Low-x workshop on deep inelastic scattering, diffraction, final states and related subjects
3-7. June 2011
Santiago de Compostela

# *Forward Neutron and Photon results from HERA*

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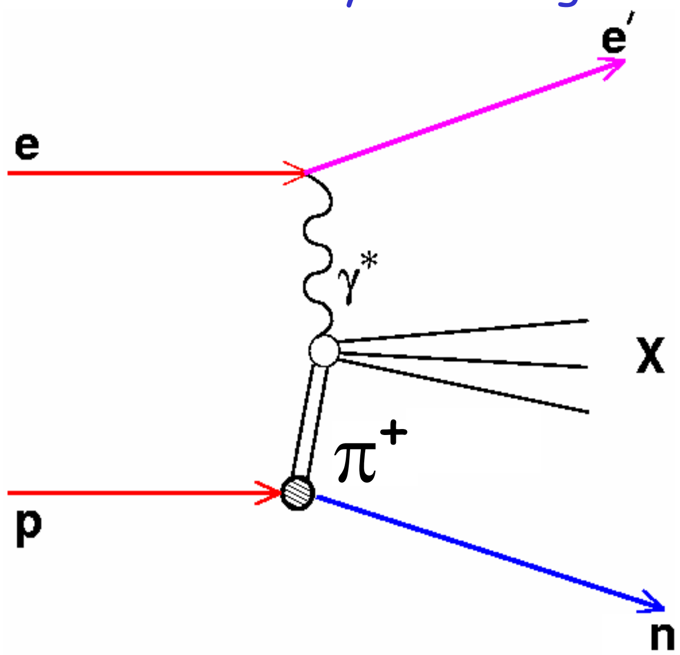
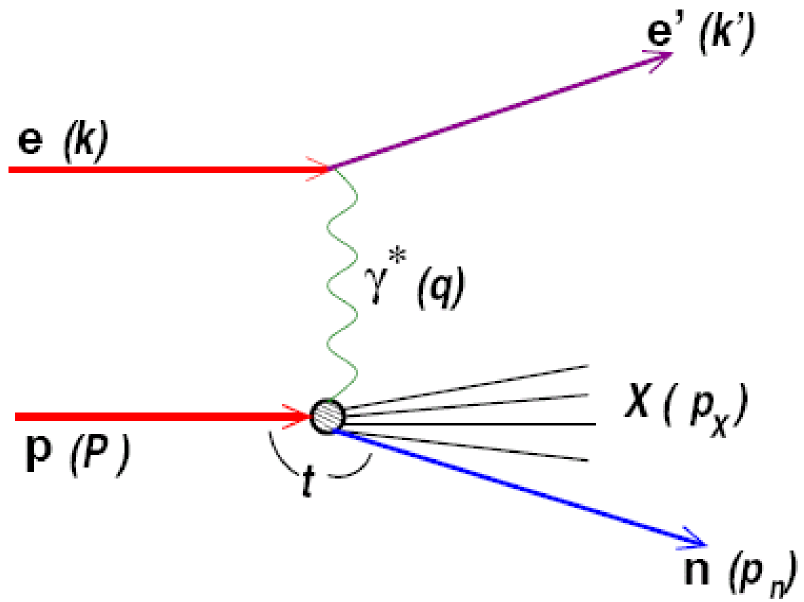
On behalf of the H1 and ZEUS Collaborations

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

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




**e+p→e'+n+X**

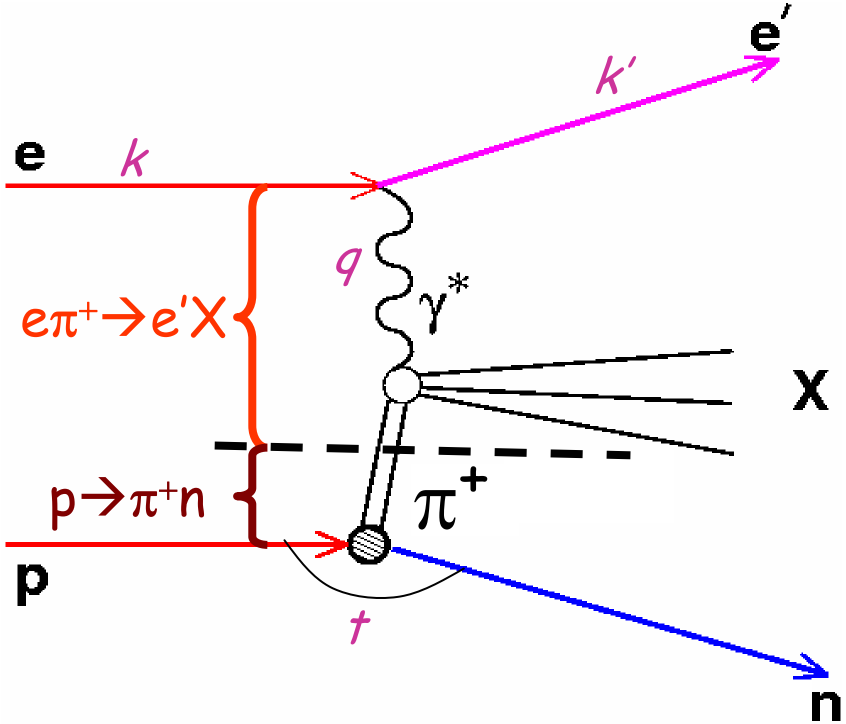



**exchange of virtual particle ($\pi^+$,$\rho^+$, .)**

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

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

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




**ep→ e'nX**

Lepton variables:

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

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

Leading neutron variables:

$x_L=E_n/E_p$

$t=(p-p_n)^2$ (or $p_T^2$)

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

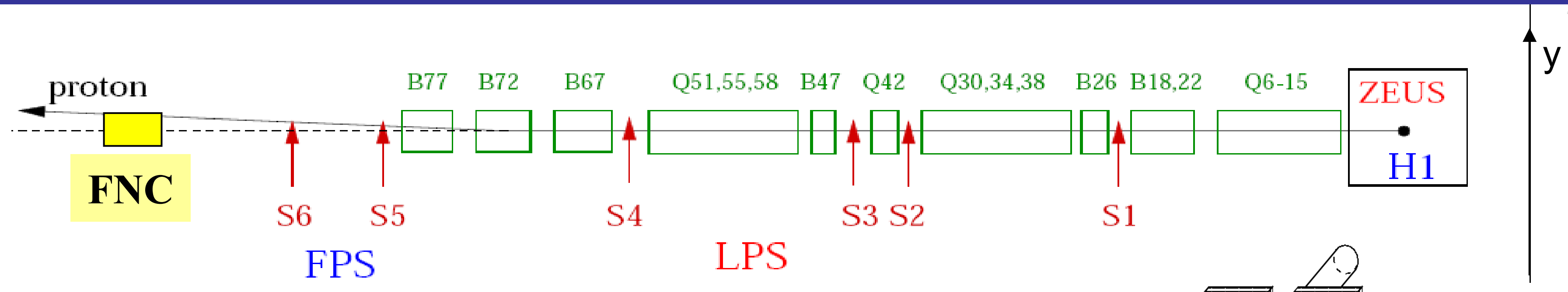
$$\sigma(ep\rightarrow e'nX) = f_{\pi/p}(x_L,t) \times \sigma(e\pi\rightarrow e'X)$$

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

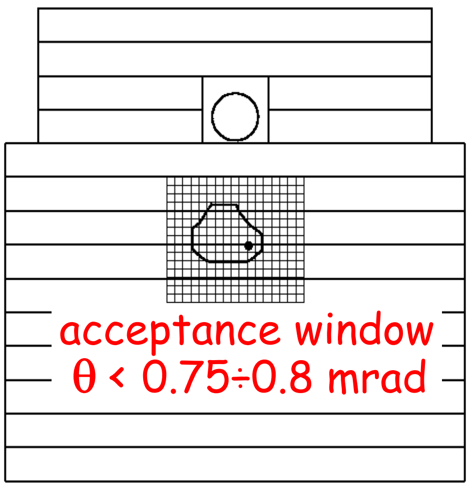
$\sigma(e\pi\rightarrow e'X)$ - cross-section of eπ scattering

- 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

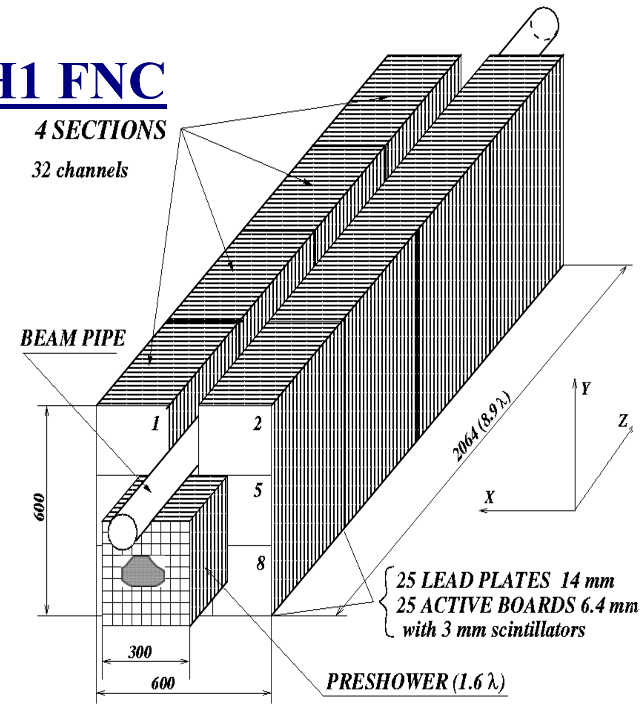



## ZEUS FNC+FNT




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

## H1 FNC



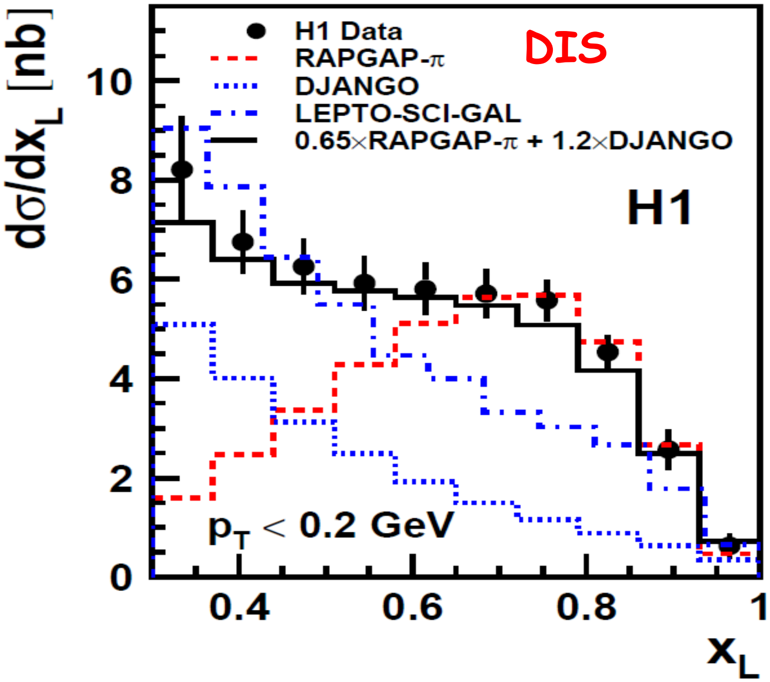

$\sigma_E/E \approx 0.63/\sqrt{E} \oplus 2\%$

position resolution 2-3mm

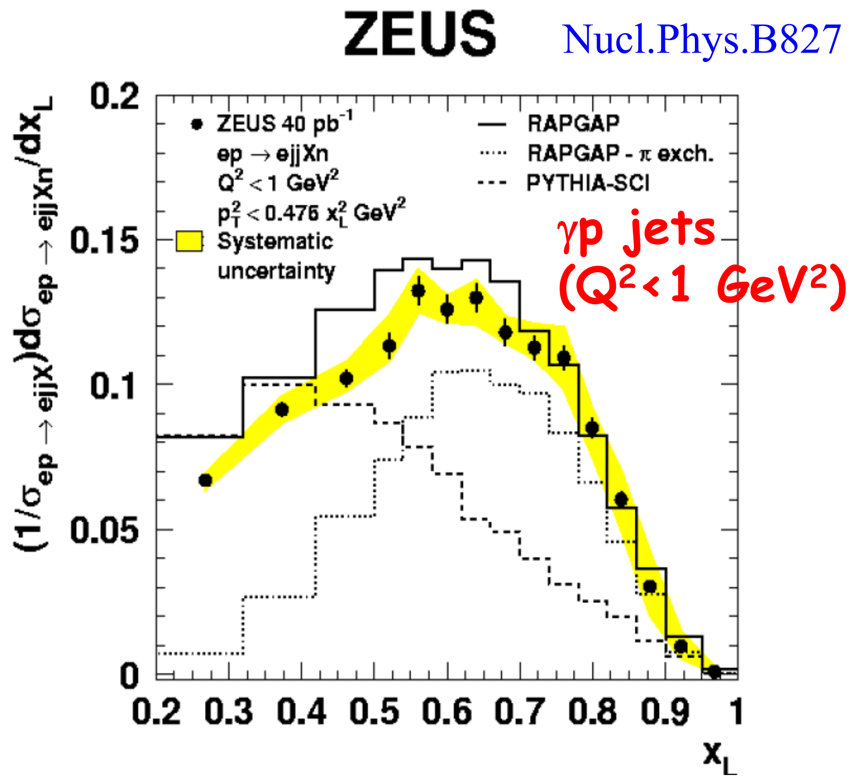
- Longitudinal segmentation allows reliable discrimination between e/m and hadronic showers (i.e. between photons and neutrons)
- Acceptance limited by beam apertures and detector size
- $p_T$ resolution is dominated by $p_T$ spread of proton beam (50-100 MeV)

# Forward neutron cross section vs $x_L$: DIS and γp jets

Eur.Phys.J.C68 (2010) 381




Nucl.Phys.B827 (2010) 1




· Data described by a combination of <u>standard fragmentation</u> (DJANGO, RAPGAP) and <u>$\pi^+$-exchange</u> (RAPGAP-π) MC models over the full range

· 'Standard' fragmentation models (DJANGO, RAPGAP) don't describe the shape at high $x_L$

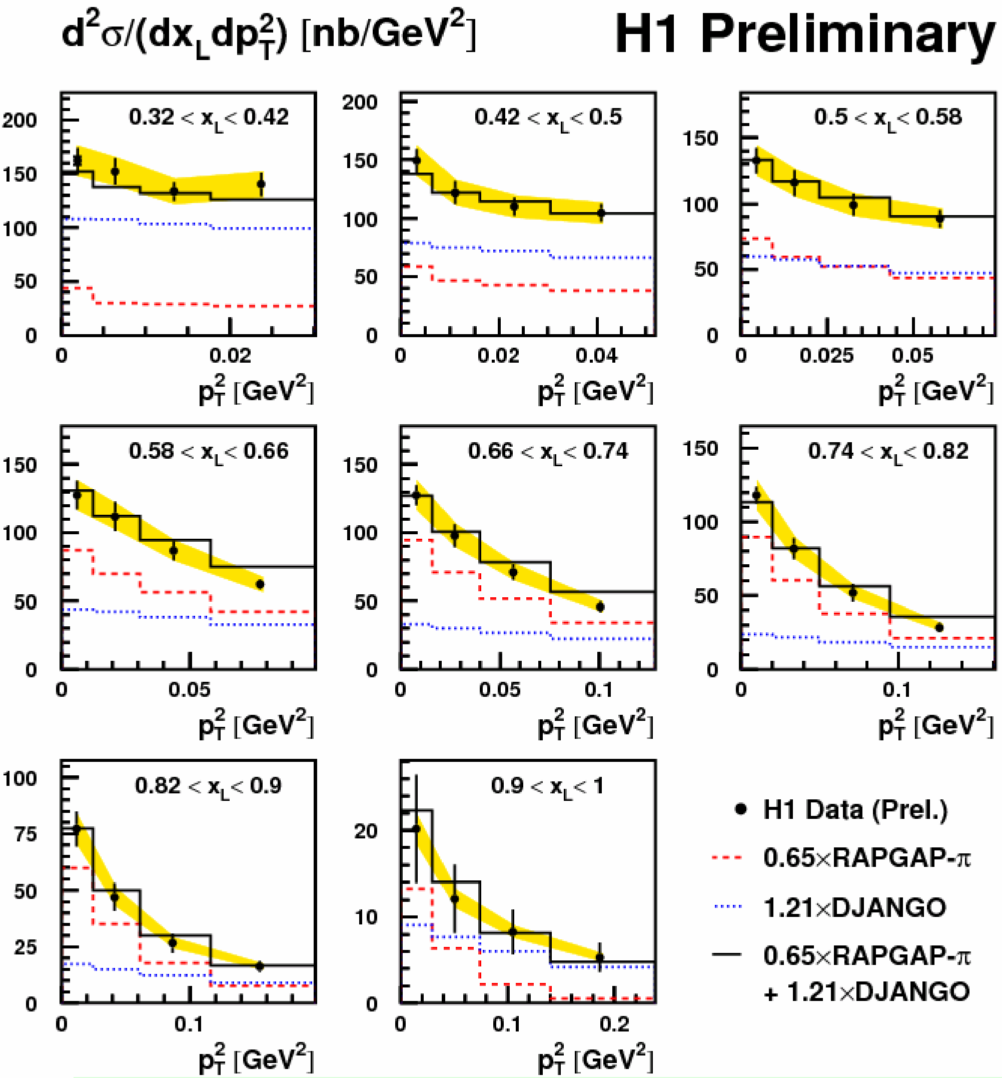
· SCI (soft colour interactions) models too low at high $x_L$

· $\pi^+$-exchange model (RAPGAP-π) describes the shape of data distribution well for $x_L$>0.7

**<u>π-exchange- the dominant mechanism at large $x_L$</u>**

**Extend the measurement differentially in transverse momentum of neutron $p_T$**

H1prelim-10-113 ($6 < Q^2 < 100$ GeV², $0.05 < y < 0.6$)

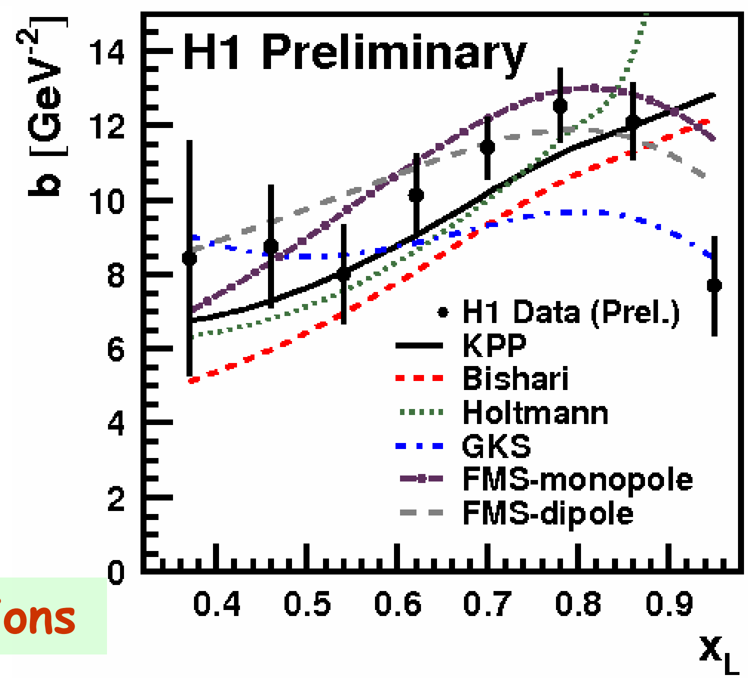



Combination of RAPGAP-π and DJANGO describes well the $p_T^2$ distributions (using same weighting factors as for $x_L$)

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

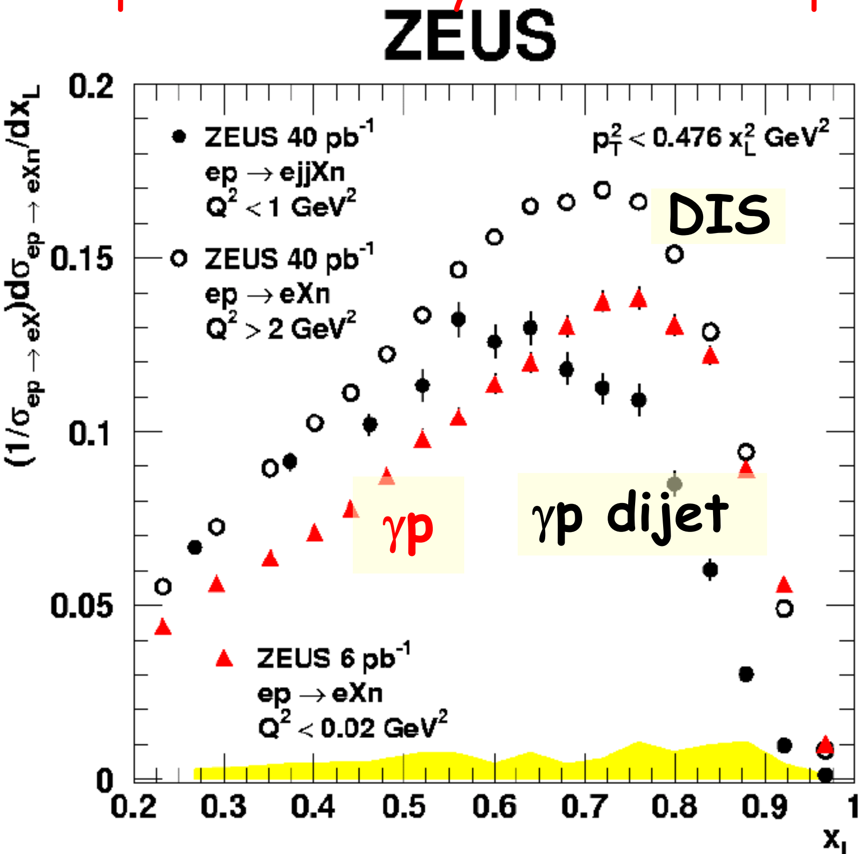
Fit the distributions by a single exponent.

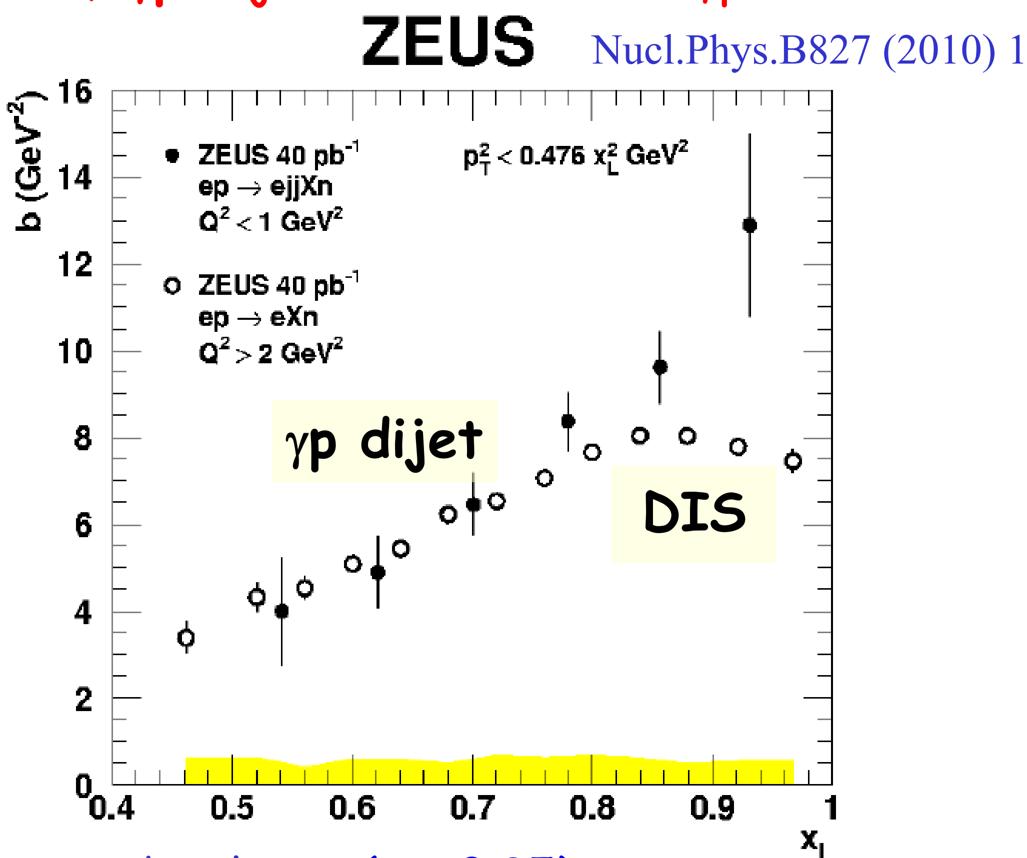
$$\frac{1}{\sigma_{inc}} \frac{d\sigma_{LN}}{dp_T^2\, dx_L} = a(x_L) \cdot e^{-b(x_L)\, p_T^2}$$




**Measurement sensitive to the π flux parameterisations**

Compare neutron yield and b-slopes in DIS, $\gamma$p-dijets and inclusive $\gamma$p.

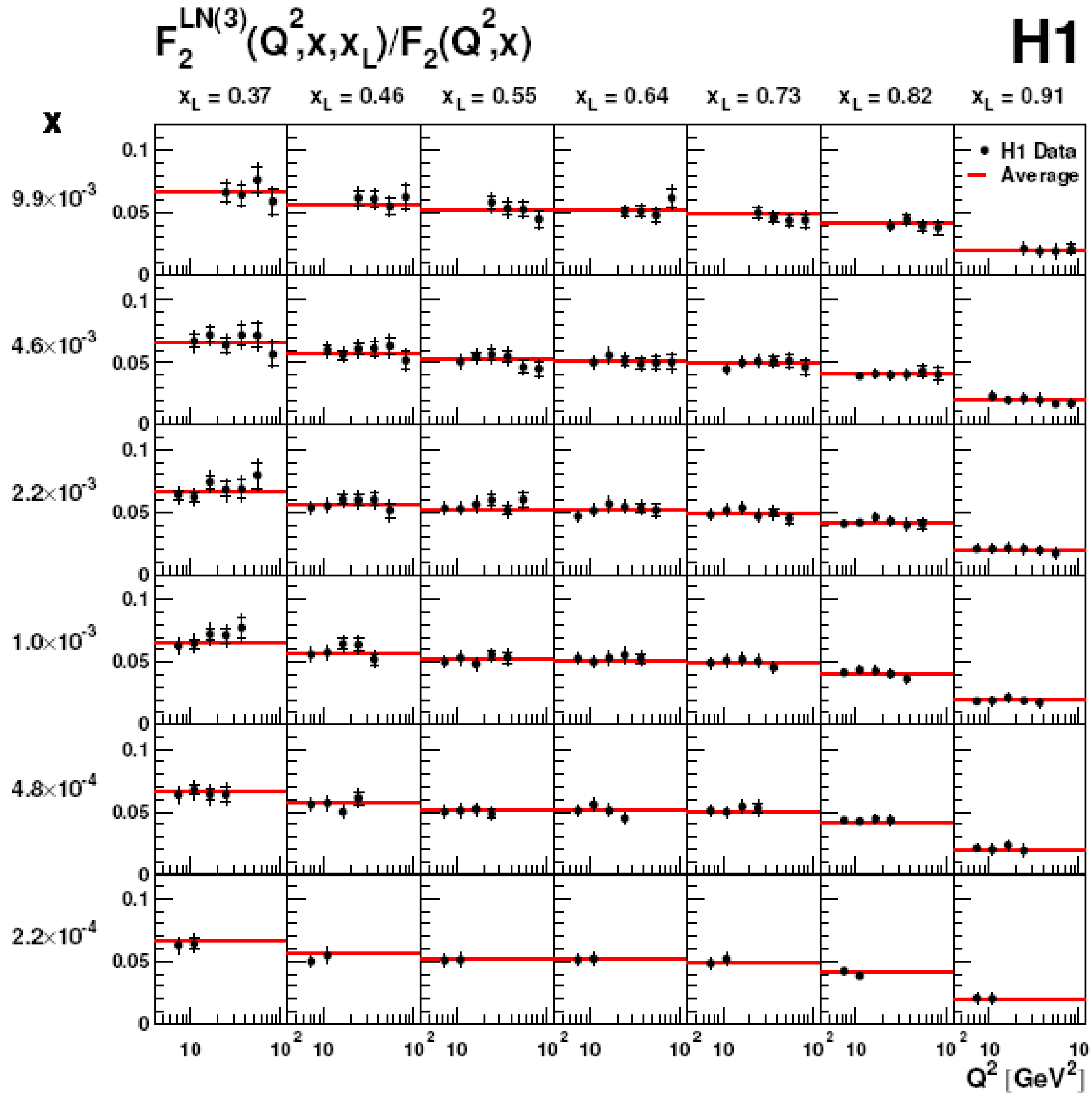



- photoproduction of forward neutrons suppressed at low $x_L$ ($x_L < 0.85$)
  ➔ consistent with neutron absorption through rescattering (more absorption in $\gamma$p than in DIS due to larger transverse size of real photon)
- Suppression is not so prominent in jet production (hard scale provided by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

Eur.Phys.J.C68 (2010) 381

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



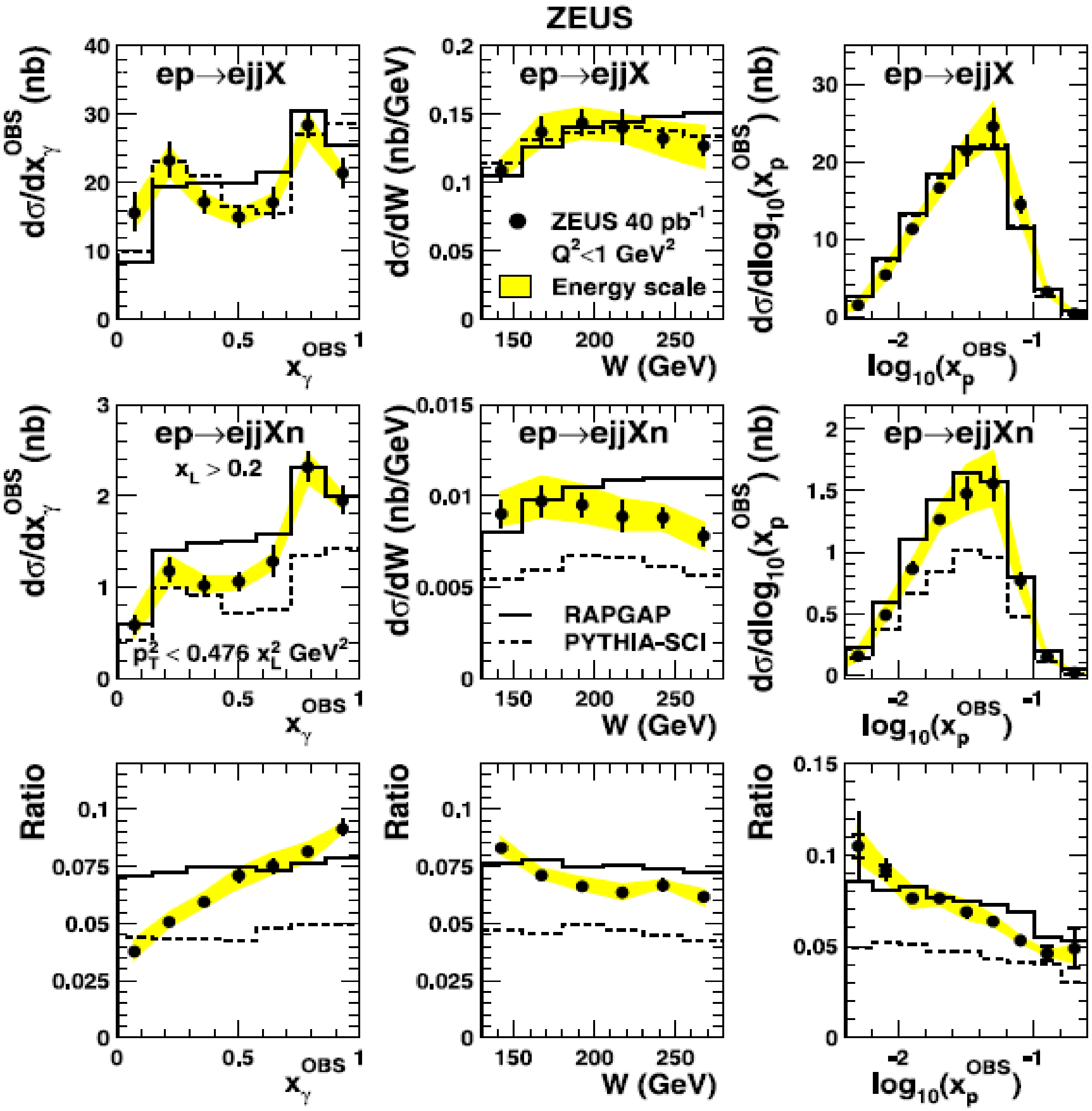

$F_2^{LN}(Q^2,x,x_L)/F_2(Q^2,x)$ is mostly flat in $Q^2$ and $x$

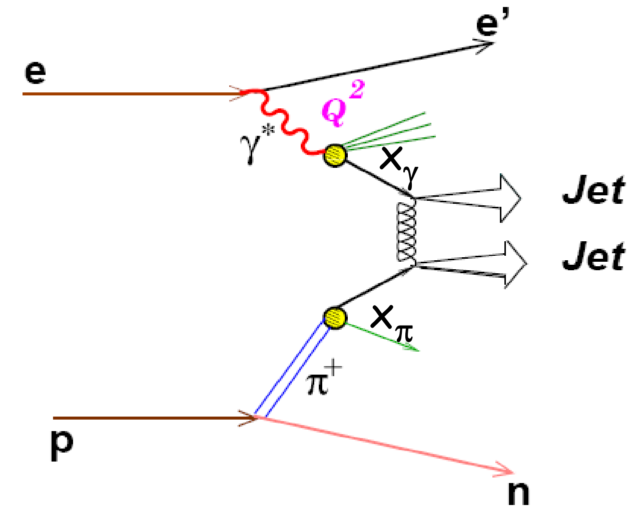
i.e. LN production rate, kinematics is approx. independent of $(Q^2,x)$
➔ consistent with factorisation, limiting fragmentation (overall suppression of LN events is also possible)

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

Nucl.Phys.B827 (2010) 1

Dijet cross sections in inclusive $\gamma p$ and in $\gamma p$ with LN, and their ratios.




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

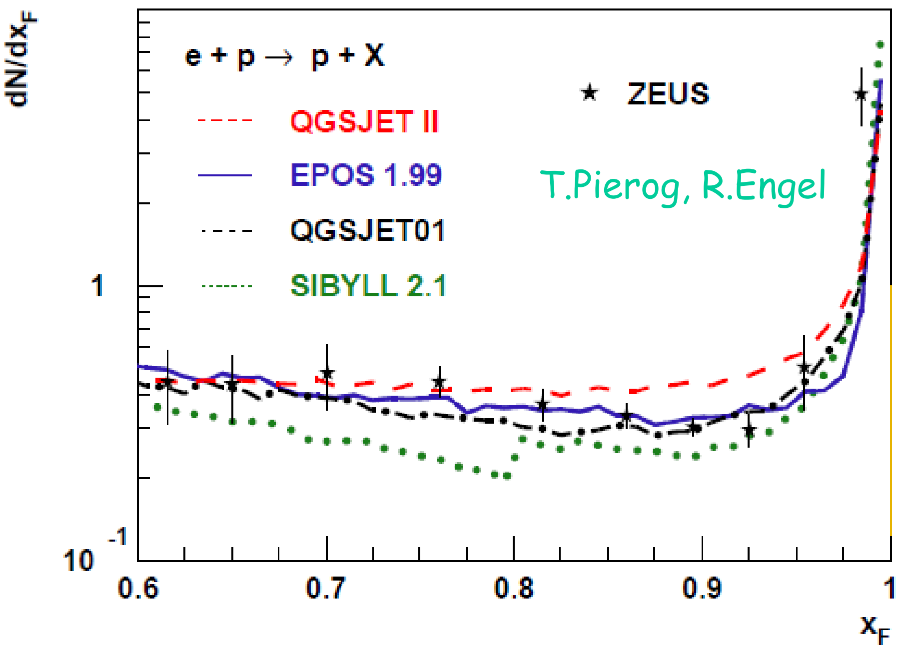
**- strong dependence of ratio of $x_\gamma$ distributions for data, flat in MC**

**- resolved photon is suppressed in events with neutron.**

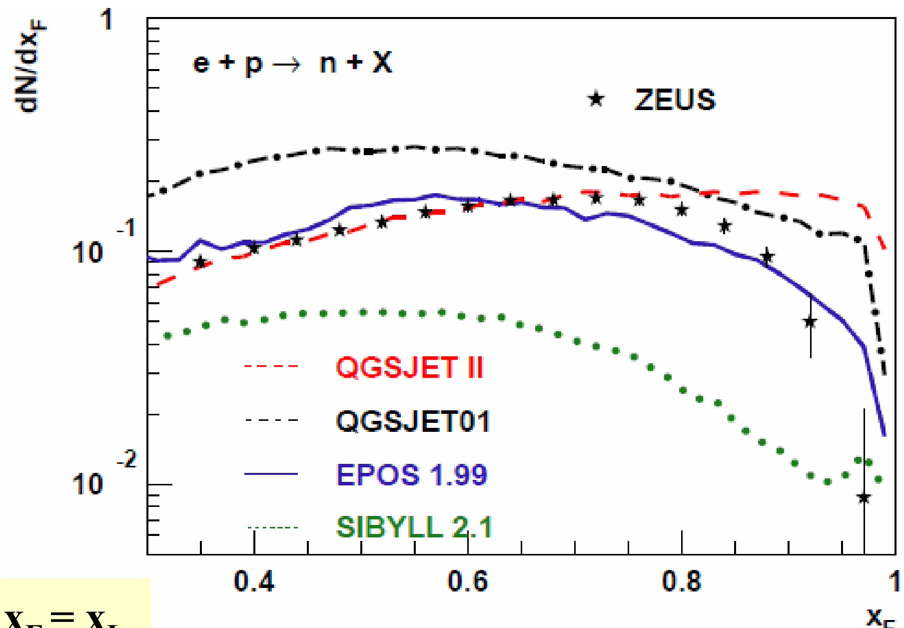
# Interplay of forward particle production and Cosmic Ray physics

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

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




$x_F = x_L$




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

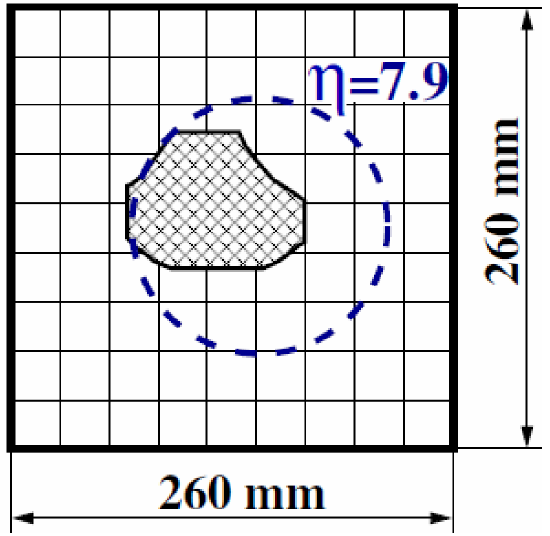
EPOS 1.9: *(Pierog, Werner)*,

QGSJET 01 and II: (*Kalmykov, Ostapchenko*),

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

H1prelim-11-012

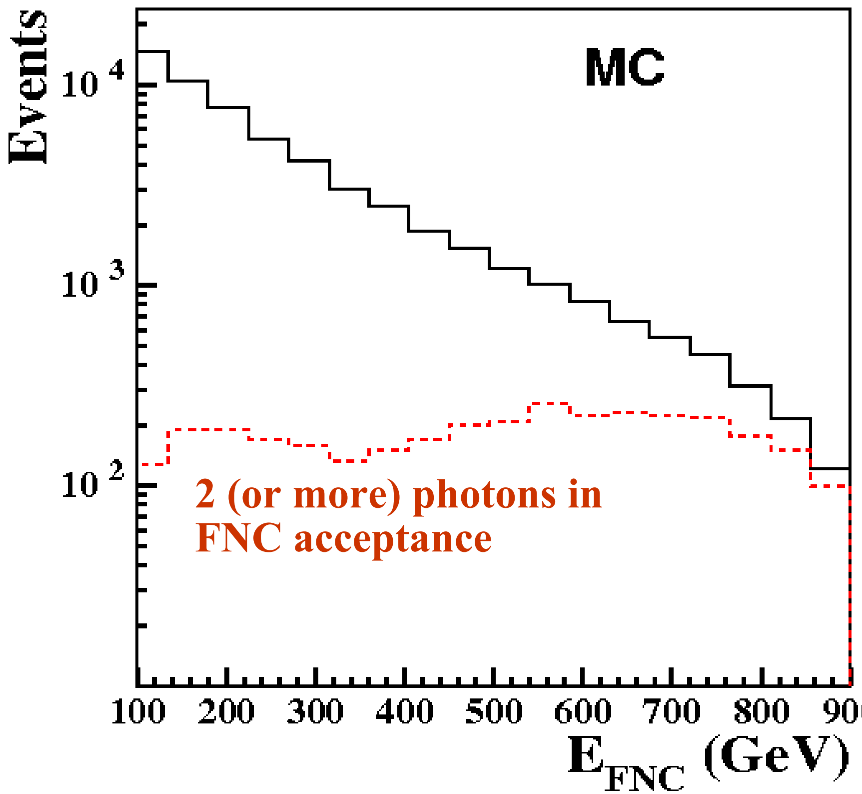
Measure forward photons in FNC, compare to
- MC models (CDM and LEPTO)
- hadronic interaction models used for analysis of cosmic rays (EPOS, SIBYLL, QGSJET)




**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

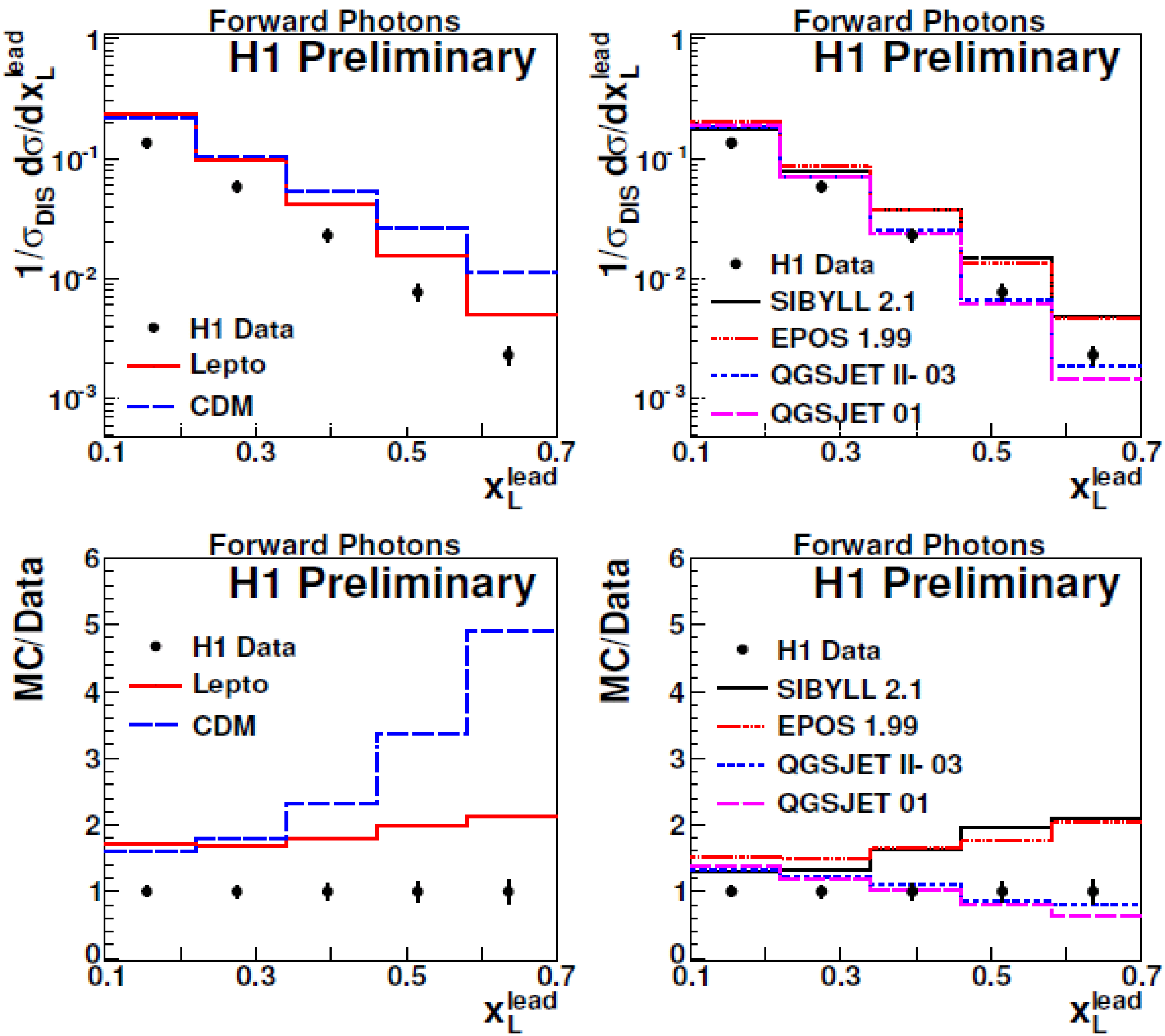
H1prelim-11-012

$6 < Q^2 < 100$ GeV$^2$, $0.05 < y < 0.6$,
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 $x_L$**



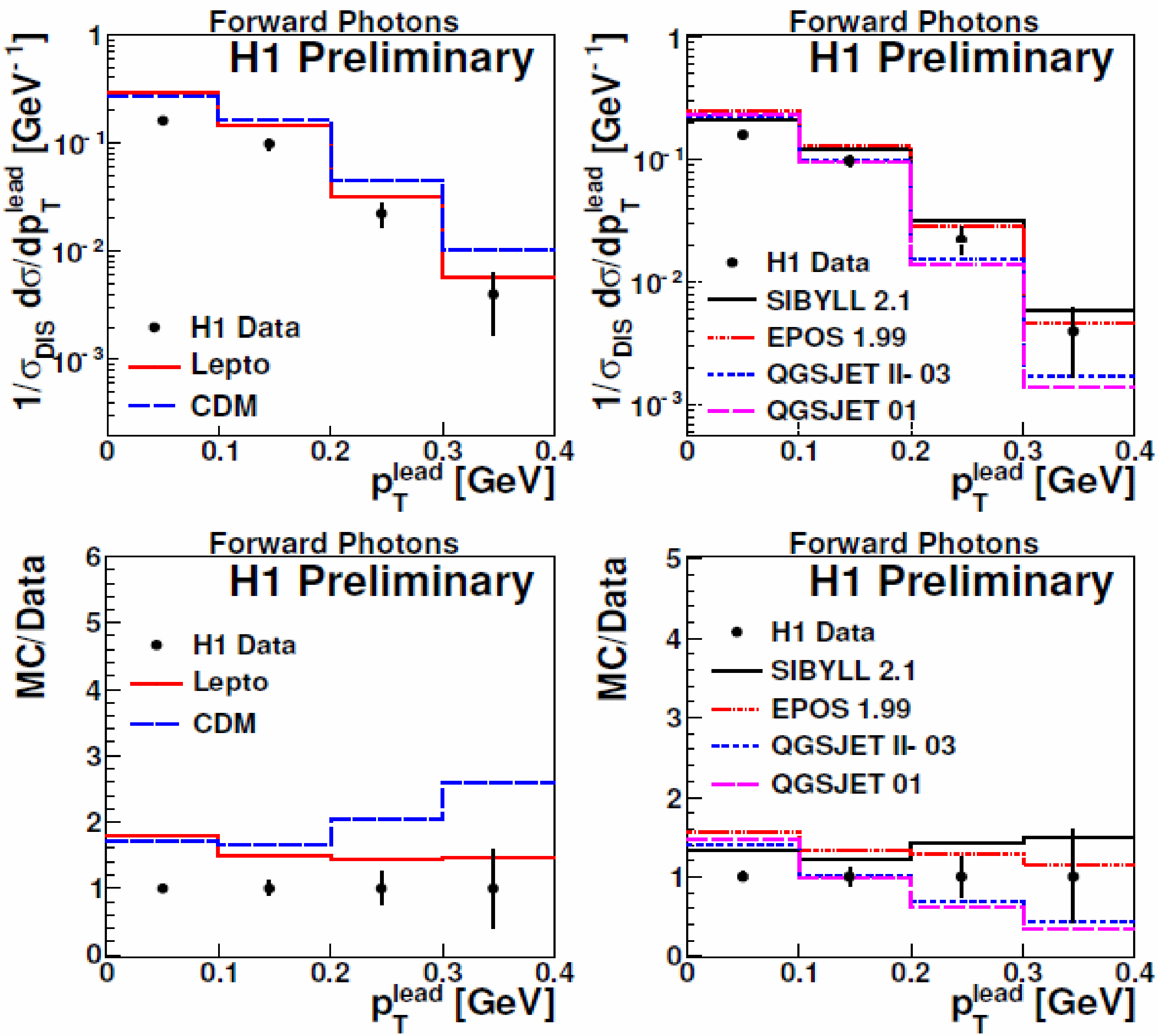
# Forward photon production cross sections

H1prelim-11-012

**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 $p_t$)**

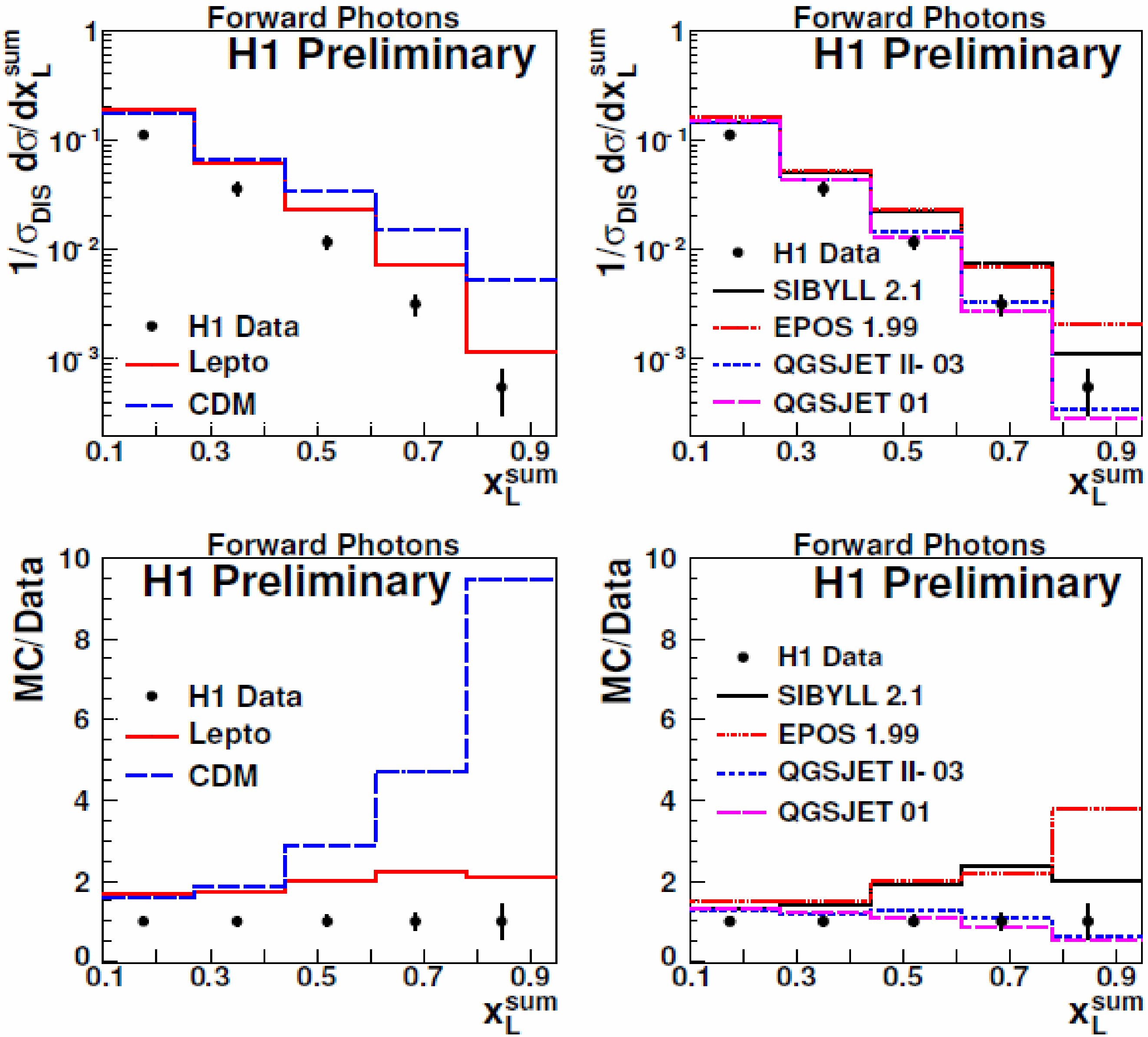


H1prelim-11-012

**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**




$x_L^{sum} = \Sigma E_i / E_{p\text{-}beam}$ **sum of all photons with η>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
- $x_\gamma$ 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 $F_2^{LN}(Q^2,x,x_L)$

within $\pi^+$-exchange model we may try to estimate $F_2^{\pi}$ 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)

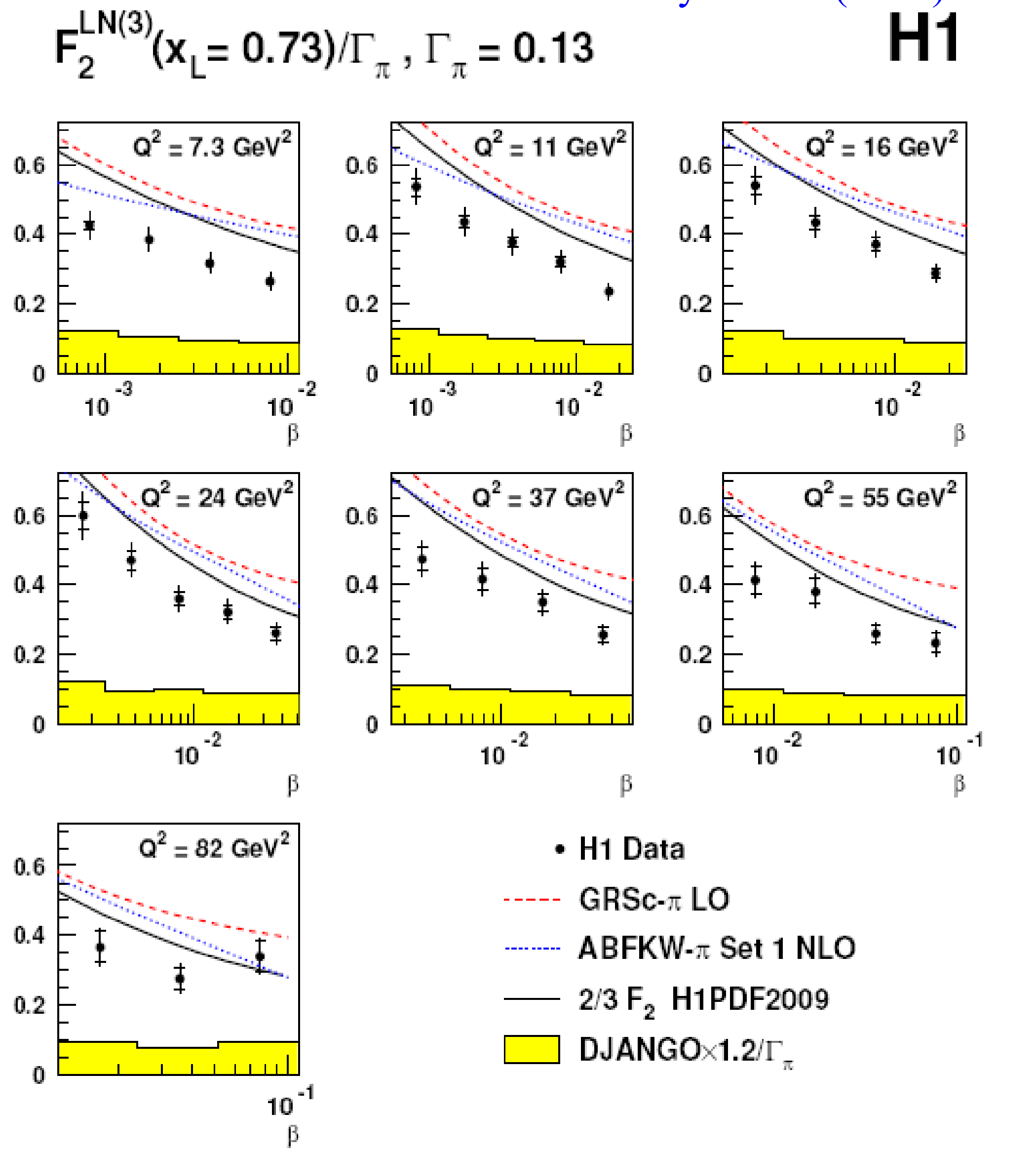
$\Gamma_\pi(x_L)$ is integrated over t pion flux

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

use pion flux parameterisation (Holtmann et al.):

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

Eur.Phys.J.C68 (2010) 381




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

Eur.Phys.J.C68 (2010) 381

within $\pi$-exchange model we can estimate $F_2^{\pi}$ 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

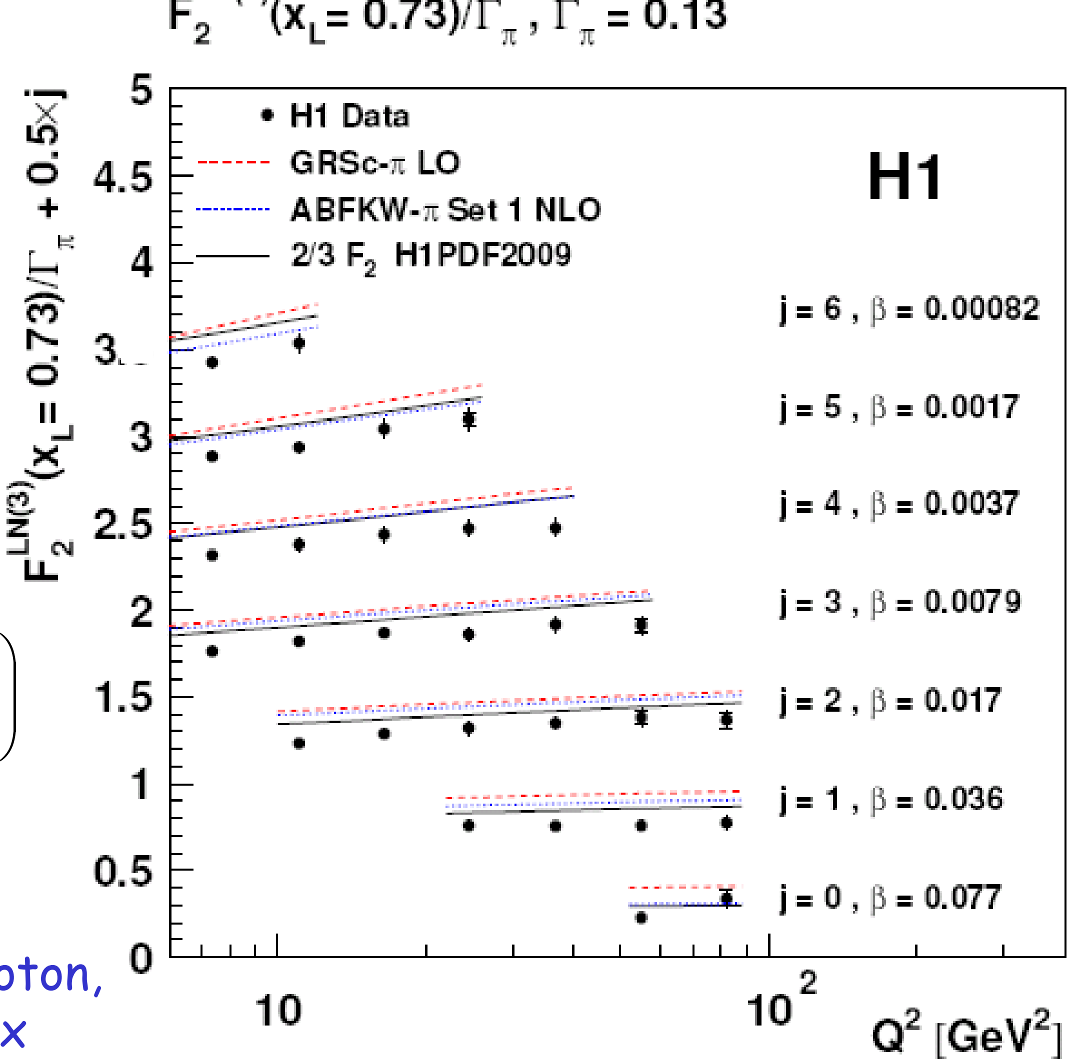
$\beta=x/(1-x_L)$

$\Gamma_\pi(x_L)$ 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.):

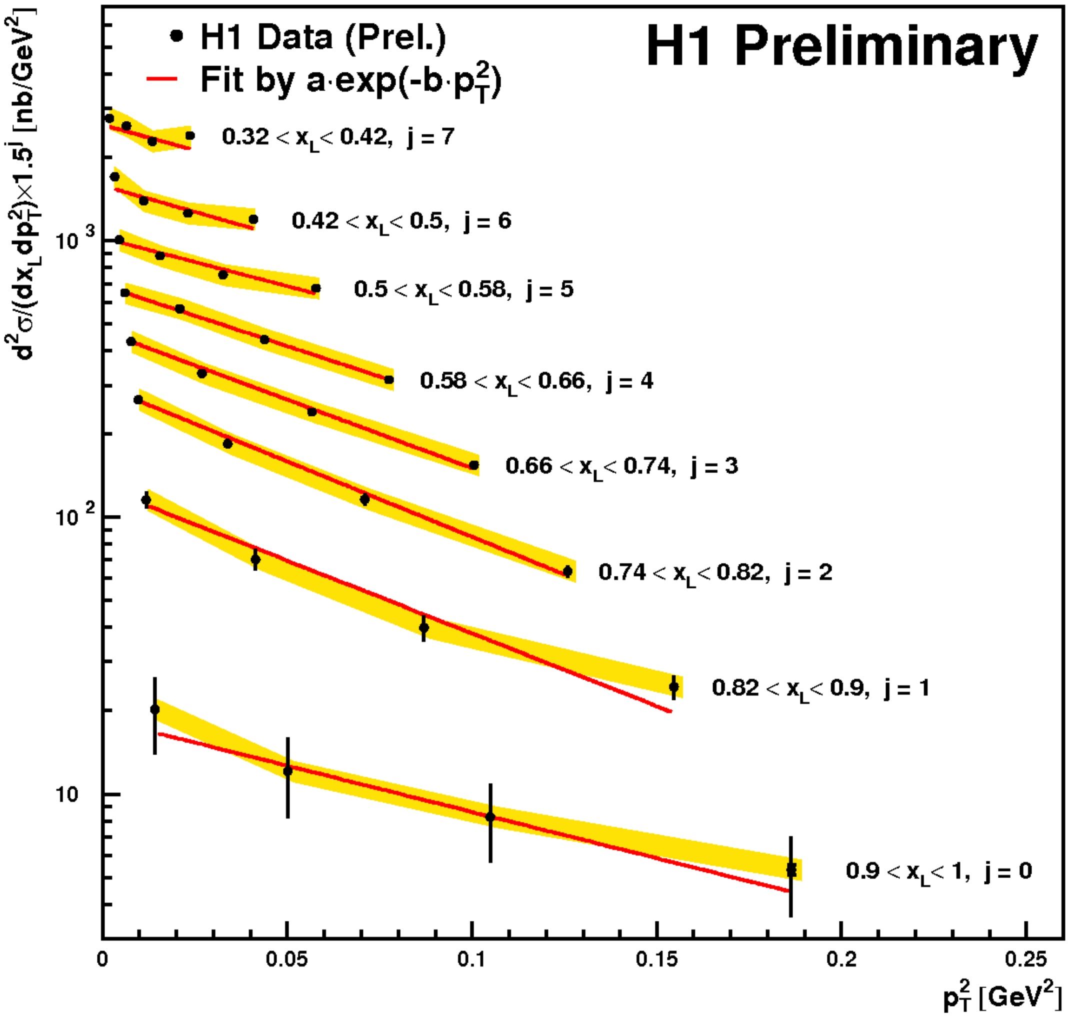
$$f_{\pi^+/p}=\frac{1}{2\pi}\frac{g^2_{p\pi\pi}}{4\pi}(1-x_L)\frac{-t}{(m_\pi^2-t)^2}\cdot\exp\left(-R^2_{\pi n}\frac{m_\pi^2-t}{1-x_L}\right)$$




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

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

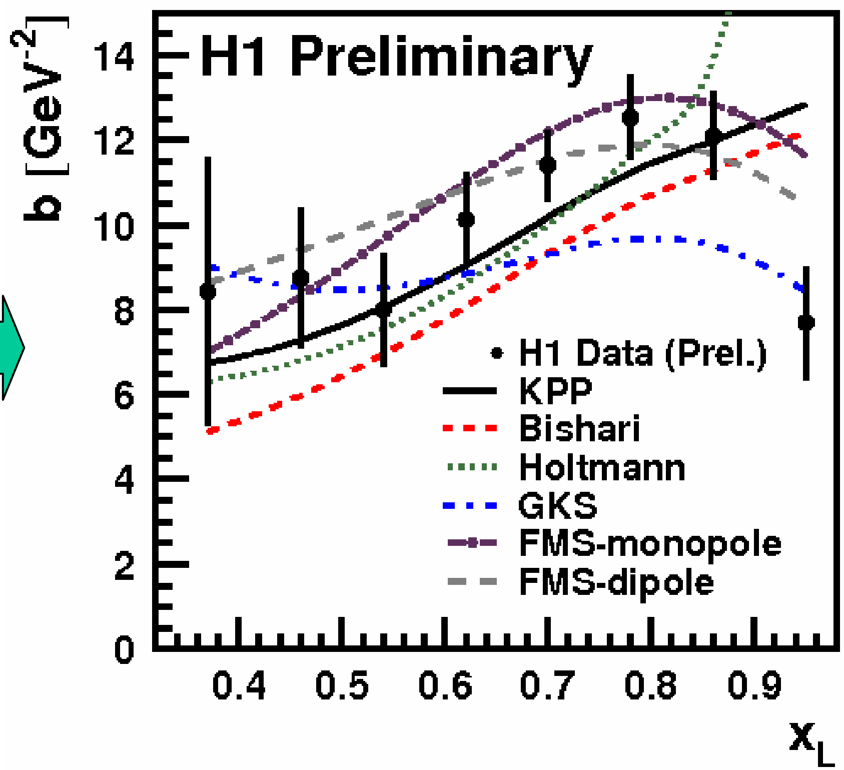
H1prelim-10-113




Fit the distributions by a single exponent.

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

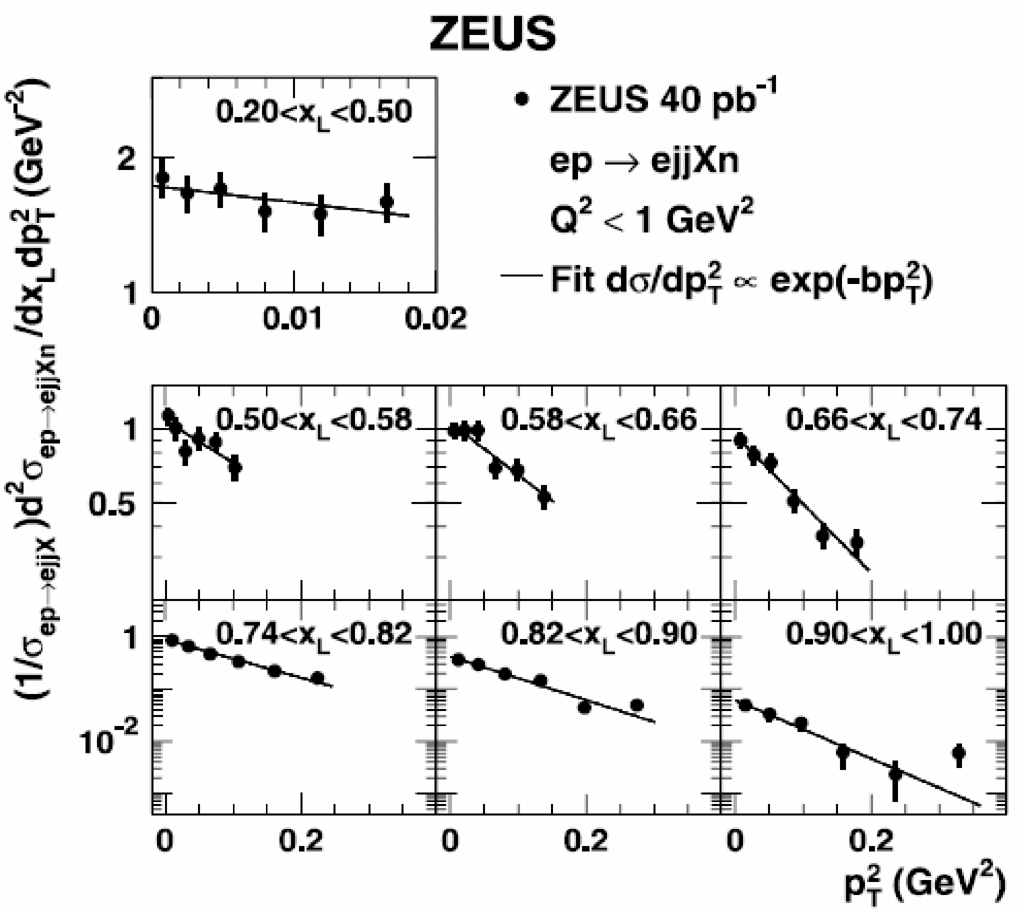
Compare slopes with different parameterisations of pion flux




**Measurement sensitive to the pion flux parameterisations**

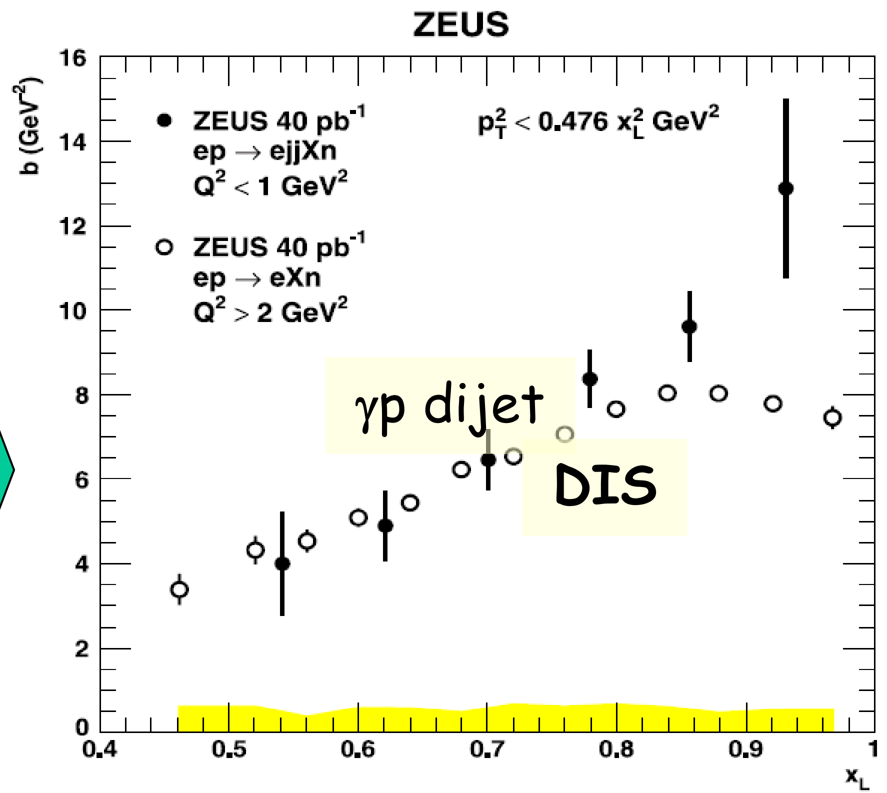
KPP: B.Kopeliovich, B.Povh, I.Potashnikova
Bishari: M.Bishari
Holtmann: H.Holtmann
GKS: K.J.Golec-Biernat, J.Kwiecinski, A.Szczurek
FMS: L.L.Frankfurt, L.Mankiewicz, M.I.Strikman

Nucl.Phys.B827 (2010) 1




Well described by exponential fall-off in $p_T^2$

slopes $b(x_L)$




similar b-values in DIS and γp+dijet, slightly different at high $x_L$

→ same production mechanism

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, $\gamma$, $\pi^0$) are of the greatest importance for the model tuning, since the shower development is dominated by the forward, soft interactions.