



Leading Baryons at HERA



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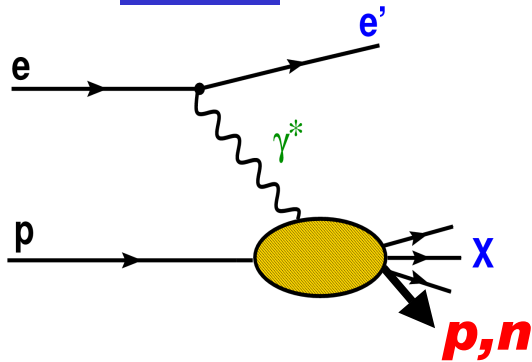
On behalf of the ZEUS and H1

- 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

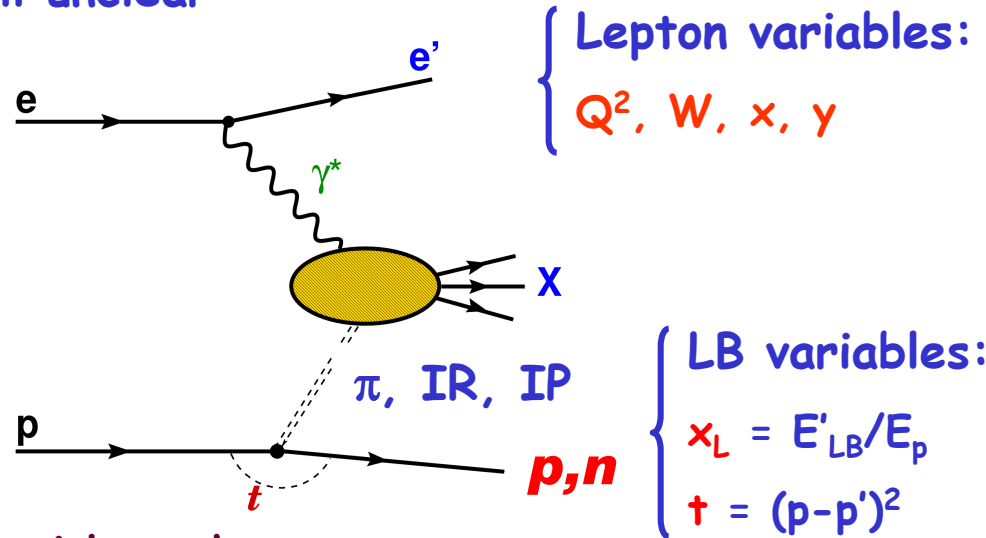
Introduction

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



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

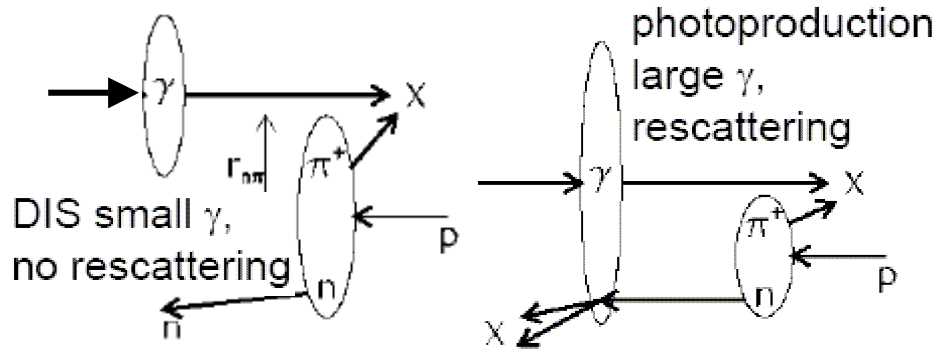
$$d\sigma(\gamma^*p \rightarrow nX) = f_{\pi/p}(x_L, t) d\sigma(\gamma^*\pi \rightarrow X)$$

- \Rightarrow LB production independent on photon vertex
- \Rightarrow probe structure function of the exchanged particle
- Models predict factorization violation (absorption)

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

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

Absorption models: LN via π exchange



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

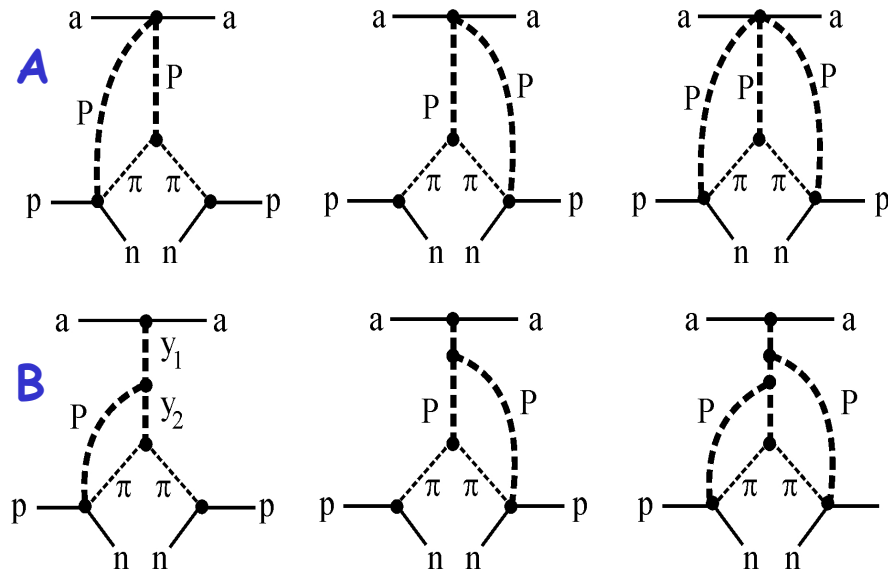
- the larger the photon, the fewer the n's detected (more absorption in γp than DIS)
- the smaller the $n\pi$ system ($r_{n\pi}$), the fewer the n's detected (more absorption at high p_T , low x_L)

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

(Kaidalov), Khoze, Martin, Ryskin

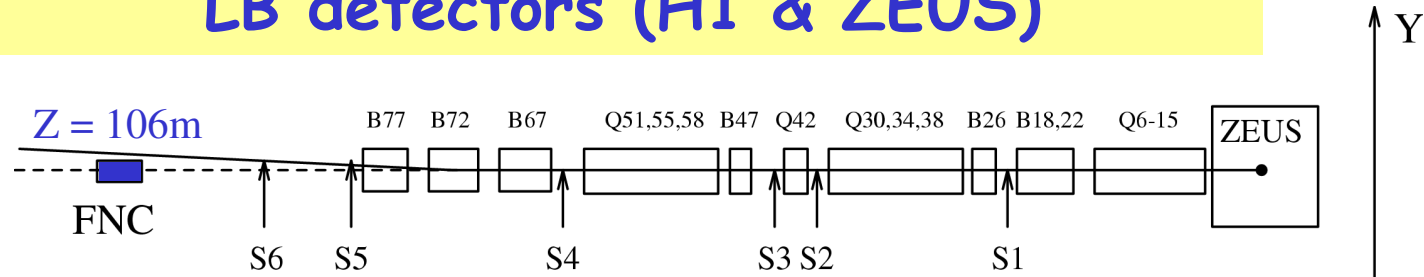
EPJ C 47 (2006) 385;

EPJ C 48 (2006) 797;



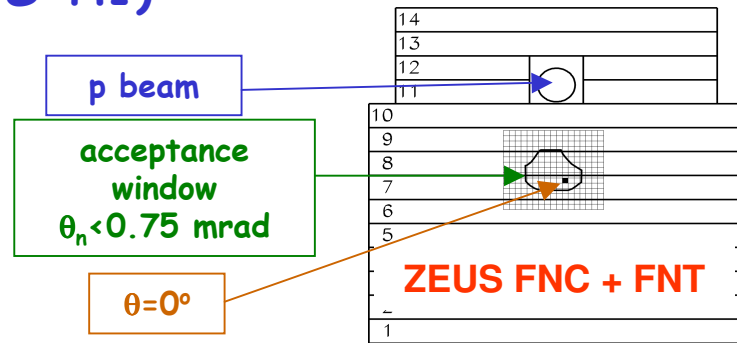
- evaluate correction due to enhanced absorptive diagrams B (~ 15%)
- show importance of distortion of energy spectra (**migration**) due to rescattering for $x_L < 0.8$
- include effects of ρ , a_2 exchange
- estimate the **gap survival factor S^2** (important for LHC!) which takes into account that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

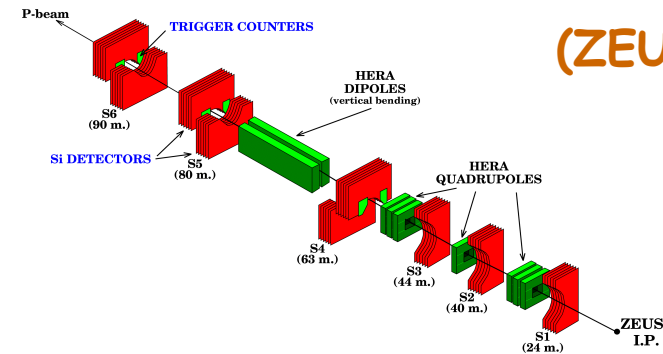


Pb-sci. calorimeters + veto counters @107 m

- $\sigma/E = 70\%/\sqrt{E}$ ($\approx 63\%/\sqrt{E} \oplus 3\%$ for H1)
- e-scale accuracy $\pm 2\%$ ($\pm 20\%/\sqrt{E}$ for H1)
- **Position reconstruction accuracy**
 $\sigma_{X,Y} = 0.23 \text{ cm} \Rightarrow \sigma_{\theta} = 22 \mu\text{rad}$
- allows to measure neutron p_T

Leading Proton Spectrometer

(ZEUS)



6 stations with μ strip detectors

- hit position resolution $\approx 30 \mu\text{m}$

$$\sigma_{XL} < 1\%$$



$$\sigma_{PT} \sim \text{few MeV}$$

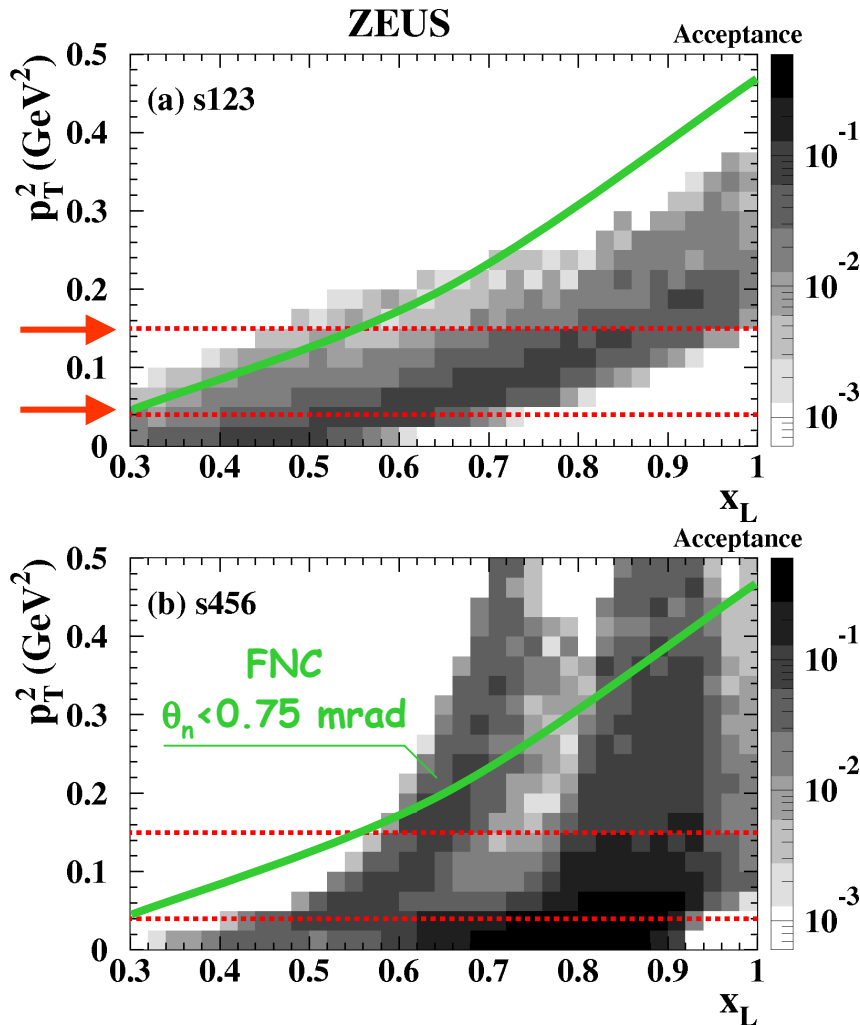
- momentum accuracy $< 1\%$

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 $\theta_n < 0.75$ mrad
- p_T range increases with x_L ;
- for $x_L > 0.6$, $\theta_n < 0.75$ 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: $x_L > 0.2$

$$\theta_n < 0.75 \text{ mrad} \Rightarrow p_T^2 < 0.476 x_L^2 \text{ GeV}^2$$

proton: $x_L > 0.32$

$$p_T^2 < 0.5 \text{ GeV}^2$$

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

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

122 pb⁻¹, $Q^2 > 6 \text{ GeV}^2$ (H1, LN) \leftarrow HERA II

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

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

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

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

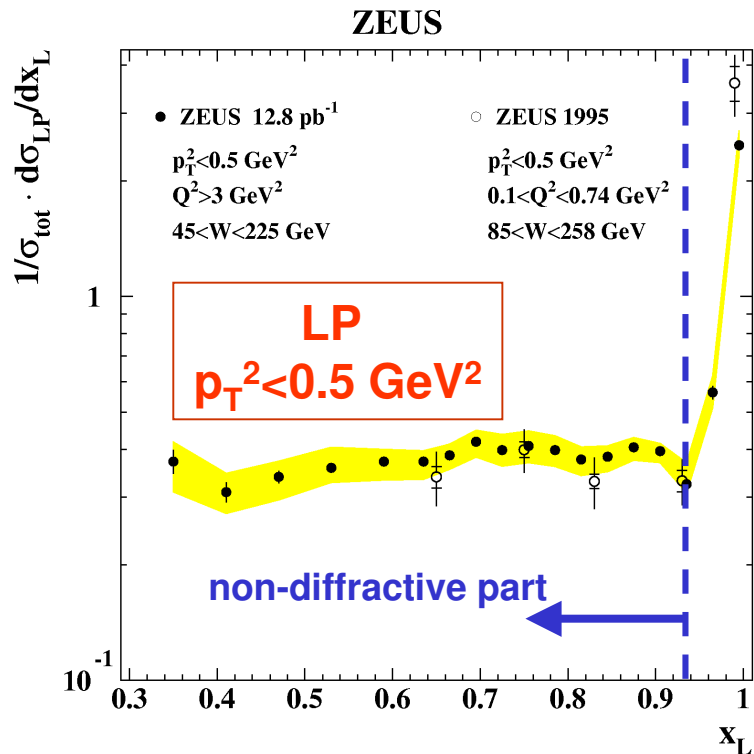
DIS and γp have very different inclusive cross sections σ_{inc}

\Rightarrow for sensible comparisons look at $\sigma_{\text{LN}}/\sigma_{\text{inc}}$

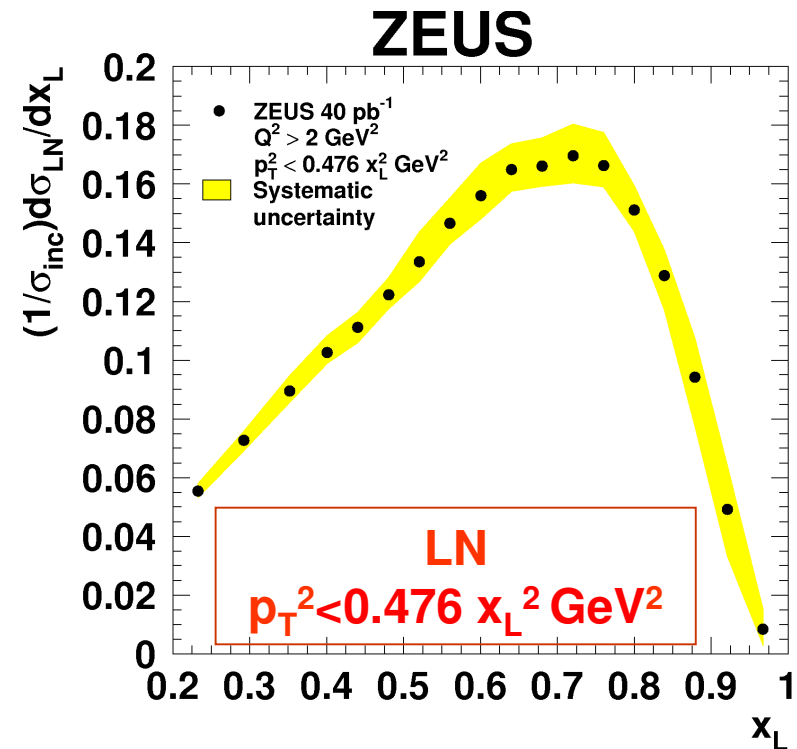
Additional benefit: systematic uncertainties of central detector cancel

DIS: normalized cross sections vs x_L

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



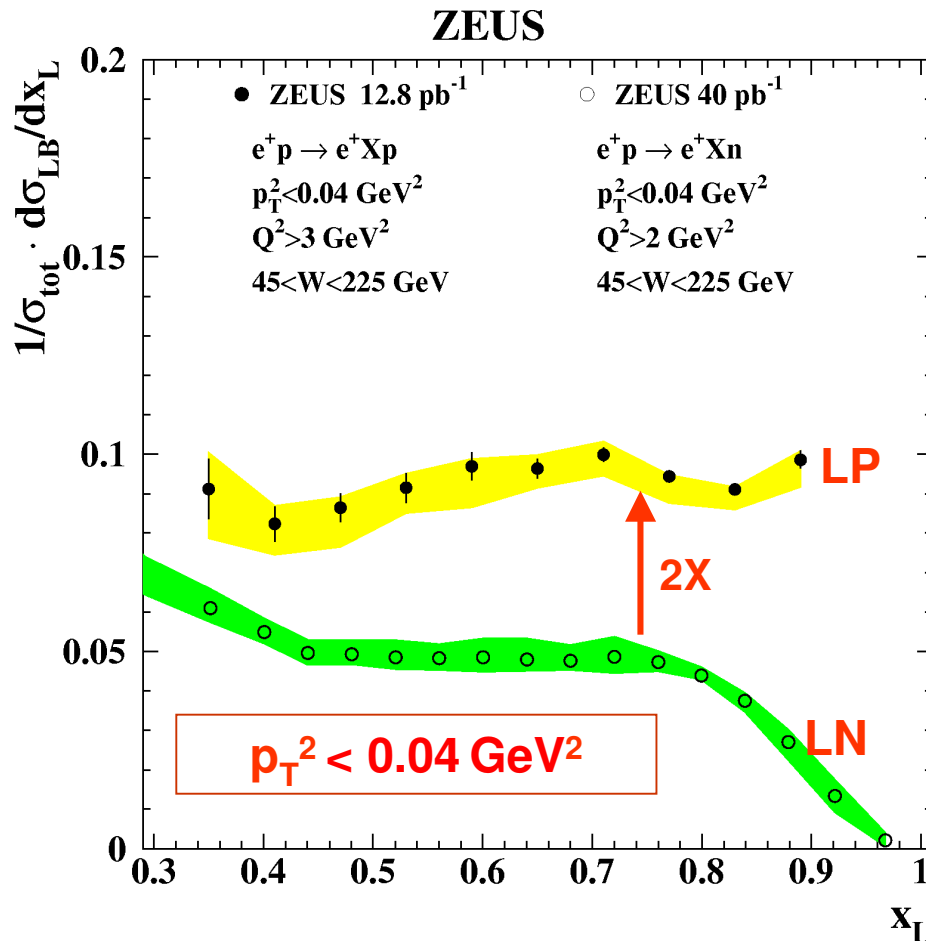
- clear diffractive peak $x_L \rightarrow 1$
- proton yield flat below $x_L \approx 0.95$
- consistent with earlier low- Q^2 data



- LN yield $\rightarrow 0$ at kinematic limit $x_L \rightarrow 1$
- 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

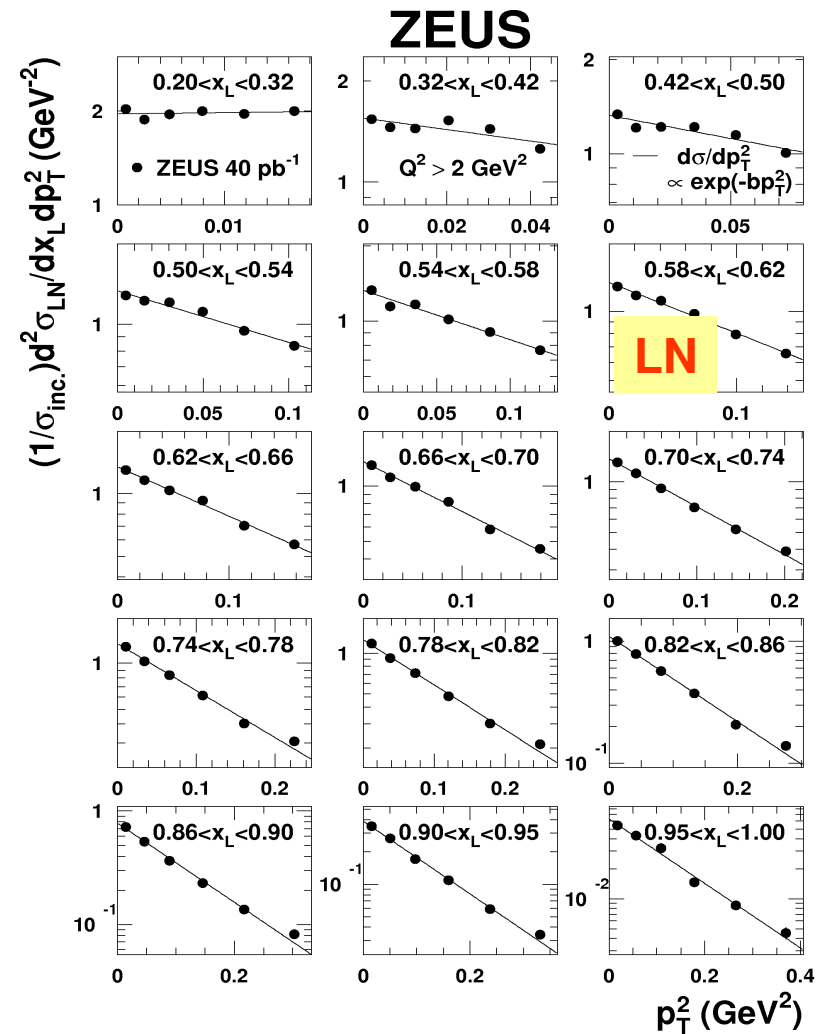
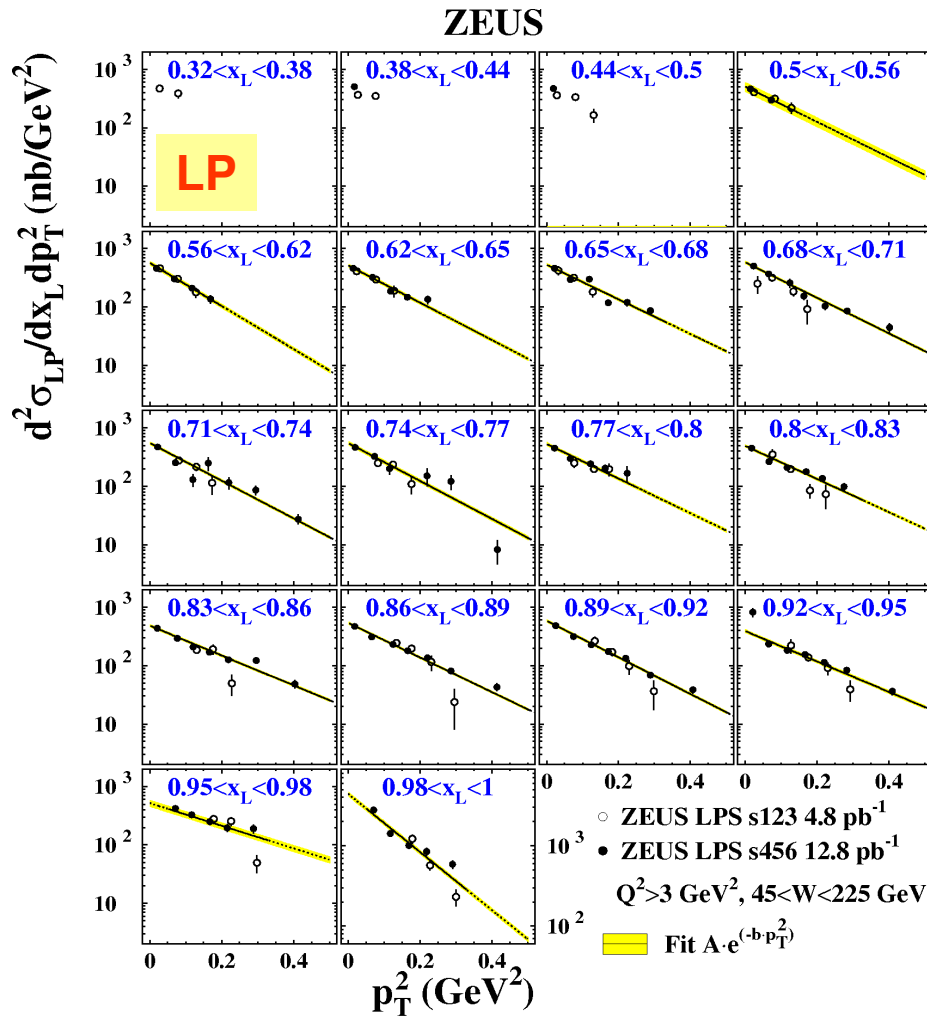
$$LP = \frac{1}{2} LN$$

- data suggest $LP \approx 2 LN$



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

DIS: p_T^2 distributions



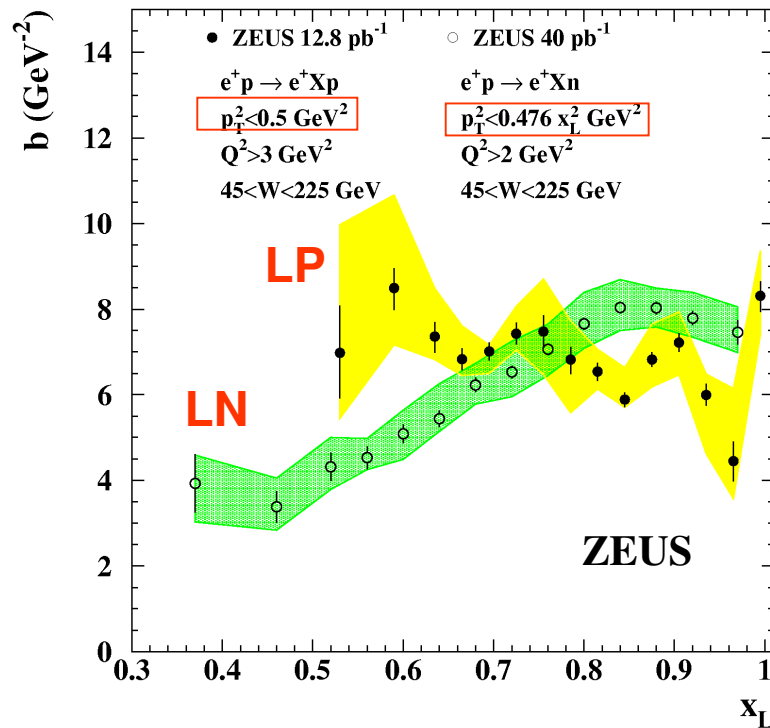
Note: varying p_T^2 ranges

Well described by exponential fall-off in $p_T^2 \Rightarrow$ intercepts and slopes

DIS p_T^2 distributions: slopes and intercept

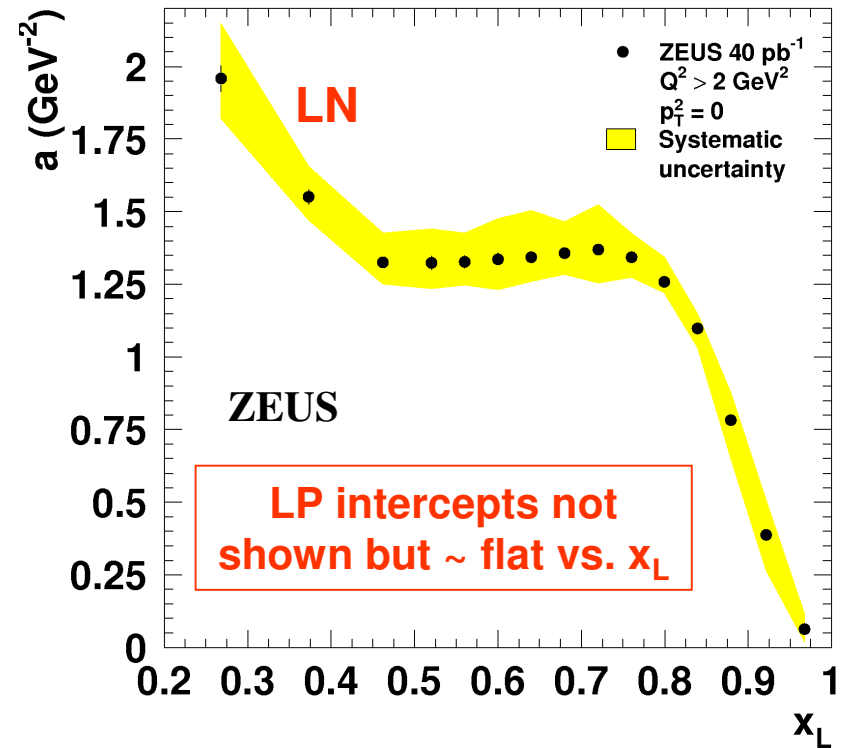
Fit LB data to $\frac{1}{\sigma_{inc}} \frac{d\sigma_{LB}}{dp_T^2 dx_L} = a(x_L) e^{-b(x_L) p_T^2}$

• slopes $b(x_L)$



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

• intercepts $a(x_L)$

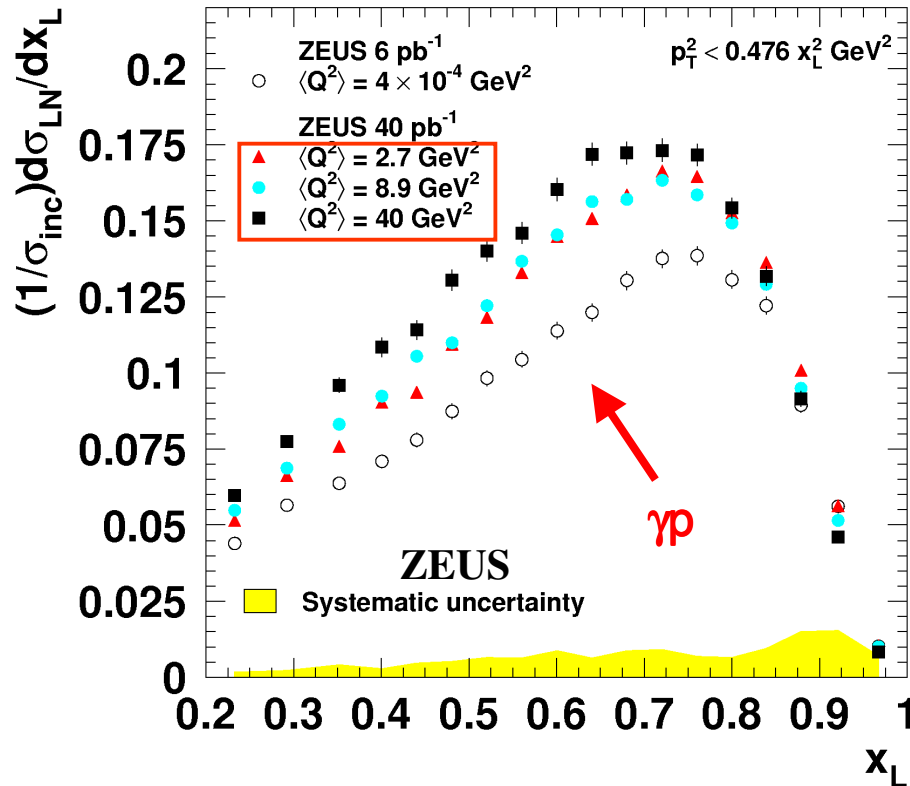


- LN intercepts fall with x_L
- plateau for $0,4 < x_L < 0,8$

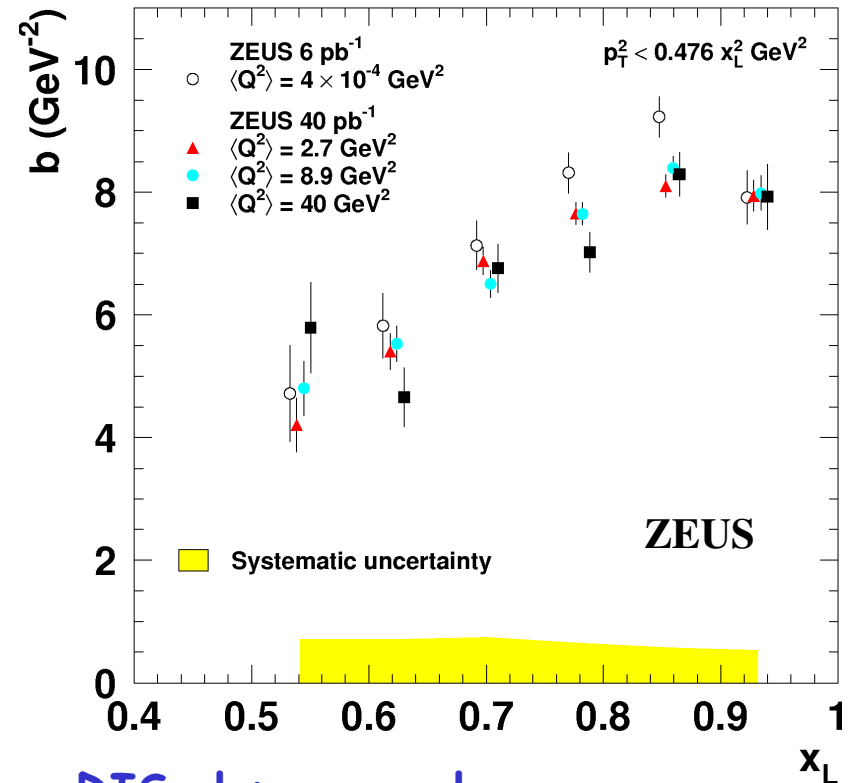
Q^2 dependence: LN production

- 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 $0,6 < x_L < 0,9$

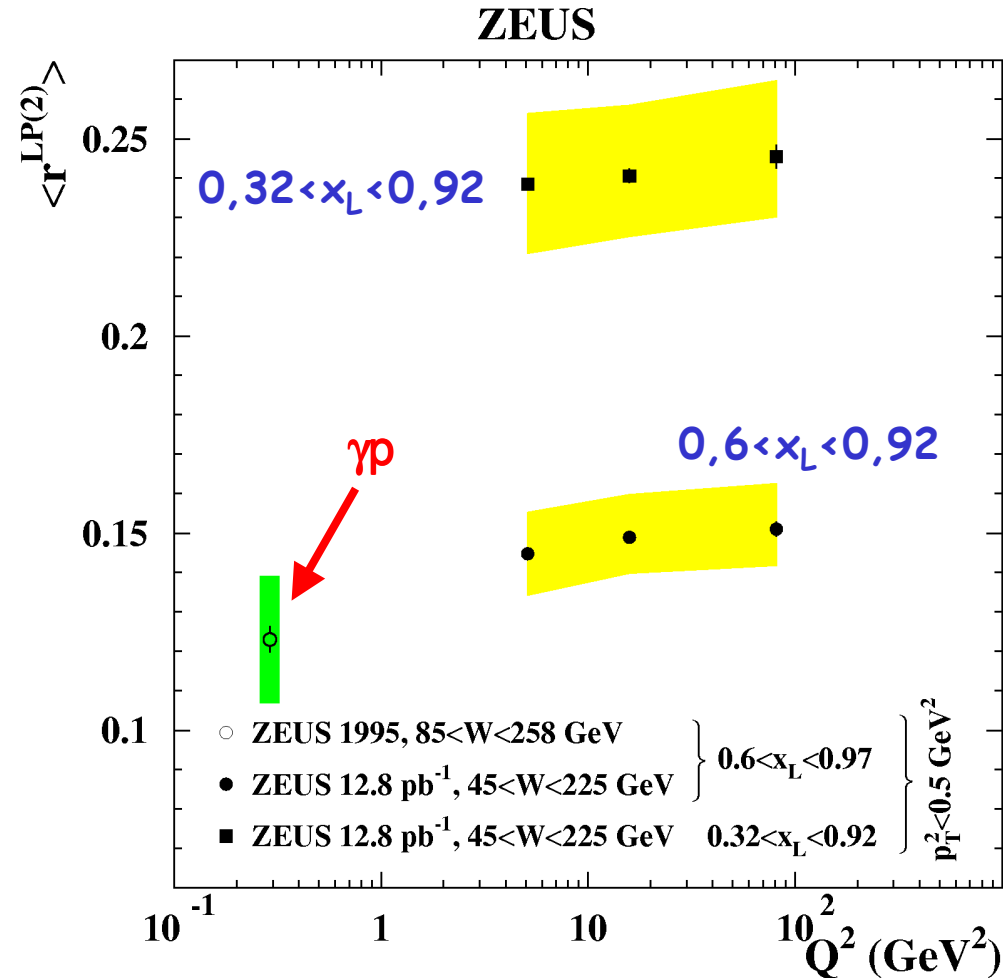
suggests violation of vertex factorization

Q² dependence: LP production

Average LP yield vs. Q²

- $P_T^2 < 0,5 \text{ GeV}^2$
- 2 different x_L ranges

✓ Steady rise with Q² also observed.



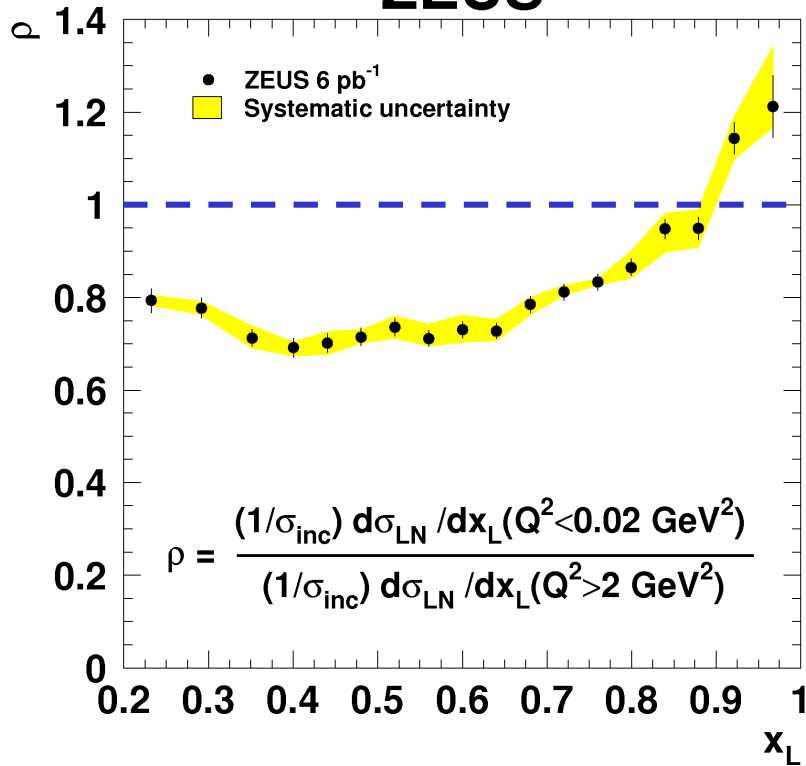
Results shown are consistent with absorptive effects:
 smaller Q² \Rightarrow larger γ^* transv. size \Rightarrow more absorption

Comparison γp /DIS: LN x_L spectra

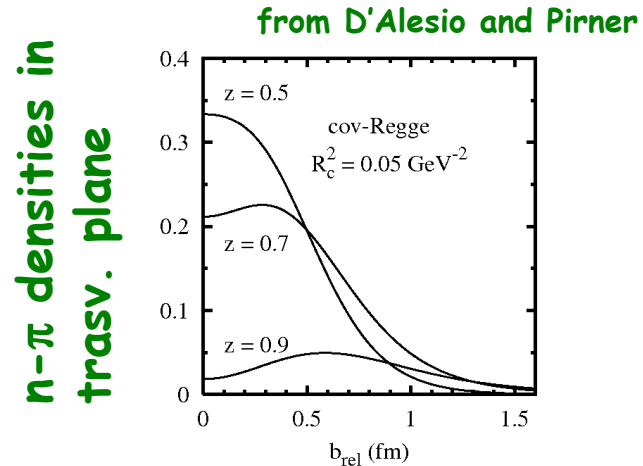
All DIS $Q^2 > 2 \text{ GeV}^2$ combined together

- Ratio γp /DIS LN yields

ZEUS



- ✓ Ratio rises with increasing x_L
- ✓ Consistent with absorption picture:

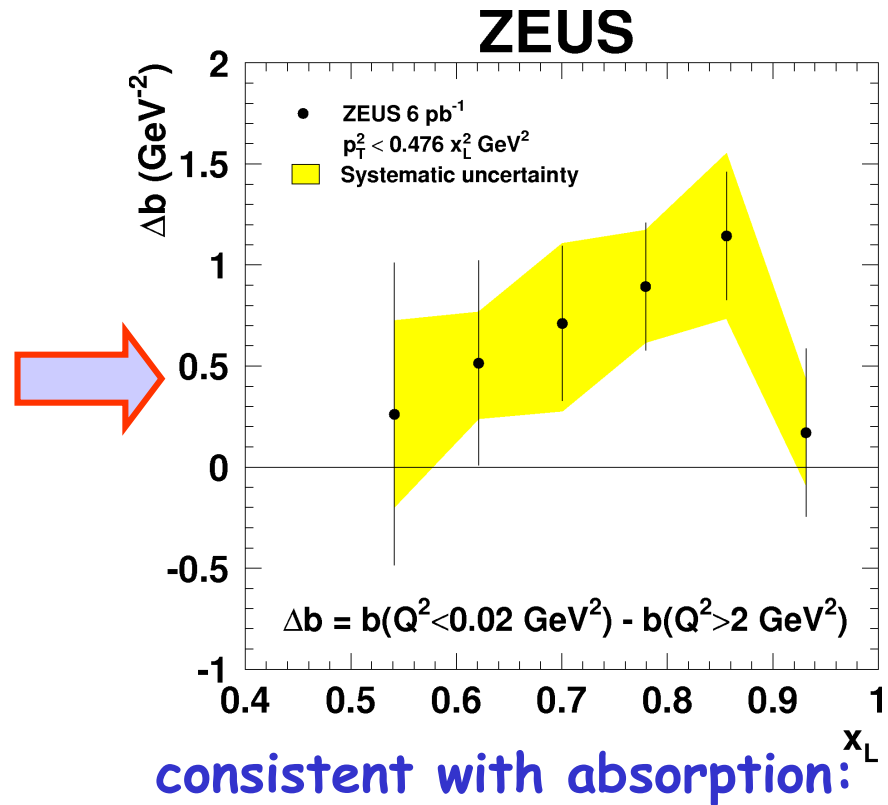
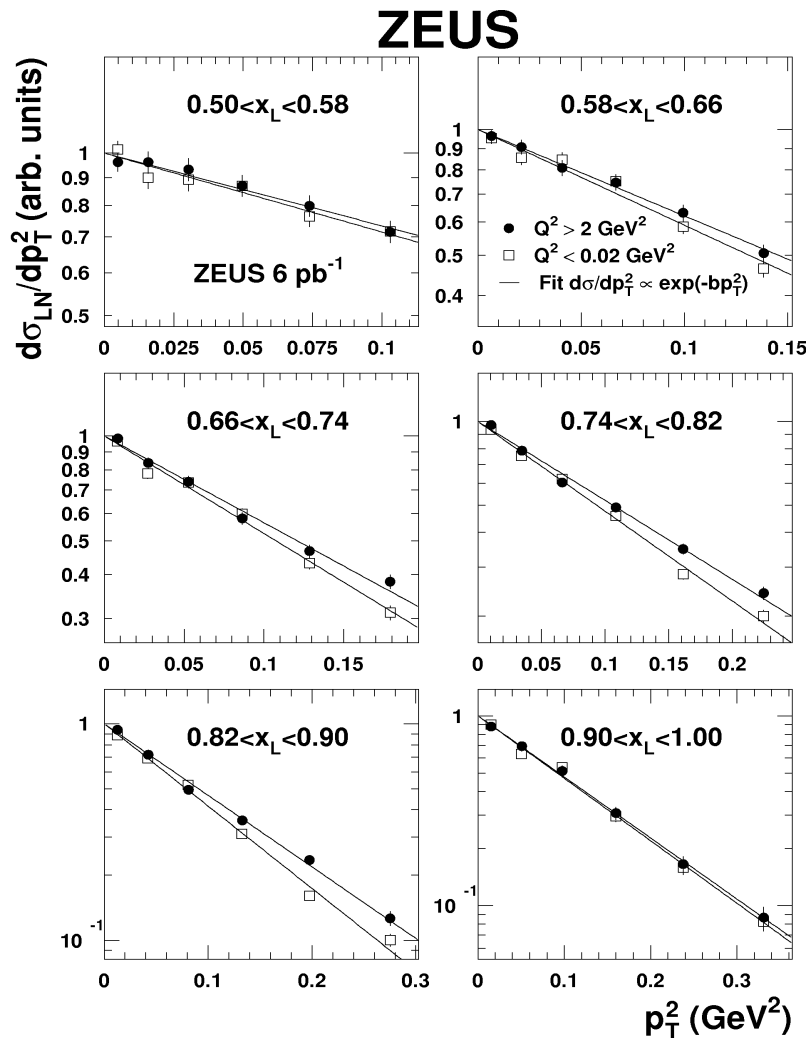


average n- π separation
 $r_{n\pi}$ increases with x_L

small n- π separation \rightarrow larger absorption

Comparison γp /DIS: LN p_T^2 distributions

Small but clear slope difference
DIS- γp at intermediate x_L



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 \rightarrow soft scale

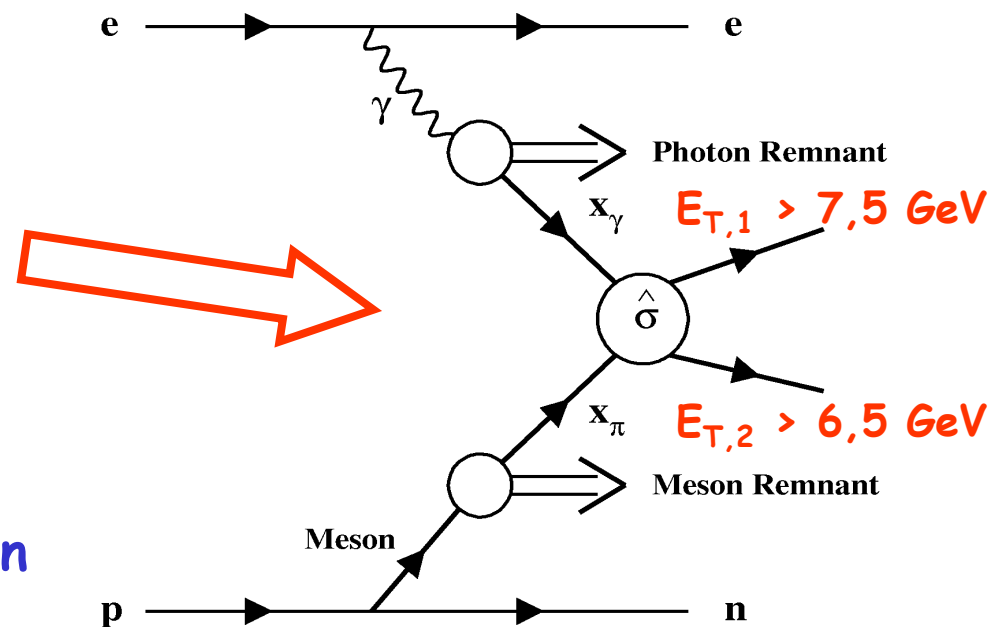
A hard scale in γp can be introduced by requiring high E_T jets

Still signs of absorption ?

Note:

Factorization breaking observed in diffractive dijet photoproduction.

(see Armen's talk \Rightarrow)



look at preliminary (2007) results from ZEUS !

Dijet photoproduction with LN: p_T^2 distributions

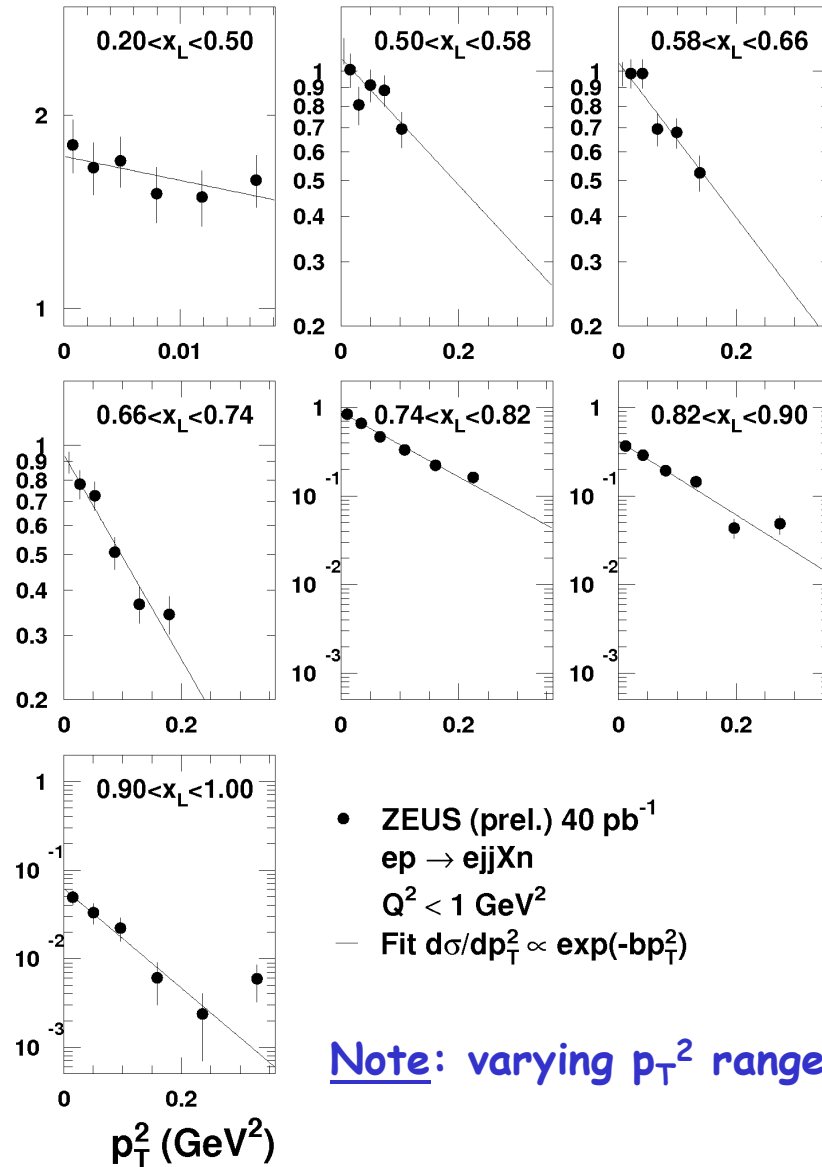
$$\frac{1}{\sigma_{inc}} \frac{d\sigma_{LN}}{dp_T^2 dx_L}$$

Normalized to the inclusive dijet cross section

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

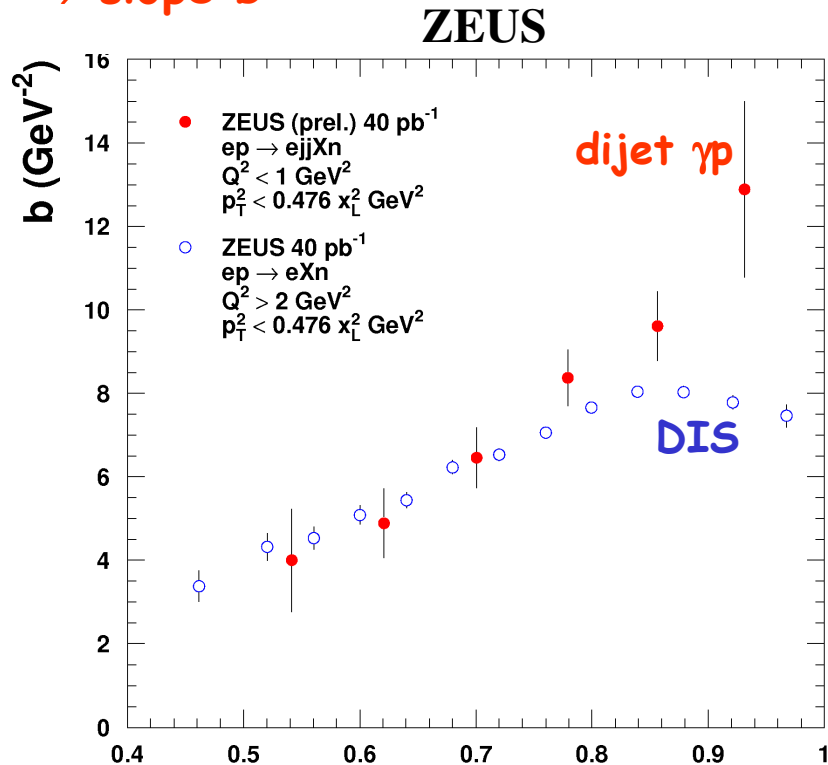
$$\frac{1}{\sigma_{inc}} \frac{d\sigma_{LB}}{dp_T^2 dx_L} \sim e^{-b(x_L)p_T^2}$$

ZEUS



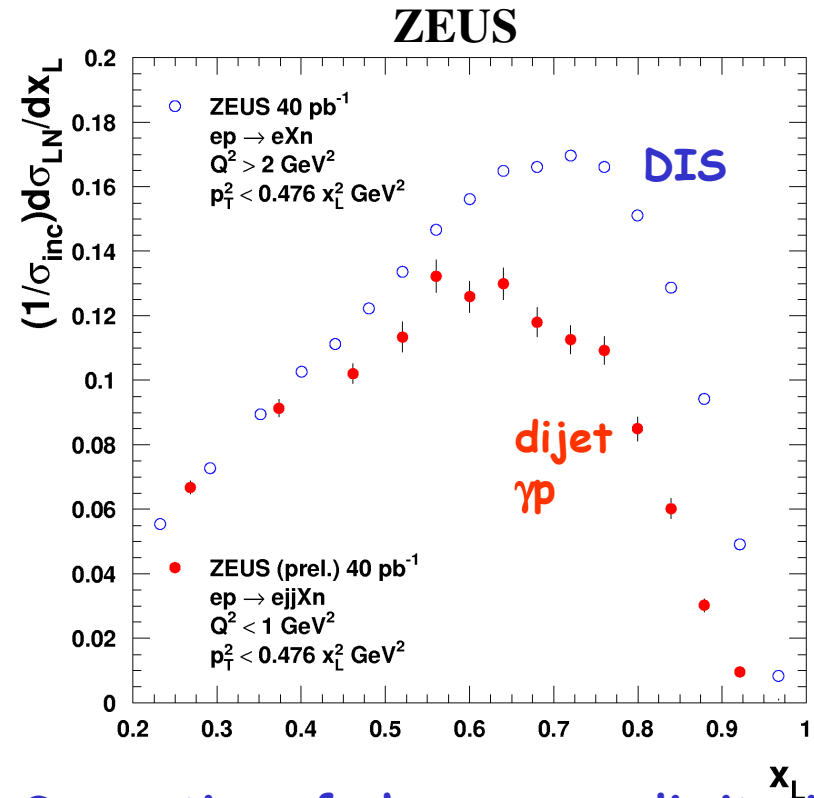
Dijet photoproduction with LN vs. DIS

LN p_T^2 dist. fitted with exponential
 \Rightarrow slope b



- Slopes have similar magnitude x_L
- 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



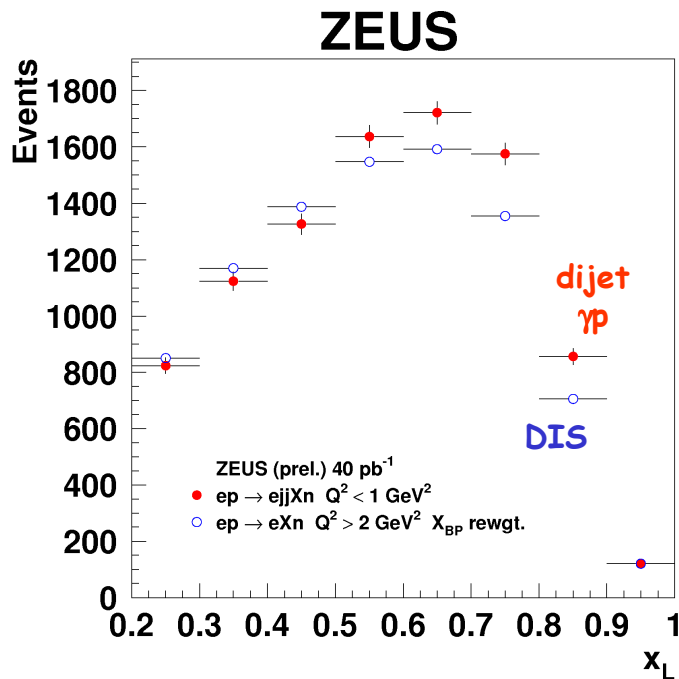
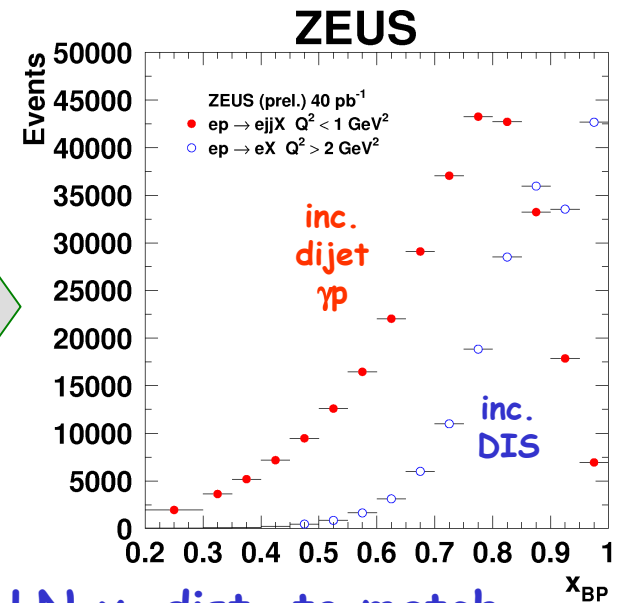
LN in dijet γp vs. DIS: kinematic constraints

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

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

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

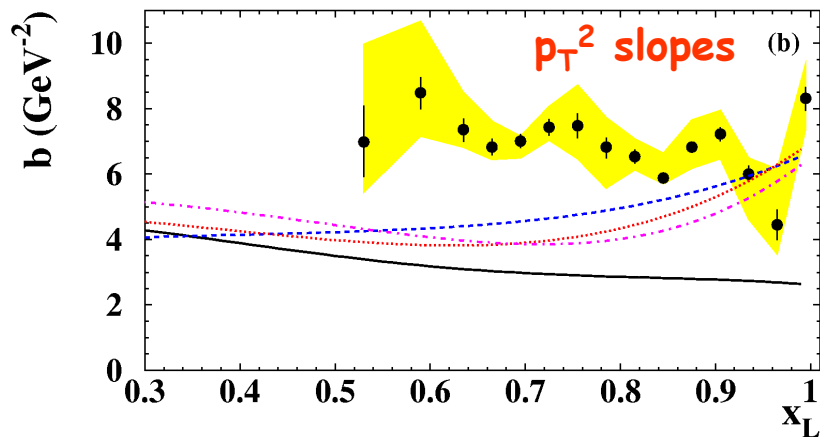
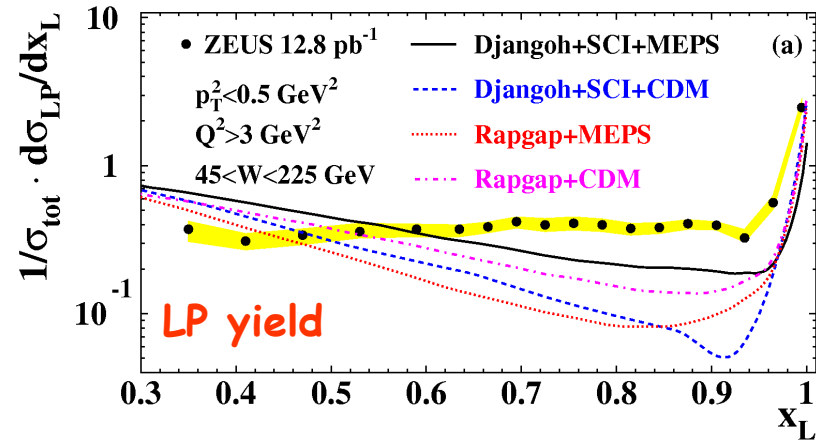
Tentatively: differences in the x_L spectra due to kin. suppression. More accurate MC studies of kinematic effects ongoing ...

Hard to draw any conclusion on absorption !

Comparisons with models

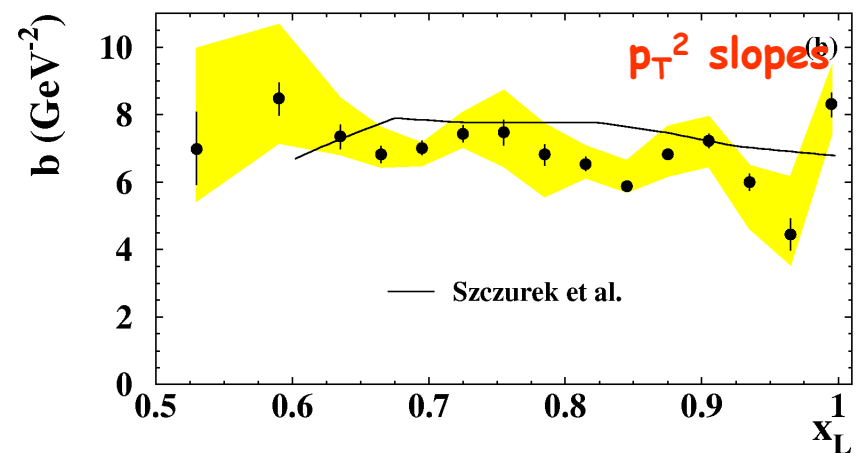
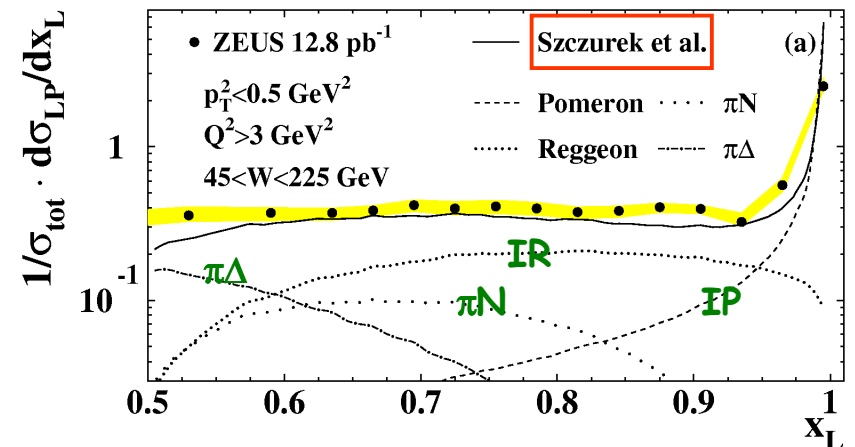
Model comparisons: DIS LP

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

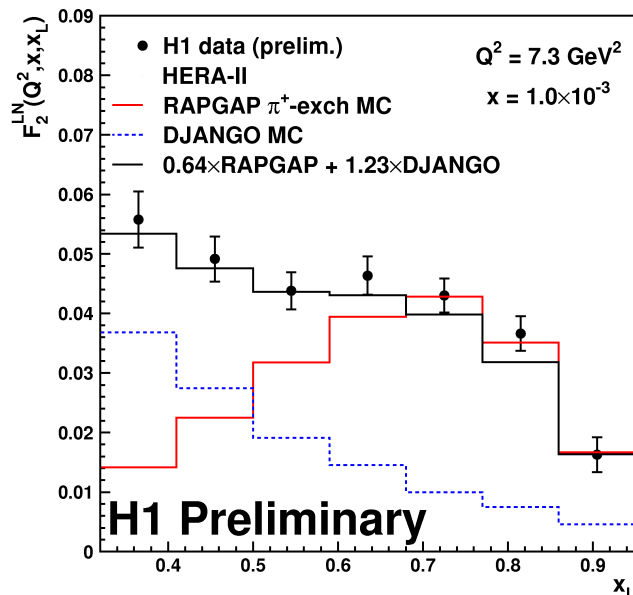


- Good description of LP yield and slope by adding different exch.
- iso-scalar reggeon dominant at intermediate x_L

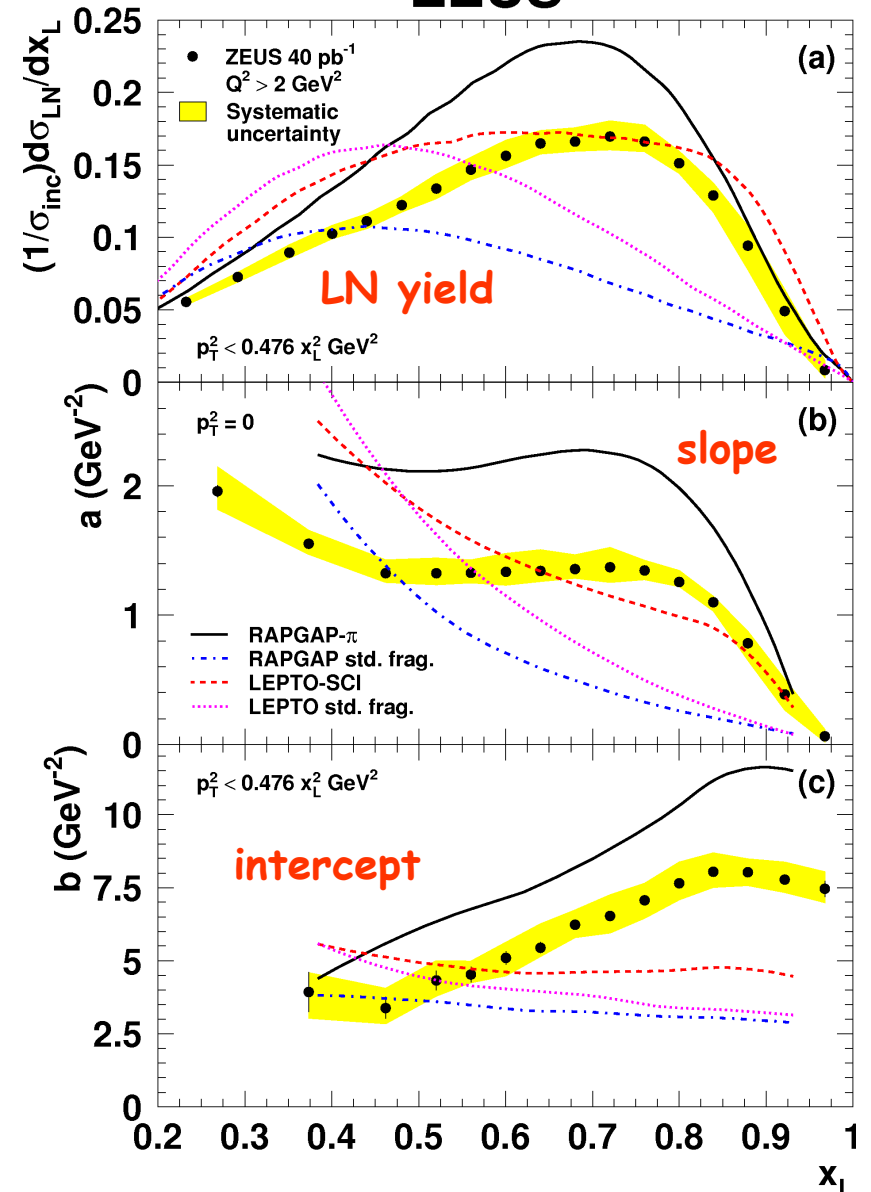
Comparisons of DIS LN with MC models

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



ZEUS



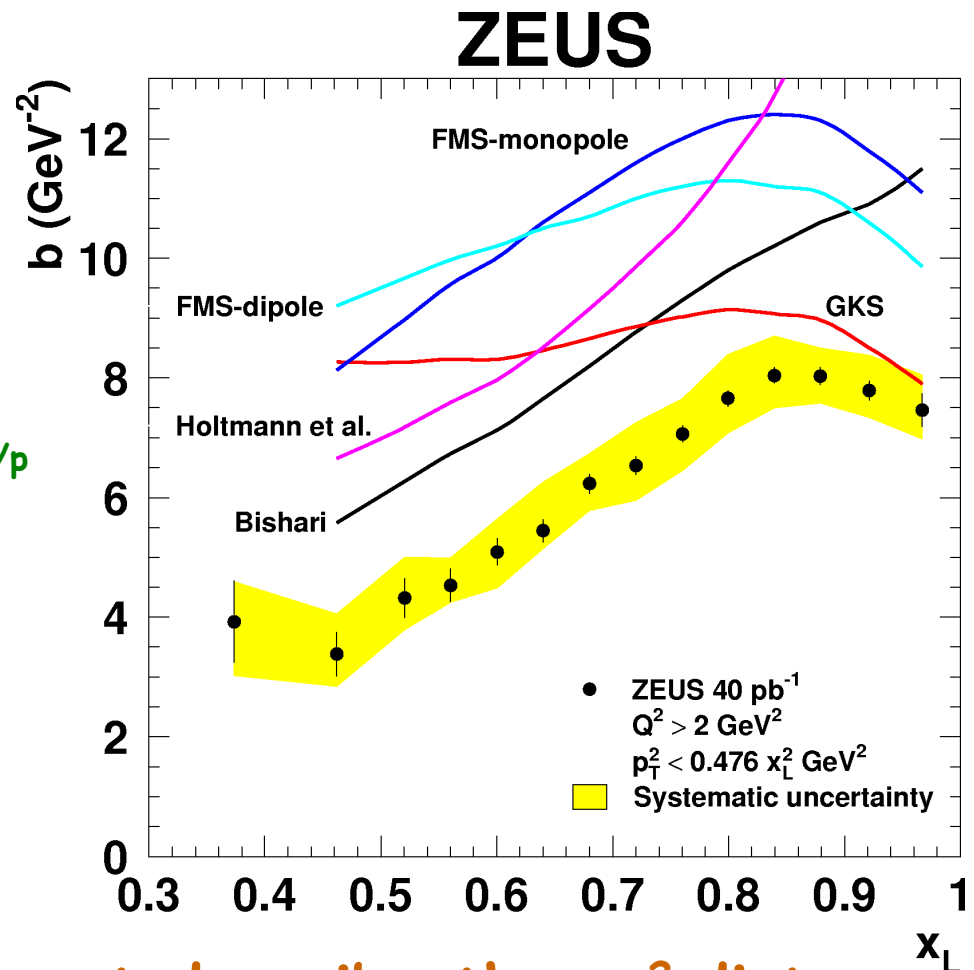
Comparisons of DIS LN with pion exch. models

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

- ✓ 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

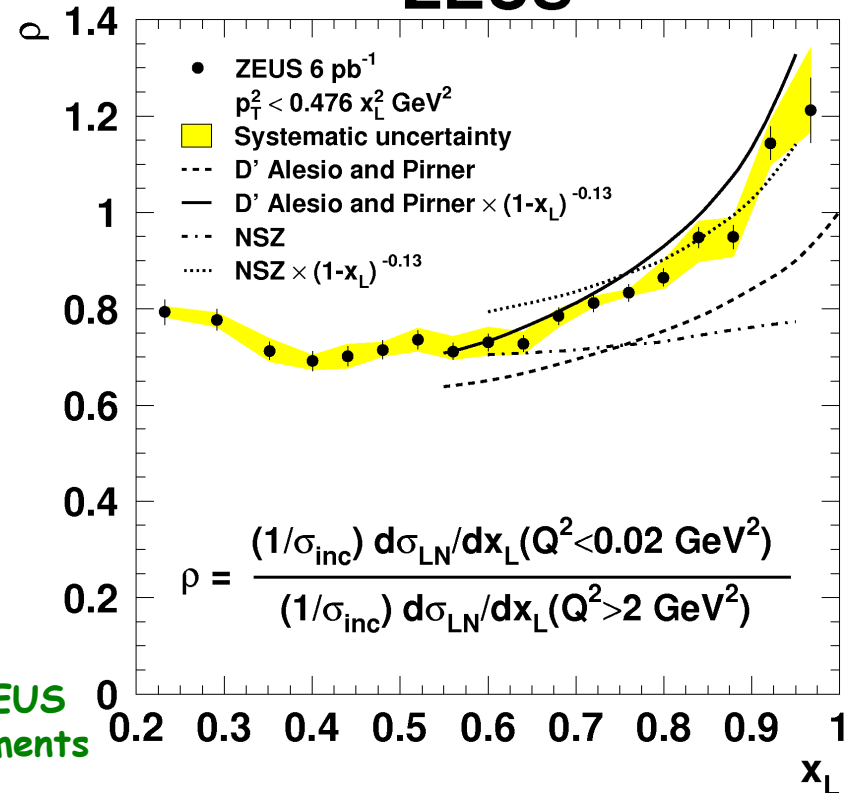
Scaling absorption ratio by $(1 - x_L)^{-0.13}$



better agreement with data

Ratio γp /DIS vs. x_L

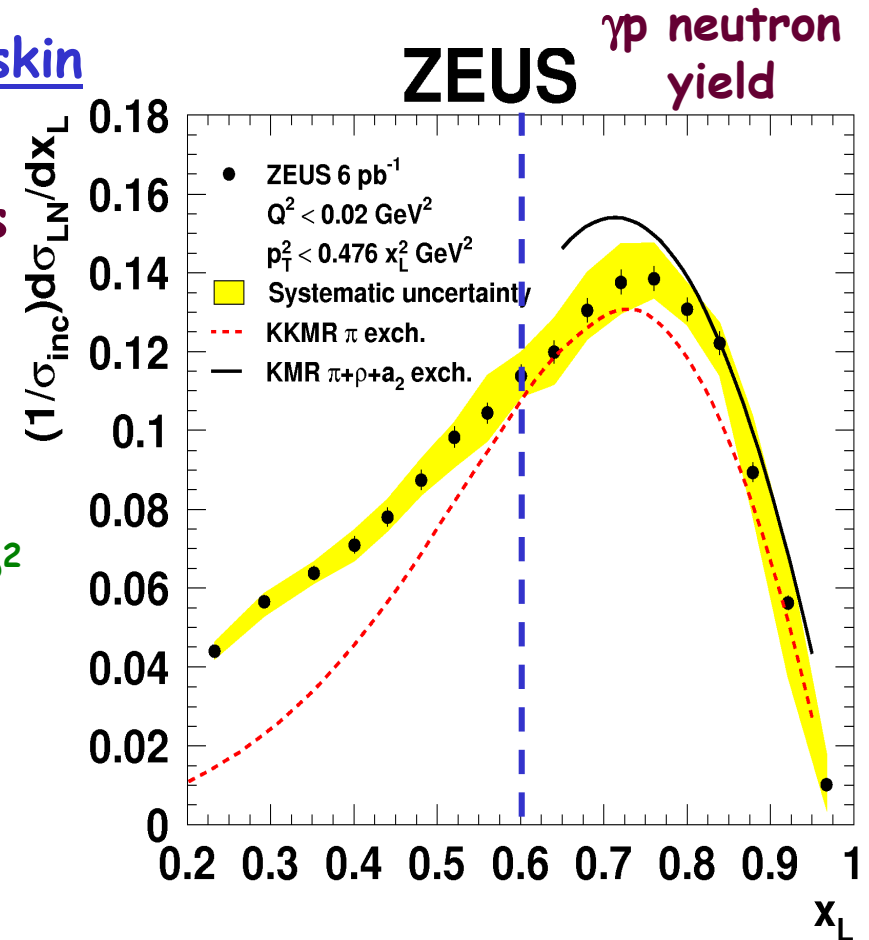
ZEUS



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 $\sim 50\%$ abs. loss in γp
 - related to gap survival prob. S^2
- extended (KMR) to include exchange of secondary (ρ, a_2) reggeons.



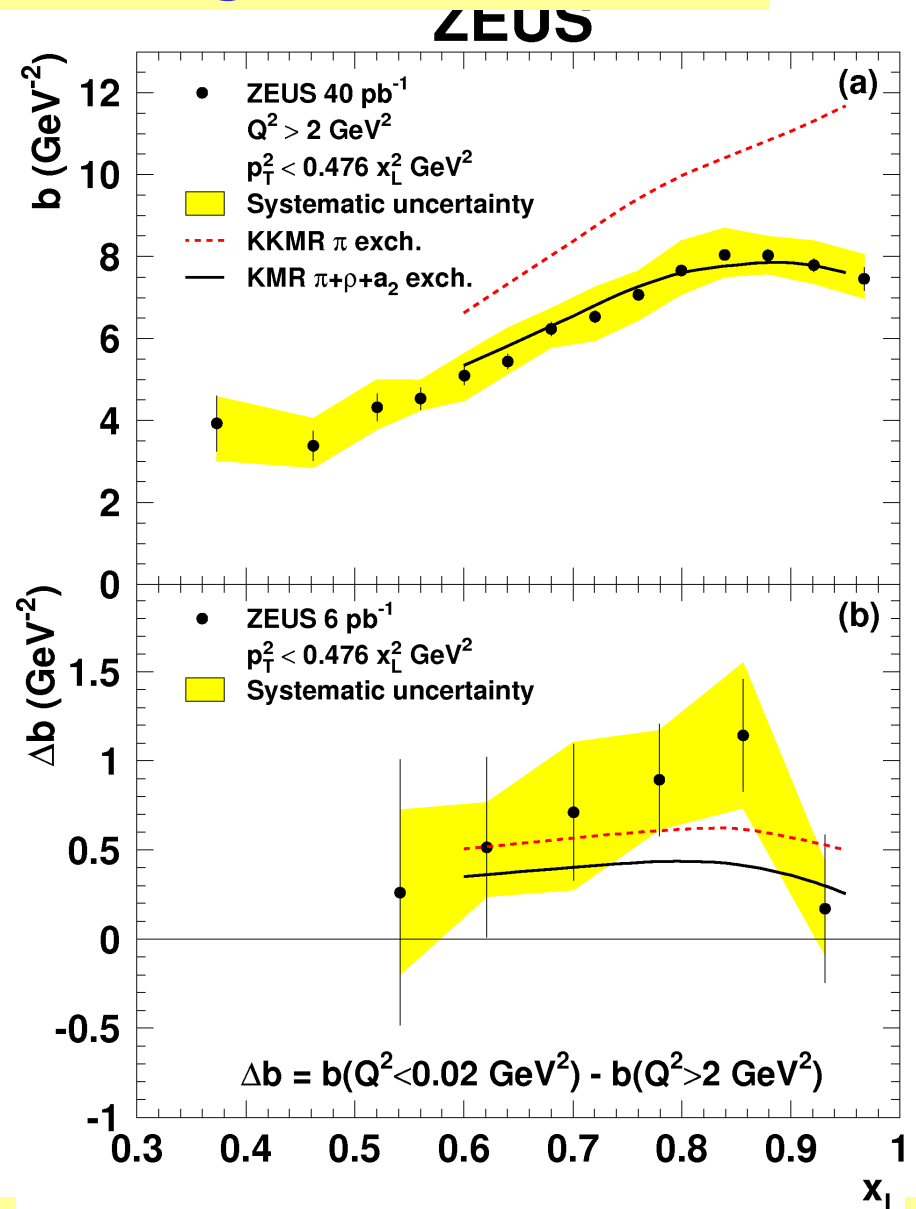
Good description of LN yield in γp

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

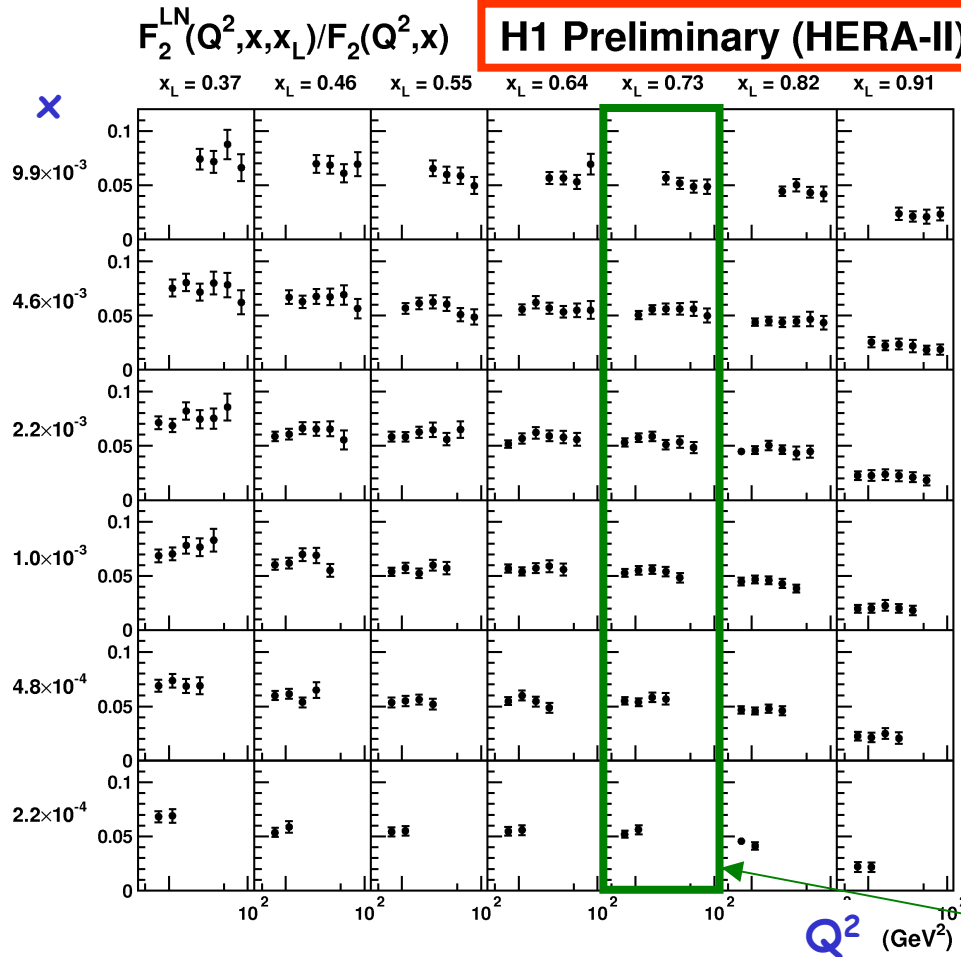


LB structure functions and F_2^π

LN structure function F_2^{LN}

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

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



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

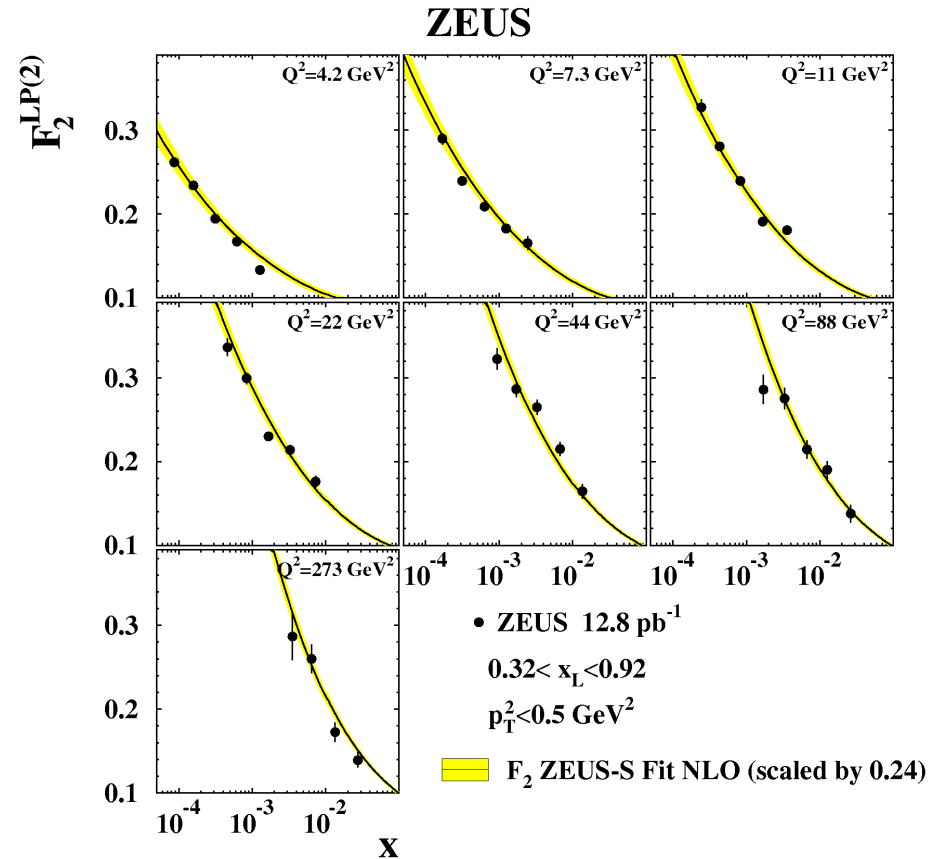
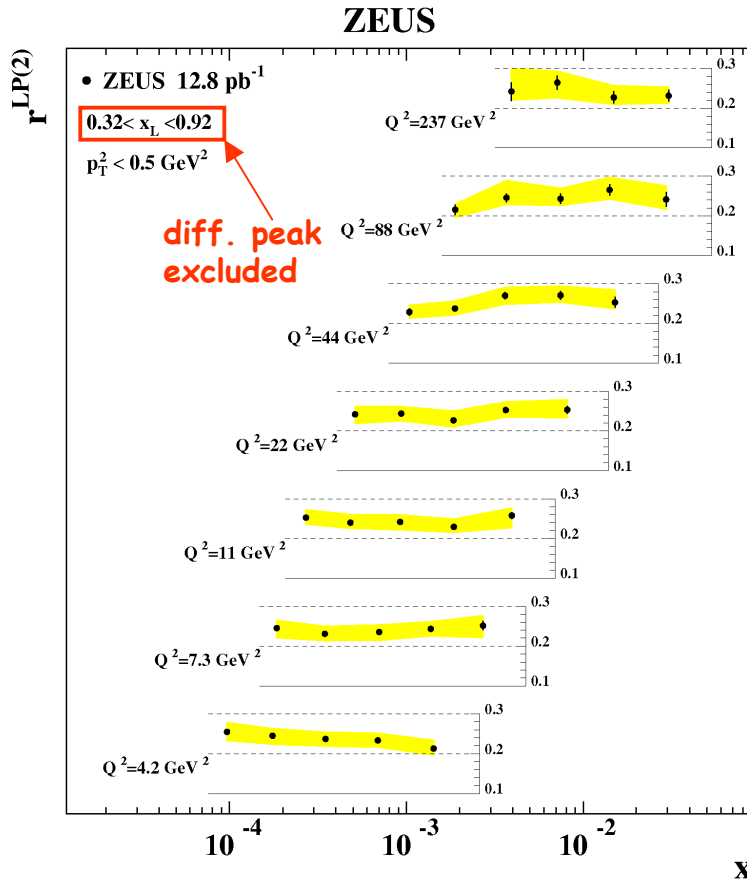
x_L bin used for π str. function

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

LP structure function F_2^{LP}

Similar behaviour for LP structure function F_2^{LP}

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



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

same trend as F_2 observed

Pion structure function F_2^π

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

$\beta = x/(1-x_L) \Rightarrow$ 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

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

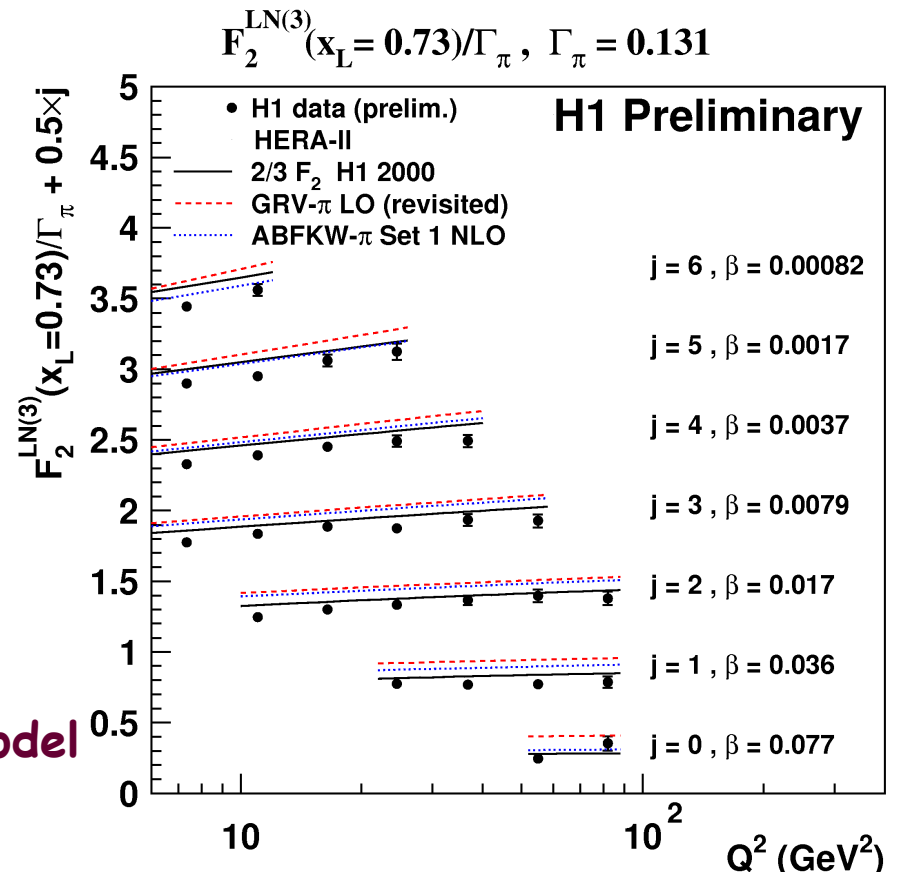
then extract $F_2^\pi = F_2^{\text{LN}}/\Gamma_\pi$

Results compared with:

• expectations from additive quark model

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

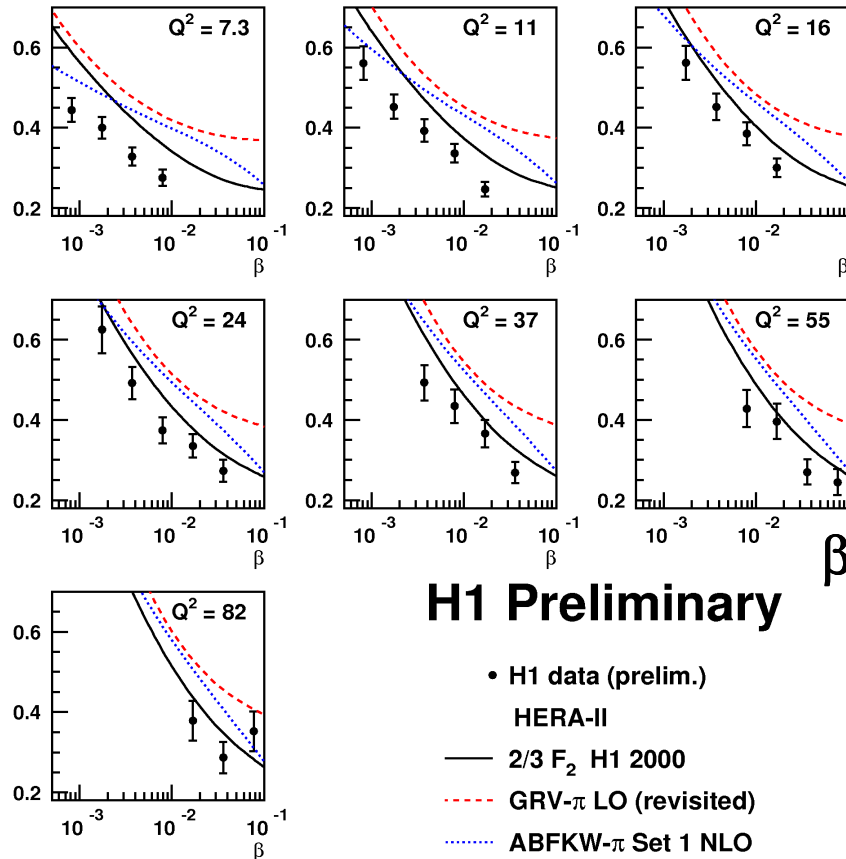
• Pion p.d.f. parametrizations (GRV, ABFKW shown here)



Pion structure function F_2^π

F_2^π vs β at fixed Q^2

$$F_2^{\text{LN}(3)}(x_L = 0.73)/\Gamma_\pi, \Gamma_\pi = 0.131$$



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 $F_{\pi}^2(x, Q^2)$