Resonance/Parton Duality in Electroproduction of Pions

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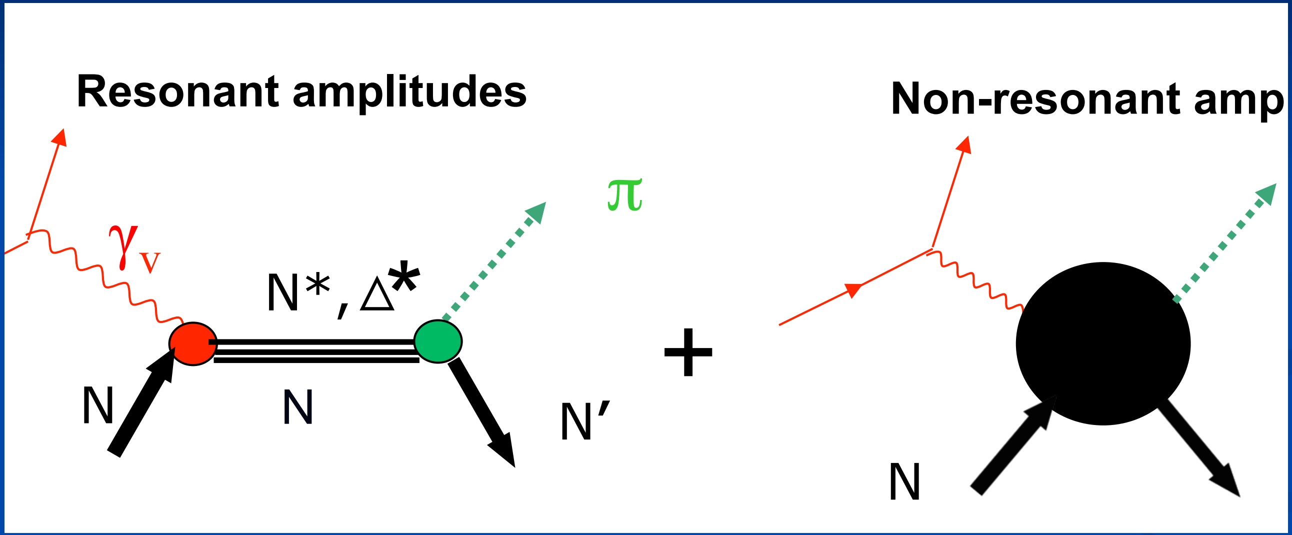
General Motivation

- Extraction of Resonance properties (and pion formfactor) relies on model: how good is it?
  - QCD expect: $\sigma_L / \sigma_T \propto 1/Q^2$ but σ_T is large, and seems to grow
- Where does pQCD start to work: at JLAB@6 or JLAB@12?
- Pion production in JLAB, HERMES, Cornell expts.
- Role of Resonances?

Electro-Pionproduction

N*



F_π

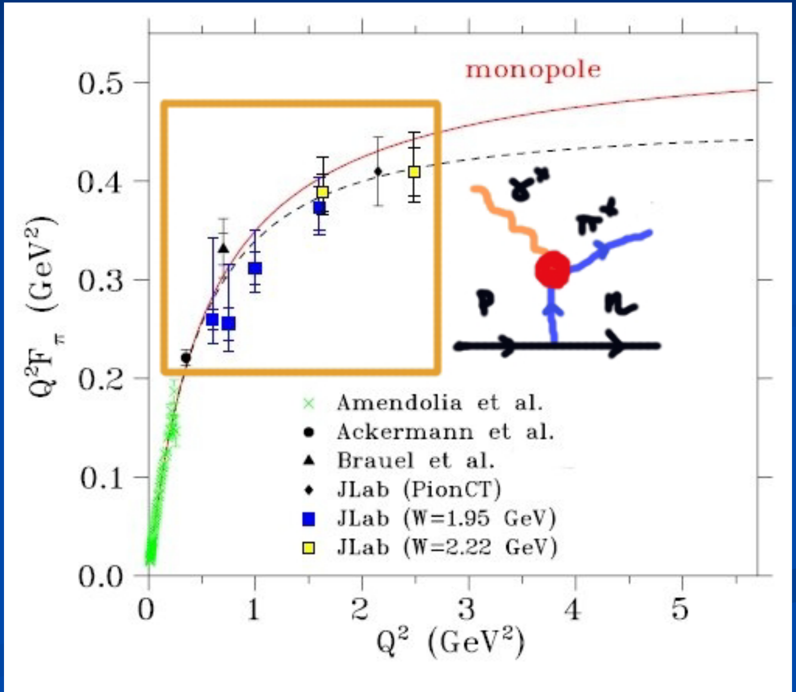
V. Mokeev

Both needed for gauge invariance

Pion e.m. Formfactor

- Pion e.m. FF at larger Q^2 mainly from JLAB, extracted from model for long. X-section

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



VGL model:

t-channel exchange + Born-graph and $F_p = \boldsymbol{F_\pi}$

Extended VGL Model

- Current for π^+ production

$$
\begin{aligned}
-i J_s^\mu(\gamma^* p \to \pi^+ n) \\
= \sqrt{2} g_{\pi NN} \bar{u}_{s'}(p')\gamma_5 \Bigg[\mathcal{F}_{\gamma\pi\pi}(Q^2, t) \frac{(k+k')^\mu}{t - m_\pi^2 + i0^+} \\
+ \mathcal{F}_s(Q^2, s, t) \frac{(p+q)_\sigma \gamma^\sigma \gamma^\mu + M_p \gamma^\mu}{s - M_p^2 + i0^+} \\
+ [\mathcal{F}_{\gamma\pi\pi}(Q^2, t) - \mathcal{F}_s(Q^2, s, t)] \frac{(k-k')^\mu}{Q^2} \Bigg] u_s(p),
\end{aligned}
$$

Reggeize propagator

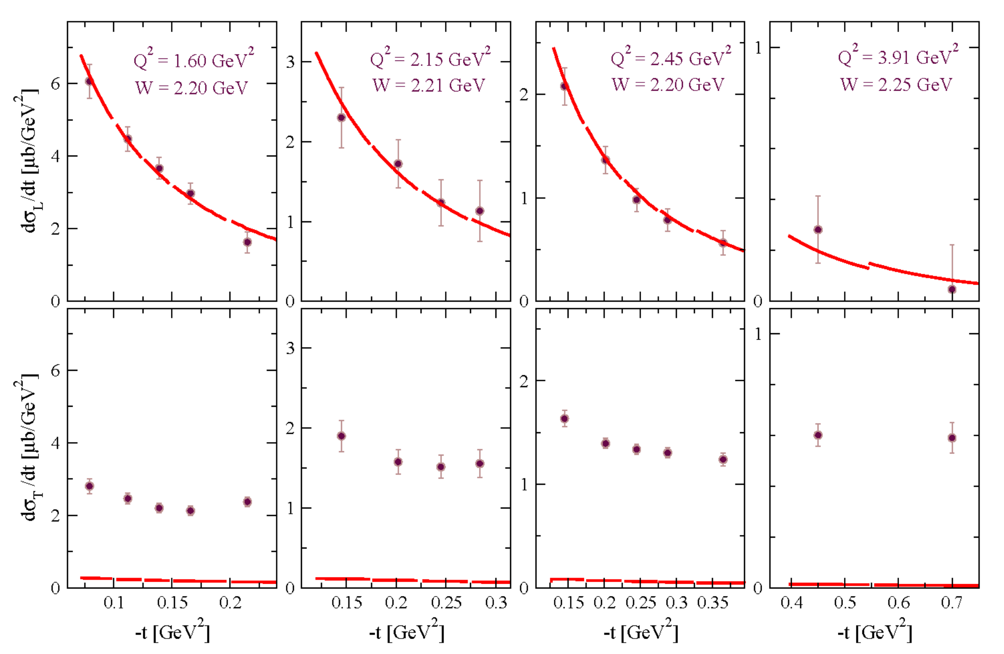
$$
\begin{aligned}
\mathcal{D}(t) &= \frac{1}{t - m_\pi^2 + i0^+} \\
&\Longrightarrow \mathcal{R}[\alpha_\pi(t)] \\
&= \left[\frac{1 + e^{-i\pi\alpha_\pi(t)}}{2} \right] (-\alpha'_\pi) \Gamma[-\alpha_\pi(t)] e^{\alpha_\pi(t) \ln(\alpha'_\pi s)},
\end{aligned}
$$

Different e.m. formfactors for π and p, still gauge invariant (Gross-Riska)

Extended VGL Model

- Extended VGL model very good for *L*

- **still dramatically bad for *T***



Data: Jlab, Horn et al.

Partons in Electro-Pionproduction

- Observe
  1. $\sigma_{\mathrm{T}}(e,e'\pi)(Q^2) \sim \sigma_{\mathrm{DIS}}(Q^2)$ Bebek et al, 1978
  2. $\sigma_L/\sigma_T \to 0 \quad \text{for} \quad Q^2 \to \infty$ DIS

➔ Take excl. limit of DIS:

- $p(e,e'\pi^+)X \to p(e,e'\pi^+)n \quad \text{for} \quad z \to 1$

$$\sigma = \sigma(t - \text{channel}) + \sigma(\text{Born}) + \sigma(\text{DIS})$$

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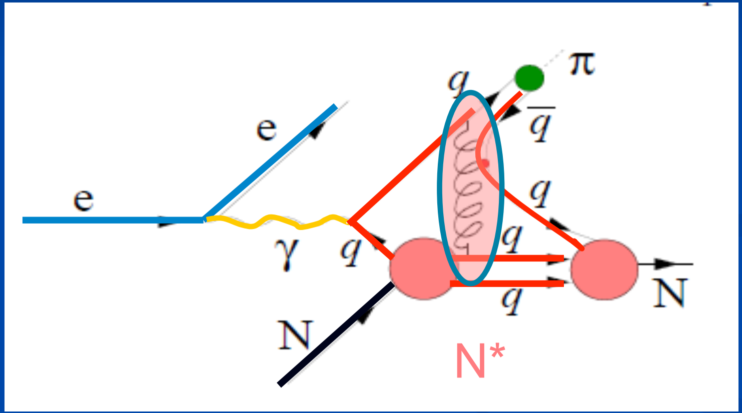
Partons in Electro-Pionproduction

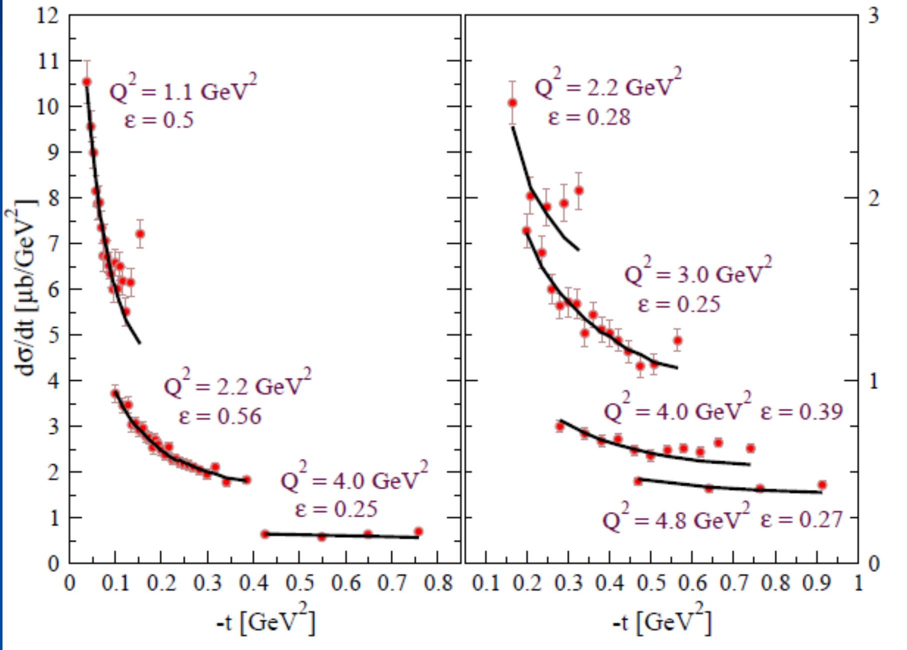
- Use PYTHIA to calculate excl. DIS
- Stringbreak → DIS



- DIS = N* (W > 2 GeV, resonances overlap)

$$d\sigma/dt = d\sigma_T/dt + \varepsilon d\sigma_L/dt$$

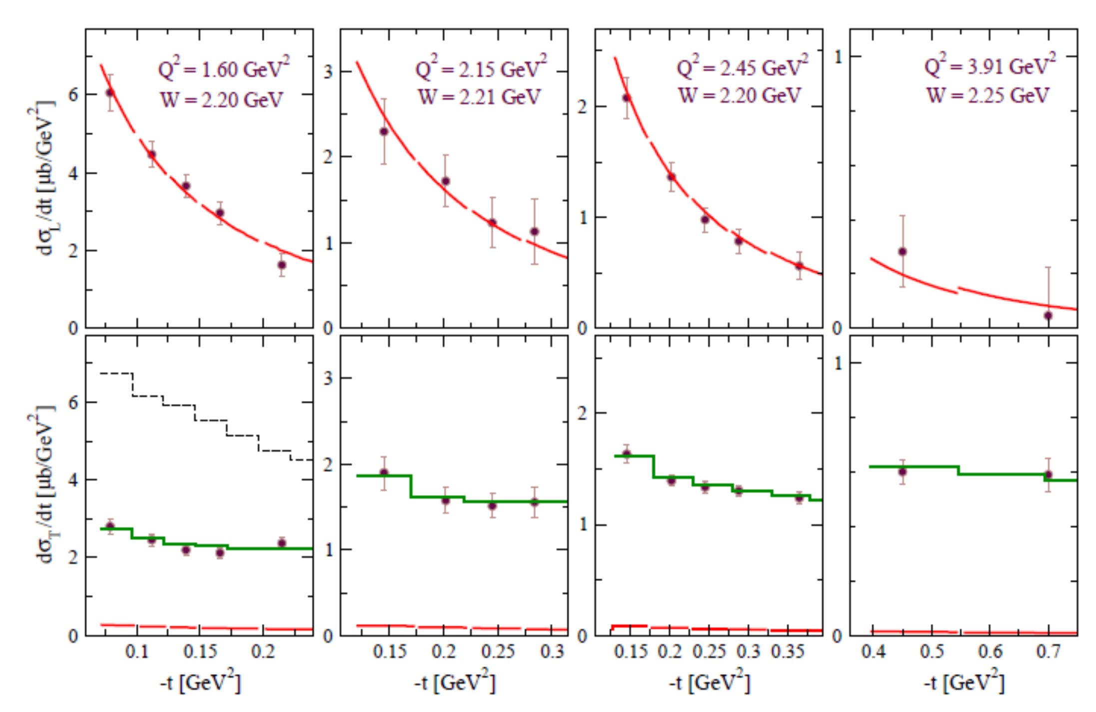
- JLAB Data:
  Perfect fit!



Data: JLAB, Quian et al

‚exclusive‘ DIS describes *T*

- Excellent Description of *L*, determined by *t*-channel + Born (red)
- Excellent description of *T*, determined by DIS (green)



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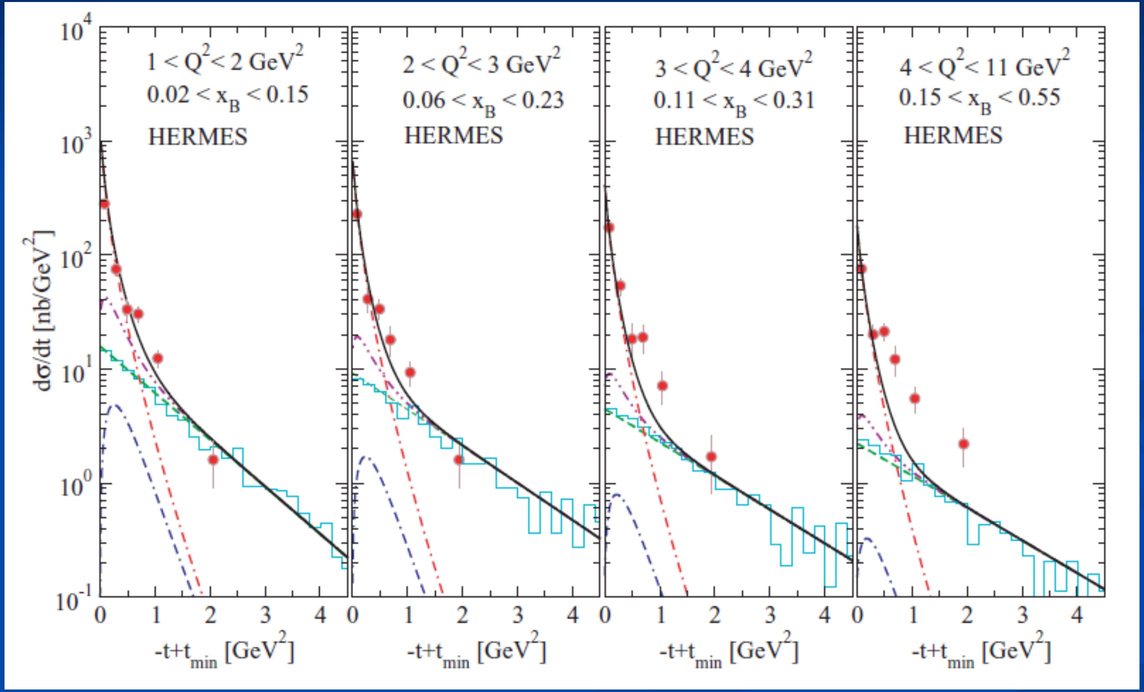
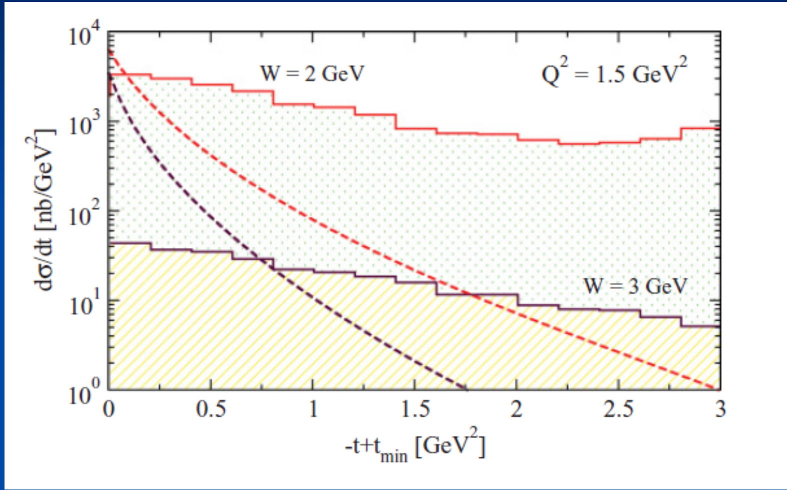
‚exclusive‘ DIS describes *T*



L and *T* at JLAB and HERMES



solid: transverse
dashed: longitudinal

- JLAB@12: *L* wins at forward angles, F_π extract. less contaminated by transverse (partonic) part

Improvement: amplitudes

- Model works very well, but cannot give mixed *LT* X-sections
- String breaking gives only X-sections, not amplitudes

Improvement: amplitudes

- Exps. (JLAB, HERMES) cover W ~ 2 – 4 GeV region of overlapping nucleon resonances
- Add sum over (many) N*s to Born-term
- Use duality to obtain infos on coupling of high N* and to connect N* with partons

N* contribution to π⁺ production

- Current for π⁺ production

$$
\begin{aligned}
&-iJ_s^\mu(\gamma^* p \to \pi^+ n) \\
&= \sqrt{2} g_{\pi NN} \bar{u}_{s'}(p')\gamma_5 \Bigg[\mathcal{F}_{\gamma\pi\pi}(Q^2,t)\frac{(k+k')^\mu}{t-m_\pi^2+i0+} \\
&\quad + \mathcal{F}_s(Q^2,s,t)\frac{(p+q)_\sigma \gamma^\sigma \gamma^\mu + M_p\gamma^\mu}{s-M_p^2+i0+} \\
&\quad + [\mathcal{F}_{\gamma\pi\pi}(Q^2,t)-\mathcal{F}_s(Q^2,s,t)]\frac{(k-k')^\mu}{Q^2}\Bigg] u_s(p),
\end{aligned}
$$

- Replace

$$
\frac{F_s(Q^2,M_p)}{s-M_p^2+i0+} \to \sum_i r(M_i)c(M_i)\frac{F(Q^2,M_i^2)}{s-M_i^2+i0+},
$$

and

$$
\sum_i \to \int_{M_p^2}^{\infty} dM_i^2 \rho(M_i^2).
$$

e.m. Coupling strong

Density of N* resonances

N* contribution to π^+ production

- Local Bloom-Gilman duality:

$$F_2^p(x_B, Q^2) = \sum (M_i^2 - M_p^2 + Q^2) W(Q^2, M_i)\delta(s - M_i^2),$$

with
$$W(Q^2, M_i) = r^2(M_i)[F(Q^2, M_i)]^2, \quad F(0, M_i) = 1.$$

- Integrate over M_i

$$F_2^p(x_B, Q^2) = (s - M_p^2 + Q^2) r^2(s)[F(Q^2, s)]^2 \rho(s).$$

Density of resonances

Relation between F_2 and Formfactor F

N* contribution to π^+ production

Duality

$$F_2^p(\omega') \propto (\omega' - 1)^3,$$

$$\omega' = 1 + W^2/Q^2$$

$$F(Q^2, M_i^2) = \left(\frac{1}{1 + \xi \frac{Q^2}{M_i^2}} \right)^2,$$

$$(\omega' - 1)^3 \propto Q^2 \frac{(\omega' - 1)^4}{\xi^4} r^2(s) \rho(s).$$

$$r^2(s)\rho(s) \propto \frac{1}{Q^2(\omega' - 1)} = \frac{1}{s}.$$

e.m. coupling *r(s)* decreases with *s*

-> Integral over all resonances converges

N* contribution to π^+ production

- Absorb all N*s into Born term:

$$\sum_i r(M_i)c(M_i)\frac{F(Q^2,M_i^2)}{s-M_i^2+i0+}$$

$$\Longrightarrow \int_{M_p^2}^{\infty} dM_i^2 \rho(M_i^2) r(M_i^2) c(M_i^2) \frac{F(Q^2,M_i^2)}{s-M_i^2+i0+}$$

$$= \int_{M_p^2}^{\infty} ds_i \frac{s_i^{-\beta}}{\lambda} \frac{F(Q^2,s_i)}{s-s_i+i0+} \equiv \frac{F_s(Q^2,s)}{s-M_p^2+i0+},$$

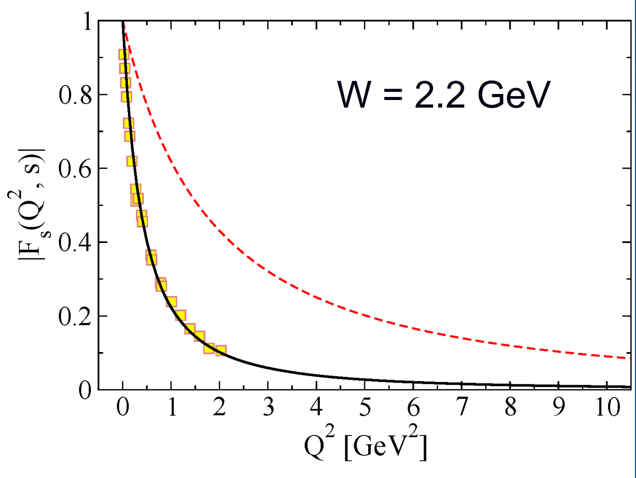
with

$$\rho(s_i)r(s_i)c(s_i) = \frac{1}{\lambda}s_i^{-\beta},$$

N* contribution to π^+ production

- ‚effective Born-Term FF'

$$F_s(Q^2, s) = \frac{\int_{M_p^2}^{\infty} ds_i \frac{s_i^{-\beta}}{s - s_i + i0^+} \left(\frac{1}{1 + \xi \frac{Q^2}{s_i}} \right)^2}{\int_{M_p^2}^{\infty} ds_i \frac{s_i^{-\beta}}{s - s_i + i0^+}},$$

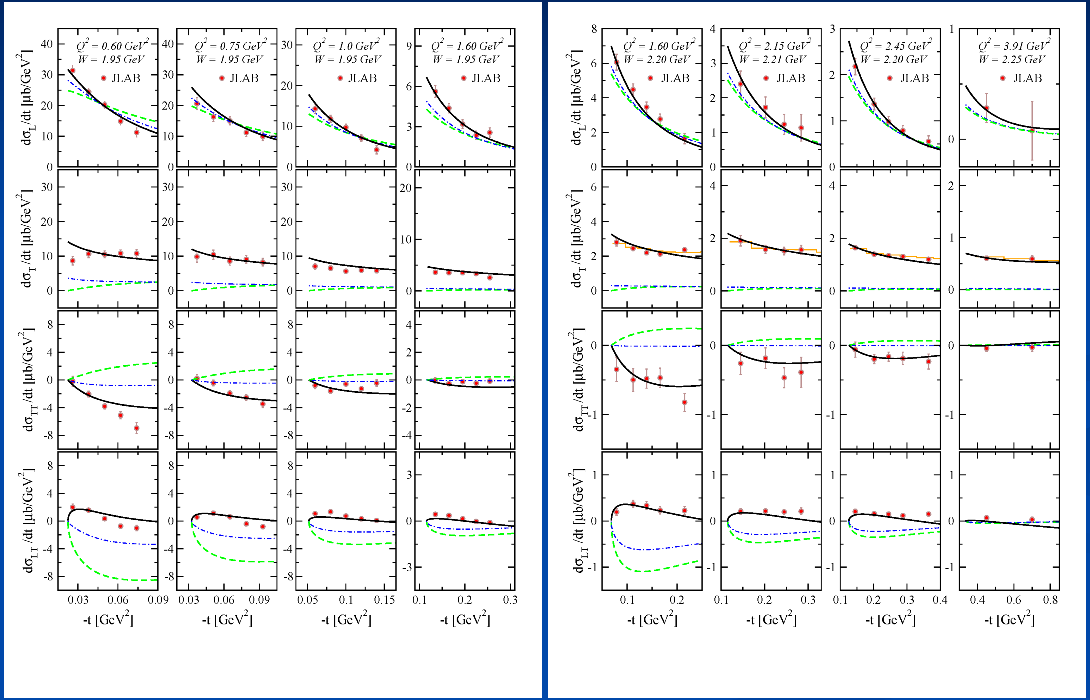


harder for higher resonances:
consequence of BG duality

Dashed: model
Solid: free proton

N* contribution to π^+ production

Perfect agreement over wide range of Q^2



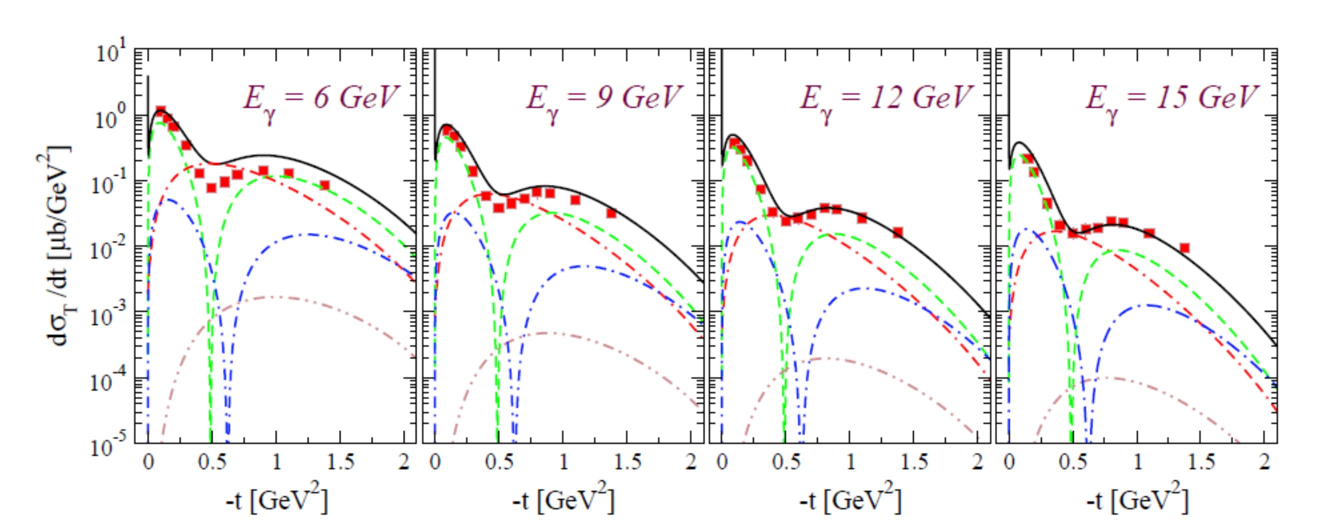
Green: *t*-channel

dashed: *t* + Born

solid: *t* + Born + res

Data from F-π2, π-CT expts.

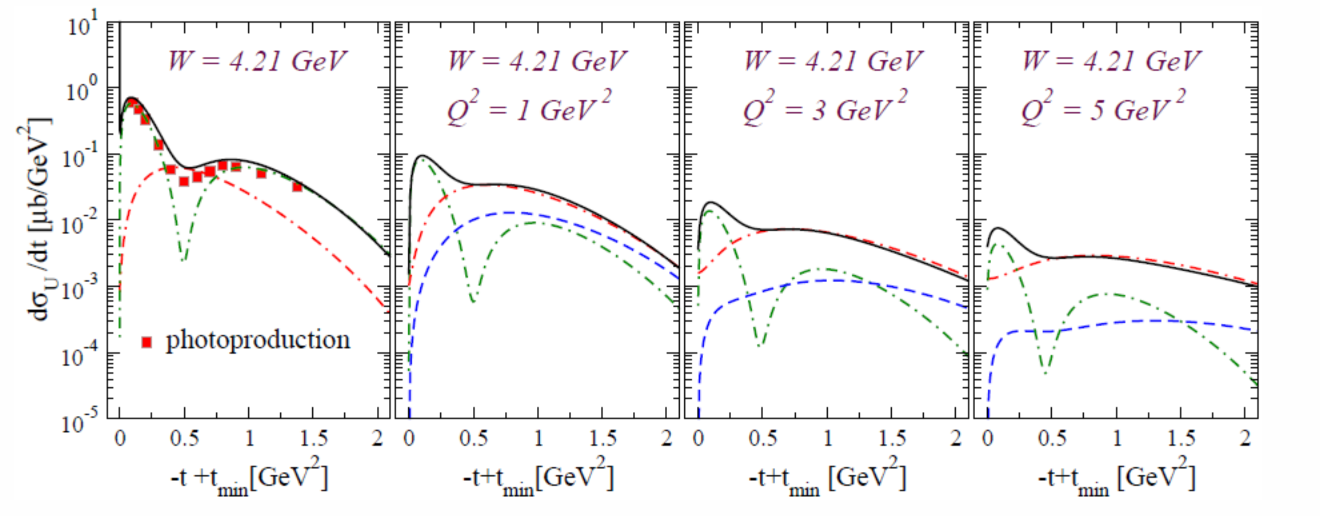
π_0 photoproduction



Dash-dash-dotted: resonance, dashed: t-channel omega

M. Kaskulov,
arXiv:1105.1993 [nucl-th]

π_0 photo- + electroproduction

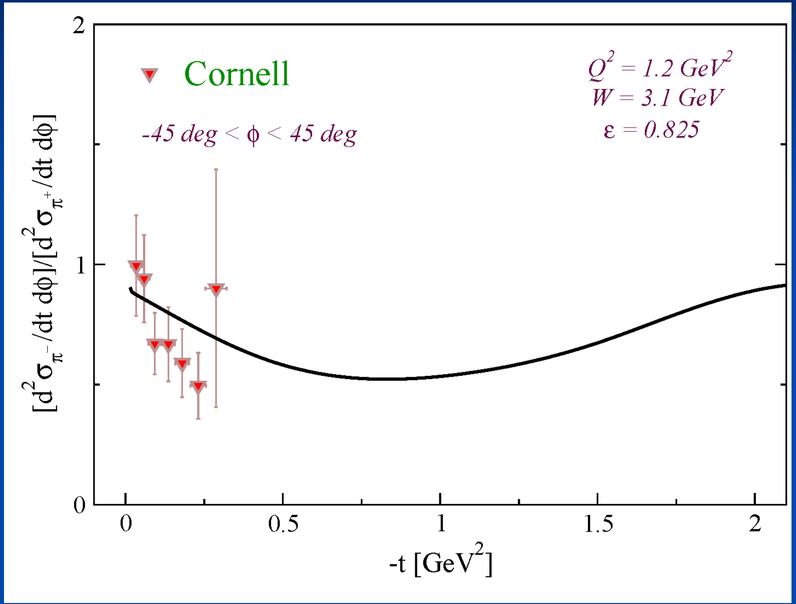


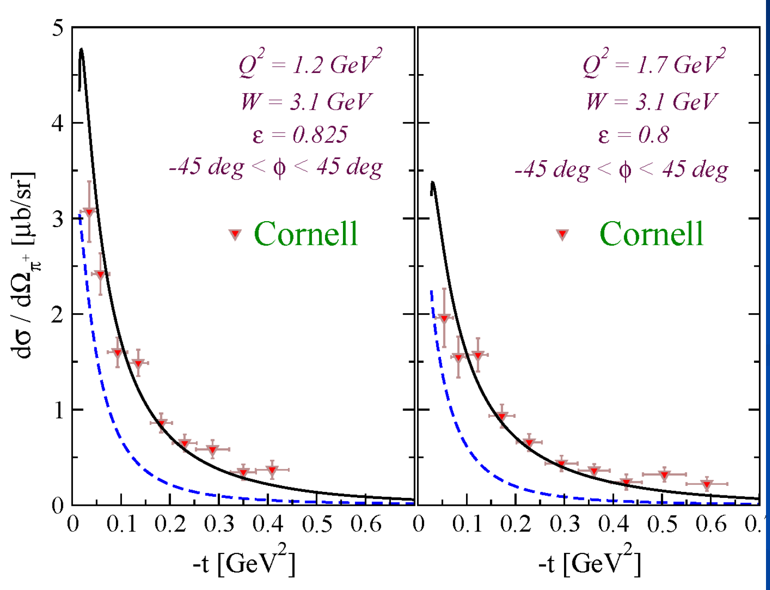
Data:
HERMES

dash-dash-dotted: resonance, dash-dotted: *t*-channel, dashed: *L*-contrib

M. Kaskulov,
arXiv:1105.1993 [nucl-th]

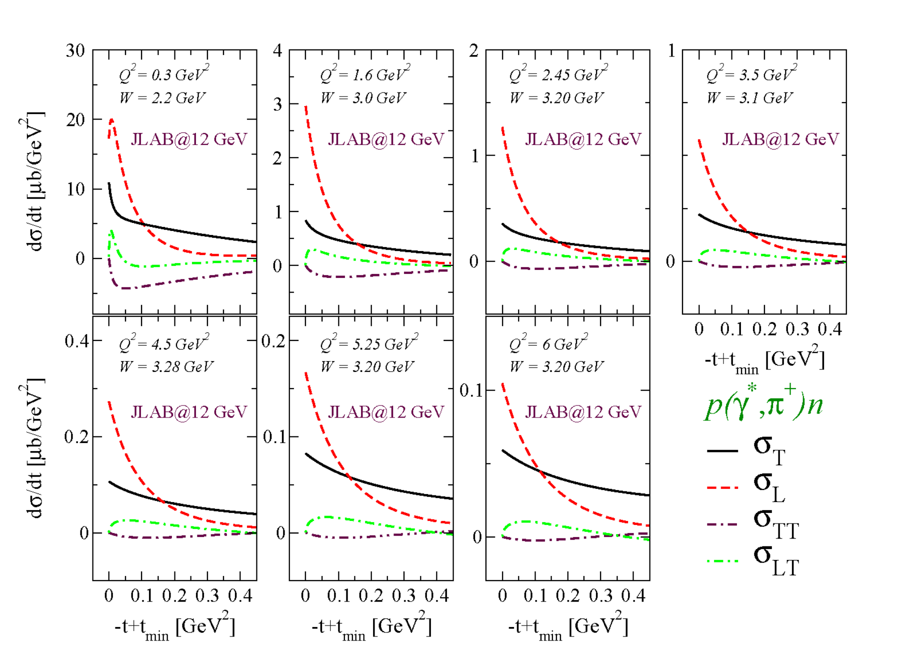
Benchmark for JLAB@12





W ~ 3 GeV

JLAB@12 Predictions for $(e,e'\pi^+)$



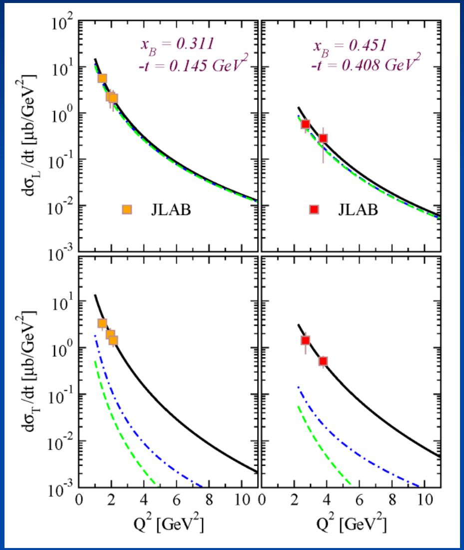
σ_L dominates at forward angles -> cleaner determination of F_π

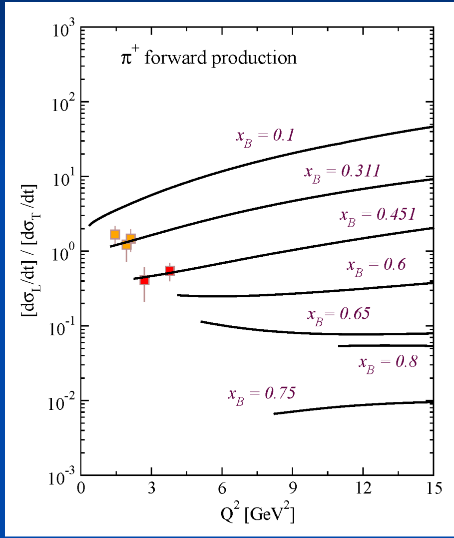
σ_T grows with Q^2 relative to σ_L

Q^2 scaling of *L* and *T*

T

L





Hard scattering Prediction:
$\sigma_L/\sigma_T \sim Q^2$

T very different from hard scattering prediction (Horn et al)
Res/parton model predicts increase with Q^2
only for smaller x

Summary

- Any good reaction model or pion production has to describe both t-channel and s-channel (N*)
- Transverse pion production does not follow QCD scaling law at JLAB@5 and JLAB@12
- Transverse strength from resonance contributions
- Duality fixes e.m. formfactors of high-lying resonances
- Cornell, DESY and JLAB data are all described, with same model, same parameters
- QCD scaling for *L/T* holds only for small x < 0.5

References

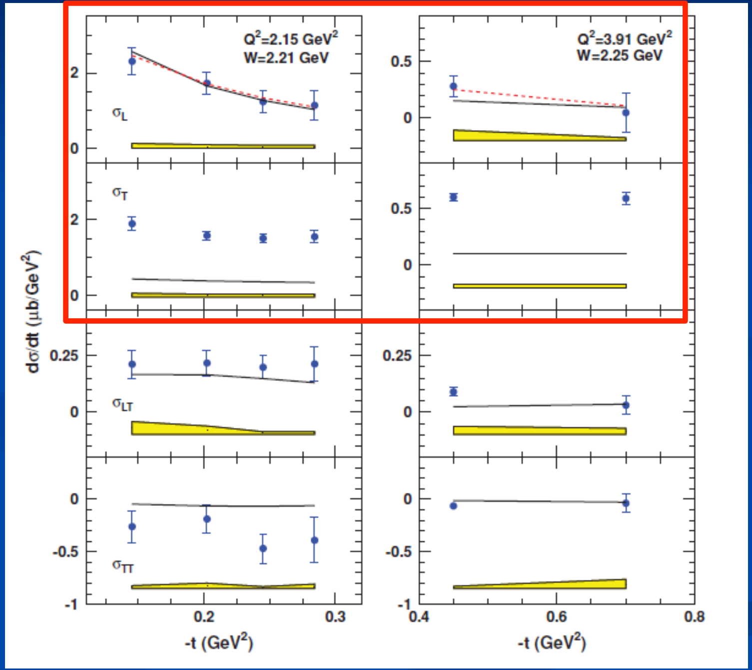
- Neutral pion electroproduction in p(e,e′π0)p above s√>2 GeV
  Murat M. Kaskulov. May 2011. 12 pp. e-Print: arXiv:1105.1993 [nucl-th]
- Exclusive pion electroproduction off nucleons and nuclei.
  Murat M. Kaskulov, Ulrich Mosel (Giessen U.). Mar 2011. 15 pp. NAPP 2010, e-Print: arXiv:1103.1602 [nucl-th]
- Beam spin asymmetry in deeply virtual π production.
  Murat M. Kaskulov, Ulrich Mosel. Jan 2011. 5 pp. SPIN 2010, e-Print: arXiv:1101.6042 [hep-ph]
- Deep exclusive charged π electroproduction above the resonance region.
  Murat M. Kaskulov, Ulrich Mosel (Giessen U.). Jan 2010. 29 pp. Phys.Rev. C81 (2010) 045202
  e-Print: arXiv:1001.1952 [hep-ph]
- Deep exclusive electroproduction of pi+ from data measured with the HERMES detector at DESY.
  Murat M. Kaskulov, Ulrich Mosel (Giessen U.). Apr 2009. 10 pp., Phys.Rev. C80 (2009) 028202
  e-Print: arXiv:0904.4442 [hep-ph]
- Deeply inelastic pions in the exclusive reaction p(e, e' pi+)n above the resonance region.
  Murat M. Kaskulov, Kai Gallmeister, Ulrich Mosel (Giessen U.). Apr 2008. 4 pp.
  Phys.Rev. D78 (2008) 114022, e-Print: arXiv:0804.1834 [hep-ph]

Backups

*L*ong and *T*ransv Pion Production

- VGL model
  very good for *L*
  dramatically bad for *T*

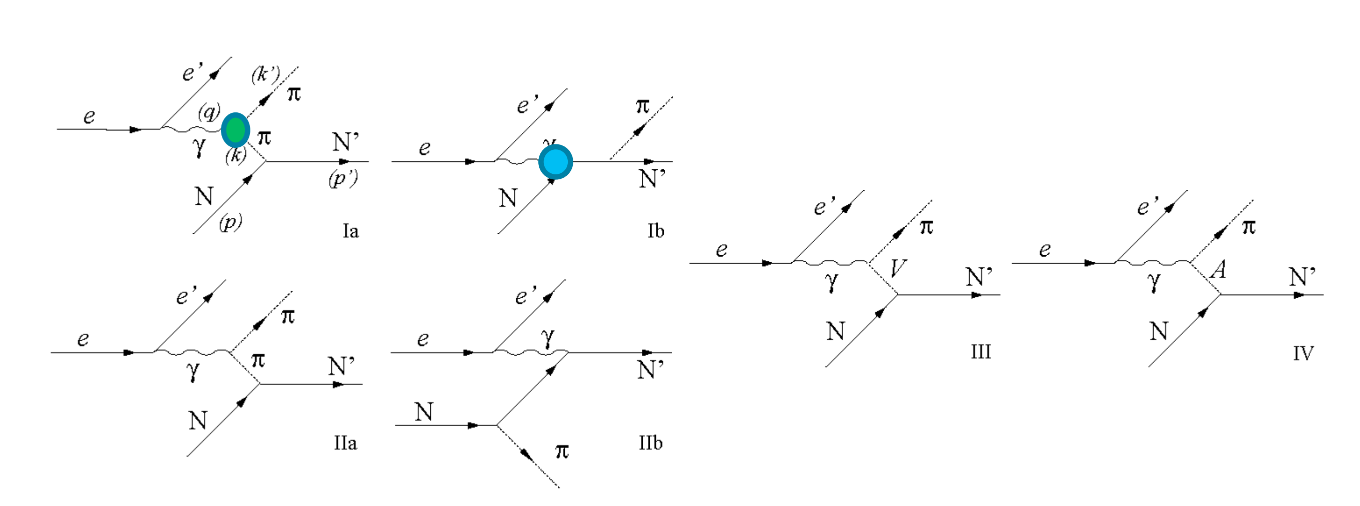
Nagging thought: can F_π be reliably extracted from a model that fails for *T*?



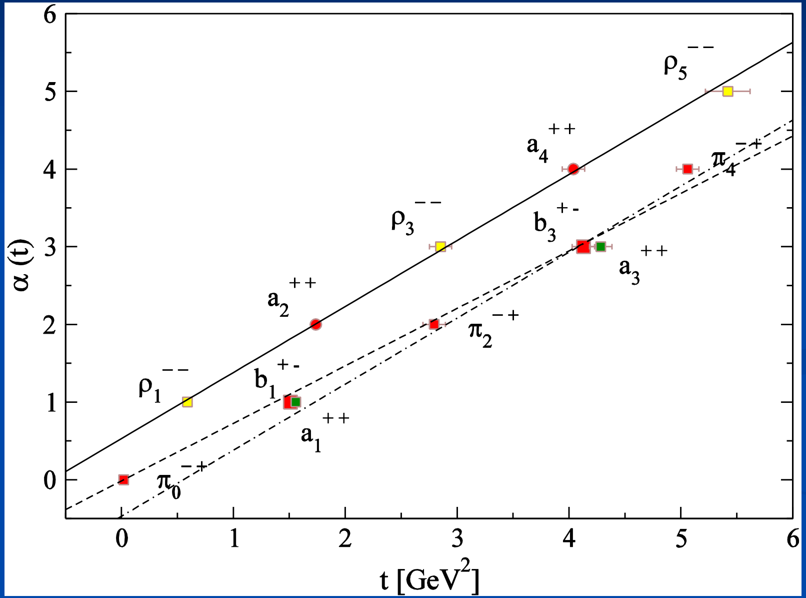
Data from π-CT Exp. at JLAB,
T. Horn et al., PR C78, 058201 (2008)

Extended VGL Model

- Extends VGL model, allows for gauge-invariant treatment of different FFs for pion and proton (Gross-Riska)



Extended VGL Model



Regge trajectories in t-channel

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Prediction for π^- on *n*

- For *L*:
  - π-pole dominance: $\sigma_L^n/\sigma_L^p \approx 1$
- For *T*:
  - Dominated by structure functions:

$$\sigma_T^n/\sigma_T^p \approx F_1^n/F_1^p \approx F_2^n/F_2^p < 1$$

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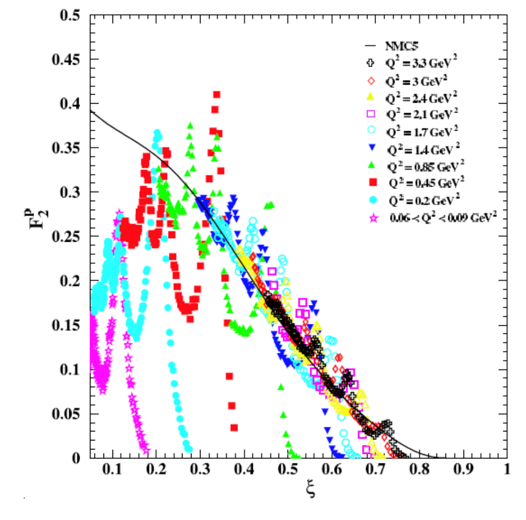
Resonance/Parton connection

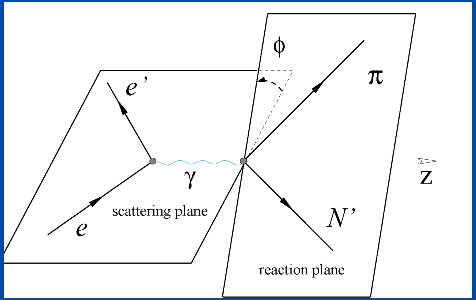
- Use BG duality to keep strong transverse contribs of partons: N* ~ partons

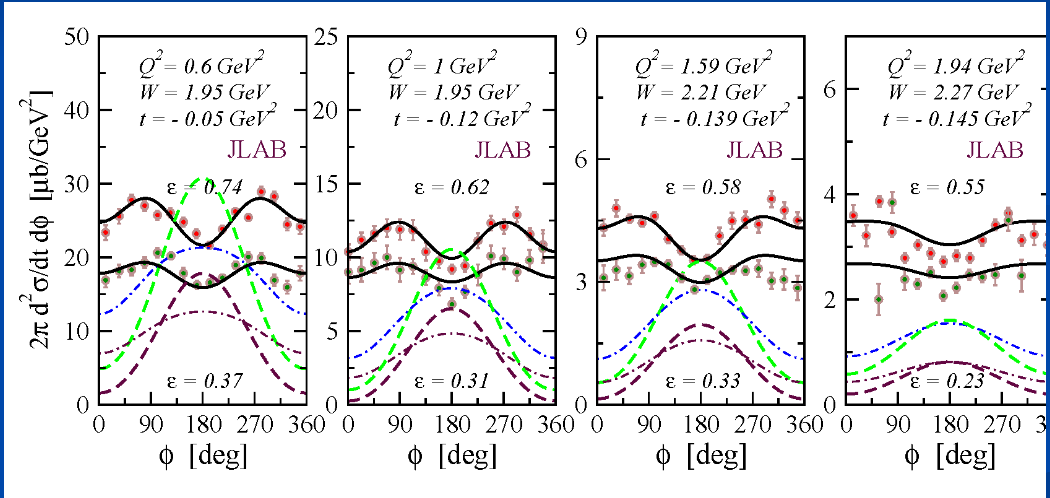


From:
W. Melnitchouk, Proc. MENU 2007

N* contribution to π^+ production

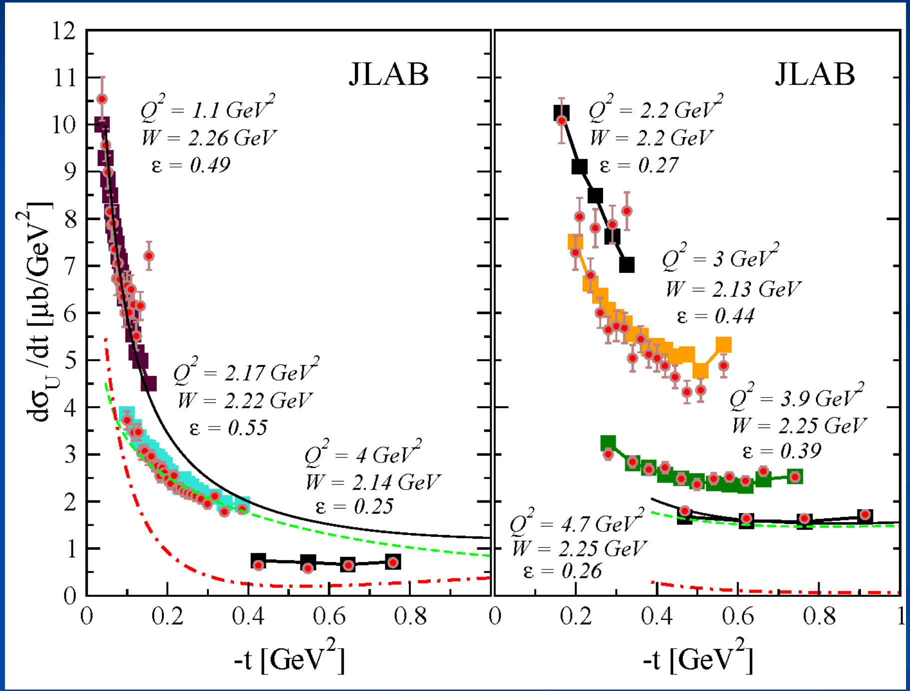
- ϕ dependence determined by N*



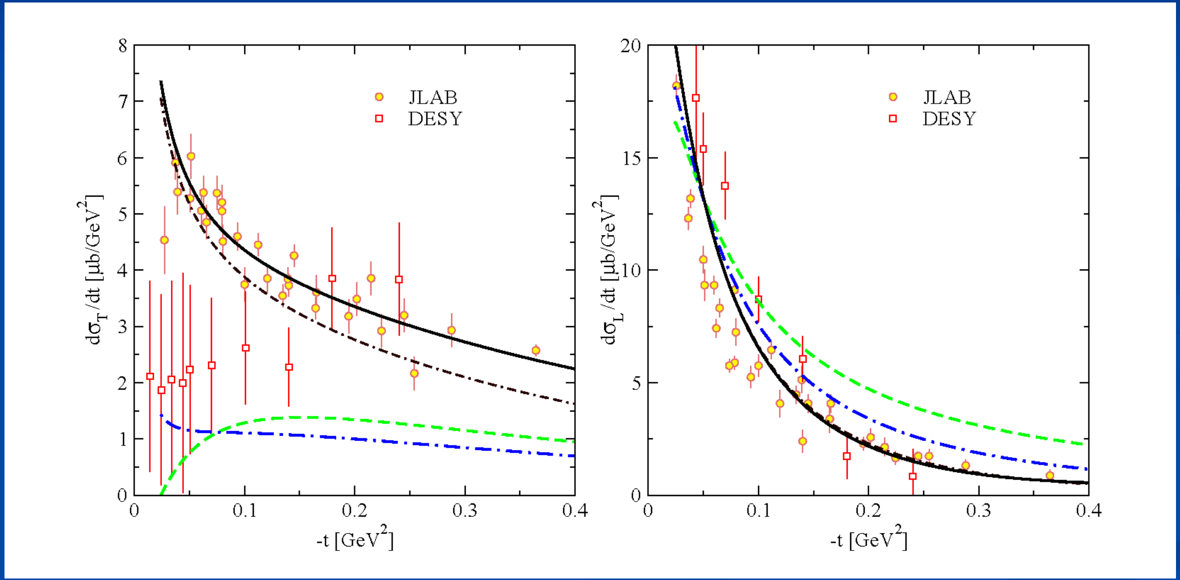


Data from JLAB, T. Horn et al, V. Tadevosyan et al

Q^2-, ε-dependence

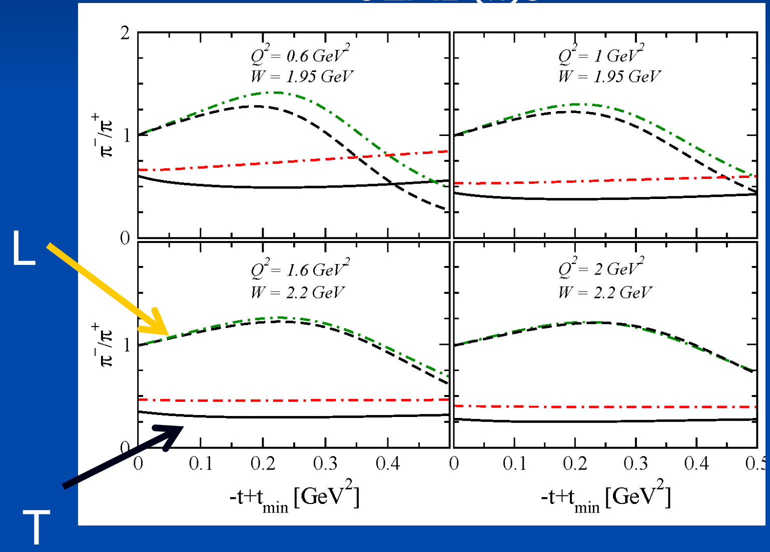


T, *L* X-sections at DESY, JLAB

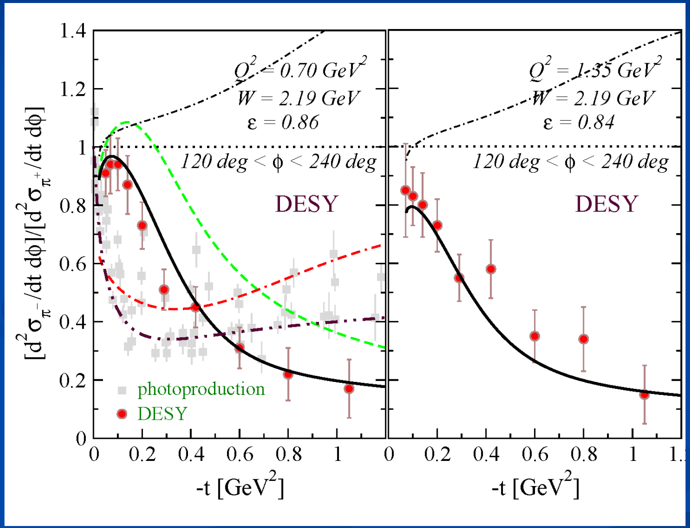


π^-/π^+ ratio

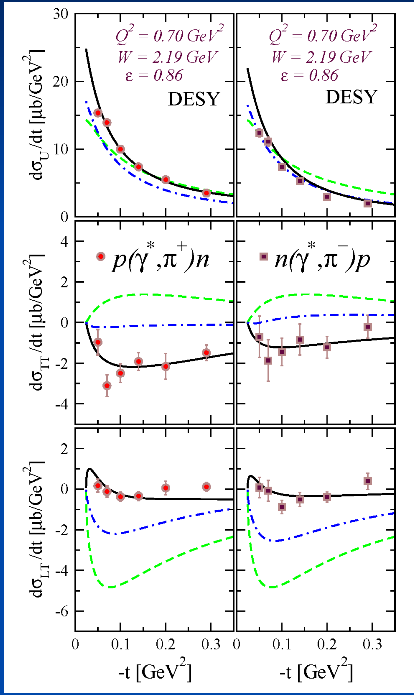
JLAB@5

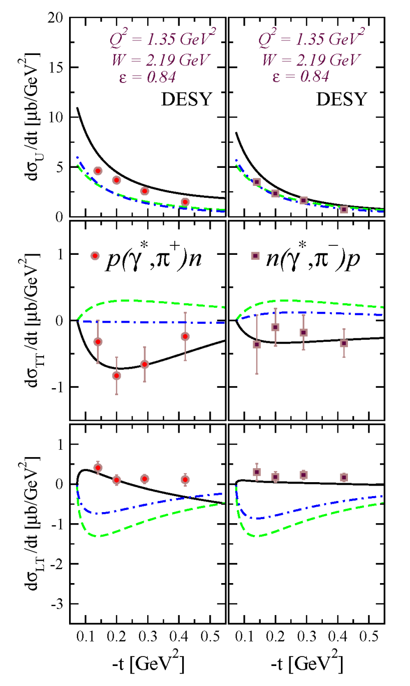


HERMES

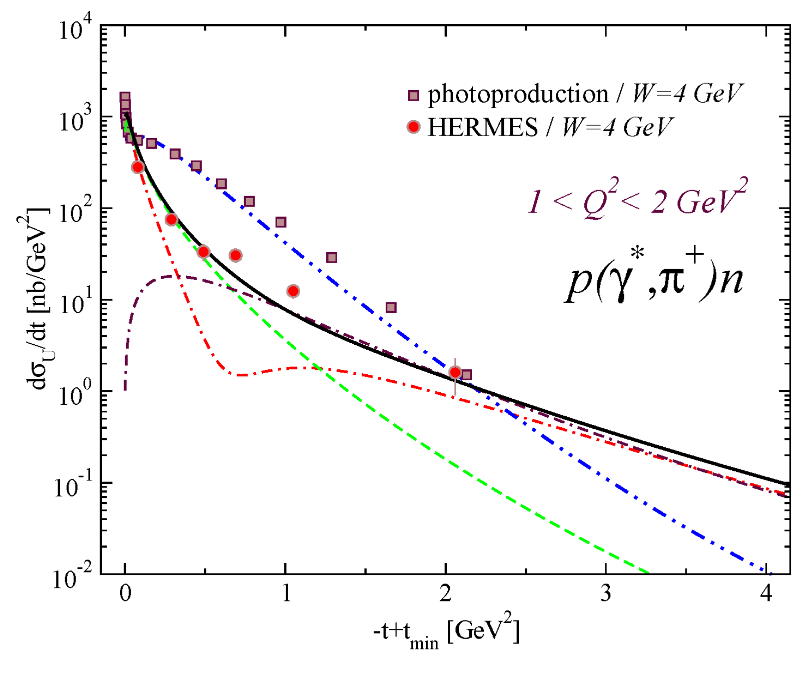


DESY Data


$Q^2 = 0.70\ GeV^2$
$W = 2.19\ GeV$
$\varepsilon = 0.86$
DESY
$p(\gamma^*,\pi^+)n$
$n(\gamma^*,\pi^-)p$
$d\sigma_U/dt\ [\mu b/GeV^2]$
$d\sigma_{TT}/dt\ [\mu b/GeV^2]$
$d\sigma_{LT}/dt\ [\mu b/GeV^2]$
-t [GeV^2]

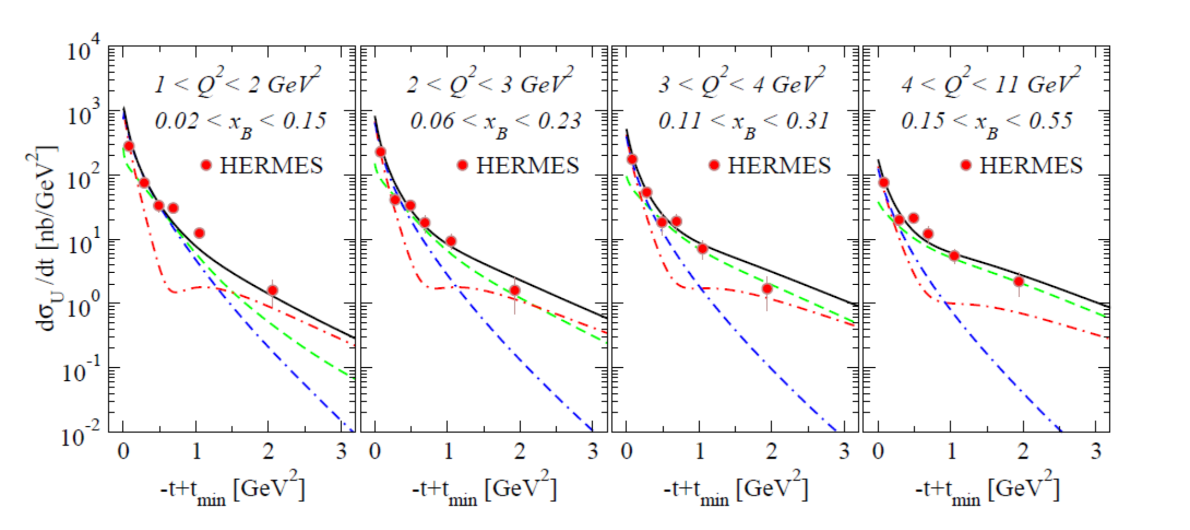

$Q^2 = 1.35\ GeV^2$
$W = 2.19\ GeV$
$\varepsilon = 0.84$
DESY
$p(\gamma^*,\pi^+)n$
$n(\gamma^*,\pi^-)p$
$d\sigma_U/dt\ [\mu b/GeV^2]$
$d\sigma_{TT}/dt\ [\mu b/GeV^2]$
$d\sigma_{LT}/dt\ [\mu b/GeV^2]$
-t [GeV^2]

HERMES Data



photoproduction / W=4 GeV
HERMES / W=4 GeV
1 < Q^2 < 2 GeV^2
p(γ*,π+)n
dσ_U/dt [nb/GeV^2]
-t+t_min [GeV^2]

π^+ production at HERMES



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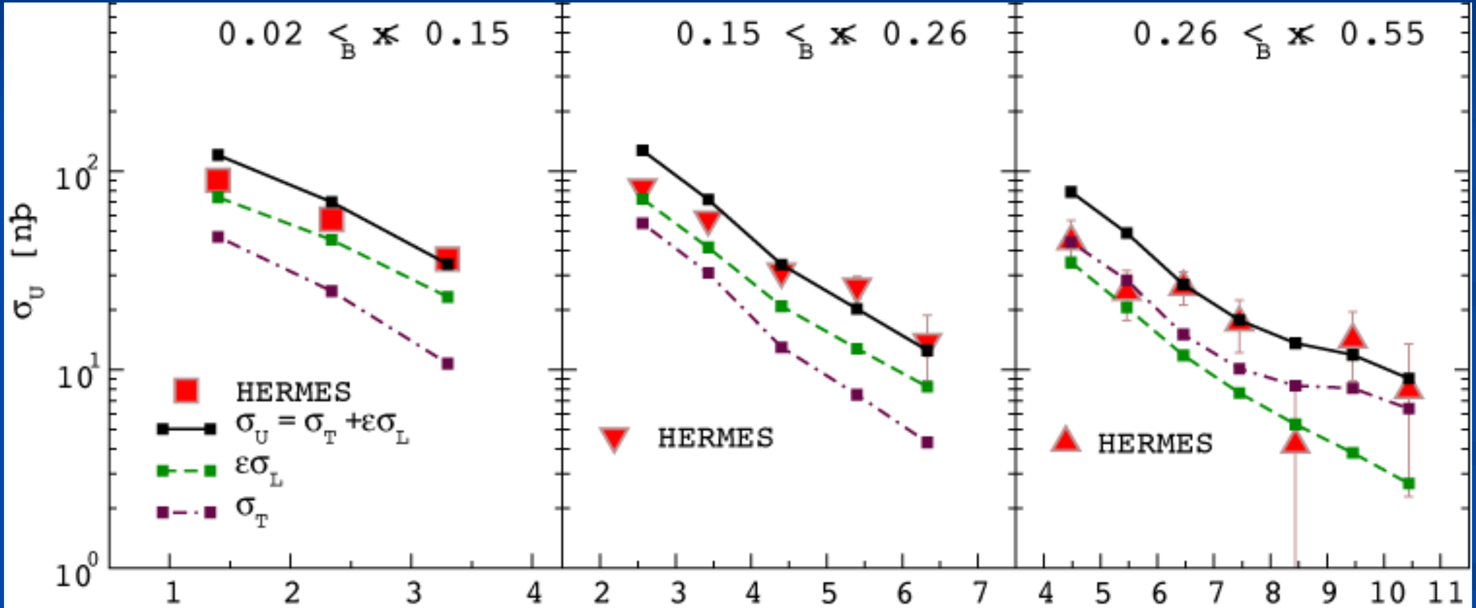
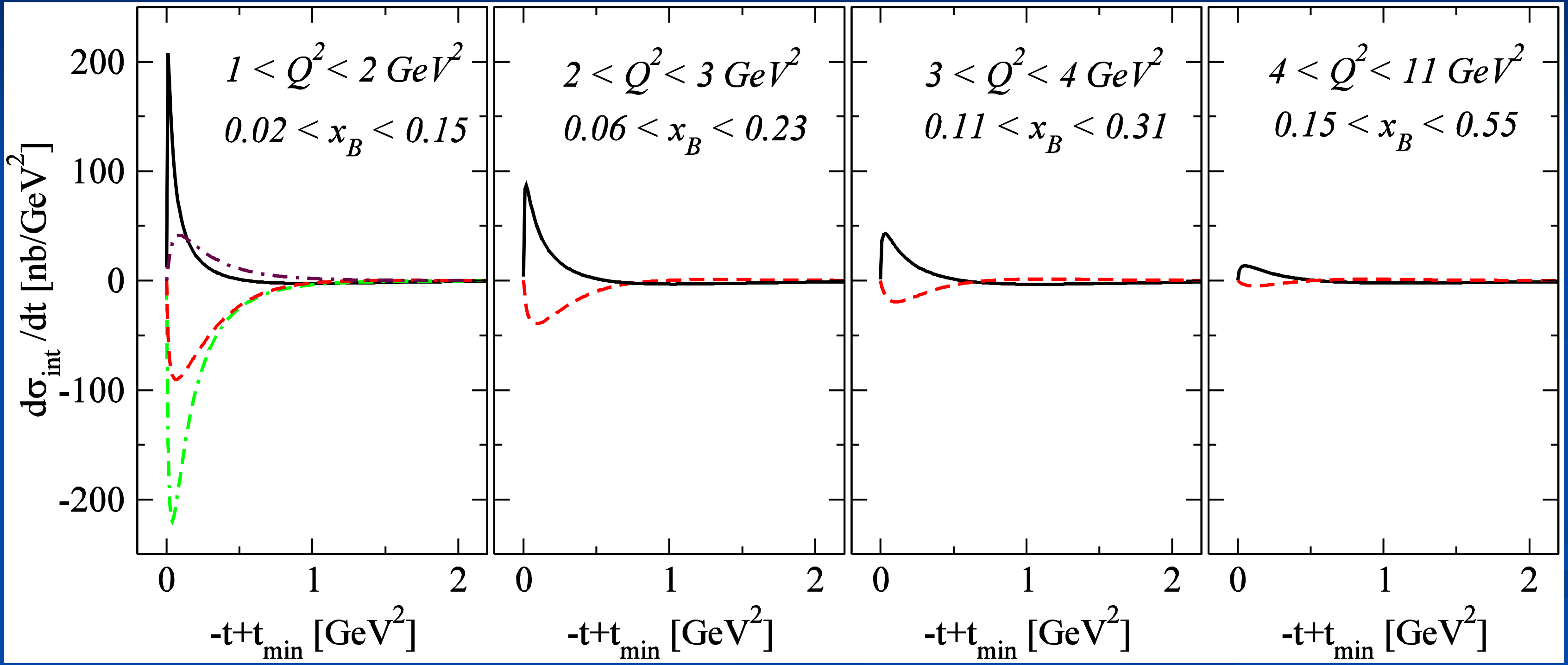
HERMES Data



0.02 < x_B < 0.15
0.15 < x_B < 0.26
0.26 < x_B < 0.55
σ_U [nb]
HERMES
σ_U = σ_T + εσ_L
εσ_L
σ_T
HERMES
HERMES

TT(solid) and LT(dashed) at HERMES



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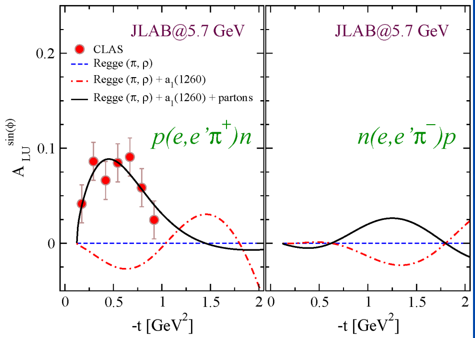
Beam Spin Azimuthal Moment



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