Leading Baryons at HERA

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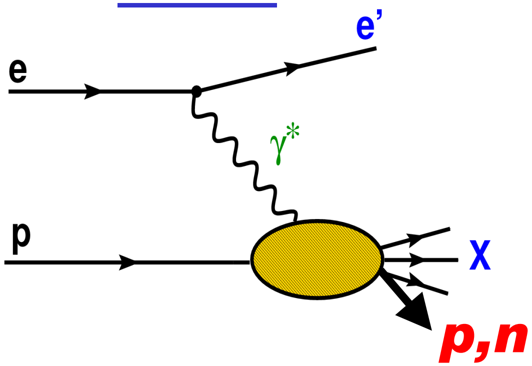
On behalf of the ZEUS and H1

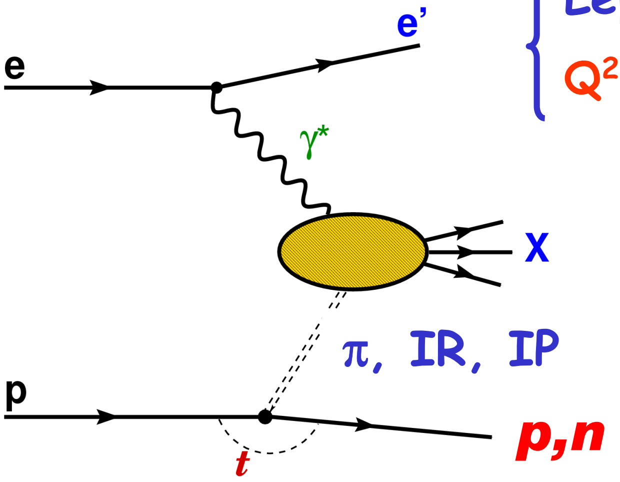
- Introduction and models
- Data sets
- LB normalized cross sections in DIS and γp
- LN + dijets in γp
- Comparisons with models
- F_2^{LB} and pion structure function
- Summary

Legenda: LP = Leading Proton
LN = Leading Neutron
LB = Leading Baryon
OPE = One Pion Exchange
γp = photoproduction

Introduction

- Events with LB are a large fraction of the HERA cross-section
- Production mechanism is still unclear
- Models:





Lepton variables:
Q^2, W, x, y

LB variables:
$x_L = E'_{LB}/E_p$
$t = (p-p')^2$

Standard fragmentation

- LB from hadronization of p remenant
- "standard" MC generators

Virtual particle exchange

- LP: neutral iso-scalar iso-vector (π, IR, IP)
- LN: charged iso-vector (π^+, ρ^+, a^+ ...)
- In the dominant process (e.g. OPE) cross section factorizes

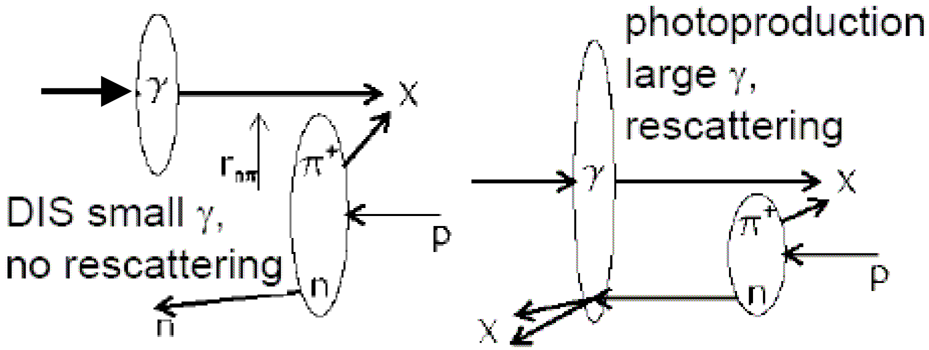
$$d\sigma(\gamma^* p \to nX) = f_{\pi/p}(x_L, t)\, d\sigma(\gamma^* \pi \to X)$$

⇒ LB production independent on photon vertex

⇒ probe structure function of the exchanged particle

- Models predict factorization violation (absorption)

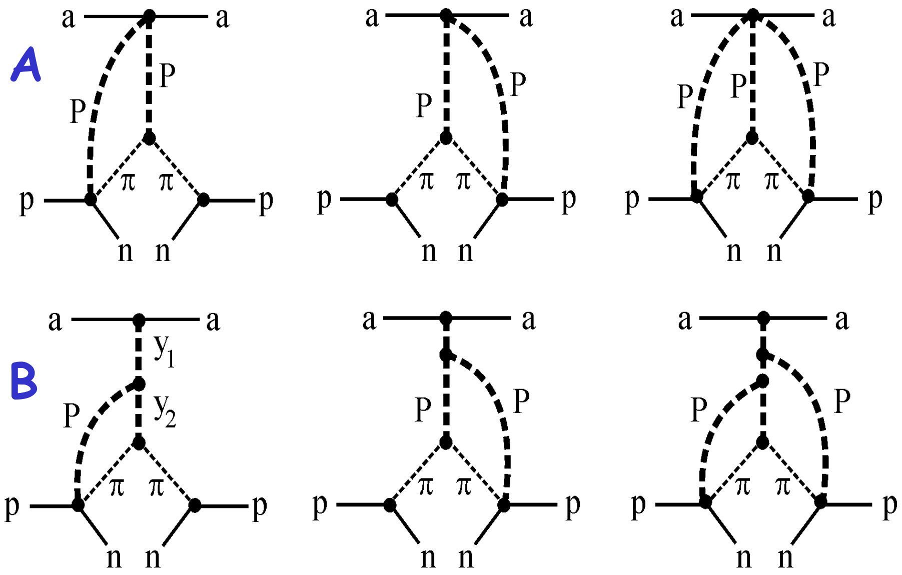
Absorption models: LN via π exchange



d'Alesio and Pirner, EPJ A7 (2000) 109

- the larger the photon, the fewer the n's detected (more absorption in γp than DIS)
- the smaller the nπ system ($r_{n\pi}$), the fewer the n's detected (more absorption at high p_T, low x_L)

Absorption from additional pomeron exchange:
(Nikolaev, Speth, Zakharov, hep-ph/9708290)



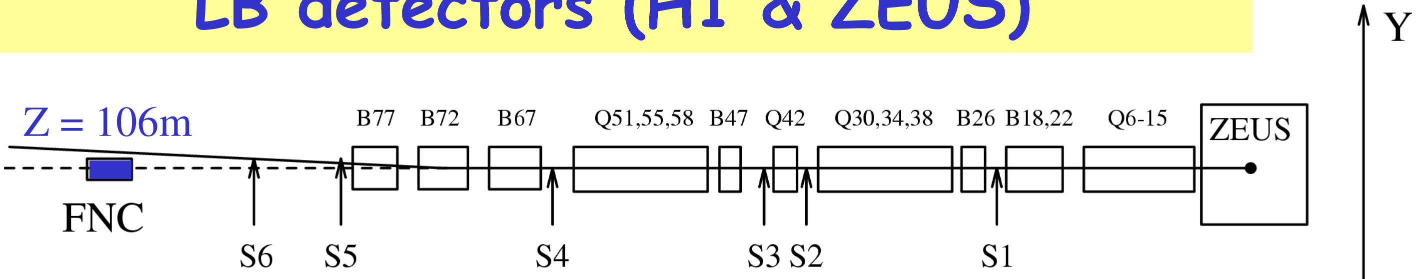
(Kaidalov), Khoze, Martin, Ryskin

EPJ C 47 (2006) 385;

EPJ C 48 (2006) 797;

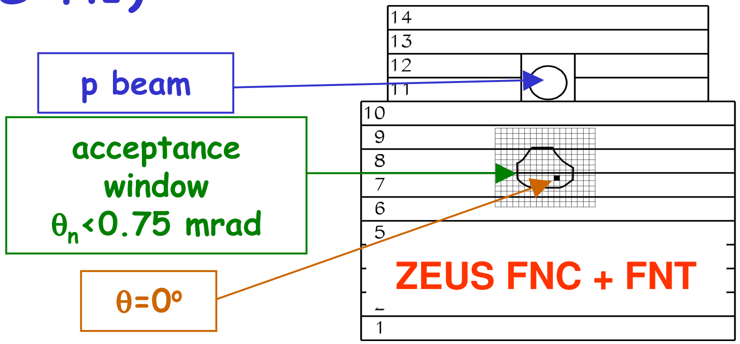
- evaluate correction due to enhanced absorptive diagrams B (~ 15%)
- show importance of distortion of energy spectra (migration) due to rescattering for $x_L < 0.8$
- include effects of ρ, a_2 exchange
- estimate the gap survival factor S^2 (important for LHC!) which takes into account that rescattering may populate the rapidity gap with secondary particles carrying away energy from the leading neutron

LB detectors (H1 & ZEUS)



Forward Neutron Calorimeter

(ZEUS+H1)



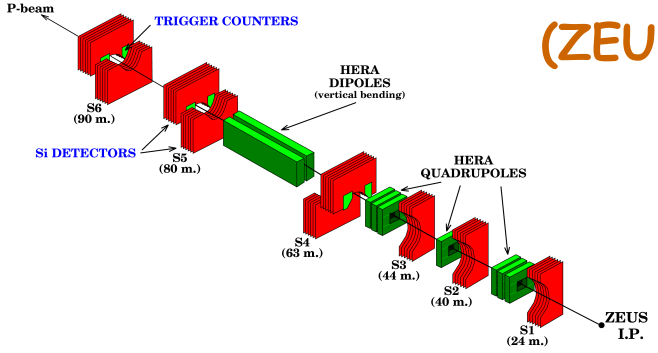
Pb-sci. calorimeters + veto counters @107 m

- $\sigma/E = 70\%/\sqrt{E}$ ($\approx 63\%/\sqrt{E} \oplus 3\%$ for H1)
- e-scale accuracy ± 2% ($\pm$ 20%/$\sqrt{E}$ for H1)
- Position reconstruction accuracy

  $\sigma_{X,Y}$ = 0.23 cm $\Rightarrow$ σ_θ = 22 μrad
- allows to measure neutron p_T

Leading Proton Spectrometer

(ZEUS)



6 stations with μstrip detectors

- hit position resolution ≈ 30 μm

  ⇨ σ_{X_L} < 1%

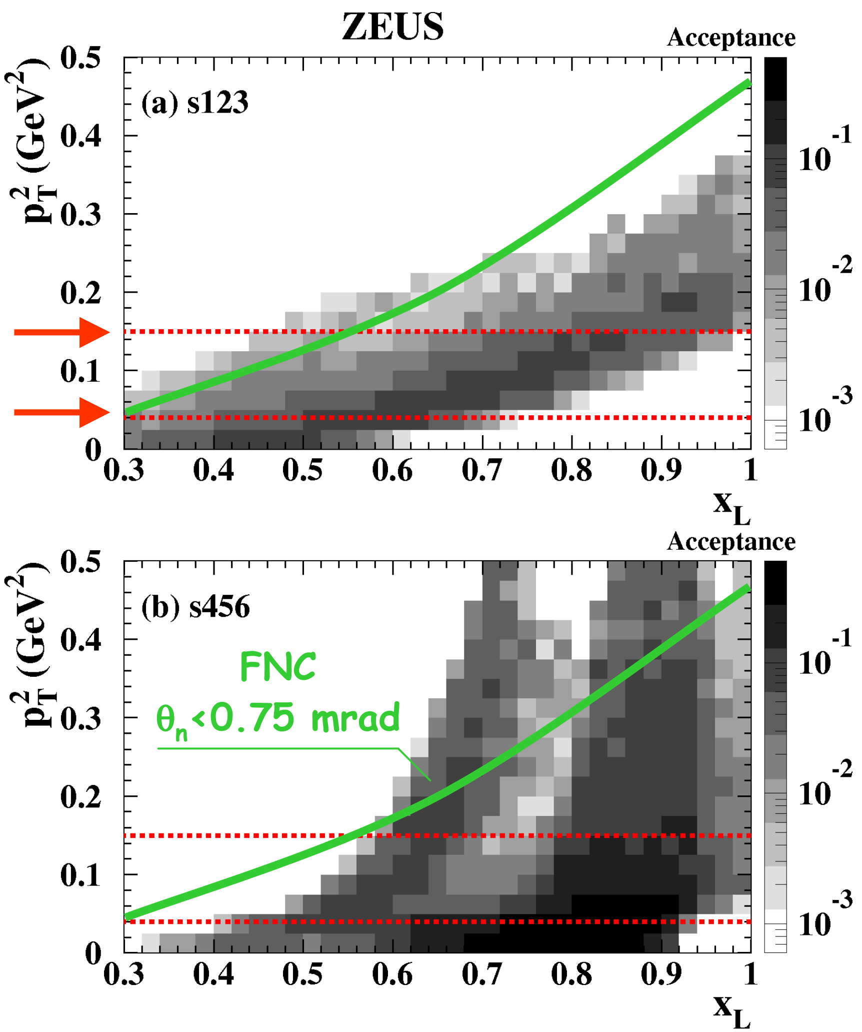
  σ_{p_T}~ few MeV
- momentum accuracy <1%

For both, p_T resolution is dominated by p_T spread of p-beam (50-100 MeV)

LB detectors: acceptance

Limited by beam apertures and detector size (LPS)

Integrating over the azimuth:



LPS:

- s1-s3 and s4-s6 have very little overlap
- p_T range varies with x_L;
- for x_L>0.6, p_T^2<0.5 GeV^2

  acceptance ≈ 15 %

FNC:

- restricted to θ_n<0.75 mrad
- p_T range increases with x_L;
- for x_L>0.6, θ_n < 0.75 mrad

  acceptance ≈ 25 %

Main Issues in LB analyses

- Measure x_L, p_T spectra of LB for various reactions;
- Verify absorption effects and test vertex factorization;
- Compare to hadronization/particle exchange/absorption models
- In LN production, F_2^{LN} and F_2^{π}

In the following:

- **ZEUS**: Leading neutron energy and p_T distributions in DIS and γp at HERA
  (Nucl. Phys. B 776 (2007) 1-37)
- **ZEUS**: Leading proton production in DIS at HERA
  (Submitted for publication)
- **ZEUS**: Measurement of dijet cross section for events with LN in γp at HERA
  (EPS07 #62)
- **H1**: Leading neutron production in DIS at HERA
  (ICHEP08 #864)

DATA Sets

For all samples: neutron: $x_L > 0.2$

$\theta_n < 0.75$ mrad ⇨ $p_T^2 < 0.476\, x_L^2$ GeV^2

proton: $x_L > 0.32$ $p_T^2 < 0.5$ GeV^2

Deep Inelastic Scattering (DIS): 40 pb^{-1}, $Q^2 > 2$ GeV^2 (ZEUS, LN)

12.8 pb^{-1}, $Q^2 > 3$ GeV^2 (ZEUS, LP)

122 pb^{-1}, $Q^2 > 6$ GeV^2 (H1, LN) ⇦ HERAII

Photoproduction (γp): 6 pb^{-1}, $Q^2 < 0.02$ GeV^2

Dijets in photoproduction: 40 pb^{-1}, $Q^2 < 1$ GeV^2, $130 < W < 280$ GeV

$E_T^{jet1} > 7.5$ GeV, $E_T^{jet2} > 6.5$ GeV

$-1.5 < \eta^{jet1,2} < 2.5$

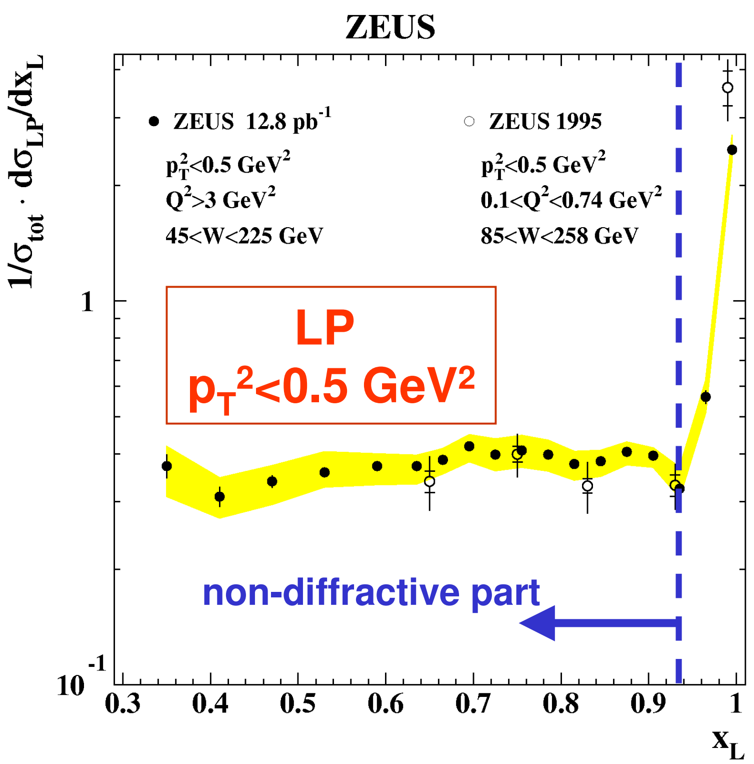
DIS and γp have very different inclusive cross sections σ_{inc}

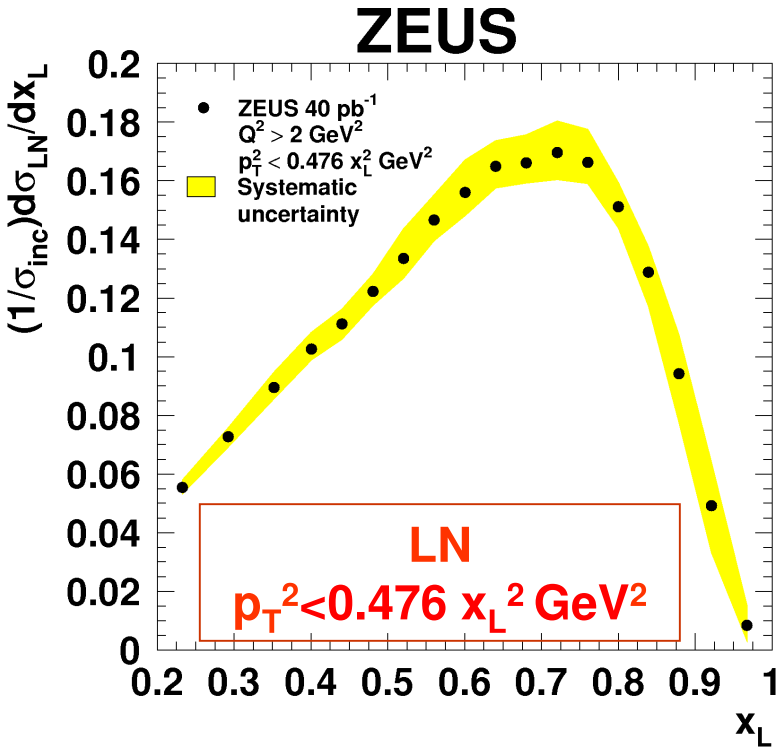
⇨ for sensible comparisons look at σ_{LN}/σ_{inc}

Additional benefit: systematic uncertainties of central detector cancel

DIS: normalized cross sections vs x_L

$d\sigma_{LB}/dx_L$ normalized to the inclusive DIS cross sections



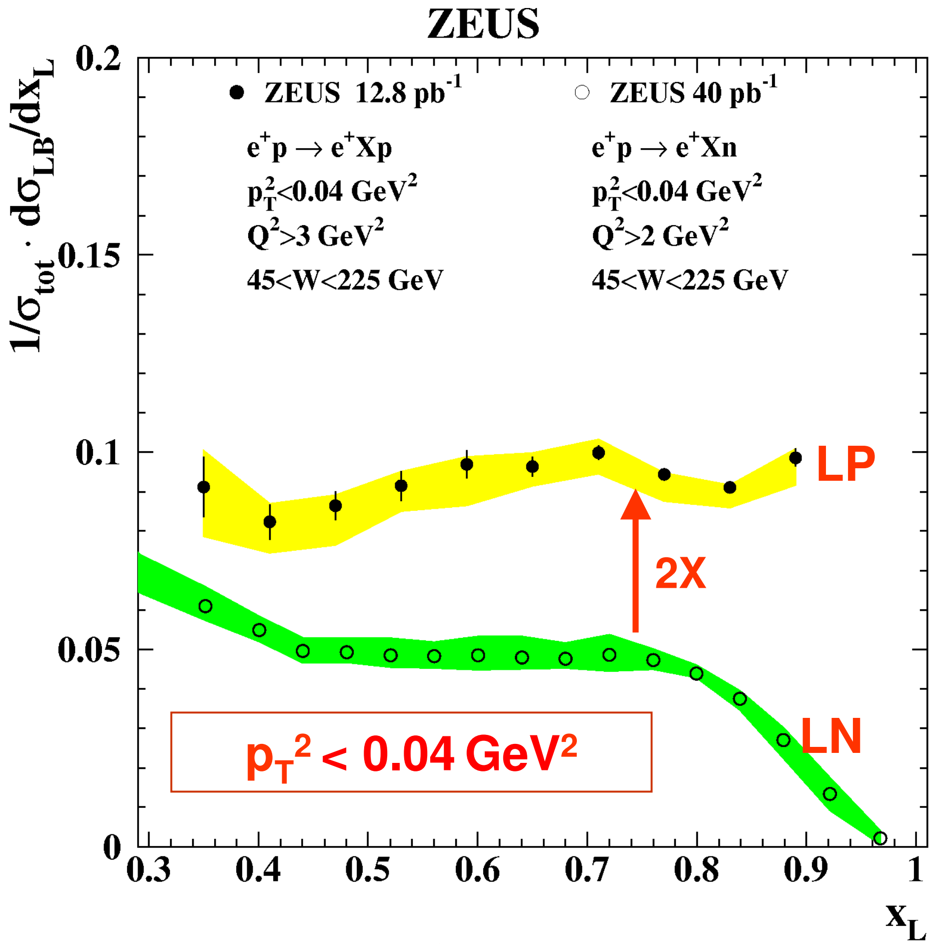


- clear diffractive peak $x_L \to 1$
- proton yield flat below $x_L \approx 0.95$
- consistent with earlier low-Q^2 data

- LN yield → 0 al kinematic limit $x_L \to 1$
- below $x_L \approx 0{,}7$ yield drops due to decreasing of p_T^2 range

DIS: normalized cross sections vs x_L

Comparison LP – LN yields



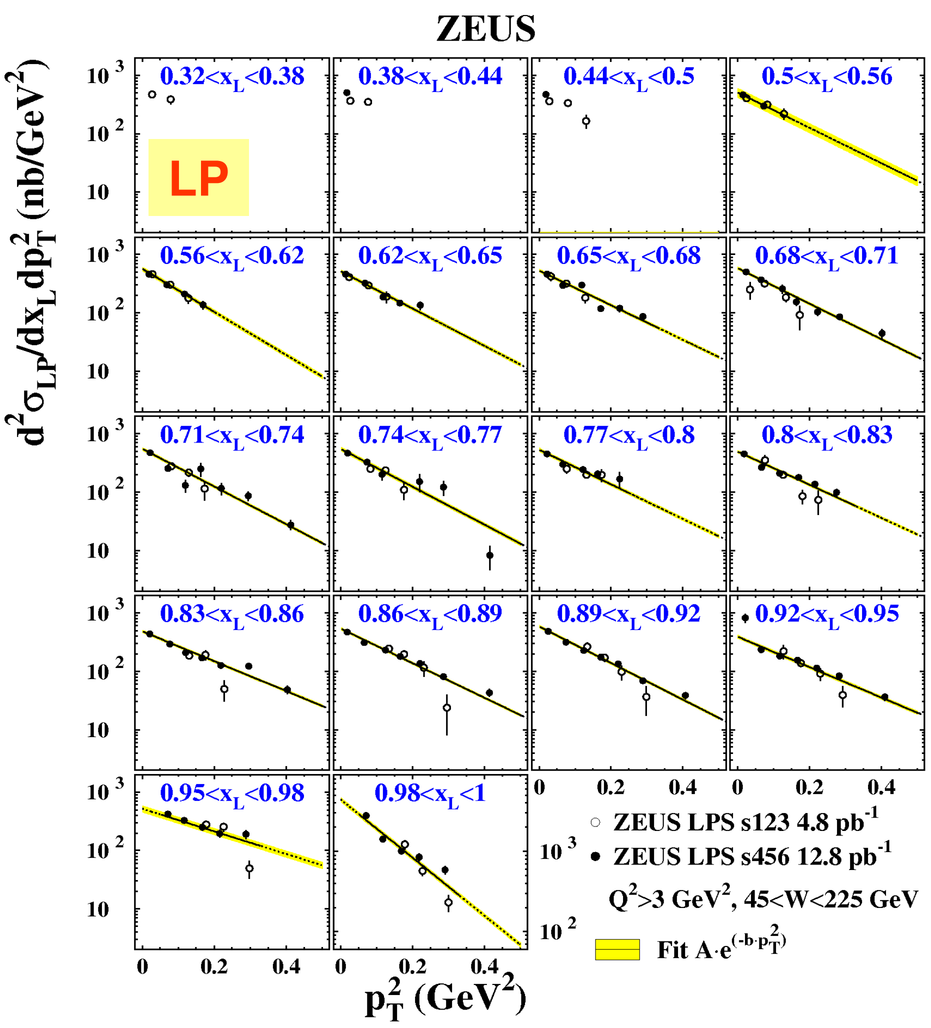
- Restricted to a common p_T^2 range where the detector acceptances overlap
- For pure isovector (e.g. pion) particle exchange one expects

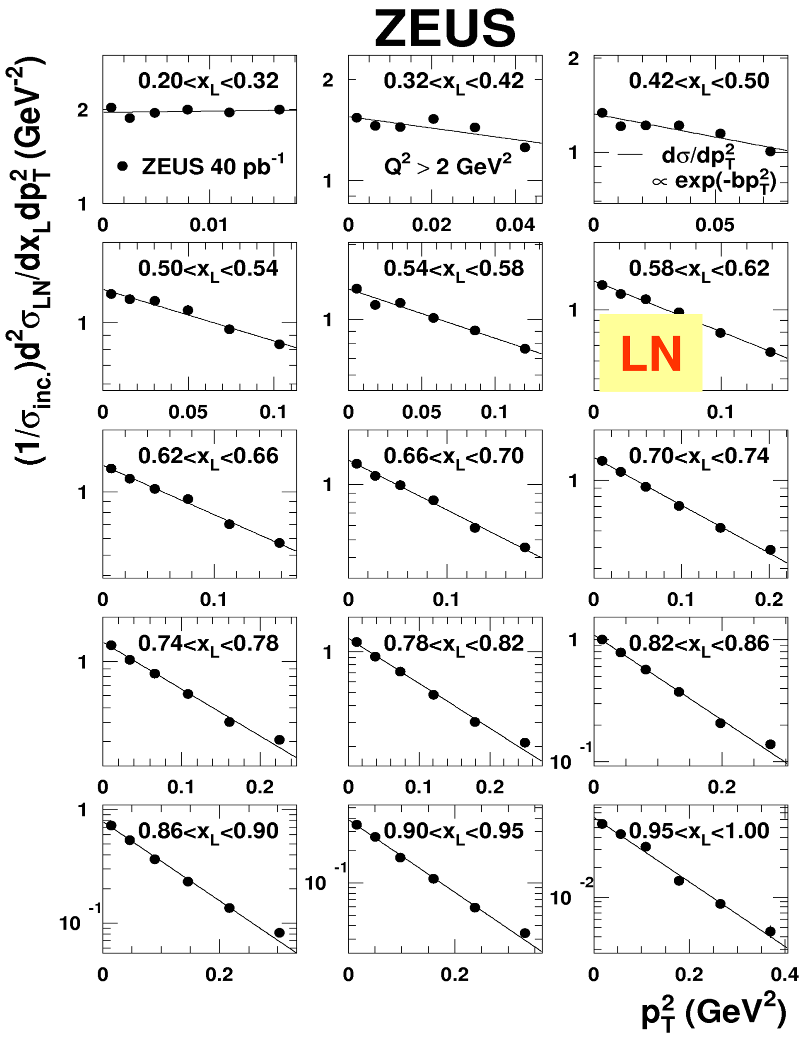
  LP = ½ LN

- data suggest LP ≈ 2 LN

Additional isoscalar exchanges are needed to account for the observed LP rates

DIS: p_T^2 distributions





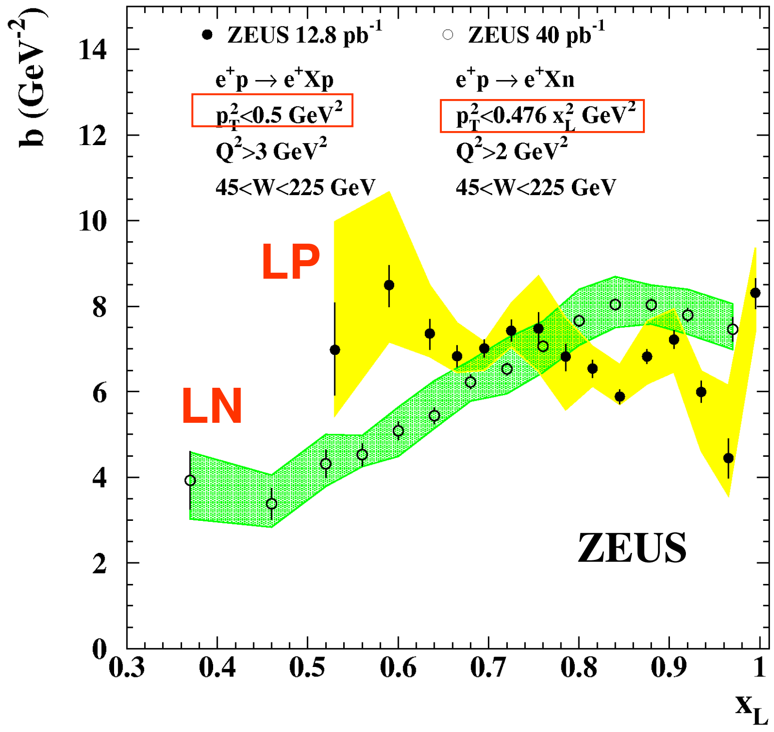
Note: varying p_T^2 ranges

Well described by exponential fall-off in p_T^2 ⇒ intercepts and slopes

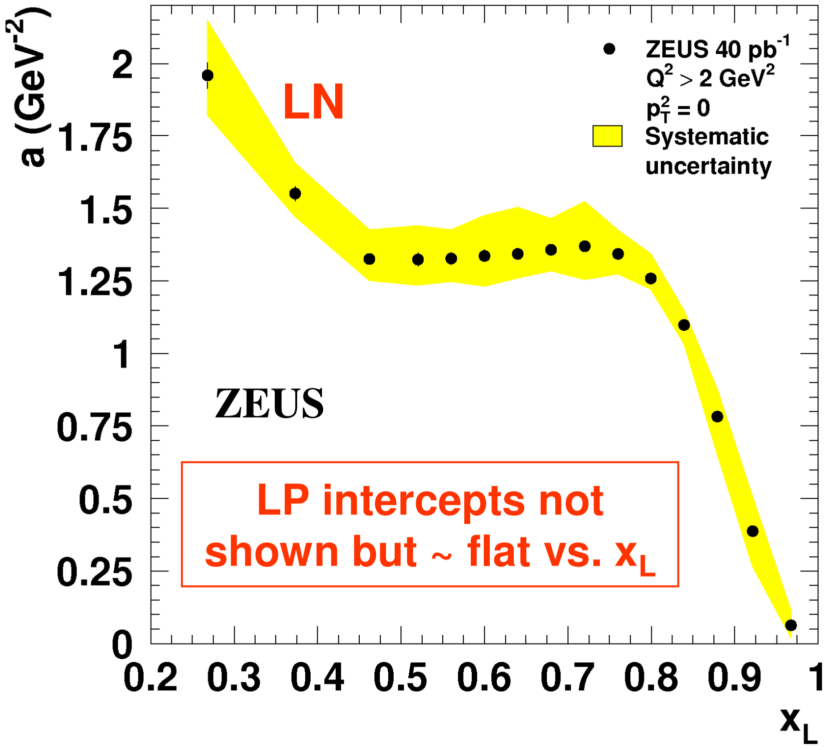
DIS p_T^2 distributions: slopes and intercept

Fit LB data to $$\frac{1}{\sigma_{inc}}\frac{d\sigma_{LB}}{dp_T^2 dx_L} = a(x_L)\, e^{-b(x_L)\, p_T^2}$$

- **slopes $b(x_L)$**



- **intercepts $a(x_L)$**



LP intercepts not shown but ~ flat vs. x_L

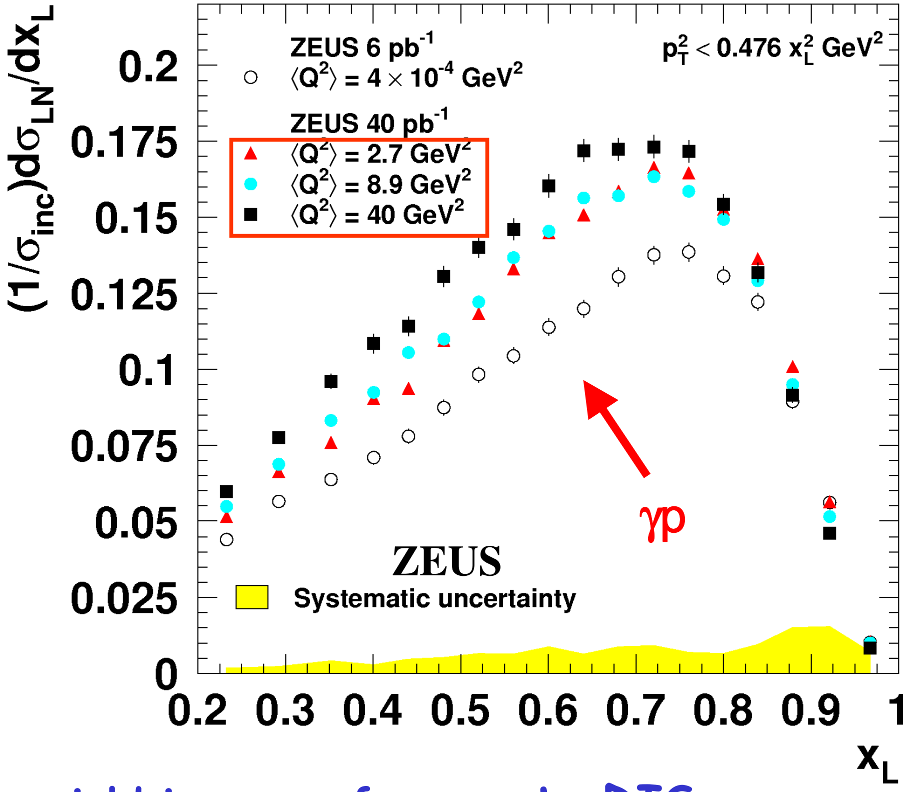
- clear different trends for LP - LN
- similar magnitude for x_L ~ 0,65-0.8 where π exch. dominates

- LN intercepts fall with x_L
- plateau for $0,4 < x_L < 0,8$

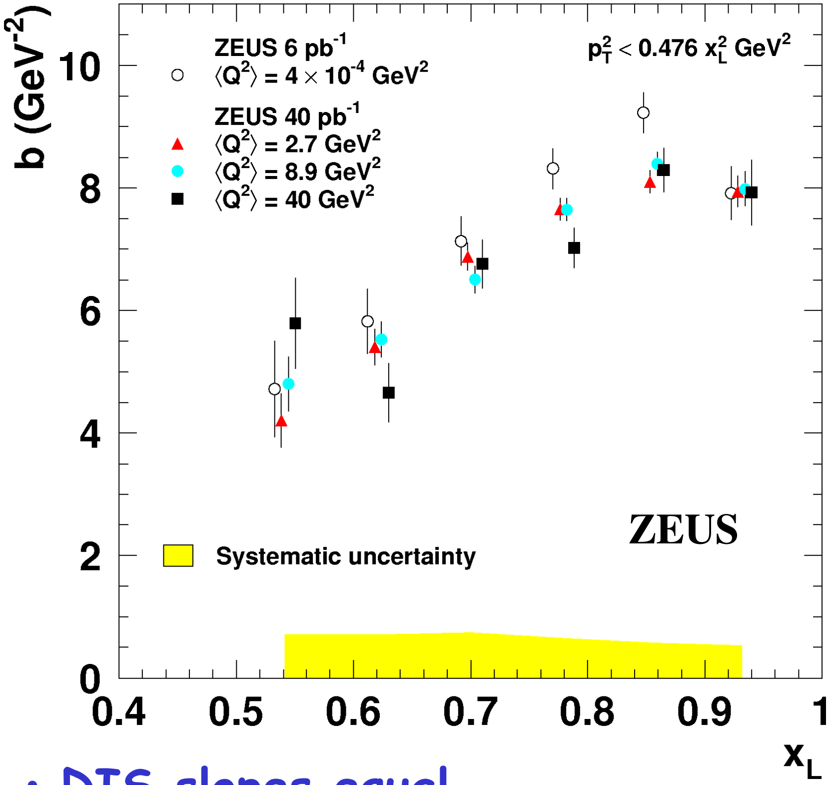
Q^2 dependence: LN production

- DIS (3 Q^2 bins) and γp

x_L distributions



slopes $b(x_L)$



- yield increase from γp to DIS
- small but significant increase from mid- to high-Q^2

- DIS slopes equal
- γp slopes higher for $0,6<x_L<0,9$

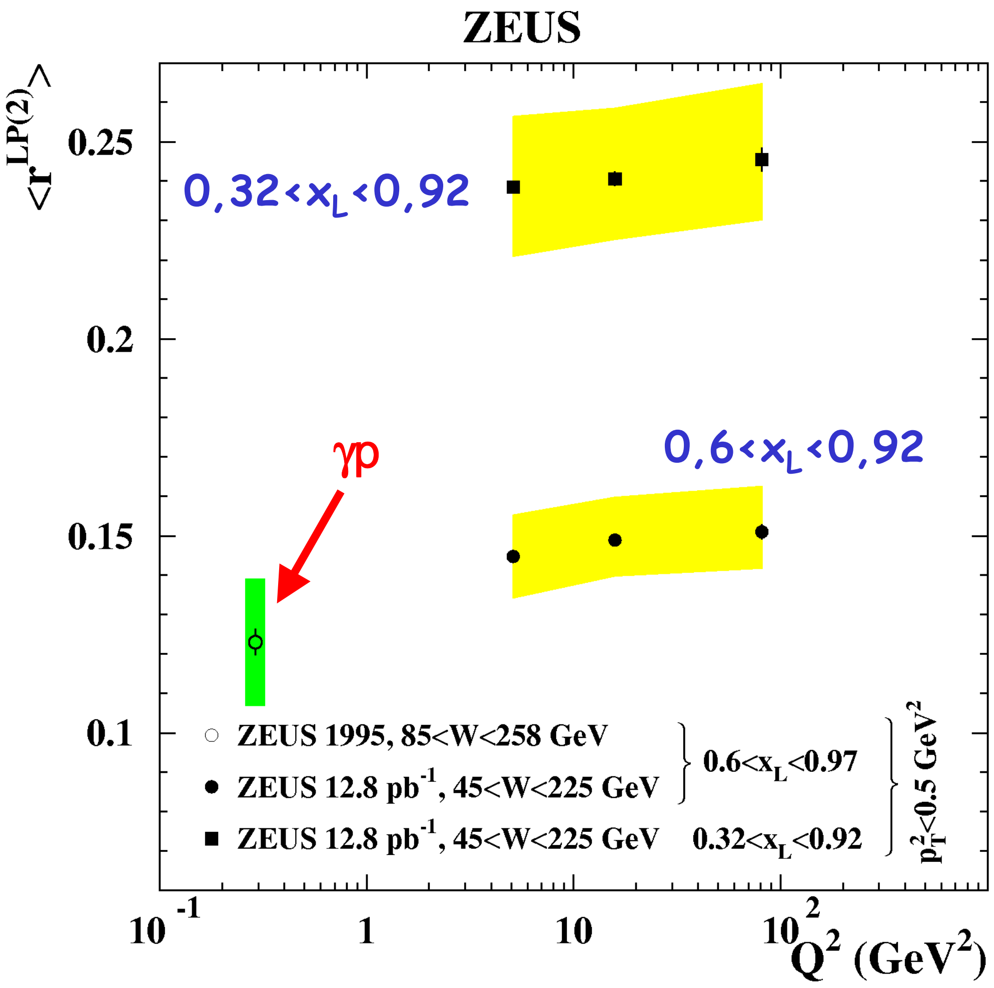
suggests violation of vertex factorization

Q^2 dependence: LP production

Average LP yield vs. Q^2

- $P_T^2 < 0,5$ GeV^2
- 2 different x_L ranges

✓ Steady rise with Q^2 also observed.



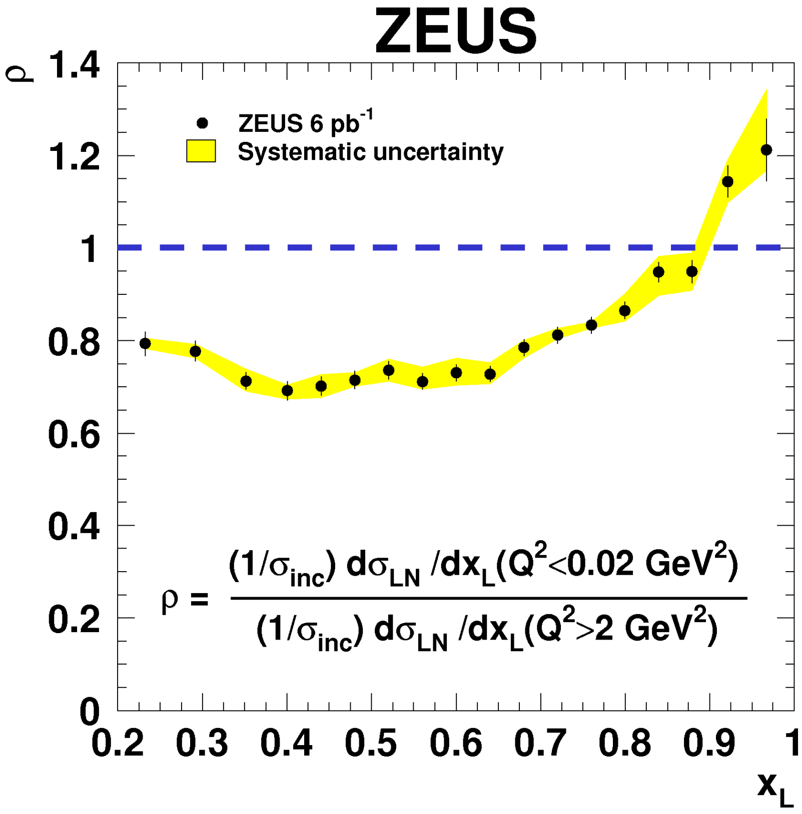
Results shown are consistent with absorptive effects:

smaller Q^2 ⇨ larger γ* transv. size ⇨ more absorption

Comparison γp/DIS: LN x_L spectra

All DIS $Q^2>2$ GeV^2 combined together

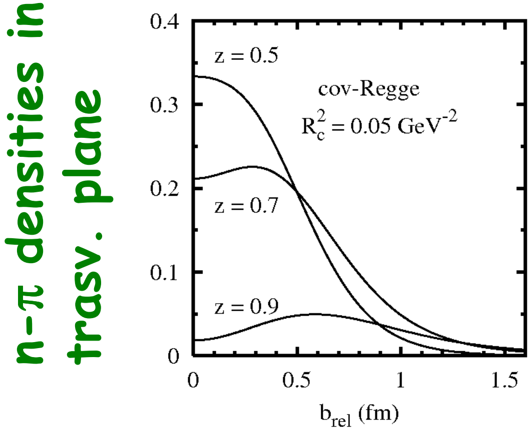
- Ratio γp/DIS LN yields



✓ Ratio rises with increasing x_L

✓ Consistent with absorption picture:

from D'Alesio and Pirner

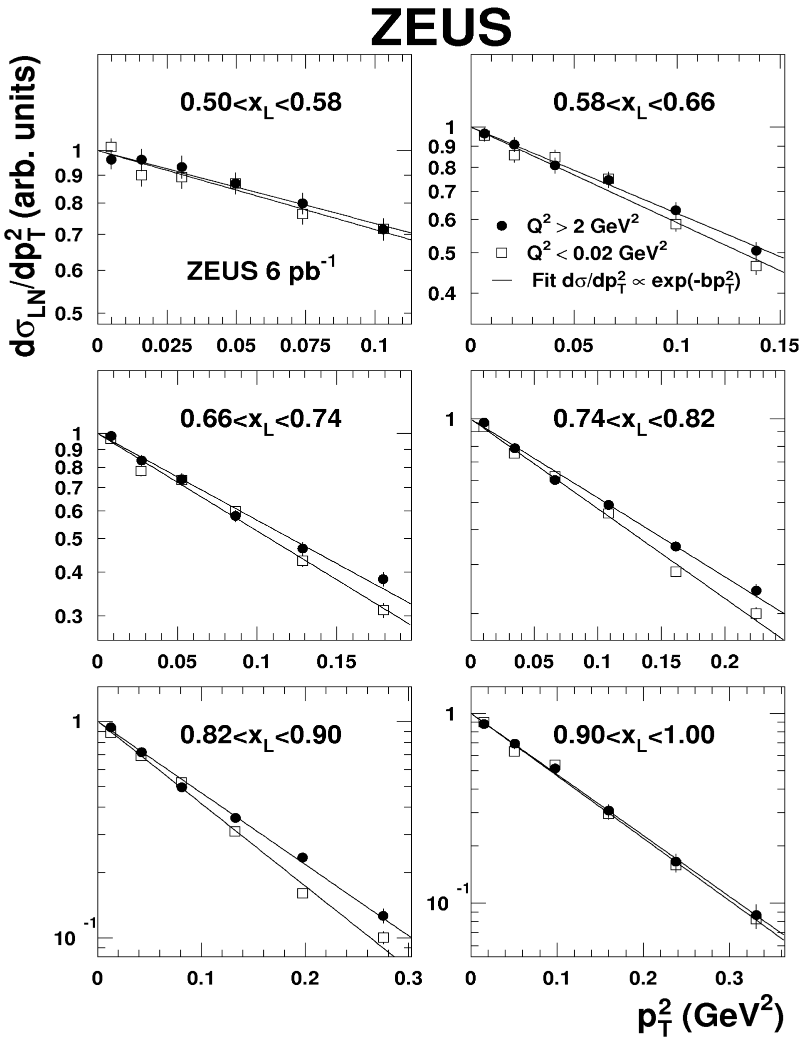


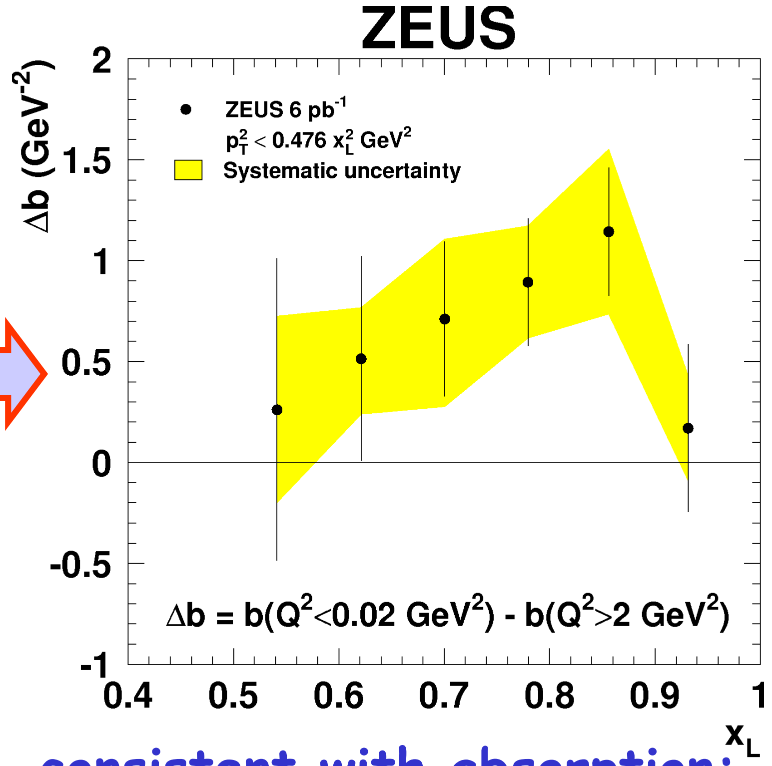
average <u>n-π separation</u> $r_{n\pi}$ increases with x_L

small n-π separation → larger absorption

Comparison γp/DIS: LN p_T^2 distributions

Small but clear slope difference DIS-γp at intermediate x_L





consistent with absorption:

large $p_T \Rightarrow$ small $r_{n\pi} \Rightarrow$ more abs.

⇩

fewer LN at large p_T

⇩

steeper slope

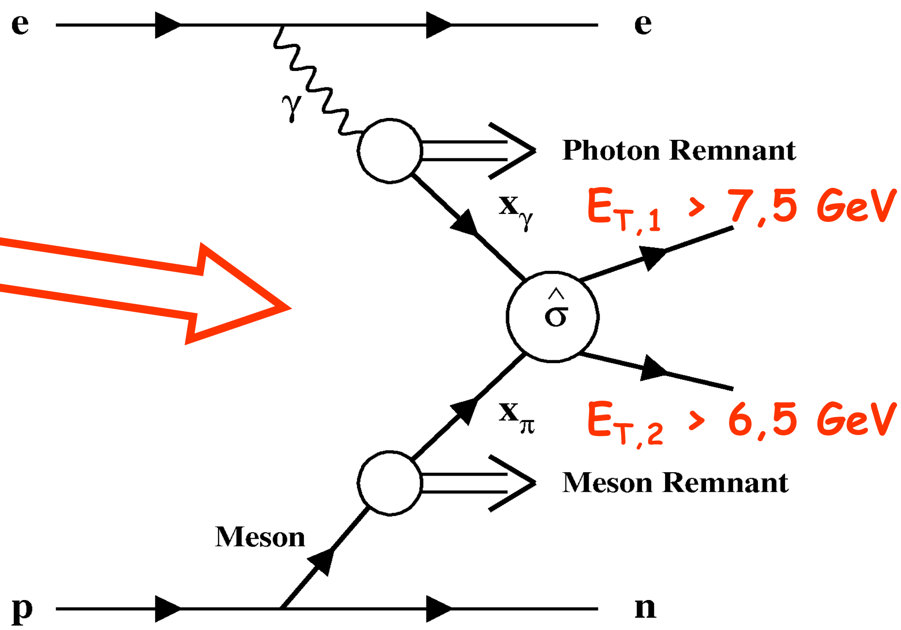
Dijet photoproduction with LN

Absorption effects increase from high $Q^2 \rightarrow \gamma p$

i.e. from hard → soft scale

A hard scale in γp can be introduced by requiring high E_T jets

Still signs of absorption ?



Note:

Factorization breaking observed in diffractive dijet photoproduction.

(see Armen's talk ⇒)

look at preliminary (2007) results from ZEUS !

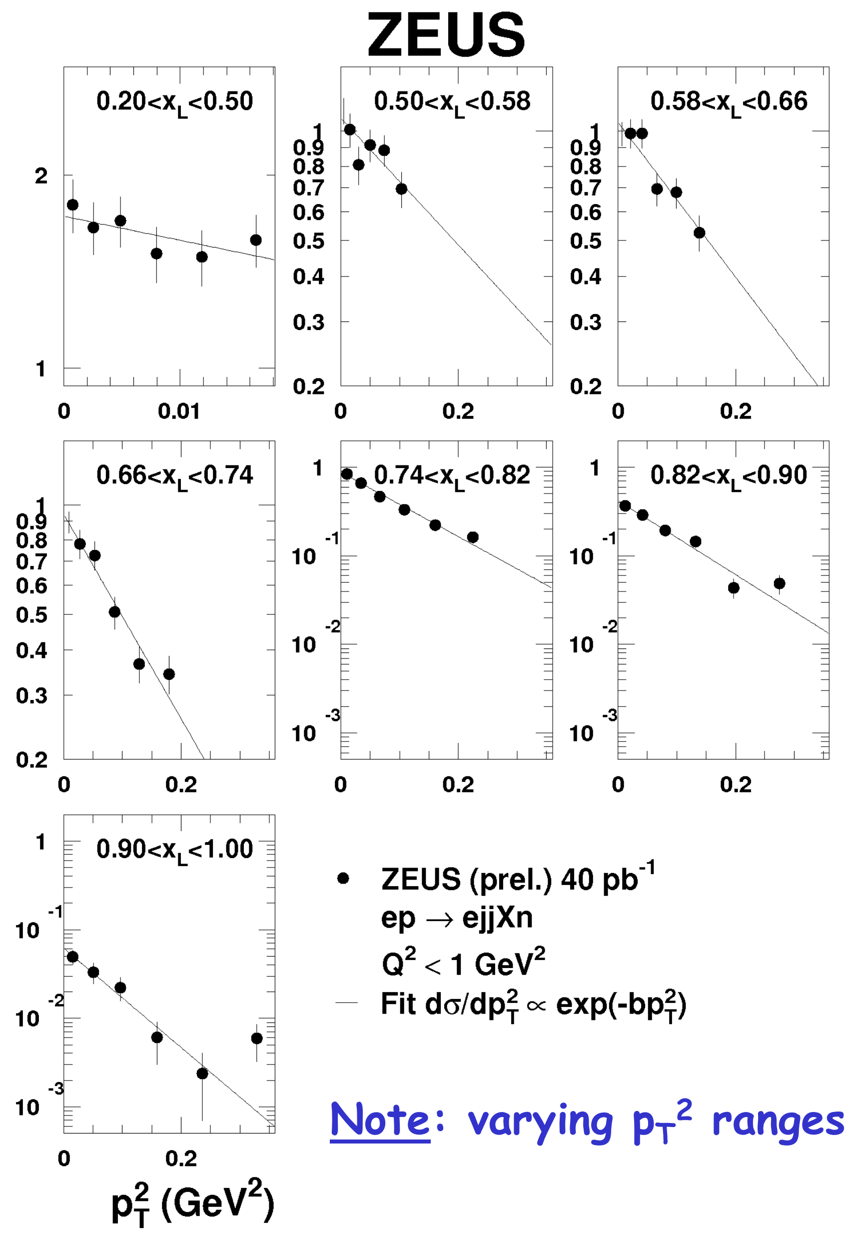
Dijet photoproduction with LN: p_T^2 distributions

$$\frac{1}{\sigma_{inc}}\frac{d\sigma_{LN}}{dp_T^2 dx_L}$$

Normalized to the inclusive dijet cross section

Well described by exponential fall-off in p_T^2 with single slope

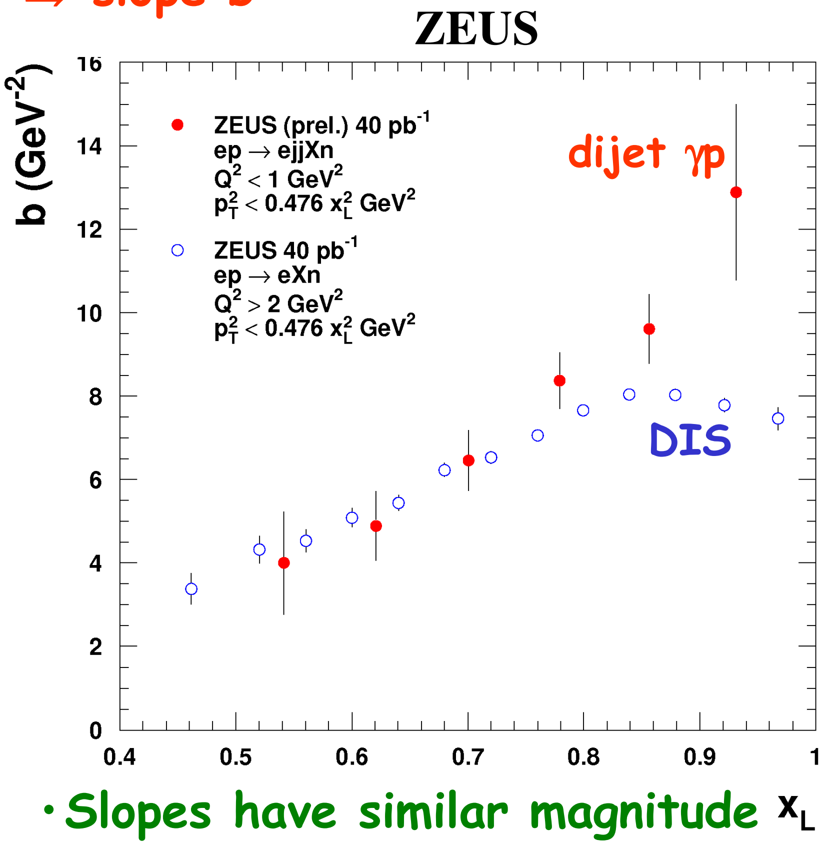
$$\frac{1}{\sigma_{inc}}\frac{d\sigma_{LB}}{dp_T^2 dx_L} \sim e^{-b(x_L)p_T^2}$$



<u>Note</u>: varying p_T^2 ranges

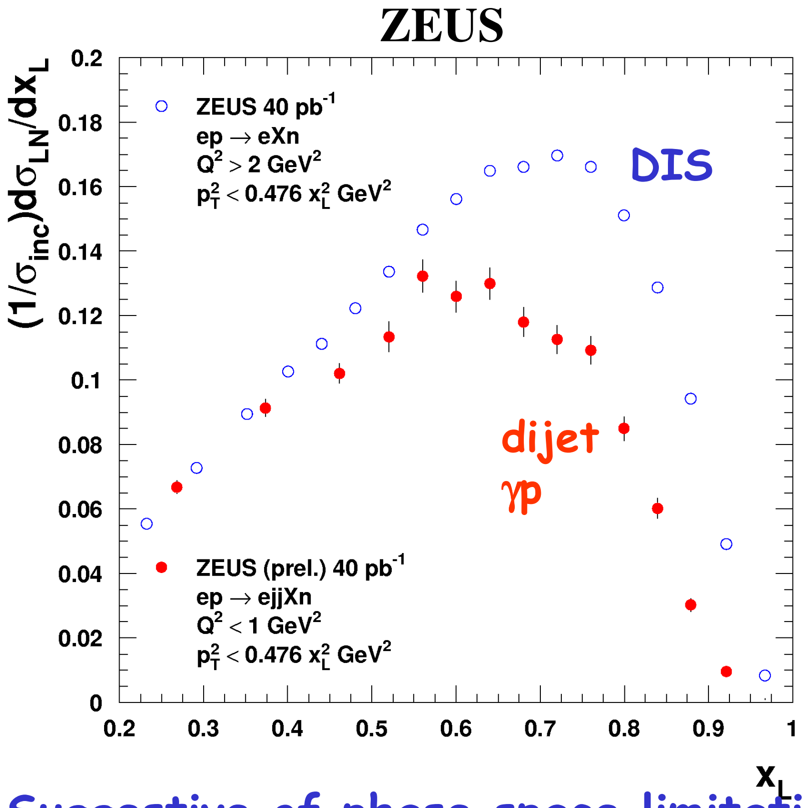
Dijet photoproduction with LN vs. DIS

LN p_T^2 dist. fitted with exponential
⇒ slope b



- Slopes have similar magnitude
- Statistics limits any conclusion on possible differences

x_L distr.show suppression at high x_L !



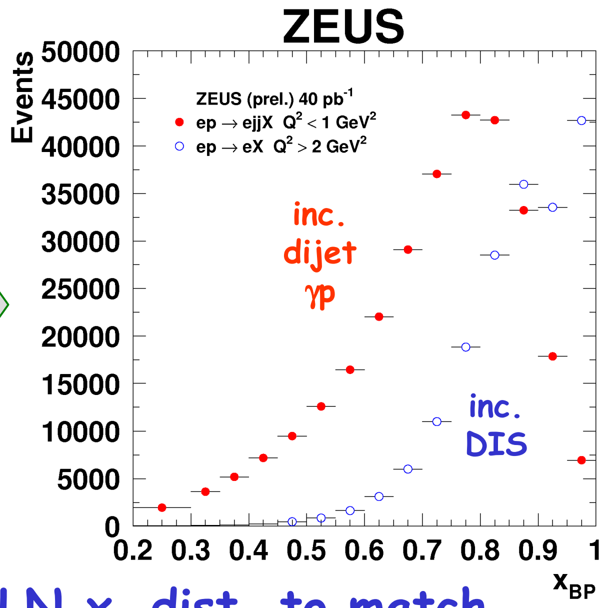
Suggestive of phase space limitation: dijets in the final state leave little room for energetic high-x_L neutrons

LN in dijet γp vs. DIS: kinematic constraints

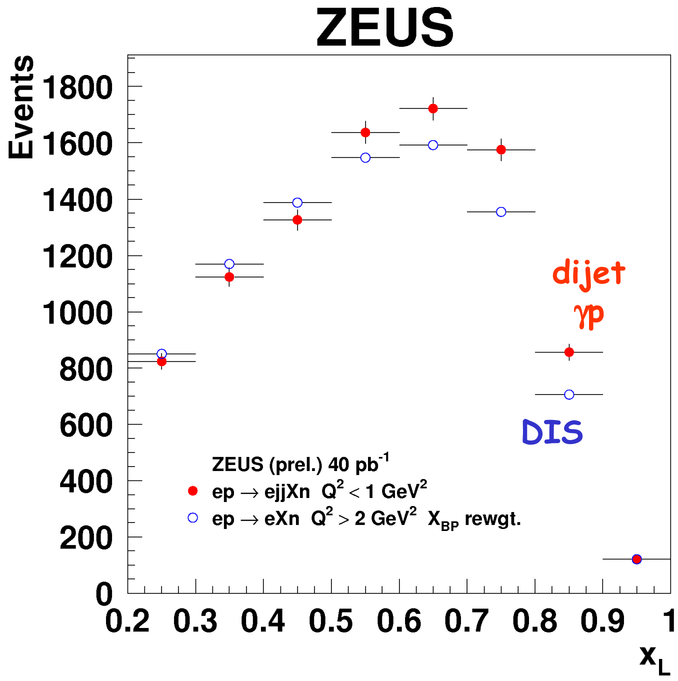
Consider X_{BP} = fraction of p-energy available for LN production down the beam pipe

$$\boxed{x_L < X_{BP} = 1-(E+P_Z)/2E_P}$$

X_{BP} dist. is different in DIS and dijet γp:



much less energy available in dijet γp for LN production



Test: reweight DIS LN x_L dist. to match the X_{BP} dist. in dijet γp:

- ✓ suppression @ high x_L mostly gone
- ✓ large suppression @ low x_L seen in γp without jets not there

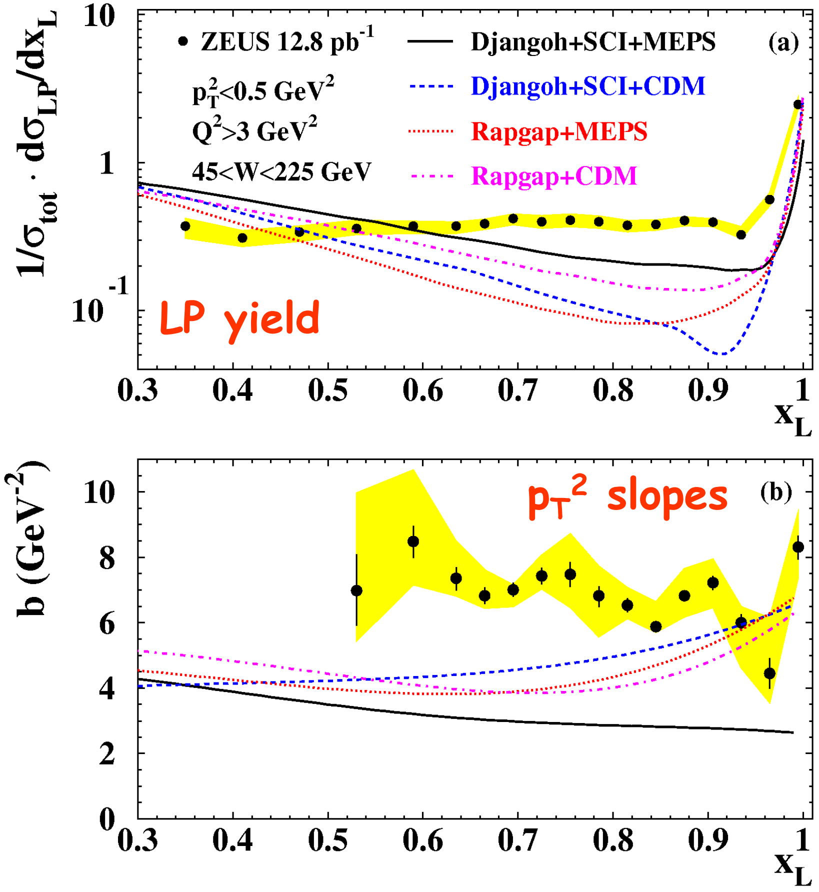
Tentatively: differences in the x_L spectra due to kin. suppression. More accurate MC studies of kinematic effects ongoing ...

Hard to draw any conclusion on absorption !

Comparisons with models

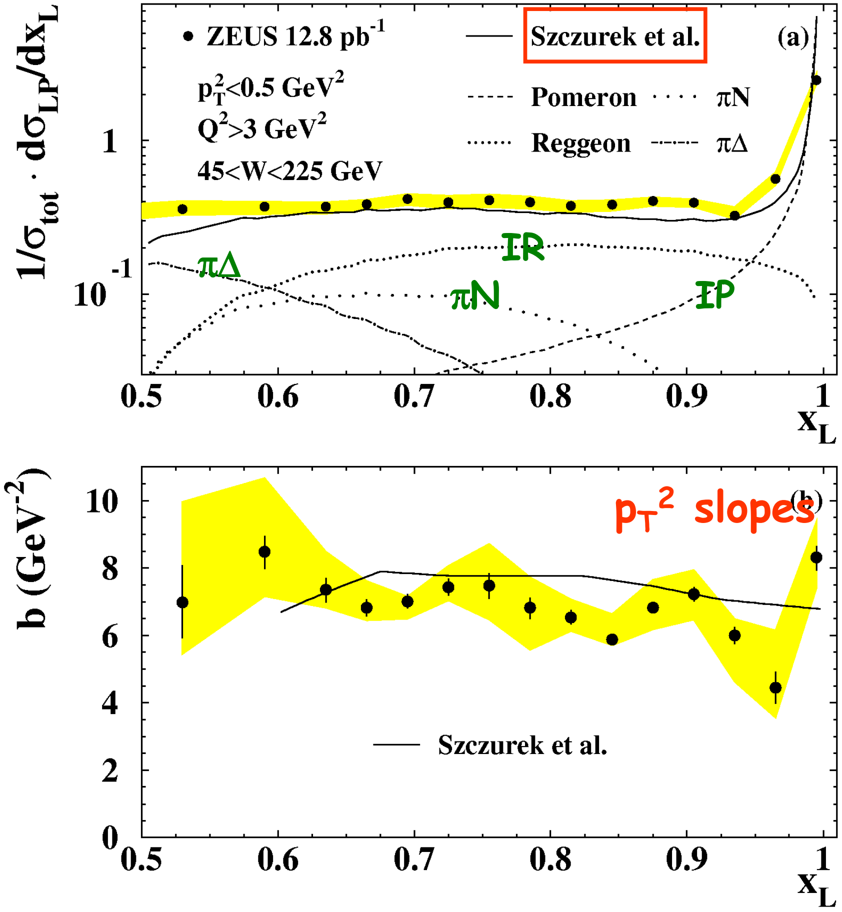
Model comparisons: DIS LP

Std. fragmentation MCs



- good description of diff. peak but all fail at low x_L
- slopes too low at low x_L

Model with multiple exchanges

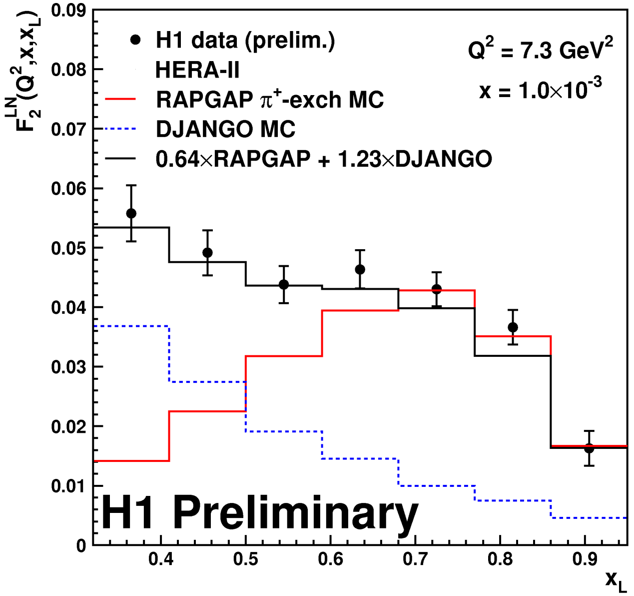


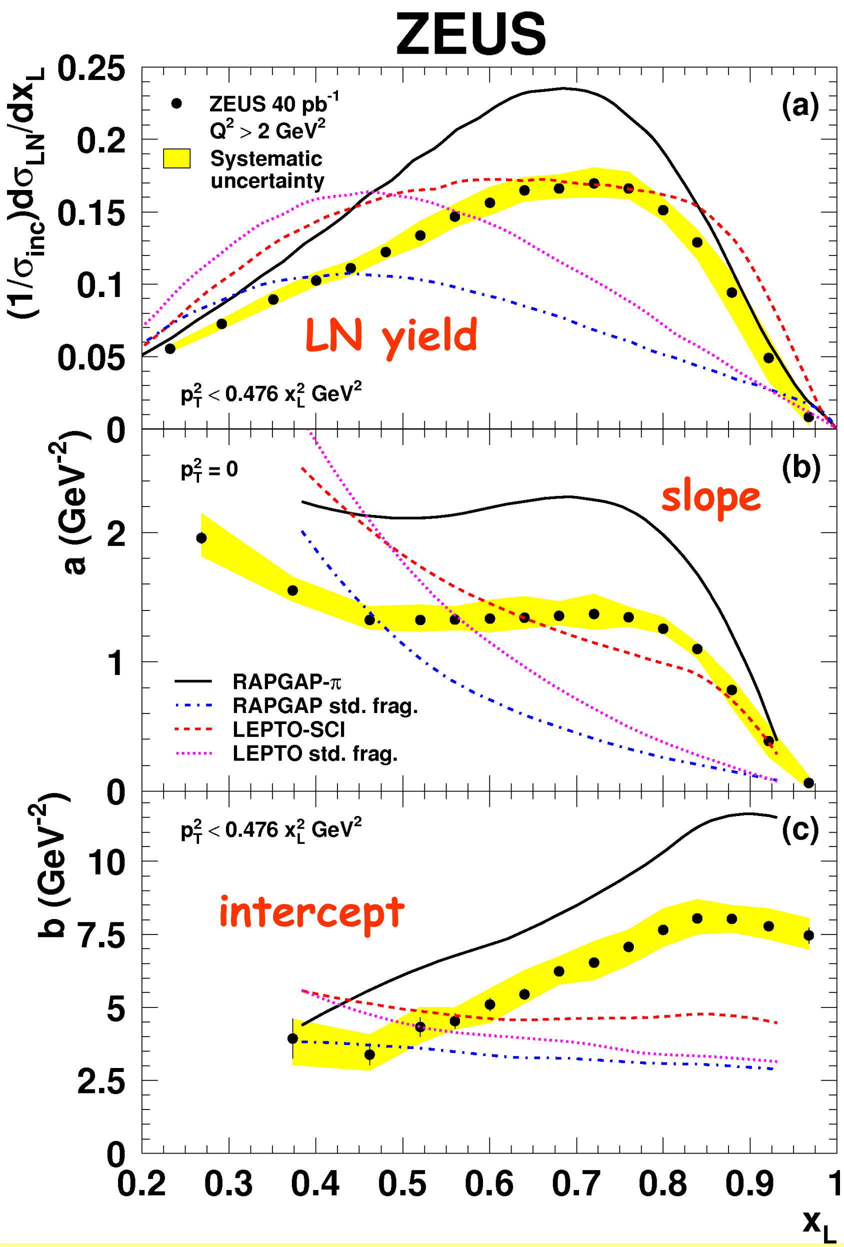
- Good description of LP yield and slope by adding different exch.
- iso-scalar reggeon domininant at intermediate x_L

Comparisons of DIS LN with MC models

Comparison with several MC models

- ✓ all std. frag. predict to few *n* and too low x_L;
- ✓ LEPTO-SCI correct yield but no x_L dependence of slopes;
- ✓ RAPGAP-π ~ OK in shape @ x_L>0,6
- ✓ Best description found with mixture DJANGO and RAPGAP-π





LN yield

slope

intercept

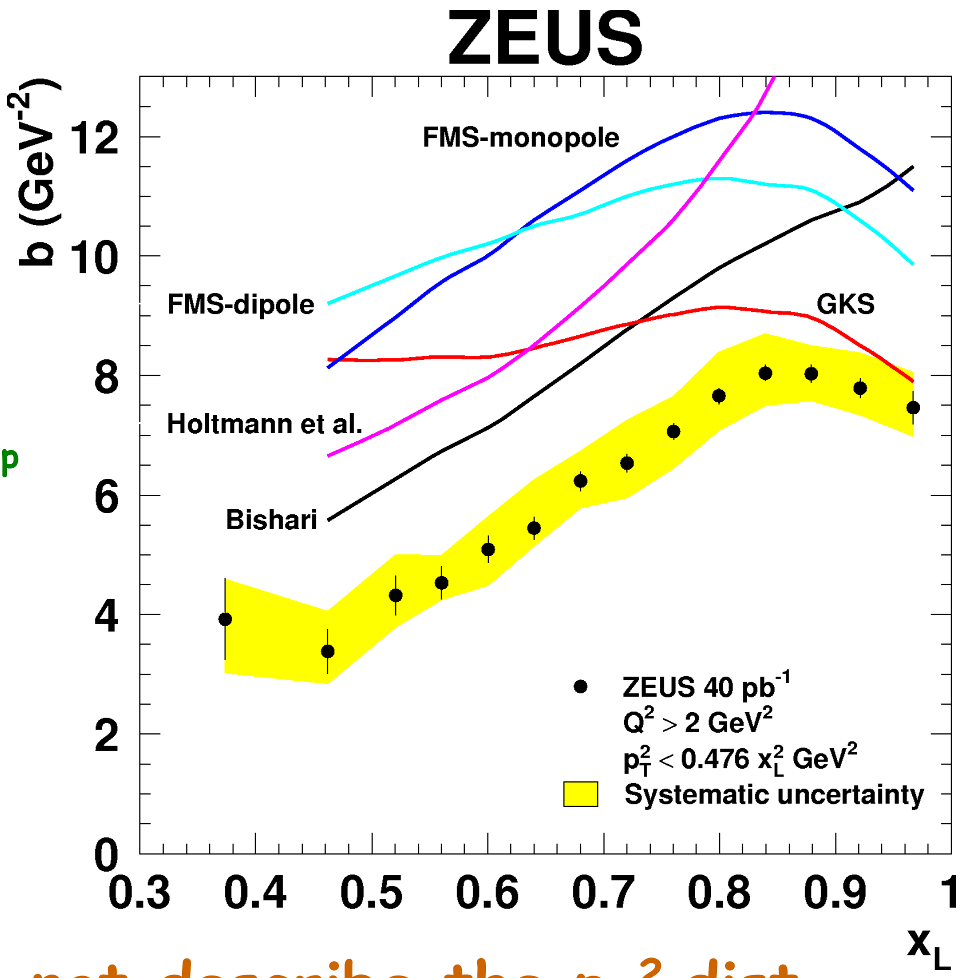
Comparisons of DIS LN with pion exch. models

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

- ✓$p_T{}^2$ distribution is determined solely by the pion flux

$$f_{\pi/p}(x_L, t)$$

- ✓various parametrizations of $f_{\pi/p}$
- ✓compare to DIS slope vs x_L (only best agreeing models)
- ✓all models give too large $b(x_L)$



pion exchange alone do not describe the $p_T{}^2$ dist.

Comparison with pion exch. + absorption

Expectations from

- geometrical absorption model (D'Alesio and Pirner);
- Regge-based model with multi-pomeron exchanges (Nikolaev, Speth, Zakharov)

Note on energy dependence:

Different dependence of $\sigma_{\gamma\pi}$ on c.m. energy

$$s'=(1-x_L)W^2$$

in DIS and γp.

Assuming same power-law dependence of γp and $\gamma\pi$ cross-section, at fixed W

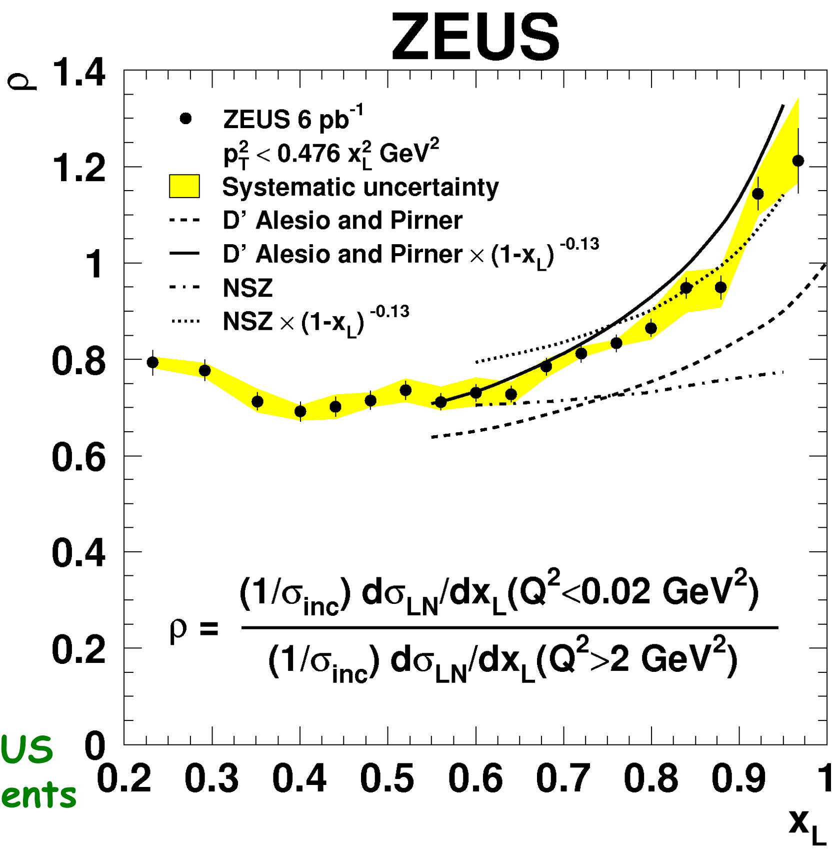
$$\sigma_{\gamma\pi}/\sigma_{\gamma^*\pi} \sim (1-x_L)^{-0,13}$$

from ZEUS measurements

Scaling absorption ratio by $(1-x_L)^{-0,13}$

→ better agreement with data

Ratio γp/DIS vs. x_L



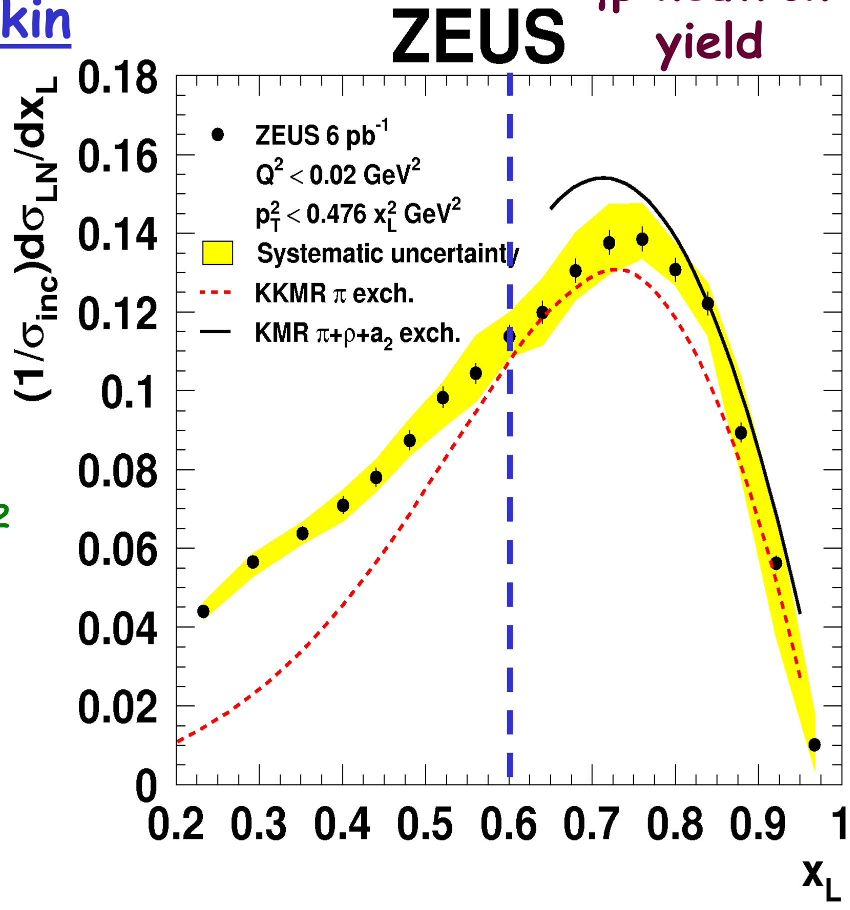
Comparison with enhanced absorption model + secondary exchanges

Model of Kaidalov, Khoze, Martin, Ryskin (KKMR):

- rescattering on intermediate partons in central rapidity region;
- migration of LN after rescattering
- prediction of ~ 50% abs. loss in γp

→ related to gap survival prob. S^2

- extended (KMR) to include exchange of secondary (ρ,a_2) reggeons.



γp neutron yield

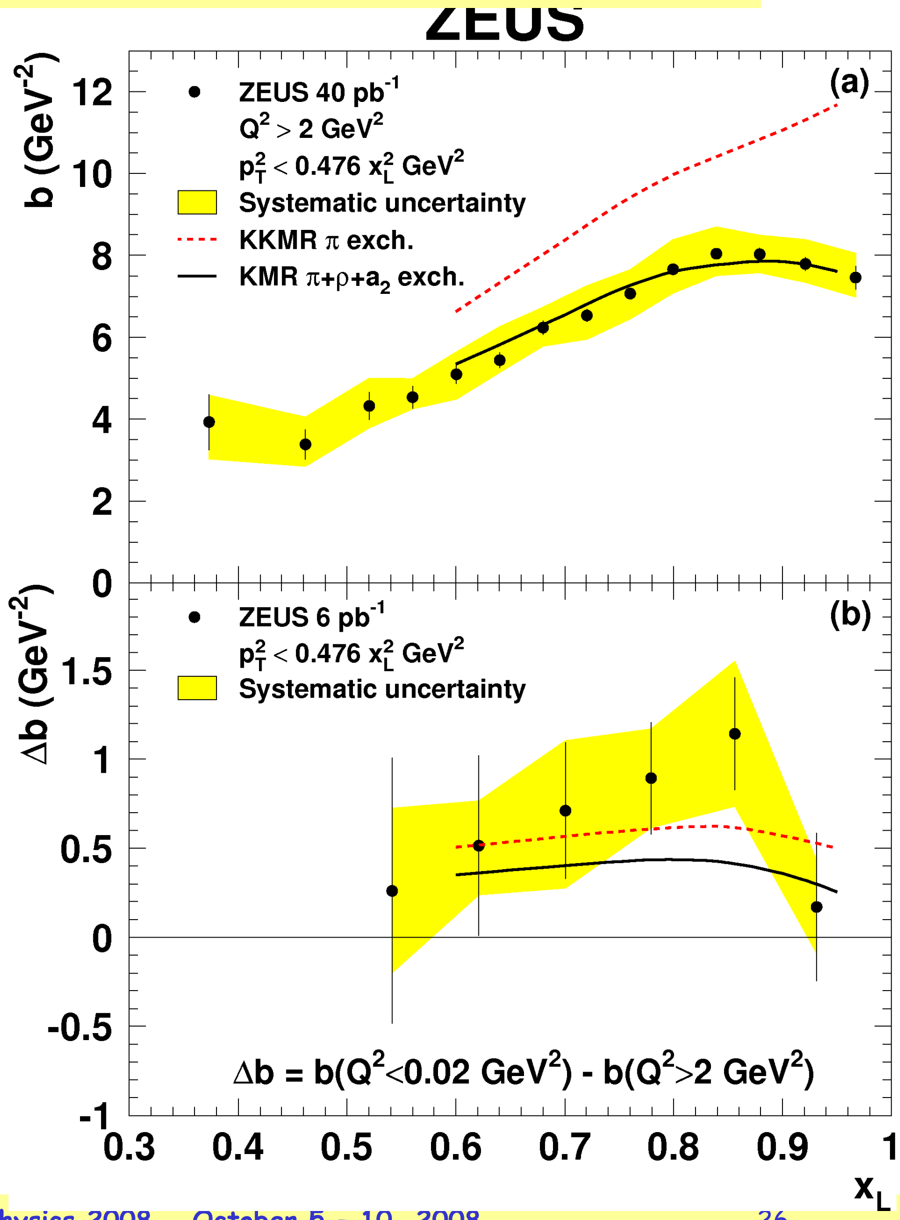
Good description of LN yield in γp

Comparison with enhanced absorption model + secondary exchanges

Absorption + migration with pion exchange alone do not describe LN slopes in DIS:

- too large values;
- no turnover at large x_L

Adding (ρ, a_2) exchanges good description of slopes vs x_L achieved

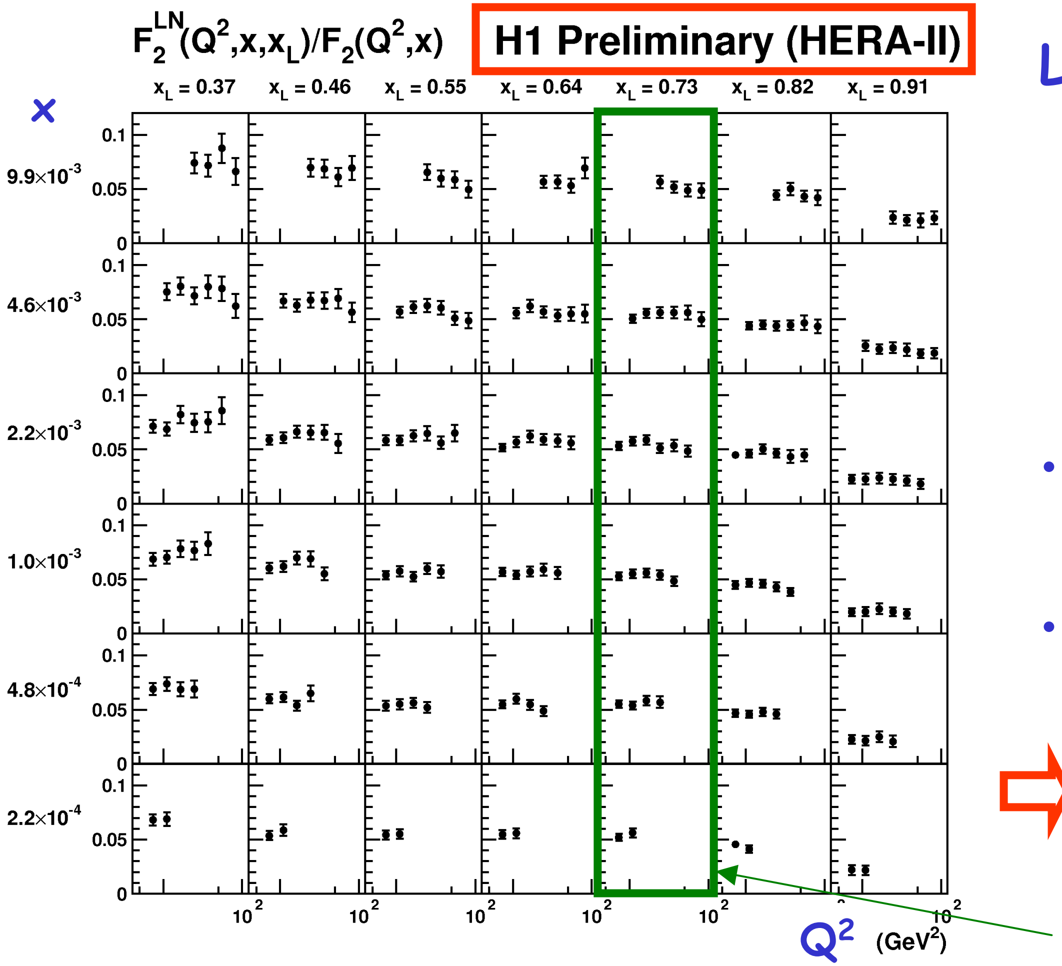


LB structure functions and F_2^{π}

LN structure function F_2^{LN}

Semi-inclusive LB s.f. can be defined analogous to proton s.f. F_2

e.g.
$$F_2^{LN}(Q^2, x, x_L) = \int F_2^{LN(4)}(Q^2, x, x_L, t)\,dt$$



x_L bin used for π str. function

Look at ratio

$F_2^{LN}(Q^2,x,x_L)/F_2(Q^2,x)$

~ flat in all x or Q^2 bins

- same behaviour of F_2 and F_2^{LN} vs (x,Q^2)
- LN production mechanism independent of (x,Q^2)

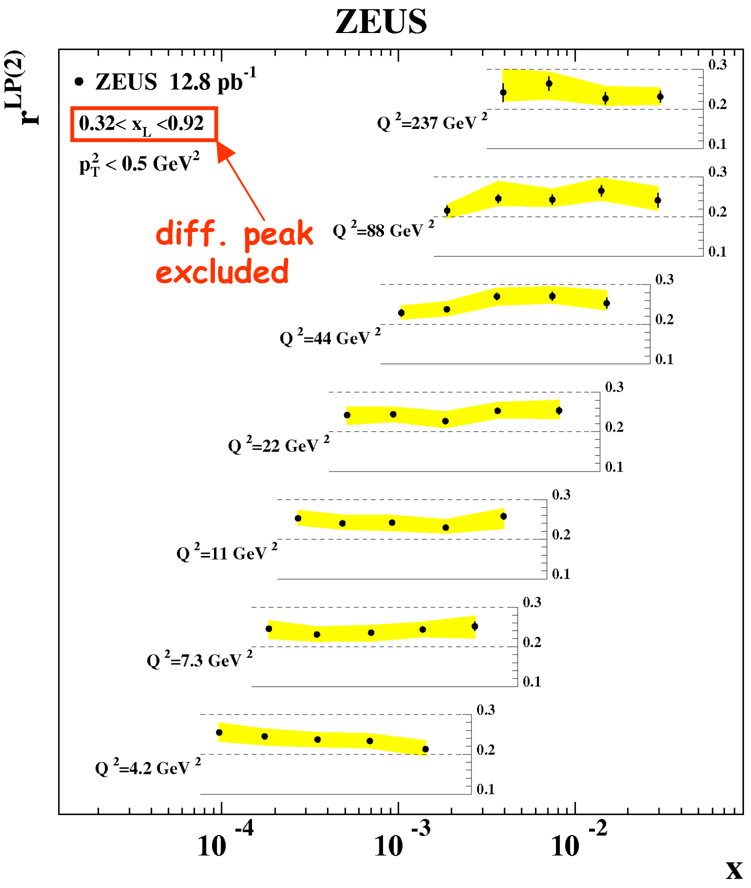
⇨ **factorization as in exch. models**

$6<Q^2<100$ GeV^2 ; $0<p_T<0{,}2$ GeV

LP structure function F_2^{LP}

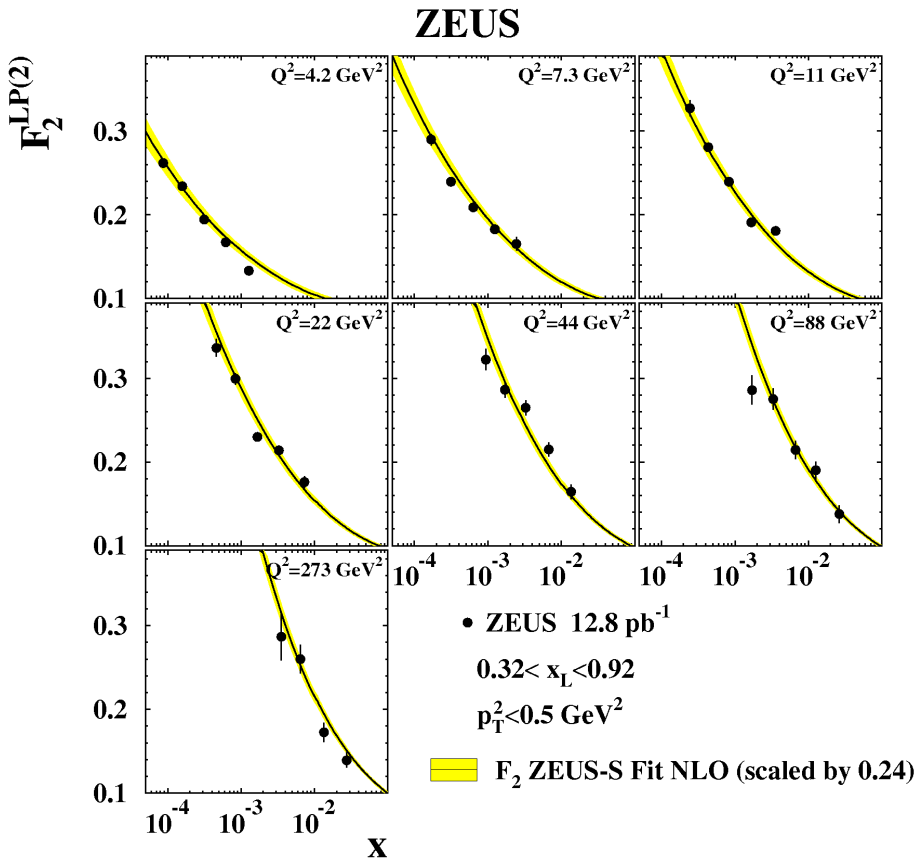
Similar behaviour for LP structure function F_2^{LP}

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



diff. peak excluded

$r^{LP(2)}$ approx. constant vs. x and Q^2 with average value ~ 0,24



same trand as F_2 observed

Pion structure function F_2^π

Assuming factorization: $F_2^{LN}(Q^2,x,x_L,t) = f_{\pi/p}(x_L,t) \cdot F_2^\pi(Q^2,\beta)$

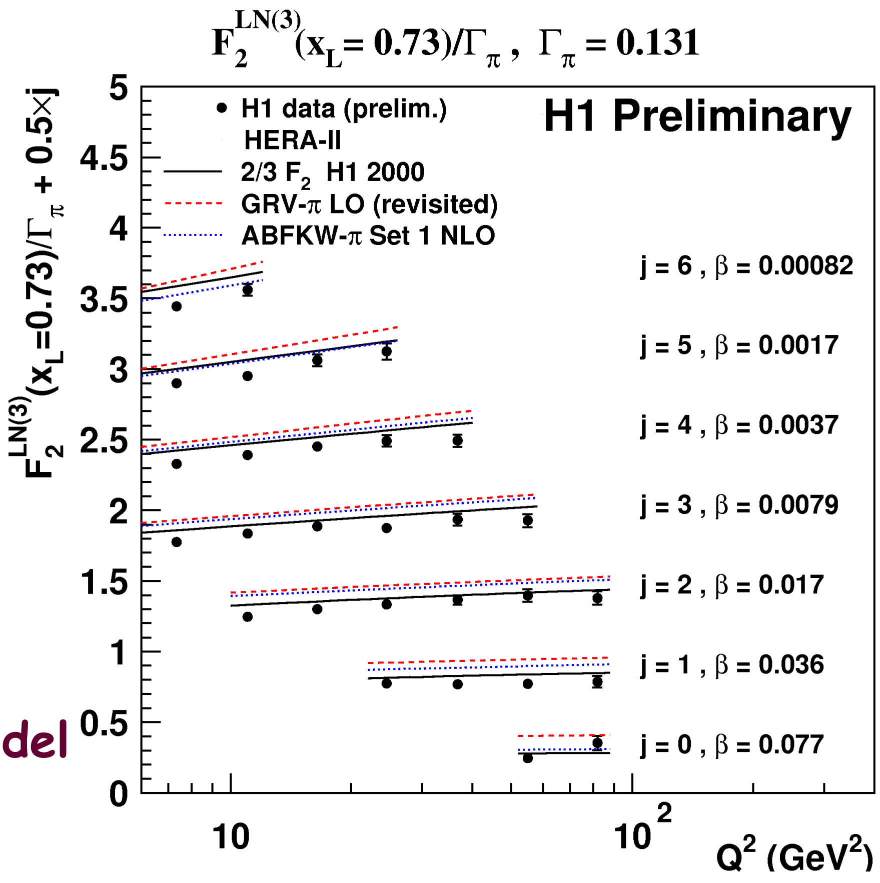
$\beta = x/(1-x_L) \Rightarrow$ fraction of π-momentum carried by parton

✓ use F_2^{LN} measurement @ x_L=0,73

✓ take $f_{\pi/p}(x_L,t)$ from Regge exch. model and integrate over t

$$\Gamma_\pi = \int f_{\pi/p}(x_L = 0{,}73, t)\, dt$$

then extract $F_2^\pi = F_2^{LN}/\Gamma\pi$



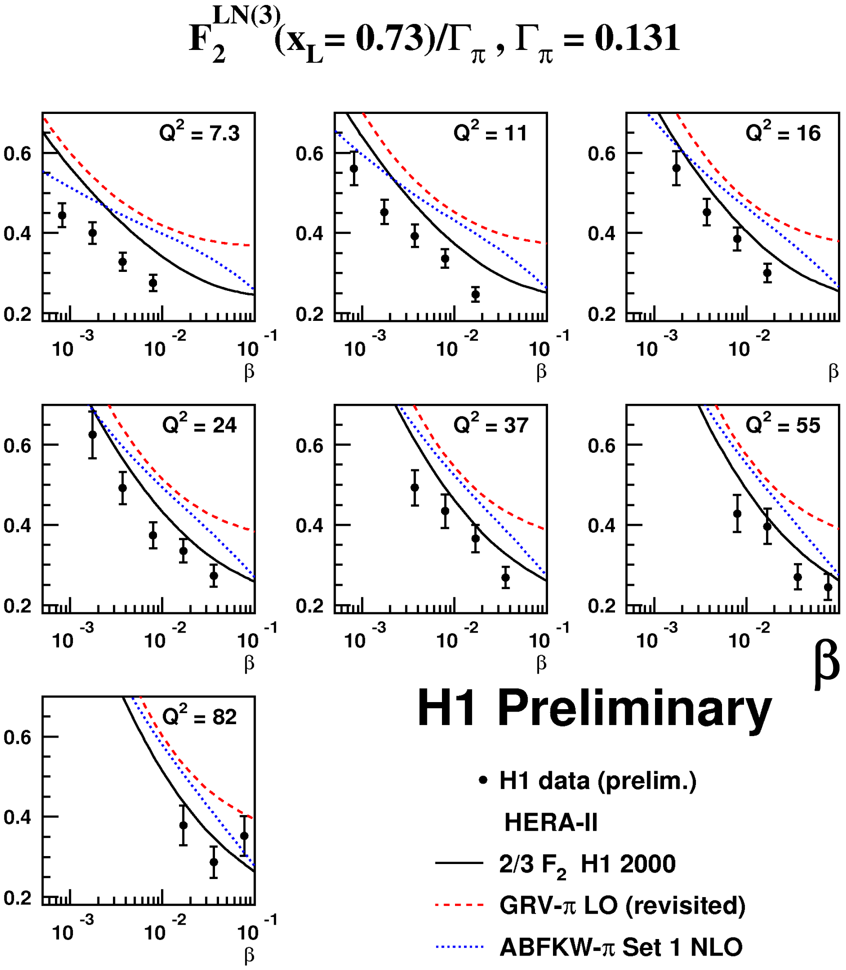
Results compared with:

- expectations from additive quark model

$$F_2^\pi = 2/3\ F_2$$

- Pion p.d.f. parametrizations (GRV, ABFKW shown here)

Pion structure function F_2^{π}



F_2^{π} vs β at fixed Q^2

Data slightly below expectations

- absorptive effects may play a role
- also uncertainties in pion flux need to be considered.
- work ongoing...

Summary

LB is a good ground to study soft vs. hard physics

- Precise measurements of LB x_L and p_T^2 presented in γp, DIS, γp+dijet;
- suppression in γp @ low x_L, high p_T, in agreement with absorption;
- reintroducing hard scale in γp with high E_T jets: absorption effect ?
- MCs with `standard` fragmentation do not describe the data
- multiple exch. model describes LP data, but pure OPE fails to describe LN slopes

⇒ better description including ρ, a_2 exchanges

- The neutron energy spectrum in γp compatible with effects of absorption and migration as calculated by Kaidalov, Khoze, Martin and Ryskin

⇒ gap survival factor $S^2 \sim 0.5$ has been evaluated

- For LN production, extract pion structure $F^2_\pi(x,Q^2)$