Exclusive pion electroproduction off nucleons and nuclei

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Electroproduction of π above $\sqrt{2}$ GeV

- Motivation
- Color Transparency
  - Exclusive π production off nuclei
  - Onset of Color Transparency in $A(e, e', \pi^+ n)A - 1$ at JLAB
- Exclusive π production off nucleons
  - Reaction mechanism in $N(e, e'\pi)N$
    - Puzzles
    - More Puzzles
  - Charged pion electroproduction
  - Neutral pion electroproduction
- Summary

Color Transparency (CT) in $A(e, e'\pi^+)A^*$

- CT effect in $A(e, e'\pi^+)A'$ off nuclei
  - QCD factorization (GPD based models) requires CT effect

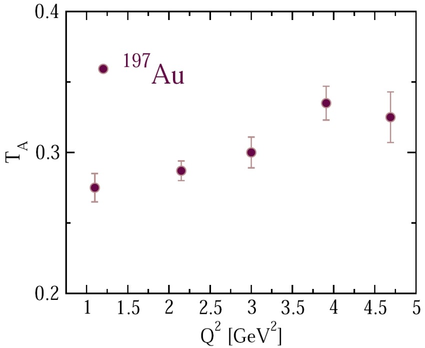
$$A(e, e'\pi^+)A^*$$

$$T_A = \sigma_A / A\sigma_N$$

$$\sigma(FSI) \propto d_\perp^2 \sim 1/Q^2$$

- M. M. Kaskulov, K. Gallmeister and U. Mosel, Phys. Rev. C **79**, 015207 (2009)
  - A. Larson, G. A. Miller, M. Strikman, Phys. Rev. **C74**, 018201 (2006). W. Cosyn, M. C. Martinez, J. Ryckebusch, Phys. Rev. **C77**, 034602 (2008).
  - CT: Longitudinal (γ_L^*) and/or Transverse (γ_T^*)

JLAB: B. Clasie *et al.*, Phys. Rev. Lett. **99**, 242502 (2007)



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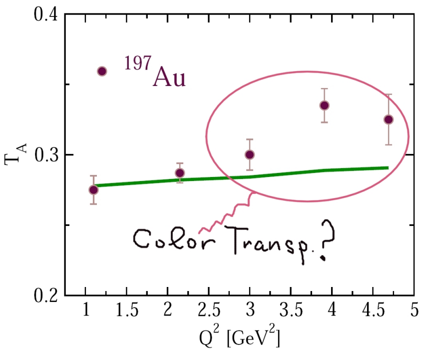
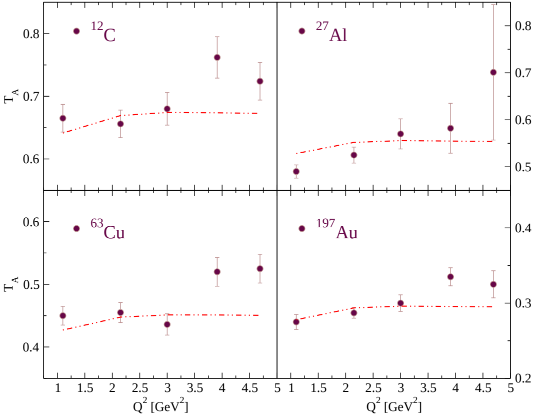


Color Transparency in $A(e, e'\pi^+)A^*$

CT: Longitudinal (γ_L^*) or Transverse (γ_T^*)???



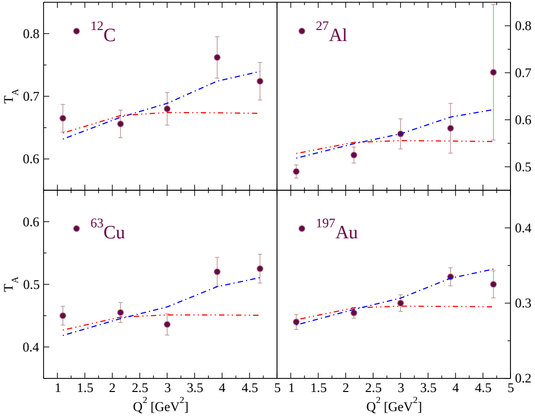
Color Transparency in $A(e, e'\pi^+)A^*$

CT: Longitudinal $(\gamma^*_{\rm L})$ or Transverse $(\gamma^*_{\rm T})$???

CT is Transverse !!!

1) Why $\gamma^*_{\rm T}$?

2) Physics of $\gamma^*_{\rm L}/\gamma^*_{\rm T}$?



Deep Exclusive $N(e, e'\pi^{\pm})N'$

- DIS region: $\sqrt{s} > 2$ GeV, $Q^2 > 1$ GeV^2
- Experimental data base is extremely rich:
  - Cambridge Electron Accelerator (CEA) (1973)
  - Wilson Synchrotron Laboratory at Cornell (1974,1976,1978)
  - DESY two independent groups (1976,1977,1978,1979)
  - JLAB@5 (2006,2007,$[2008]^3$) $\Longrightarrow$ JLAB@12
  - HERMES/DESY (2008)
- Theory: in QCD σ_{T} is power suppressed by $1/Q^2$: $\sigma_L \gg \sigma_T$
- Exp.: σ_{T} is large: $\sigma_{\mathrm{T}} > \sigma_L$

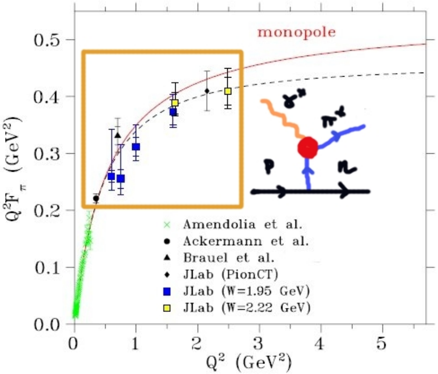
A remarkably rich experimental data base remains unexplained !!!

σ_{L} in (γ^*, π^+): π quasi-elastic knockout

- π-exchange dominates in σ_{L} because of the pole at low -t

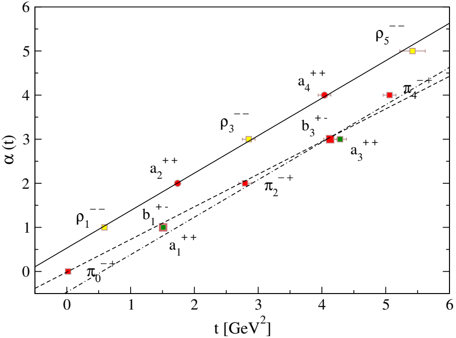
$$\sigma_{\mathrm{L}} \propto \left[\frac{F_\pi(Q^2)}{t - m_\pi^2 + i0^+} \right]^2$$

- σ_{L} dominates in the cross section ???



- The $(\gamma_{\mathrm{L}}, \pi^{\pm})$ is the only source of exp. information about the charge form factor of π at $Q^2 > 0.3$ GeV^2

Modelling $\pi^{\pm}$ photoproduction:

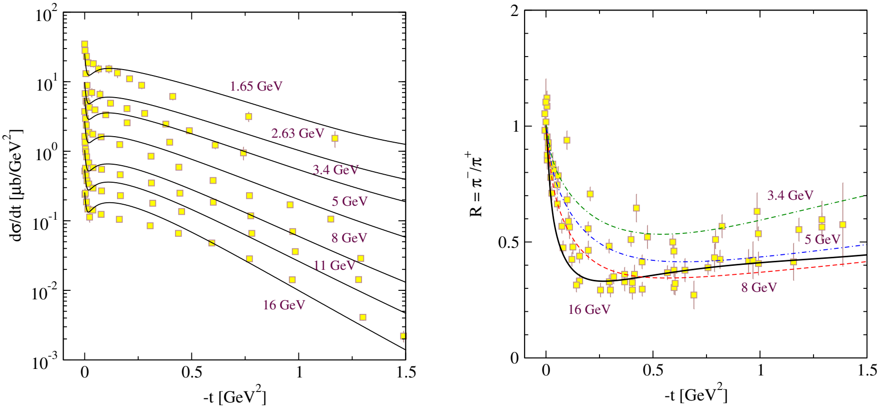


$\pi, \rho(770), a_1(1260), b_1(1235)$ and $a_2(1300)$ Regge trajectories

$$\mathcal{R}(s,t) = -\alpha' \left[\frac{1 + (-)^{\tau} e^{-i\pi\alpha(t)}}{2} \right] \Gamma(\tau - \alpha(t)) \left(\frac{s}{s_0} \right)^{\alpha(t)-\tau}$$

where $\alpha(t) = \alpha_0 + \alpha' t = \tau + \alpha'(t - m^2)$

$\pi^{\pm}$ photoproduction: Regge-pole model

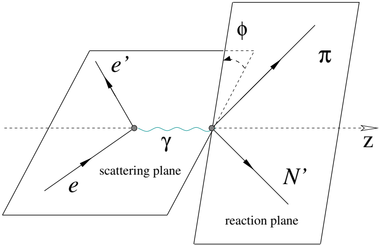


Exclusive reaction $N(e, e'\pi)N'$

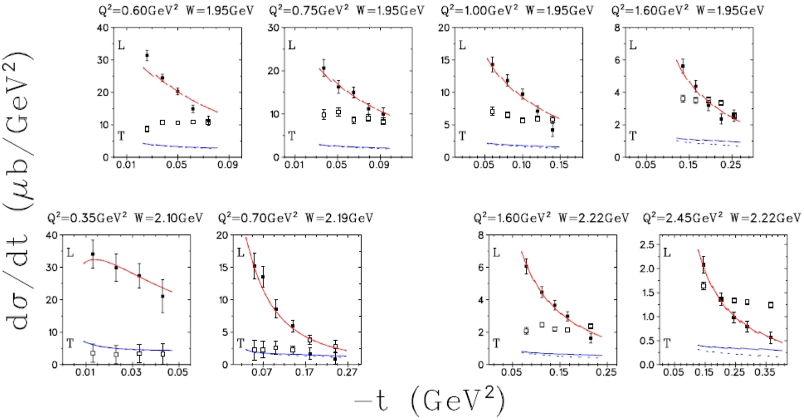
The cross section with polarized electrons

$$\frac{d\sigma}{dQ^2 d\nu dt d\phi} = \frac{\Phi}{2\pi}\left[\frac{d\sigma_{\rm T}}{dt} + \varepsilon\,\frac{d\sigma_{\rm L}}{dt} + \sqrt{2\varepsilon(1+\varepsilon)}\frac{d\sigma_{\rm LT}}{dt}\cos(\phi) + \varepsilon\,\frac{d\sigma_{\rm TT}}{dt}\cos(2\phi) + h\sqrt{2\varepsilon(1-\varepsilon)}\frac{d\sigma_{\rm LT'}}{dt}\sin(\phi)\right]$$

- $\sigma_{\rm T}$ - Transverse CS
- $\sigma_{\rm L}$ - Longitudinal CS
- $\sigma_{\rm LT}, \sigma_{\rm TT}, \sigma_{\rm LT'}$ - Interference CS's
- ε - polarization of γ^*
- h -helicity of the electron



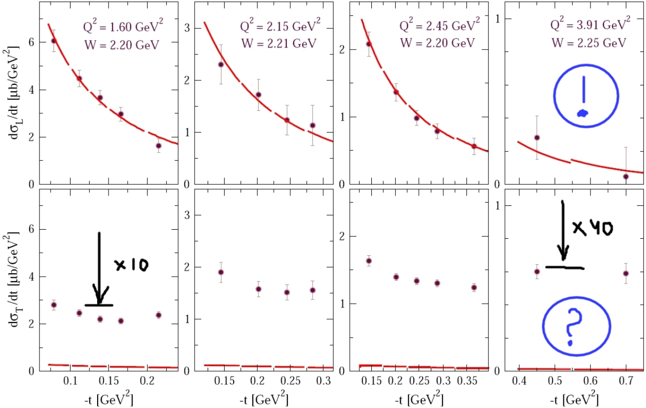
Exp. data *vs.* theory $p(e, e'\pi^+)n$



G. M. Huber *et al.*, Phys. Rev. C **78**, 045203 (2008).

Regge-pole model in π^+ electroproduction

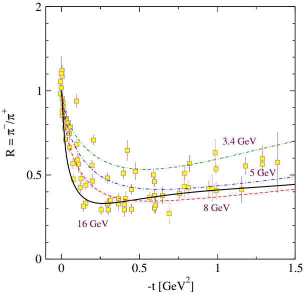
- JLAB
- $F_\pi(Q^2) = \frac{1}{Q^2/\Lambda^2+1}$

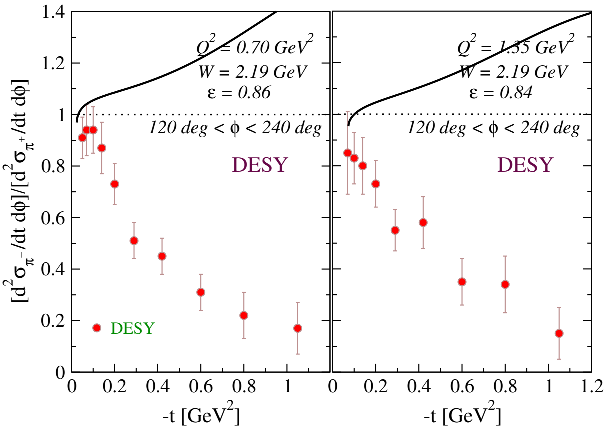


Long-standing issue: Regge-exchange cannot explain the transverse cross section σ_T and interference cross sections [CEA (1973)]

Exp. data *vs.* theory $n(e, e'\pi^-)p$

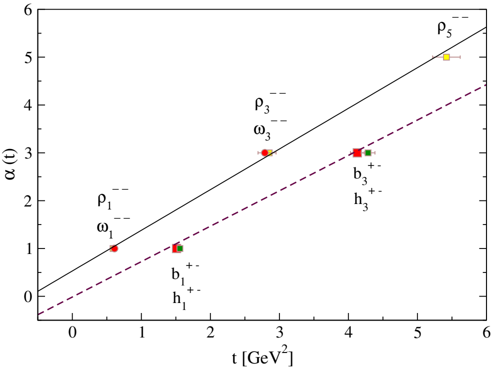
M. M. Kaskulov and U. Mosel, Phys. Rev. C **81**, 045202 (2010).



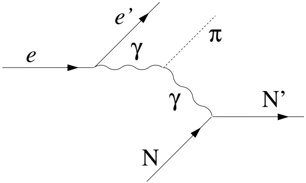


Neutral Pion Electroproduction

Regge poles: $\omega(785)$, $\rho(770)$, $b_1(1235)$, $h_1(1170)$

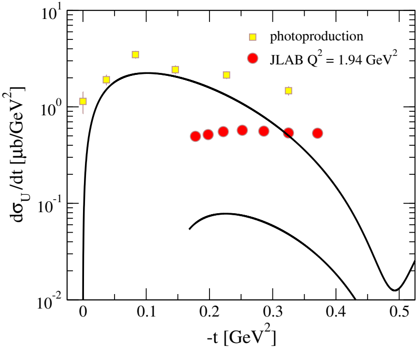


+ Primakoff effect



New puzzle in $p(e, e'\pi^0)p$ from JLAB

- In $\gamma^* + p \to \pi^0 + p$ the character of the reaction apparently changes drastically when going to electroproduction.



arXiv:1003.2938 [nucl-ex]: JLAB Hall A data are at $Q^2 = 2$ GeV^2.

Beam spin asymmetry: CLAS data

$$\frac{d\sigma}{dQ^2 d\nu dt d\phi} \rightarrow \frac{\Phi}{2\pi}\left[h\sqrt{2\varepsilon(1-\varepsilon)}\frac{d\sigma_{\mathrm{LT'}}}{dt}\sin(\phi)\right]$$

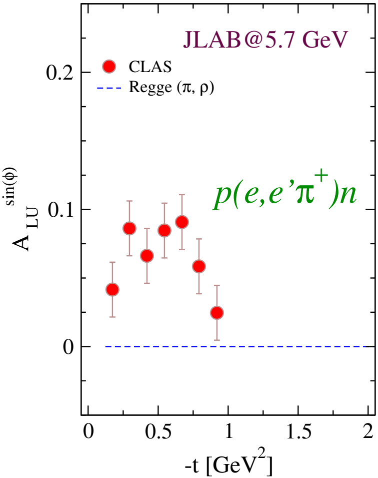
$$A_{\mathrm{LU}}(\phi) \equiv \frac{d\sigma^{\rightarrow}(\phi) - d\sigma^{\leftarrow}(\phi)}{d\sigma^{\rightarrow}(\phi) + d\sigma^{\leftarrow}(\phi)},$$

$$A_{\mathrm{LU}}^{\sin(\phi)} = \frac{\sqrt{2\varepsilon(1-\varepsilon)}d\sigma_{\mathrm{LT'}}}{d\sigma_{\mathrm{T}} + \varepsilon d\sigma_{\mathrm{L}}}$$

1) $A_{\mathrm{LU}}(\phi)$ demands interference between single helicity flip and nonflip or double helicity flip amplitudes

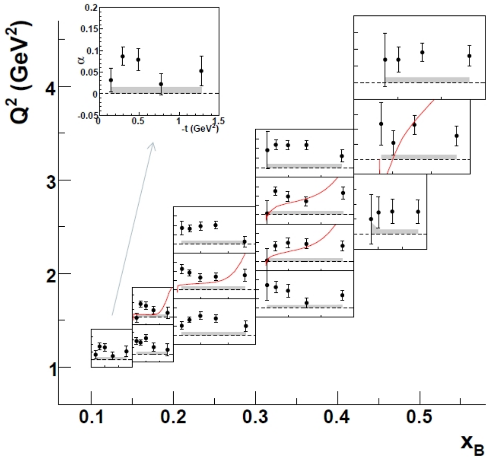
2) In Regge models the asymmetry may result from Regge cut corrections to single Reggeon exchange

3) A nonzero beam SSA can be also generated by the interference pattern of amplitudes where particles with opposite parities are exchanged.



Beam spin Asymmetry in $p(\vec{e}, e'\pi^0)p$

4



Photo– *vs.* Electroproduction

- What is the physics behind these drastic changes with Q^2
- σ_{T} at JLAB, DESY and Cornell cannot be described by the hadronic models
- Therefore, we conclude that something is not understood in the tranverse γ_T^* channel

Scattering off partons

- At $W > 2$ GeV many resonances can contribute to 1π
- How to model the contribution of nucleon resonances
- Direct hard interaction of virtual photons with partons (DIS) since DIS involves all possible transitions of the nucleon from its ground state to any excited state
- The idea followed here is complement the soft hadron-like interaction types which dominate in photoproduction and low Q^2 electroproduction by direct interaction of virtual photons with partons followed by the hadronization process into $\pi^+ n$

  $\Longrightarrow$ Exclusive limit of SIDIS

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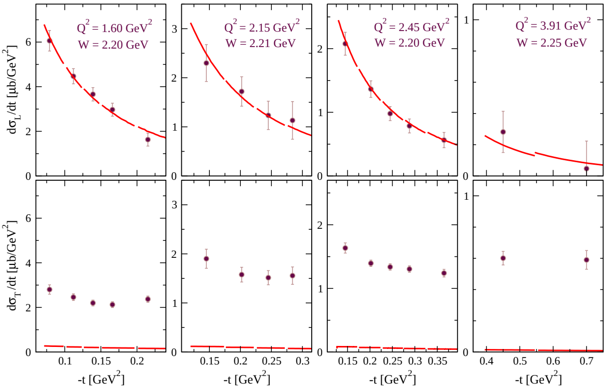
  $\Longrightarrow$ Exclusive limit of SIDIS

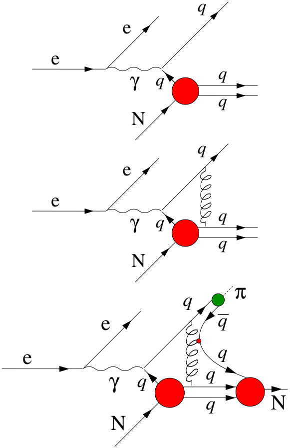
$p(e, e'\pi^+)n$: soft and hard contributions

M. M. Kaskulov, K. Gallmeister and U. Mosel, Phys. Rev. D **78**, 114022 (2008)

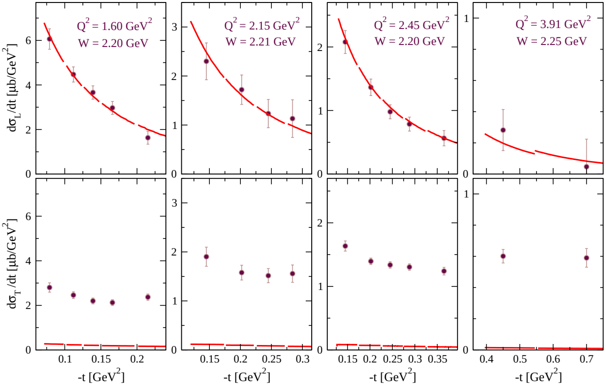


Exclusive limit ($z \to 1$) of SIDIS (Lund model)

$p(e, e'\pi^+)n$: soft and hard contributions



M. M. Kaskulov, K. Gallmeister and U. Mosel, Phys. Rev. D **78**, 114022 (2008)



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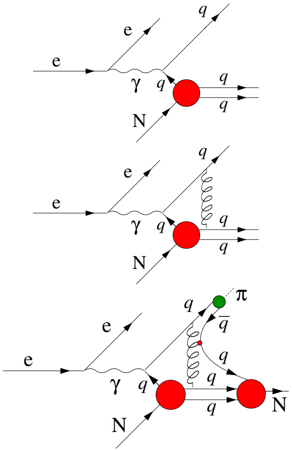

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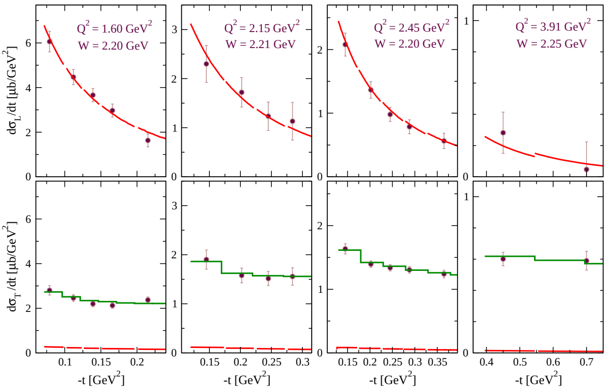
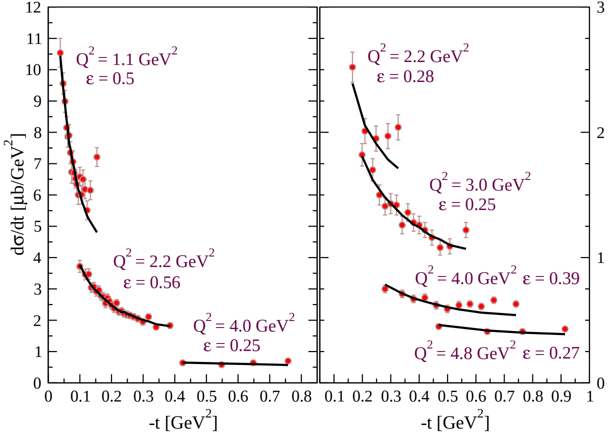


Exclusive limit ($z \to 1$) of SIDIS (Lund model)

Exclusive-Inclusive connection

Q^2 dependence of Exclusive π^+ σ_T exactly follows Q^2 dependence of inclusive $F_2(x, Q^2)$ structure function

$$\sigma_T^{Excl}(Q^2) \sim \sigma_T^{Incl}(Q^2) \propto F_1(x, Q^2)$$



Dual Exclusive-Inclusive connection

We connect the partonic and hadronic sectors
Incoherent sum over quarks in DIS

$$F_2^p(x_{\rm B}, Q^2) = x_{\rm B} \sum_q e_q^2 f_q(x_{\rm B}, Q^2)$$

Dual Bloom-Gilman connection $\Longrightarrow$ Coherent sum over the resonances

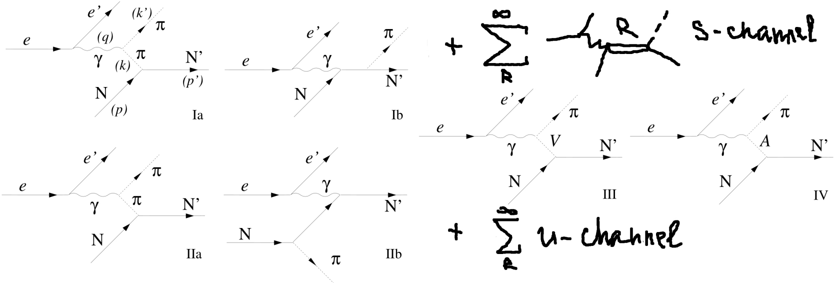
$$F_2^p(x_{\rm B}, Q^2) = \sum_R (M_R^2 - M_p^2 + Q^2) W(Q^2, M_R) \delta(s - M_R^2)$$

$$\sum |N^*\rangle\langle N^*| = 1 \rightarrow \sum |q\rangle\langle q| = 1$$

How to sum up an infinite tower of resonances ???
$\Longrightarrow$ M. M. Kaskulov and U. Mosel, Phys. Rev. C **81**, 045202 (2010).

Modeling $\pi^{\pm}$ electroproduction:

Diagramatic approach:



Interpretation of the Regge behavior:
a sum of all possible one-particle exchanges in the t-channel

*) How to sum up an infinite tower of resonances ??? $\Longrightarrow$

M. M. Kaskulov and U. Mosel, Phys. Rev. C **81**, 045202 (2010).

Dual Exclusive-Inclusive Connection

Resonance Transition Form Factors: Bloom-Gilman connection

$$F_s(Q^2,s) = \frac{s \ln\left[\frac{\xi Q^2}{M_p^2}+1\right]\frac{(2\xi Q^2+s)}{(\xi Q^2)^2} - \frac{s(\xi Q^2+s)}{\xi Q^2\,(\xi Q^2+M_p^2)} + \ln\left[\frac{s-M_p^2}{M_p^2}\right] - i\pi}{\left(\frac{\xi Q^2}{s}+1\right)^2\left(\frac{s^2+2sM_p^2}{2M_p^4}+\ln\left[\frac{s-M_p^2}{M_p^2}\right]-i\pi\right)},$$

$$F_u(Q^2,u) = \frac{u \ln\left[\frac{\xi Q^2}{M_p^2}+1\right]\frac{(2\xi Q^2+u)}{(\xi Q^2)^2} - \frac{u(\xi Q^2+u)}{\xi Q^2\,(\xi Q^2+M_p^2)} + \ln\left[\frac{M_p^2-u}{M_p^2}\right]}{\left(\frac{\xi Q^2}{u}+1\right)^2\left(\frac{u^2+2uM_p^2}{2M_p^4}+\ln\left[\frac{M_p^2-u}{M_p^2}\right]\right)}.$$

1) $F_s(Q^2,s) \Longrightarrow p(e,e'\pi^+)n$
2) $F_u(Q^2,u) \Longrightarrow n(e,e'\pi^-)p$
3) $F_s(Q^2,s)$ and $F_u(Q^2,u) \Longrightarrow p(e,e'\pi^0)p$

Scaling factor $\xi \to$ density of states

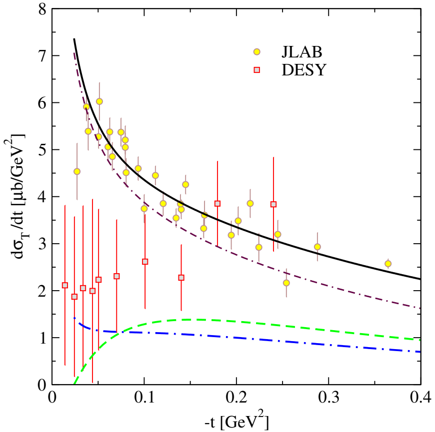
At $Q^2 = 0.7$ GeV^2 & $W = 2$ GeV

$\boxed{\xi = 0.4} \Longrightarrow$

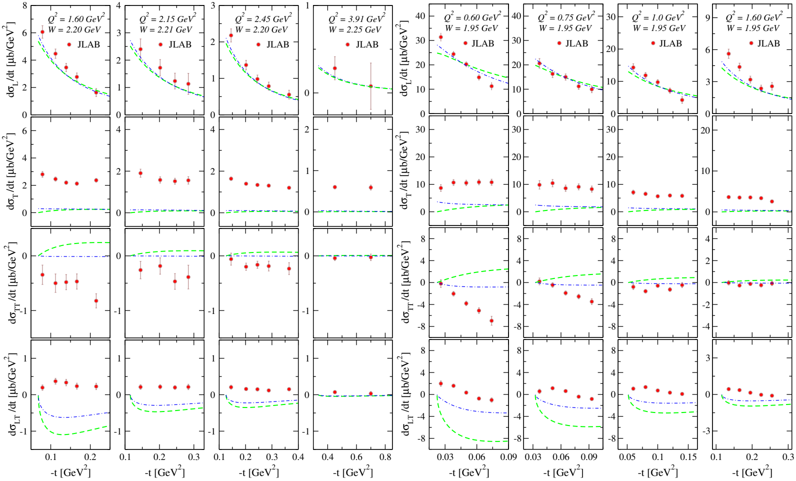
Five independent observables in the range
$0 < Q^2 < 11$ GeV^2
W^2 up to 16 GeV ^{2}
JLAB, HERMES/DESY, Cornell

Reactions:

1) $p(\vec{e}, e'\pi^+)n$
2) $n(\vec{e}, e'\pi^-)p$
3) $p(\vec{e}, e'\pi^0)p$



JLAB high Q^2 data



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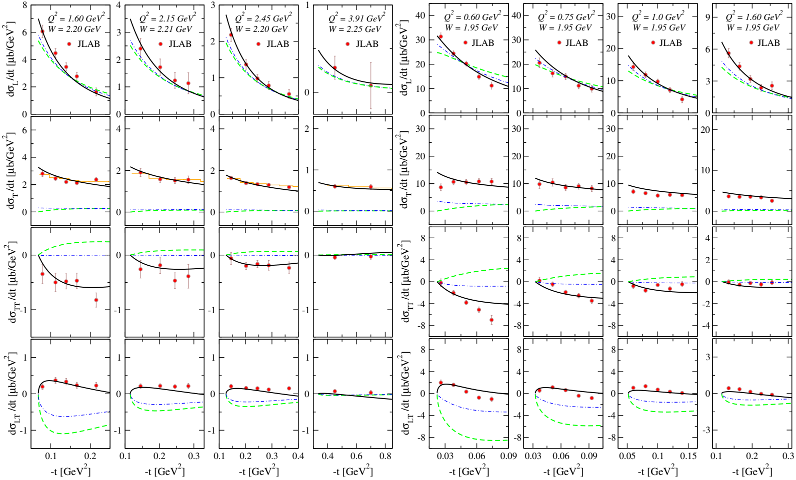
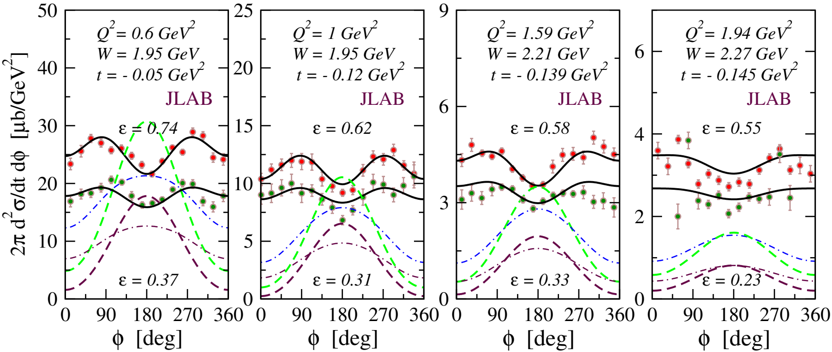
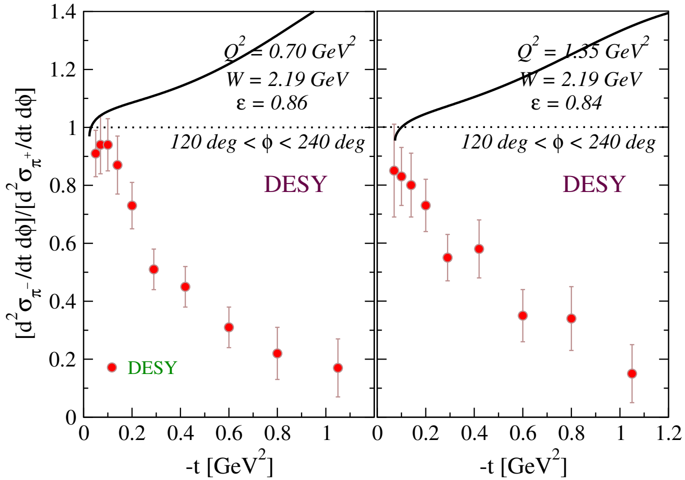


Azimuthal dependence in $p(e, e'\pi^+)n$



DESY data: $n(e, e'\pi^-)p$ is parameter free



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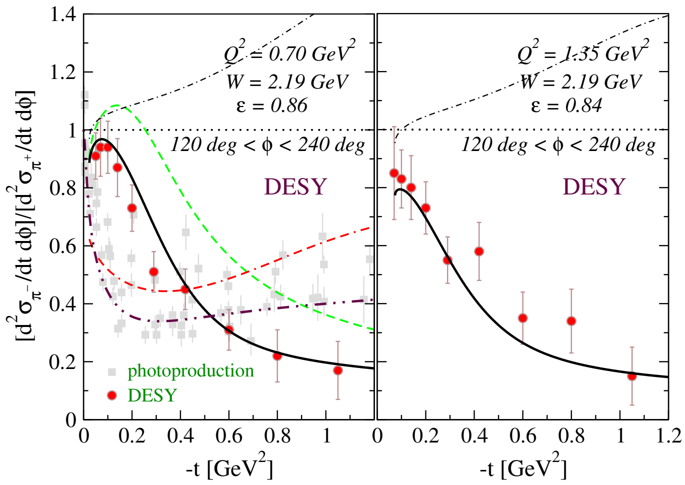
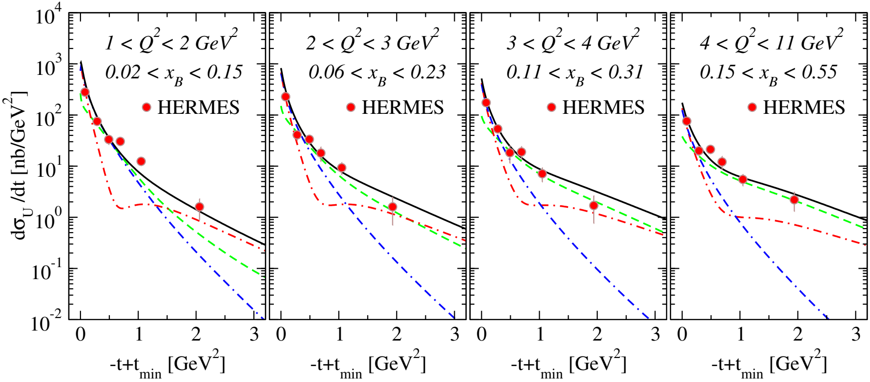


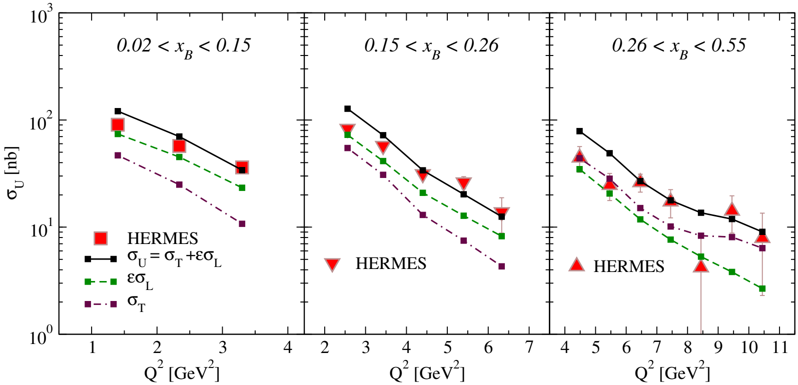
HERMES: Deeply virtual $p(e, e'\pi^+)n$

True DIS region:
$s = 16$ GeV^2 & 1 GeV^2 $< Q^2 <$11 GeV^2



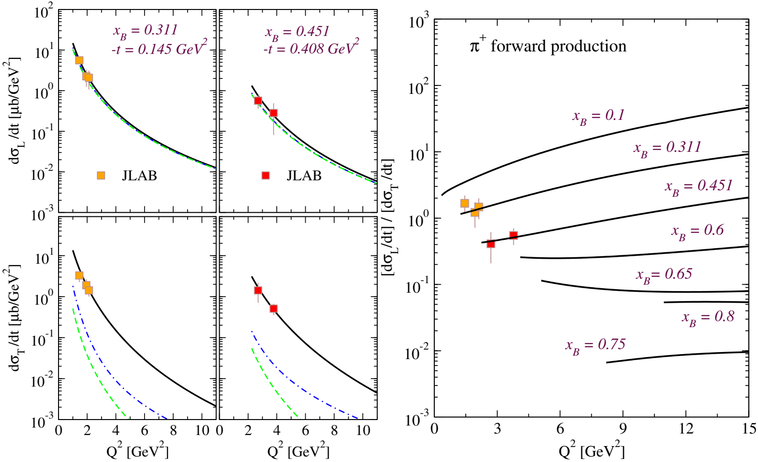
HERMES: Q^2-dependence in $p(e, e'\pi^+)n$

GPD models: σ_L must dominate at high Q^2 ???

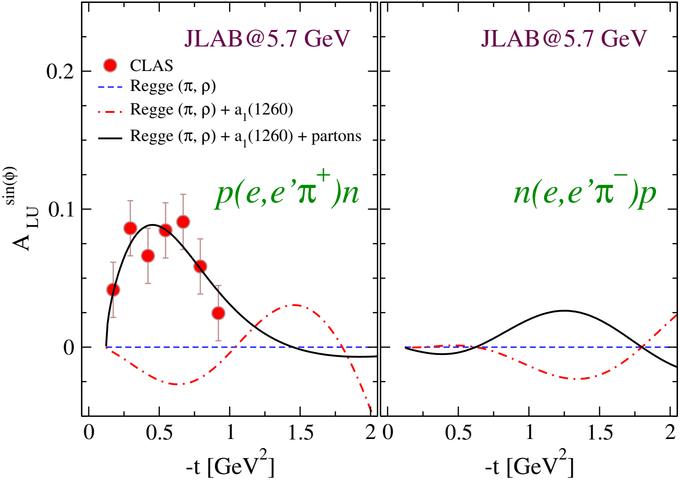


We get just opposite behavior !!!

Q^2-dependence in $p(e, e'\pi^+)n$

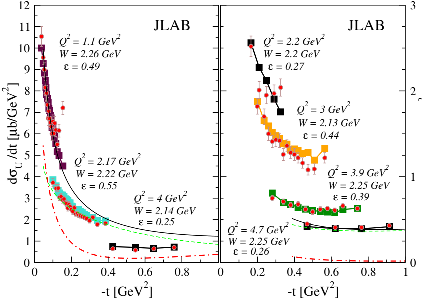


Beam spin asymmetry: CLAS data

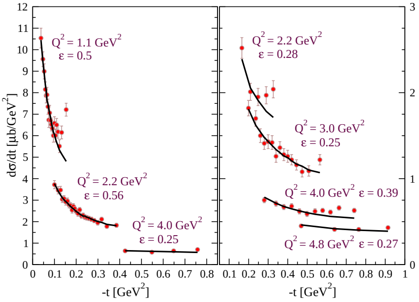


Hadronic *vs* partonic: JLAB data

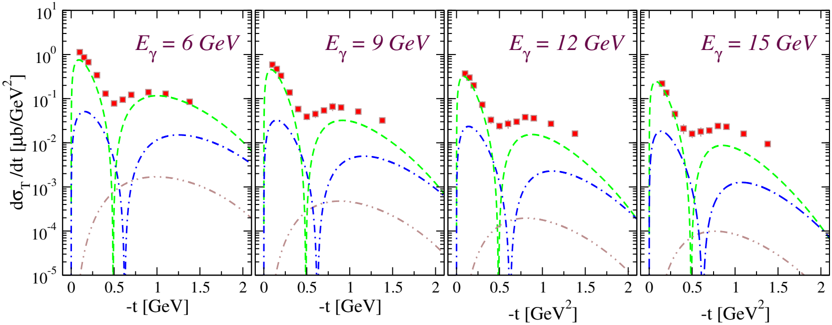
(1) Phys. Rev. C**81**, 045202 (2010)



(2) Phys. Rev. D**78**, 114022 (2008)



Neutral Pion Photoproduction



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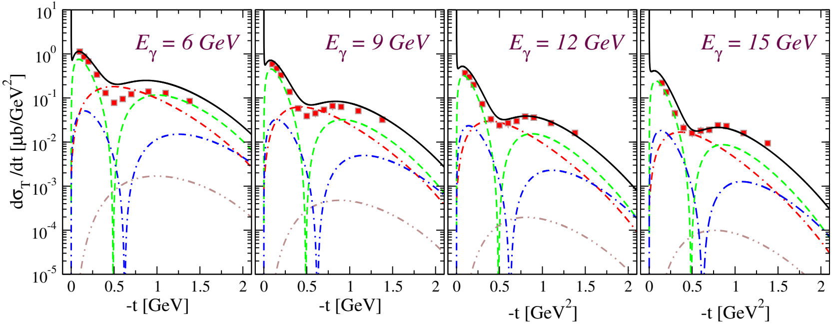
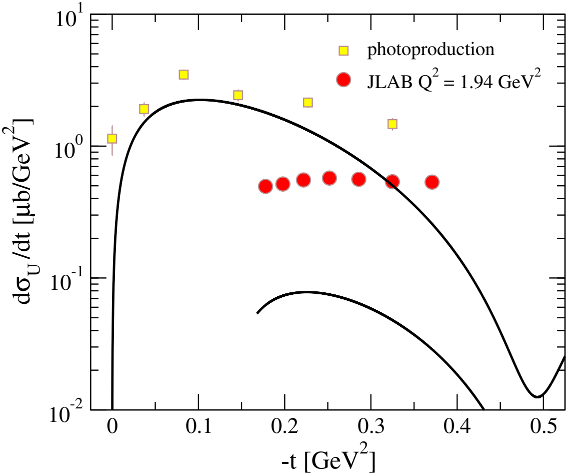
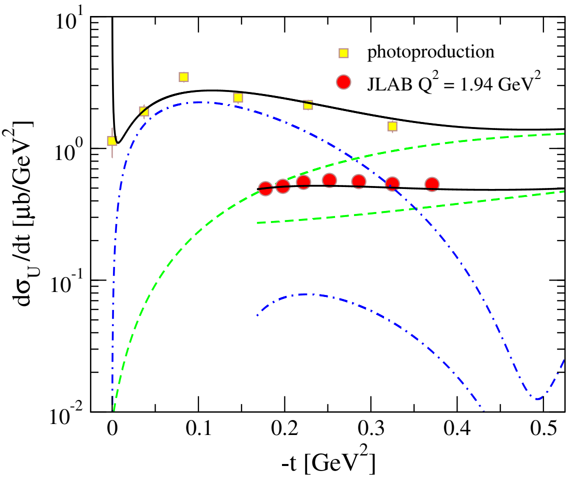


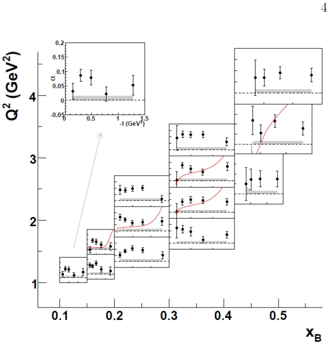
Neutral Pion Electroproduction in DVS



Neutral Pion Electroproduction

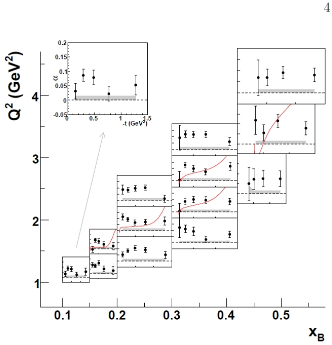


Beam spin Asymmetry in $p(\vec{e}, e'\pi^0)p$

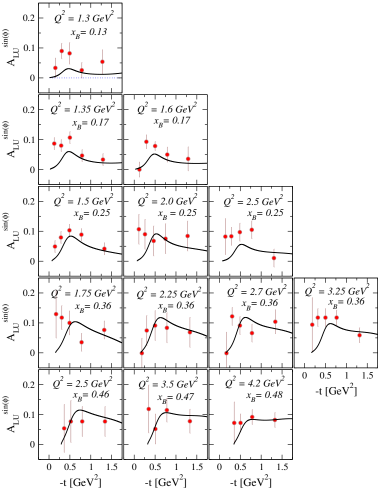


$$A_{\rm LU}(\phi) \equiv \frac{d\sigma^{\rightarrow}(\phi) - d\sigma^{\leftarrow}(\phi)}{d\sigma^{\rightarrow}(\phi) + d\sigma^{\leftarrow}(\phi)},$$

Beam spin Asymmetry in π^0 DVS



$$A_{\rm LU}(\phi) \equiv \frac{d\sigma^{\rightarrow}(\phi) - d\sigma^{\leftarrow}(\phi)}{d\sigma^{\rightarrow}(\phi) + d\sigma^{\leftarrow}(\phi)},$$

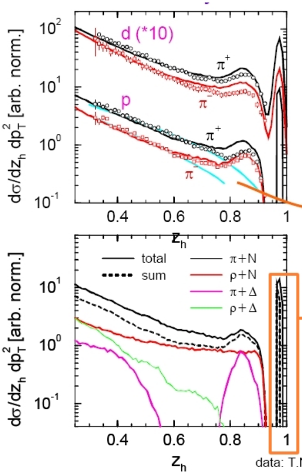


Summary

- A detailed knowledge of the $p(e, e'\pi)n$ reaction above the resonances $\sqrt{s} > 2$ GeV is mandatory for the interpretation of the Color Transparency signal observed in $(e, e'\pi)$ reaction off nuclei
- Our main idea is to separate the soft hadronic (exchange of Regge trajectories) and hard partonic (excitation of nucleon resonances) reaction mechanisms
- There must be a connection between the resonances and Regge cuts

Back slides

Exclusive limit of fragmentation in SIDIS



$$\frac{dN}{dz_h} \sim \sum_q e_q^2 \underbrace{q(x,Q^2)}_{\text{CTEQ5}} \underbrace{D_{q\to\pi}(z_h,Q^2)}_{\text{BKK}}$$

$$x = \frac{Q^2}{2m\nu} = \text{fix}$$

$$z_h = \frac{E_h}{\nu}$$

EXCLUSUVE EVENTS

data: T.Navasardyan et al., PRL 98(2007), 022001

Transverse Target Polarization at HERMES: $\vec{p}(e, e'\pi^+)n$