Leading Neutrons at HERA

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On behalf of the H1 and ZEUS collaborations

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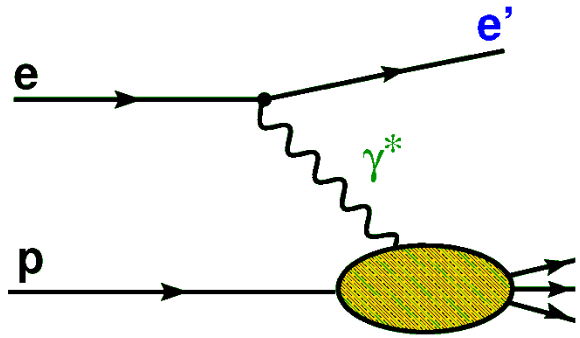
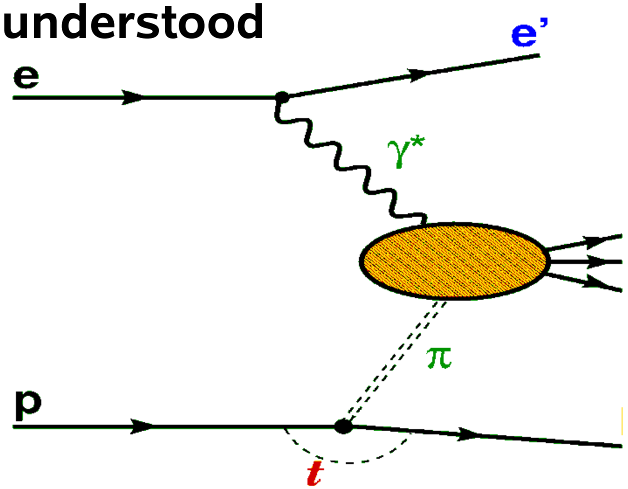
Motivation

- Significant fraction of *ep* scattering events contain a leading neutron in the final state carrying a substantial portion of the energy of the incoming proton:
  $e+p \rightarrow e+n+X$
- Production mechanism is not yet completely understood



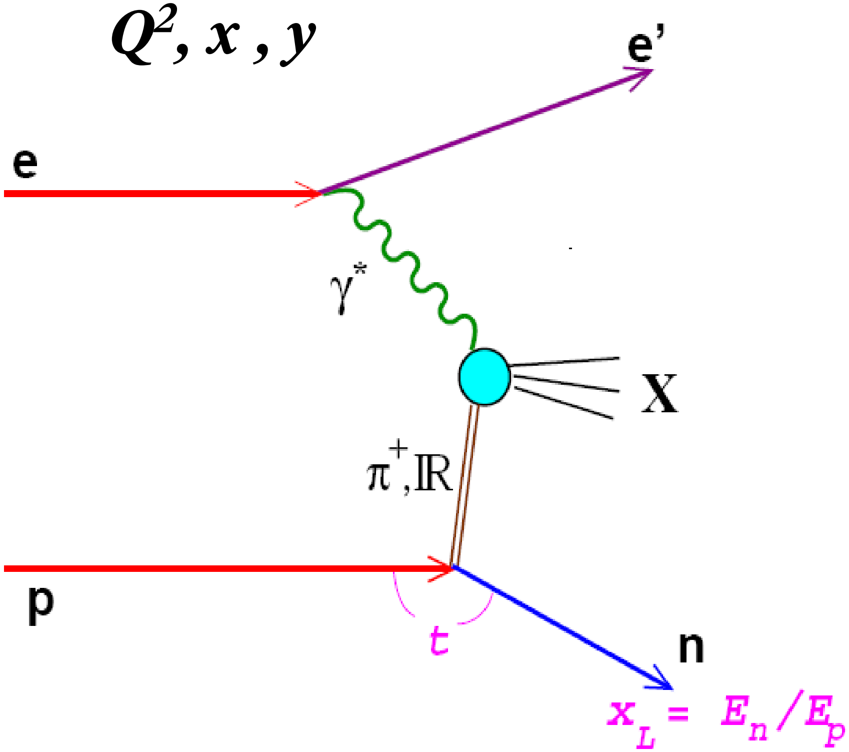


Leading neutron can come from "standard fragmentation"
- From hadronization of p remnant
- Implemented in MC models (e.g. Lund)

Leading neutron can be produced via exchange of virtual particle
- charged iso-vector (π^+, ρ^+)

Results discussed in this talk:
- Leading Neutron spectra in DIS and photoproduction
- Leading Neutron production cross section
- Comparison with models

Photon vertex:
lepton variables:
Q^2, x, y



Proton vertex:
leading baryon variables:

$$x_L = E_n / E_p$$

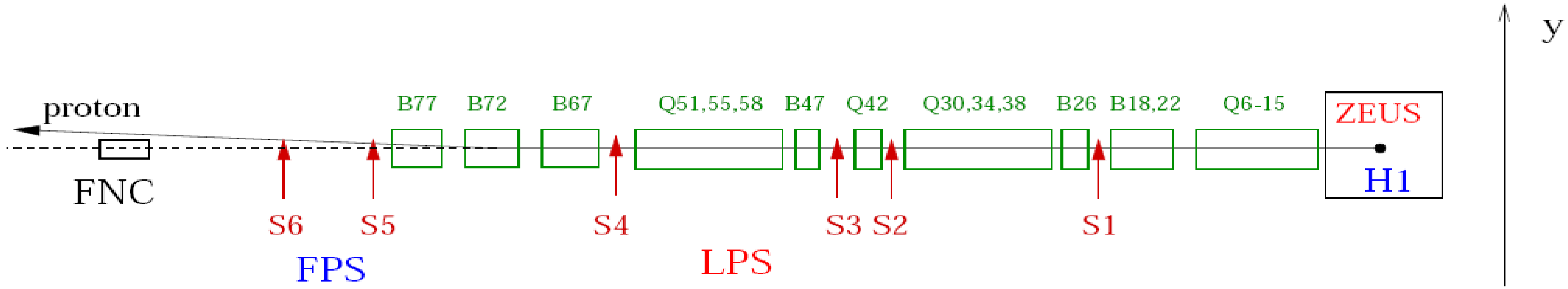
$$t = (p - p')^2 \approx -\frac{p_T^2}{x_L} - \frac{(1-x_L)^2}{x_L} m_n^2$$

In the π-exchange model cross section dependence on leading baryon variables is independent of kinematics at photon vertex

$$\sigma_{ep \to enX}(x, Q^2, x_L, t) = f_{\pi^+/p}(x_L, p_T) \cdot \sigma_{e\pi \to eX}(x/(1-x_L), Q^2)$$

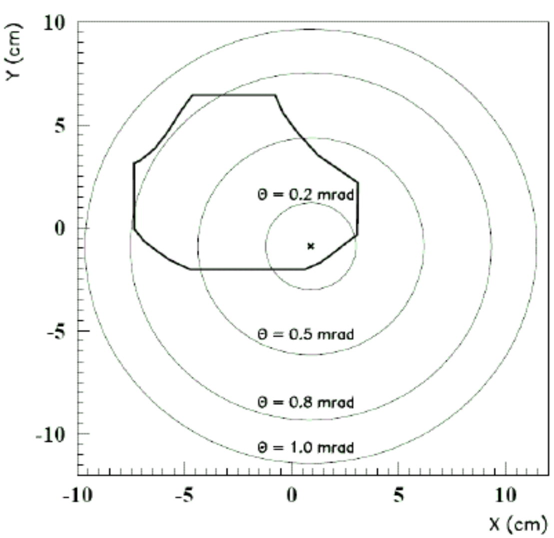
Leading Neutron production affected by absorption and rescattering effects: evidences of vertex factorization violation

H1 and ZEUS Forward Neutron Calorimeters

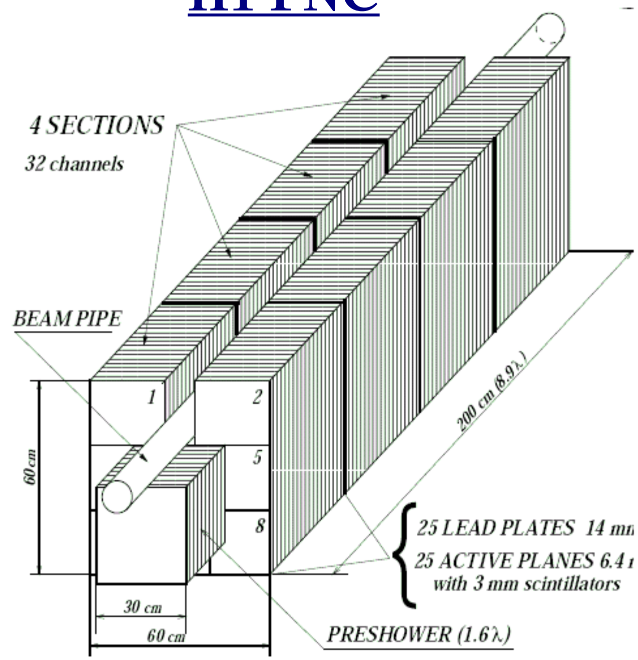


Position – 105m from the interaction point.
Geometrical acceptance is limited by beam-line elements: < 0.8 mrad.

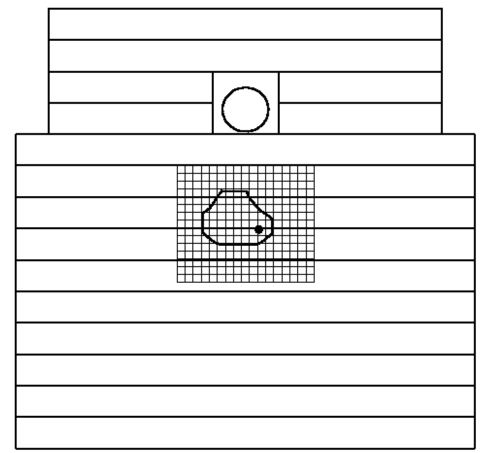
Geometrical Acceptance



H1 FNC



ZEUS FNC



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

~ 10 λ lead-scintillator sandwich calorimeters

H1: $F_2^{LN(3)}(Q^2,x,x_L)$ - triple diff. cross section of LN production in DIS

H1prelim-08-111

- HERA-II data, much higher statistics compared to old result
- Upgraded Forward Neutron Calorimeter (better resolution and photon identification)
- Kinematic range: $6\ \text{GeV}^2 < Q^2 < 100\ \text{GeV}^2$, $1.5\times10^{-4} < x < 3\times10^{-2}$, $p_{T,n} < 0.2$ GeV

ZEUS: relative to inclusive cross section vs x_L and p_T in DIS and γp

Leading Neutrons are selected from inclusive data sets (i.e. no LN tag):

Nucl.Phys.B776 (2007) 1

- DIS: $Q^2 > 2\text{-}3\ \text{GeV}^2$, 3 subsets $Q^2 \approx 2.7, 8.9, 40\ \text{GeV}^2$
- γp: $Q^2 < 0.02\ \text{GeV}^2$, e^+ tagged => $150 < W_{\gamma p} < 270$ GeV

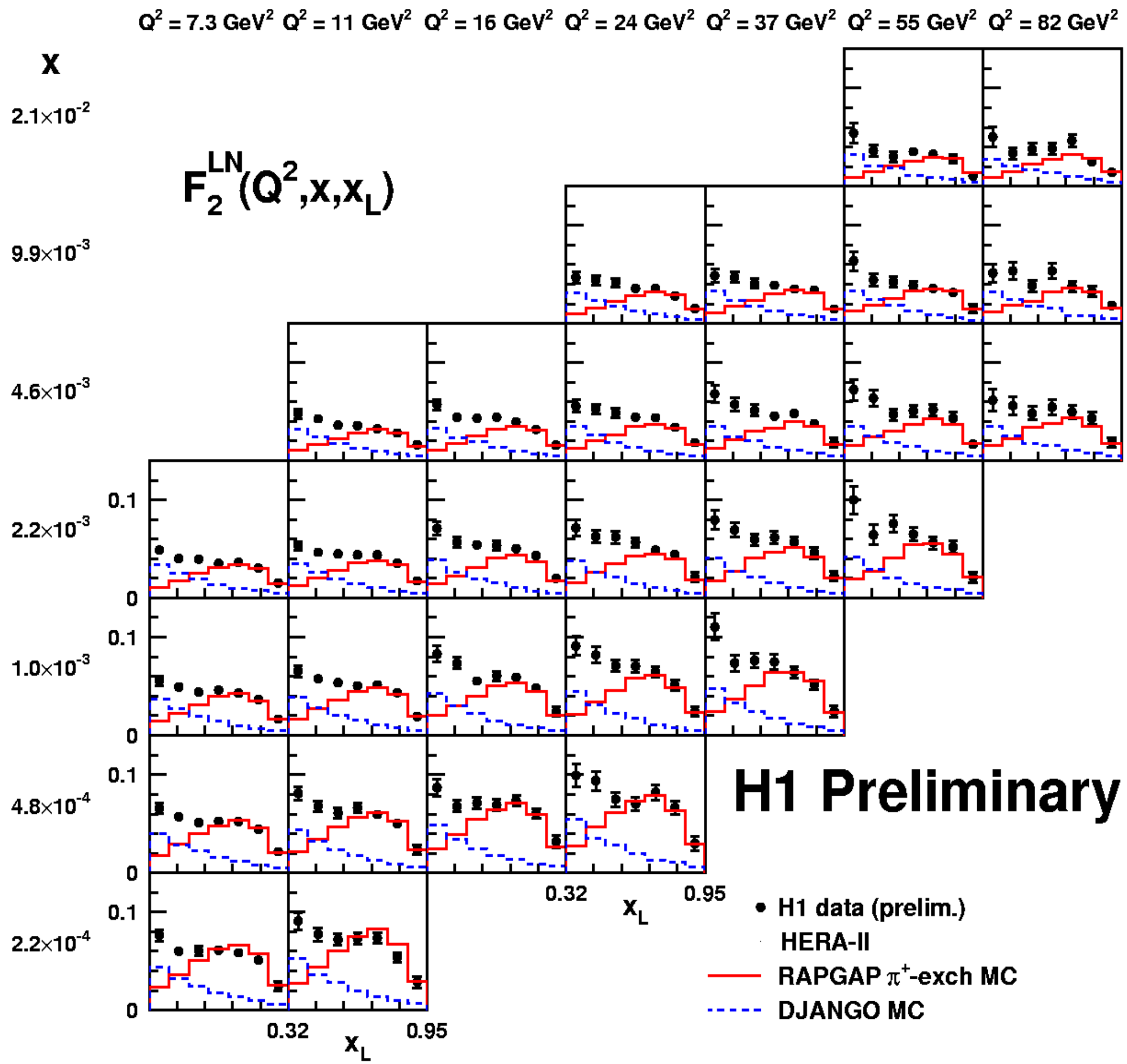
Leading Neutron yields:

- DIS, γp have very different inclusive cross sections σ_{inc}
- For sensible comparisons look at LN yields: $r_{LB} = \sigma_{LB}/\sigma_{inc}$
- Additional benefit: systematic uncertainties of central detector cancel

Triple differential reduced cross section

$$\frac{d^3\sigma(ep\rightarrow eNX)}{dQ^2\,dx\,dx_L}=$$

$$=\frac{4\pi\alpha^2}{x\,Q^4}\left[1-y+\frac{y^2}{2}\right]F_2^{LN}(Q^2,x,x_L)$$



- DJANGO (standard fragmentation) predicts too low cross section + x_L spectrum shape is too different
- RAPGAP π^+-exch. describes data well for $x_L > 0.7$

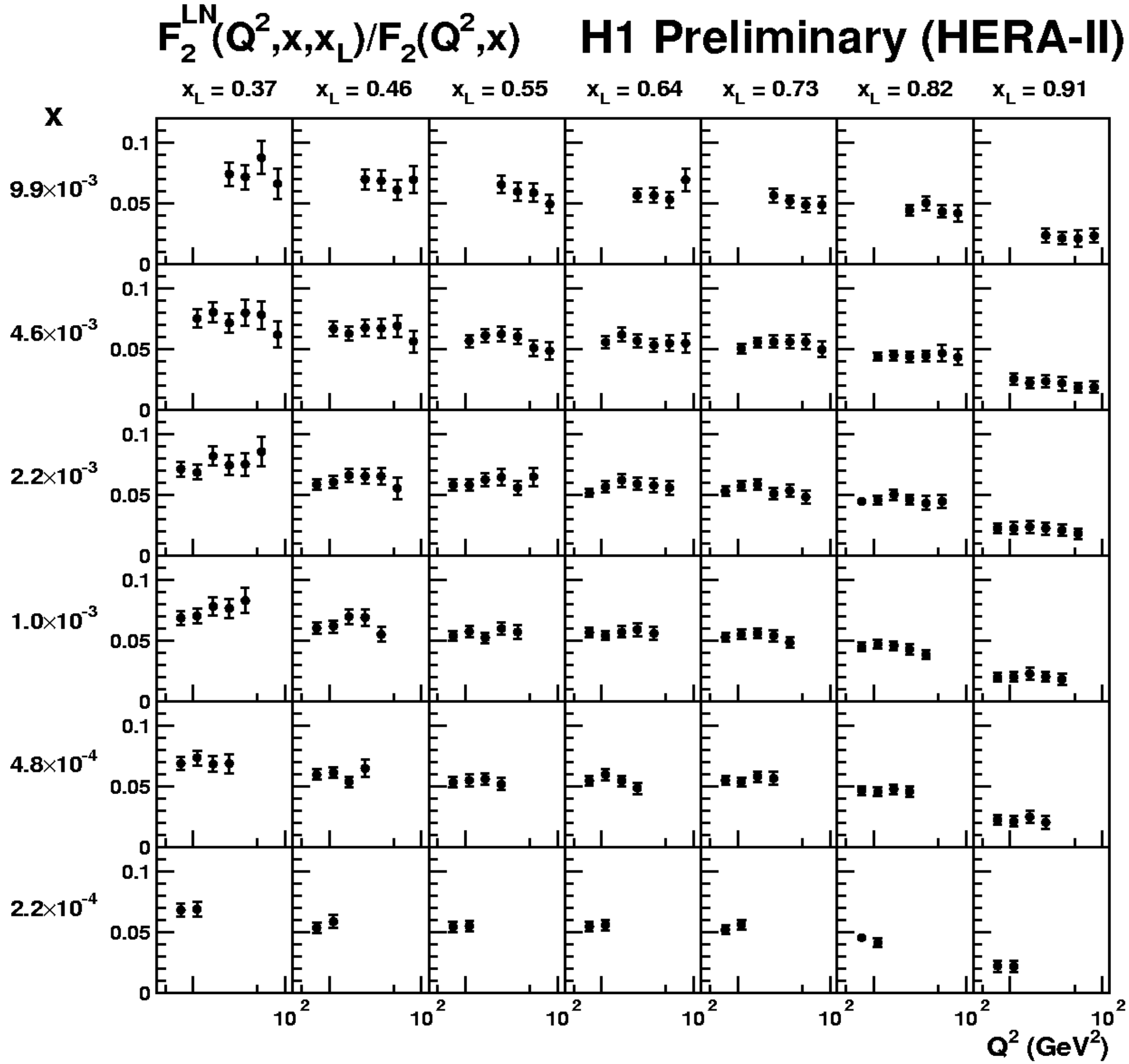
$F_2^{LN}(Q^2,x,x_L)$ to $F_2(Q^2,x)$ ratio

$F_2(Q^2,x)$ from the H1 parameterization (Eur.Phys.J.C21 (2001) 33)

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

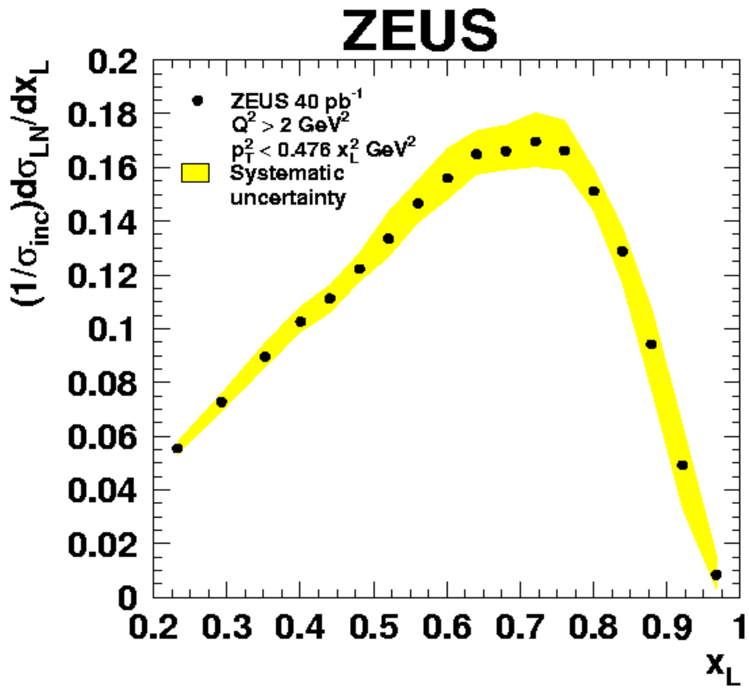
=> consistent with vertex factorization (or common suppression of LN cross section)

LN production rate, kinematics is approx. independent of (Q^2,x)



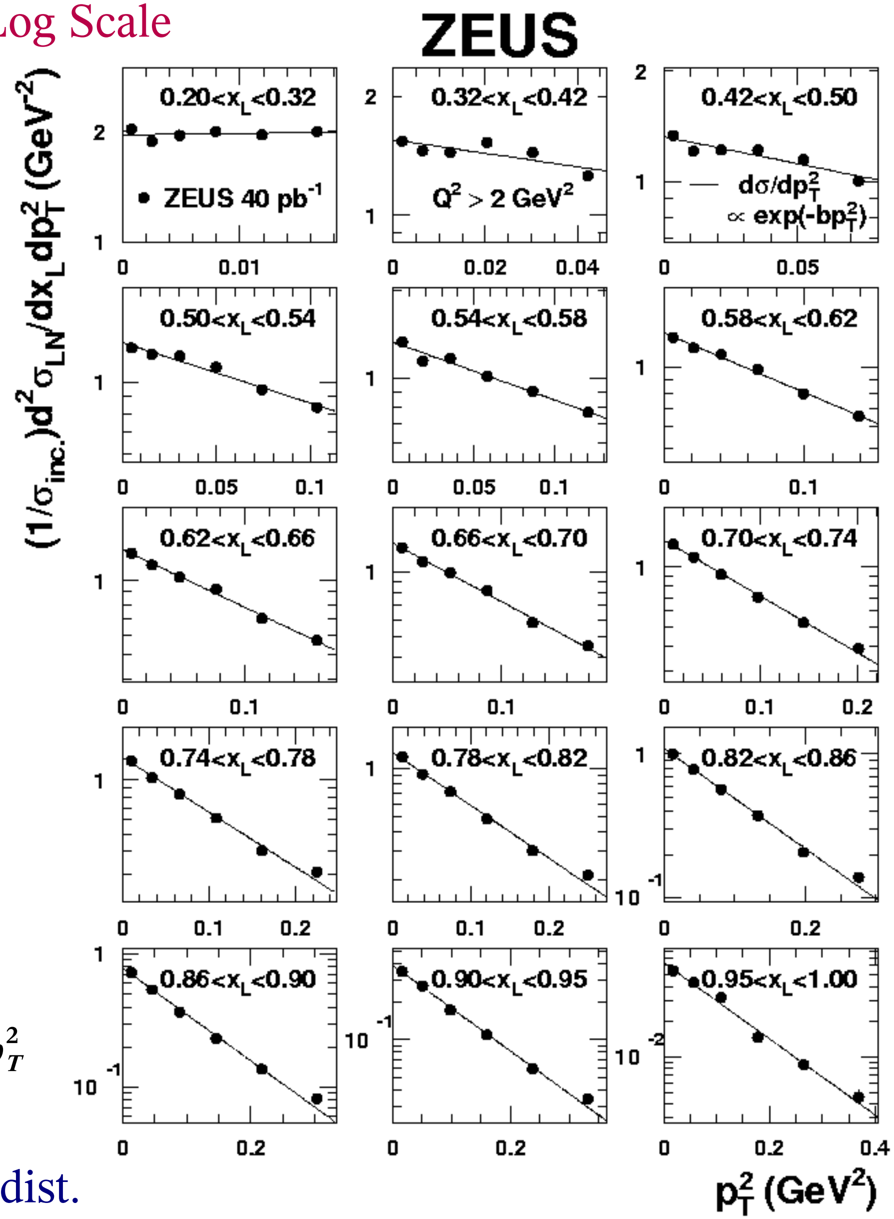
DIS: x_L and p_T^2 distributions

Leading Neutron: $p_T^2 < 0.476\, x_L^2$ GeV^2



- LN yield → 0 at kin. limit $x_L \to 1$
- Below $x_L \approx 0.7$ yield drops due to decreasing p_T^2 range

Log Scale



Fit by exp. in p_T^2:

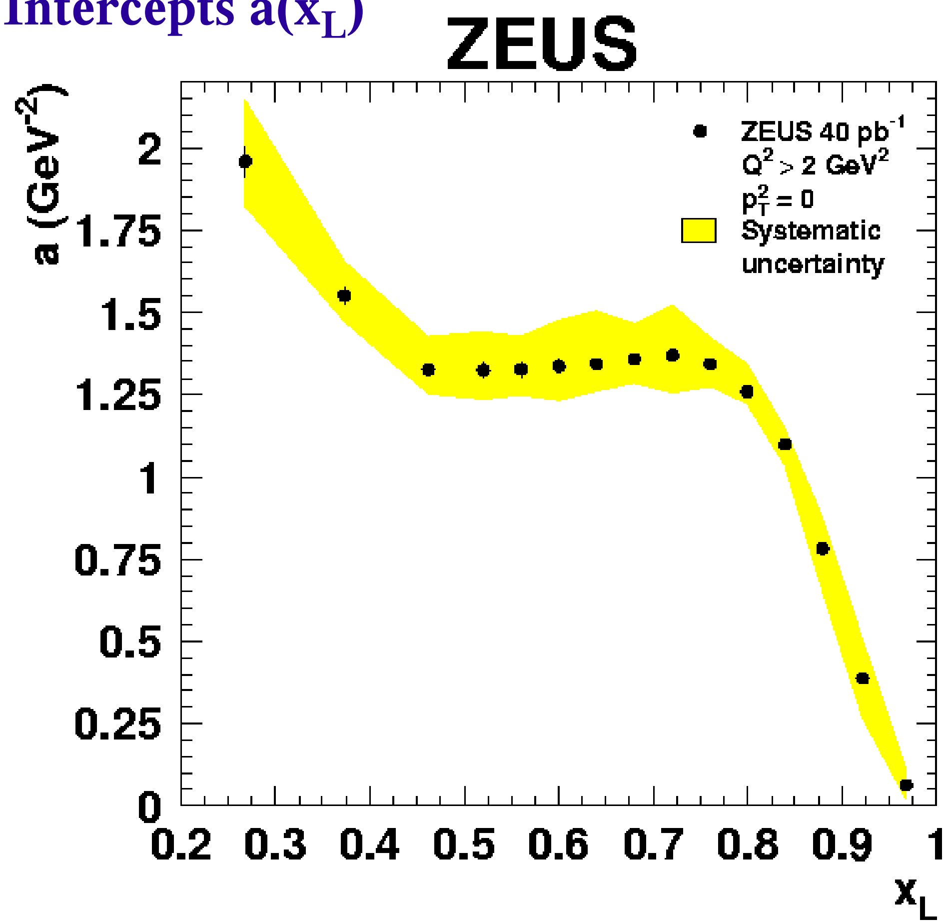
$$\frac{1}{\sigma_{inc}} \frac{d^2\sigma_{LN}}{dx_L\, dp_T^2} = a(x_L) \cdot e^{-b(x_L)\, p_T^2}$$

Intercept $a(x_L)$ and slope $b(x_L)$ fully describe (x_L, p_T^2) dist.

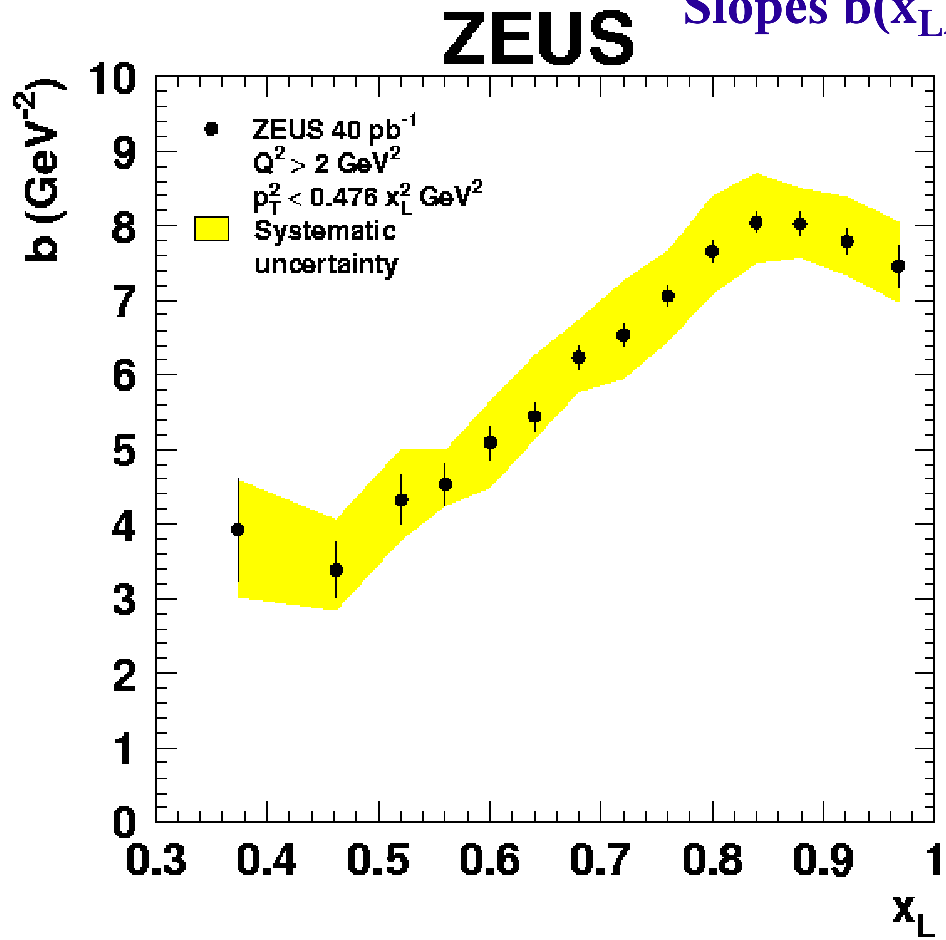
DIS p_T^2 distributions: intercepts and slopes

$$\frac{1}{\sigma_{\rm inc}} \frac{d^2\sigma_{\rm LN}}{dx_L\,dp_T^2} = a(x_L)\cdot e^{-b(x_L)\,p_T^2}$$

Intercepts $a(x_L)$



Slopes $b(x_L)$

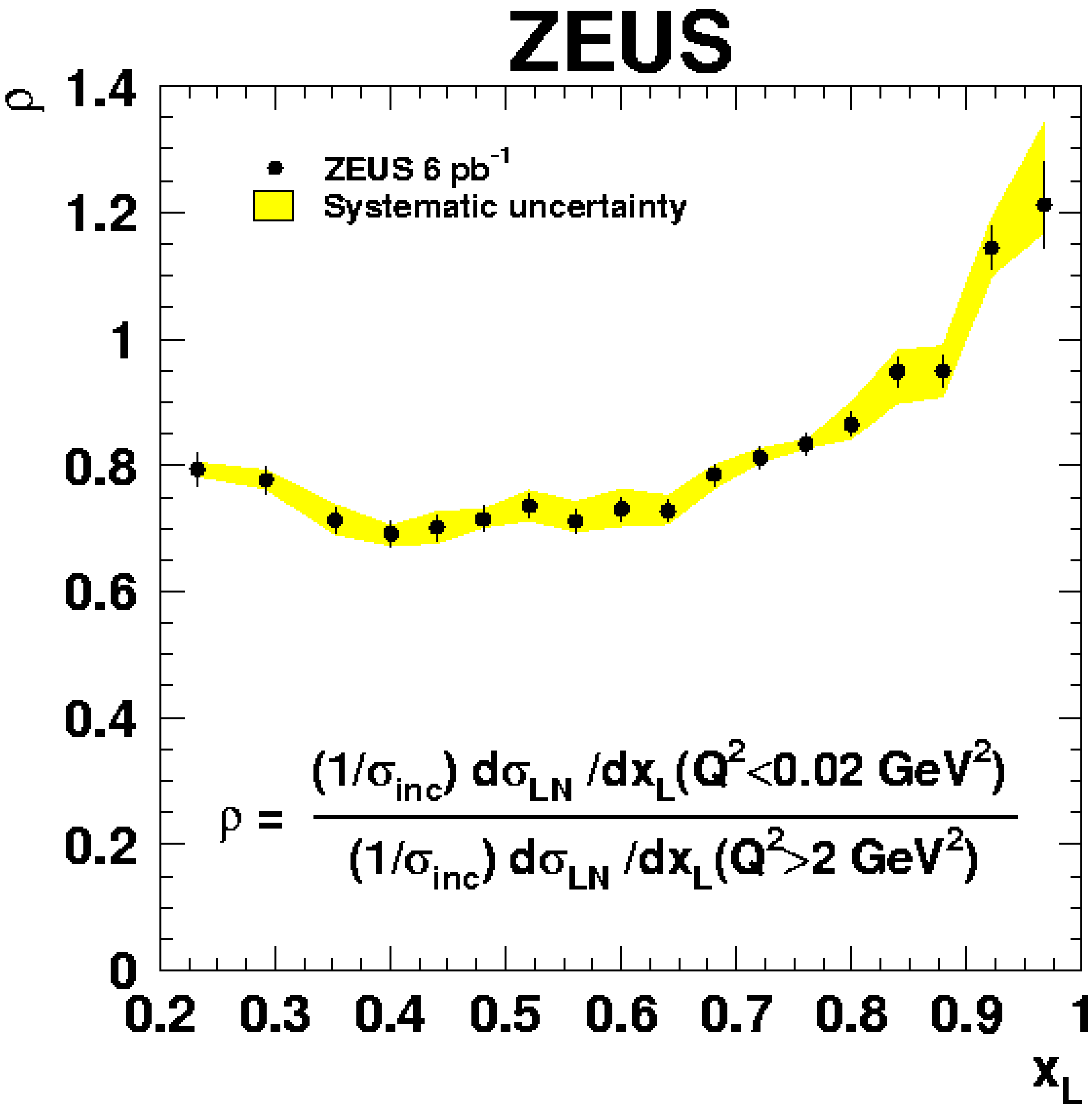


- LN intercepts fall with x_L
- bump/plateau/shoulder $0.4<x<0.8$

- LN slopes sharp rise with x_L

Compare γp/DIS: x_L distributions

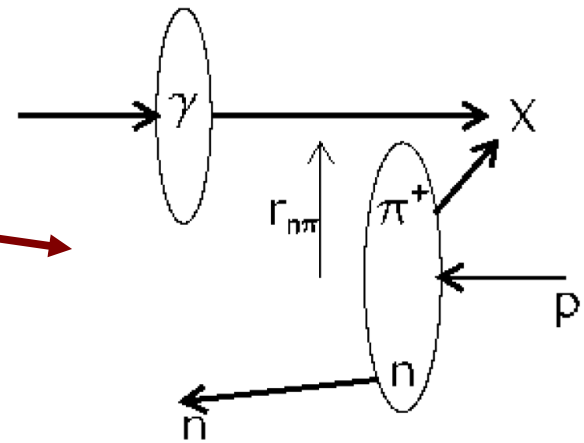
- Combine all DIS $Q^2>2$ GeV^2, compare to γp x_L dist.
- Ratio ~70% mid-x_L, rising above 1 as $x_L \rightarrow 0.9$



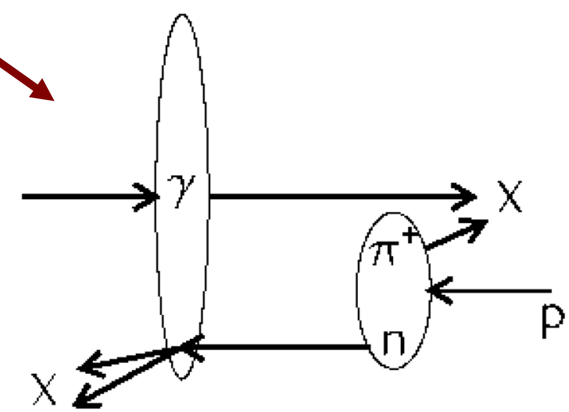
Exchange model refinements: Absorptions (Rescattering)

For e.g. LN production via π-exchange:

- In DIS γ^* is small; small chance both n,π scatter on γ^*: n reaches detector



- In photoproduction γ^* large; if n-π separation smaller rescattering of n may occur: n kicked to lower x_L and higher p_T (migration) and may escape detection (absorption loss)



- In another language: multi-Pomeron exchange

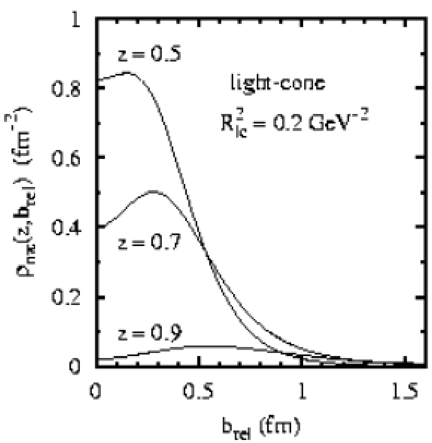
- Compare photoproduction and DIS:
  - x_L , p_T distributions
  - effects of absorption?
- Effects of absorption/migraton estimated:
  D' Alesio, Pirner;
  Nikolaev, Speth, Zakharov;
  Kaidalov, Khoze, Martin, Ryskin;
  Kopeliovich, Potashnikova, Schmidt, Soffer

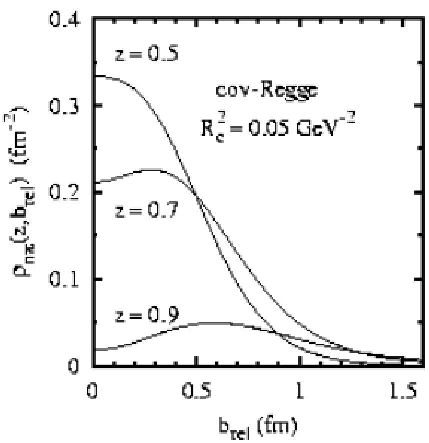
Compare γp/DIS: x_L distributions

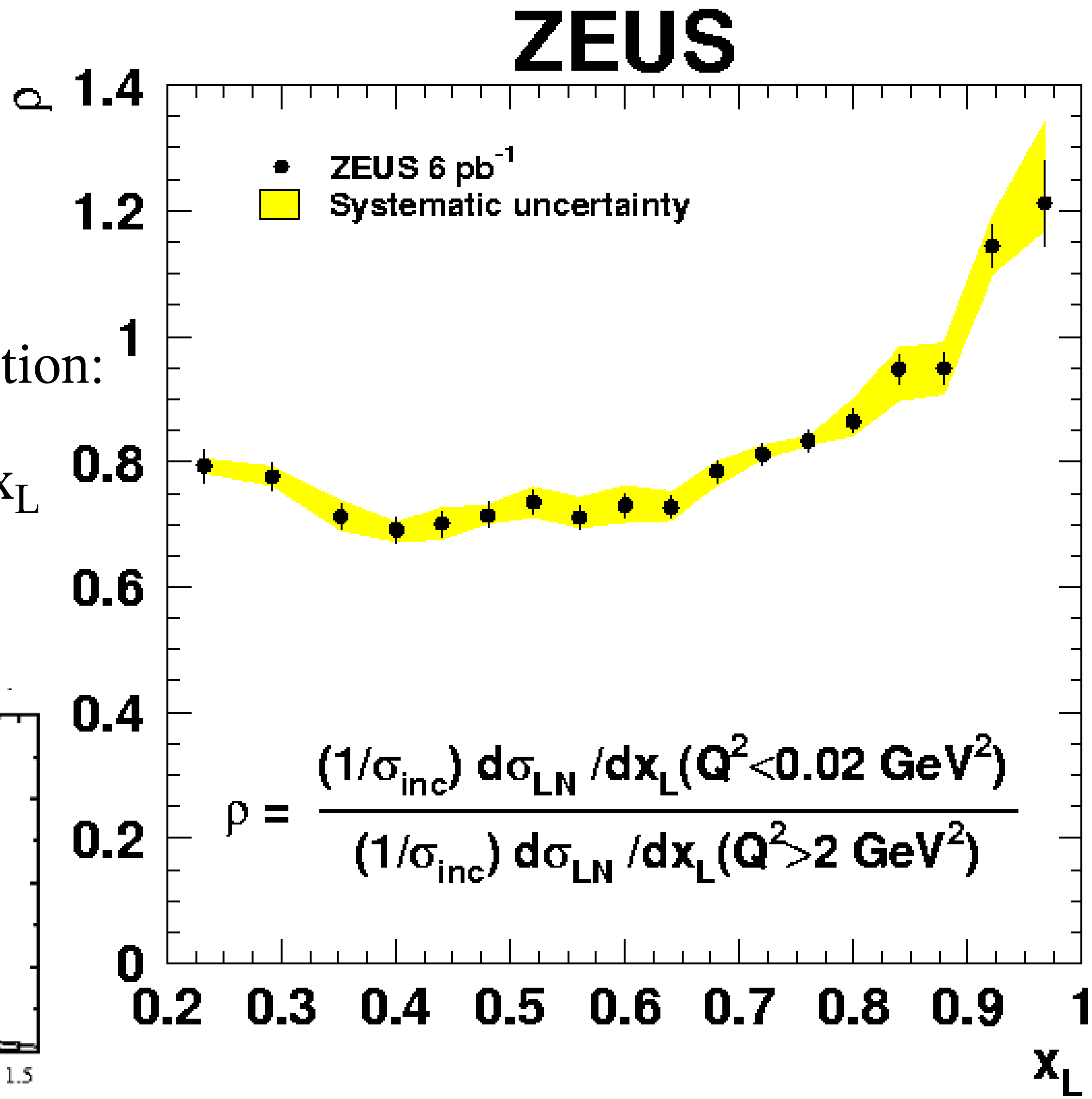
- Combine all DIS $Q^2 > 2$ GeV^2, compare to γp x_L dist.
- Ratio ~70% mid-x_L, rising above 1 as $x_L \rightarrow 0.9$

Qualitatively consistent with absorption:

- Exchange model: mean n-π separation $\boldsymbol{r_{n\pi}}$ decreases at lower x_L
- Smaller $\boldsymbol{r_{n\pi}}$ => more absorption at lower x_L

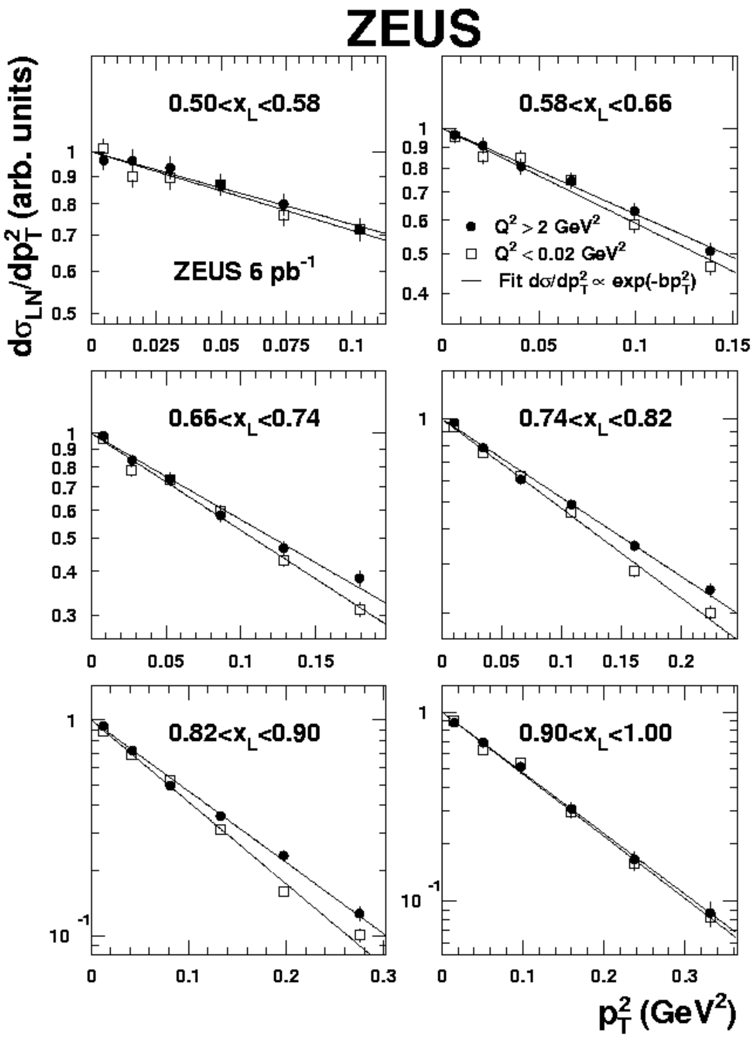




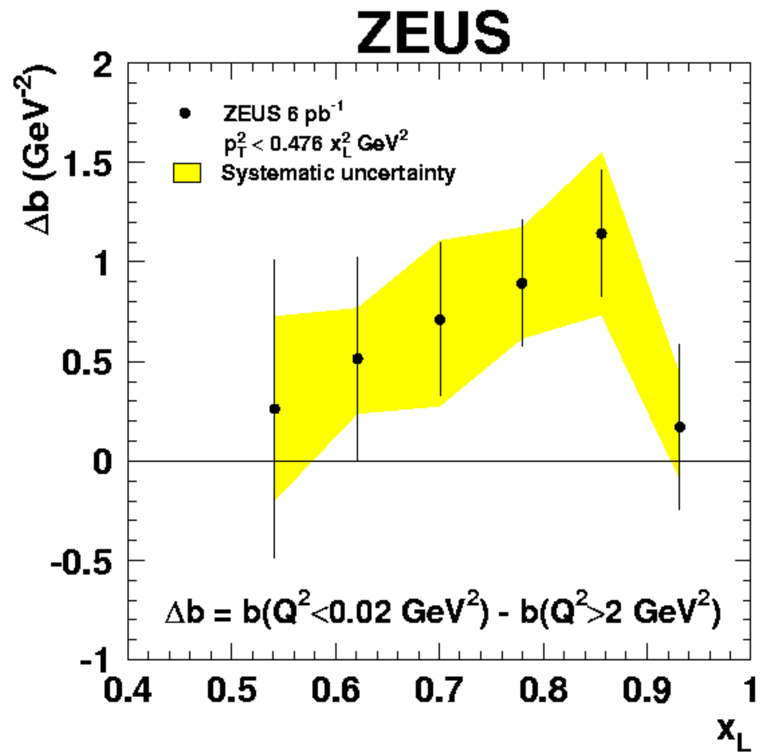


Compare γp/DIS: p_T^2 distributions

normalized at $p_T^2 = 0$



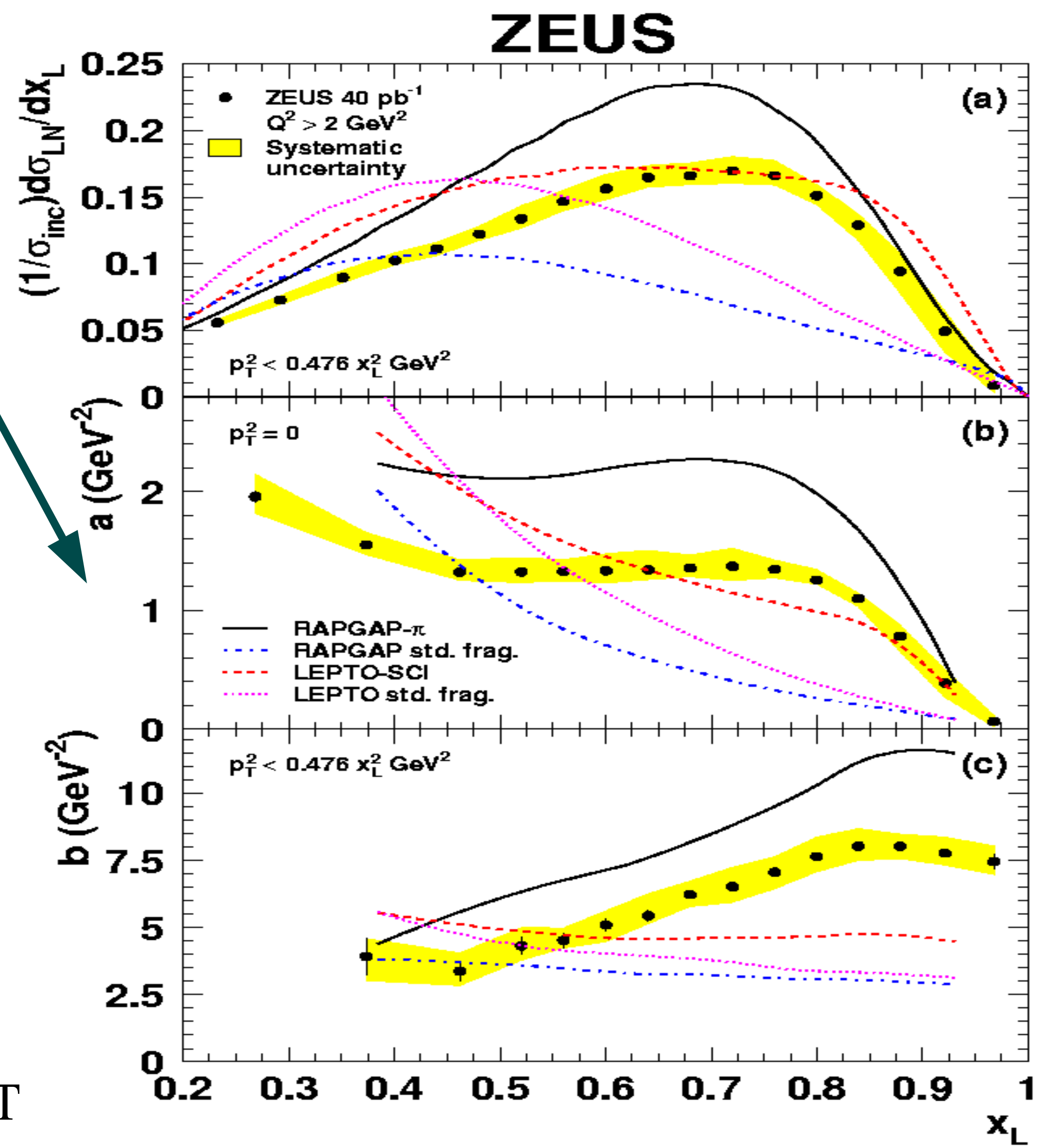
$\Delta b = b(\gamma p)$ - b(DIS)



- Small but clear difference: $b(\gamma p) > b(\text{DIS})$ for $0.6 < x_L < 0.9$
- Qualitatively consistent with absorption: more absorp. at small $\boldsymbol{r_{n\pi}}$ ~ large p_T fewer LN at high p_T => larger slope

Model comparisons: DIS

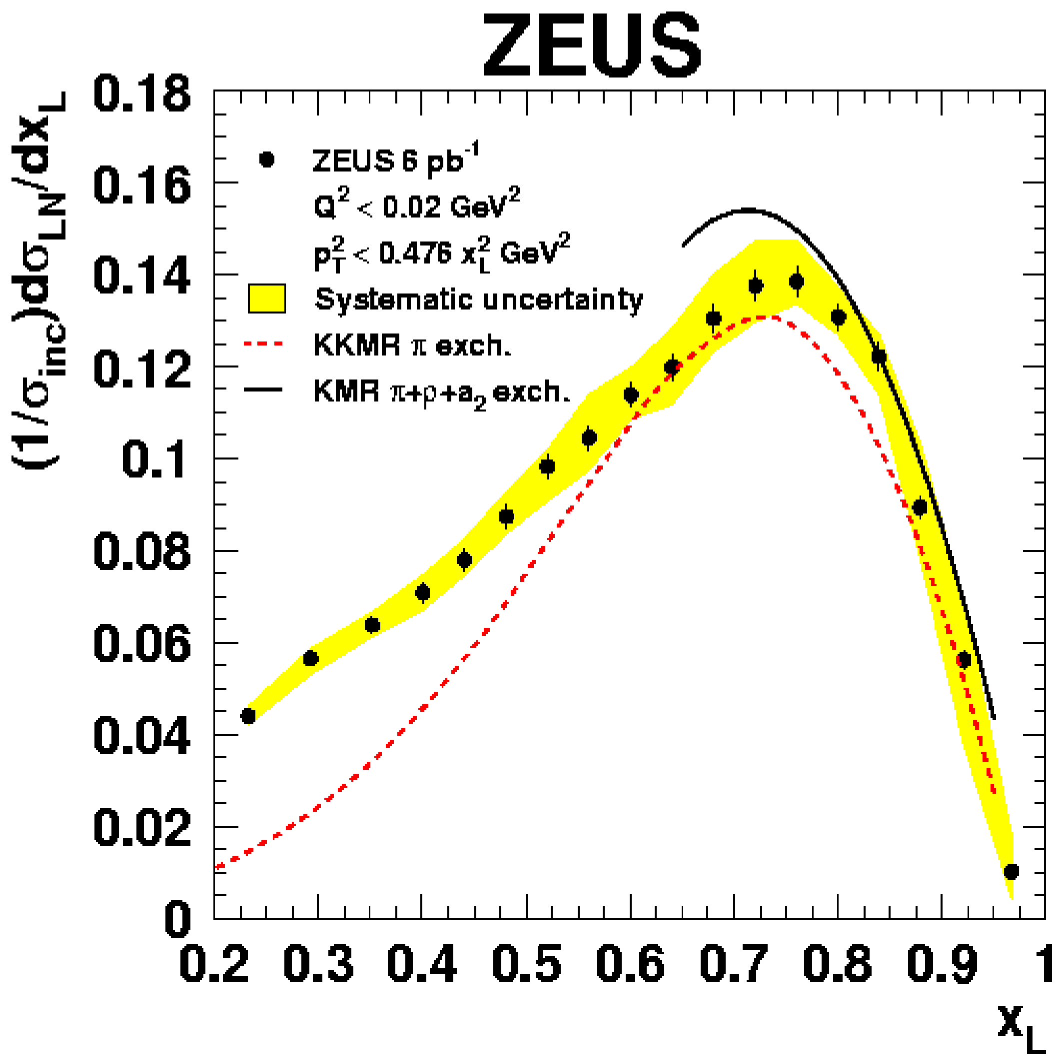
- ● DATA
- RAPGAP π-exchange
- RAPGAP std. fragmentation
- LEPTO soft color interactions
- LEPTO std. fragmentation



- None of models describe data well
- Both std. frag. too few n, too low x_L
- LEPTO-SCI ~ OK in shape, magnitude, but slopes too small, not x_L dependent
- RAPGAP π-exch. closest to data (but slopes too high)
- Other DIS, γp std. frag. models also fail: ARIADNE,CASCADE,PYTHIA,PHOJET

Compare: π-exch. with absorption and (ρ, a_2) exchanges

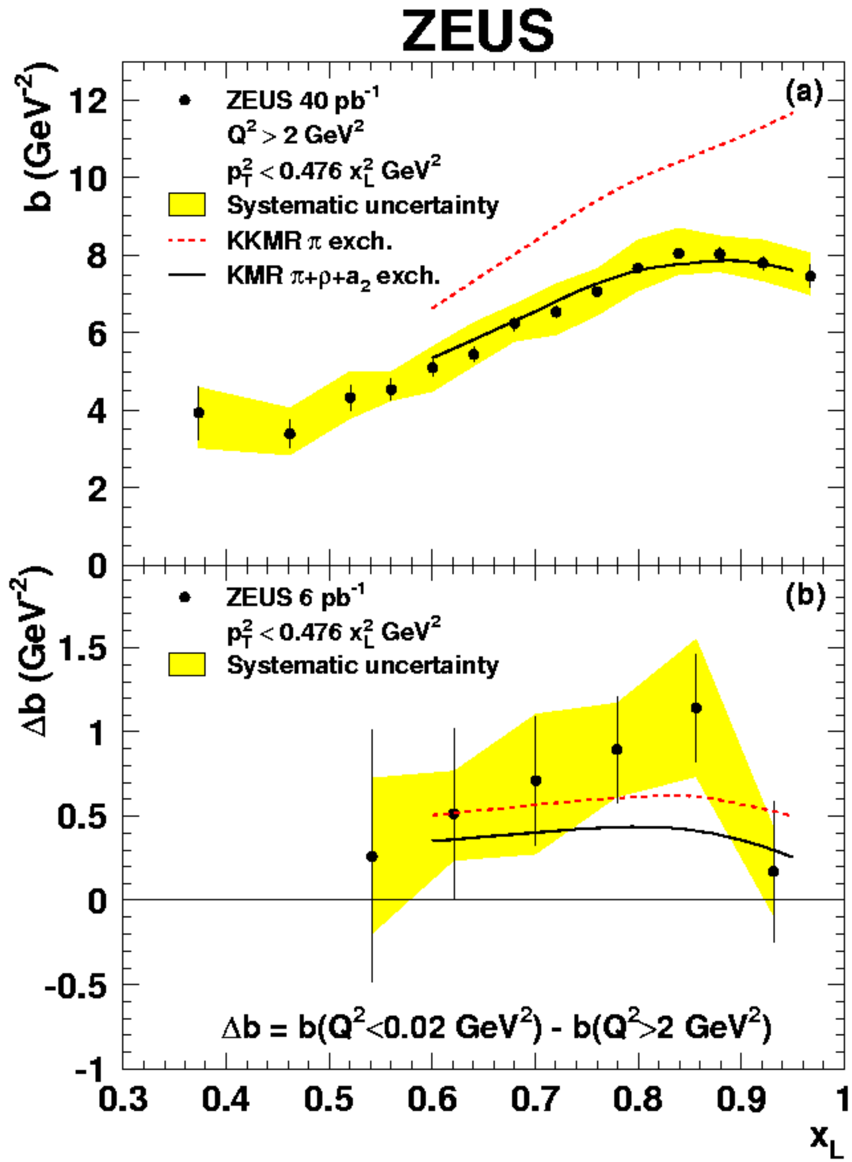
- Compare with calculations of Kaidalov, Khoze, Martin and Ryskin:
  - start with pure π-exch.
  - some *n* rescatter on γ
  - rescattered *n* migrate in (x_L, p_T)
  - add (ρ, a_2) exchanges
- Overall loss ~50% from pure OPE
- Reasonable agreement with LN in γp



π–exch. with absorption and (ρ, a_2) exchanges

- Absorption+migration with pion exchange alone doesn't describe slopes; too high in magnitude, no turnover at high x_L; Δb is ~ OK

- Addition of (ρ, a_2) exchanges gives good description of both slopes magnitude and x_L dependence, Δb is still OK



Pion Structure Function from F_2^{LN}

According to π-exchange model we can extract 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

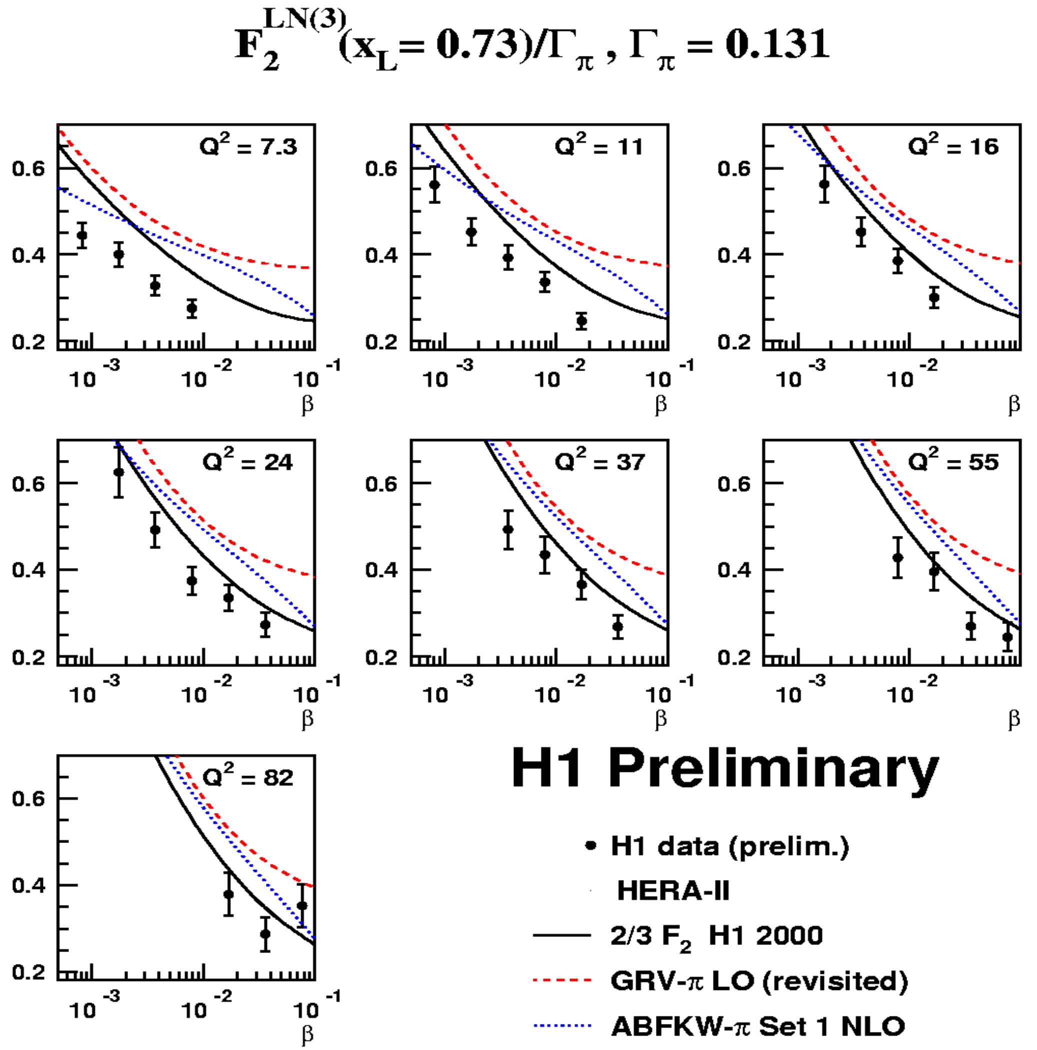
$\beta = x/(1-x_L)$

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

For pion flux

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

at $x_L = 0.73$ we obtained $\Gamma_\pi = 0.131$



Data compared to parameterizations:

- 2/3 of F_2 => additive quark model
- GRV-π LO (revisited)
- ABFKW-π Set 1 NLO

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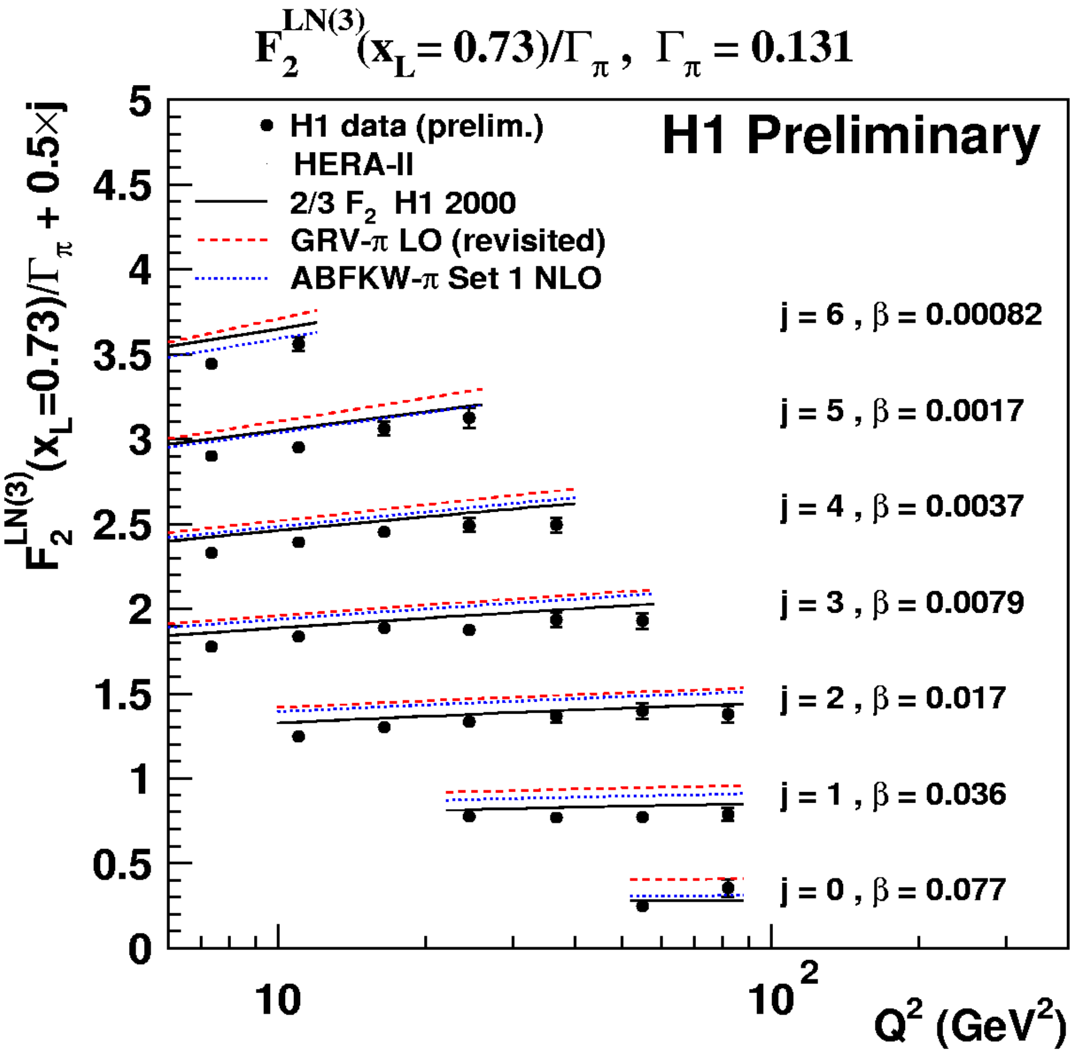


Summary

- **New measurement of $F_2^{LN(3)}(Q^2,x,x_L)$ structure function from HERA-II data.**
  => F_2^{LN}/F_2 ratio is consistent with vertex factorisation
  => $F_2^{LN(3)}$ is interpreted in terms of pion structure function F_2^{π} and compared to different parameterizations of F_2^{π}

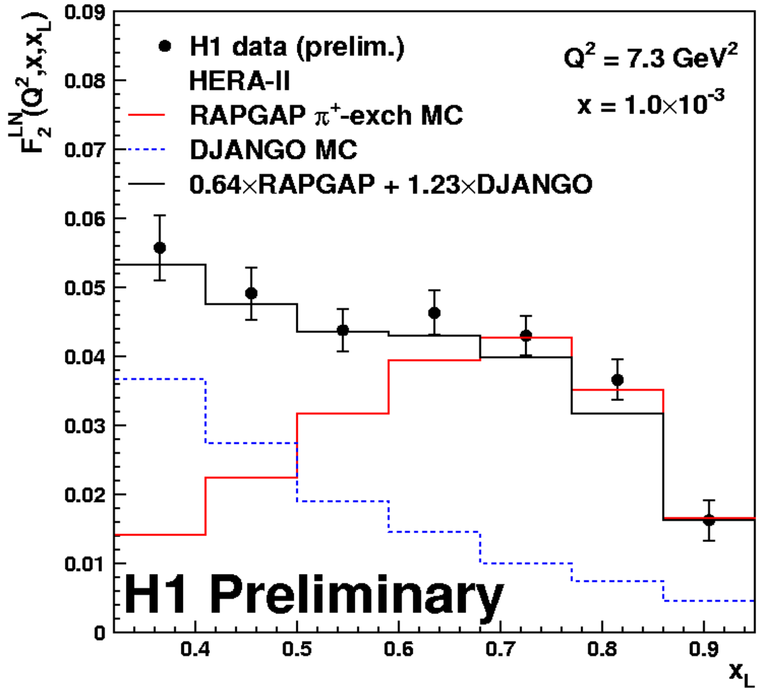
- **Standard fragmentation models do not describe leading neutron production**

- **Models with virtual particle exchange describe data much better: x_L shape and magnitude are OK but p_T slopes are still off**

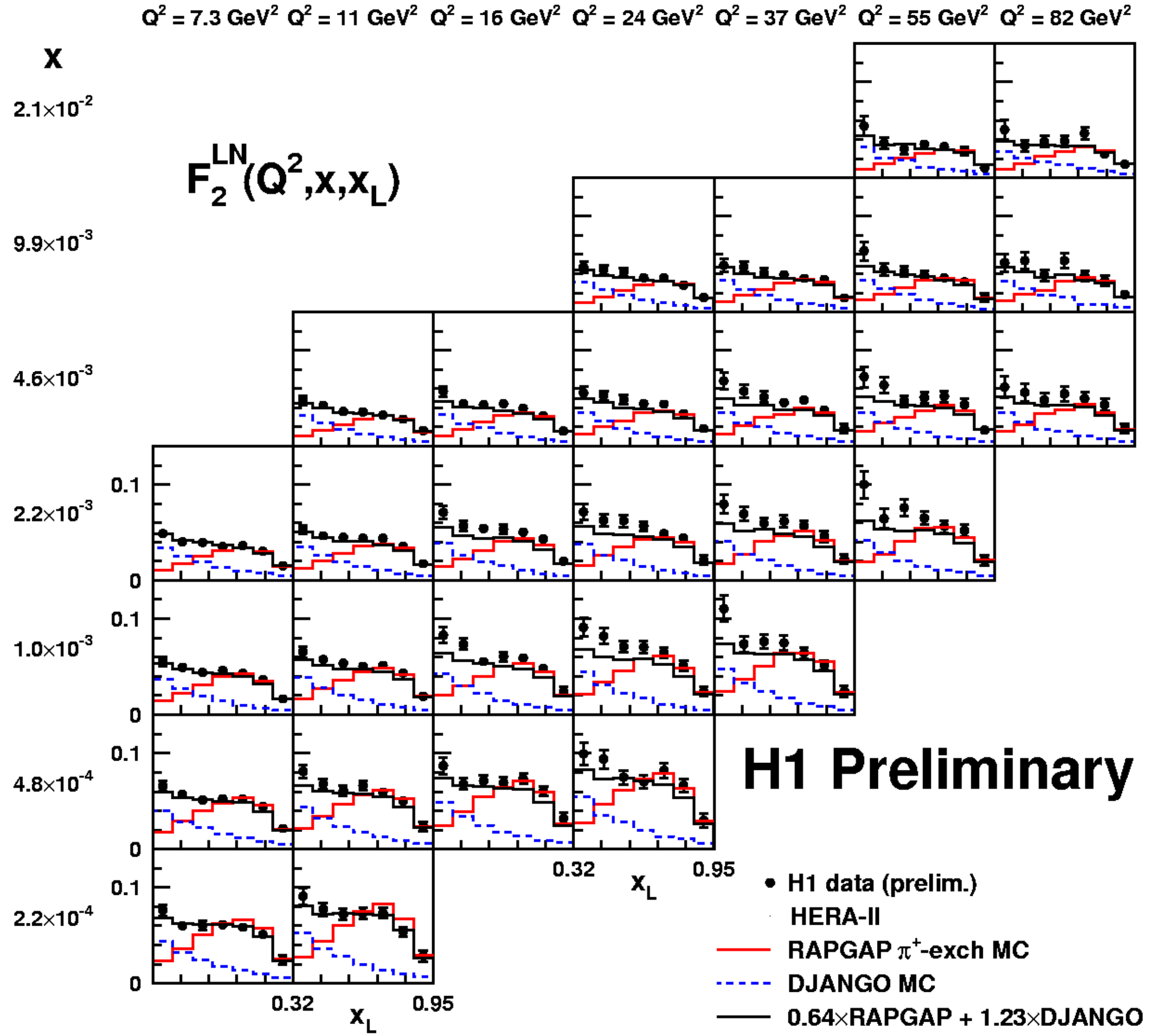
- **Account for absorption and (ρ,a_2) exchanges => promising agreement with data**

Backup

Backup



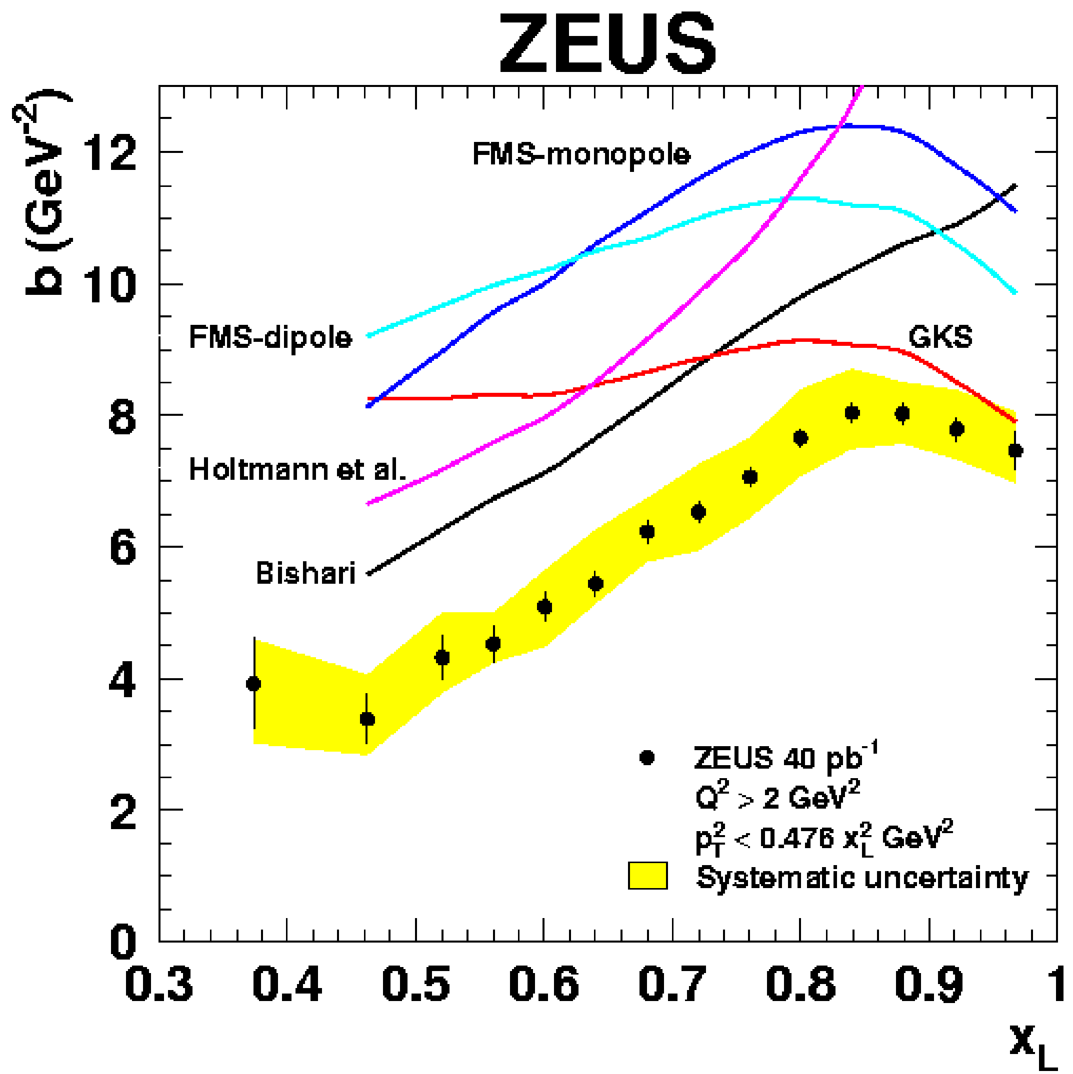
H1 data (prelim.)
HERA-II
RAPGAP π+-exch MC
DJANGO MC
0.64×RAPGAP + 1.23×DJANGO
Q² = 7.3 GeV²
x = 1.0×10⁻³
H1 Preliminary
F2LN(Q²,x,xL)
xL



Q² = 7.3 GeV² Q² = 11 GeV² Q² = 16 GeV² Q² = 24 GeV² Q² = 37 GeV² Q² = 55 GeV² Q² = 82 GeV²
x
2.1×10⁻²
9.9×10⁻³
4.6×10⁻³
2.2×10⁻³
1.0×10⁻³
4.8×10⁻⁴
2.2×10⁻⁴
F2LN(Q²,x,xL)
H1 Preliminary
0.32 xL 0.95
H1 data (prelim.)
HERA-II
RAPGAP π+-exch MC
DJANGO MC
0.64×RAPGAP + 1.23×DJANGO

Model comparisons: DIS slopes

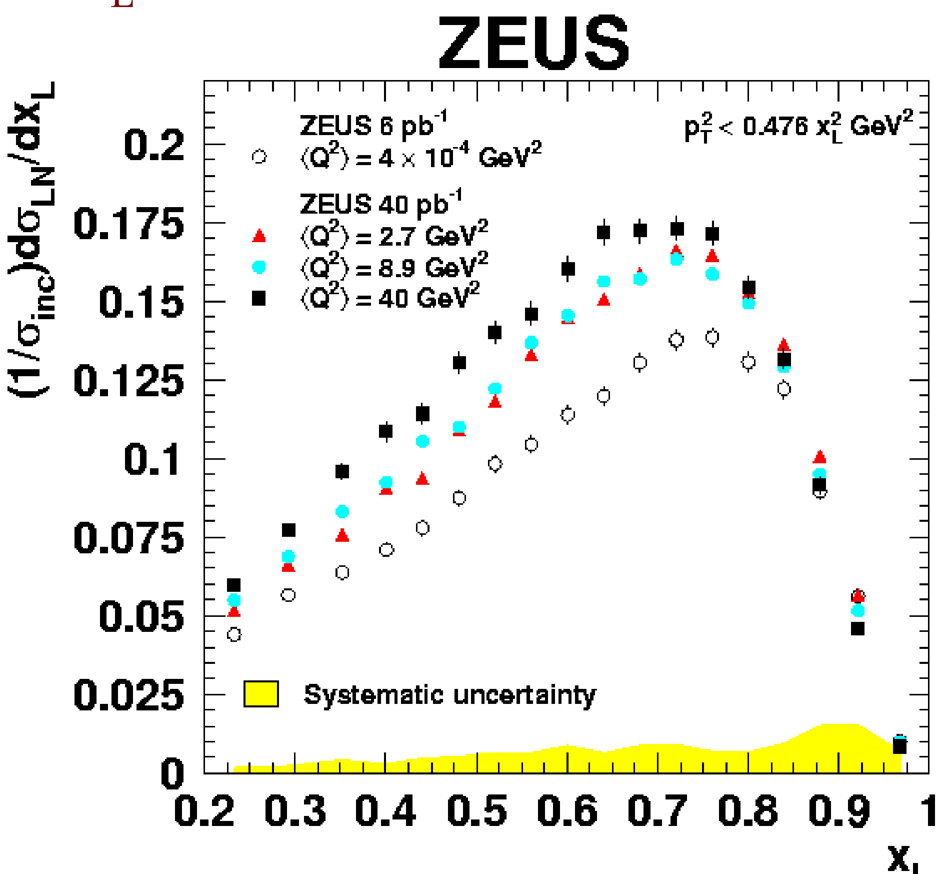
- Numerous parameterizations of pion flux $f_{\pi/p}(x_L,p_T)$ in literature
- Here compare to measured DIS $b(x_L)$:
- Best agreeing models shown here; others wildly off
- All give too large $b(x_L)$
- More refinement needed: absorption/migration



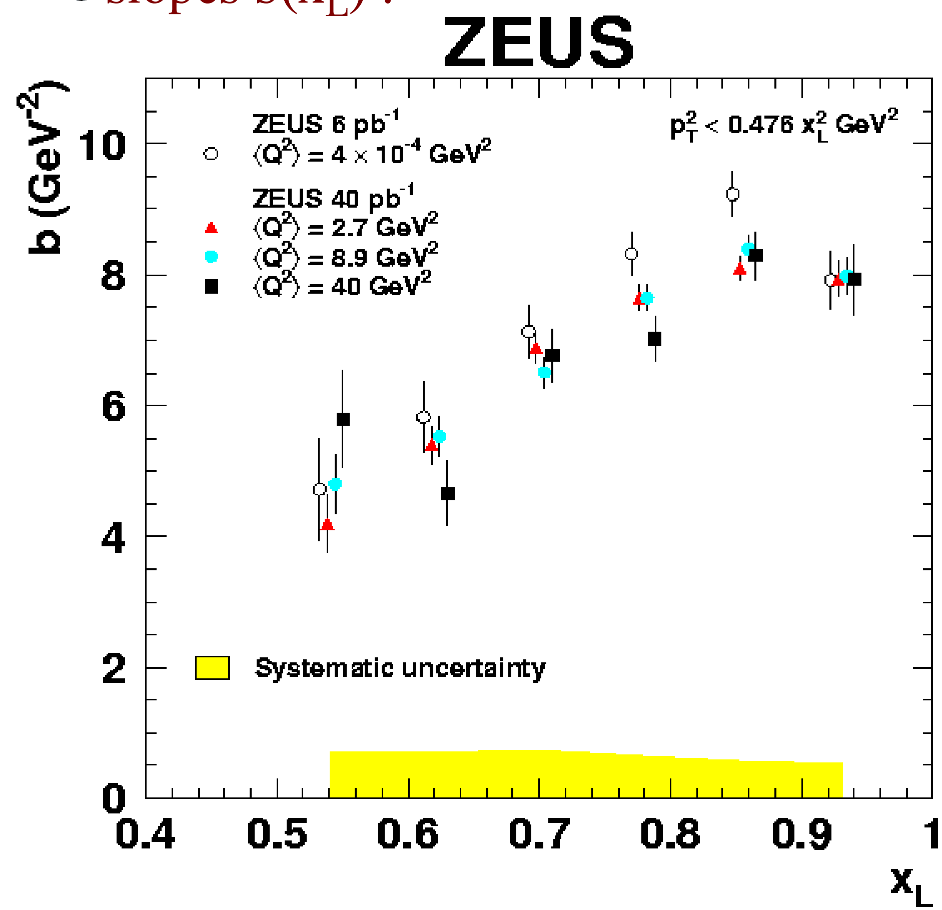
Q^2 dependence of LN production

3 Q^2 bins in DIS + 1 Q^2 bin in γp

- x_L distributions:



- slopes $b(x_L)$:



- LN yield increases monotonically w/ Q^2
- Consistent with absorption:
  larger Q^2 => smaller γ^* less absorption

- Slopes for 3 Q^2 approx. same
- Slope for γp significantly larger

Compare php/DIS and