Leading Baryons at HERA

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On behalf of H1 and ZEUS Collaborations

Outline

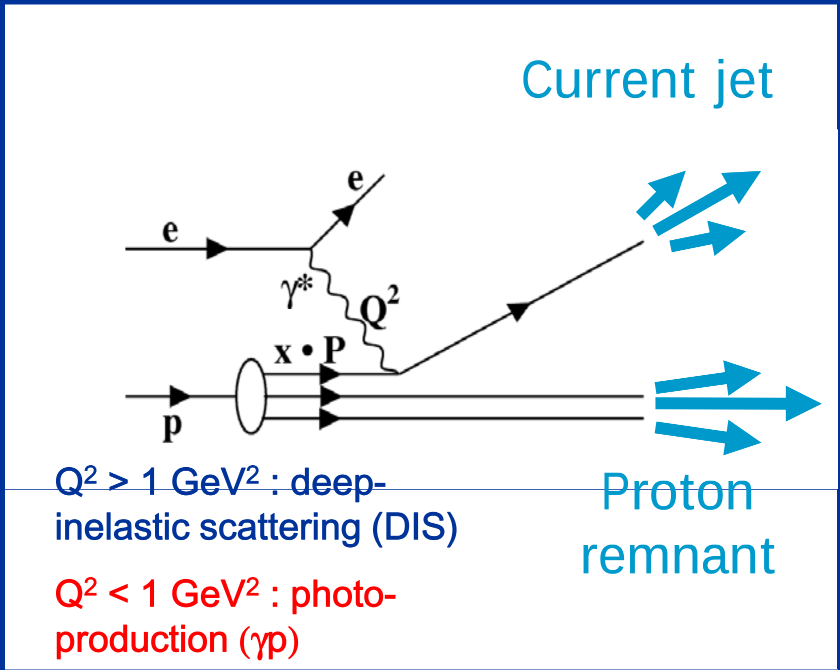
- Physics case
- Recent and new results on:
  - Leading protons (new)
  - Leading neutrons
  - Comparison with models
  - Leading neutron + 2 jets in γp
- Summary

Semi-inclusive reaction

$$ep \rightarrow ehX$$

h = LB = p, n

X = hadronic state



DIS regime

Scale for secondary particle production decreases from Q^2 (current region) to a soft hadronic scale (proton fragmentation region)

Photoproduction (γp) regime

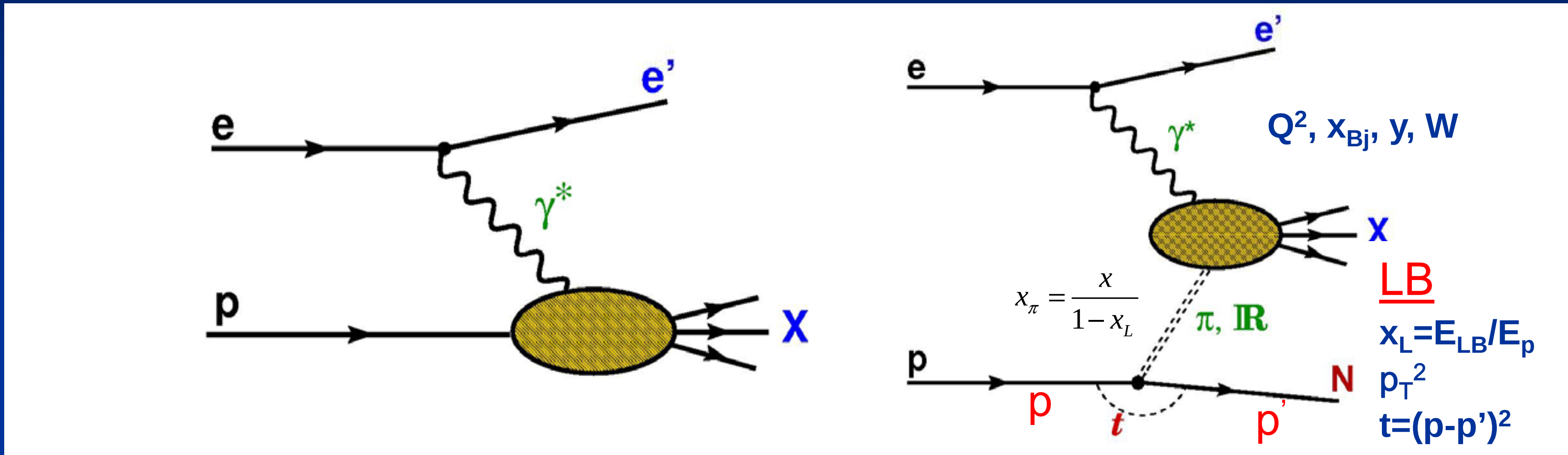
Hadronic component of the photon.

Can re-introduce hard scale (e.g. requiring high-p_T jets)

Some approaches

- Fracture Functions (L.Trentadue, G.Veneziano Phys. Lett. B323, 201 (1994))
  - Not discussed here
- MC fragmentation models
- Dynamical particle-exchange models

Production models



- <u>Hadronisation of proton remnant</u>
  - Herwig (cluster model)
  - MEPS (parton shower,SCI)
  - Ariadne (CDM)

- <u>Exchange of virtual particles</u>
  - leading protons: π^0, IR, IP (isoscalar + isovector)
  - leading neutrons: π^+, ρ^+, … (isovector)

Rescattering and absorption

e.g. LN production via π-exchange

Neutron absorption through rescattering

D'Alesio and Pirner

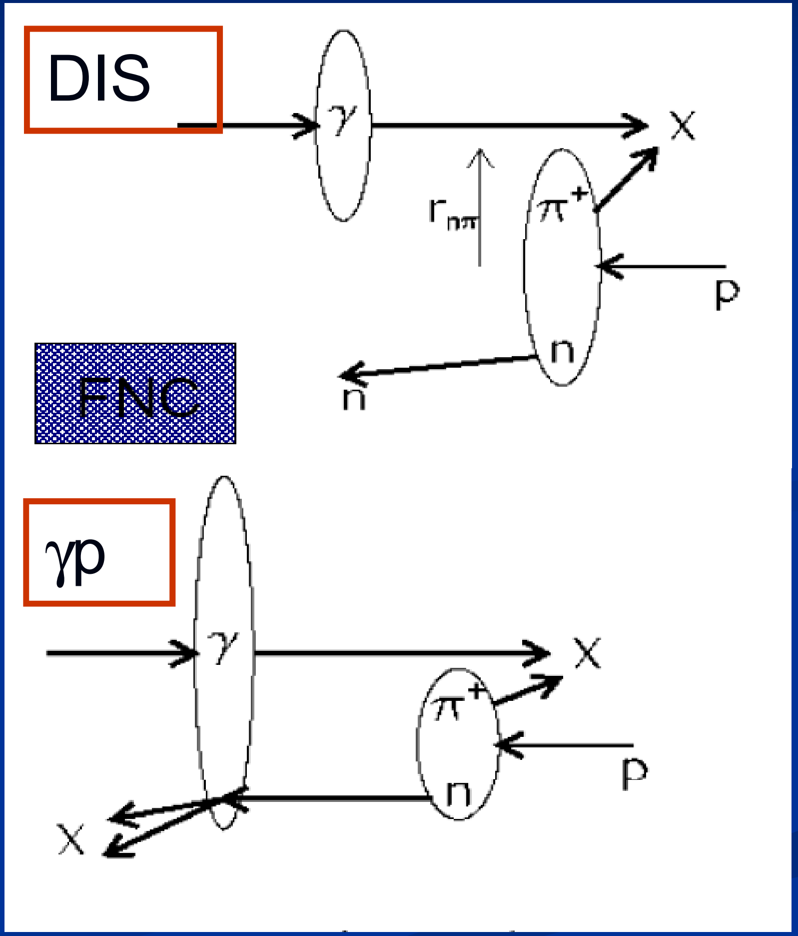
(EPJ A7(2000) 109)

- Neutron rescatters on γ hadronic component.

Absorption enhanced when π-n system size $r_{\pi n}$ small w.r.to the γ: **$r_{\pi n} \sim 1/p_T$** .

Dependence on the pion-flux from x_L: $\langle r_{\pi n} \rangle$ increases with x_L ➔ more absorption at low x_L .

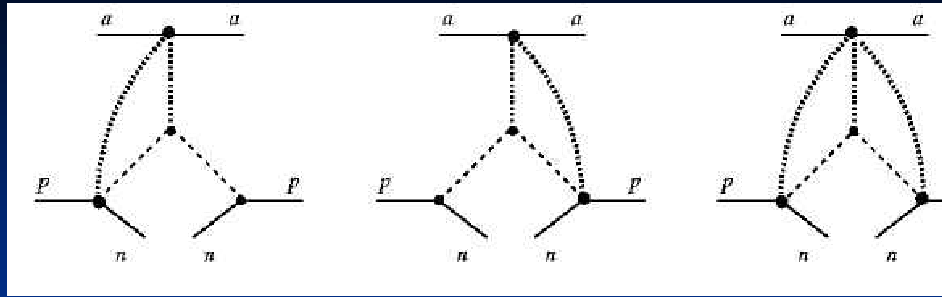
- n kicked to lower x_L & higer p_T (migration)
- may escape detection (absorption loss)



- more absorption in photoproduction than DIS

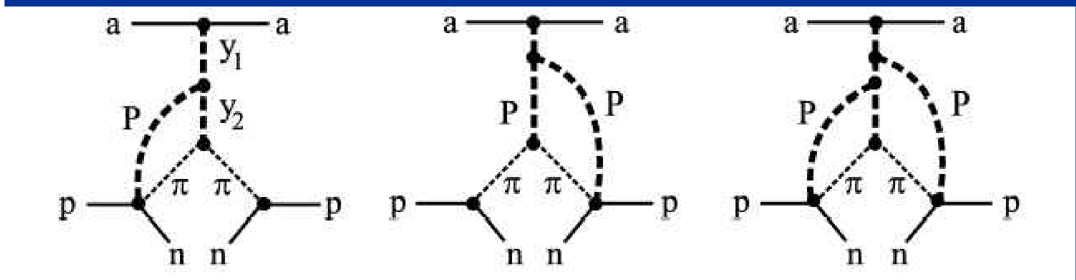
(γ "size" larger)

Nikolaev,Speth and Zakharov (NSZ)
(hep-ph/9708290)
Re-scattering processes via additional pomeron exchanges + Optical Theorem



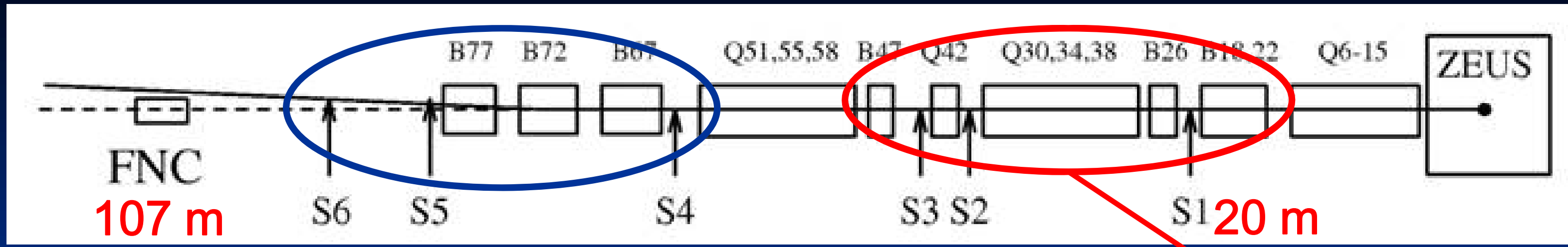
(→ Uncertainties in π structure function extraction)

(Kaidalov,) Khoze, Martin, Ryskin (KKMR)
(hep-ph/0602215, hep-ph/0606213)
Enhanced absorptive corrections, calculation of migrations, include also ρ and a_2 exchange (different x_L & p_T dependences)



- Measure x_L and p_T^2 distributions
- Study dependence on Q^2
- Compare γp and DIS
- Look for effects due to absorption

Experimental tools



ZEUS Leading Proton Spectrometer (LPS)

- 6 stations each made by 6 Silicon-detector planes
- Stations inserted at $10\sigma_{beam}$ from the proton beam during data taking
- $\sigma_{x_L} < 1\%$, $\sigma_{p_T^2} \sim$ few MeV^2 (better than p-beam spread ~ 50 - 100 MeV)

ZEUS Forward Neutron Calorimeter (FNC) + Forward Neutron Tracker (FNT)

- 10λ lead-scintillator sandwich
- $\sigma/E = 0.65/\sqrt{E}$, Energy scale 2%
- Acceptance $\theta_n < 0.8$ mrad, azimuthal coverage 30%
- FNT: Scint. hodoscope @ $1\lambda_{int}$, $\sigma_{x,y} = 0.23$ cm, $\sigma_\theta = 22$ μrad

H1 Forward Proton Spectrometer (FPS)

- 2 stations each made by 4 planes of sci-fiber hodoscopes + trigger scintillators
- $\sigma_x = \sigma_y = 100$ μm, $\sigma(E) < 8$ GeV, $|E_{scale}| = 10$ GeV, $<\varepsilon_{track}> \sim 50\%$

H1 Forward Neutron Calorimeter (FNC)

- Lead-scintillator calorimeter @ 107m from I.P. + veto hodoscopes
- $\sigma(E)/E \approx 20\%$, neutron detection eff. 93±5%

Leading Protons (DIS-regime)

$$\frac{d^2\sigma}{dxdQ^2} \square K(x,Q^2)\times F_2(x,Q^2)$$

Fully inclusive: ep → eX

$$\frac{d^4\sigma}{dxdQ^2dx_L dp_T^2} \square K(x,Q^2)\times F_2^{LP(4)}(x,Q^2,x_L,p_T^2)$$

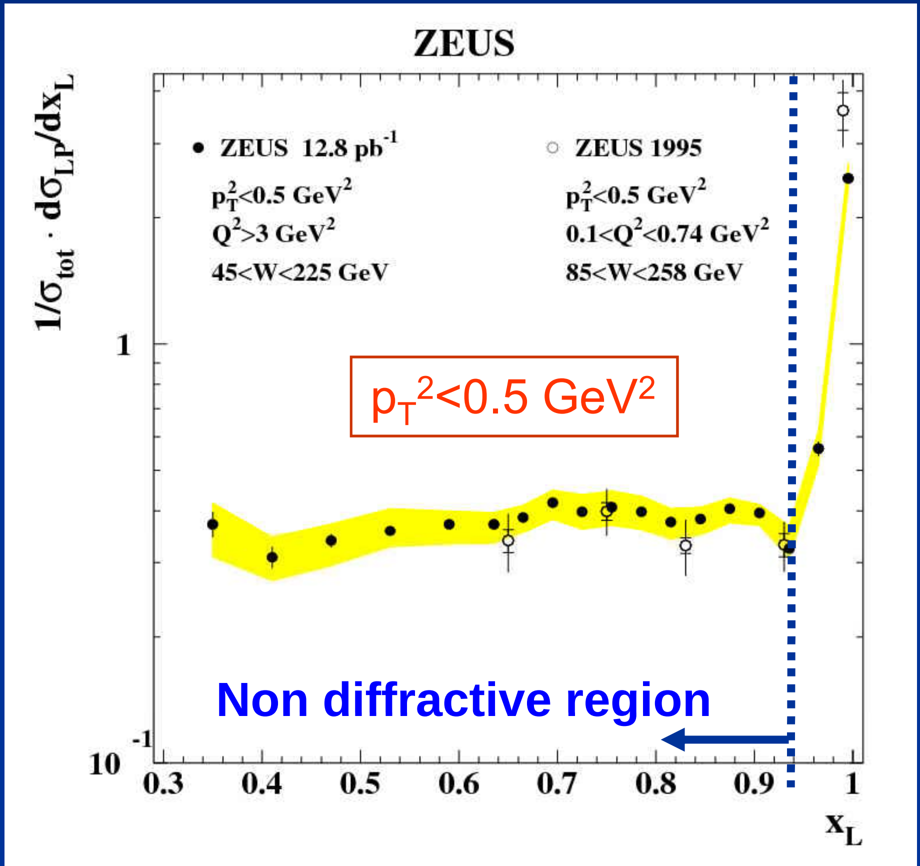
Semi-inclusive: ep → epX

$$\longrightarrow \quad \boldsymbol{F_2^{LP(3)}(x,Q^2,x_L)\,,\quad F_2^{LP(2)}(x,Q^2)}$$

x_L cross-section

NEW ZEUS Results

12.8 pb^{-1}

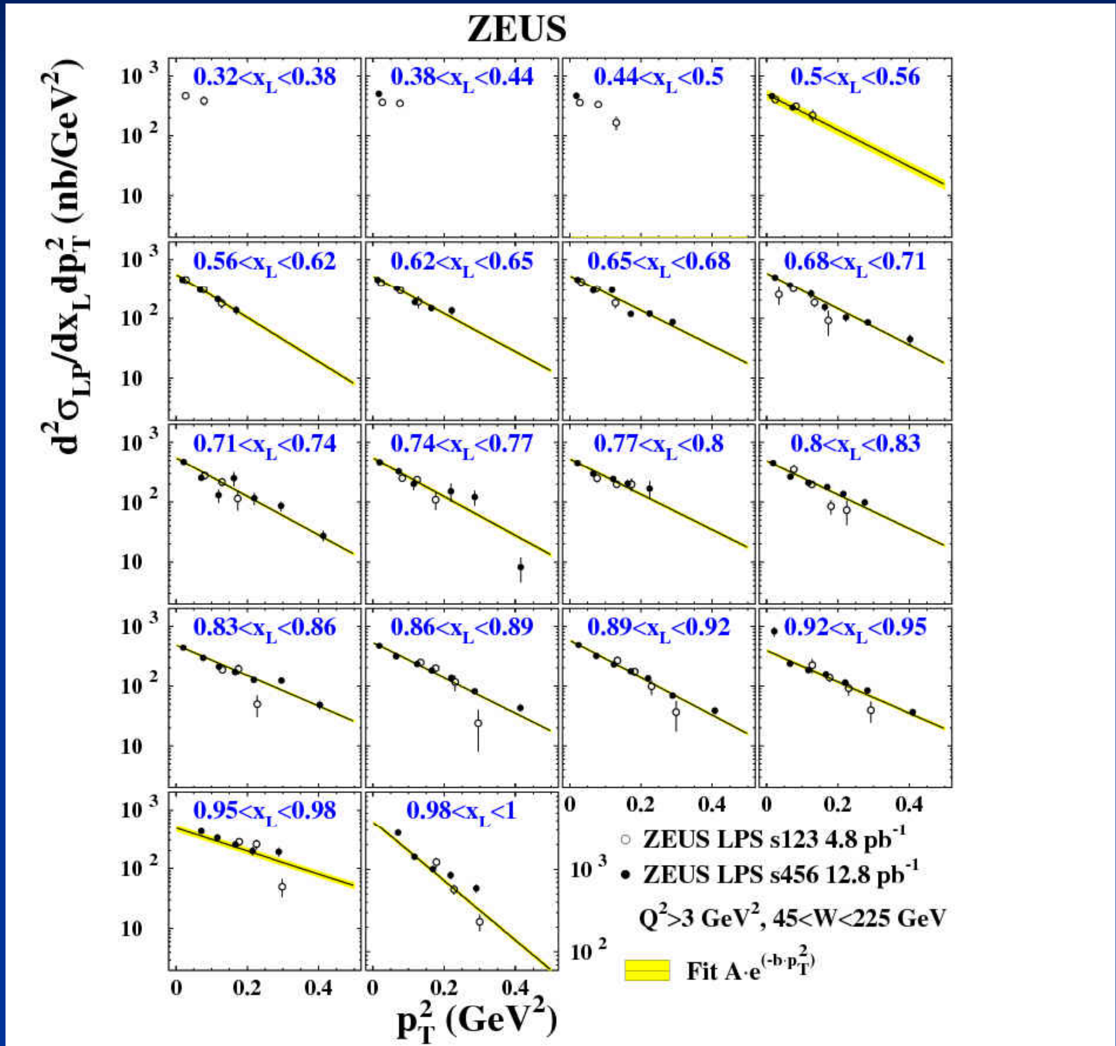


Cross section normalised to inclusive DIS cross section

Flat below diffractive peak

DIS and low Q^2 data are compatible

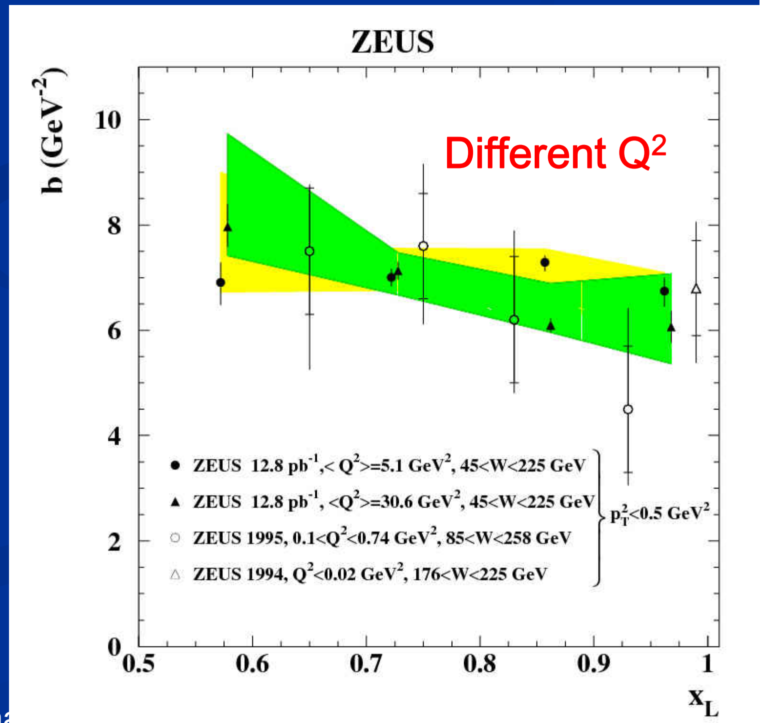
P_T^2 cross-section in bins of x_L



Exponential behaviour

Fit to ~ $\exp(-b\, p_T^2)$

No strong dependence of b on x_L



Rates to inclusive DIS

Structure function ratio

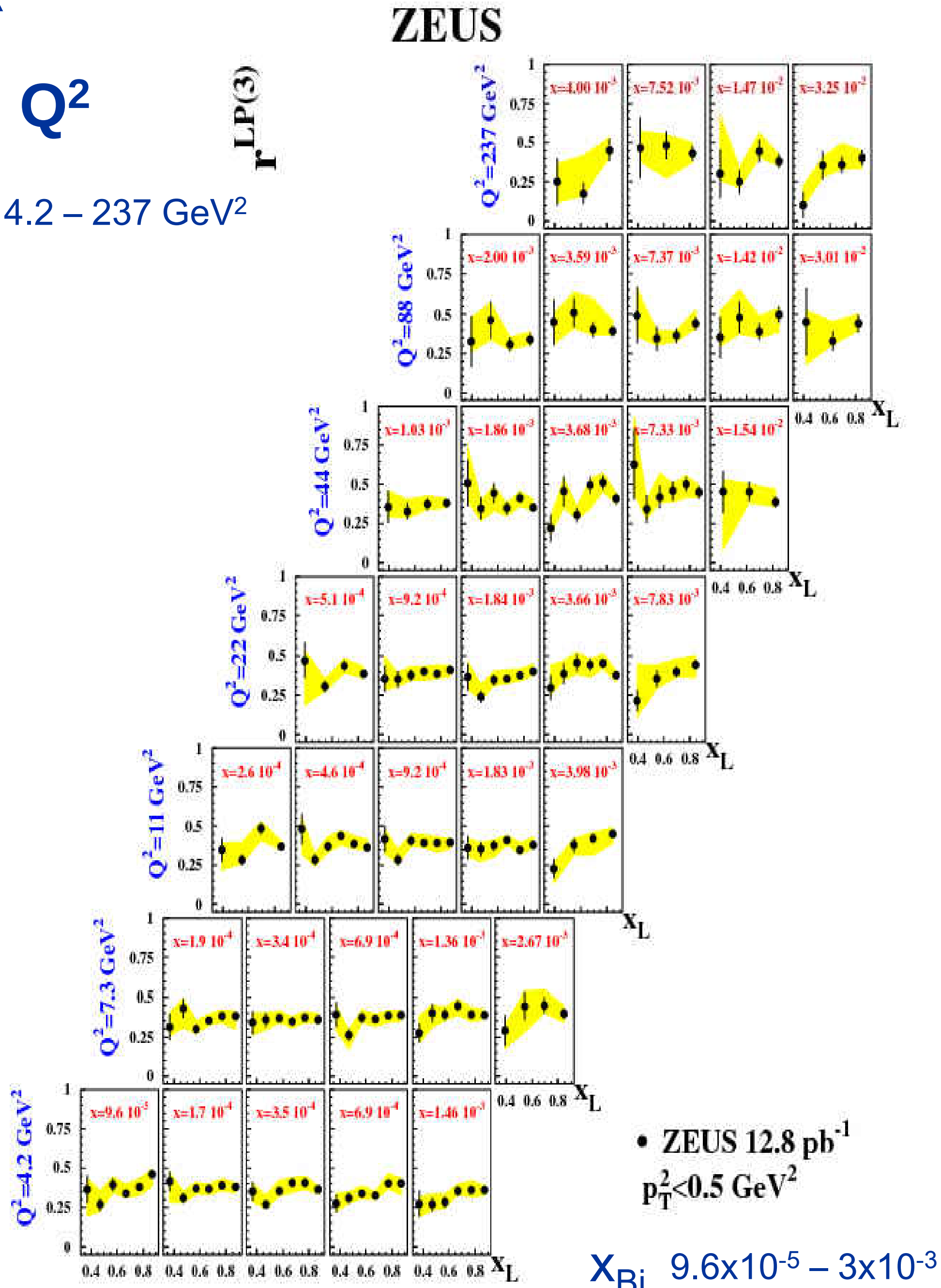
$$r^{LP(3)}(x,Q^2,x_L) = \frac{F_2^{LP(3)}(x,Q^2,x_L)}{F_2(x,Q^2)}$$

Measurement for $0.32<x_L<0.92$
(diffractive peak excluded)

$r^{LP(3)}$ almost independent of x and Q^2 with average value ~0.4

Q^2

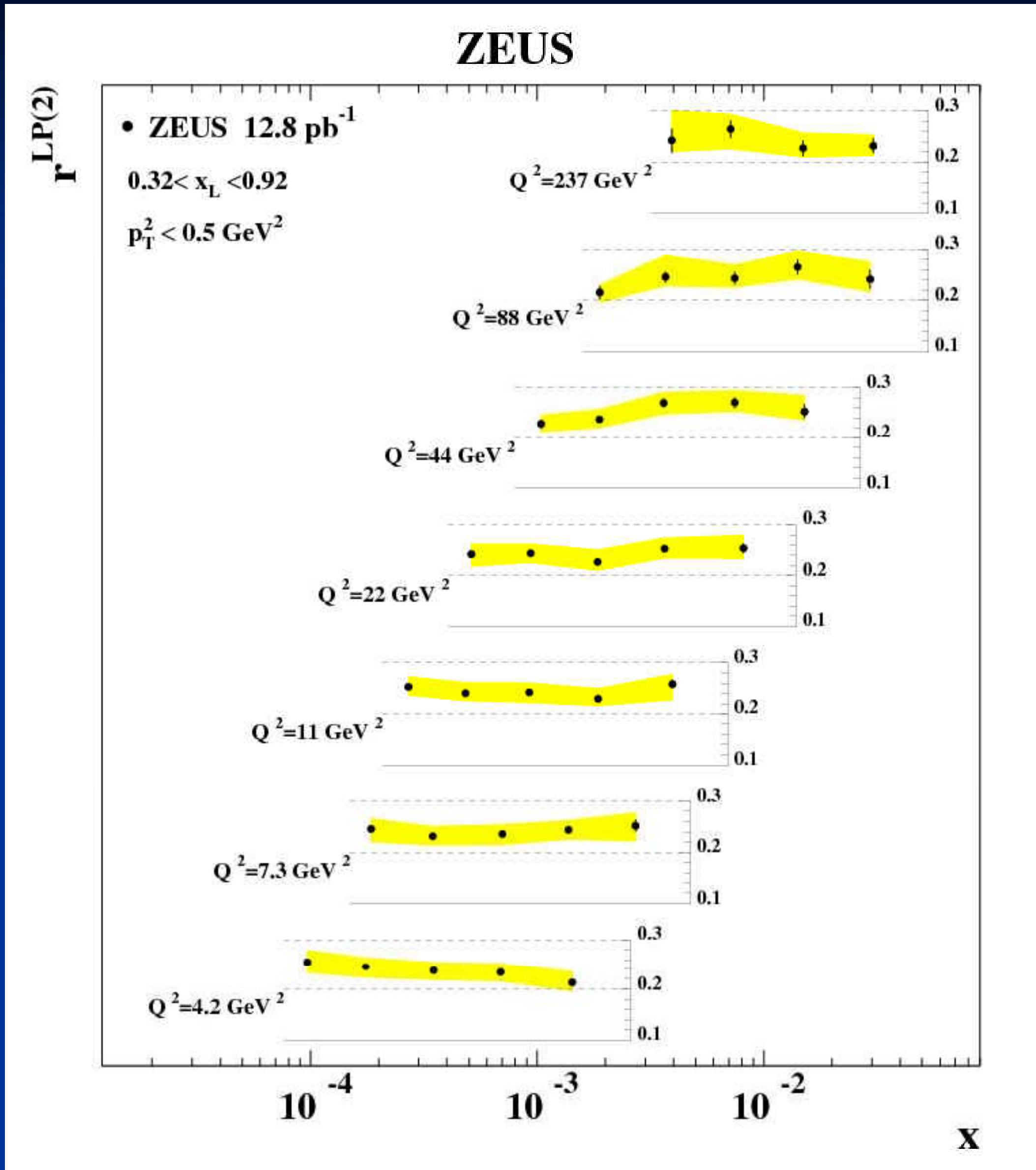
4.2 – 237 GeV^2

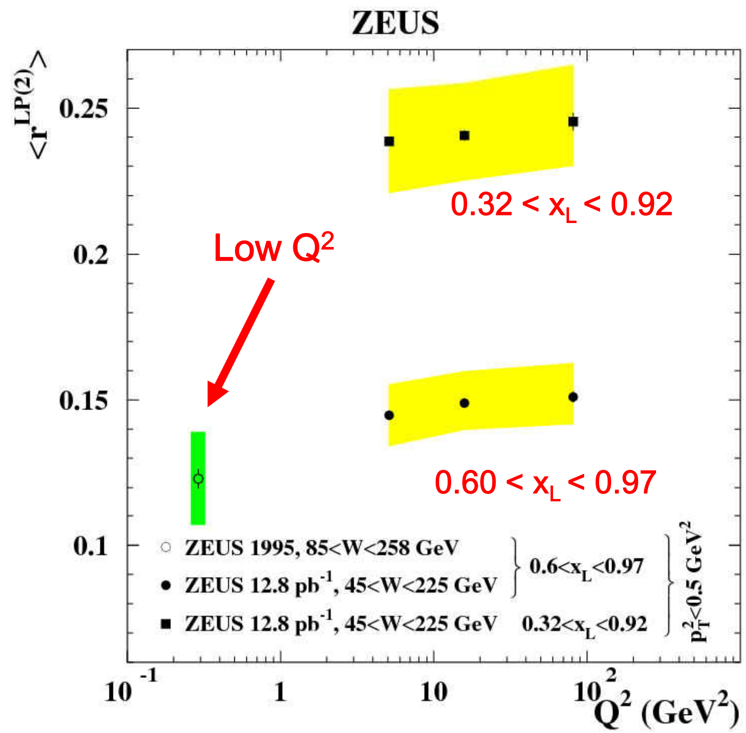


x_{Bj} $9.6\times10^{-5} - 3\times10^{-3}$

$$r^{LP(2)} = \frac{F_2^{LP(2)}(x,Q^2)}{F_2(x,Q^2)}$$

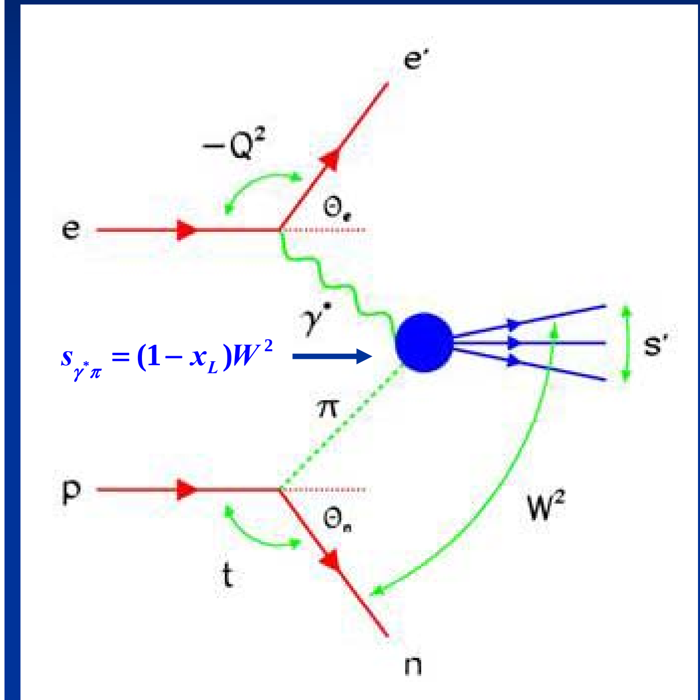
$$< r^{LP(2)} >$$





Slight increase with Q^2 not excluded

Leading neutrons



- One Pion Exchange is the leading contribution at large x_L
- (Regge)-factorization of the cross section $\gamma^* p \rightarrow nX$

$$\frac{d\sigma}{dx_L dt} = f_{\pi/p}(x_L, t) \cdot \sigma_{\gamma^*\pi}((1-x_L)W^2, Q^2)$$

Flux-factor

Elementary cross-section

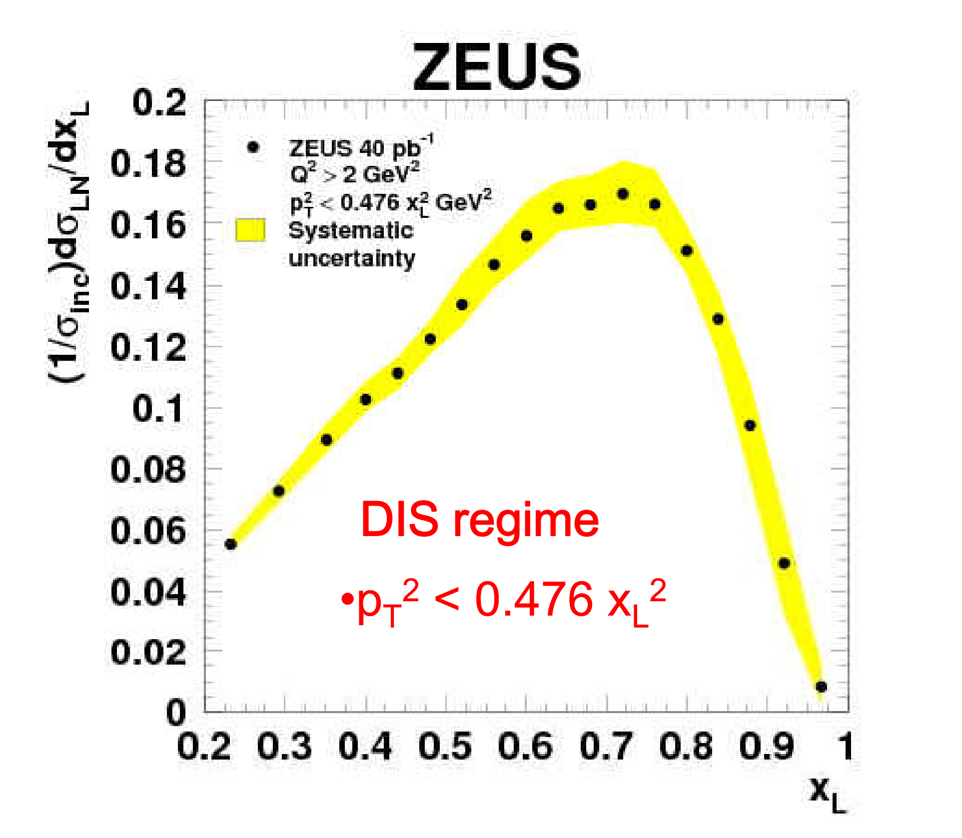
(notice x_L dependence)

Limiting Fragmentation (in the proton target region the production of particles is independent on the incident particle) ➔ Vertex Factorization

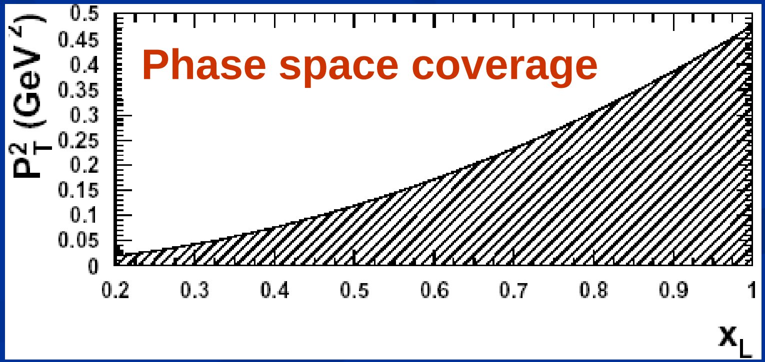
$$\frac{d\sigma}{dx_L dp_T^2} = g(x_L, p_T^2) \cdot G(W^2, Q^2)$$

← Broken if absorption

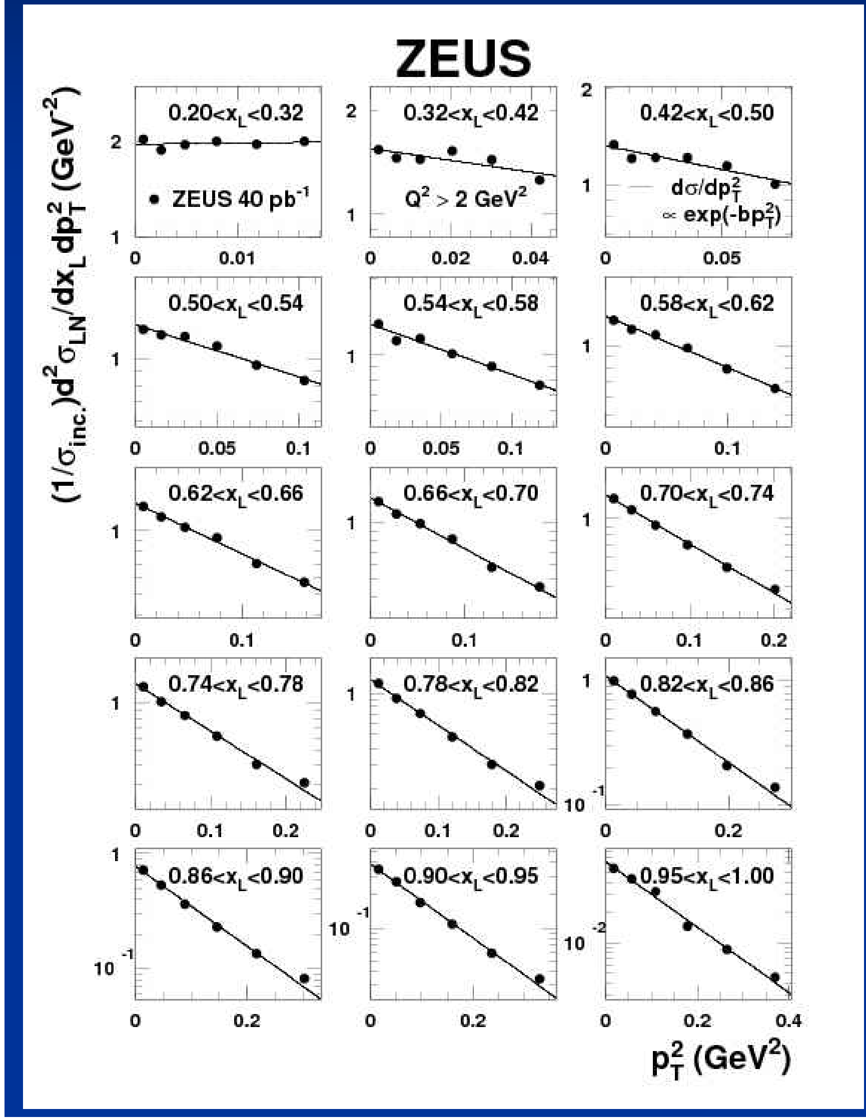
x_L spectrum



- LN yield decreases for $x_L \to 1$ due to kinematic limit
- Below $x_L \sim 0.7$ the yield drops due to decreasing p_T^2 range: $p_T^2 < 0.476\ x_L^2$

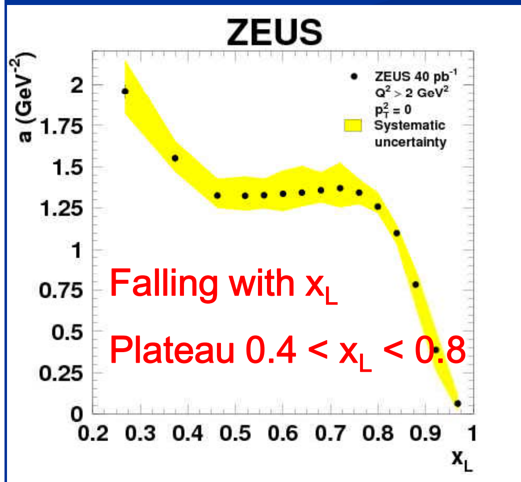


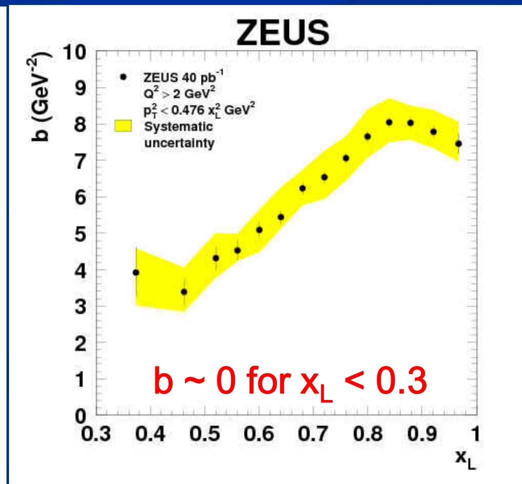
DIS cross section vs p_T^2 in bins of x_L



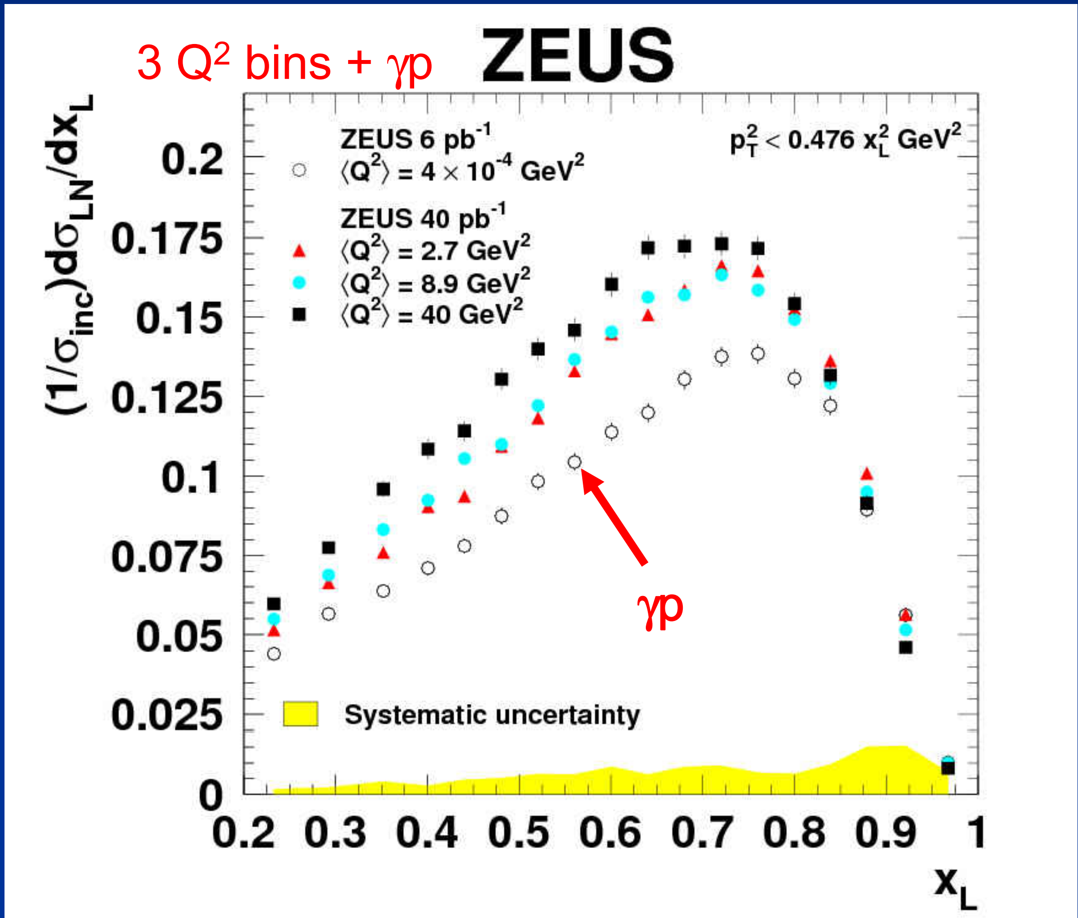
Good description through a single exponential in each x_L bin

$$\frac{1}{\sigma_{inc}} \frac{d^2\sigma_{LN}}{dx_L dp_T^2} = a(x_L) \cdot e^{-b(x_L)p_T^2}$$



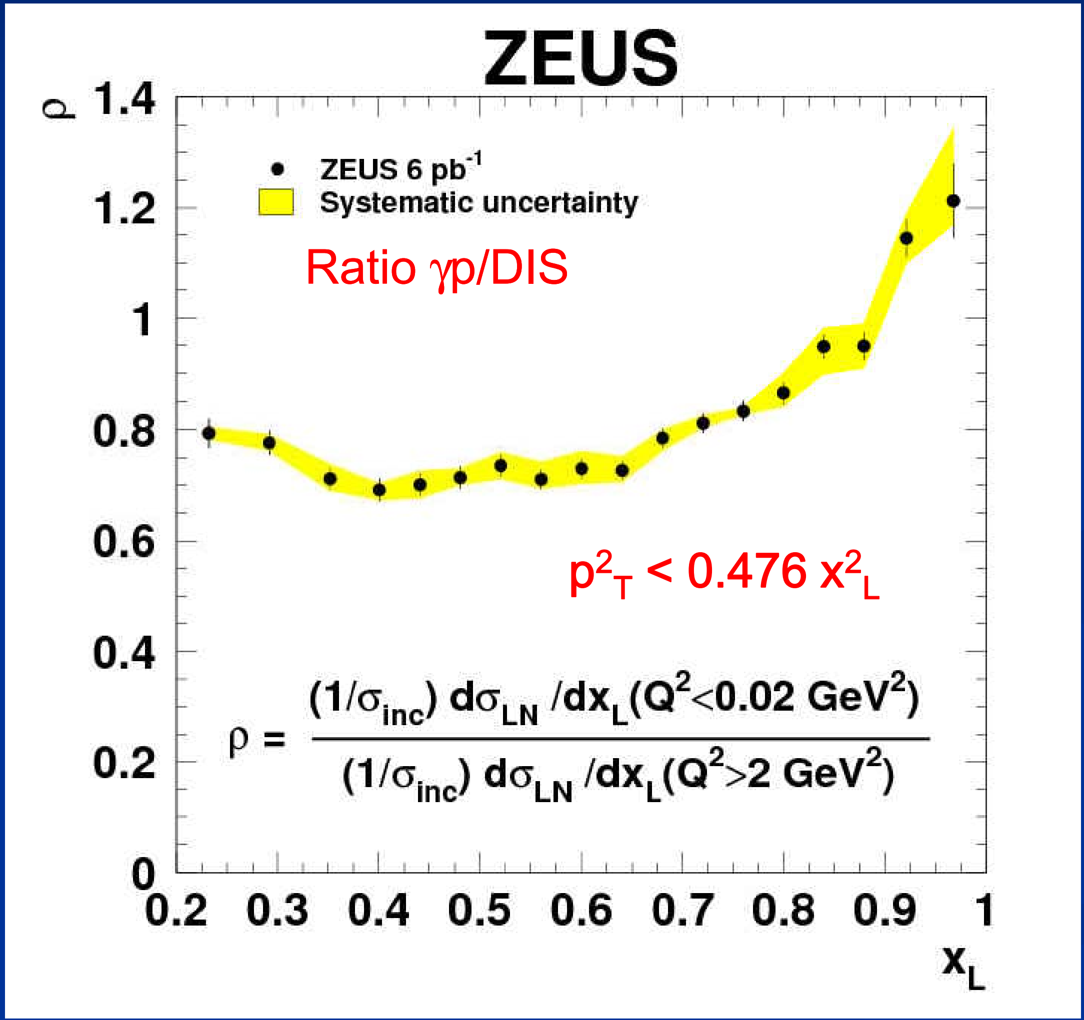


Q^2 – dependence: x_L spectra



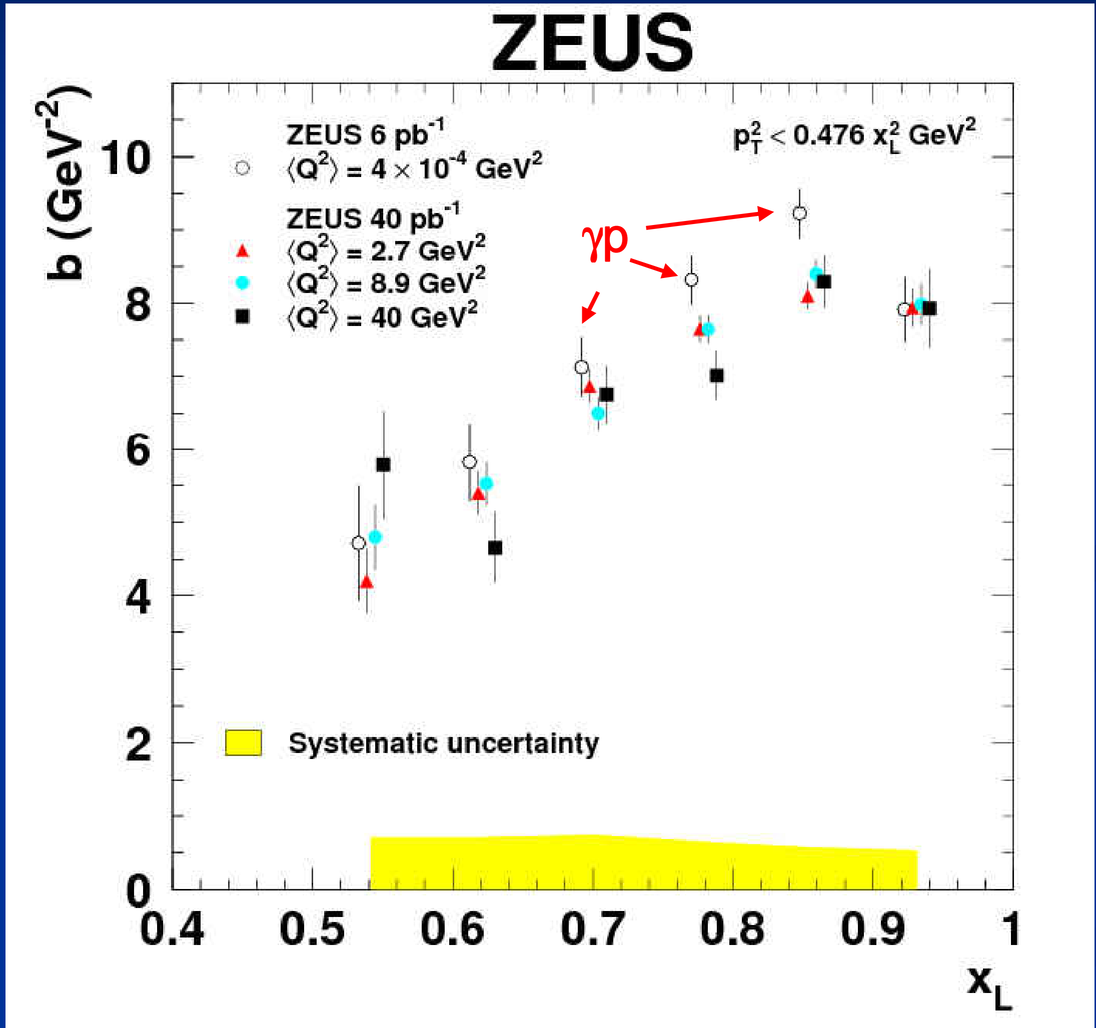
- Yield increases with Q^2: large increase from γp to DIS
- Smaller Q^2 dependence at intermediate values
- Violation of vertex factorization

Q^2 – dependence: x_L spectra
Comparison γp vs DIS



- Ratio γp/DIS
- ~ 70% intermediate x_L
- Rises above 1 as $x_L \rightarrow 1$
- Consistent with absorption:
  - separation π-n decreases at low x_L
  - smaller separation → more absorption at low x_L

Q^2 – dependence: p^2_T slopes



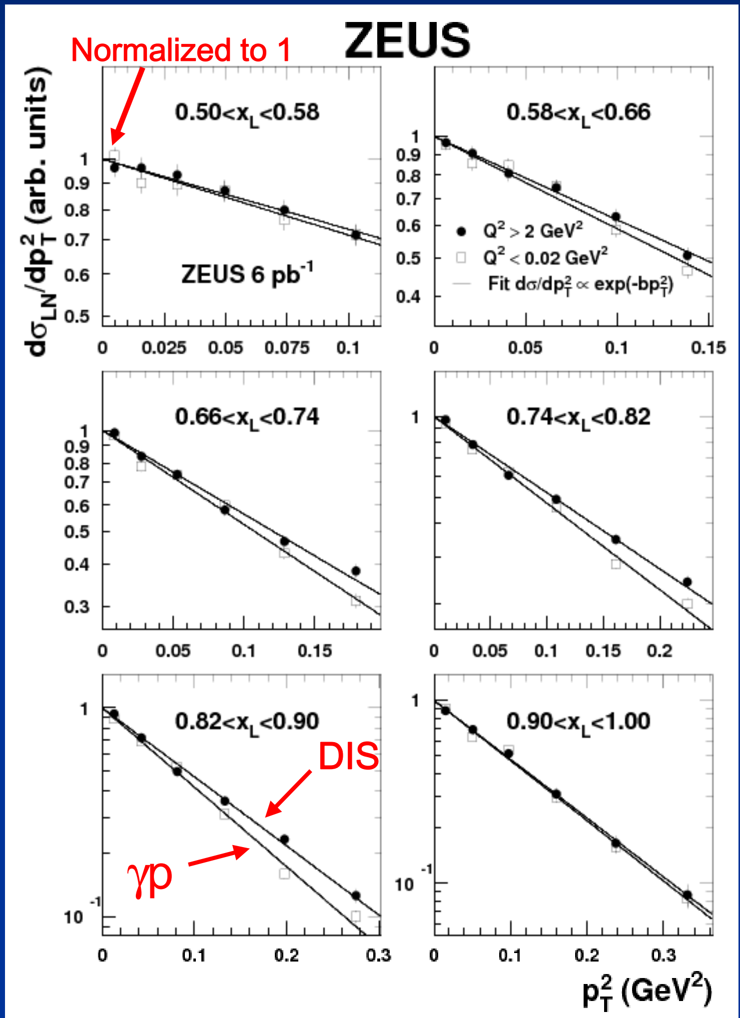
- DIS – slopes:

~ no Q^2 dependence

- γp – slopes:

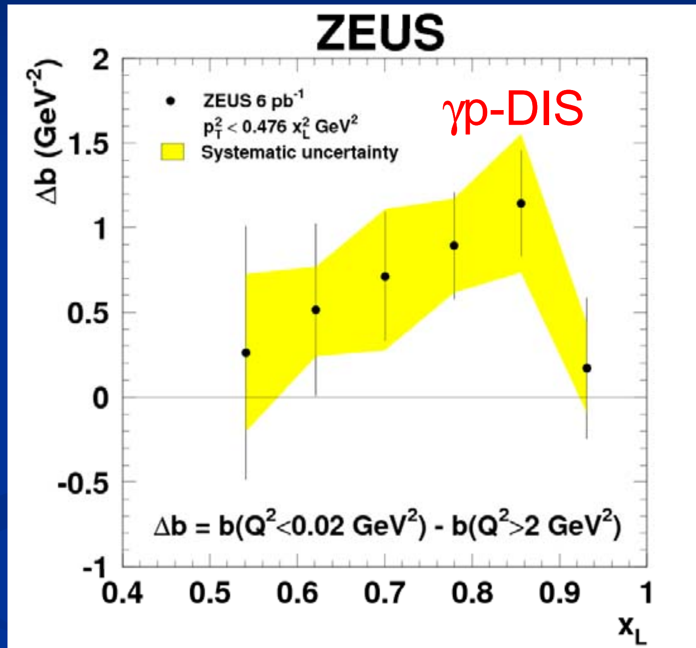
higher in $0.6 < x_L < 0.9$

Q^2 – dependence: p^2_T slopes. Comparison γp vs DIS



$b_{\gamma p} > b_{DIS}$ for $0.6 < x_L < 0.9$

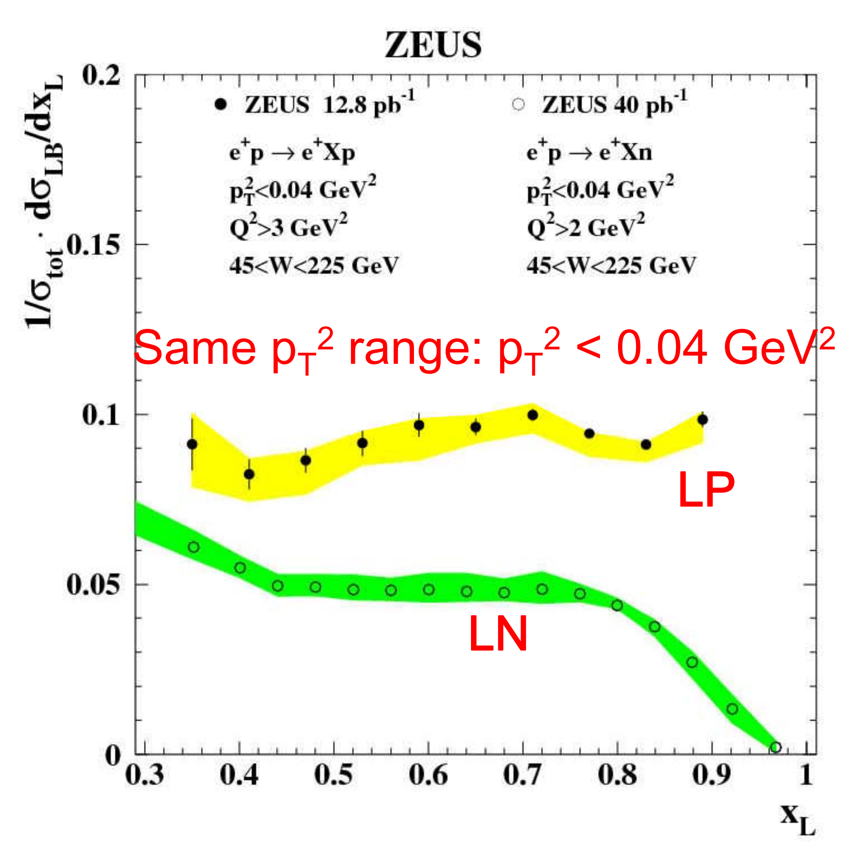
Depletion at large p_T

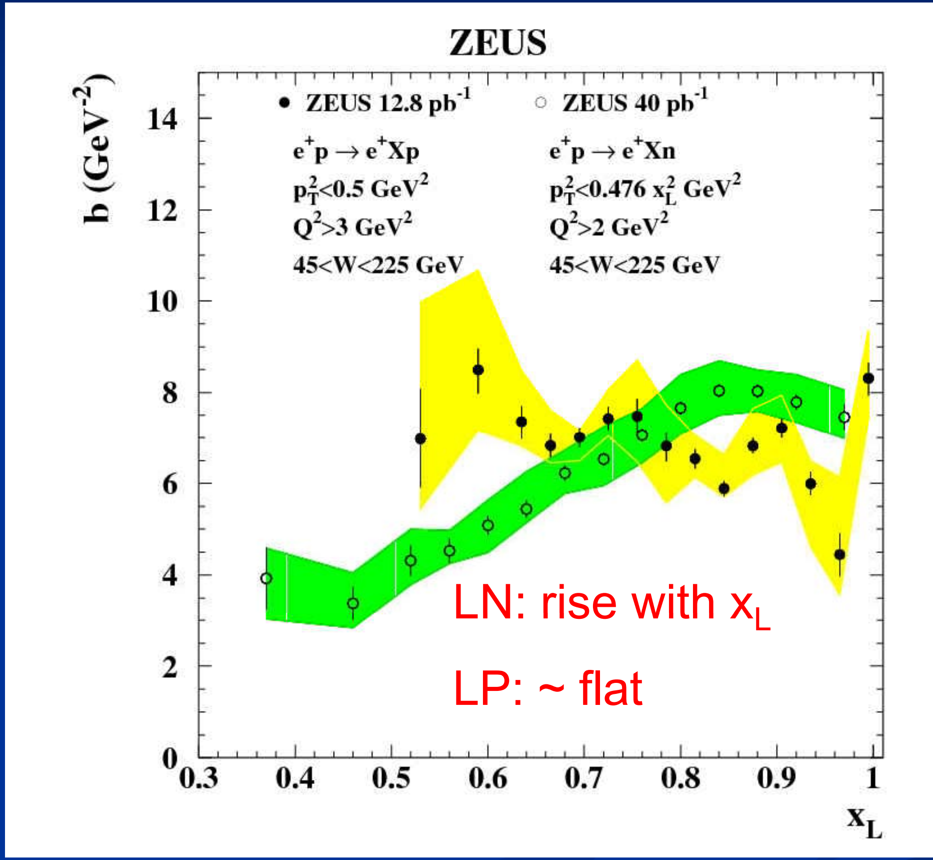


Consistent with vertex factorization violation from absorption:

- more absorption at small $r_{\pi n}$ → large p_T
- loss of LN at high p_T → larger slope

Comparison LP - LN



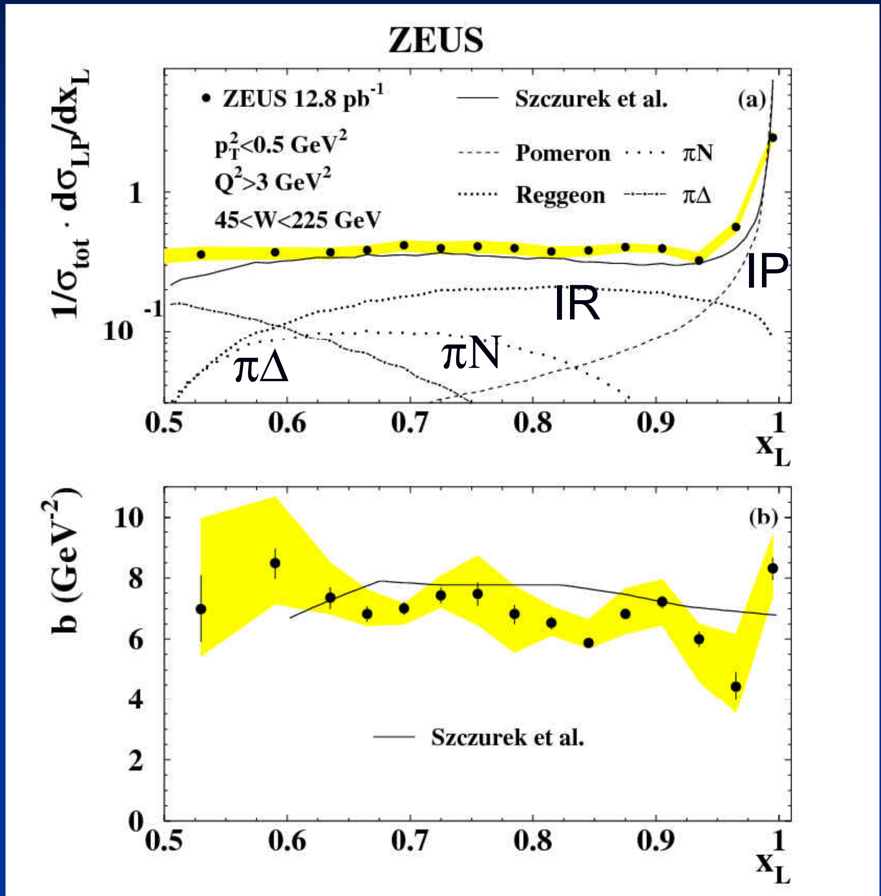


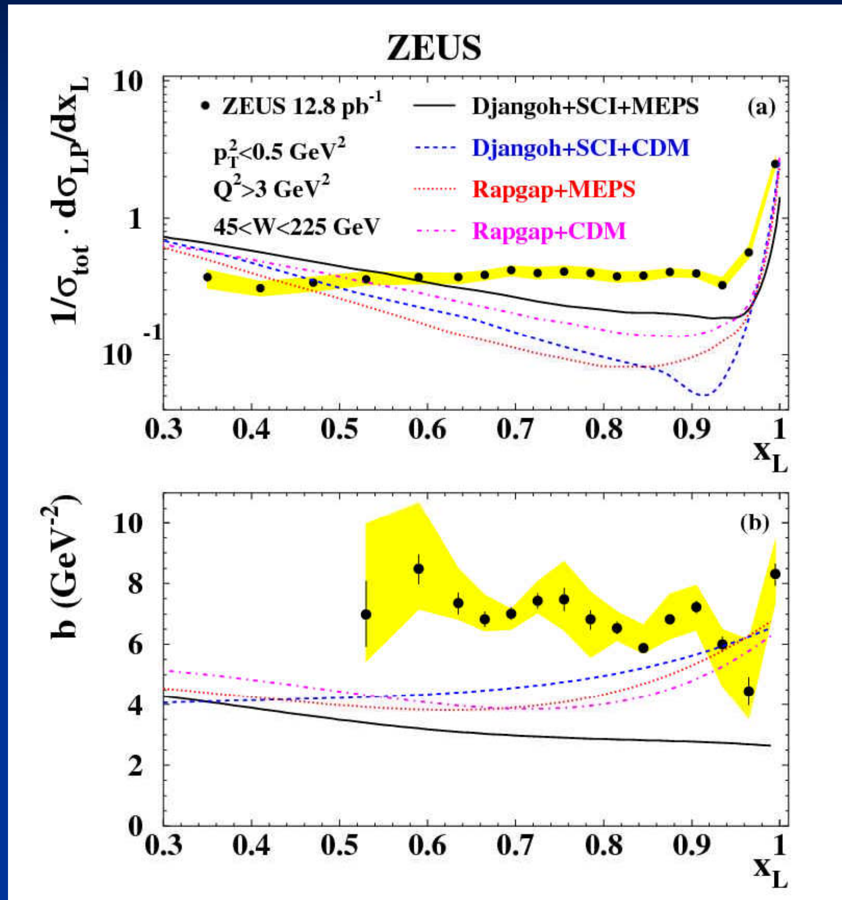
Pure isovector exchange: LP = ½ LN
➔ Other IR contributions in LP

Similar slopes in $0.7 < x_L < 0.85$

Comparison to models

Leading Protons



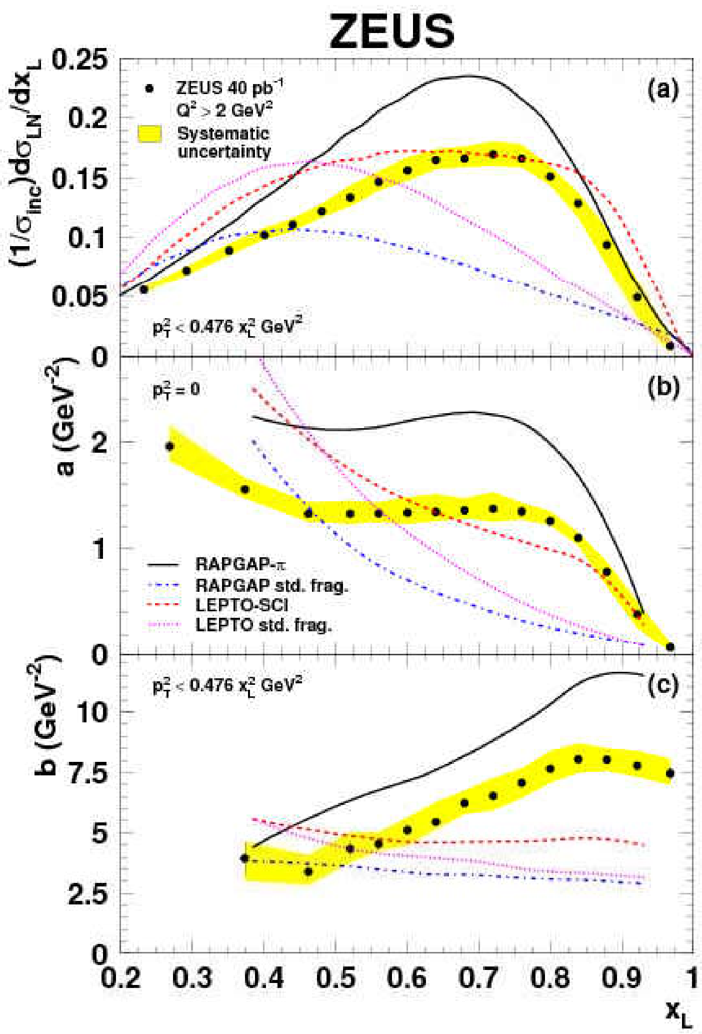


Reasonable description by π, IR, IP exchange model

Standard fragmentation MC models fail to describe the data

DJANGOH+SCI+MEPS ~ ok $b(x_L)$ shape

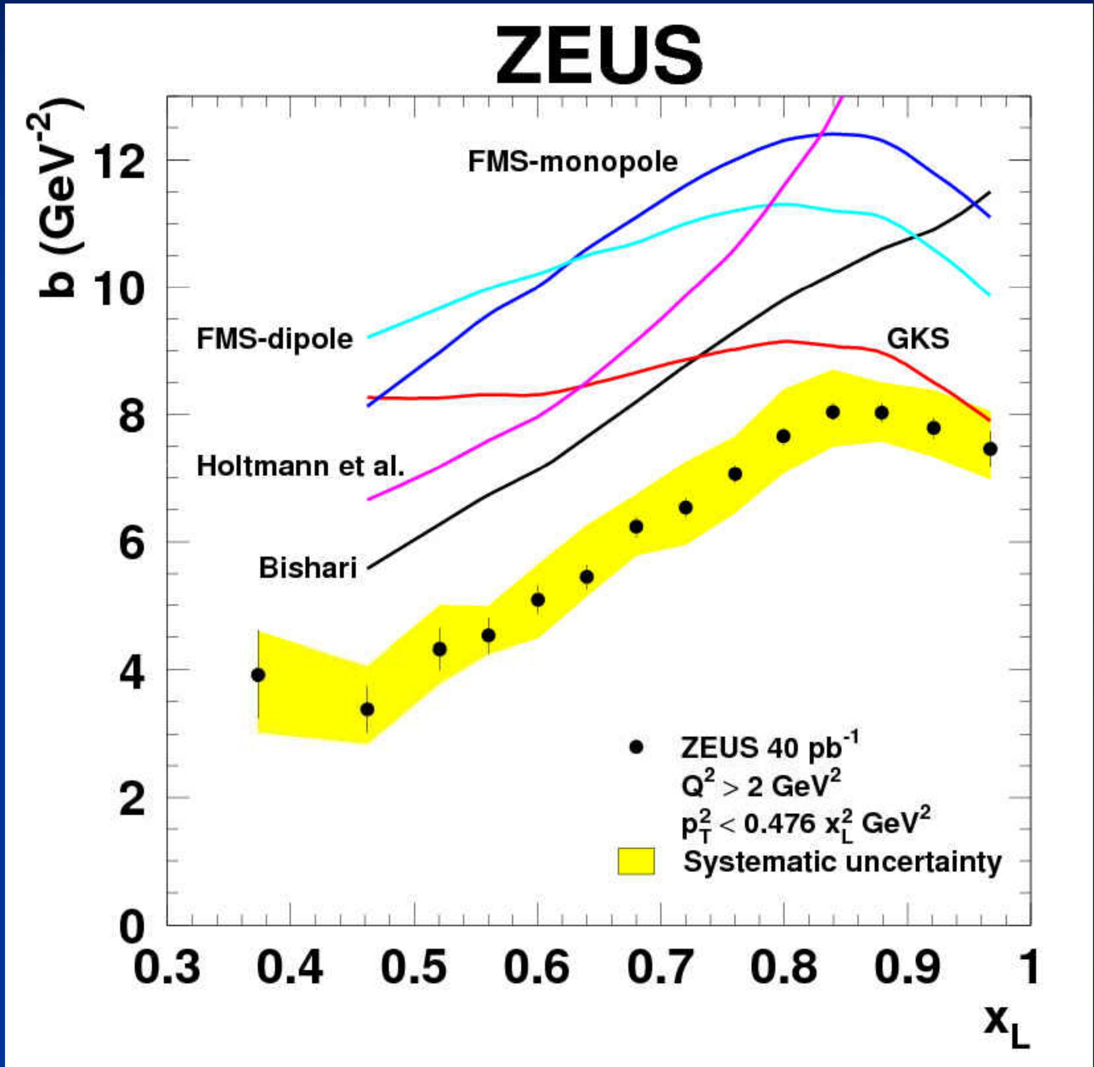
Leading neutrons



MC models generally fail to fully reproduce the data

- Shapes ~ ok by RAPGAP with standard fragmentation + π-exch.
- LEPTO+SCI: x_L shapes ~ ok, not slopes

One-Pion Exchange Models



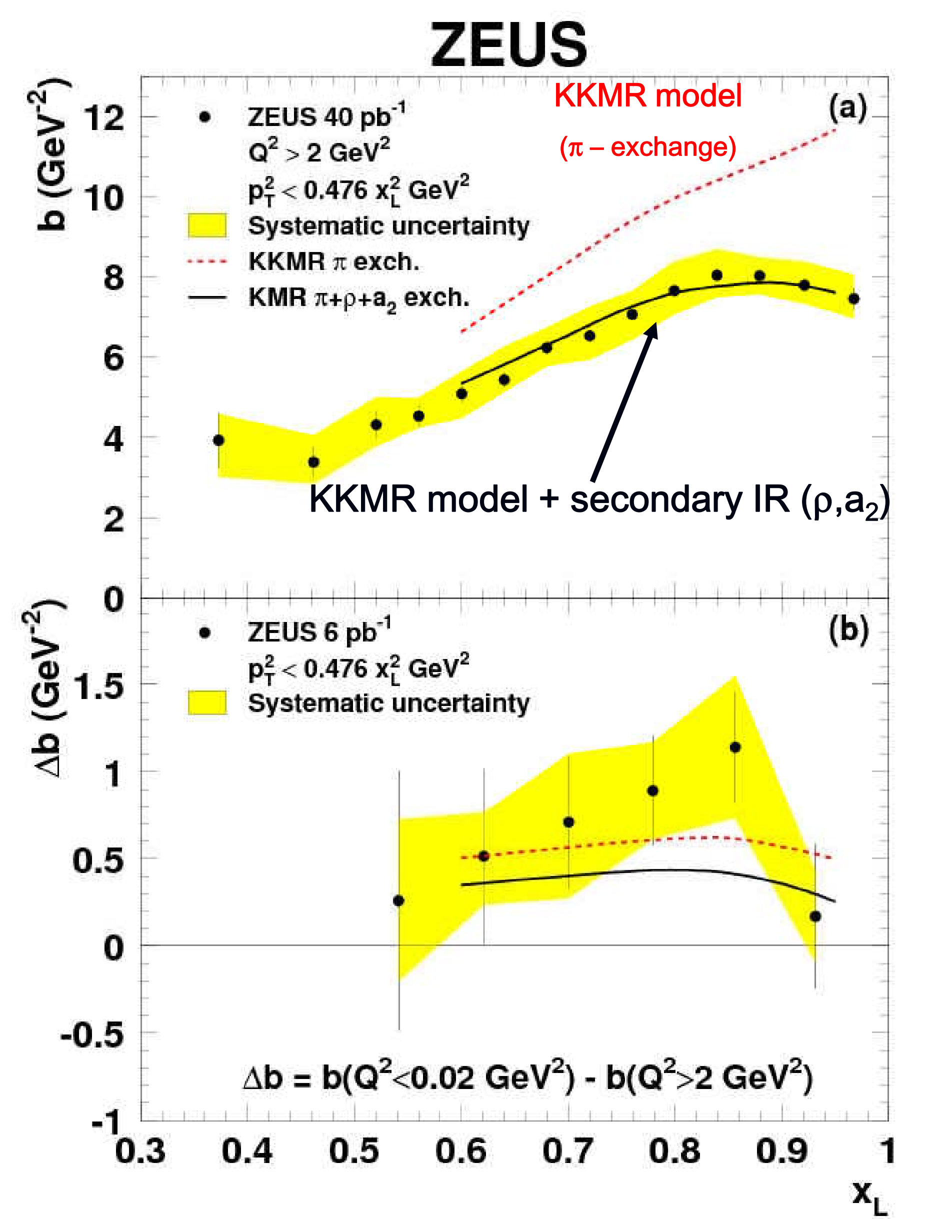
$$\frac{d\sigma_{ep\to enX}}{dx_L dp_T^2} = f_\pi(x_L, p_T^2)\times\sigma_{e\pi}(s_{e\pi})$$

$$f_\pi \propto \frac{-t}{(t-m_\pi^2)}(1-x_L)^{1-2\alpha(t)}[F(x_L,t)]^2$$

Models differ by α and F

Reasonable agreement in shape, not in rate

Slopes - DIS

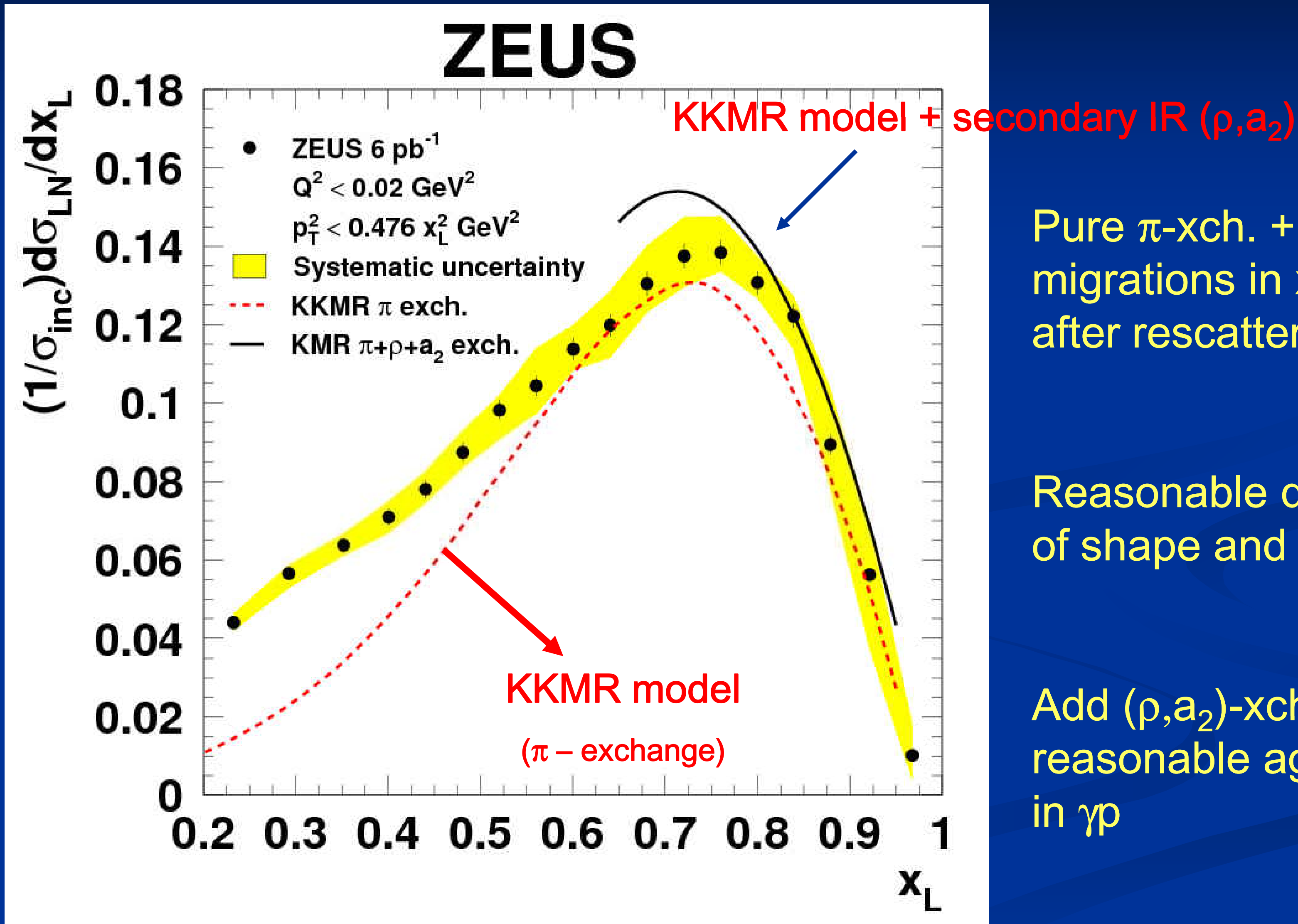


KKMR model

Absorption & migration included in the predictions: not sufficient to describe the slopes

Good description of data when additional IR included

X_L - γp

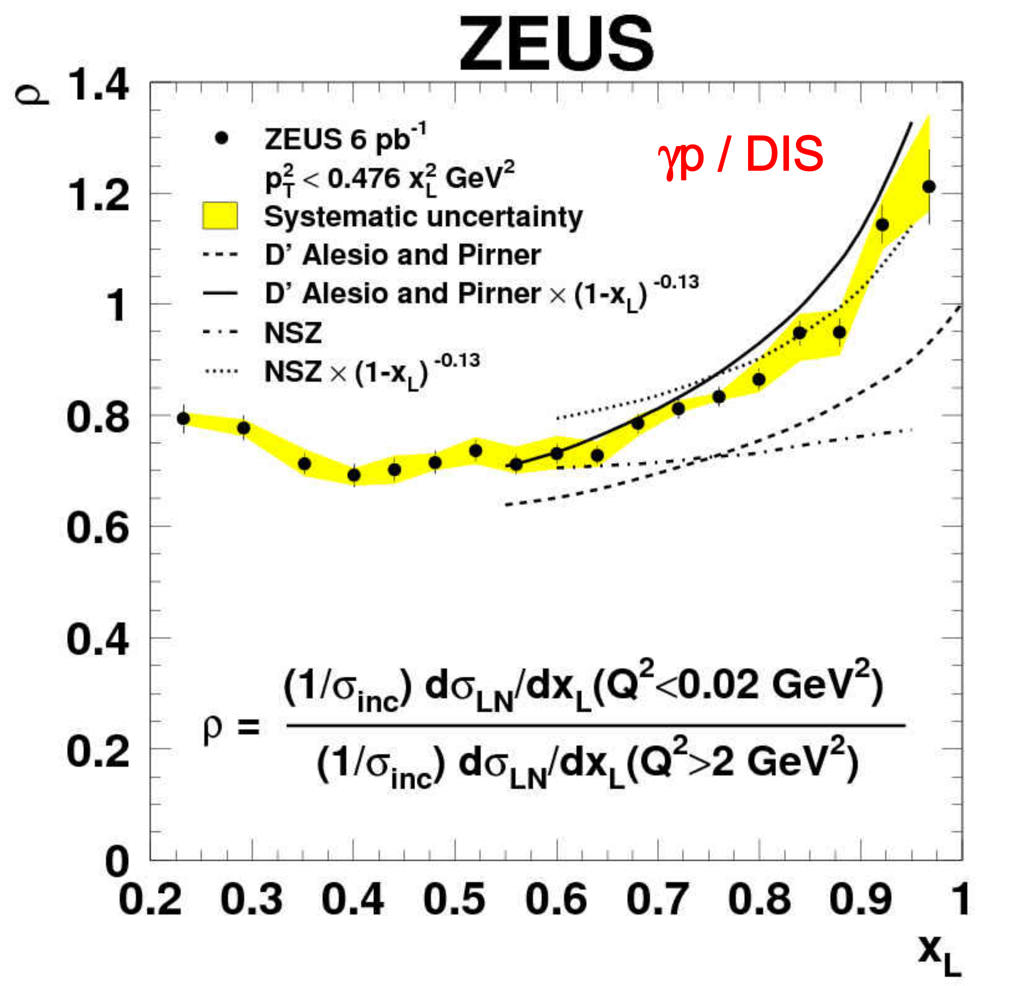


Pure π-xch. + inclusion migrations in x_L and p^2_T after rescattering

Reasonable description of shape and normaliz.

Add (ρ,a_2)-xch: again reasonable agreement in γp

Comparison DIS - γp



Models: OPE + absorption

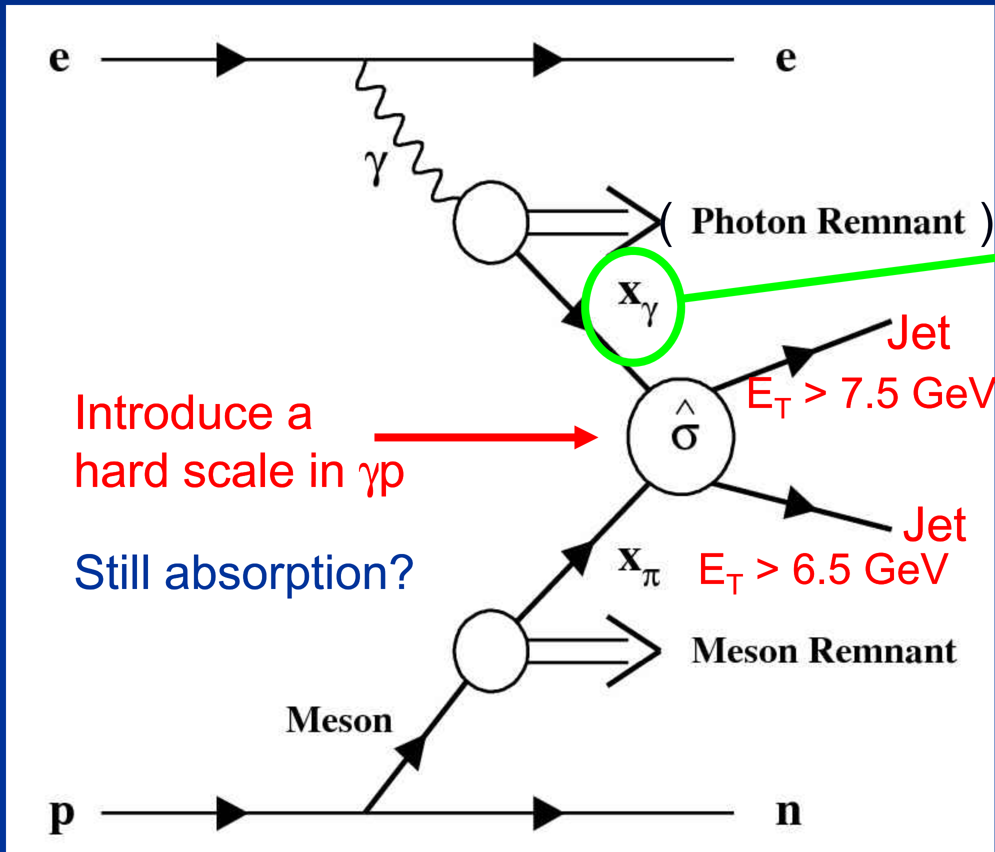
$$\sigma_{\gamma\pi} \propto s_{\gamma\pi}{}^{\lambda} = [(1-x_L)\times W_{\gamma p}{}^2]^{\lambda}$$

$$\frac{\sigma_{\gamma\pi}}{\sigma_{\gamma^*\pi}} = (1-x_L)^{\Delta\lambda} = (1-x_L)^{-0.13}$$

(different cms energy dependence)

Good agreement with the data

Leading n in γp + dijets



Absorption effects seen going from hard → soft scale

High Q^2 → Low Q^2 → γp

Photon momentum fraction that enters in the hard scattering

$x_\gamma = 1$ direct PHP, DIS

$x_\gamma < 1$ resolved PHP

(hadron-like photon)

$$x_\gamma^{obs} = \frac{\sum_{jet1,2} E_T e^{-\eta}}{(E - p_z)_{had}}$$

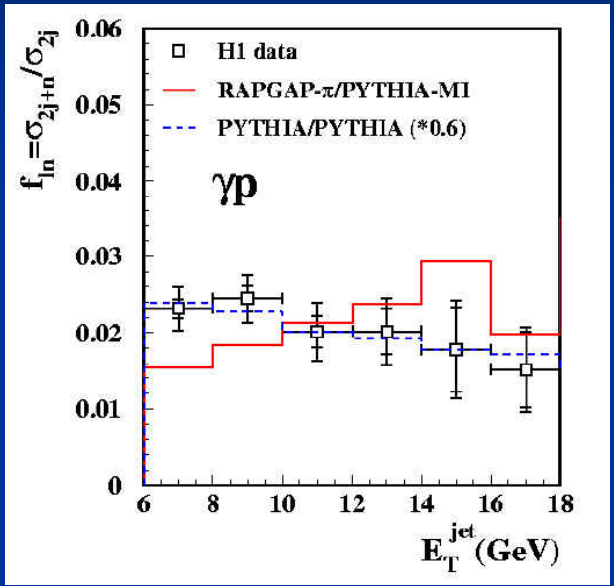
Factorization tests $\frac{\sigma_{2j+n}}{\sigma_{2j}}$

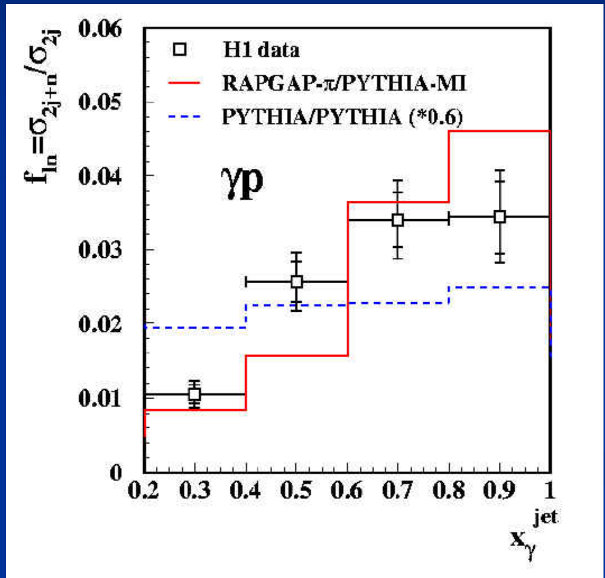
H1-DATA - (Eur. Phys. J. C41 (2005) 273-286)

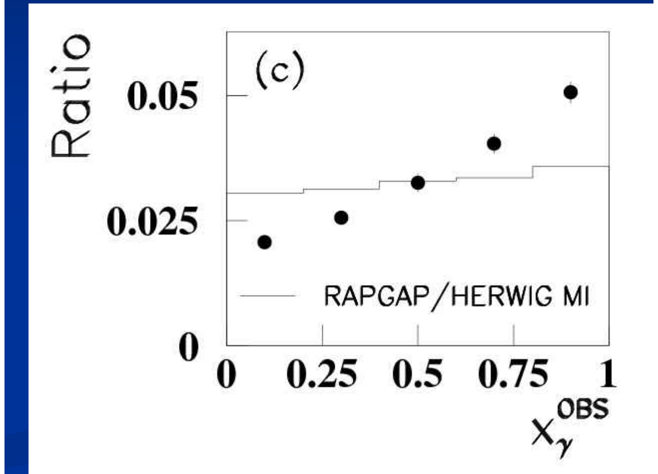
RAPGAP/PYTHIA-MI

ZEUS-DATA - Nucl.Phys.B596,3(2001)

RAPGAP / HERWIG MI



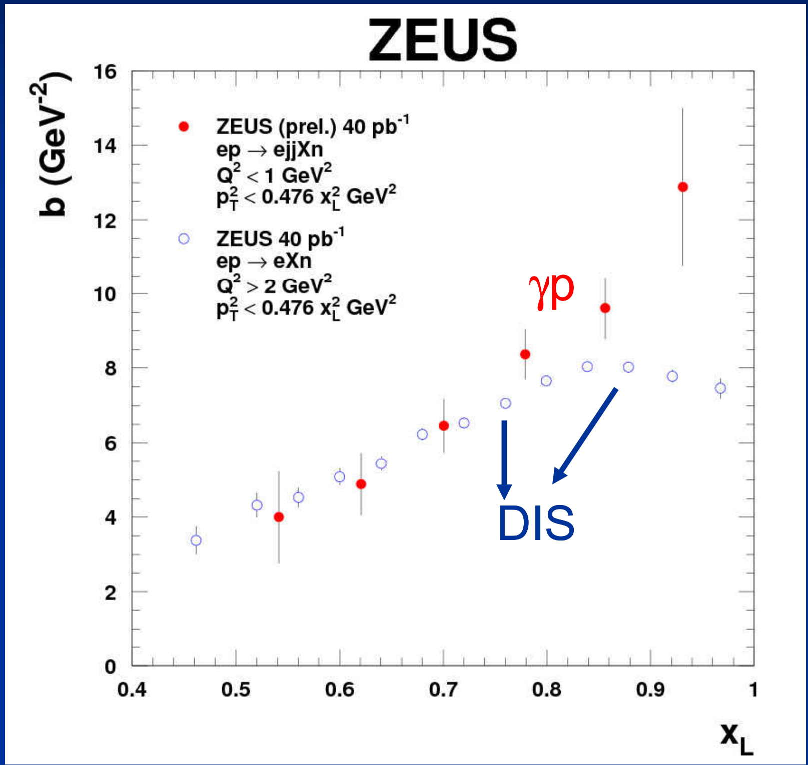


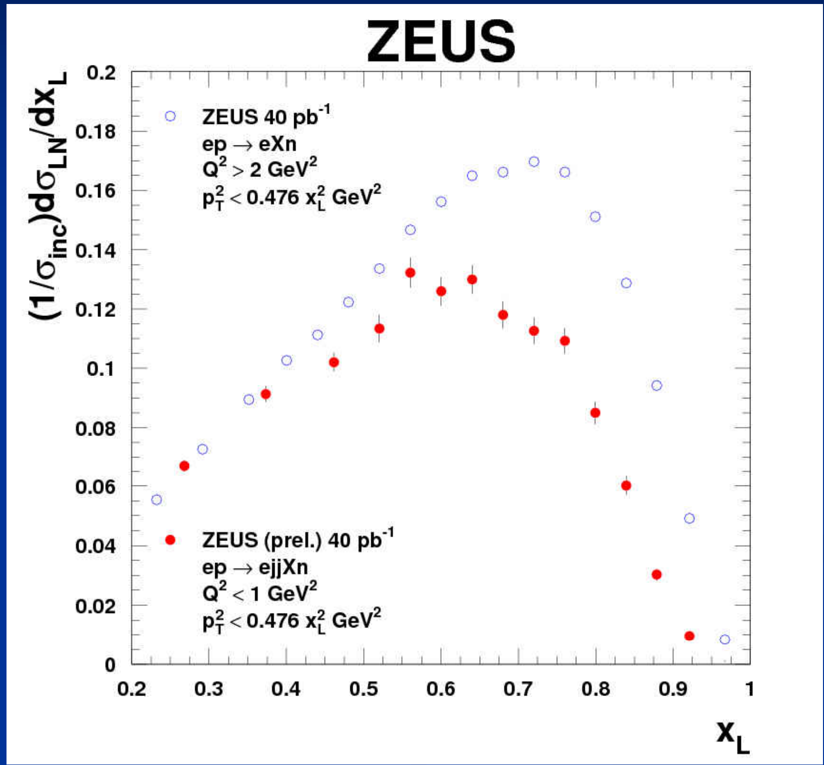


- Ratio almost independent on E_T^{jet}: factorization
- Strong dependence on x_γ: breaking of factorization
- Fewer neutrons in the resolved region

Not yet conclusions on factorization breaking in resolved γp (x_γ<1)

LN+jj (γp) vs LN (DIS)





b-slopes similar in magnitude and shape in DIS and γp+dijet

→ Same production mechanism

- γp without jets: suppression at low x_L
- γp with jets: suppression at high x_L

Not yet firm conclusions on absorption

Summary

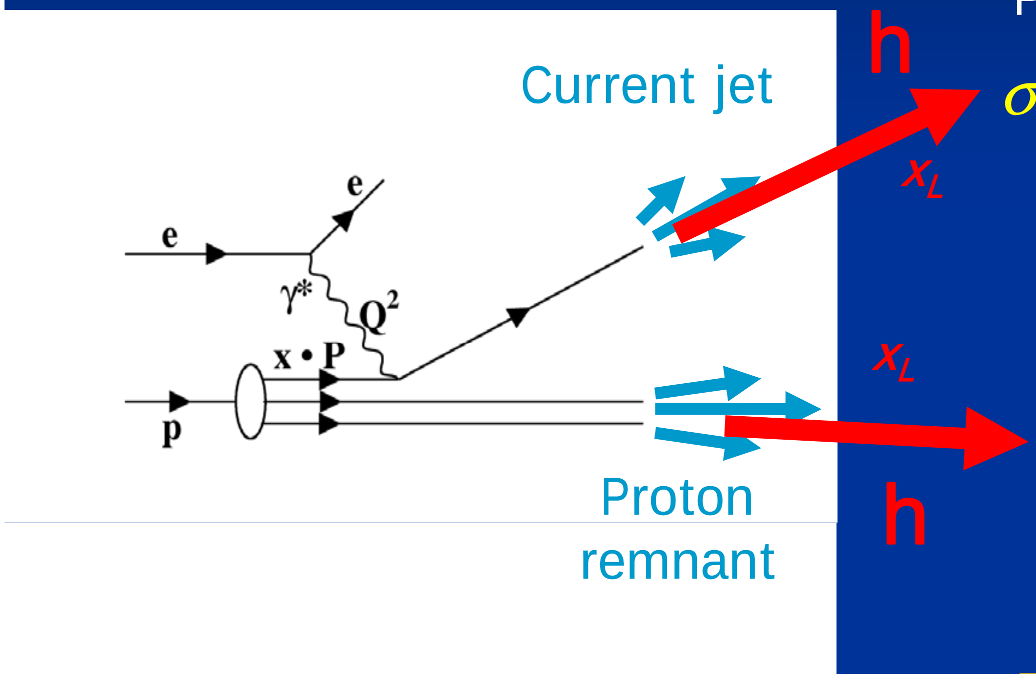
- New data from HERA on LB production and properties, new ZEUS LP results
- Observation of factorization breaking effects going from hard to soft scales, mostly in LN
- γp + hard jets: more work needed
- LP needs isoscalar-IR contributions to explain the data
- Standard fragmentation MC-models fail to describe the data
- Improvement in MC models with particle-exchange implemented
- LN: pure π exchange not sufficient (slopes not described)
- Recent calculations with π exchange and absorption/migration effects improve the agreement in magnitude and shape of the x_L spectra
- Additional exchanges (ρ, a_2) improve further

Additional slides

Fracture Functions approach

L.Trentadue, G.Veneziano

Phys. Lett. B323, 201 (1994)



Production in the current region

$$\sigma_{current} \propto \sum_q c_q f_{q/p}(x) D_{h/q}(x_L)$$

Fragmentation function

Production in the target region: F.F.

$$\sigma_{target} \propto \sum_q c_q (1-x) M_{q,h/p}[x,(1-x)x_L]$$

Fracture function

$$\sigma = \sigma_{current} + \sigma_{target}$$

Dynamical models allow to link them to concepts like structure-functions of exchanged objects (e.g. IR trajectories)

- F.F. are non-perturbative universal functions

- Q^2 dependence governed by evolution equations