L-T Separation in Pseudoscalar Meson Production

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Exclusive Meson Production and Short Range Hadron Structure

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Motivation for L-T separations

- Inclusive Deep Inelastic Scattering
  - Primary interest is in F_2 structure function – dominated by transverse photons
  - $R=\sigma_L/\sigma_T$ small (~0.2)
  - Measurements of unseparated cross sections, combined with fits to R often yield sufficient precision for extraction of PDFs
- Exclusive Meson Production
  - Access to leading twist GPDs requires σ_L, transversity GPD requires σ_T
  - $R=\sigma_L/\sigma_T$ relatively poorly known – large for some π^+ kinematics, now expected to be small for π^0

Unpolarized Pion Cross Section

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

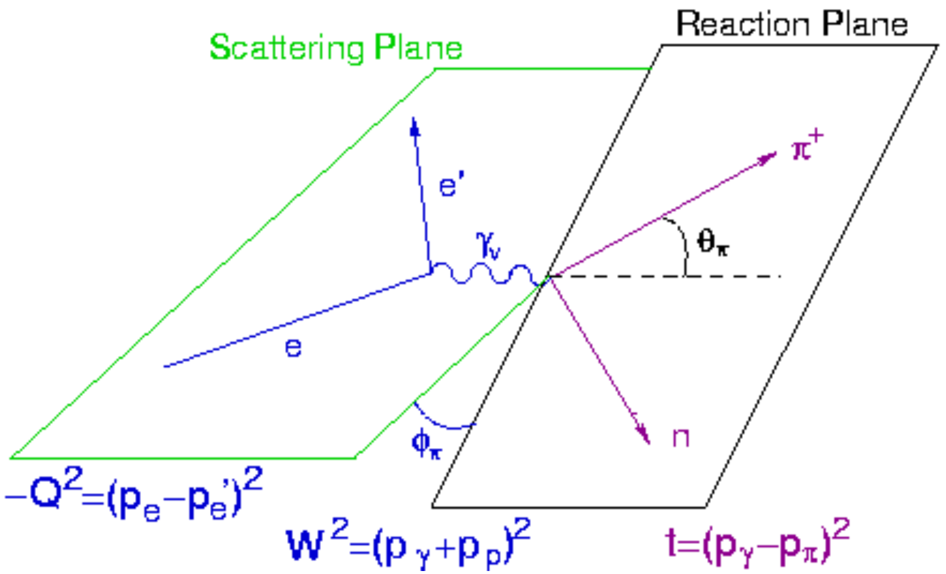
***t* = four-momentum transferred to nucleon**
= (mass)^2 of struck virtual pion

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 and σ_T

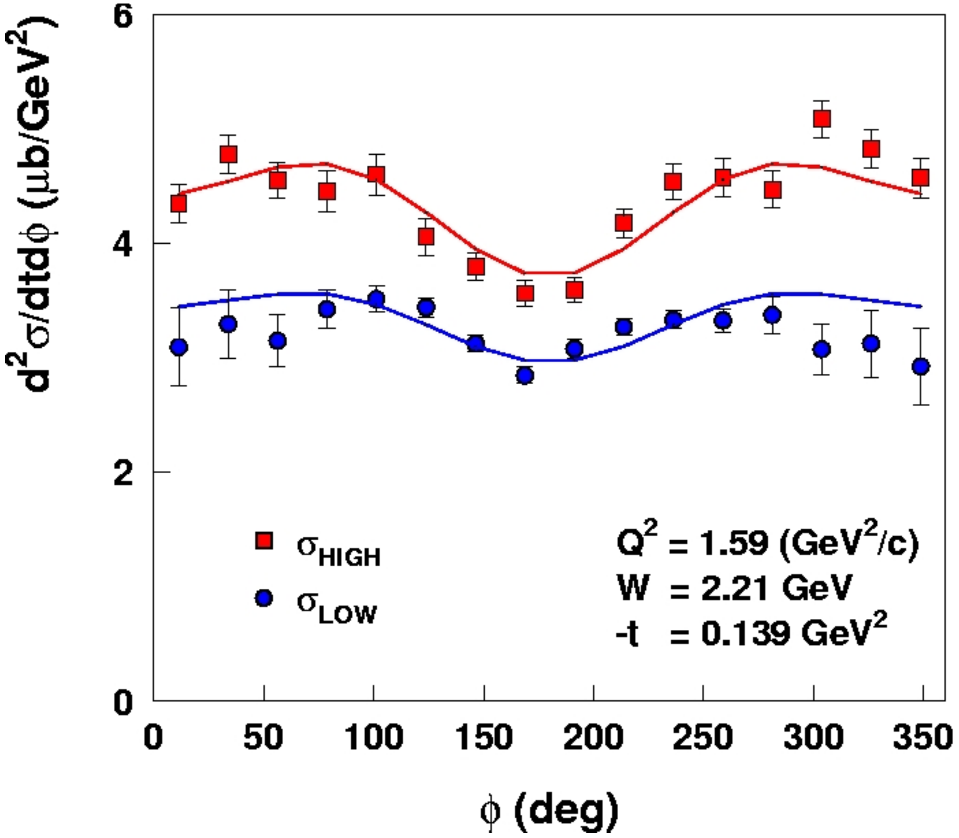
Measuring σ_L and σ_T

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

Rosenbluth separation required to isolate σ_L

→Measure cross section at fixed (*W,Q2,-t*) at 2 beam energies

→Simultaneous fit at 2 ε values to determine σ_L, σ_T, and interference terms



Control of point-to-point systematic uncertainties crucial due to ***1/ε*** error amplification in σ_L

Careful attention must be paid to spectrometer acceptance, kinematics, efficiencies, …

Separated Cross Sections - Precision

Final precision on separated cross sections (σ_L and σ_T) dictated by things we can and cannot control

1. Point-to-point systematic uncertainties

   Can be optimized, but at some point a “floor” is reached → 1.5 to 1.6%

2. $\Delta\varepsilon$

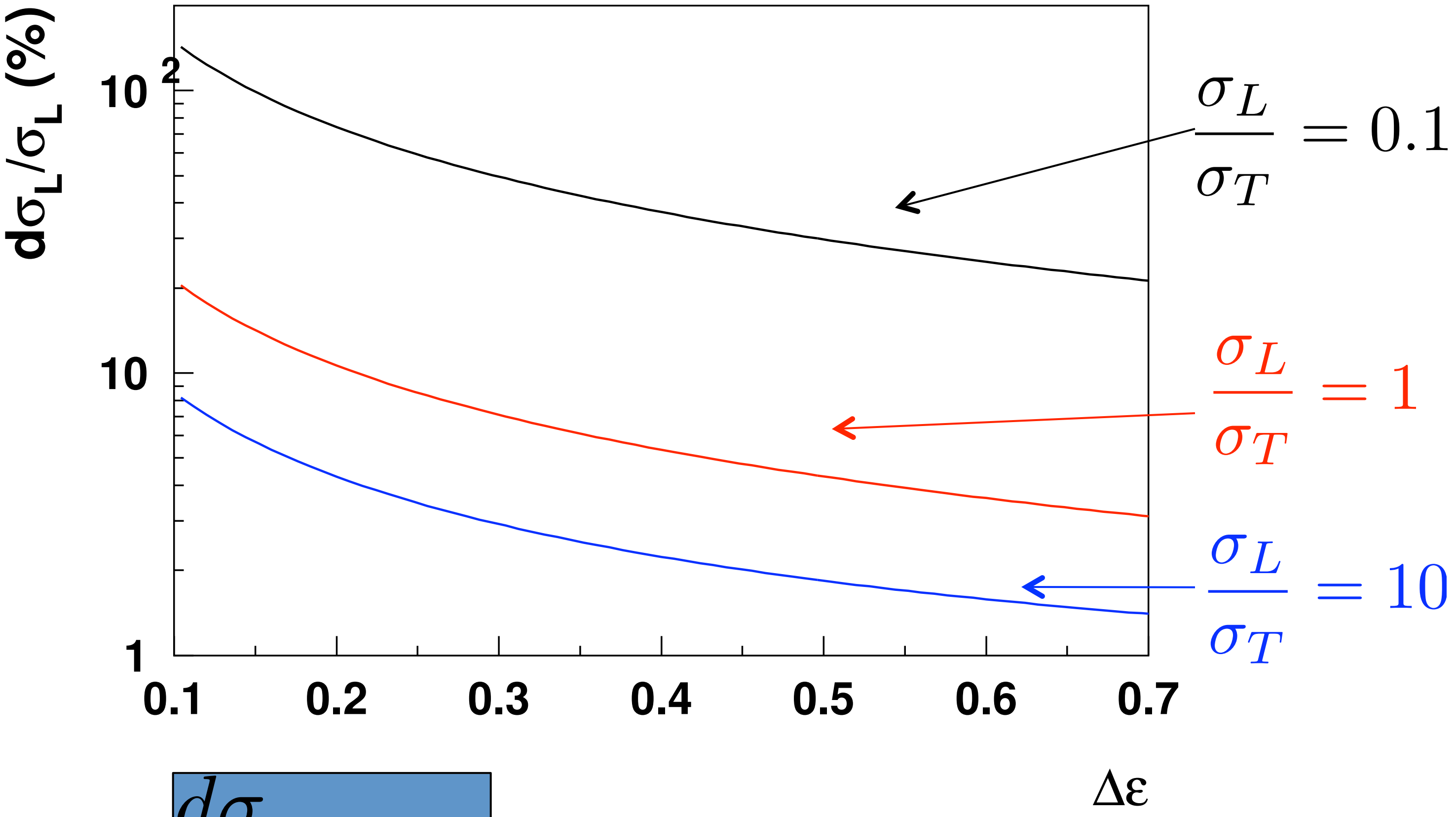
   Dictated by beam energy, capability of spectrometers

3. $R=\sigma_L/\sigma_T$

   Relative precision on separated cross section dictated by the physics of the reaction

σ_L Uncertainties

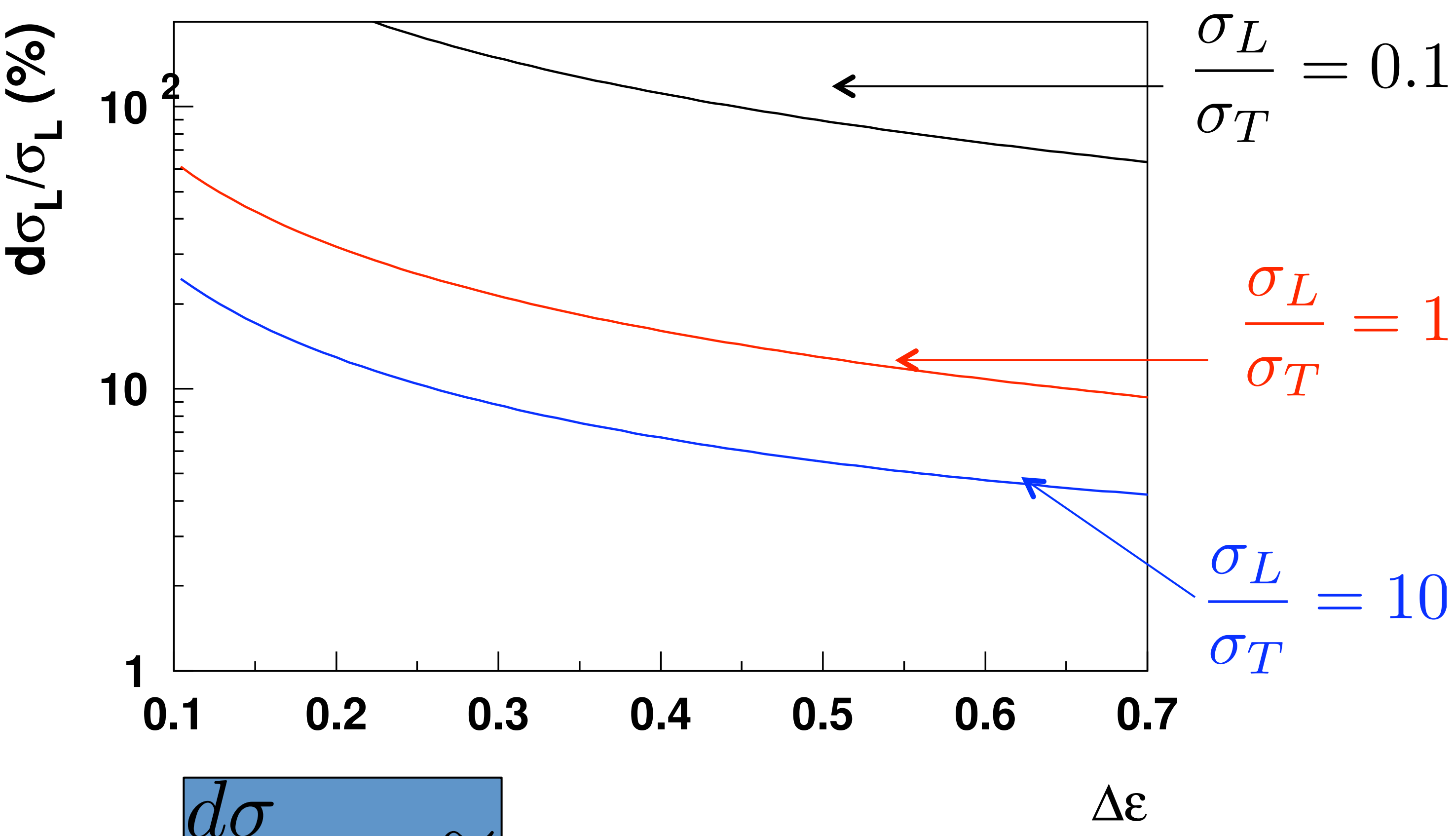
$$\frac{d\sigma_L}{\sigma_L} = \frac{d\sigma}{\sigma}\frac{1}{\epsilon_1 - \epsilon_2}\sqrt{(1/R + \epsilon_1)^2 + (1/R + \epsilon_2)^2}$$



$$\frac{d\sigma}{\sigma} = 1\%$$

σ_L Uncertainties

$$\frac{d\sigma_L}{\sigma_L} = \frac{d\sigma}{\sigma}\frac{1}{\epsilon_1 - \epsilon_2}\sqrt{(1/R+\epsilon_1)^2 + (1/R+\epsilon_2)^2}$$



$$\frac{d\sigma}{\sigma} = 3\%$$

Example: F_π Experiments

F_π-1 (F_π-2) ran in Hall C in 1997 (2003)

→ Used SOS/HMS (well understood magnetic focusing spectrometers)

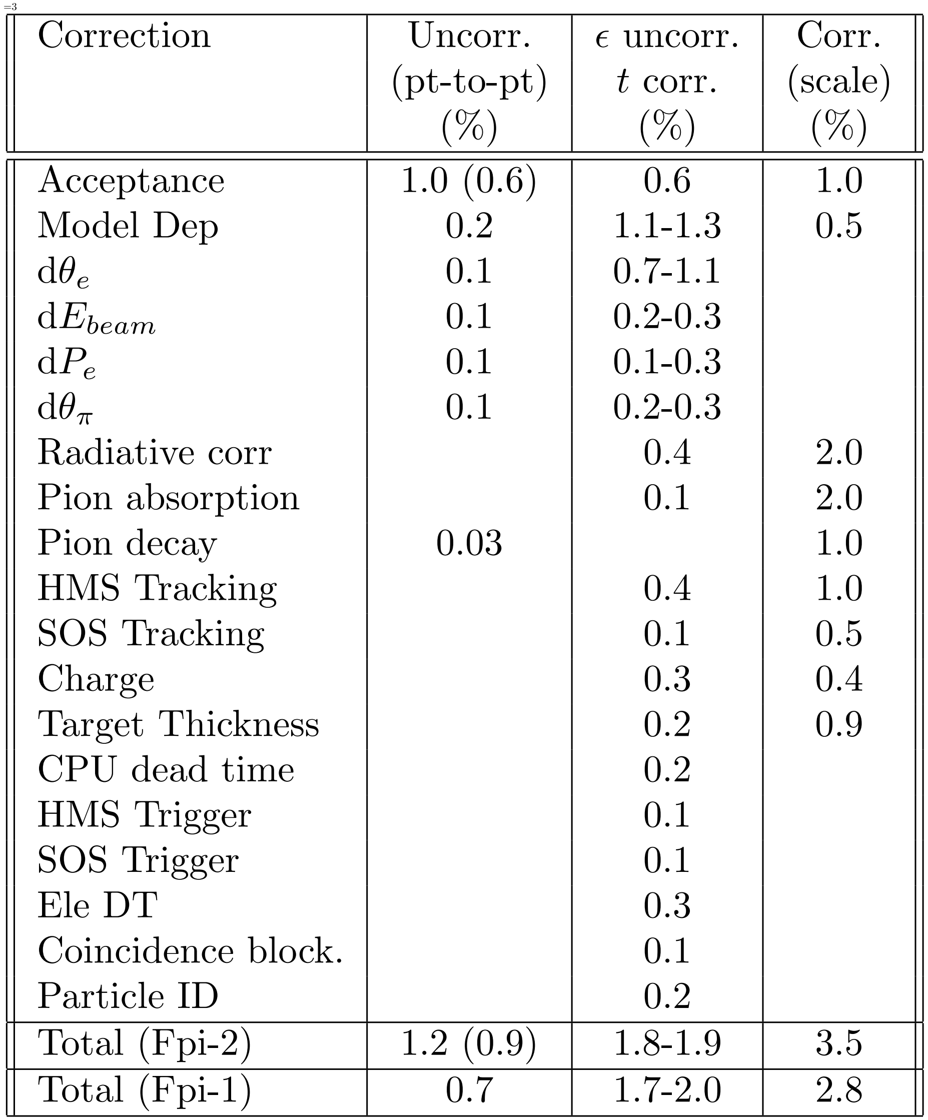
→ Good control of kinematic offsets

Total ε uncorrelated uncertainty ~ 2%

Largest contributions

1. Model dependence (bin centering, radiative corrections)
2. Electron scattering angle
   → 0.5 mrad
3. Acceptance

Even if systematic uncertainties small, final unc. on σ_L can still be large



Correction	Uncorr. (pt-to-pt) (%)	ϵ uncorr. t corr. (%)	Corr. (scale) (%)
Acceptance	1.0 (0.6)	0.6	1.0
Model Dep	0.2	1.1-1.3	0.5
$d\theta_e$	0.1	0.7-1.1	
dE_{beam}	0.1	0.2-0.3	
dP_e	0.1	0.1-0.3	
$d\theta_\pi$	0.1	0.2-0.3	
Radiative corr		0.4	2.0
Pion absorption		0.1	2.0
Pion decay	0.03		1.0
HMS Tracking		0.4	1.0
SOS Tracking		0.1	0.5
Charge		0.3	0.4
Target Thickness		0.2	0.9
CPU dead time		0.2	
HMS Trigger		0.1	
SOS Trigger		0.1	
Ele DT		0.3	
Coincidence block.		0.1	
Particle ID		0.2	
Total (Fpi-2)	1.2 (0.9)	1.8-1.9	3.5
Total (Fpi-1)	0.7	1.7-2.0	2.8

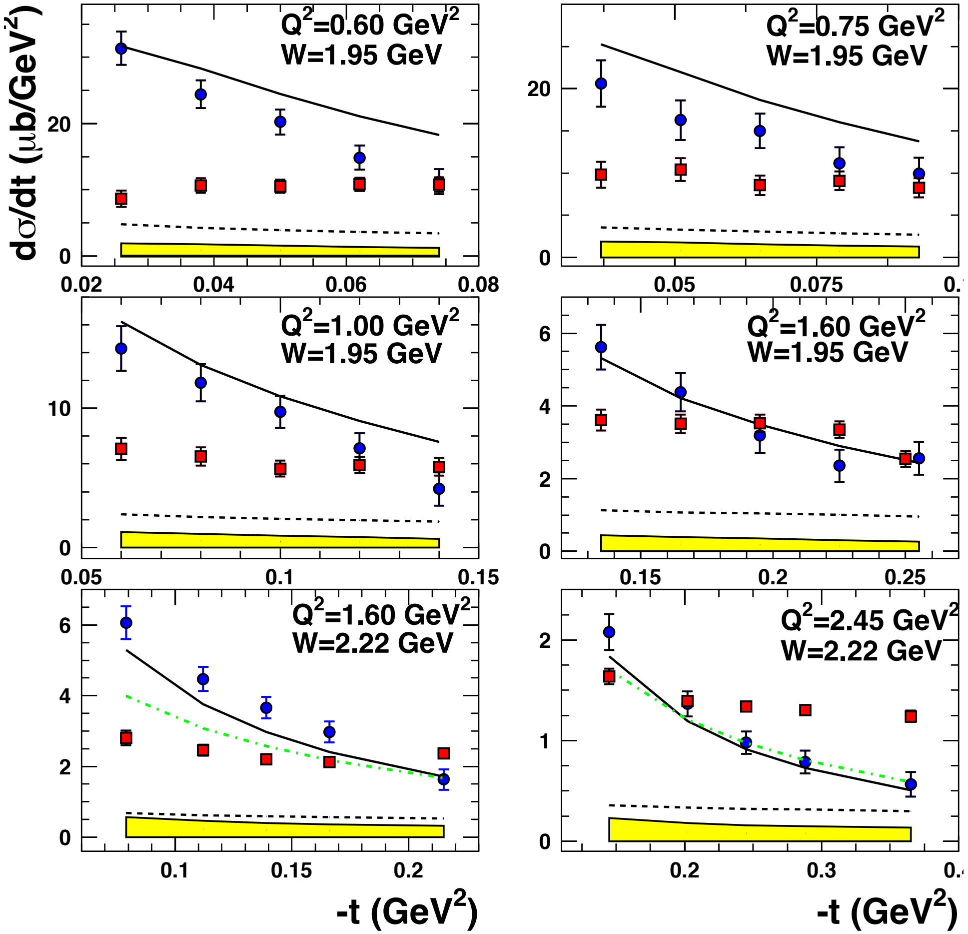
Blok et al, Phys.Rev. C78 (2008) 045202

Example: F_π Experiments

Results and precision

$Q^2=1.6\ \mathrm{GeV}^2$:
$\Delta\varepsilon = 0.25$
$R=\sigma_L/\sigma_T = 2.16$ to 0.69
$d\sigma_L/\sigma_L \sim 9.3$-$19.3\%$
$d\sigma_T/\sigma_T \sim 9.6$-$8\%$

$Q^2=2.45\ \mathrm{GeV}^2$:
$\Delta\varepsilon = 0.27$
$R=\sigma_L/\sigma_T = 1.27$ to 0.45
$d\sigma_L/\sigma_L \sim 10$-$24\%$
$d\sigma_T/\sigma_T \sim 6.5\%$



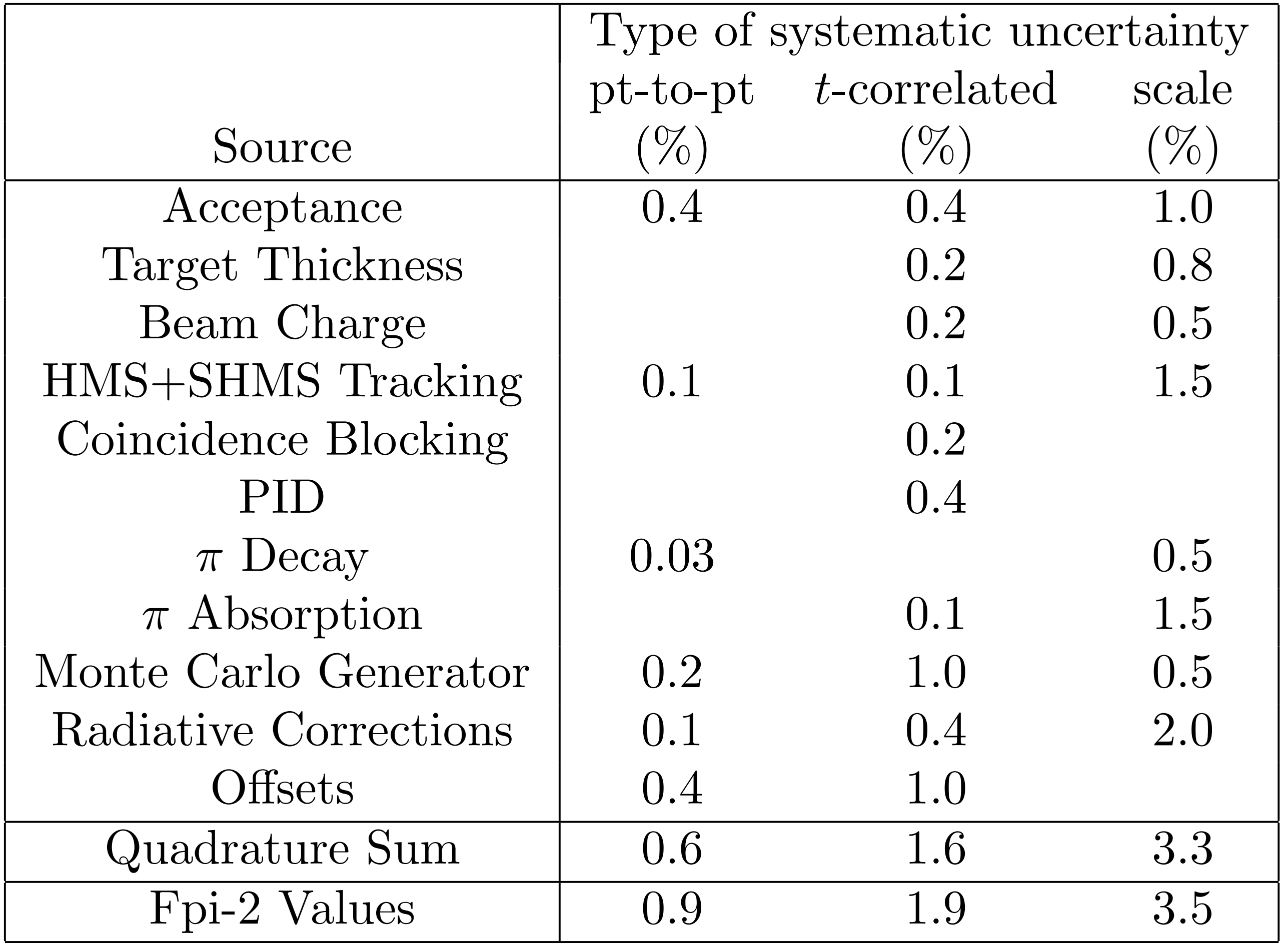
Blok et al, Phys.Rev. C78 (2008) 045202

F_π-12 Precision

F_π-12 precision will be improved by new SHMS

→ Acceptance and optics should be easier to understand

→ Total ε-uncorrelated uncertainty = ***1.7%***



Source	Type of systematic uncertainty pt-to-pt (%)	 t-correlated (%)	 scale (%)
Acceptance	0.4	0.4	1.0
Target Thickness		0.2	0.8
Beam Charge		0.2	0.5
HMS+SHMS Tracking	0.1	0.1	1.5
Coincidence Blocking		0.2	
PID		0.4	
π Decay	0.03		0.5
π Absorption		0.1	1.5
Monte Carlo Generator	0.2	1.0	0.5
Radiative Corrections	0.1	0.4	2.0
Offsets	0.4	1.0	
Quadrature Sum	0.6	1.6	3.3
Fpi-2 Values	0.9	1.9	3.5

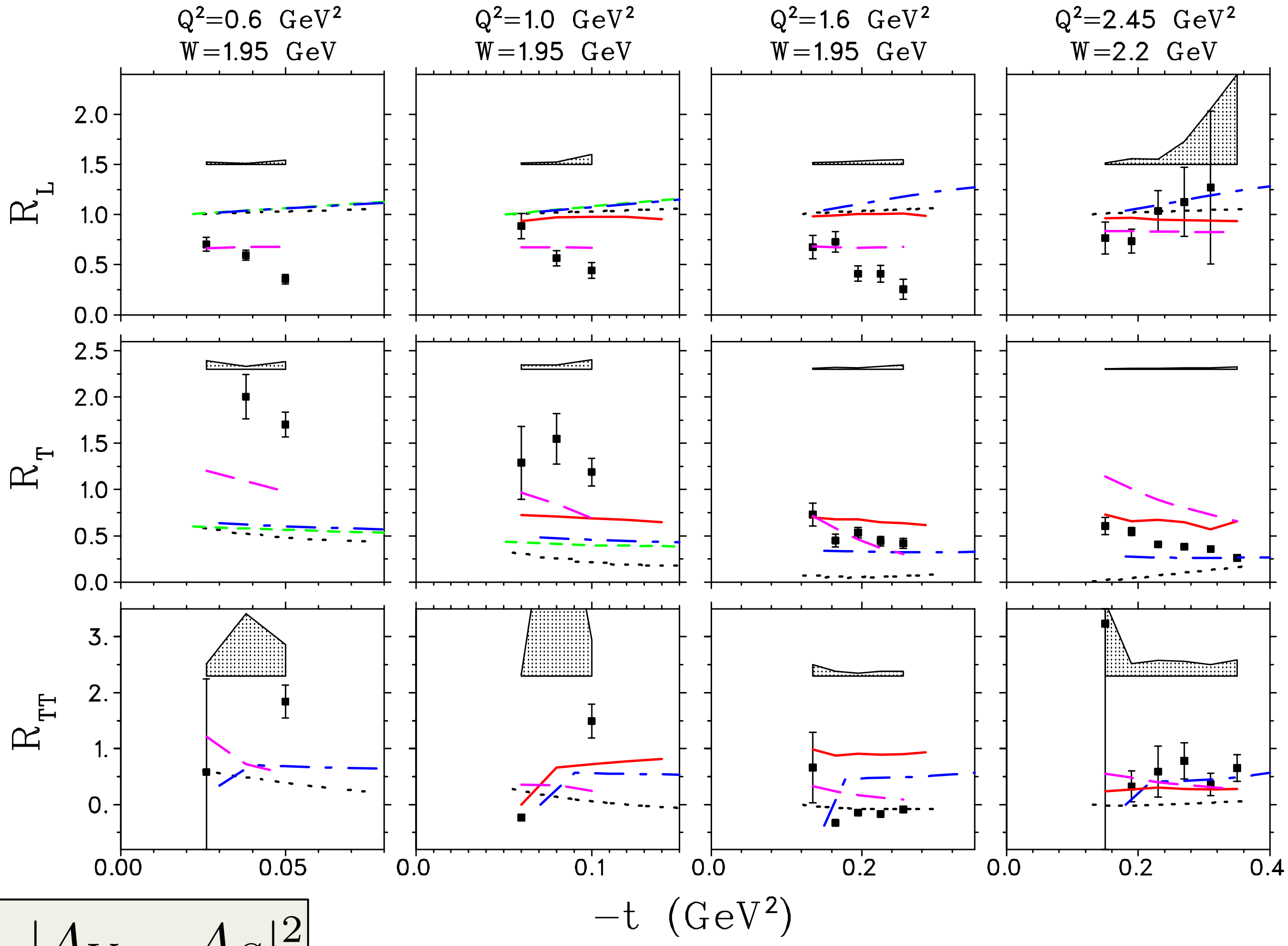
6 GeV L-T Separations: π^-/π^+ Ratios

F_π experiments also took D(e,e'π) data for π+ and π-

→ Extracted separated cross sections

→ Emphasis on π-/π+ ratios of separated cross sections

→ $R_L \to 1$ for pole dominance



$$R_L = \frac{\gamma^*_L n \to \pi^- p}{\gamma^*_L p \to \pi^+ n} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

Huber et al, Phys.Rev. C91 (2015) 015202

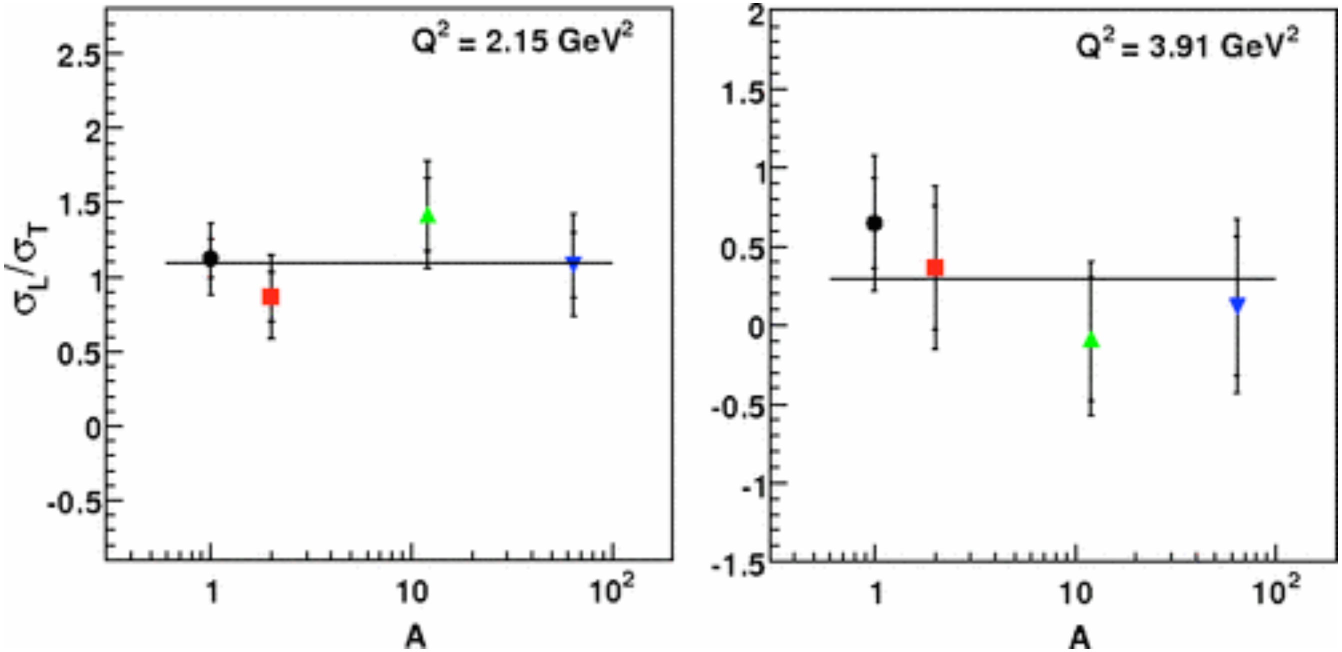
6 GeV L-T Separations: PionCT

PionCT experiment:

→ Ran in Hall C in 2004

→ Look for color transparency via A(e,e'π+)/H(e,e'π+)

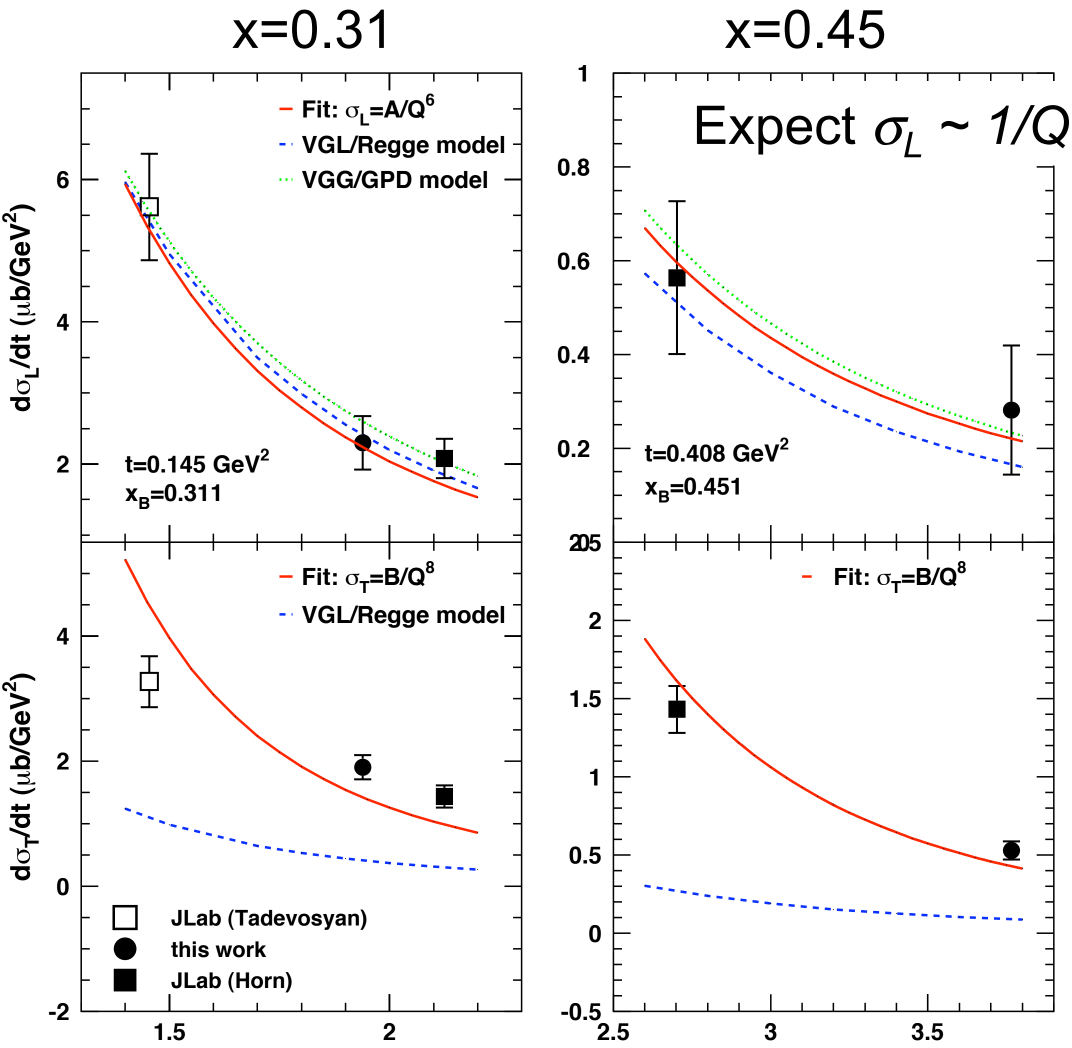
→ Measured L-T separated cross sections at Q^2=*2.15* and Q^2=*3.91* GeV^2 for hydrogen, deuterium, carbon, and copper



X. Qian, et al, Phys.Rev. C81 (2010) 055209

Q^2 dependence of π^+ σ_L, σ_T

Combination of F_π and PionCT data



Expect $\sigma_L \sim 1/Q^6$ for factorization

$\sigma_L \sim 1/Q^{5.1+/-0.9}$

$\sigma_T \sim 1/Q^{4.2+/-0.8}$

$\sigma_L \sim 1/Q^{4.2+/-2.9}$

$\sigma_T \sim 1/Q^{6.0+/-0.9}$

For π^+, σ_L is not even close to dominating at Q^2=4 GeV^2

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Horn et al Phys.Rev. C78 (2008) 058201

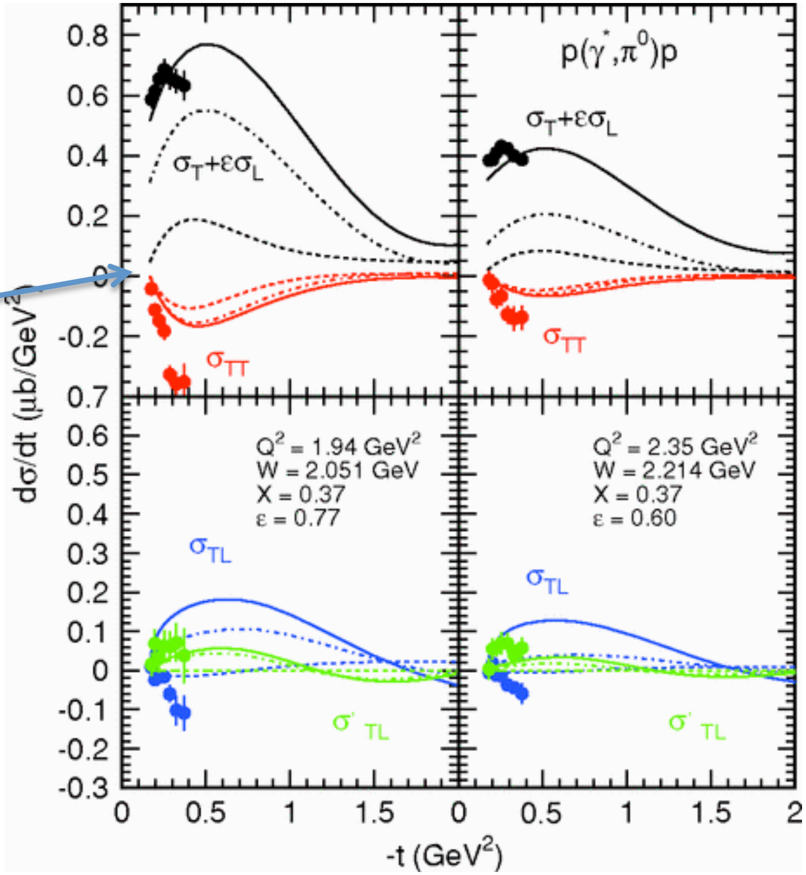
6 GeV L-T Separations: π^0 Cross Sections

E07-007:Separation of Deeply Virtual Photon and pi-0 Electroproduction Observables of Unpolarized Protons

→ Ran in Hall A in 2010. Analysis ongoing.

First Hall A DVCS experiment extracted unseparated π^0 cross sections near Q^2=2 GeV^2

2010 experiment will perform Rosenbluth separation at Q^2=*1.5* to *2.3* GeV^2



Fuchey et al, Phys.Rev. C83 (2011) 025201

L-T Separated Cross sections at 12 GeV

- Experiments with 11 GeV will build on experience gained during 6 GeV era
- Hall C: new Super-HMS
  - Designed with very small angle capability in mind (5.5 degrees) → Δε reach
  - Well-matched to HMS for coincidence acceptance
- Additional new equipment: Neutral Particle Spectrometer (NPS) → π^0 Rosenbluth separations
- Approved program includes $\pi^{+/-}$, K^+, π^0

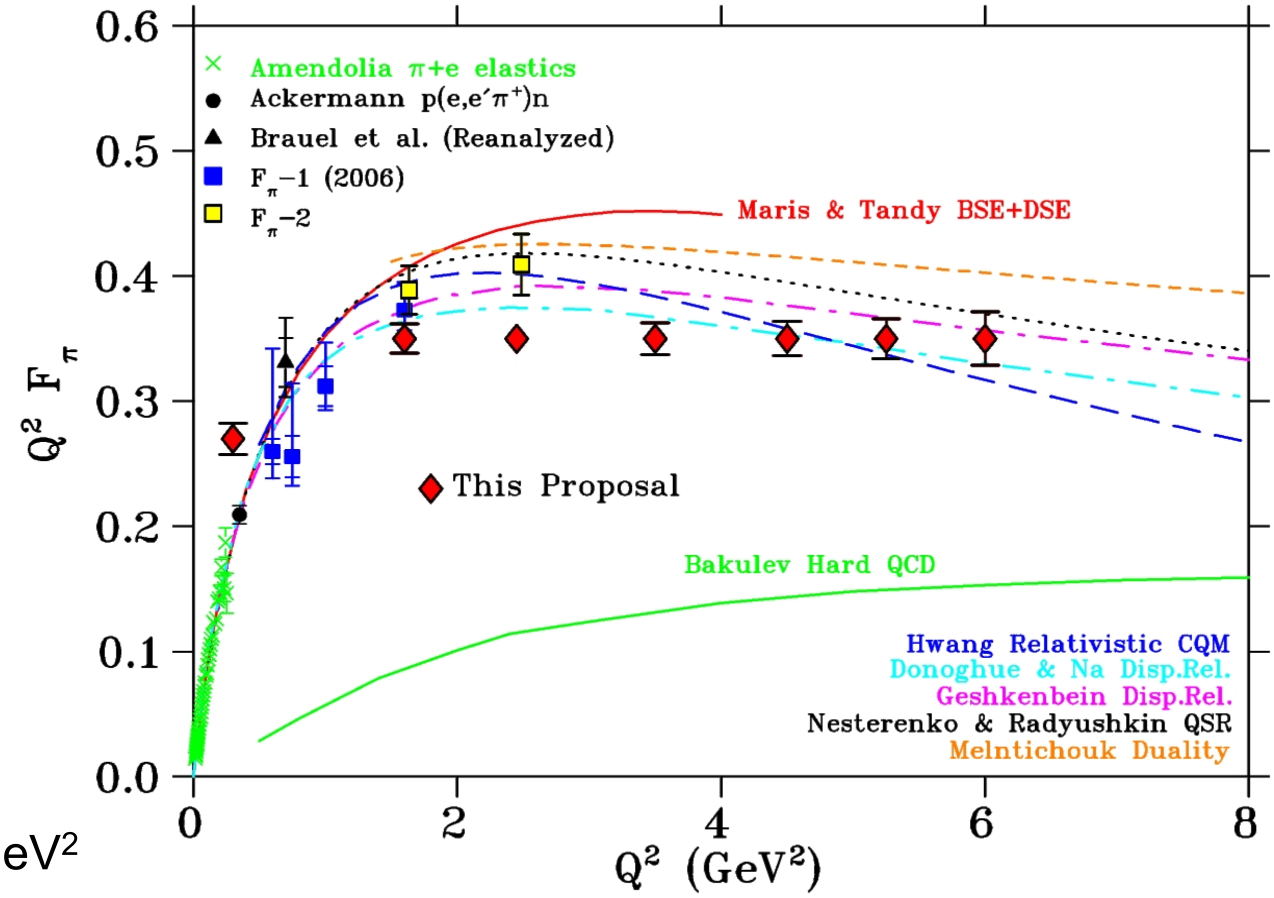
F_π at 12 GeV

L-T separated π+ cross sections near *W*=*3* GeV for *Q*^{2}*=1.6,2.45, 3.5, 4.5, 5.25, 6* GeV^2

→ *Q*^{2}*=0.3* GeV^2 at *W=2.2* GeV

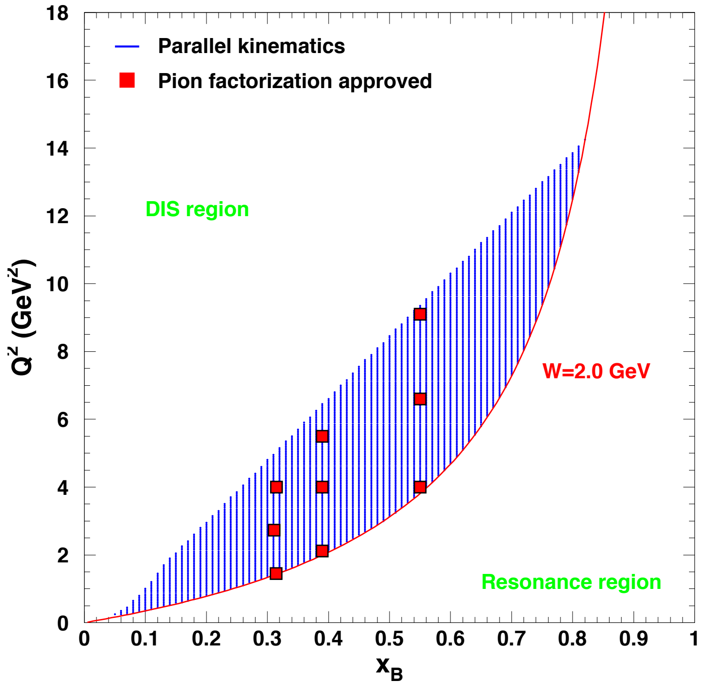
D(e,e'π) at Q^2=1.6 and 3.5 GeV^2
→ Both π+ and π-

Require |-t_{min}|<*0.21* GeV^2 to ensure pole dominance

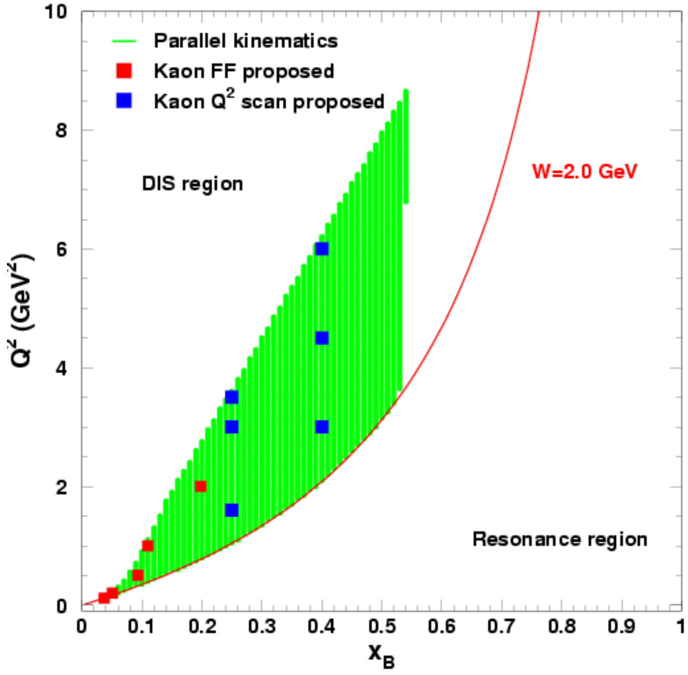


E12-06-101: G. Huber and DG spokespersons

Deep Exclusive π+ and K+



E12-07-105: T. Horn, G. Huber



E12-09-011: T. Horn, G. Huber, P. Markowitz

π-/π+ measurements at x=0.4 setting

Deep exclusive π+ and K+ in Hall C
→ Look for scaling in cross section
→ Study reaction mechanism

Kaon Form Factor

E12-09-11:
Can we extract the kaon form factor from electroproduction data?

Pion pole:

$$\sigma_L \sim \frac{-t}{(t-m_\pi^2)^2}$$

Kaon pole:

$$\sigma_L \sim \frac{-t+(m_p-m_\Lambda)^2}{(t-m_K^2)^2}$$

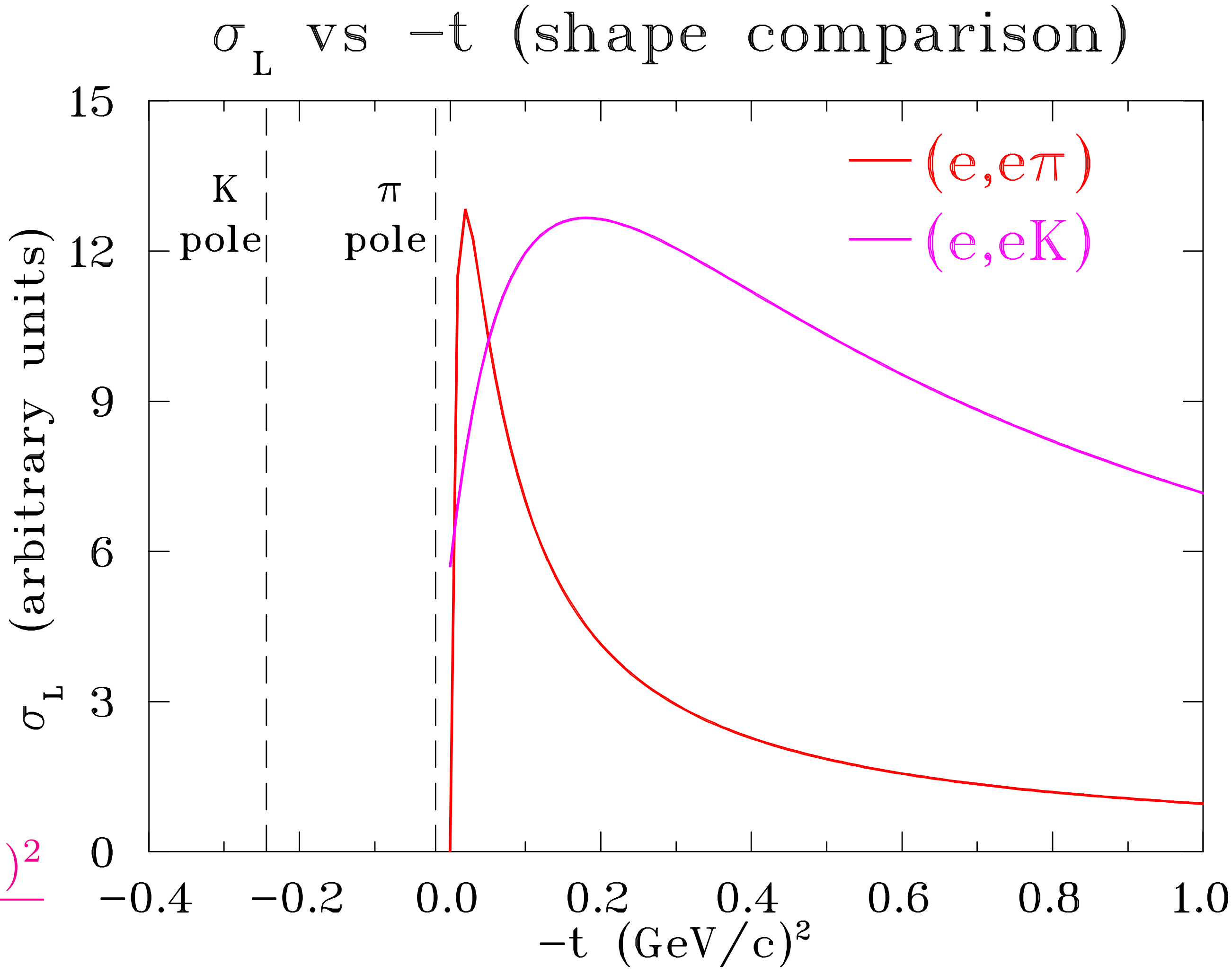


Figure courtesy D. Mack

Deep Exclusive π^0

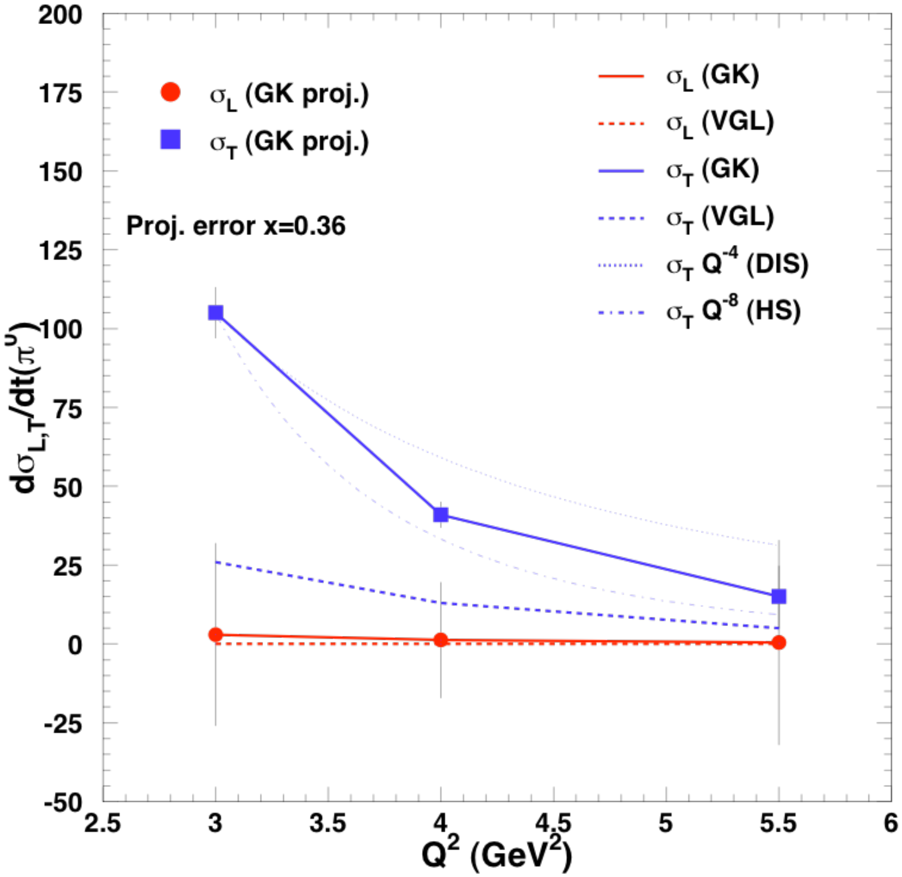
σ_L → access to leading twist GPDs

σ_T → access to transversity GPD, H_T

Requires new, neutral particle spectrometer in Hall C to detect high energy photons

No existing L-T separated data above resonance region

$x=0.36$, $Q^2=3\text{-}5.5$ GeV^2
$x=0.5$, $Q^2=3.4$, 4.8 GeV^2
$x=0.6$, $Q^2=5.1$, 6.0 GeV^2



E12-13-10: C. Munoz Camacho, T. Horn, C. Hyde, R. Paremuzyan, J. Roche

π^0 cross sections and F_π

Much interest in extracting the pion form factor at larger Q^2

→ F_π-12 will measure to Q^2=6 GeV^2

→ Upper limit in part dictated by requirement for pole dominance

→ Only one quantitative calculation that estimates contribution of non-pole backgrounds *[Carlson and Milana, PRL 65, 1717 (1990)]*

→ Pole dominates only for $|t_{min}| < 0.2$

Can also estimate non-pole backgrounds using GPDs

→ π^0 and π^+ cross sections involve different combinations of same GPDs

π^0

$$A_{p\pi^o} \sim (e_u \widetilde{H}^u - e_d \widetilde{H}^d)$$
$$B_{p\pi^o} \sim (e_u \widetilde{E}^u - e_d \widetilde{E}^d)$$

π^+

$$A_{p\pi^+} \sim (\widetilde{H}^u - \widetilde{H}^d)(e_u + e_d)$$
$$B_{p\pi^+} \sim (\widetilde{E}^u - \widetilde{E}^d)(e_u + e_d)$$

Measurement of σ_L in π^0 production could help us access F_π at larger Q^2

→ But large fractional uncertainties due to unfavorable *R* could make this difficult

Extract σ_L with no Rosenbluth 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

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

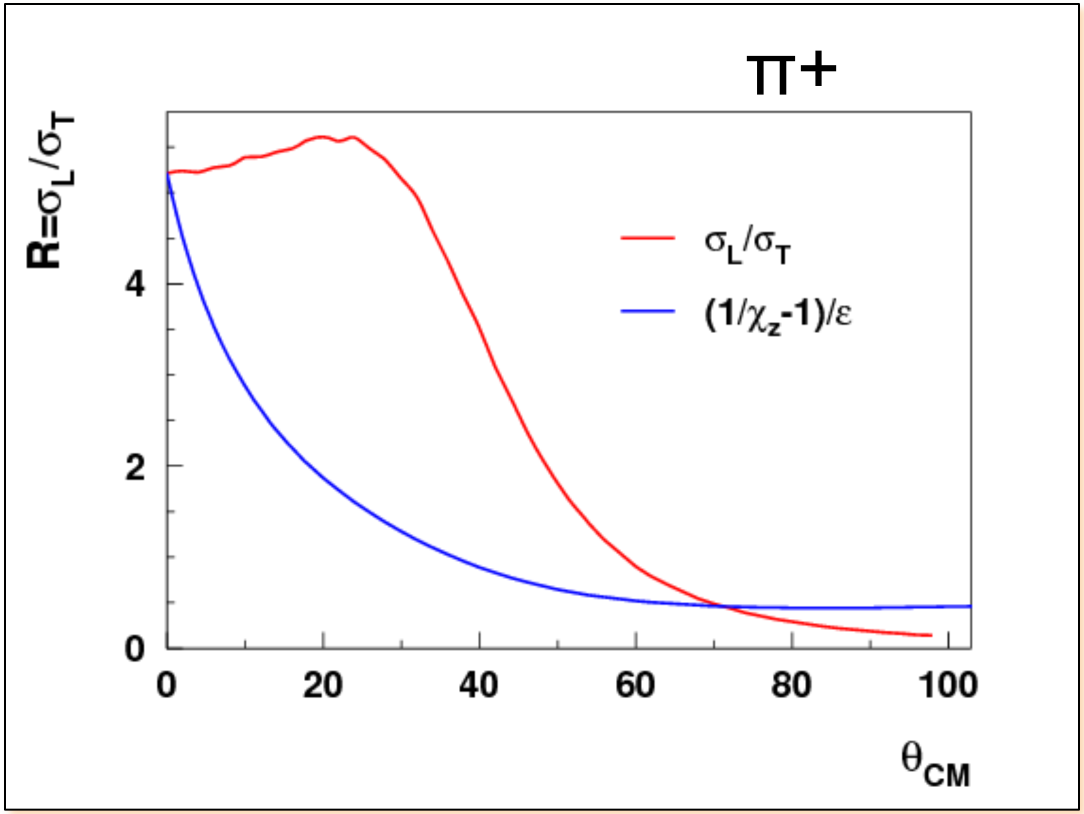
A_z = target double-spin asymmetry

Parallel Kinematics

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

MAID2007

Q^2=5 GeV^2
$W = 1.95$ GeV



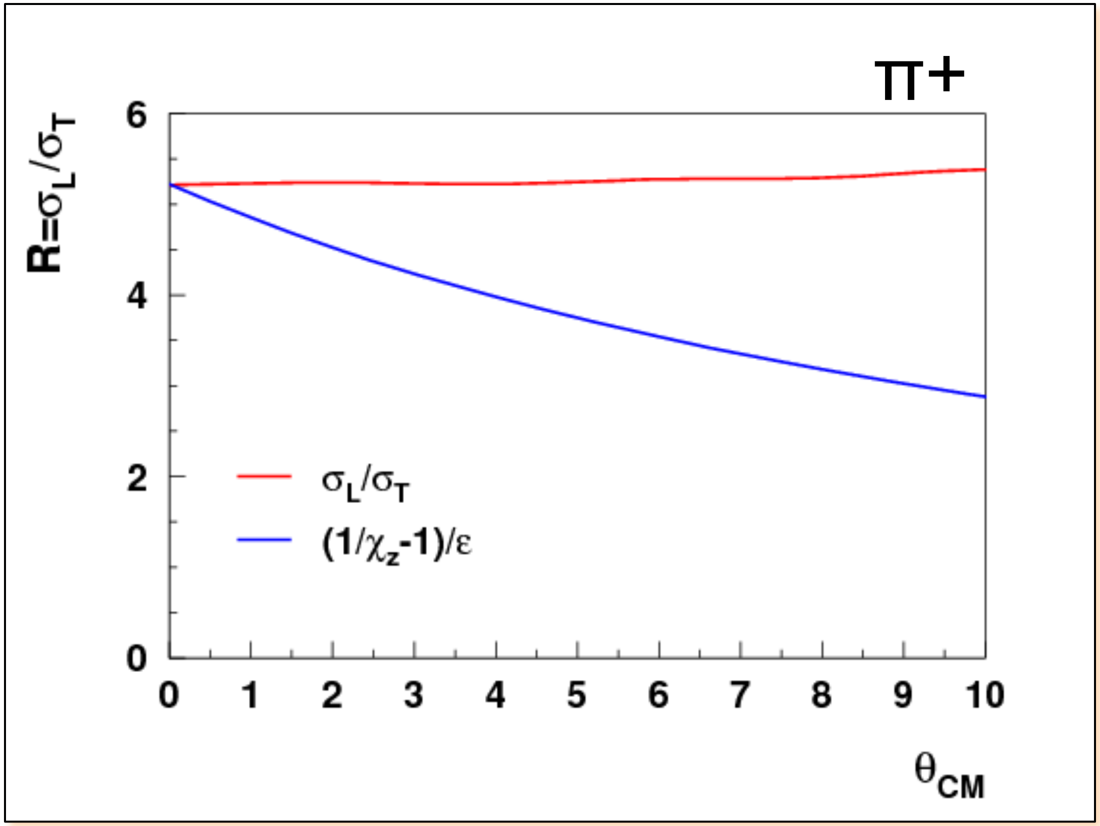
L/T Extraction

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

At 1 degree, polarization observable already ~ 15% different from true value

→ very tight cuts will be needed (0.1 degrees?)

→ Limited phase space – rates will likely be a factor



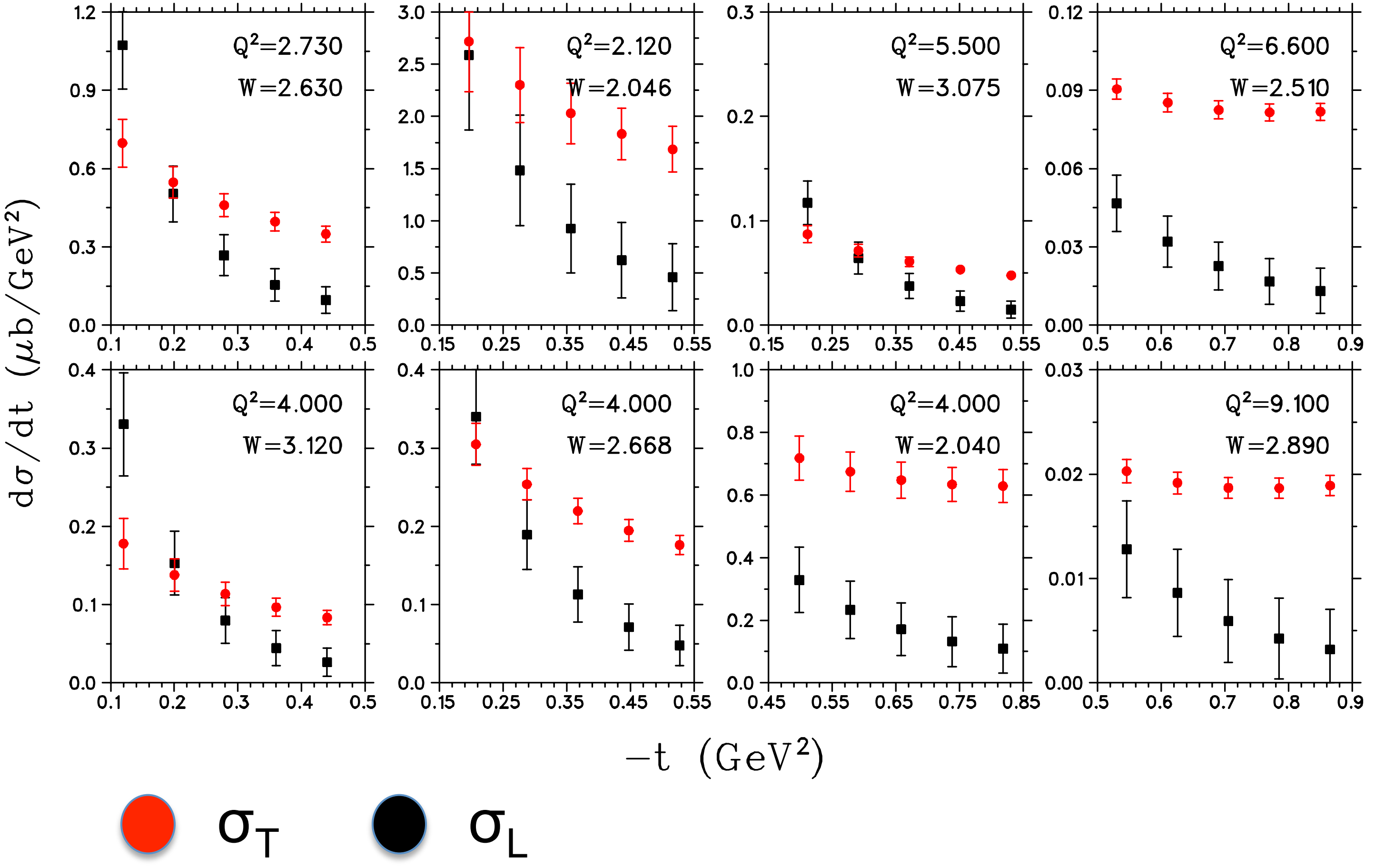
Summary

- Rosenbluth separations extremely challenging from experimental perspective
  - Excellent control of point-to-point systematics absolutely required
  - Even then, unfavorable value of $R=\sigma_L/\sigma_T$ may limit relative precision
- Existing L-T (JLab 6 GeV) separated data mostly charged pions
  - π^0 data from Hall A DVCS program under analysis
  - Some kaon data at W<2 GeV
- In 12 GeV era, a broader range of L-T separated data will be available
  - Increased kinematic reach for charged pions
  - First ever kaon data above resonance region
  - π^0 data at larger Q^2
- In some cases, we may not get the precision/information needed or desired (e.g., π^0 longitudinal cross sections)
  - Polarization degrees of freedom may help – but only in limited kinematics

Extra

σ_L Precision at large -t

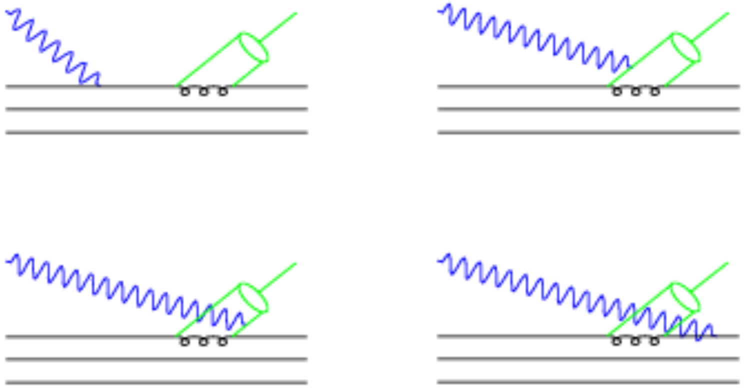
Projections based on VR model



Vrancx and Ryckebusch, Phys. Rev. C 89, 025203 (2014)

pQCD Contributions to *$H(e,e'\pi^+)$*

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**

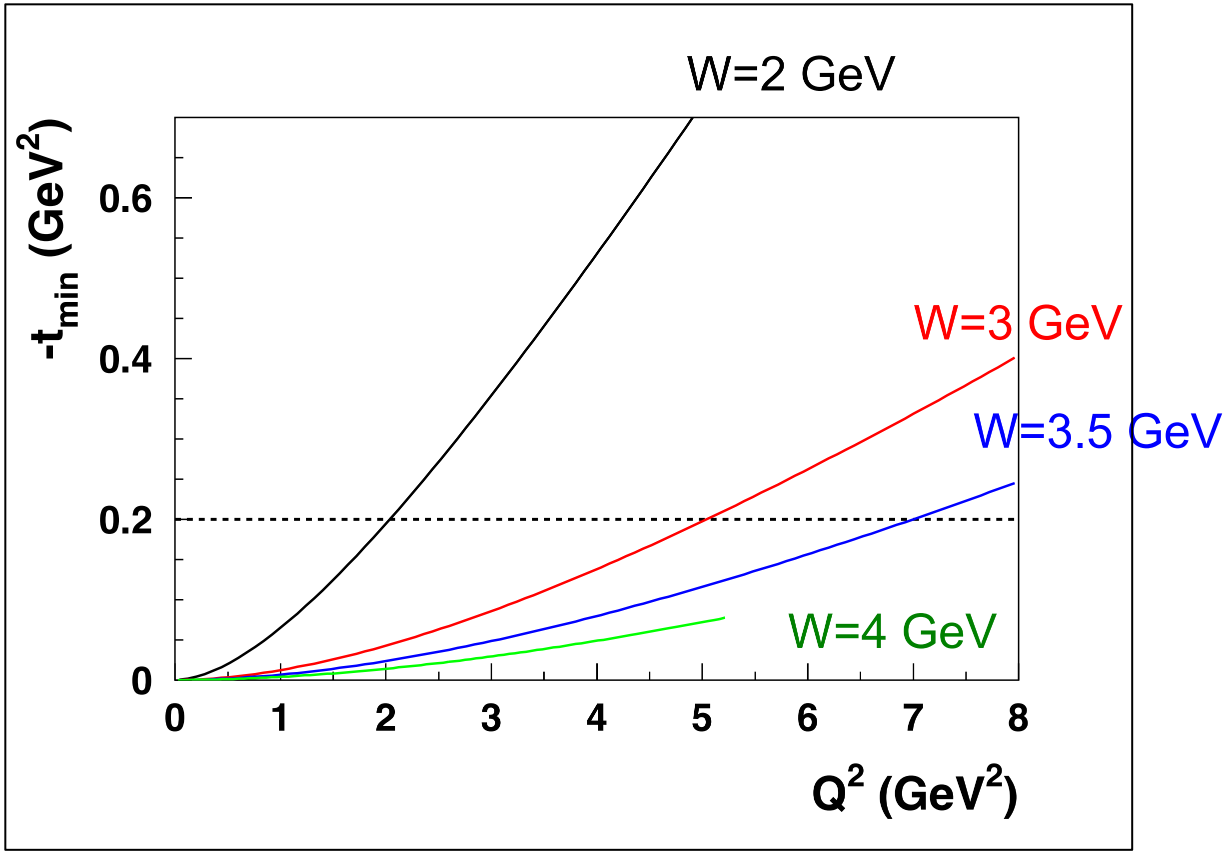
Kinematic Constraints on *$-t_{min}$*

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

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

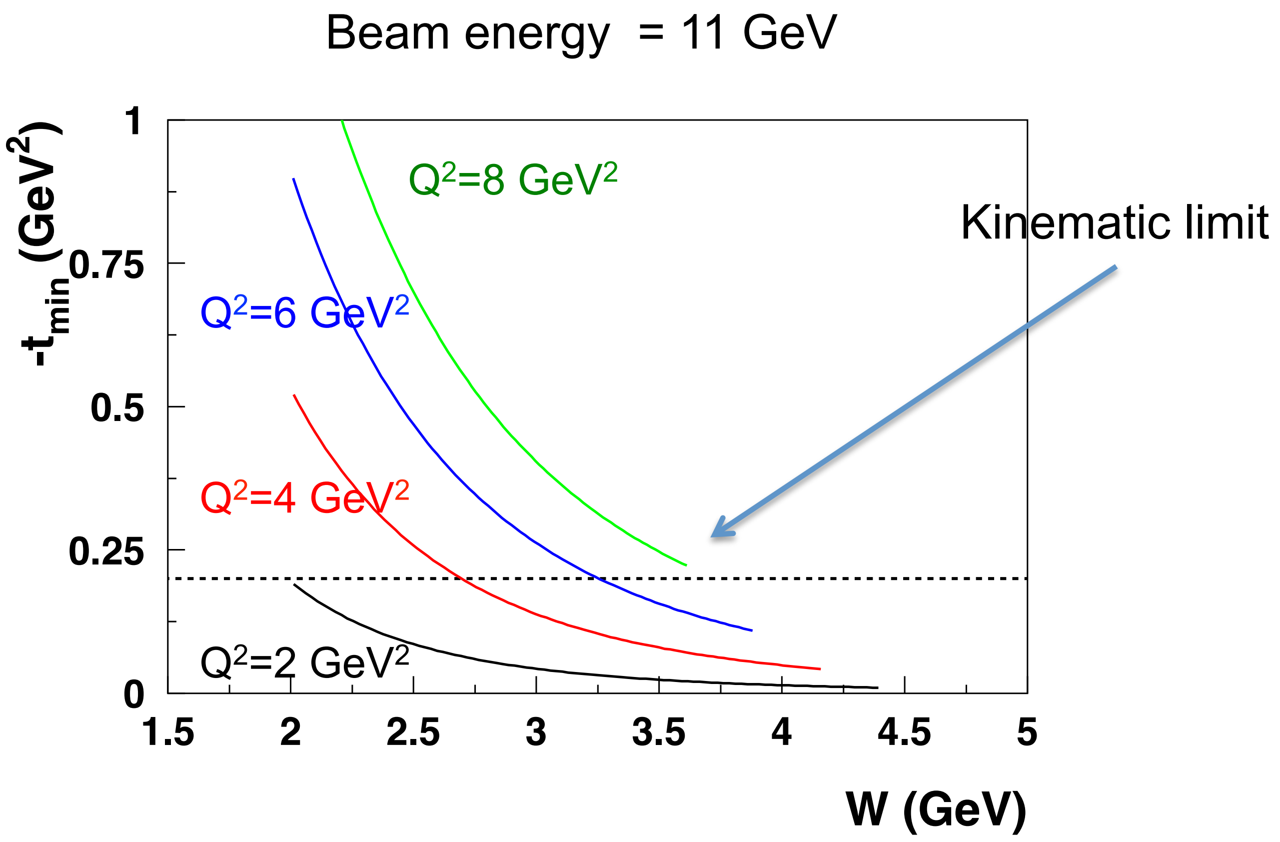
F_π-12 will reach $Q^2=6$ GeV^2 detecting scattered electron and pion

Beam energy = 11 GeV



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?