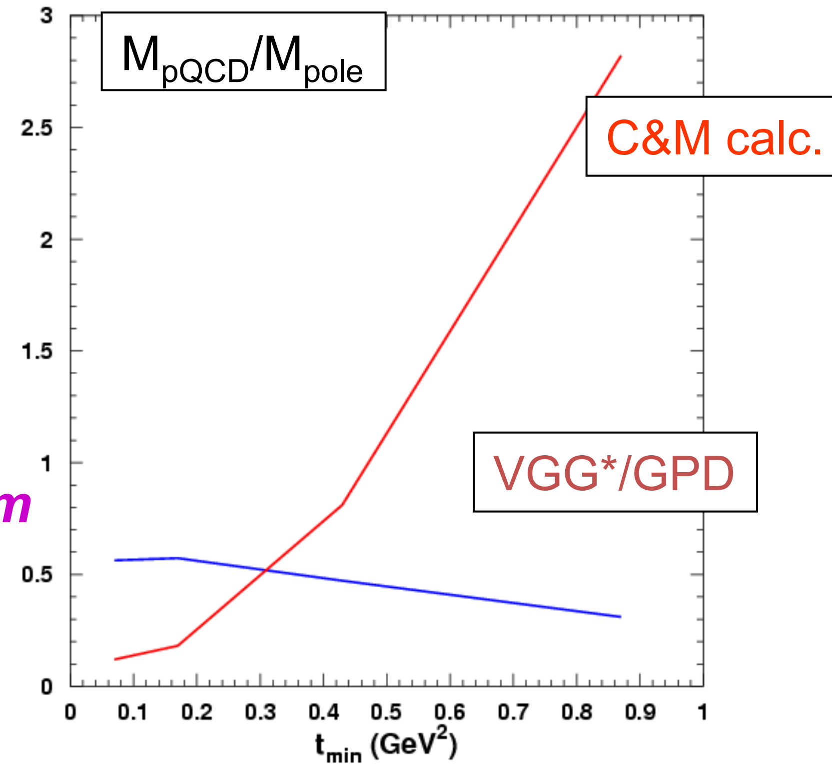
$H(e,e'\pi^+)$ in GPD framework

Non-pole backgrounds can also be calculated in a GPD framework
→ $\boldsymbol{M_{\pi+}}$ proportional to linear combination of:

$$\tilde{H}^{(3)}(x,\xi,t) = \tilde{H}^{u/p} - \tilde{H}^{d/p}$$

$$\tilde{E}^{(3)}(x,\xi,t) = \tilde{E}^{u/p} - \tilde{E}^{d/p} \longleftarrow \textit{pole term}$$





VGG model *[PRD 60, 094017 (1990)]* calculation of non-pole backgrounds shows different –*t* dependence than C&M calculation

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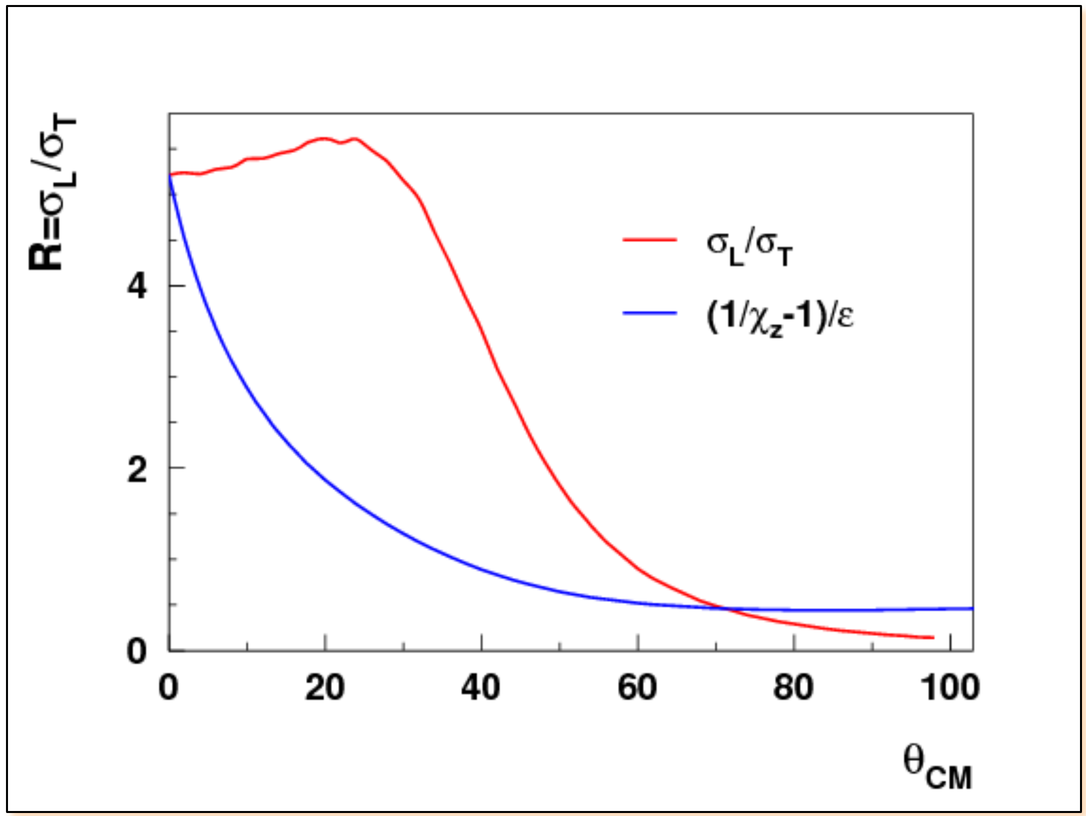
Parallel Kinematics

Polarization relation for extracting s_L/s_T only applies in parallel kinematics – how quickly does this relation break down away from q_{CM} = 0?

MAID2007

Q^2=5 GeV2
W = 1.95 GeV



L/T Extraction

Extraction via this technique requires strict cuts on θ_{CM}

Q^2=5 GeV^2, (3 on 20):
→ 1 degree CM cut corresponds to ~ 30 mrad in the lab

Q^2=25 GeV^2, (5 on 50):
→ 1 degree CM cut corresponds to 20 mrad in the lab

At 1 degree, polarization observable already ~ 15% different from true value
→ very tight cuts will be needed (0.1 degrees?)