

# Leading baryon production at HERA

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INFN – Padova

for the H1 and ZEUS Collaborations



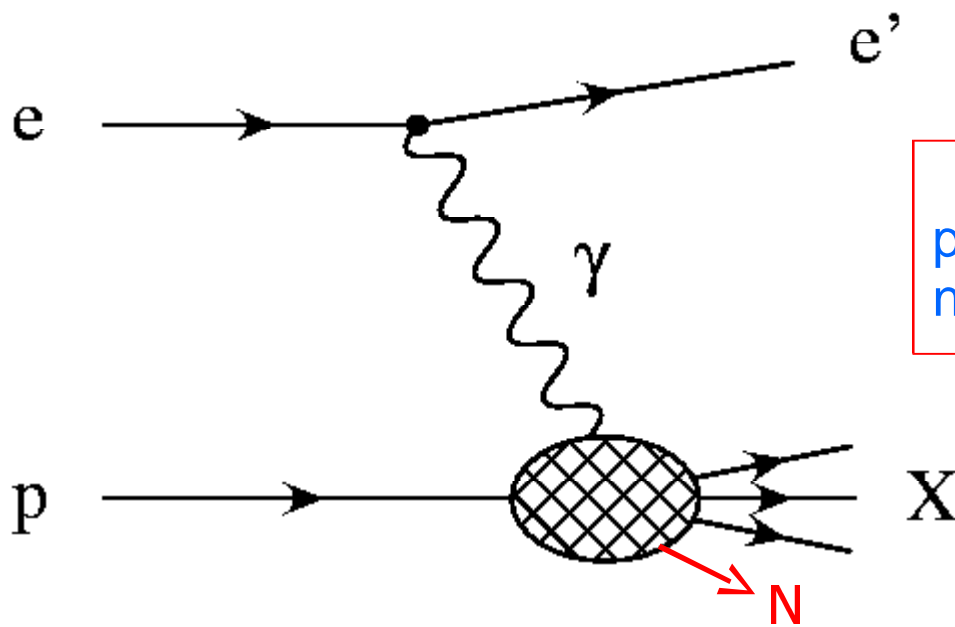
## Highlights:

- ✓ Leading proton production models;
- ✓ Vertex factorization and violation: absorption/re-scattering models;
- ✓ Leading baryons w/ di-jet activity;
- ✓ Pion structure function.
- ✓  $D^*$  production w/ leading neutrons.

# Introduction

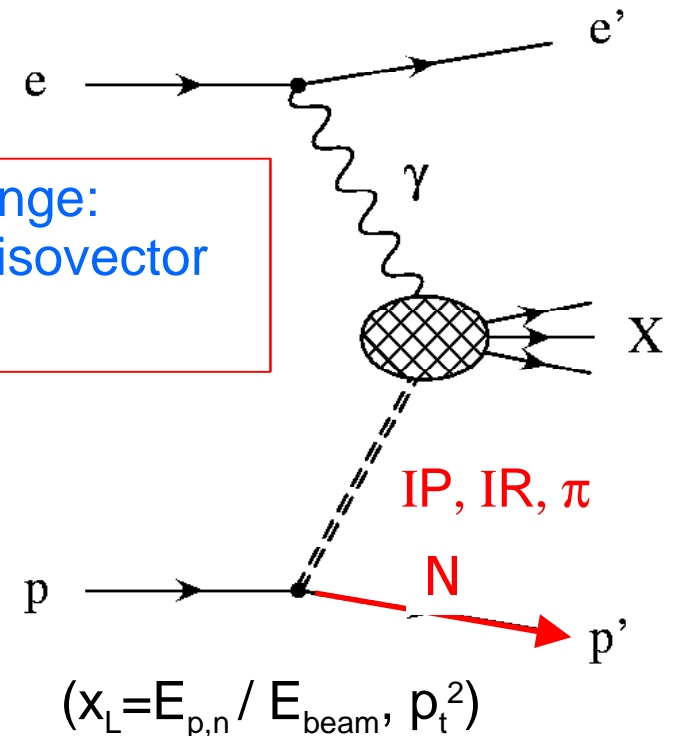
Leading baryon production at small  $t$  in hadronic interactions  $\Rightarrow$  soft process.  
 Conserving baryon number  $\rightarrow$  p or n in final state.

In standard fragmentation:  
 final state N from p remnant



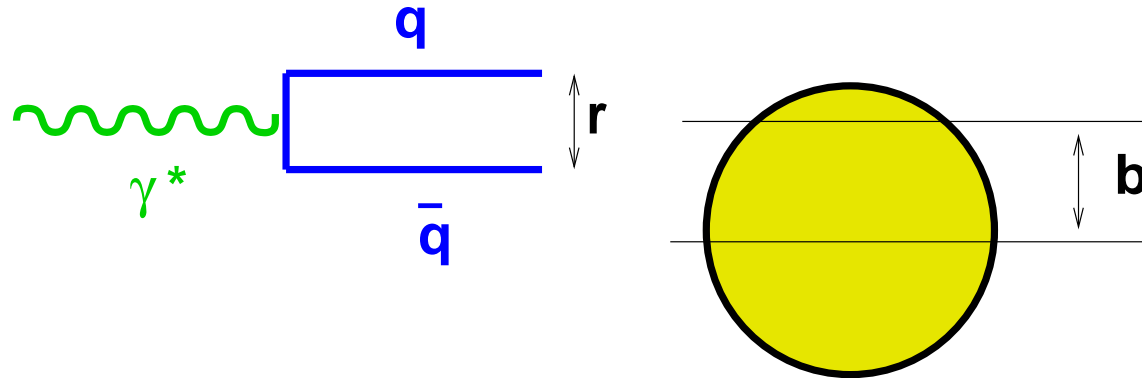
In particle exchange models:  
 baryon from exchange of virtual  
**Pomeron, Reggeon (e.g.  $\rho, \omega, f_2$ ),  $\pi$ .**

Exchange:  
 p: isoscalar, isovector  
 n: isovector.



# Proton dipole picture

In the proton rest frame:



where:

- ✓  $r \sim 0.2 \text{ fm}/Q$ , transverse size of probe;
- ✓  $ct \sim 0.2 \text{ fm} (W^2/2m_p Q^2)$  – scale over which photon fluctuations survive;

Tagging the leading baryon, can vary the impact parameter

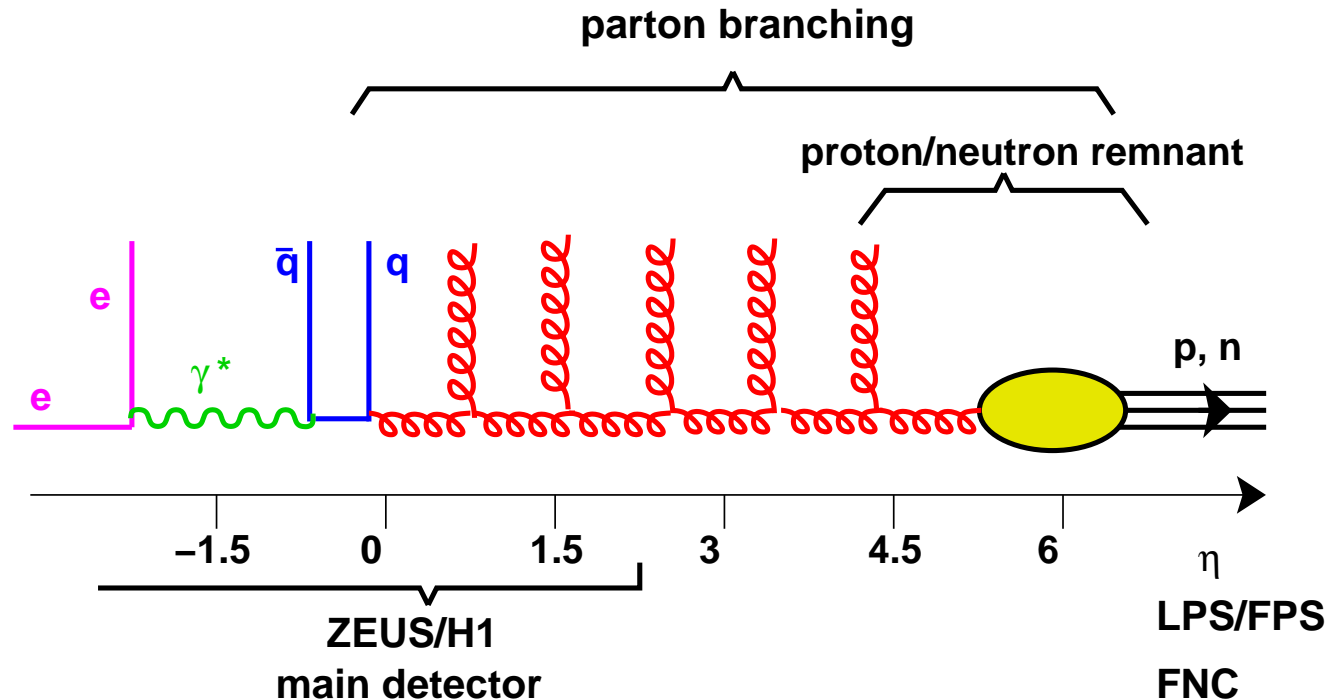
- ✓  $b \sim 0.2 \text{ fm}/\sqrt{t}$ , with  $t = (p - p')^2$ .

Seeing these parameters experimentally, can scan the distribution of strongly interacting matter in hadrons.

# Process scales

By means of semi-inclusive/exclusive processes, can probe different scales:

- ✓ **Hard scale:**
  - $Q^2$  for DIS samples;
  - $m_c^2$  for charm production;
  - $E_T$  for jet requirements;
- ✓ **Soft scale:**
  - ✓  $p_T$  of the leading baryon.

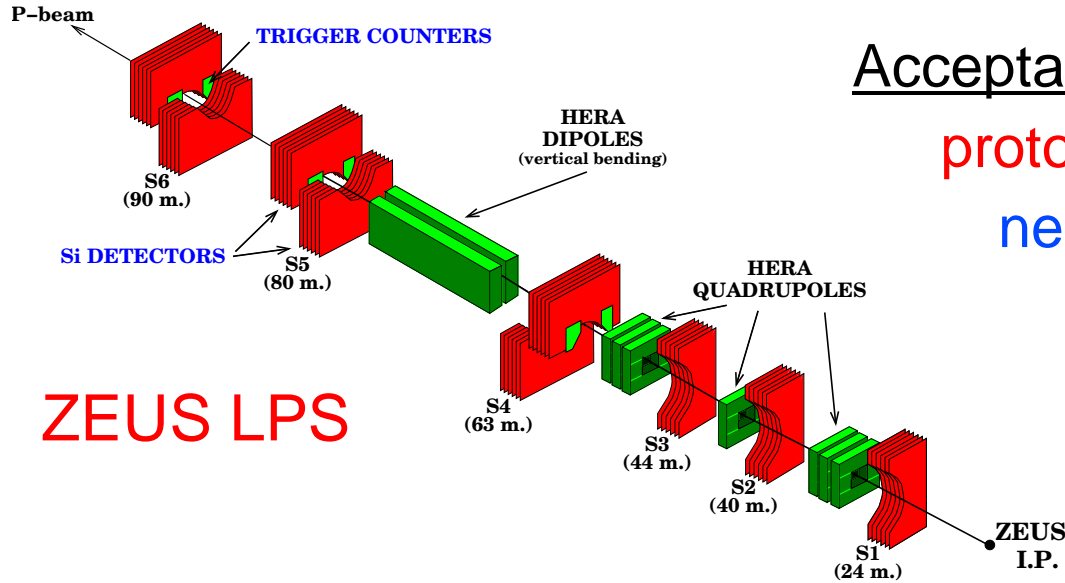


# Forward detectors acceptance

Acceptances limited by magnet apertures:

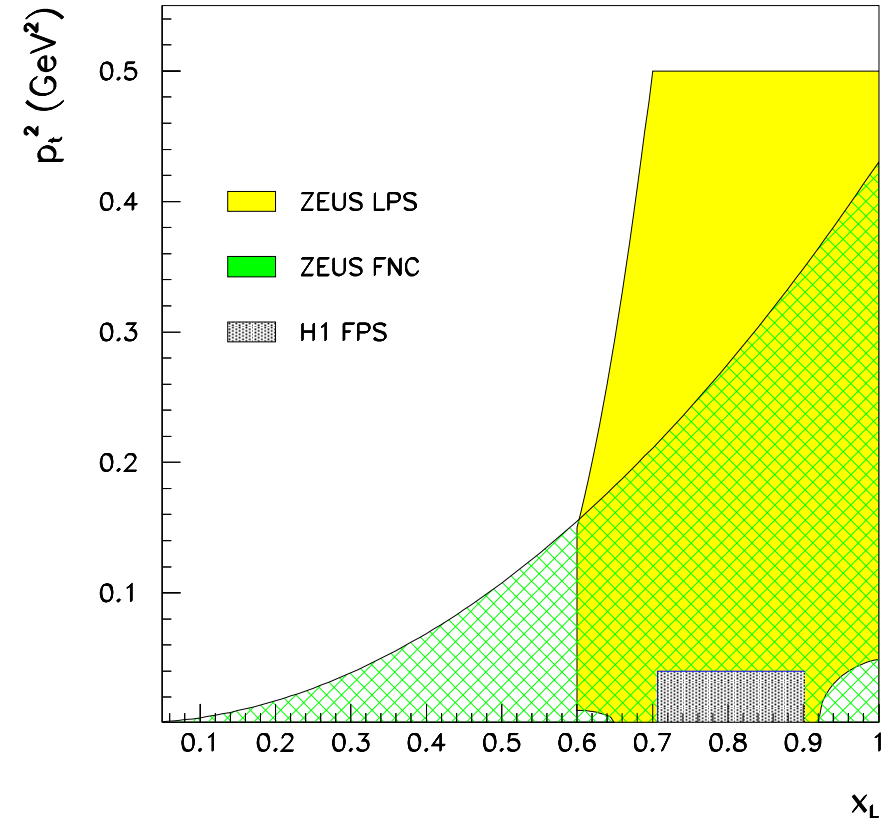
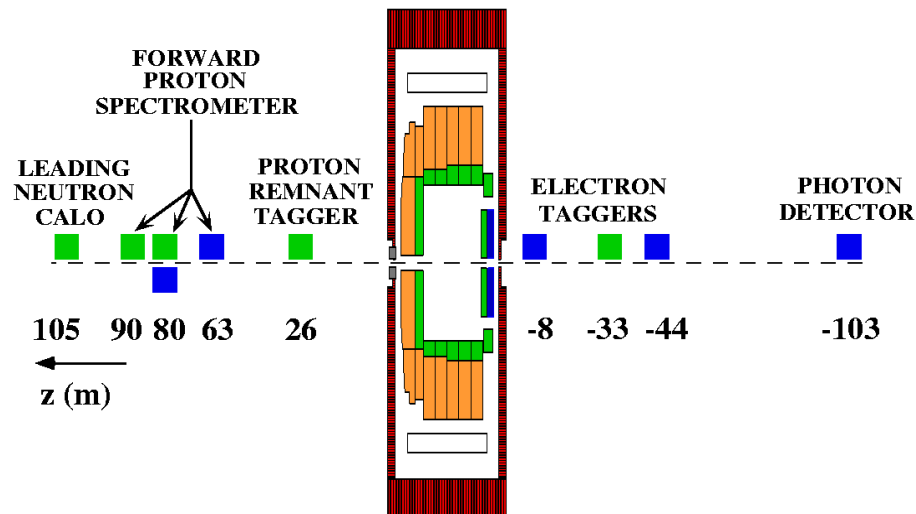
protons:  $0.6 < x_L < 1, p_t^2 < 0.5 \text{ GeV}^2$

neutrons:  $x_L > 0.2 \theta_n < 0.8 \text{ mrad}$ .



ZEUS LPS

## H1 BEAM-LINE INSTRUMENTATION



# List of presented results

ZEUS

- ✓ “Leading proton production in  $e^+p$  collisions at HERA”, Nucl. Phys. B 658 (2003) 3.
- ✓ “Leading neutron production in  $e^+p$  collisions at HERA”, Nucl. Phys. B 637 (2002) 3.
- ✓ ICHEP02 paper 824, “Properties of events containing leading neutrons in DIS and PHP at HERA”.
- ✓ “Observation of photoproduction of  $D^{*\pm}(2010)$  mesons associated with and energetic neutron”, paper in preparation, results shown at DIS03.

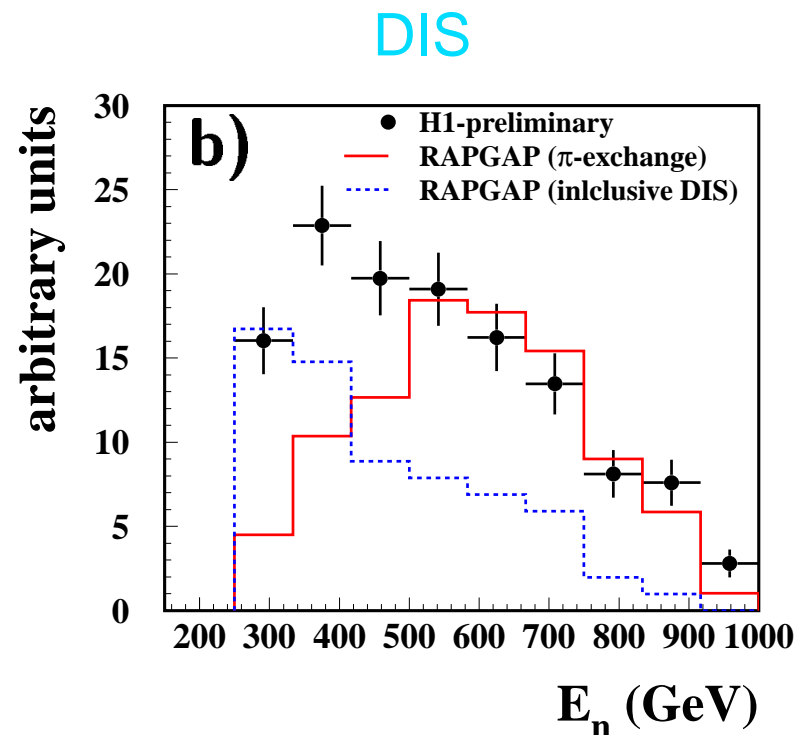
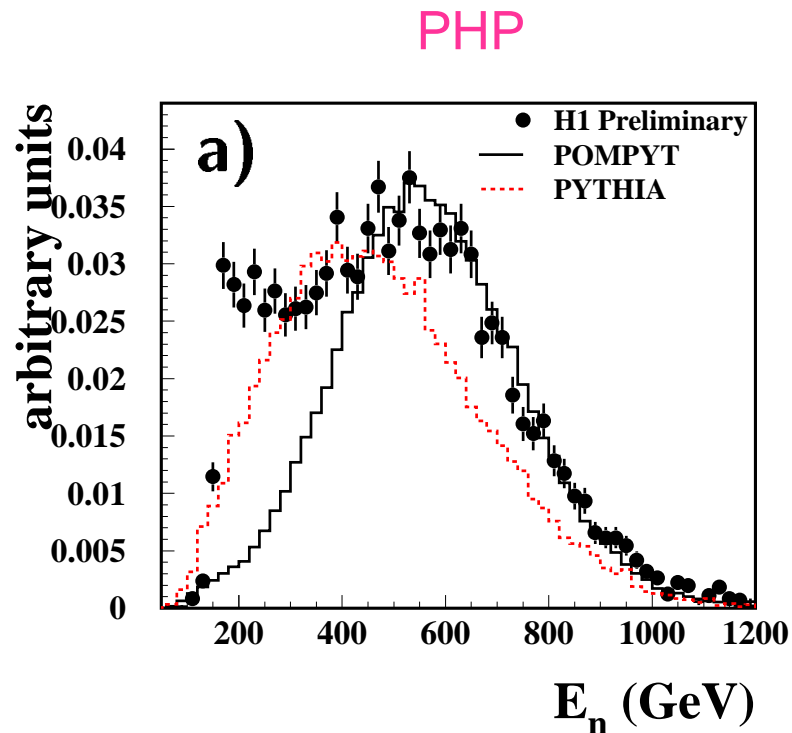
H1

- ✓ ICHEP02 paper 988, “Measurement of Dijet Cross-Section with Leading Neutrons in ep interactions at HERA”.

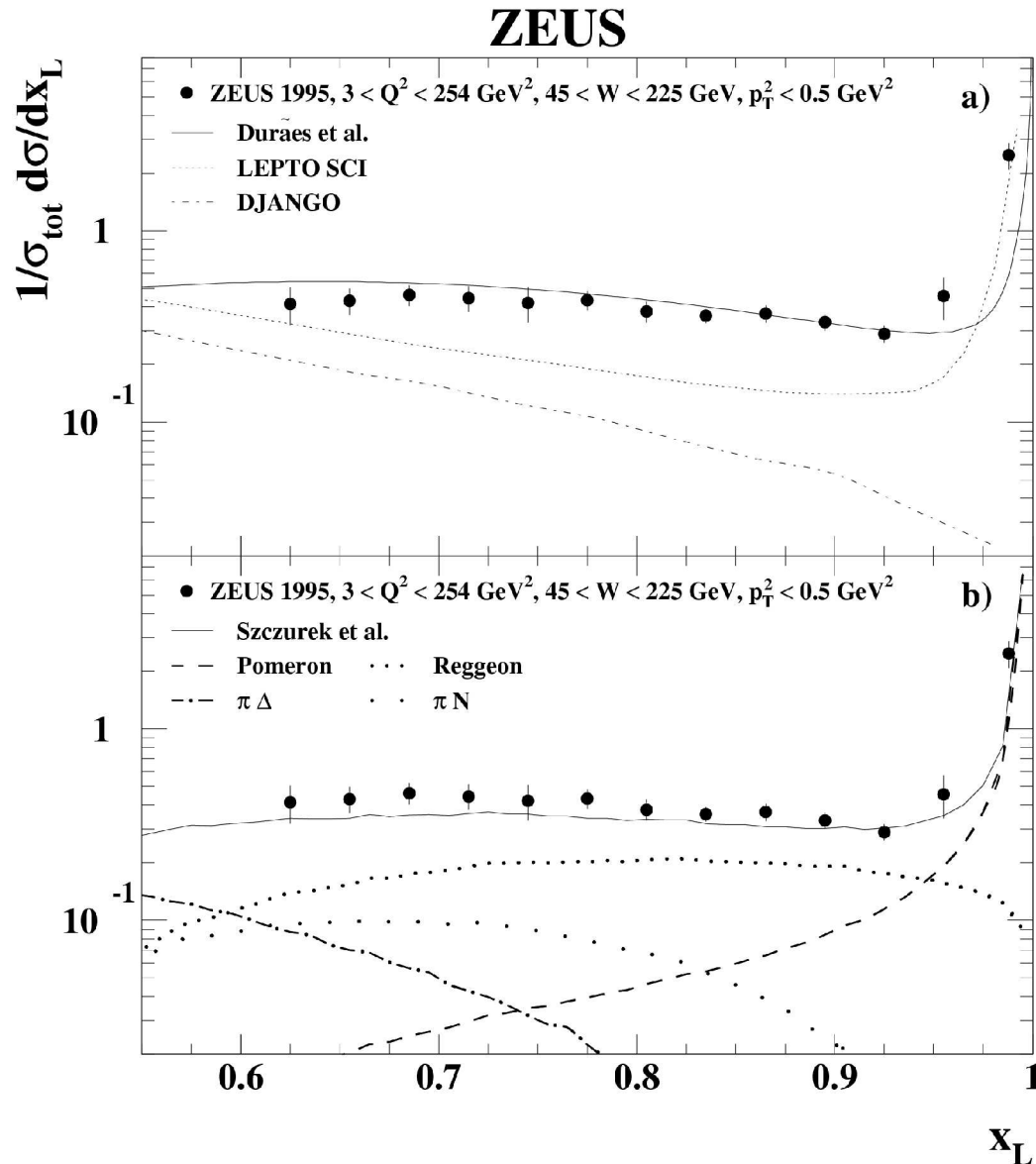
# LN energy spectra

LN cross section and energy spectra compared to different Monte Carlo production models:

- ✓ standard fragmentation Monte Carlo fail;
- ✓  $\pi$  exchange needed to describe shape.



# Proton energy spectra – model comparison



Shape and data normalization is compared to:

- ✓ standard fragmentation models  
→ do not describe data;
- ✓ QCD inspired model, the Gluon-Interacting model of Durães et al. Gives a better description;
- ✓ exchange models, need multiple processes (Pomeron, Reggeon,  $\pi^\circ$  and  $\pi-\Delta$ ) to describe the data.

# Vertex factorization

Under the factorization hypothesis,  
 $\sigma(ep \rightarrow eNX) \propto G_{p,p'} \times G_{e,e'}$

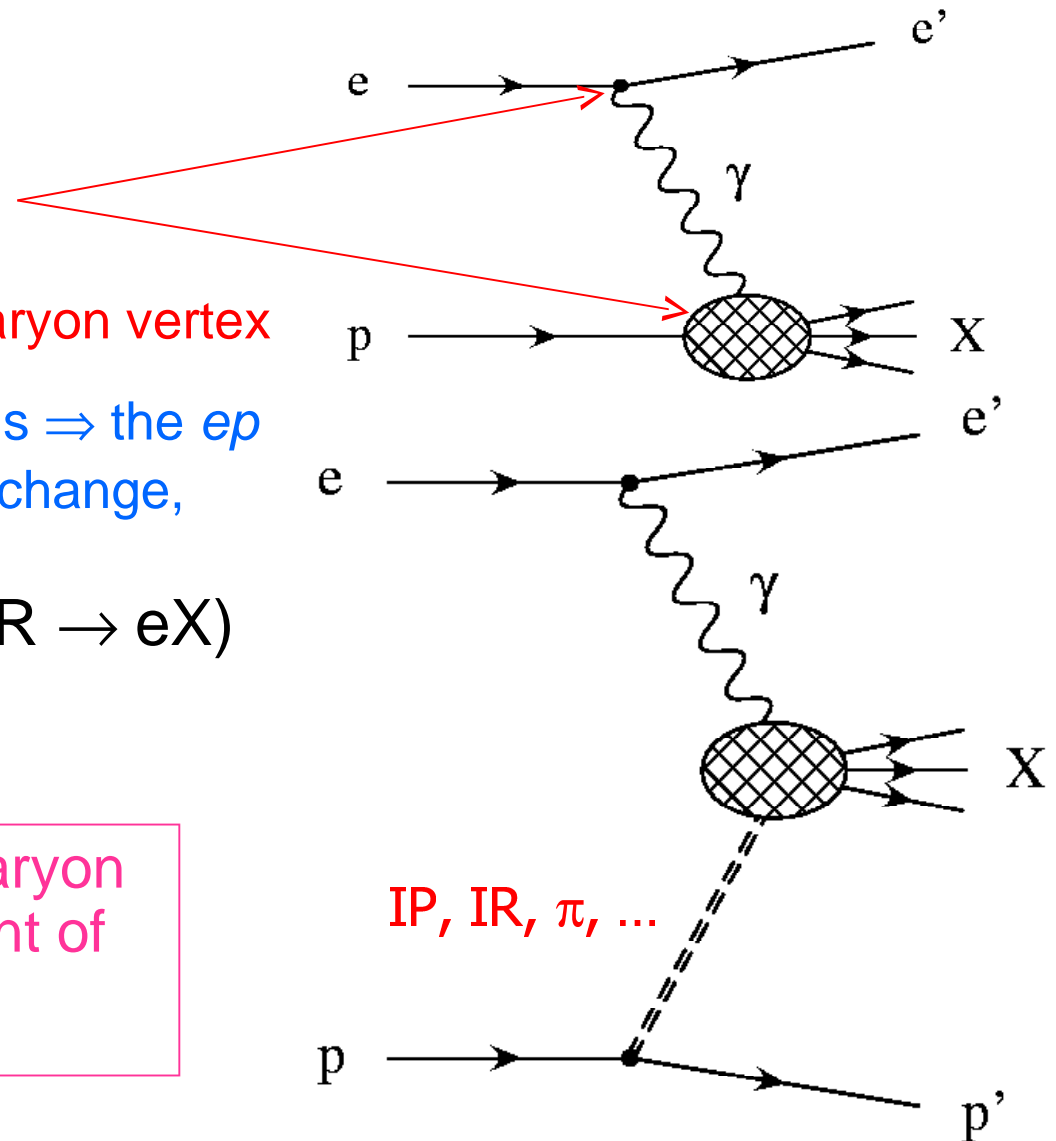
i.e lepton vertex ~ independent of baryon vertex

Direct implication of exchange models  $\Rightarrow$  the  $ep$  cross section factorizes, e.g. for  $\pi$  exchange,

$$\sigma(ep \rightarrow eNX) = f_{IP/p}(x_L, t) \times \sigma(eIR \rightarrow eX)$$

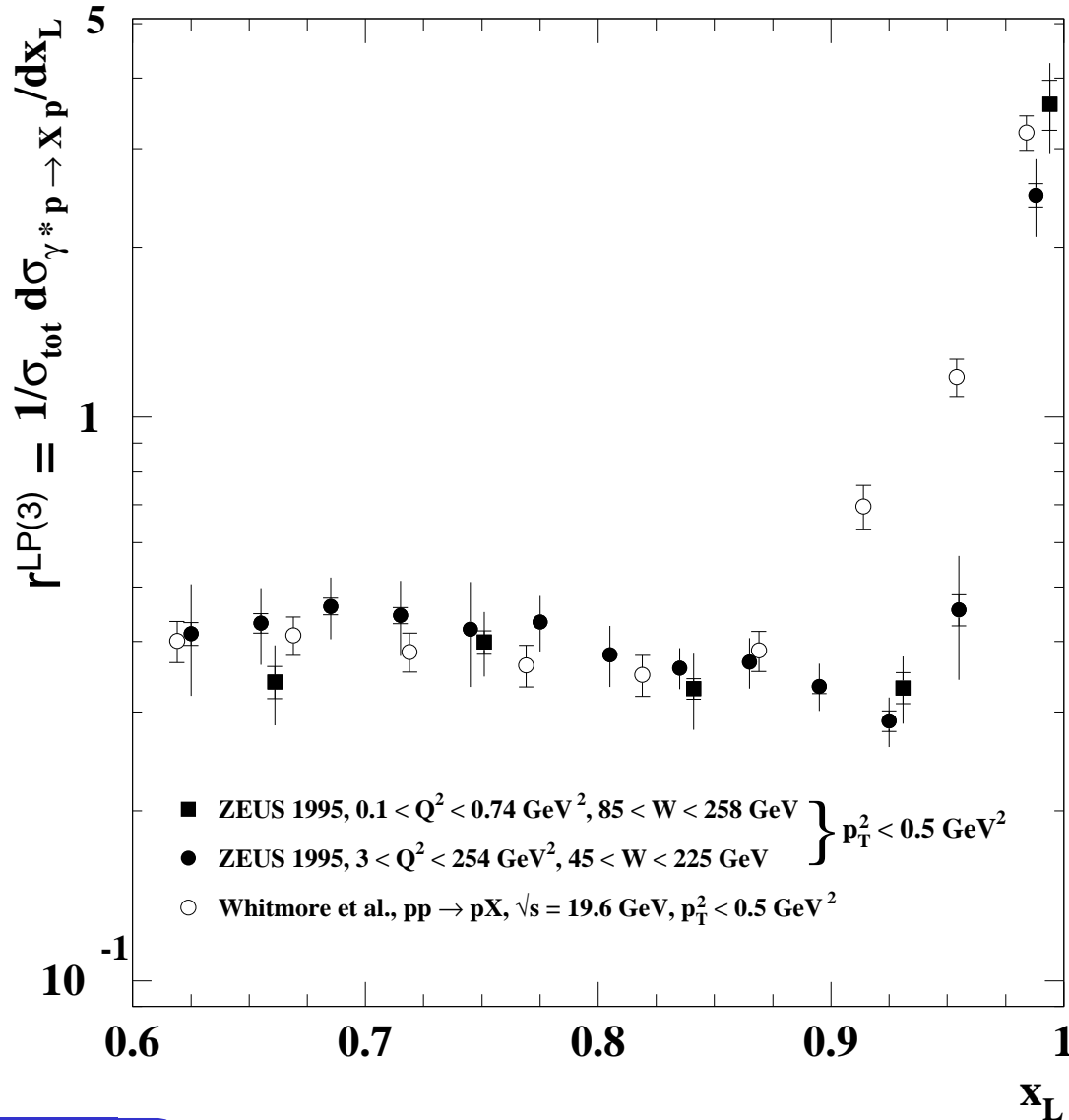
IR flux in  $p$

Cross section dependence on baryon variables ( $x_L$  and  $p_t^2$ ) independent of those at the lepton vertex



# LP energy spectra

ZEUS



LP normalized cross section for BPC ( $0.1 < Q^2 < 0.74 \text{ GeV}^2$ ) and DIS ( $3 < Q^2 < 254 \text{ GeV}^2$ ).

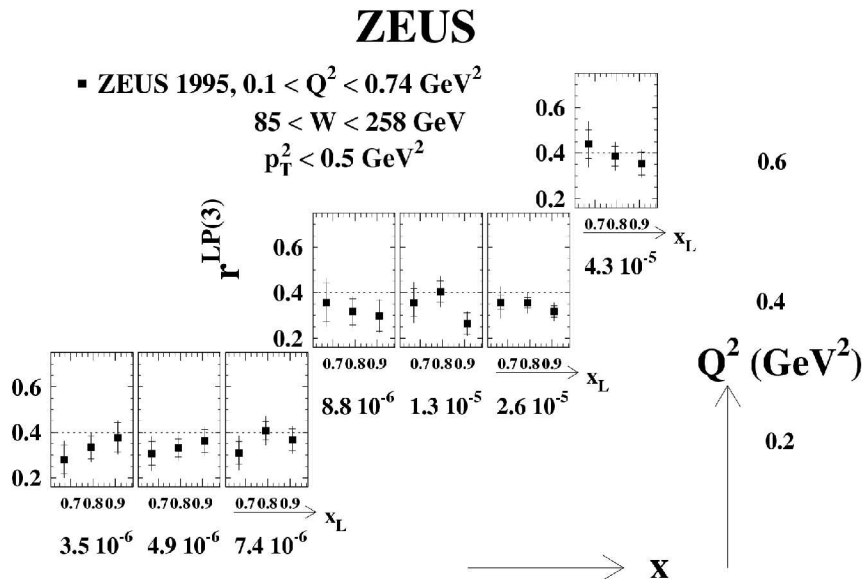
Clear diffractive peak at  $x_L \sim 1$ ;  
cross section flattens for  $x_L \leq 0.9$

For  $x_L \leq 0.9$ ,  $r^{LP(3)}$  consistent w/ pp data and  $\gamma^* p$  data sets.

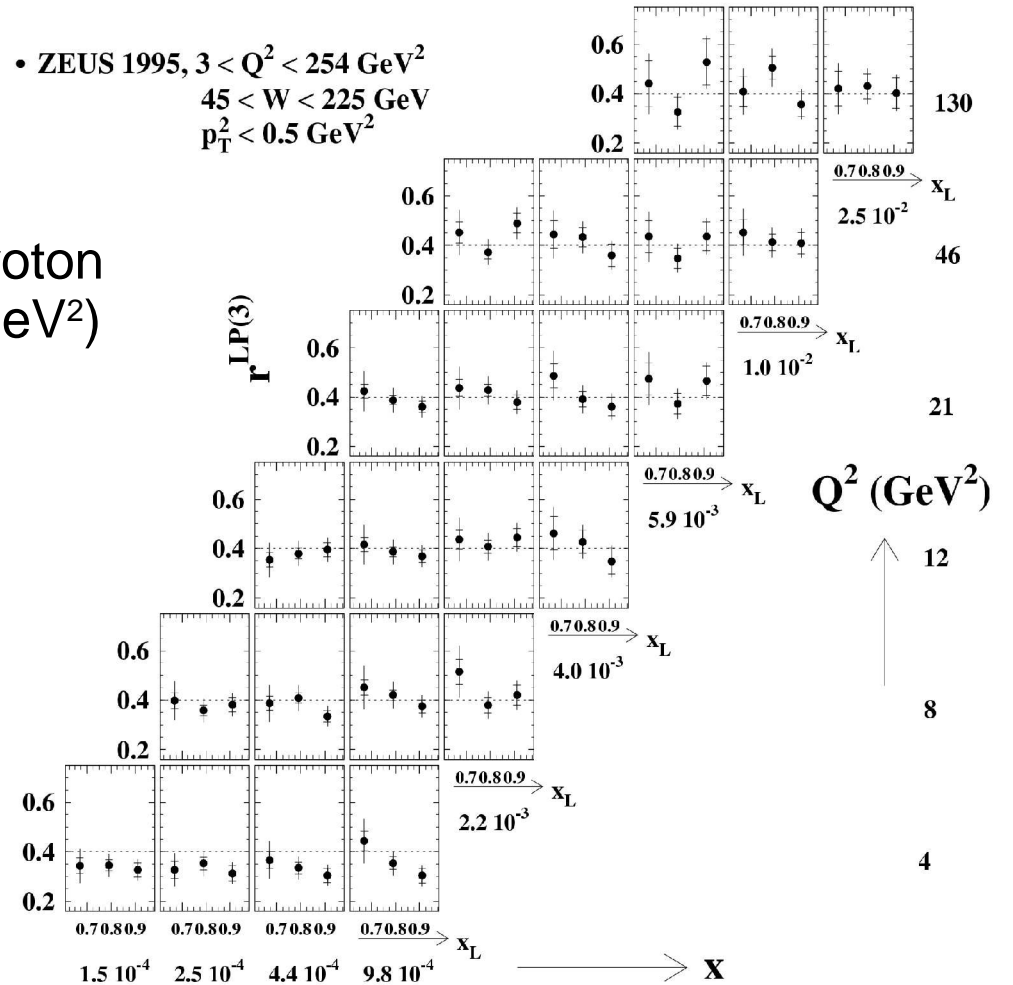
→ approximate vertex factorization.

# Proton yield

Fraction of events with a leading proton with  $(0.6 < x_L < 0.97$  and  $p_T^2 < 0.5 \text{ GeV}^2$ )

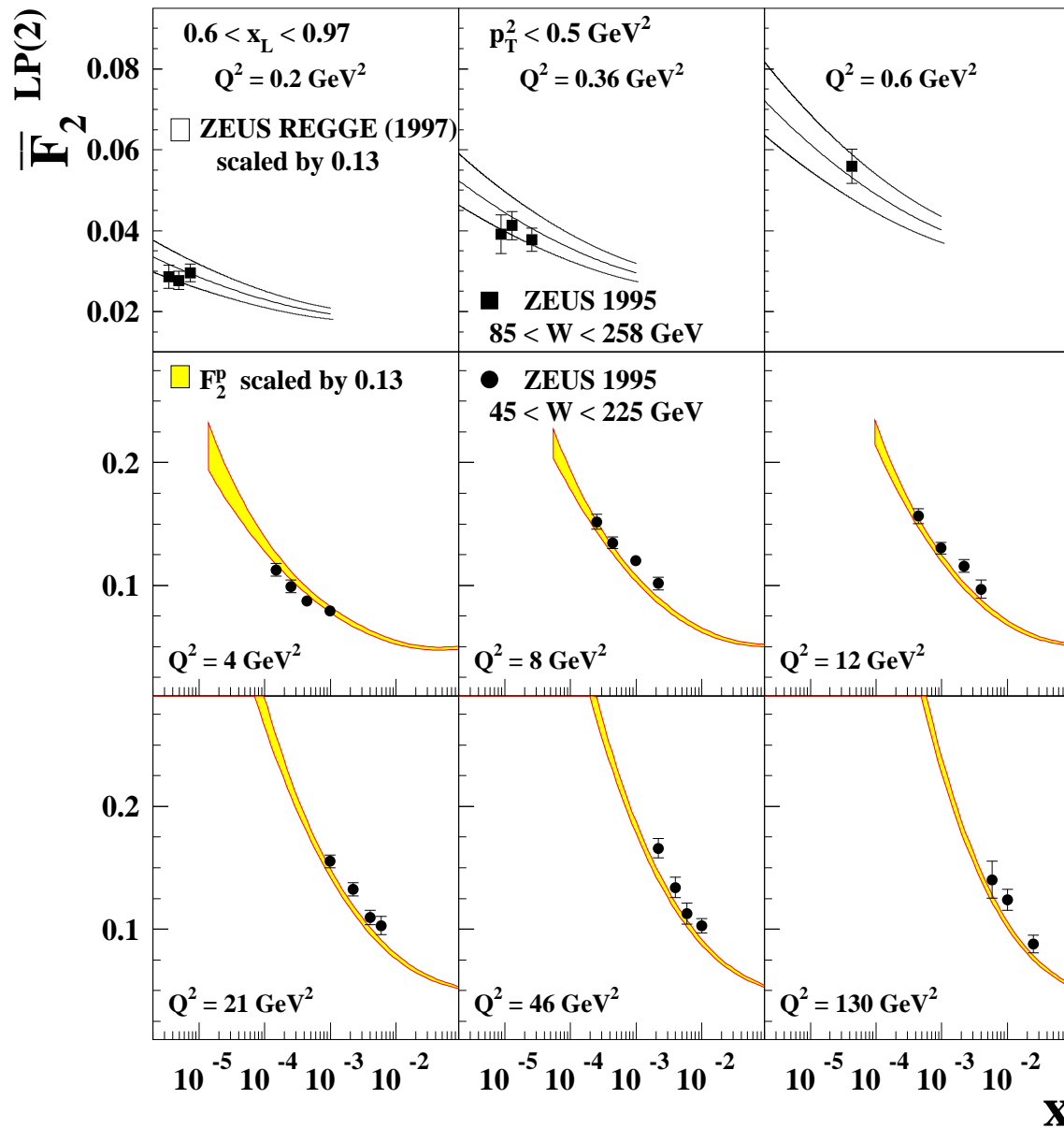


- ZEUS 1995,  $3 < Q^2 < 254 \text{ GeV}^2$
- $45 < W < 225 \text{ GeV}$
- $p_T^2 < 0.5 \text{ GeV}^2$



⇒ approximately no  $x_L$  or  $Q^2$  dependence

# ZEUS



$$\overline{F}_2^{LP(2)}$$

Ratio multiplied by:

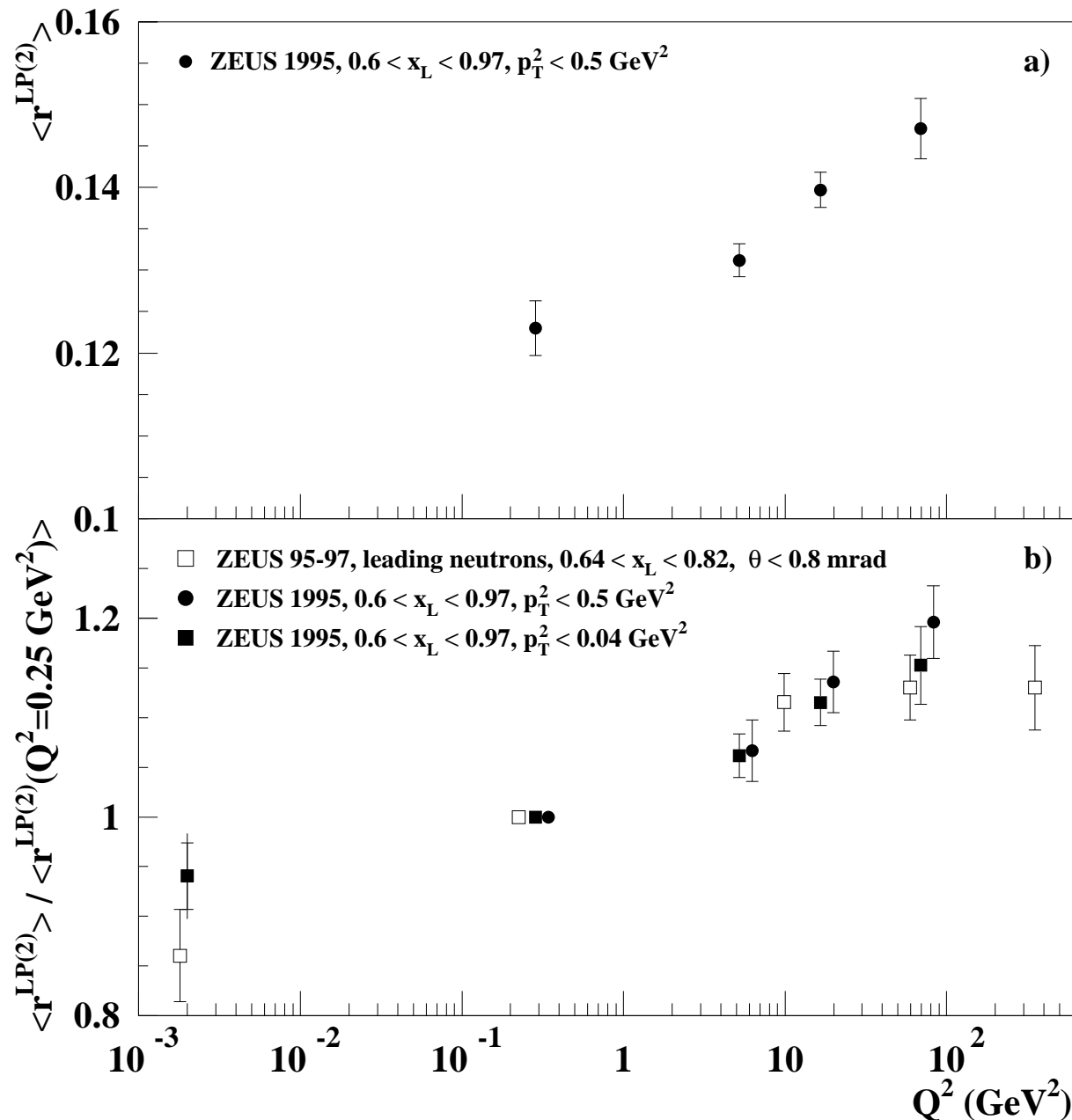
- ✓ fit to published ZEUS low  $Q^2$   $F_2$  data (ZEUS Regge);
- ✓  $F_2$  parameterization (M.Botje QCD fit)

$$F_2^{LP(2)} = F(x_{Bj}, Q^2) \langle r^{LP(2)} \rangle$$

⇒  $F_2$ , scaled down, well describes  $F_2^{LP}$  (small variations w/  $Q^2$ )

Result for neutrons similar

# ZEUS



## Factorization violation

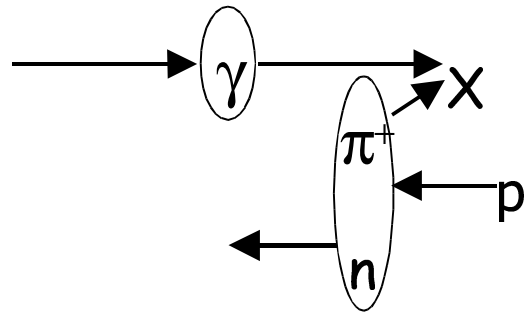
Averaging  $r^{LP(3)}$  over  $x$  and  $x_L$  reveals a small violation of factorization: 15-20% for  $Q^2 \sim 0.02$  to  $100 \text{ GeV}^2$  (somewhat higher for  $n$ )

- Different evolution of  $F_2$  and  $F_2^{LP(2)}$  ?
- Absorptive effects in the  $\gamma^*p$  system (smaller  $\gamma$  size at higher  $Q^2$ )?

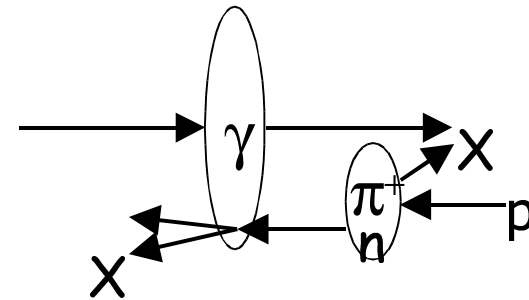
# Factorization Violation

Within exchange picture, factorization can be violated, e.g. via rescattering models (D'Alesio & Pirner).

e.g. n production via  $\pi^+$  exchange:



No rescattering,  
n detected



Rescattering, n lost  
(lower  $x_L$ , higher  $p_t$ )

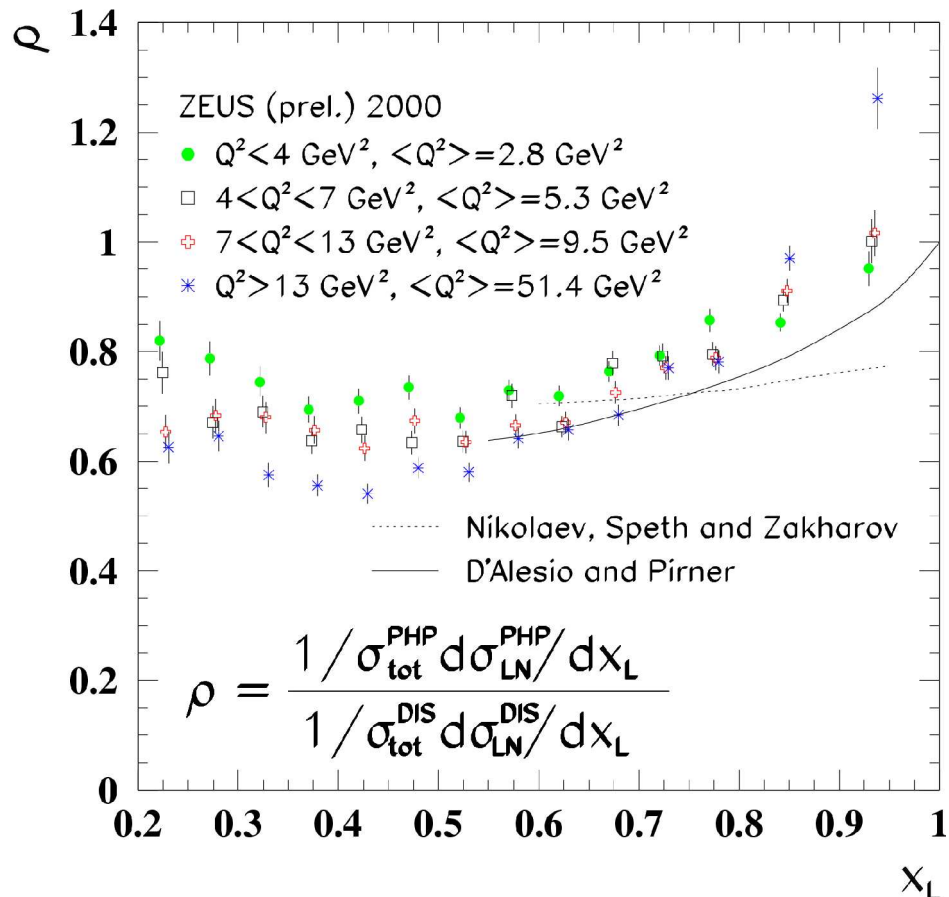
DIS:  $\gamma^*$  ~ point like

PHP:  $\gamma$  ~ hadron like, (size  $\sim 1/Q$ ),  $\Rightarrow$  rescattering more probable

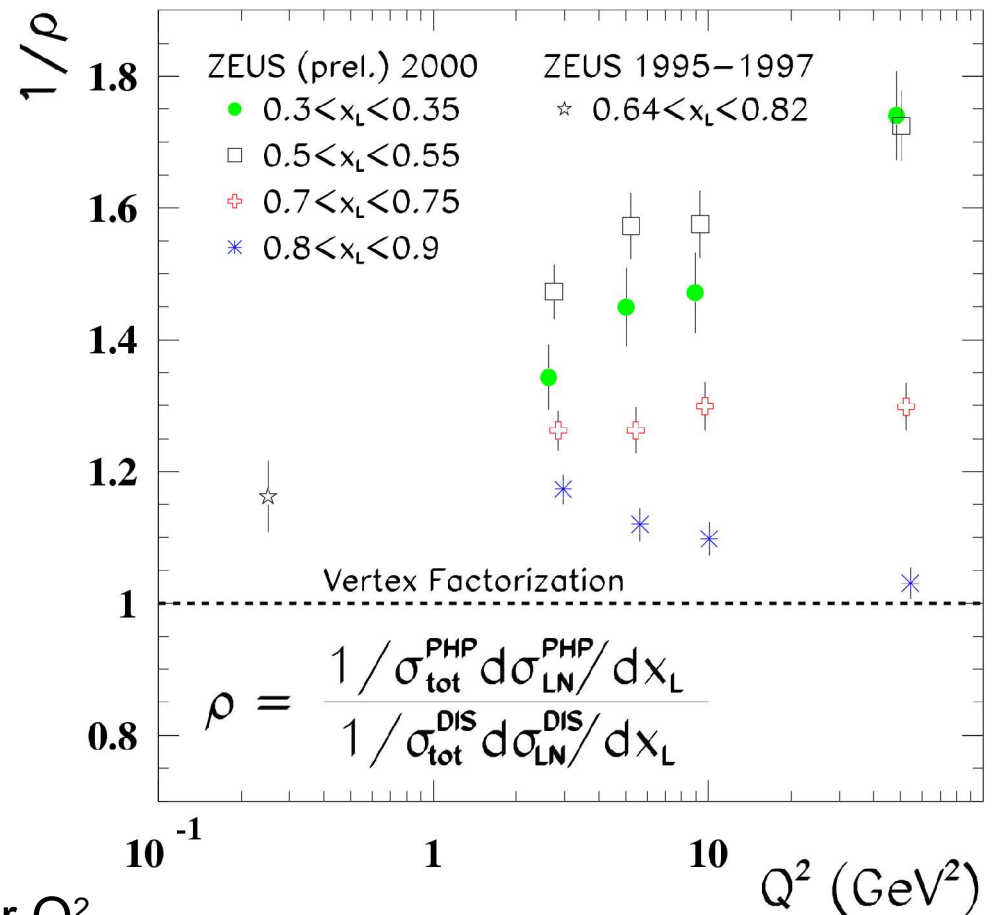
In OPE  $\langle r_{n\pi} \rangle$  smaller at lower  $x_L \Rightarrow$  more rescattering at lower  $x_L$

# Neutron $x_L$ spectra vs $Q^2$

Ratio PHP/DIS ZEUS



Ratio DIS/PHP ZEUS



- fewer neutrons at lower  $x_L$  and lower  $Q^2$
- rescattering model (valid for  $Q^2 \sim 10\text{-}100 \text{ GeV}^2$ )  $\Rightarrow$  qualitative description
- ratio is also function of  $x_L$

# Leading baryons w/ di-jets

H1 – Leading neutrons:

- ✓  $E_n > 400 \text{ GeV}$  ( $x_L > 0.49$ );
- ✓  $\theta_n < 0.8 \text{ mrad}$ .

ZEUS – Leading protons:

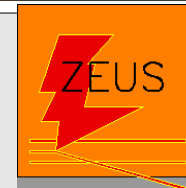
- ✓  $0.6 < x_L < 0.97$
- ✓  $p_t^2 < 0.5 \text{ GeV}^2$



DIS:

- ✓  $2 < Q^2 < 80 \text{ GeV}^2$
- ✓  $0.1 < y < 0.7$ ;
- ✓ PHP:
  - ✓  $Q^2 < 10^{-2} \text{ GeV}^2$
  - ✓  $0.3 < y < 0.65$ .

$e^+$  selection:



DIS:

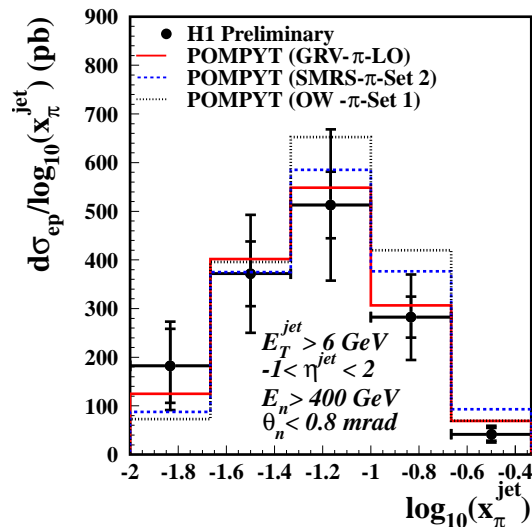
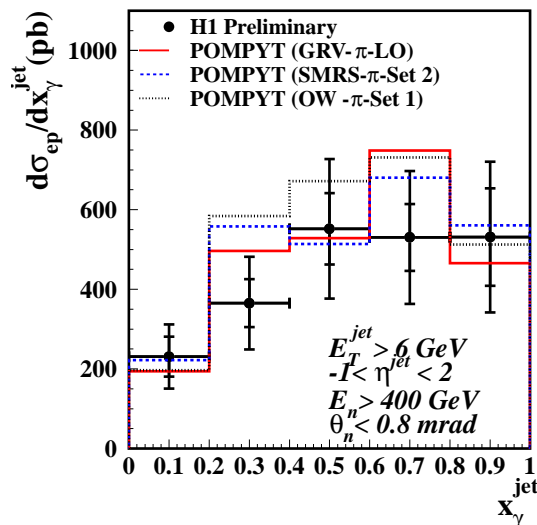
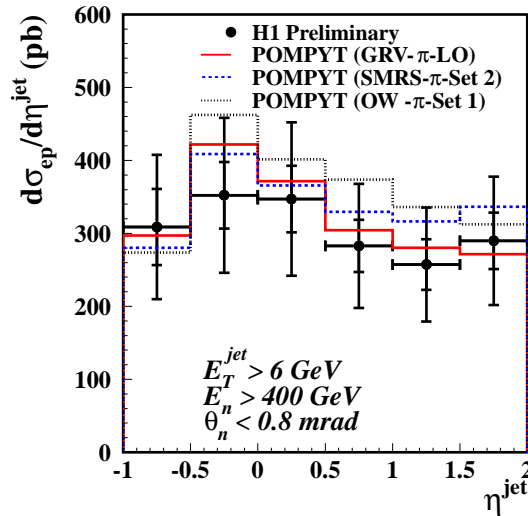
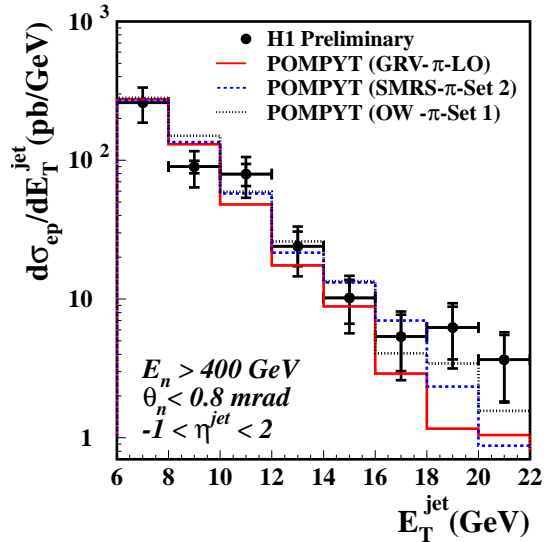
- ✓  $4 < Q^2 < 256 \text{ GeV}^2$
- ✓  $45 < W < 225$ ;

di-jet selection:

- ✓ cone algorithm;
- ✓ require 2 jets (in  $\gamma^*$  p CMS) w/
  - ✓  $E_t^{\text{jet}} > 6 \text{ GeV}$ ;
  - ✓  $-1 < \eta^{\text{jet}} < 2$  (in LAB).

- ✓  $k_T$  algorithm;
- ✓ require 2 jets (in  $\gamma^*$  p CMS) w/
  - ✓  $E_t^{\text{jet}} > 4 \text{ GeV}$ ;
  - ✓  $-2 < \eta^{\text{jet}} < 2.2$  (in LAB).

# LN di-jet cross sections



Di-jet cross sections compared to  $\pi$  Monte Carlo (**POMPYPY**) with different  $\pi$  pdfs.

→ current data do not have sensitivity to discriminate between different  $\pi$  fluxes.

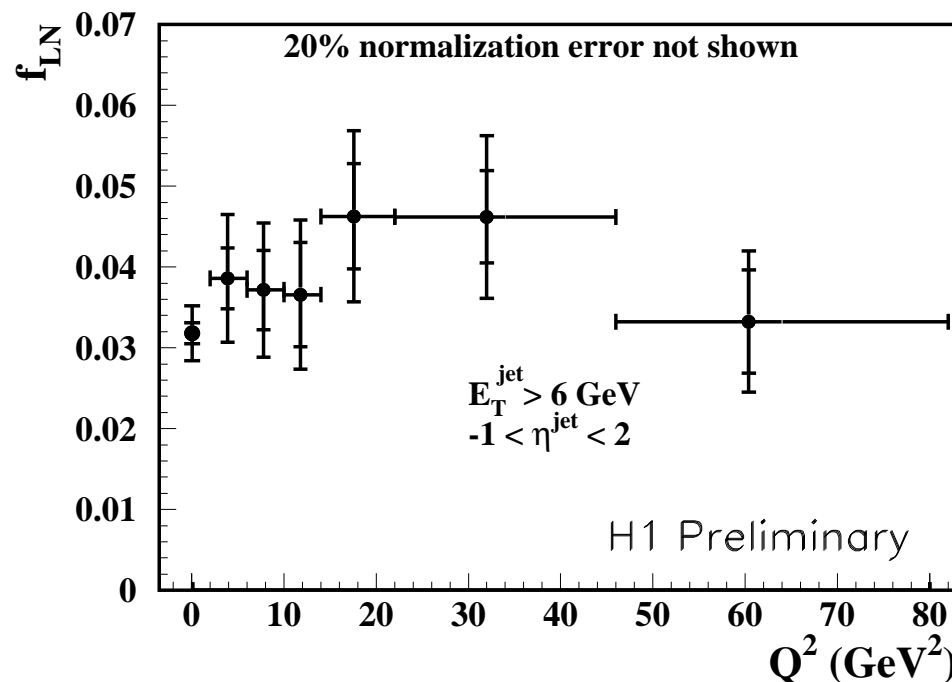
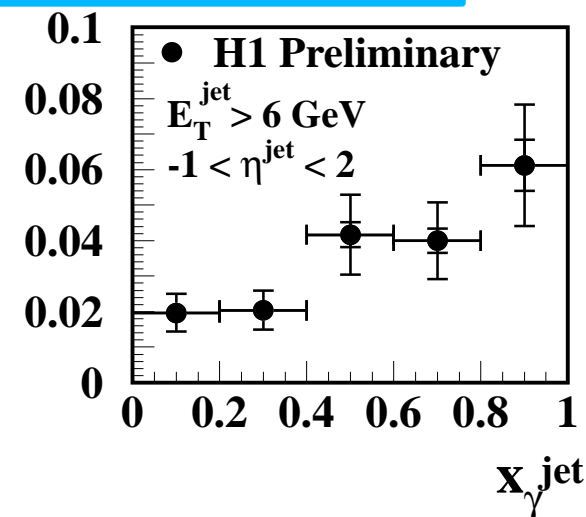
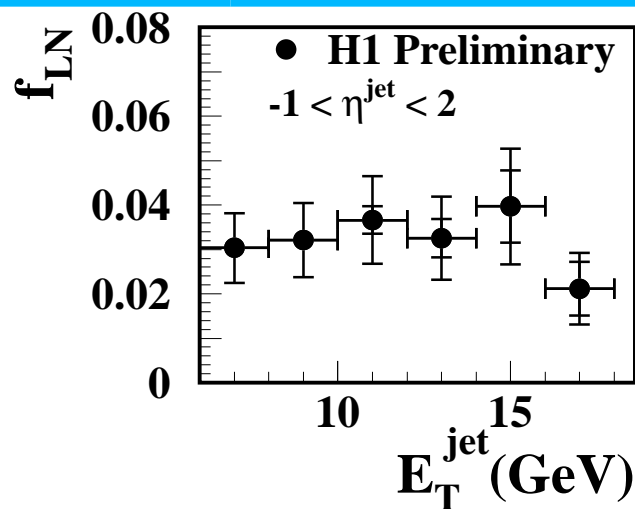
# Dijet neutron yield (PHP sample)

$f_{LN}$  = fraction of di-jets w/  
leading neutrons.

LN dijet yield is flat w/  $E_t^{jet}$   
but grows w/  $x_\gamma^{jet}$  (due to  
process kinematics, remnant  
interactions, or parton  
distributions in LN vs inclusive ?)

No effect is seen in  $Q^2$  distributions.

→ agreement with  
factorisation hypothesis.

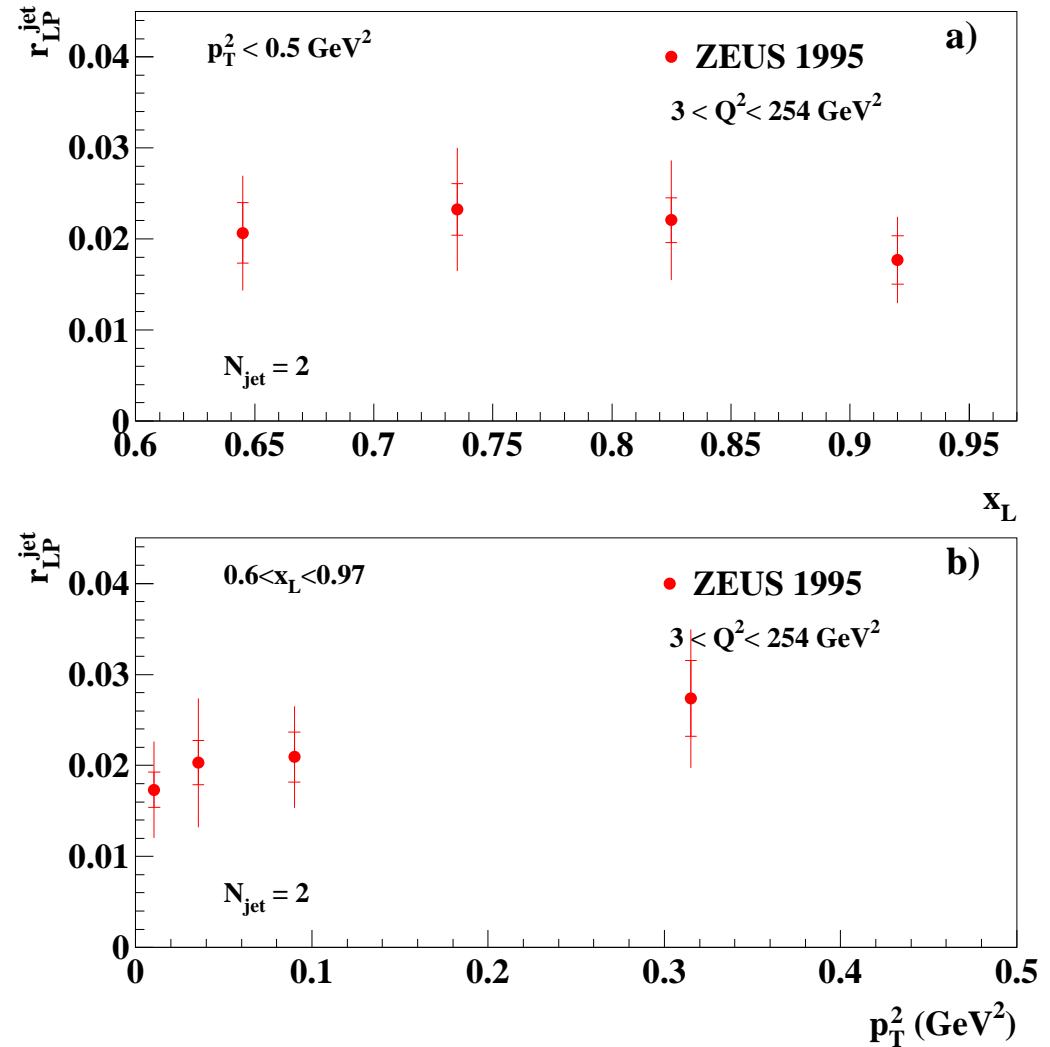


# ZEUS di-jet with protons

$r_{LP}^{jet}$  = leading proton yield w/  
jet production.

→ longitudinal and  
transverse momentum  
distribution of proton not  
affected by jet activity  
(hard scale =  $E_T^{jet}$ ).

ZEUS



# Di-jet w/ protons (ZEUS)

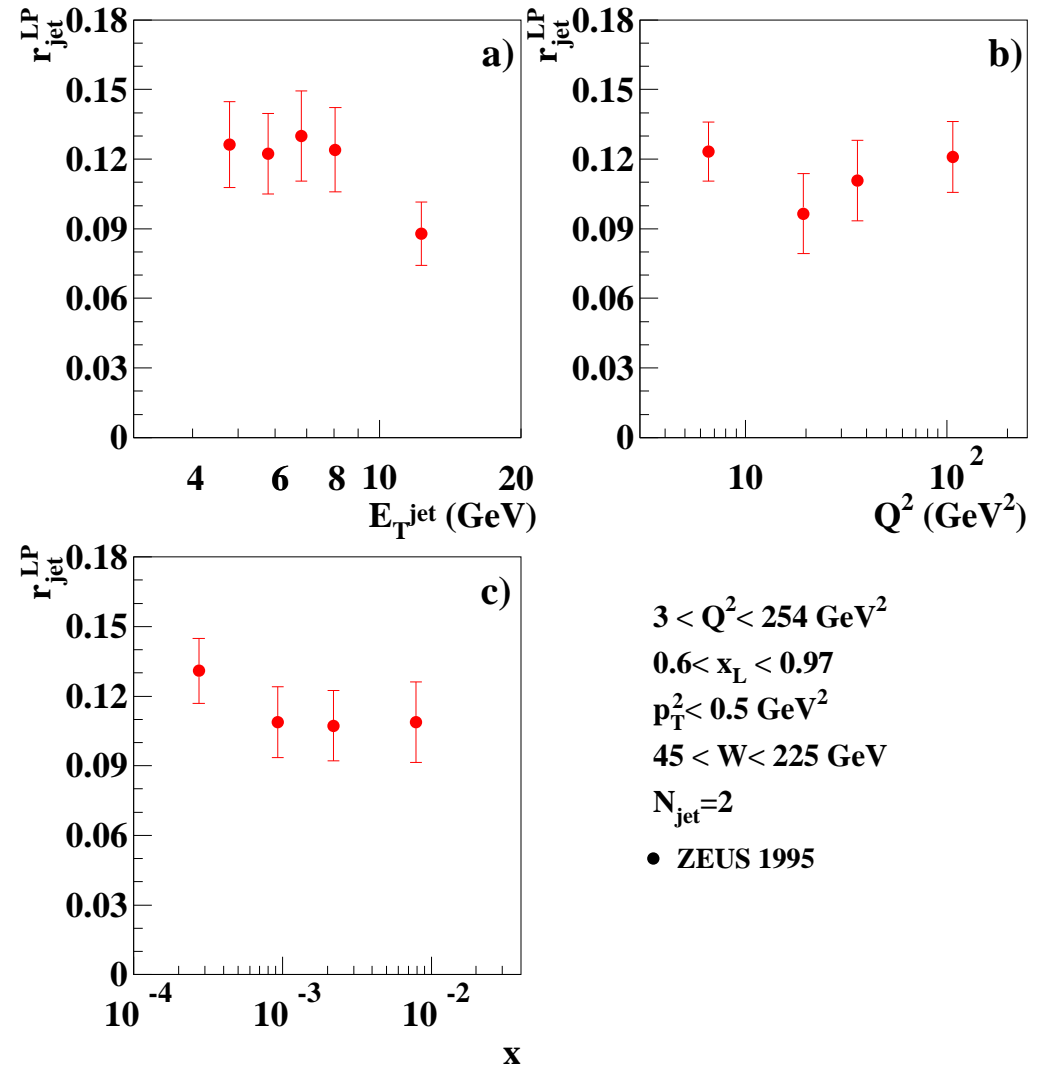
$r_{\text{jet}}^{\text{LP}}$  = fraction of dijet events w/  
a leading proton.

→ ratio independent of jet  
variables ( $E_{\text{t}}^{\text{jet}}$ ,  $Q^2$ ,  $x$ ).

$r_{\text{jet}}^{\text{LP}} \sim r^{\text{LP}(2)} \sim 0.12$ .

→ fraction of dijet events w/  
LP  $\cong$  fraction of inclusive  
events w/ LP.

**ZEUS**



# Neutron tagged $D^*$

ZEUS 1998-2000.  $\int \text{Lumi} = 80.17 \text{ pb}^{-1}$

$e^+$  in LUMI (PHP):

→  $117.3 < W < 274.3 \text{ GeV}$

$n$  in FNC:

→  $0.2 < x_L < 1, \theta_n < 0.8 \text{ mrad.}$

$D^*$  decay mode:  $D^{*\pm} \rightarrow D_0 \pi_s^\pm$   
→  $K \pi^\pm$

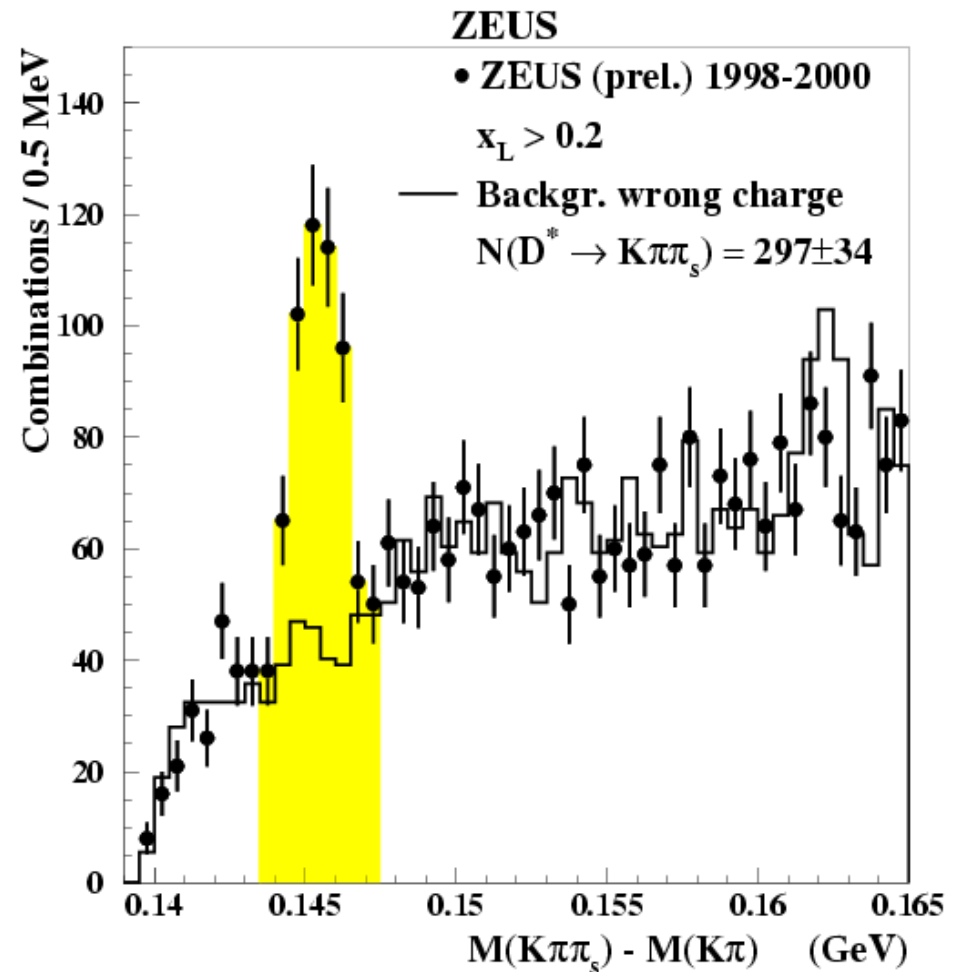
✓  $p_t(D^*) > 1.9 \text{ GeV}$

✓  $-1.5 < \eta(D^*) < 1.5$

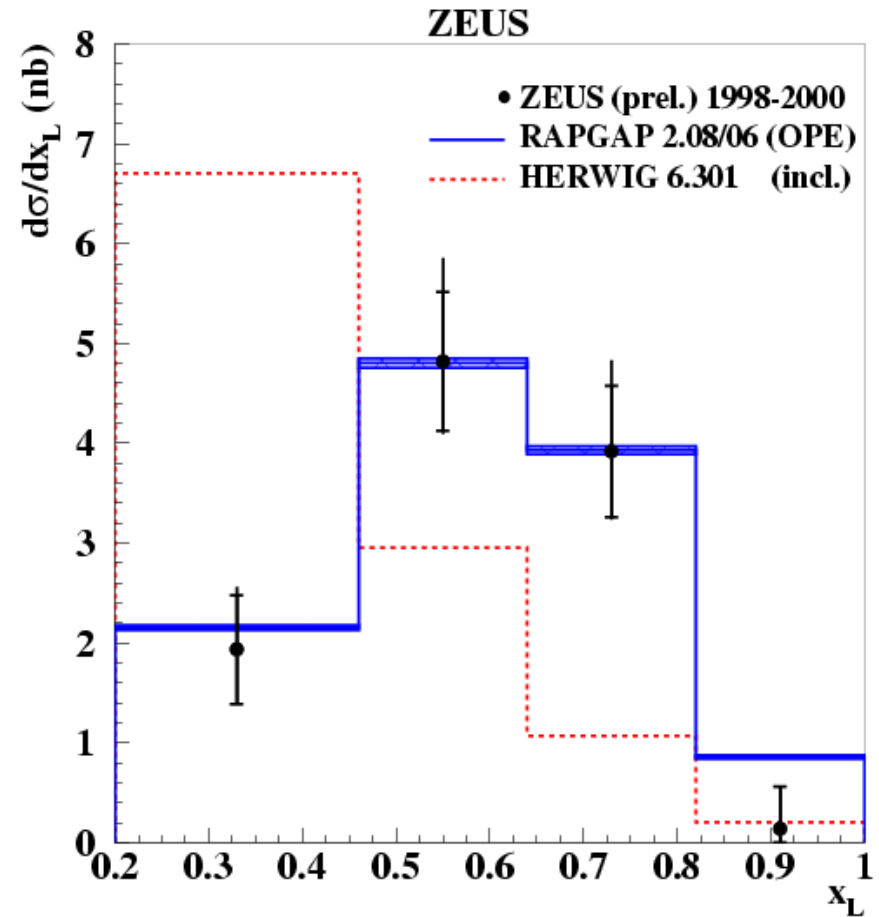
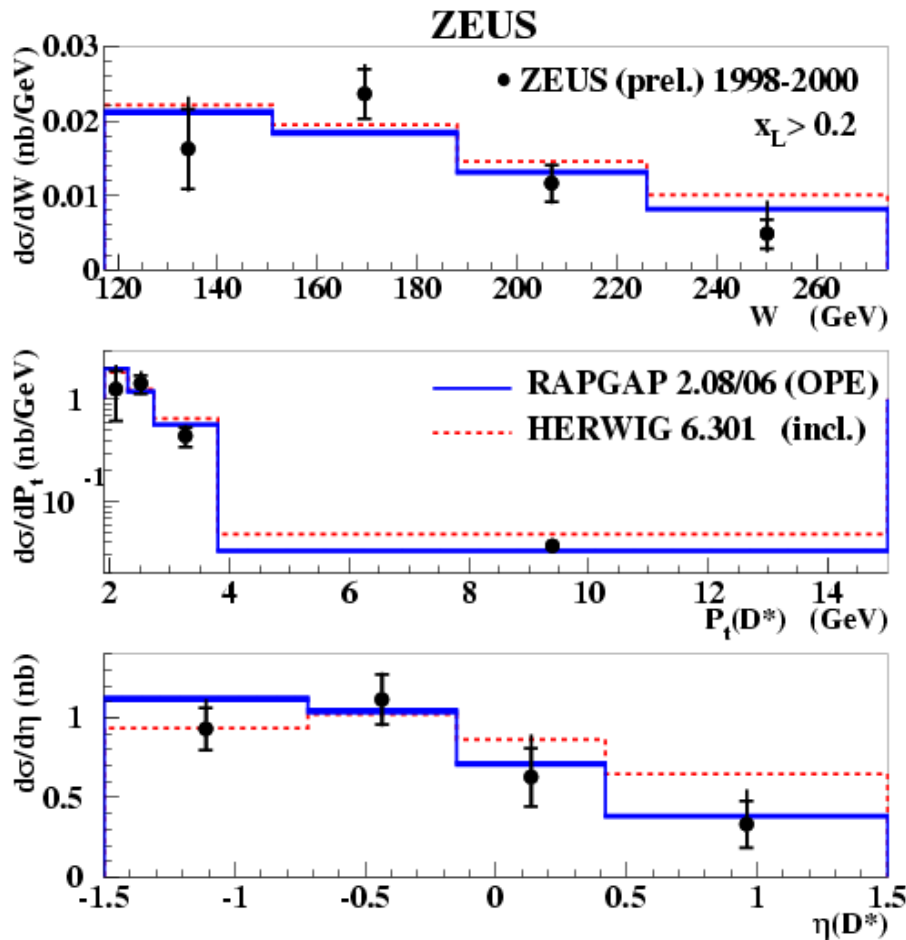
For the decay products:

✓  $P_t(\pi) > 0.120, 0.45$  (from  $D_0$ )

✓  $P_t(K) > 0.45$  (from  $D_0$ )



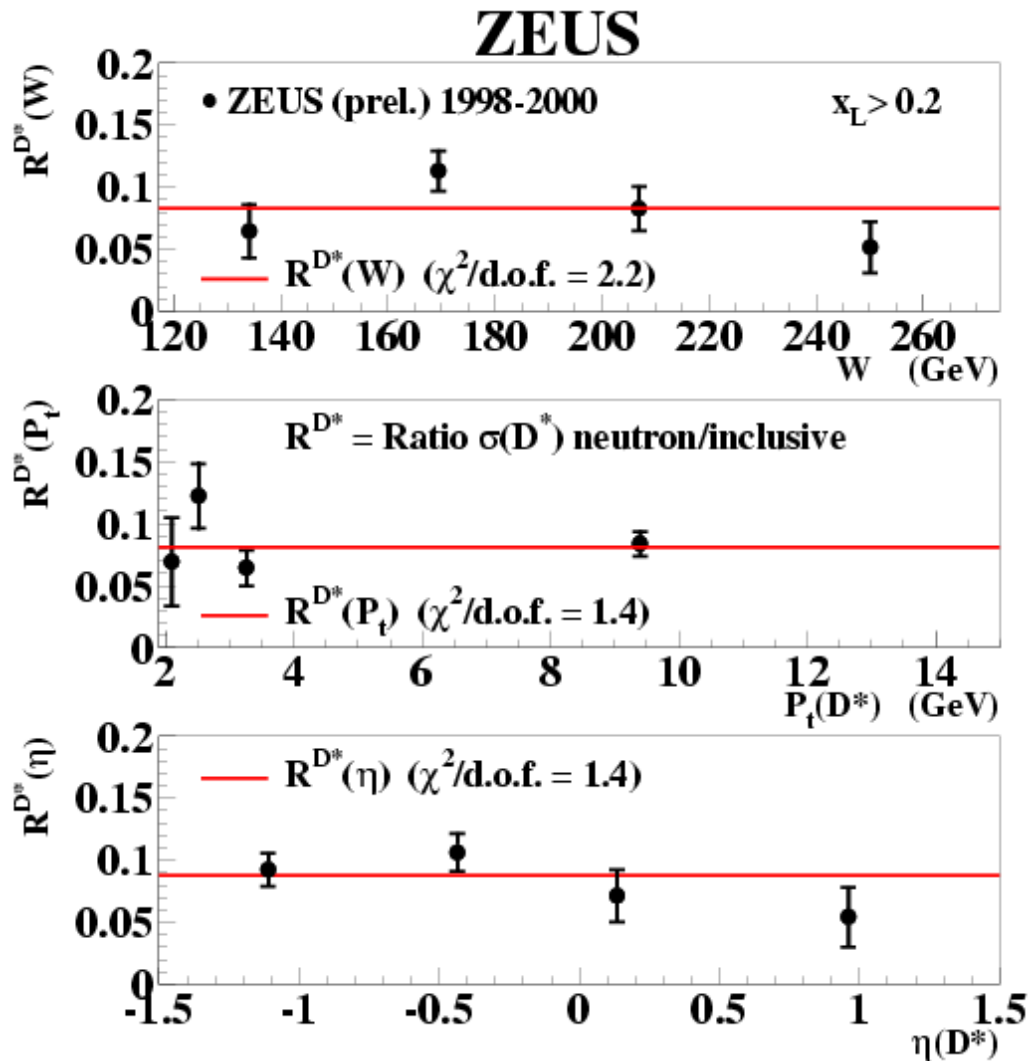
# Neutron tagged $D^*$



Both standard fragmentation (HERWIG) and OPE (Rapgap) describe  $D^*$  variables

OPE is needed for  $x_L$  distribution

# D\* yield



$$R^{D^*} = \left( \frac{\sigma_{LN}^{D^*}}{\sigma_{inc}^{D^*}} \right)$$

$$= 8.1 \pm 0.9 \text{ (stat.)} \pm 0.3 \text{ (sys.)} \%$$

$$0.2 < x_L < 1,$$

$$p_t(D^*) > 1.9 \text{ GeV},$$

$$|\eta(D^*)| < 1.5,$$

$$117.3 < W < 274.3 \text{ GeV}$$

# Pion structure function, $F_2^\pi$

- **WHERE**: in the region where factorization is  $\sim$  valid: high  $Q^2$  and high  $x_L$  and OPE describes the spectra.
- **HOW**: as the cross section, the structure function factorizes:

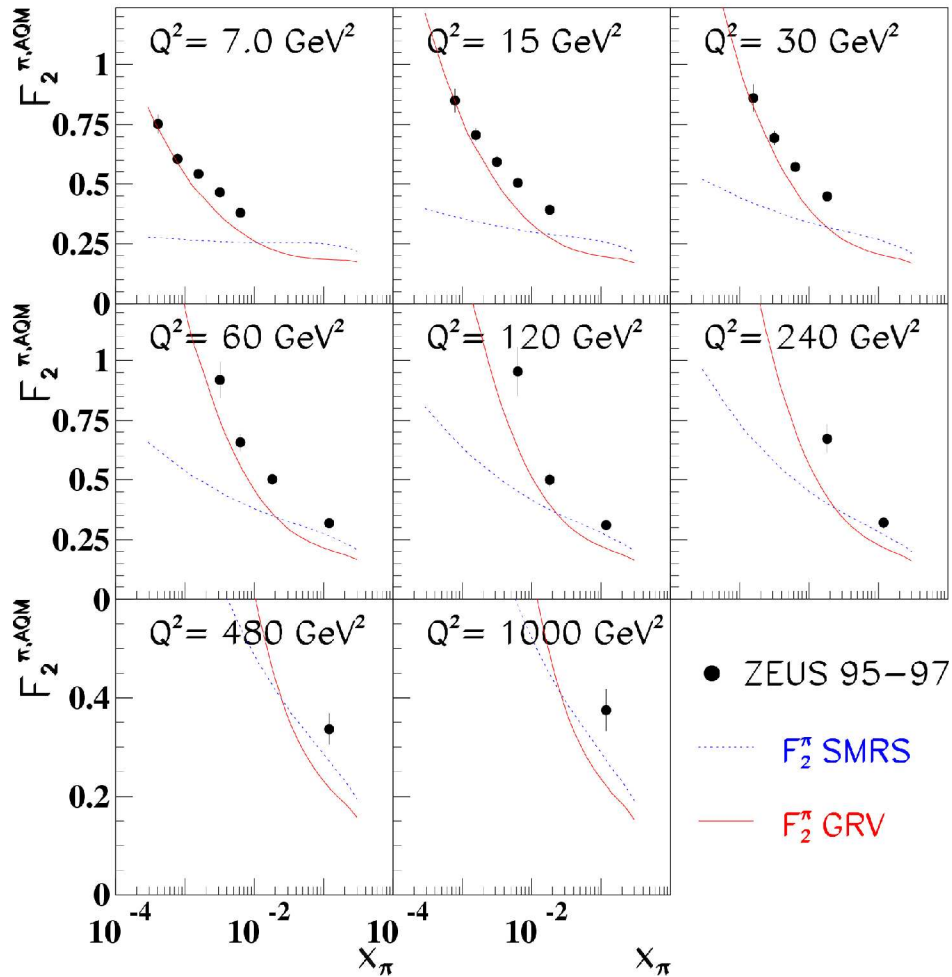
$$F_2^{LN}(x_{Bj}, Q^2; x_L, t) = f_{\pi/p}(x_L, t) \times F_2^\pi(x_{Bj}/(1 - x_L), Q^2)$$

- Use measured  $F_2^{LN}$ ,  $f_{\pi/p}$  from literature, then extract  $F_2^\pi$ .
- Use the  $x_L$  region where the background is smallest ( $x_L = 0.73$ ).
- In the literature, at  $x_L = 0.73$ , flux value varies by a factor  $\sim 2$ .
- Use extremes of flux.
- Compare to parametrization of  $F_2^\pi$  extracted from pp data (low  $Q^2$ , high  $x_{Bj}$  fixed target data).

# Pion structure function, $F_2^\pi$

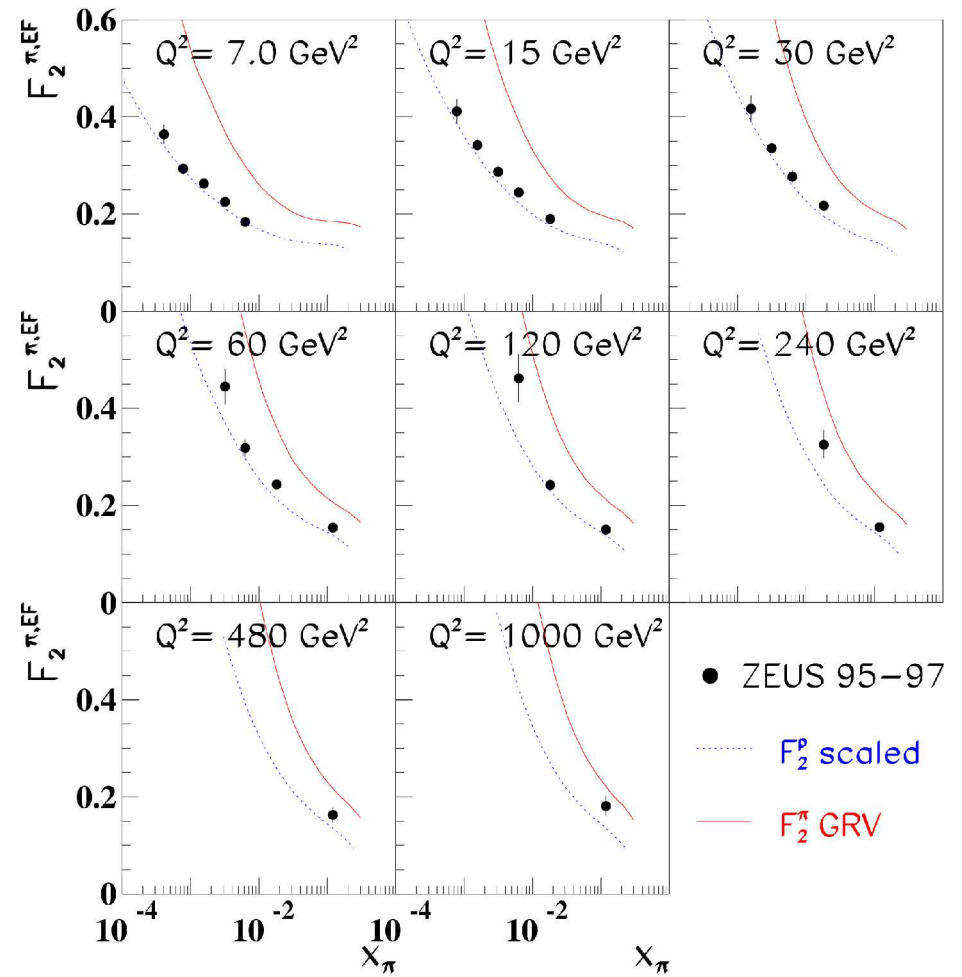
Lower flux

ZEUS



Higher flux

ZEUS



Can discriminate between parametrizations at high  $Q^2$ , low  $x$

$F_2^\pi$  approx.  $\propto F_2^p$

# Conclusions

Standard fragmentation models fail to describe baryon production.  
Particle exchange models describe rate and spectra ( $x_L$  and  $p_t^2$ ):

- ✓  $\pi$  dominant for  $n \rightarrow$  extract  $F_2^\pi$ ;
- ✓ need multiple exchanges for  $p$ .

Vertex factorization:

- ✓ approx. valid at high  $Q^2$ , is broken at low  $Q^2$ ;
- ✓ form of violation varies w/  $x_L$  (neutron case);
- ✓ violation consistent w/ re-scattering in particle exchange.

$$F_2^\pi \text{ and } F_2^{\text{LP}(2)} \propto F_2$$

Data selected w/ additional hard scales, di-jet activity and  $D^*$  production, show apparent agreement w/ factorisation (statistics lower than inclusive case).