Measurement of the Charged Pion Form Factor at EIC

Garth Huber and Dave Gaskell
(U. Regina and JLab)

Electron-Ion Collider Workshop:
Electron Nucleon Exclusive Reactions
March 14, 2010

pQCD and the Pion Form Factor

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

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

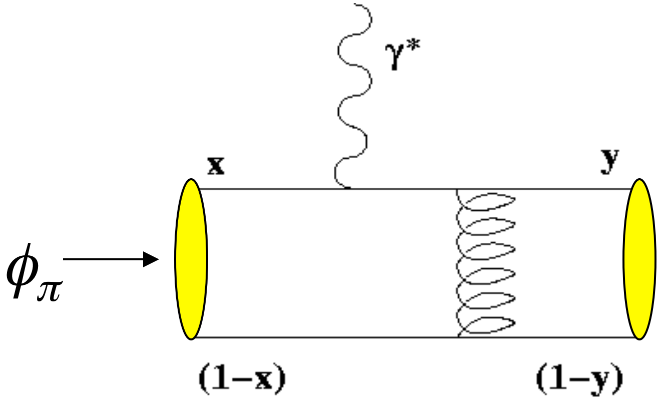
at asymptotically high Q^2, only the hardest portion of the wave function remains

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

and F_π takes the very simple form

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

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



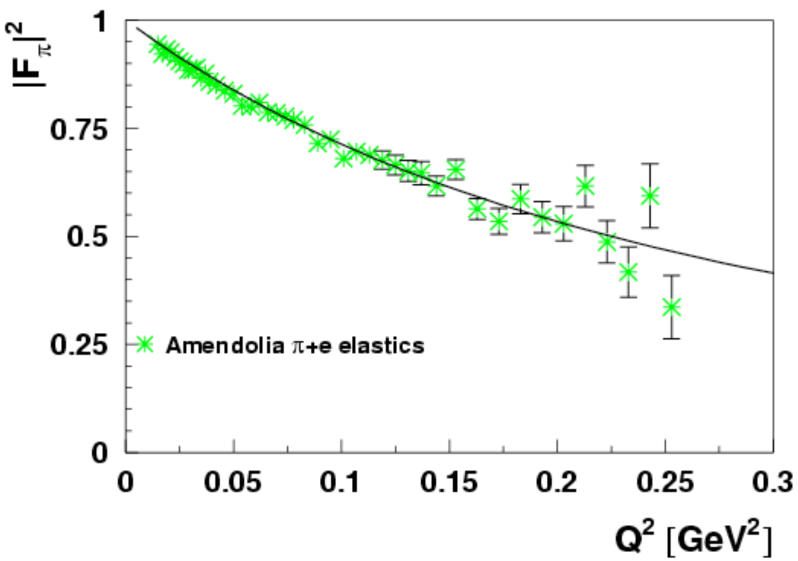
where f_π=93 MeV is the $\pi^+ \to \mu^+ \nu$ decay constant.

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)]
  - 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 GeV^2 requires 1000 GeV pion beam

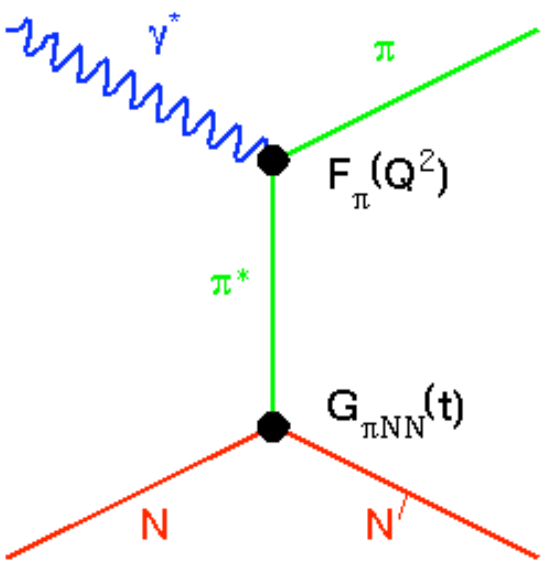


Measurement of π^+ Form Factor – Larger Q^2

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



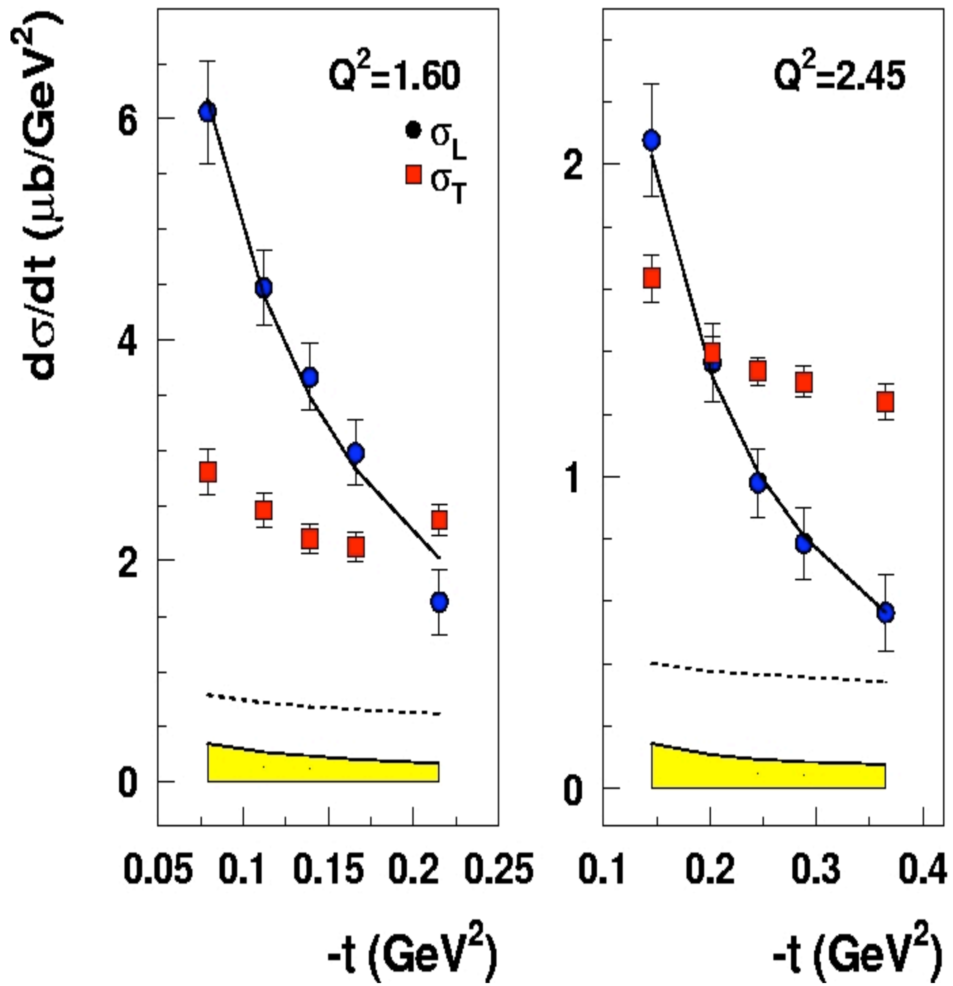
F_π Extraction from JLab data

Horn et al, PRL97, 192001,2006

VGL Regge Model

- Feynman propagator replaced by π and ρ 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).

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



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

Unpolarized Pion Cross Section

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

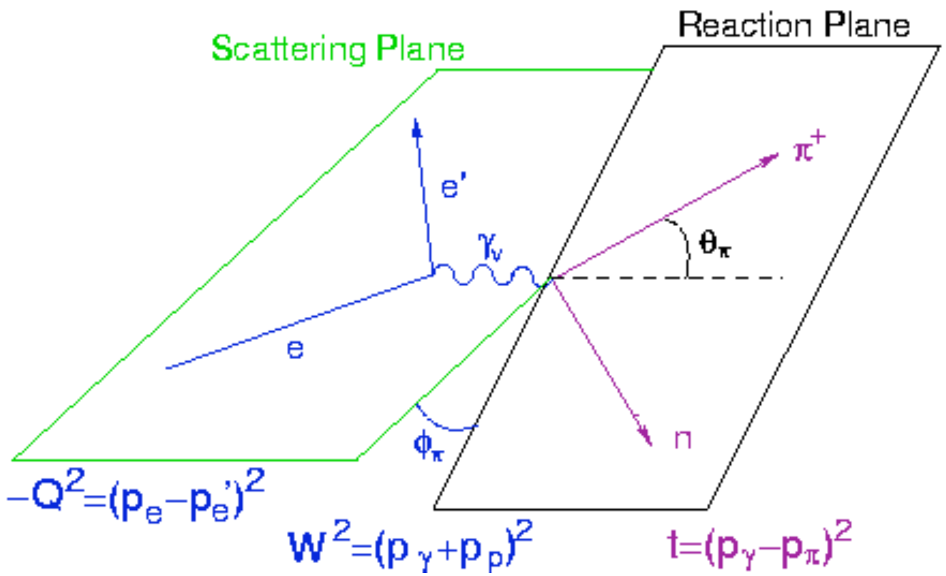
***t* = four-momentum transferred to nucleon**
= (mass)^2 of struck virtual pion

W = total energy in virtual photon-target center of mass

***Q*^{2}= -(mass)^2 of virtual photon**

ε= virtual photon polarization, 0→1

ϕ= azimuthal angle between reaction plane and scattering plane



L-T separation required to extract σ_L

L-T Separation in an e-p Collider

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

- Systematic uncertainties in σ_L are magnified by $1/\Delta\varepsilon$.
  - desire $\Delta\varepsilon>0.2$.
- $\varepsilon\approx1$ is simple to access.
  - 5 GeV (*e*-) on 50 GeV (*p*) typically assumed, but the exact energies are almost immaterial.
- 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).**

Scattered electron detection requirements

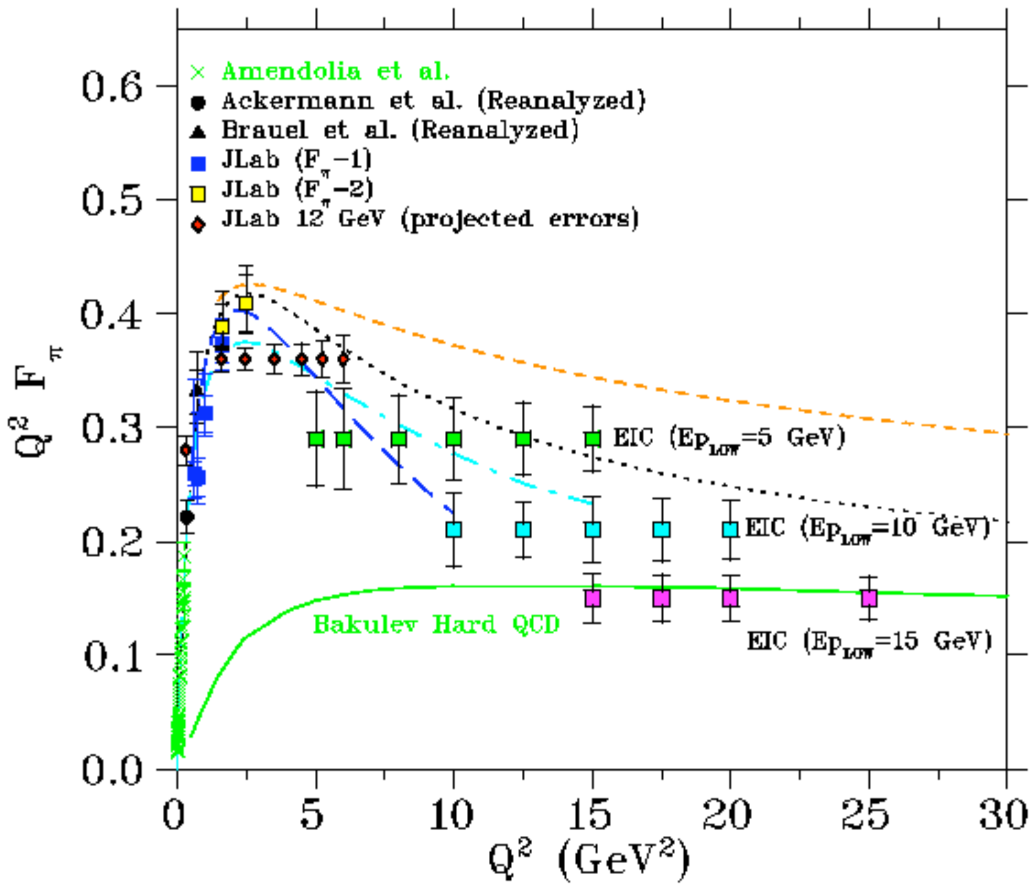
- **High $\varepsilon \approx 1$ measurements** (5 GeV e^- on 50 GeV *p*):
  - Scattered electron angles of 20^o-60^o (wrt incident electron beam).
- **Low ε measurements** (2-6 GeV *e*- on 5-15 GeV *p*):
  - In some cases, need to detect scattered electrons up to 135^o.
- **Resolution requirements:**

  $\delta P/P \approx 3\mathrm{x}10^{-3}$ $\delta\theta \approx 1\mathrm{mr}.$

Recoil detector requirements

- **Easiest way to assure exclusivity of the $p(e,e'\pi^+)n$ reaction is by detecting the recoil neutron.**
- **Parallel-kinematics measurements (e.g. pion form factor and QCD scaling tests):**
  - Neutrons are emitted at small angle ($\theta < 0.35^o$), with momentum typically about 80% of the proton beam.
  - Current discussions for mEIC detector envision neutron/hadron detector relatively close to the interaction region after an “ion dipole”, and/or very far away → I’ll come back to this

Kinematic Reach (Pion Form Factor)

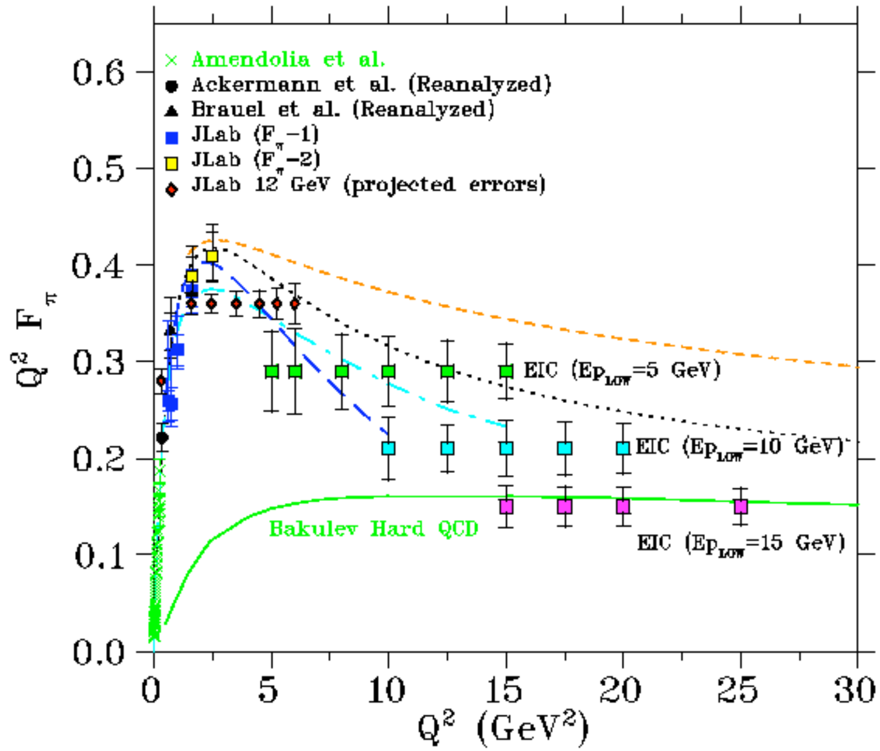


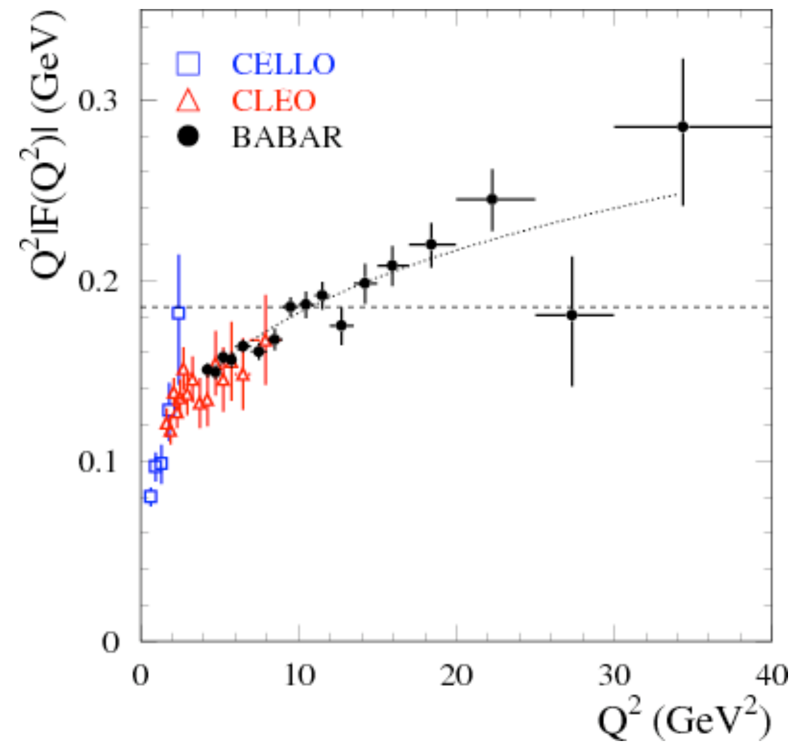
Assumptions:

- **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.

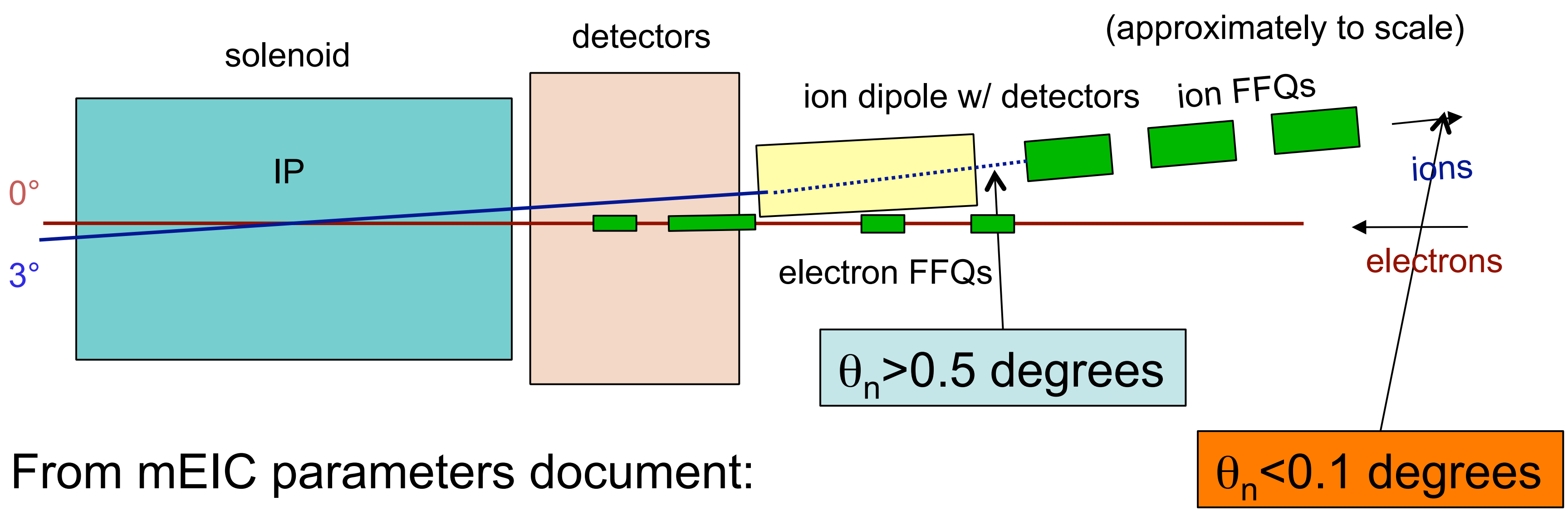
Kinematic Reach (Pion Form Factor)





Q^2 reach comparable to that of recent $\gamma\gamma \rightarrow \pi^0$ transition form factor measurements from Babar

F_π Compatible with mEIC?



From mEIC parameters document:

→ E_e = 3-11 GeV (mostly ok)

→ E_p = 20-60 GeV (not ok for low ε at lowest Q^2)

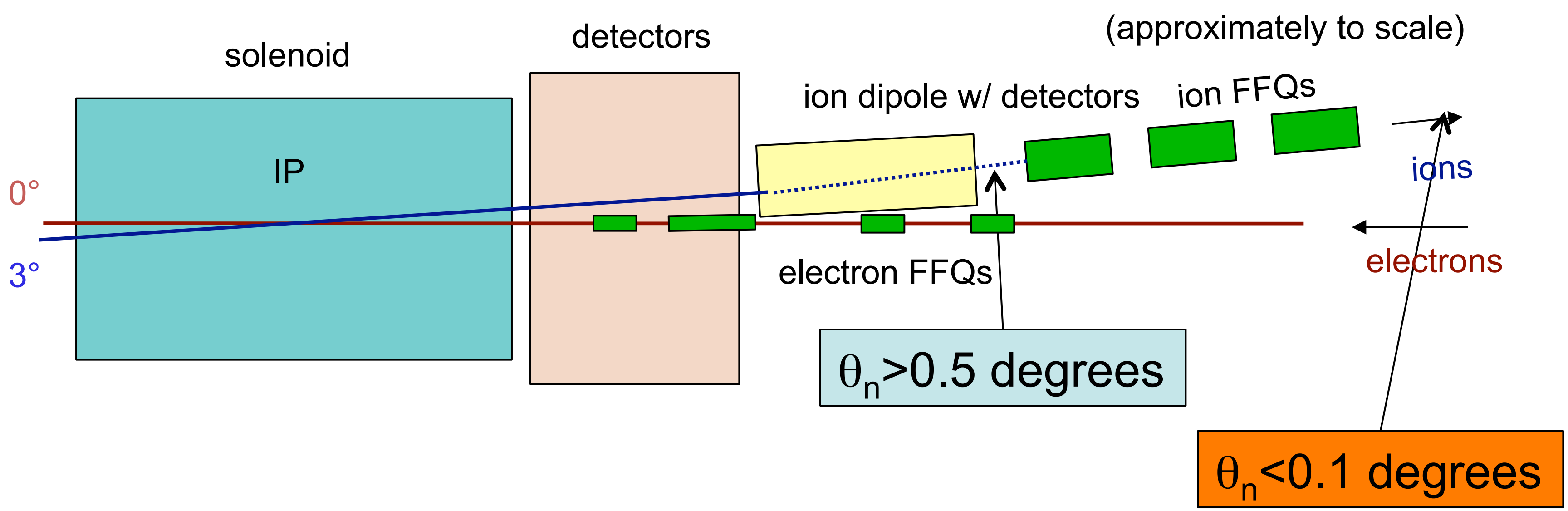
Recoil neutron detection:

→There will be a "dead zone" in which recoil neutrons cannot be detected → 0.1 to 0.5 degrees likely not accessible[1]

→ Low ε points require neutron detection between θ_n=0.2-0.3 for Q^2 below 12.5 GeV^2

[1]Rolf Ent, private communication

F_{π} Compatible with mEIC?



Kinematics may be adjusted to accommodate nominal (m)EIC parameters depending on ability to detect neutrons at VERY small angles

→In general, increasing *W* allows ε=0.8 for nominal mEIC energies

- ***This pushes neutrons very far forward***

→Example – shift W from 10 to 10.5 GeV at Q^2=10 GeV^2 allows us to use 3 GeV e on 20 GeV p for ε= 0.8; (θ_n=0.01 degrees)

- But at large ε, θ_n becomes 0.005 degrees

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

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

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

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

A_z = target double-spin asymmetry

Isolating σ_L with Polarization D.O.F

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

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)

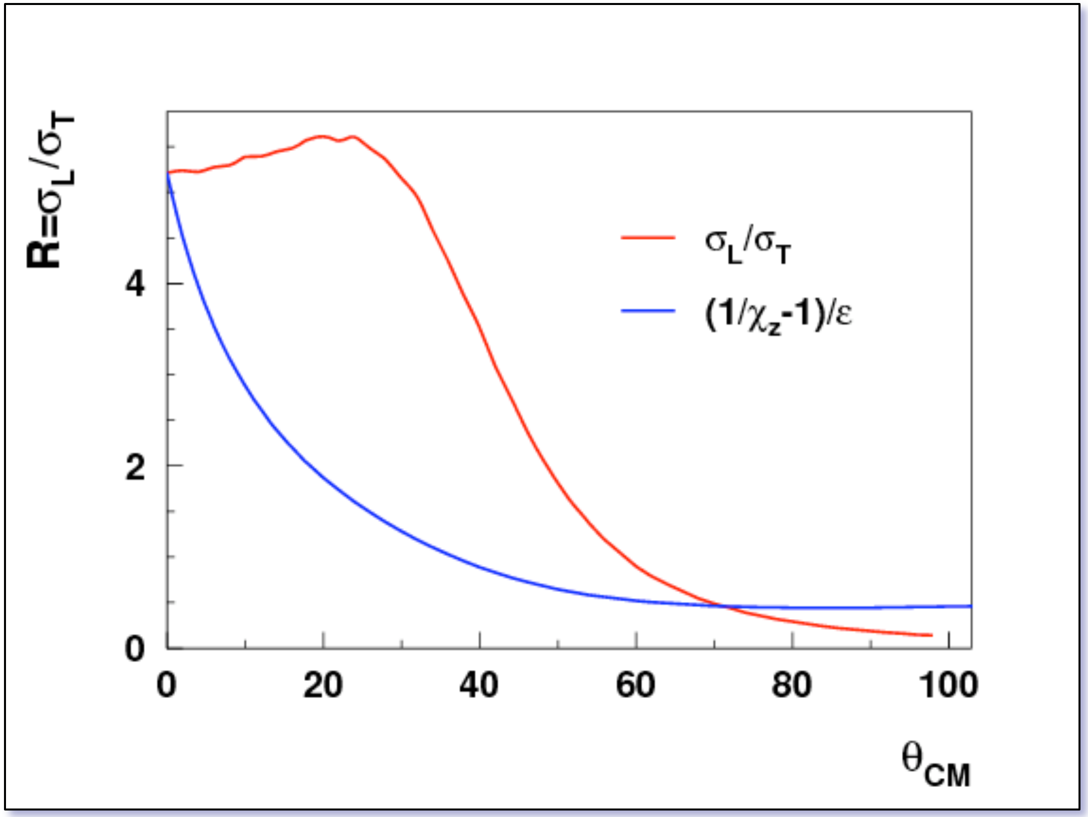
Additional issue: A_z = component of *p* polarization parallel to q → proton polarization direction ideally tunable at IP

Parallel Kinematics

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

MAID2007

Q^2=5 GeV2
W = 1.95 GeV



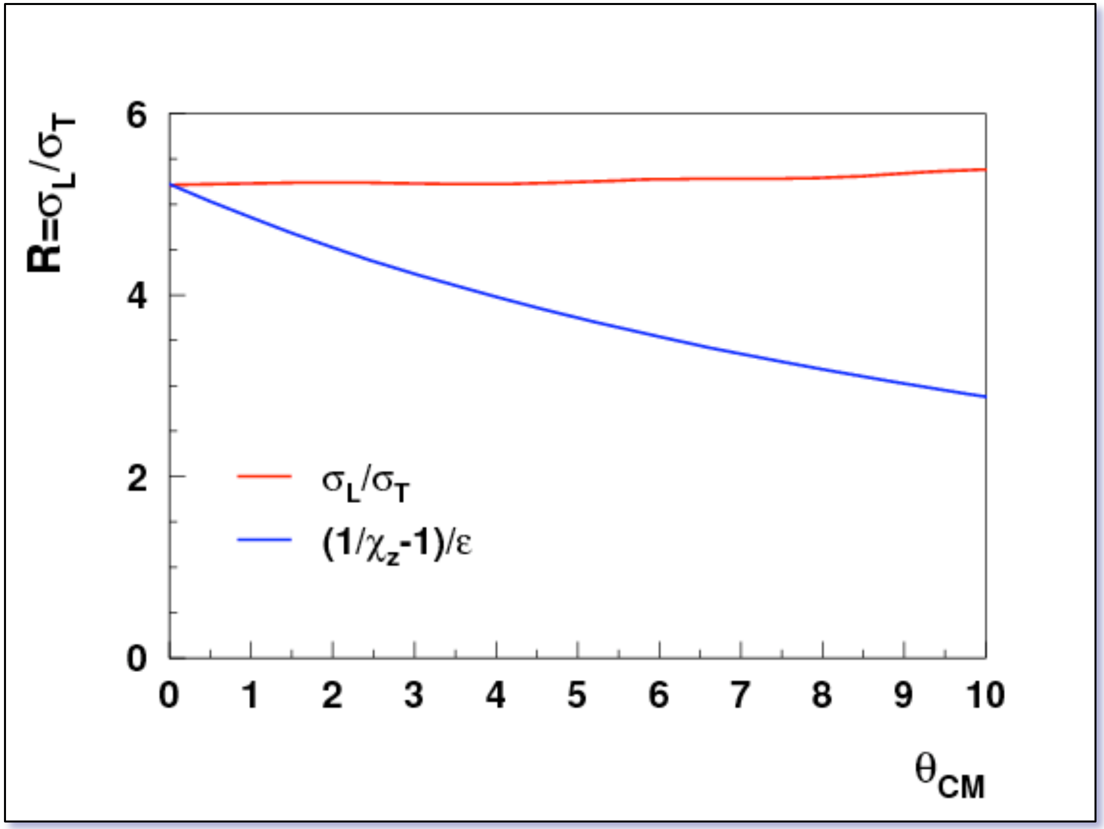
L/T Extraction

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?)



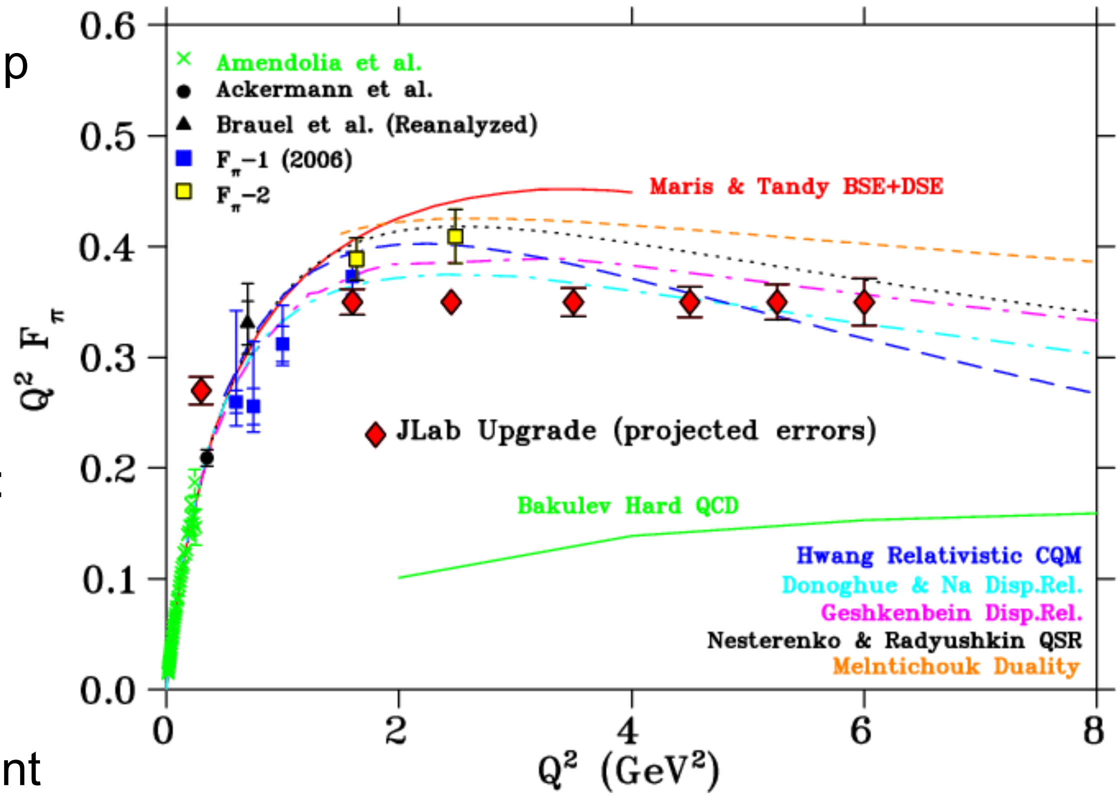
Summary

- Measurement of F_π at EIC will be challenging
  - Use of L-T separation made easier with energies outside of "nominal"
  - Reduction of neutron detection "dead zone" would also be beneficial
  - Extreme forward neutron detection (<0.01 degrees) would alleviate both of the above
  - ***Another option: measure away from $-t_{min}$ so neutron angle > 0.5 degrees → phase space for this is quite small and –t pretty large (-t ~ 0.2)***
- Measurement using polarization degrees of freedom seems, at first glance, ~~feasible~~ not impossible
  - Very tight cuts on pion angle will be required
  - More detailed studies required → a model incorporating all response functions needed to simulate how close to parallel we must be

Extra

$F_{\pi^+}(Q^2)$ after JLAB 12 GeV Upgrade

- JLab 12 GeV upgrade will allow measurement of F_π up to 6 GeV^2
  - Will we see the beginning of the transition to the perturbative regime?
- Additional point at Q^2=*1.6* GeV^2 will be closer to pole: will provide another constraint on $-t_{min}$ dependence
- Q^2=*0.3* GeV^2 point will be best direct test of agreement with elastic π+*e* data



Low ε F_π Kinematics

Q^2	P_p	P_e	-t	ε	θ_n
5	5	2	0.047	0.78	0.32
6	5	3	0.031	0.80	0.19
8	5	3	0.052	0.77	0.28
10	5	4	0.042	0.75	0.19
10	10	5	0.008	0.80	0.02
12.5	5	4	0.062	0.72	0.26
12.5	10	4	0.013	0.64	0.02
15	5	4	0.085	0.69	0.32
15	10	5	0.018	0.78	0.04
15	15	6	0.006	0.79	0.01
17.5	10	5	0.024	0.77	0.04
17.5	15	6	0.008	0.78	0.01
20	10	5	0.030	0.75	0.05
20	15	6	0.010	0.77	0.01
25	15	6	0.015	0.76	0.02