Leading Baryons at HERA

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Outline

- **Introduction**
- Leading Baryon detectors at HERA
- Results: Leading protons
- Results: Leading neutrons
    - Rescattering Models
    - Leading Neutrons in photoproduction and DIS
    - Leading Neutrons in association with jets
  - Comparison LP & LN
- Summary

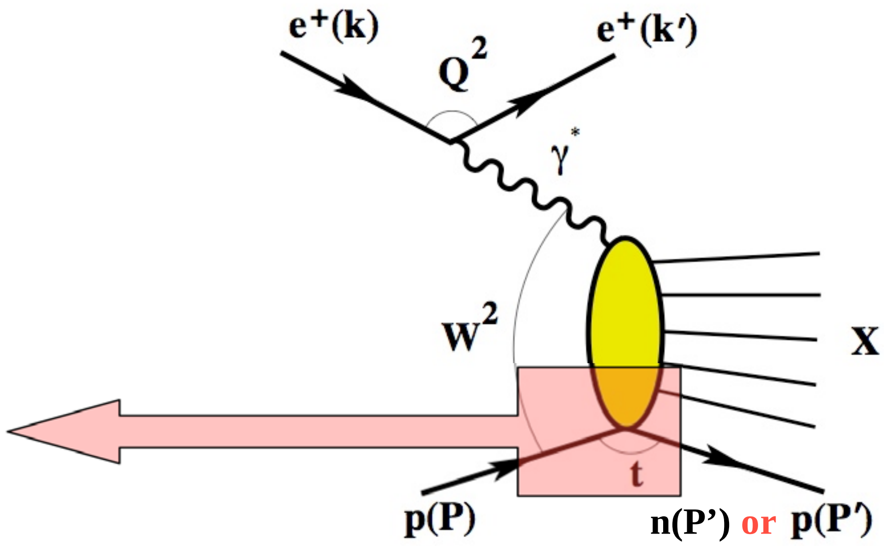
Physics of the Leading Baryons:

. A semi-inclusive reaction :

ep→enX

or ep→epX

x_L : $E_{(n' \text{ or } p')}/E_p$	BIG
t : P-P'	small

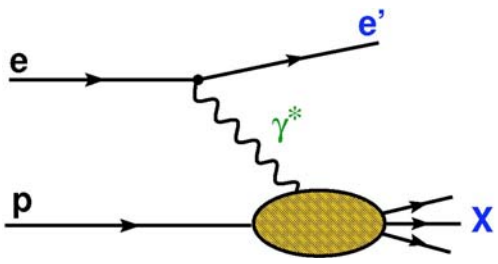


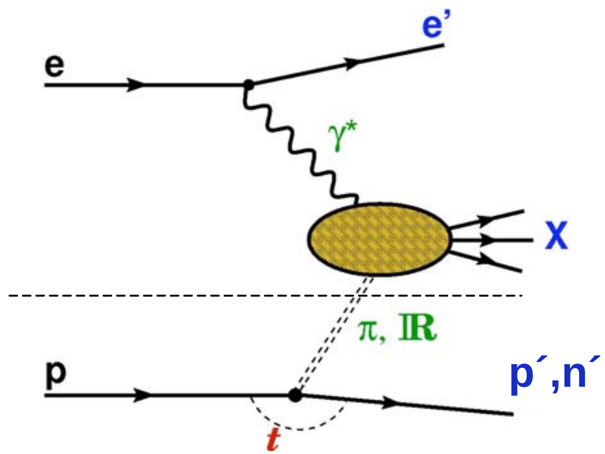
. Leading protons, x_L~1: diffraction *(not in this talk)*

. DIS regime: scale for secondary particle production
Q^2 (hard) and low-p_T (soft)

. Photoproduction regime: $Q^2 \approx 0$

Typical models:





✷ Protons produced at high-x_L but low-p_T: non-perturbative approach

- Perturbative: **standard fragmentation**
  - models usually implemented in MC (DJANGOH, RAPGAP, etc)

- Non-perturbative: **Regge-based models**
  - dynamical particle-exchange of virtual particles (ρ,IP,π,etc)
  - implies ~ vertex factorization

✷ "In between": Soft Color Interactions

- quarks,gluons+non-perturbative elements

Physics of LB - motivations:

- Understanding non-perturbative aspects of hadronic interactions requires precise experimental data

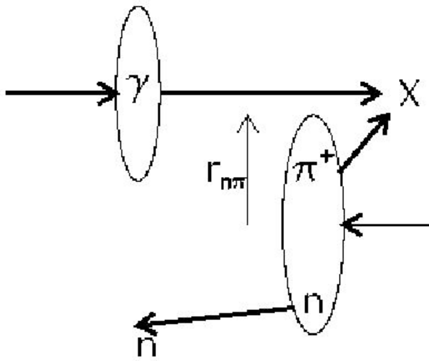
- Rescattering
  - leading neutron data: a good testing ground to understand gap survival probability problem
  - same phenomena responsible for destroying rapidity gaps in diffractive events at Tevatron
  - very large effects expected in central exclusive production at Tevatron and LHC

Exclusive Central Higgs Production:

Rescattering is one of the main (and few) backgrounds for this important channel for potencial Higgs discovery

Rescattering models

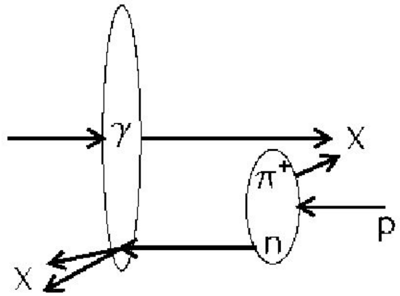
- D´Alesio and Pirner



usual case:

n detected!

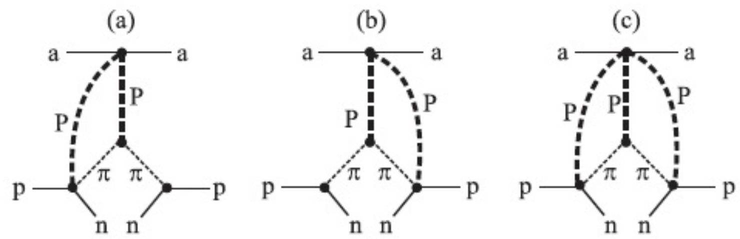
- As size of n-pi system ~ size of the photon:



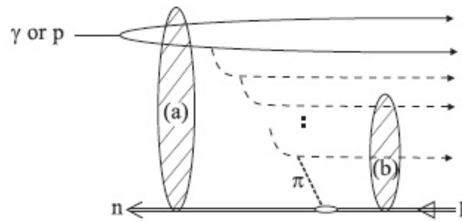
rescattering!

- (high p_T, low x_L), low Q^2

- Nikolaev, Speth, Zakharov
  (hep-ph 9708290)
- Additional pomeron exchange



- Kaidalov,Khoze, Martin, Ryskin
  (EPJC 47:385 (2006) EPJC 48:797 (2006))



- distorted n energy spectra due to rescattering
- include a_2 and ρ exchange

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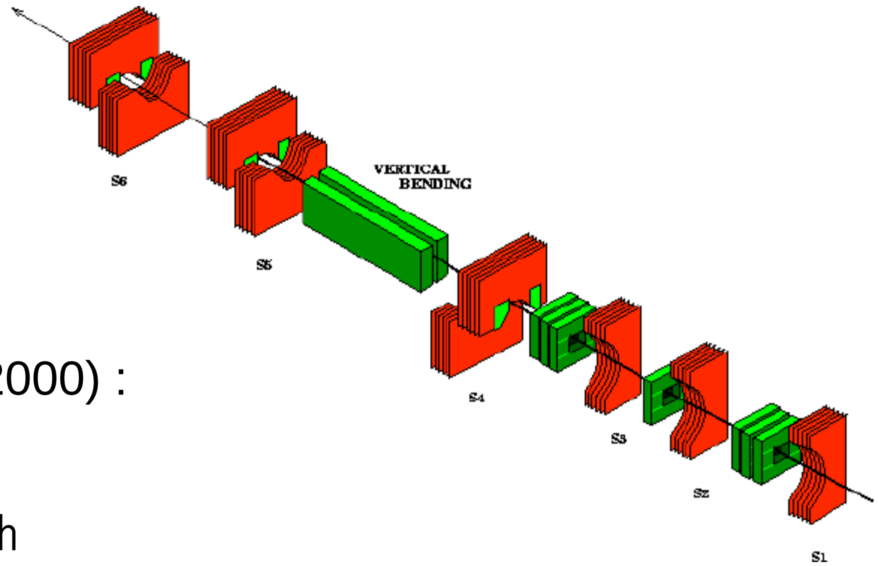
Proton Detectors - H1 and ZEUS

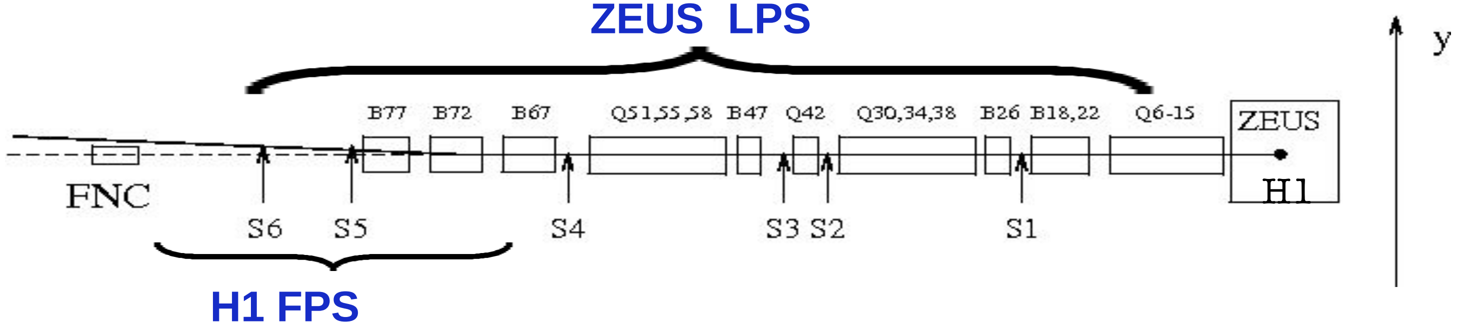


- **ZEUS Leading Proton Spectrometer** (1994-2000) :
  . Six stations along proton beamline
  . 6 Silicon-strip detectors , 3 planes each
  . S123 and S456
  . $\sigma_{xL} < 1\%$, $\sigma_{pT}^2 \sim$ a few MeV^2
  (better than p-beam spread ~ 50 - 100 MeV^2)

- **H1 Forward Proton Spectrometer** (until 2007):
  . new detector at 200 m from IP, VFPS (will gain acceptance)
  . two stations along proton beamline
  . 4 planes scintilator fiber hodoscope + trigger scintilator
  . $\sigma_{px} = \sigma_{py} \sim$ a few MeV

(No H1 data today)

Neutron Detectors

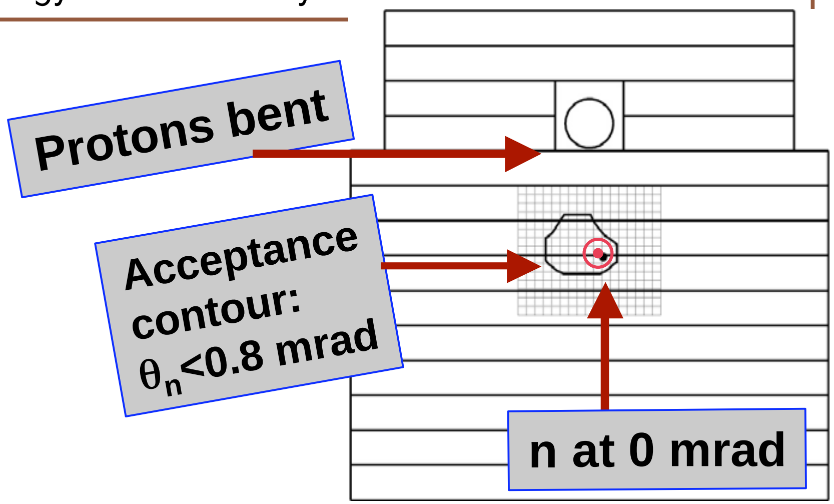


- **Forward Neutron Calorimeter (FNC)**

H1 (1994-2007) :	ZEUS (1994-2000) :
. Lead scintillator calorimeter at 107m from Interaction Point . Energy resolution: 63%/√E +3% . Position resolution $\sigma_{x,y}$ = 0.2 cm (numbers for HERA II)	. Lead scintillator calorimeter at 103m from IP . Covers 10 interaction lenghts . $\sigma(E) = 0.65/\sqrt{E}$ (E in GeV) . Energy scale accuracy: 2%

- **ZEUS Forward Neutron Tracker (FNT)** (2000):

. two hodoscope planes of scintillator strips (x,y)
. Placed inside FNC at 1interation lenght
. $\sigma_{x,y}$ = 0.23 cm



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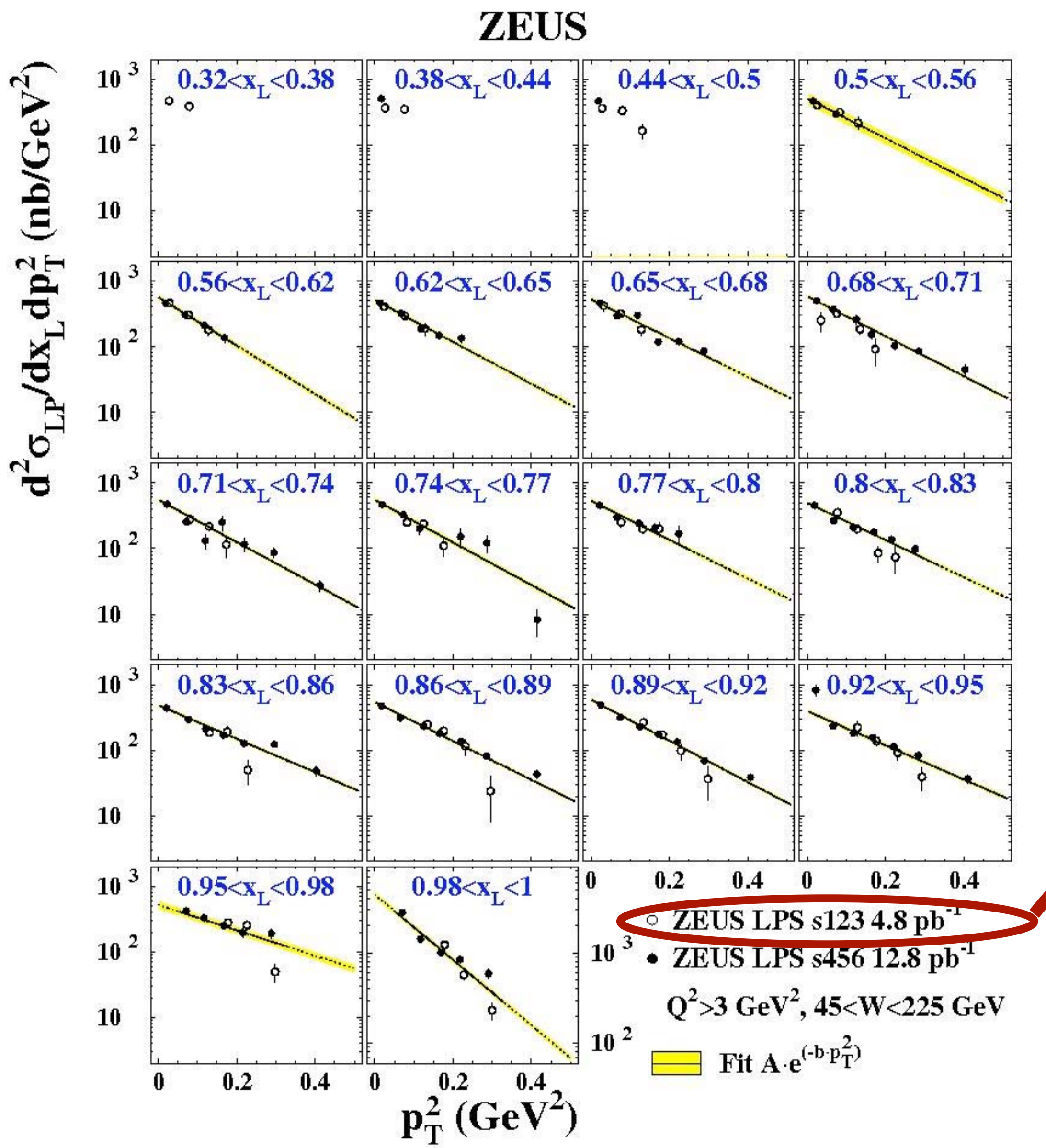
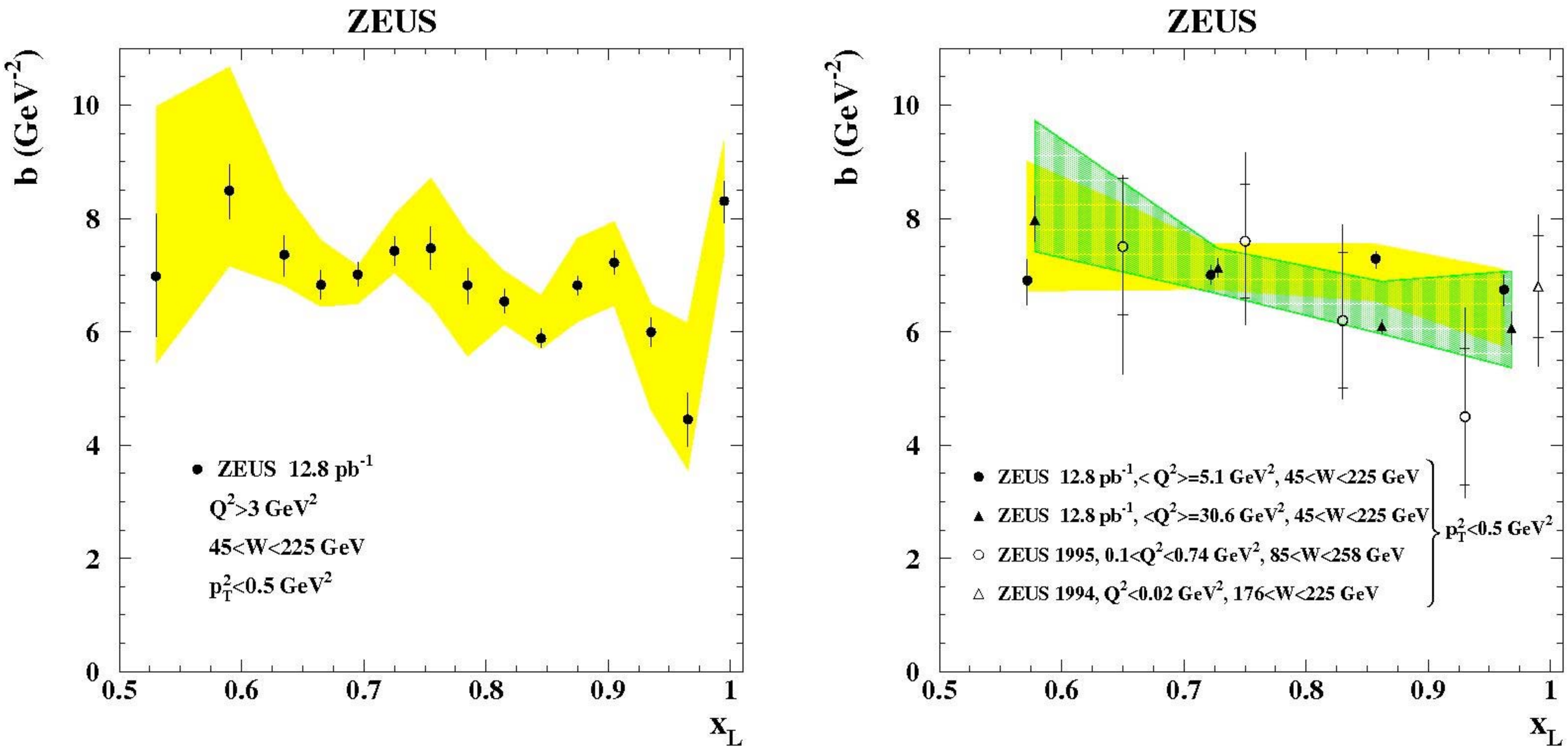
Results: transverse momentum



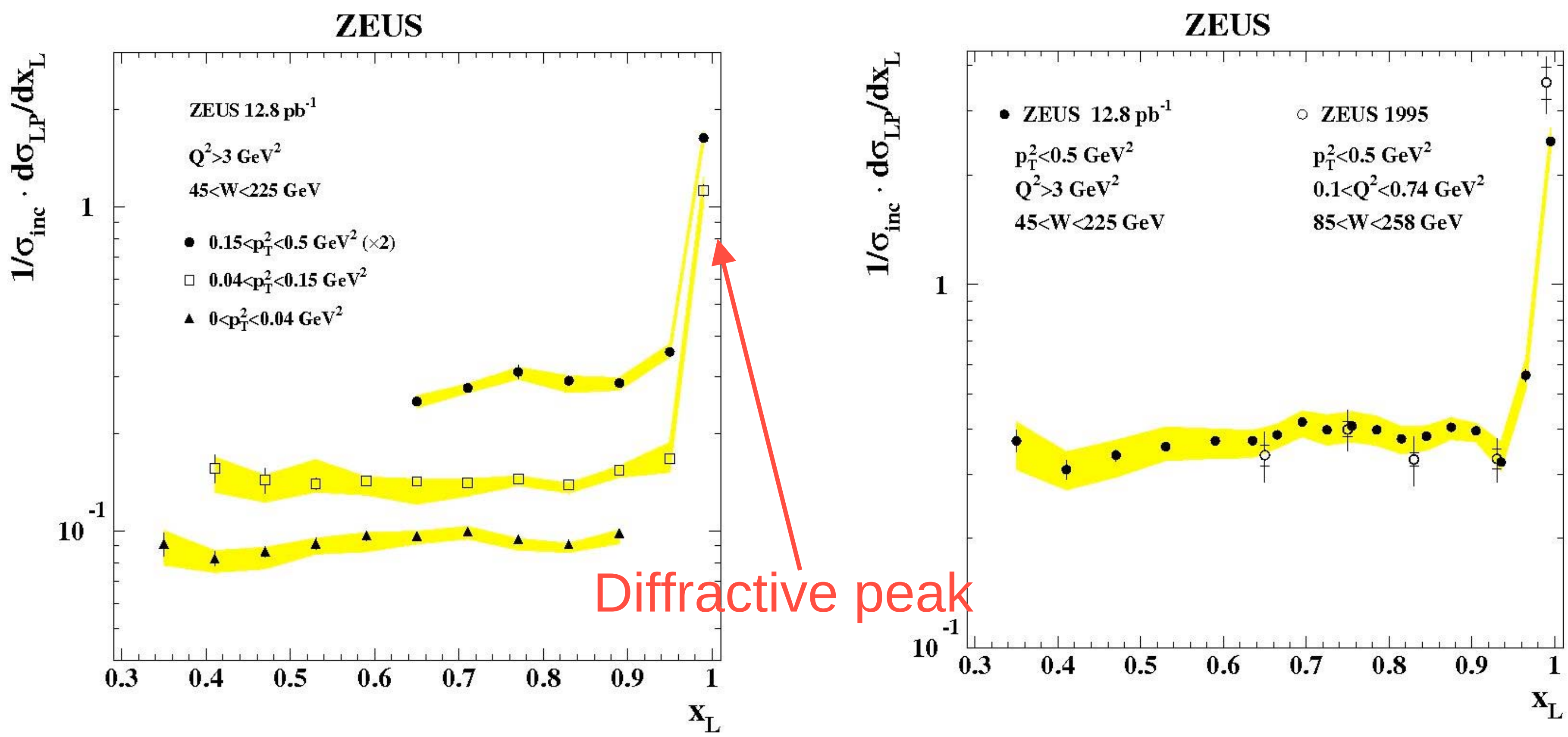
- Fits to exponential:
  $A.e(-bp_T^2)$
- b-slopes *(next)*
- **NEW:** first (and only) measurement with LPS S123
- S123 and S456 data in good agreement

Results: transverse momentum



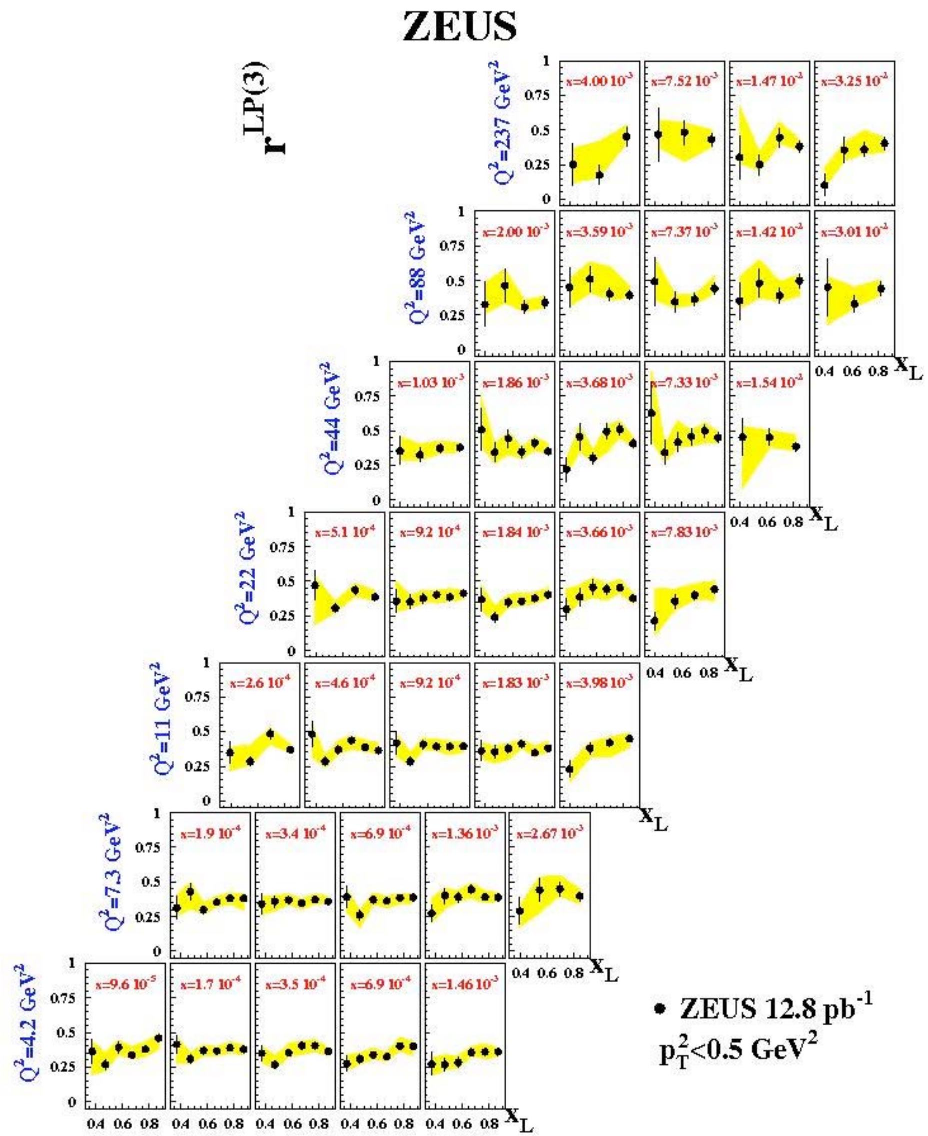
- *b*-slopes: no x_L dependence
- no Q^2 dependence

Results: longitudinal momentum



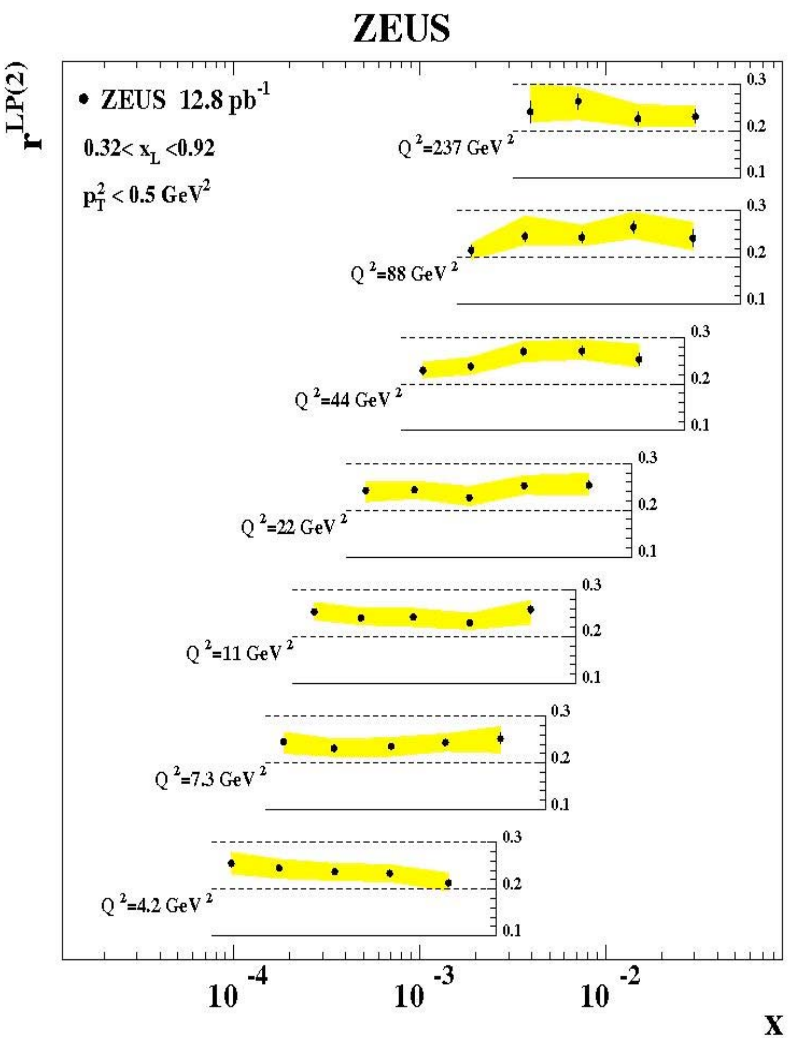
- Data normalized by total (no *p*-tag) DIS cross section
- Below diffractive peak: no x_L dependence
- Comparison to very low-Q^2 data : no Q^2 dependence

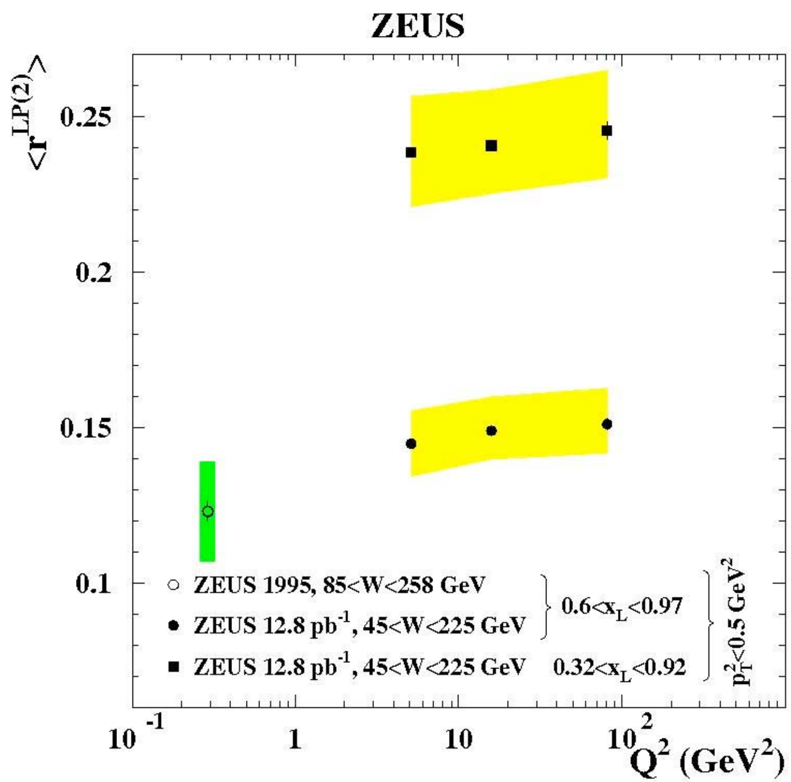
Results: $F_2^{LP(4)} / F_2$



- $F_2^{LP(4)}$ analogous to proton F_2 for events containing a leading proton
- Known as *Fracture functions* in some models
- LP: apart from (x,Q^2) is also function of (x_L,p_T)
- no x_L,p_T dependence

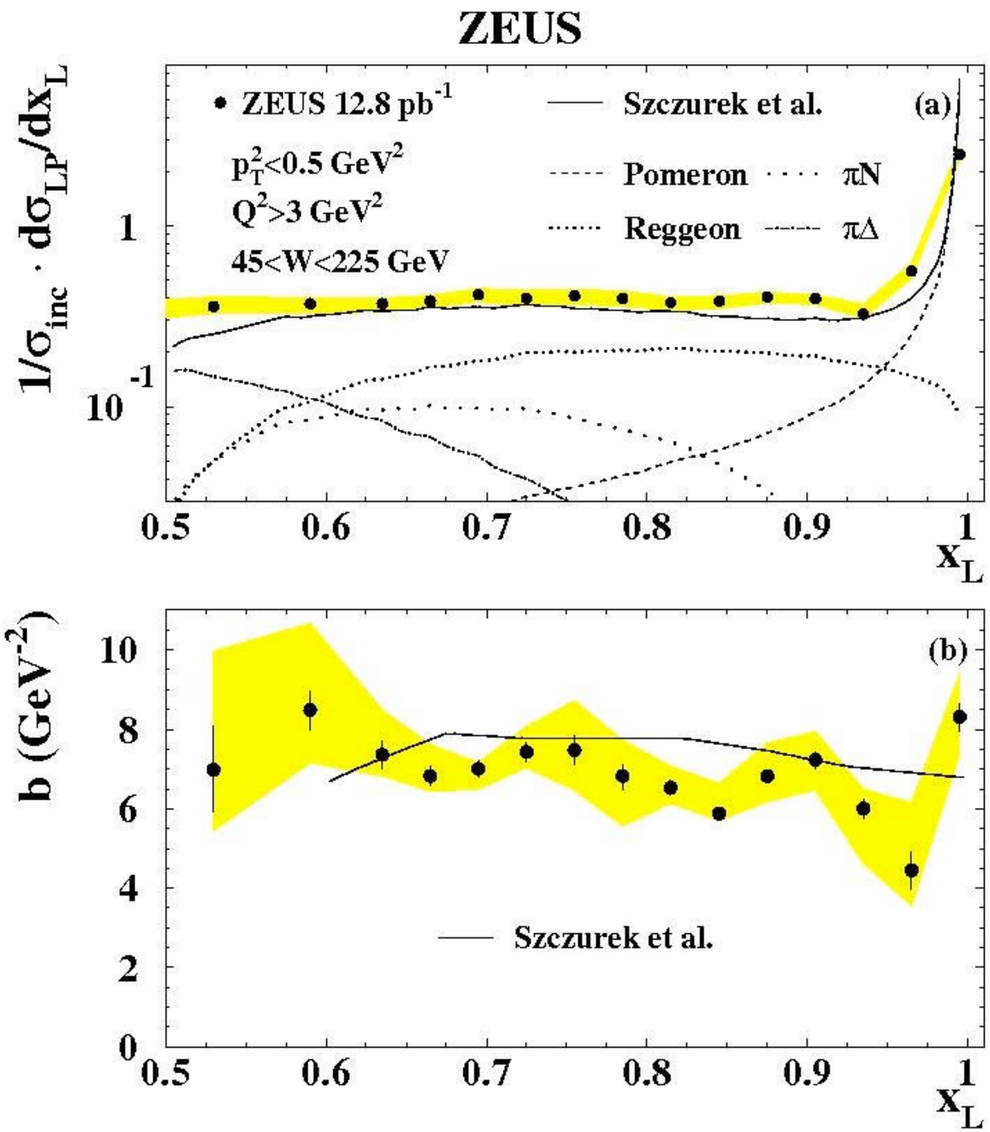
Results: $F_2^{LP(4)}/F_2$





- Rates ~ flat
- Mild Q^2 dependence not excluded
- Compatible with particle-exchange prediction of vertex factorization

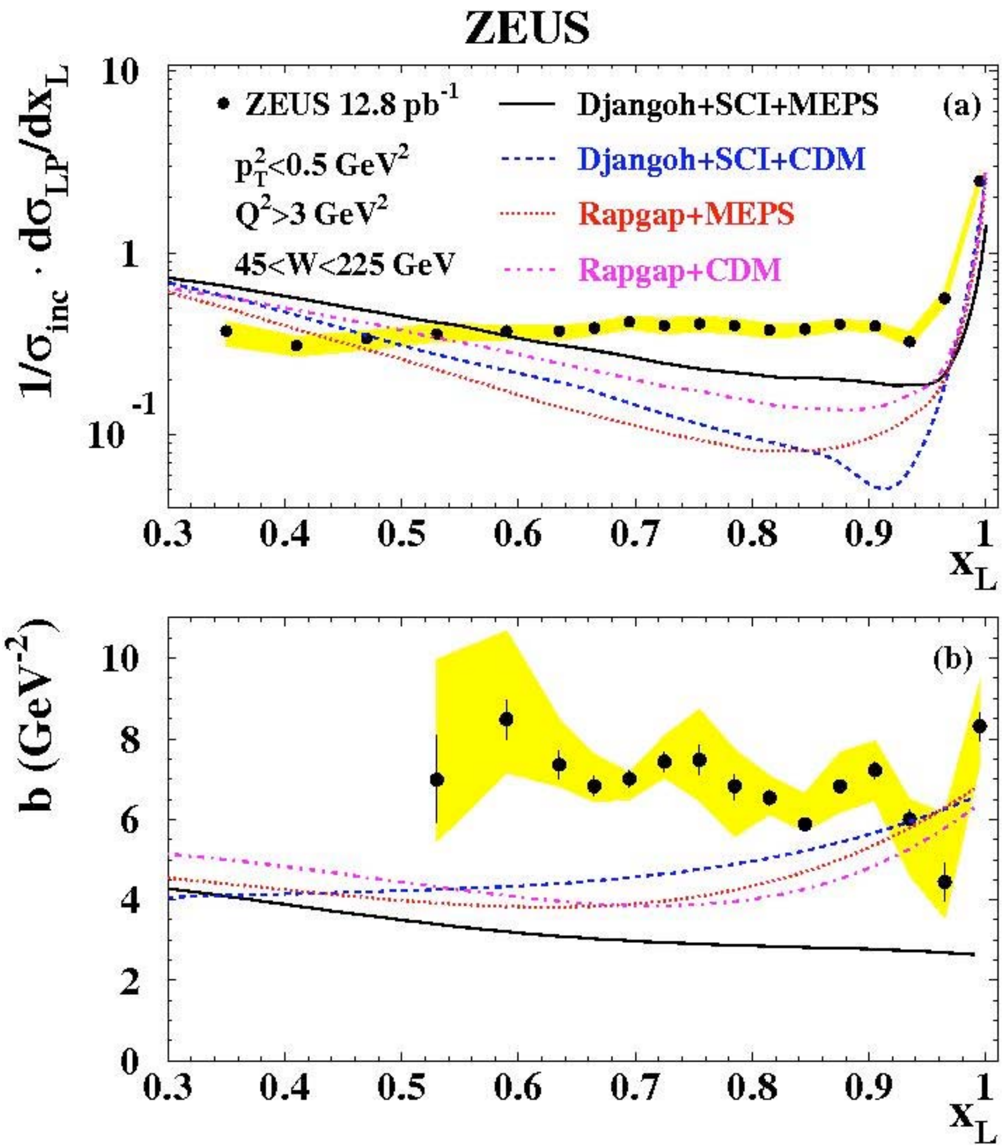
Comparison to models



- Particle exchange is able to describe the data
- Different exchanges populate different regions of leading-proton energy spectra
- b-slopes (angular distribution) also well described

A.Szczurek,N.N.Nikolaev,J.Speth, Phys.Lett. B428 (1998) 383

Comparison to models



- DJANGOH with Soft Color Interaction + MEPS describes reasonably well x_L spectra
- Same MC describes reasonably well b-slopes in shape but not normalization
- Other MC models fail to describe the data

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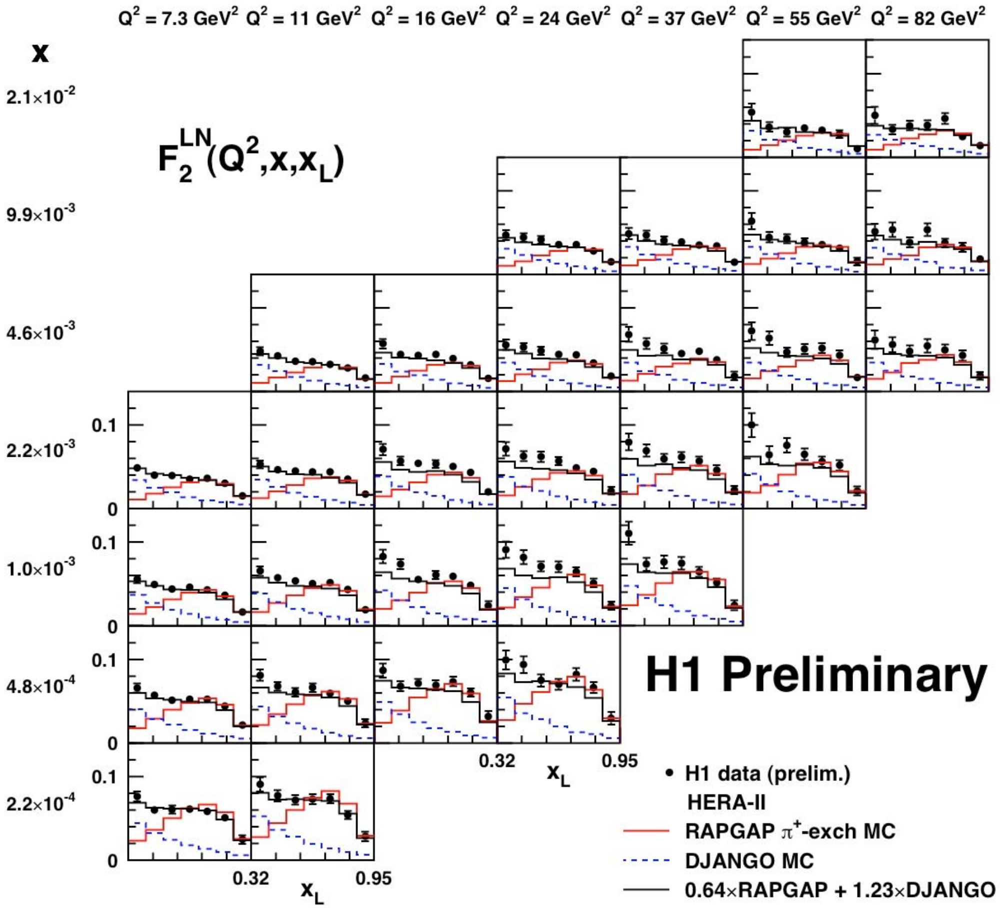
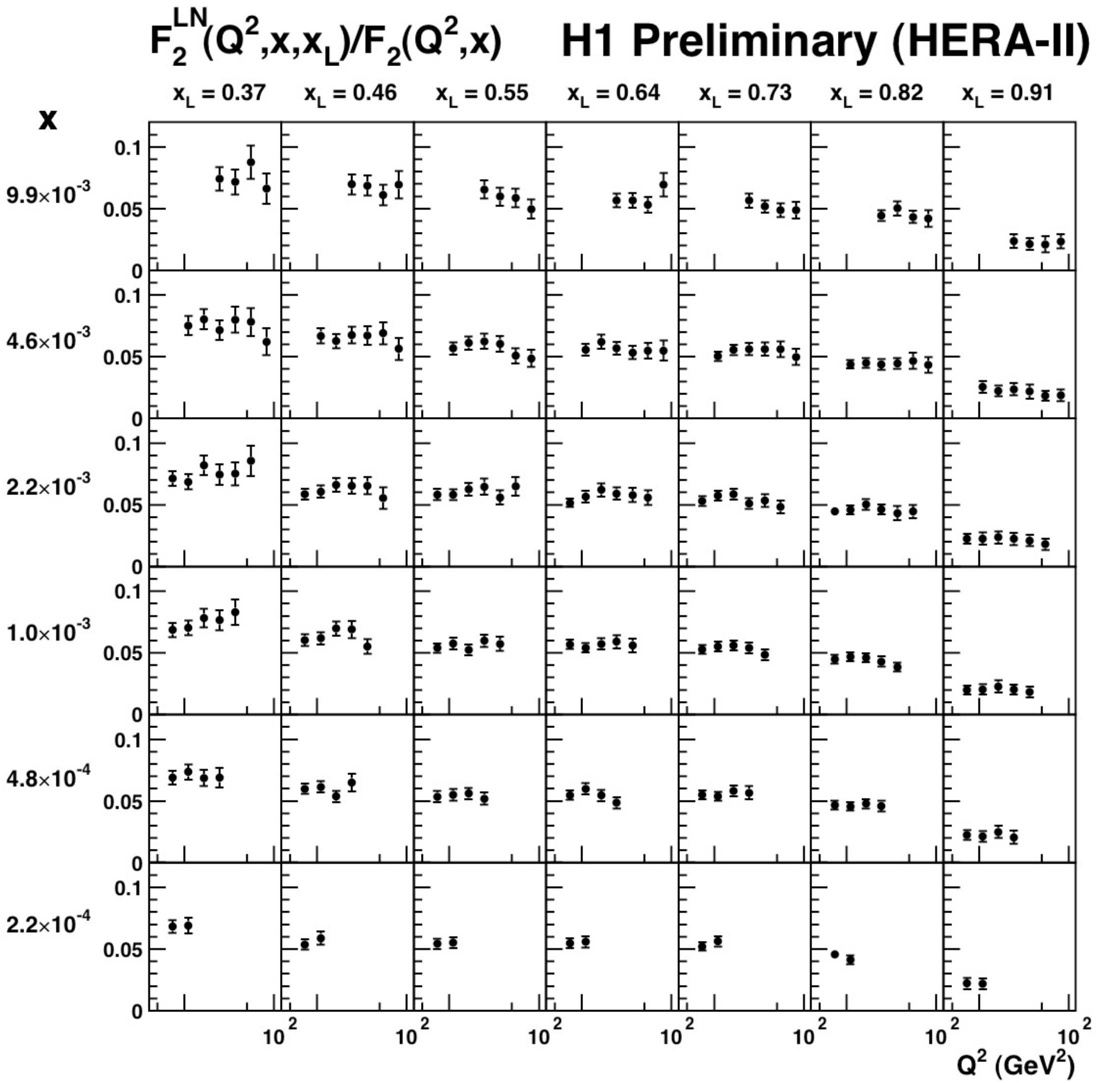
LN cross section (DIS): F_2^{LN}



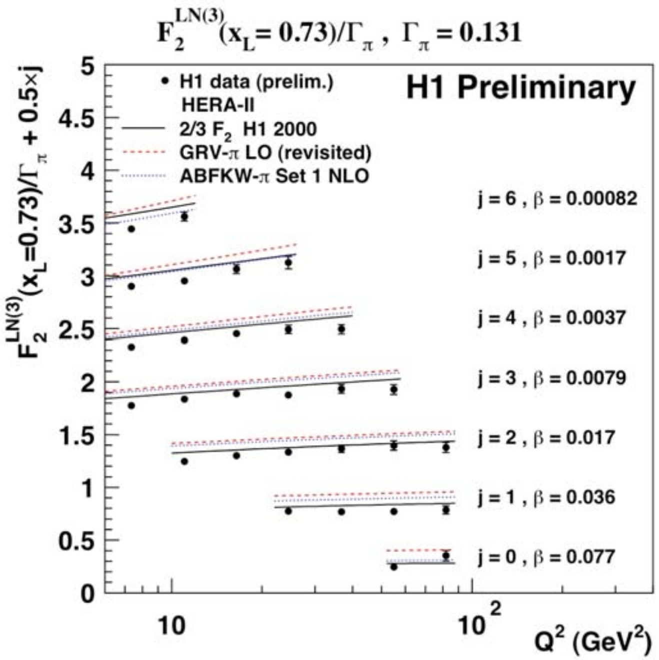
- F_2^{LN} analogous to proton F_2 for events containing a leading neutron
- Combination of RAPGAP (pion exchange) with DJANGO (standard fragmentation) gives a good description of the data

LN cross section (DIS): F_2^{LN}



- Compare to F_2
- No x, Q^2 dependence
- Result compatible with vertex vactorization hypothesis
- Same conclusion as leading protons

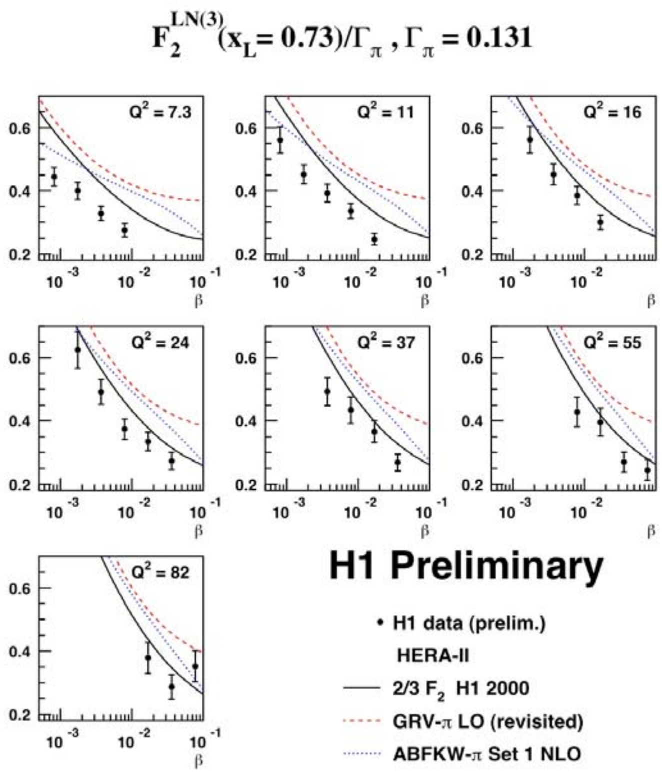
Estimate of F_2^{π} from F_2^{LN} data



In pion-exchange framework:

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

$$\beta = \frac{x}{1-x_L}, \quad \Gamma_\pi(x_L) = \text{t-integrated pion flux}$$



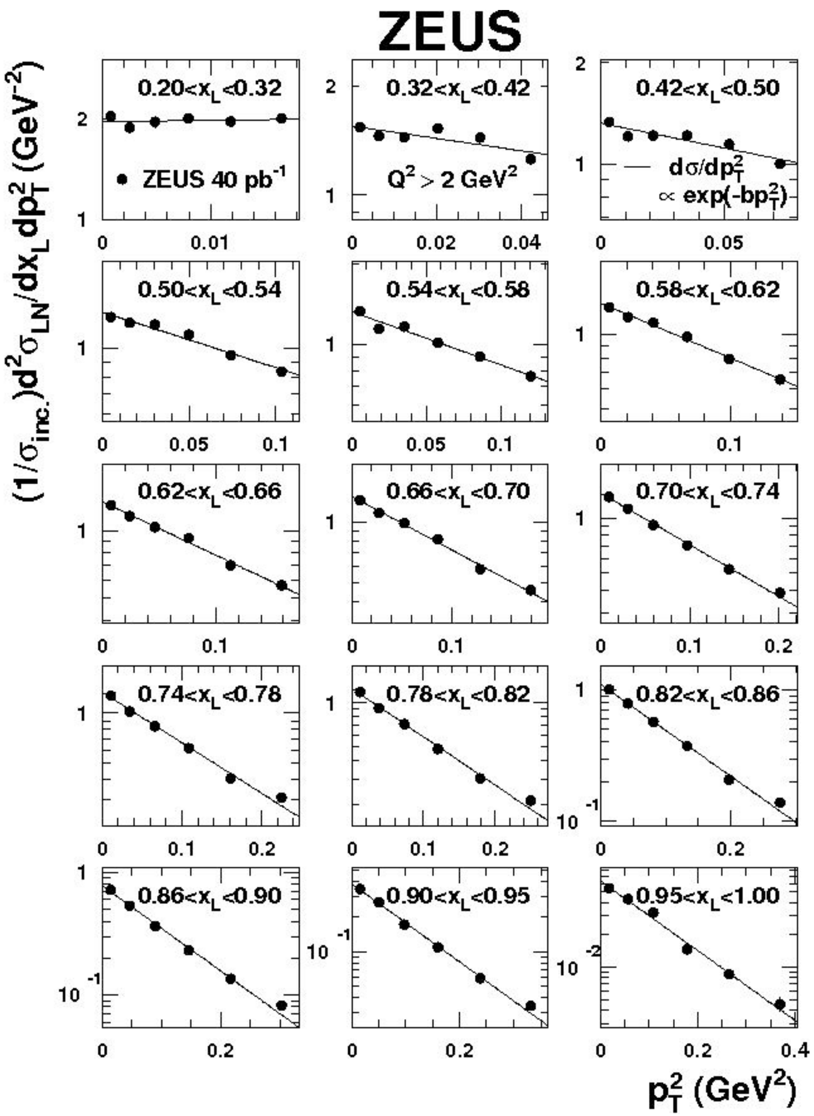
. **Assumption:** pion flux parameterisation:

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

☛ *Γ_π= 0.131 for xL = 0.73*

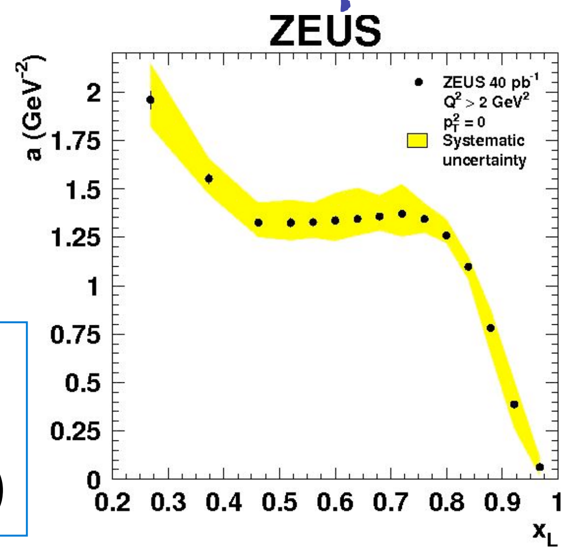
. Compare to known pion pdf parameterisations

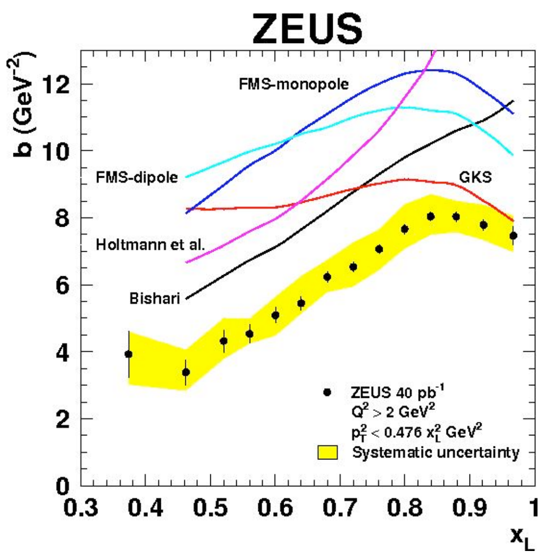
LN cross section (DIS): p_T



DATA:

$a\, e(-bp_T^2)$

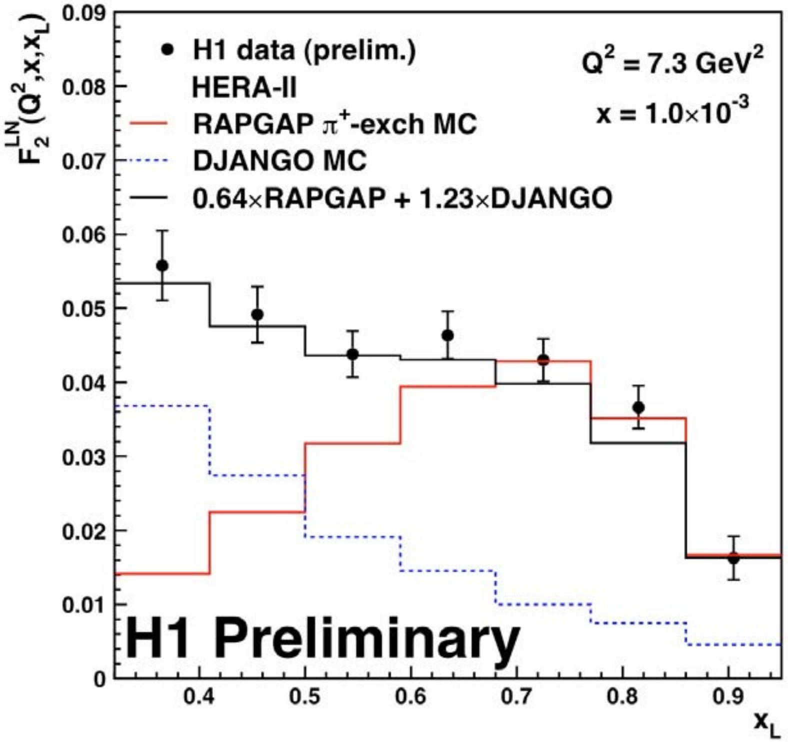


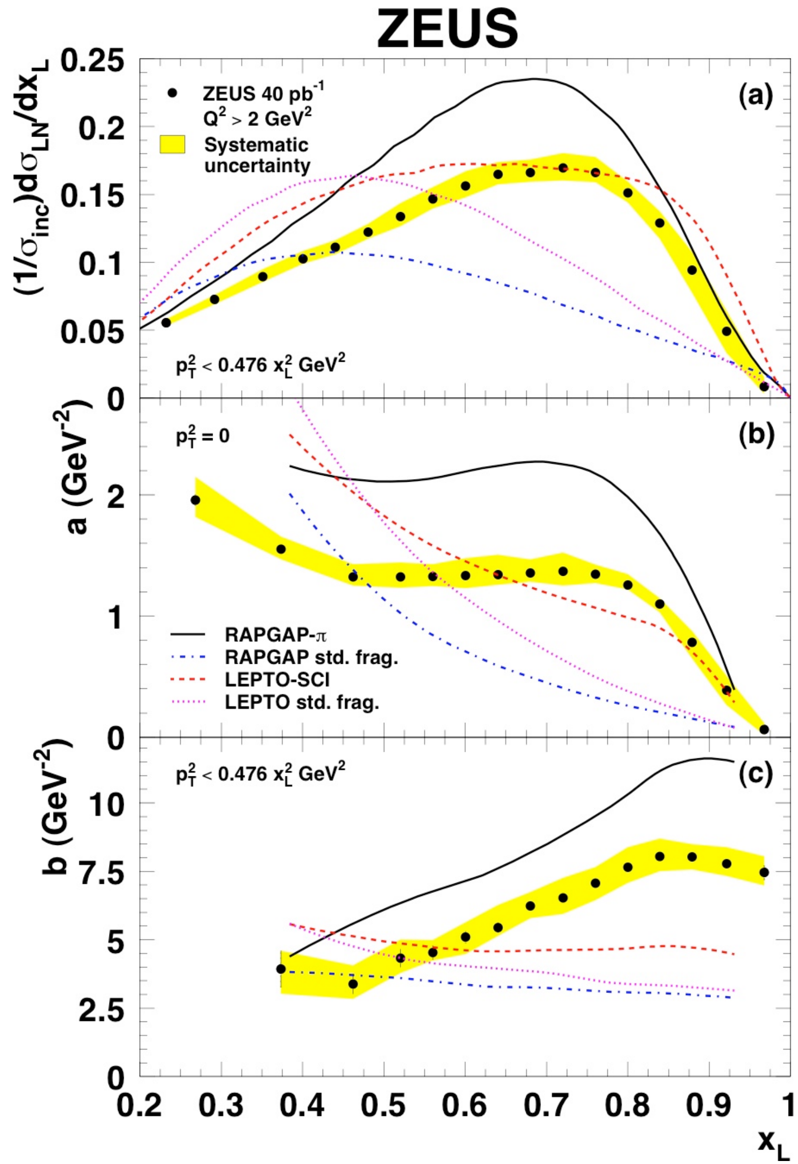


First time ever measured

no model does well on the *b* description

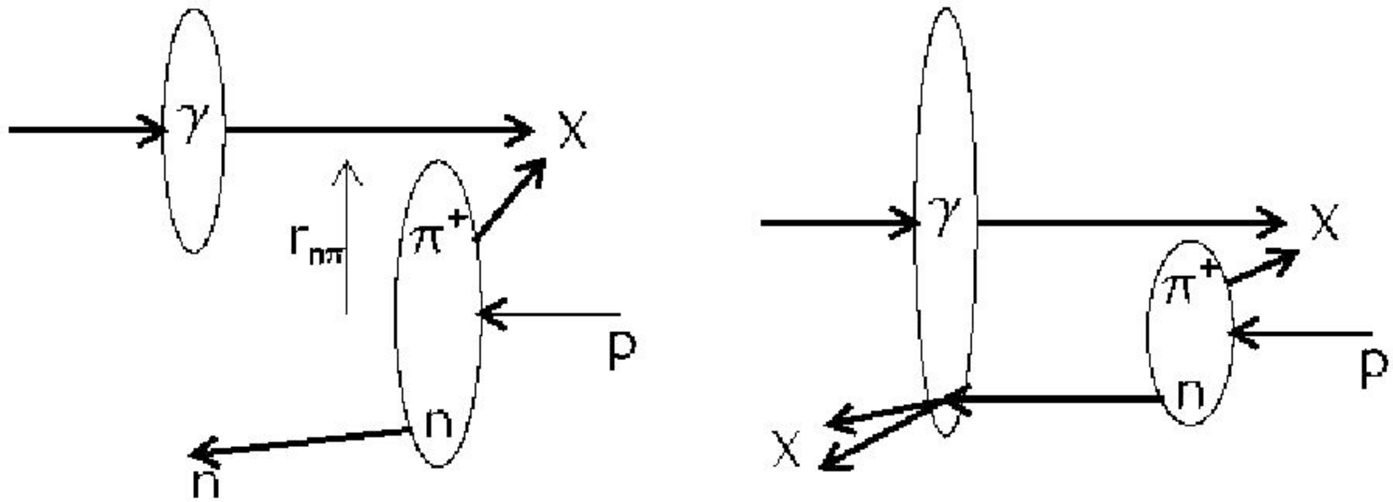
LN cross section (DIS): x_L





Neither pion exchange nor standard fragmentation alone can describe LN DIS data

Back to rescattering:



. since size of the photon ~ 1/Q, may be scale-dependent

⇒ must be tested in processes with different scales

. affetcs the relative rate of produced neutron

⇒ look at $\sigma(ep \to enX)$ / σ $(ep \to eX)$ for different processes

Leading neutrons rates

Charm PhP: $R_{LN}^{D^*}(x_L > 0.49) = 6.55 \pm 0.76^{+0.35}_{-0.45}\ \%$ PLB 590:143 (2005)

ep→eD*nX

Inclusive DIS: $R_{LN}^{DIS}(x_L > 0.49) = 5.8 \pm 0.3\ \%$ NPB 776:1 (2007)

ep→enX, $Q^2>2\ GeV^2$

Dijets PhP: $R_{LN}^{jj}(x_L > 0.49) = 4.8 \pm 0.4\ \%$ NPB 596:3 (2001)

ep→ejjnX

Inclusive PhP: $R_{LN}^{PhP}(x_L > 0.49) = 4.3 \pm 0.3\ \%$ PLB 610:199 (2005)

ep→enX, $Q^2\sim 0\ GeV^2$

Larger γ ⇒ ⇒ ⇒ smaller γ

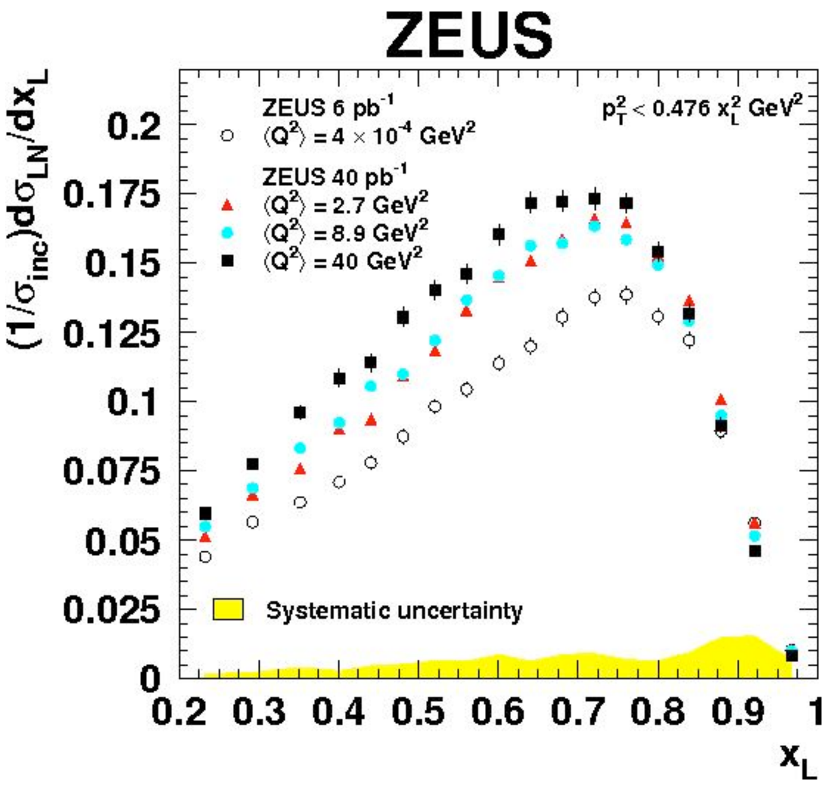
$$R_{LN}^{PhP} < R_{LN}^{jj} < R_{LN}^{DIS} \approx R_{LN}^{D^*}$$

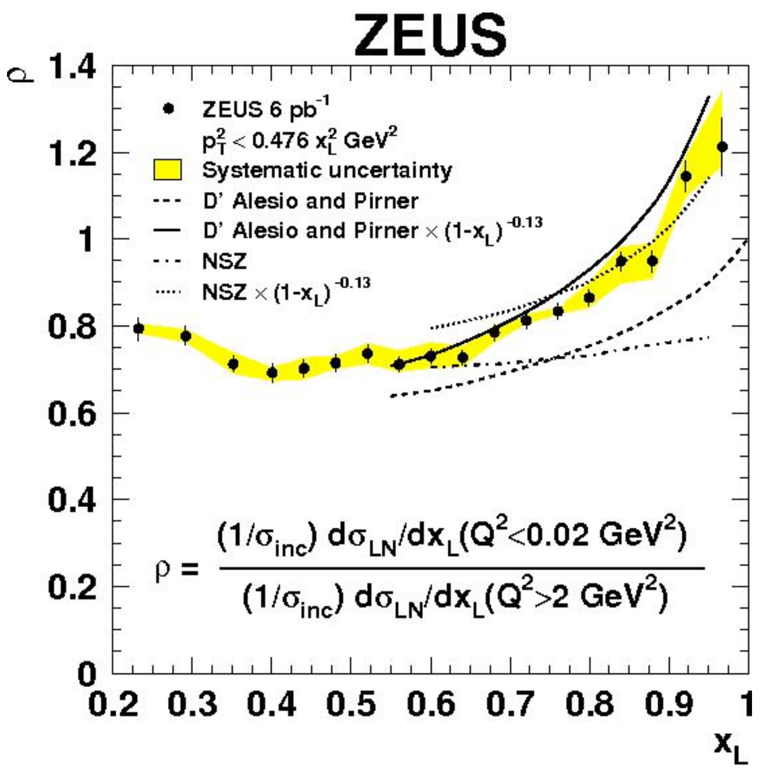
Neutrons production suppression correlated to resolved-photon contribution

Hypothesis in agreement with rescattering

Leading neutrons rates: Q^2 dependence

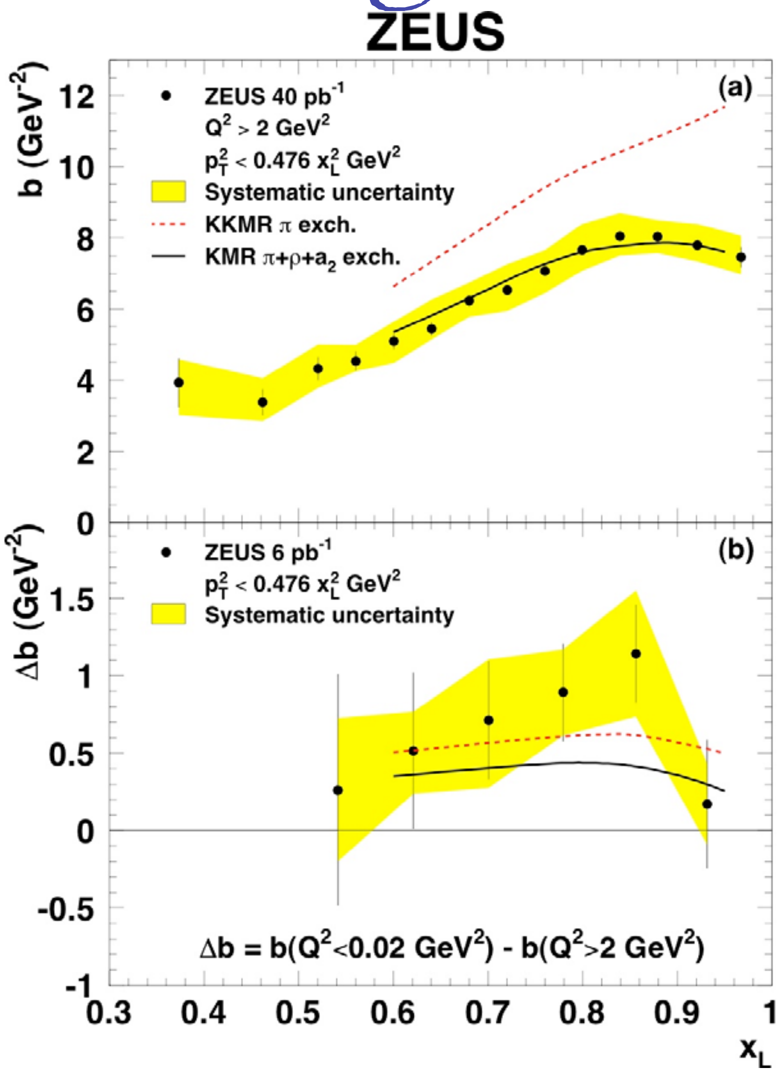
Scale dependency: compare directly LN production in PhP and DIS

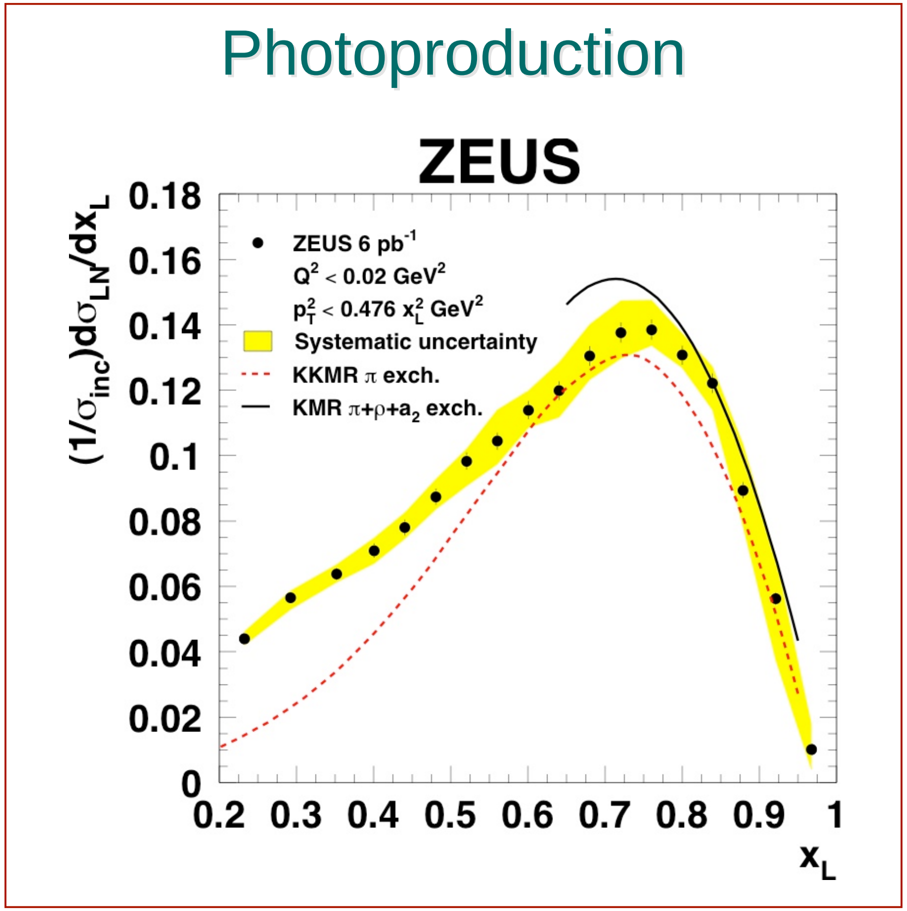




HERA DATA COMPATIBLE WITH RESCATTERING MODELS

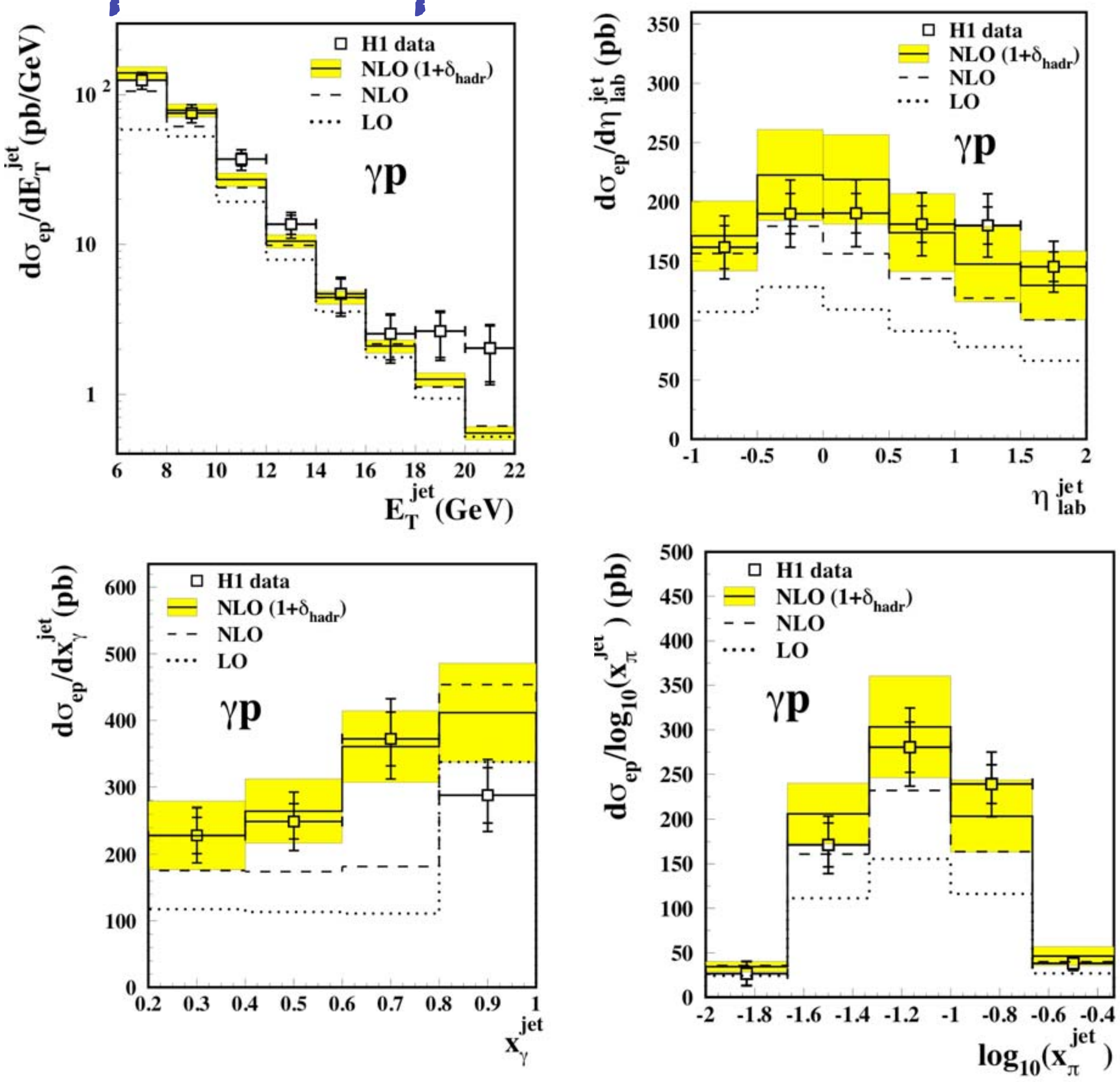
Leading neutrons: rescattering





KKMR: adding absorptive corrections (and more exchanges) to one pion exchange model fixes the description of the data

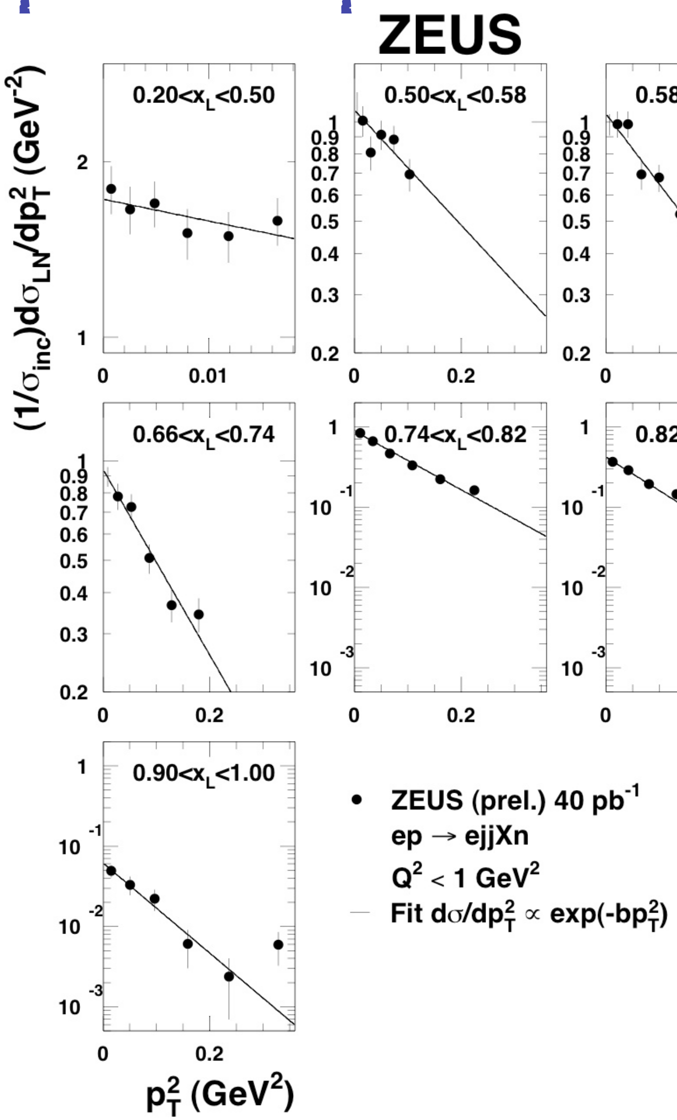
Leading neutrons with dijets (photoproduction)



- NLO calculation by Klasen & Kramer describes well the shape of the data
- Uncertainties on flux factor and pion PDF
- If calculation is normalized to describe leading neutrons with dijets in DIS, a global suppression of 0.64 is needed

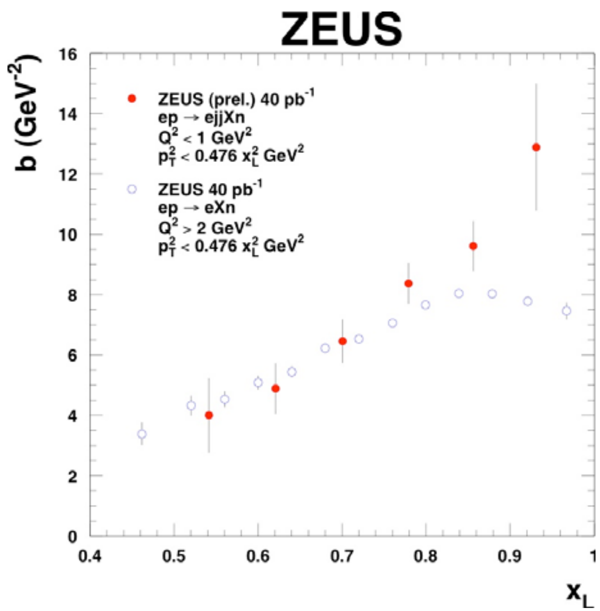
(EPJC 49:957 (2007))

Leading neutrons with dijets (photoproduction)



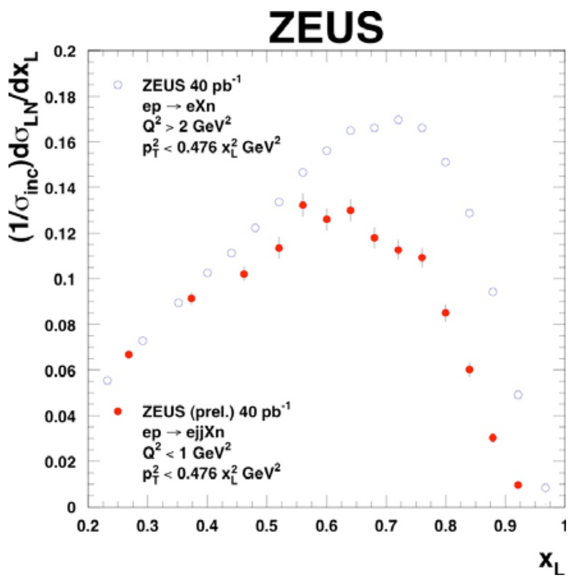
- p_T distribution measured for the first time in events with jets

- Comparison with DIS: slopes somewhat steeper



Leading neutrons with dijets: rates

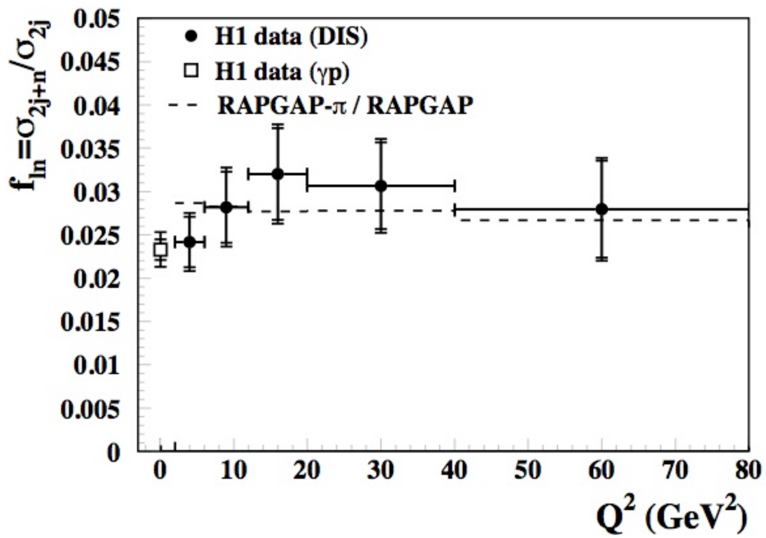
✷ Comparison LN DIS and LN with dijets in photoproduction



✷ Suppression at mid-high x_L

** less phase space for neutron production when jj required **

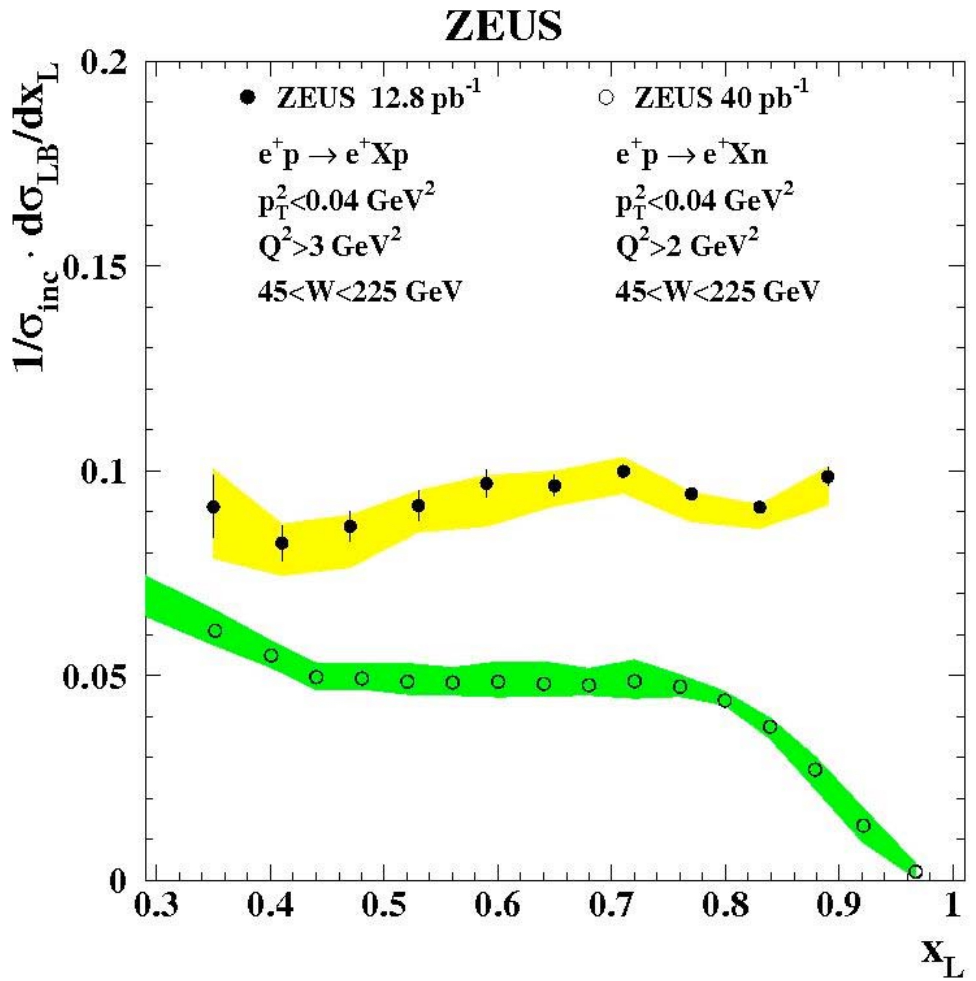
✷ Q^2 dependence for ep -> ejjnX production rate:



✷ Suppression at low Q^2

** rescattering **

Leading protons versus neutrons: yields



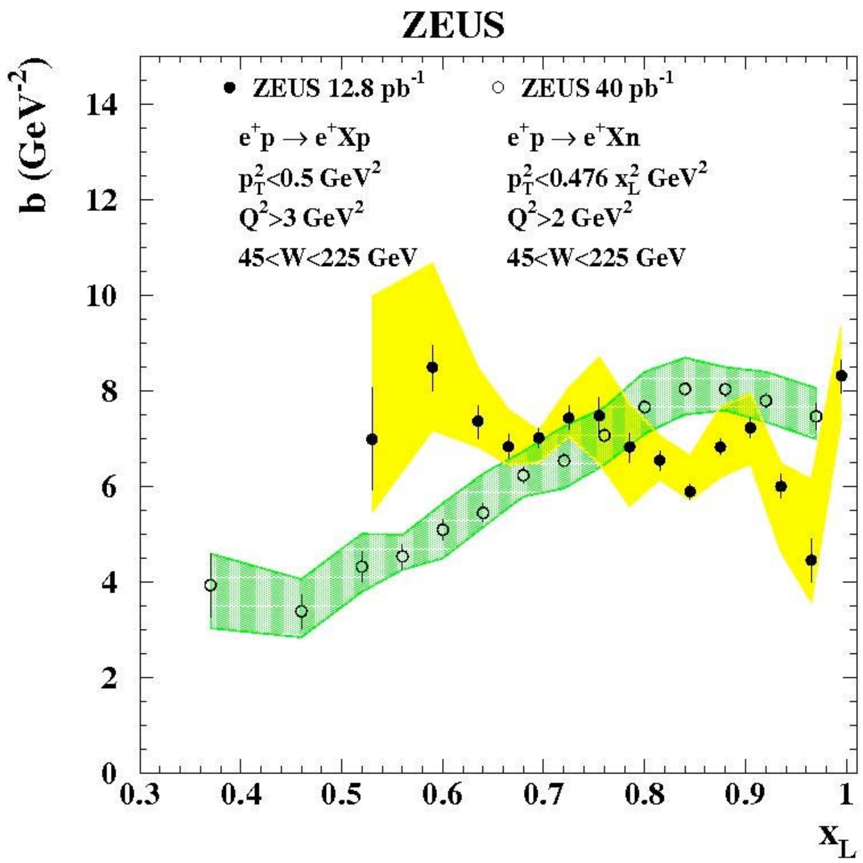
- Expected in case of pure isovector exchange:
  LP = 1/2 LN (Clebsh-Gordan)

- Data: LP = 2 LN
  (compared at same p_T range, $p_T^2 < 0.04\ \mathrm{GeV}^2$)

- Conclusion: leading proton production involves other IR contributions (isoscalar)

Leading protons versus neutrons: slopes

- Similar kinematic region
- Clear rise with x_L for LN
- Flat distribution for LP
- Similar slopes for x_L>0.7 where pion exchange dominates



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Summary:

- HERA data on leading baryons are in general agreement with the hypothesis of particle-exchange

. Neutrons:

- Rescattering effects seen on leading neutron rates at processes of different scales
- HERA data can be used to test and tune models

  ⇨ *crucial for central exclusive/diffractive production at LHC and Tevatron*

- LN with dijets: global suppression (no explicit kinematical variable dependence)
- F_2^{LN} : interpreted in terms of pion F_2^{π}

. Protons:

- First measurements with ZEUS LPS S123 were presented
- Model incorporating particle-exchange hypothesis is in agreement with the data

- $F_2^{LP/LN}$: in agreement with vertex vactorization hypothesis
- Comparison LP with LN suggests isoscalar-IR contributions are present