Leading Baryon production at HERA

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<u>Outline LB proton (LP) and neutron (LN) production:</u>

- Motivations: LB production, virtual particle exchange, rescattering
- HERA & detectors: LP&LN detectors, resolutions, acceptances
- Data sets: DIS, photoproduction γp (inclusive, D*, dijets); LB yield
- LB in DIS & γp: energy, p_T distributions, LP↔LN rate
- Comparison: LB in MC models, w/o & with virtual particle exchange
- LB production photon virtuality Q^2 dependences
- Comparison: LN exchange models with rescattering
- Comparison: LN in DIS & γp with hard scale (charm, high E_T dijets)
- Total LB rate → EIC

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

Historical context

- The HERA data are > 13 years old
  ZEUS LB results from HERA-I, ≥ 20 years old

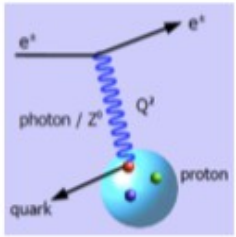
- The published data compared to models *circa* ~15 years ago, including: meson exchange, rescattering (absorption)
- Some pictures may still be in favor
  others may be out of fashion or obsolete
- Here: will stick to published interpretations
  plots with curves easily available

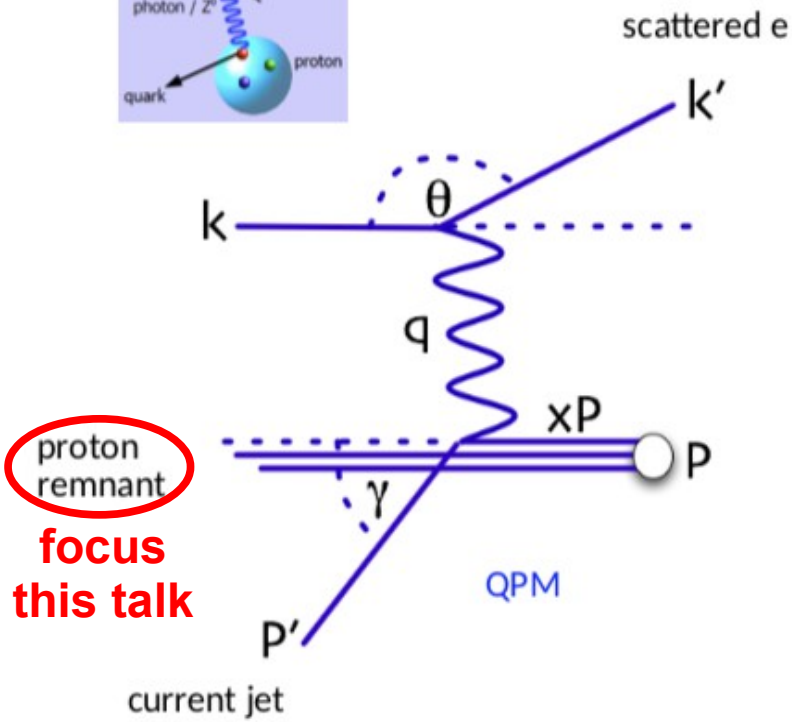
<u>However:</u>
the data are the data and speak for themselves

- Also:
  - ZEUS published more detailed LB spectra, emphasized here
  - I'm more familiar w/ ZEUS results
  - H1 had similar results, some also shown here

Deep Inelastic Scattering (DIS)

- Photon probe of proton structure:





$$Q^2 = -q^2 = (k - k')^2$$

$$x = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot k}$$

$$Q^2 = s \cdot x \cdot y$$

resolving power
(virtuality of the exchanged photon)

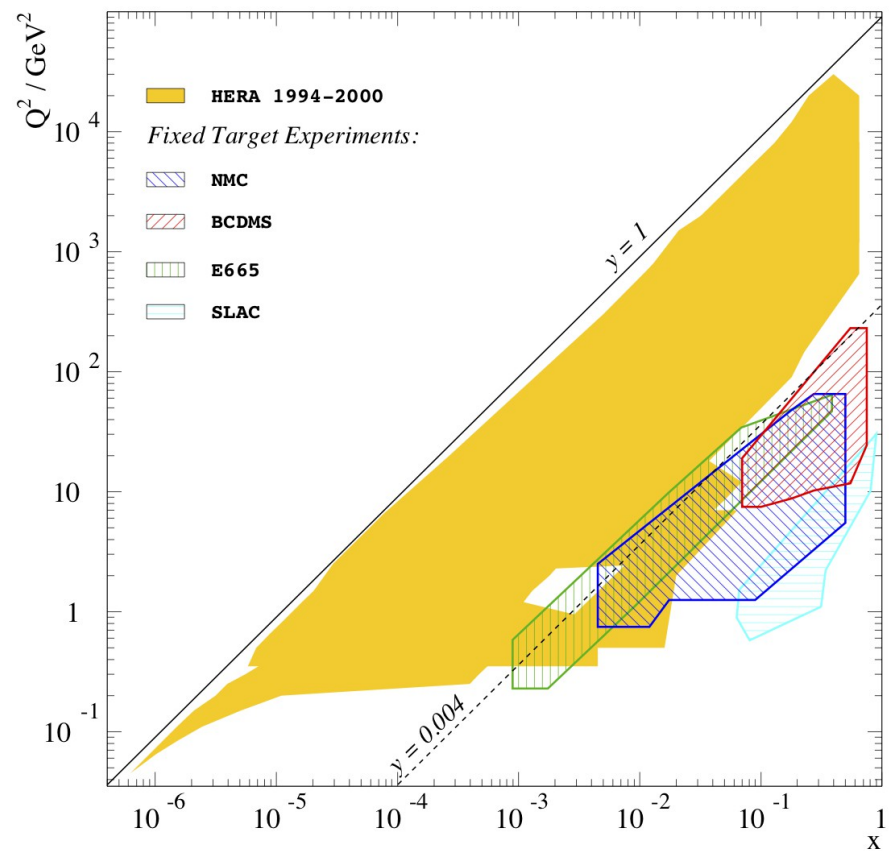
the Bjorken scaling variable
(momentum fraction of the struck quark)

the inelasticity

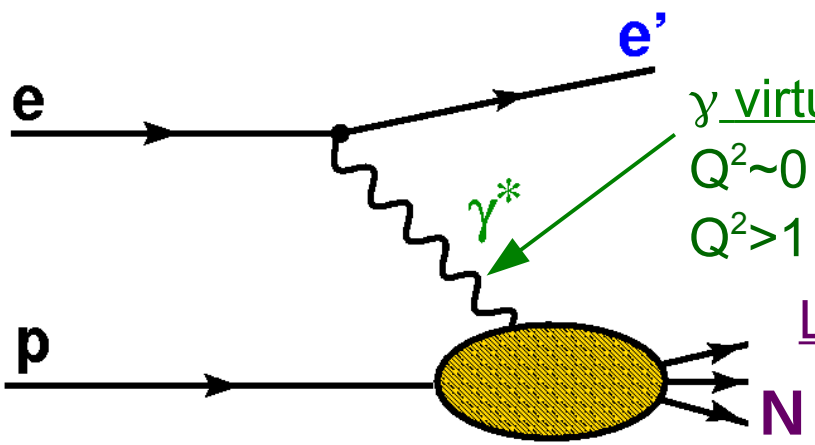
$$W_{\gamma p}^2 \approx y \cdot s - Q^2 \approx \frac{Q^2}{x}$$

γ-p c.m. energy

- HERA ~ kinematic range:
  - $0 < Q^2 < 40000\ \mathrm{GeV}^2$
  - $x > 10^{-6}$

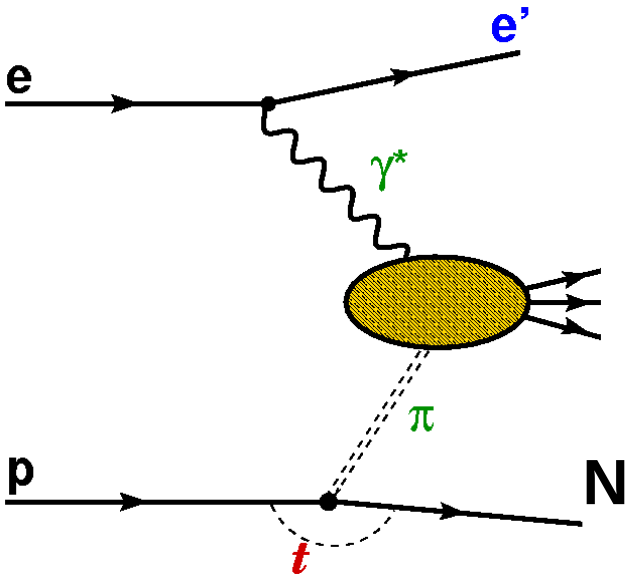


Pictures: LB production, virtual exchange



γ virtuality Q^2:
Q^2~0 photoprod. (γp)
Q^2>1 GeV^2 DIS

LB variables:
$x_L = E_N/E_p$
p_T



e.g. π-xch.

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

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

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

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

Compare: LP↔LN (x_L,p_T^2) data↔data

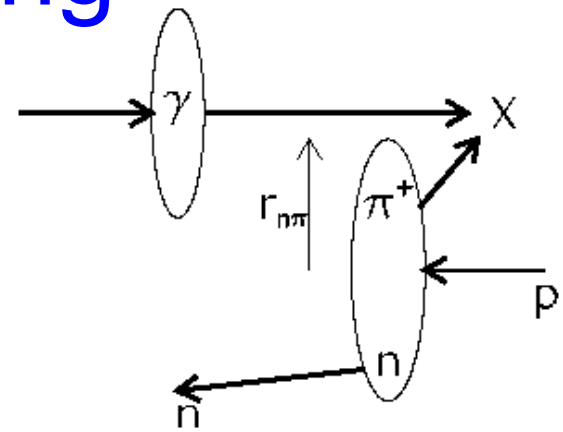
Compare: LB (x_L,p_T^2) data to

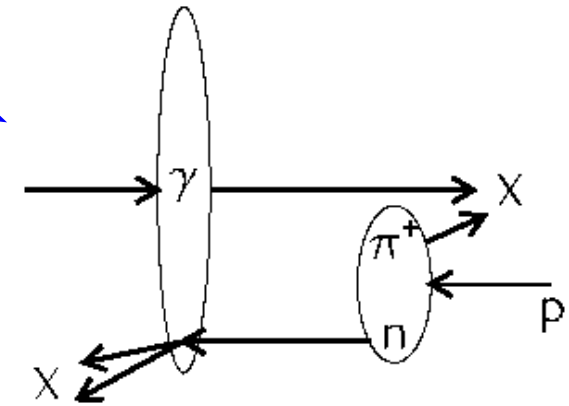
- **MC fragmentation models**
- **Exchange model parameterizations**

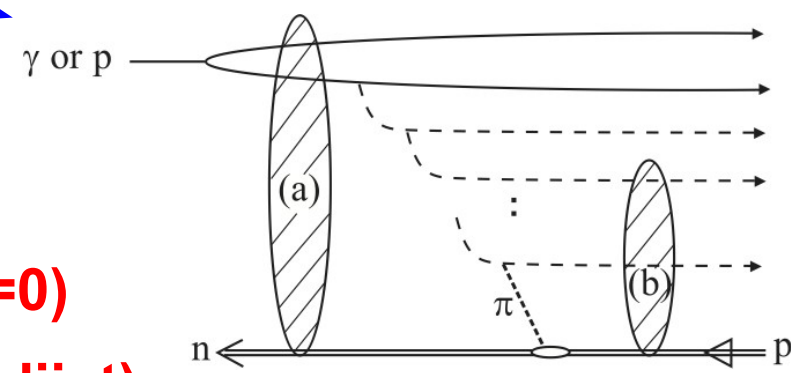
Pictures: Rescattering

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, absorption)
- Alternative language: multi-Pomeron exchanges







<u>Compare:</u> data↔data (x_L,p_T^2) distributions:

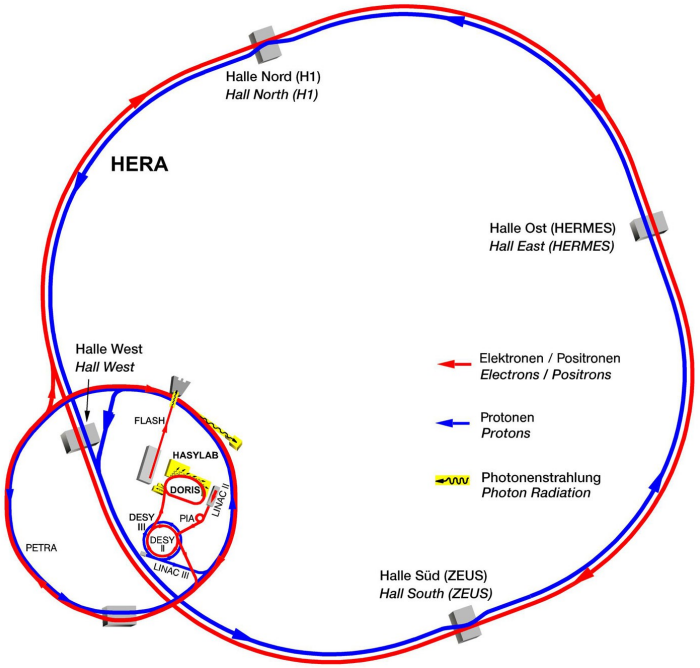
- **Vary Q^2 (γ size) in DIS; compare DIS↔γp (Q^2=0)**
- **In γp reintroduce hard scale (charm, high E_T dijet)**

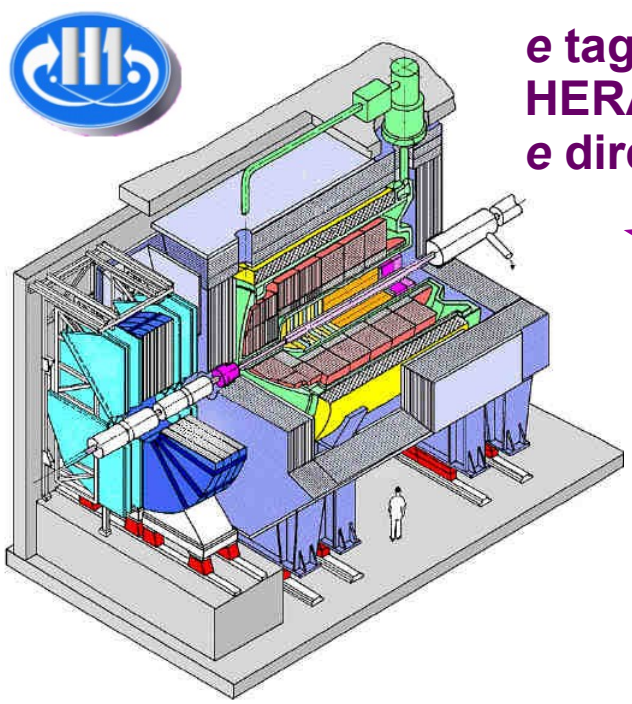
<u>Compare data↔models: particle exchange w/ rescattering</u>

HERA Collider & ZEUS Detector:

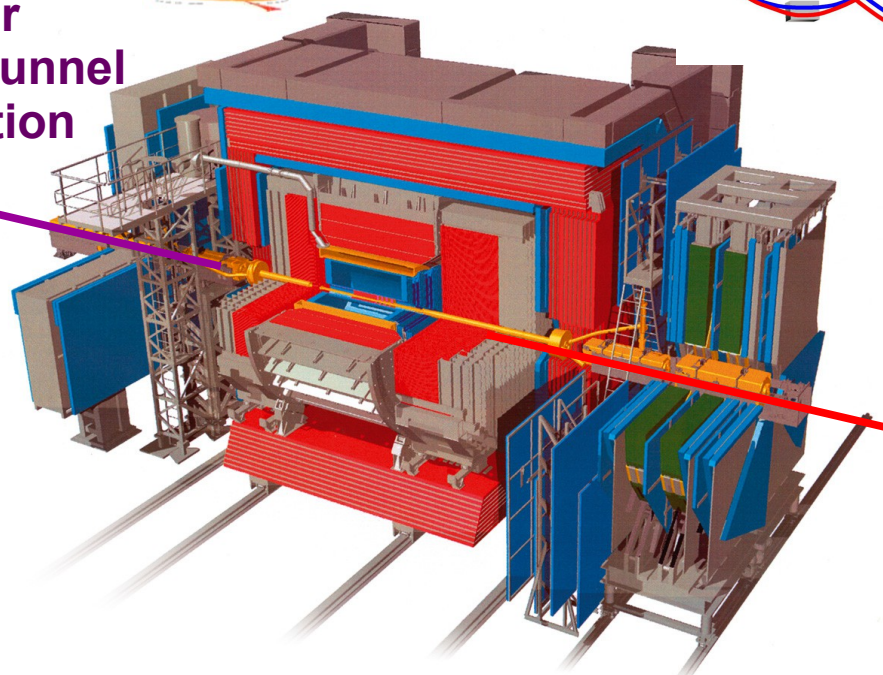
- H1 & ZEUS:
  General purpose collider detectors:
  - EM & hadronic calorimeter
  - solenoid field tracking
  For these results:
- DIS: scattered *e* in EM calorimeter
- γp: scattered *e* in tagger
- $\gamma p + D^*$: decay products in tracking
- γp+dijets: jets in calorimeter

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





e tagger
HERA tunnel
e direction

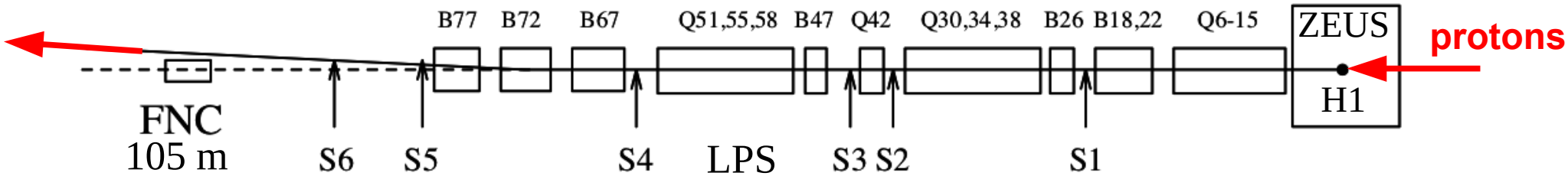


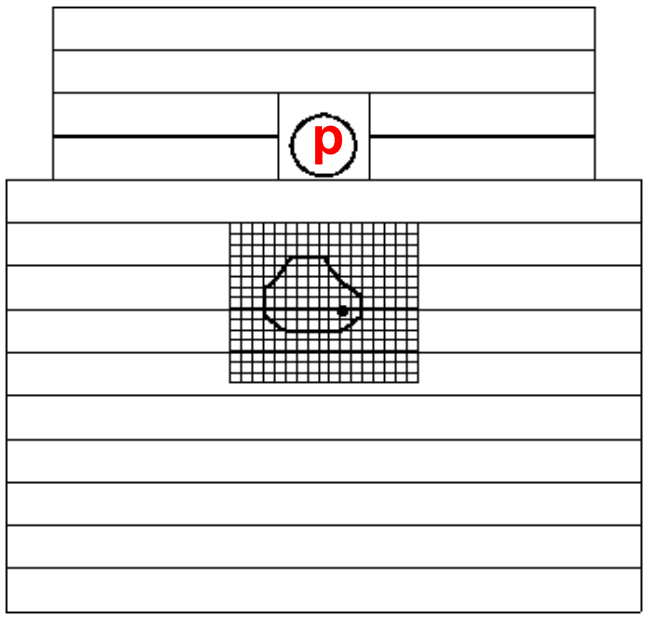
LB:
fwd. detectors
HERA tunnel
***p* direction**

LB Detectors:

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

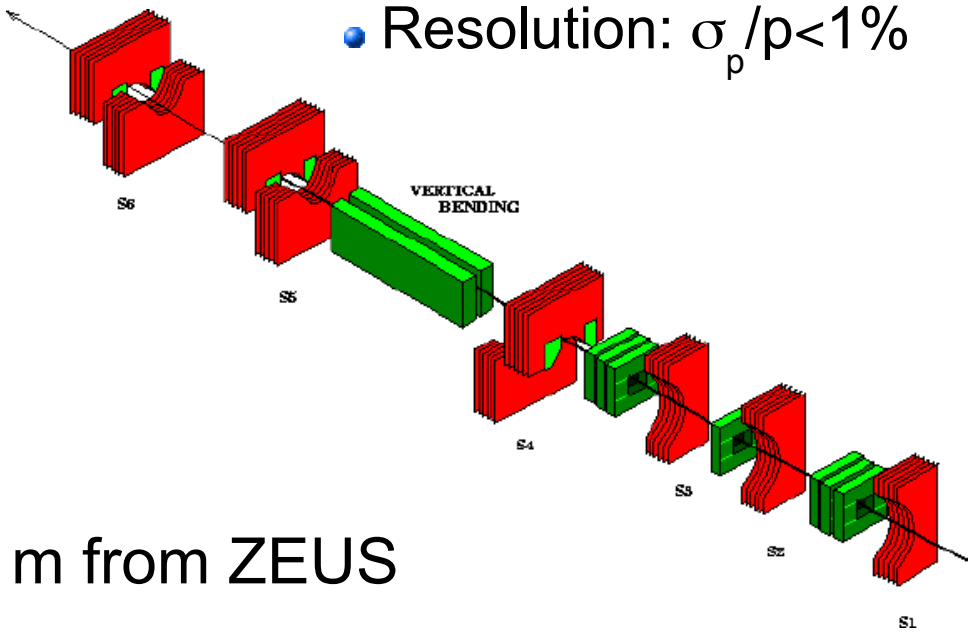
- Analyzing magnet for Leading Proton Spectrometer (LPS) for LP
- Sweeping magnet for Forward Neutron Calorimeter (FNC) for LN





LPS: Si-strip detectors

- Resolution: $\sigma_p/p<1\%$

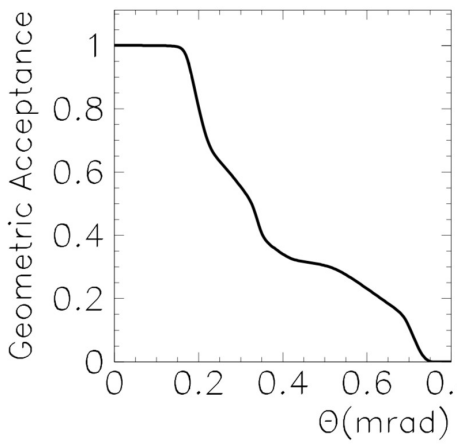


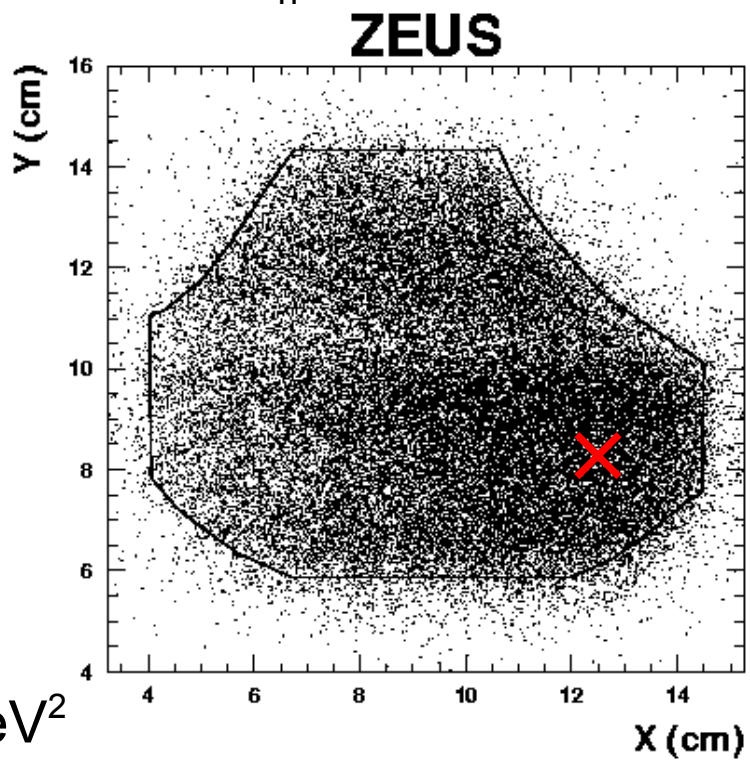
FNC: Pb-Sci calorimeter @ 0° 105 m from ZEUS

- Energy resolution: $\sigma_E/E\approx0.7/\sqrt{E}$
- Sci-hodoscope position detector $1\lambda_I$ into FNC

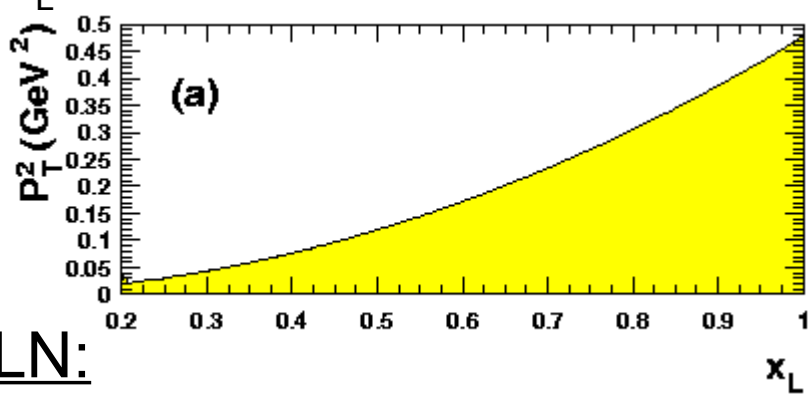
Detector acceptances

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

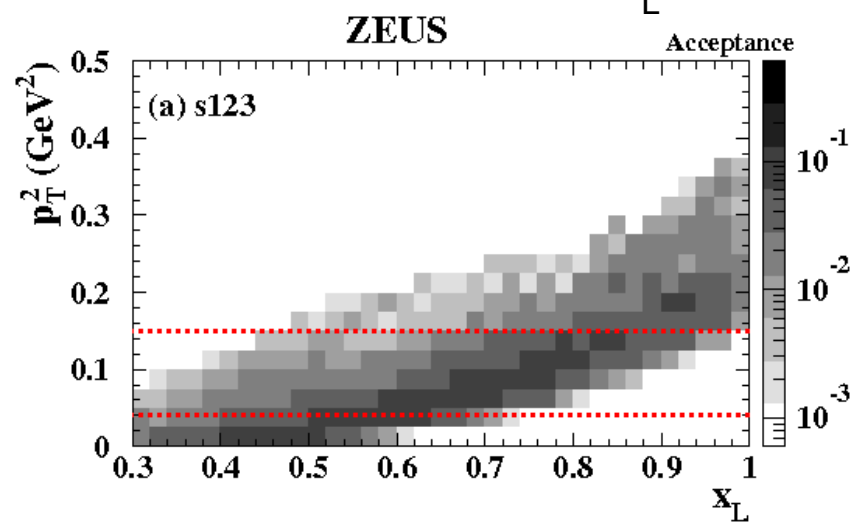


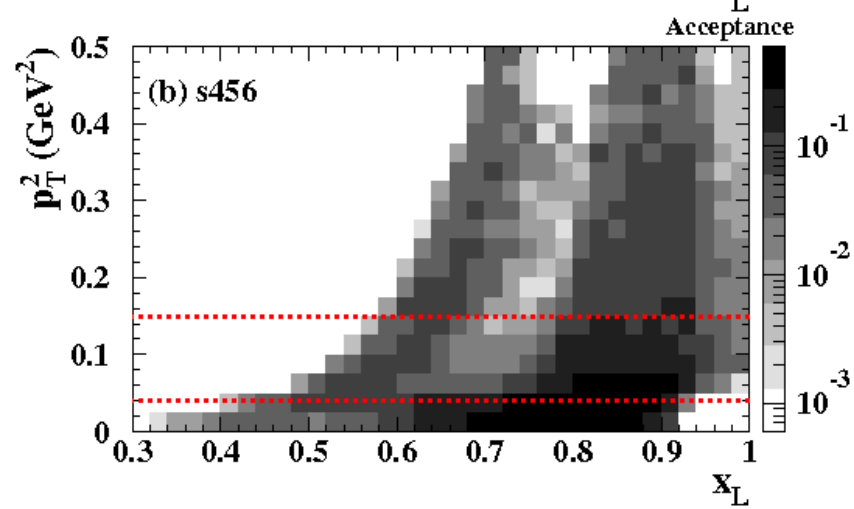


- p_T^2<0.476 x_L^2 GeV^2



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





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

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

Data sets, LB measurement

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

- DIS: $Q^2 > 2\text{-}3\ \mathrm{GeV}^2$, $\langle Q^2 \rangle \approx 13\ \mathrm{GeV}^2$; subsets with various $\langle Q^2 \rangle$
- γp: $Q^2 < 0.02\ \mathrm{GeV}^2$, e^+ tagged $\Rightarrow$ $150 < W_{\gamma p} < 270$ GeV
- γp+D*: $Q^2 < 1\ \mathrm{GeV}^2$, $130 < W_{\gamma p} < 280$ GeV, $|\eta(D^*)| < 1.5$, $p_T(D^*) > 1.9$ GeV
- γp+dijets: $Q^2 < 1\ \mathrm{GeV}^2$, $130 < W_{\gamma p} < 280$ 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:

$$r_{LB} \equiv \sigma_{LB} / \sigma_{inc}$$

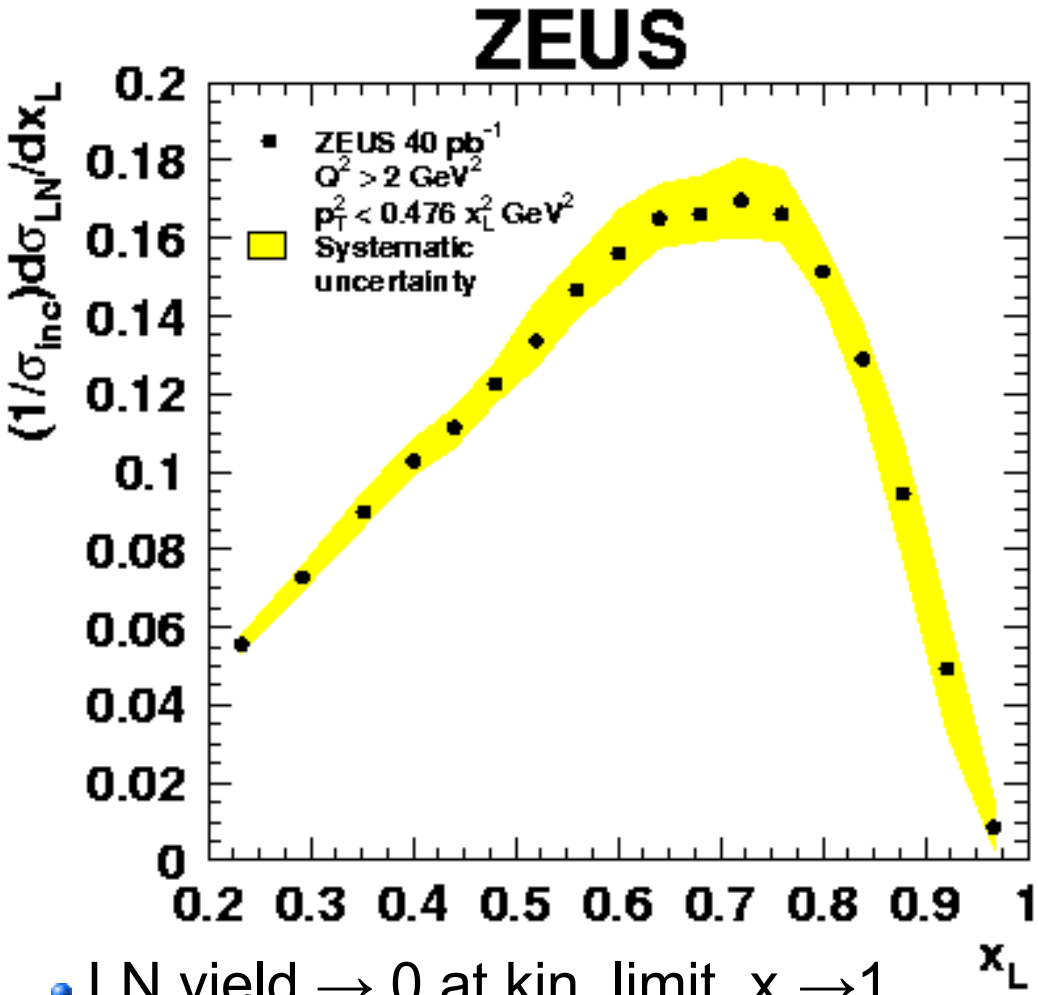
$$\text{e.g.:}\ \ r_{LB}(x_L, p_T^2) \equiv \frac{1}{\sigma_{inc}} \frac{d^2\sigma_{LN}}{dx_L dp_T^2}$$

- Additional benefit:

  systematic uncertainties of central detector cancel;
  only have LB systematic uncertainties

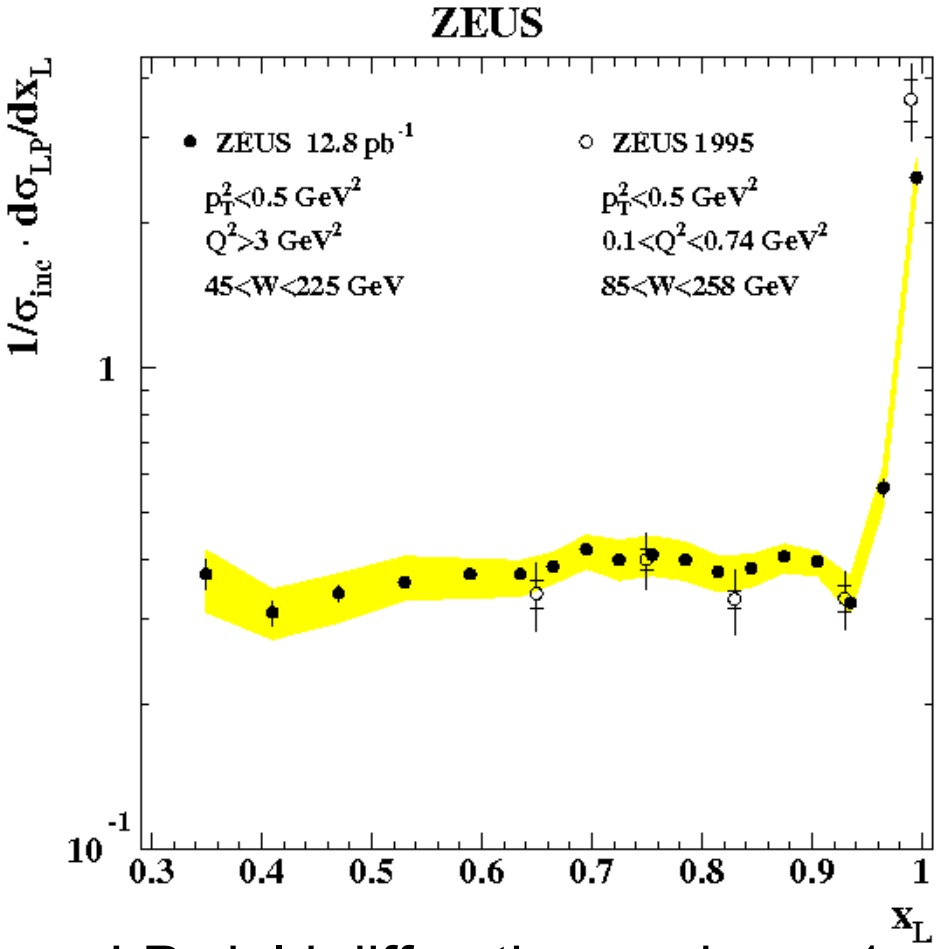
DIS x_L distributions: max. p_T ranges

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



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

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



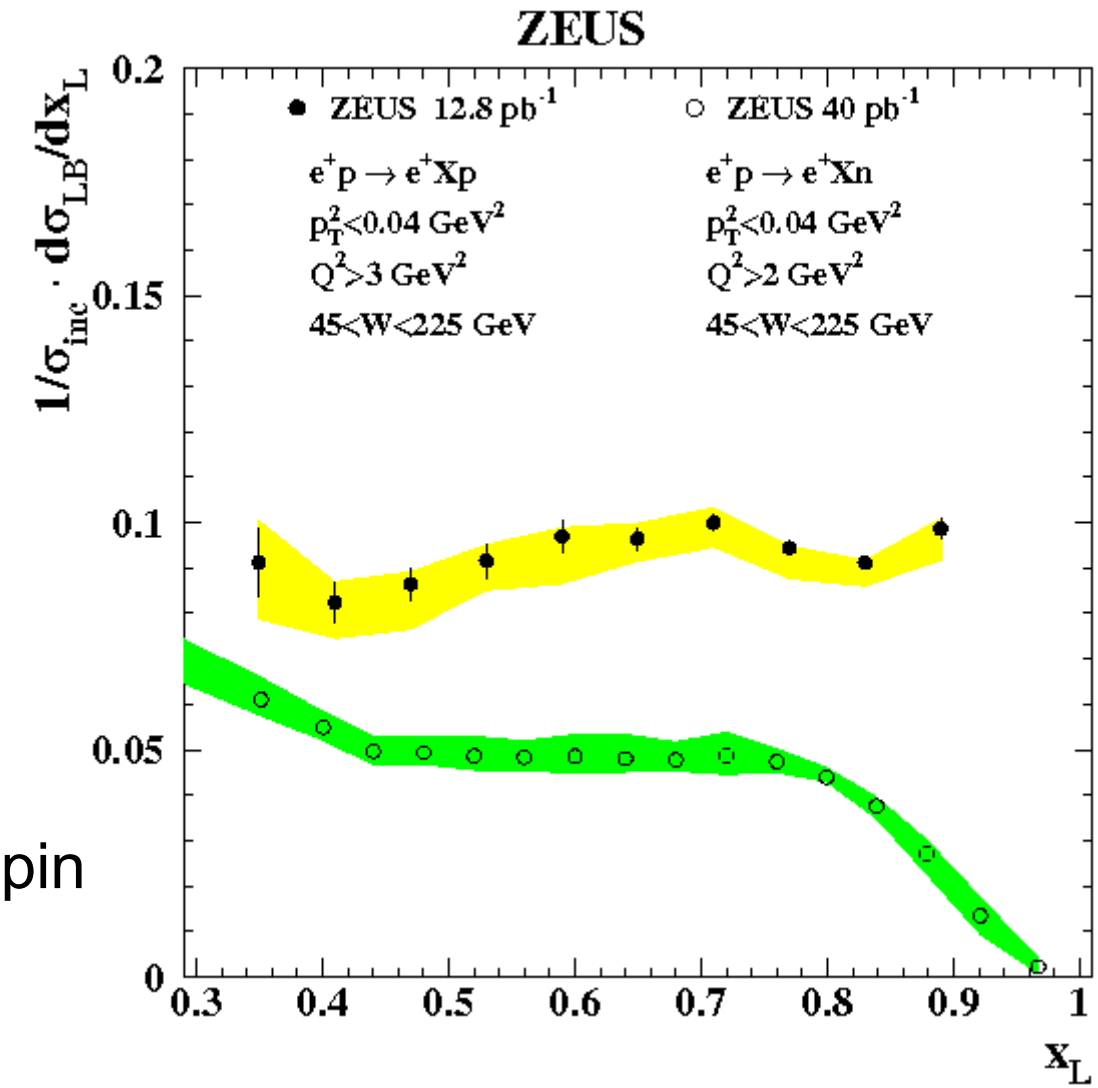
- LP yield diffractive peak $x_L \to 1$
- Below $x_L \approx 0.95$ yield ~flat

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

yield $r_{LB}(x_L)$ for $0.35<x_L<0.9$:

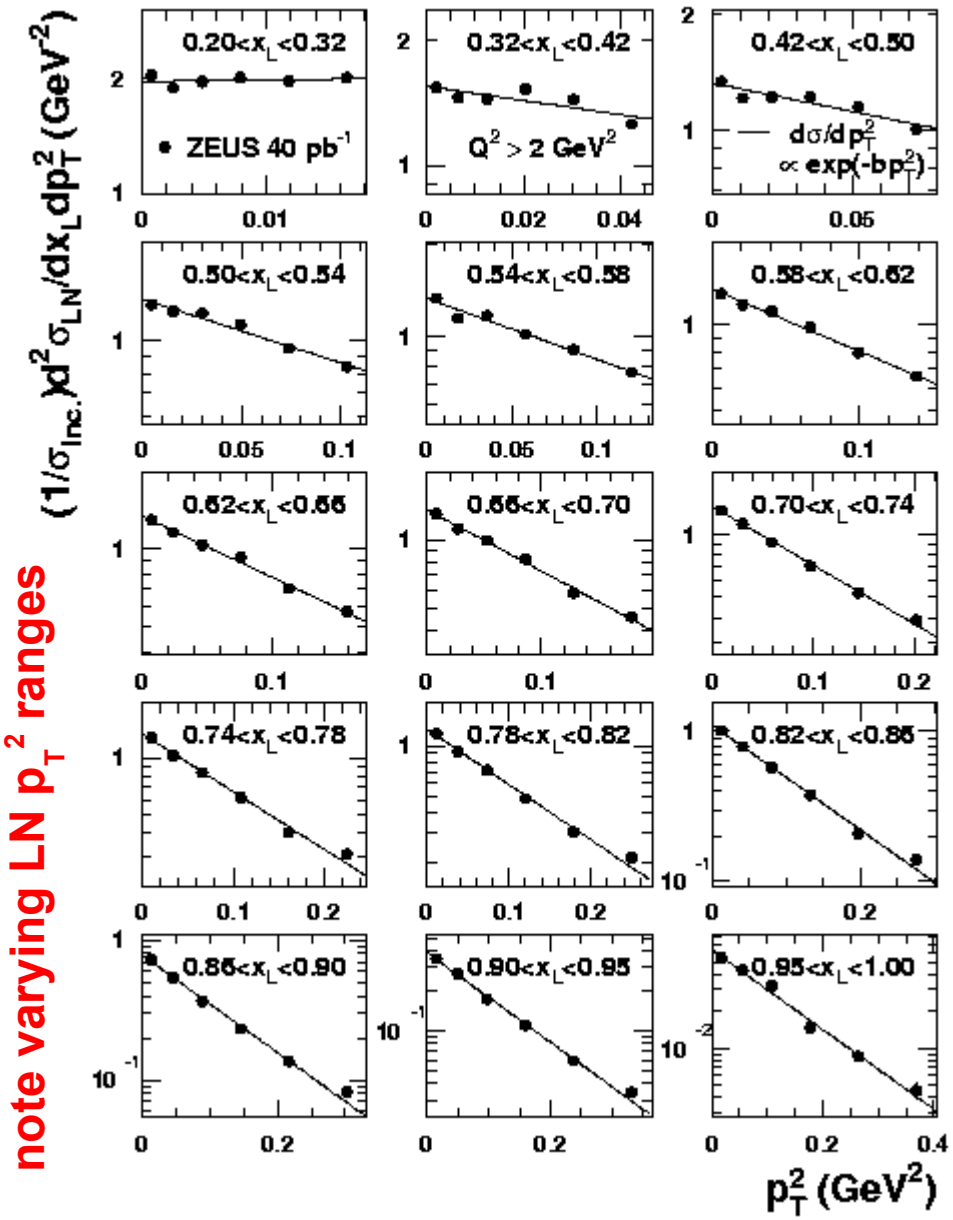


- For pure *isovector* exchange isospin Clebsch-Gordan $\Rightarrow r_{LP} = ½\, r_{LN}$
- Data: $r_{LP} \approx 2\, r_{LN}$
- $\Rightarrow$ additional exchanges (*isoscalar*) needed for LP

p_T^2 distributions DIS

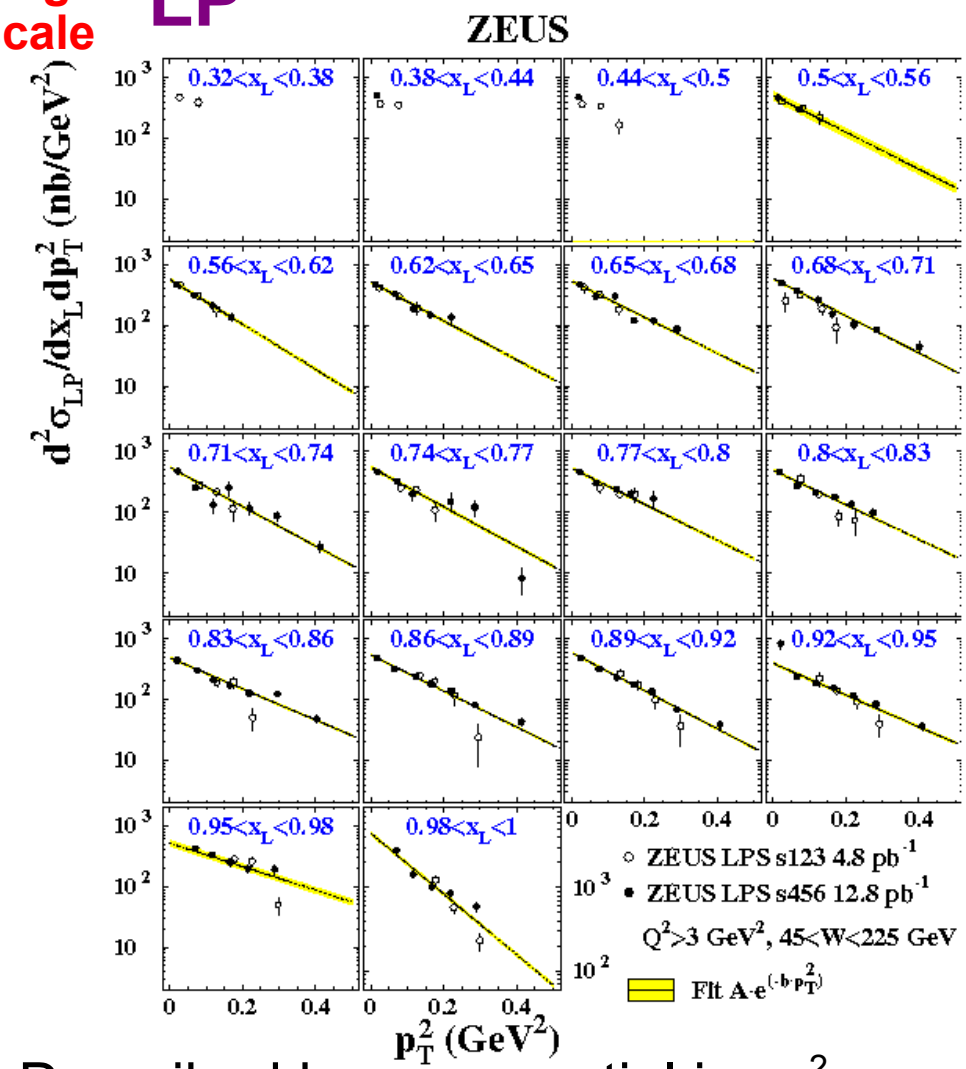
$$\frac{1}{\sigma_{inc}}\frac{d^2\sigma_{LN}}{dx_L dp_T^2}$$

ZEUS **LN**



note varying LN p_T^2 ranges

log scale **LP**



fixed LP p_T^2 range

- Described by exponential in p_T^2:

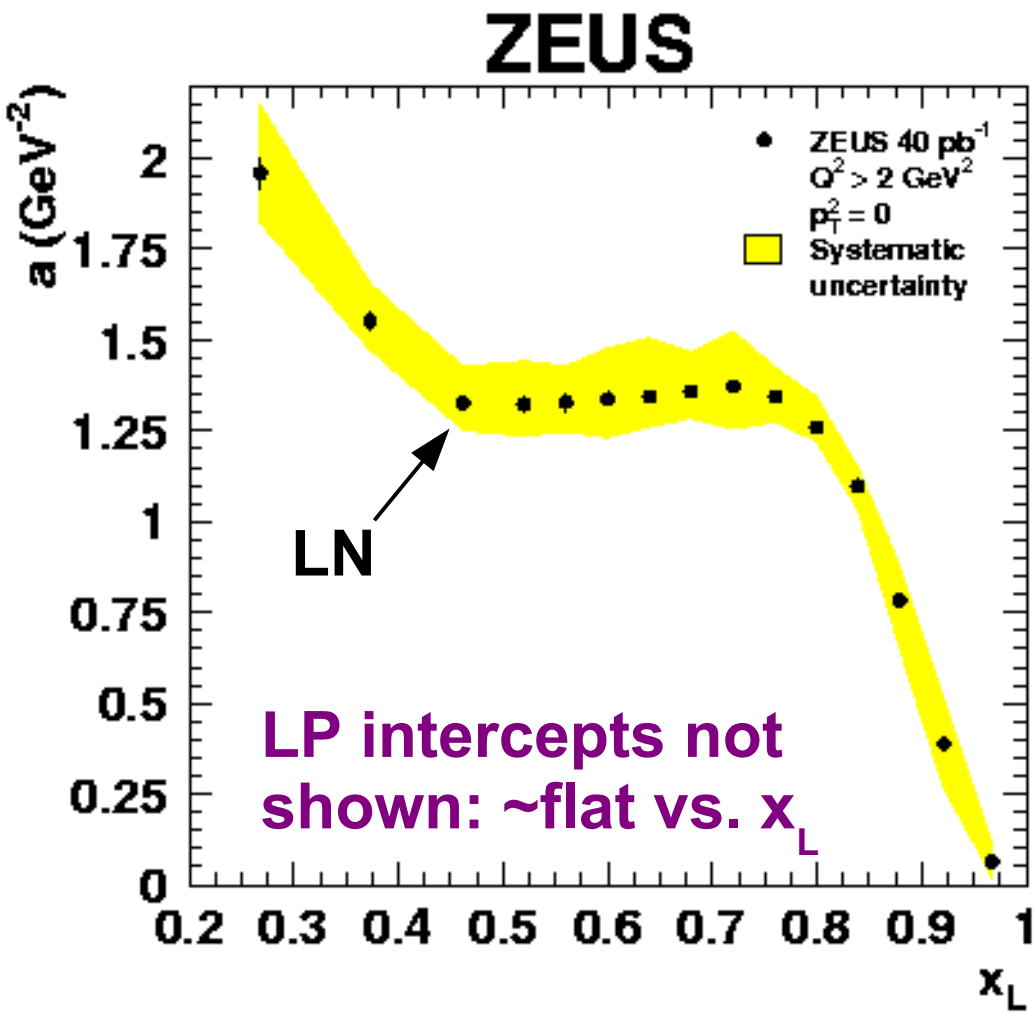
$$\frac{1}{\sigma_{inc}}\frac{d^2\sigma_{LN}}{dx_L dp_T^2} = a(x_L)e^{-b(x_L)p_T^2}$$

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

DIS p_T^2 distributions: slopes & intercepts

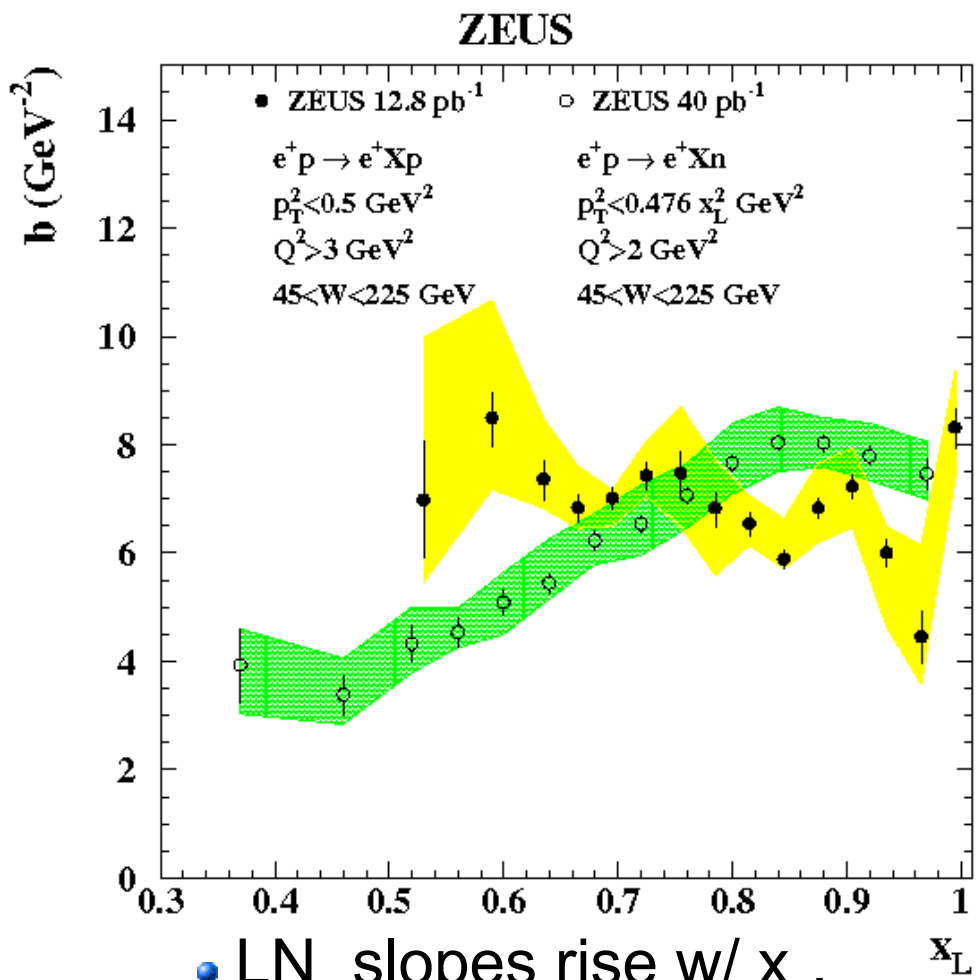
$$\frac{1}{\sigma_{inc}}\frac{d^2\sigma_{LN}}{dx_L dp_T^2} = a(x_L)e^{-b(x_L)p_T^2}$$

- LN intercepts $a(x_L)$:



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

- LB slopes $b(x_L)$:



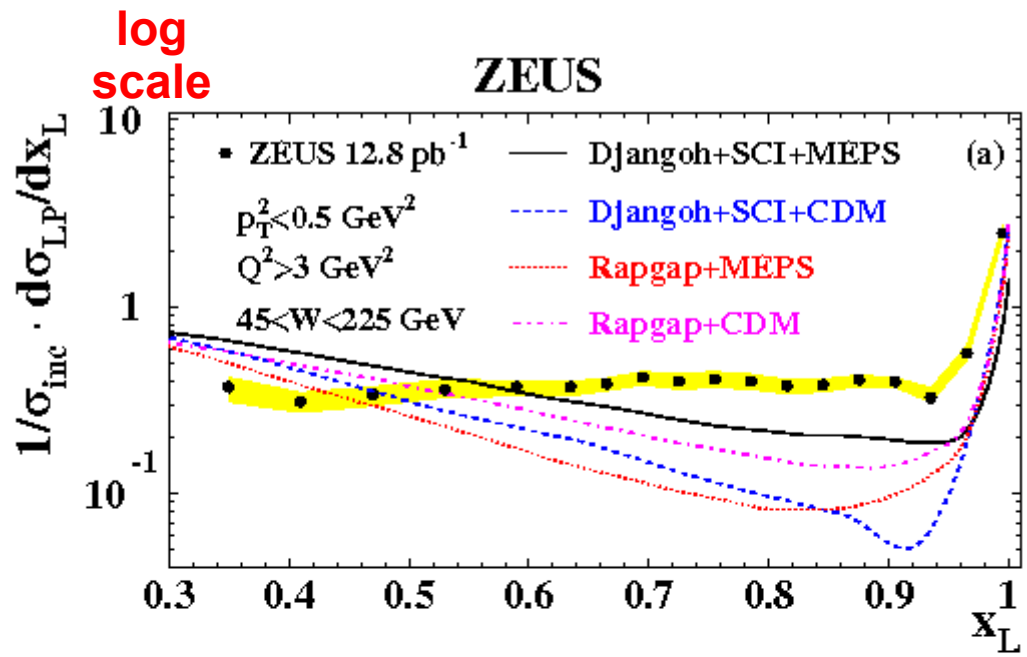
- LN slopes rise w/ x_L, turnover $x_L \to 1$
- LP slopes ~flat w/ x_L

Model comparisons: DIS LP x_L

'Standard fragmentation' MCs:

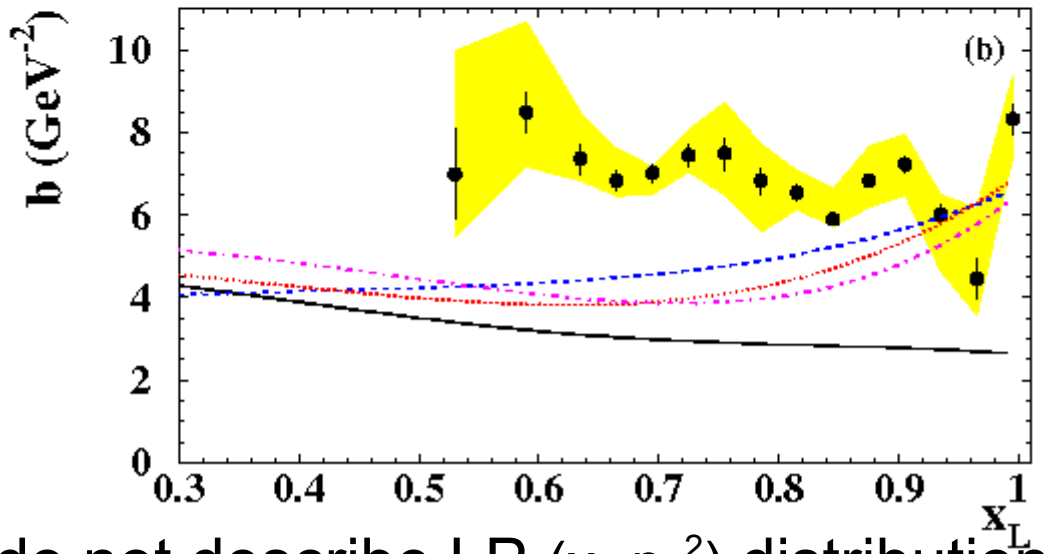
- MC yields all fall with x_L

  (except diff. peak ~1)
- Not flat like data, fail



- MC 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

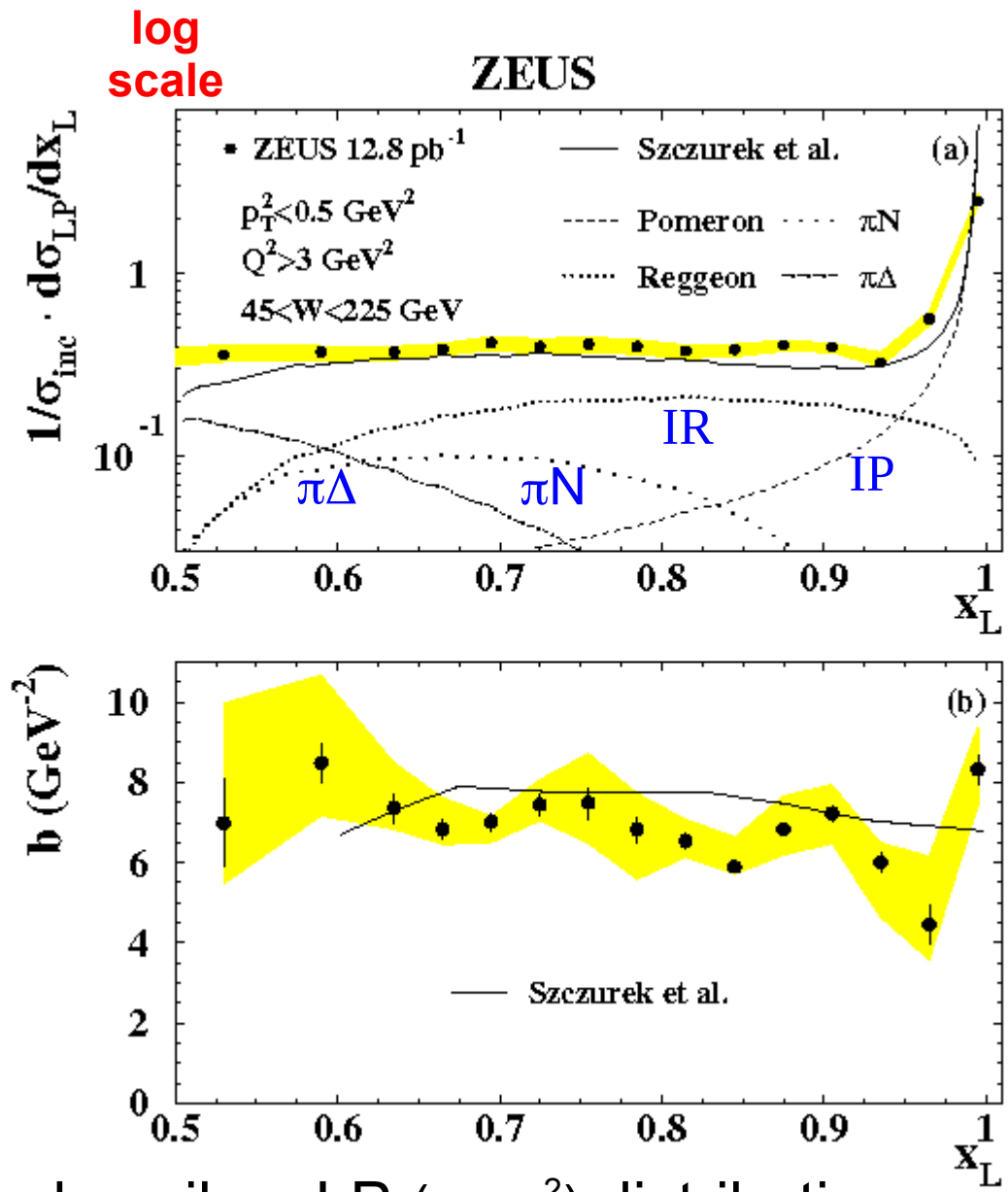
Model comparisons: DIS LP x_L

Model with exchanges of

<u>several isoscalars/vectors:</u>

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

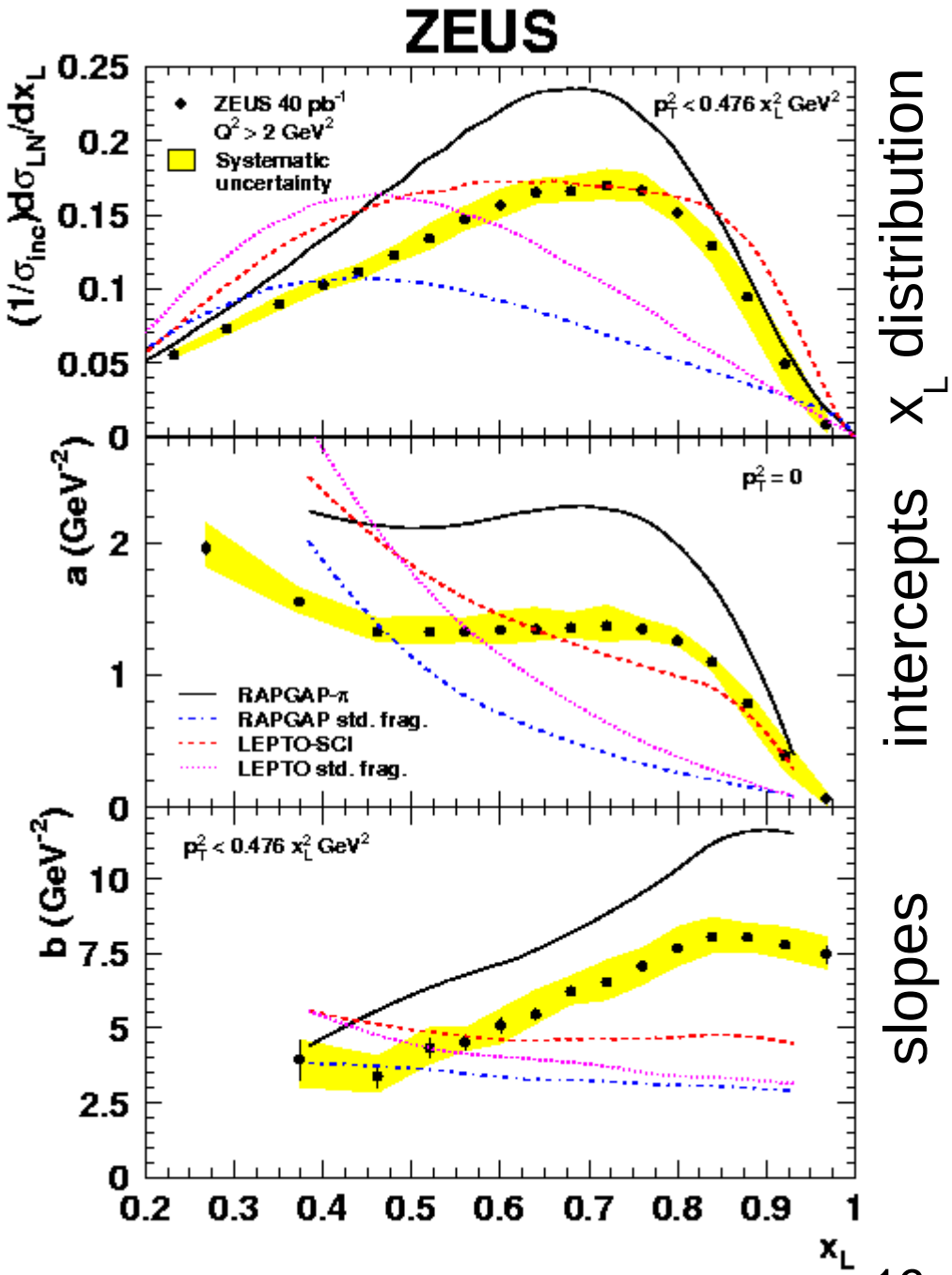
- Different xch's sum to flat slope b as function of x_L



- <u>Model with multiple exchanges describes LP (x_L, p_T^2) distributions</u>

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
- Std. frag.: too few *n*, peak too low x_L
- LEPTO-SCI ~OK in shape, magnitude, but slopes too small, ~not x_L dependent
- **RAPGAP w/ π-xch. closest to data**
  normalization and slopes too high

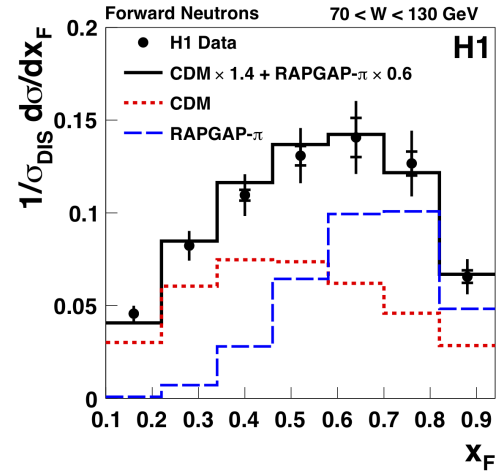


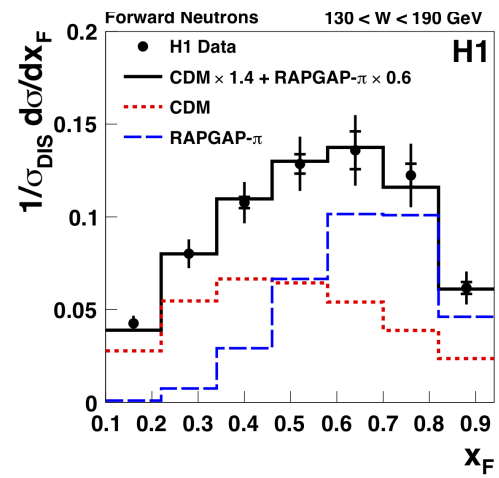
Model comparisons: DIS LN

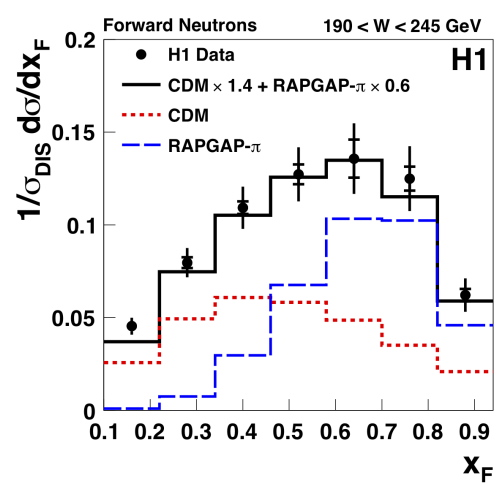
- Compare to MC models:
  - Color Dipole Model (ARIADNE, in DJANGOH)
  - RAPGAP pure π-exchange
- Each model alone: wrong x_L shape

  CDM too low x_L, RAPGAP-π too high x_L
- Sum of models describes x_L shape
- Other DIS, γp std. frag. models also fail:

  ARIADNE, CASCADE, PYTHIA, PHOJET, ...







Compare π-xch. models: DIS LN slopes

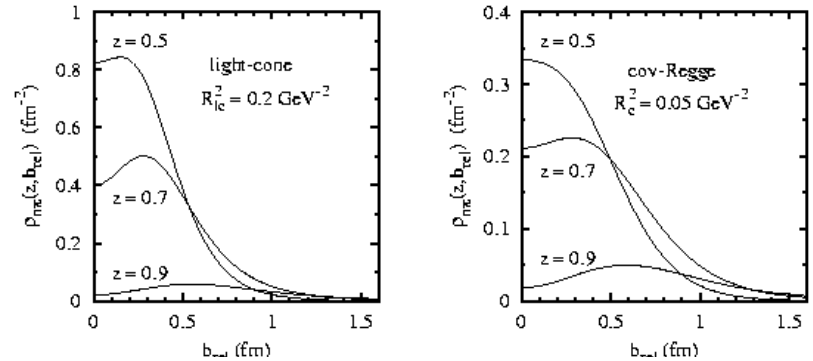
- Numerous parameterizations of pion flux $f_{\pi/p}(x_L,p_T)$ in literature
- Coordinate space $r_{n\text{-}\pi}$ distributions:

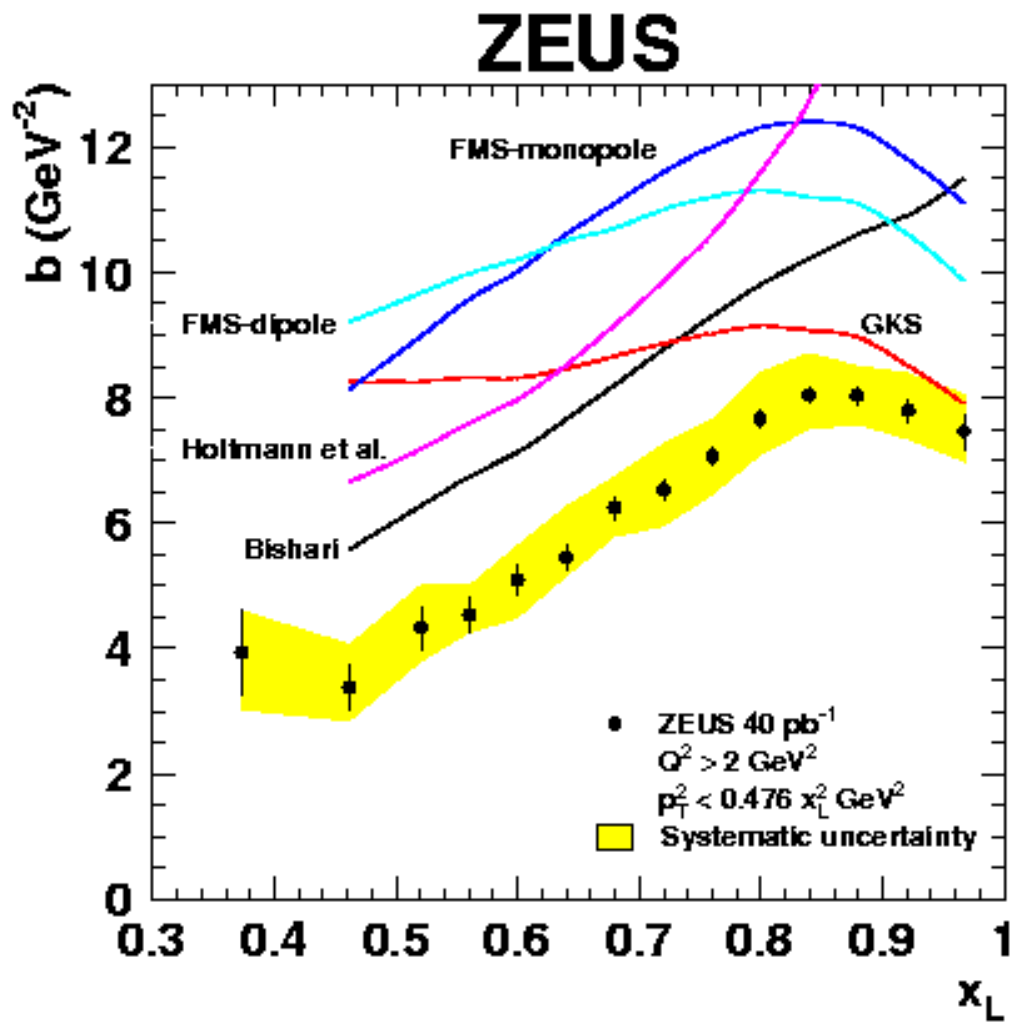
  @ lower x_L=z ⇒ lower mean $r_{n\text{-}\pi}$

  ⇒ higher mean p_T ⇒ lower slope b
- Compare measured DIS $b(x_L)$:
- Best agreeing models shown here; others wildly off
- All give too large $b(x_L)$
- More refinement needed:

  ⇒ rescattering migration & loss

  ⇒ investigate Q^2 dependences

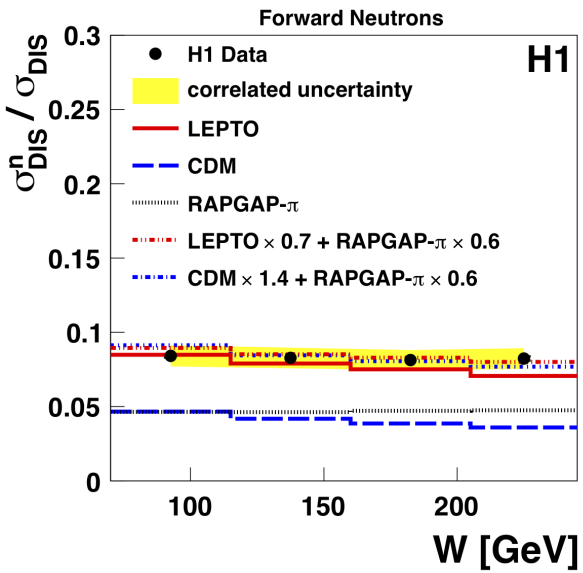




$W_{\gamma p}$, y, Q^2 dependence of LN production

- DIS kinematic variables, LB yield dependences:

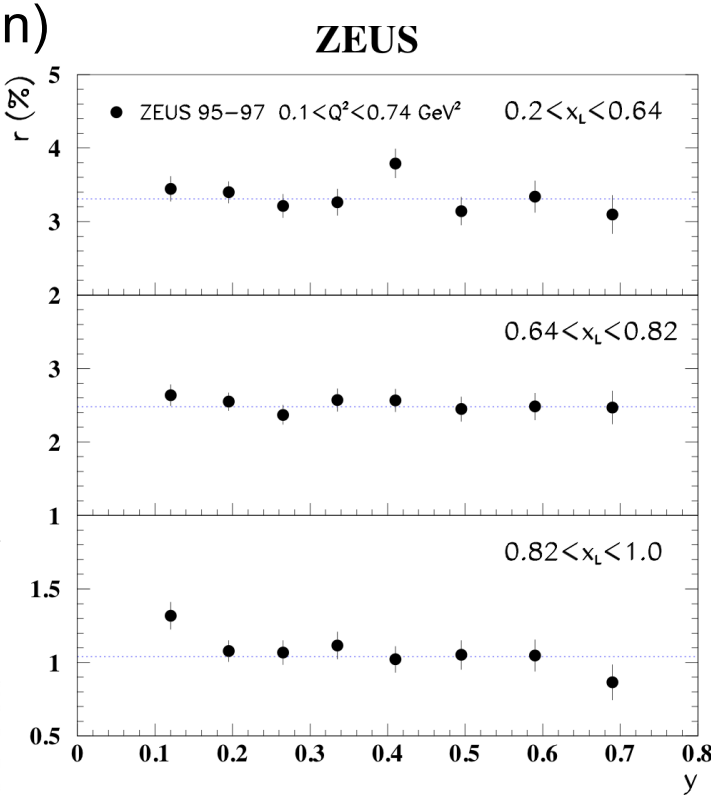
  (detector acceptance induces some variable correlation)

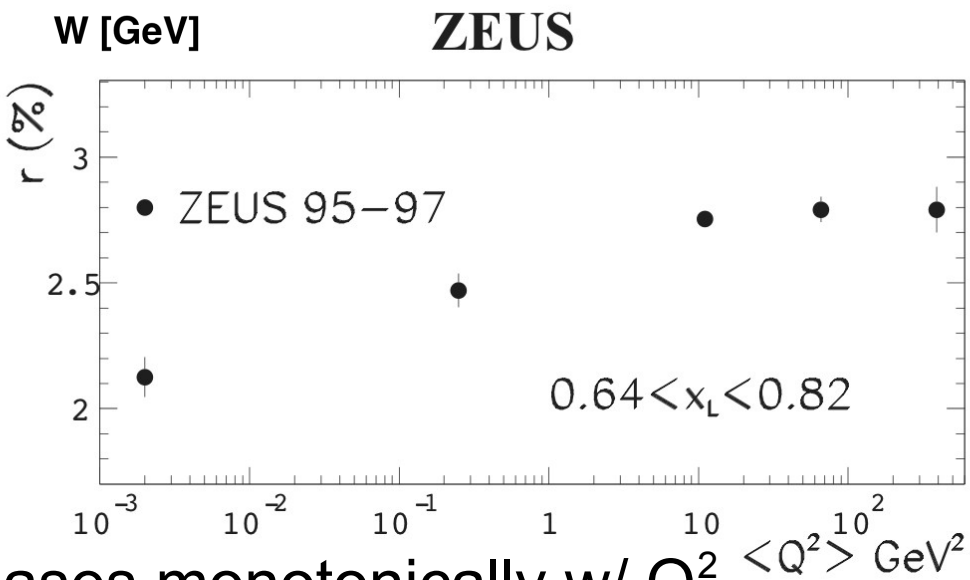


- LN yield independent of:

  ← $W_{\gamma p}$

  inelasticity y →



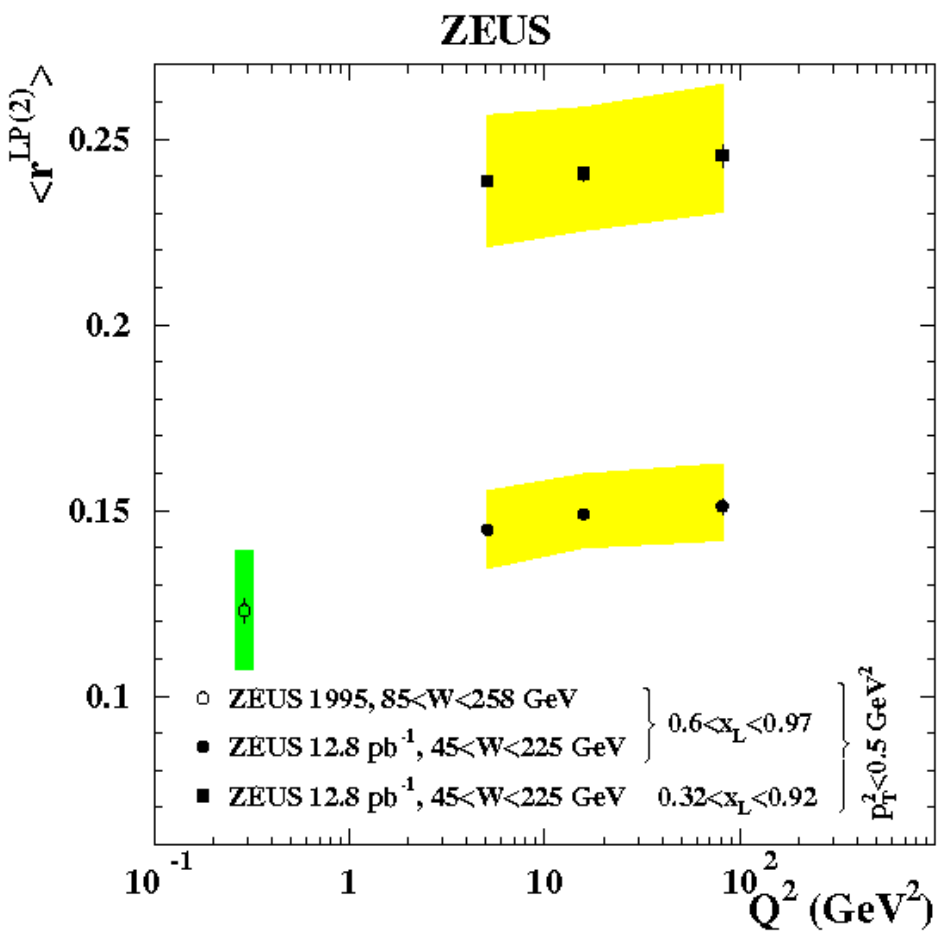


- LN yield increases monotonically w/ Q^2
- Consistent w/ rescattering: larger $Q^2 \Rightarrow$ smaller γ, less rescattering

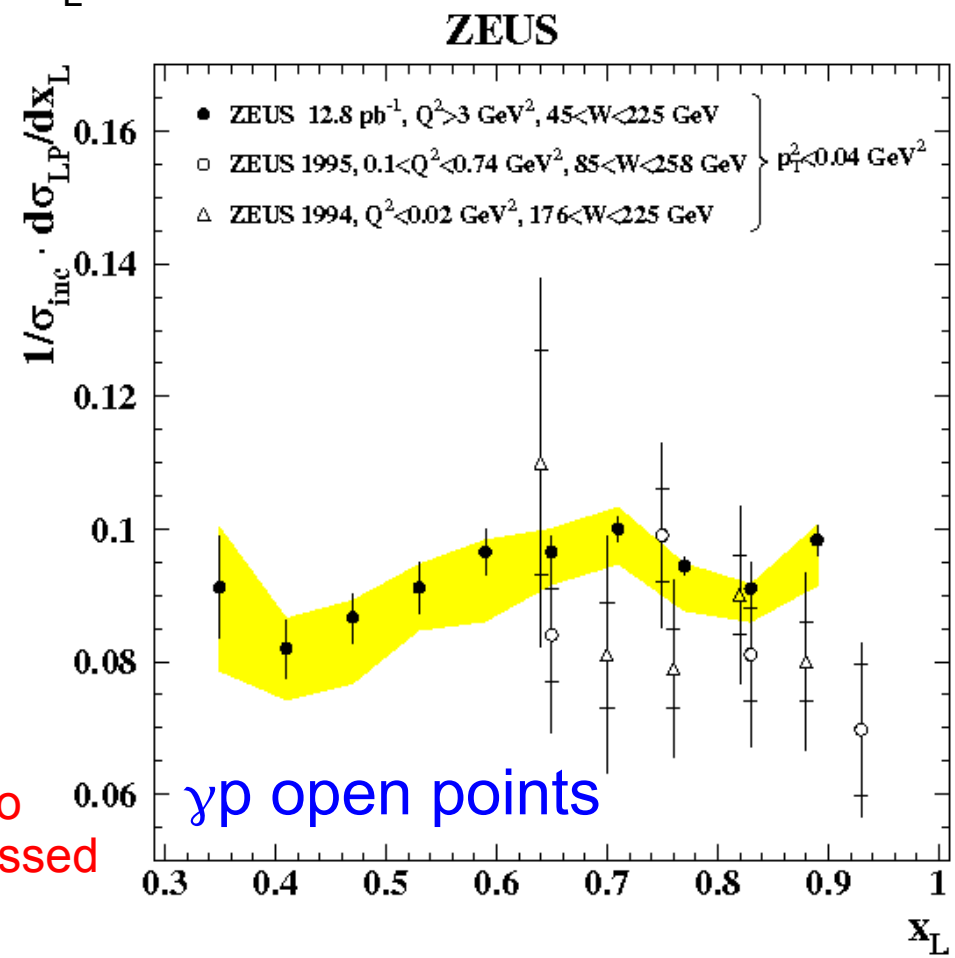
Q^2 dependence of LP production

DIS + γp:

- Total yield vs. Q^2, 2 x_L ranges:



- x_L distributions:



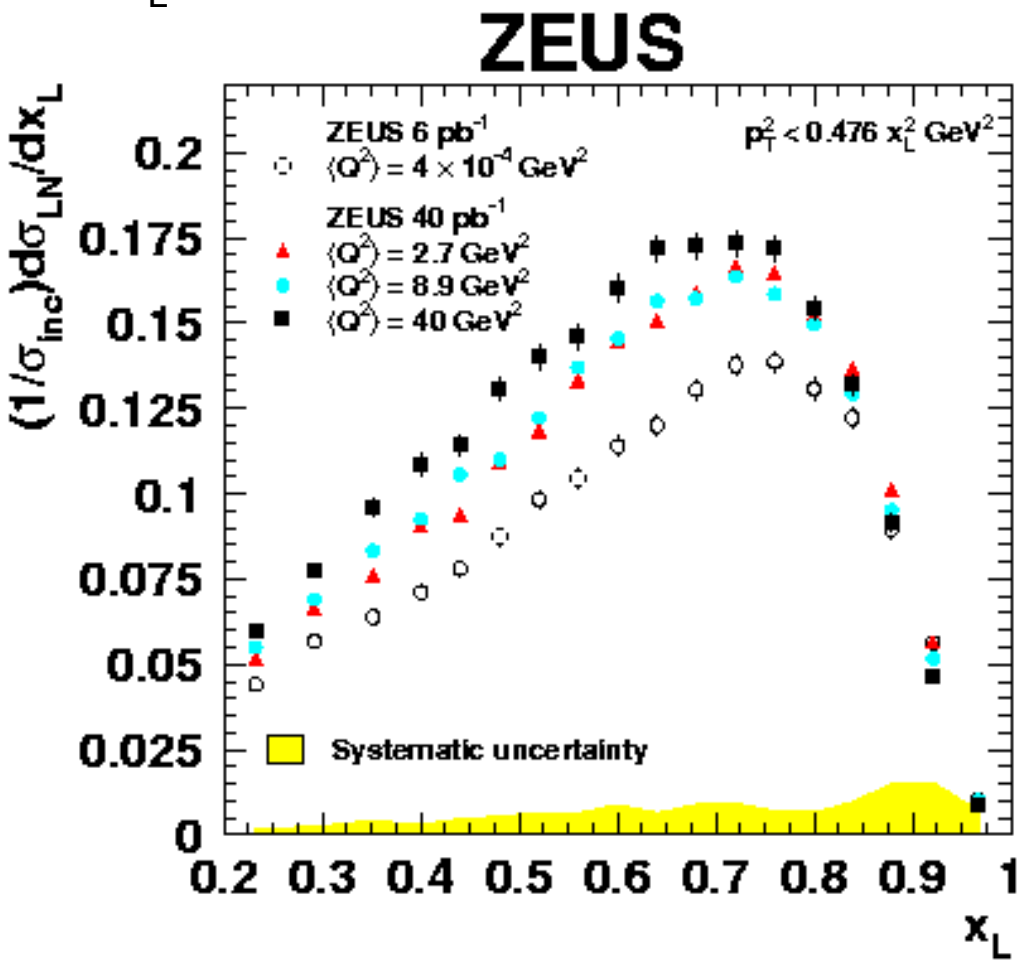
zero suppressed

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

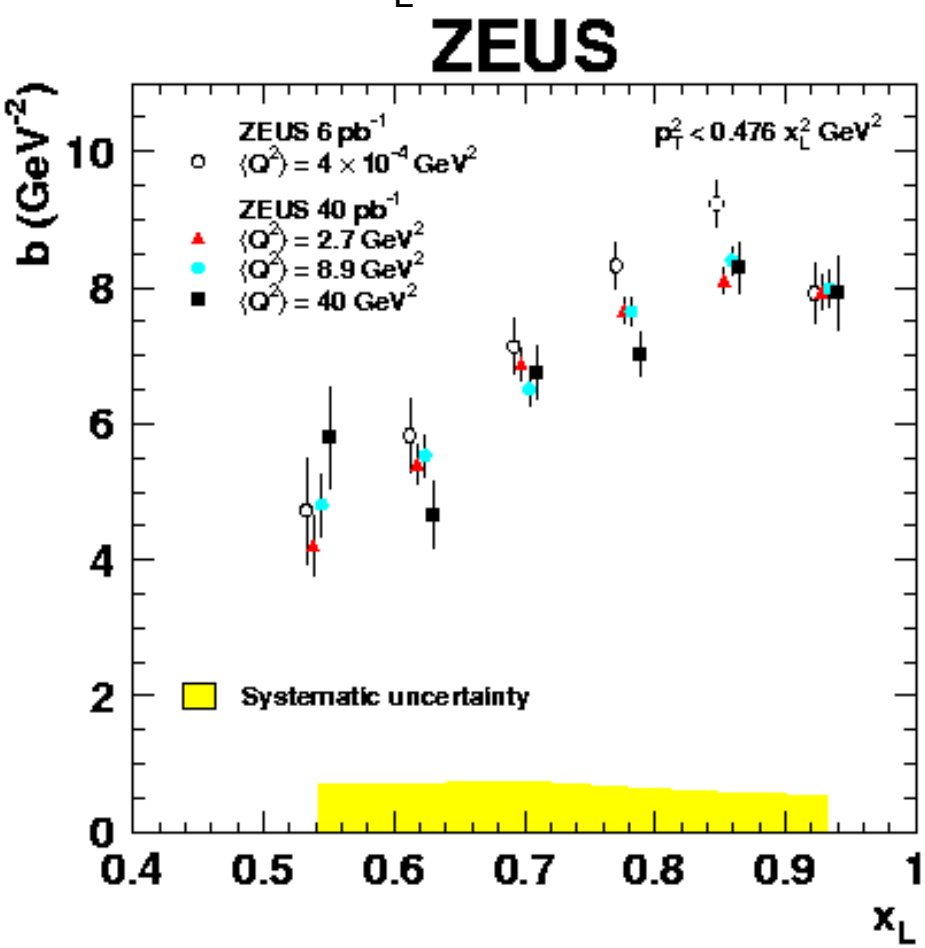
Q^2 dependence of LN production

3 Q^2 bins DIS + γp:

- x_L distributions:



- slopes $b(x_L)$:



- LN yield increases monotonically w/ Q^2
- Consistent w/ rescattering:

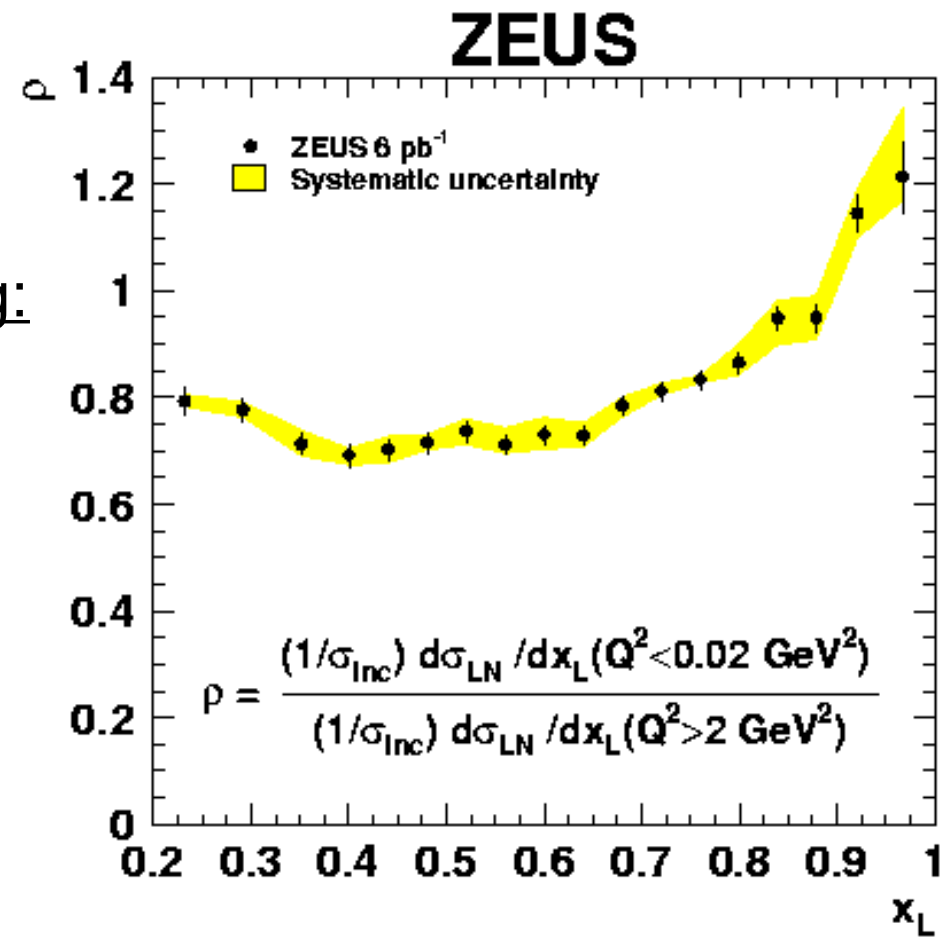
  larger $Q^2 \Rightarrow$ smaller γ, less rescattering

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

Compare γp/DIS: LN x_L distributions

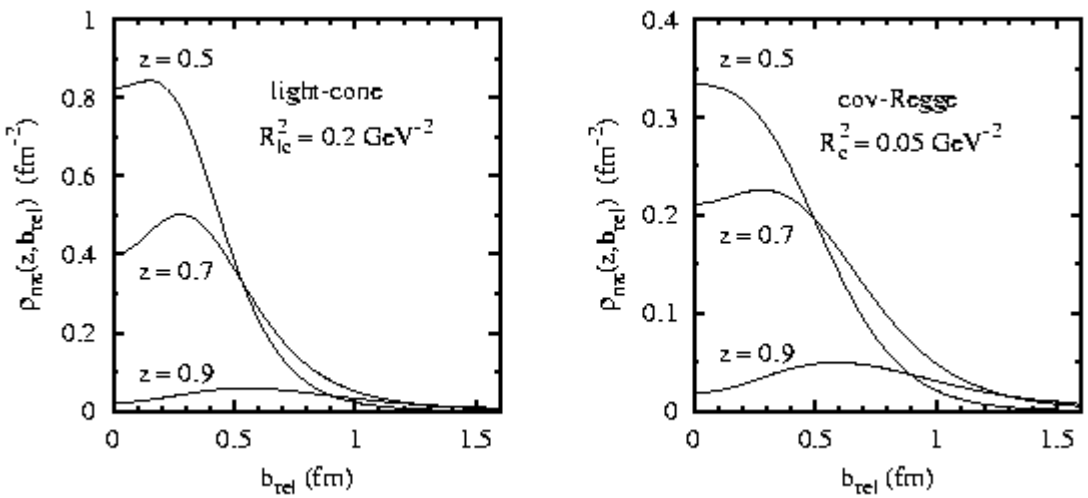
- Combine all DIS Q^2>2 GeV^2, compare to γp x_L dist.: ratio

Ratio γp/DIS: ~70% mid-x_L
rising higher x_L



<u>Qualitatively consistent w/ rescattering:</u>

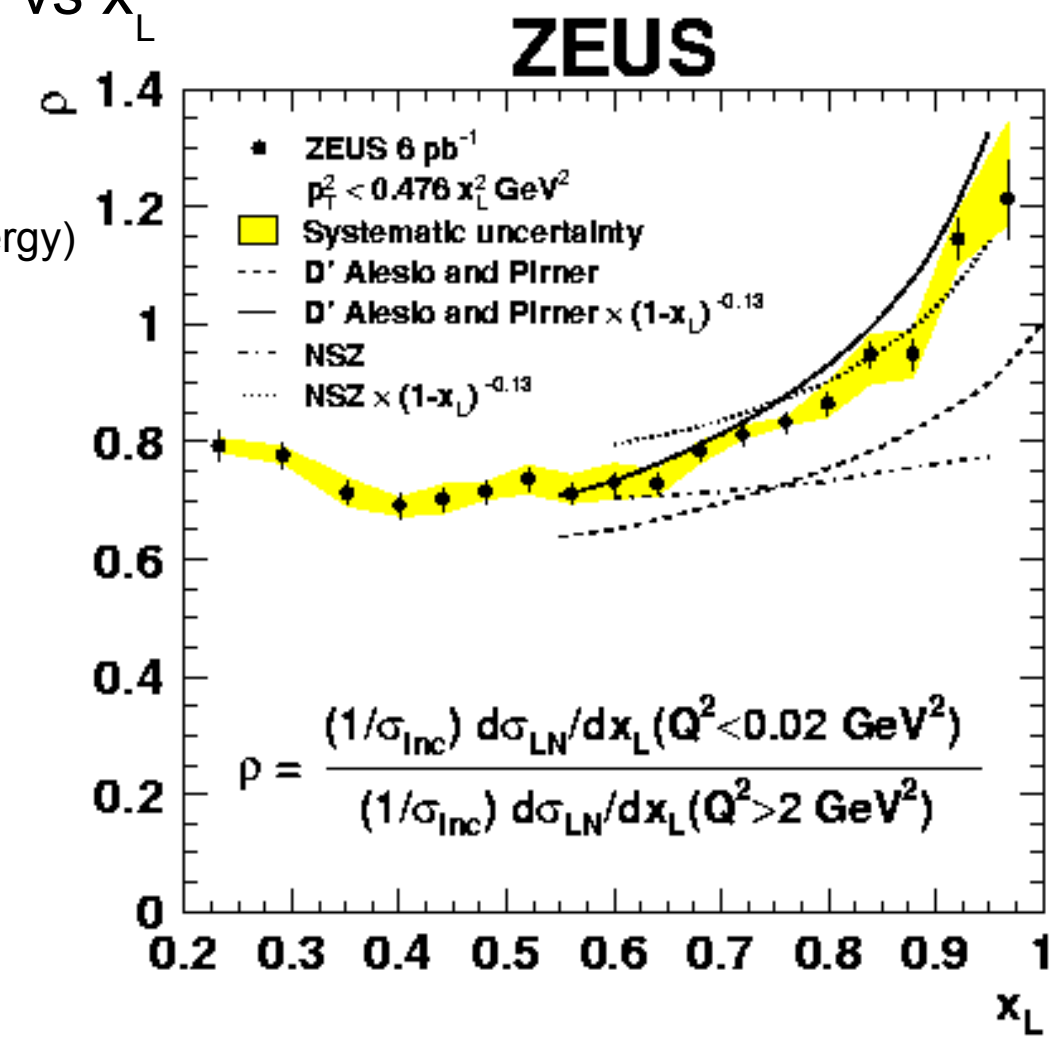
- Exchange model: mean n-π separation $r_{n\text{-}\pi}$ smaller at lower x_L=z:



- Or from b(x_L): @ lower x_L ⇒ lower b-slope ⇒ higher mean p_T ⇒ smaller mean $r_{n\text{-}\pi}$
- Smaller $r_{n\text{-}\pi}$ ⇒ more rescattering at lower x_L as in data

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

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



<u>Also W dependence:</u>

- Know for $\gamma^{(*)}p$: $\sigma \propto W^{\alpha}$ (W = $\gamma^{(*)}$p c.m. energy)

  $\sigma_{\gamma p}$, $\sigma_{DIS\text{-}p}$ have different α's
- Assume same α's for p$\rightarrow\pi$
- Also: $W^2_{\gamma\pi} = (1-x_L)W^2_{\gamma p}$
- LN $\sigma_{\gamma p}/\sigma_{DIS\text{-}p}$ inherits x_L dependence

  $\Rightarrow$ scale rescattering factor

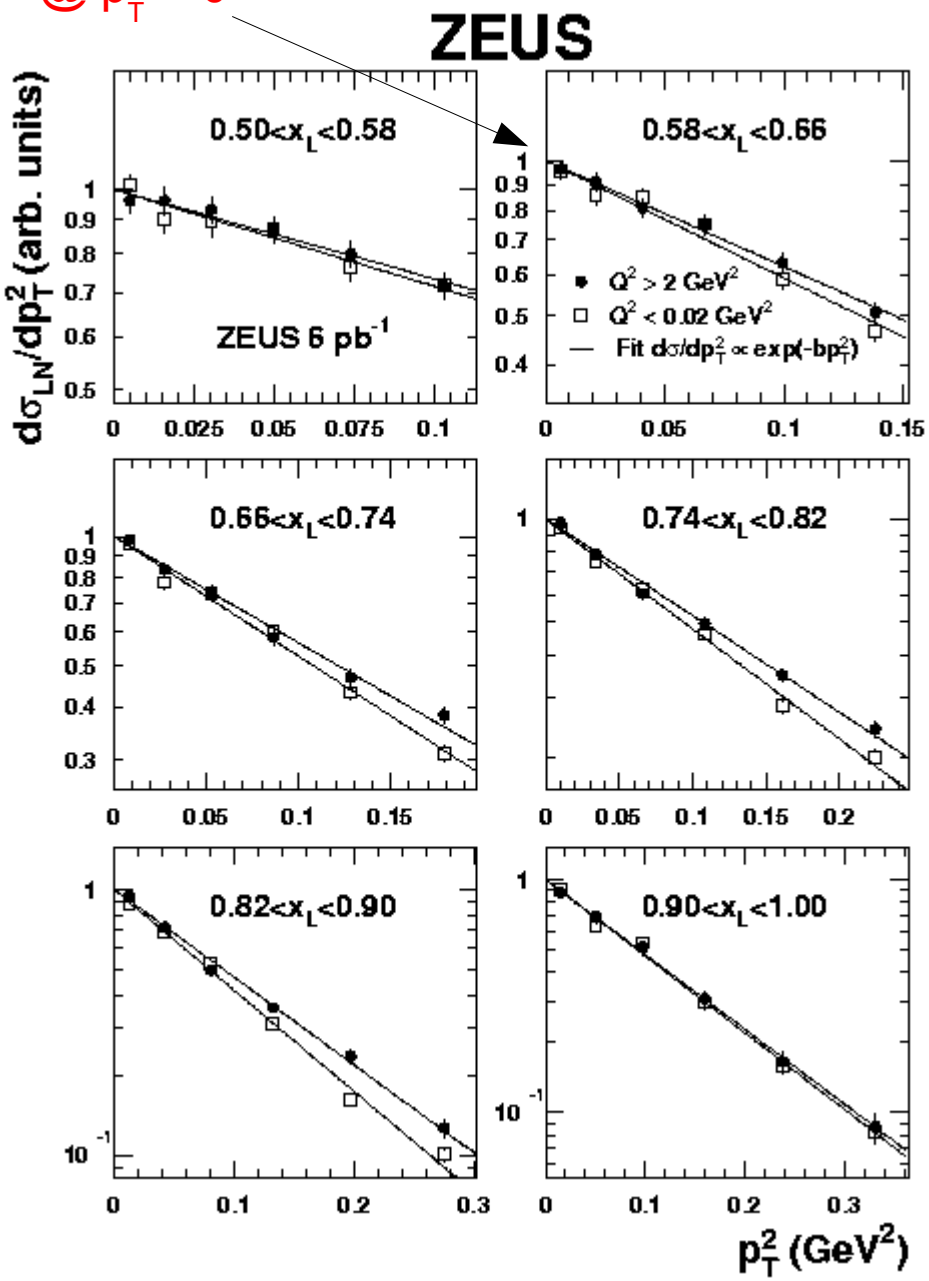
  by $(1-x_L)^{-0.13}$ (0.13 from different α's)
- Nice agreement with data (solid line)

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

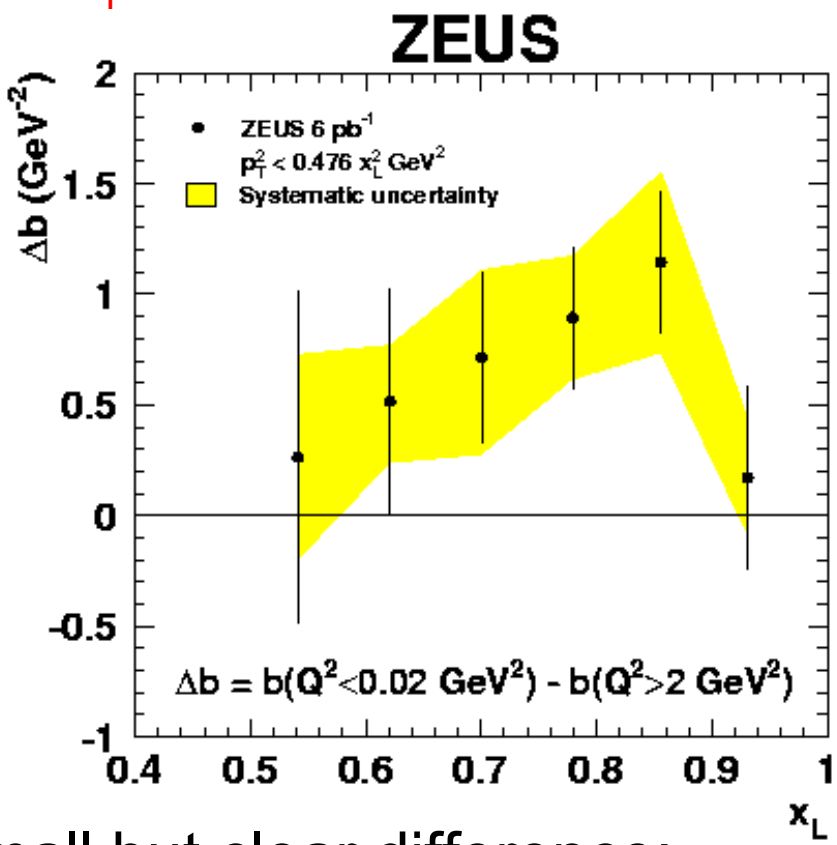
Compare γp/DIS: LN p_T^2 distributions

normalized @ $p_T^2 = 0$

p_T^2 distributions:



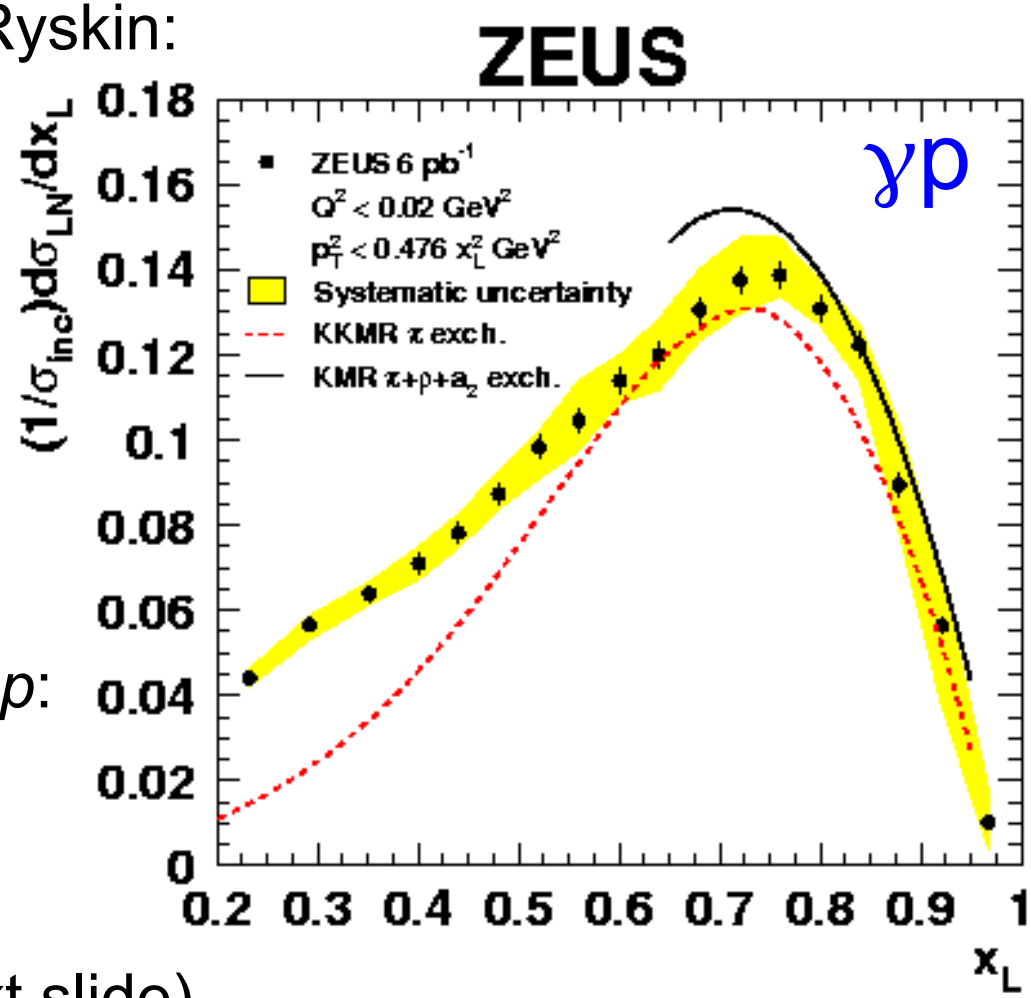
p_T^2 slope differences Δb:



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

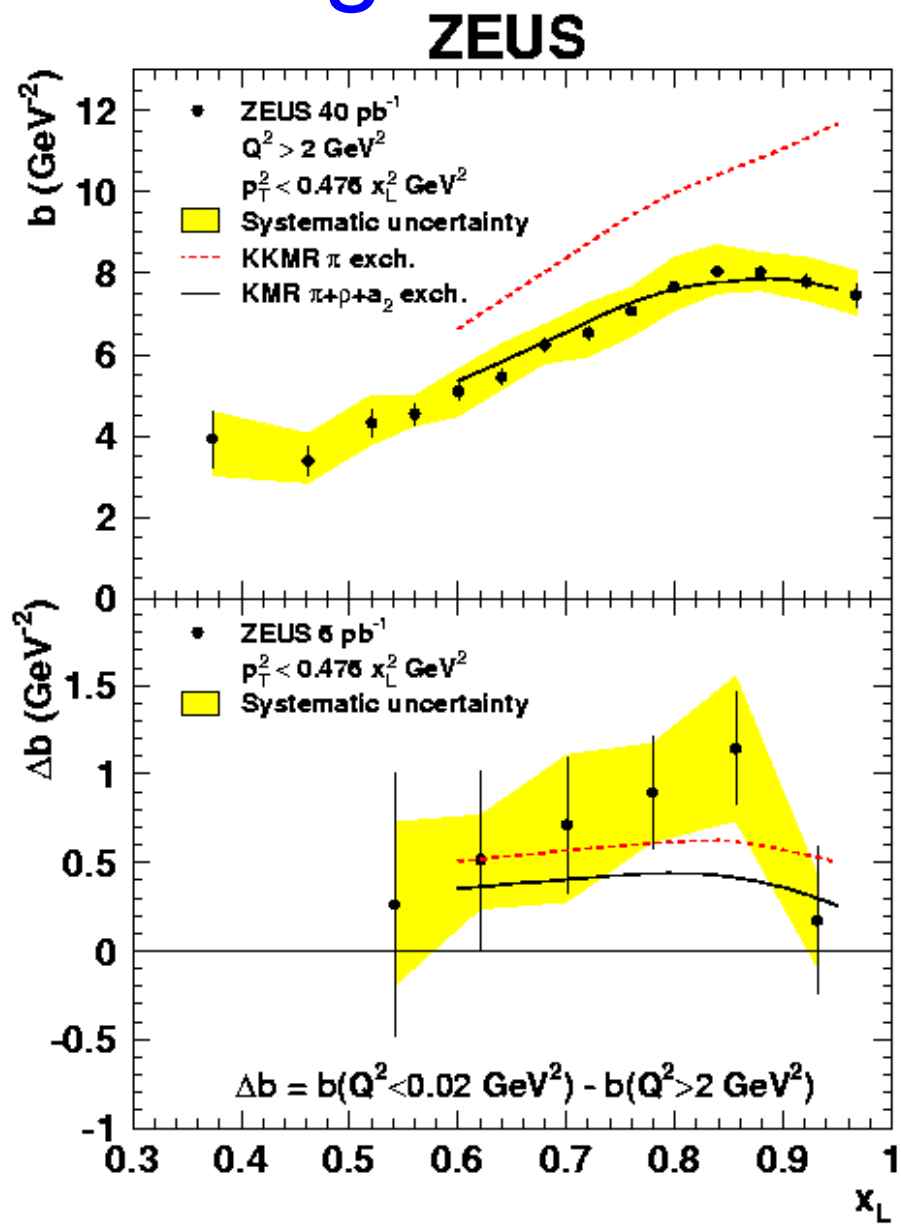
Compare: π-xch. w/ rescattering loss, migration, other exchanges

- 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 next slide)
- Again reasonable agreement with LN in γp



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

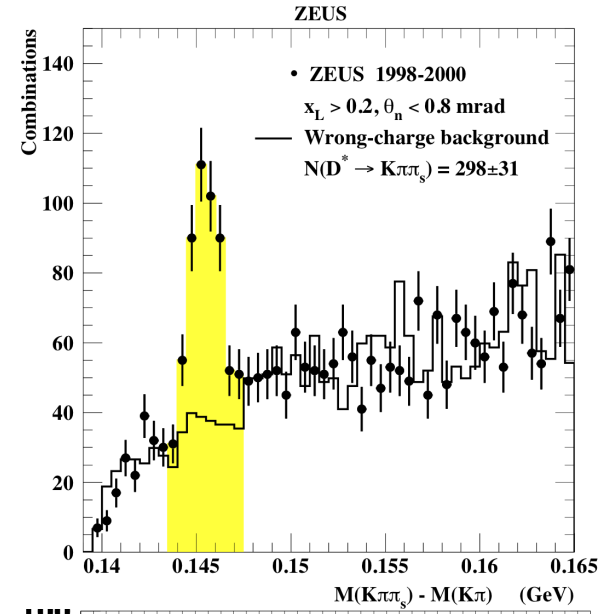
- Rescattering loss+migration with pion exchange alone does not describe slopes; too high in magnitude, no turnover @ high x_L, Δb ~ OK
- Addition of (ρ,a_2) exchanges gives good description of both slope magnitudes and x_L dependence, Δb still OK

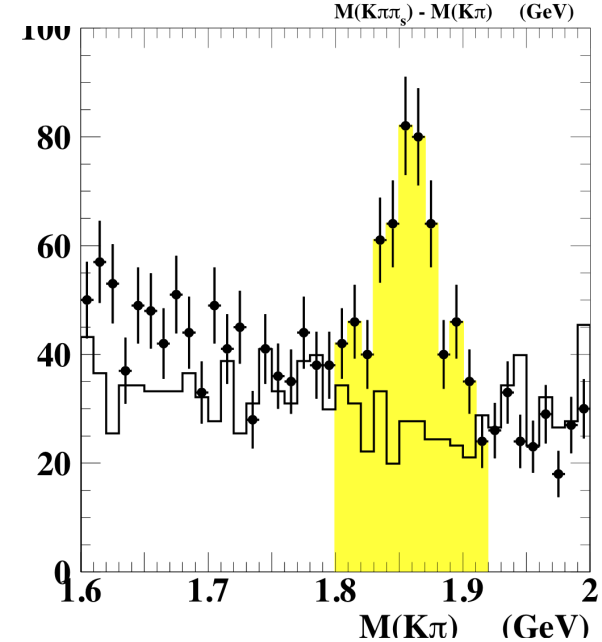


- <u>Full model with multiple exchanges, rescattering best describes LN</u>

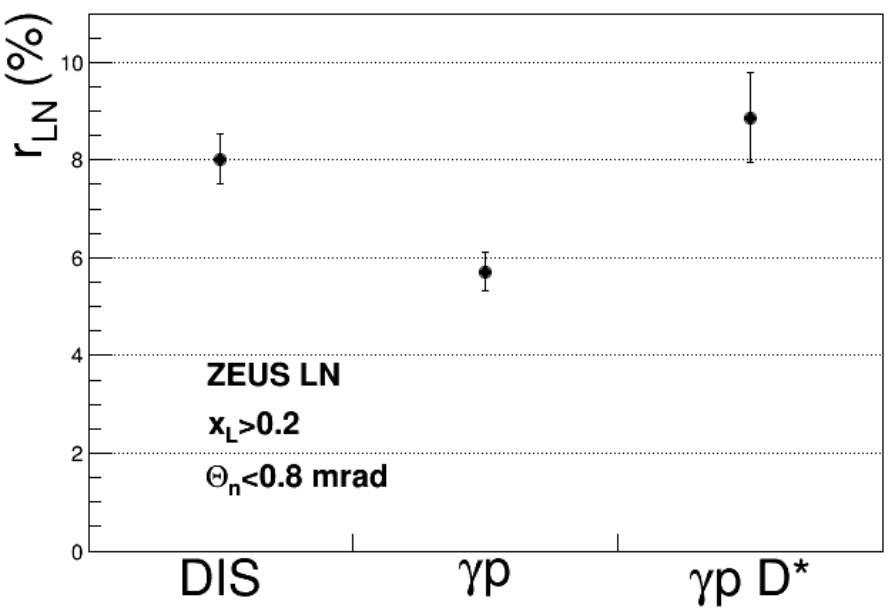
Compare LN in γp+D*, DIS & inclusive γp

- We have seen clear effects consistent with rescattering going hi-$Q^2 \rightarrow$lo-$Q^2 \rightarrow \gamma p$
- Going from hard→soft scale increase in rescattering
- Suppose in γp we reintroduce a hard scale by requiring heavy flavor: γp+D* with LN:





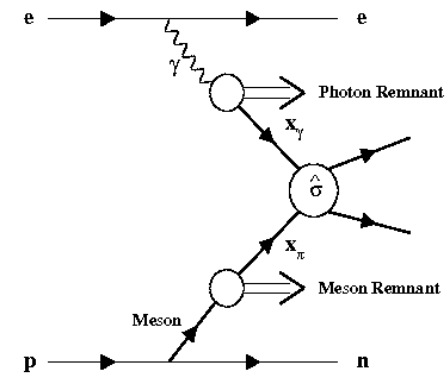
- Yield γp+D* ~ DIS, clearly higher than inclusive γp:

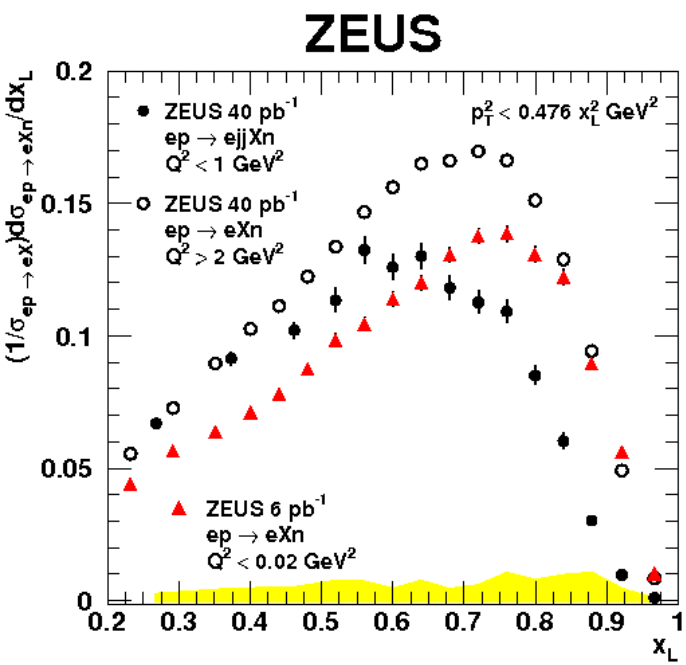


- Hard scale (charm) in γp, small photon, no clear rescattering

Compare LN in γp+jj, DIS & inclusive γp

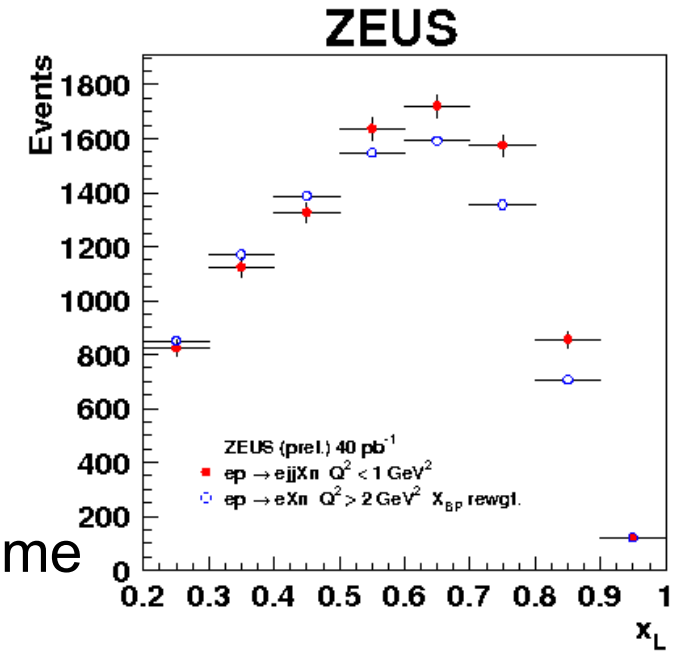
- Suppose in γp we reintroduce a hard scale by requiring high E_T dijet: γp+jj with LN:
- LN x_L in γp+jj very different from DIS, inclusive γp suppression @ high x_L, not low x_L
- Kinematics of high E_T dijets?





data → reweighted DIS

- Reweight DIS distribution, account for dijet/DIS kinematic constraints
- After reweight: shape & normalization ~same

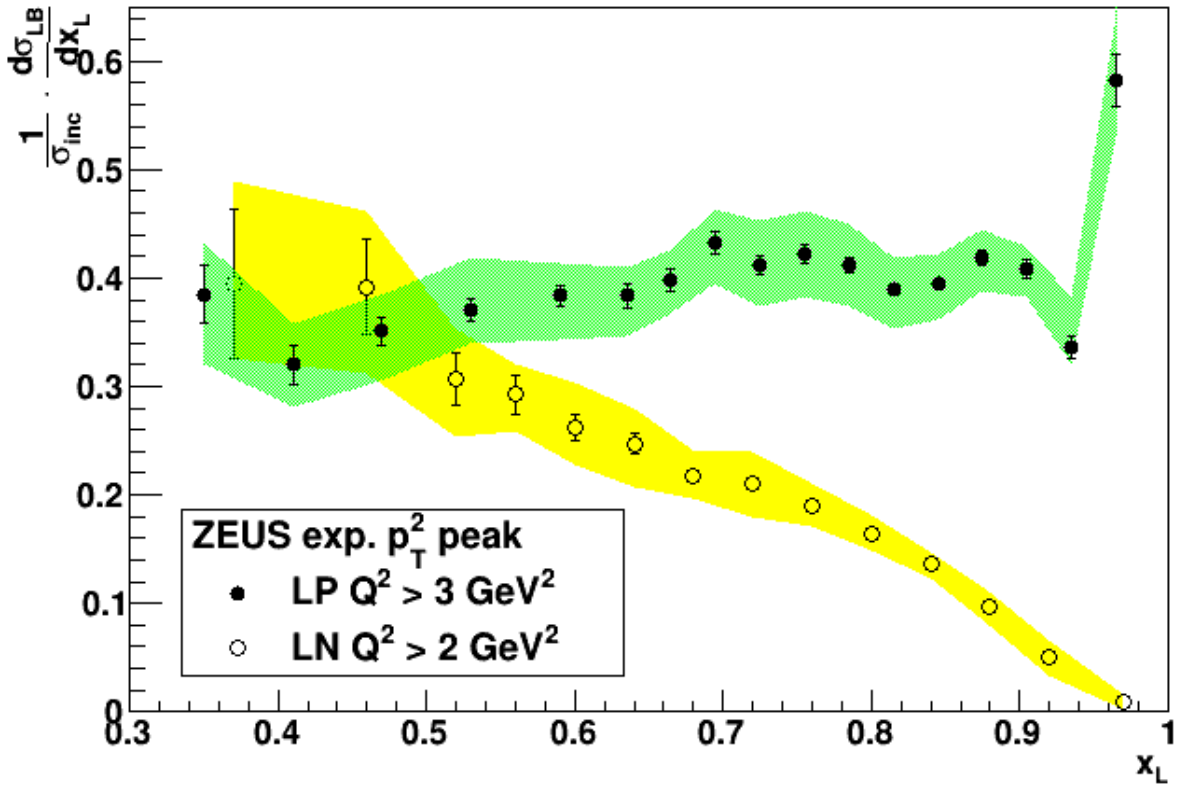


- Interpretation complicated by kinematics, but to 1st order: Hard scale (dijet) in γp, small photon, no clear rescattering

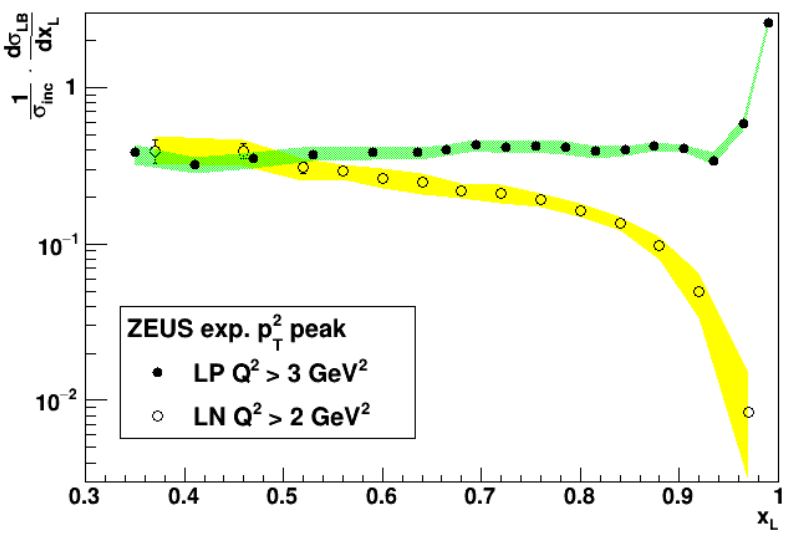
More details on extra slides, ZEUS LN+jj publication

Total LB rate in DIS

- ~ Exponential p_T^2 distributions observed in LB detector acceptance
- Extrapolate to $p_T^2 \rightarrow \infty$: LB rate in exponential peak



log scale



Integrate over x_L:

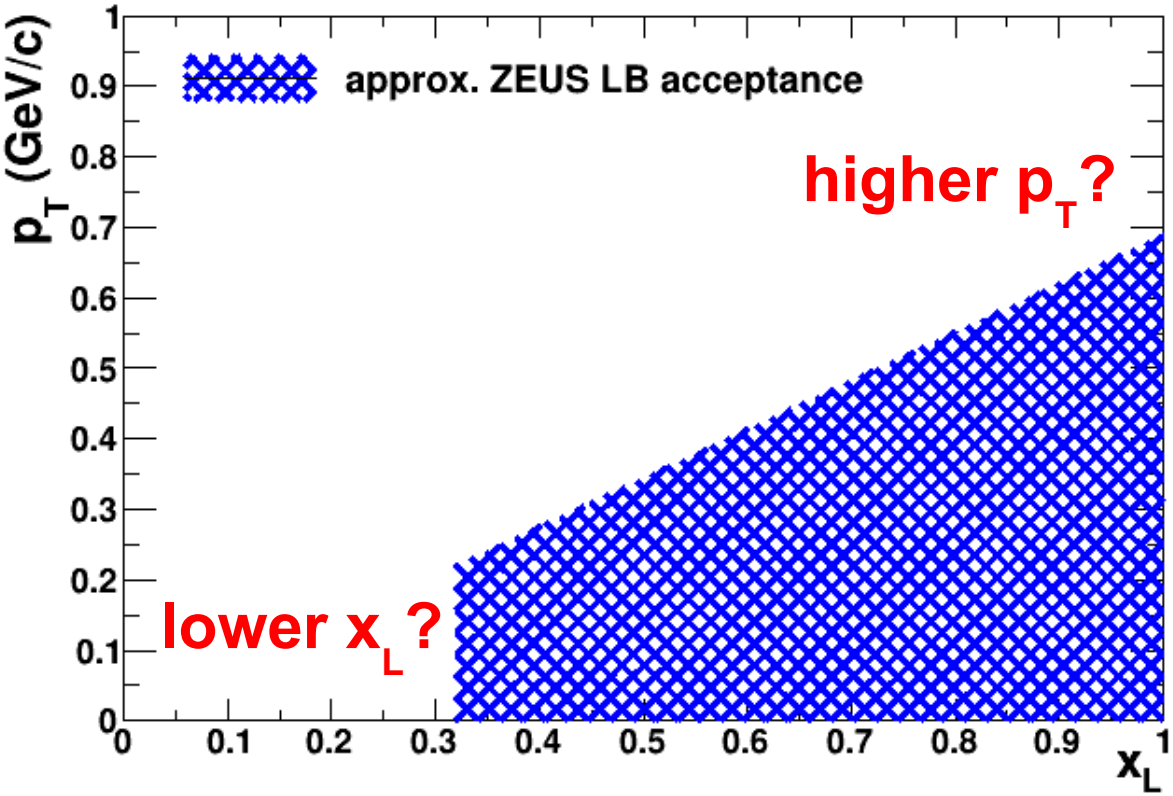
- $r_{LP}(x_L > 0.32) = 0.310 \pm 0.003$ (stat.) ± 0.008 (syst.)
- $r_{LN}(x_L > 0.32) = 0.159 \pm 0.008$ (stat.) ± 0.012 (syst.)
- $r_{LB}(x_L > 0.32) = 0.469 \pm 0.009$ (stat.) ± 0.014 (syst.)

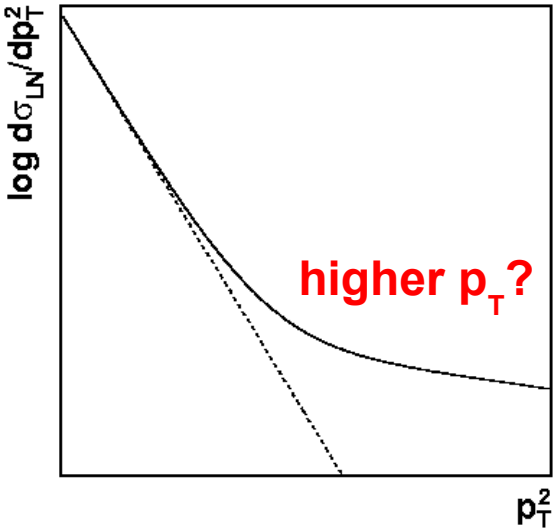
Total LB rate in DIS

Sum for total LB rate in exponential peak:

- $r_{LB}(x_L > 0.32) = 0.469 \pm 0.009$ (stat.) ± 0.014 (syst.)

- Nearly ½ final state baryons in exp. p_T^2 peak
- Impressive that these low-acceptance detectors account for ~half of baryons
- Where are the rest?

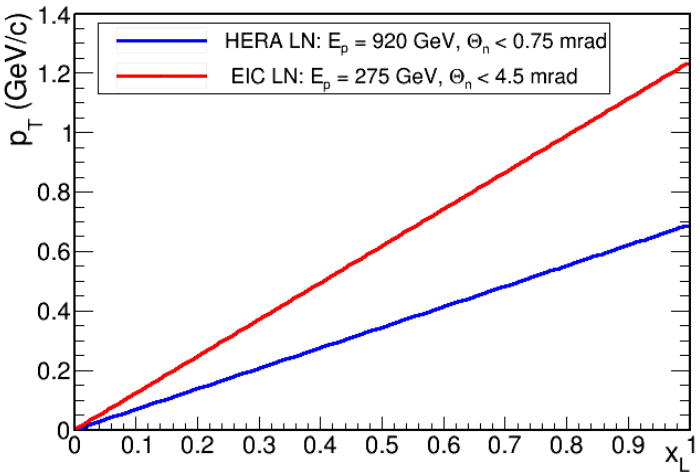




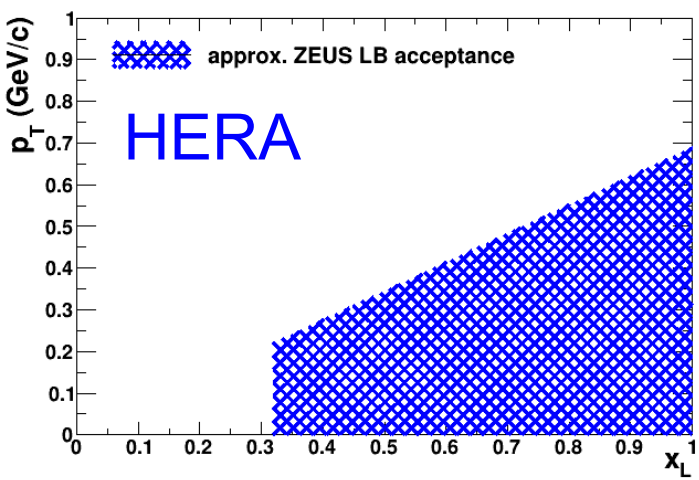
Open question, address @ EIC?

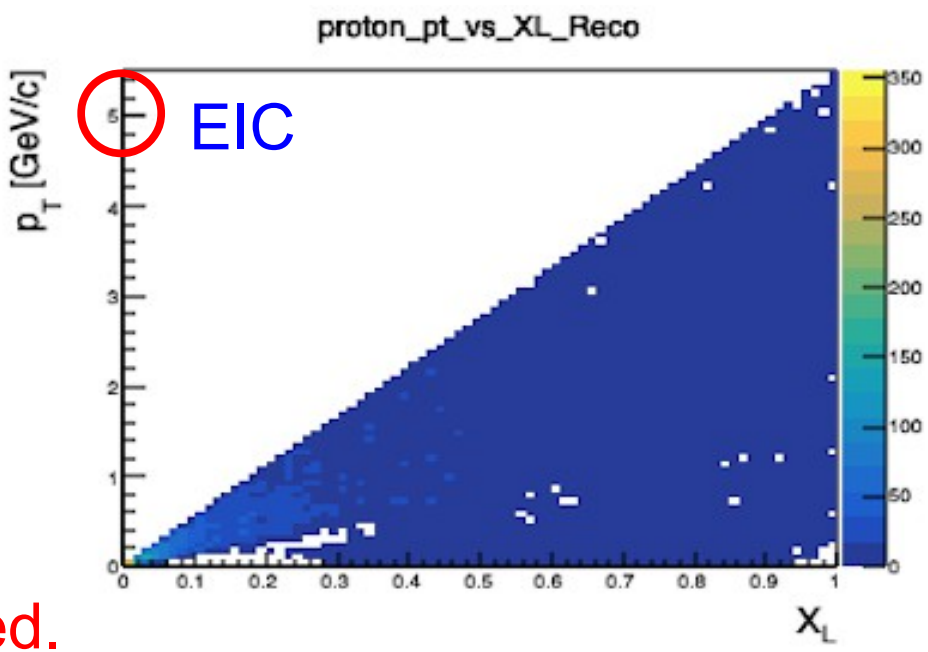
Total LB rate: HERA→EIC acceptance

- EIC will accept wider angle LN:
  Θ_{max} 0.75 → 4.5 mrad
- Factor ~2 greater p_T range
  ~4 greater p_T^2 range



- EIC LP 3 detector systems:
  1st magnet spectrometer, off momentum detector, Roman pots
- Coverage to p_T ~5 GeV @ high x_L
- Vast improvement over HERA, address total LB rate





Info from Alex Jentsch, see his talk Wed.

Summary

- HERA measured leading baryon x_L, p_T distributions in DIS, γp
- 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: $\Rightarrow$ good agreement with LN data
- Reintroduce hard scale in γp: LN rescattering reduced
- Total LB rate: ~½ of baryons accounted for; more @ EIC...

Extras

Partial bibliography

<u>HERA data</u>

data on most plots in tables in papers

boldface: bulk of results shown here

- ZEUS LN in DIS & γp: Nucl. Phys. B 637 (2002) 3-56
- ZEUS LN in D* γp: Phys. Lett. B 590 (2004) 143-160
- **ZEUS LN in DIS & γp: Nucl. Phys. B 776 (2007) 1-37**
  data on most plots in computer readable acsii:
  https://www-zeus.desy.de/zeus_papers/ZEUS_PAPERS/DESY-07-011-table.txt
- **ZEUS LP in DIS: JHEP 06 (2009) 074**
- ZEUS LN in dijet γp: Nucl. Phys. B 827 (2010) 1-33
  data on most plots in computer readable acsii:
  https://www-zeus.desy.de/zeus_papers/ZEUS_PAPERS/DESY-09-139-table.txt
- H1 LN in DIS: Eur.Phys.J.C68 (2010) 381
- H1 LN & forward photons in DIS: Eur.Phys.J.C74 (2014) 2915

Partial bibliography

Scattering / absorption papers

Older:

- N.N. Nikolaev, J. Speth and B.G. Zakharov, hep-ph/9708290
- U. D'Alesio and H.J. Pirner,
  Eur. Phys. J. A 7, 109 (2000)

'Durham group':

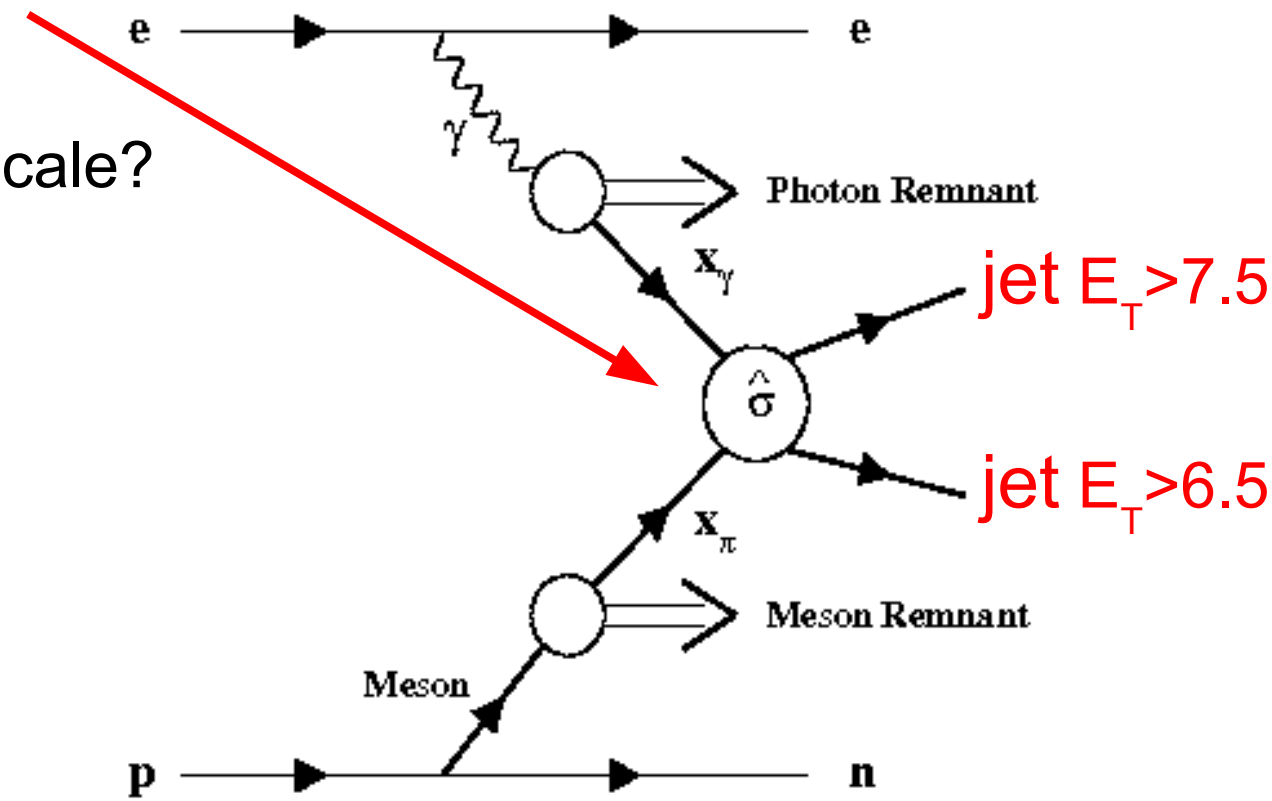
- A.B. Kaidalov, V.A. Khoze, A.D. Martin and M.G. Ryskin,
  Eur. Phys. J. C 47, 385 (2006)
- V.A. Khoze, A.D. Martin and M.G. Ryskin,
  Eur.Phys.J.C 48, 797 (2006)

Compare LN in γp+jj & DIS

- We have seen effects 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:

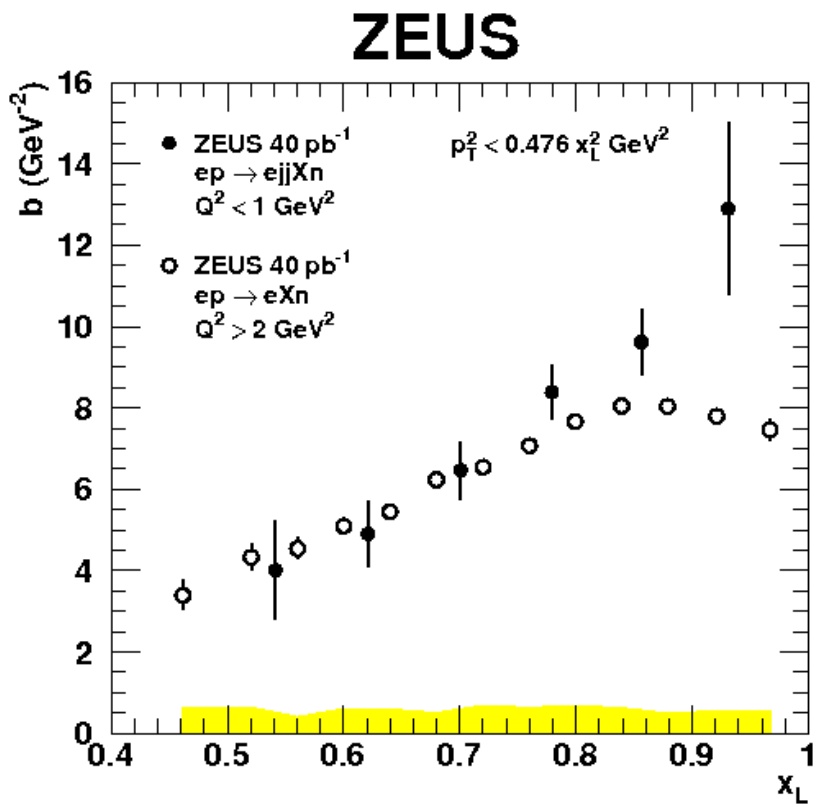
- Still signs of rescattering?
- Or eliminated by high E_T scale?

- LN in γp+jj results...



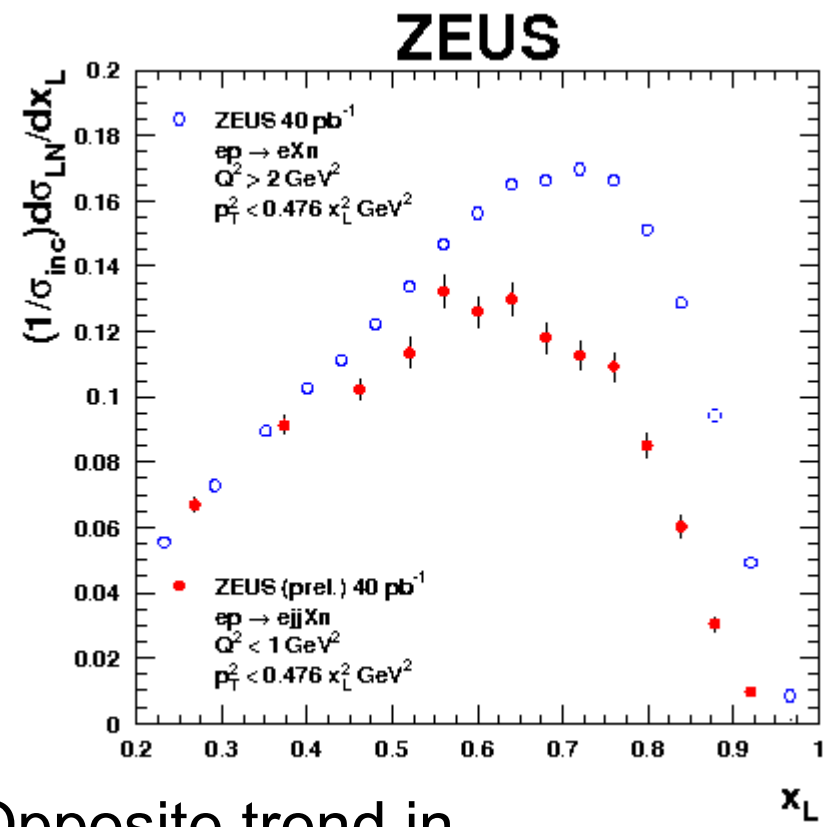
Compare LN in γp+jj & DIS : p_T^2 & x_L dist.

- 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!

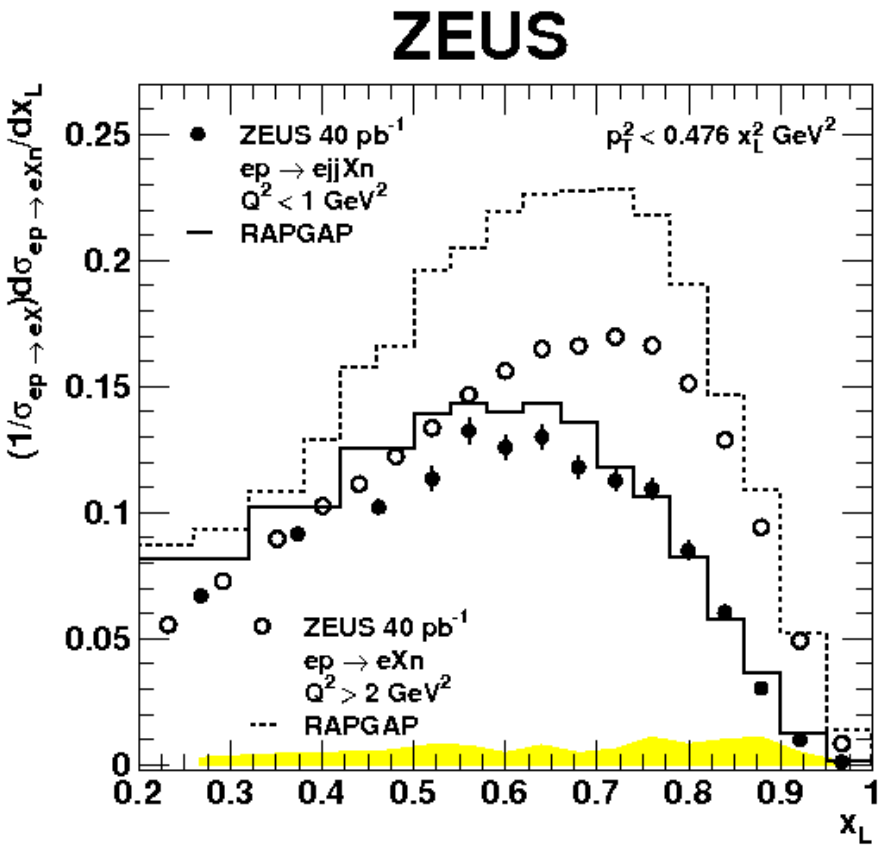


- Opposite trend in hi-Q^2→lo-Q^2→γp w/o jet requir.
- There suppression @ *low* x_L
- Here suppression @ *high* x_L
- Kinematic suppression?

Compare LN in γp+jj & DIS : x_L dist.

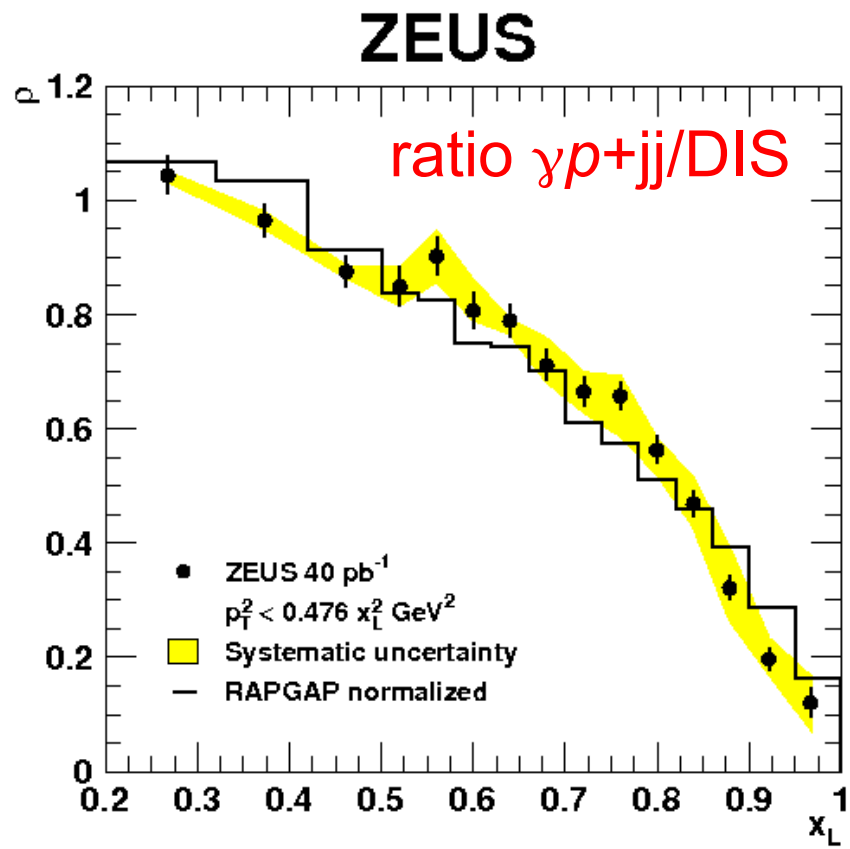
Compare to RAPGAP MC with:

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



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

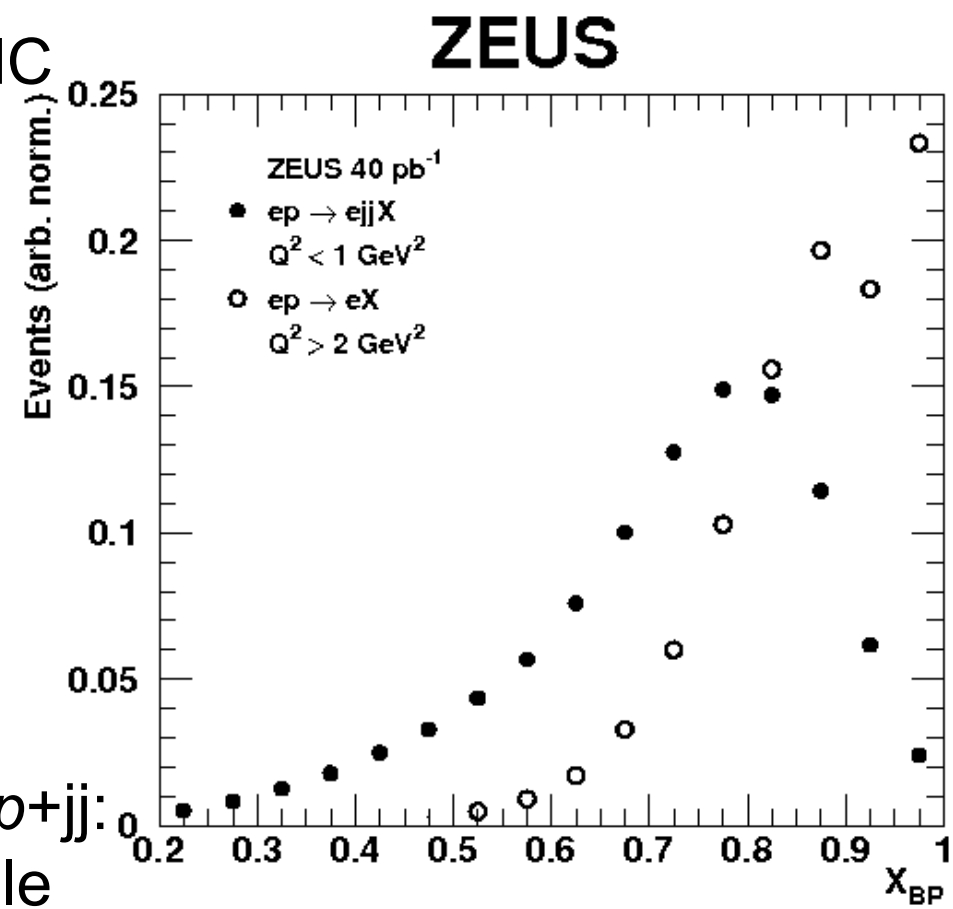
- Normalize each MC set to data
- Take ratio of x_L distributions:



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:

  $X_{BP} = E + P_z$

  = fraction *p*-energy available for LB down beam-pipe (BP)

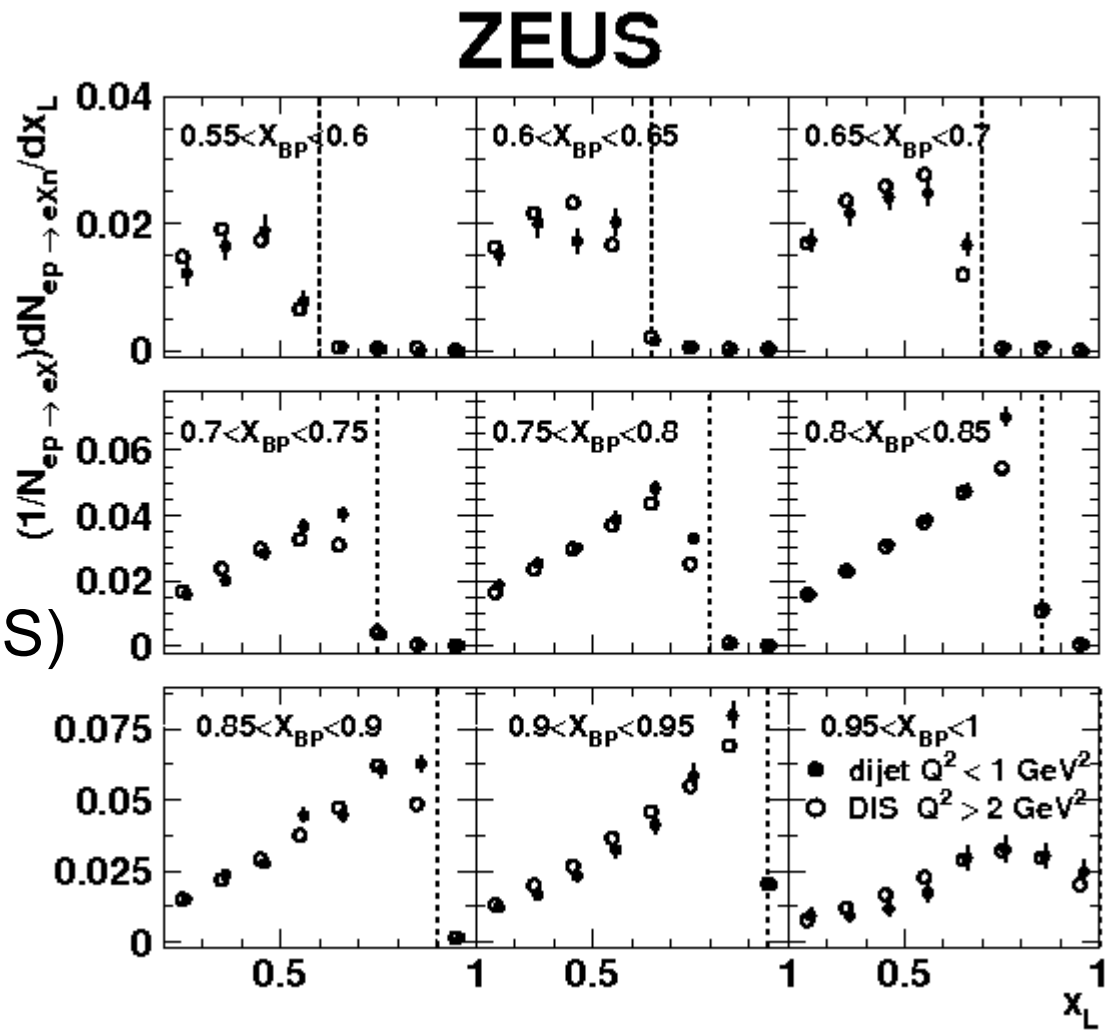
  → kinematic constraint: $x_L < X_{BP}$

- 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

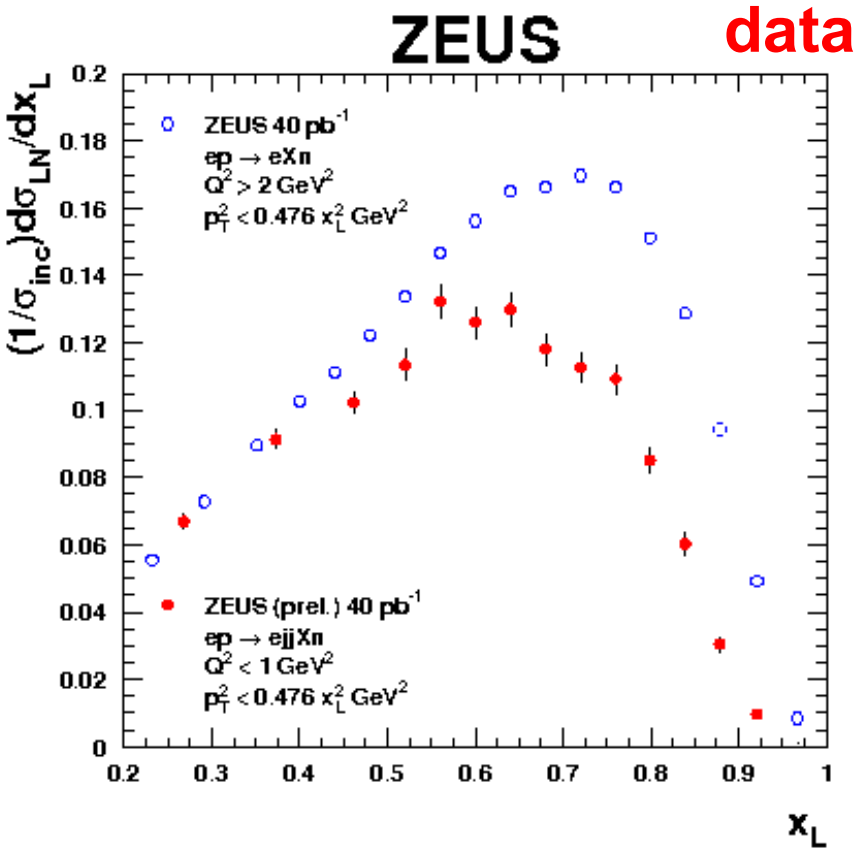
- In bins of X_{BP} the x_L dist. for γp+jj, DIS are ~same both normalization, shape
- <u>Universality</u>: for a given X_{BP}, LN x_L dist. is same regardless of process (at least γp+jj vs. DIS)
- So different overall x_L dist. for γp+jj vs. DIS explained by different event kinematics (as seen with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

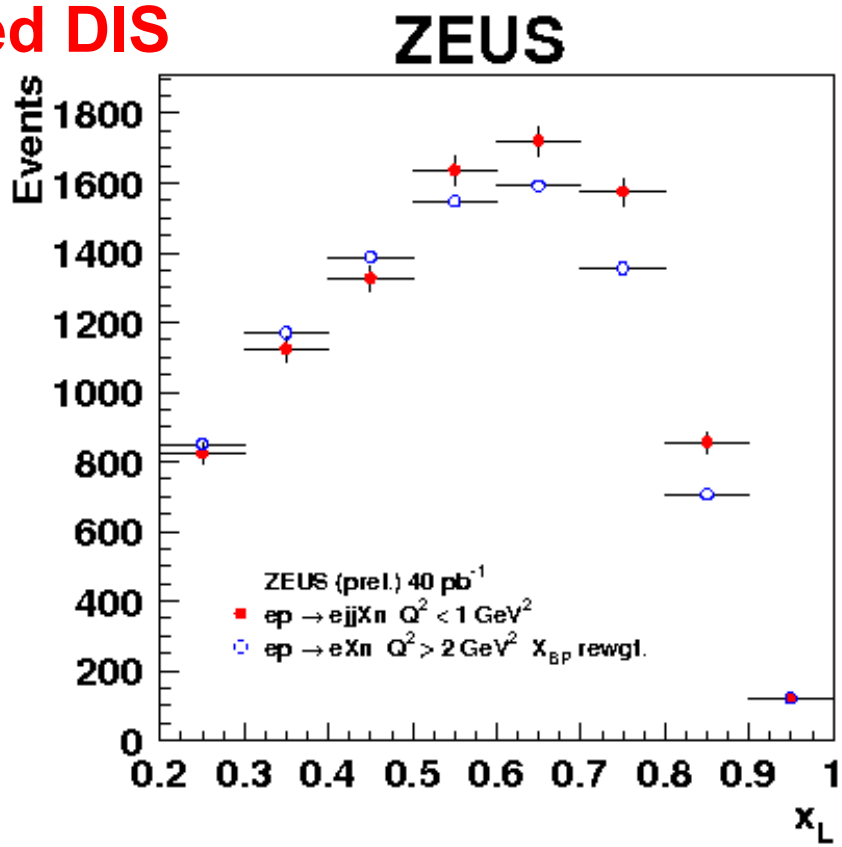


LN in γp+jj & DIS : x_L in X_{BP} bins

- In X_{BP} bins: bin-by-bin reweight DIS x_L distribution
  by ratio X_{BP} distributions γp+jj / DIS, sum x_L distributions

data → reweighted DIS



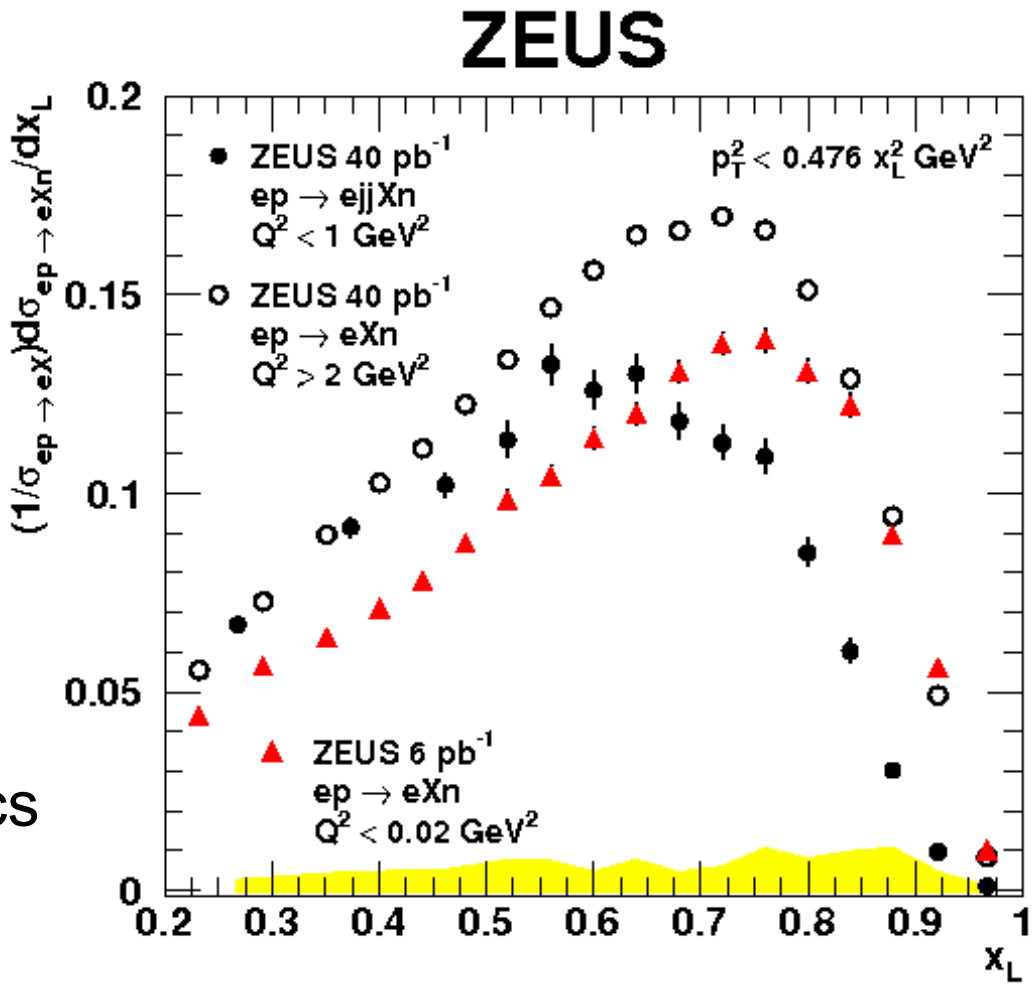


- Accounting for kinematic constraints: shape & normalization ~same
- No clear sign of suppression in γp with high E_T jet scale

EPS07 contribution: https://zeusdp.desy.de/physics/diff/pub/eps07/lnjj.ps

LN x_L in γp, γp+jj & DIS :

- Large suppression @ low x_L seen in inclusive γp w/o jet requirement, consistent with rescattering, 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



- Needed: input from theoretical community...