Leading Baryon production at HERA

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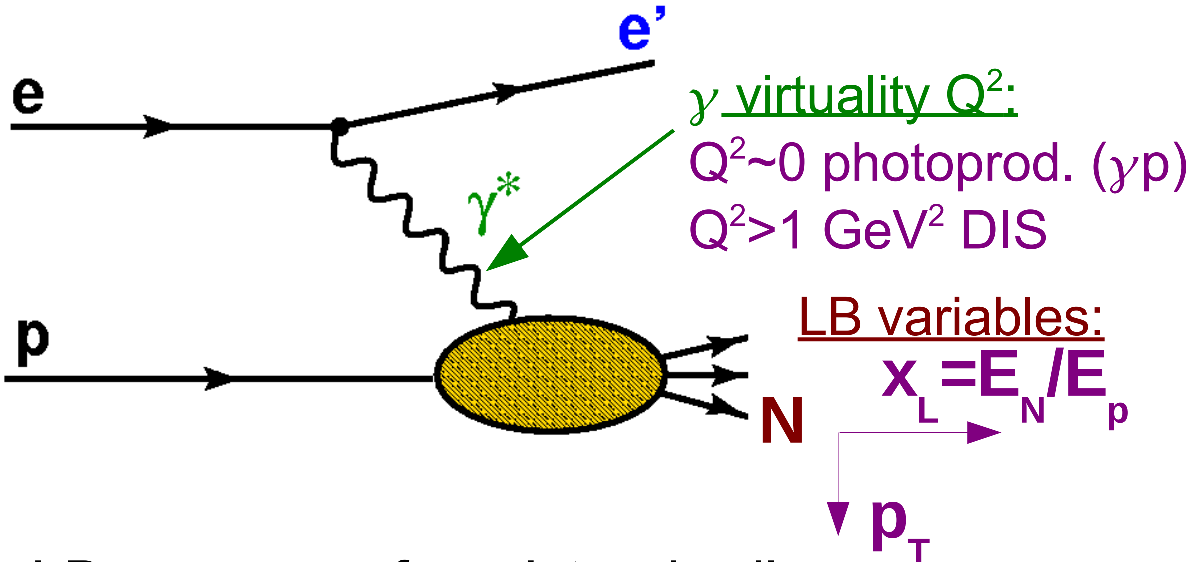
BNL seminar 07.04.10

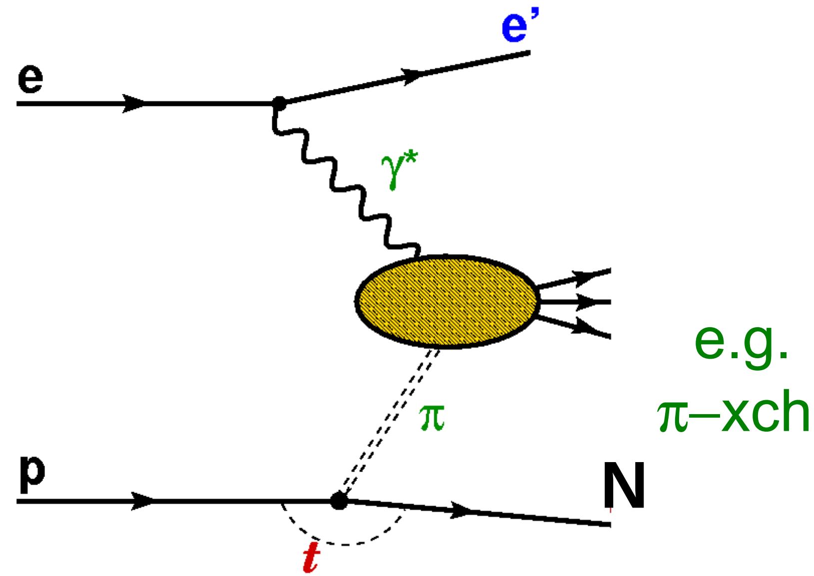
Outline LB proton (LP) and neutron (LN) production:

- Motivations: LB production, virtual particle exchange, rescattering
- Detectors: ZEUS @ HERA; LP&LN detectors, resolutions, acceptances
- Data sets: DIS, photoproduction (γp), dijets in γp; LB measurement
- LB in DIS & γp: energy, p_T distributions
- Comparison: LB in MC models, w/ & w/o virtual particle exchange
- LB production Q^2 dependences
- Comparison: LN π-xch. models with rescattering
- Comparison: LN in DIS & γp+jj (high E_T dijets)

Not discussed here: diffraction, LP with $E_p' \approx E_p$

Motivations: LB production, virtual exchange





- LB can come from 'standard' fragmentation
  (baryon # has to go somewhere)

Compare LP↔LN (x_L,p_T^2) data↔data

Compare LB (x_L,p_T^2) data to:

- **MC fragmentation models**
- **Exchange model parameterizations**

- LB can be produced via exchange of virtual particles: isovector (*p*&*n*) and isoscalar (*p* only).
- Cross section factorizes:

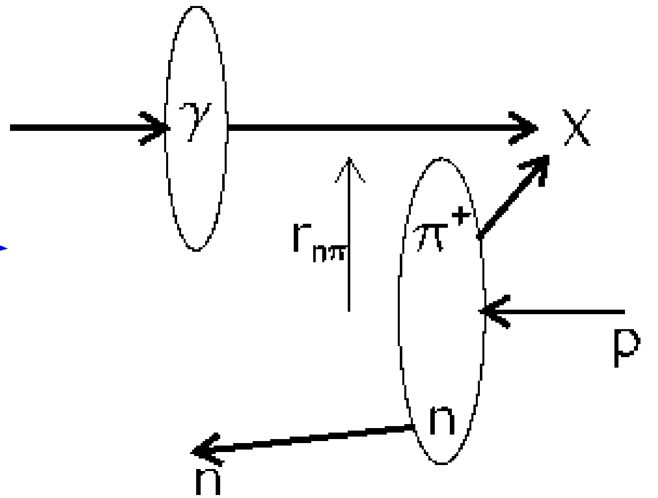
$$\sigma_{ep\rightarrow eNX}(x_L,p_T^2) = f_{\pi/p}(x_L,p_T^2) \times \sigma_{e\pi\rightarrow eX}$$

- Flux $f_{\pi/p}$ params. from low energy hadronic data.

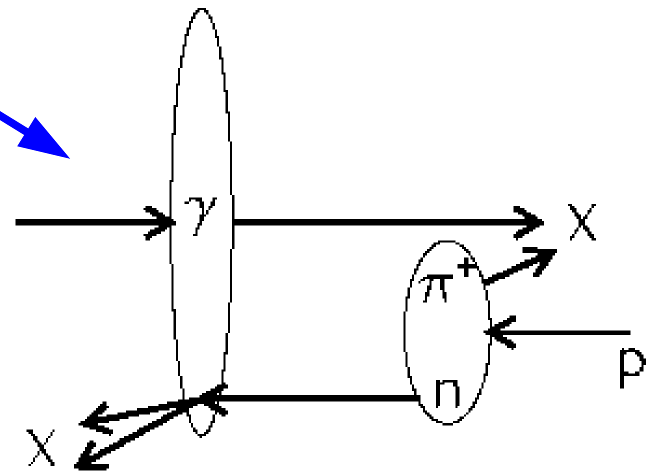
Motivations: Rescattering

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 n may 'rescatter' on γ: n kicked to lower x_L & higher p_T (migration) and may escape detection (rescattering loss)



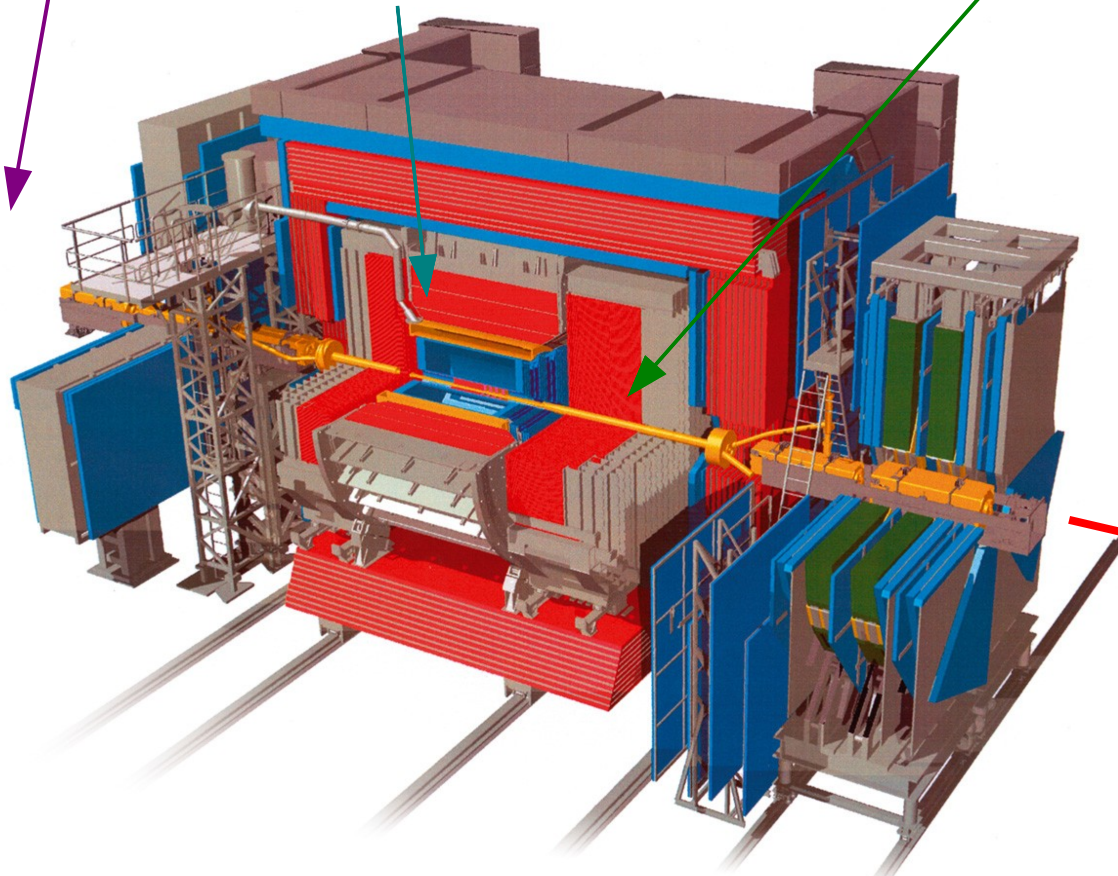
Compare data↔data (x_L,p_T^2) distributions:

- **Vary Q^2 (γ size) in DIS; compare DIS↔γp (Q^2=0)**
- **In γp reintroduce hard scale with hi E_T dijets**

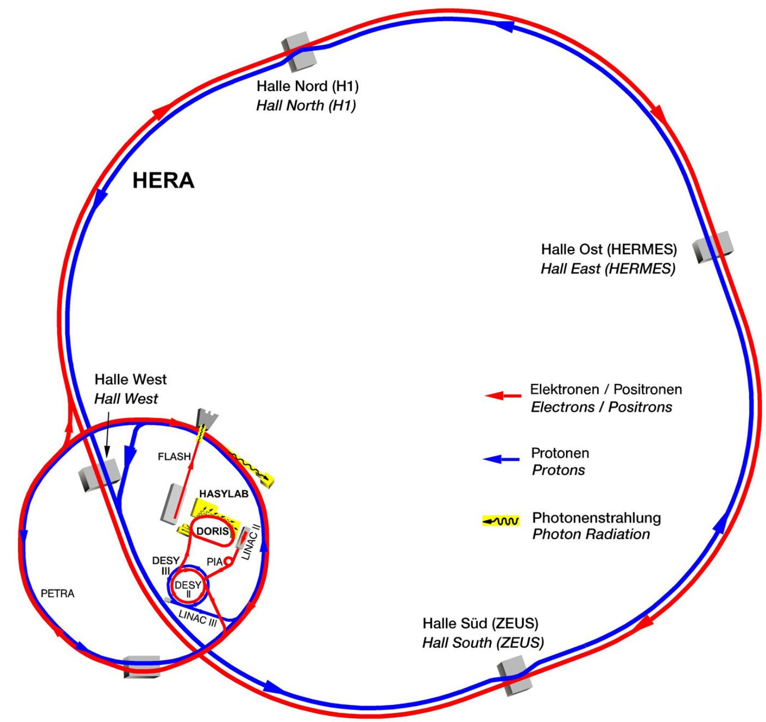
Compare data↔ MC models: particle exchange w/ rescattering

HERA Collider & ZEUS Detector:

- ZEUS:
  General purpose collider detector
  U-Sci calorimeter, solenoid field tracking
  For these results:
- DIS: scattered *e* in U-Sci calorimeter
- γp: scattered *e* in tagger
- γp+dijets: jets in U-Sci calorimeter



- HERA: 920 GeV $p \times$ 27.6 GeV e

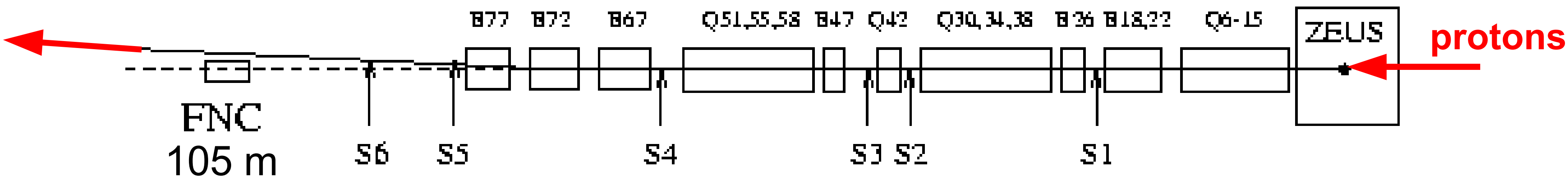


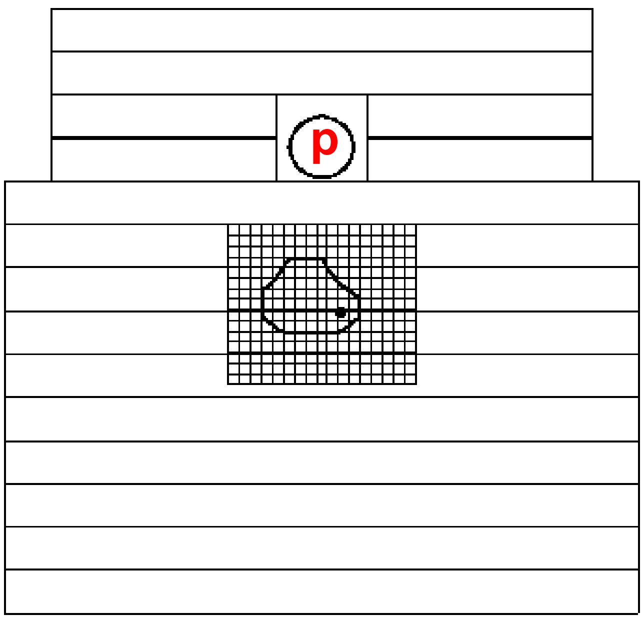
LB:
forward detectors in HERA tunnel
p direction

LB Detectors:

HERA beamline in *p* direction from ZEUS: Vertical dipole acts as

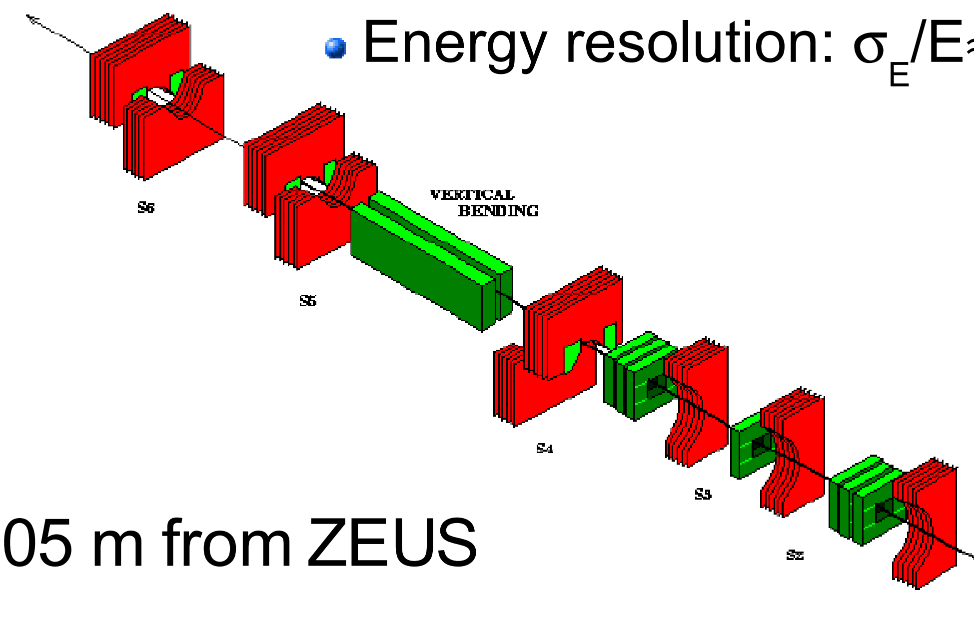
- Analyzing magnet for Leading Proton Spectrometer (LPS) for LP
- Sweeping magnet for Forward Neutron Calorimeter (FNC) for LN





LPS: Si-strip detectors

- Energy resolution: $\sigma_E/E \approx < 1\%$

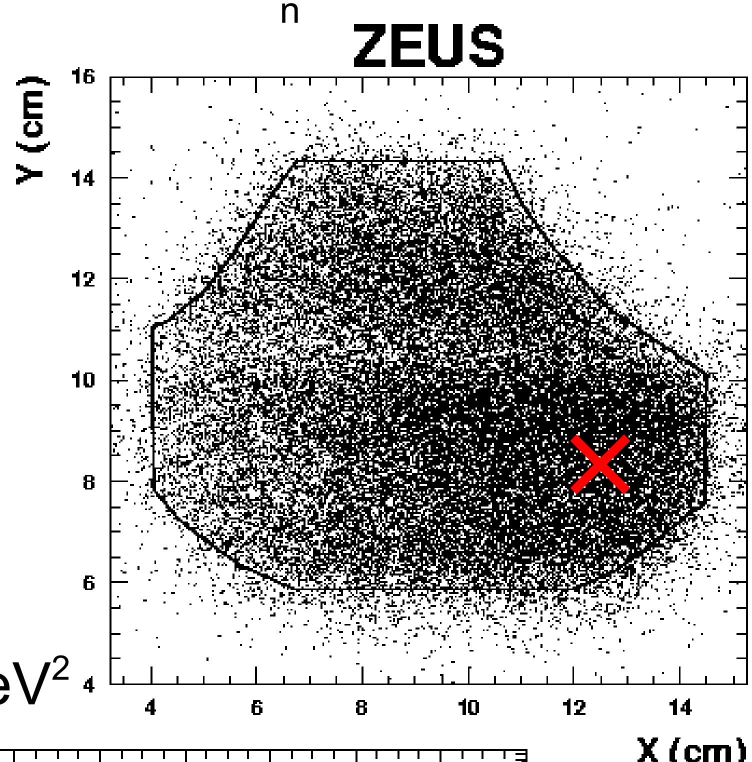


FNC: Pb-Sci calorimeter @ 0° 105 m from ZEUS

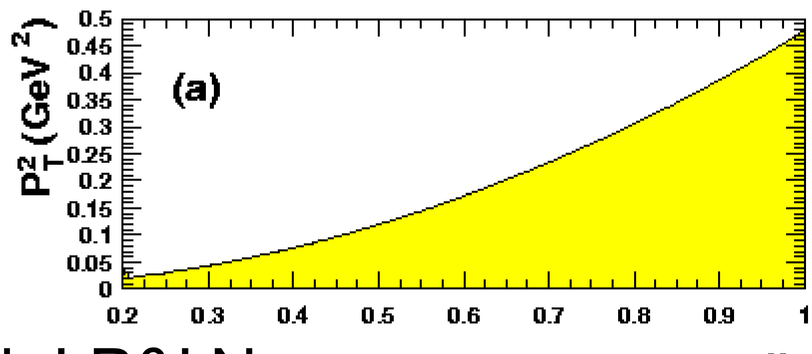
- Energy resolution: $\sigma_E/E \approx 0.7/\sqrt{E}$
- Sci-hodoscope position detector $1\lambda_I$ into FNC

Detector acceptances

- Magnet apertures limit Θ_n<0.75 mrad
- Scatter plot neutron hits:



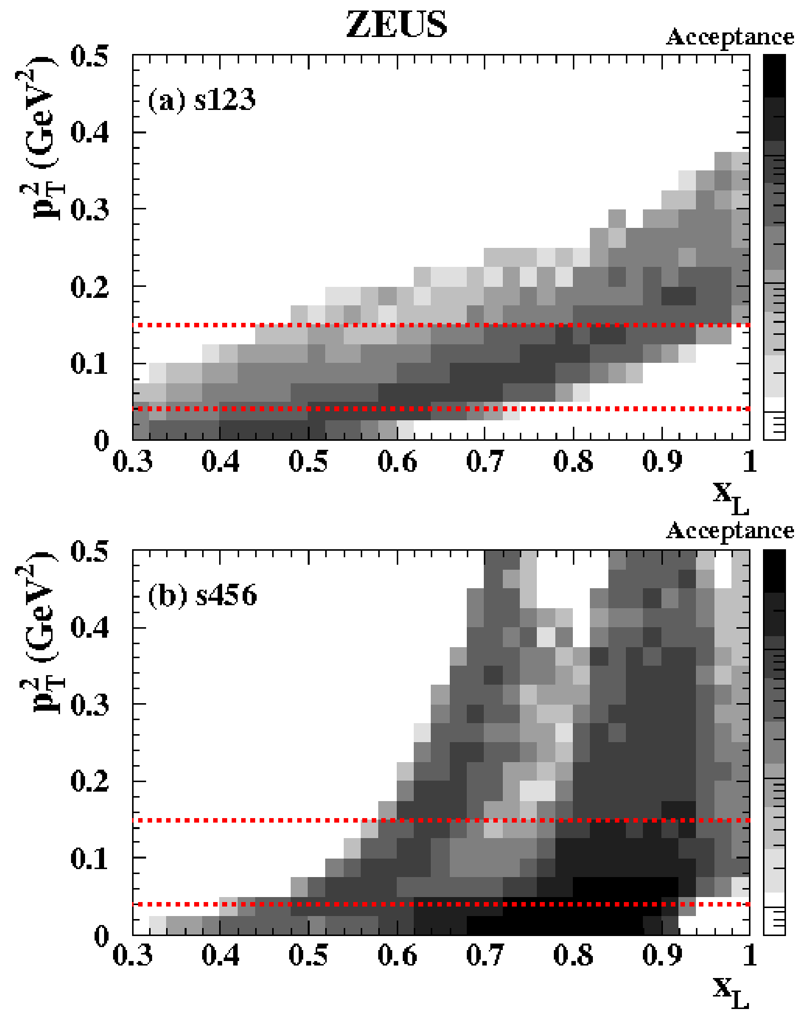
- p_T^2<0.476 x_L^2 GeV^2



<u>Both LP&LN:</u>

- p_T resolution dominated by proton beam p_T spread; σ_{PT}~50-100 x_L MeV

- LPS different acceptance first/last 3 detector station
- Acceptance ~p_T^2<0.5 GeV^2 for xL>0.7



Data sets, LB measurement

LB are selected from inclusive data sets (i.e. no LB tag):

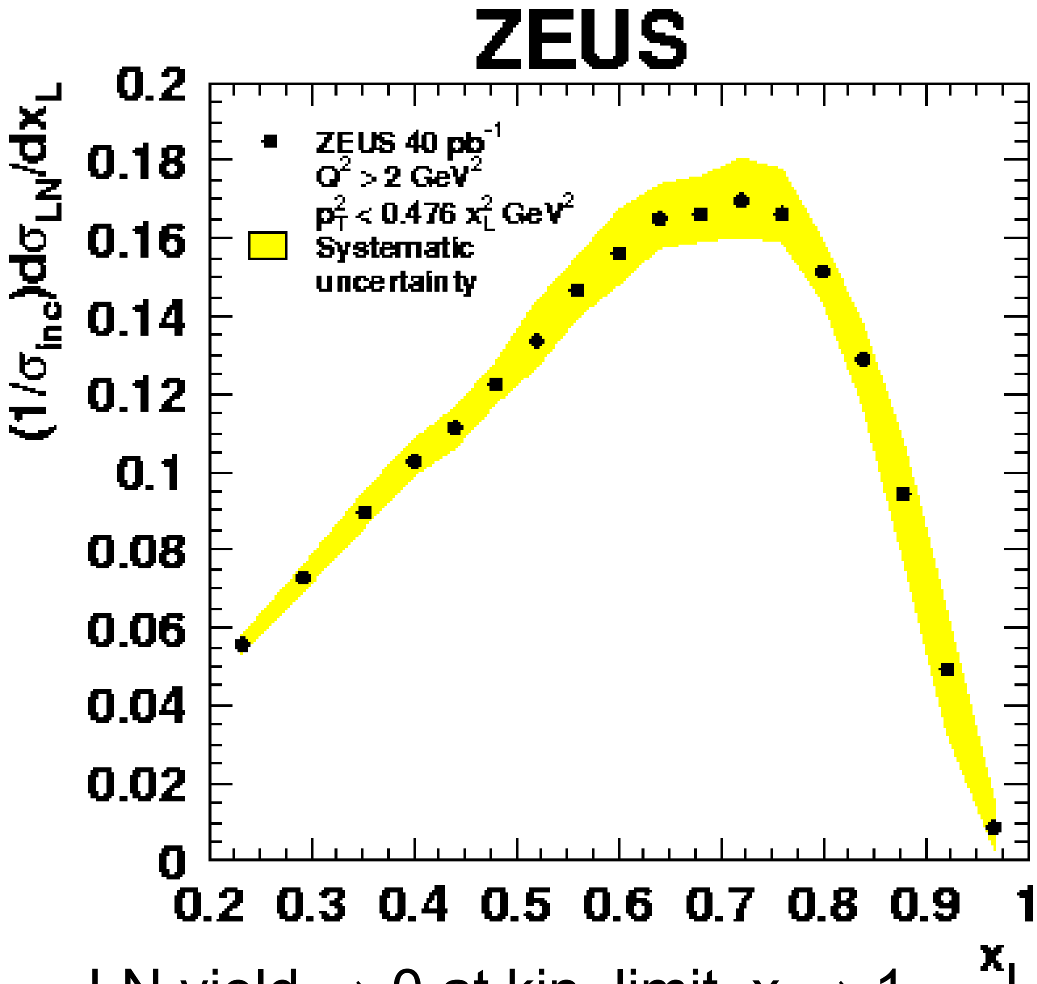
- DIS: $Q^2 > 2\text{-}3$ GeV^2, $\langle Q^2 \rangle \approx 13$ GeV^2; subsets with various $\langle Q^2 \rangle$
- γp: $Q^2 < 0.02$ GeV^2, e^+ tagged $\Rightarrow$ $150 < W_{\gamma p} < 270$ GeV
- γp+dijets: $Q^2 < 1$ GeV^2, $130 < W_{\gamma p} < 280$ GeV, $E_T^{1(2)} > 7.5(6.5)$ GeV

LB yields:

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

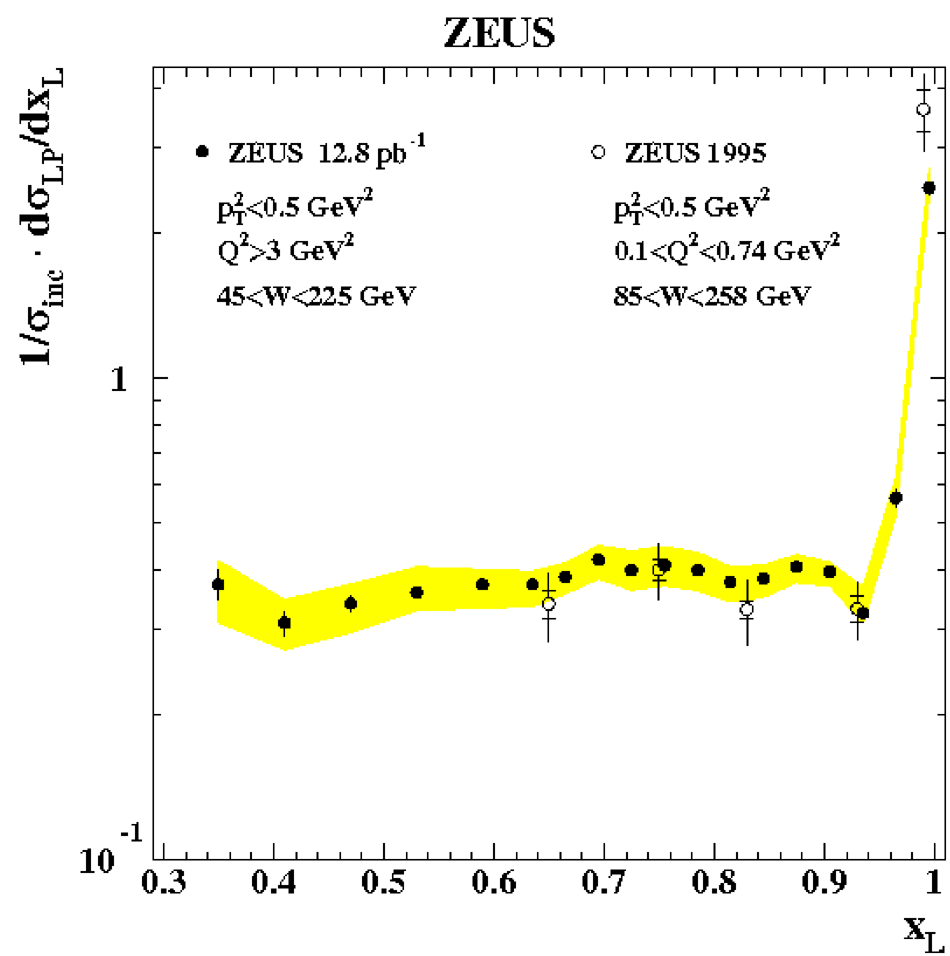
DIS x_L distributions: max. p_T ranges

- LN: $p_T^2 < 0.476\, x_L^2$ GeV^2



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

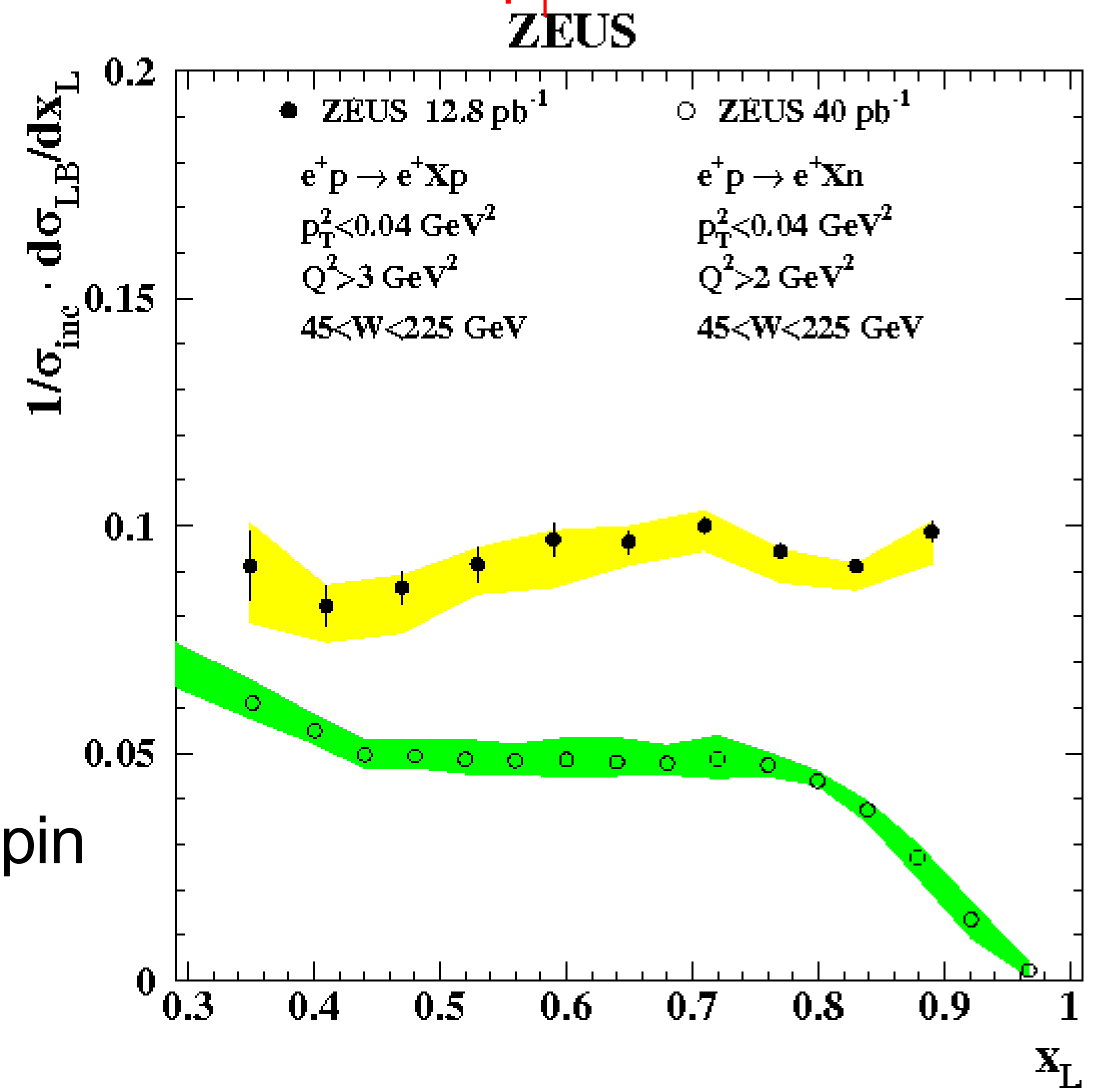
- LP: $p_T^2 < 0.5$ GeV^2



- LP yield diffractive peak $x_L \rightarrow 1$
- Below $x_L \approx 0.95$ yield flat

DIS x_L distributions: same p_T range

- LP/LN: $p_T^2 < 0.04$ GeV^2



Both detectors acceptances overlap at low p_T for $0.35 < x_L < 0.9$:

- For pure *isovector* exchange isospin Clebsch-Gordan $\Rightarrow r_{LP} = \frac{1}{2} r_{LN}$
- Data: $r_{LP} \approx 2\, r_{LN}$
- $\Rightarrow$ additional exchanges (*isoscalar*) needed for LP

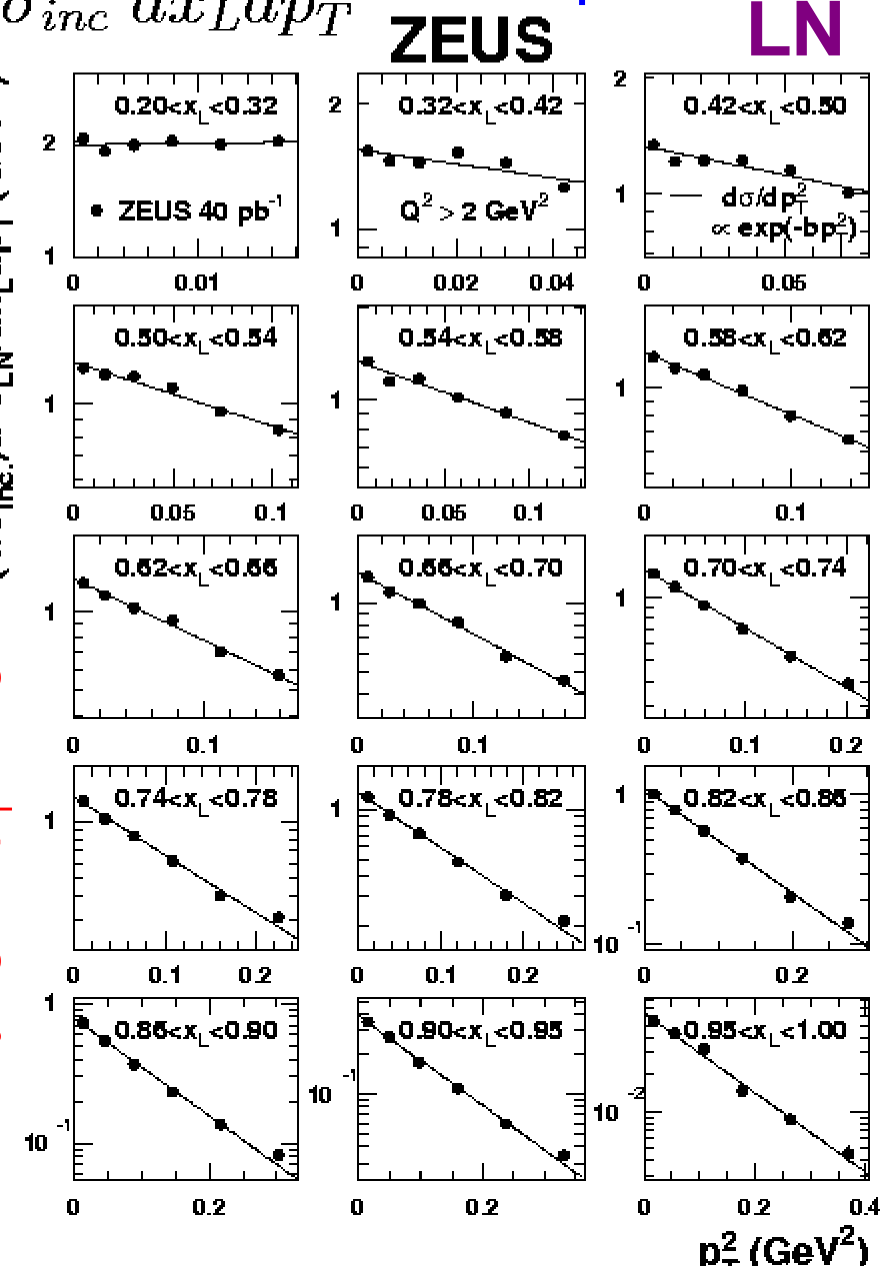
$$\frac{1}{\sigma_{inc}}\frac{d^2\sigma_{LN}}{dx_L dp_T^2}$$

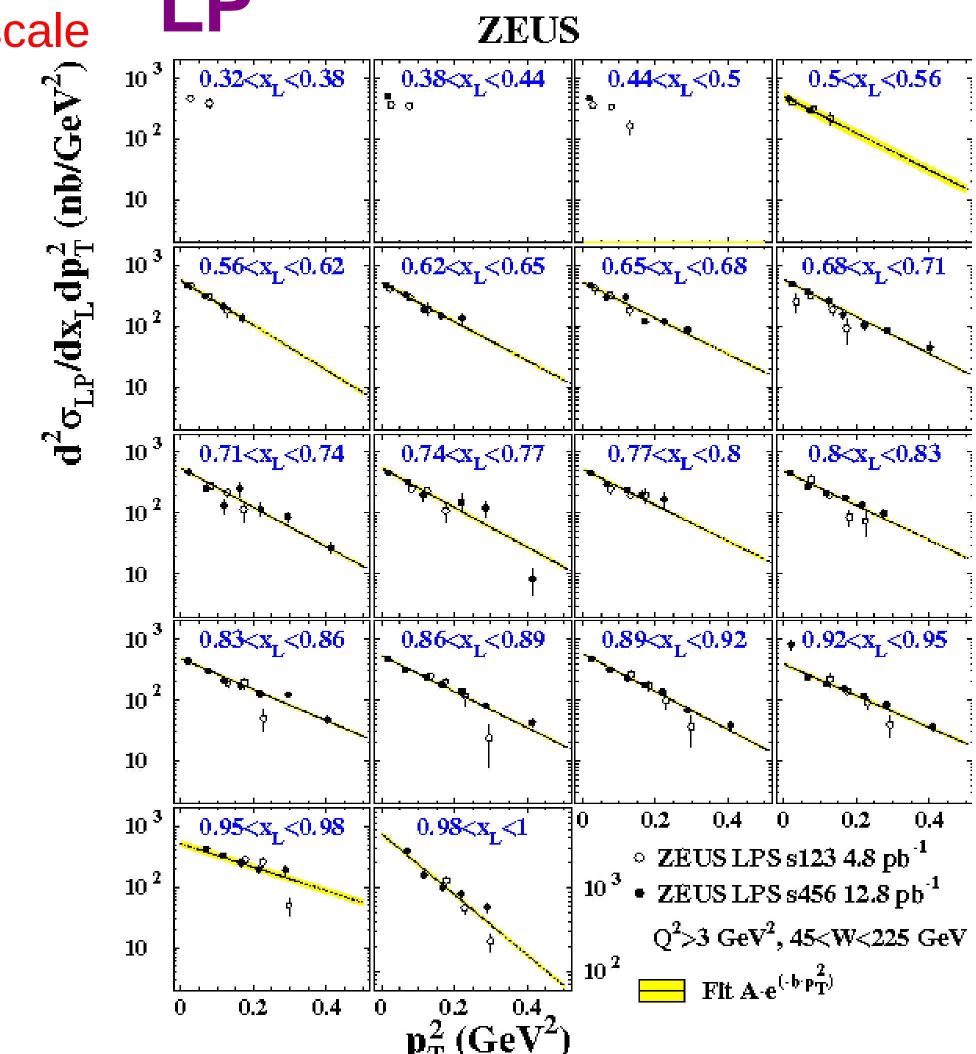
p_T^2 distributions DIS

LN

log scale

LP





note varying LN p_T^2 ranges

- Described by exponential in p_T^2:

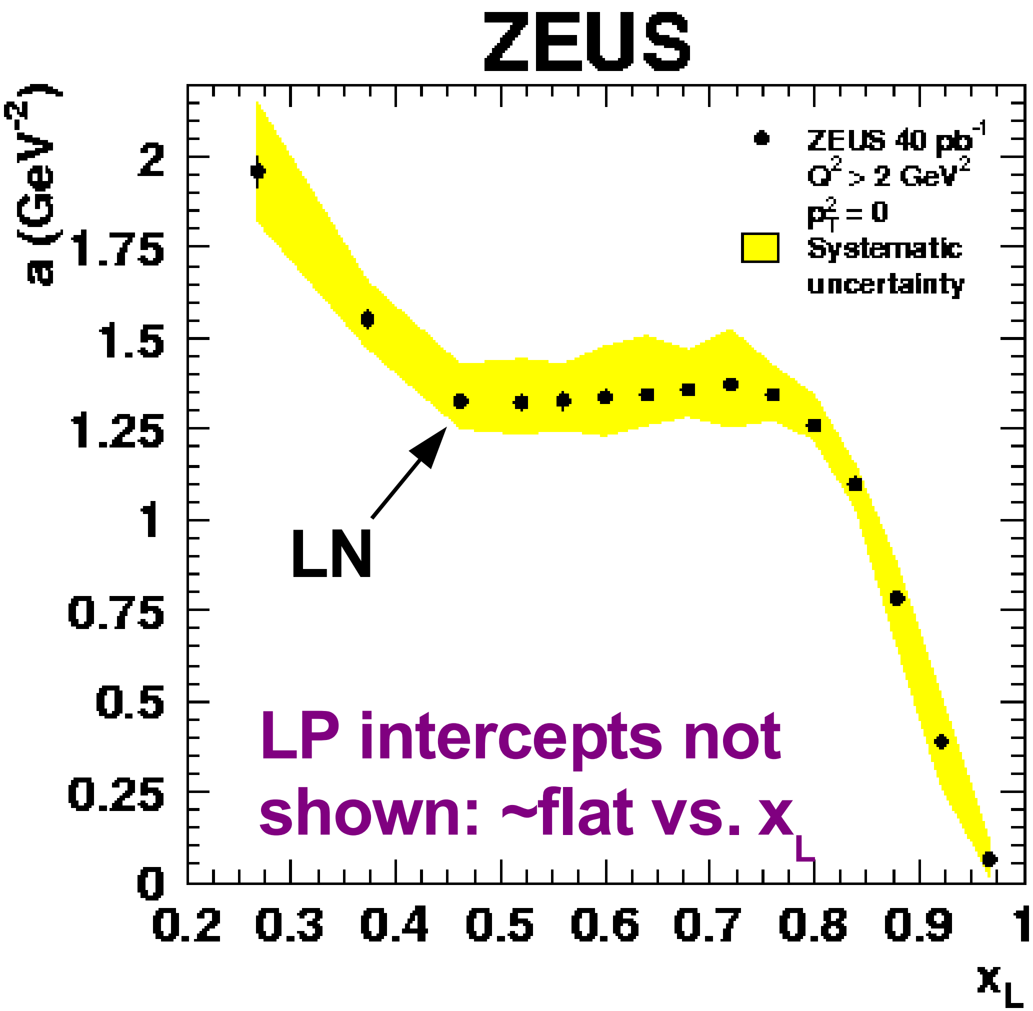
$$\frac{1}{\sigma_{inc}}\frac{d^2\sigma_{LN}}{dx_L dp_T^2} = a(x_L)e^{-b(x_L)p_T^2}$$

- Intercepts $a(x_L)$ and slopes $b(x_L)$ fully characterize (x_L,p_T^2) dist.

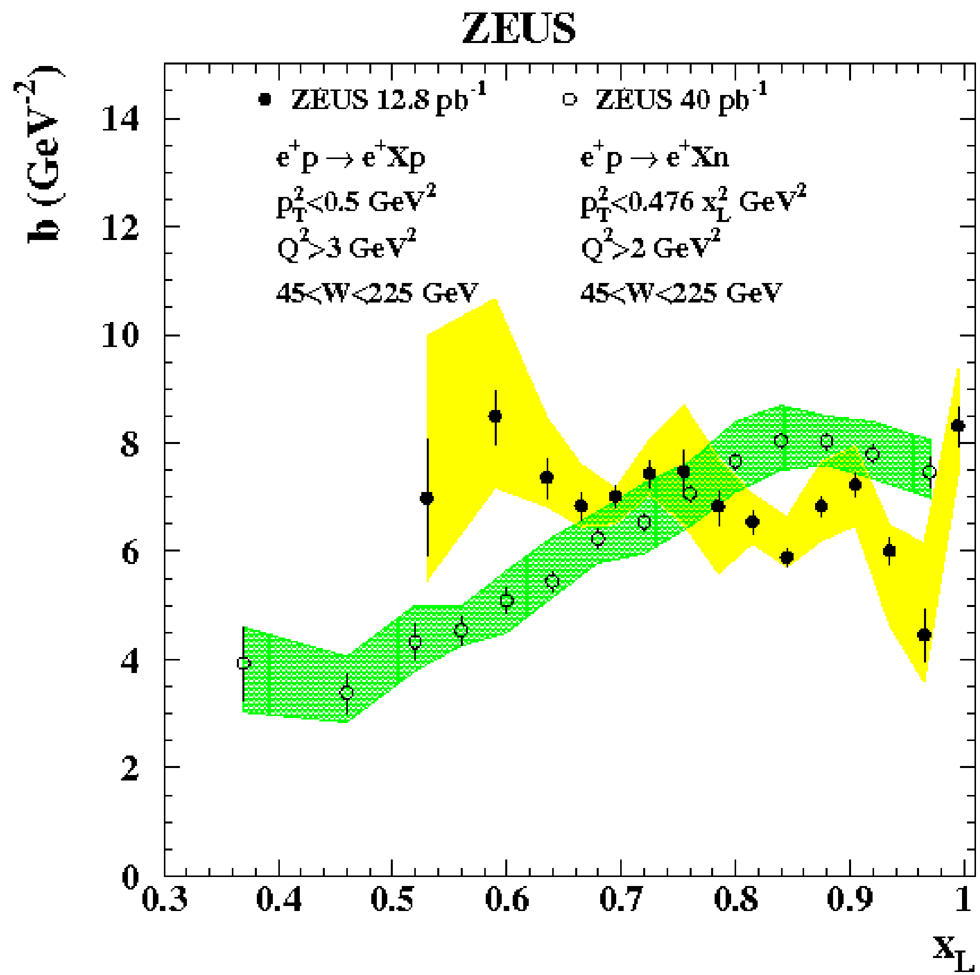
DIS p_T^2 distributions: slopes & intercepts

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

- LN intercepts $a(x_L)$:



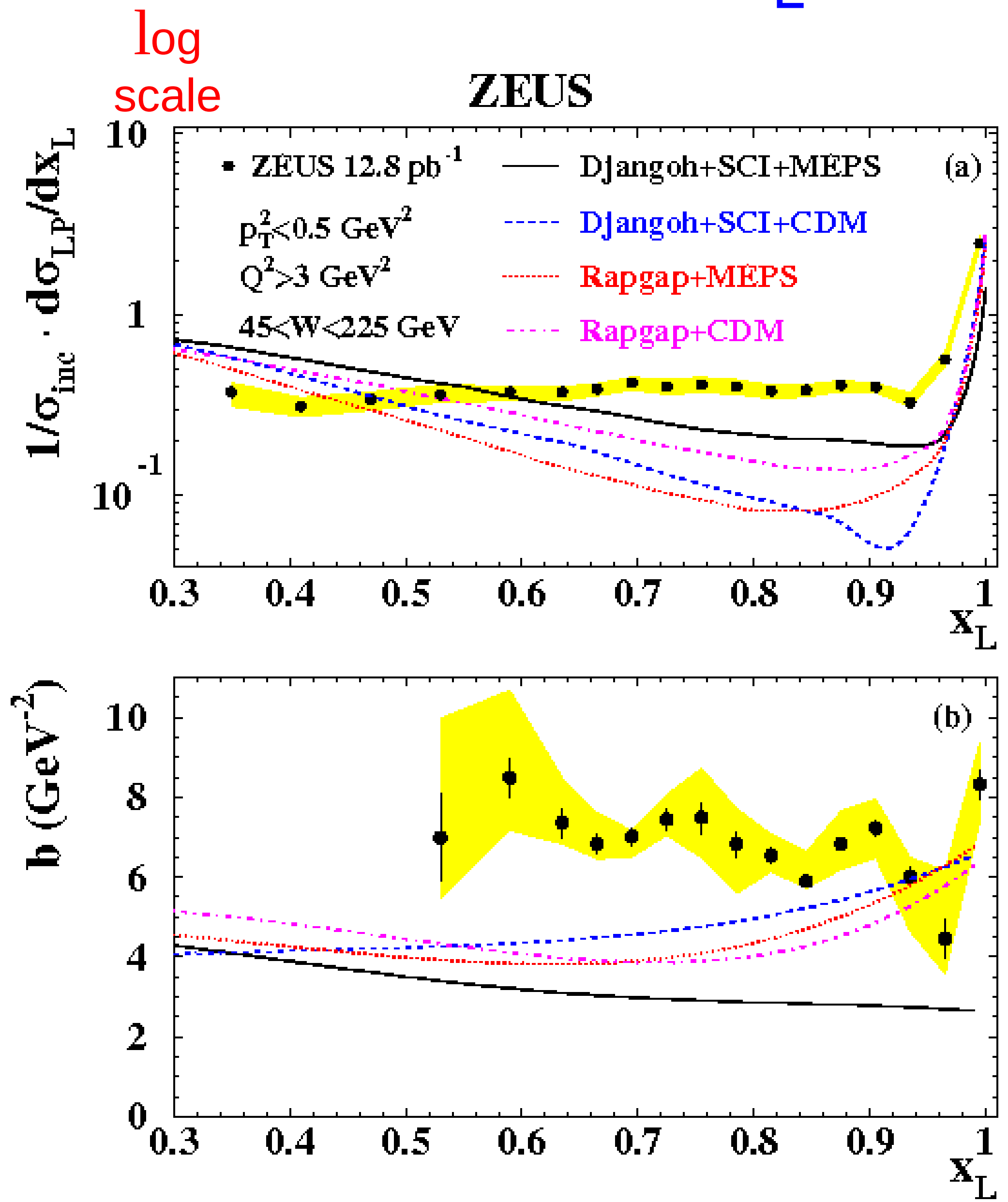
- slopes $b(x_L)$:



- LN intercepts fall with x_L, bump/plateau/shoulder $0.4<x_L<0.8$
- LN slopes sharp rise w/ x_L
- LP slopes ~flat w/ x_L

Model comparisons: DIS LP x_L

'Standard fragmentation' MCs:



- Yields all fall with x_L

  (except diff. peak ~1)

- Not flat like data, fail

- p_T^2 slopes *b* smaller than

  data except highest x_L

- Standard fragmentation MCs do not describe LP (x_L,p_T^2) distributions

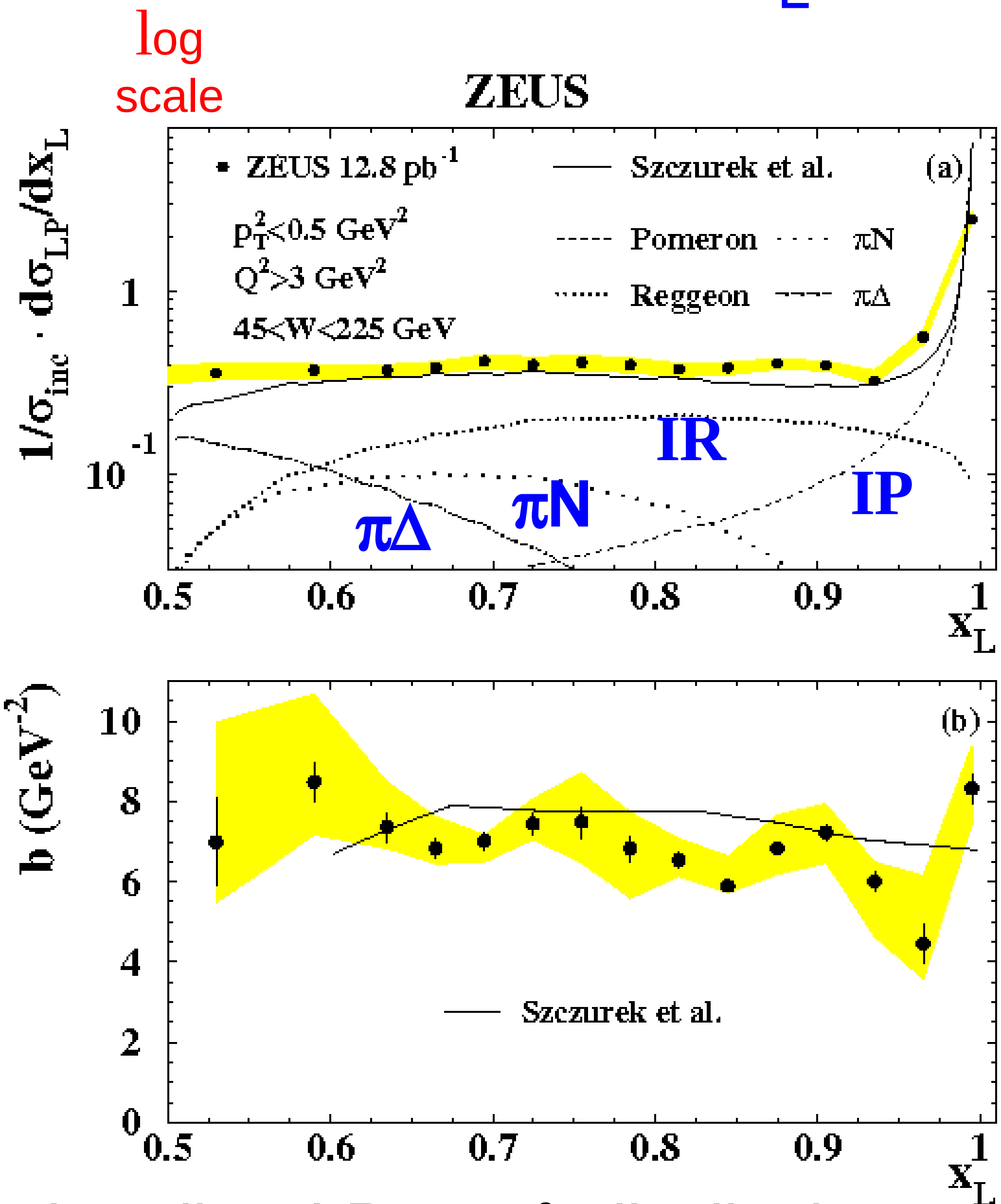
Model comparisons: DIS LP x_L

Model with exchanges of

several isoscalars/vectors:

- Different xch's sum to flat yield as function of x_L

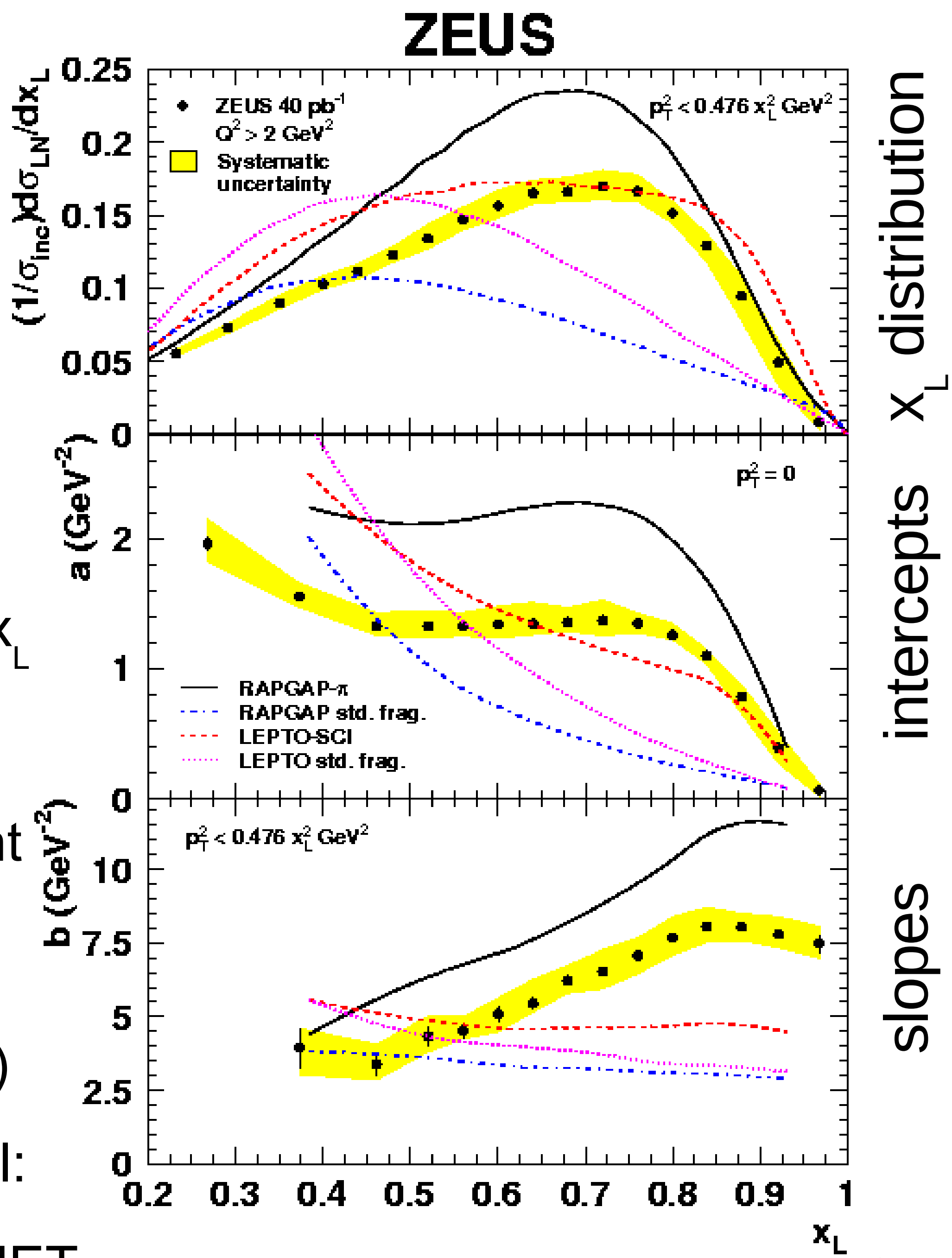
- Different xch's sum to flat yield as function of x_L



- Model with multiple exchanges describes LP (x_L,p_T^2) distributions

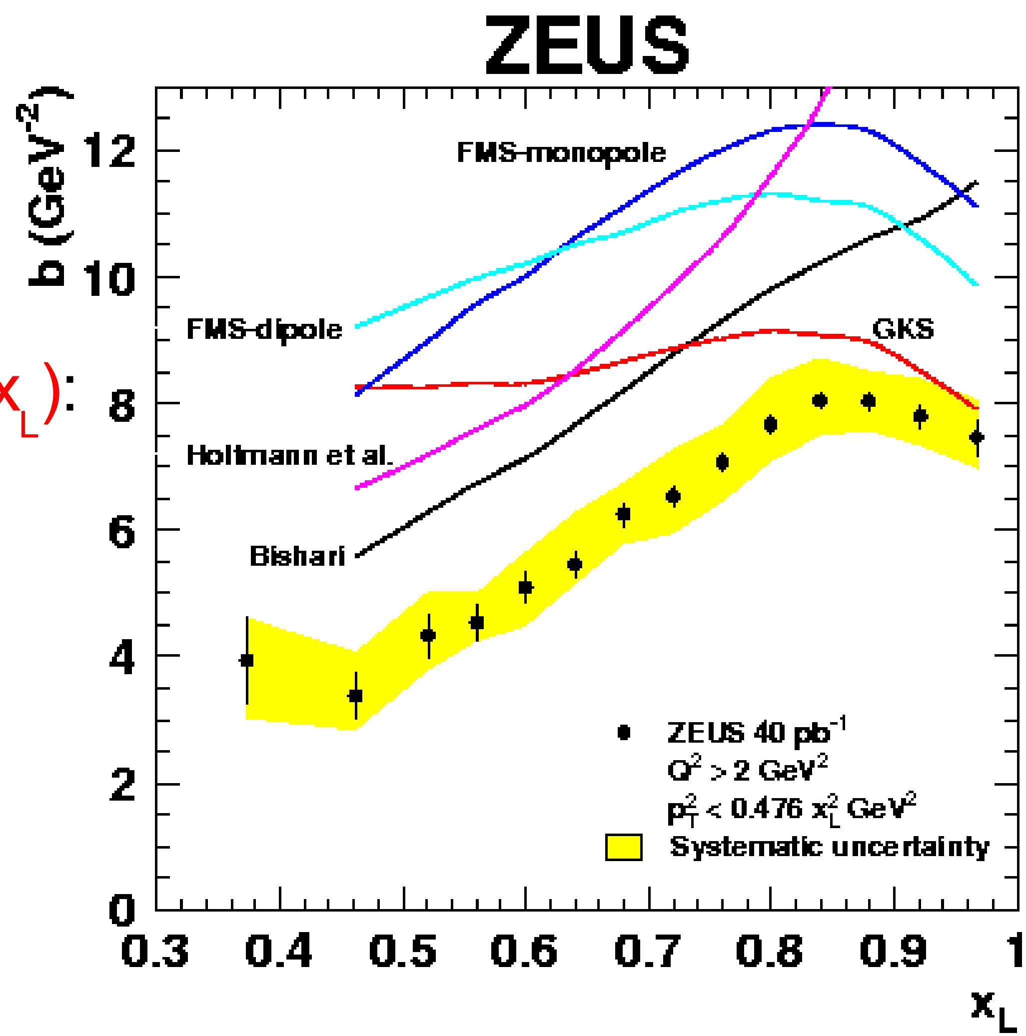
Model comparisons: DIS LN

- Compare to 2 MC models, 2 options:
  - RAPGAP w/ 'std. fragmentation'
  - RAPGAP mixture
    'std. fragmentation' & π-exchange
  - LEPTO w/ 'std. fragmentation'
  - LEPTO w/ soft color interactions
- Both std. frag. too few *n*, peak too low x_L
- LEPTO-SCI ~OK in shape, magnitude,
  but slopes too small, ~not x_L dependent
- **<u>RAPGAP w/ π-xch.</u> closest to data**
  (normalization off, and slopes too high)
- Other DIS, γp std. frag. models also fail:
  ARIADNE, CASCADE, PYTHIA, PHOJET



Compare π-xch. models: DIS LN slopes

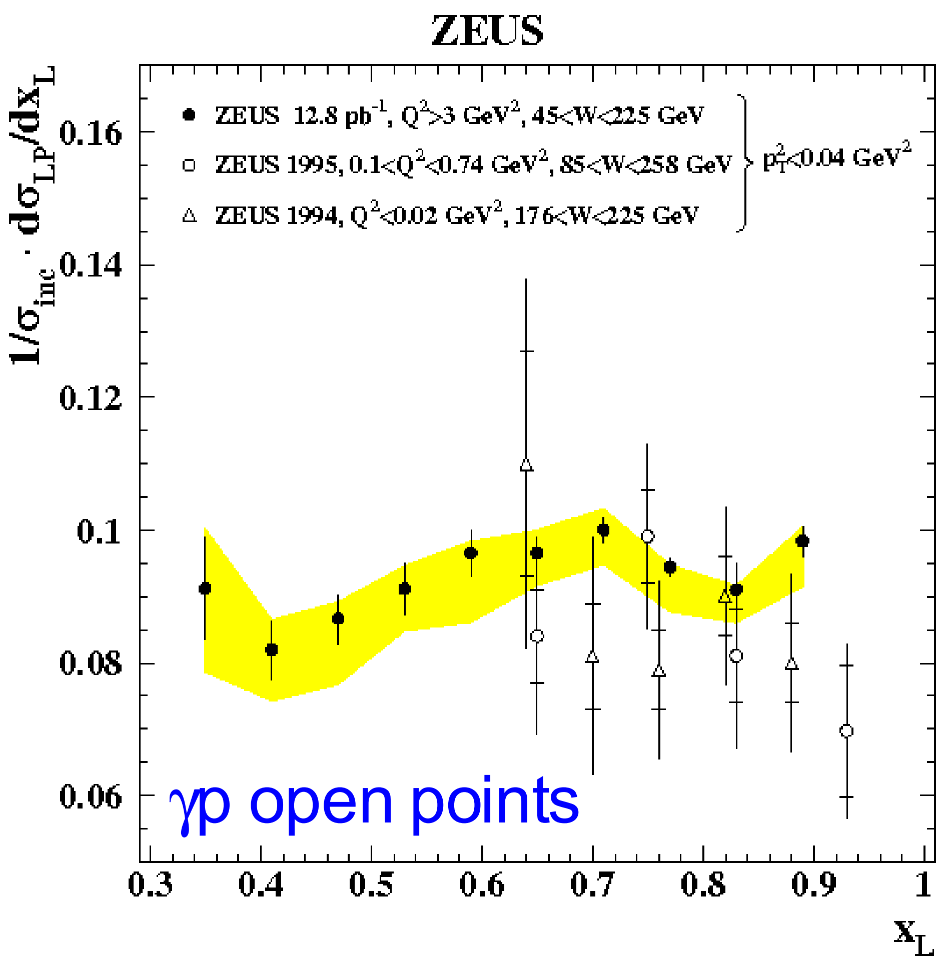
- Numerous parameterizations of pion flux $f_{\pi/p}(x_L,p_T)$ in literature
- Here compare to measured DIS $b(x_L)$:
- Best agreeing models shown here; others wildly off
- All give too large $b(x_L)$
- More refinement needed:
  - $\Rightarrow$ rescattering migration & loss
  - $\Rightarrow$ investigate Q^2 dependences



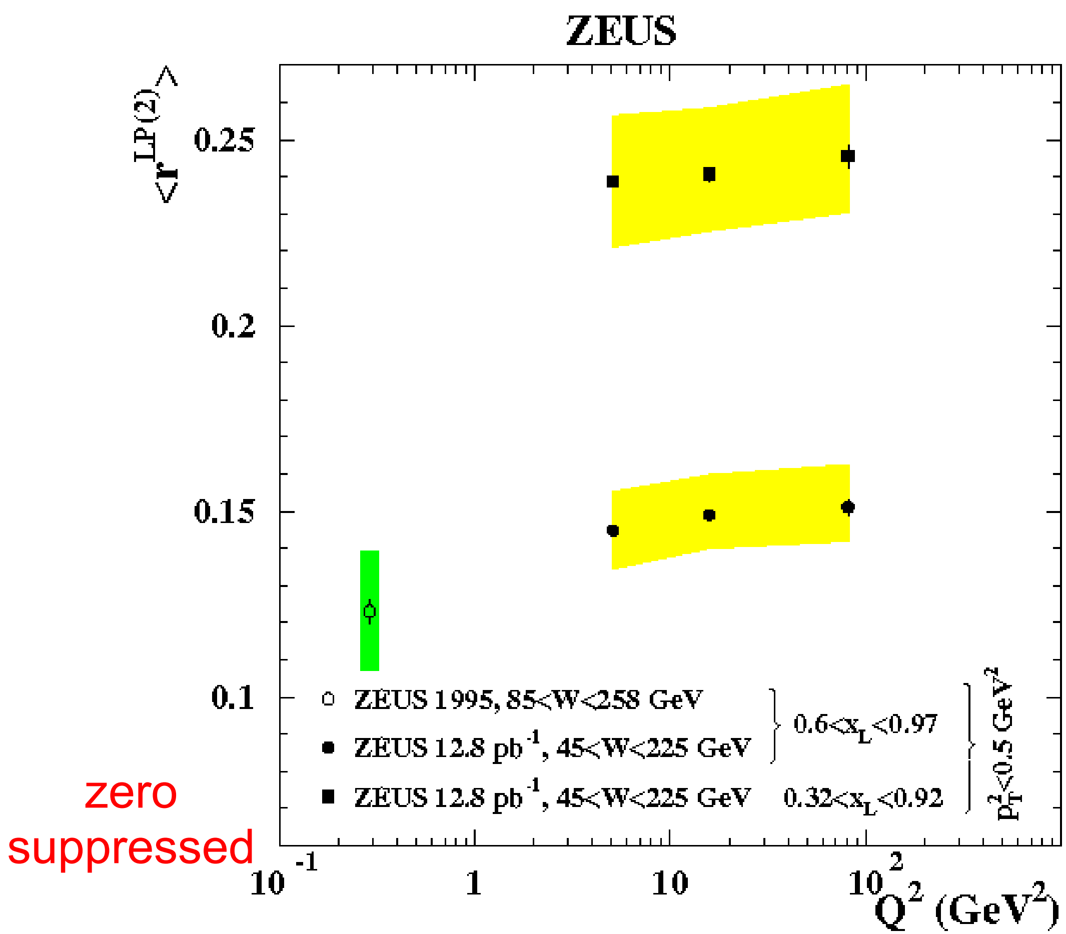
Q^2 dependence of LP production

DIS + γp:

- x_L distributions:



- Total yield x_L ranges:

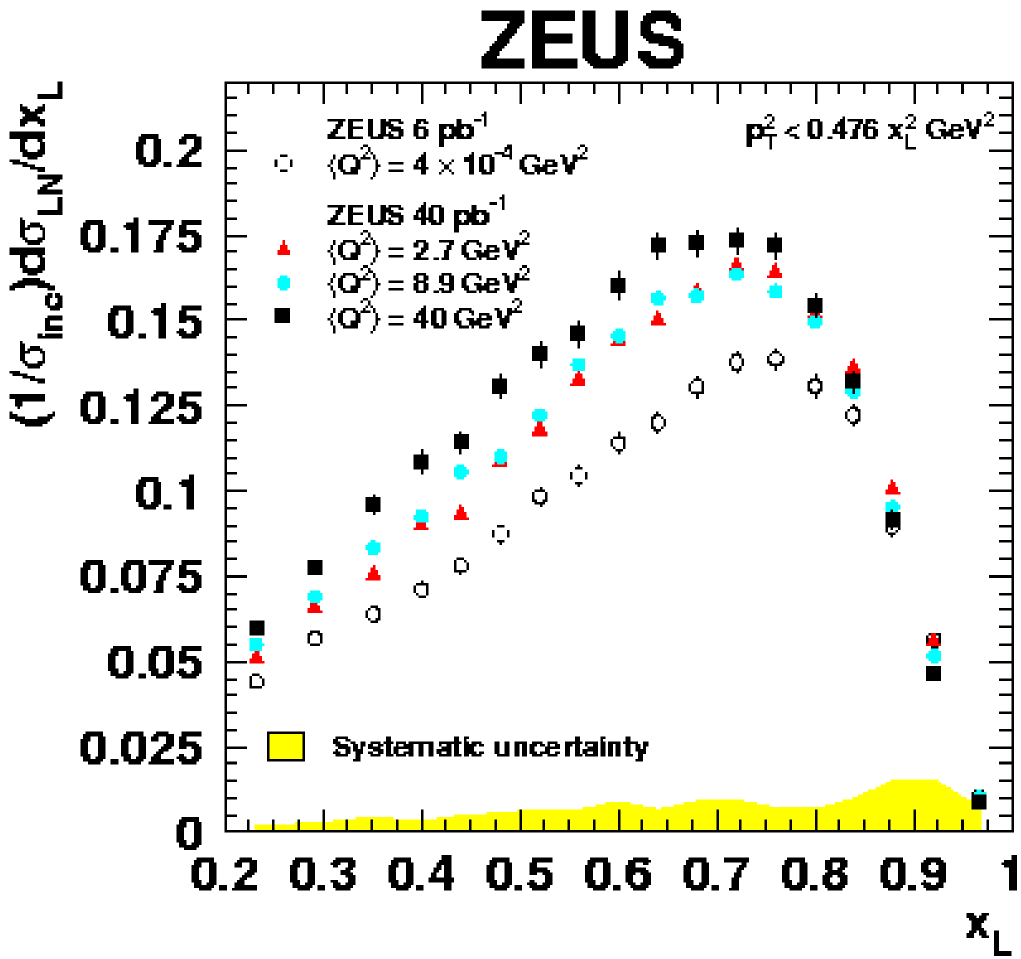


- LP yield increases monotonically w/ Q^2
- Consistent w/ rescattering: larger $Q^2 \Rightarrow$ smaller γ, less rescattering

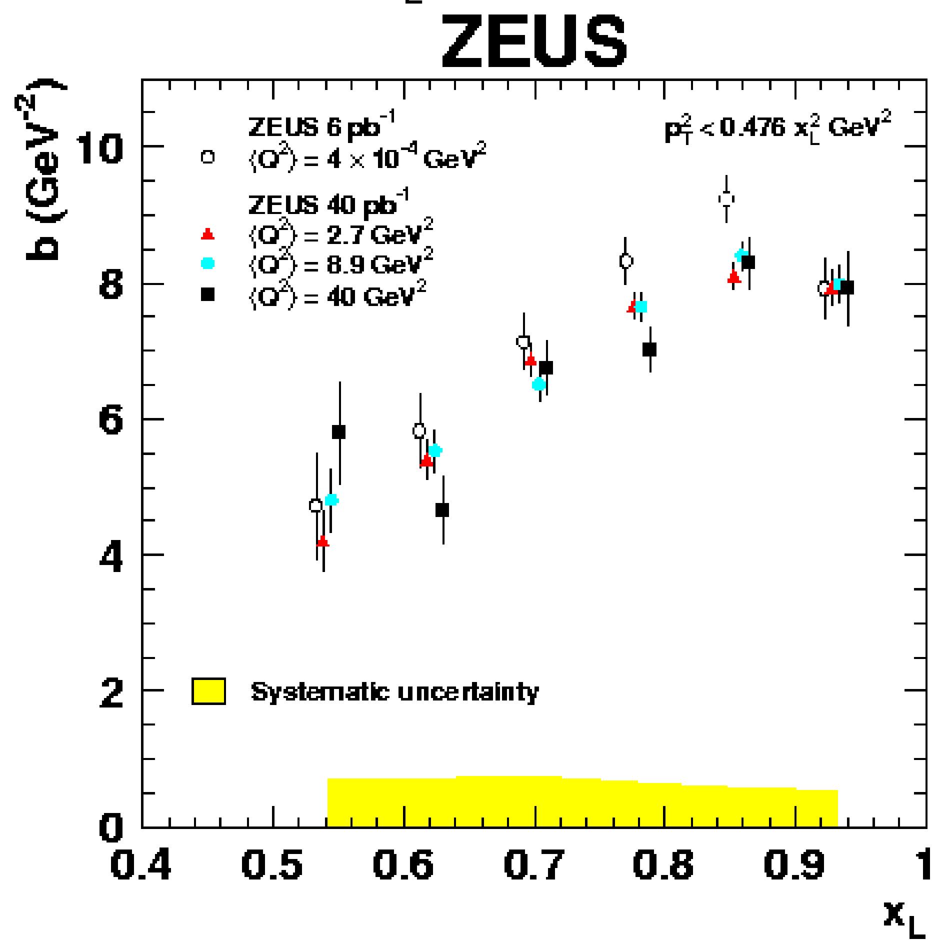
Q^2 dependence of LN production

3 Q^2 bins DIS + γp:

- x_L distributions:



- slopes $b(x_L)$:



- LN yield increases monotonically w/ Q^2
- Consistent w/ rescattering:
  larger $Q^2 \Rightarrow$ smaller γ, less rescattering

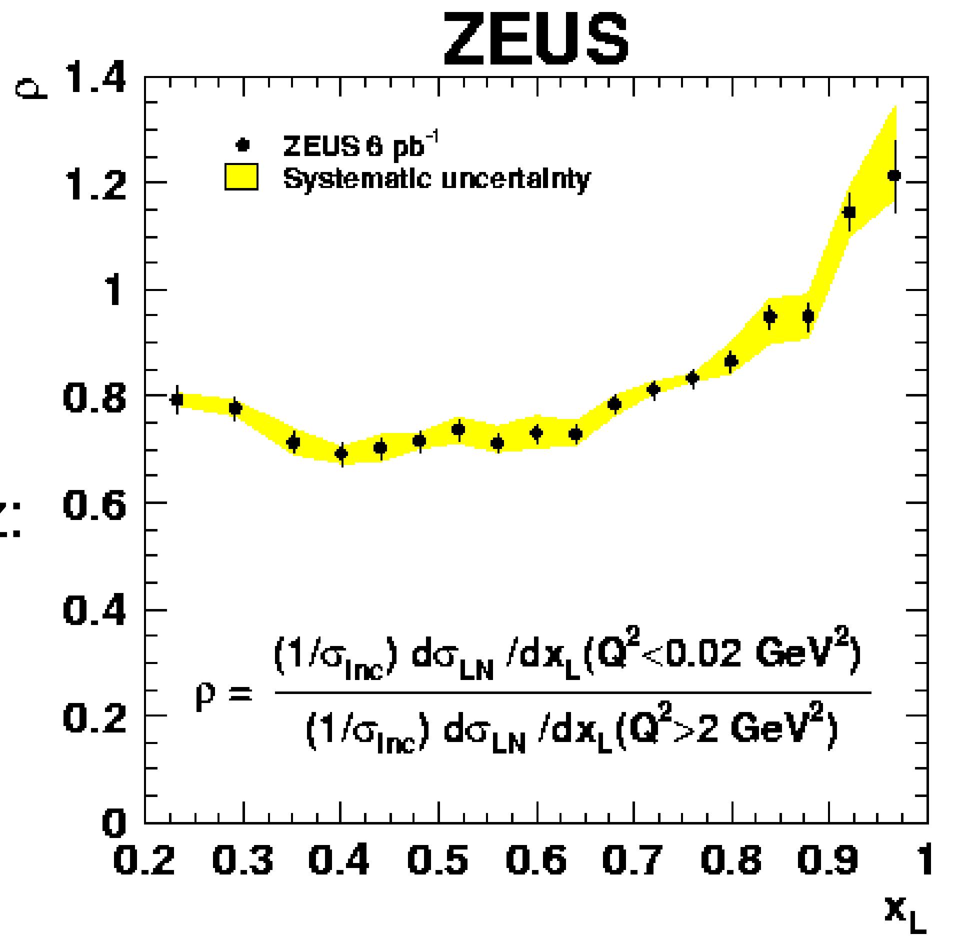
- slopes for 3 Q^2 bins ~same
- slope for γp significantly larger

Compare γp/DIS: LN x_L distributions

- Combine all DIS $Q^2>2$ GeV^2, compare to γp x_L dist.: ratio

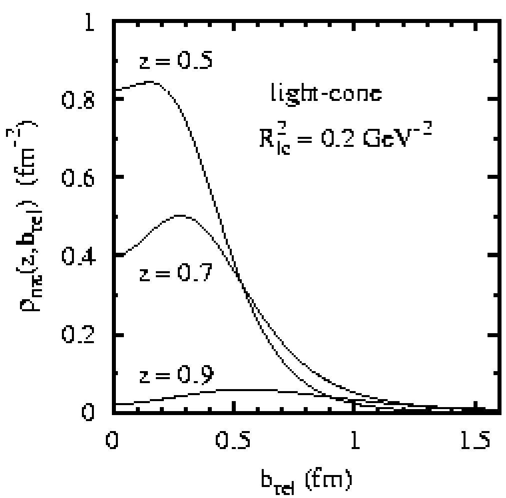
Ratio ~70% mid-x_L,

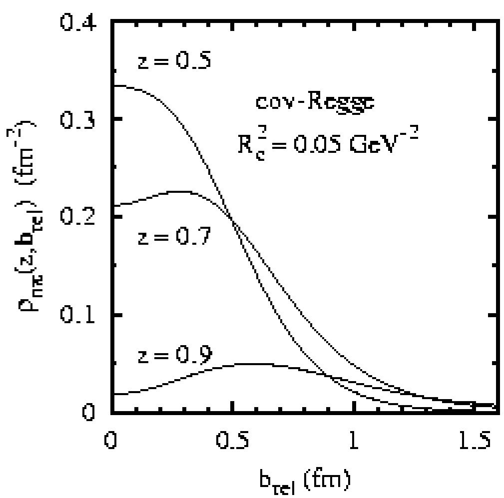
rising above 1 as $x_L \to 0.9$



Qualitatively consistent w/ rescattering:

- Exchange model: mean n-π separation $r_{n\pi}$ decreases at lower x_L=z:

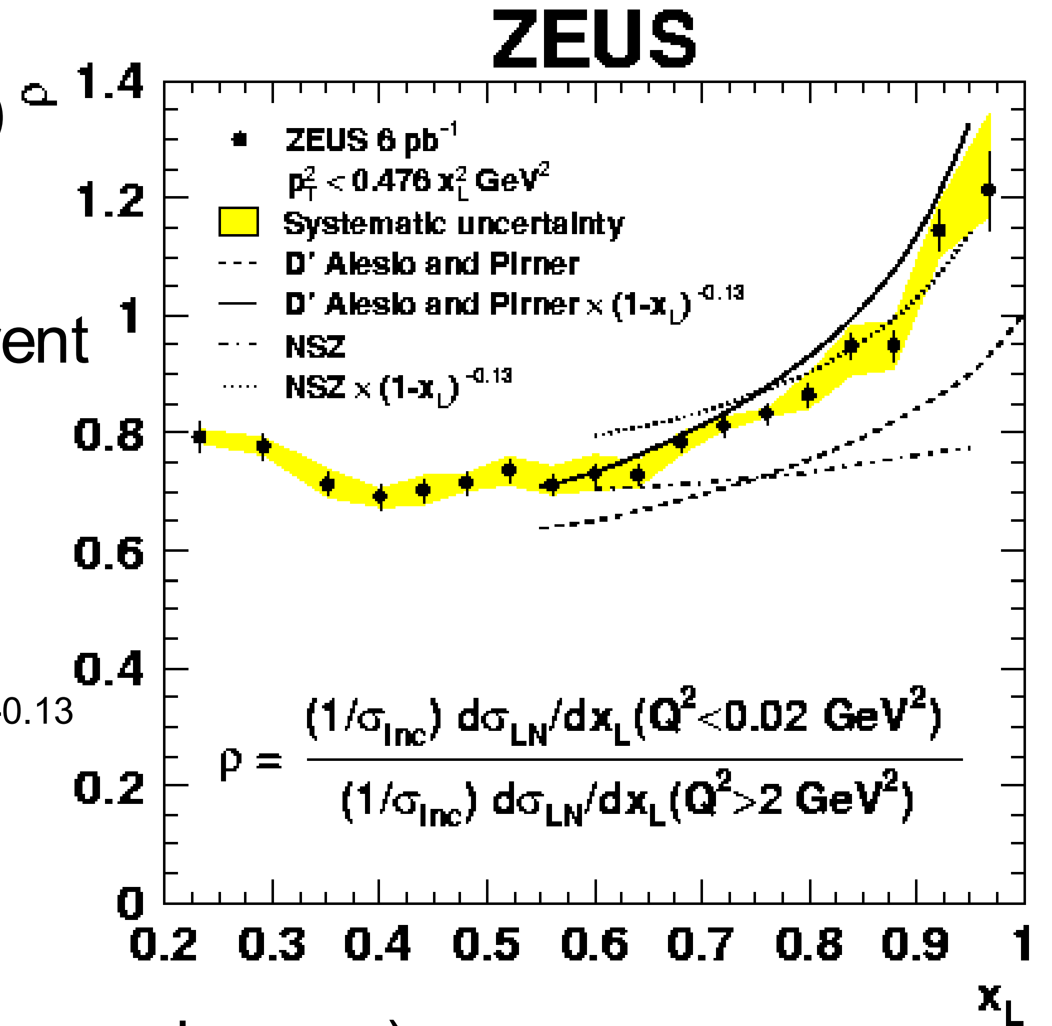




- smaller $r_{n\pi} \Rightarrow$ more rescattering at lower as x_L as in data

Compare γp/DIS: π-xch. w/ rescattering

- Ratio x_L dist. γp/DIS:
- Qualitatively similar to D' Alesio & Pirner (loss through rescattering)



<u>W dependence:</u>

- Know for $\gamma^{(*)}p$: $\sigma_{\gamma p}$, $\sigma_{DIS\text{-}p}$ have different α's: $\sigma \propto W^\alpha$ (W = $\gamma^{(*)}$p c.m. energy)
- Assume same α's for $\sigma_{\gamma\pi}$, $\sigma_{DIS\text{-}\pi}$
- Also: $W^2_{\gamma\pi} = (1-x_L)W^2_{\gamma p}$
- $\Rightarrow$ scale rescatterig factor by $(1-x_L)^{-0.13}$
- Nice agreement with data

- Also shown: model of Nikolaev, Speth and Zakharov (muliti-Pomeron exchanges)
- Similar, but weaker x_L dependence

Compare: π-xch. w/ rescattering loss, migration, other exchanges

- Work of Kaidalov,

  Khoze, Martin & Ryskin:

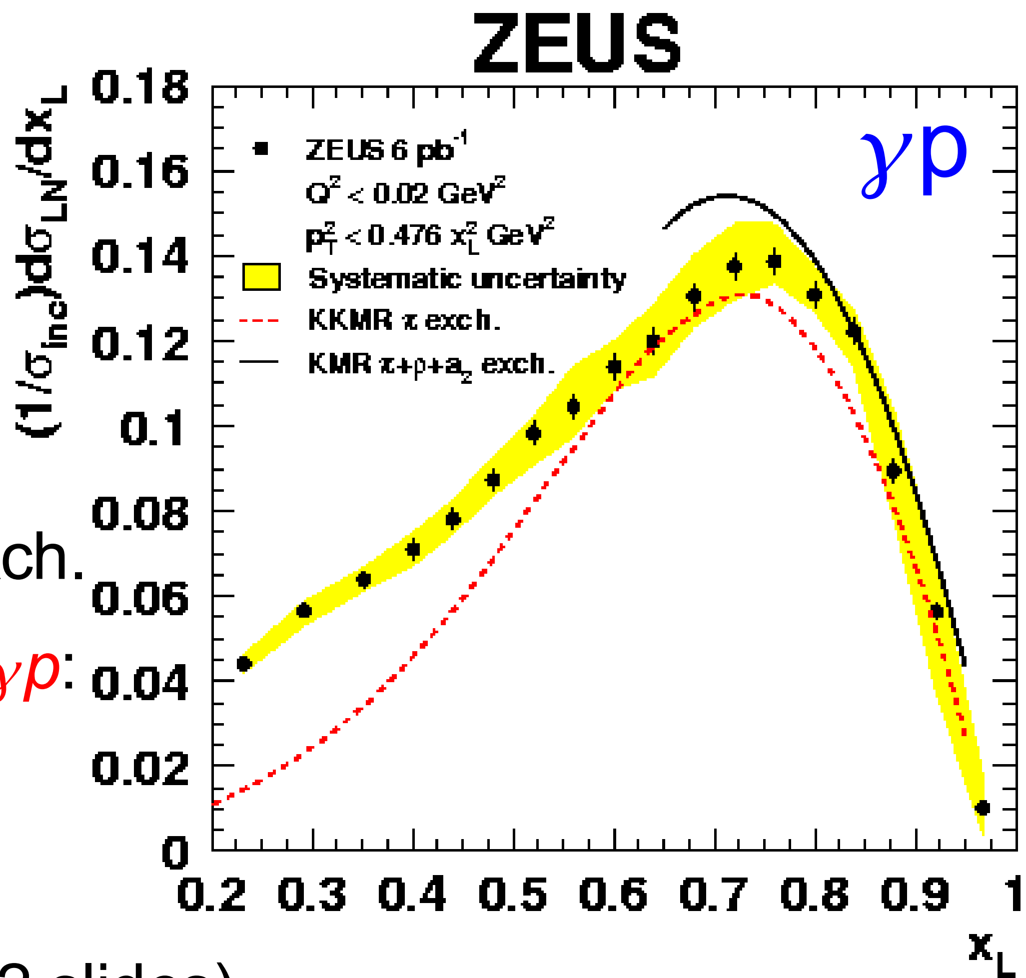
  - start with pure π-xch.
  - some *n* rescatter on γ
  - rescattered *n* migrate in (x_L, p_T)

- γp overall ~50% loss from pure π-xch.
- Reasonable agreement with LN in γp:
- Subsequent work of

  Khoze, Martin & Ryskin:

  - add (ρ, a_2) exchanges (motive in 2 slides)

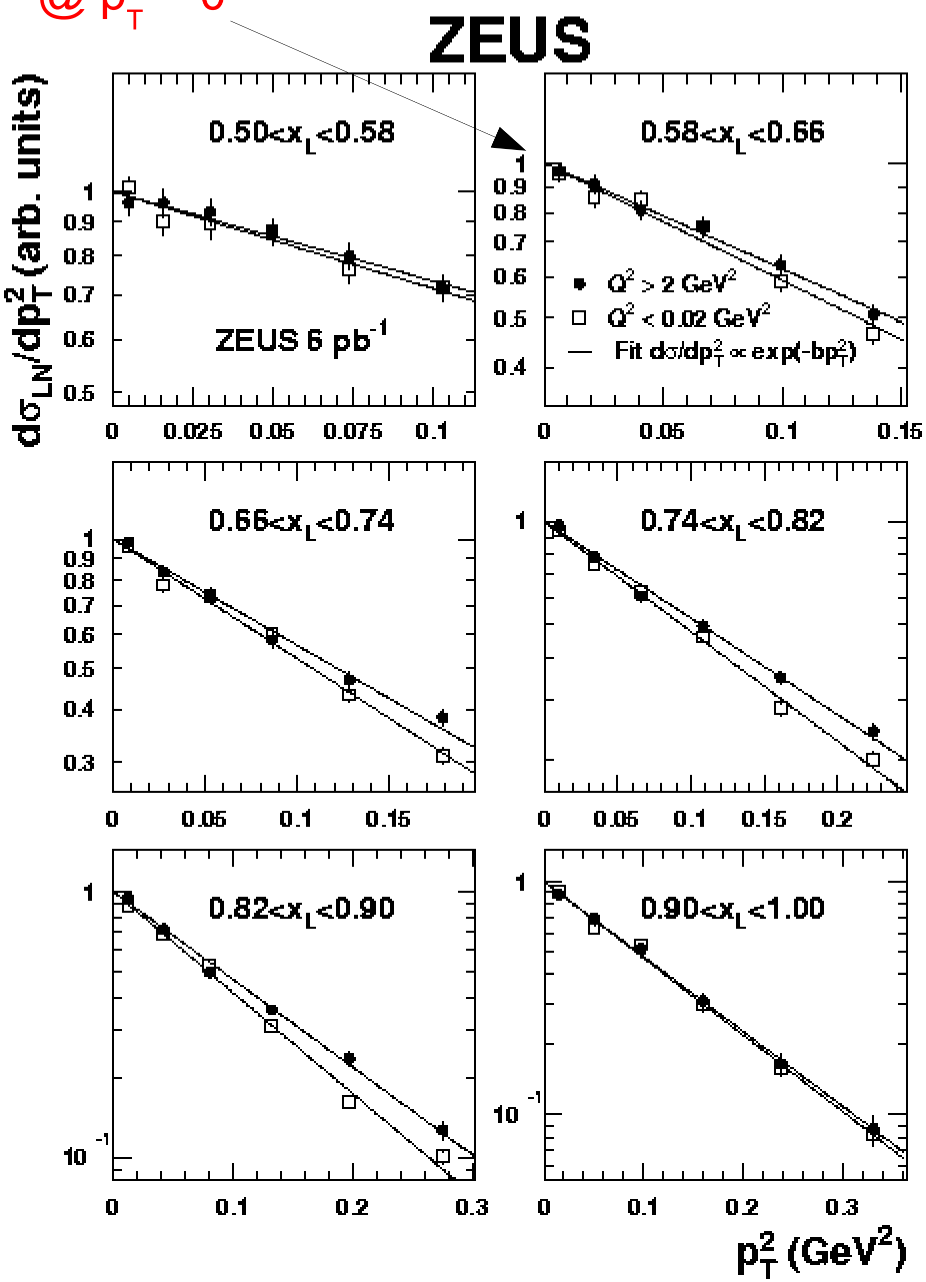
- Again reasonable agreement with LN in γp



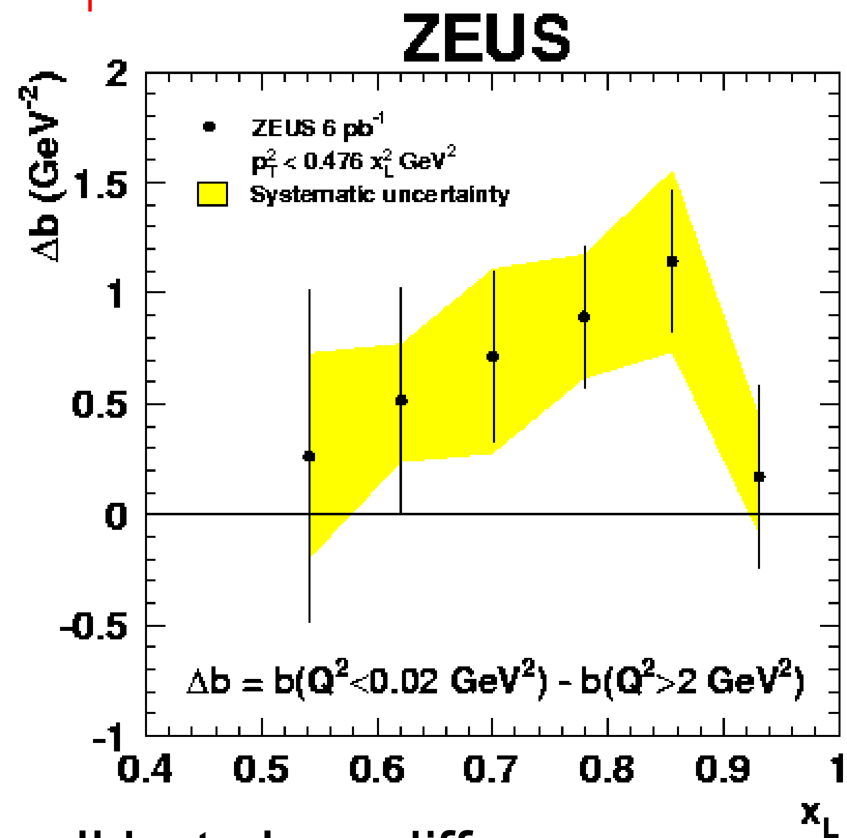
Compare γp/DIS: LN p_T^2 distributions

normalized @ p_T^2 =0

p_T^2 distributions:



p_T^2 slopes differences Δb:

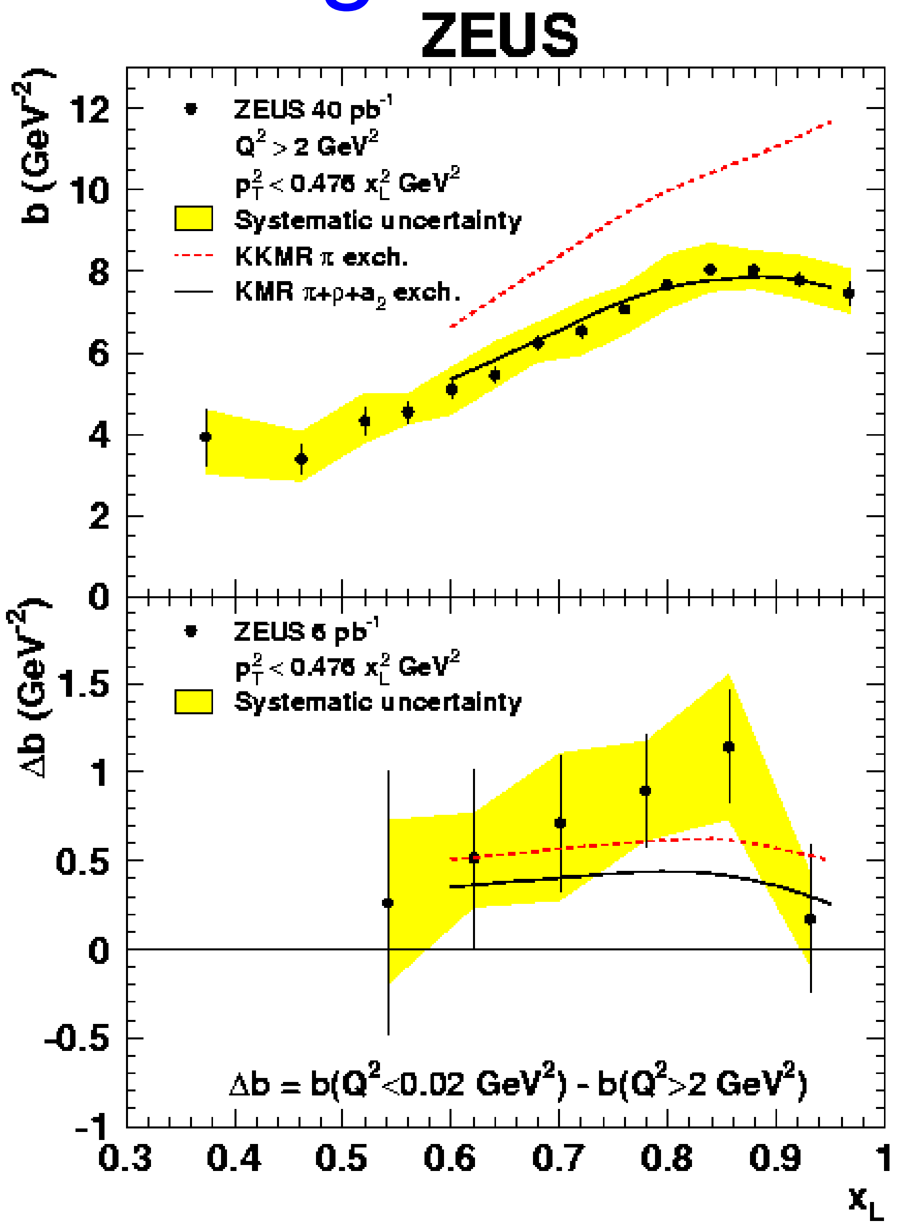


- Small but clear difference: $b(\gamma p) > b(DIS)$ for $0.6<x_L<0.9$
- Qualitatively consistent w/ rescattering: more rescat. @ small $r_{n\pi}$ ~ large p_T fewer LN @ high p_T ⇒ larger slope

Compare: π-xch. w/ rescattering loss, migration, other exchanges

- Rescattering loss+migration with pion exchange alone does not describe slopes; too high in magnitude, no turnover @ high x_L, Δb ~ OK

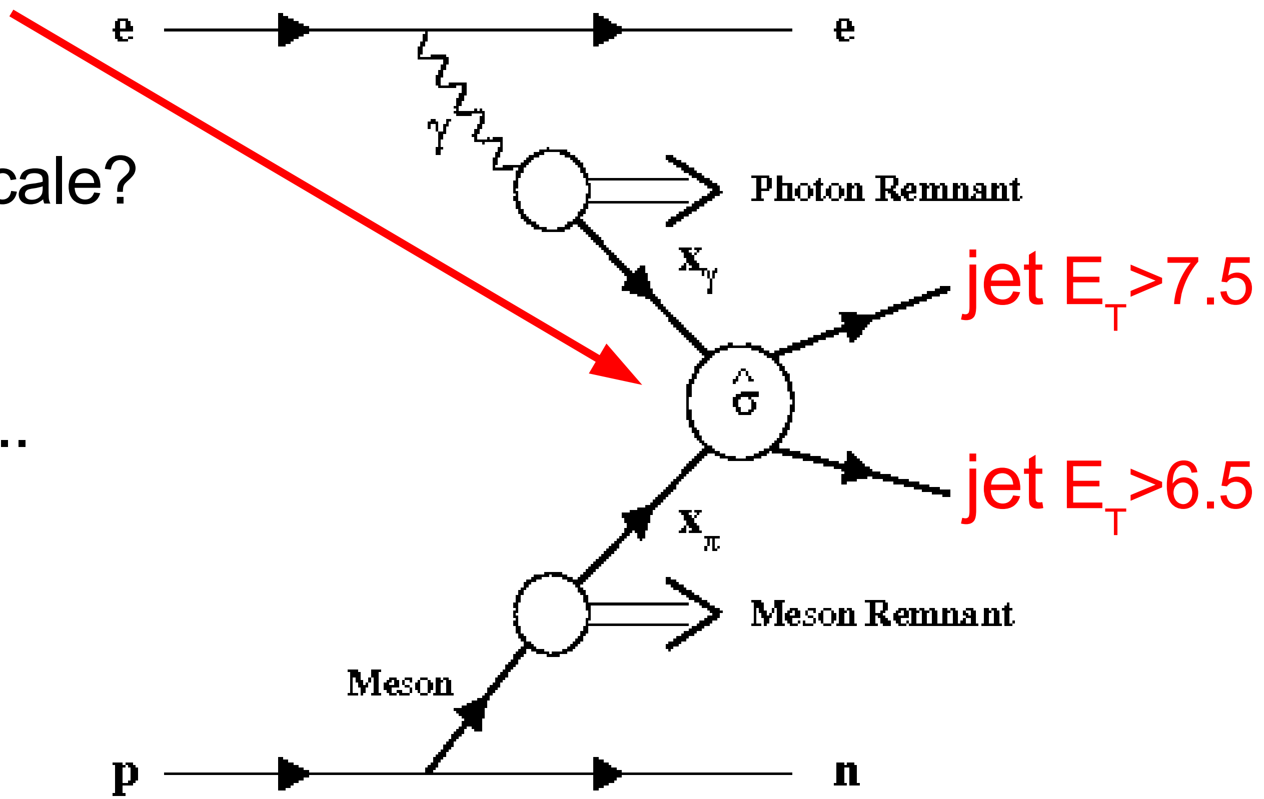
- Addition of (ρ, a_2) exchanges gives good description of both slopes magnitude and x_L dependence, Δb still OK



- Full model with mulitple exchanges, rescattering best describes LN

Compare LN in γp+jj & DIS

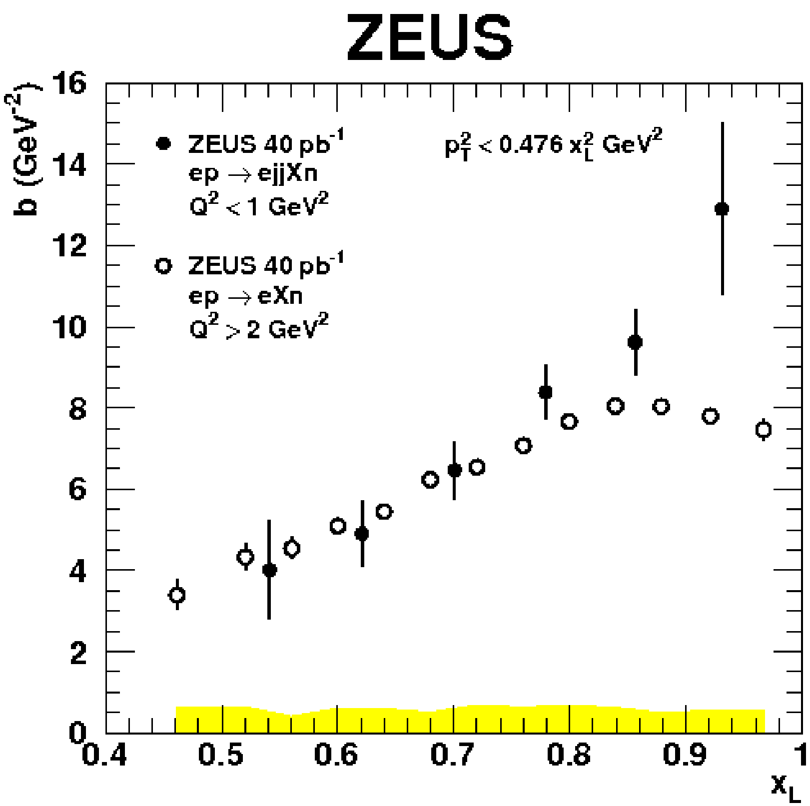
- We have seen effects qualitatively consistent with rescattering going hi-$Q^2$$\rightarrow$lo-$Q^2$$\rightarrow$$\gamma p$
- Going from hard$\rightarrow$soft scale increase in rescattering
- Suppose in γp we reintroduce a hard scale by requiring high E_T dijets:



- Still signs of rescattering?
- Or eliminated by high E_T scale?
- Recent LN in γp+jj results...

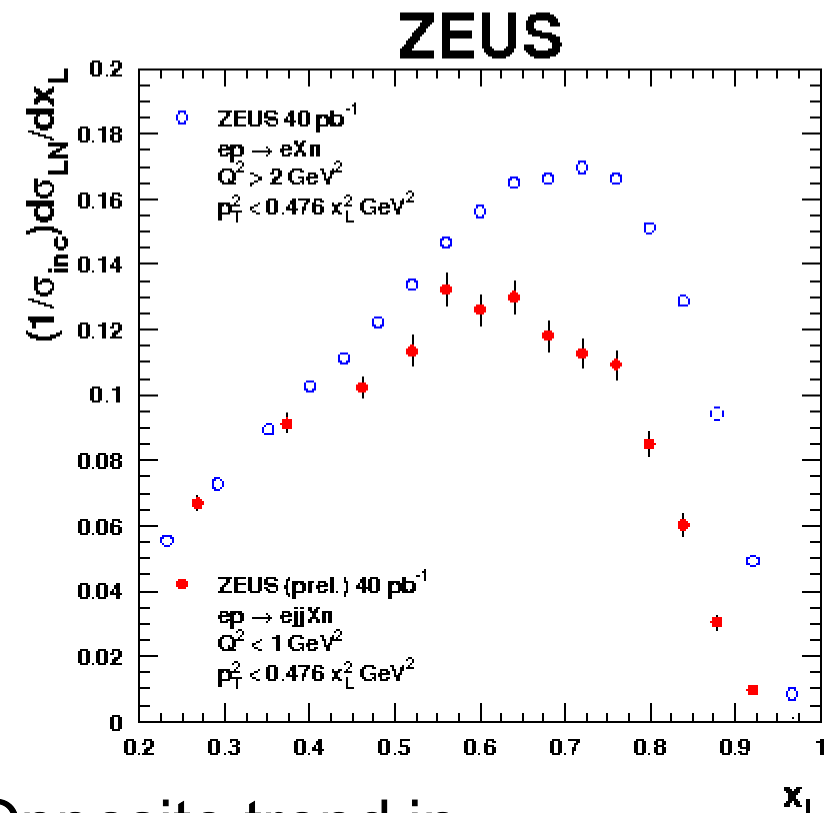
Compare LN in γp+jj & DIS : p_T^2 & x_L dist.

- The p_T^2 dist. in γp+jj again exponentials w/ slope b:



- Still ~same as DIS: ⇒ same production mechanism
- Statistics limit further conclusions

- But the x_L dist. strikingly different!



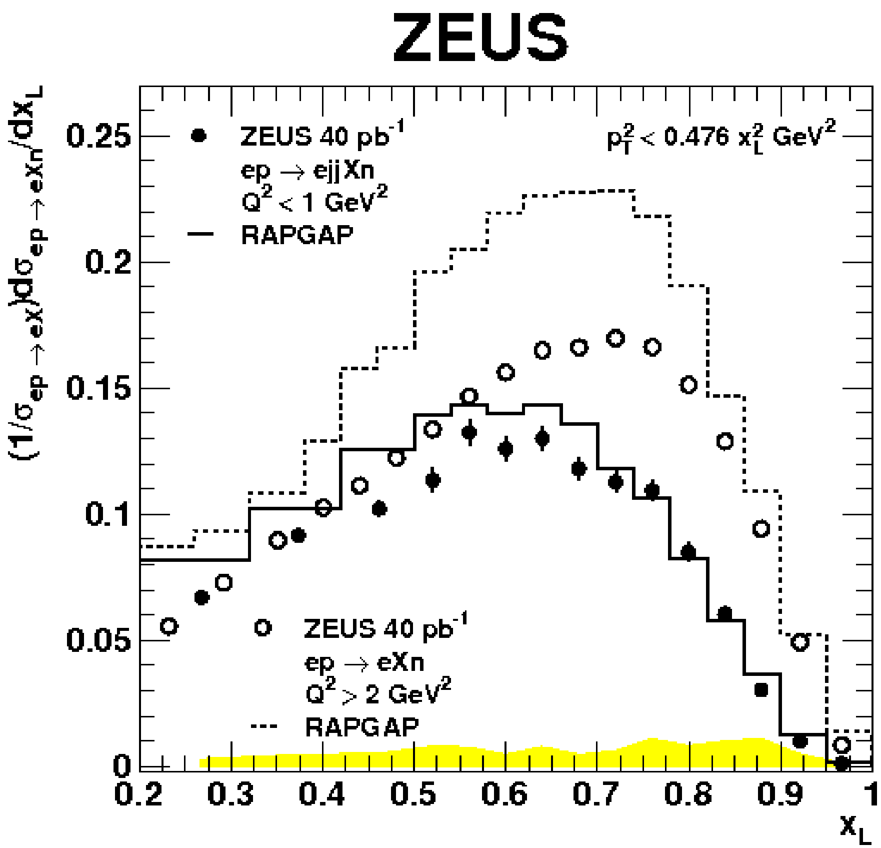
- Opposite trend in hi-Q^2→lo-Q^2→γp w/o jet requir.
- There supression @ *low* x_L
- Here supression @ *high* x_L
- Kinematic suppression?

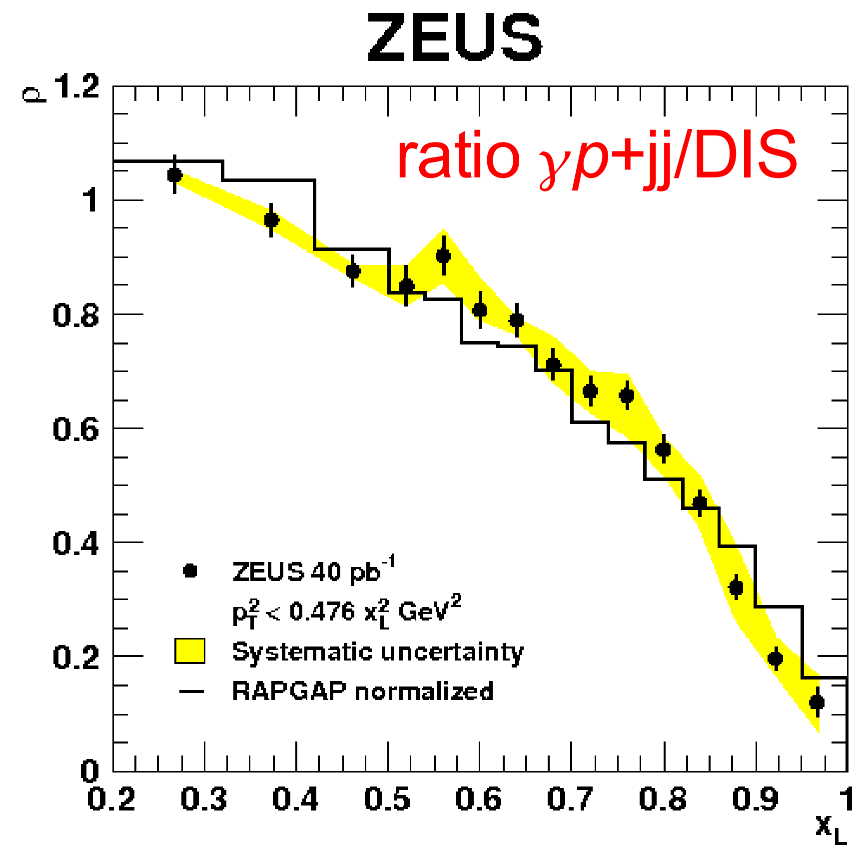
Compare LN in γp+jj & DIS : x_L dist.

<u>Compare to RAPGAP MC with:</u>

- π-xch. and full event kinematics
- NO rescattering

- Normalize each MC set to data
- Take ratio of x_L distributions:





- RAPGAP DIS normalization high
- But shapes are described:
  dijets suppressed @ hi x_L

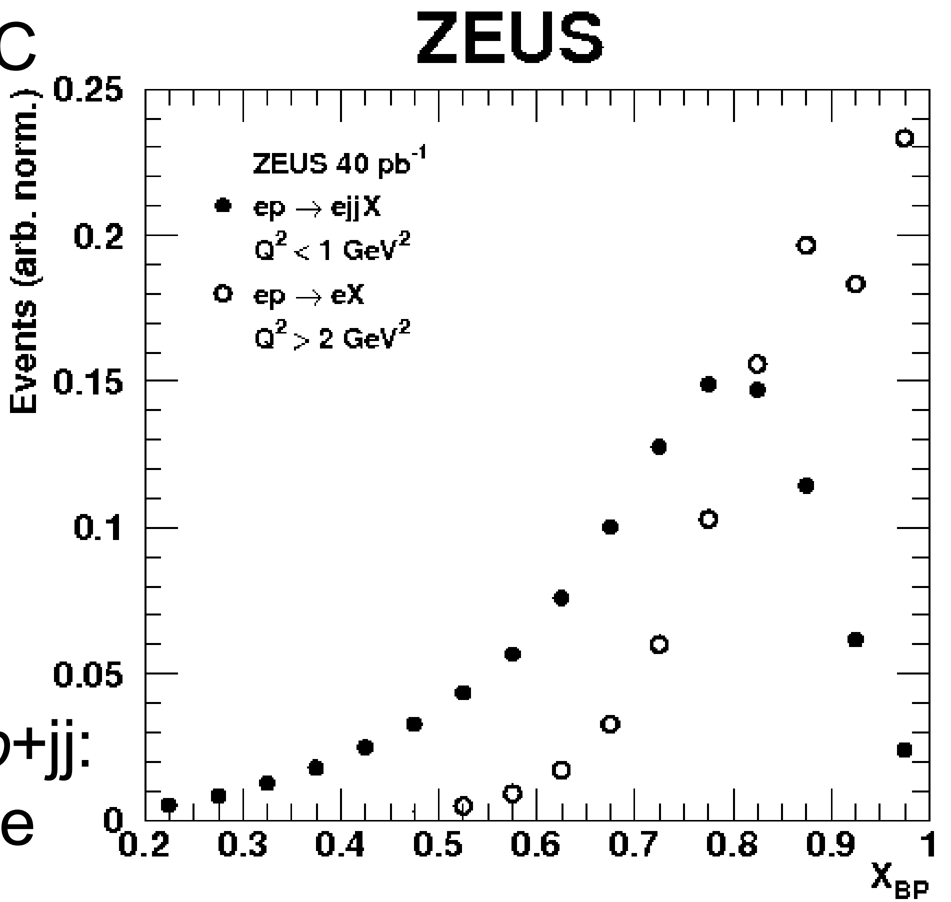
RAPGAP with π-xch., full event kinematics describes different shapes x_L distributions

LN in γp+jj & DIS : kinematic constraints

- The requirement of high-E_T dijets exacts a price on the phase space available for LB production, seen in MC

<u>Can also investigate w/ data alone:</u>

- We can quantify kinematics w/ energy measurement in the central detector:
  X_{BP} = fraction p-energy available for LB down beam-pipe (BP)
  kinematic constraint: $x_L < X_{BP}$

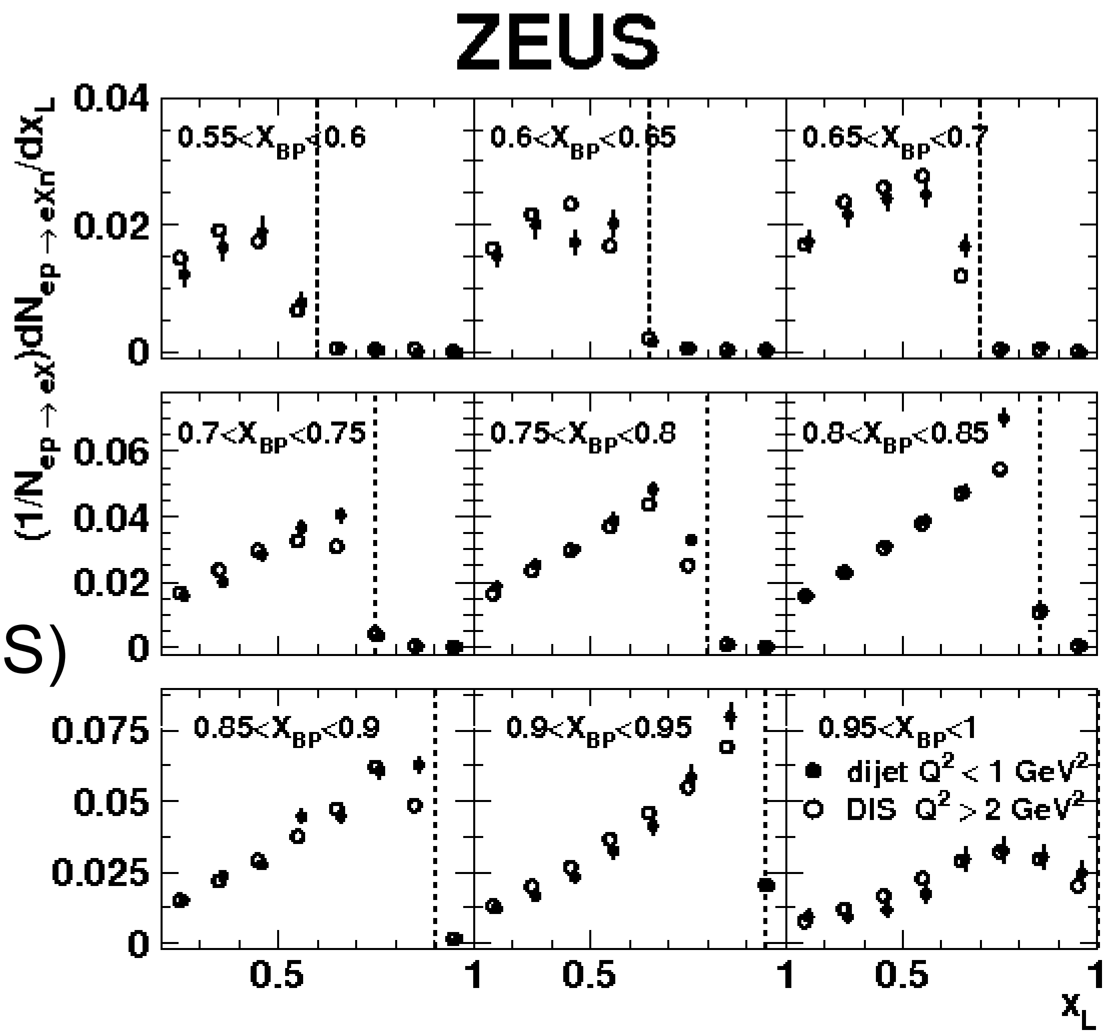


- Very different for distributions DIS & γp+jj:
  - DIS typically >80% p-energy available
  - in γp+jj much less available

- Now consider LN x_L distributions in X_{BP} bins ➘

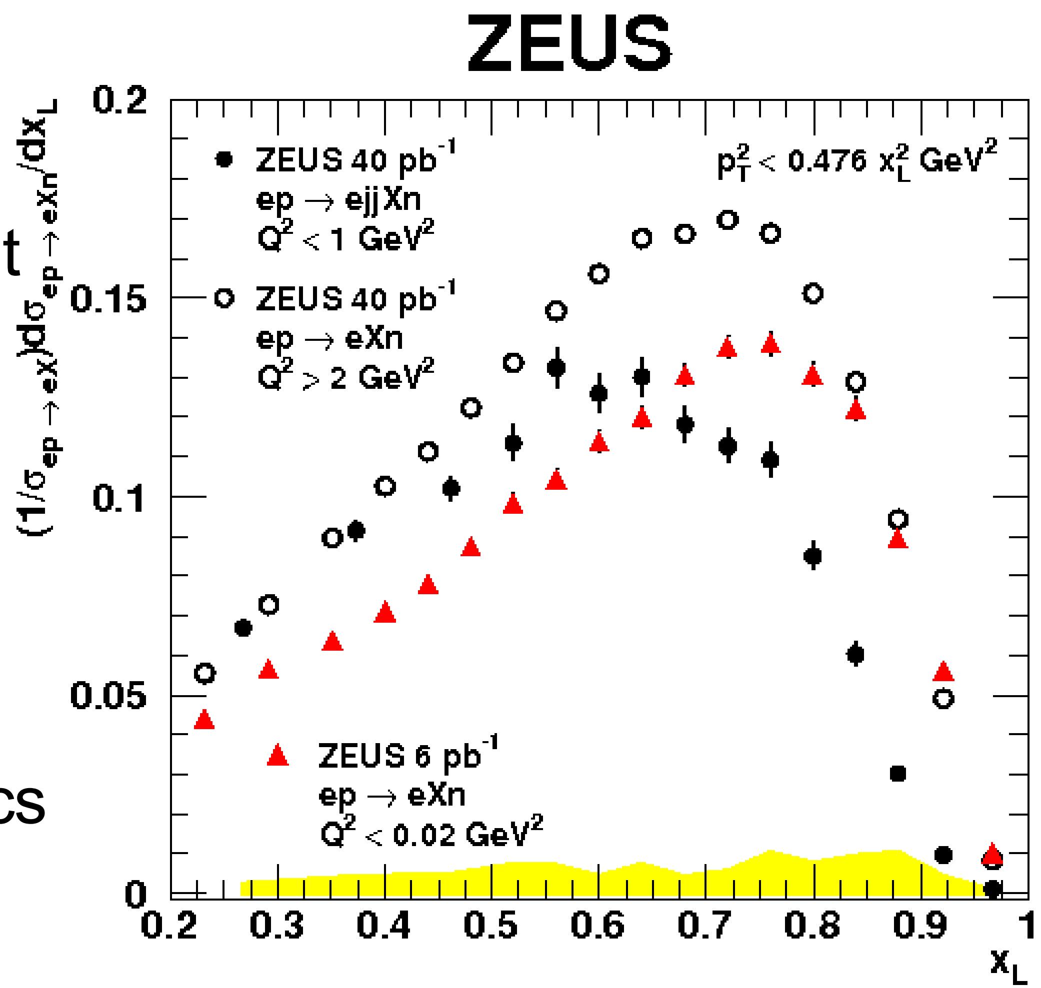
LN in γp+jj & DIS : x_L in X_{BP} bins

- In bins of X_{BP} the x_L dist. for γp+jj, DIS are ~same both normalization, shape
- Universality: for a given X_{BP}, LN x_L dist. is same regardless of process (at least γp+jj vs. DIS)
- So different overall x_L dist. for γp+jj vs. DIS explained by different event kinematics (as seen with MC)



LN x_L in γp, γp+jj & DIS :

- Large suppression @ low x_L seen in γp w/o jet requirement, consistent with rescatteing, is not seen in γp+jj
- Conclusion (tentative): introducing a hard scale via high jet E_T reduces/removes rescattering effects
- But complications of event kinematics prevents a firm conclusion
- Relatively recent result, hope for input from theoretical community...



Summary

- Best measured leading baryon x_L, p_T distributions in DIS, γp, γp+jj
- MC models with 'standard' fragmentation do not describe the data
- Models with virtual particle exchange much better
- Pure π-xch. does not fully describe LN data: slopes wrong
- Evolution hi-$Q^2 \rightarrow$lo-$Q^2 \rightarrow \gamma p$: evidence for rescattering of LB in large γ
- More refined calculations w/ π-xch.+rescattering loss+migration:

  for LN reasonable x_L shape, magnitude; slopes still off
- Addition of (ρ,a_2) exchanges: $\Rightarrow$ very promising agreement with LN data
- Reintroduce hard scale in γp w/ high ET jets: LN rescattering reduced