

Forward Neutron and Photon results from HERA



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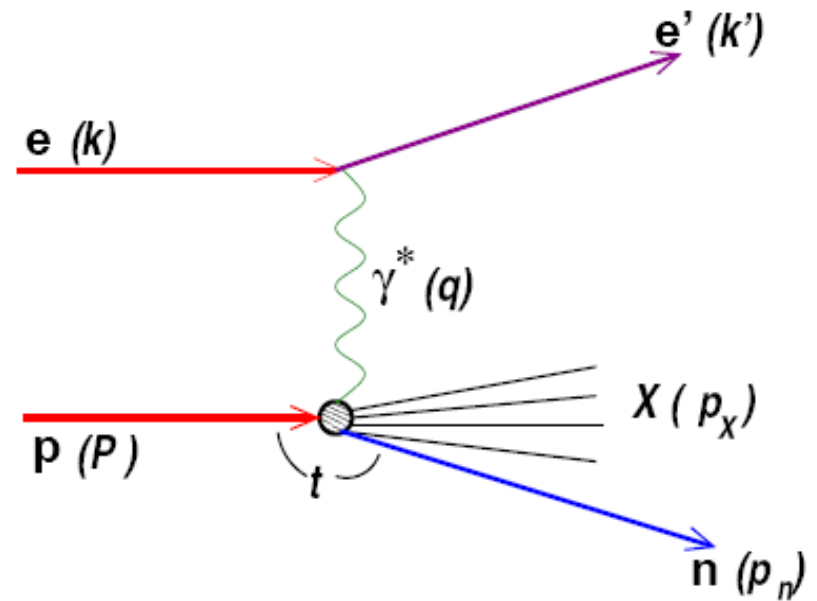
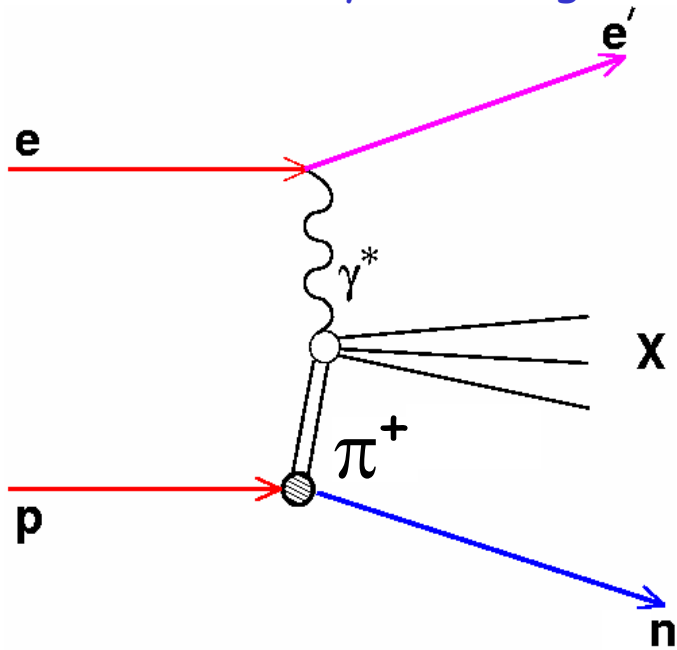
On behalf of the H1 and ZEUS Collaborations



- Outline:
- Forward neutron measurements in DIS
- Forward neutrons in dijet photoproduction
- Forward photon spectra in DIS

Introduction

Significant fraction of ep scattering events contains a high energy forward neutron produced at very small angles.

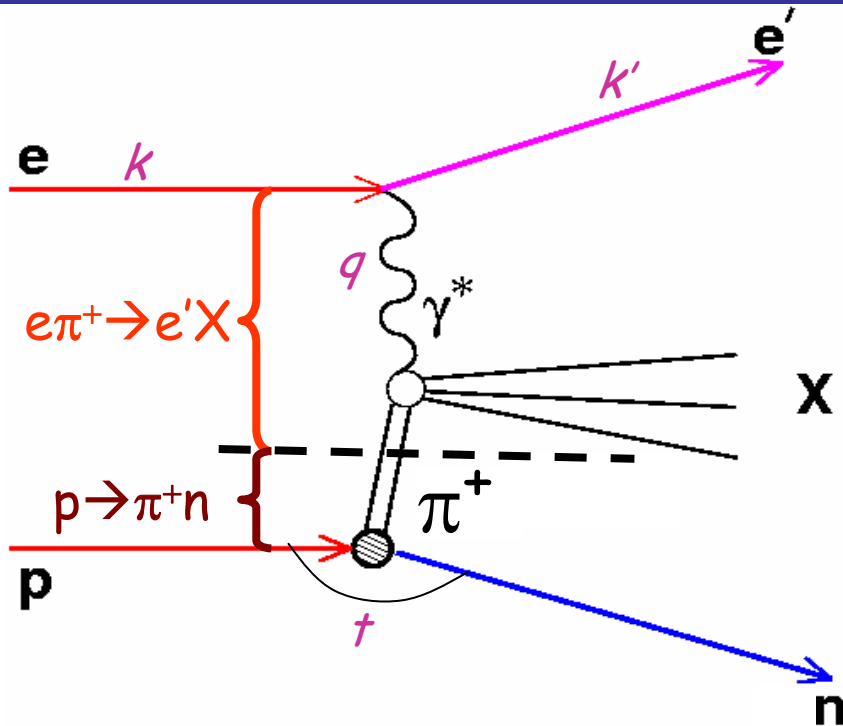


exchange of virtual particle (π^+ , ρ^+ , ...)

(a virtual particle from the proton undergoes DIS with virtual photon)

→ expected to dominate the forward neutron production at large x_L ($=E_n/E_p$) and low $p_{T,n}$

fragmentation of proton remnant (e.g. Lund string)



$ep \rightarrow e'nX$

Lepton variables:

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

$$x = Q^2 / (2p \cdot q)$$

Leading neutron variables:

$$x_L = E_n / E_p$$

$$t = (p - p_n)^2 \quad (\text{or } p_T^2)$$

In the exchange model the cross sections factorise, e.g. for one pion exchange

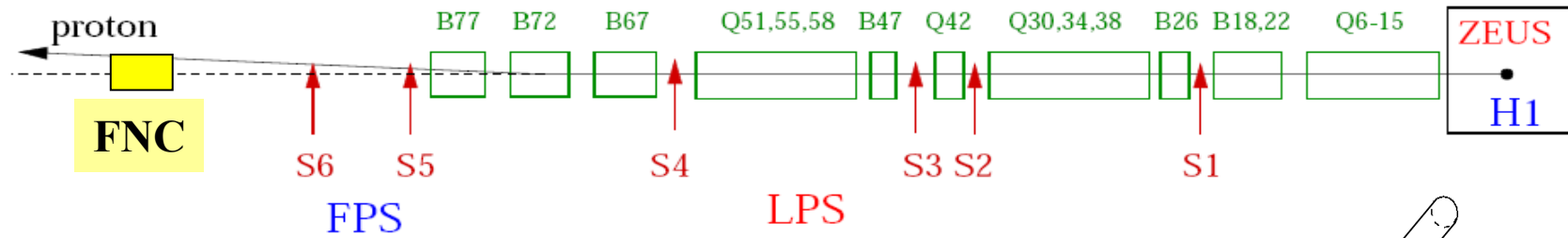
$$\sigma(ep \rightarrow e'nX) = f_{\pi/p}(x_L, t) \times \sigma(e\pi \rightarrow e'X)$$

$f_{\pi/p}(x_L, t)$ - pion flux:
probability to emit pion from the photon with given x_L, t

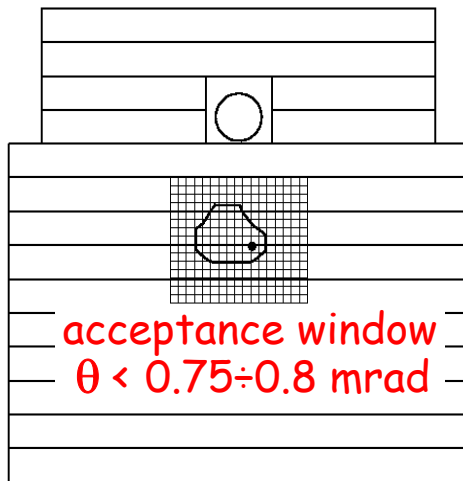
$\sigma(e\pi \rightarrow e'X)$ - cross-section
of $e\pi$ scattering

- Leading Neutron production independent from photon vertex
→ probe structure of exchanged particle
- factorisation violation due to absorption/rescattering

H1 and ZEUS detectors for leading neutrons



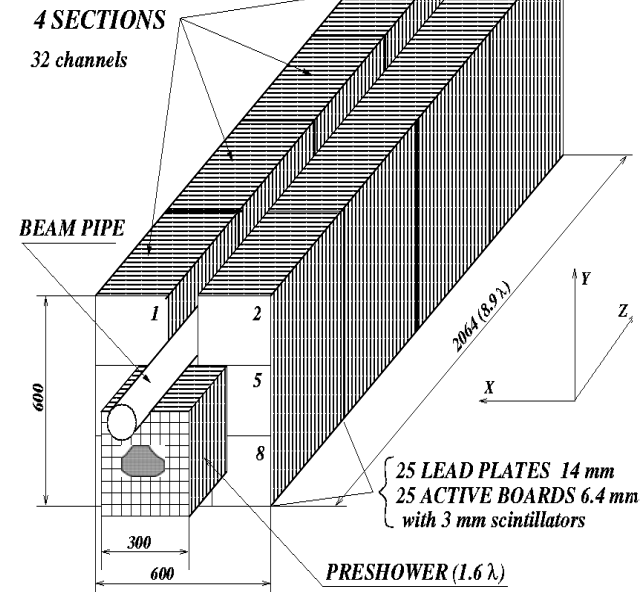
ZEUS FNC+FNT



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

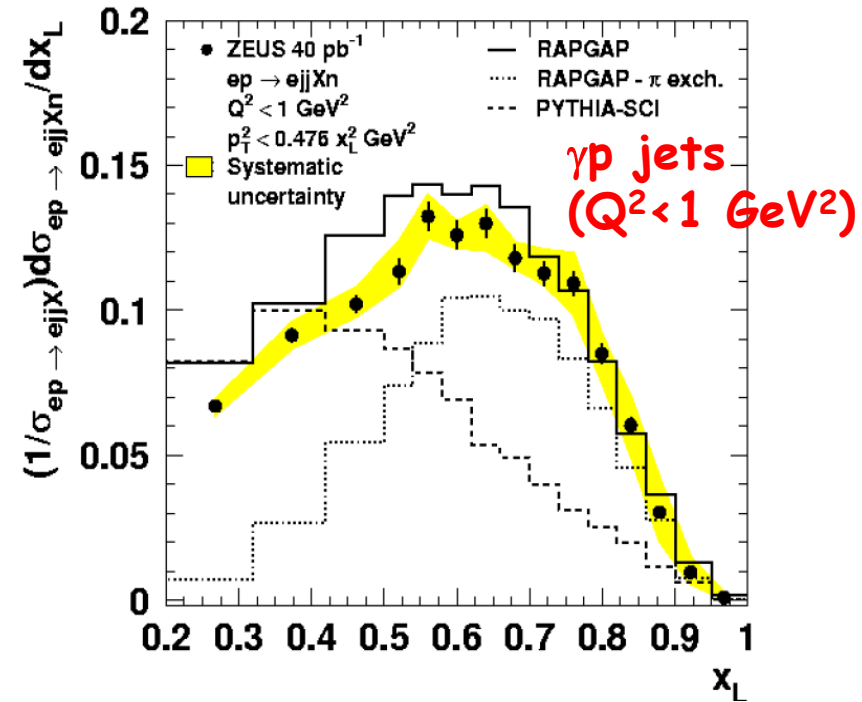
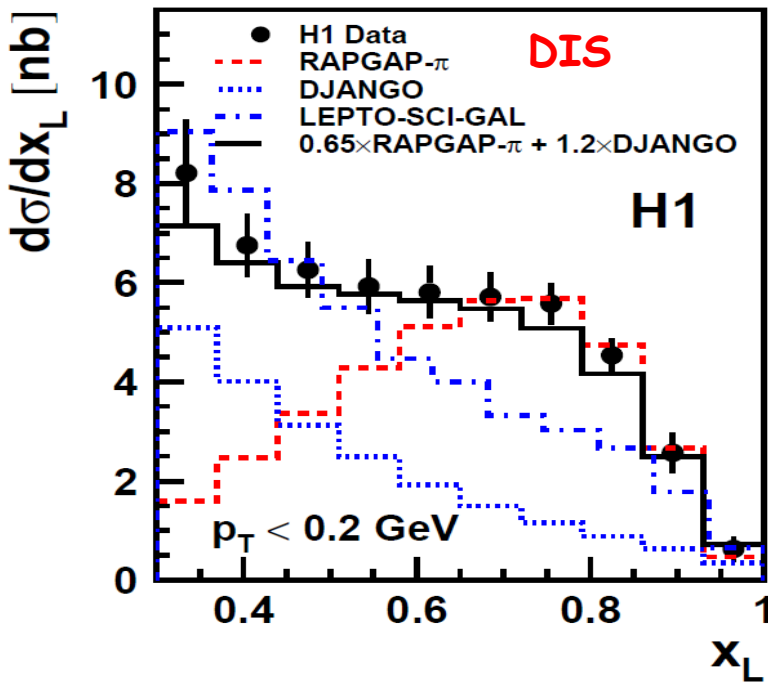
position resolution 2-3mm

H1 FNC



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

- Longitudinal segmentation allows reliable discrimination between e/m and hadronic showers (i.e. between photons and neutrons)
- Acceptance limited by beam apertures and detector size
- p_T resolution is dominated by p_T spread of proton beam (50-100 MeV)



- Data described by a combination of standard fragmentation (DJANGO, RAPGAP) and π^+ -exchange (RAPGAP- π) MC models over the full range
- 'Standard' fragmentation models (DJANGO, RAPGAP) don't describe the shape at high x_L
- SCI (soft colour interactions) models too low at high x_L
- π^+ -exchange model (RAPGAP- π) describes the shape of data distribution well for $x_L > 0.7$

π -exchange - the dominant mechanism at large x_L

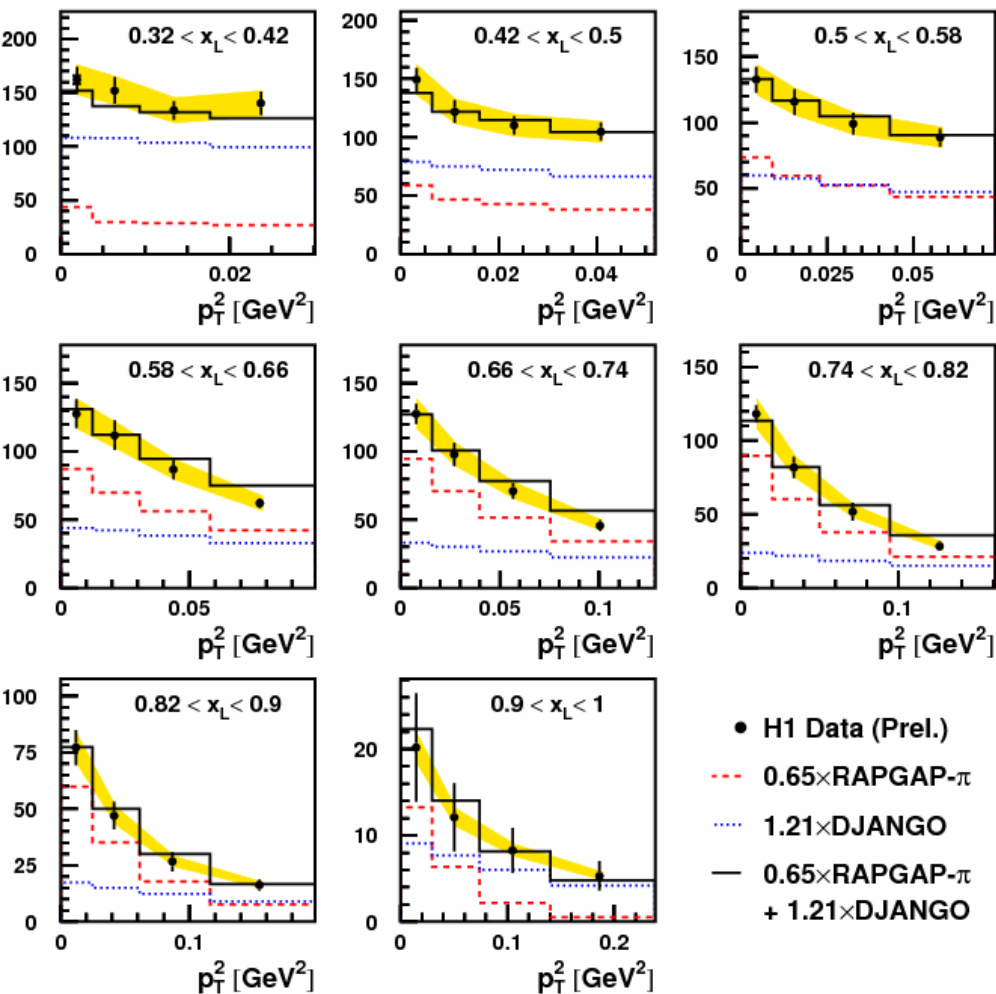
Forward neutron: double differential cross section in p_T^2 and x_L

Extend the measurement differentially in transverse momentum of neutron p_T

H1prelim-10-113 ($6 < Q^2 < 100 \text{ GeV}^2$, $0.05 < \gamma < 0.6$)

$d^2\sigma/(dx_L dp_T^2)$ [nb/GeV²]

H1 Preliminary



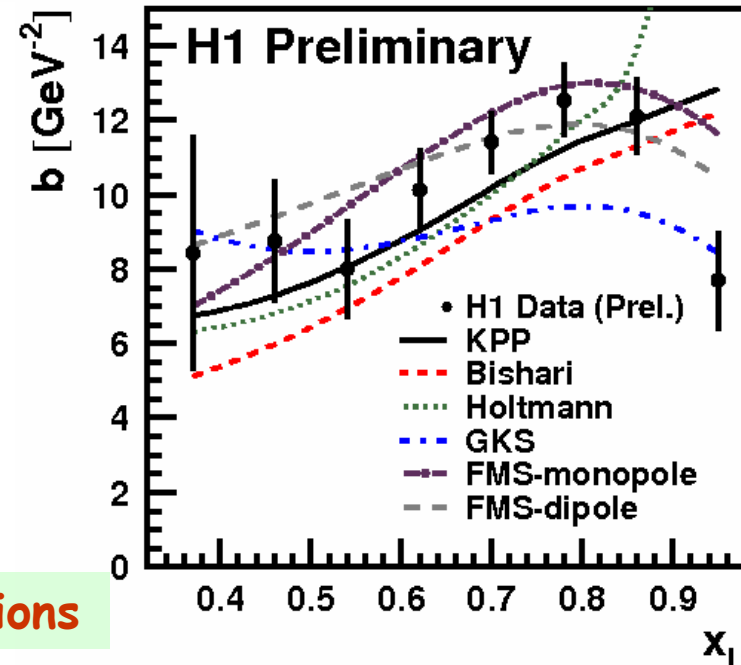
Measurement sensitive to the π flux parameterisations

Combination of RAPGAP- π and DJANGO describes well the p_T^2 distributions (using same weighting factors as for x_L)

different p_T^2 slopes for standard fragmentation and pion-exchange:
 \sim constant vs x_L for DJANGO; increasing with x_L for RAPGAP- π

Fit the distributions by a single exponent.

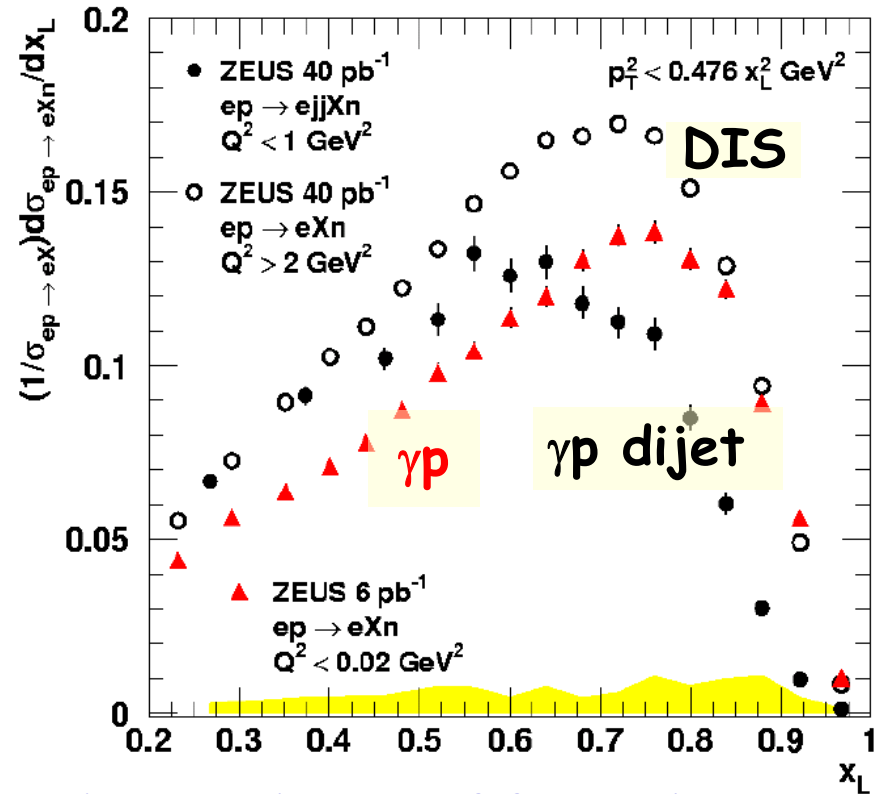
$$\frac{1}{\sigma_{inc}} \frac{d\sigma_{LN}}{dp_T^2 dx_L} = a(x_L) \cdot e^{-b(x_L) p_T^2}$$



Forward neutrons: photoproduction of jets vs DIS

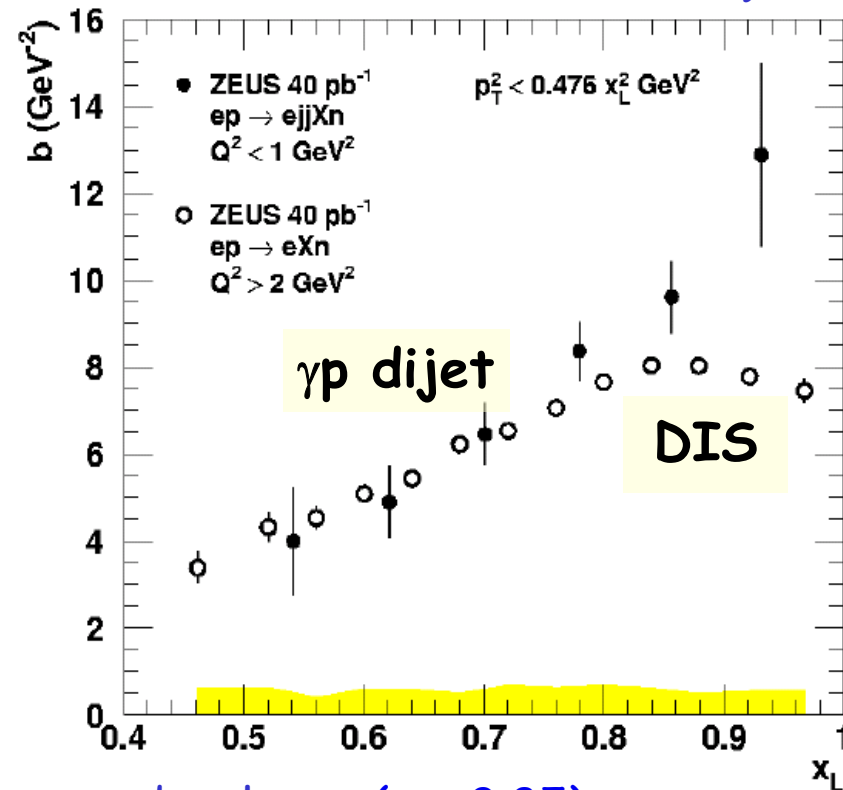
Compare neutron yield and b-slopes in DIS, γp -dijets and inclusive γp .

ZEUS



ZEUS

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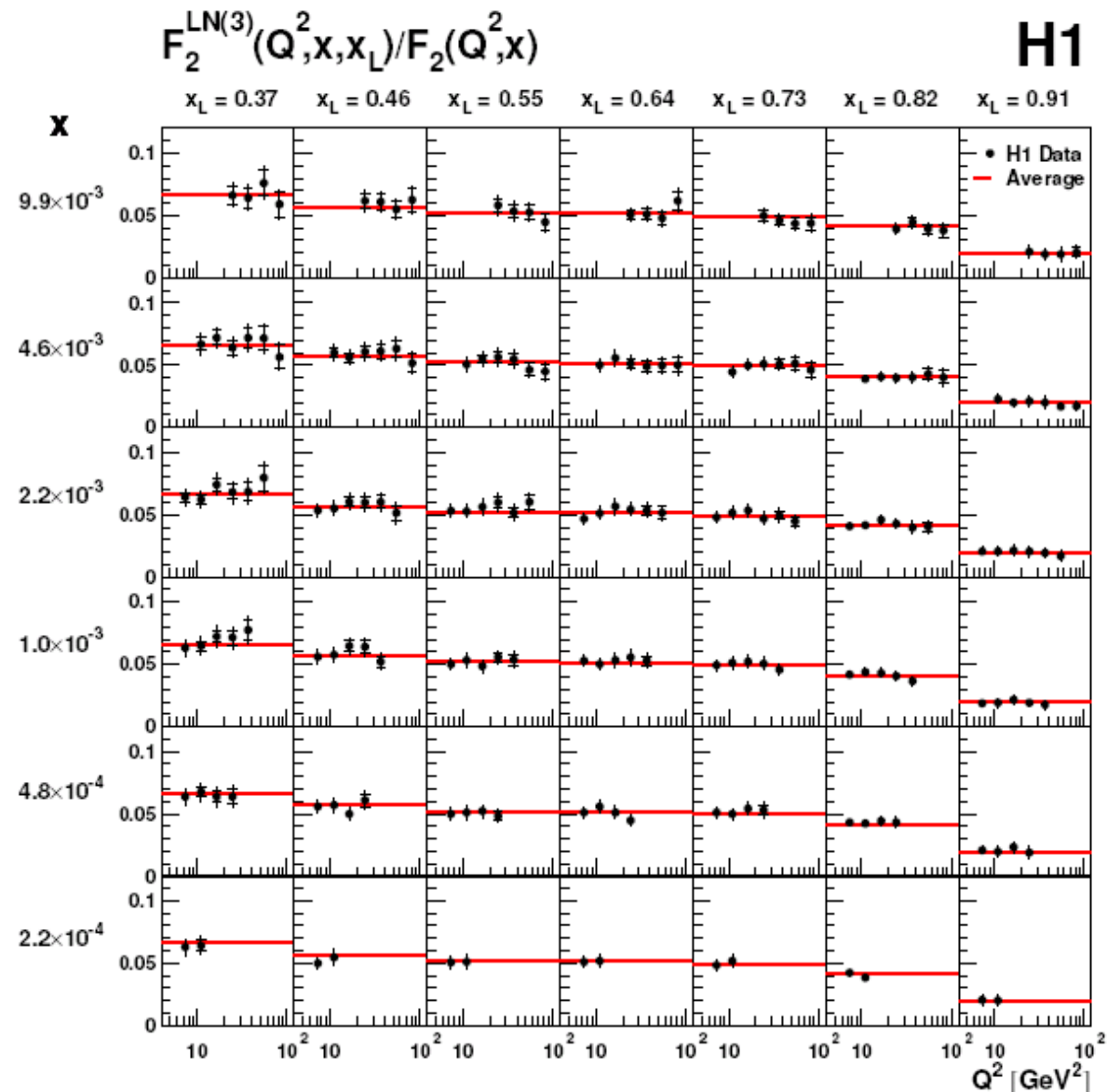


- photoproduction of forward neutrons suppressed at low x_L ($x_L < 0.85$)
 → consistent with neutron absorption through rescattering (more absorption in γp than in DIS due to larger transverse size of real photon)
- Suppression is not so prominent in jet production (hard scale provided by E_{T}^{jet})
- dijets suppressed at high x_L → phase space limitation
- similar b-slopes in DIS & γp -dijets; slightly different at high x_L
 → same production mechanism for forward neutrons

$$\frac{d^3\sigma(ep \rightarrow eNX)}{dQ^2 dx dx_L} = \frac{4\pi\alpha^2}{xQ^4} \left[1 - y + \frac{y^2}{2} \right] F_2^{LN}(Q^2, x, x_L)$$

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

i.e. LN production rate, kinematics is approx. independent of (Q^2, x)
 → consistent with factorisation, limiting fragmentation (overall suppression of LN events is also possible)

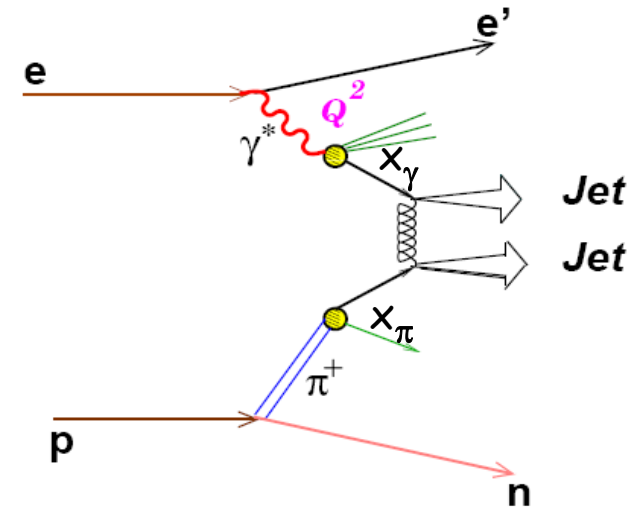
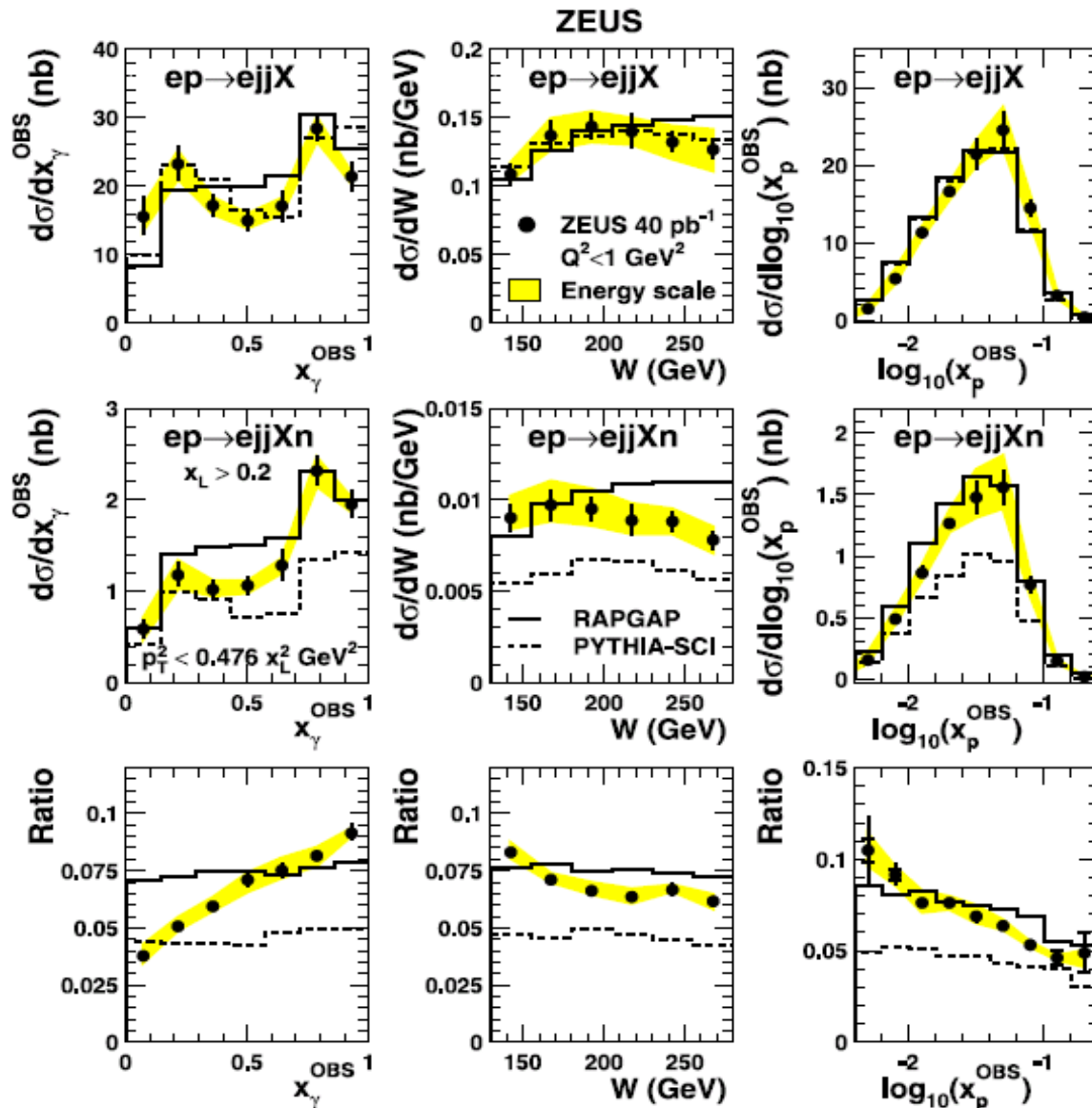


*) $F_2(Q^2, x)$ from the H1PDF2009 parameterisation

Dijet photoproduction with Leading Neutrons

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Dijet cross sections in inclusive γp and in γp with LN, and their ratios.



- W - total energy of γp system
- $x_\gamma = \sum_{\text{jets}} (E - p_z) / (2yE_e)$
- $x_p = \sum_{\text{jets}} (E + p_z) / (2E_p)$

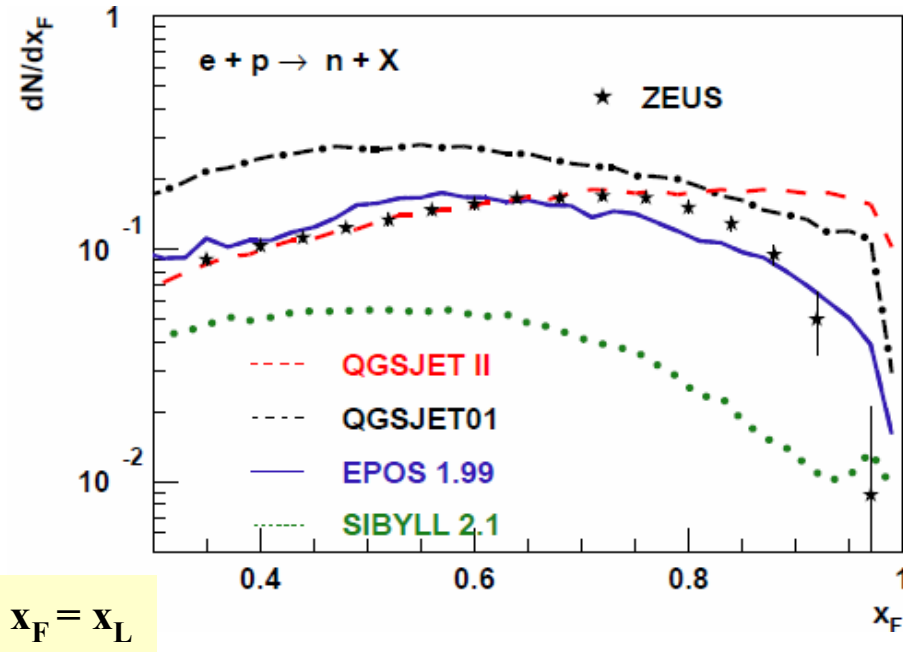
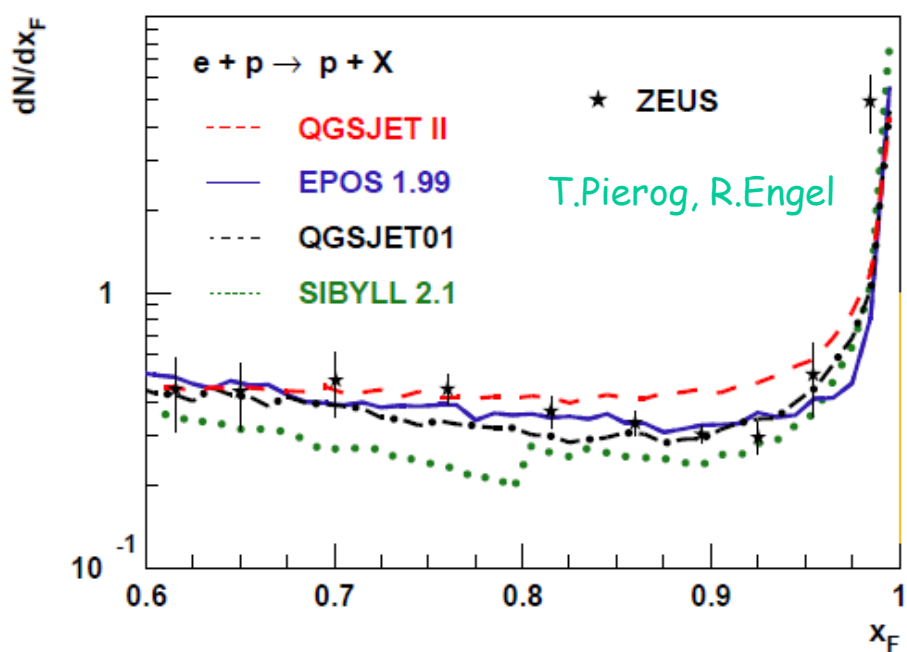
- strong dependence of ratio of x_γ distributions for data, flat in MC

- resolved photon is suppressed in events with neutron.

Interplay of forward particle production and Cosmic Ray physics

The tuning of cosmic ray interaction models crucially depends on the input from the measurements at accelerators

In particular, the forward measurements (baryons, π^0 , γ) are of the greatest importance for the model tuning, since the shower development is dominated by the forward, soft interactions.



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

EPOS 1.9: (Pierog, Werner),

QGSJET 01 and II: (Kalmykov, Ostapchenko),

SIBYLL 2.1: (Engel, Fletcher, Gaisser, Lipari, Stanev)

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Measure forward photons in FNC, compare to

- MC models (CDM and LEPTO)
- hadronic interaction models used for analysis of cosmic rays (EPOS, SIBYLL, QGSJET)

What are our photon candidates?

At high x_L , many FNC clusters are from two photons!

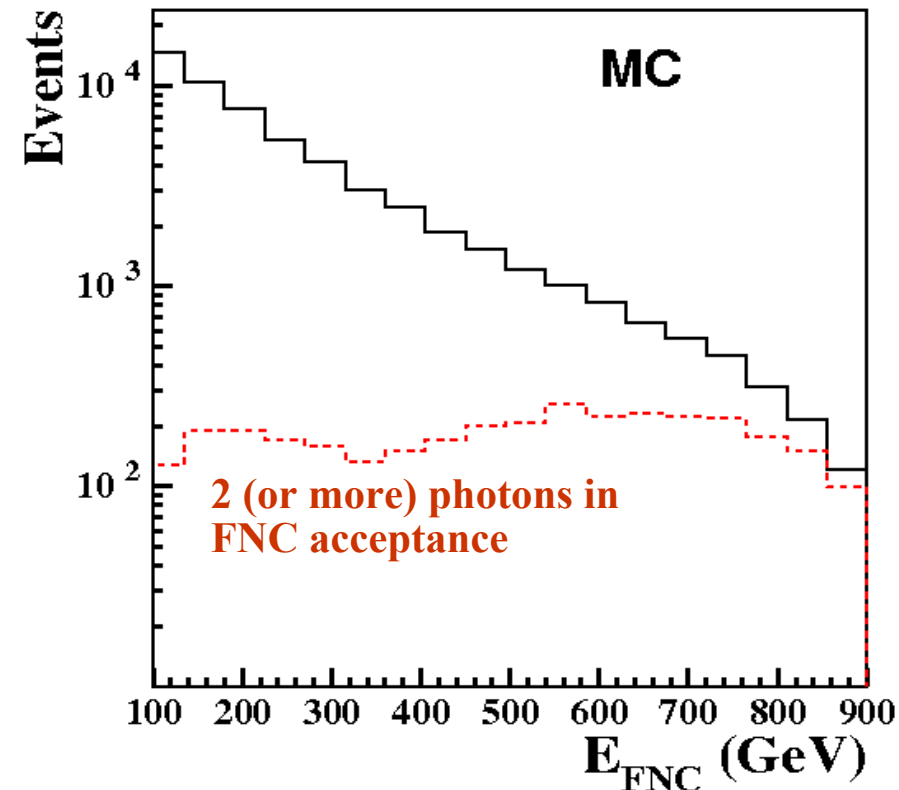
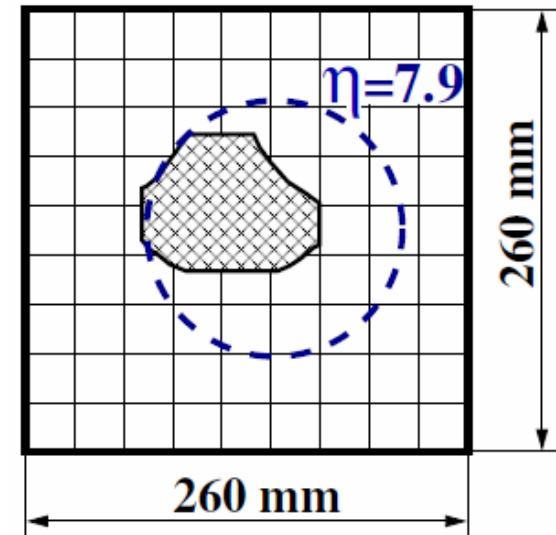
→ the measurement represents the sum of photons inside the angular range defined by the FNC geometrical acceptance ($\eta > 7.9$).

At lower x_L we can assume that to a good approximation to measure single photon.

For photons with $\eta > 7.9$ provide cross sections:

- x_L and p_T of most energetic photon in the range $0.1 < x_L < 0.7$

- x_L of sum of all photons



Forward photon production cross sections

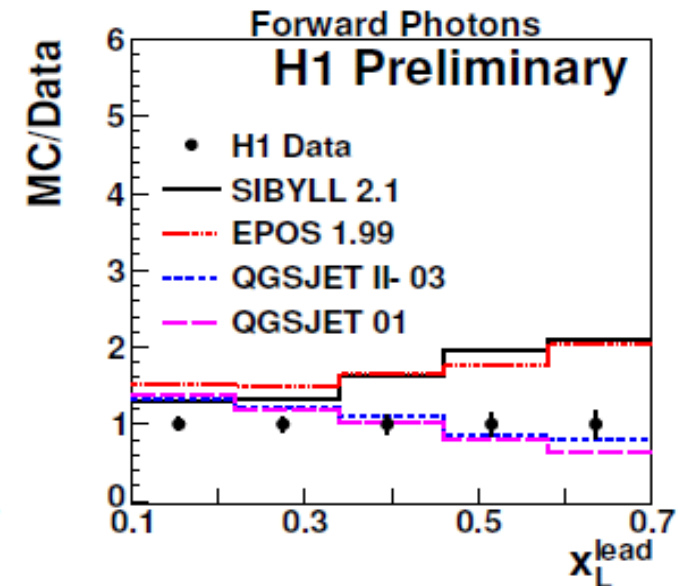
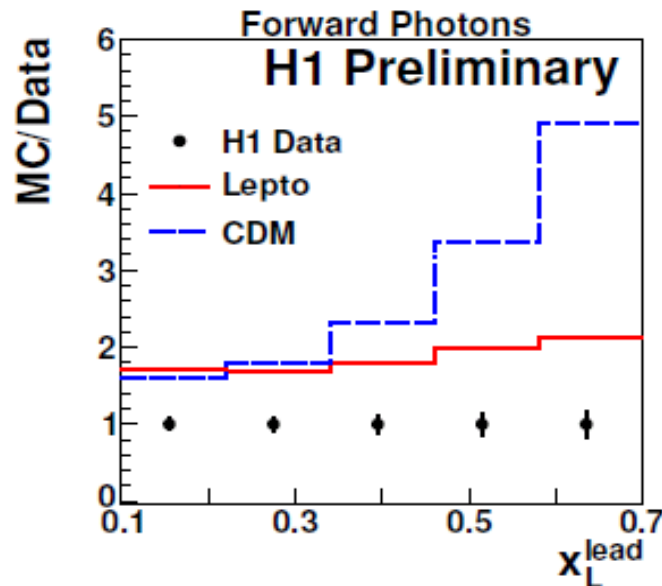
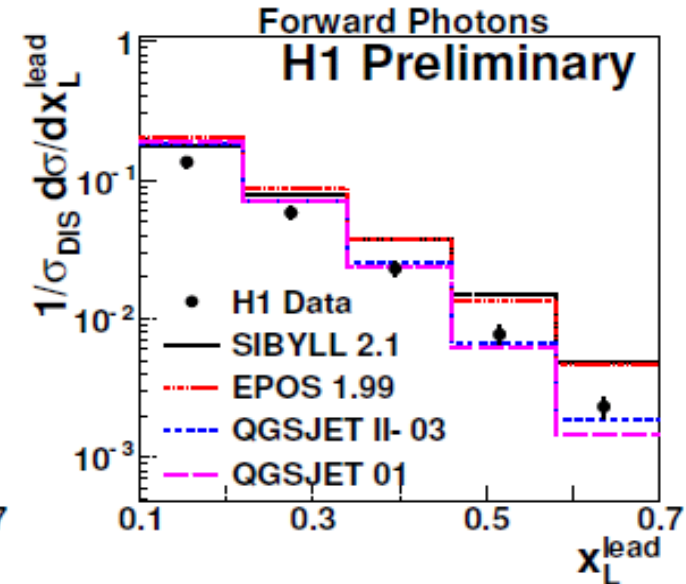
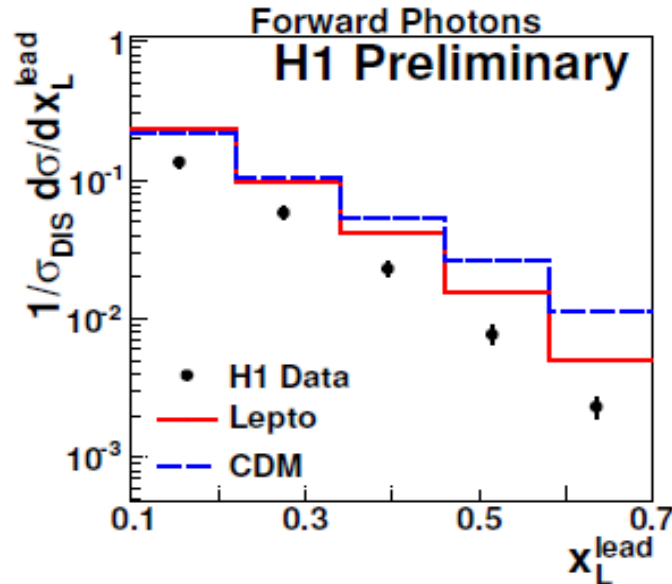
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$6 < Q^2 < 100 \text{ GeV}^2$, $0.05 < \gamma < 0.6$,
2006-2007 data, Lumi=126pb⁻¹

Photon rate in all tested MC 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



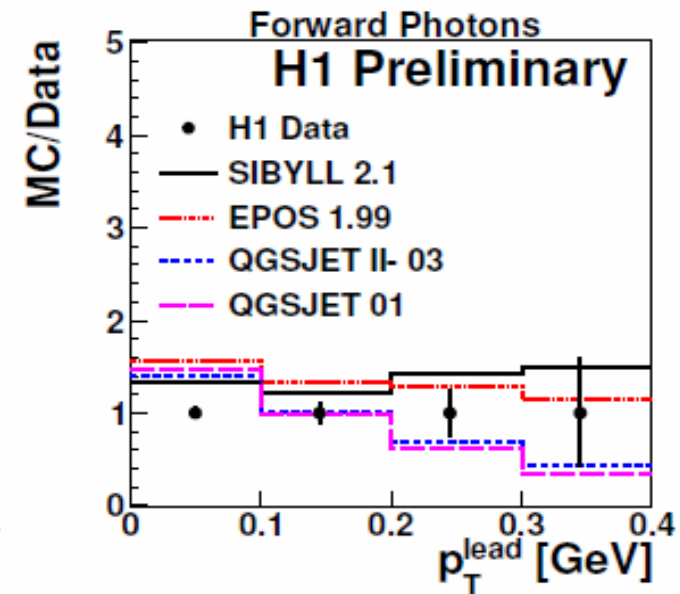
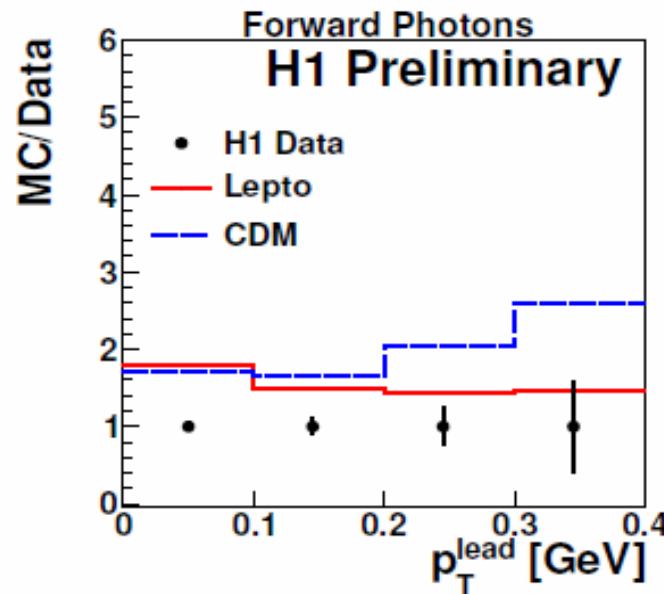
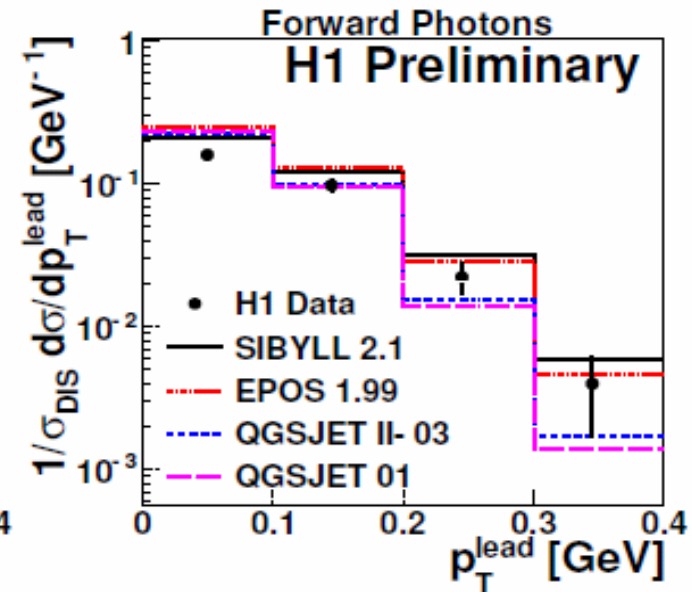
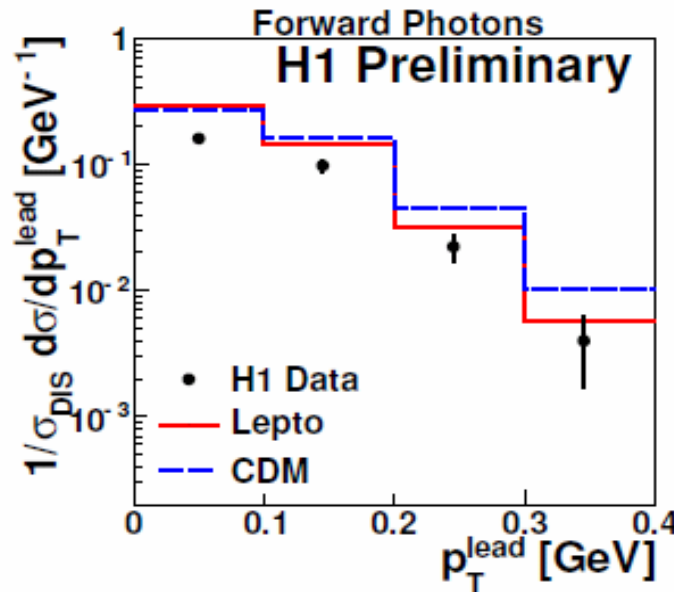
Forward photon production cross sections

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

LEPTO model describes the shape reasonably well.

p_T^2 spectrum shape is well described by SIBYLL and EPOS models. QGSJET also agree with data within uncertainties (except lowest p_T)



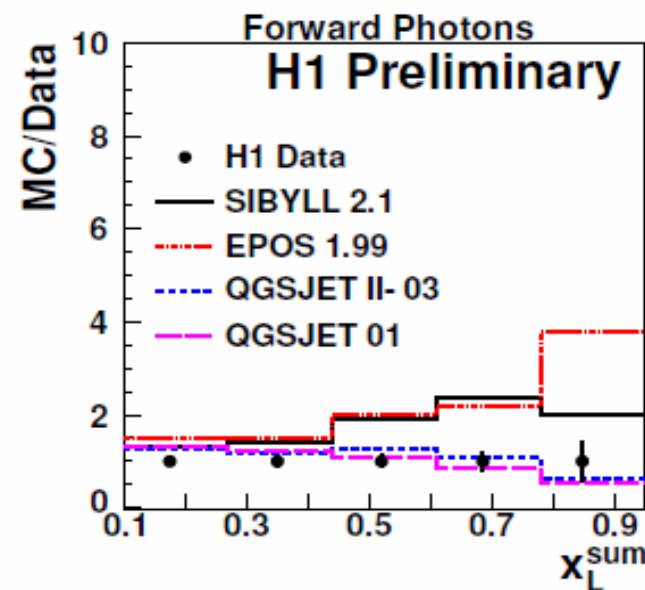
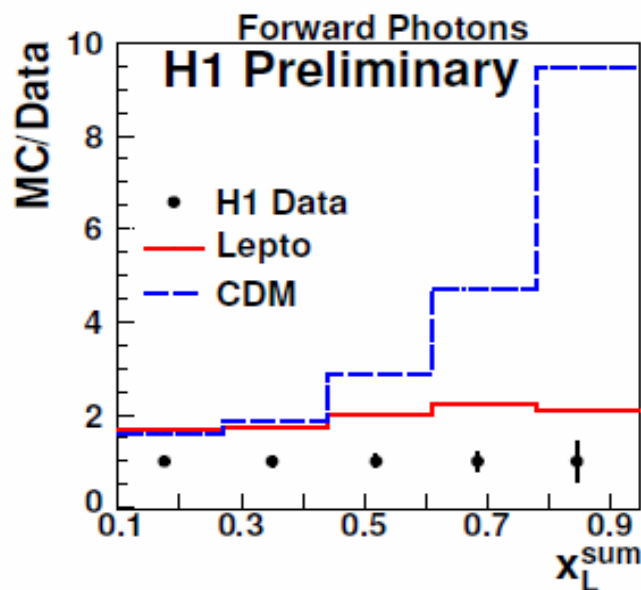
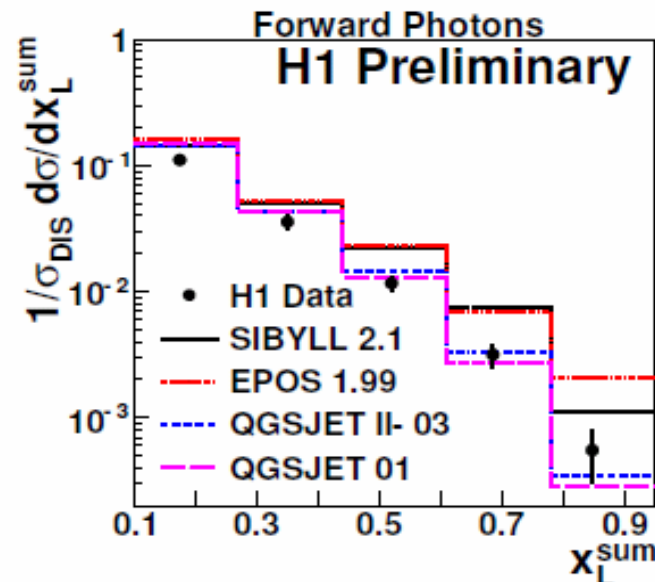
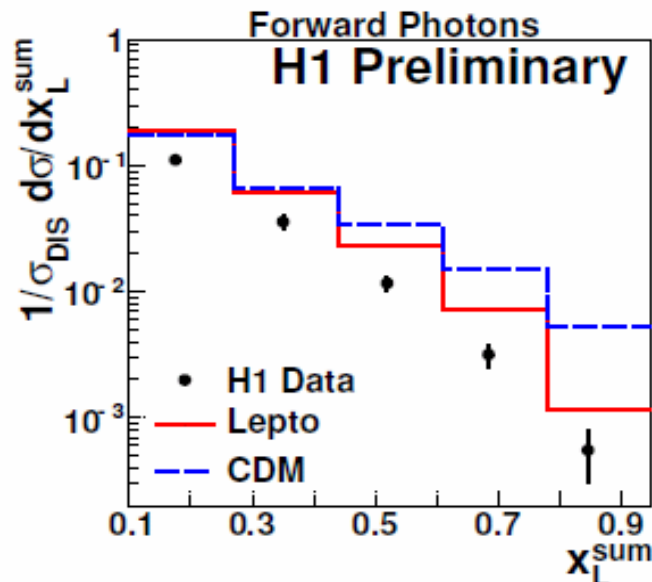
Forward photon production cross sections

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

LEPTO model describes the shape reasonably well. CDM - large discrepancy at higher x_L

QGSJET models describe data shape better than SIBYLL and EPOS



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

Summary

- precise measurements of forward neutron x_L and p_T^2 in DIS and dijet photoproduction
- the measurements well described by the combination of 'standard' fragmentation models and models with pion exchange
- Pion flux can be further constrained using the measurement.
- In photoproduction the leading neutron production is suppressed at $x_L < 0.85$. Suppression is not prominent in dijet photoproduction
- x_γ distribution: different shapes observed in events with neutrons and inclusive photoproduction- not reproduced in MC

- First measurement of very forward photon production in DIS.
- Measurements show sensitivity to proton fragmentation MC models
- MC models predict significantly higher yield of photons than in the data
- LEPTO describes the shape well; too many photons at high energies in CDM
- Useful input for models of cosmic ray interactions with matter

Estimate the Pion structure function from $F_2^{LN}(Q^2, x, x_L)$

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H1

within π^+ -exchange model we may try to estimate 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

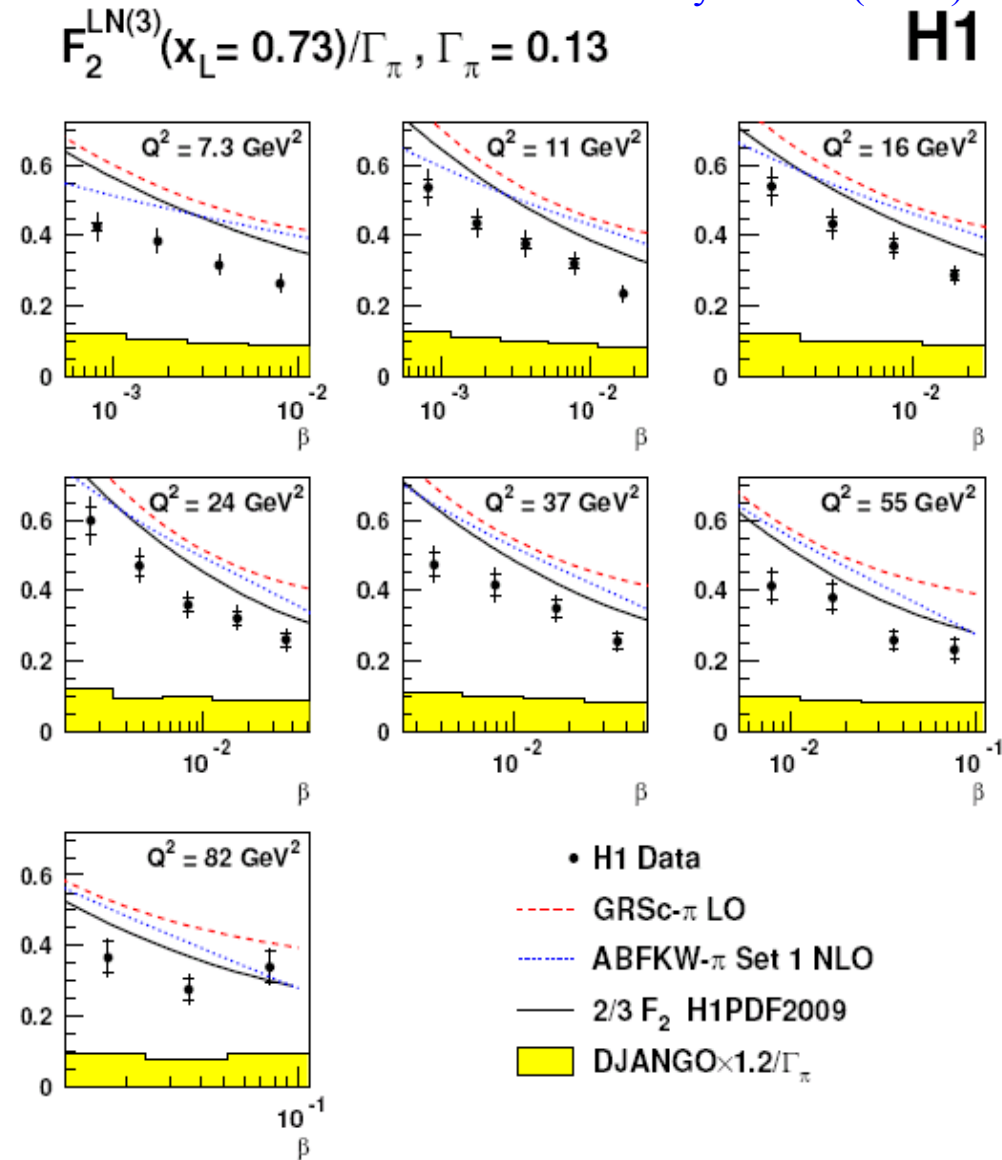
$\beta = x/(1-x_L)$ - fraction of pion momentum carried by struck quark (i.e. x_{Bj} for pion)

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

$$\Gamma_\pi = \int f_{\pi/p}(x_L = 0.73, t) dt$$

use pion flux parameterisation (Holtmann et al.):

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



Data are sensitive to the parameterisations of the pion structure function (constrained for $x > 0.1$ from the fixed target experiments).

Estimate the Pion structure function from $F_2^{LN}(Q^2, x, x_L)$

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within π -exchange model we can estimate 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

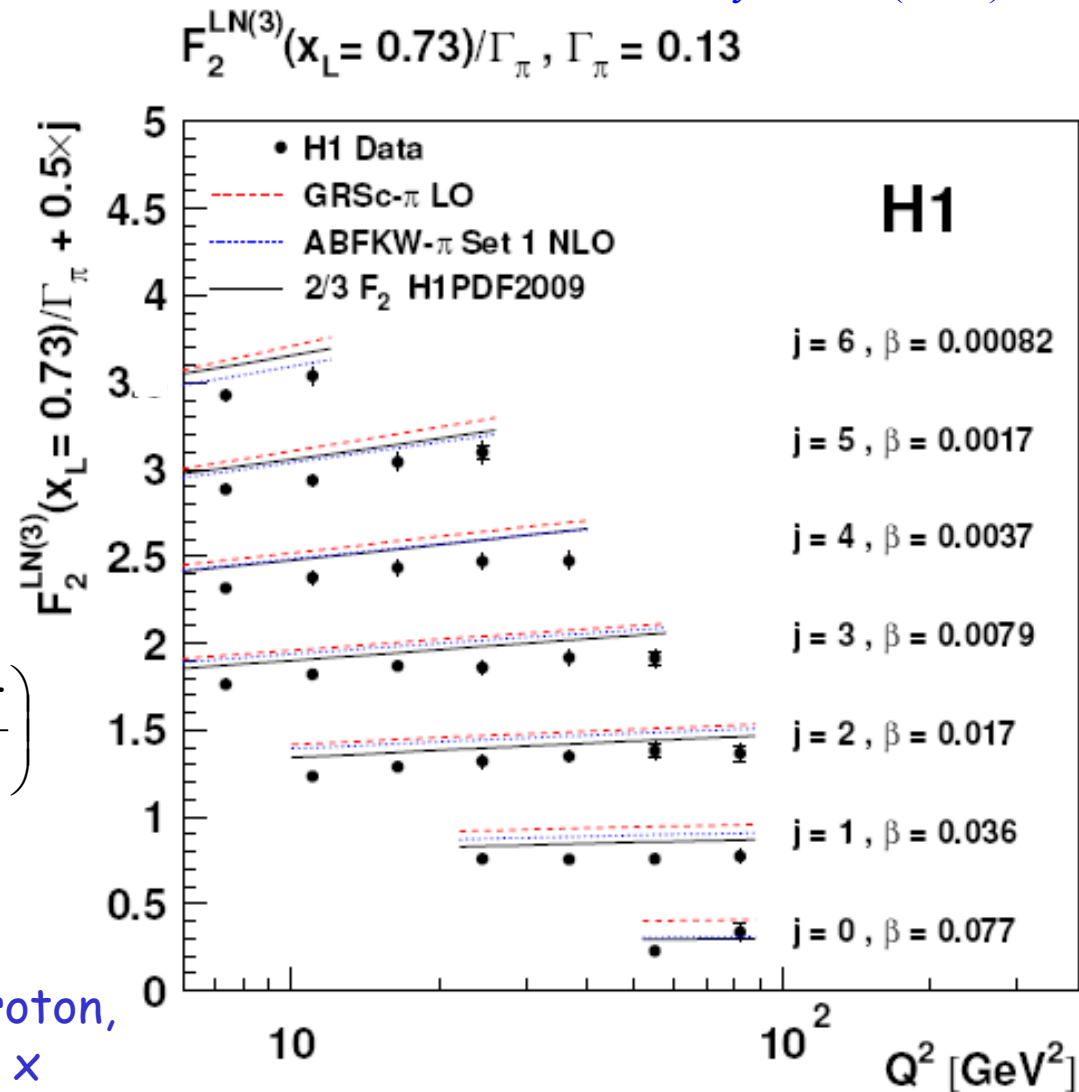
$$\Gamma_\pi = \int f_{\pi/p}(x_L = 0.73, t) dt$$

use pion flux expression (Holtmann et al.):

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

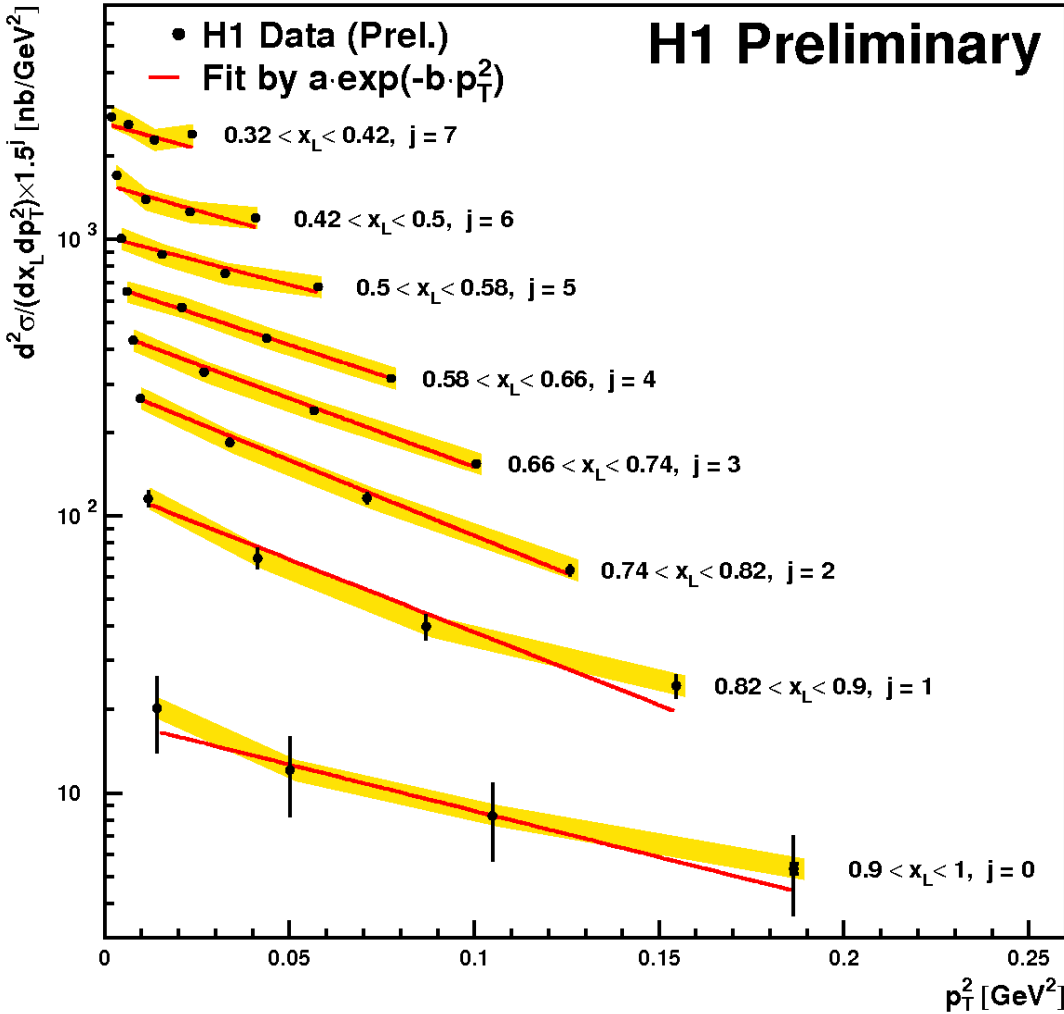
- F_2^{LN} dependence on x and Q^2 similar to proton, \rightarrow universality of hadron structure at low x
- in absolute values F_2^{LN}/Γ below the F_2^π and F_2

However: large uncertainty of pion flux normalisation: choice of pion flux (formfactor), absorption/rescattering, background...



Forward neutron production: fit to p_T^2 distribution

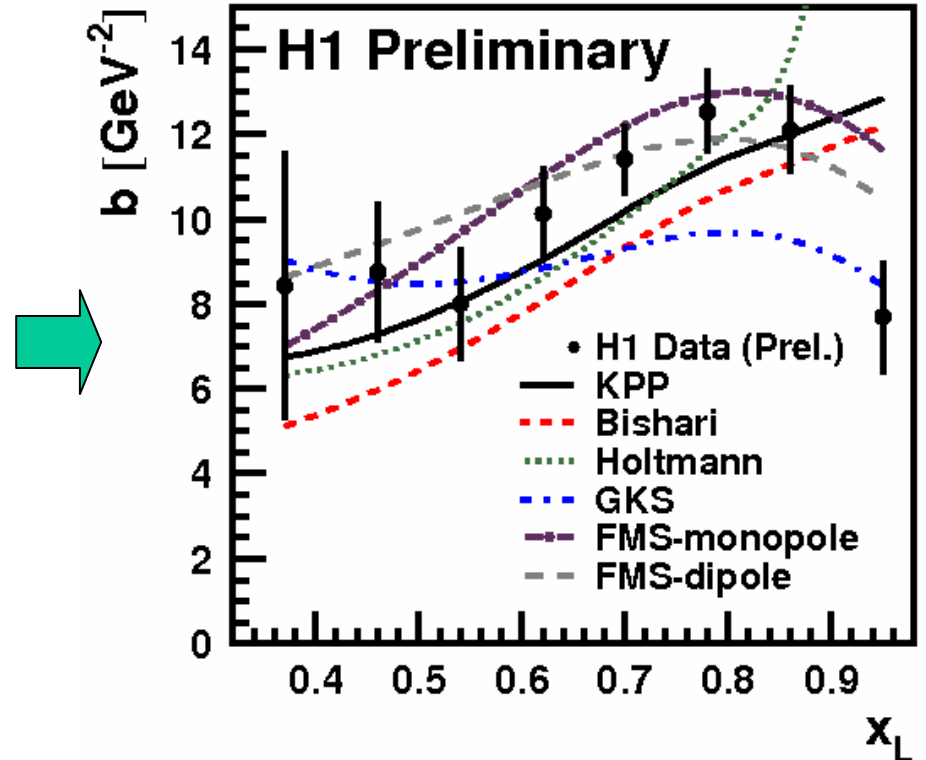
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Fit the distributions by a single exponent.

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

Compare slopes with different parameterisations of pion flux



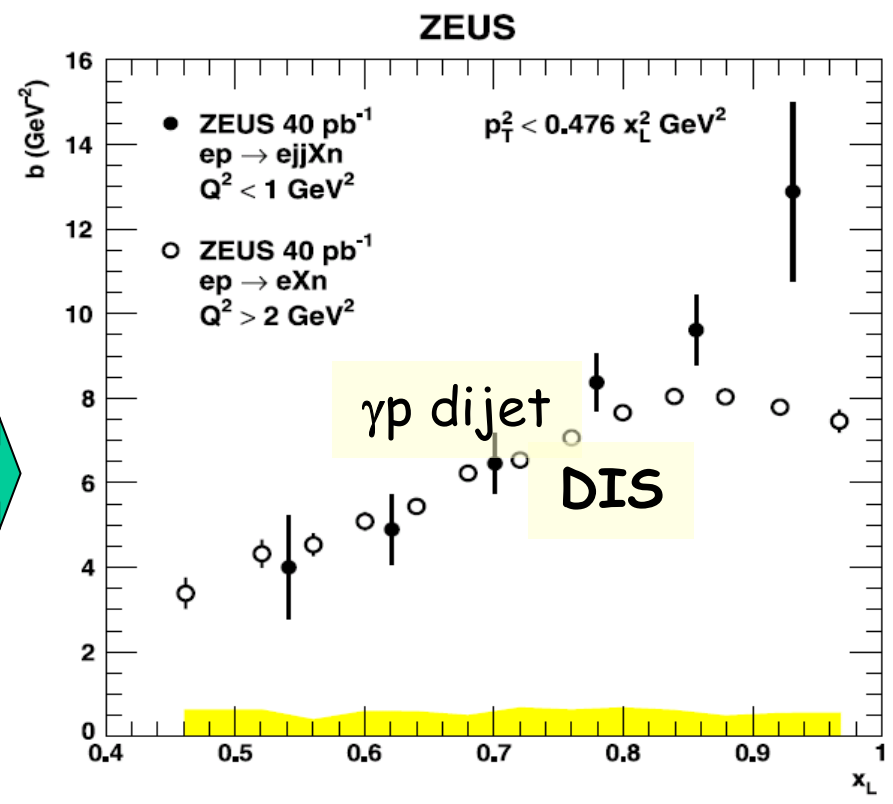
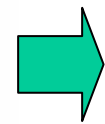
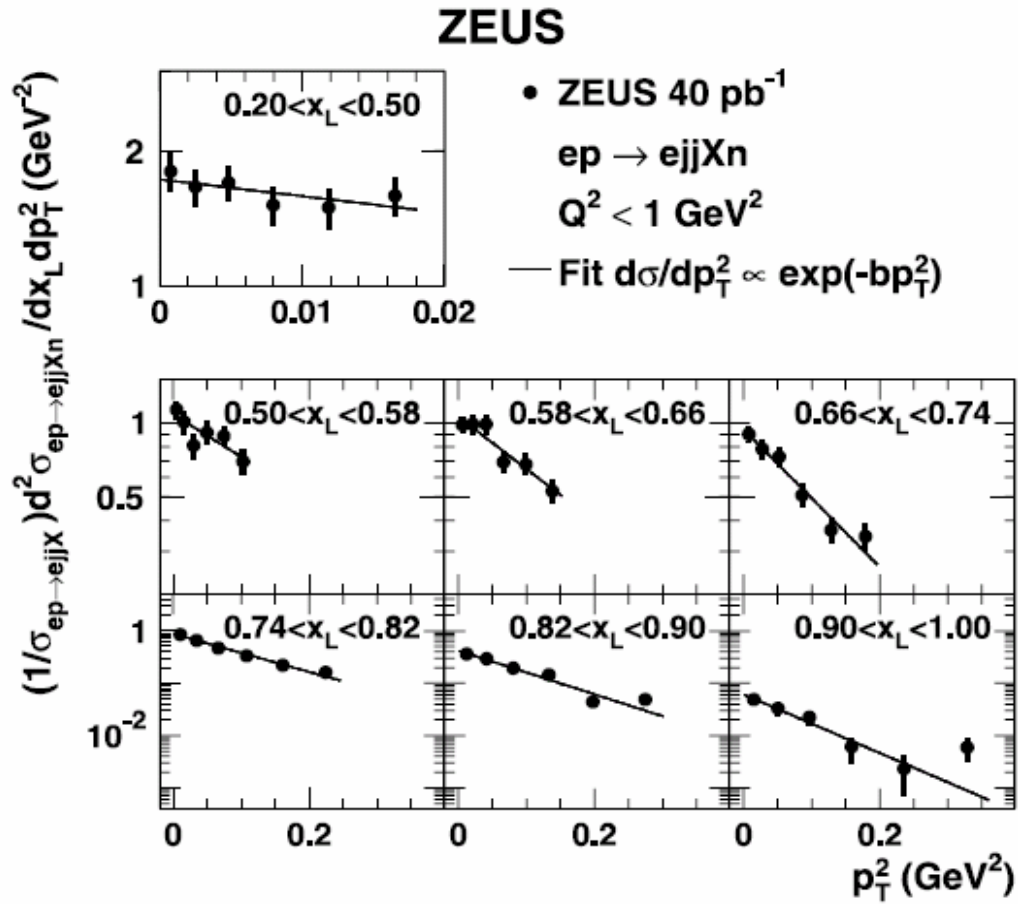
Measurement sensitive to the pion flux parameterisations

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

Dijet photoproduction with Forward Neutrons: p_T^2 distributions in x_L bins; slopes

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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

Forward particle measurements and cosmic ray air shower models

Above 10^{14} eV, primary cosmic rays particles are detected via air showers- determination of their primary energy and mass relies on the modeling of hadronic interactions.

Precision of analyses limited by modeling of hadronic interactions; significant differences between the model predictions for particle multiplicities, energy flow etc.

→ **The collider experiments can contribute to the tuning of the models**

In particular, the forward measurements (baryons, γ , π^0) are of the greatest importance for the model tuning, since the shower development is dominated by the forward, soft interactions.

