International Conference on the Structure and the Interactions of the Photon
including the 19th International Workshop on Photon-Photon Collisions
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Forward neutrons and photons at HERA

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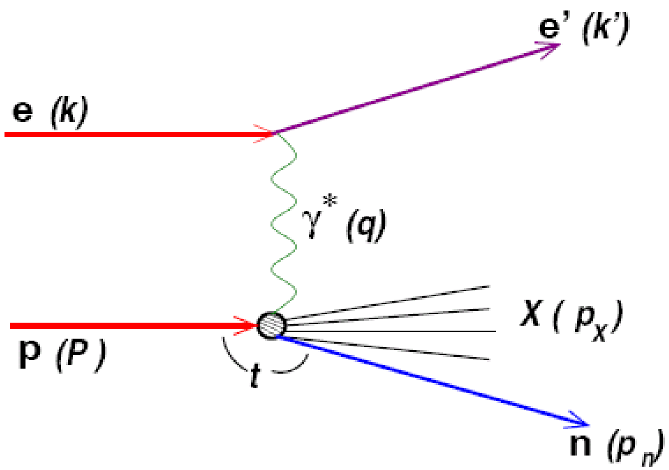
On behalf of the H1 and the ZEUS Collaborations

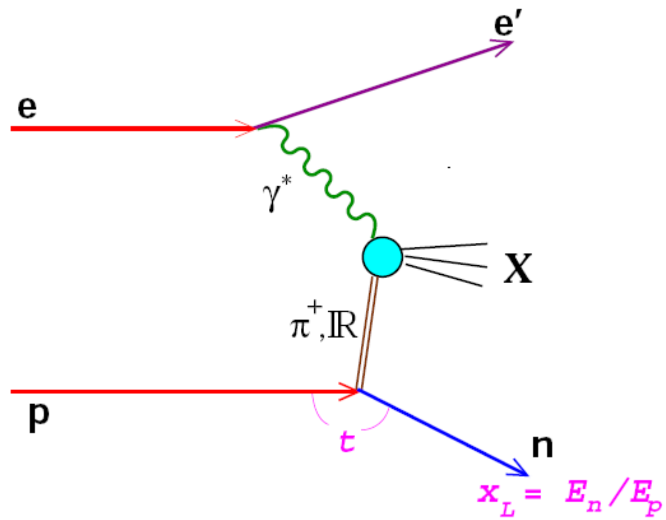
- **Outline:**
- **Forward neutron p_T and x_L distributions in DIS**
- **Forward neutrons in dijet photoproduction**
- **Forward photon spectra in DIS**

Introduction

Significant fraction of *ep* scattering events contain a leading neutron (called sometimes forward neutron) in the final state carrying a substantial portion of the energy of the incoming proton:
e+p → e+n+X . Different production mechanisms are available:



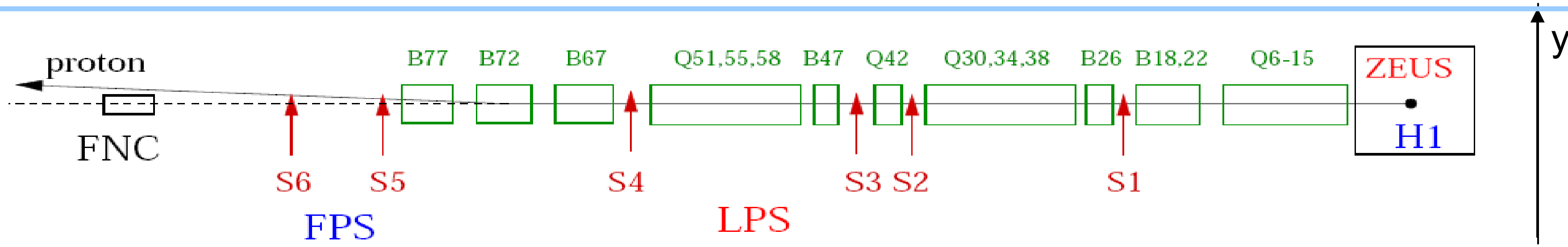
$x_L = E_n/E_p$



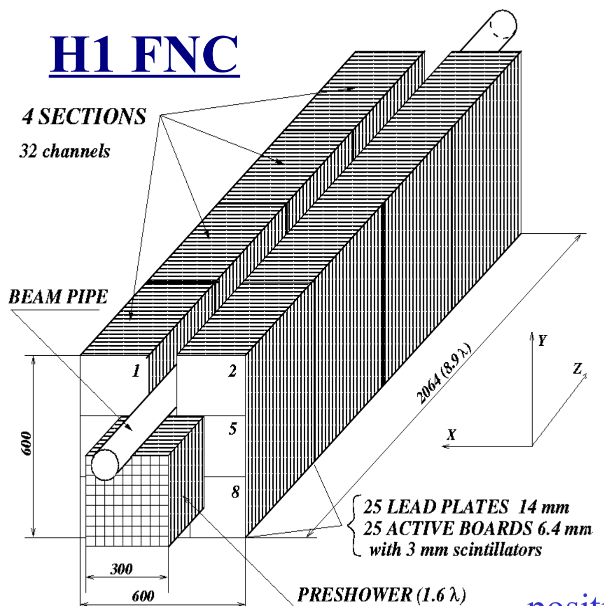
Fragmentation of proton

Exchange of virtual particle: π^+, ρ^+, a_2^+

Detectors of Forward Neutrons and Photons



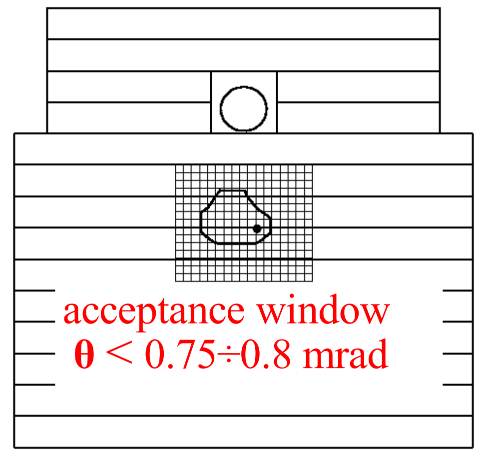
H1 FNC



position resolution 2-3 mm

$\sigma_E/E \approx 0.63/\sqrt{E} \oplus 2\%$

ZEUS FNC+FNT



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

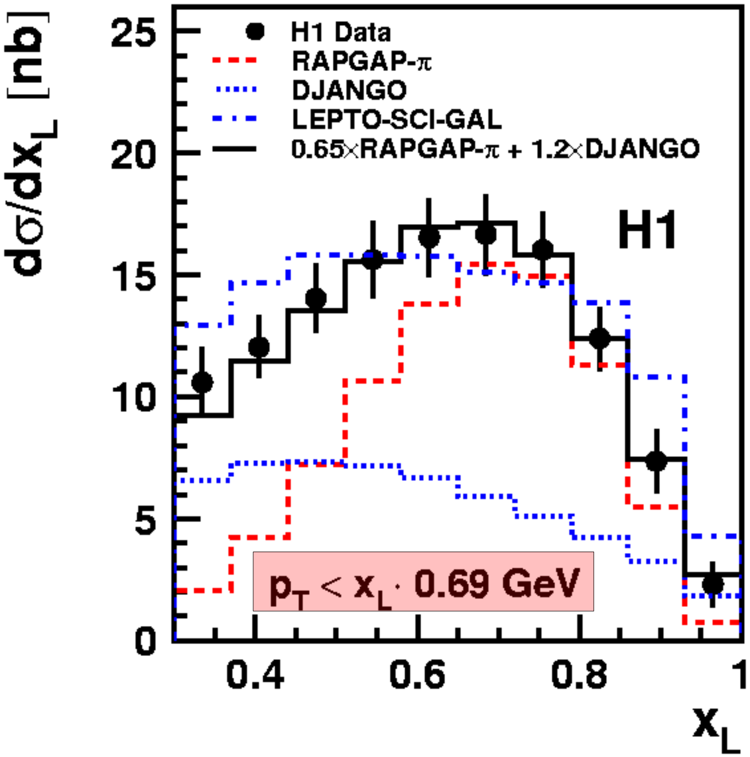
- Segmentation in depth (Z-axis) allows reliable discrimination between electromagnetic and hadronic showers, that is between photons and neutrons.
- Acceptance limited by beam apertures (defined by beam line elements).
- p_T resolution is dominated by p_T spread of proton beam (50-100 MeV).

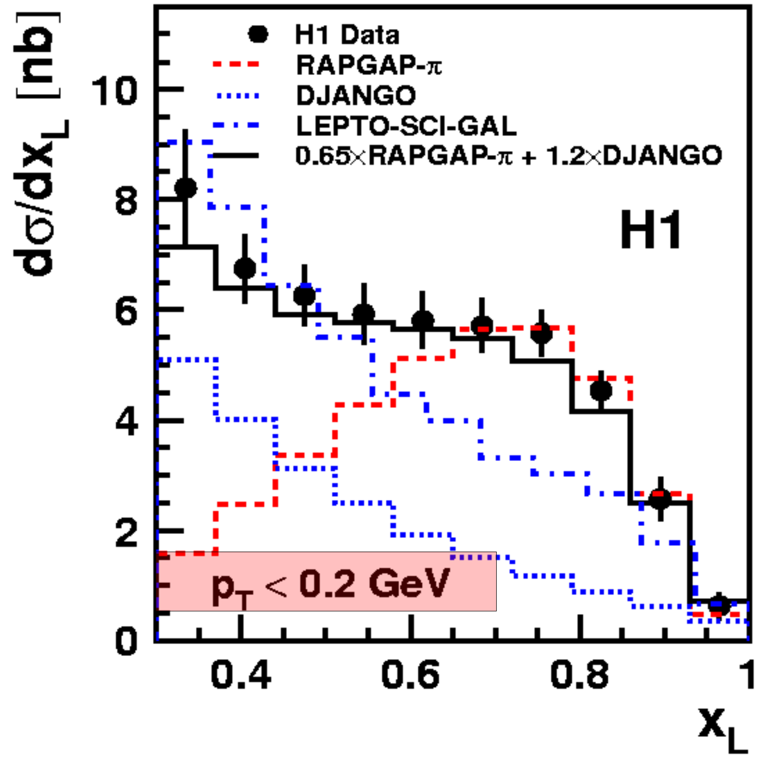
Forward neutrons in DIS:

Differential cross sections vs x_L

$e+p \rightarrow e+n+X$

(Eur.Phys.J.C68:381-399,2010)





Data can be described by a combination of standard fragmentation (DJANGO-CDM) and pion-exchange (RAPGAP-π+)

Forward neutron p_T^2 distributions in x_L bins

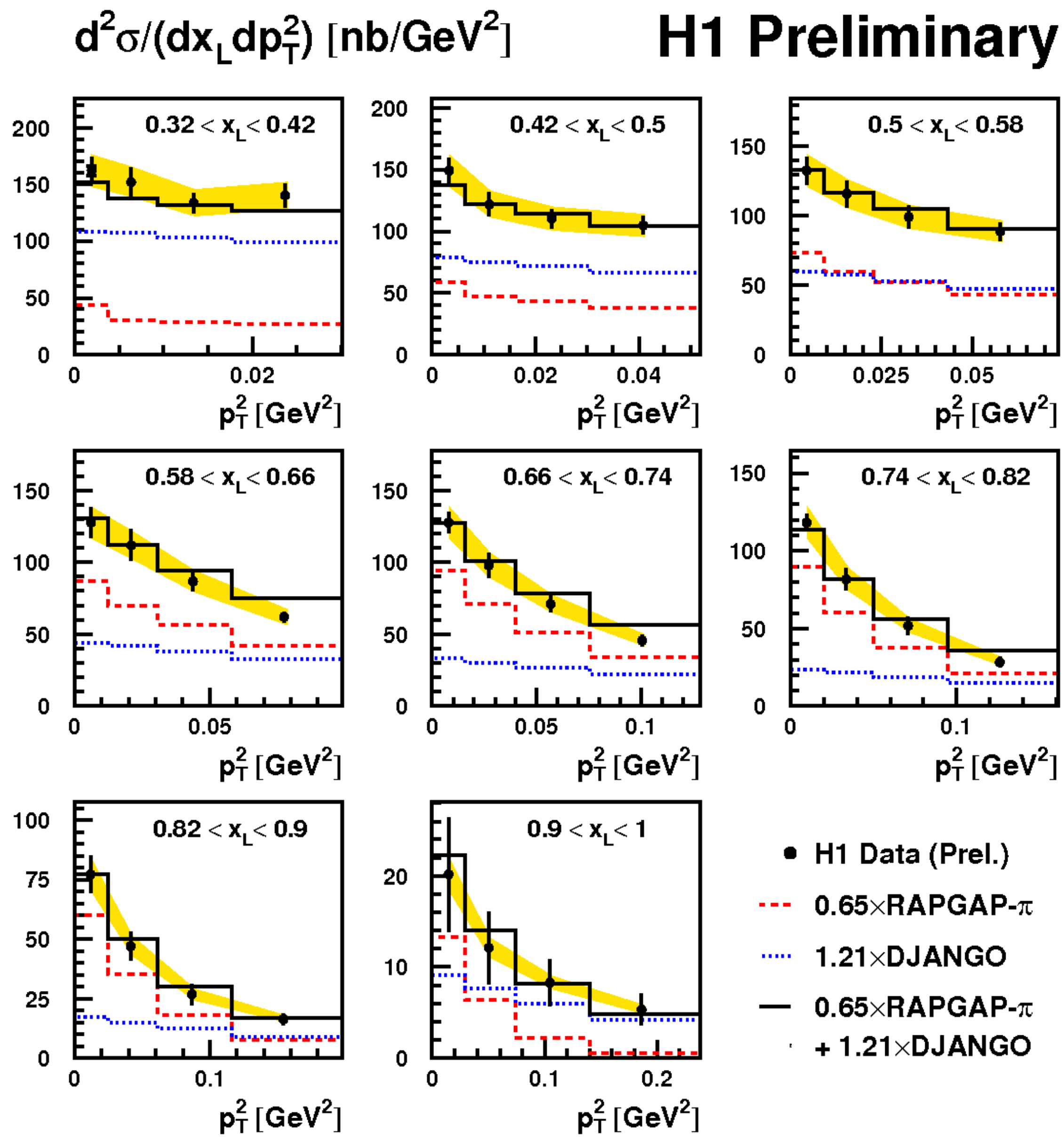
$e+p \rightarrow e+n+X$

Kinematic range: $6 < Q^2 < 100$ GeV^2, $0.05 < y < 0.6$, 2006-2007 data, Lumi=122pb^{-1}

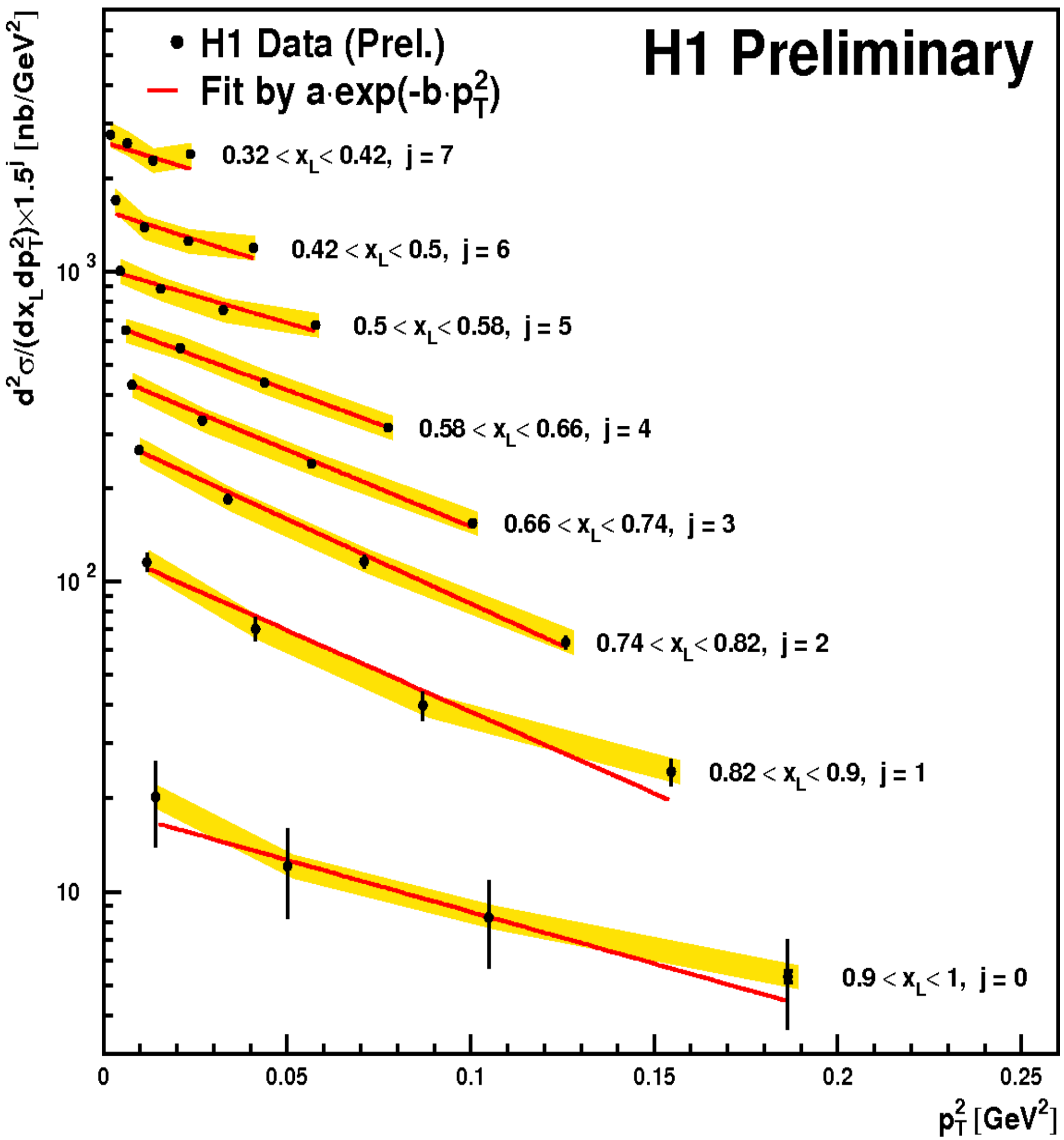
Now we extend the measurement differentially in transverse momentum of neutron p_T

MC weight factors of 0.65 and 1.21 for RAPGAP and DJANGO correspondingly taken from the fit to x_L distribution also well describe p_T^2 distributions

p_T^2 slopes are different for standard fragmentation and pion-exchange, constant vs x_L for DJANGO and increasing with x_L for RAPGAP



Forward neutron p_T^2 distributions with fit

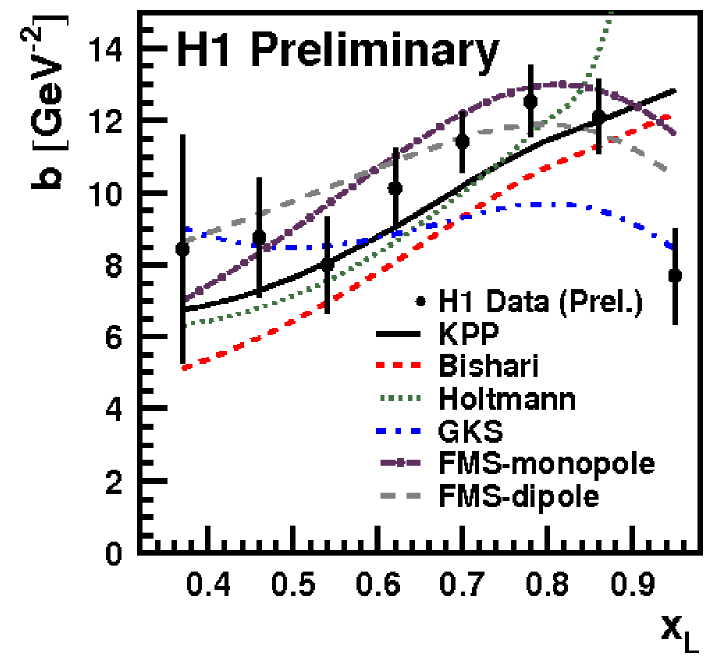


e+p → e+n+X

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

p_T^2 slopes change with increasing p_T^2

Fit the distributions by a single exponent and compare slopes with different parameterizations of pion flux

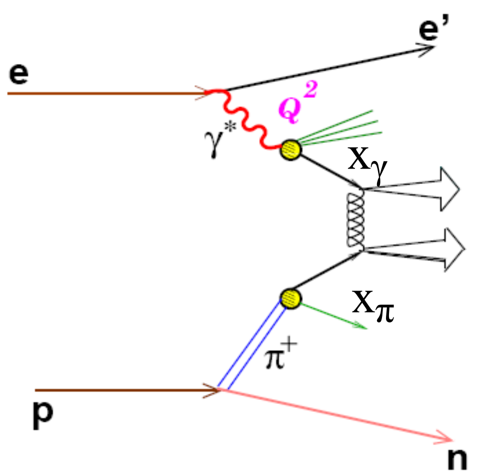


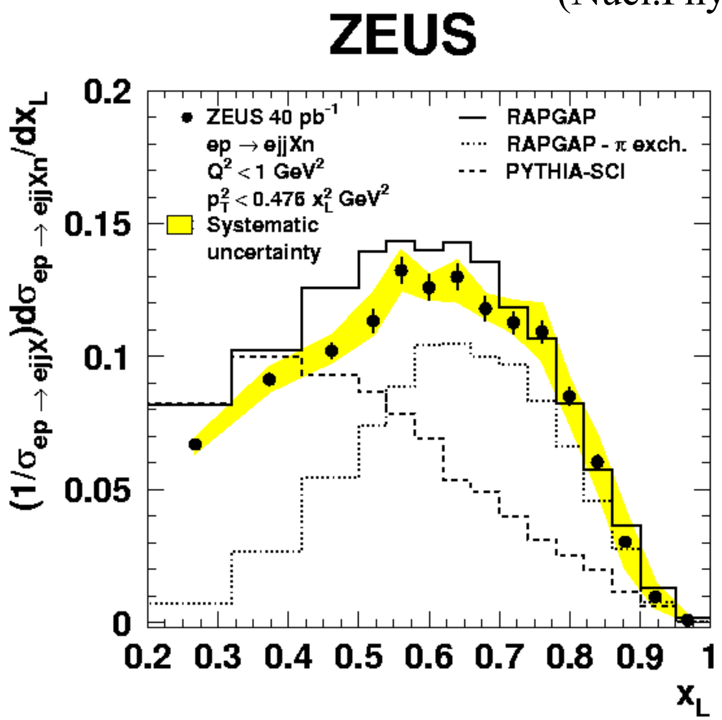
LN + dijets in γp:

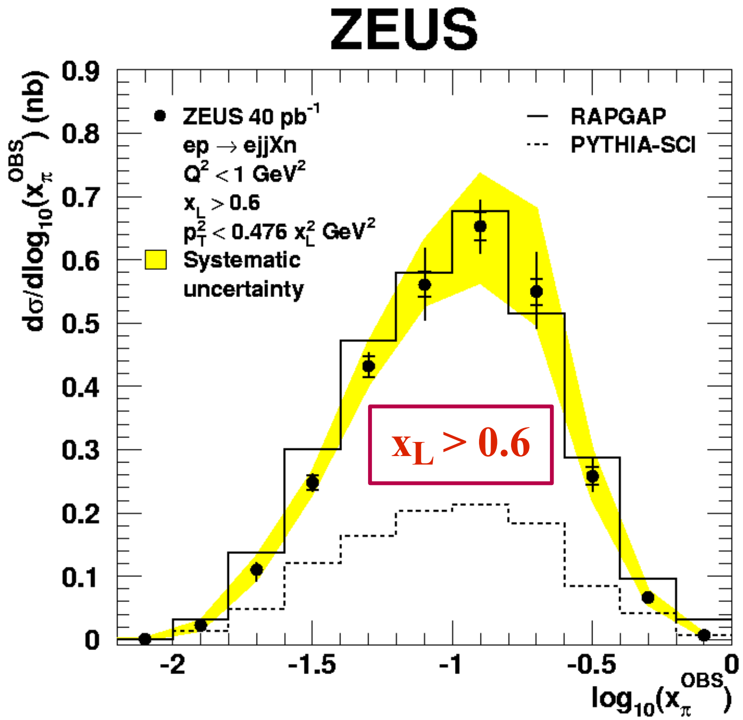
Dijet photoproduction with Leading Neutron

(Nucl.Phys.B827 (2010) 1)

e+p → e+n+j+j+X







$x_\pi = x_p/(1-x_L)$

40 pb^{-1}, $Q^2 < 1$ GeV^2, $p_T^2 < 0.475\ x_L^2$ GeV^2, $x_L > 0.2$,
$130 < W < 280$ GeV, $E_T^{jet1} > 7.5$ GeV, $E_T^{jet2} > 6.5$ GeV, $-1.5 < \eta^{jet1,2} < 2.5$

In photoproduction ($Q^2 \sim 0$) hard scale provided by jets with high p_T^{jet}

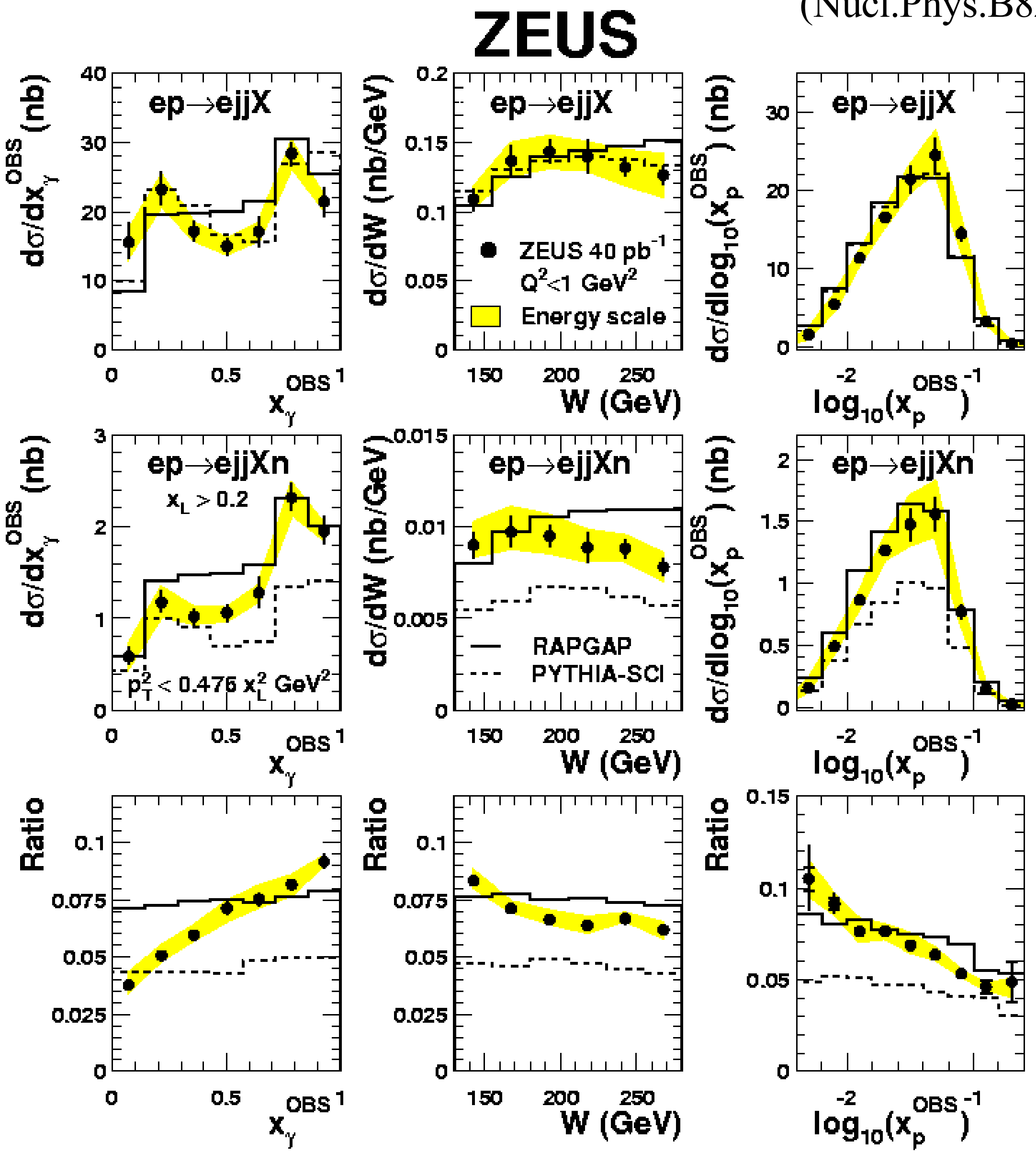
RAPGAP π-exchange and PYTHIA-SCI describe data poor

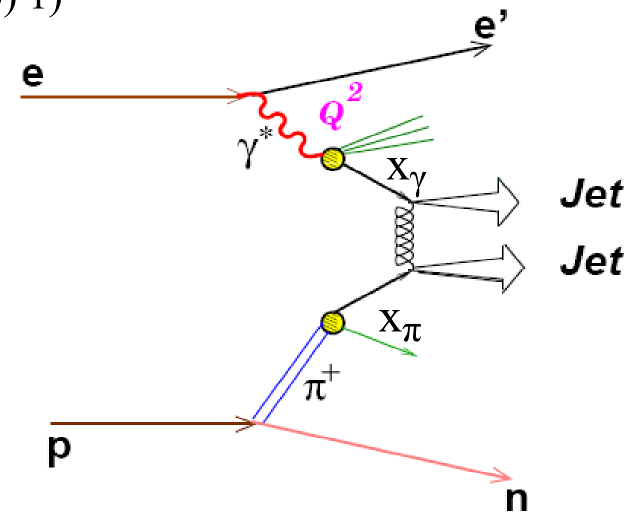
Pion-exchange is dominating mechanism at high x_L

Full RAPGAP (pion-exchange + inclusive γp) gives good description of data

Jet variables distributions

(Nucl.Phys.B827 (2010) 1)





W – total energy of γp system

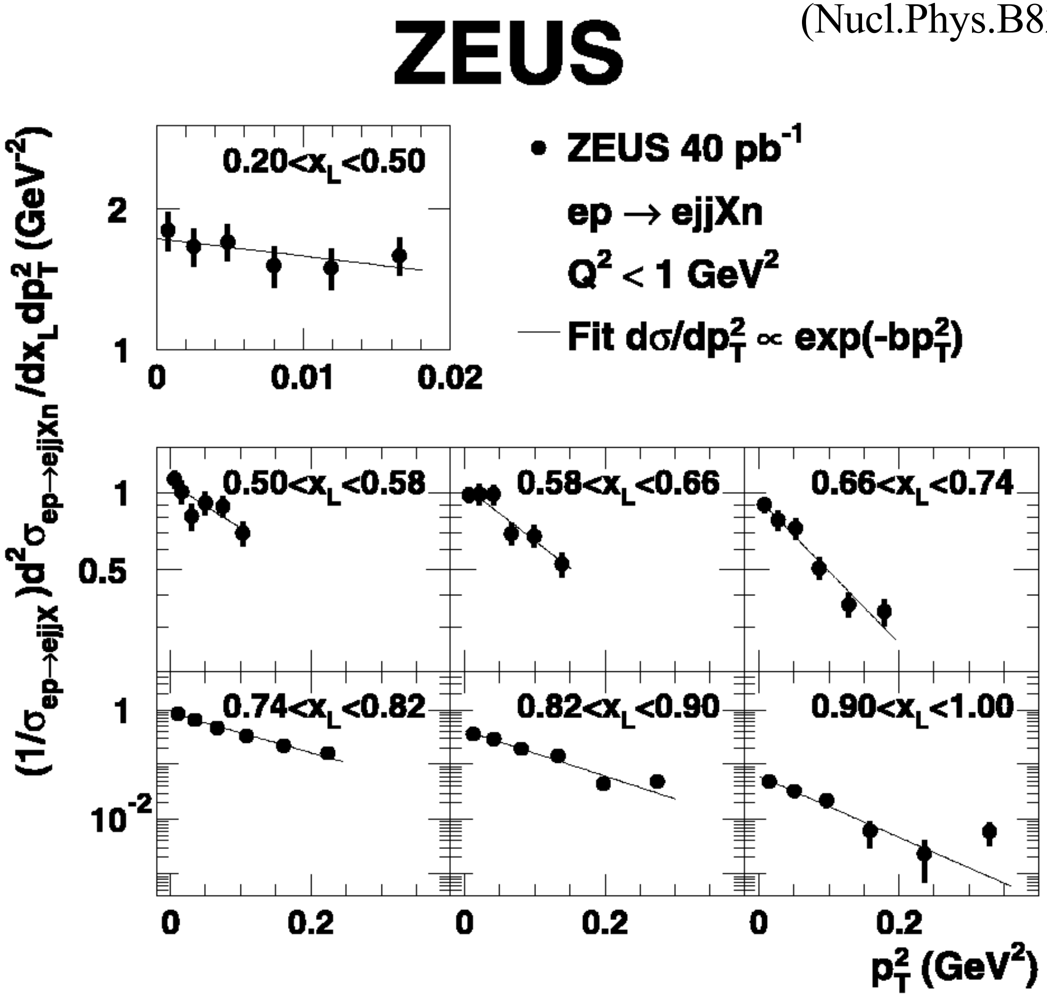
$x_\gamma = \Sigma_{jets}(E-p_z)/(2yE_e)$

$x_p = \Sigma_{jets}(E+p_z)/(2E_p)$

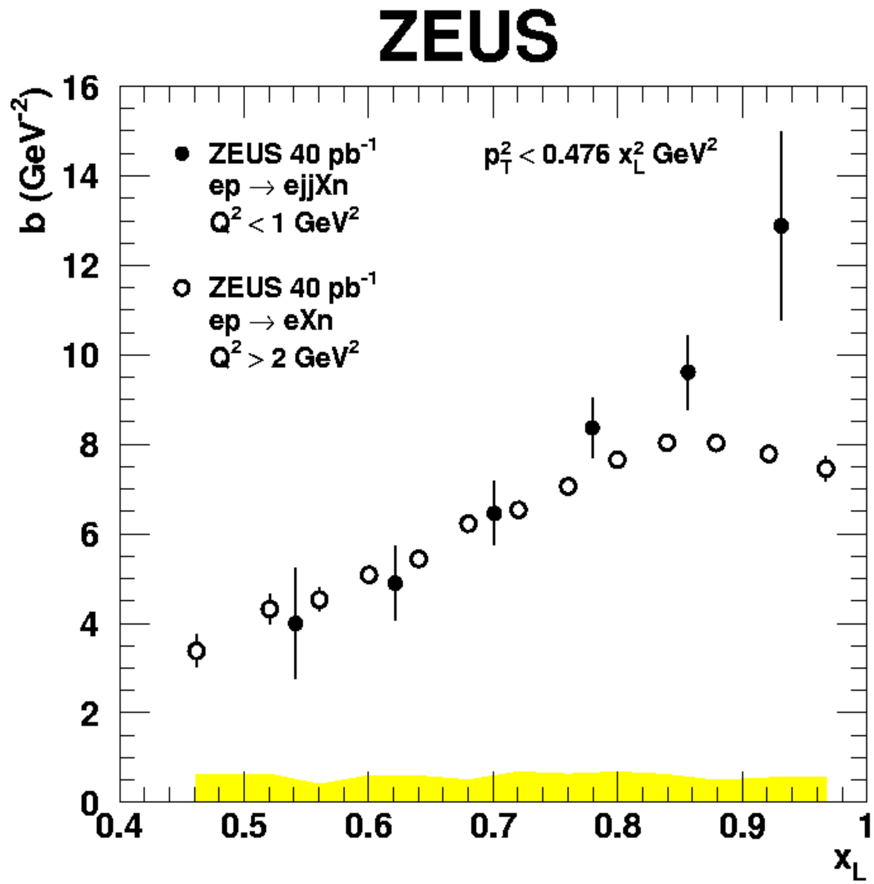
- **strong dependence of ratio of x_γ distributions for data, flat in MC**
- **resolved photon is suppressed in events with neutron.**

p_T^2 distributions in x_L bins; slopes

(Nucl.Phys.B827 (2010) 1)



slopes - $b(x_L)$

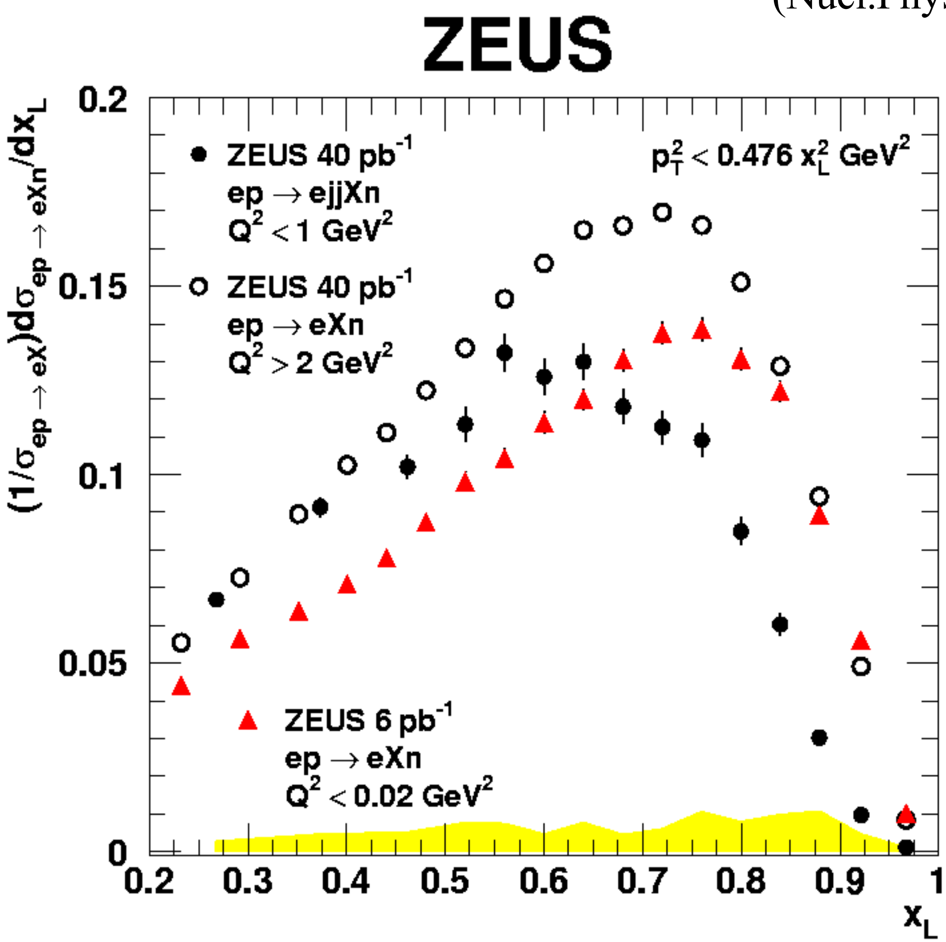


Well described by exponential fall-off in p_T^2

similar b-values in DIS and γp+dijet, slightly different at high x_L
=> same production mechanism

LN + dijets in γp: “LN + dijet in γp” vs “LN in DIS” vs “LN in γp”

(Nucl.Phys.B827 (2010) 1)



○ LN in DIS
▲ LN in γp
● LN + dijet in γp

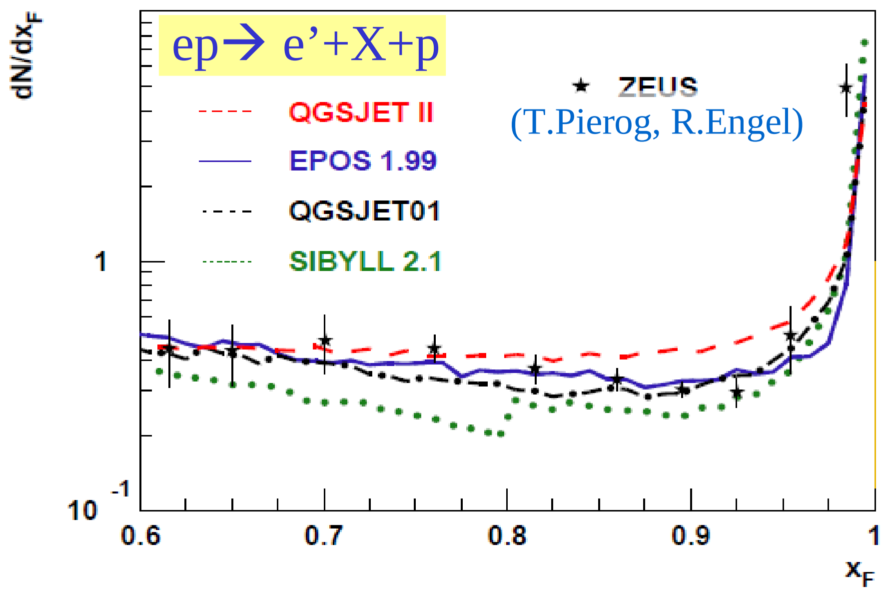
LN production in photoproduction is suppressed vs DIS at lower x_L ($x_L < 0.85$)
=> consistent with neutron absorption through rescattering models (more absorption in γp than in DIS due to larger transverse size of real photon)

Suppression is not so prominent in dijet photoproduction (hard scale provided by high E_T^{jet})

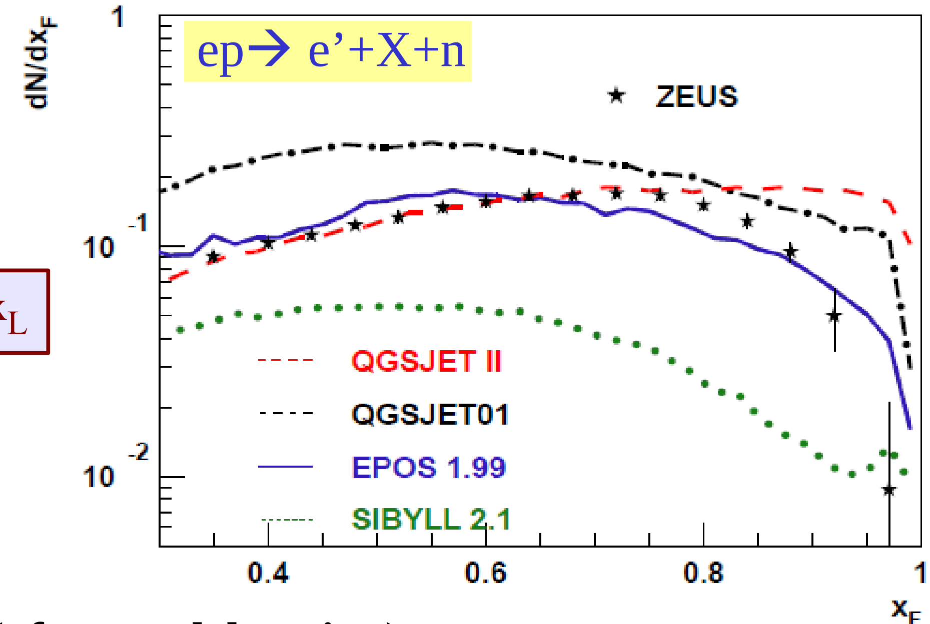
Suppression of dijet protoproduction rate at higher x_L is due to phase space limitation: dijets in the final state leave little room for energetic neutrons

Forward particles production

- **Forward particles sensitive to proton fragmentation.**
- **Forward particles at HERA can contribute to the understanding of high energy cosmic rays**



$x_F = x_L$



- **reasonable predictions for leading proton data (after model tuning)**
- **none of models describe leading neutron data well**
- ***What about π^0 ? => measure photons***

Data compared to
- CDM and LEPTO MC
- Hadronic interaction models used for analysis of cosmic rays
EPOS, SIBYLL, QGSJET II, QGSJET 01

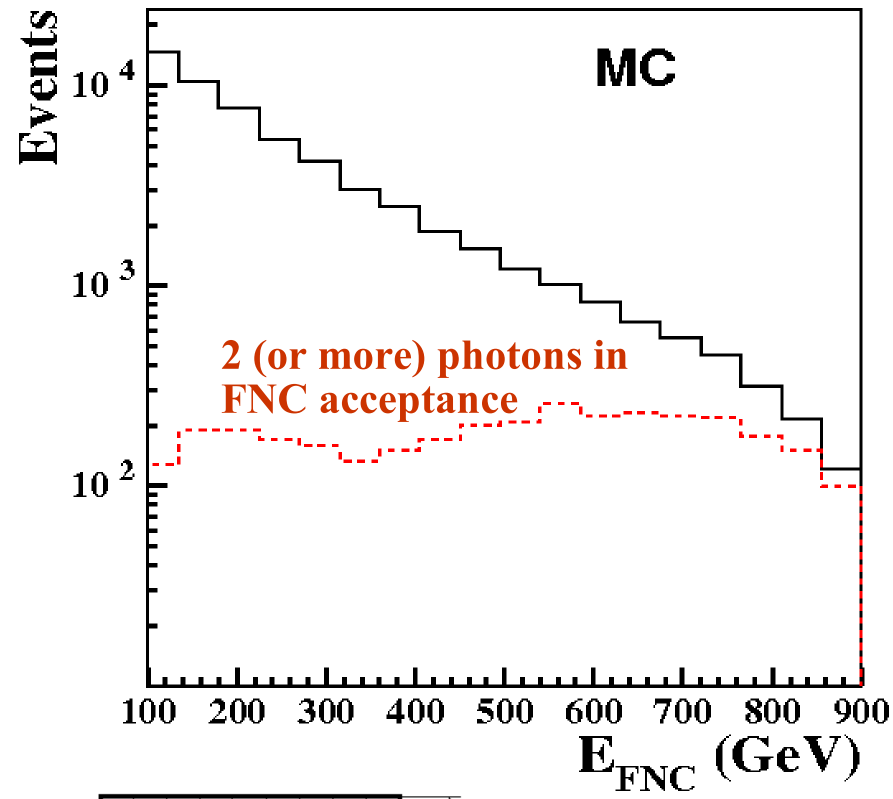
(EPOS 1.9: *(Pierog,Werner),*   QGSJET 01 and II: (*Kalmykov,Ostapchenko),*   SIBYLL 2.1: *(Engel,Fletcher,Gaisser,Lipari,Stanev))*

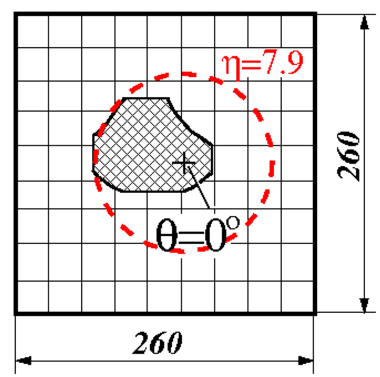
Forward photon candidates

What are our photon candidates ?

At high x_L, many FNC clusters are from more than one photon! So measurement represents the sum of photons inside the angular range defined by the FNC geometrical acceptance (η>7.9).

But at lower x_L we can assume that to a good approximation we measure one photon.





provide cross sections:
- x_L and p_T of most energetic photon in a range η>7.9 for x_L < 0.7
- x_L of sum of photons in a range η>7.9

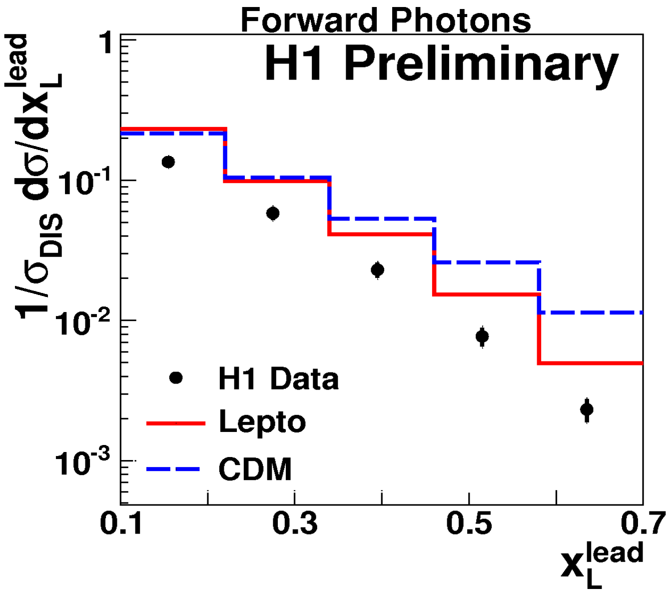
Forward photon production cross sections vs x_L

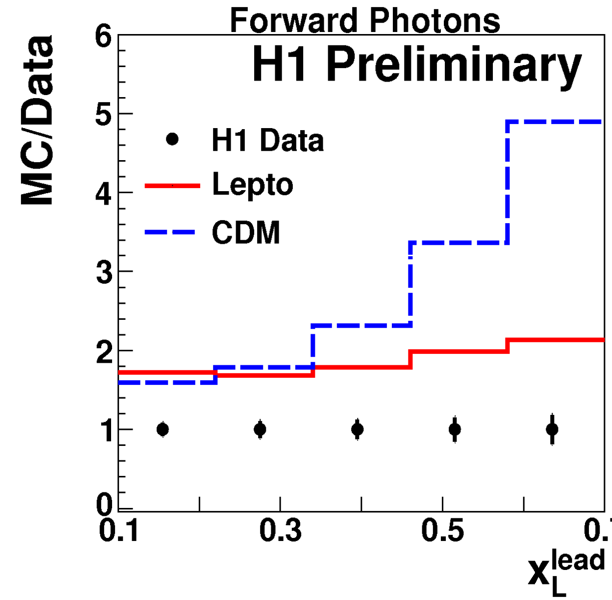
Kinematic range: $6 < Q^2 < 100$ GeV^2, $0.05 < y < 0.6$, 2006-2007 data, Lumi=126pb^{-1}. σ_{DIS} is inclusive cross section in the same kinematic range

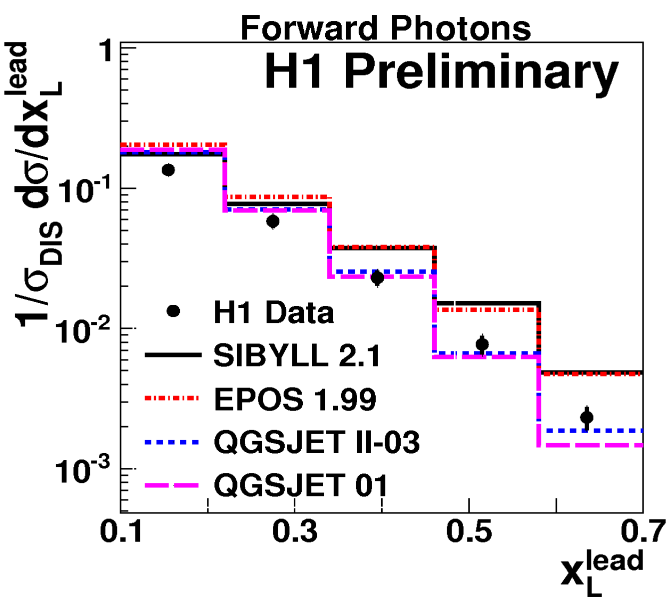
Photon rate in all tested Monte Carlo models is significantly higher than in data.

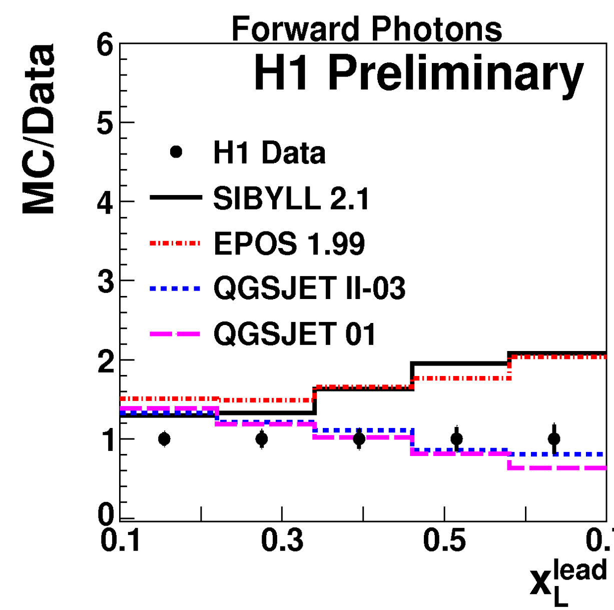
LEPTO model describes the shape reasonably well. CDM to data discrepancy larger at higher x_L

QGSJET models describe data well except at low x_L









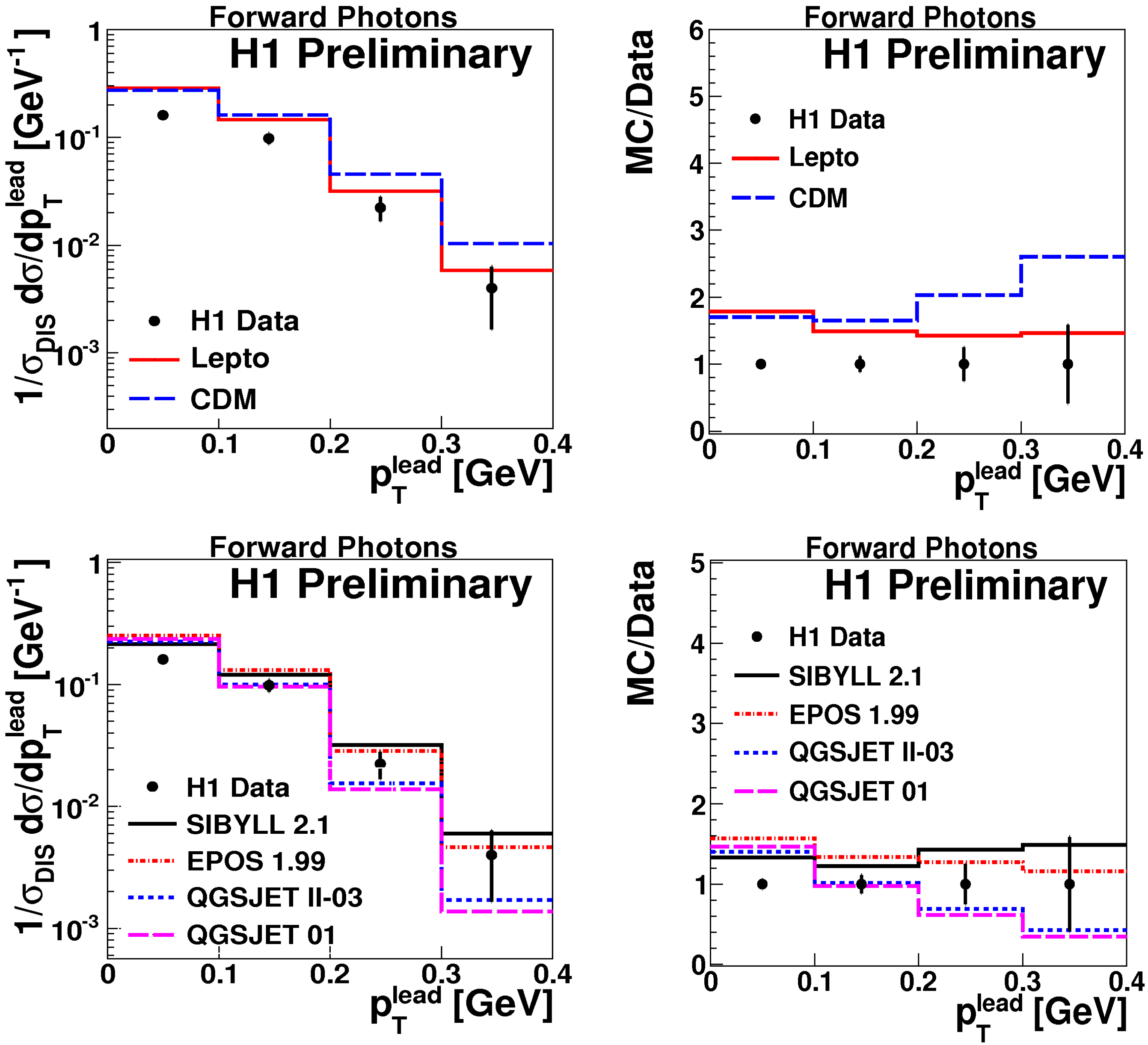
Forward photons:

Forward photon production cross sections vs p_T

Photon rate in all tested Monte Carlo models is significantly higher than in data.

LEPTO describes the shape reasonably well.

p_T^2 spectrum shape is well described by SIBYLL and EPOS models.



Forward photons:

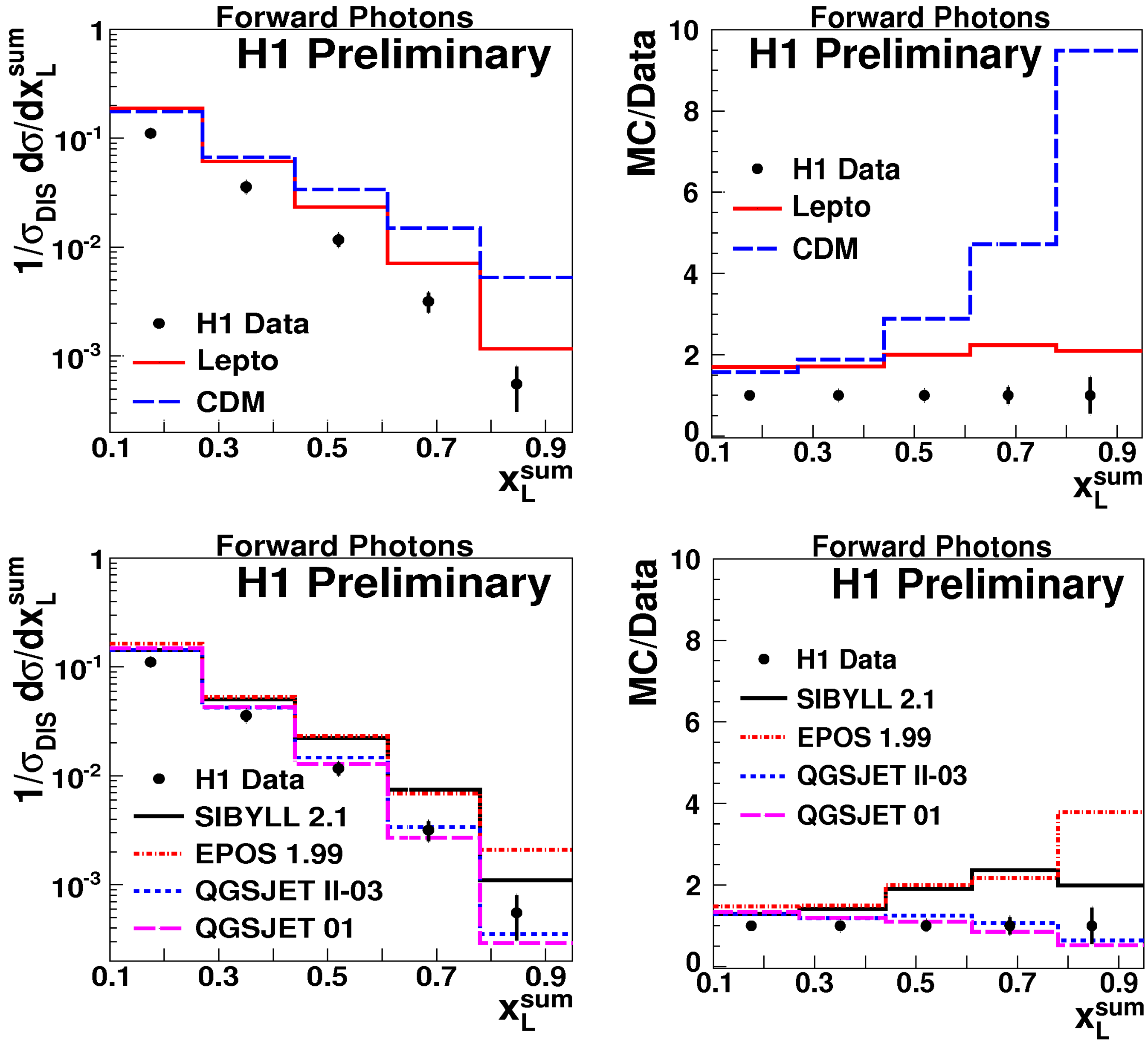
Photon production cross sections vs sum of x_L

$x_L^{sum} = \Sigma E_i / E_{p\text{-beam}}$ of γ with $\eta > 7.9$

Photon rate in all tested Monte Carlo models is significantly higher than in data.

LEPTO describes the shape reasonably well. At higher x_L CDM to data ratio is even worse.

For energy sum QGSJET models describe data shape better than SIBYLL and EPOS.



Summary

- **Measurement of double-differential cross section vs x_L and p_T^2 of leading neutron production is presented in DIS.**
- **Fragmentation MC-models without meson exchange do not describe the data, addition of model with pion exchange mechanism allows a better description of the data.**
- **Pion flux can be further constrained using the measurement.**

- **Precise measurements of leading neutron x_L and p_T^2 presented in γp with dijets.**
- **Reintroducing hard scale in γp with high E_T jets: absorption effect not prominent.**
- **Unlike Monte Carlo predictions x_γ distributions ratio (dijet+LN)/(dijet) is not flat in data.**
- **Leading neutron production in γp rate is suppressed at $x_L < 0.85$.**

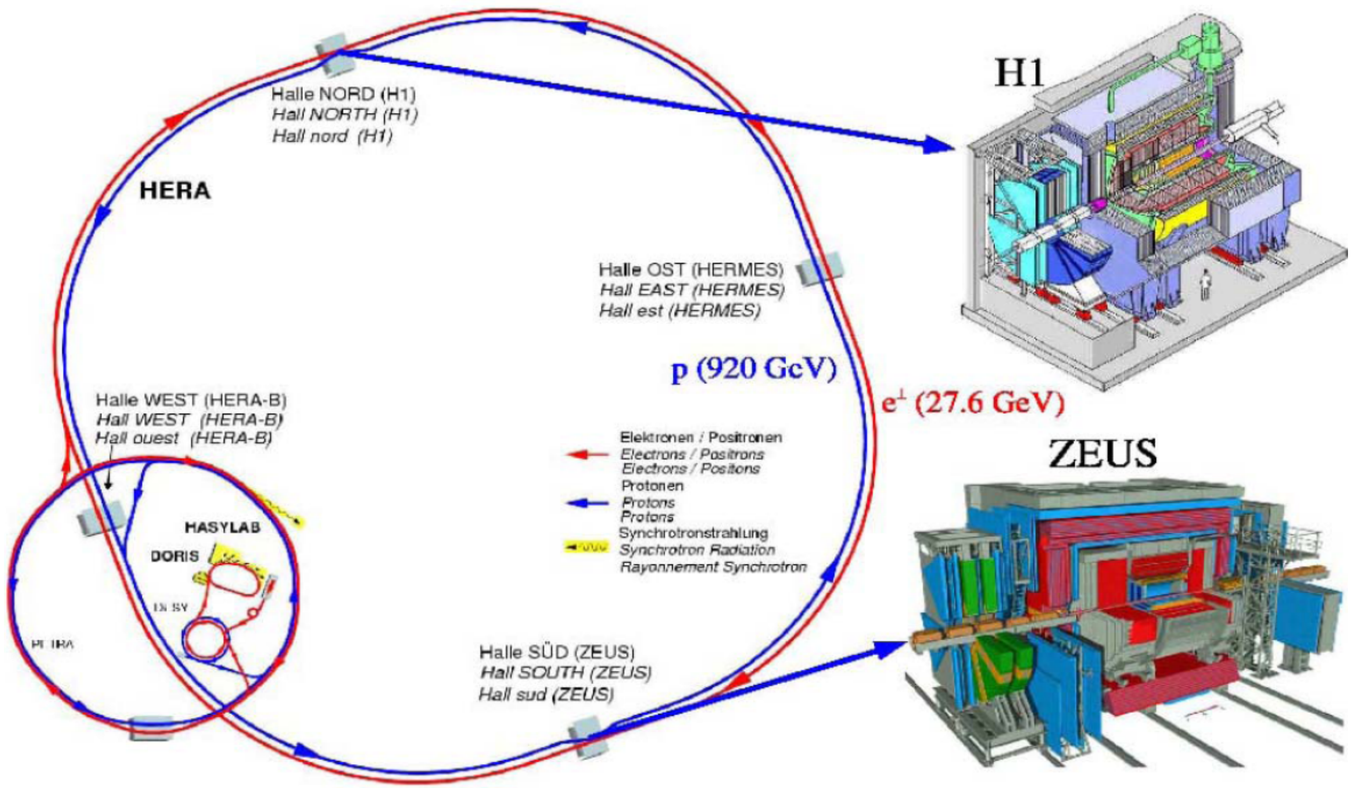
- **First measurement of $1/\sigma_{DIS}$ normalized cross section of Forward Photons production in DIS.**
- **Measurements show sensitivity to proton fragmentation MC models.**
- **Photon rate in Monte Carlo models is significantly higher than in data.**
- **LEPTO describes the shape reasonably well, CDM predicts too many photons at high energies**
- **QGSJET models provide reasonable description of x_L dependence while EPOS and SIBYLL provide similar level of description of p_T dependence.**
- **None of the models describes data either in normalization or in shape.**

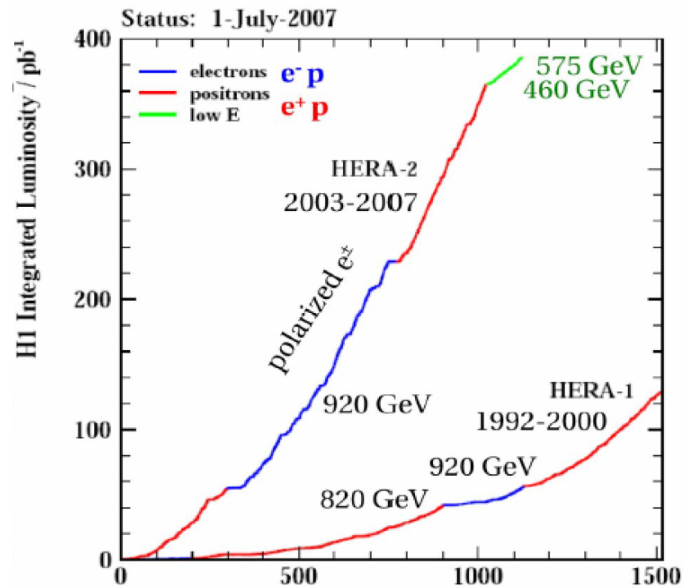
Backup

HERA

The world's only electron/positron-proton collider at DESY, Hamburg.

E_e = 27.6 GeV, E_p = 920 GeV (also 820, 460 and 575 GeV). √s up to 320 GeV.





HERA-1: 1992 - 2000
HERA-2: 2003 - 2007

Two colliding experiments: H1 and ZEUS

Total lumi: 0.5 fb^{-1} per experiment

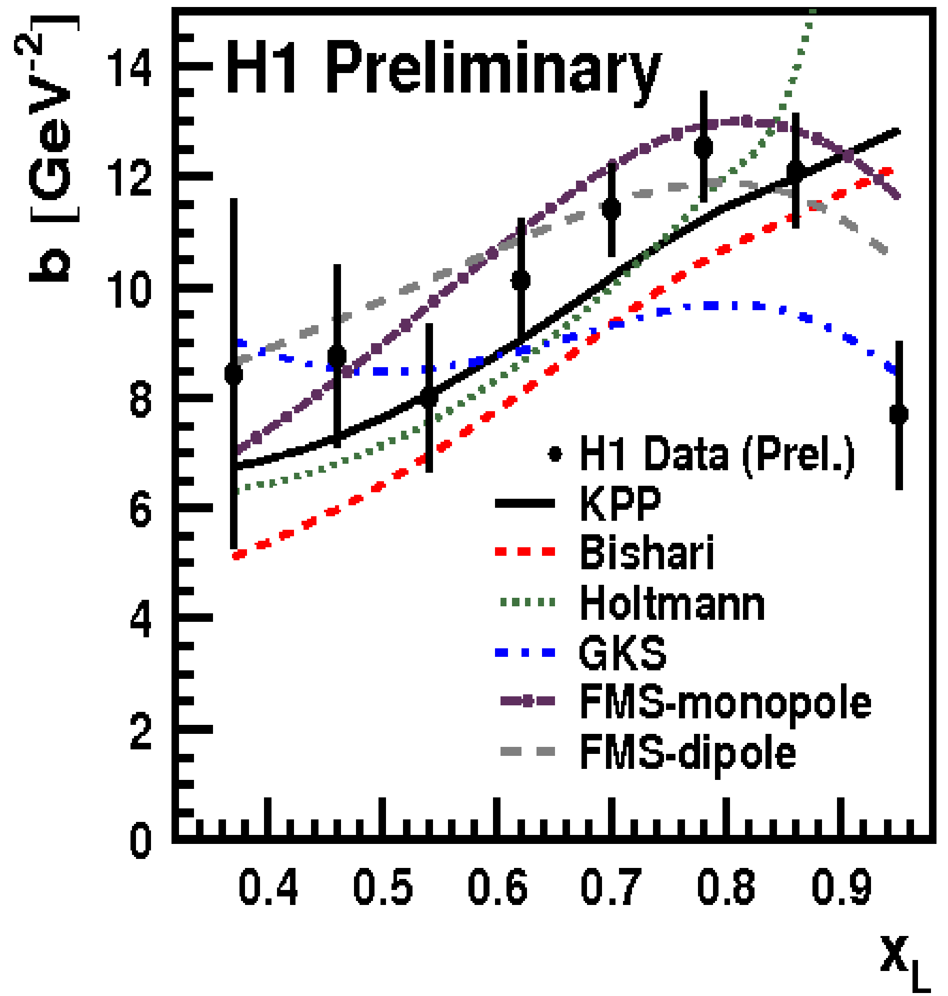
Forward neutron p_T^2 slopes

e+p → e+n+X

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

Slopes $b(x_L)$ as a function of x_L compared to several selected pion flux parameterizations:

KPP:
B.Kopeliovich, B.Povh, I.Potsahnikova
Bishari:
M.Bishari
Holtmann:
H.Holtmann
GKS:
K.J.Golec-Biernat, J.Kwiecinski, A.Szczurek
FMS:
L.L.Frankfurt, L.Mankiewicz, M.I.Strikman

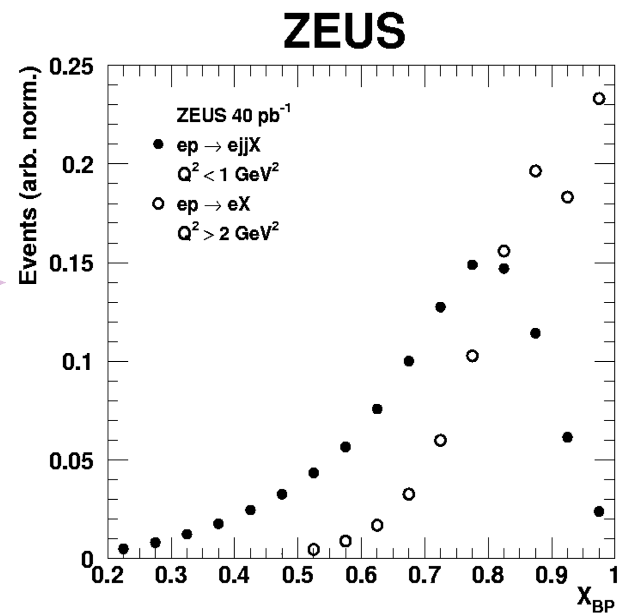


LN in dijet γp vs DIS: kinematic constraints

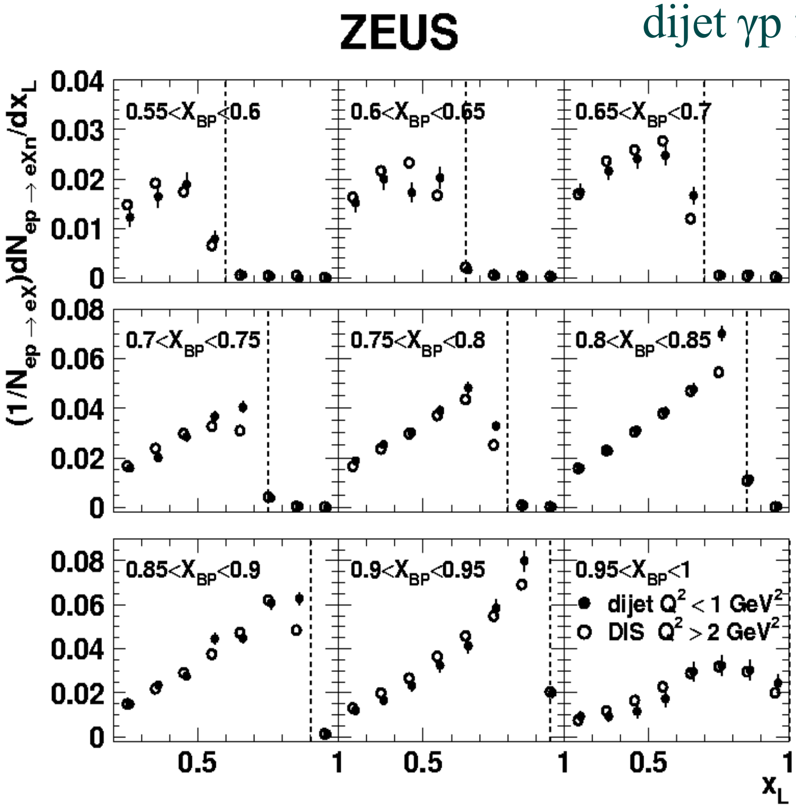
Consider X_{BP} = fraction of p-energy available for LN production

$$x_L < X_{BP} = 1 - (E+P_Z)/(2E_P)$$

X_{BP} dist. is different in DIS and dijet γp: much less energy available in dijet γp for LN production



Reweight DIS LN x_L dist. to match the X_{BP} dist. in dijet γp

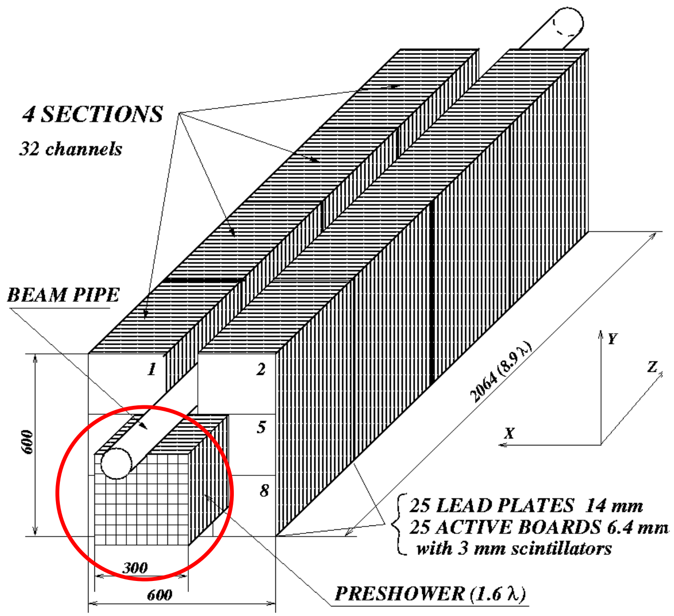


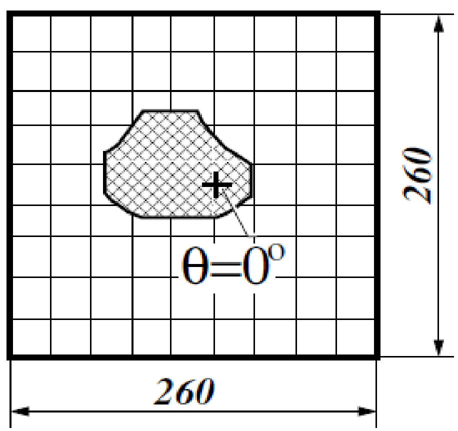
suspression at high x_L dist. mostly gone
large suppression at low x_L seen in γp without jets not there

For fixed X_{BP}, same LN rate and x_L spectrum

Differences in the x_L spectra due to kinematic suppression.

Preshower of Forward Neutron Calorimeter





Preshower detector

- *26x26x40 cm*^{3}
- *60* X_0*, 1.6* λ_i
- *readout 9 X and 9 Y projection strips*

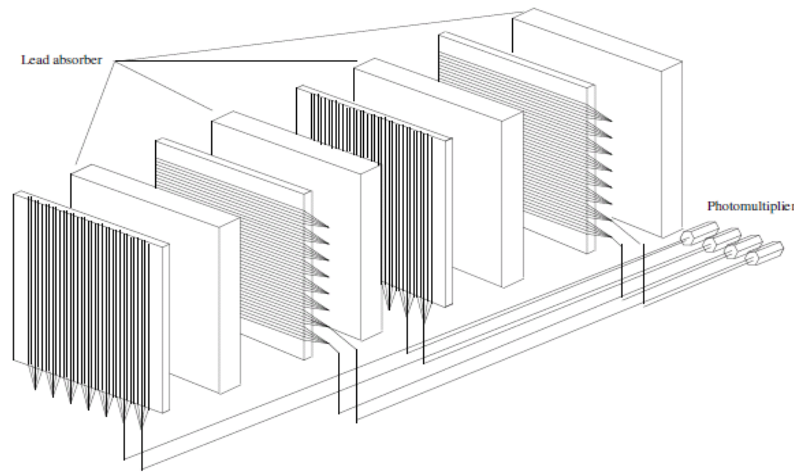


Figure 3: *The scheme of light collection for the Preshower.*

Segmentation in depth (Z-axis) allows reliable discrimination between electromagnetic and hadronic showers, that is between photons and neutrons.

At low energy (x_L<0.1) neutrons can be misidentified as photons => measure cross sections for $x_L > 0.1$