13th International Conference on Elastic & Diffractive Scattering
CERN, 29th June - 3rd July 2009

Soft interaction processes at HERA (leading baryons, multiple interactions)

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representing the H1 and ZEUS Collaborations

Outline:

- Leading baryon production
  - comparison with models
  - estimation of pion structure function
  - absorption/rescattering effects

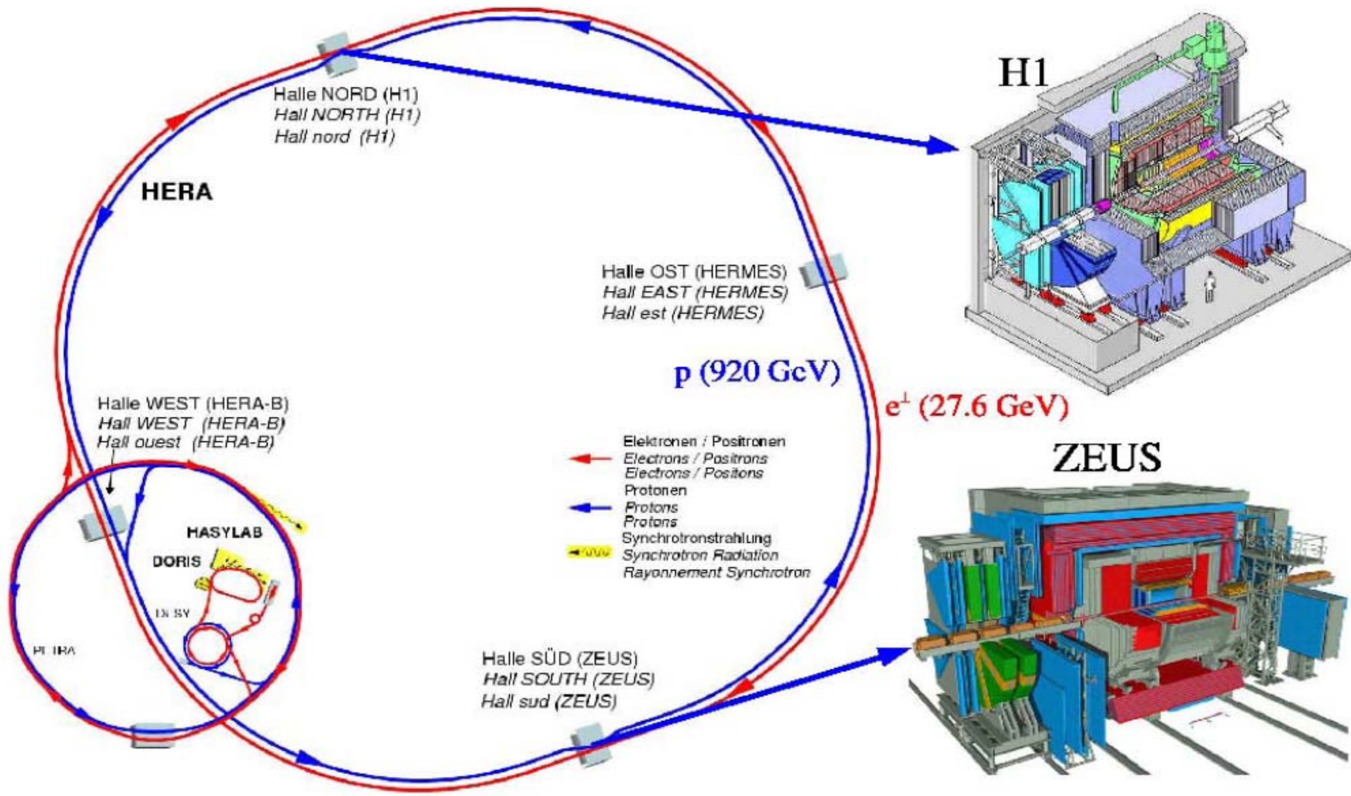
- Studies of multi-parton interactions in photoproduction

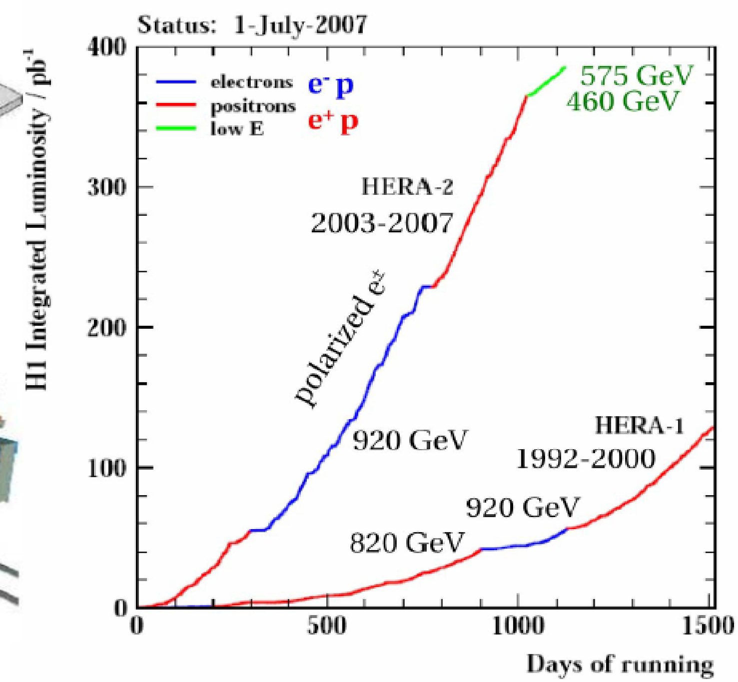
HERA

The world's only electron/positron-proton collider at DESY, Hamburg

E_e = 27.6 GeV E_p = 920 GeV (also 820, 460 and 575 GeV)

(total centre-of-mass energy of collision up to $\sqrt{s} \approx$ 320 GeV)



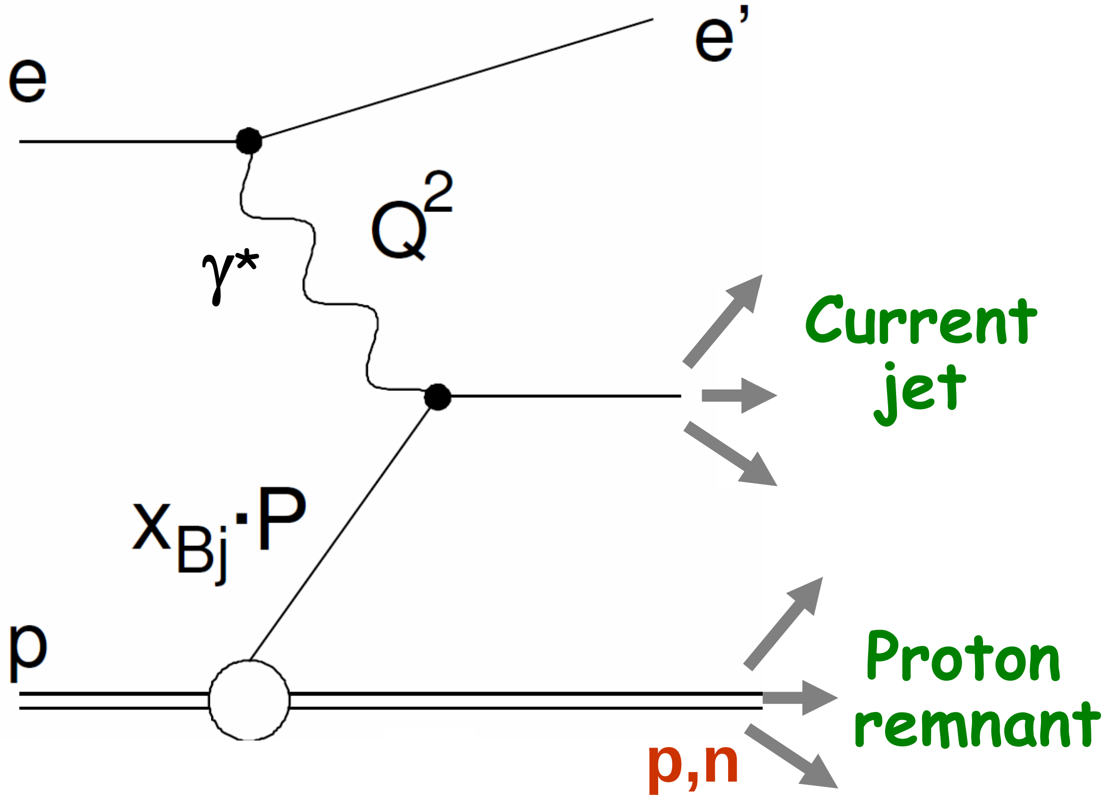


Two colliding experiments: H1 and ZEUS

HERA-1: 1992 – 2000

HERA-2: 2003 - 2007

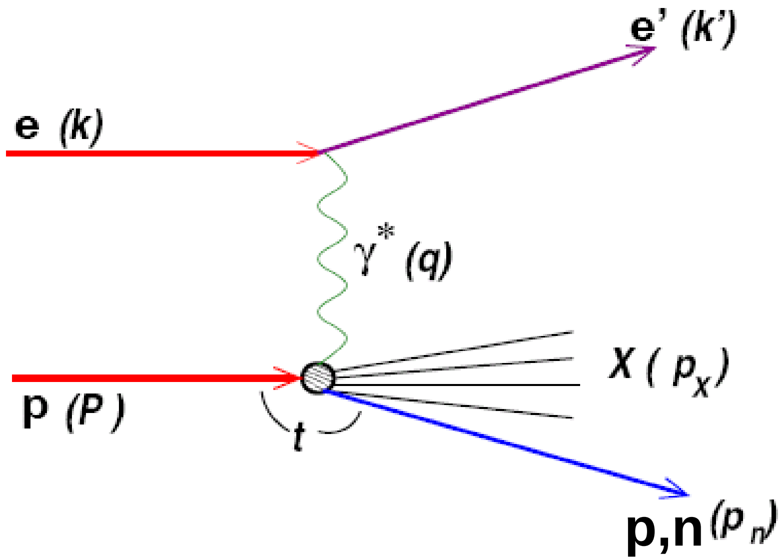
total lumi: 0.5 fb^{-1} per experiment

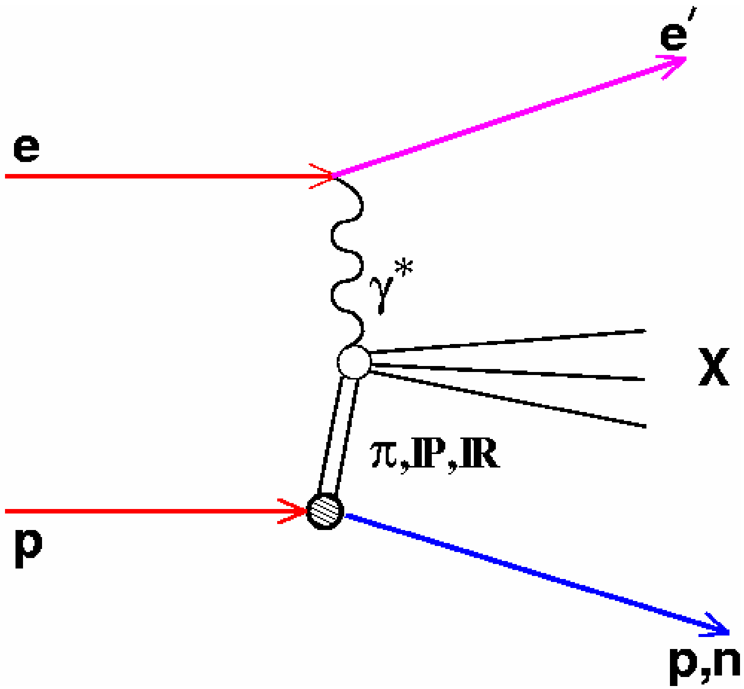


scale for secondary particle production decreases from Q^2 in current region (or high P_T jets if Q^2~0) to a soft hadronic scale (proton fragmentation region)

Significant fraction of *ep* scattering events contains in the final state a leading proton or neutron which carry a substantial portion of the energy of the incoming proton: e+p → e'+n+X or e'+p+X

Production mechanism of leading baryons:

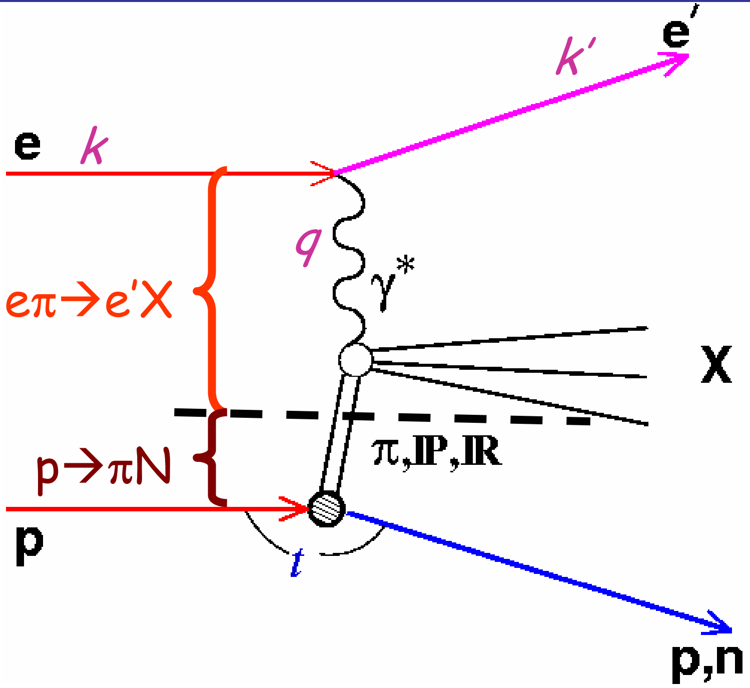




'conventional' fragmentation of proton remnant (e.g. Lund string)

exchange of virtual particle

- LP: neutral iso-scalar, iso-vector (π, IR, IP)
- LN: charged iso-vector ($\pi+$, $\rho+$, a_2..)



ep→ e'XN

Lepton variables:

$Q^2=-(k-k')^2$

$x=Q^2/(2p\cdot q)$

Leading baryon variables:

$x_L=E_{LB}/E_p$

$t=(p-p_{LB})^2$ (or $p^2_{T,LB}$)

In the exchange model the cross sections factorise, e.g. for one pion exchange

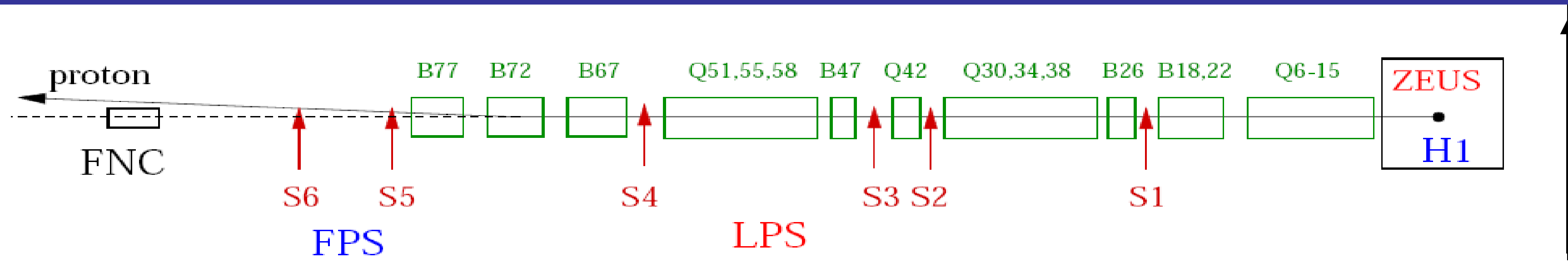
$$\sigma(ep\rightarrow e'NX) = f_{\pi/p}(x_L,t) \times \sigma(e\pi\rightarrow e'X)$$

$f_{\pi/p}(x_L,t)$ - pion flux:
probability to emit pion from the photon with given x_L,t

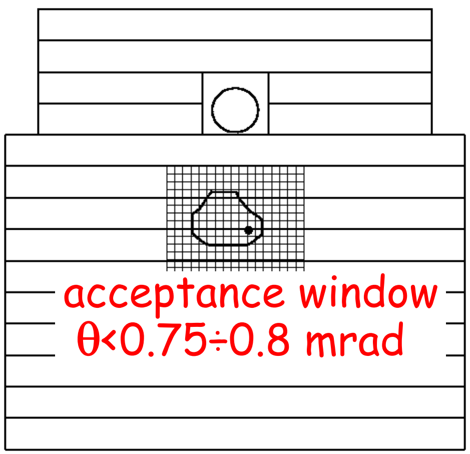
$\sigma(e\pi\rightarrow e'X)$ - cross-section of eπ scattering

-LB production independent from photon vertex
-probe structure of exchanged particle
-factorisation violation predicted– absorption/rescattering

H1 and ZEUS detectors for leading baryons

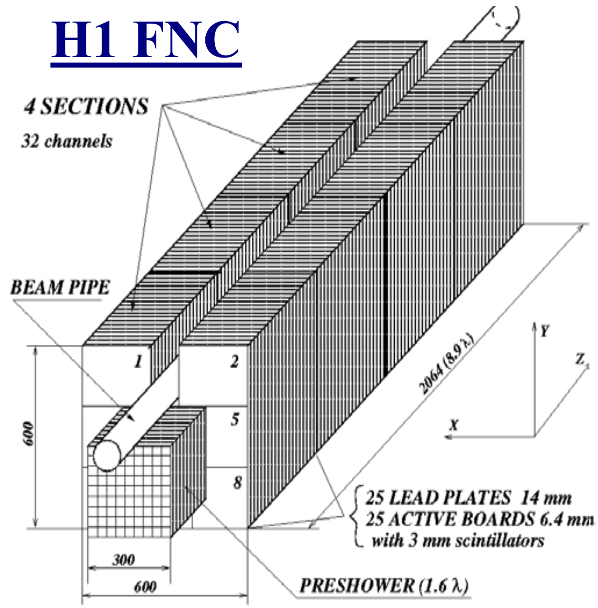


ZEUS FNC+FNT



14 towers, 17x15 grid
of the FNT hodoscopes,
$\sigma_E/E \approx 0.7/\sqrt{E}$

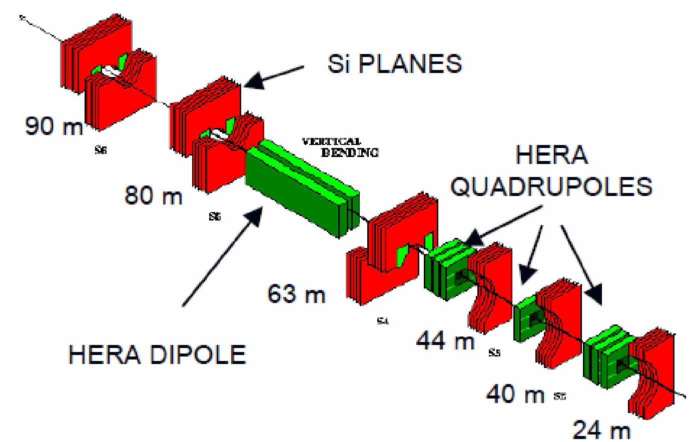
H1 FNC



$\sigma_E/E \approx 0.63/\sqrt{E} \oplus 2\%$

position resolution 2-3mm

ZEUS LPS

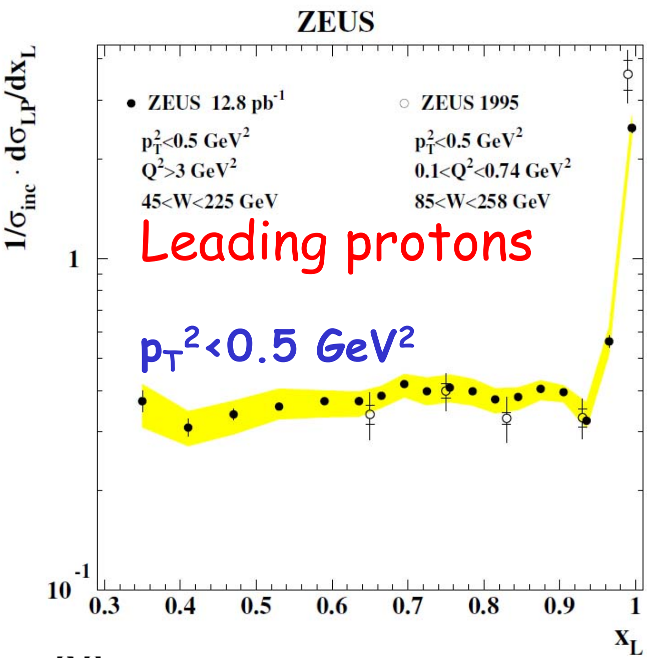


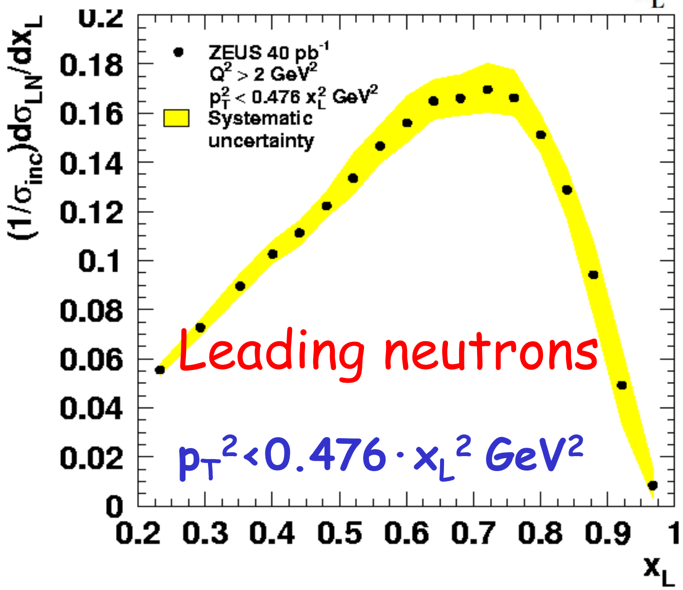
6 stations with μstrip detectors
hit position resolution ~30μm
$\sigma_{XL}<1\%$, σ_{PT}~few MeV

momentum accuracy <1%

Acceptance limited by beam apertures and detector size
p_T resolution is dominated by p_T spread of proton beam (50-100 MeV)

Cross sections vs x_L normalised to σ_{DIS} ($1/\sigma_{DIS} \cdot d\sigma/dx_L$)





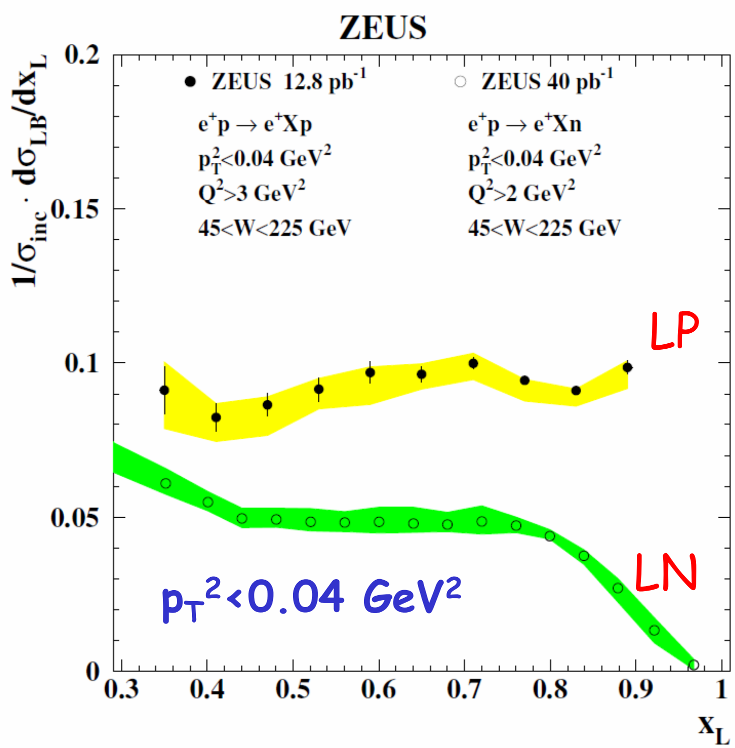
Leading protons: (DESY-08-176)

- diffractive peak at x_L=1 ; flat at x_L<0.95

Leading neutrons: (Nucl.Phys.B776(2007)1)

- yield → 0 as x_L → 1 ;
- drop at x_L< 0.7 due to drop in acceptance

restrict to the same p_T^2 range

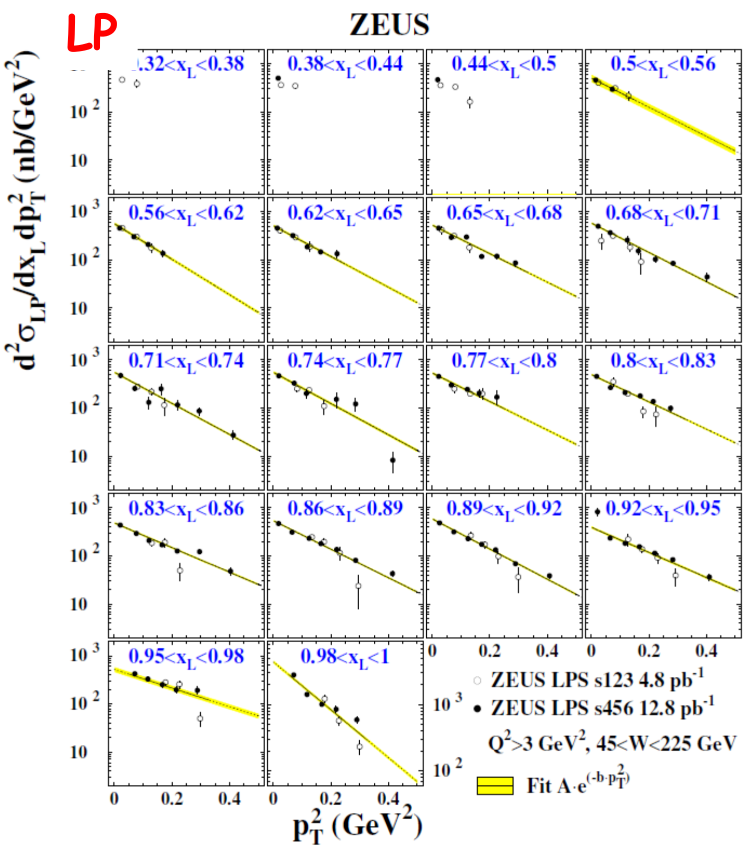


- measurement:
  LP ~ 2·LN
- for pure isovector particle exchange (e.g. pion) one expects
  LP = ½·LN

  → more isoscalar exchanges contribute to the LP rates

Double differential cross sections vs p_T^2, x_L

DESY-08-176



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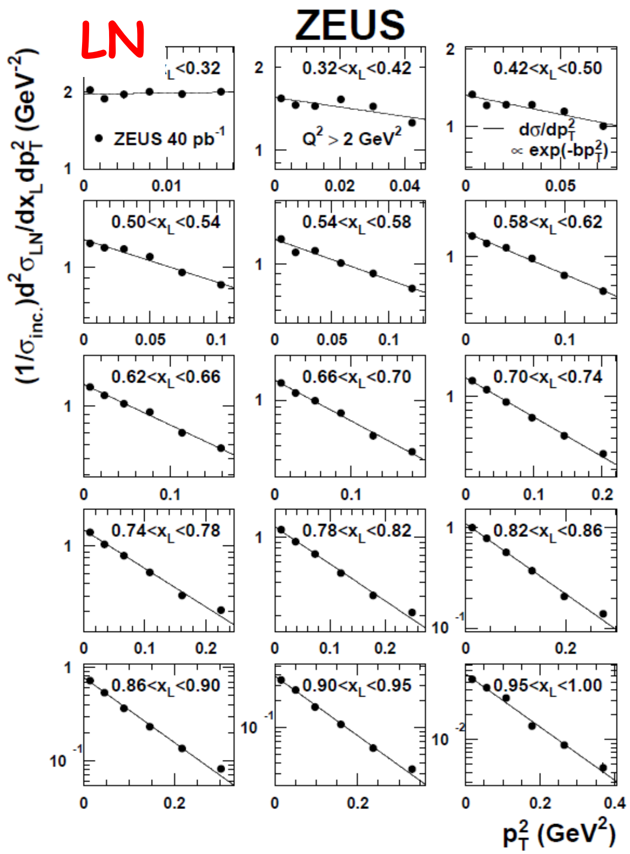
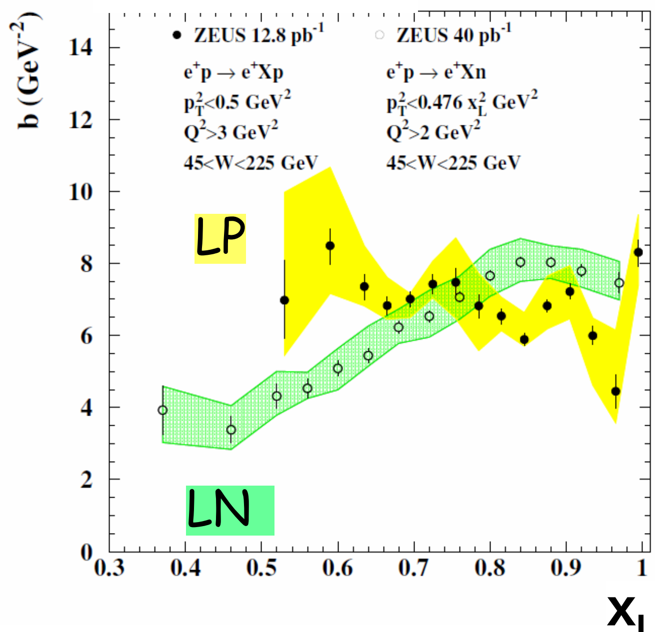


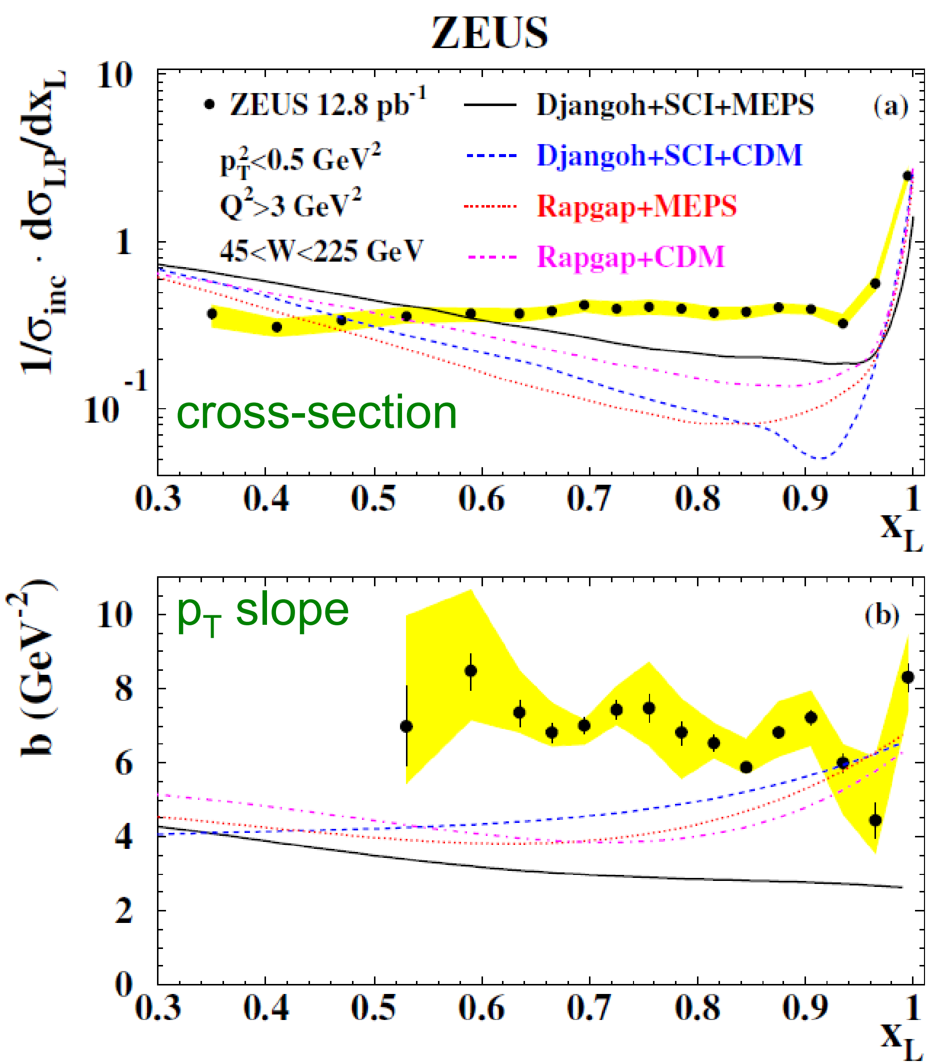
Exponential behavior

$$\frac{d^2\sigma}{dx_L dp_T^2} \sim a(x_L)\, e^{-b(x_L)p_T^2}$$

slope $b(x_L)$



- different behavior for LP and LN
- similar around $x_L \sim 0.7$



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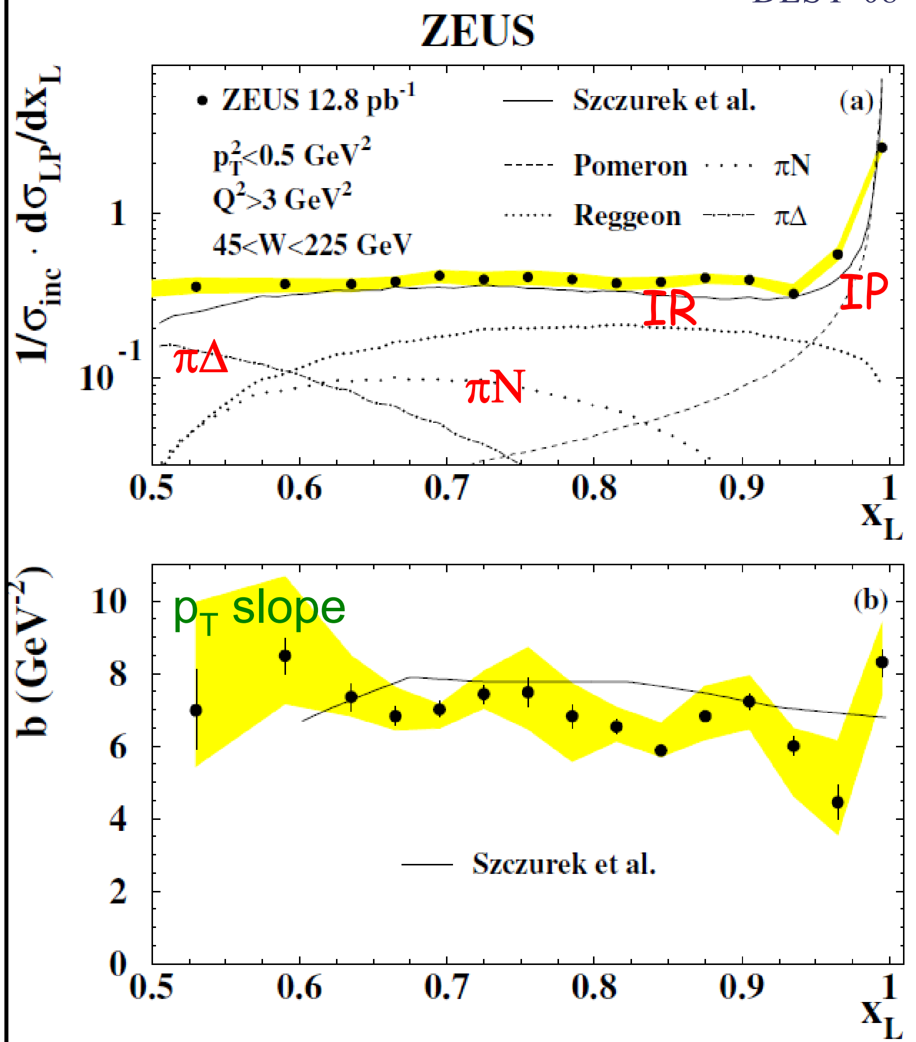

- standard fragmentation MC models don't describe the data out of the diffractive peak
- slopes too low at low x_L

- good description by exchange models
- isoscalar reggeon dominant at intermediate x_L

- all standard fragmentation models underestimate the neutron yield at high x_L
- LEPTO-SCI better for x_L shape, but not for the slope

- RAPGAP-π-exchange describes data well for x_L>0.6, underestimate data at lower x_L

- Mixture of RAPGAP-π-exchange and std. fragmentation (e.g. DJANGO-CDM) gives the best description of the data

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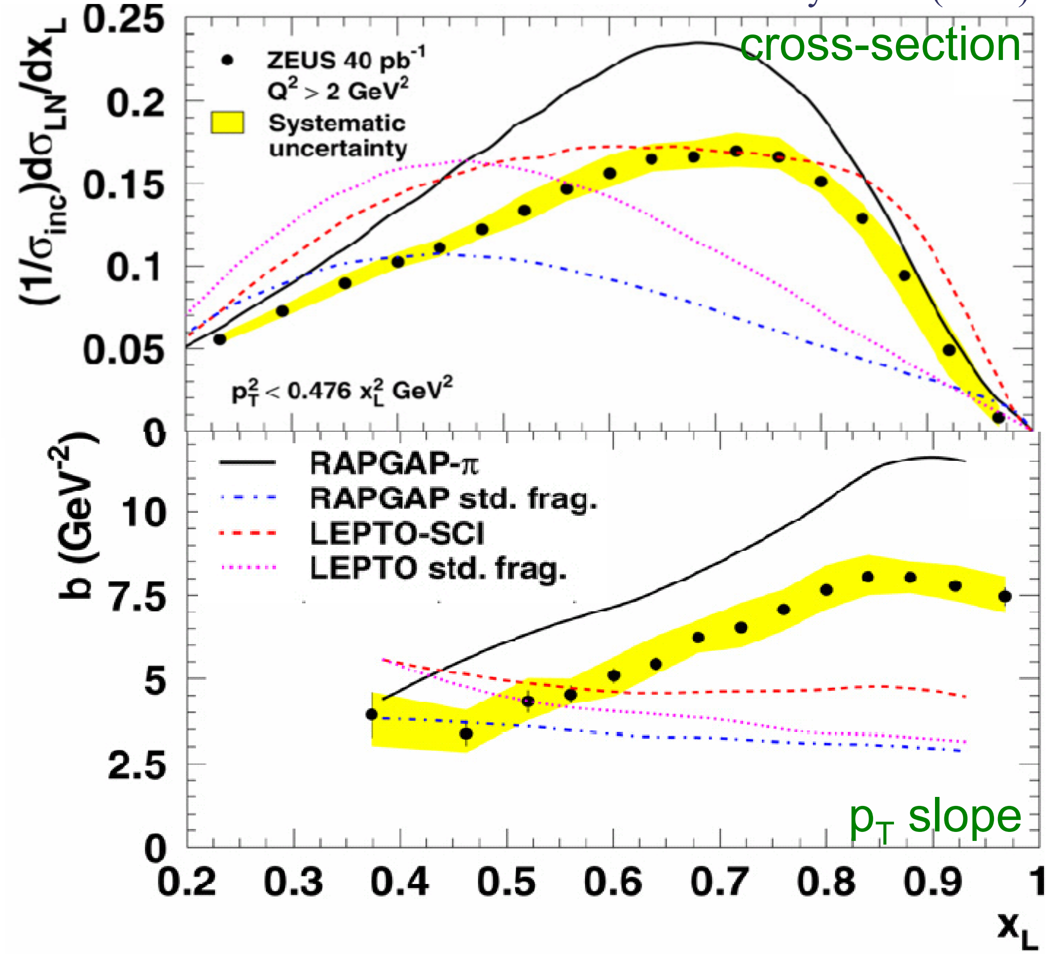

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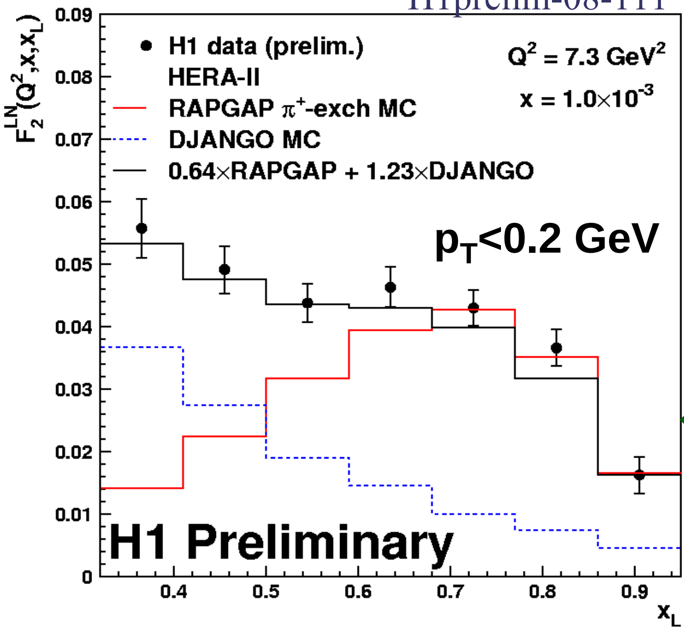

← F_2^{LN} – reduced DIS cross section

$$\frac{d^3\sigma(ep \to eNX)}{dQ^2 dx\, dx_L} = \frac{4\pi\alpha^2}{xQ^4}\left[1 - y + \frac{y^2}{2}\right]\cdot F_2^{LN}(Q^2, x, x_L)$$

Estimate the Pion structure function from $F_2^{LN}(Q^2,x,x_L)$

within π^+-exchange model we may try to estimate F_2^{π} from measured F_2^{LN}:

$$F_2^{LN(3)}(\beta,Q^2,x_L) = \Gamma_\pi(x_L)\cdot F_2^{\pi}(\beta,Q^2)$$

where

$\beta = x/(1-x_L)$ - fraction of pion momentum carried by struck quark (i.e. x_{Bj} for pion)

$\Gamma_\pi(x_L)$ is integrated over t pion flux

$$\Gamma_\pi = \int f_{\pi/p}(x_L = 0.73, t)\,dt$$

use pion flux parameterisation (Holtmann et al.):

$$f_{\pi^+/p} = \frac{1}{2\pi}\frac{g^2_{p\pi\pi}}{4\pi}(1-x_L)\frac{-t}{(m_\pi^2-t)^2}\cdot\exp\left(-R^2_{\pi n}\frac{m_\pi^2-t}{1-x_L}\right)$$

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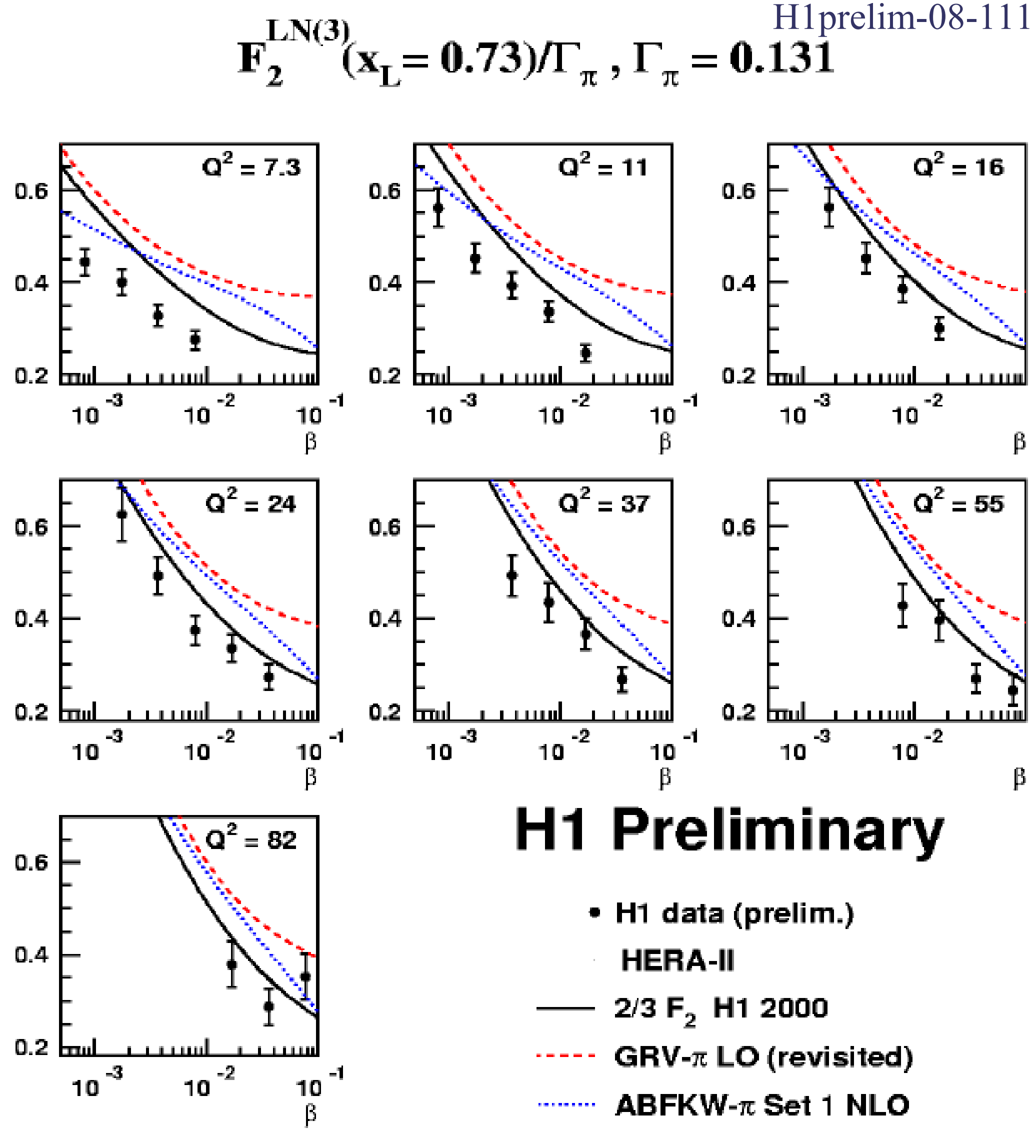

Data are sensitive to the parameterisations of the pion structure function (constrained for x>0.1 from the fixed target experiments).

Estimate the Pion structure function from $F_2^{LN}(Q^2,x,x_L)$

within π-exchange model we can estimate F_2^{π} from measured F_2^{LN}:

$$F_2^{LN(3)}(\beta,Q^2,x_L) = \Gamma_\pi(x_L)\cdot F_2^{\pi}(\beta,Q^2)$$

where

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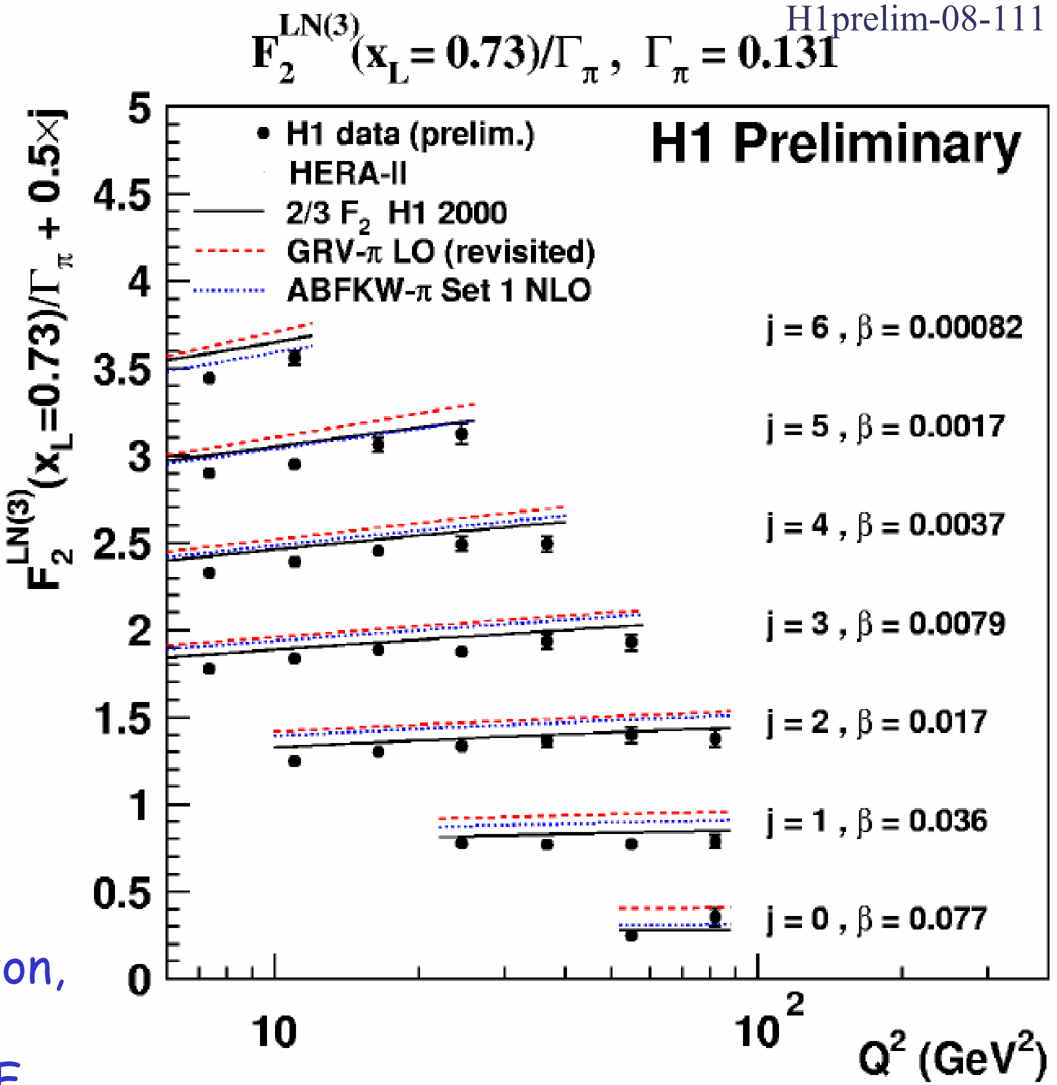


- F_2^{LN} dependence on x and Q^2 similar to proton, → universality of hadron structure at low x
- in absolute values F_2^{LN}/Γ below the F_2^{π} and F_2

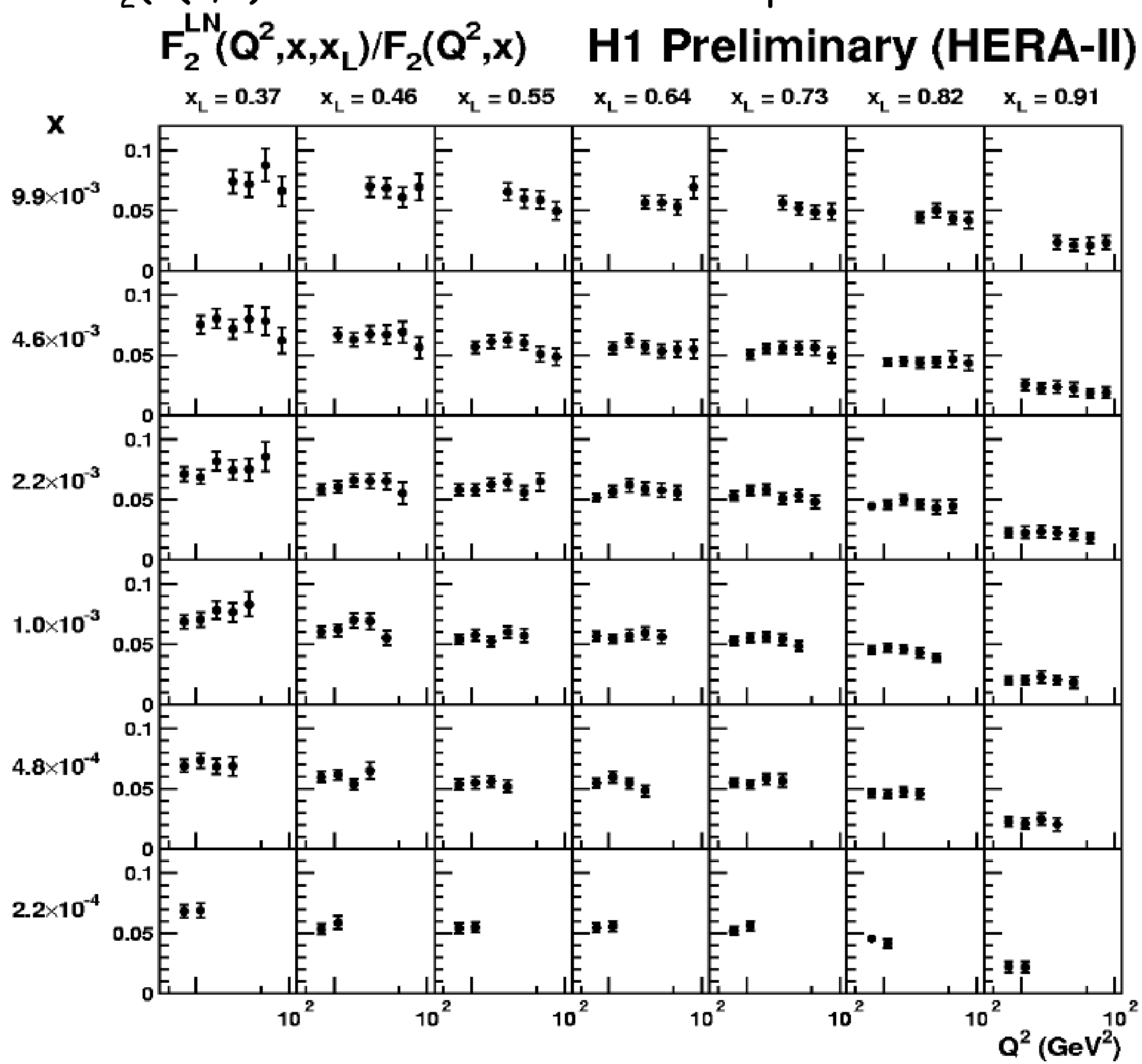
However: large uncertainty of pion flux normalisation: choice of pion flux (formfactor), absorption/rescattering, background…

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

$$\frac{d^3\sigma(ep \to eNX)}{dQ^2 dx\, dx_L} = \frac{4\pi\alpha^2}{xQ^4}\left[1 - y + \frac{y^2}{2}\right] F_2^{LN}(Q^2, x, x_L)$$

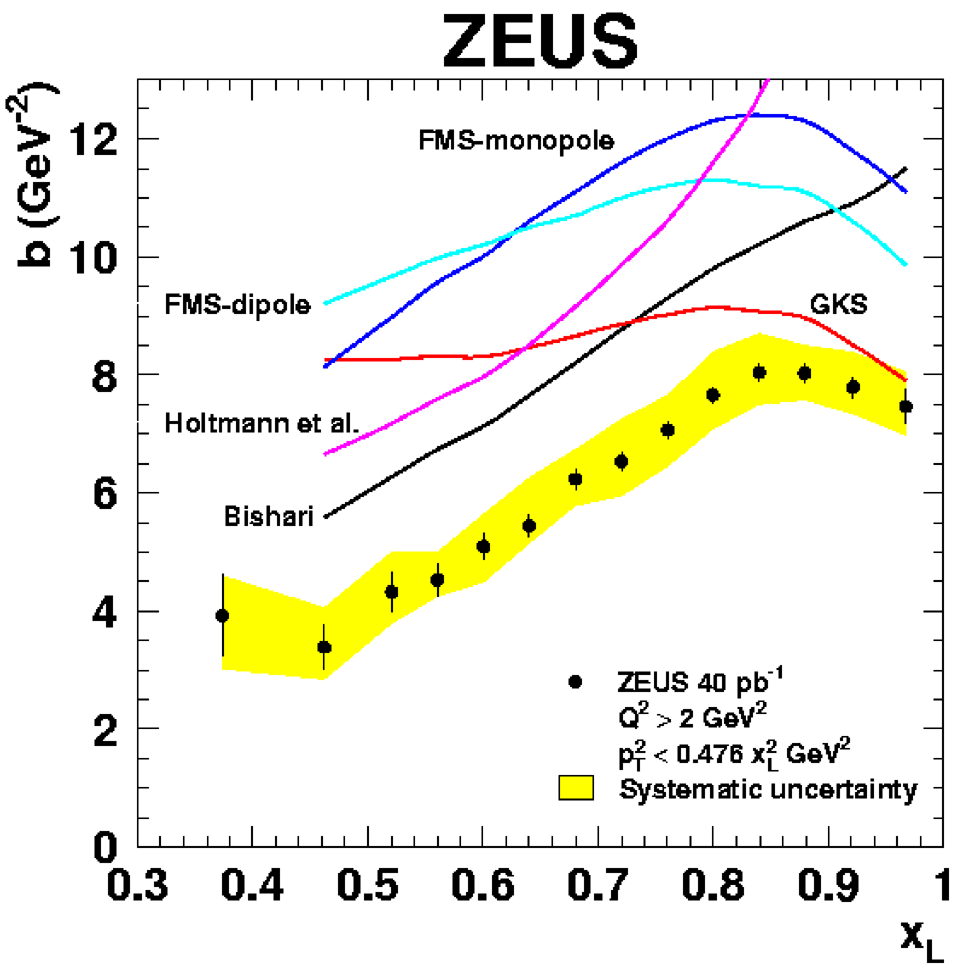
$6 < Q^2 < 100$ GeV^2 , $p_T < 0.2$ GeV

$F_2(Q^2,x)$ from the H1-2000-PDF parameterisation



$F_2^{LN}(Q^2,x,x_L)/F_2(Q^2,x)$ is mostly flat in Q^2 and x

i.e. LN production rate, kinematics is approx. independent of (Q^2,x)
➔ consistent with factorisation, limiting fragmentation (overall suppression of events is also possible)



in π-exchange

$$\sigma(ep \to e'nX) = f_{\pi/p}(x_L, t) \times \sigma(e\pi^+ \to e'X)$$

- p_T^2 (or t) distribution is determined solely by pion flux

$$f_{\pi/p} = \frac{1}{2\pi}\frac{g^2_{p\pi\pi}}{4\pi}(1-x_L)^{1-2\alpha(t)}\frac{-t}{(m_\pi^2-t)^2}\cdot|F(x_L,t)|^2$$

- many parameterizations of pion flux $f_{\pi/p}(x_L,t)$ in literature

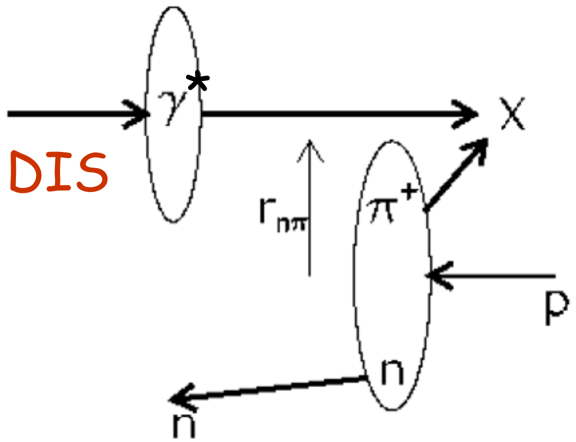
- compare measured p_T slope $b(x_L)$ with models (shown best agreeing models)

- reasonable agreement in shape but not in absolute values: all give too large $b(x_L)$

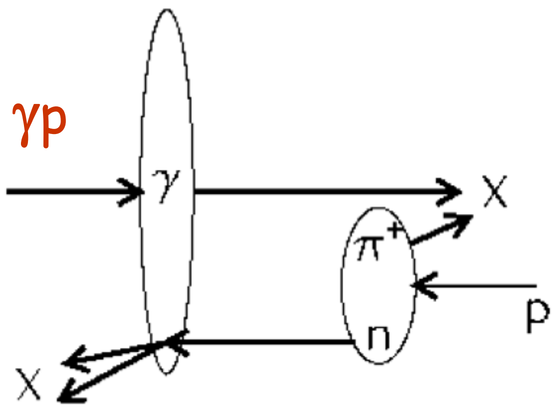
- π-exchange models alone don't describe p_T^2 -distribution

Absorption: important ingredient to interpret the results in terms of particle exchange

DIS



γp



Neutron absorption through rescattering:

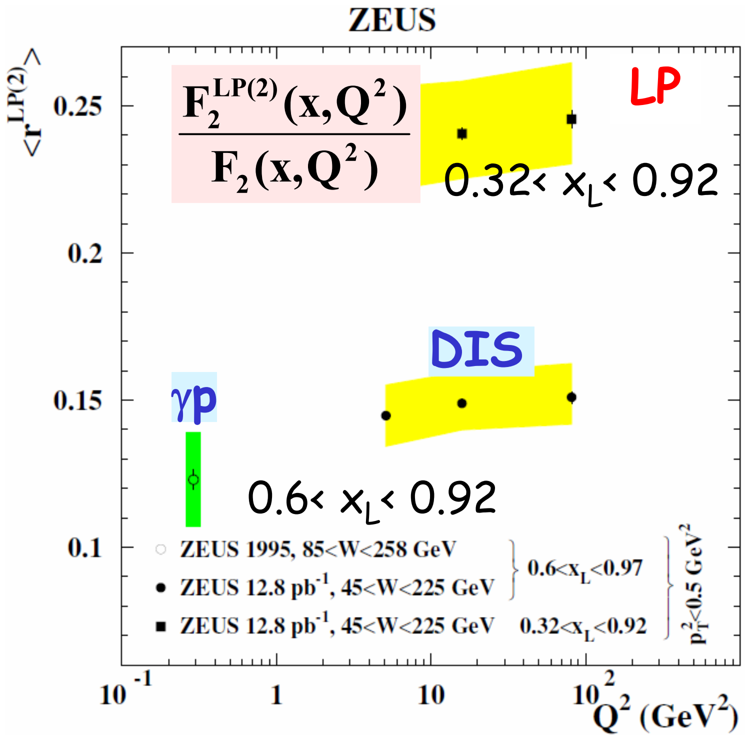
enhanced when π-n system size $r_{\pi n} \sim 1/p_T$ is small w.r.t. the γ-transverse size, e.g. at high p_T, low x_L
→neutron breaks up or
→is kicked to lower x_L,higher p_T (migration) and/or escapes detector acceptance (absorption loss)
(in other language: multi-Pomeron exchange)

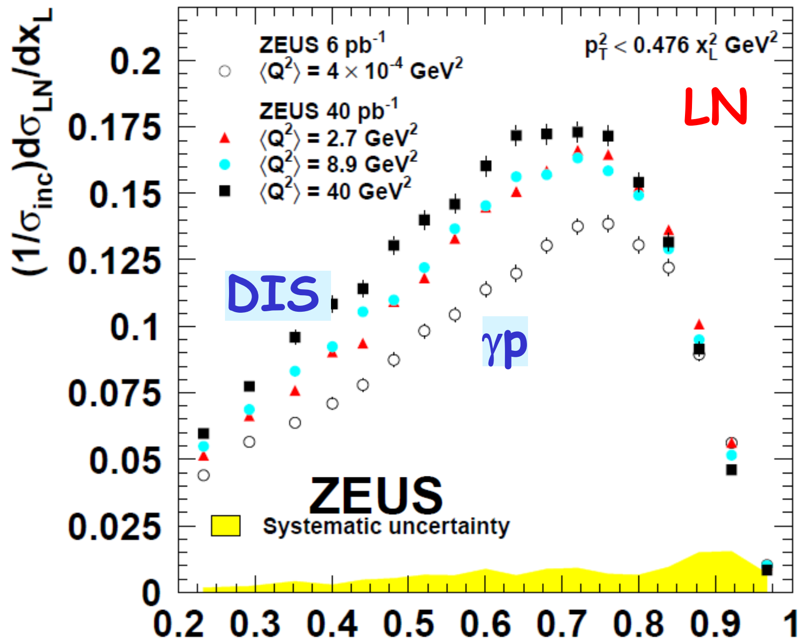
- Affects the relative rate of leading neutrons (depends on the scale Q)

more absorption in photoproduction then in DIS, (real γ transverse size larger than at higher Q^2)
→The calculations/models made without absorption may overestimate the measurements

Effects of absorption and migration estimated:
D'Alesio,Pirner; Nikolaev,Speth,Zakharov;
Kaidalov,Khoze,Martn,Ryskin ;
Kopeliovich,Potashnikova,Schmidt,Soffer

Absorption- key ingredient in calculations of gap-survival probability in pp interactions at LHC, critical in interpreting hard diffractive processes, e.g. central exclusive Higgs prod.





increase of LP and LN rate with Q^2

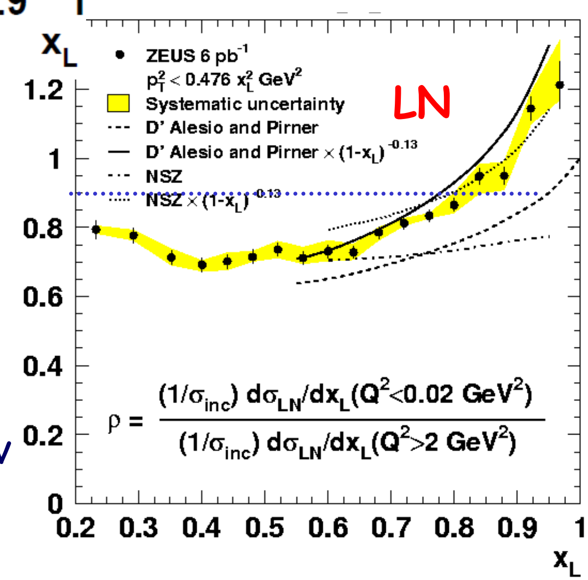
Suggest violation of vertex factorisation

From simple geometrical picture:
smaller γ* transverse size at higher Q^2
→ less absorption → larger event yield

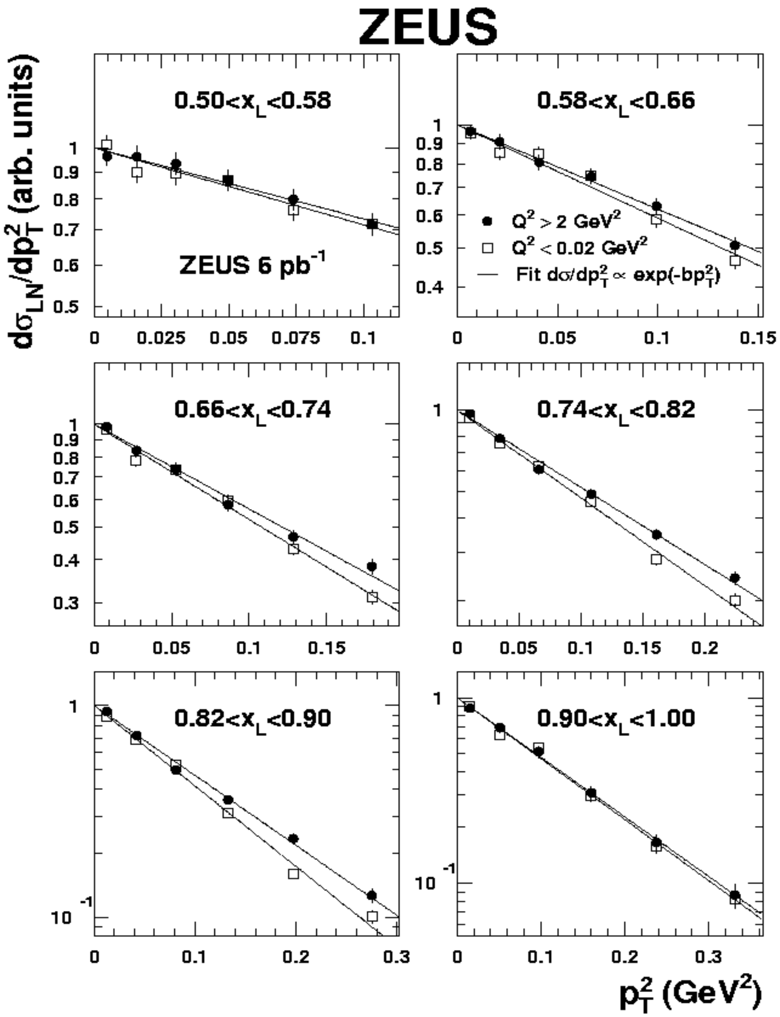
Ratio γp/DIS:
absorption models describe the data

-d'Alesio,Pirner
geometrical model

-Nikolaev,Speth,Zakharov
Regge based model with multipomeron exchanges

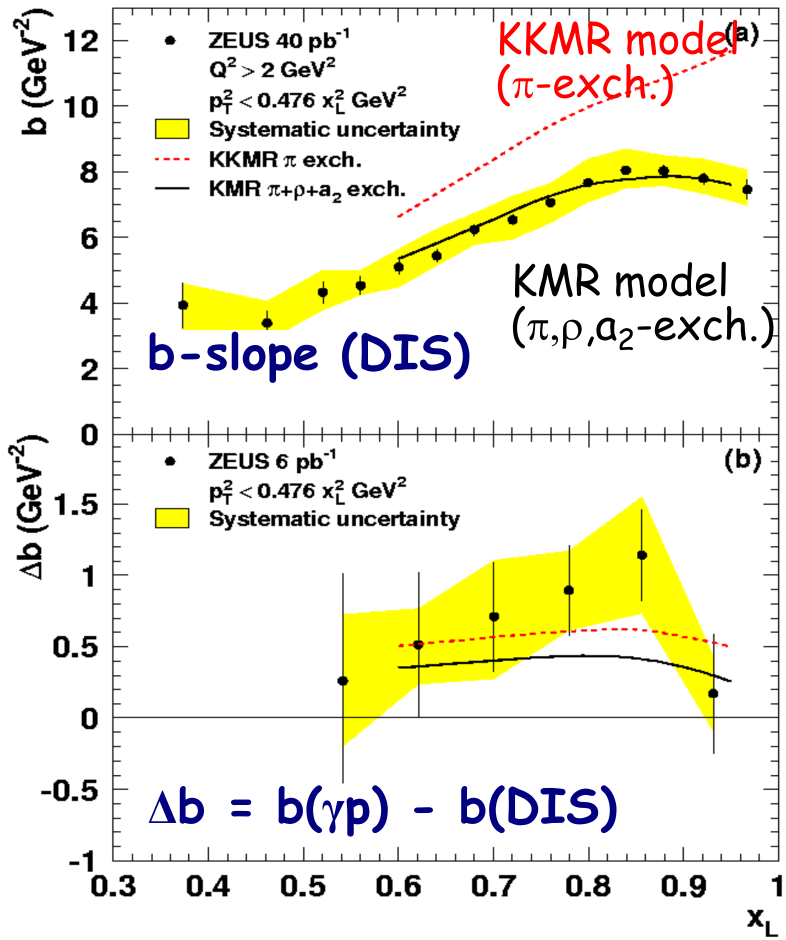


Comparison γp/DIS: p_T^2 distributions (LN)



model of Kaidalov,Khoze,Martin,Ryskin

- rescattering on intermediate partons in central rapidity region; migration of LN in (x_L,p_T)
- ~50% absorption loss in γp
- addition of (ρ,a_2) exchanges



p_T^2 slopes at γp steeper than at DIS

From simple geometrical picture:

Larger p_T → smaller $r_{\pi n}$ → more absorption → less neutrons at high p_T → steeper slope

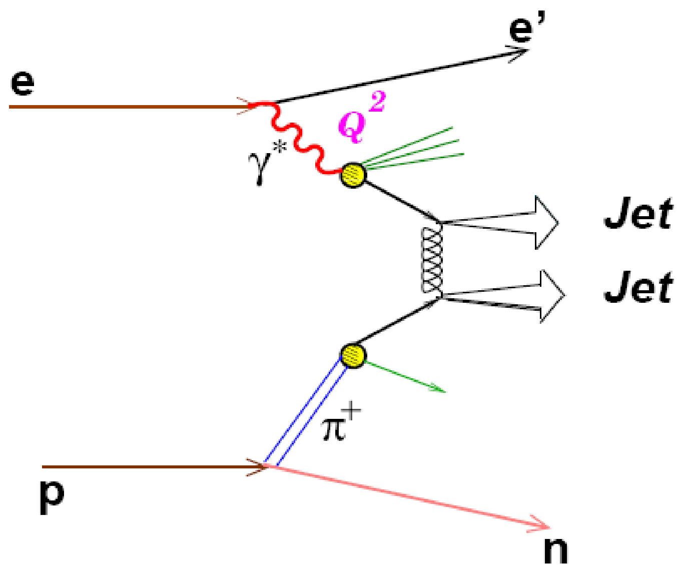
Dijet photoproduction with LN

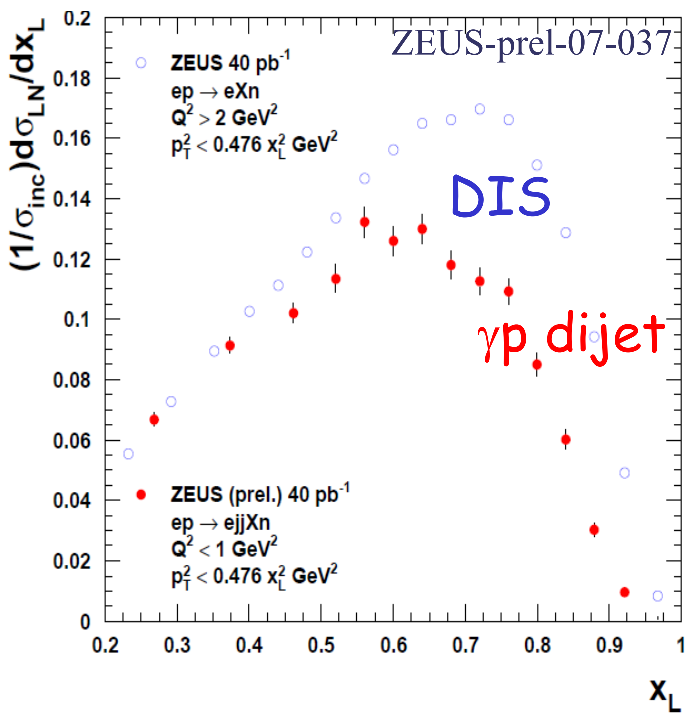
Study the jet production in event with leading neutron in the final state ($\gamma^* p \rightarrow$ jet+jet+n+X)

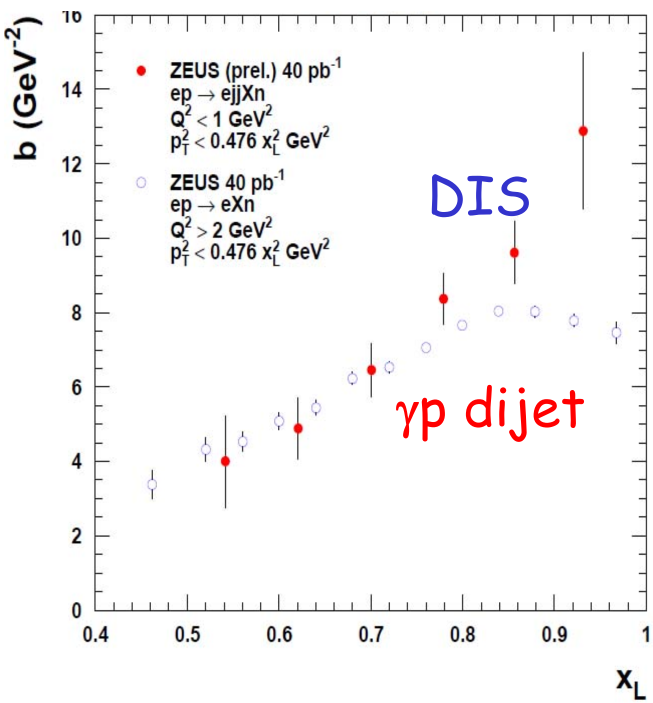
In photoproduction (Q^2~0) hard scale provided by jets with high E_T^{jet}

Do we see suppression ?

Recall: factorisation breaking observed in diffractive dijet photoproduction at HERA: in γp jets with E_T^{jet} >5 GeV are suppressed by factor 2 compared to DIS)



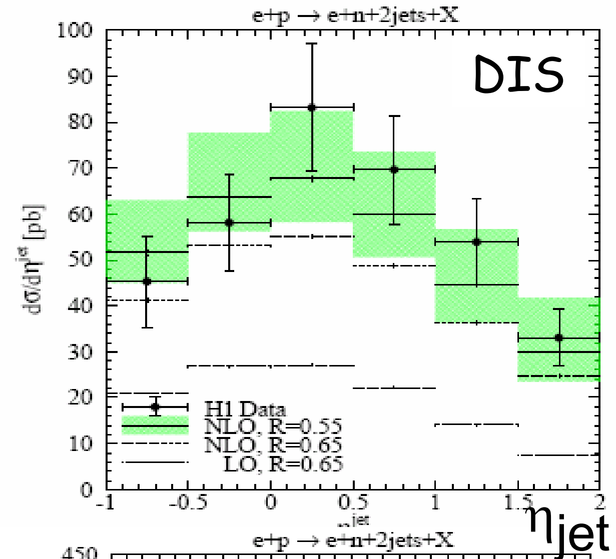


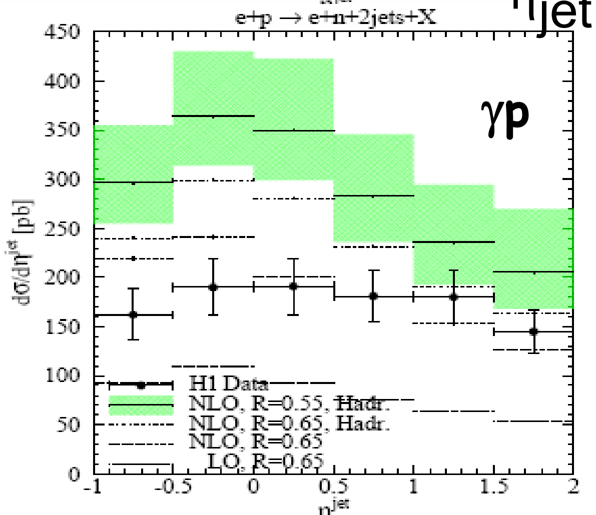


- x_L distribution shows suppression at high x_L → phase space limitation (dijets in the final state leave little room for energetic neutrons)
- b-slopes (DIS & γp-dijets) are slightly different at high x_L

Calculations (Klasen & Kramer, Eur.Phys.J.C49:957-965,2007)

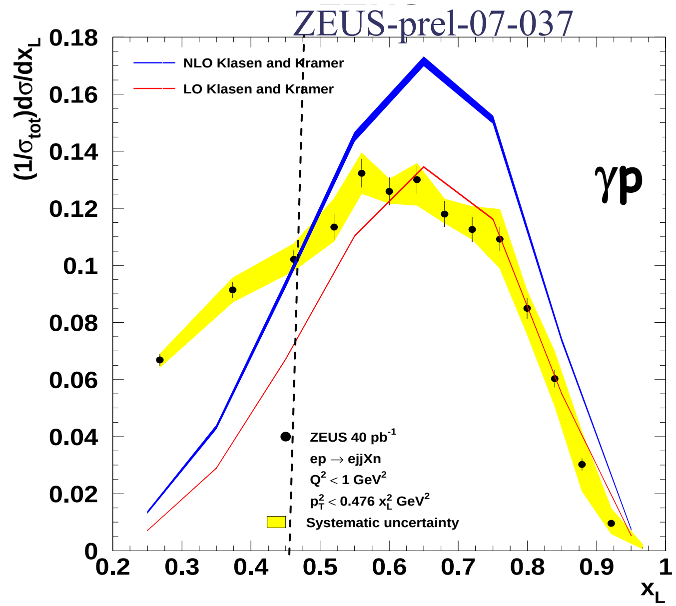
- normalise NLO (fix pion PDF, adjust pion flux) to H1-DIS data $\gamma^* p \to jj+n+X$ (Eur. Phys. J. C41 (2005) 27)
- compare to H1-γp data ($\gamma p \to jjnX$) , look for suppression



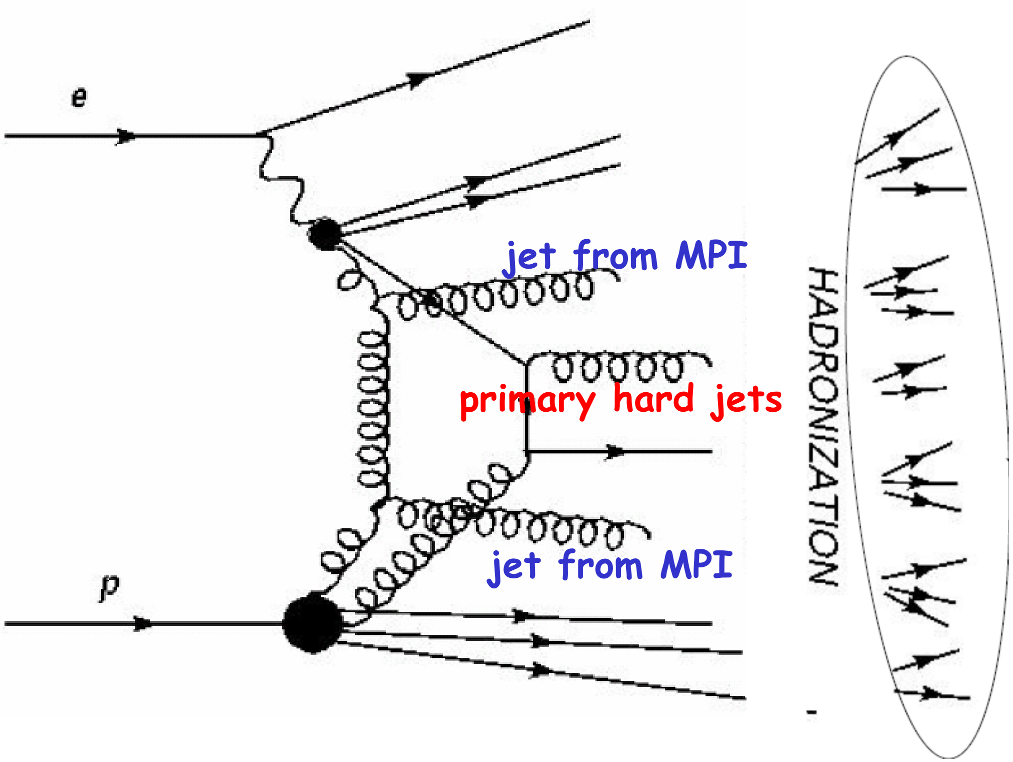


NLO vs H1 photoproduction data (E_T^{jet}>7 GeV) needs ~0.48 **suppression** of resolved component (or 0.64 global suppression)

NLO overestimates also the ZEUS γp dijet data (E_T^{jet}>7.5 GeV) for <u>x_L>0.5</u>



Underlying event / Multi-parton interactions



In addition to the primary hard parton-parton interaction with large p_T:

- interactions with lower p_T (remnant interactions)
- additional hard parton-parton interactions

➔ higher particle multiplicity, jet multiplicity, energy offset

→ **important for analyses involving jets (pedestal under the jet) !**

→ **may fake a discovery signal !**

→also to take into account
- higher order QCD corrections (e.g. parton showers)
- effects of fragmentation
- beam remnants

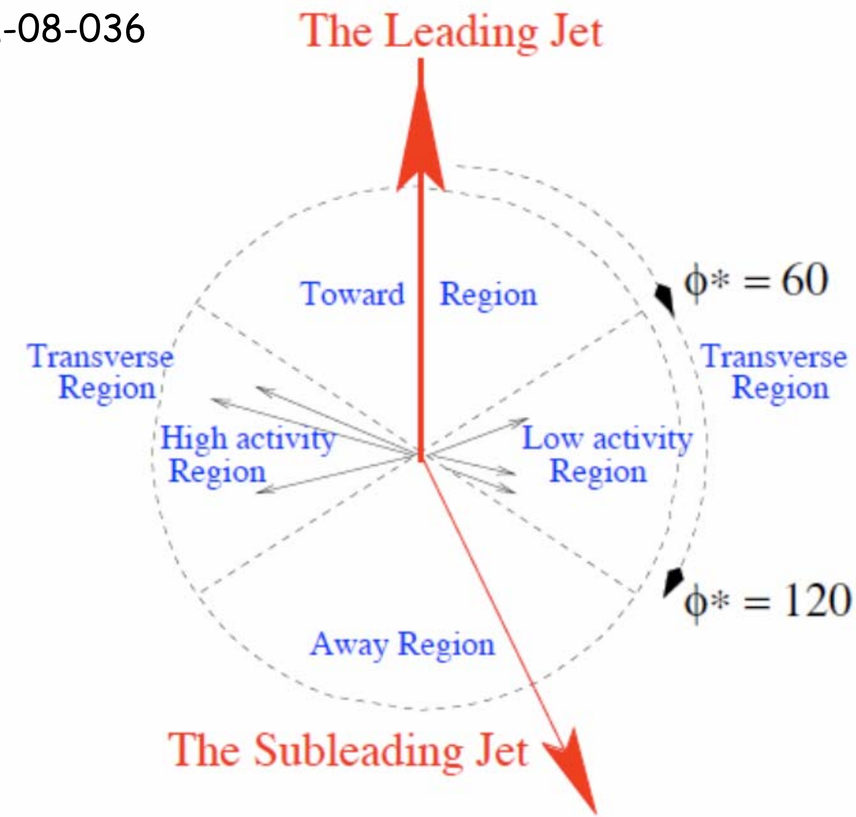
Understanding and modeling of Underlying event and multi-parton interactions crucial for all precision measurements!

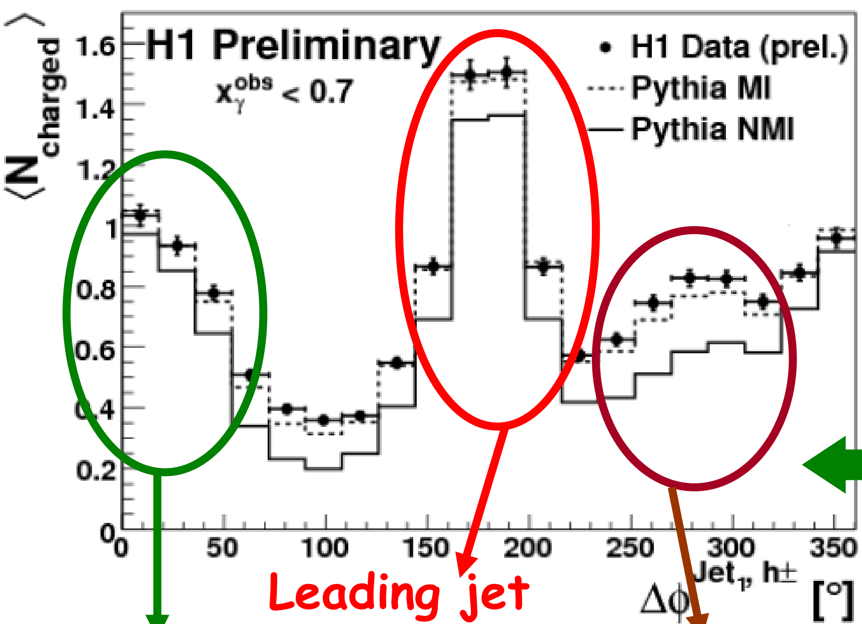
MPI studies in photoproduction ($Q^2 < 10^{-2}$ GeV^2)

- 2-jets with $P_T^{jet} > 5$ GeV and $|\eta^{jet}| < 1.5$

H1-prelim-08-036

- charged particles with $P_T > 150$ MeV and $|\eta| < 1.5$
- define two transverse regions:
  - <u>high activity region</u> with higher $P_T^{sum} = \Sigma_i^{tracks} p_{T,I}$
  - <u>low activity region</u>





Leading jet

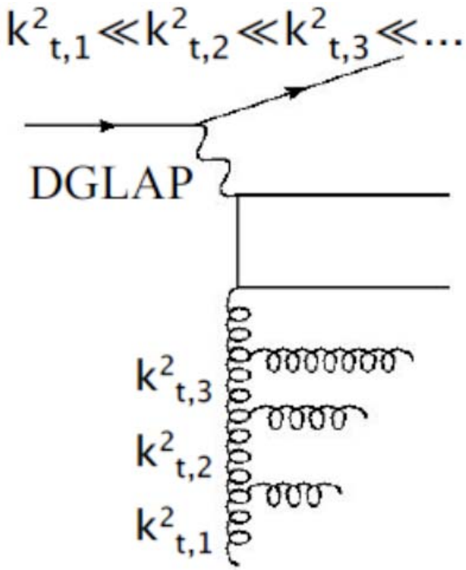
Away region

High activity transverse region

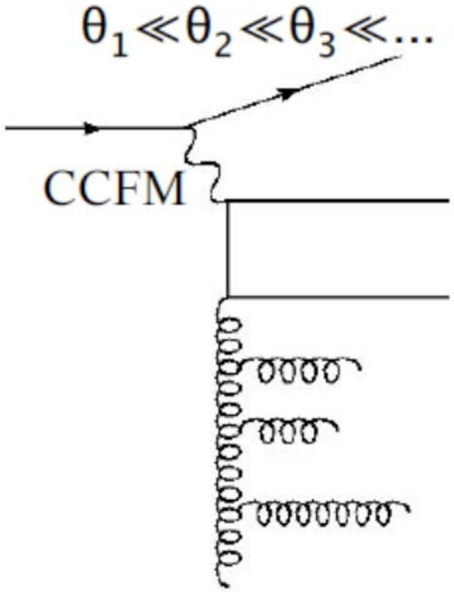
Charged particle multiplicity vs angle between leading jet and charged particles

measure charged particle multiplicity
→ expect sensitivity to MPI in transverse regions

- Pythia
  - -direct+resolved processes in LO
  - -matched DGLAP parton shower
  - -with/without MPI (additional "semi-hard" interactions down to $P_{T,min}$=1.2 GeV)



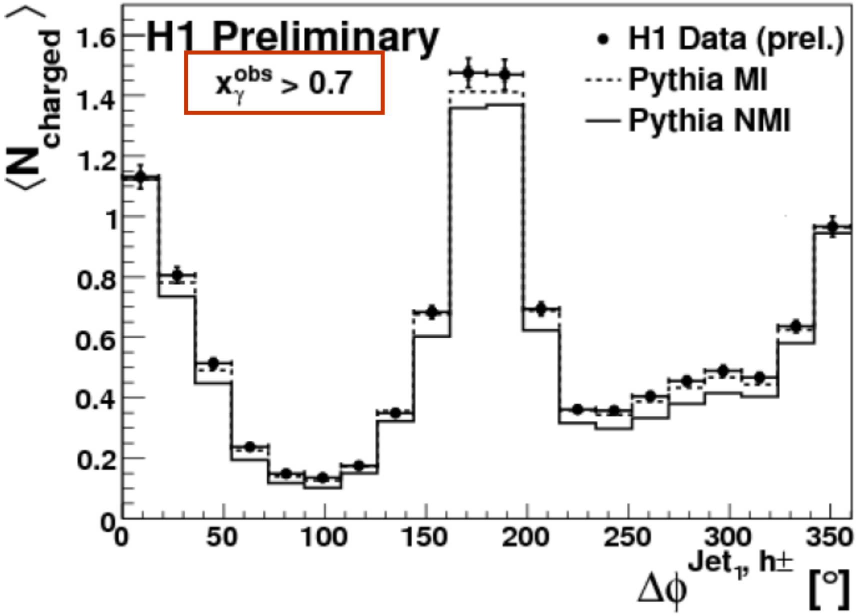
- Cascade
  - -off-shell LO ME for direct processes
  - -matched with CCFM parton showers
  - -k_t un-integrated gluon densities (set1 , set2)
  - -no resolved (VDM) photon, no MPI

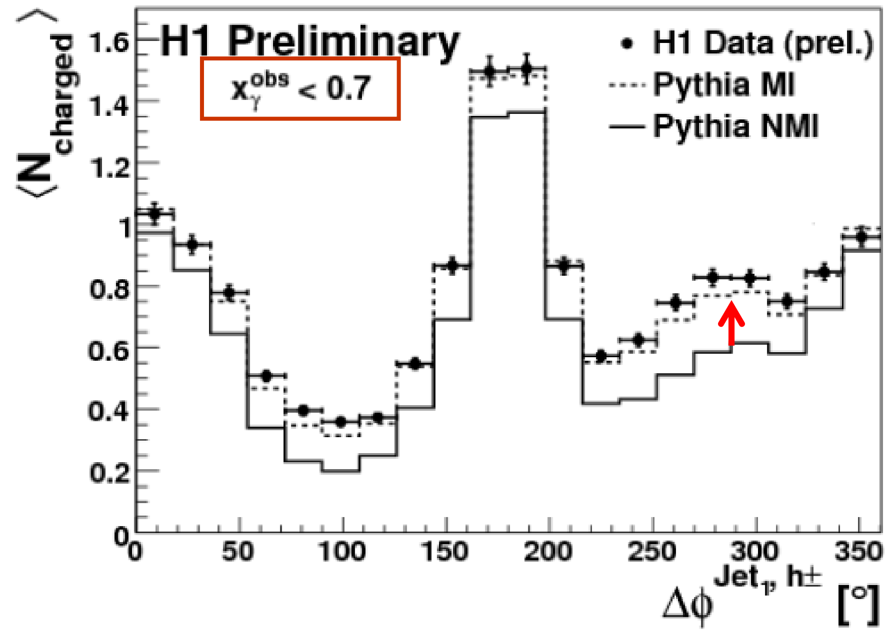


Charged particle multiplicity vs $\Delta\phi$

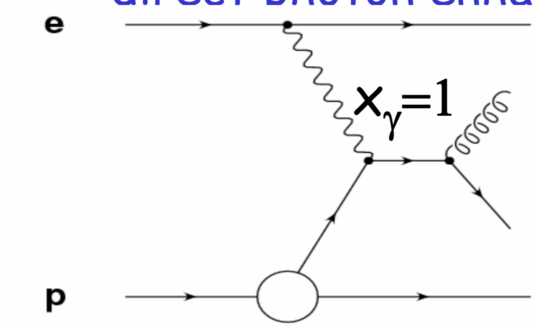
$\Delta\phi$ -angle between leading jet and charged particles

H1-prelim-08-036

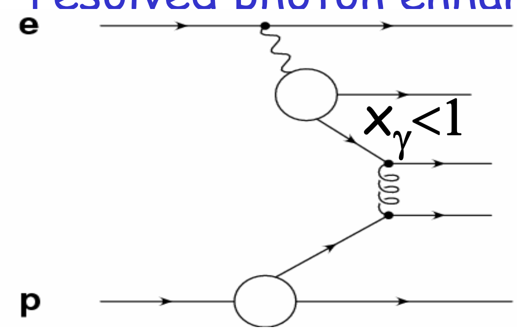




direct photon enhanced



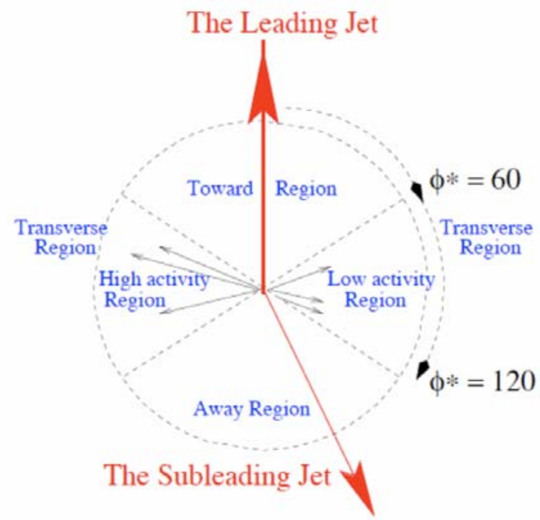
resolved photon enhanced

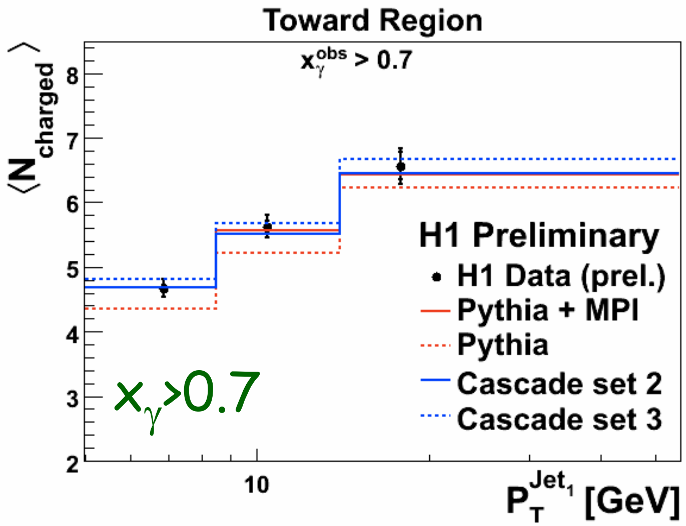


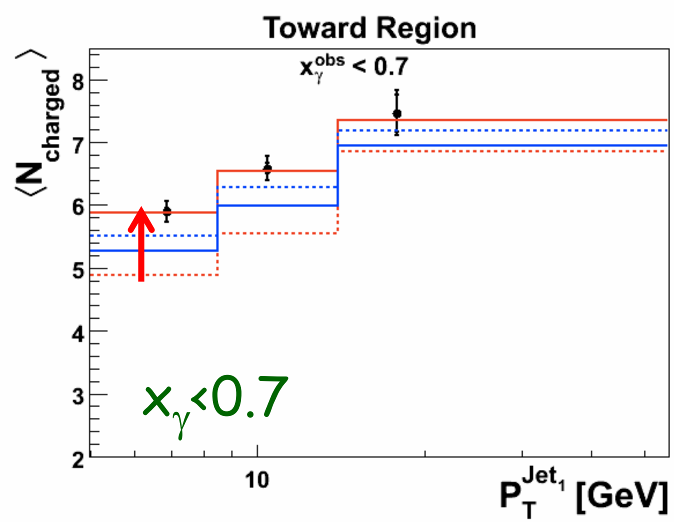
Data at low x_γ described by Pythia when multi-parton interactions are included

Charged particle multiplicity in Toward and Away regions

H1-prelim-08-036

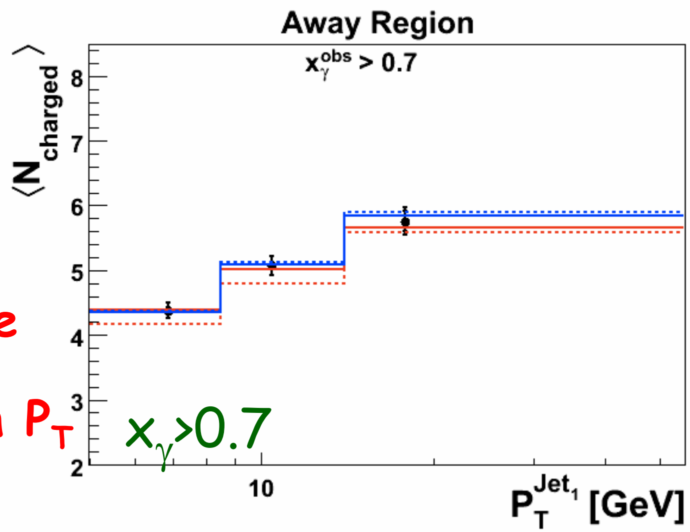


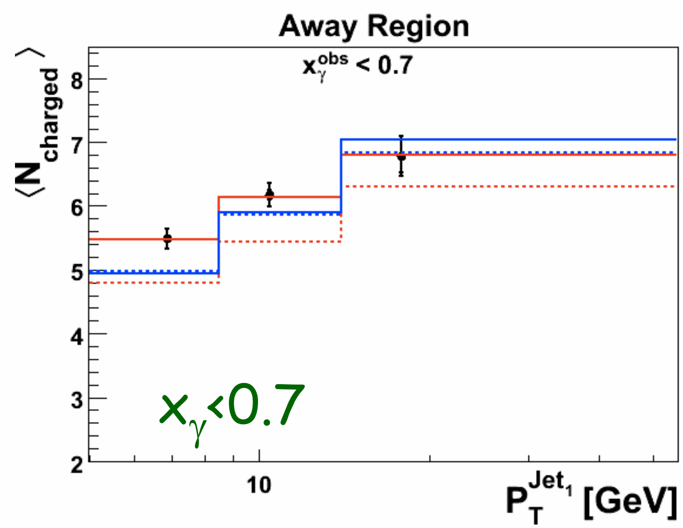




models are similar at high x_γ

higher multiplicity at x_γ<0.7





MPI in Pythia contribute more at low P_T^{jet1} 'pedestal' decrease with P_T

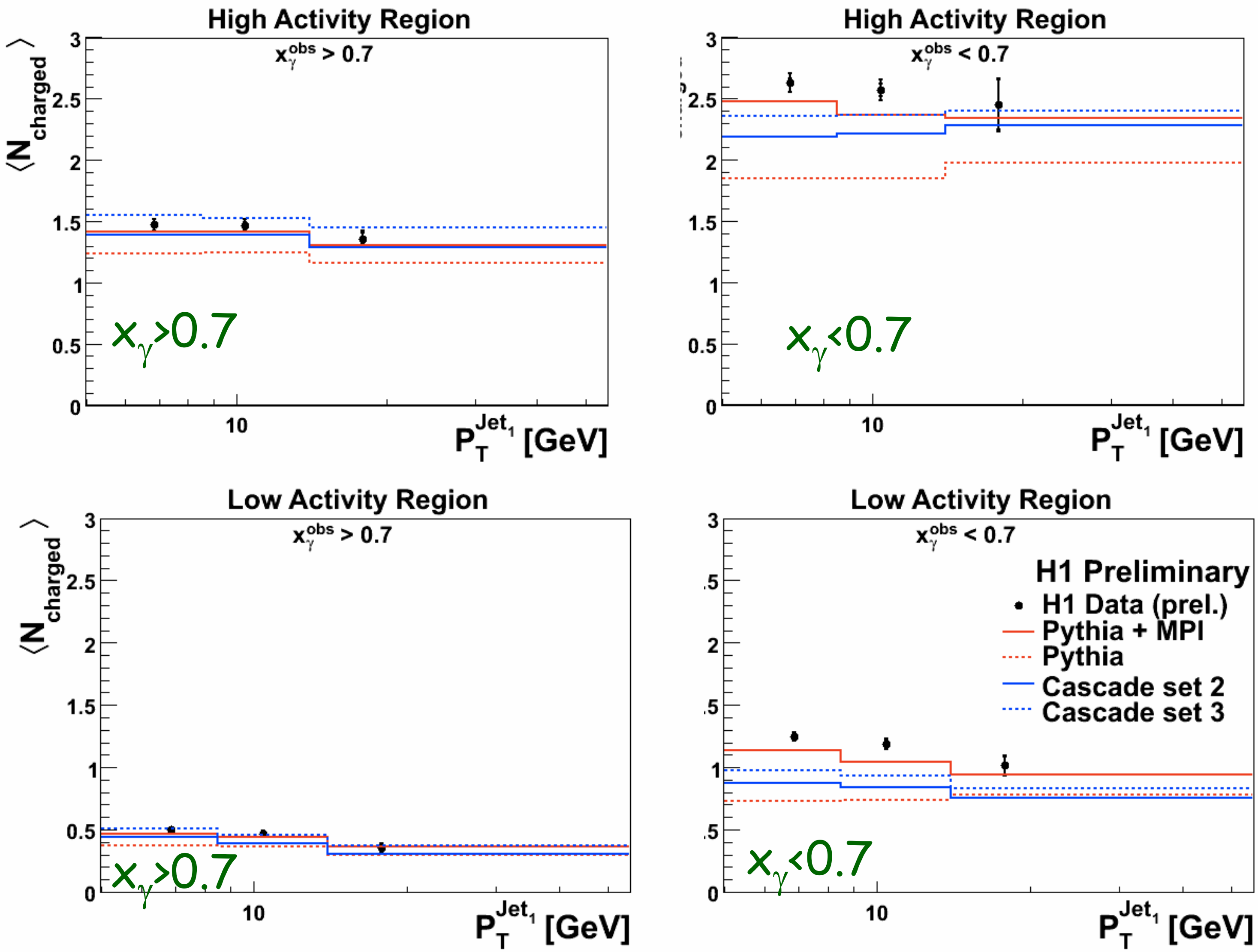
CASCADE (no MPI) not too bad

models are similar at high x_γ

higher multiplicity at $x_\gamma < 0.7$

PYTHIA+MPI provides reasonable description of data;

CASCADE is not too bad (worse than PYTHIA with MPI but better than PYTHIA without MPI)



Data described by Pythia only when multi-parton interactions are included

Summary

Leading Baryons are good ground to study soft vs. hard physics

- Precise measurements of LB x_L and p_T^2 presented in γp, DIS, γp with dijets;
- Standard fragmentation models do not describe the data;

  Models with virtual particle exchange describe data better;
- For LN production pion structure function estimated, compared with parameterisations
- F_2^{LN}/F_2 ratio is mostly independent of x and Q^2
- neutron energy spectrum in γp compatible with effects of absorption and migration; suppression in γp at low x_L, high p_T
- better agreement with data if account for absorption and for (ρ, a_2) exchanges
- suppression seen also in photoproduction of dijets

Multiple interactions are very relevant for hadronic interactions

- description of average charged particle multiplicity in resolved photon events with hard jets requires MPI (at least when using PYTHIA);
  interestingly, the model without MPI, CASCADE, is not too bad

Backup

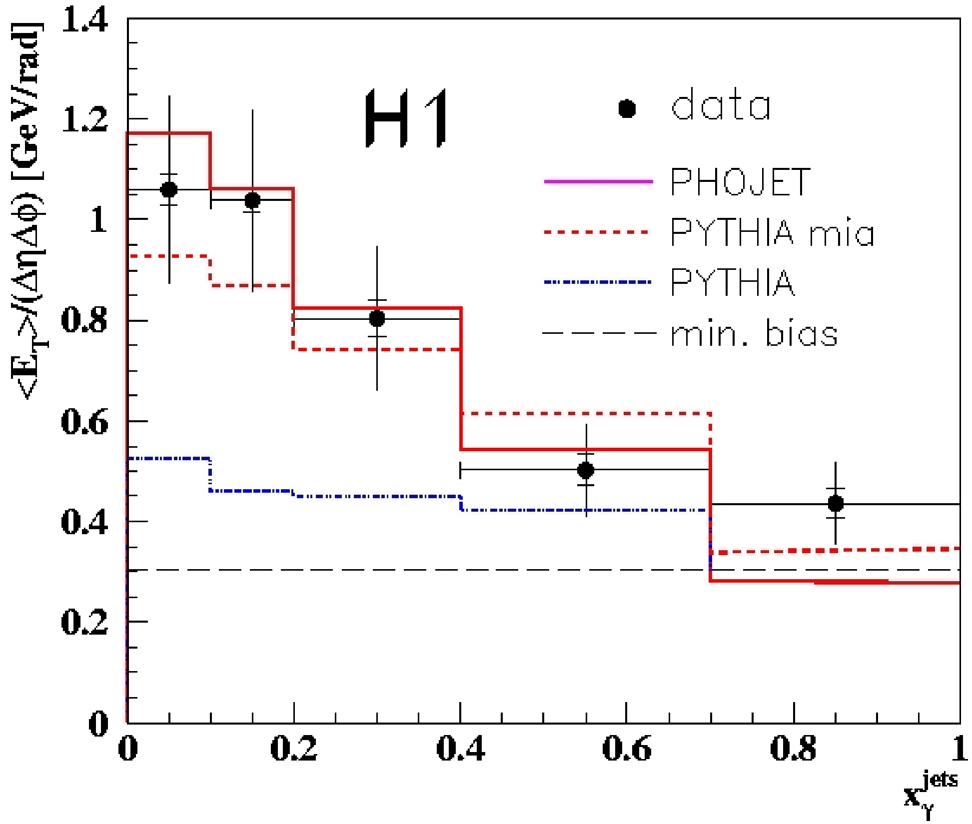
Energy flow outside jets

Z.Phys.C70 (1996)17

Photoproduction $Q^2 < 0.01$ GeV^2

At least two jets ($E_T^{jet} > 5$ GeV, $-1 < \eta_{jet} < 2.5$)

The transverse energy density outside the jets can be described when MPI are simulated.

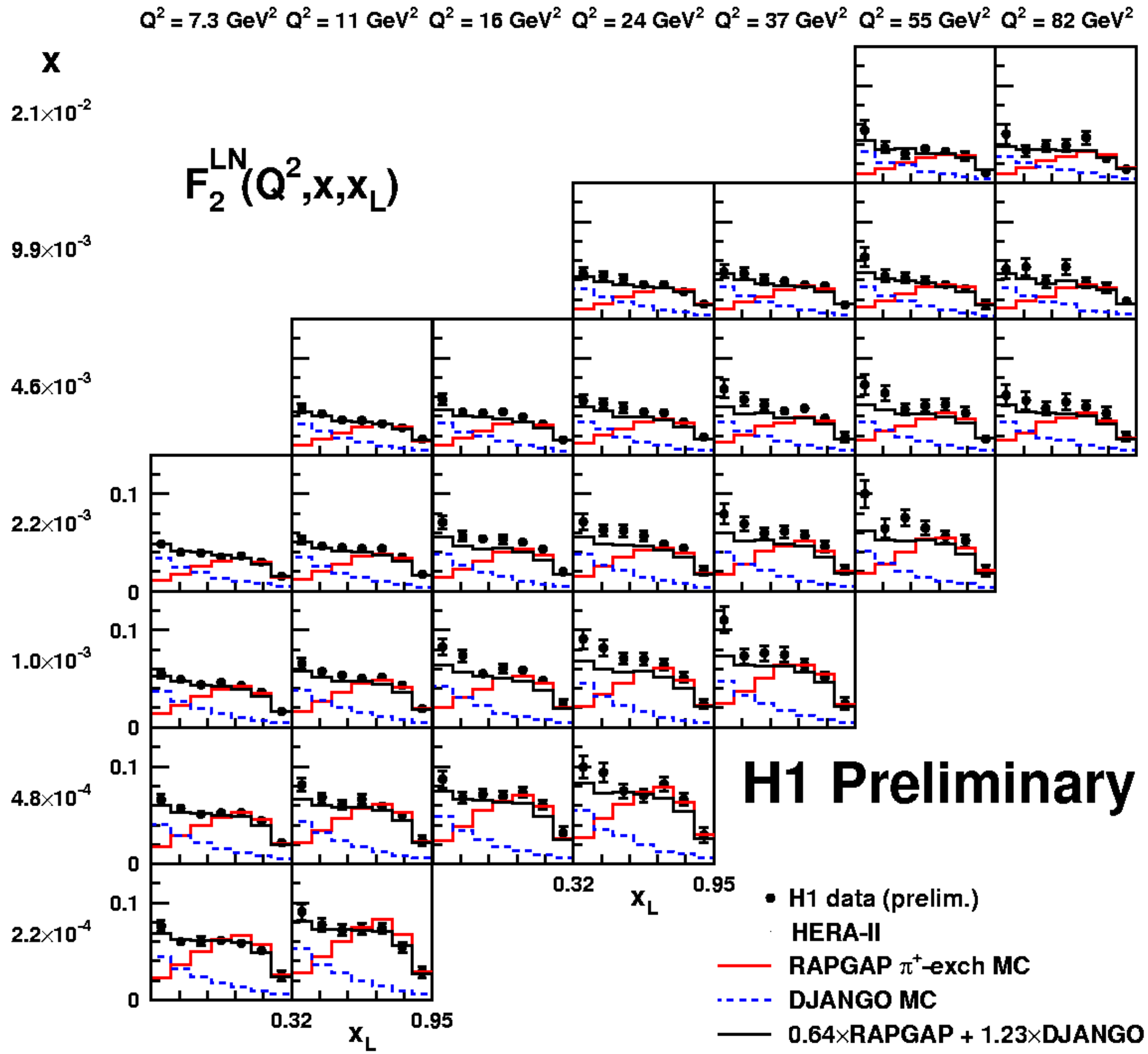


Semi-inclusive structure function F_2^{LN}

F_2^{LN} analogous to proton F_2 for events containing leading neutron

$$\frac{d^3\sigma(ep \to eNX)}{dQ^2 dx\, dx_L} = \frac{4\pi\alpha^2}{xQ^4}\left[1 - y + \frac{y^2}{2}\right] F_2^{LN}(Q^2, x, x_L)$$

6<Q^2<100 GeV^2 , 0<p_T<0.2 GeV



- RAPGAP π+-exchange model describes data well for x_L>0.7
- combination of RAPGAP-π-exch. and DJANGO (DIS, `standard' fragmentation) gives the best description of the data over full range

Leading neutron production: experimental indication of absorption

Comparison of LN production rates for different processes (ZEUS)

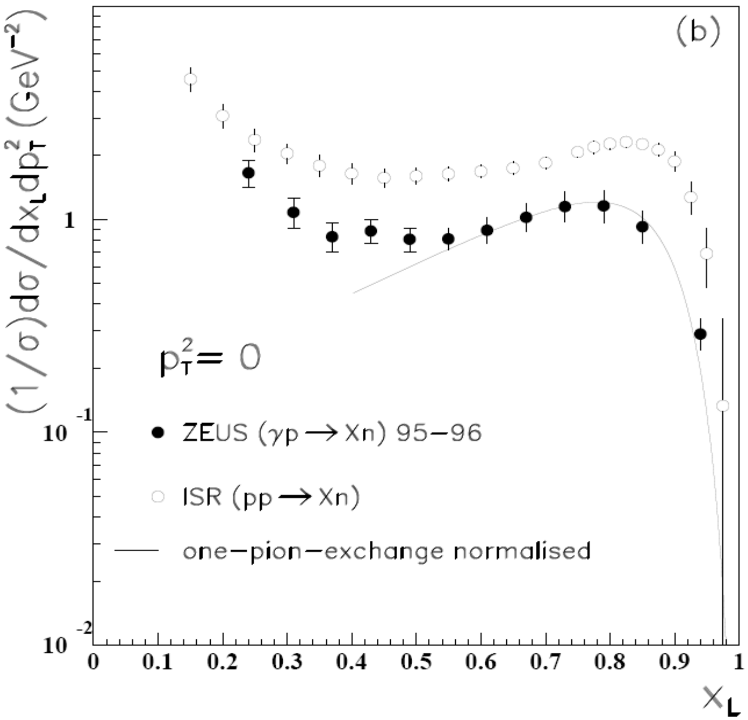
$$r^{D^*}(x_L > 0.49) = 6.55 \pm 0.76(\text{stat.})^{+0.35}_{-0.45}(\text{syst.})\%$$

$$r^{\text{DIS}}(x_L > 0.49) = 5.8 \pm 0.3\%,$$

$$r^{jj}(x_L > 0.49) = 4.9 \pm 0.4\%,$$

$$r^{\gamma p}(x_L > 0.49) = 4.3 \pm 0.3\%.$$

compatible with rescattering hypothesis: harder interaction → larger yield of LN



The normalised cross sections: compare $\gamma p \to Xn$ ($p_T^2=0$) and $pp \to Xn$ (ISR).

average number of neutrons per event at HERA is ~2 times less than at ISR pp