Nuclear Transparency in A(e,e' π/K)X
Status and Prospects

Tanja Horn

THE
CATHOLIC UNIVERSITY
of AMERICA

Small size configurations at high-t workshop

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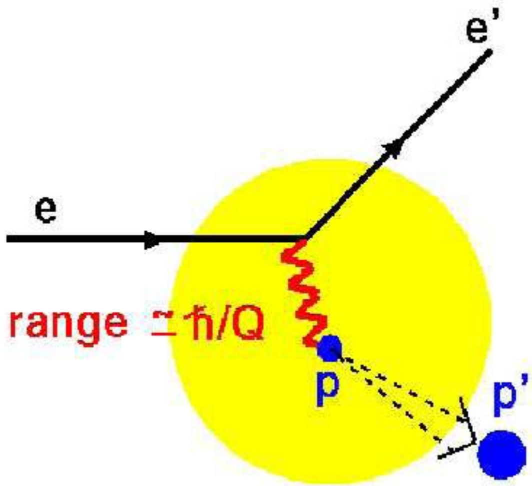
Nuclear Transparency

- Color transparency (CT) is a phenomenon predicted by QCD in which hadrons produced at large Q^2 can pass through nuclear matter with little or no interaction *[A.H.Mueller, Proc. 17th rec. de Moriond, Moriond, p13 (1982), S.J.Brodsky, Proc. 13th intl. Symp. on Multip. Dyn., p963 (1982)]*
  - At high Q^2, hadron can be created with a small transverse size (PLC)
  - Hadron can propagate through the nucleus before assuming its equilibrium size



- Currently no conclusive evidence of the onset of CT at intermediate energies
  - Proton results negative up to Q^2~8 GeV^2

- Advantage of using pions: simple $q\bar{q}$ system
  - Easier to produce a point-like configuration (PLC) of two quarks rather than three
  - Coherence lengths are small (~1 fm)

Transparency at JLab 6 GeV (E01-107)

- Took data to the highest possible Q^2 with 6 GeV electron beam at JLab in 2004
- Main goal: measurement of the nuclear transparency of pions
- Also: full L/T/LT/TT separation in π^+ production at two values of Q^2

Q^2 (GeV^2)	W (GeV)	|t| $(Gev)^2$	E_e (GeV)	ε
1.1	2.3	0.05	4.0	0.50
2.15	2.2	0.16	4.0,5.0	0.27,0.56
3.0	2.1	0.29	5.0	0.45
4.0	2.2	0.44	5.0,5.8	0.25,0.39
4.8	2.2	0.52	5.8	0.26

- LH_2, LD_2, ^{12}C, Cu, and Au targets at each kinematic setting

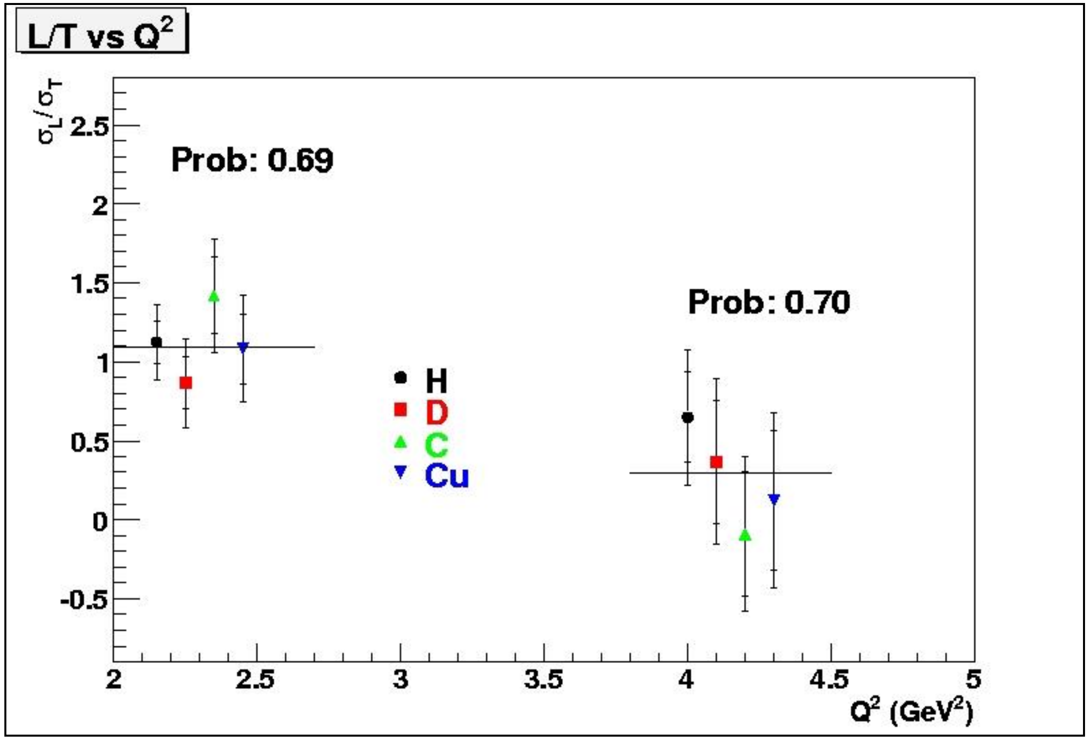
The $A(e,e'\pi^+)$ Reaction

X. Qian et al., Phys. Rev. C 81, 055209 (2010)

- If π+ production from a nucleus is similar to that from a proton we can determine nuclear transparency of pions

- Other mechanisms: NN final state interactions, pion excess, medium modifications, etc.

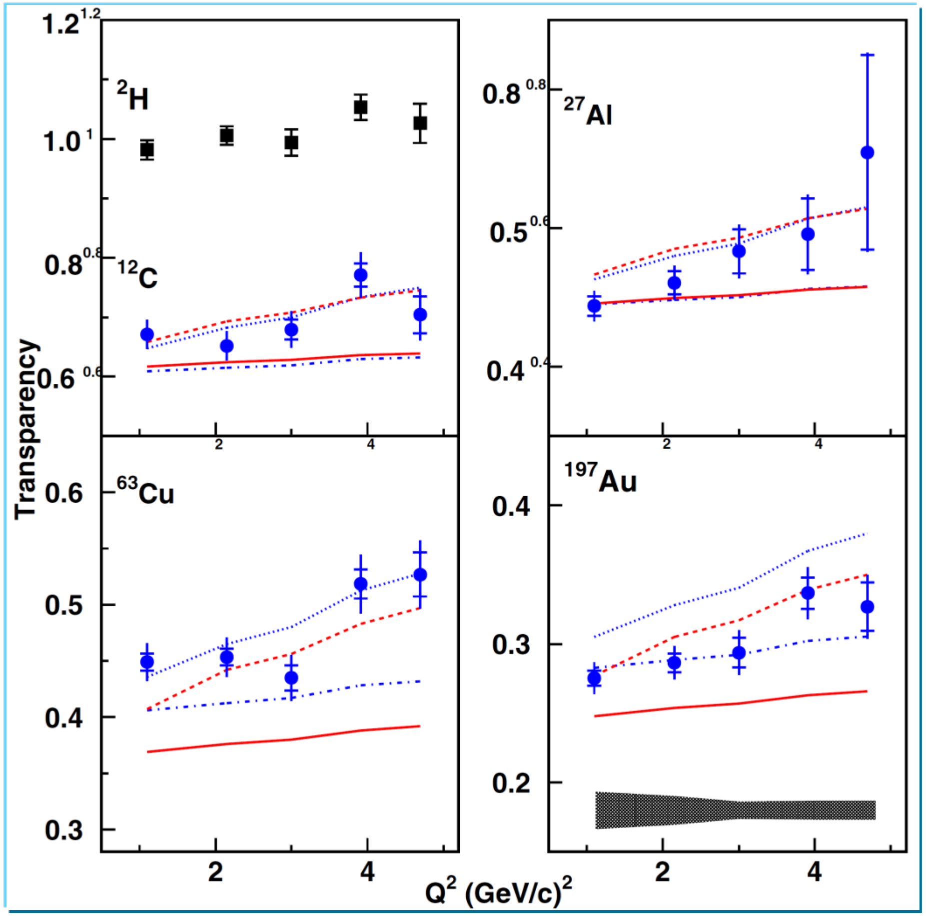
- Assumption is verified by L/T separations
  - Extracted average results over the acceptance



$$\sigma_{A(e,e'\pi^+)X} = \sigma_{p(e,e'\pi^+)n} \otimes S(E,p)$$

$S(E,\mathbf{p})$ = Spectral function for proton

Pion Nuclear Transparency - Q^2 Dependence



B. Clasie et al., PRL 99, 242502 (2007)

Covered in Phys. Rev. Focus 6/2006

Inner error bar are statistical uncertainties outer error bar are the quadrature sum of statistical and pt to pt systematic uncertainties.

$$T = \frac{\sigma_A^{Expt} / \sigma_A^{Model}}{\sigma_p^{Expt} / \sigma_p^{Model}}$$

- Larson et al., *[Phys. Rev. C74, 018201 (2006)]*
  - Semiclassical Glauber multiple scattering approximation
  - Dashed: includes CT
- Cosyn et al., *[Phys. Rev. C74, 062201R (2006)]*
  - Relativistic Glauber multiple scattering theory
  - Dash-dot: includes CT+SRC

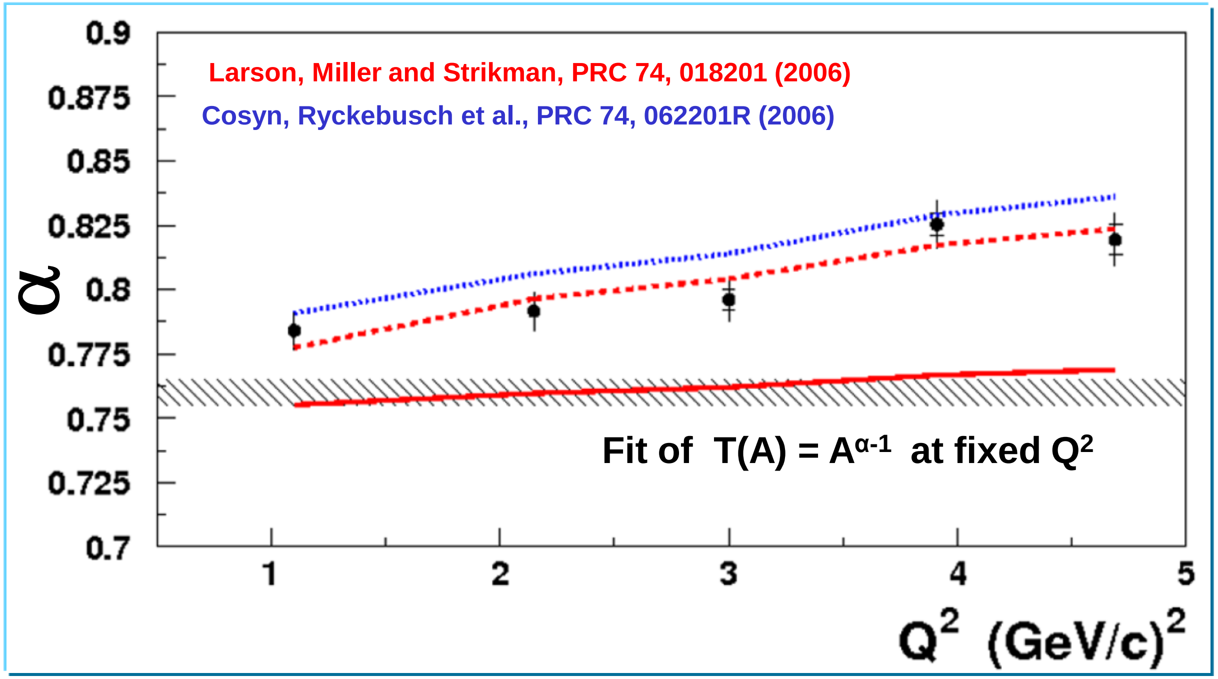
A Dependence of Pion Transparency

- Energy dependence of α, which quantifies the A dependence of nuclear transparency, can be viewed as an indication for CT-like effects

$$\sigma(A) = \sigma_0 A^{\alpha}$$

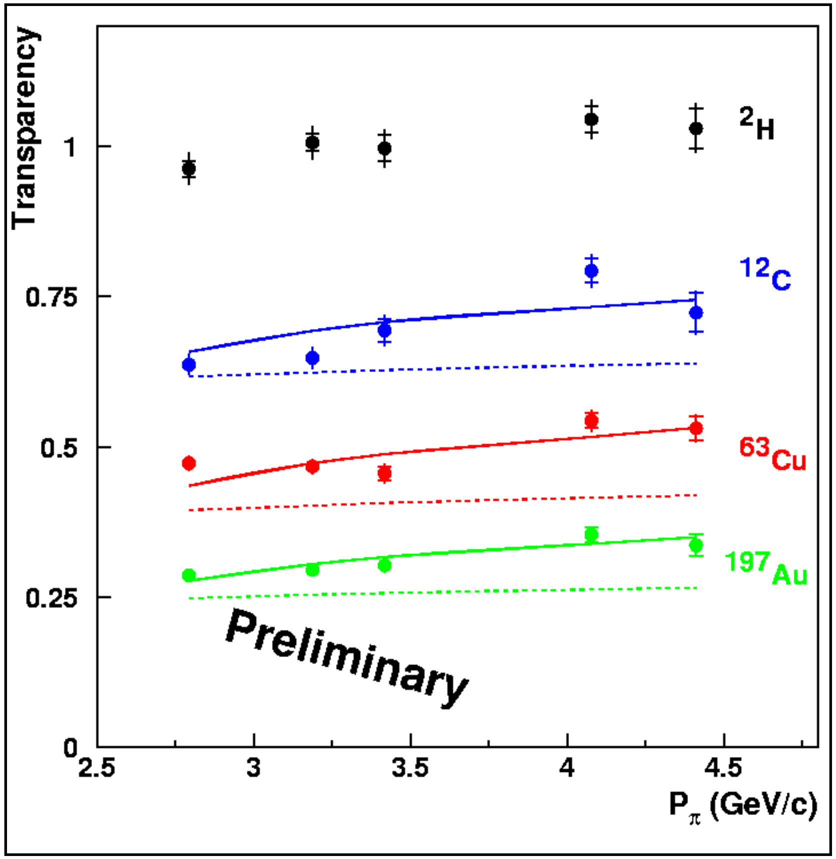
$$\therefore \quad T = A^{\alpha-1}$$

- Fits to π-N scattering cross sections give α~0.76
  - Energy independent



B. Clasie et al., PRL 99, 242502 (2007)

'P_π' Dependence of Transparency



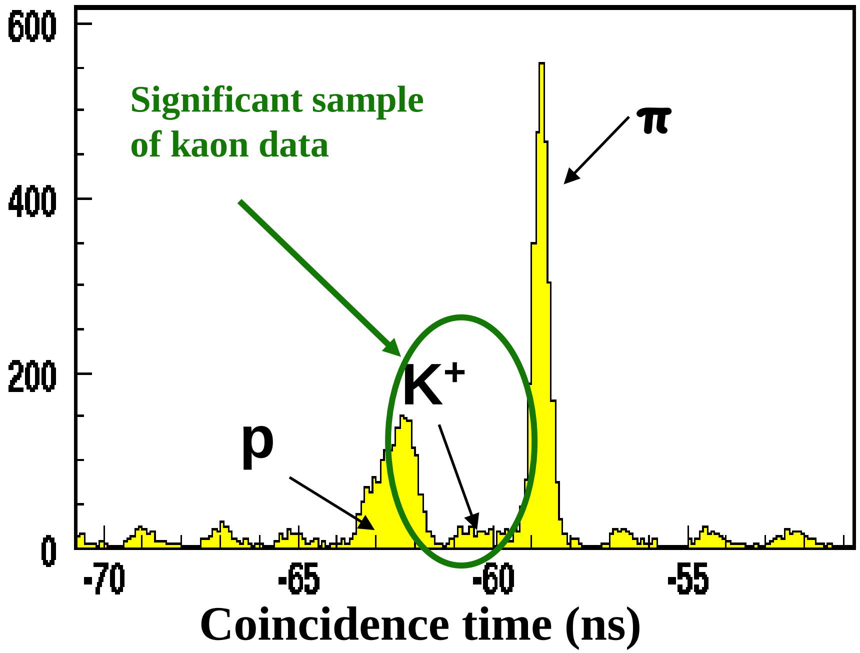
Inner error bar are statistical uncertainties

outer error bar are the quadrature sum of

statistical and pt. to pt. systematic uncertainties.

- No conflict between pionCT data and recent Hall-B e,e'ρ data
  - P_π >2.5 GeV for all pionCT kinematics while for the Hall B e,e'ρ the highest ρ momentum is <2.5 GeV
- Solid/Dashed lines are predictions with and without CT *[A. Larson, G. Miller and M. Strikman, nuc-th/0604022]*

Kaon Transparency at 6 GeV JLab



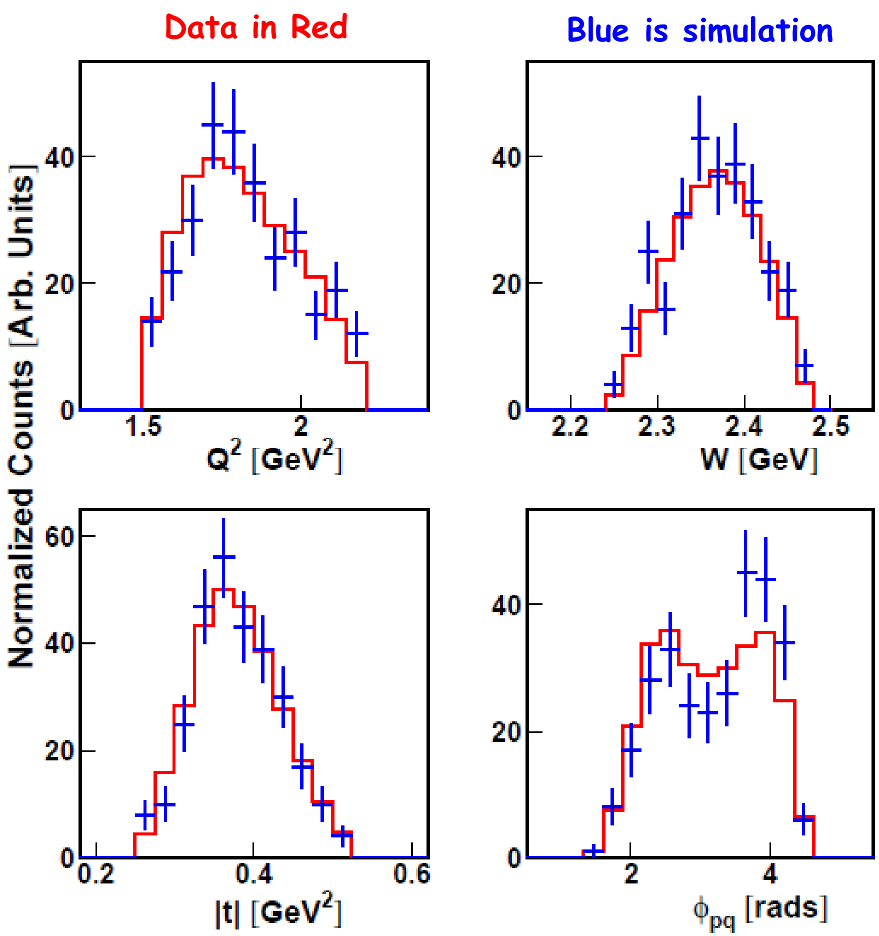
Experimental data from 6 GeV JLab also contain significant sample of kaons!

Q^2 (GeV^2)	-t (GeV^2)	E_e (GeV)	p_{K+} (GeV)
1.1	0.05	4.0	2.793
2.1	0.16	5.0	3.187
3.0	0.29	5.0	3.418

Kaon Transparency kinematics

- Kaon transparency from electroproduction has never been measured!
- Kaons contain strange quarks and thus have a very long mean free path, which makes kaons a unique probe of the nuclear force
- Kaon transparency from electroproduction may help verify the anomalous strangeness transparency seen in K-nuclei scattering *[S.M. Eliseev, NPA 680, 258c (2001)]*

Kaon Transparency Analysis Procedure



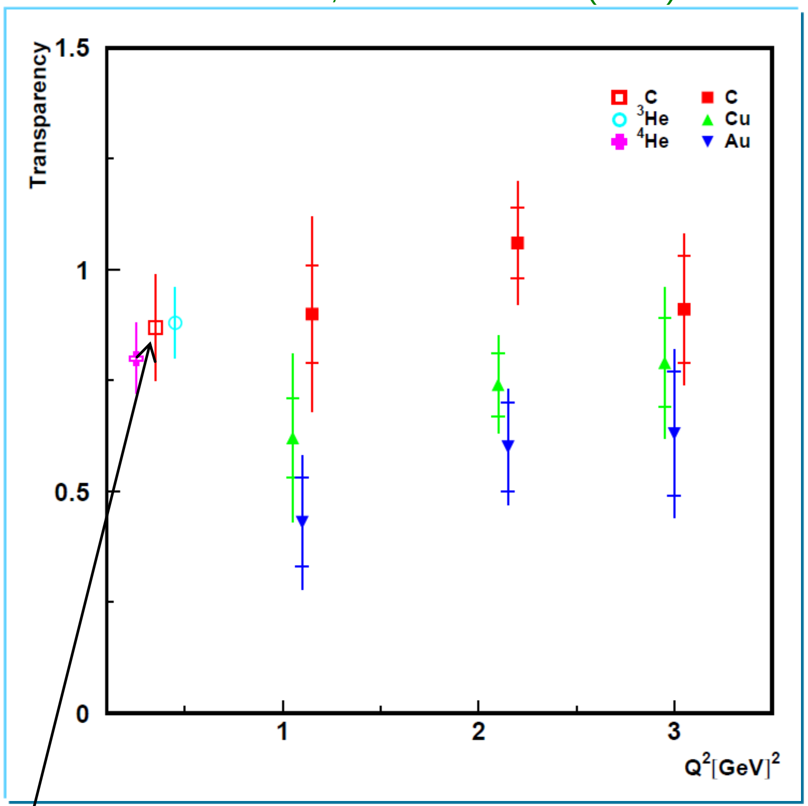
Data and simulation for ^{12}C nucleus at Q^2=2.1 GeV^2

- Build a model for $p(e,e'K^+)X$ using hydrogen data that is based on earlier kaon production data
- Monte Carlo simulation includes various corrections, e.g., experimental, reaction mechanism (Coulomb distortion), etc.
- The new parameterization of the kaon production cross section is used as an input for the quasi-free model for all target nuclei

Simulation describes shapes reasonably well for all target nuclei and kinematic settings

Kaon Nuclear Transparency - Q^2 Dependence

Nuruzzaman et al., arXiv:1103.4120 (2011)



Earlier data on quasi-free kaon production from light nuclei

[F. Dohrmann et al., Phys. Rev. C 76, 054004 (2007)]

- Kaon transparency and its Q^2 dependence for three heavy target nuclei
- Recent JLab data are in agreement with earlier JLab low Q^2 data
  - For recent data ratio of proton number from light nuclei to ^{2}H was taken

No energy dependence within uncertainty of the transparency

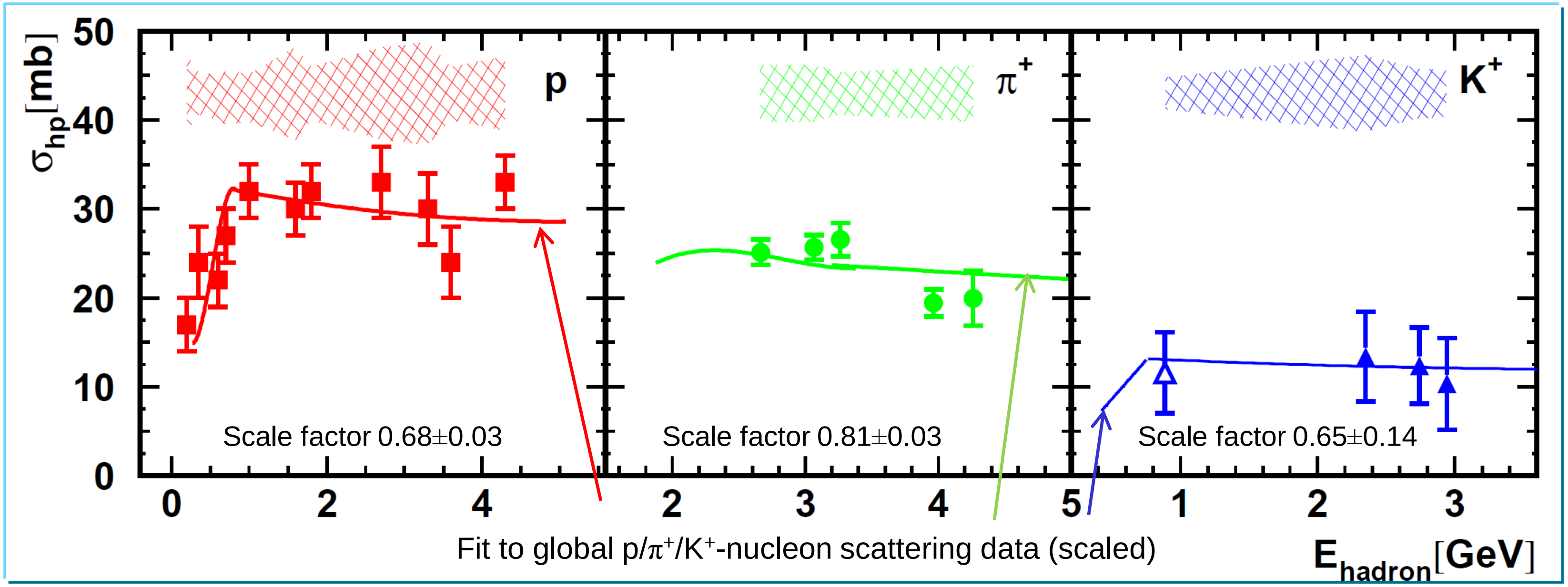
Compare to deuterium to reduce impact of non-isoscalar effects

Transparency extracted as

$$T = \frac{\sigma_A^{Expt} / \sigma_A^{Model}}{\sigma_D^{Expt} / \sigma_D^{Model}}$$

Effective Cross Sections

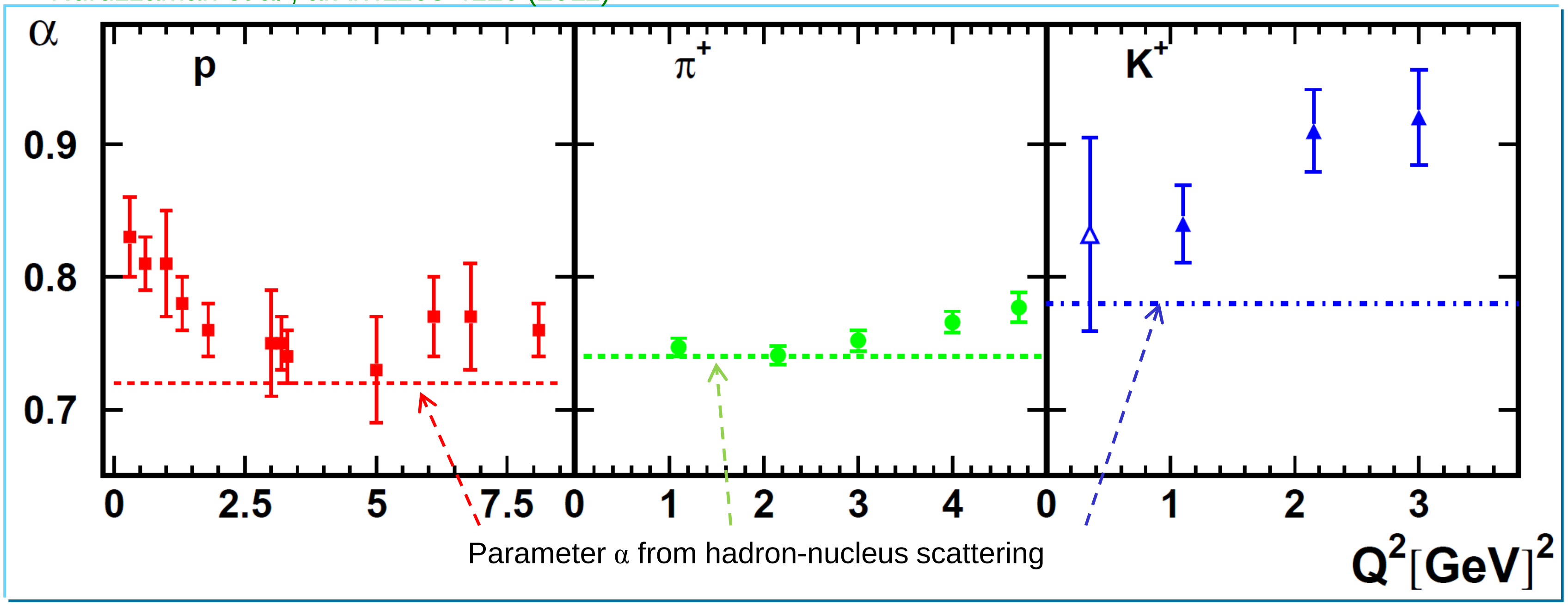
Nuruzzaman et al., arXiv:1103.4120 (2011)



- Investigate relative trends for p/π^+/K^+ by extracting effective cross sections
  - Obtained by fitting the measured transparency to an empirical geometrical model
- Energy dependence of effective p/π^+/K^+ cross sections is consistent with the one of the free cross sections, but absolute magnitudes are different
  - Kaon effective cross section significantly smaller than free cross section compared to size of the effect for p/π^+ -- would require more sophisticated models to study

A Dependence of Kaon Transparency

Nuruzzaman et al., arXiv:1103.4120 (2011)



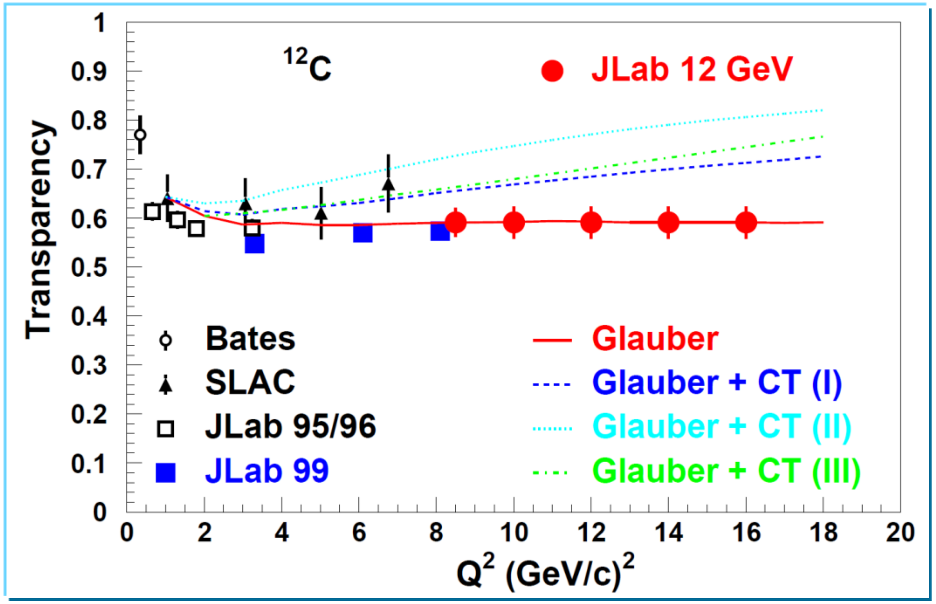
- Energy dependence of α, which quantifies the *A* dependence of nuclear transparency, can be viewed as an indication for CT-like effects

$$\sigma(A) = \sigma_0 A^{\alpha} \quad \therefore \quad T = \left(\frac{A}{2}\right)^{\alpha-1}$$

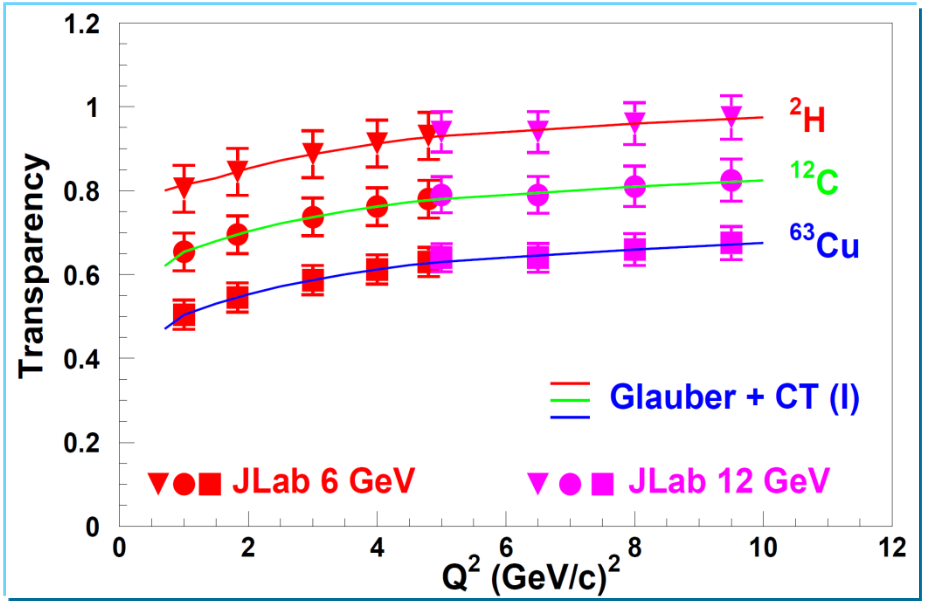
- Parameter α for p, π^+, K^+ from electron scattering is larger compared to high-energy hadron-nucleus collisions
  - For kaons, α is significantly larger contrary to traditional nuclear physics expectation

CT at 12 GeV JLab

$^{12}C(e,e'p)$



$A(e,e'\pi^+)$

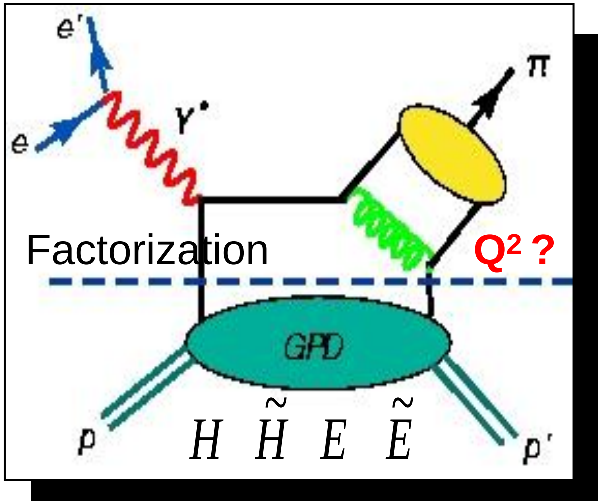


- Goals of the 12 GeV Jlab experiment (E12-06-107)
  - Search for CT with $p/\pi^+/K^+$ in a region of Q^2=5-9.5 GeV^2
  - For π^+/K^+, where reaction mechanism not well understood map out both Q^2 and *A* dependence

Hard-Soft Factorization

- To access physics contained in GPDs, one is limited to the kinematic regime where hard-soft factorization applies
  - No single criterion for the applicability, but tests of necessary conditions can provide evidence that the Q^2 scaling regime has been reached

- Factorization is not rigorously possible without the onset of CT *[Burkhardt et al., Phys.Rev.D74:034015,2006]*



- One of the most stringent tests of factorization is the Q^2 dependence of the π/K electroproduction cross section
  - σ_L scales to leading order as Q^{-6}

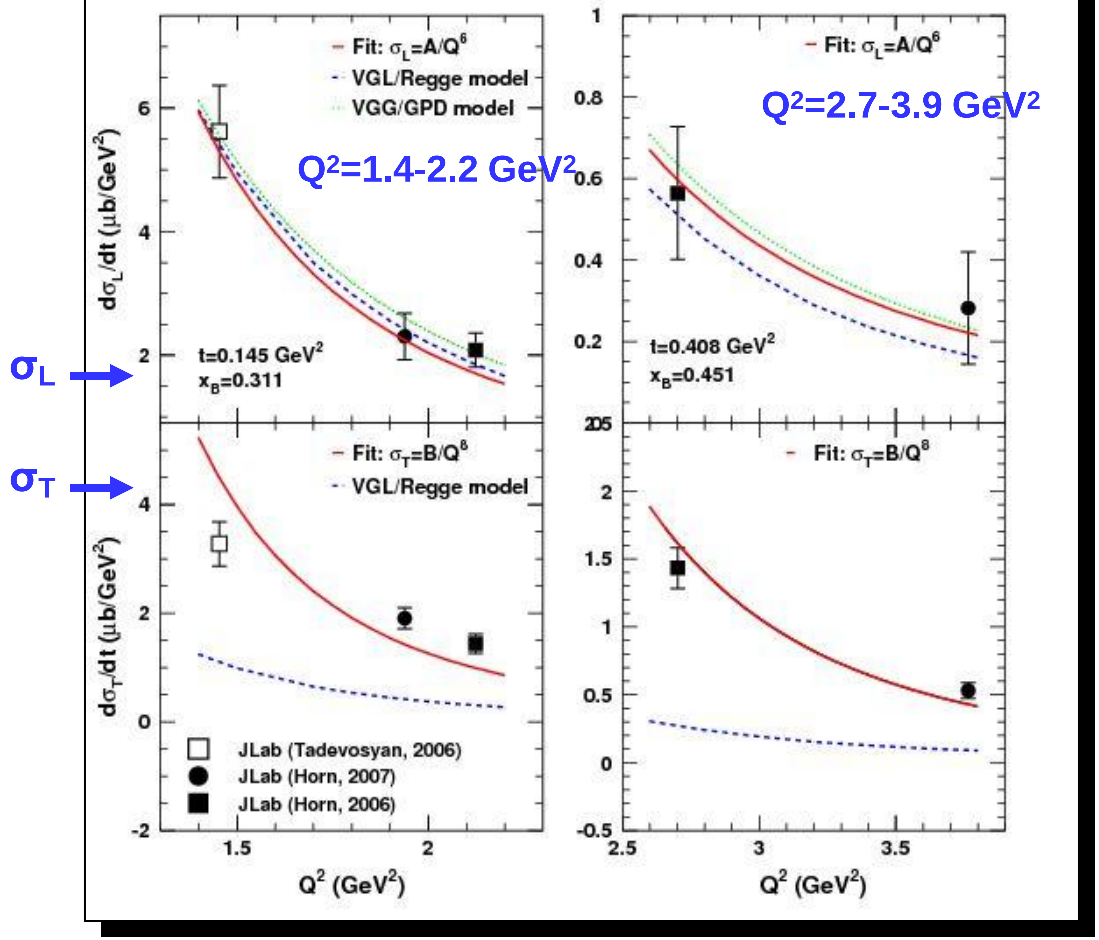
- Factorization theorems for meson electroproduction have been proven rigorously only for longitudinal photons *[Collins et al, Phys. Rev. D56, 2982 (1997)]*

Q^2 dependence of σ_L and σ_T

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

- The Q^{-6} QCD scaling prediction is consistent with the JLab σ_L data
  - Limited Q^2 coverage and large uncertainties make it difficult to draw a conclusion
- The two additional predictions that $\sigma_L >> \sigma_T$ and $\sigma_T \sim Q^{-8}$ are not consistent with the data
- Testing the applicability of factorization requires larger kinematic coverage and improved precision

Hall C data at 6 GeV: 3 different experiments

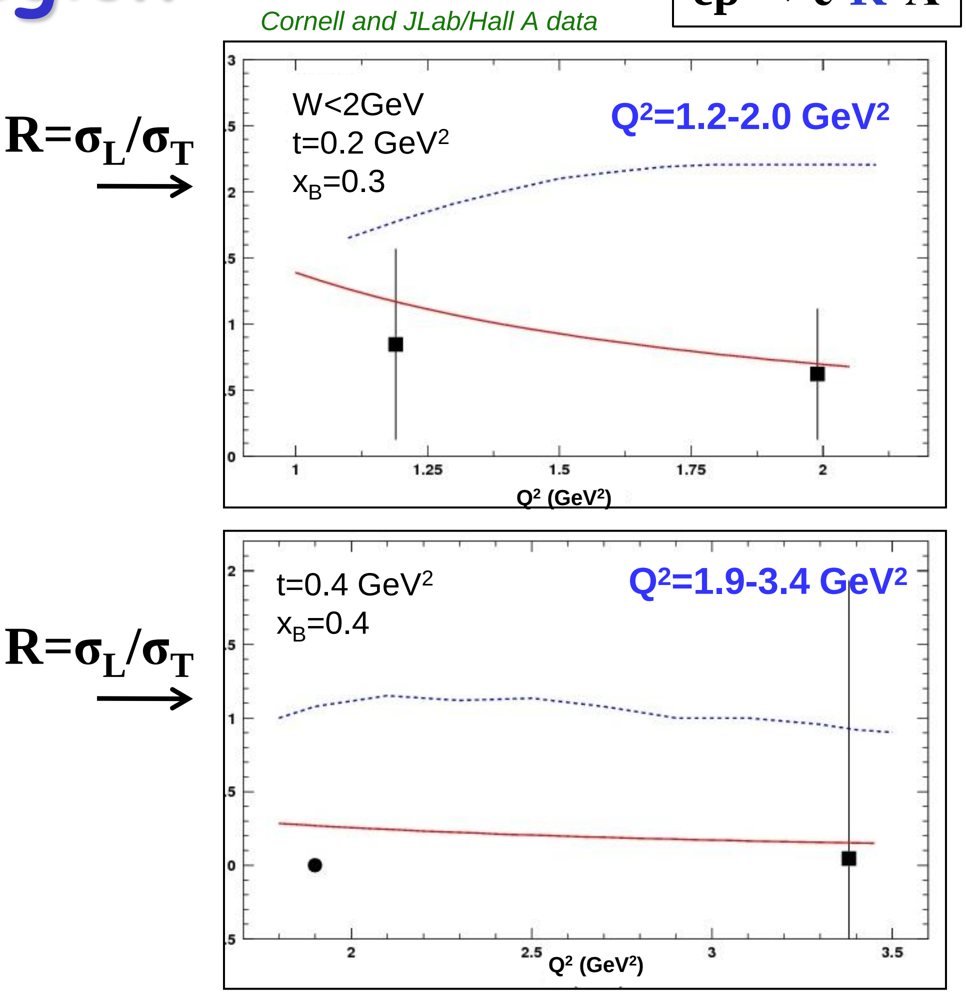


T. Horn et al., Phys. Rev. C 78, 058201, (2008); arXiv:0707.1794 (2007)

Kaons: Q^{-n} scaling of σ_L/σ_T in the resonance region

- Q^{-n} scaling trough $R=\sigma_L/\sigma_T$ is not as rigorous as the scaling test of the individual cross sections
- Current knowledge of σ_L and σ_T *above* the resonance region is insufficient
- Current models not sufficient for understanding reaction mechanism
- Difficult to draw a conclusion from current *K*$^+$ σ_L/σ_T ratios
  - Limited W and Q^2 coverage
  - Uncertainties from scaling in x, t

$ep \rightarrow e'K^+\Lambda$



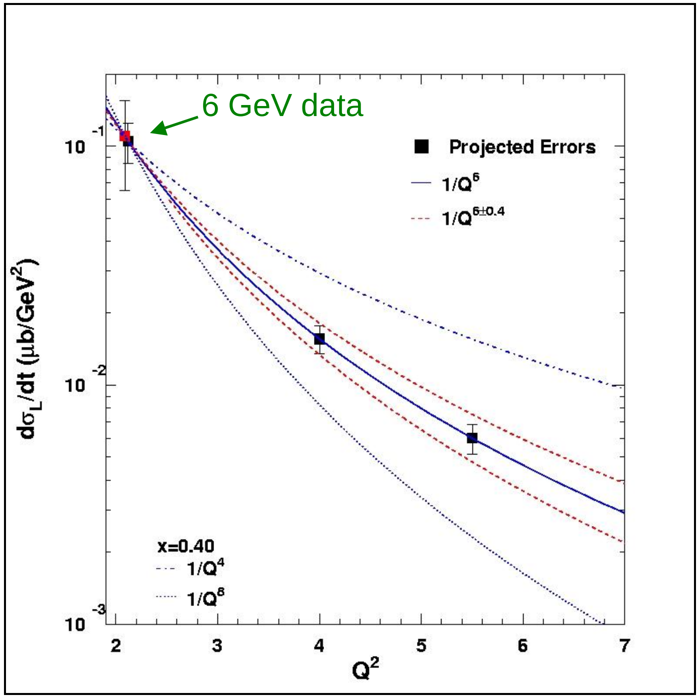
High quality σ_L and σ_T data for both kaon and pion would provide important information for understanding the meson reaction mechanism

JLab 12 GeV: Factorization Tests in π^+ Electroproduction

- JLab experiment E12-07-105 will search for the onset of factorization

- Measure the Q^2 dependence of the $p(e,e'\pi^+)n$ cross section at fixed x_B and $-t$ to search for evidence of hard-soft factorization
  - Separate the cross section components: L, T, LT, TT
  - The highest Q^2 for any L/T separation in π electroproduction

- Also determine the L/T ratio for π^- production to test the possibility to determine σ_L without an explicit L/T separation



x	Q^2 (GeV^2)	W (GeV)	-t $(GeV/c)^2$
0.31	1.5-4.0	2.0-3.1	0.1
0.40	2.1-5.5	2.0-3.0	0.2
0.55	4.0-9.1	2.0-2.9	0.5

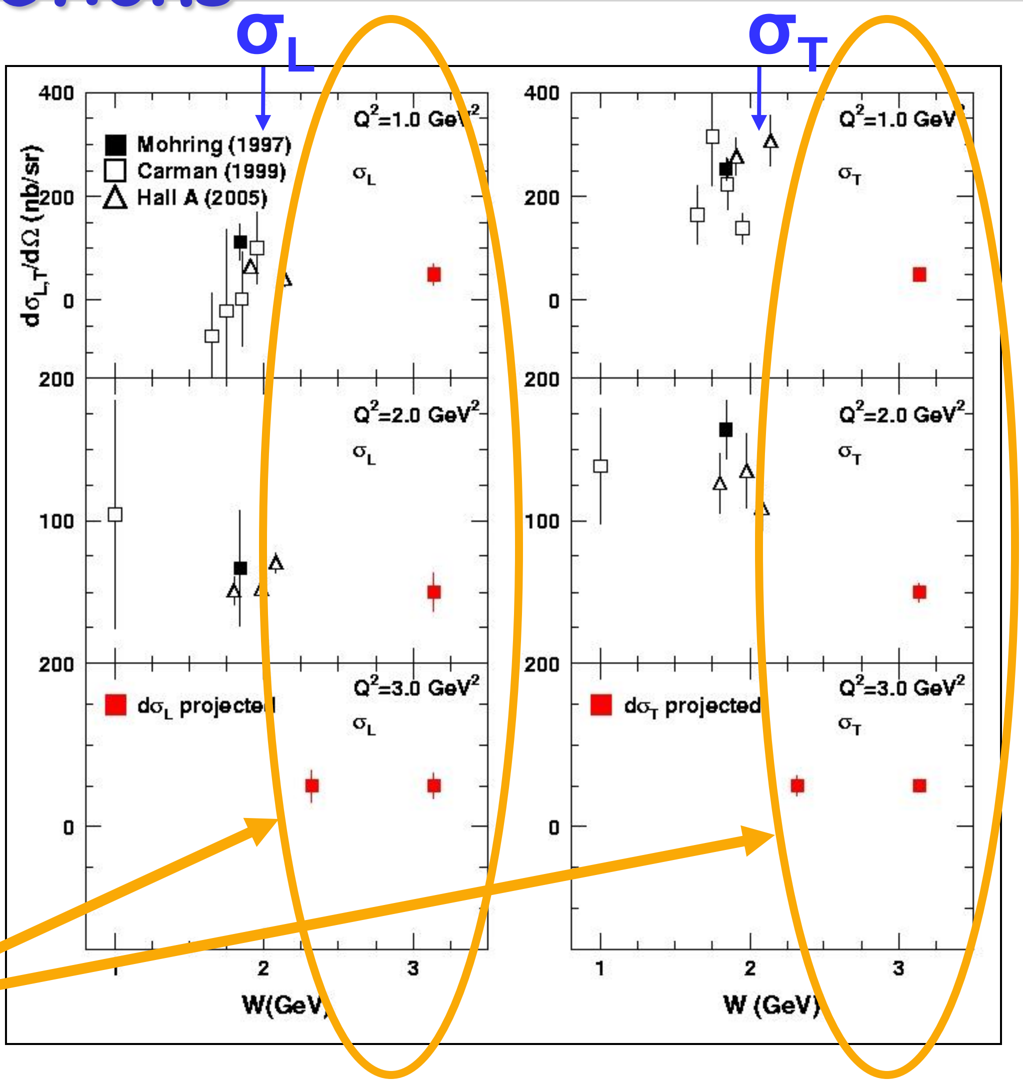
Is the partonic description applicable at JLab?

Can we extract GPDs from pion production?

JLab 12 GeV: L/T separated kaon cross sections

T. Horn et al.

- Approved experiment E12-09-011 will provide first L/T separated **kaon** data above the resonance region
- Onset of factorization
- Understanding of hard exclusive reactions
  - QCD model building
  - Coupling constants



E12-09-011: Precision data for W > 2.5 GeV

L/T separations from nuclear targets

- L/T separation from nuclear targets from JLab 6 GeV/12 GeV data

- MC model including a parameterization in missing mass, Mx, using fit to data.