ISVHECRI 2012
Symposium on Very High Energy Cosmic Ray Interactions
10-15 August 2012, Berlin

Leading Particle Production at HERA

Armen Buniatyan

Outline:

- Forward Protons and Neutrons in Deep Inelastic Scattering
- Forward Neutrons in photoproduction
- Forward Photons in Deep Inelastic Scattering
- Comparison with CR interaction models

HERA

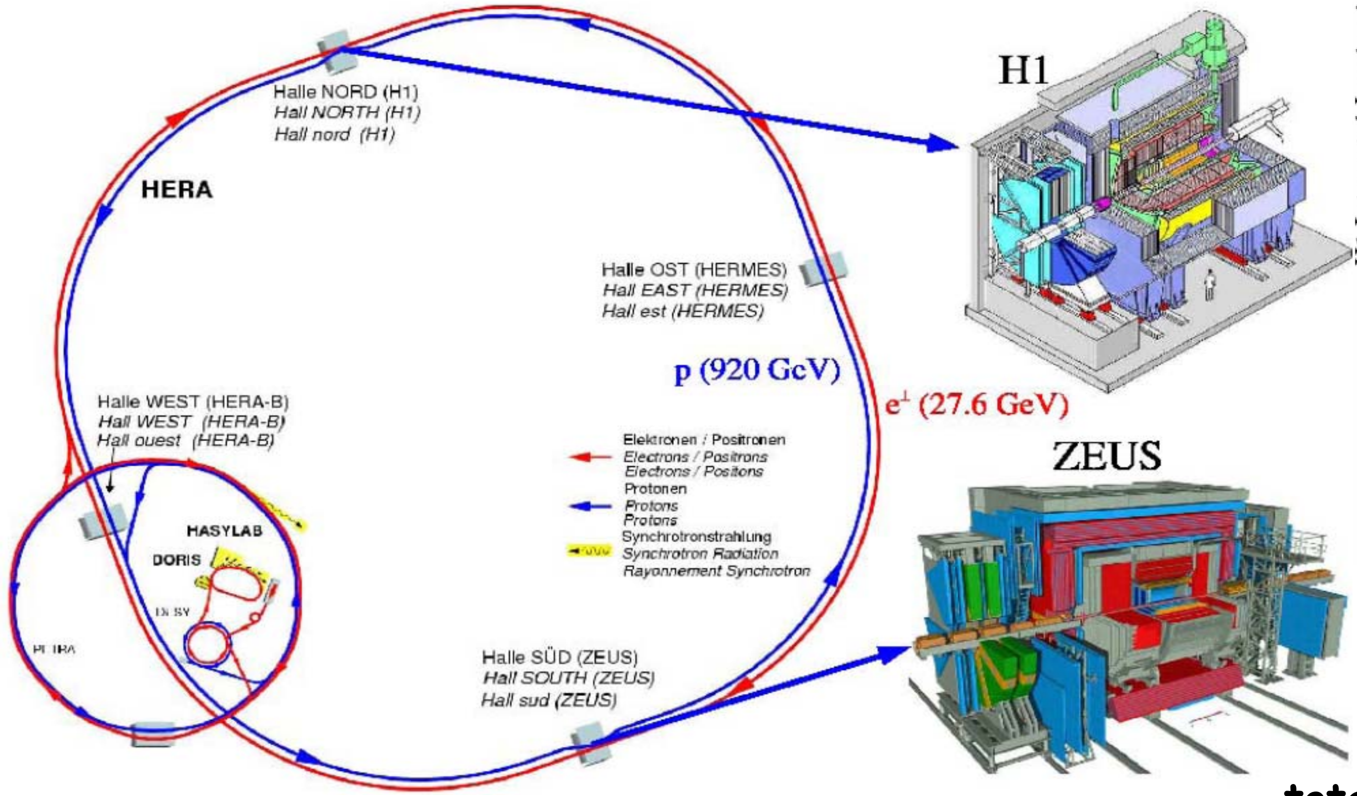
The first electron-proton collider (DESY Hamburg)

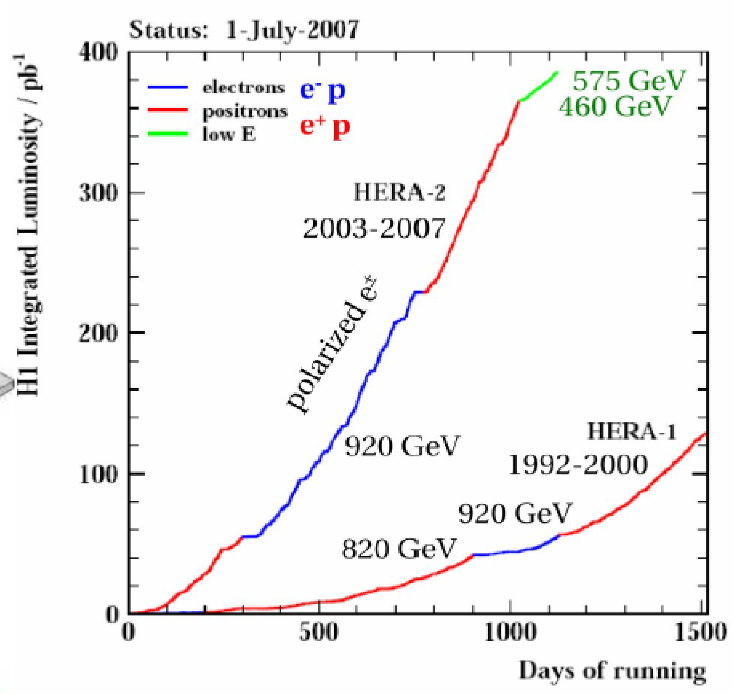
$E_{e\pm}$ = 27.6 GeV E_p = 920 GeV (also E_p=820, 460 and 575 GeV)

Total centre-of-mass energy of collision up to $\sqrt{s} \approx 320$ GeV

(equivalent to $5 \cdot 10^{13}$eV photon beam on a stationary proton target)

Two collider experiments: H1 and ZEUS





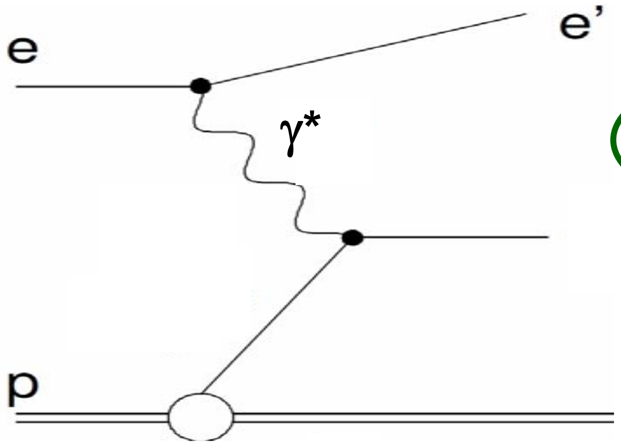
HERA-1: 1992 - 2000

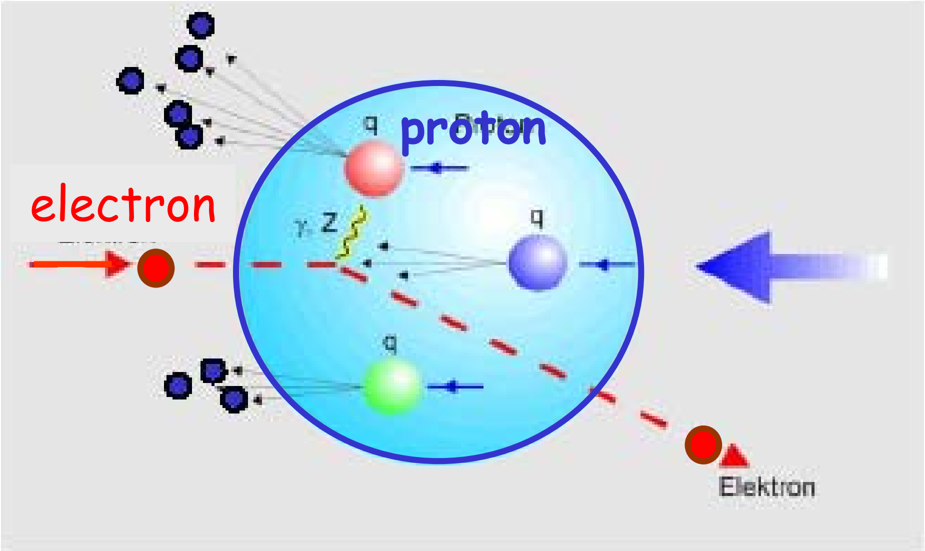
HERA-2: 2003 - 2007

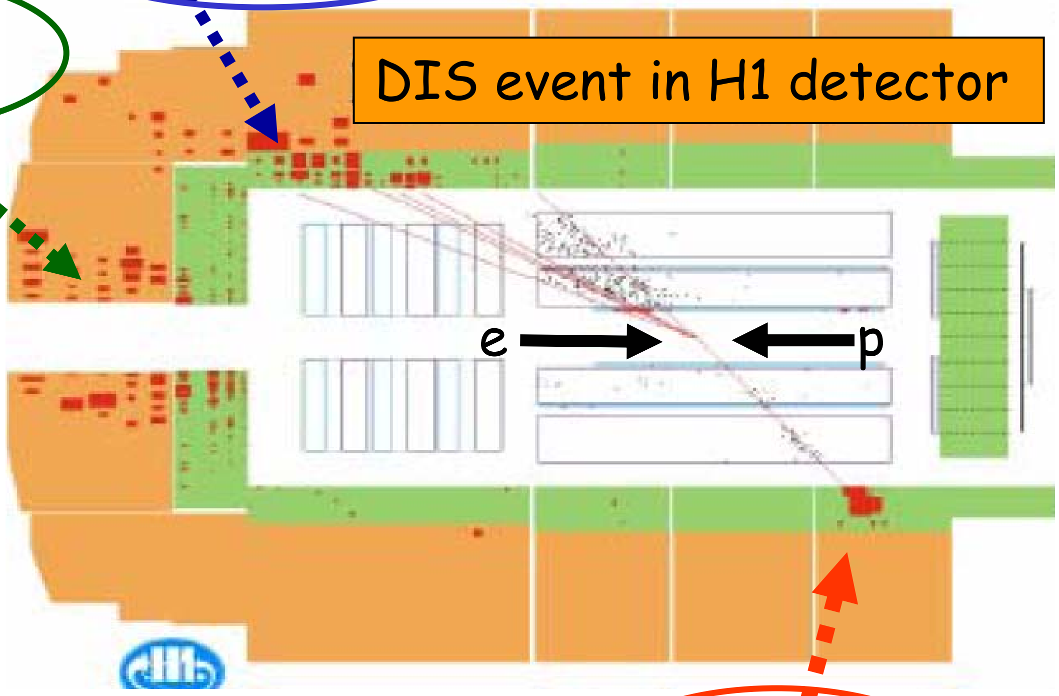
total lumi: 0.5 fb^{-1} per experiment

Deep Inelastic electron-proton Scattering (DIS) at HERA

DIS - a probe of proton structure







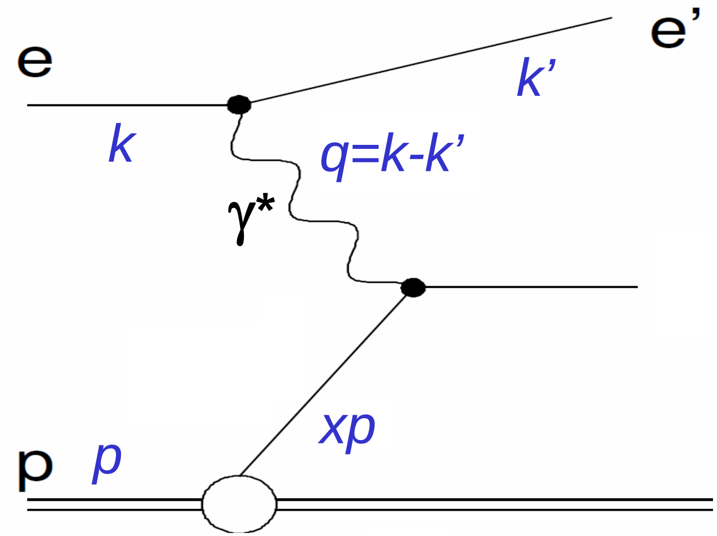
current jet

proton remnant

DIS event in H1 detector

scattered electron

Deep Inelastic Scattering, Structure functions



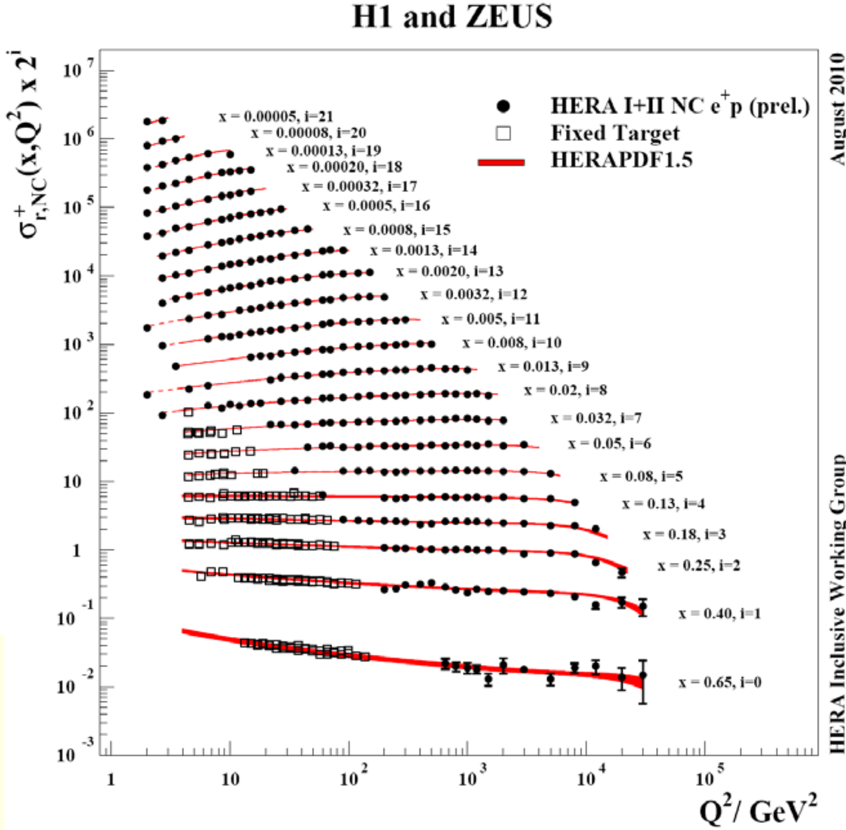
$Q^2=-(k-k')^2$	virtuality of exchanged boson - 'resolving power' of probe
$x=Q^2/2p\cdot q$	fraction of proton momentum carried by struck quark.
$y=p\cdot q/p\cdot k$	inelasticity variable: $y= Q^2/(s\cdot x)$
W	invariant mass of γ^*p system

$$\frac{d^2\sigma^{NC}_{e^\pm p}}{dx\,dQ^2} = \frac{2\pi\alpha^2 Y_\pm}{xQ^4}\cdot\underbrace{\left(F_2 - \frac{y^2}{Y_\pm}F_L\right)}_{\text{reduced cross section} \equiv \sigma_r(x,Q^2)}, \quad Y_\pm = 1\pm(1-y)^2$$

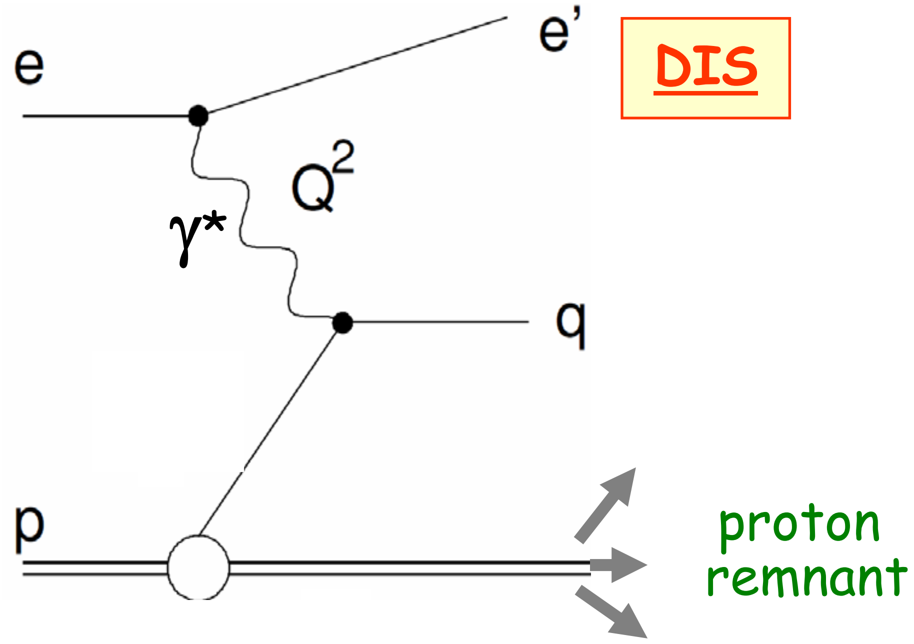
$$F_2 = x\sum e_q^2\left[q(x)+\bar{q}(x)\right] -$$

dominant contribution to cross section

<u>σ_r vs x,Q^2</u>
large kinematic reach; ➔
high precision



Forward Particles in ep interactions



Significant fraction of *ep* scattering events contains in the final state an energetic very forward particle, which carries a substantial fraction of the energy of the incoming proton

('forward'≡proton fragmentation region)

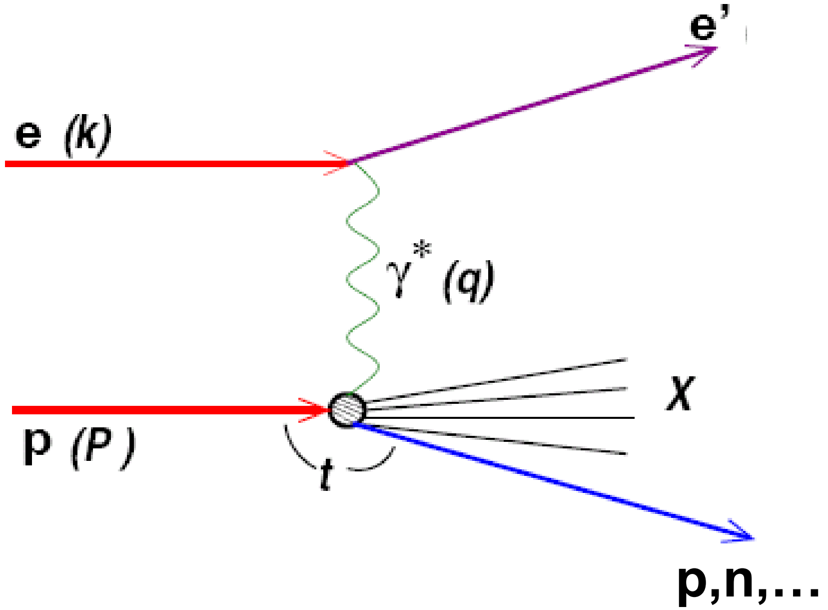
In central (current) region the hard QCD scale is given by Q^2 (and/or p_T^{jet}); the proton fragmentation region is non-pQCD regime - essential differences between theory predictions

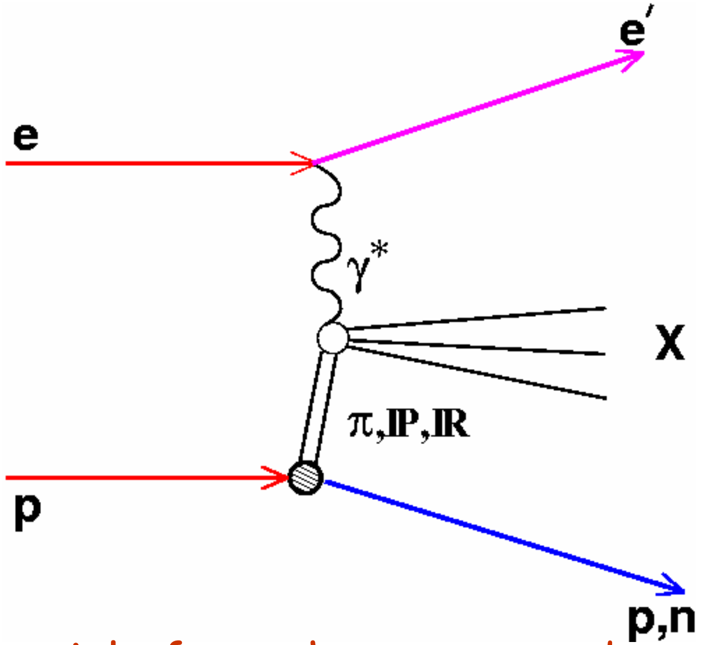
a better understanding of forward particle production is needed

***ep* collisions – a clean environment to study the proton fragmentation**

Forward Particles in ep interactions

Leading forward particles are produced at a very small angles from the fragmentation of proton remnant (e.g. Lund string) or from the exchange mechanism (Pomeron, Reggeon, π,…)



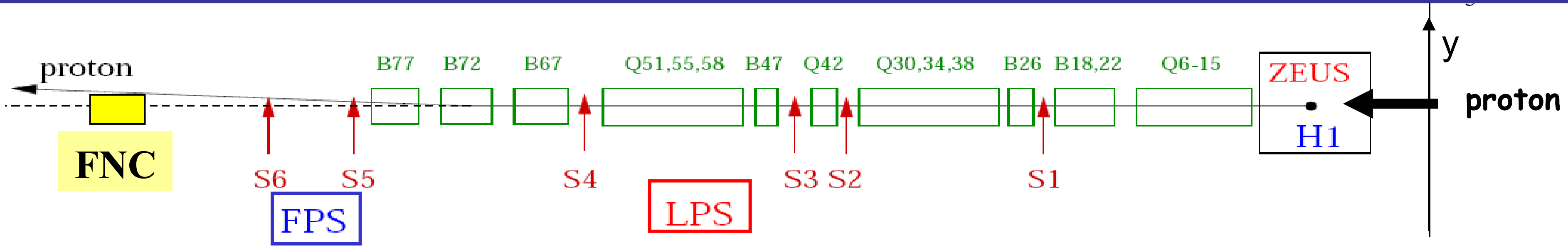


a virtual particle from the proton undergoes DIS with virtual photon.
Cross sections factorise, e.g. for π exchange

$$\sigma(ep\to e'NX) = \underbrace{f_{\pi/p}(x_L,t)}_{\text{pion flux}} \times \underbrace{\sigma(e\pi\to e'X)}_{\text{cross section of } e\pi \text{ scattering}}$$

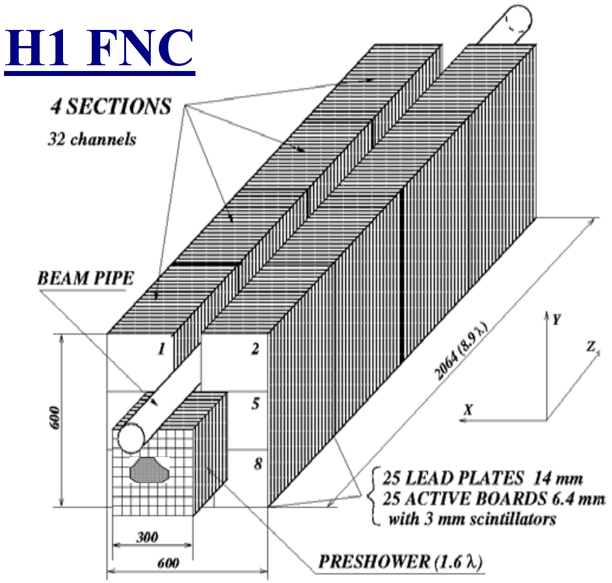
Leading baryon variables:
$x_L=E_{LB}/E_p$
$t=(p-p_{LB})^2$

H1 and ZEUS 'tunnel' detectors for leading baryons



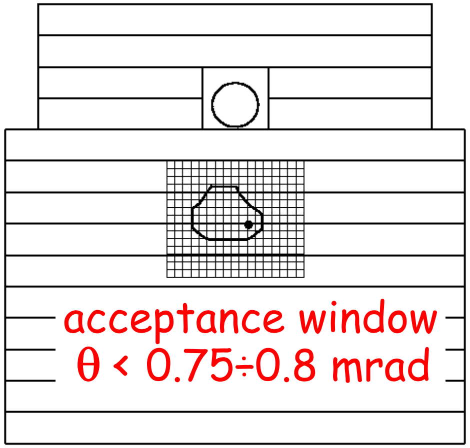
- FPS/LPS –proton spectrometers,24…220m from IP, measure scattered protons $E_{p'}/E_p = 0.4 \div 1$
- FNC –forward neutron calorimeters- 106m from IP, measure neutral particles (n,γ) with $\theta < 0.8$mrad

H1 FNC



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

ZEUS FNC+FNT

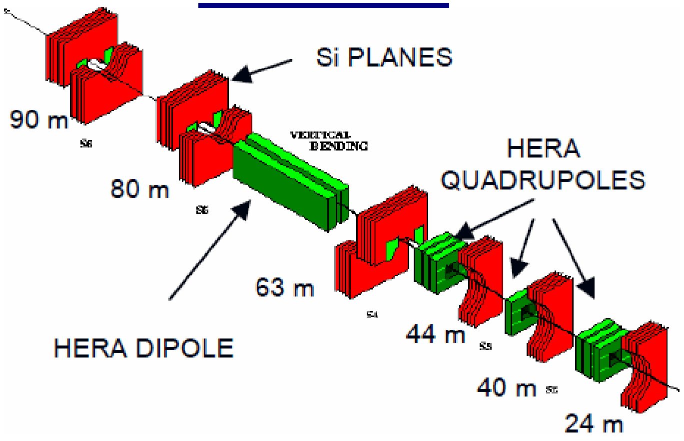


acceptance window
$\theta < 0.75 \div 0.8$ mrad

$\sigma_E/E \approx 0.7/\sqrt{E}$

position resolution 2-3mm

ZEUS LPS

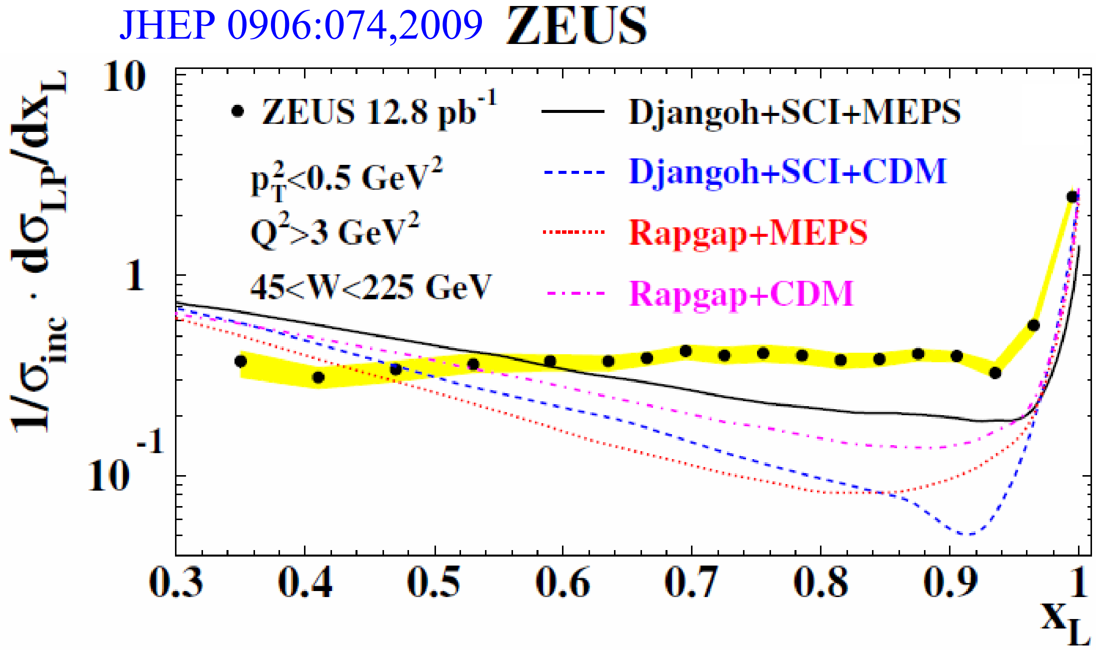


6 stations with μstrip detectors
hit position resolution ~30μm
$\sigma_{X_L} < 1\%$, $\sigma_{p_T} \sim$ few MeV

- acceptance limited by beam apertures and detector size
- p_T resolution is dominated by p_T spread of proton beam (50÷100 MeV)

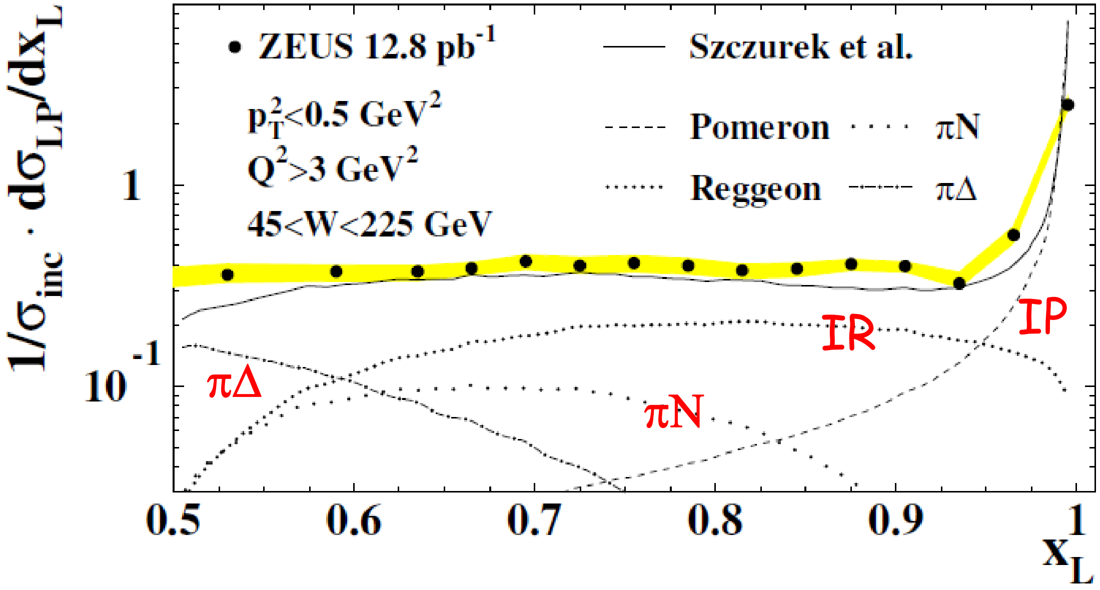
Leading Protons in DIS :Comparison with fragmentation and exchange models

JHEP 0906:074,2009



Leading proton energy spectrum: diffractive peak at $x_L=1$; flat at $x_L<0.95$

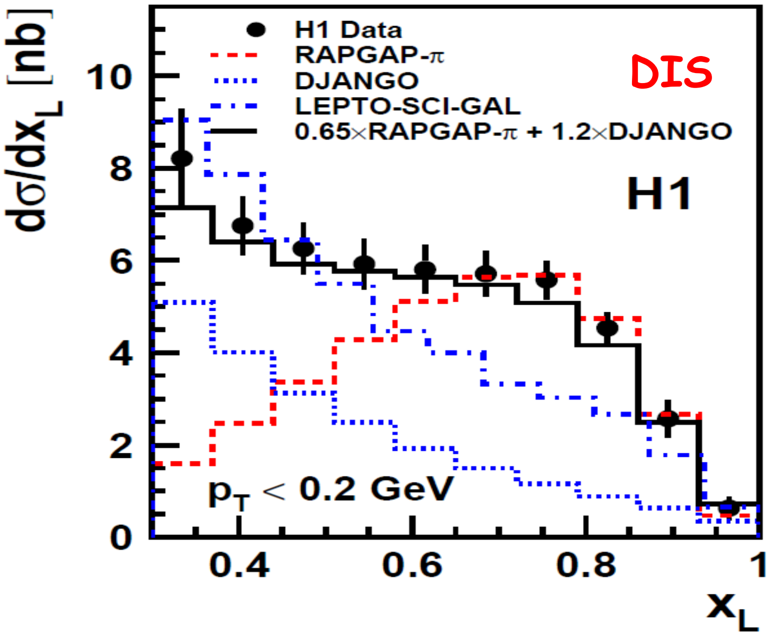
- the **standard fragmentation** MC (using either parton shower or colour dipole models for QCD radiation or including soft colour interactions) don't describe the leading proton data



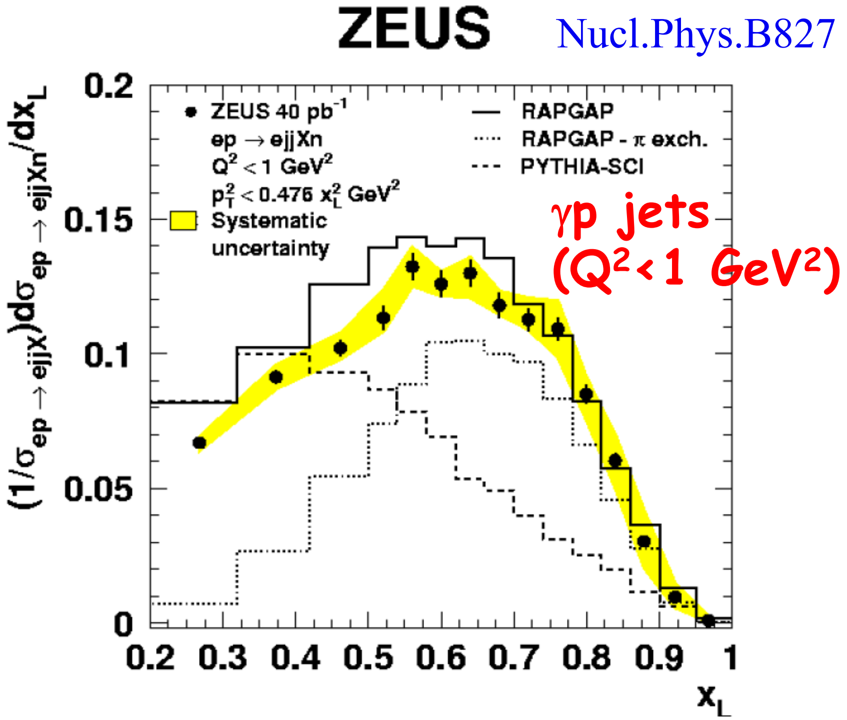
- good description by **exchange model**

Leading Neutron cross section vs x_L: DIS and γp jets

Eur.Phys.J.C68 (2010) 381



Nucl.Phys.B827 (2010) 1



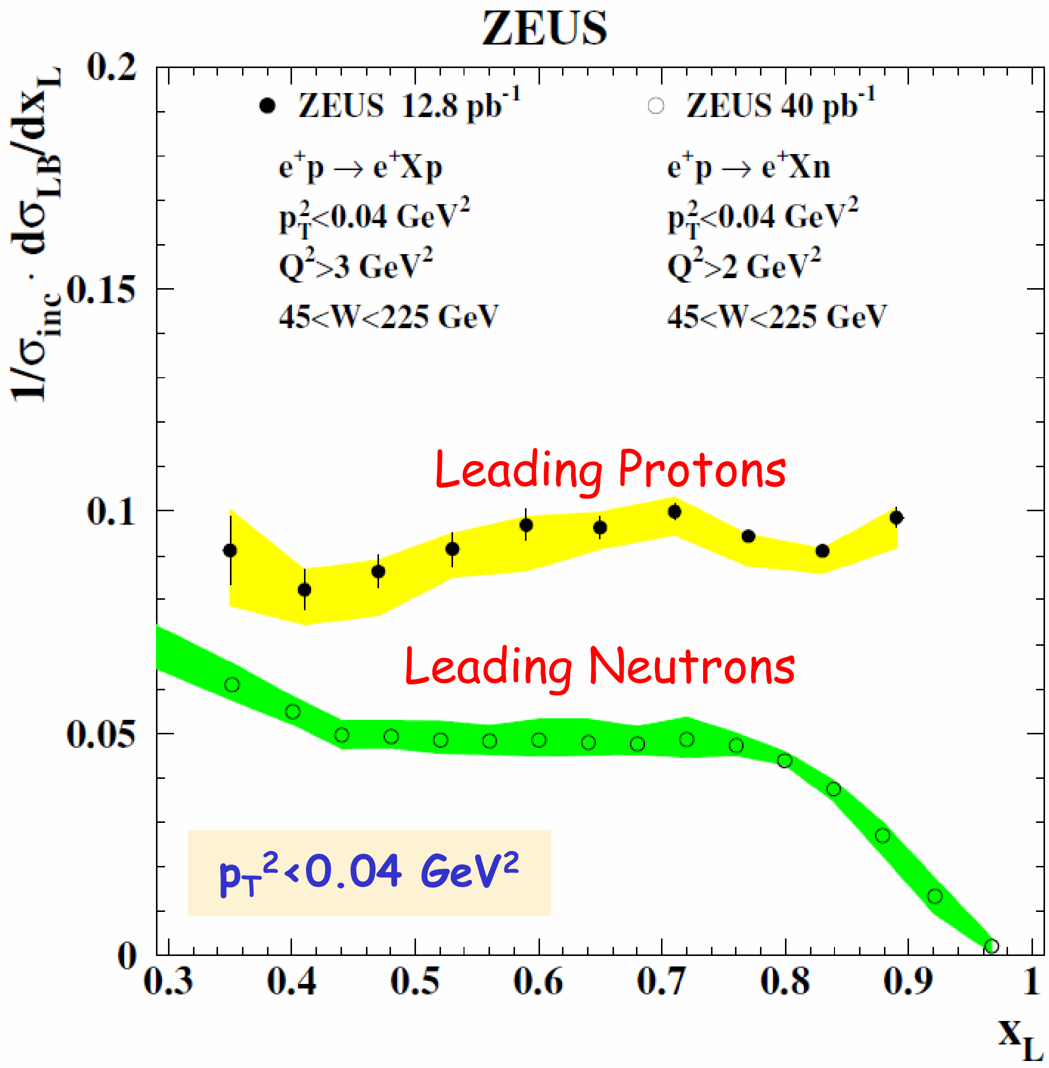
- 'Standard' fragmentation models (DJANGO, RAPGAP) don't describe the shape at high x_L
- π^+-exchange model (RAPGAP-π) describes the shape of data distribution well for x_L>0.7

- Data is described by a combination of **standard fragmentation** (DJANGO, RAPGAP) and **π^+-exchange** (RAPGAP-π) MC over the full x_L range

π^+-exchange - the dominant mechanism of LN production at large x_L

LN and LP: Cross sections vs x_L normalised to σ_{DIS} ($1/\sigma_{DIS} \times d\sigma/dx_L$)

Energy spectra: comparison LP and LN yields
(restricted to the same $p_T^2 < 0.04$ GeV^2 range)



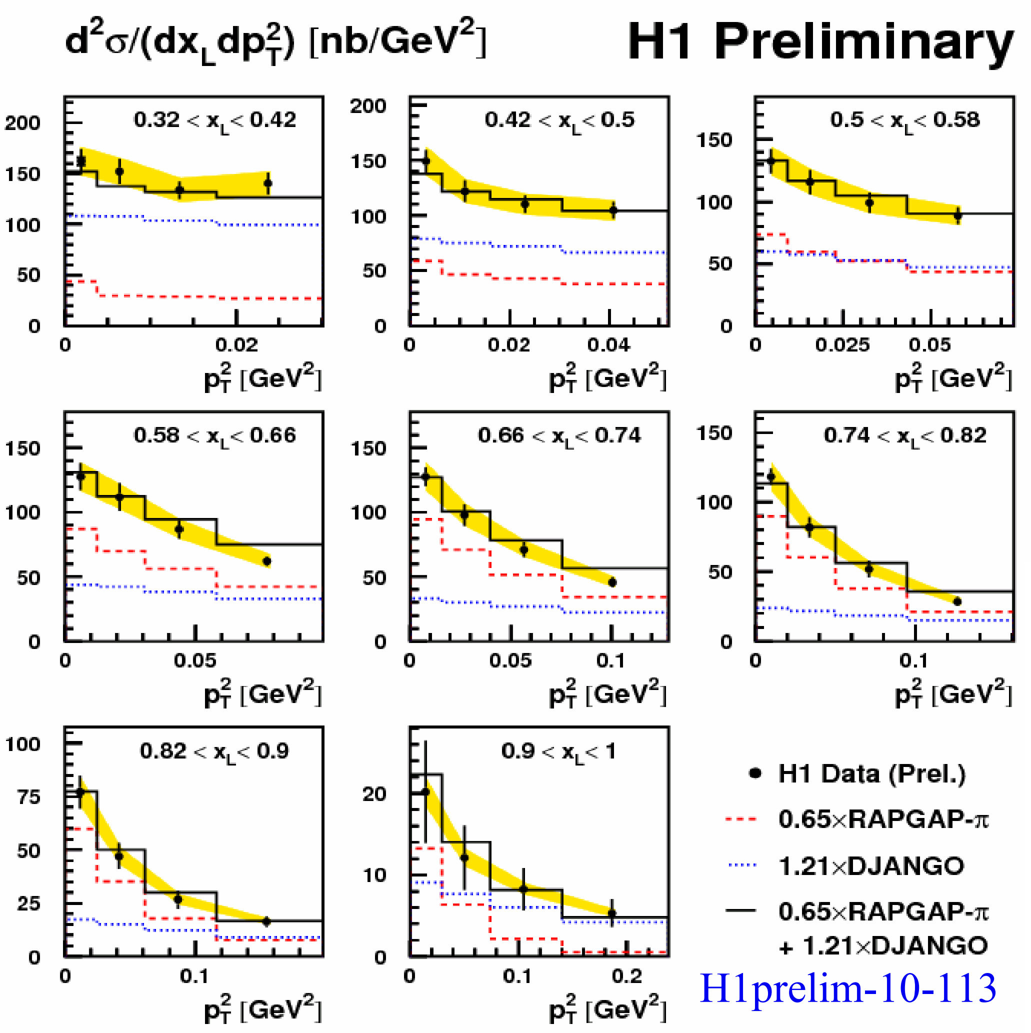
Rate of LP is about **2**× rate of LN

for pure isovector particle exchange (e.g. pion) one expects LP = ½×LN

→ more isoscalar exchanges contribute to the leading proton rates

Leading Neutrons: 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

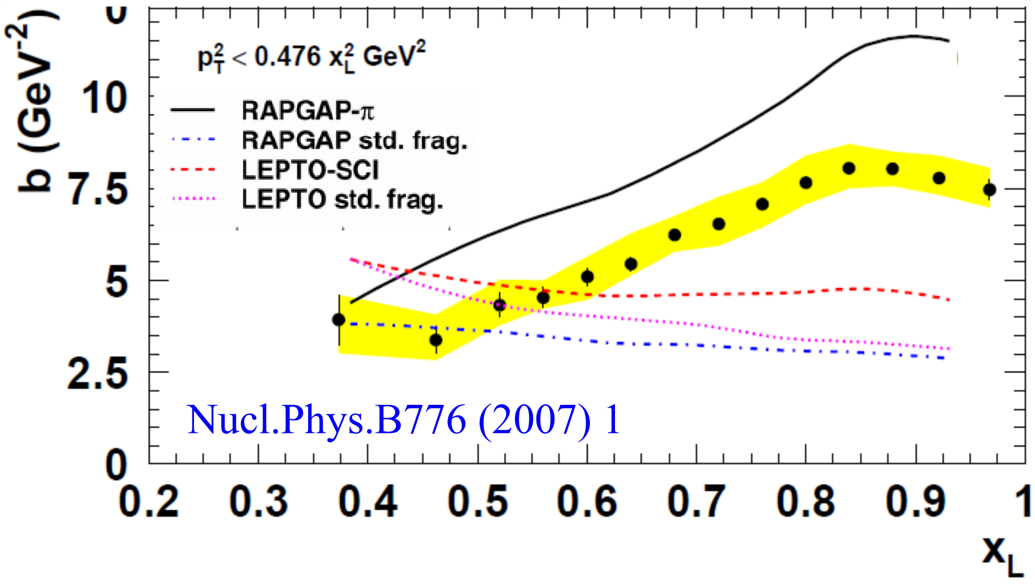
Combination of RAPGAP-π and DJANGO describes well the p_T^2 distributions

determine p_T^2 slopes with exponential fit

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

Different slopes for 'standard' fragmentation and pion-exchange:

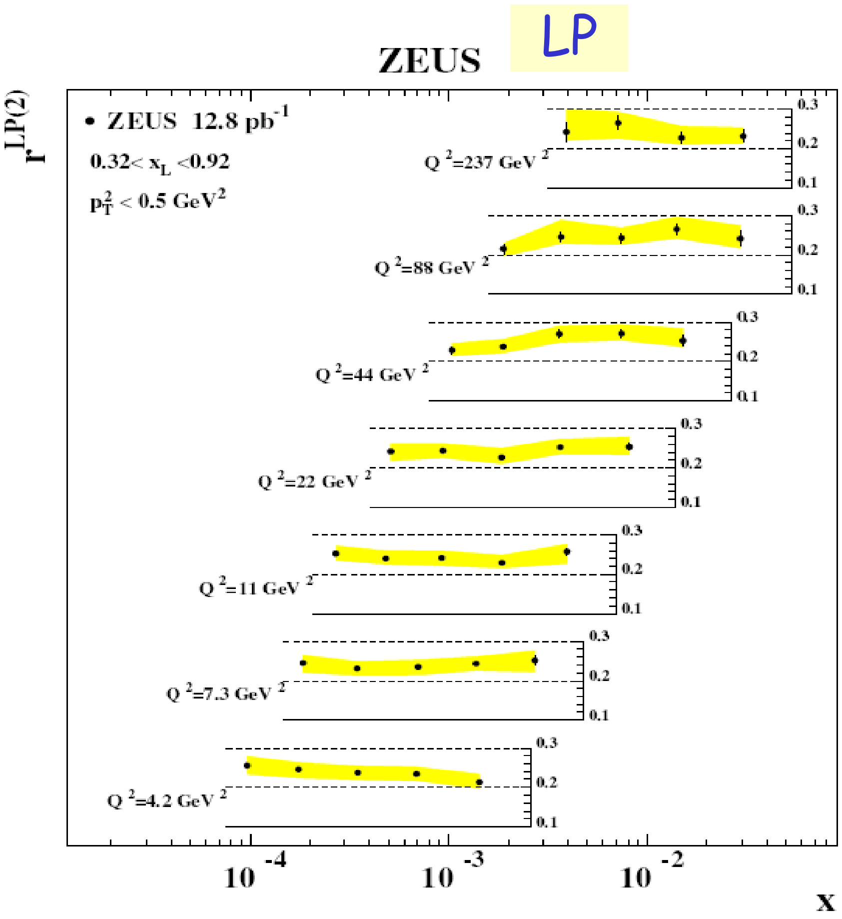
~constant vs x_L for std. fragmentation; increasing with x_L for π–exchange

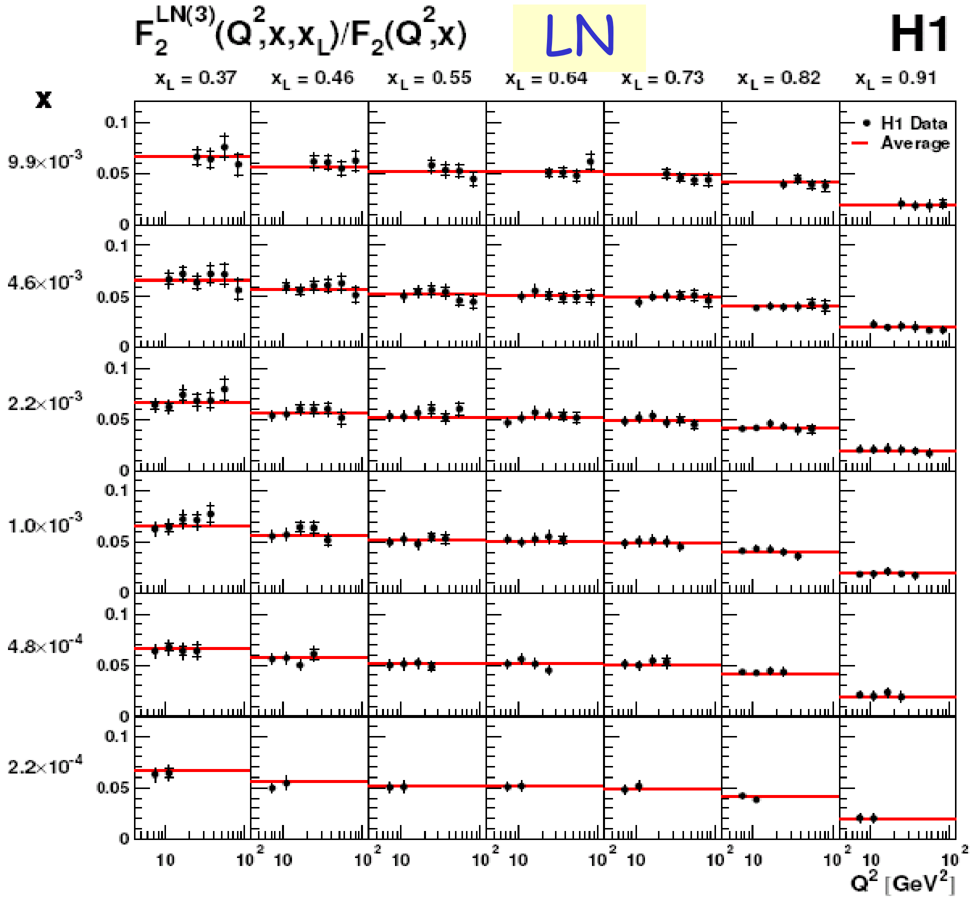


Nucl.Phys.B776 (2007) 1

Leading Baryon production rate in DIS

Ratio of cross sections $\sigma_{DIS}^{LP,LN}/\sigma_{DIS}$ (or $F_2^{LP,LN}(Q^2,x)/F_2(Q^2,x)$)





LP,LN production rate, kinematics is approx. independent of (Q^2,x)

➔ **supports** **<u>limiting fragmentation</u>**

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

Eur.Phys.J.C68 (2010) 381

within π-exchange model we estimate F_2^{π} from measured F_2^{LN}:

$$\boxed{F_2^{LN(3)}(\beta,Q^2,x_L)=\Gamma_\pi(x_L)\cdot F_2^{\pi}(\beta,Q^2)}$$

where

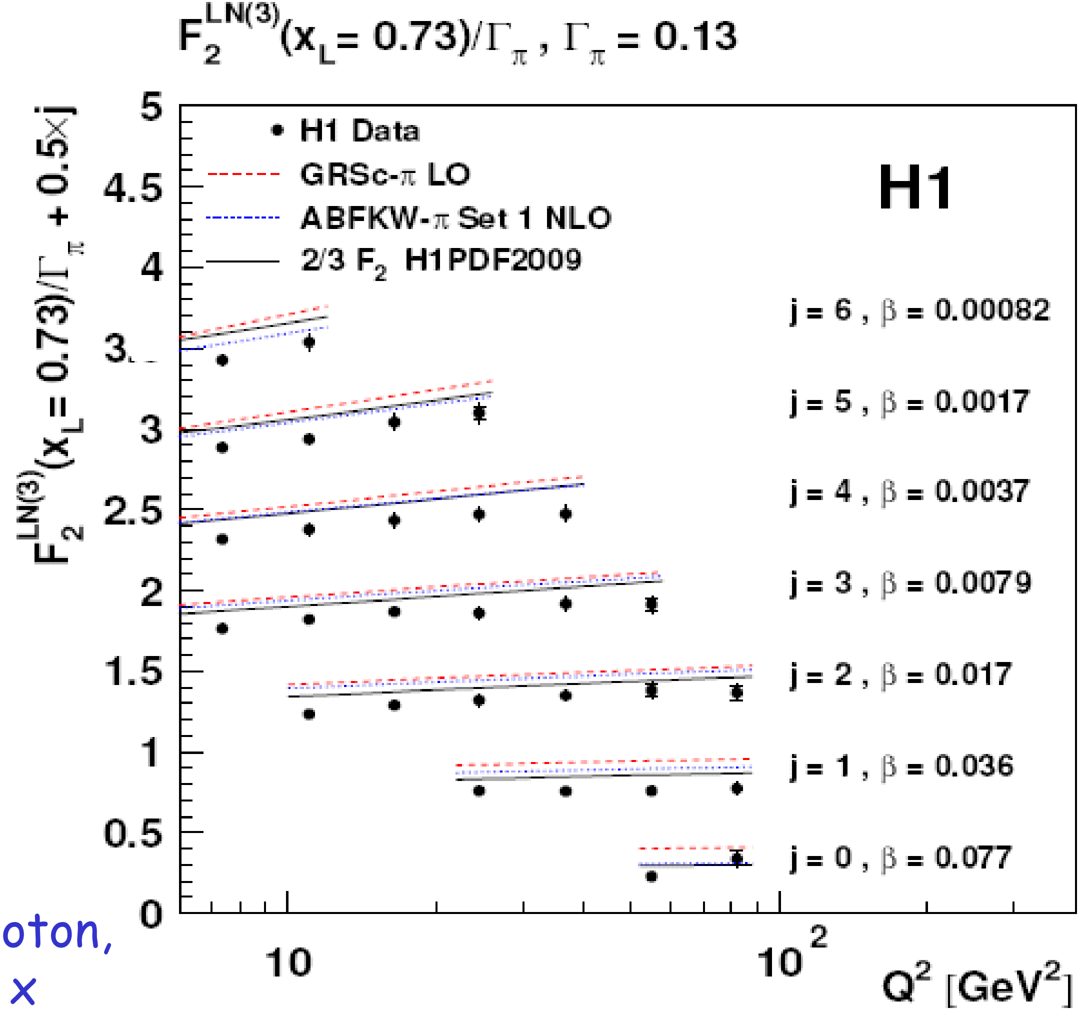
$\beta=x/(1-x_L)$

$\Gamma_\pi(x_L)$ 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}/Γ below the F_2^{π} and F_2

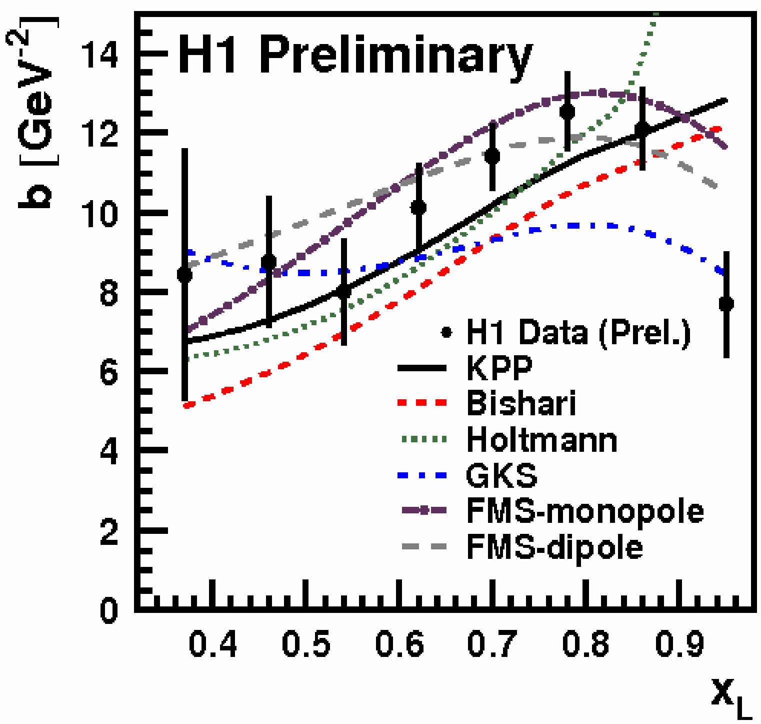
However: large uncertainty of pion flux normalisation: choice of pion flux (formfactor), absorption/rescattering, background…

Leading neutrons: compare slopes of p_T^2 distribution with fluxes

H1prelim-10-113

Fit the distributions with an exponent

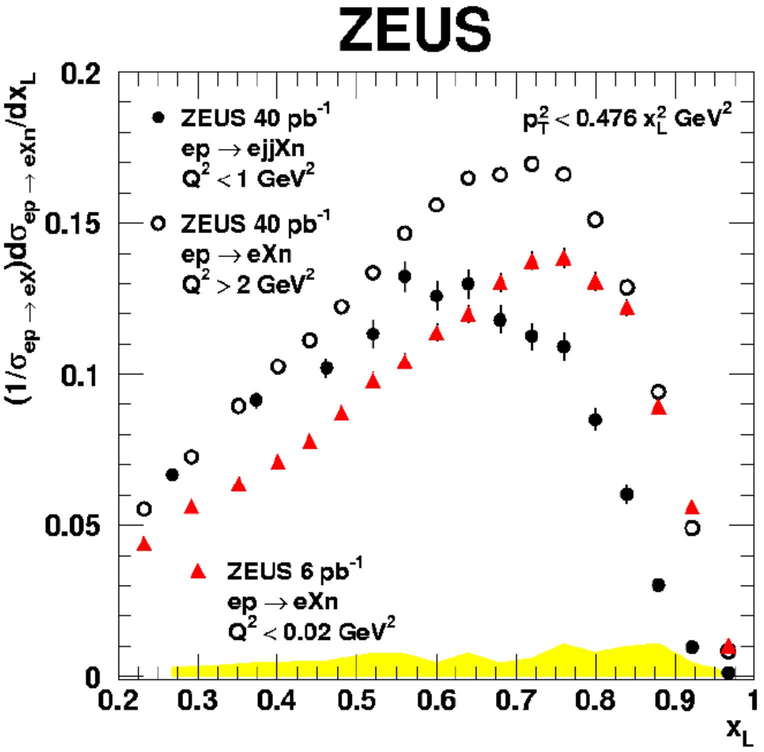
$$\frac{1}{\sigma_{inc}}\frac{d\sigma_{\mathrm{LN}}}{dp_T^2\,dx_L}=a(x_L)\cdot e^{-b(x_L)\,p_T^2}$$



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

Measurement sensitive to the pion flux parameterisations

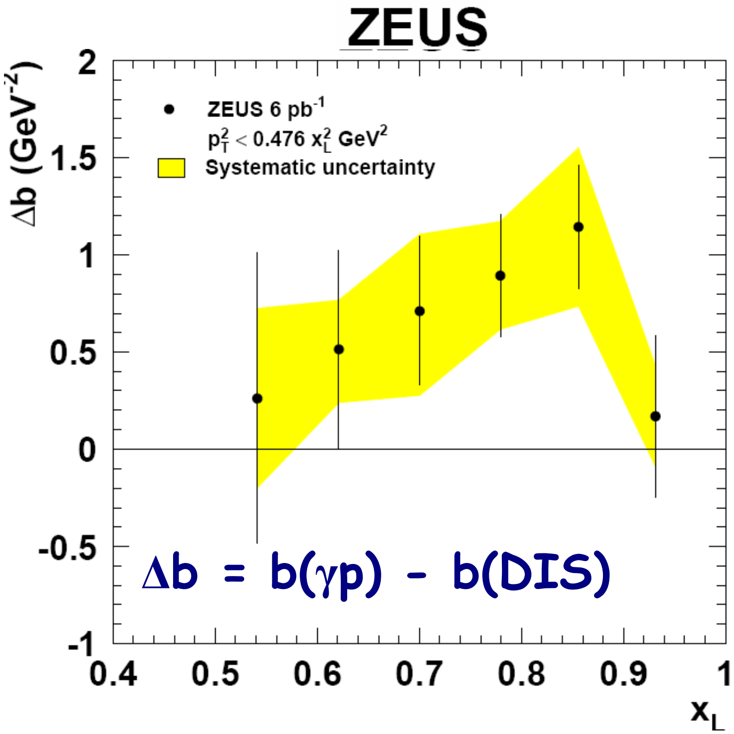
Leading Neutrons- compare rates and slopes for DIS and γp



○ DIS

▲ γp

● γp-dijet



$\Delta b = b(\gamma p) - b(\text{DIS})$

photoproduction (Q^2~0) – photon may be resolved, i.e. 'hadronic' interaction

- **photoproduction suppressed at low x_L** → consistent with neutron absorption through rescattering (more absorption in γp due to larger transverse size of real photon)

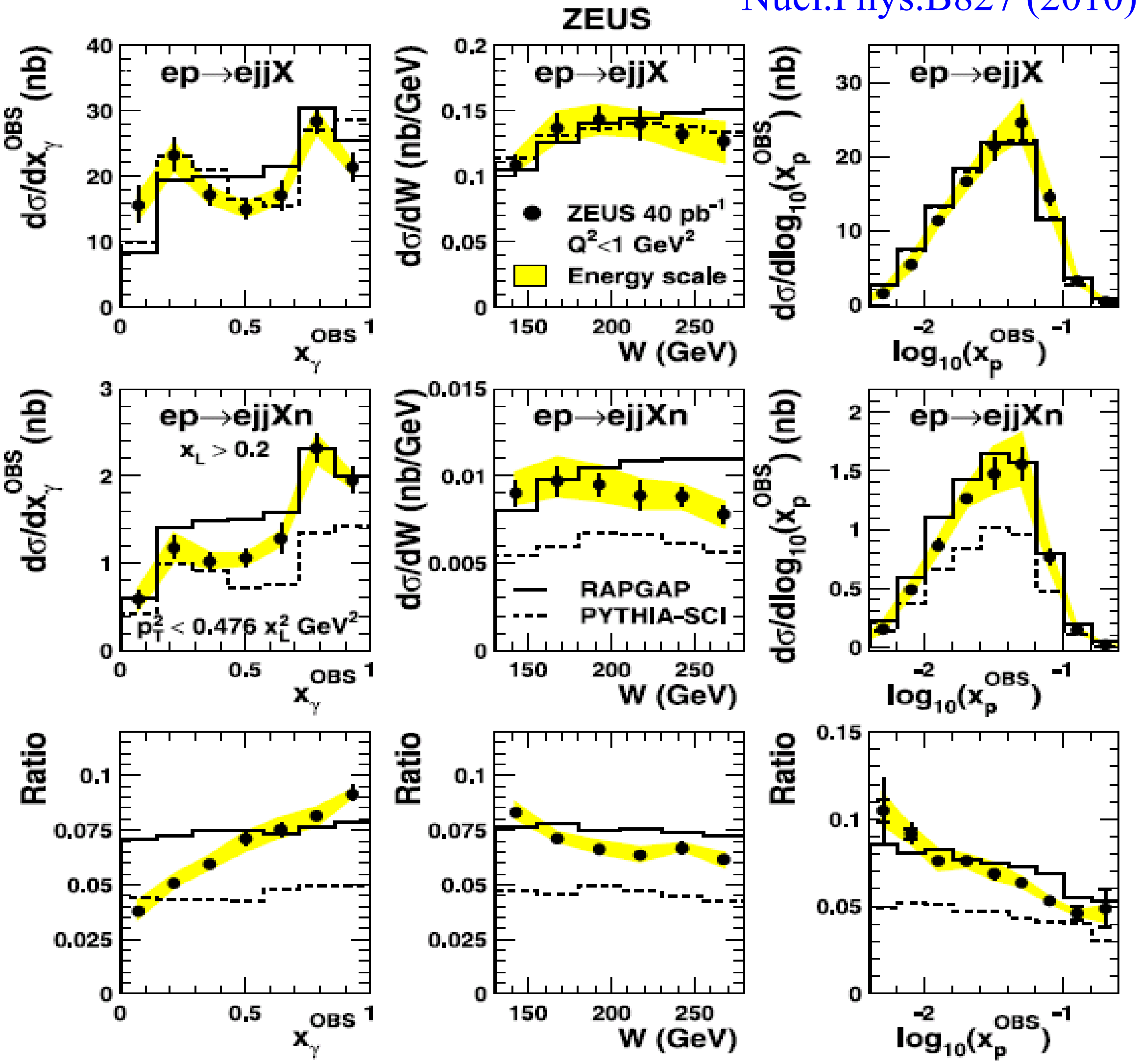
- effect is less prominent for jets; suppression at high x_L due to phase space limitation

- **p_T^2 slopes steeper in γp than in DIS** → more absorption at larger p_T → steeper slope

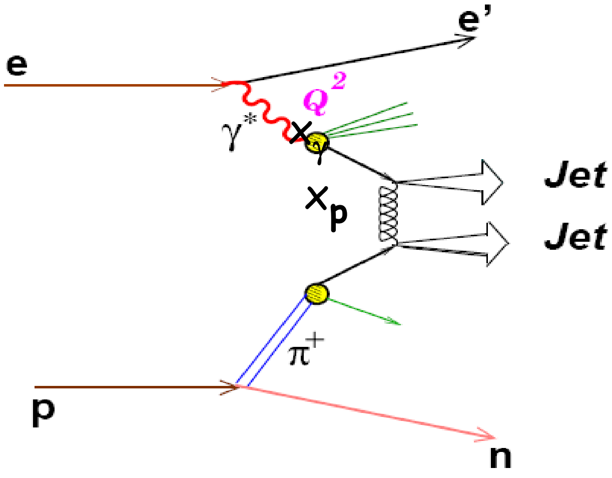
Dijet photoproduction with Leading Neutrons

Dijet cross sections in inclusive γp and in γp with LN

Nucl.Phys.B827 (2010) 1



$\gamma p \rightarrow$ jet+jet+n+X



x_γ and x_p - fractions of photon and proton momenta, entering the hard interactions

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

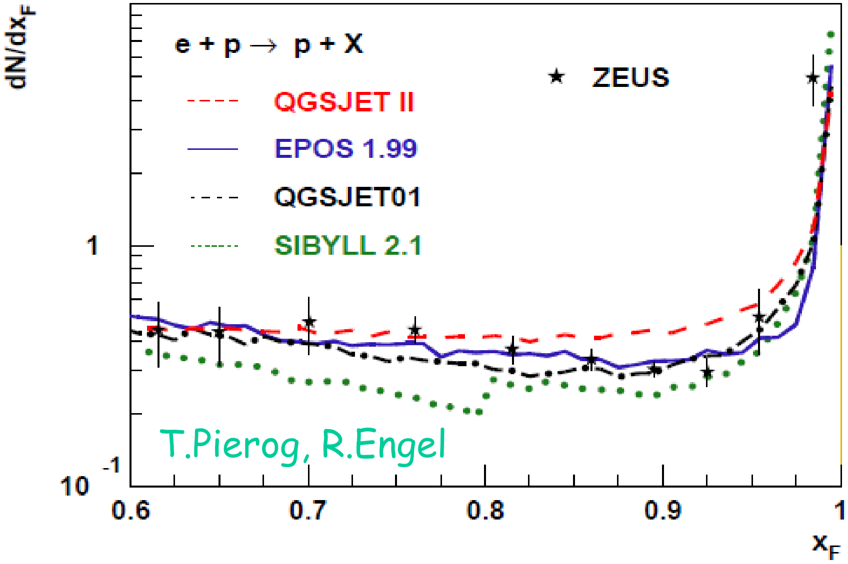
- resolved photon is suppressed in events with leading neutron

Comparison of Leading Baryons from HERA with CR interaction models

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

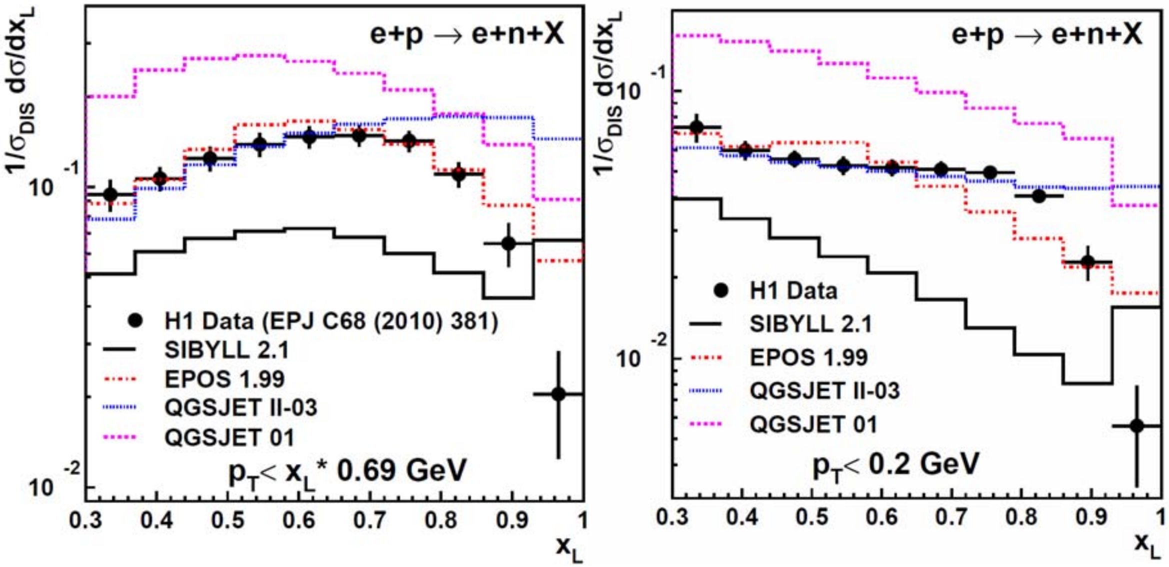
In particular, the forward measurements (baryons, π^0 , γ) are of the greatest importance, since the shower development is dominated by the forward, soft interactions.

Leading protons



T.Pierog, R.Engel

Leading neutrons



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

Comparison HERA leading baryons vs CR models:

- reasonable predictions for leading **proton** data
- large difference between models for leading **neutrons**; EPOS is closer to the data, other models fail
- how is it with π^0, photons ?

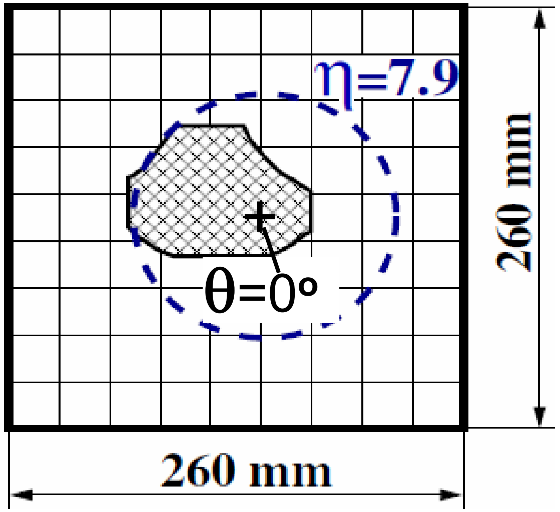
Forward photon measurements

Eur. Phys. J.C71 (2011) 1771

Photon candidates are detected in e/m part of the H1 FNC Calorimeter;

$x_L=E\gamma/Ep>0.1$; geometrical acceptance $\eta_{lab}>7.9$

Main source of photons $\pi^0 \to \gamma\gamma$



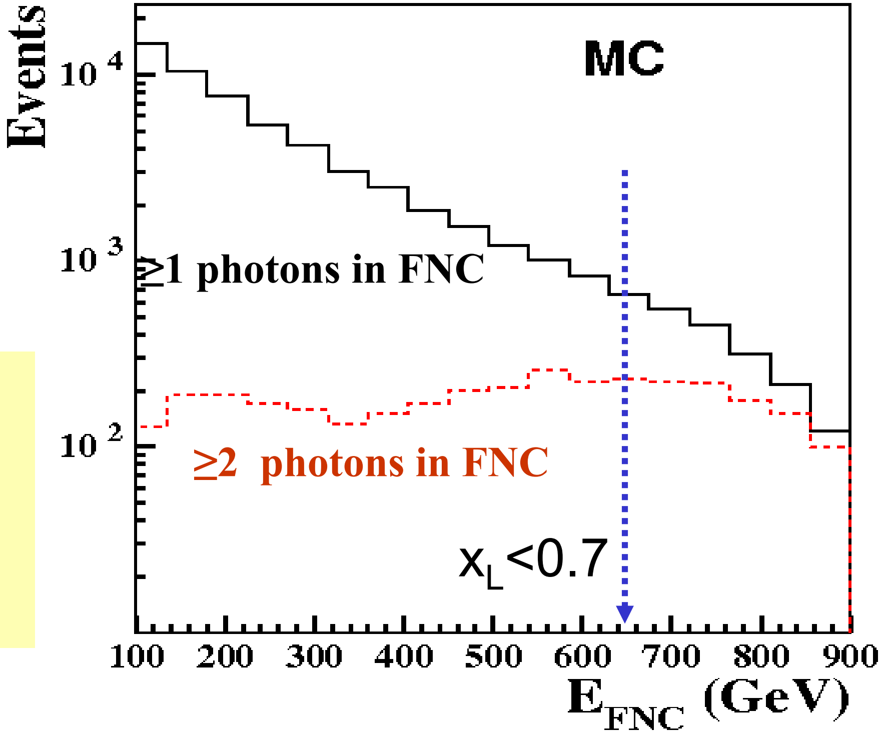
At high x_L, many photon candidates FNC clusters originate from more than one photons
So the measurement represents the sum of photons inside the detector acceptance

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

The cross sections are measured as a function of

- x_L^{lead} and p_T^{lead} of most energetic photon in the range $\eta>7.9$, $0.1<x_L< 0.7$

- x_L^{sum} of sum of all photons in angular range $\eta>7.9$



Forward photon production cross section vs x_L^{lead}

Eur. Phys. J.C71 (2011) 1771

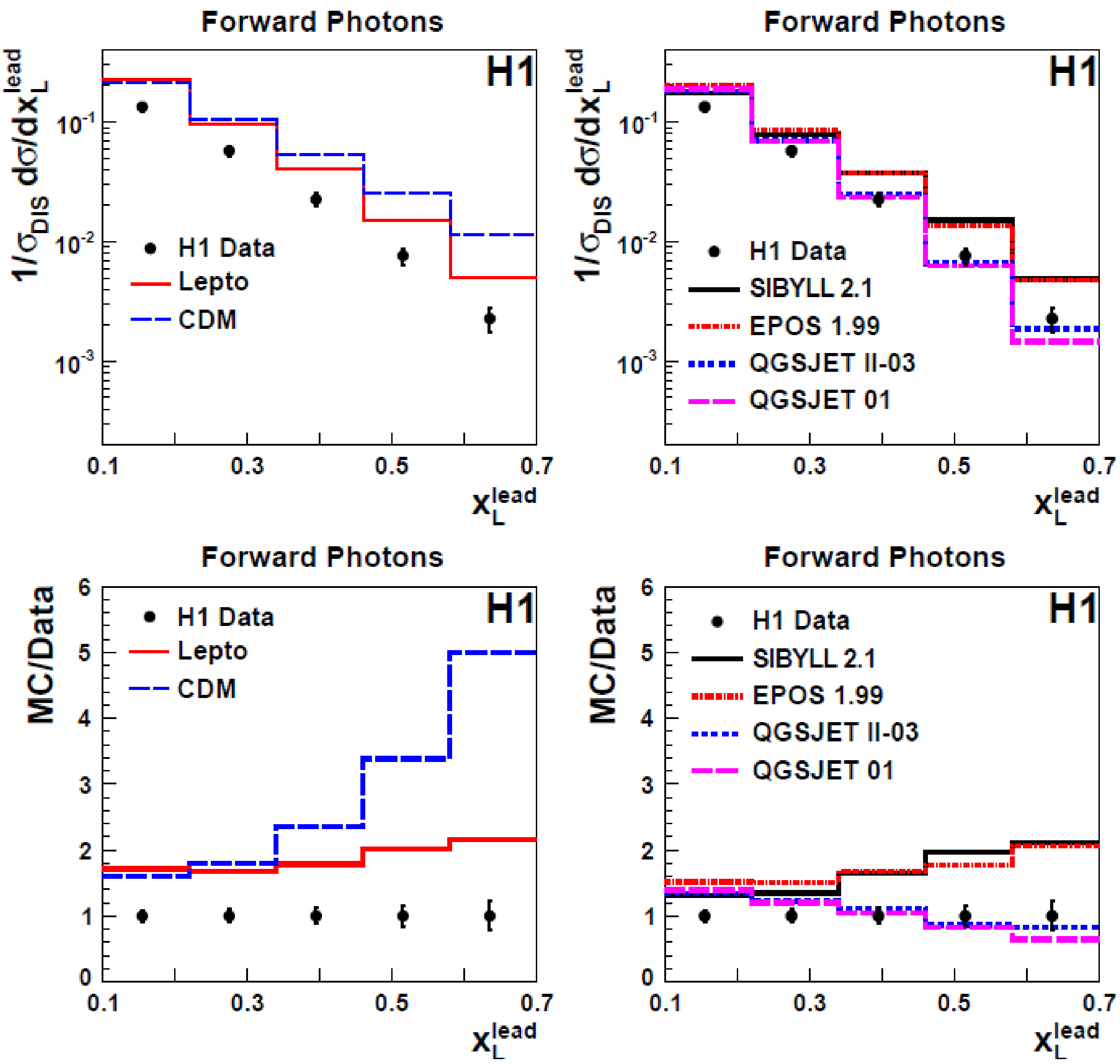
Photon rate in all tested MC models is significantly higher than in data.

LEPTO (parton shower) and CDM (colour dipole) models higher by 70%, CR models by 30-50%

LEPTO describes the shape reasonably well.

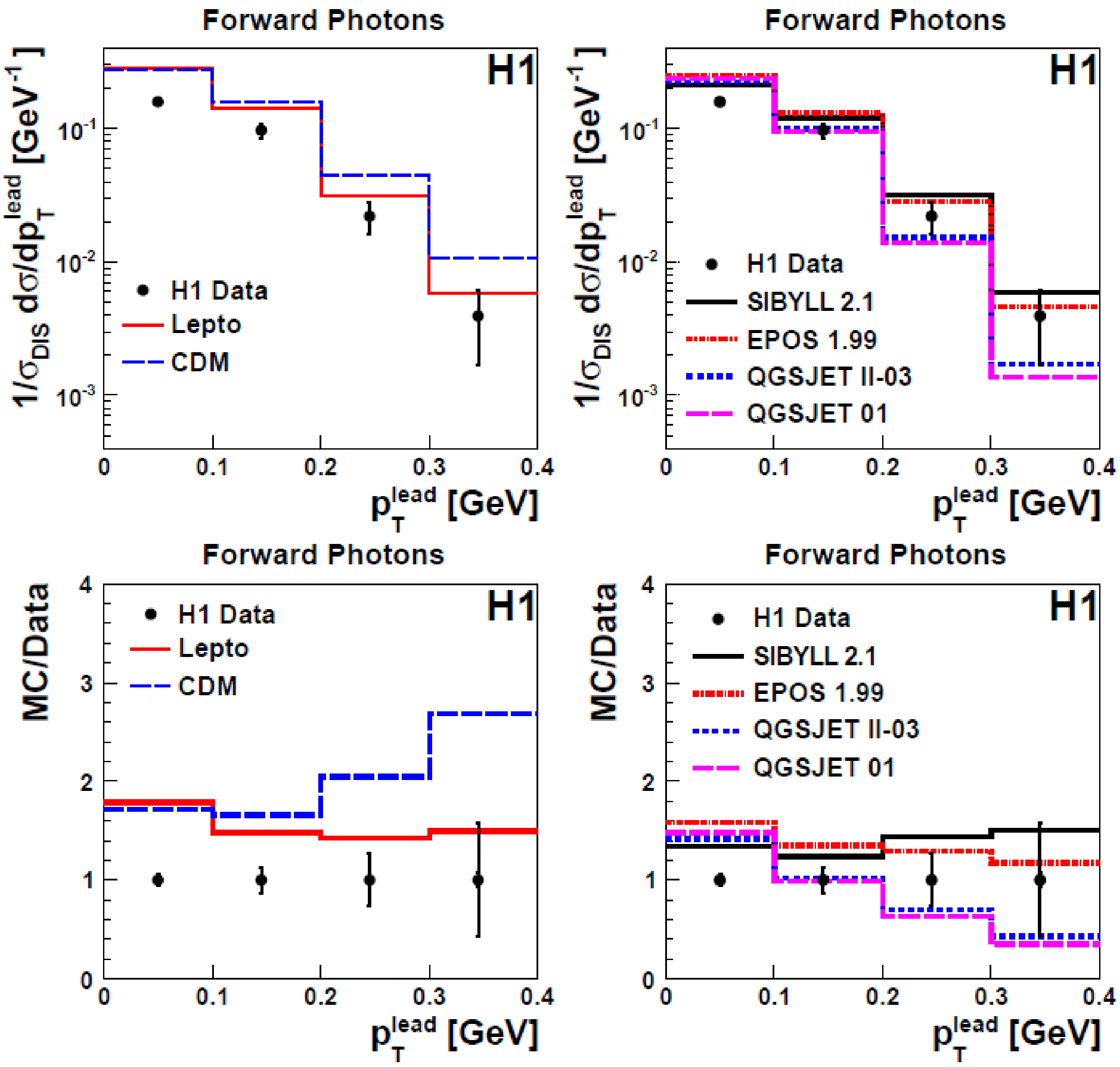
CDM to data discrepancy larger at higher x_L

QGSJET models have steeper behavior than the data, close to data in absolute values except at low x_L



Forward photon production cross section vs p_T^{lead}

Eur. Phys. J.C71 (2011) 1771



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

LEPTO model describes the shape reasonably well.

Shape of p_T spectrum is well described by SIBYLL and EPOS

QGSJET also agree with data within uncertainties (except lowest p_t)

Forward photon production cross section vs x_L^{sum}

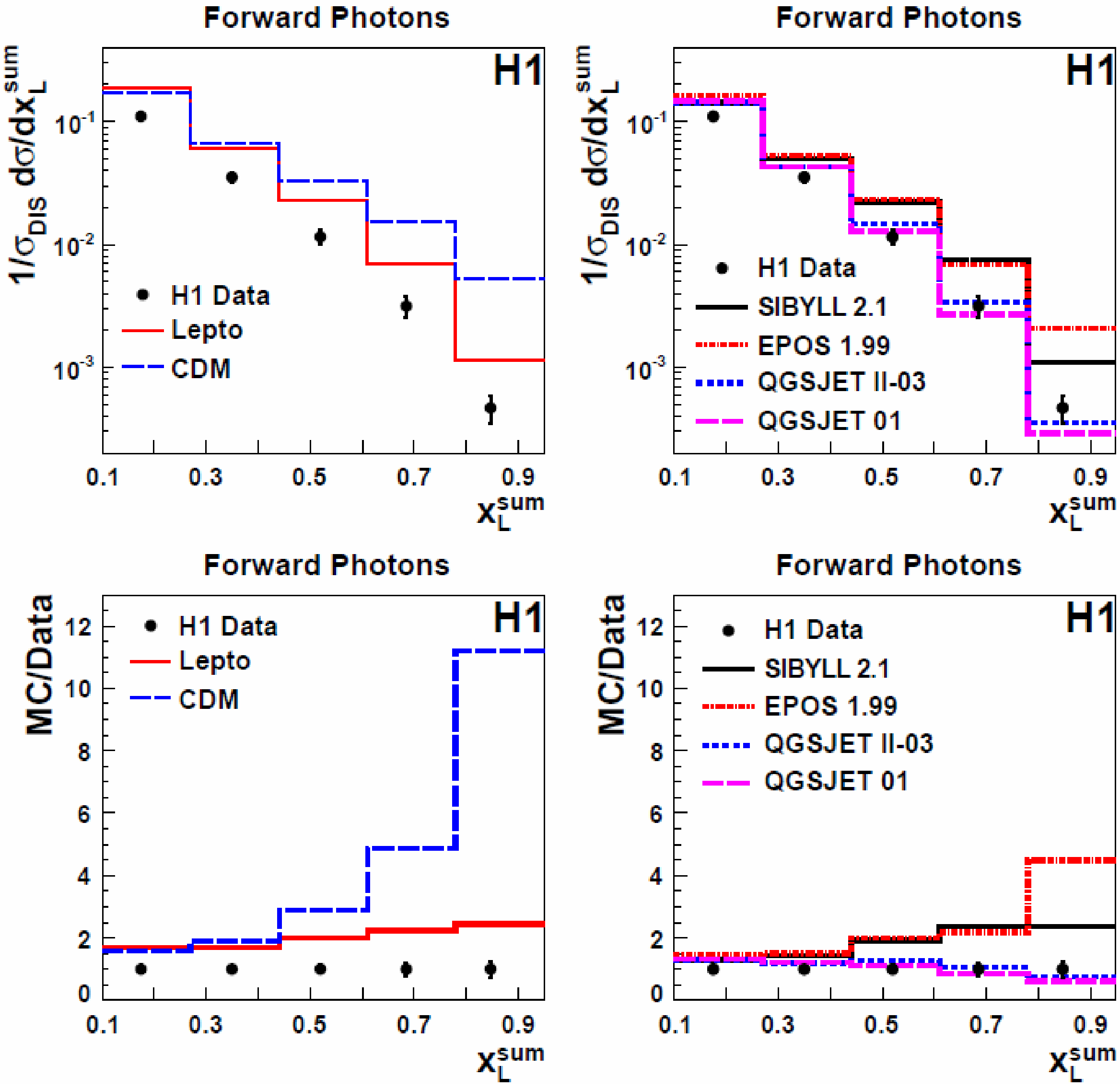
Eur. Phys. J.C71 (2011) 1771

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

LEPTO describes the shape reasonably well
CDM – large discrepancy at higher x_L

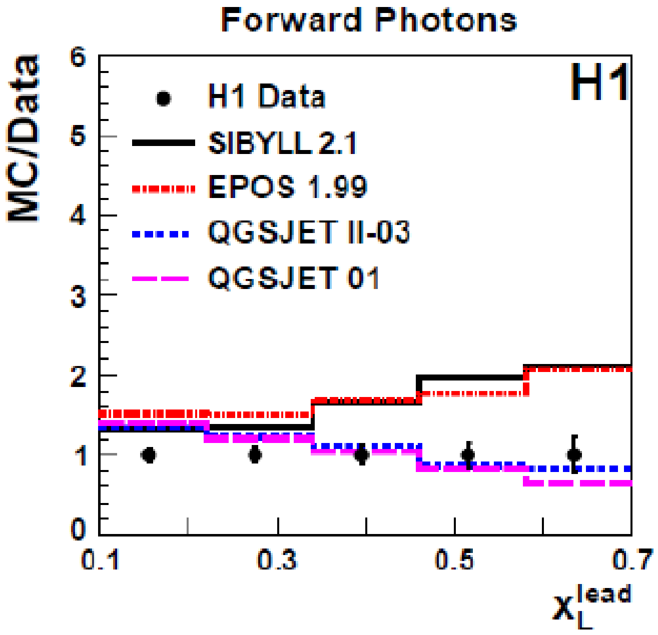
QGSJET models describe data shape better than SIBYLL and EPOS.

Difference is more pronounced for EPOS at highest x_L^{sum}

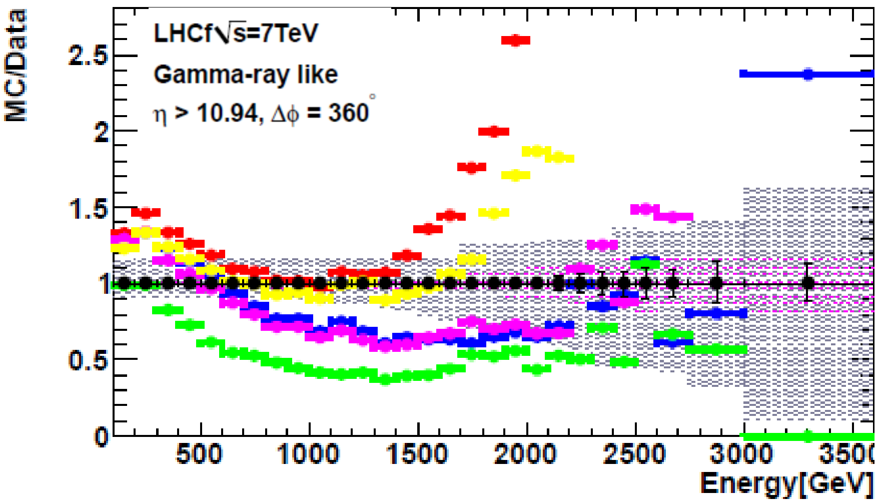


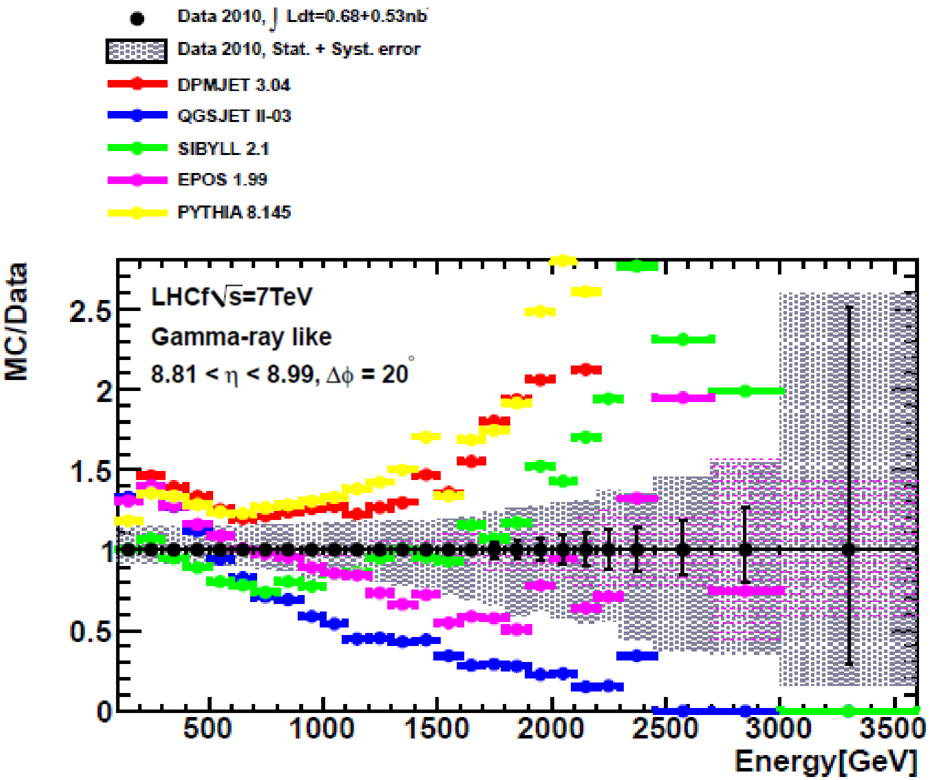
$x_L^{sum} = \Sigma E_i/E_{p\text{-beam}}$ sum of all photons with $\eta>7.9$

Forward photon production: compare H1 vs LHCF



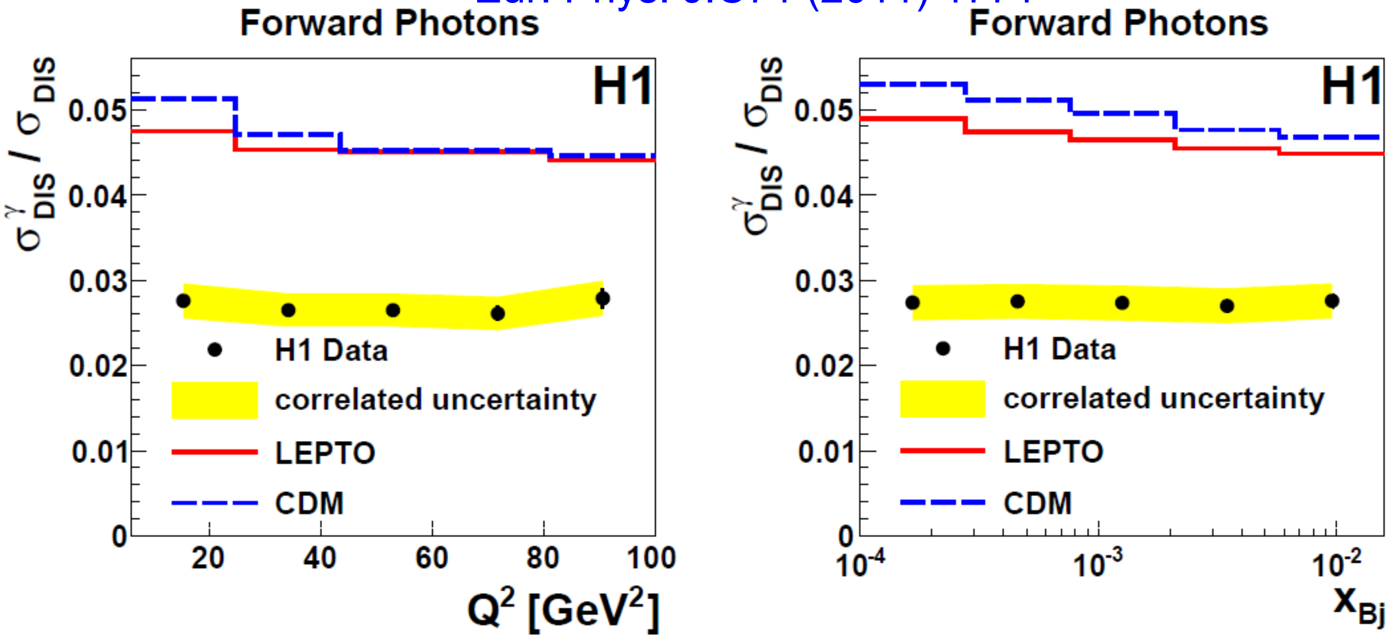
Different behaviour of MC models for H1 and LHCF data



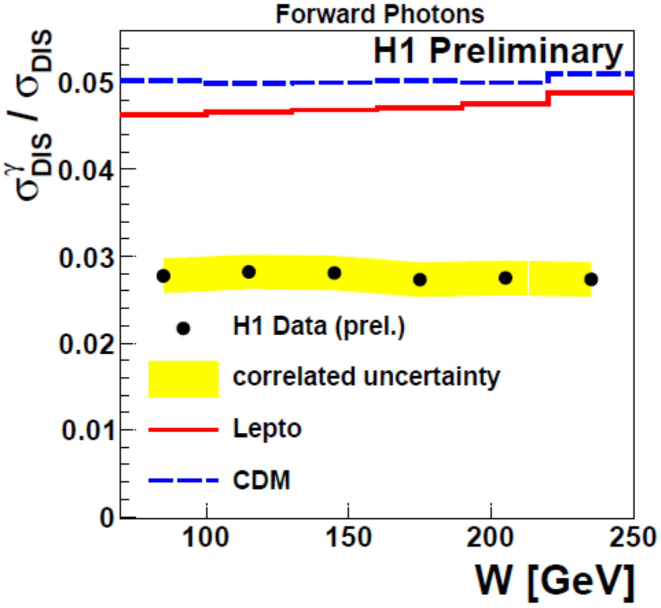


Fraction of DIS events with forward photons

Eur. Phys. J.C71 (2011) 1771



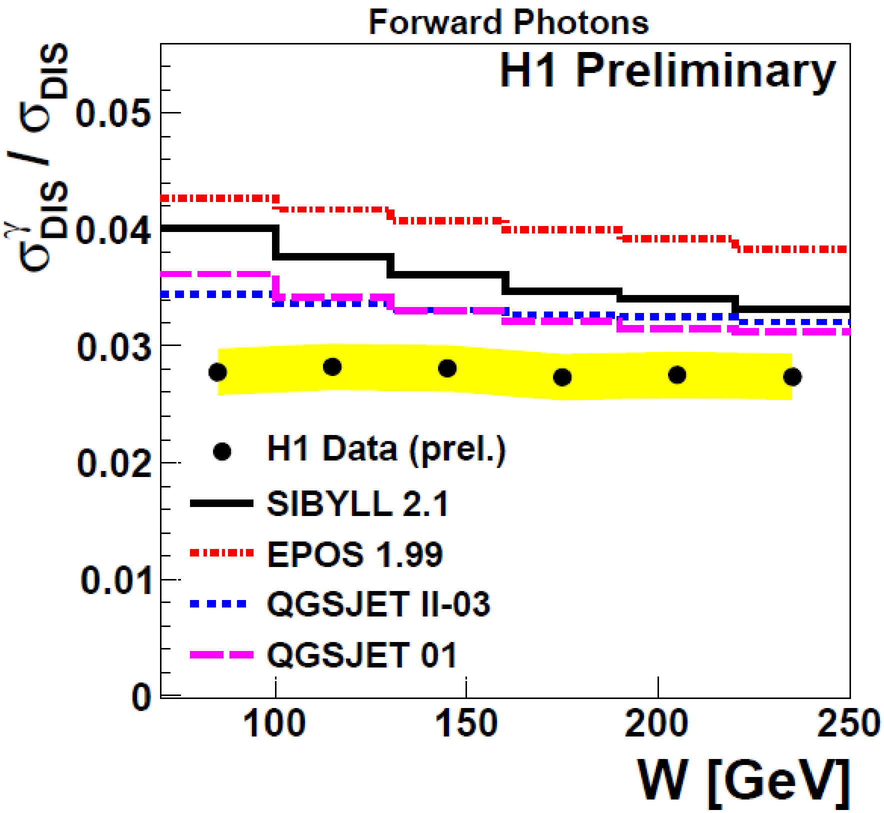
H1prelim-12-111



In the data the relative rate of forward photons is insensitive to x, Q^2 and W
- consistent with limiting fragmentation

LEPTO and CDM models predict much higher rate of forward photons and show slight Q^2 , x_{Bj} and W dependence

Fraction of DIS events with forward photons vs W, compare to CR models



H1prelim-12-111

- In the data, the rate of forward photons relative to inclusive DIS is independent of W
- CR models indicate W dependence

Study Feynman-x distributions at different $\gamma^{*}p$ CM energies

$$\boxed{x_F = \frac{p^{*}_{\|}}{p^{*}_{\|\max}} = \frac{2p^{*}_{\|}}{W}}$$

(for very forward particles $x_F \approx x_L$)

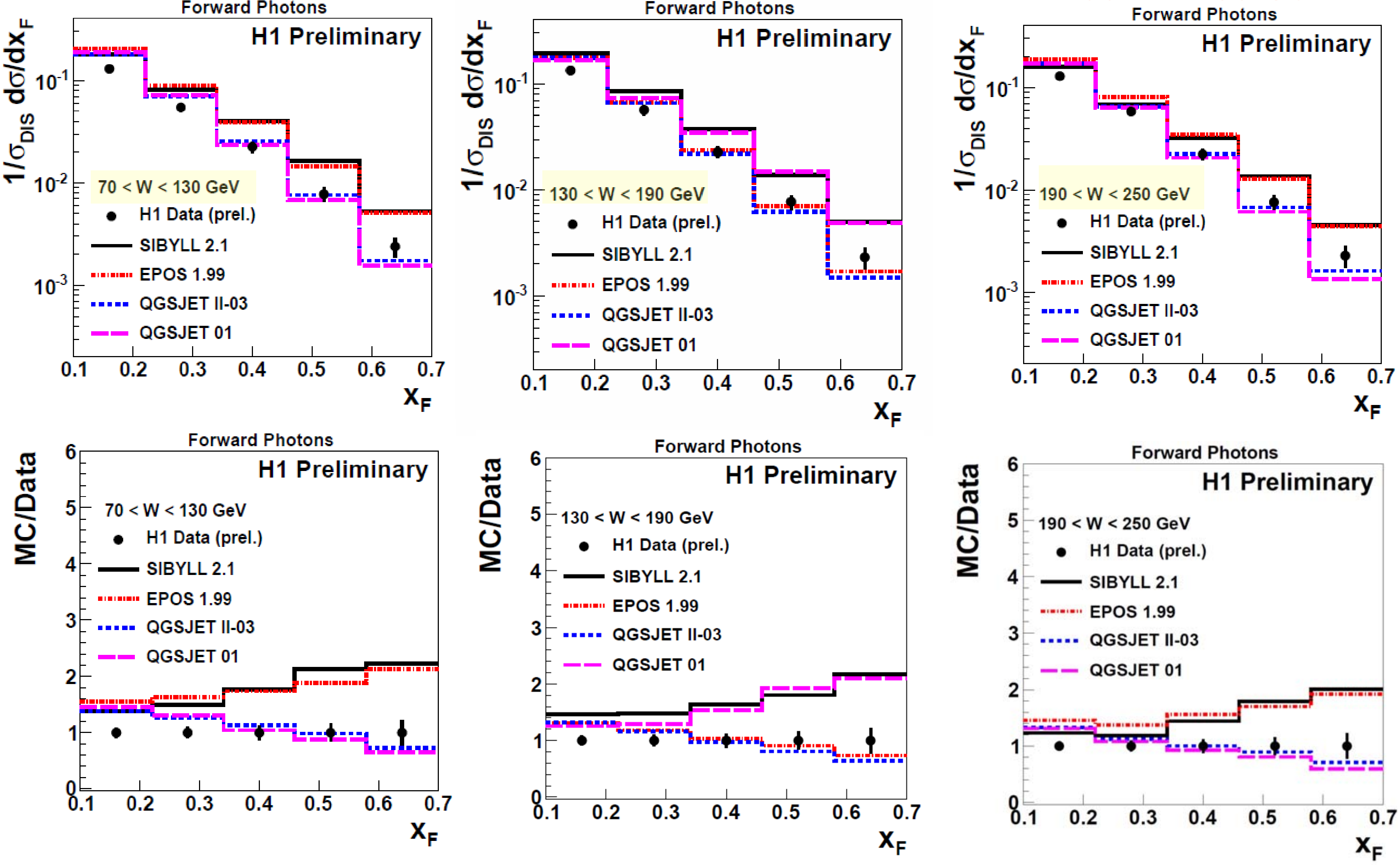
Forward photons: $1/\sigma_{DIS}\, d\sigma/dx_F$ distributions vs W

H1prelim-12-111

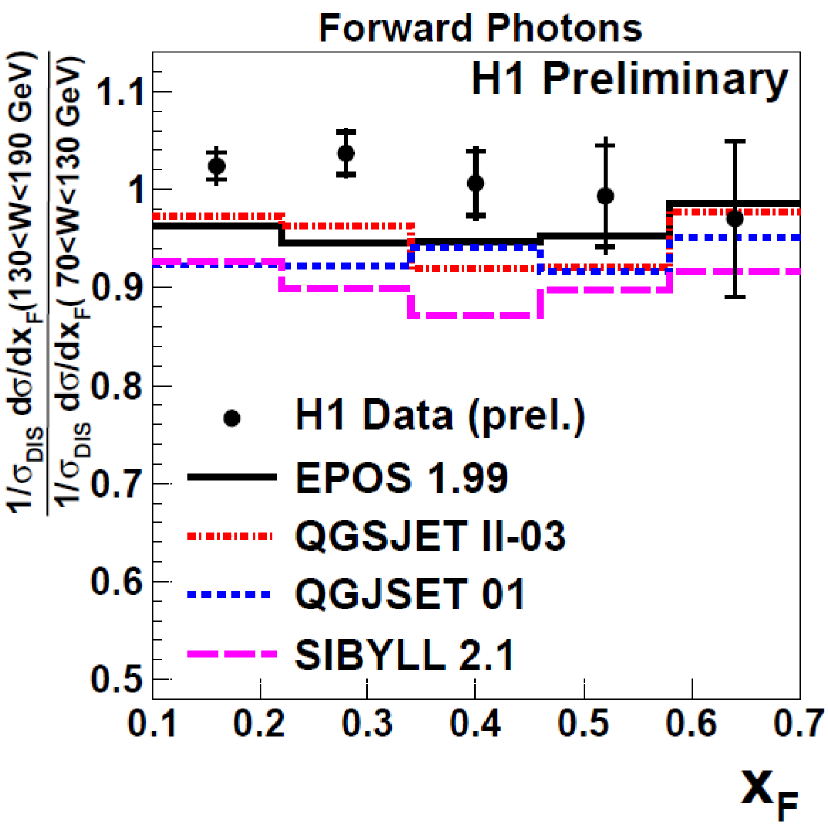
70<W<130 GeV

130<W<190 GeV

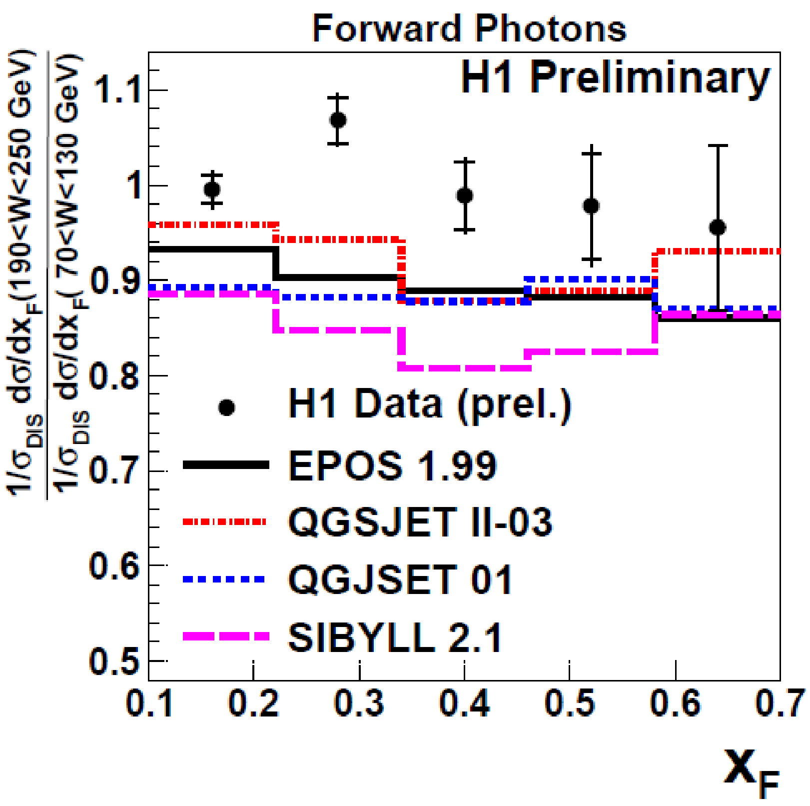
190<W<250 GeV



Forward photons: $1/\sigma_{DIS}\, d\sigma/dx_F$ distributions vs W



$$\frac{\frac{1}{\sigma_{DIS}}\frac{d\sigma}{dx_F}\left(130<W<190\,GeV\right)}{\frac{1}{\sigma_{DIS}}\frac{d\sigma}{dx_F}\left(70<W<130\,GeV\right)}$$



$$\frac{\frac{1}{\sigma_{DIS}}\frac{d\sigma}{dx_F}\left(190<W<250\,GeV\right)}{\frac{1}{\sigma_{DIS}}\frac{d\sigma}{dx_F}\left(70<W<130\,GeV\right)}$$

- Data show no W dependence of x_F distribution (consistent with Feynman scaling)
- Models show deviations from scaling – lower photon rate with increasing W

Summary

Forward hadrons are good ground to study interplay of soft and hard physics, important for an improved theoretical understanding of proton fragmentation

- precise measurements of forward protons and neutrons in ep collisions
- the standard fragmentation models underestimate the neutron yield at high x_L
- measurements well described by the combination of 'standard' fragmentation and exchange models
- LP and LN measurements are consistent with the hypothesis of limiting fragmentation
- LN measurements further constrain pion flux and pion PDF
- $\gamma p \rightarrow nX$ interactions indicate effects of neutron absorption/rescattering

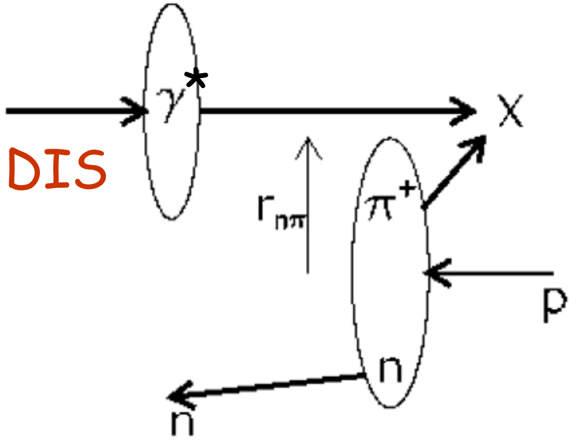
- measurement of very forward photons are sensitive to the proton fragmentation models
- all MC models predict significantly higher yield of photons than seen in the data
- within the measured kinematic range the forward photon spectra are insensitive to $W_{\gamma p}$

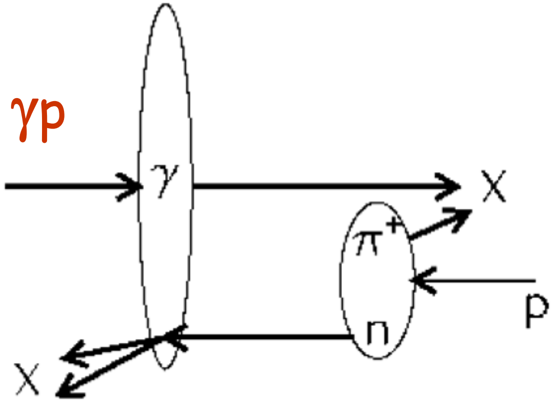
- useful input for models of cosmic ray interactions with matter

Backup

Exchange model refinement: absorptive corrections

Absorption: important ingredient to interpret the results in terms of particle exchange





Neutron absorption through rescattering:

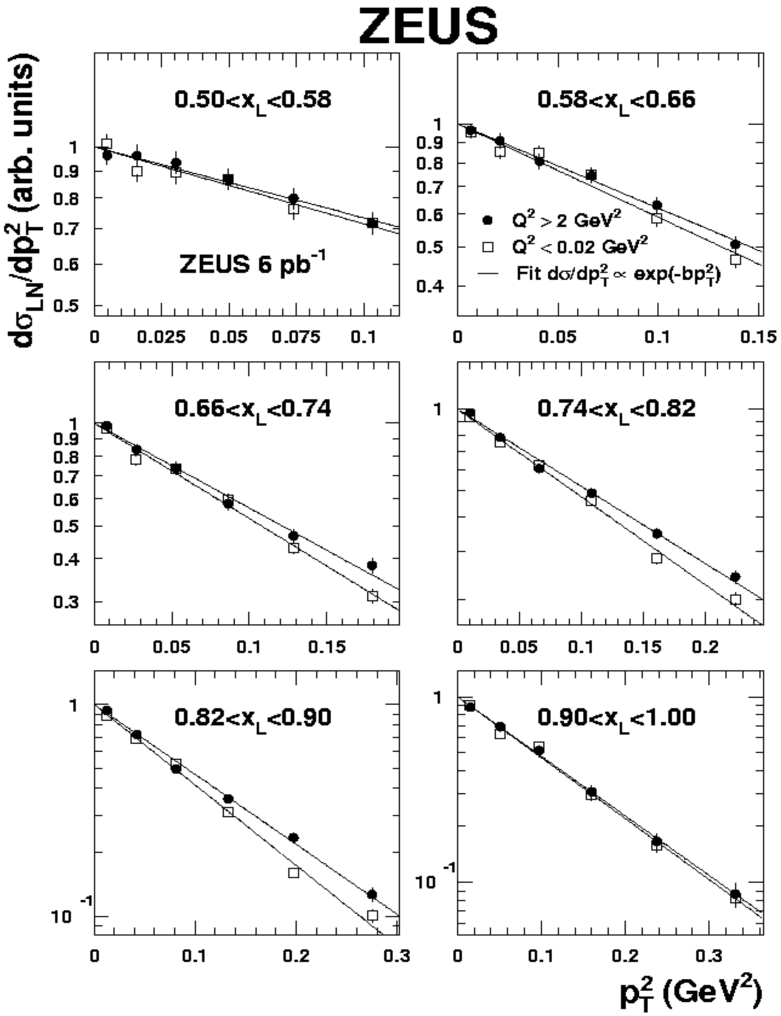
enhanced when size of π-n system $r_{\pi n} \sim 1/p_T$ is small w.r.t. the transverse size of γ, e.g. at high p_T, low x_L
→neutron breaks up or
→is kicked to lower x_L,higher p_T (migration) and/or escapes detector acceptance (absorption loss)
(in other language: multi-Pomeron exchange)

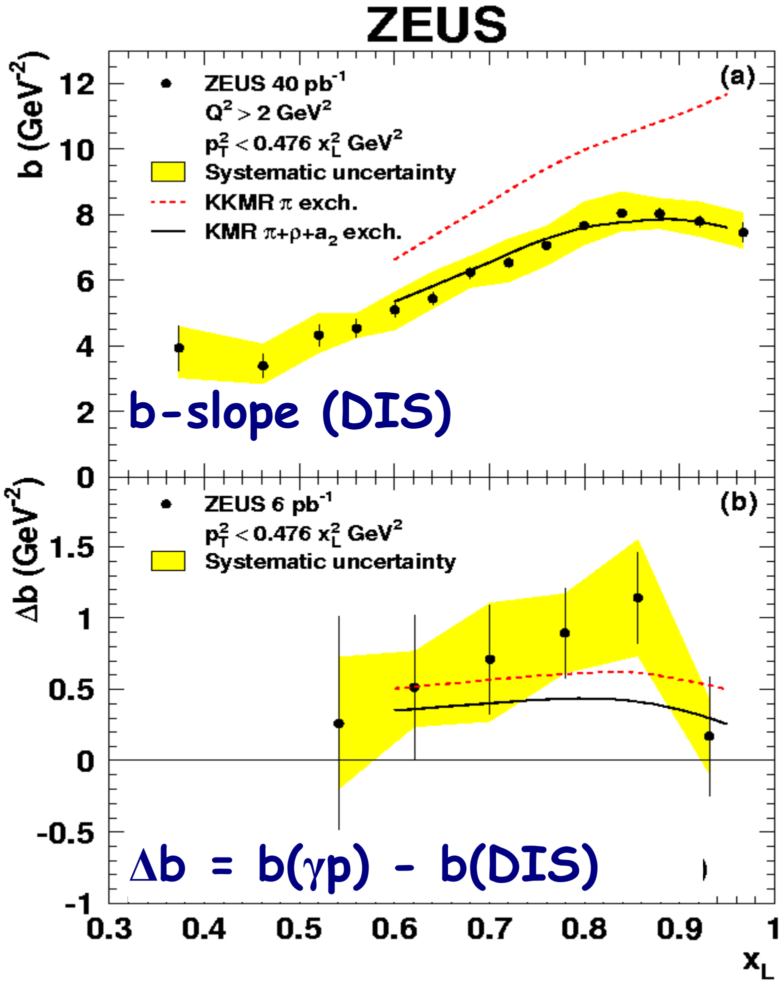
- Affects the relative rate of leading neutrons (depends on the scale Q)

more absorption in photoproduction then in DIS, (real γ transverse size larger than at higher Q^2)
→The calculations/models made without absorption may overestimate the measurements

Effects of absorption and migration estimated:
D'Alesio,Pirner; Nikolaev,Speth,Zakharov;
Kaidalov,Khoze,Martn,Ryskin ;
Kopeliovich,Potashnikova,Schmidt,Soffer

Leading Neutrons- Comparison DIS/γp: p_T^2 distributions





b-slope (DIS)

$\Delta b = b(\gamma p) - b(DIS)$

model of Kaidalov,Khoze,Martin,Ryskin

p_T^2 slopes steeper in γp than in DIS

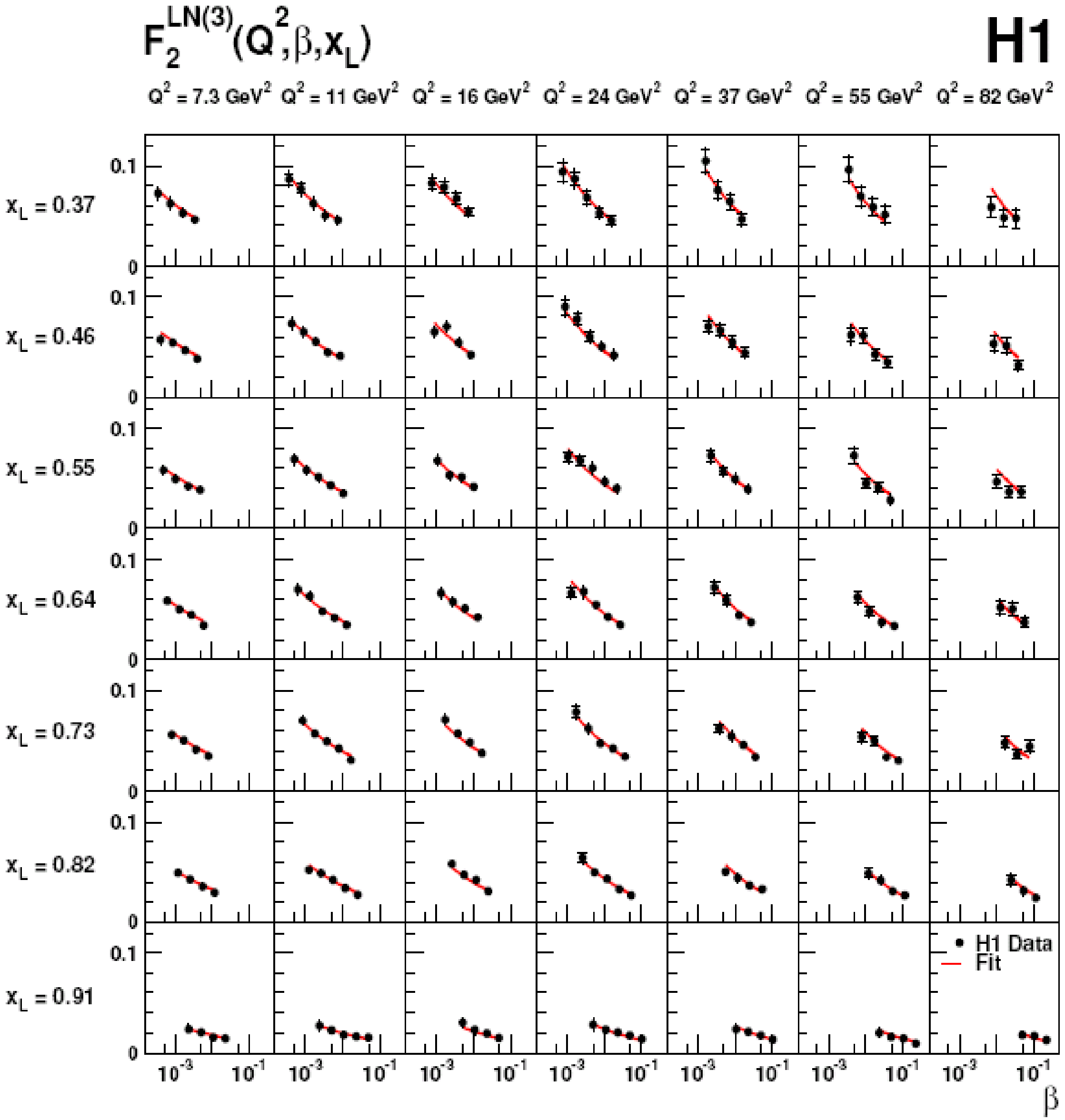
From geometrical picture:

Larger p_T→smaller $r_{\pi n}$→more absorption

→less neutrons at high p_T → steeper slope

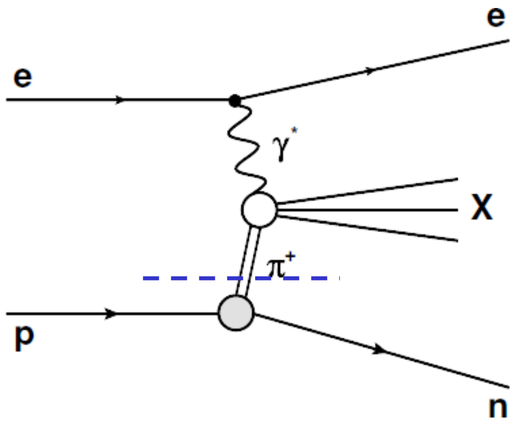
- rescattering on intermediate partons in central rapidity region; migration of LN in (x_L,p_T)
- ~50% absorption loss in γp
- addition of (ρ,a_2) exchanges

Factorisation properties of $F_2^{LN(3)}(Q^2,\beta,x_L)$



In particle exchange picture expect
proton vertex factorisation:

$$F_2^{LN(3)}(Q^2,\beta,x_L) \sim f(x_L) \times F_2^{LN(2)}(Q^2,\beta)$$



$\beta = x/(1-x_L)$ - fraction of exchange's momentum carried by the struck quark

$$F_2^{LN(3)}(Q^2,\beta,x_L) \sim \beta^{-\lambda}$$

λ is almost independent of x_L →

consistent with vertex factorisation

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

within π^+-exchange model we may try to estimate F_2^{π} from measured F_2^{LN}:

$$\boxed{F_2^{LN(3)}(\beta,Q^2,x_L)=\Gamma_\pi(x_L)\cdot F_2^{\pi}(\beta,Q^2)}$$

where

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

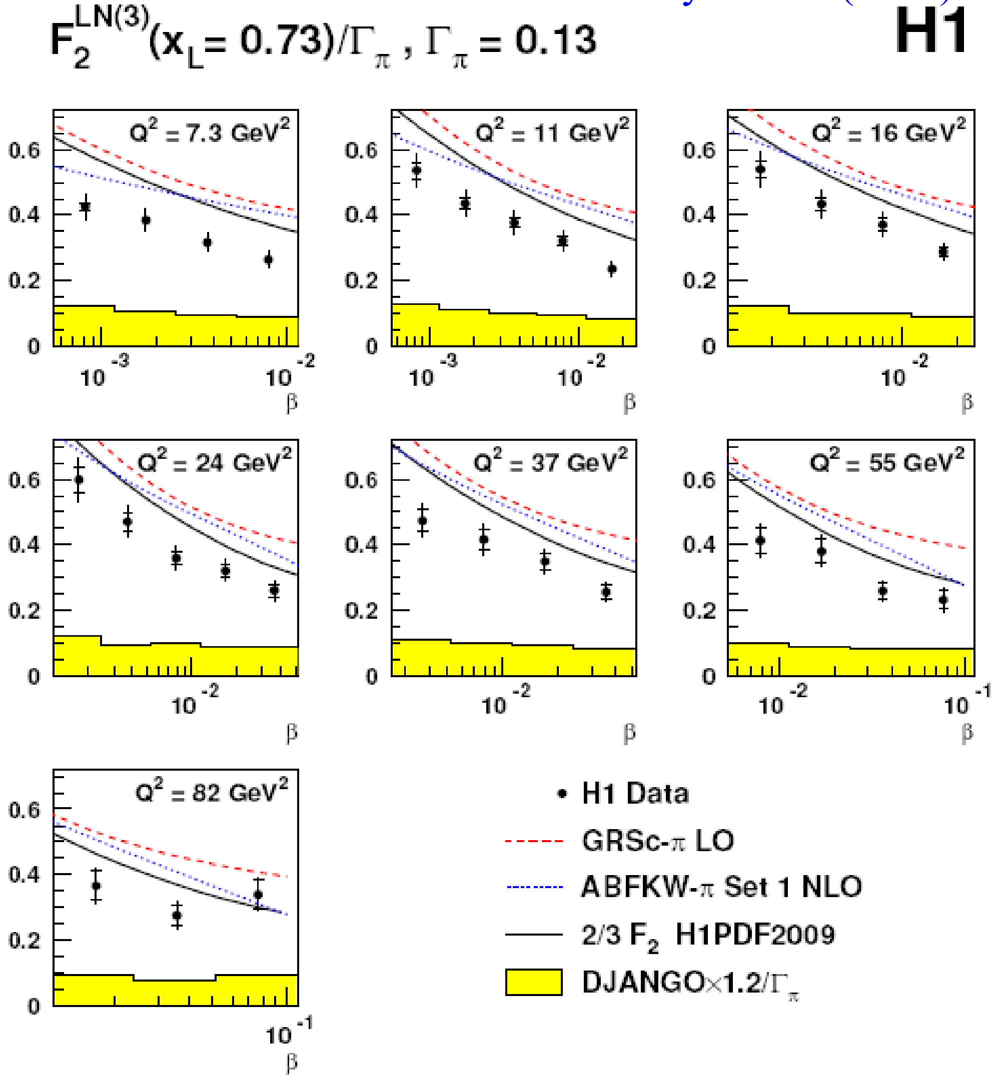
$\Gamma_\pi(x_L)$ is integrated over t pion flux

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

use pion flux parameterisation (Holtmann et al.):

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

Eur.Phys.J.C68 (2010) 381

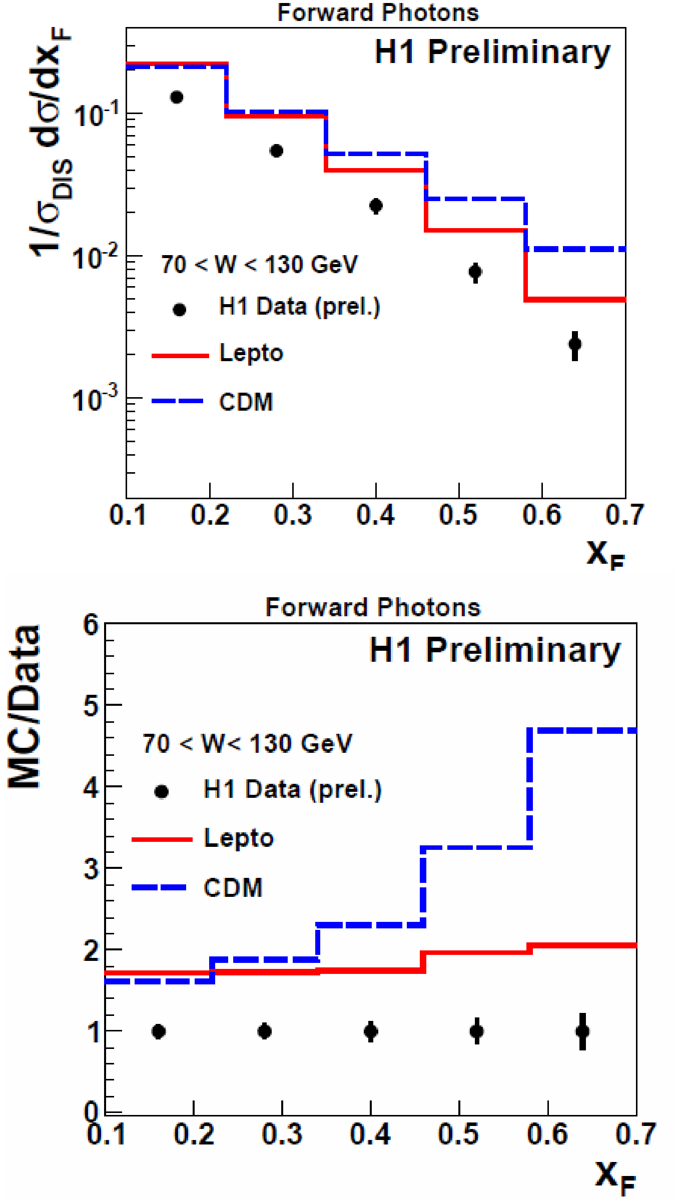


Data are sensitive to the parameterisations of the pion structure function (constrained for x>0.1 from the fixed target experiments).

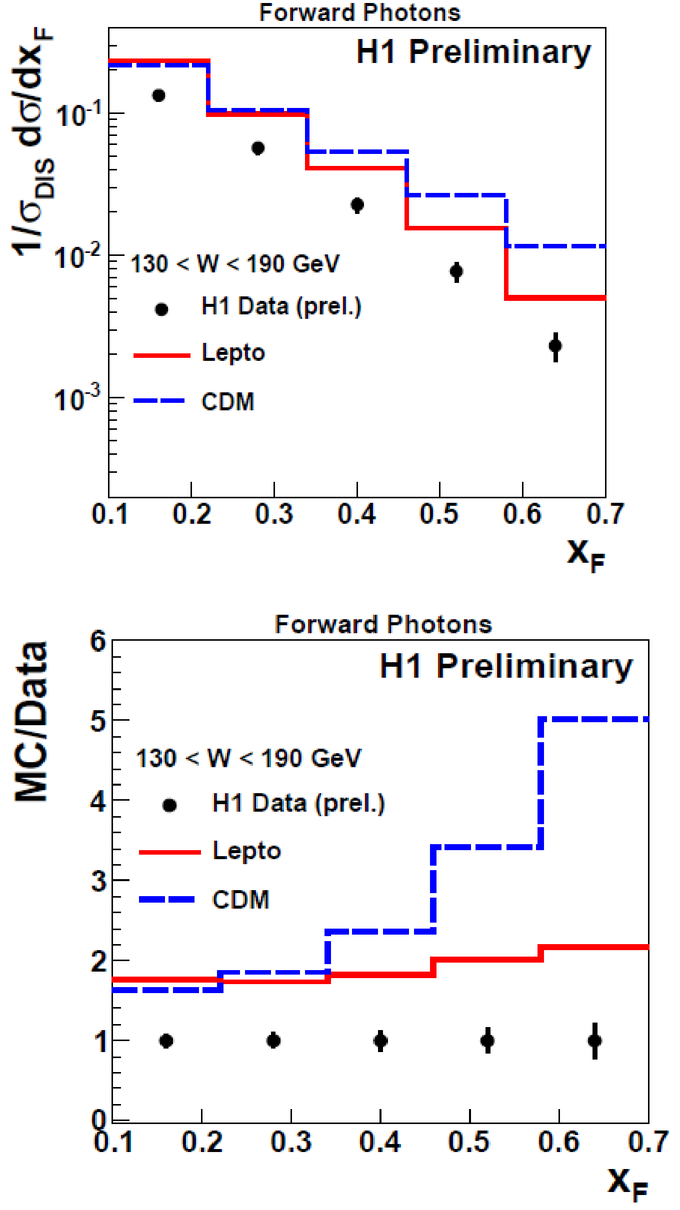
Forward photons: $1/\sigma_{DIS}\ d\sigma/dx_F$ distributions in three W ranges

H1prelim-12-111

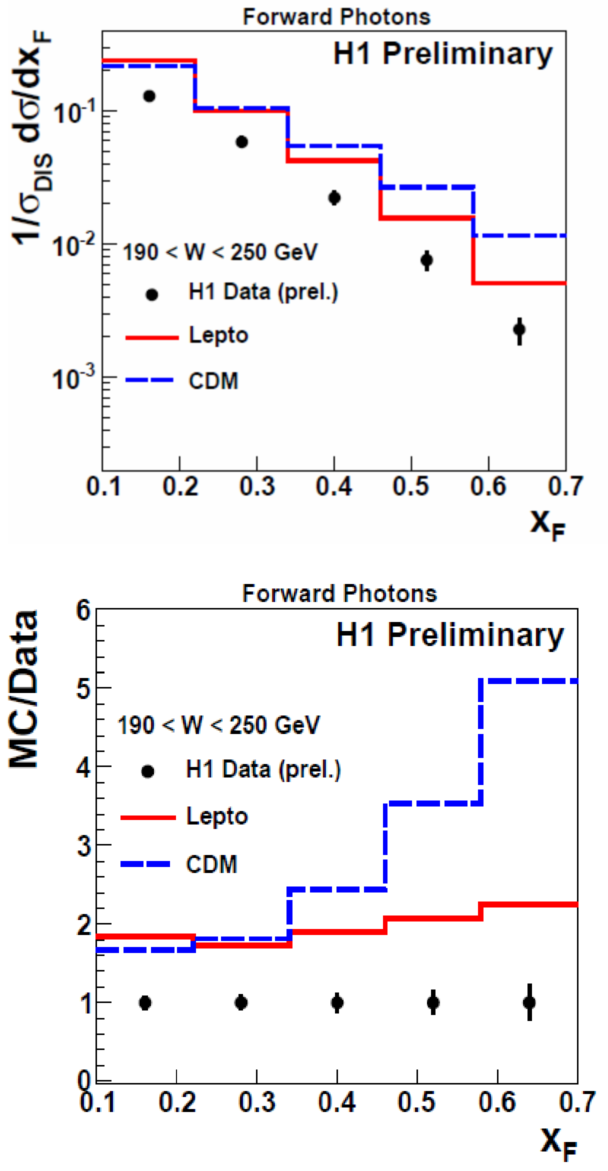
70<W<130 GeV



130<W<190 GeV



190<W<250 GeV



Forward photons: $1/\sigma_{DIS}\, d\sigma/dx_F$ distributions in three W ranges