# Leading baryon production at HERA

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for the H1 and ZEUS Collaborations

Highlights:

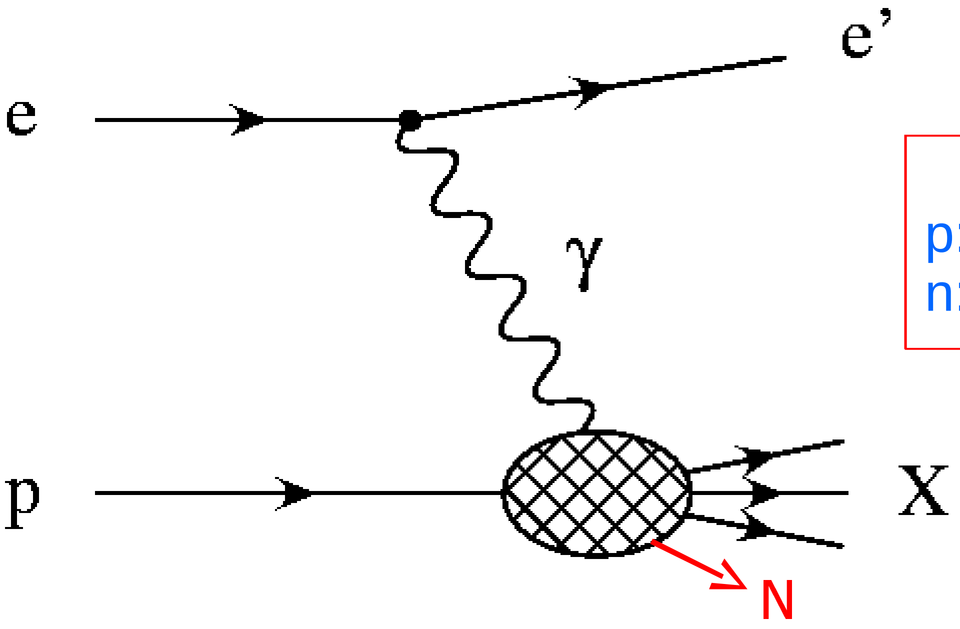
- ✓ Leading proton production models;
- ✓ Vertex factorization and violation: absorption/re-scattering models;
- ✓ Leading baryons w/ di-jet activity;
- ✓ Pion structure function.
- ✓ D* production w/ leading neutrons.

# Introduction

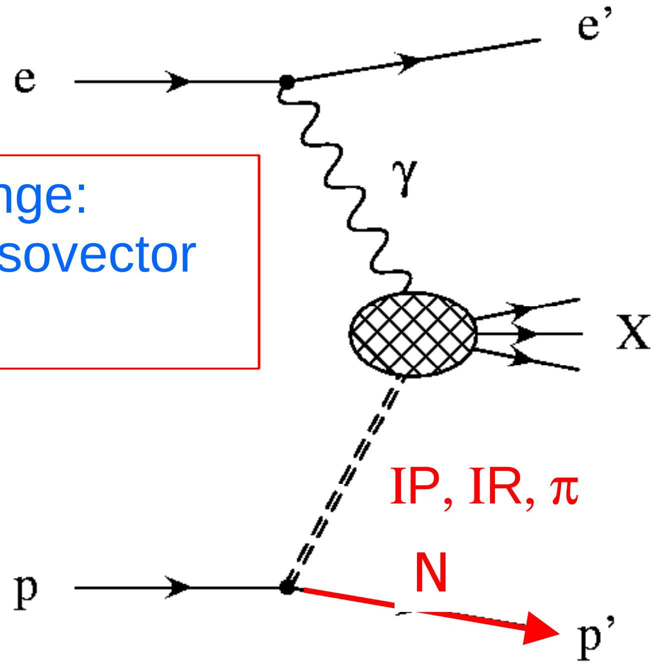
Leading baryon production at small t in hadronic interactions ⇒ soft process.
Conserving baryon number → p or n in final state.

In standard fragmentation:
final state N from p remnant

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



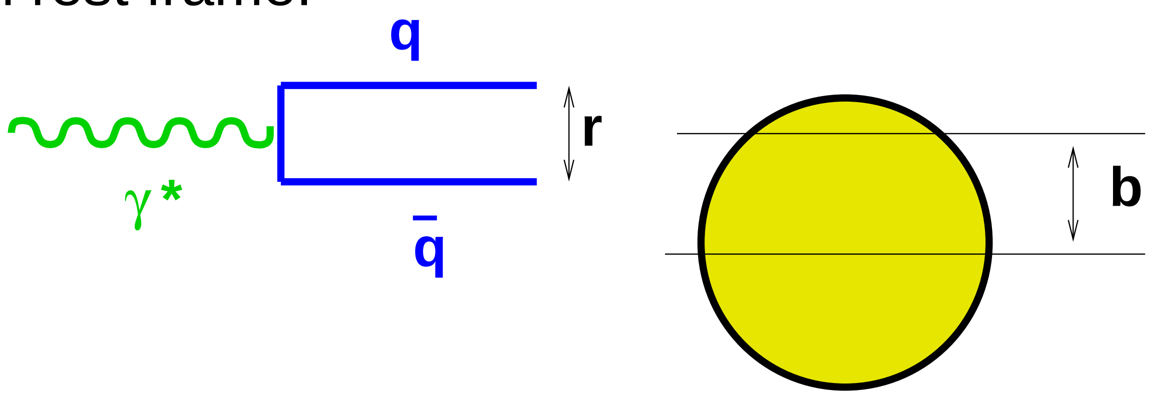

Exchange:
p: isoscalar, isovector
n: isovector.




$(x_L = E_{p,n} / E_{beam},\ p_t^2)$

# Proton dipole picture

In the proton rest frame:




where:

- ✔ r ~ 0.2 fm/Q, transverse size of probe;
- ✔ ct ~ 0.2 fm $(W^2/2m_p Q^2)$ – scale over which photon fluctuations survive;

Tagging the leading baryon, can vary the impact parameter

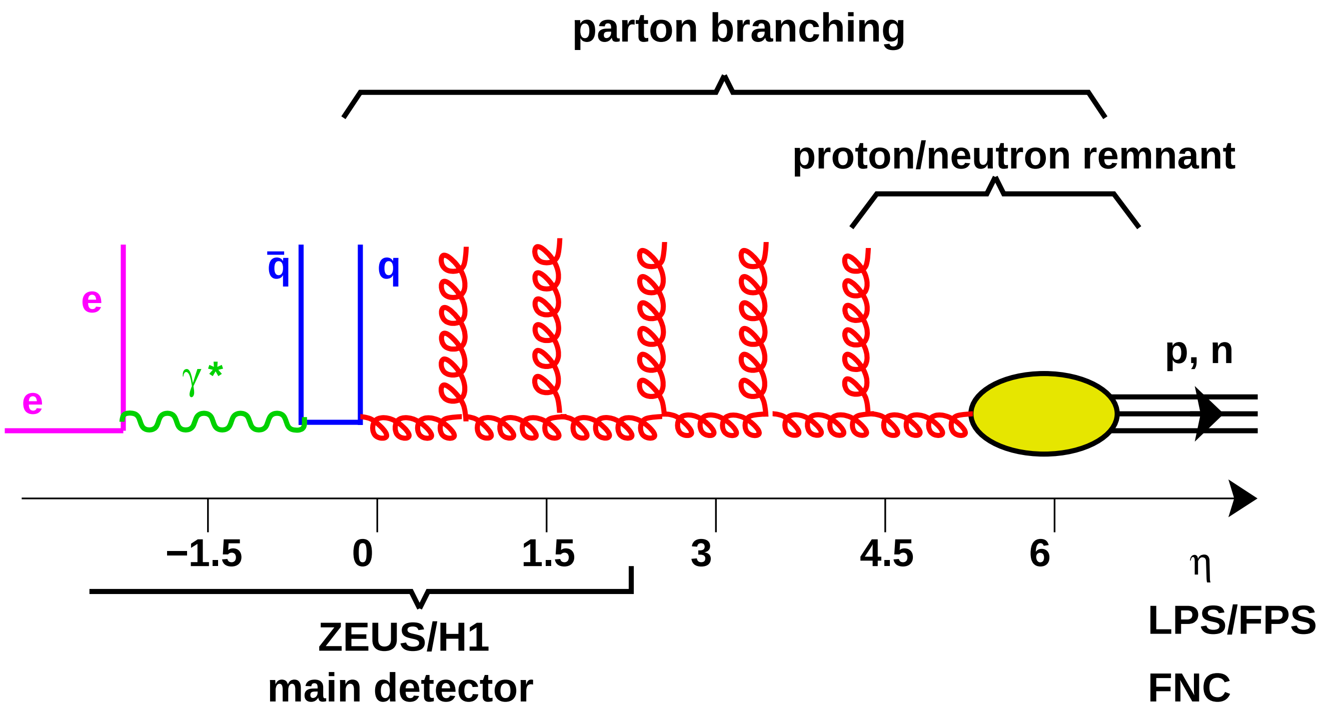
- ✔ b ~ 0.2 fm/sqrt(t), with $t = (p - p')^2$.

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

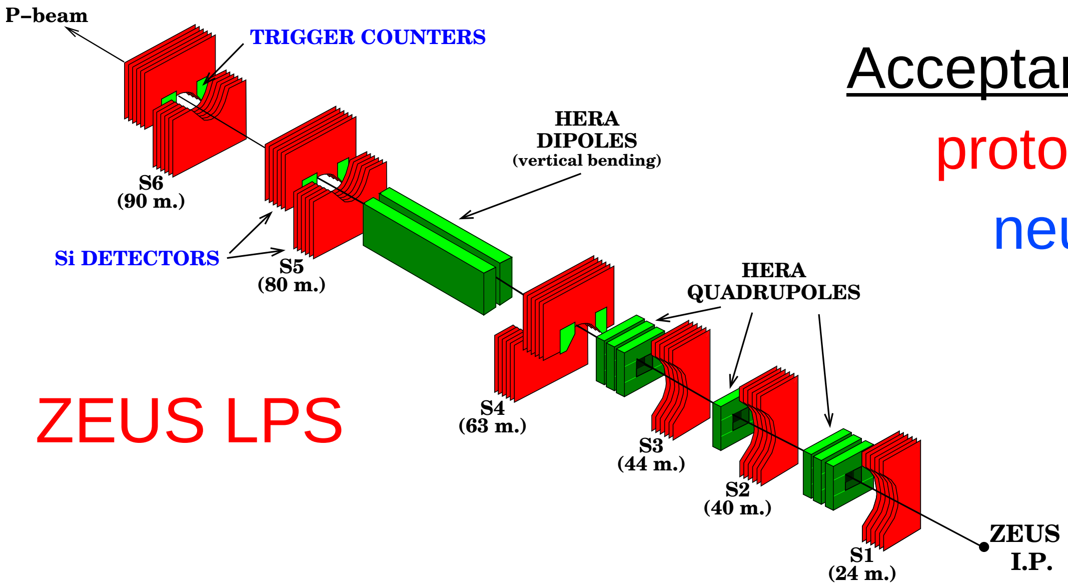
# Process scales

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



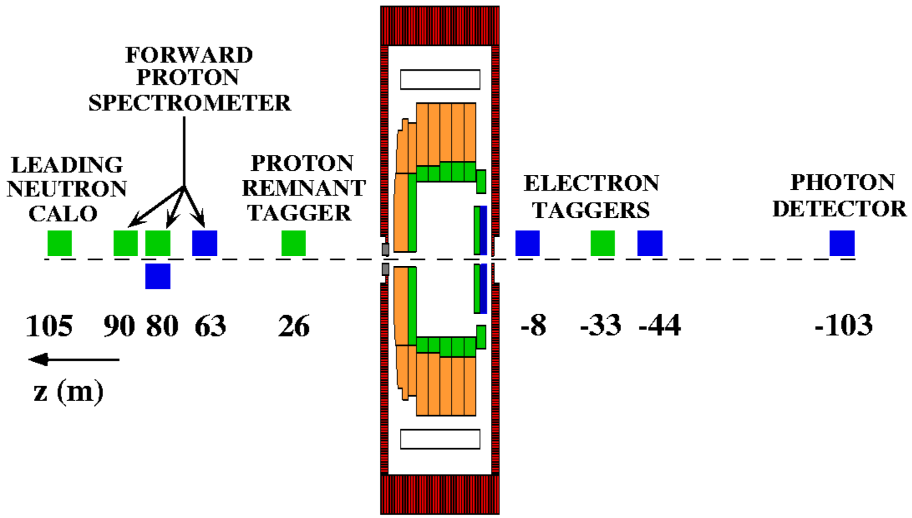

ZEUS LPS

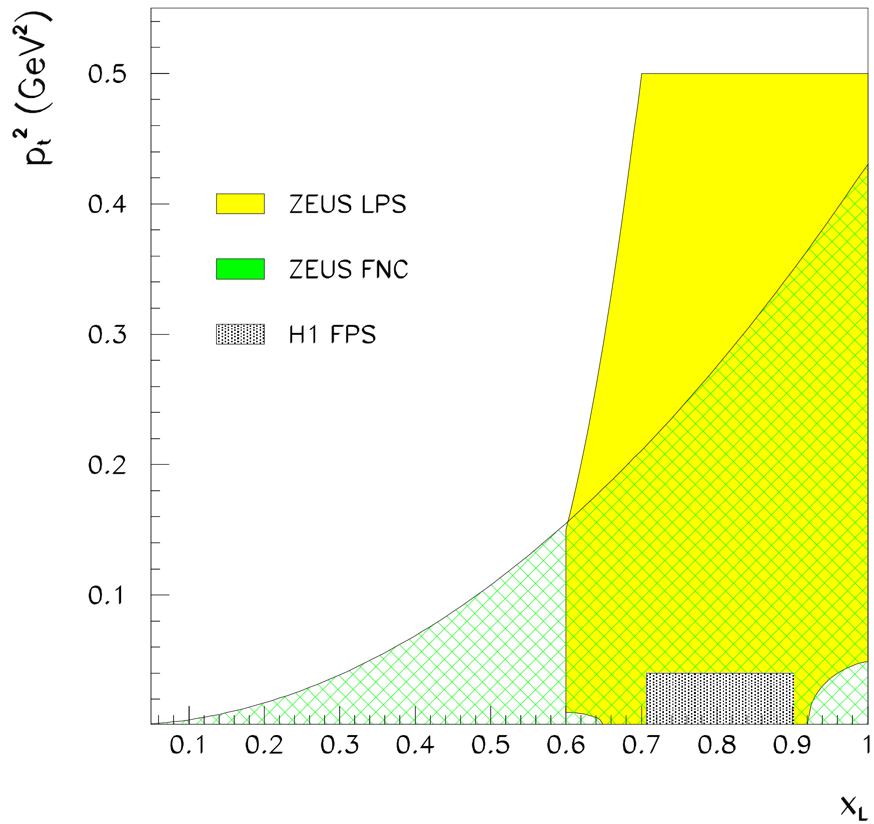
<u>Acceptances limited by magnet apertures</u>:

protons: $0.6 < x_L < 1$, $p_t^2 < 0.5$ GeV$^2$

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

H1 BEAM-LINE INSTRUMENTATION

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# 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

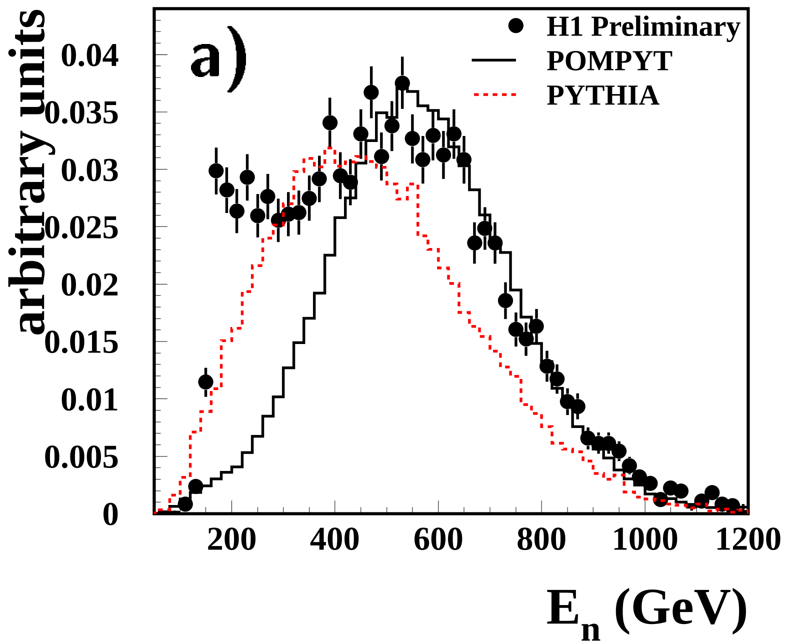
- ✓ ICHEP02 paper 988, "Measurement of Dijet Cross-Section with Leading Neutrons in ep interactions at HERA".

# LN energy spectra

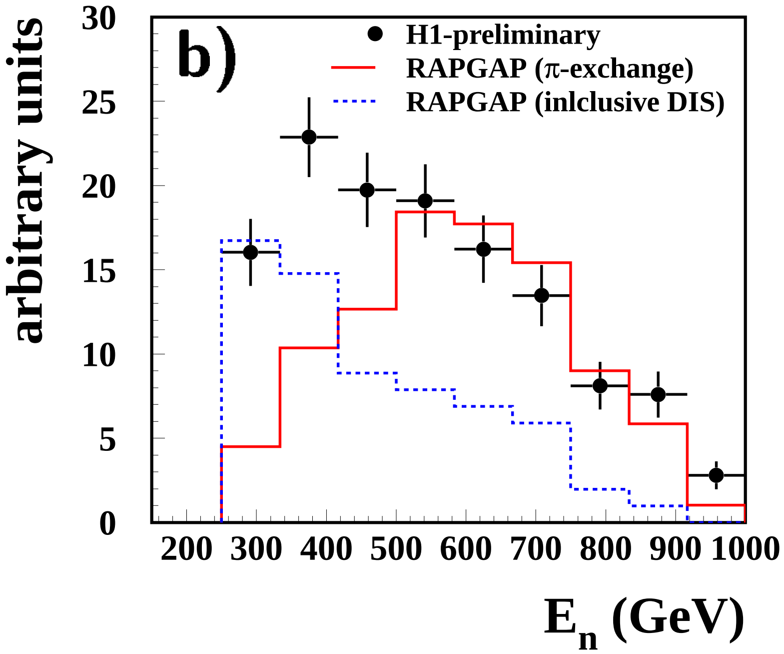
LN cross section and energy spectra compared to different Monte Carlo production models:

- standard fragmentation Monte Carlo fail;
- π exchange needed to describe shape.

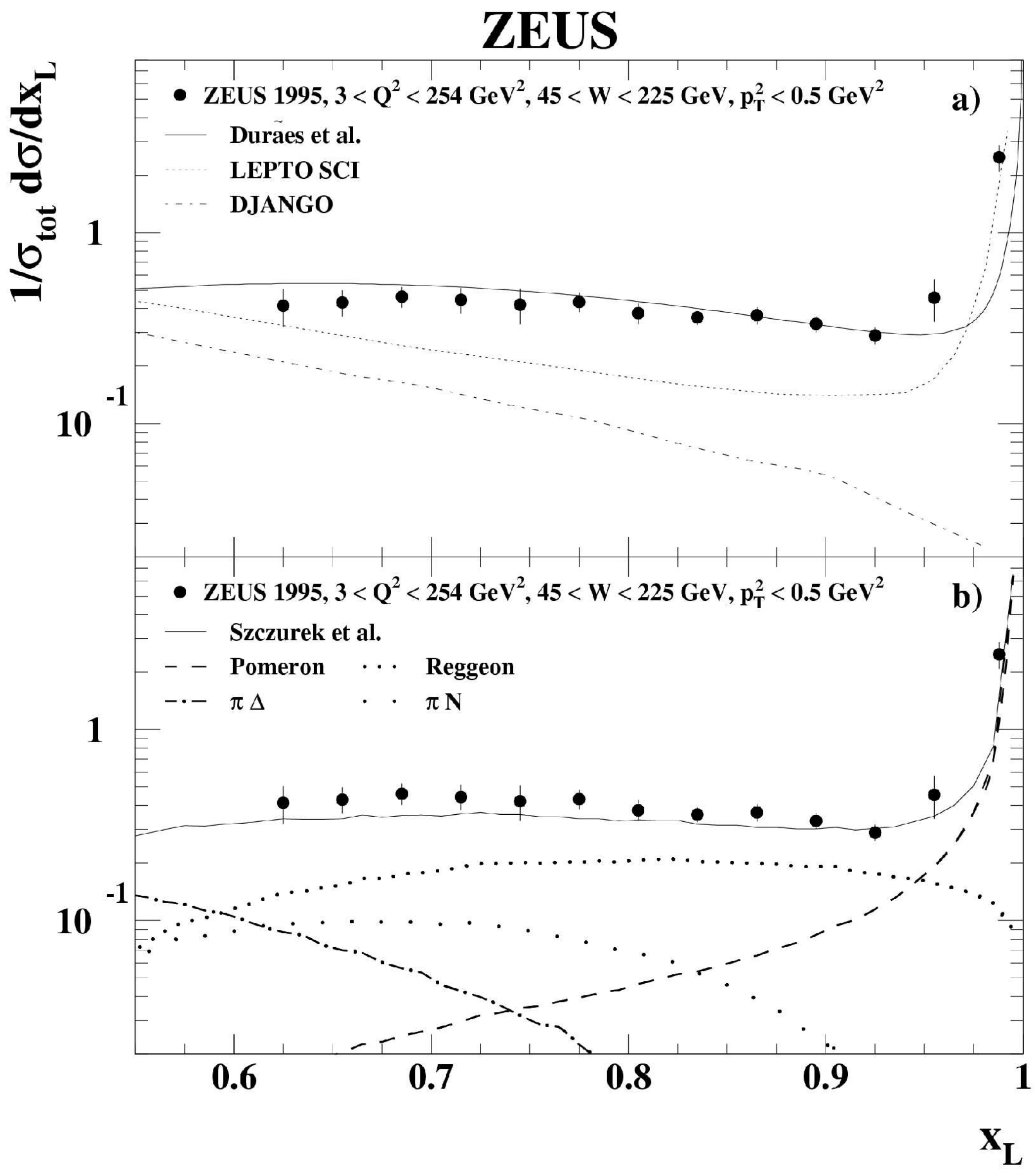
PHP




DIS



# Proton energy spectra – model comparison




Shape and data normalization is compared to:

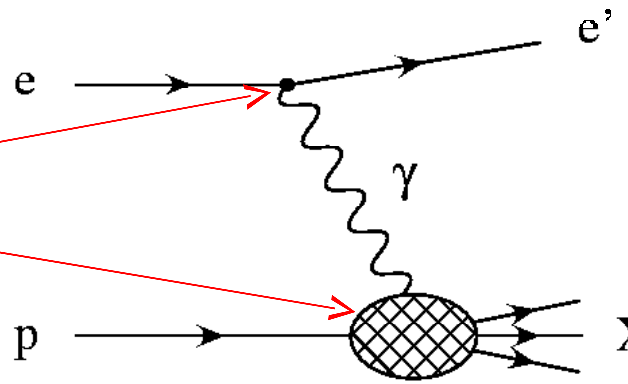
- ✓ standard fragmentation models $\rightarrow$ do not describe data;
- ✓ QCD inspired model, the Gluon-Iteracting model of Durães et al. Gives a better description;
- ✓ exchange models, need multiple processes (Pomeron, Reggeon, $\pi^\circ$ and $\pi$–$\Delta$) to describe the data.

# Vertex factorization

Under the factorization hypothesis,

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

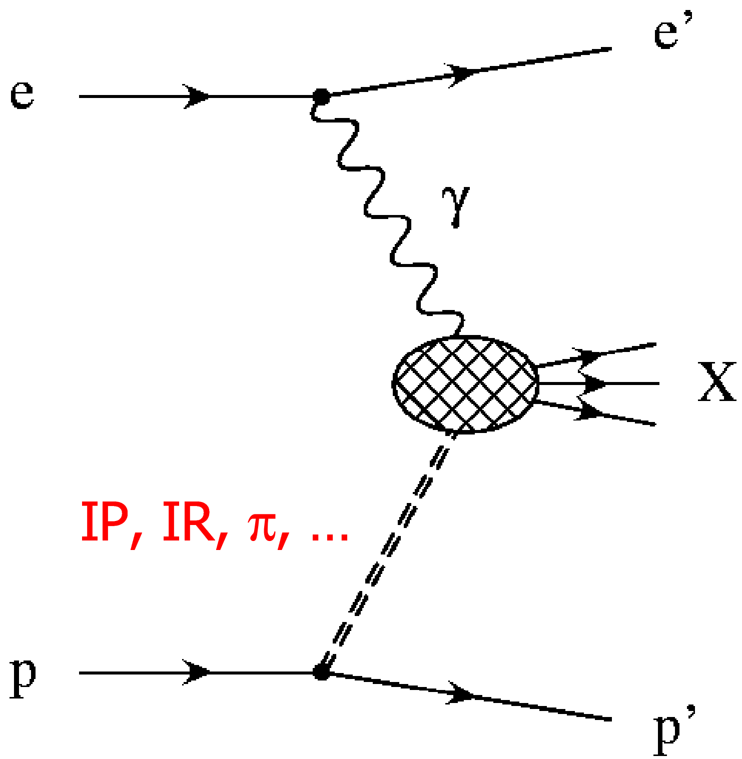
i.e lepton vertex ~ independent of baryon vertex




Direct implication of exchange models ⇒ the *ep* cross section factorizes, e.g. for π 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

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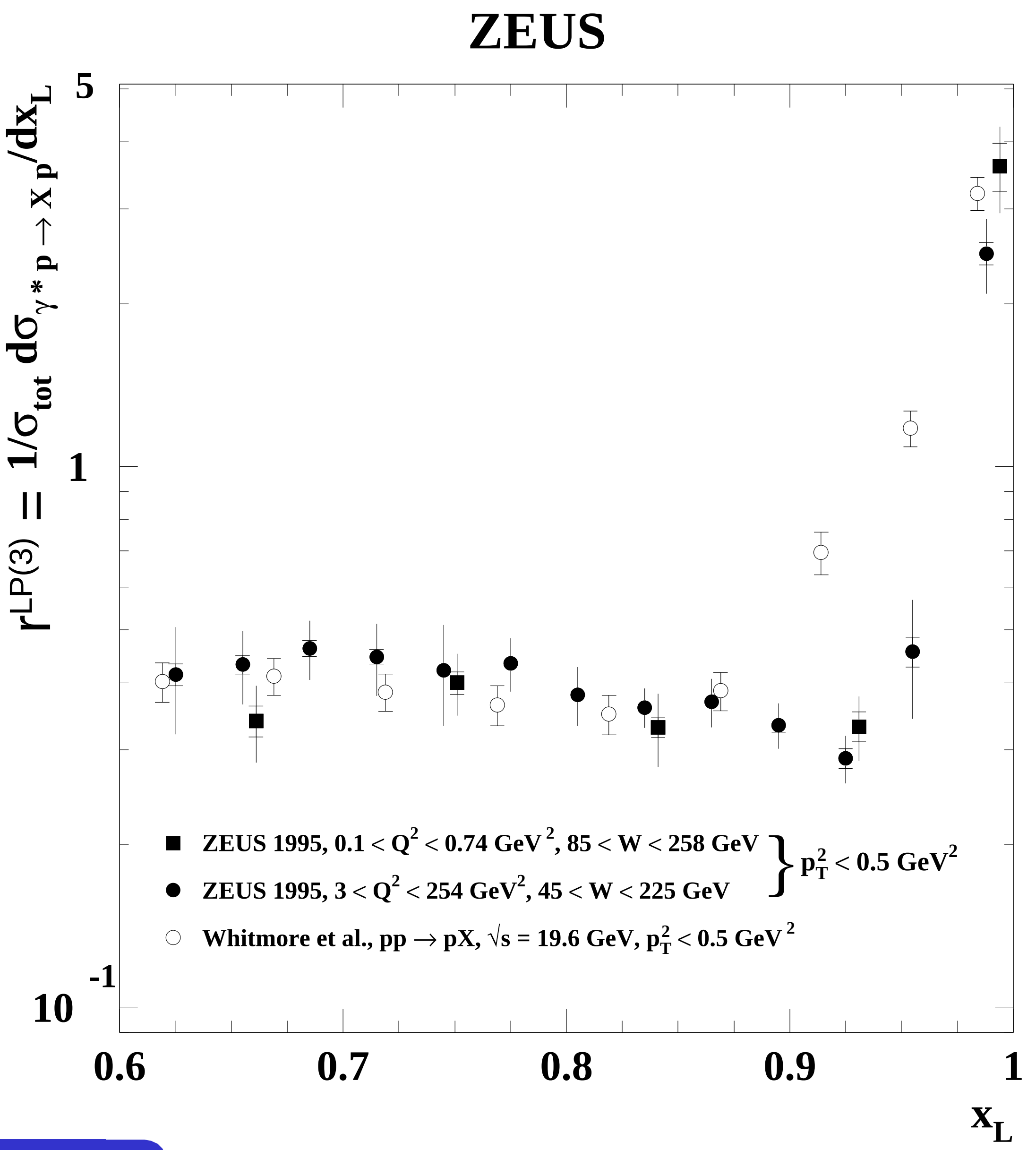
# LP energy spectra



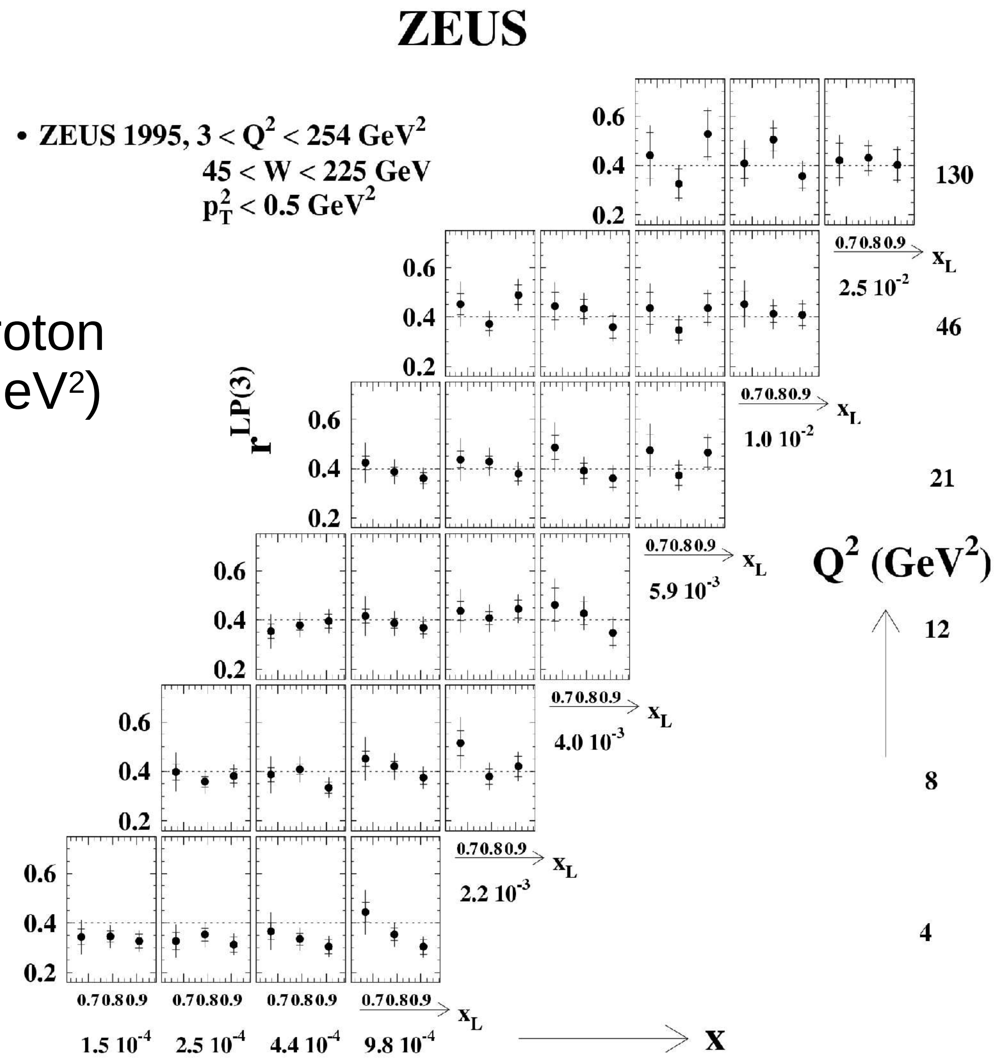

LP normalized cross section for BPC ($0.1 < Q^2 < 0.74$ GeV$^2$) and DIS ($3 < Q^2 < 254$ GeV$^2$).

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

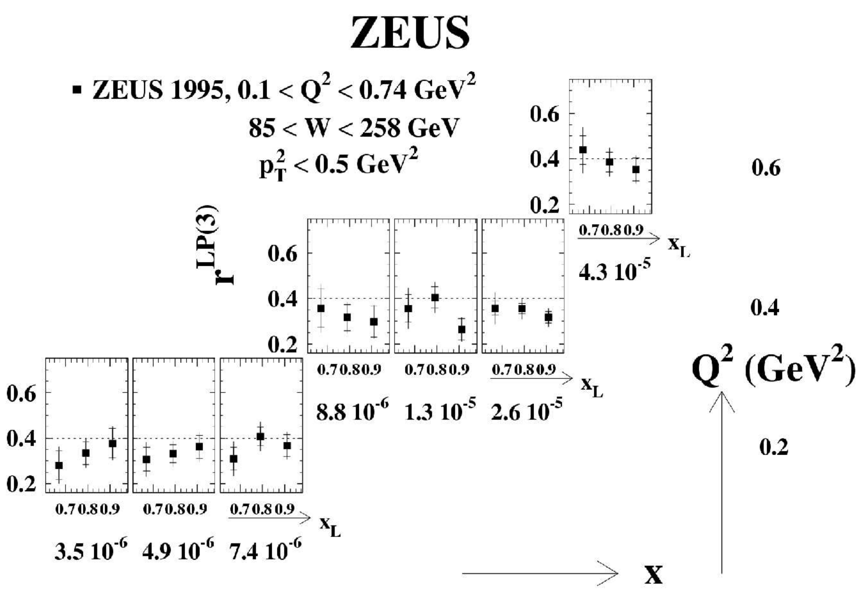
For $x_L \leq 0.9$, $r^{LP(3)}$ consistent w/ pp data and $\gamma^* p$ data sets.

→ approximate vertex factorization.

# Proton yield

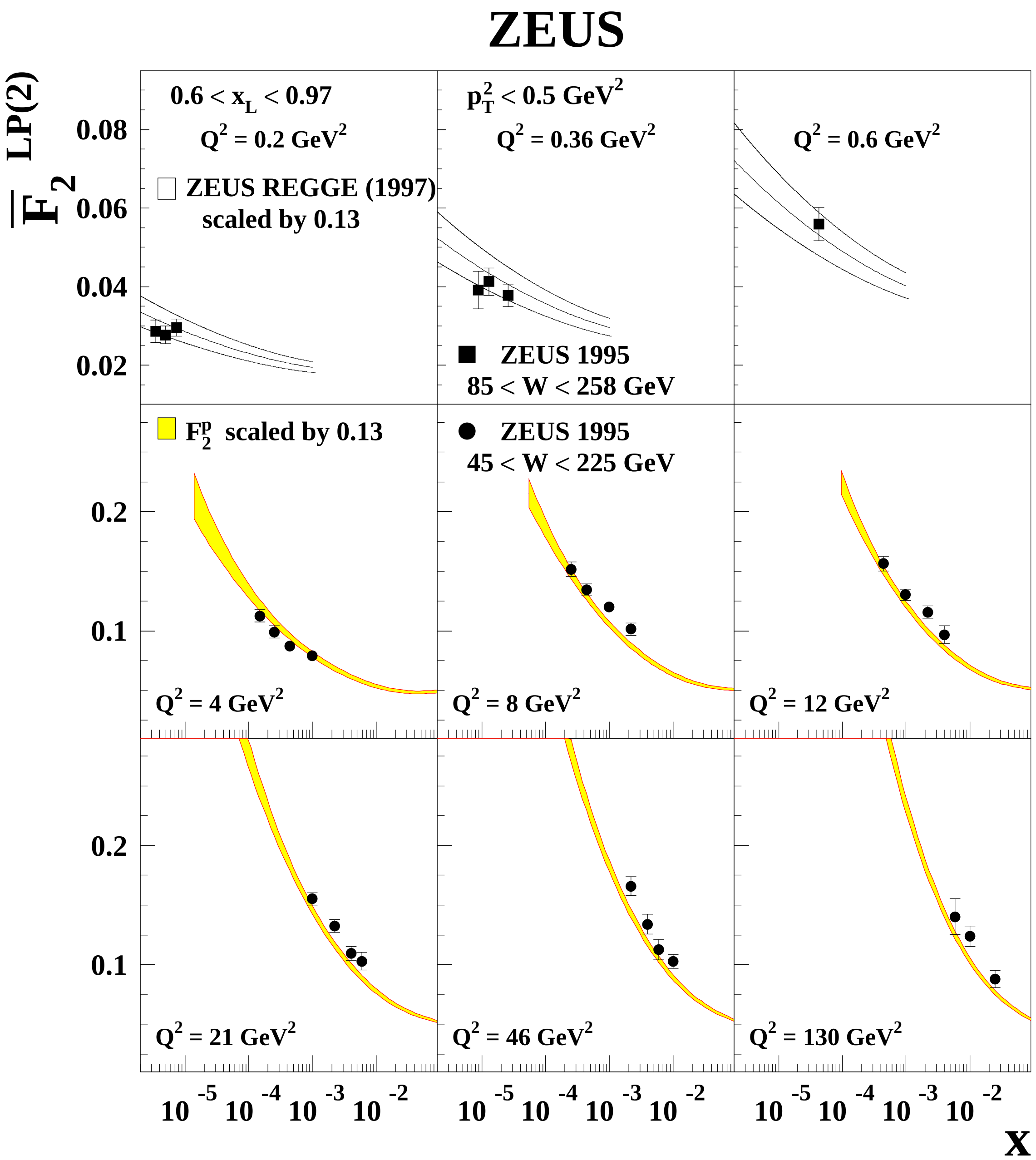



Fraction of events with a leading proton with ($0.6 < x_L < 0.97$ and $p_t^2 < 0.5$ GeV$^2$)




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

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



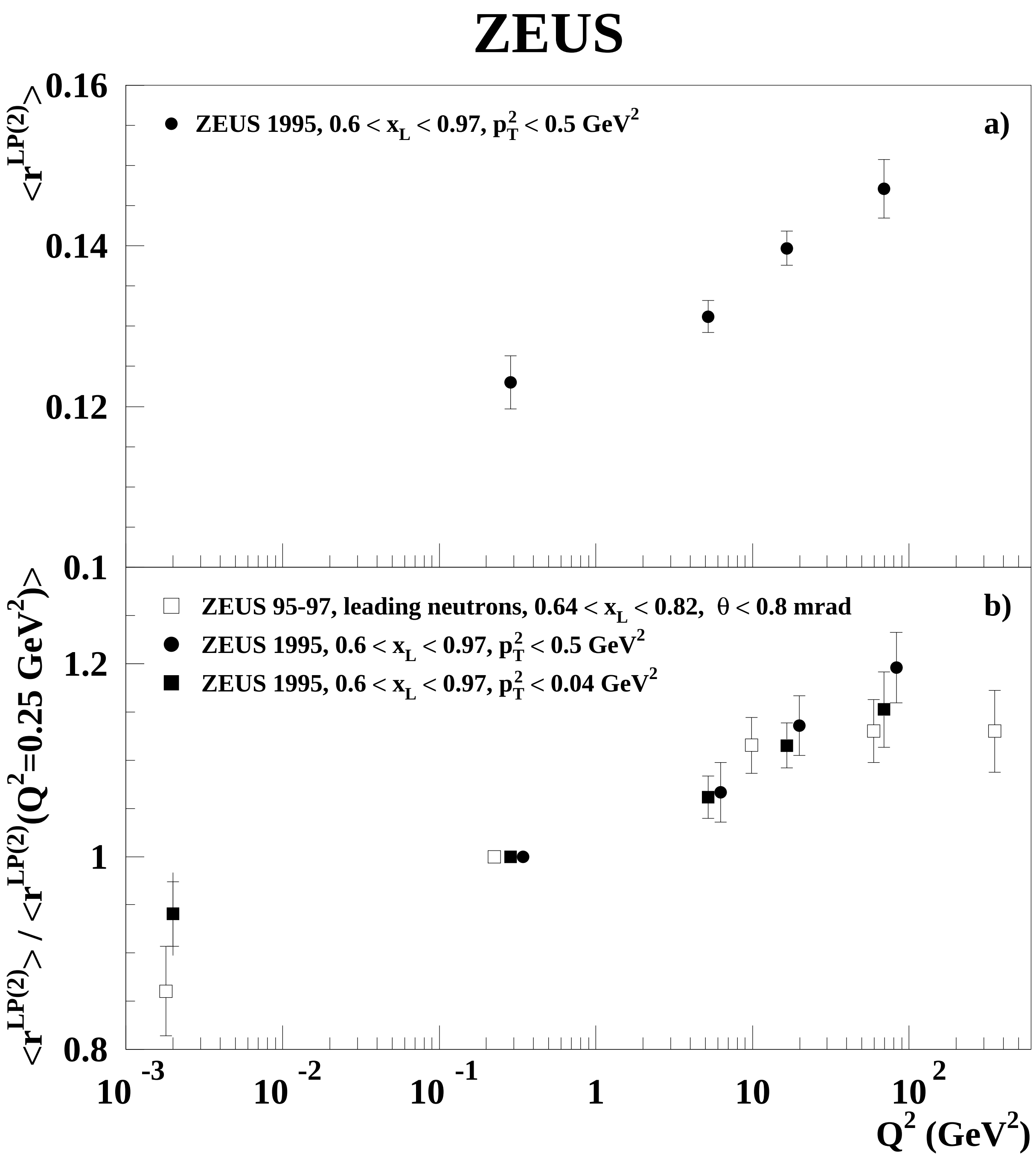

Ratio multiplied by:

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

$$F_2^{LP(2)} = F(x_{Bj},Q^2) <r^{LP(2)}>$$

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

Result for neutrons similar




# 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 $GeV^2$ (somewhat higher for n)

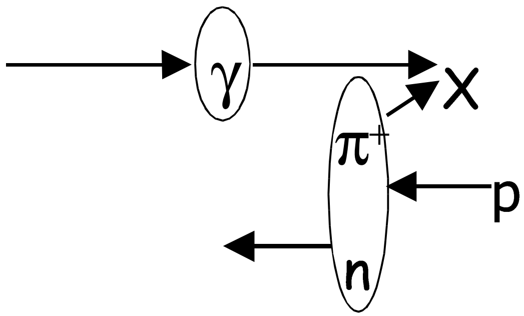
- Different evolution of $F_2$ and $F_2^{LP(2)}$ ?

- Absorptive effects in the $\gamma^* p$ system (smaller $\gamma$ size at higher $Q^2$)?

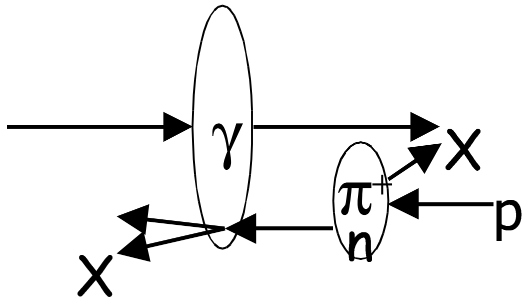
# Factorization Violation

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 $p_t$)

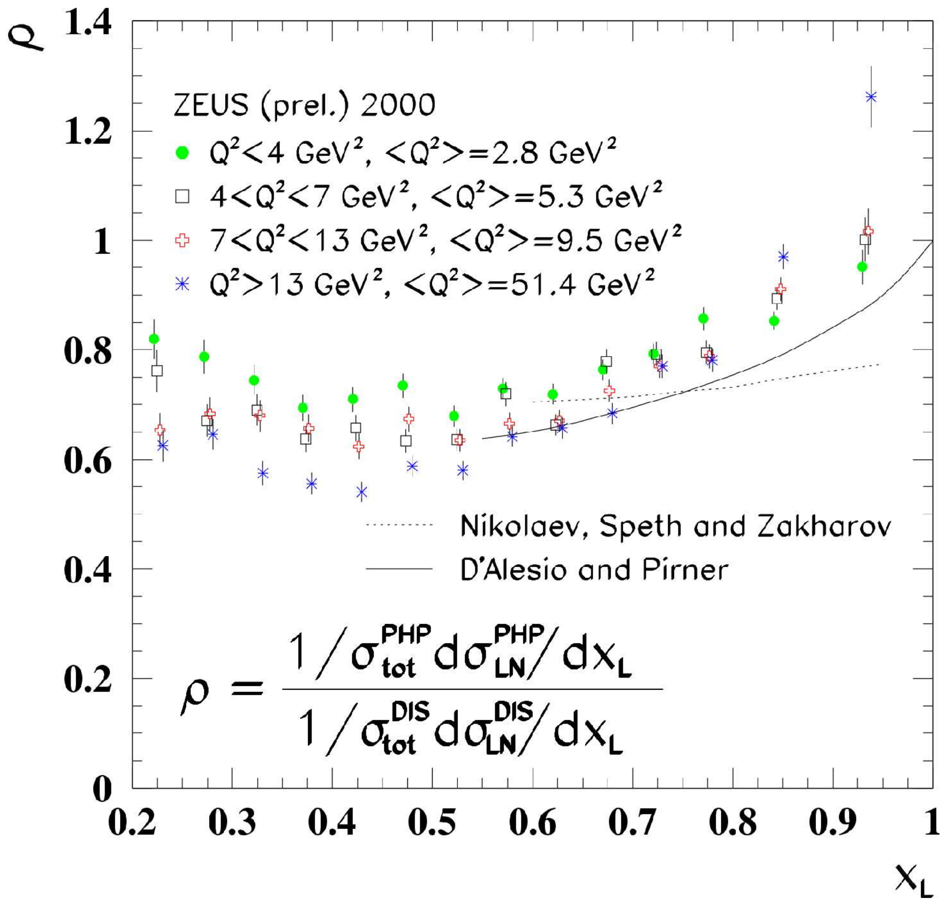
DIS: $\gamma^*$ ~ point like

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

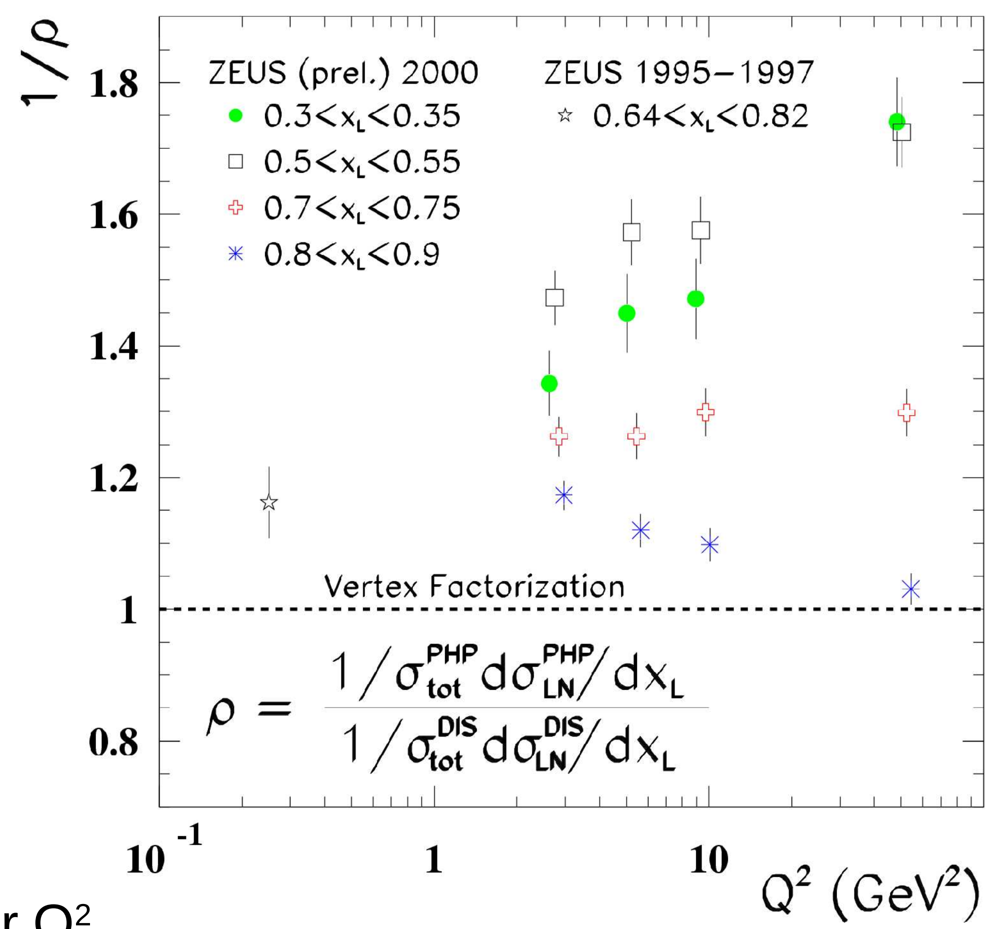
In OPE $\langle r_{n\pi} \rangle$ smaller at lower $x_L$ $\Rightarrow$ more rescattering at lower $x_L$

# 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 $Q^2$ ~ 10-100 GeV$^2$) ⇒ qualitative description
- ratio is also function of $x_L$

# Leading baryons w/ di-jets

H1 – Leading neutrons:

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

ZEUS – Leading protons:

- $0.6 < x_L < 0.97$
- $p_t^2 < 0.5$ GeV$^2$

$e^+$ selection:

DIS:

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

DIS:

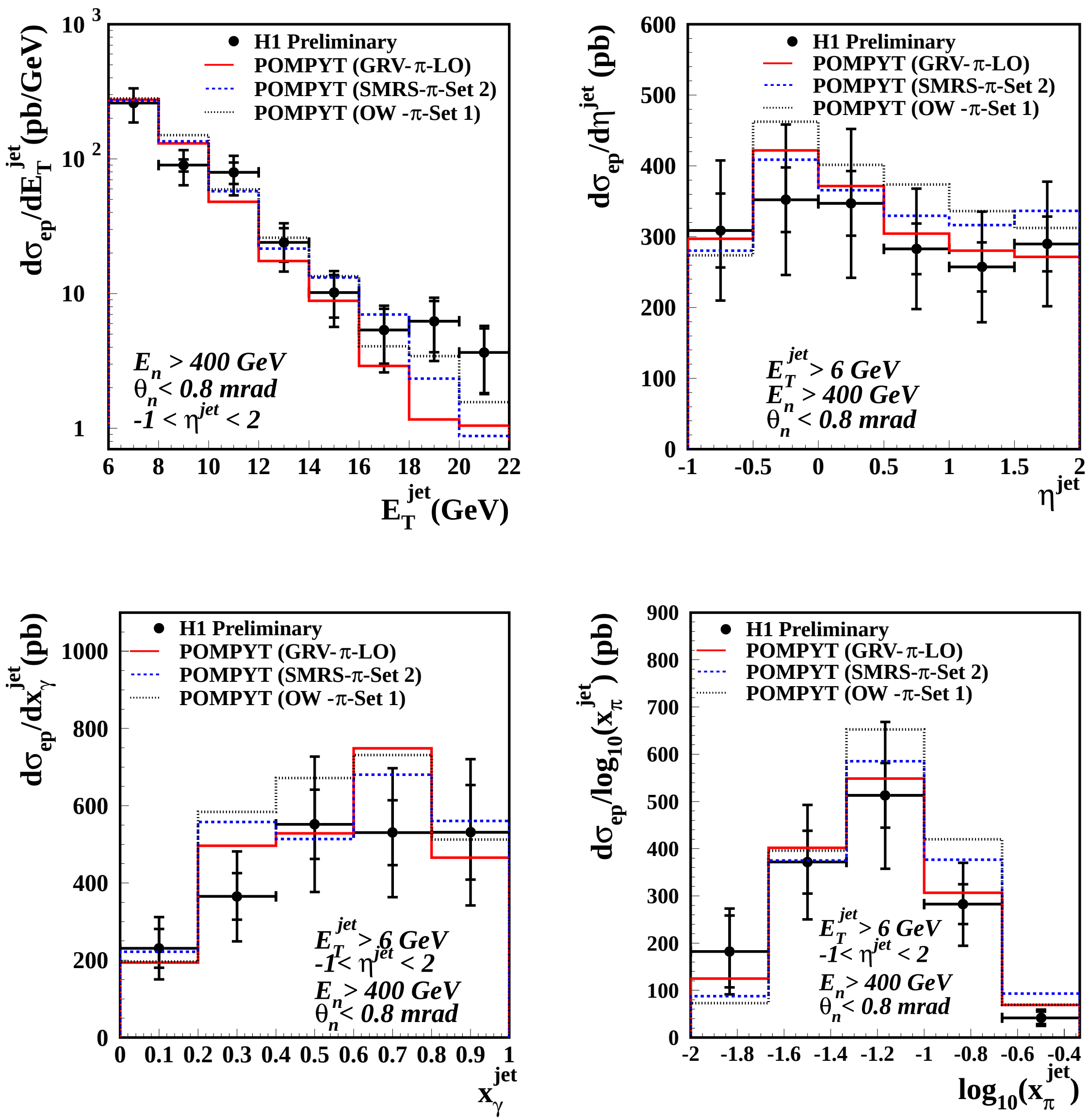
- $4 < Q^2 < 256$ GeV$^2$
- $45 < W < 225$;

di-jet selection:

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

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

# LN di-jet cross sections

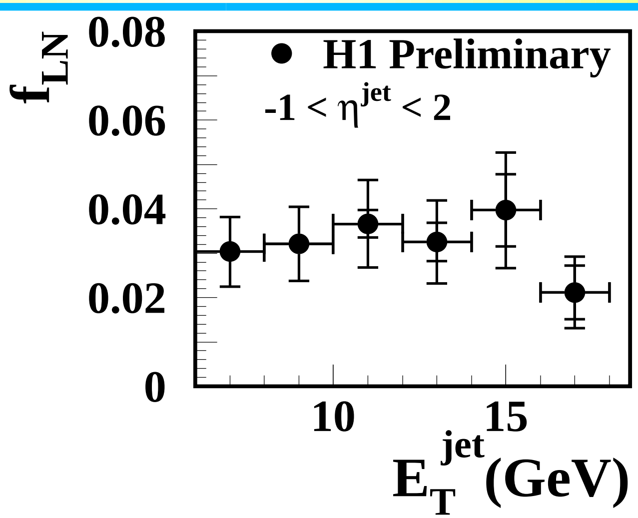


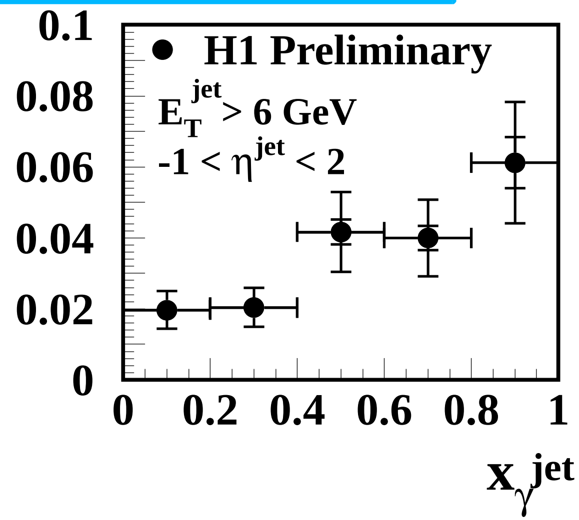

Di-jet cross sections compared to π Monte Carlo (POMPYT) with different π pdfs.

→ current data do not have sensitivity to discriminate between different π fluxes.

# Dijet neutron yield (PHP sample)

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

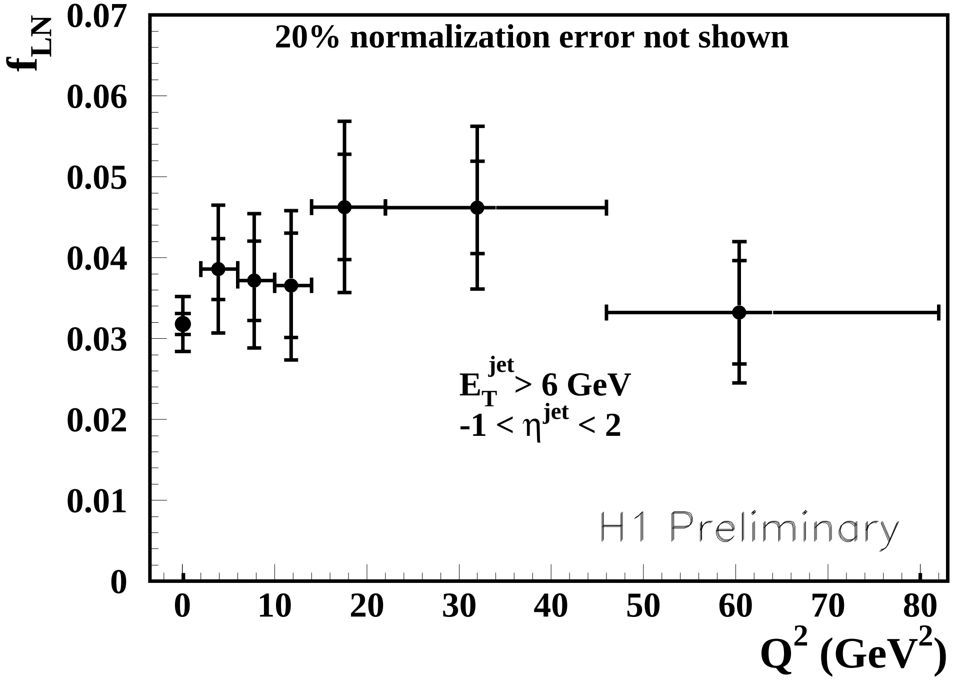



LN dijet yield is flat w/ $E_t^{jet}$ but grows w/ $x_\gamma^{jet}$ (due to process kinematics, remnant interactions, or parton distributions in LN vs inclusive ?)

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

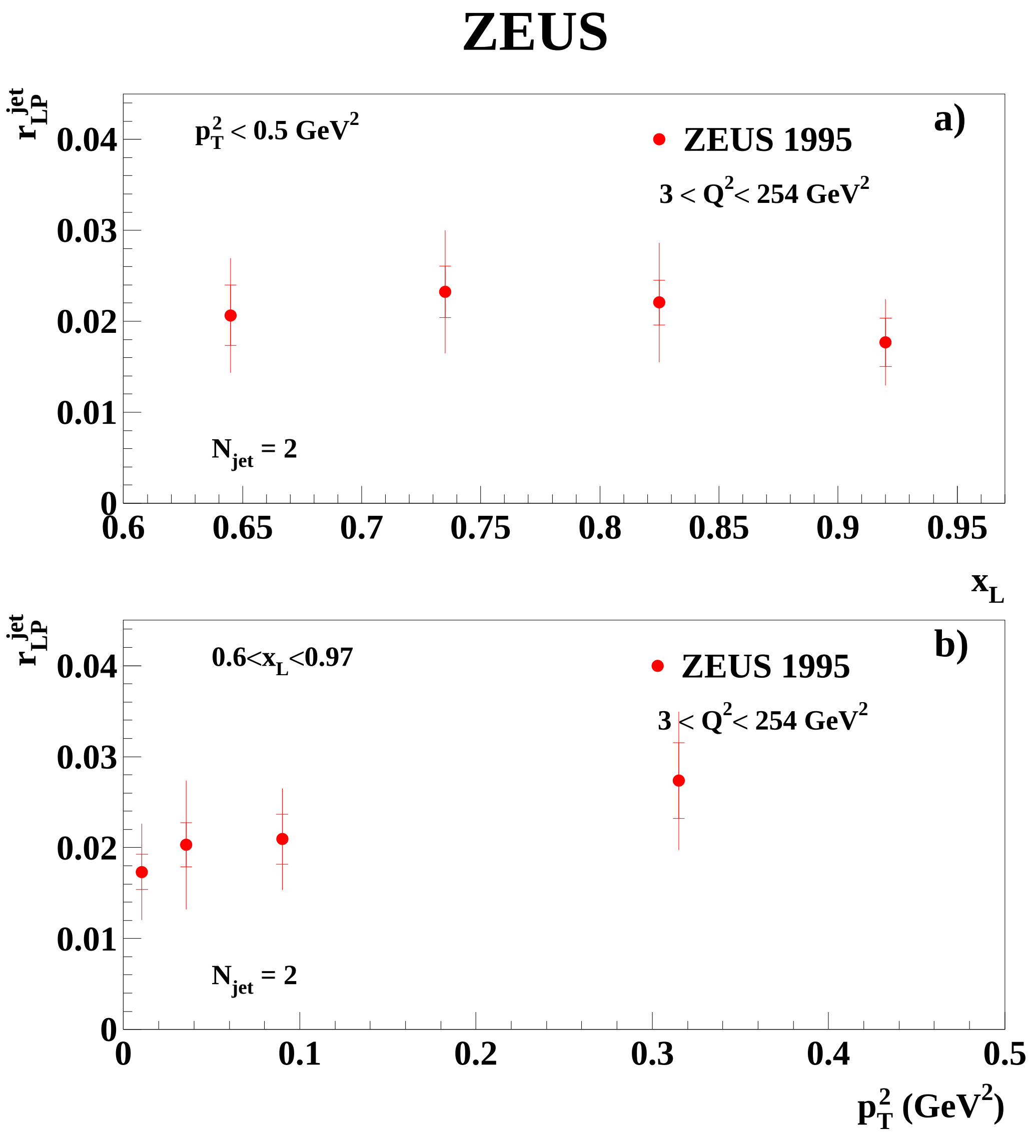
→ agreement with factorisation hypothesis.



# 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 $= E_T^{jet}$).



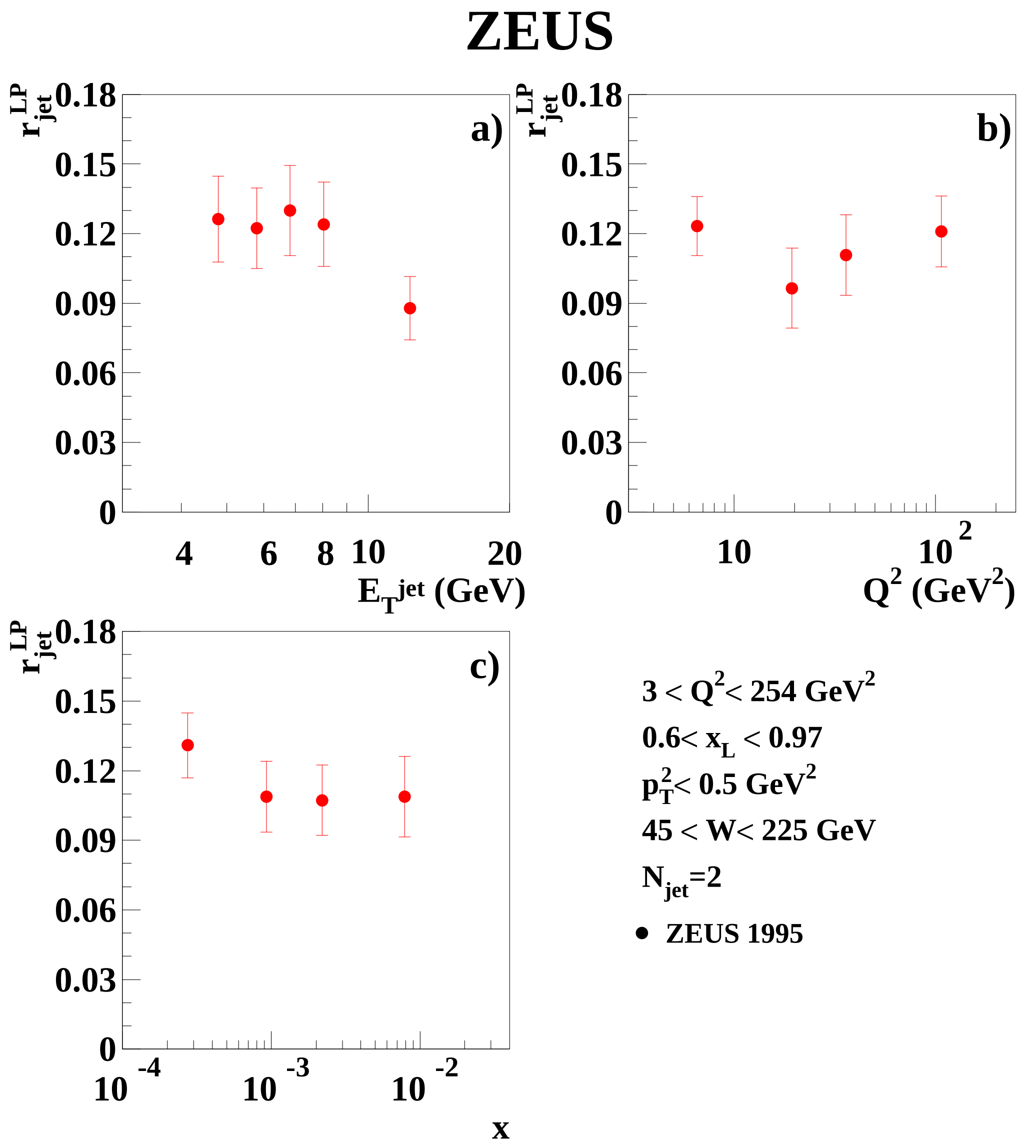
# Di-jet w/ protons (ZEUS)

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

→ ratio independent of jet variables ($E_t^{jet}$, $Q^2$, x).

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

→ fraction of dijet events w/ LP ≅ fraction of inclusive events w/ LP.



# Neutron tagged D*

ZEUS 1998-2000. ∫Lumi = 80.17 $pb^{-1}$

*e*+ in LUMI (PHP):
➔ 117.3 < W < 274.3 GeV

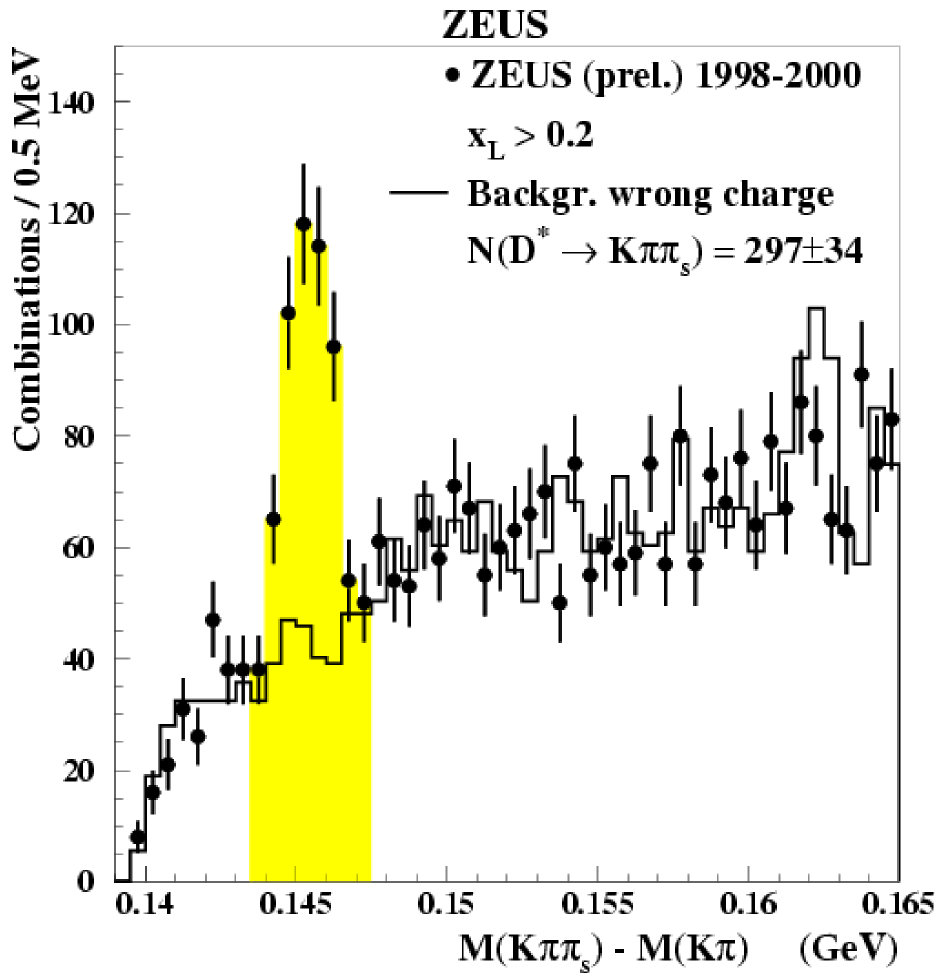
*n* in FNC:
➔ 0.2 < xL < 1, $\theta_n$ < 0.8 mrad.

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

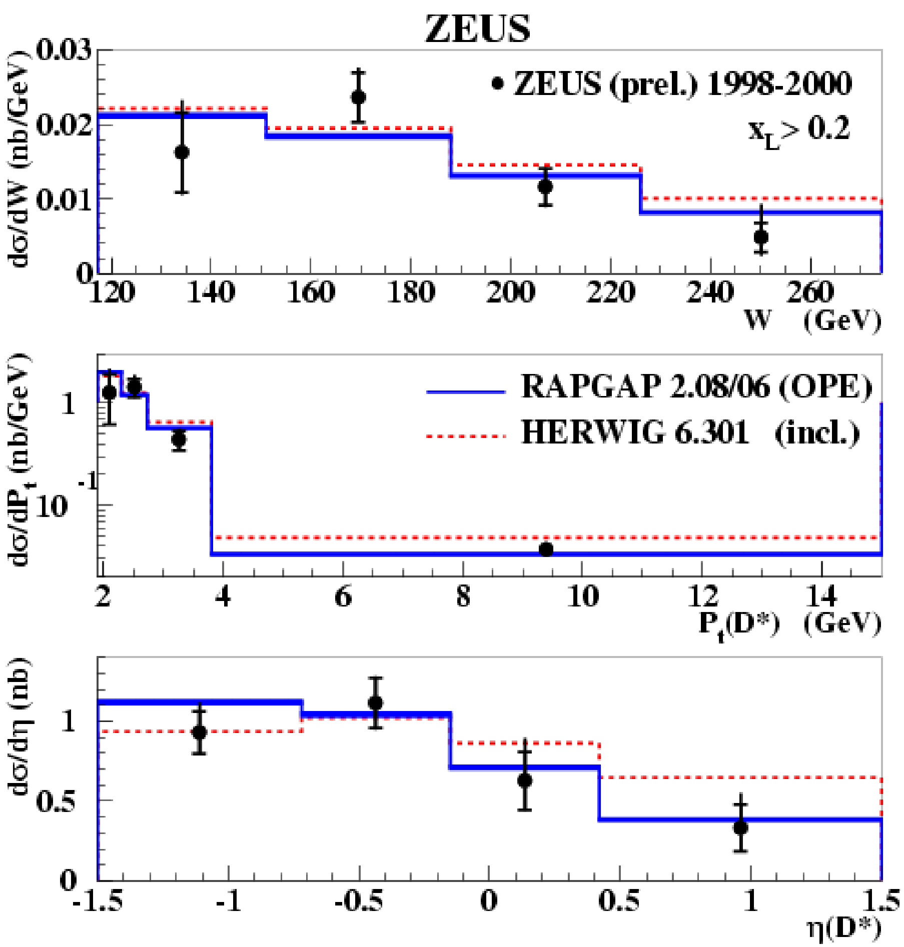
- ✓ $p_t$ (D*) > 1.9 GeV
- ✓ -1.5 < η(D*) < 1.5

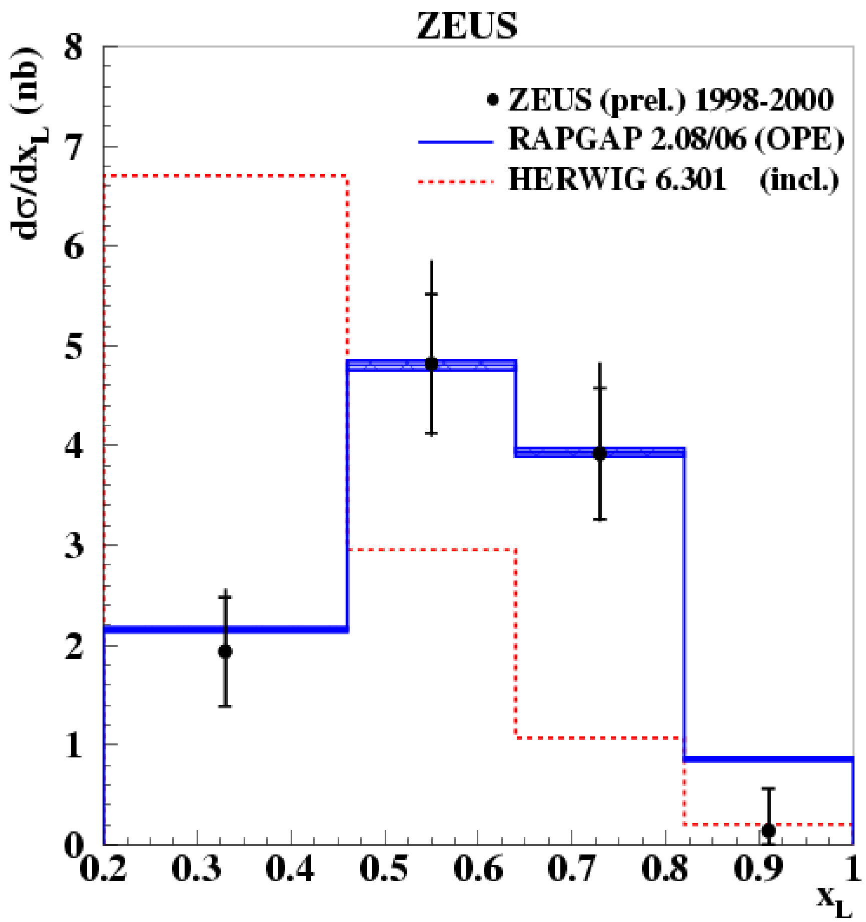
For the decay products:

- ✓ $P_t$ (π) > 0.120, 0.45 (from $D_0$ )
- ✓ $P_t$ (K) > 0.45 (from $D_0$ )



# Neutron tagged D*



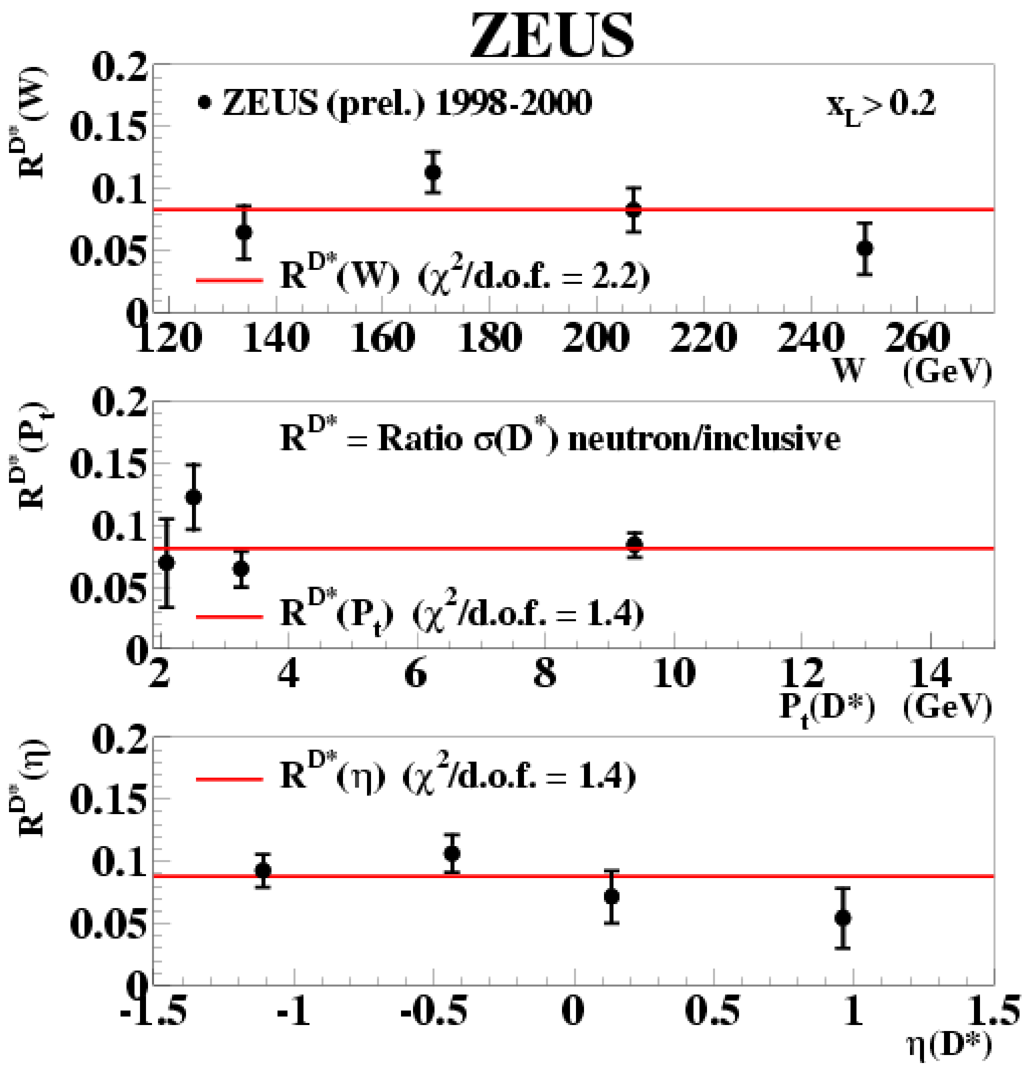




Both standard fragmentation (HERWIG) and OPE (Rapgap) describe D* variables

OPE is needed for $x_L$ distribution

# D* yield






$R^{D^*} = (\sigma^{D^*}_{LN} / \sigma^{D^*}_{inc})$

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

$0.2 < x_L < 1$,

$p_t(D^*) > 1.9$ GeV,

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

$117.3 < W < 274.3$ GeV

# Pion structure function, $F_2^{\pi}$



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

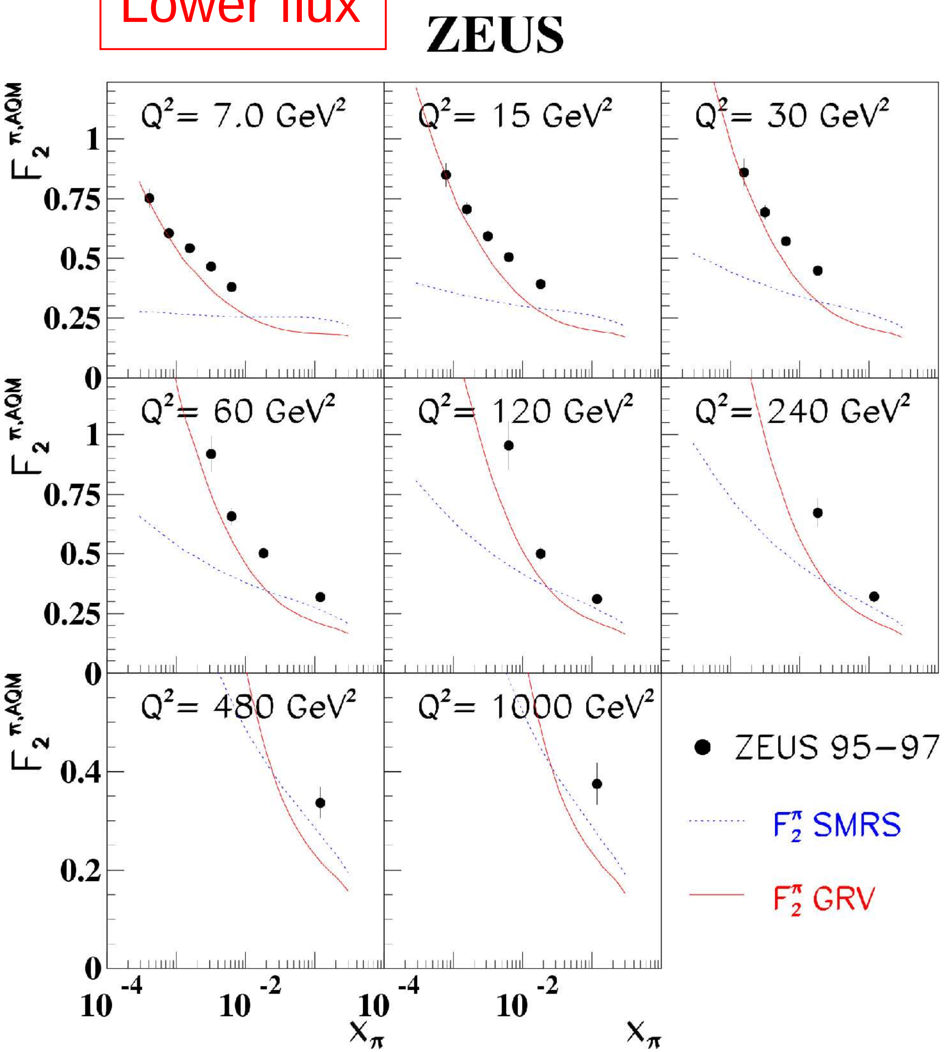
$$F_2^{LN}(x_{Bj}, Q^2; x_L, t) = f_{\pi/p}(x_L,t) \times F_2^{\pi}(x_{Bj}/(1 - x_L), Q^2)$$

  - 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 ~ 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).

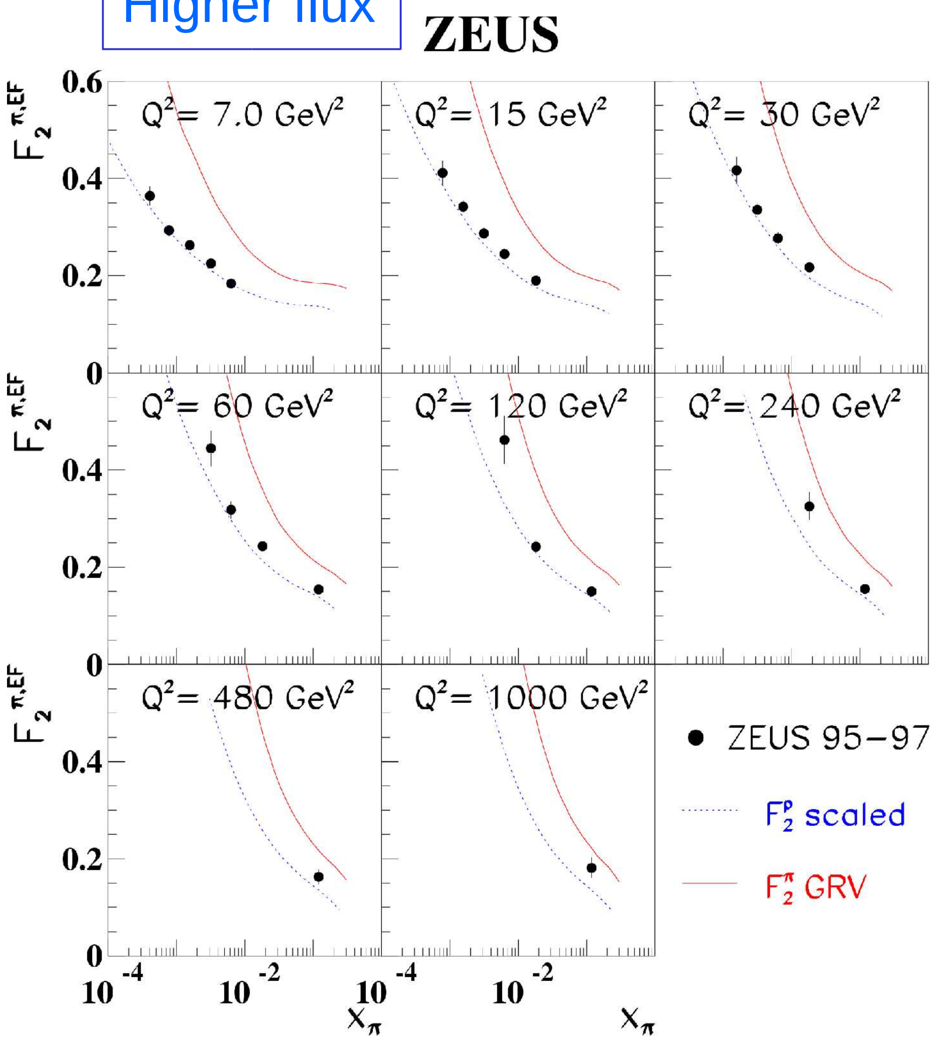
# Pion structure function , $F_2^{\pi}$



Lower flux




Higher flux




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 consistend w/ re-scattering in particle exchange.

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

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