Workshop 'HERA and the LHC'
CERN, 25-30 May 2008

Forward neutral particles at HERA and impact for cosmic ray models

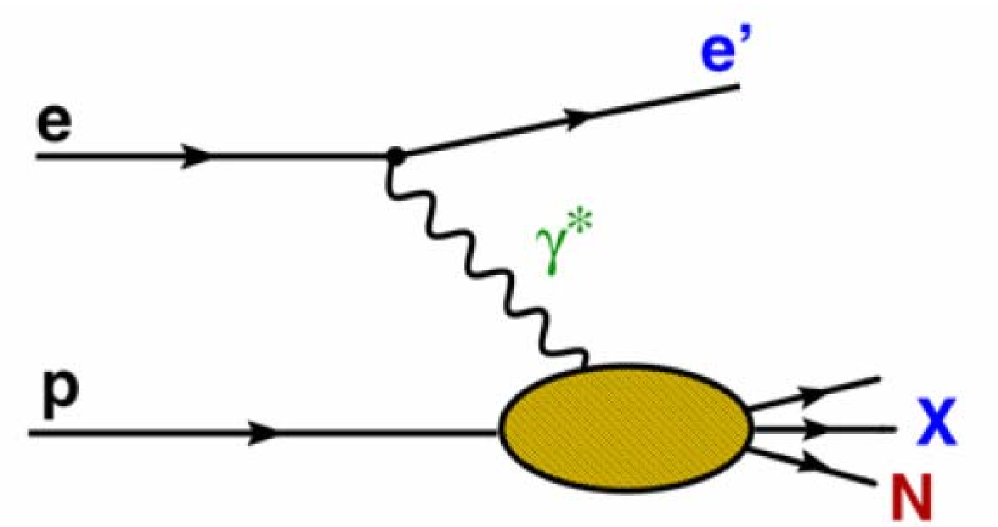
Armen Bunyatyan

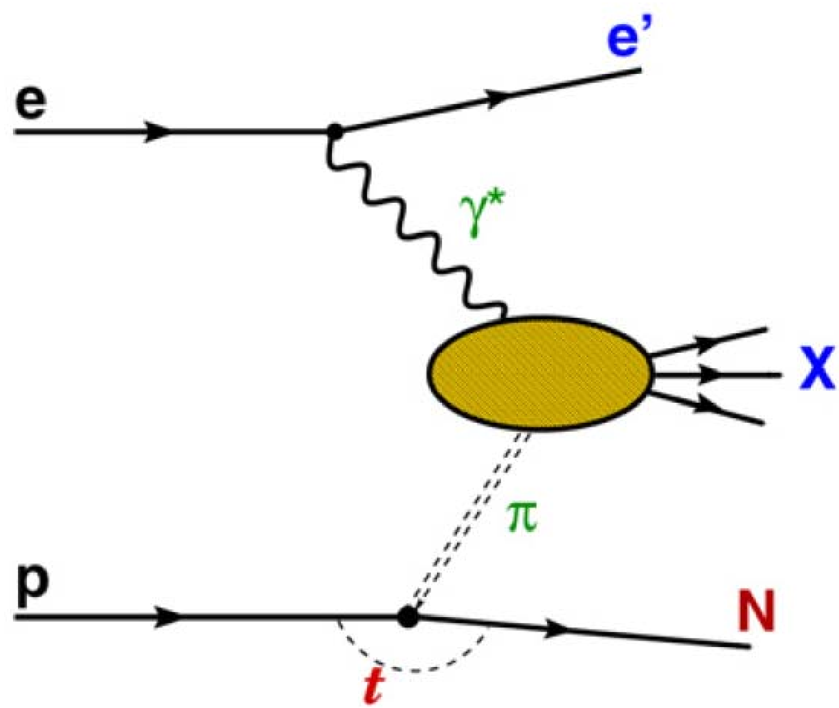
MPI-K, Heidelberg and YerPhI,Yerevan

- The Forward Neutron Calorimeter
- Physics with leading neutrons
- Impact of forward particle measurements for cosmic ray models

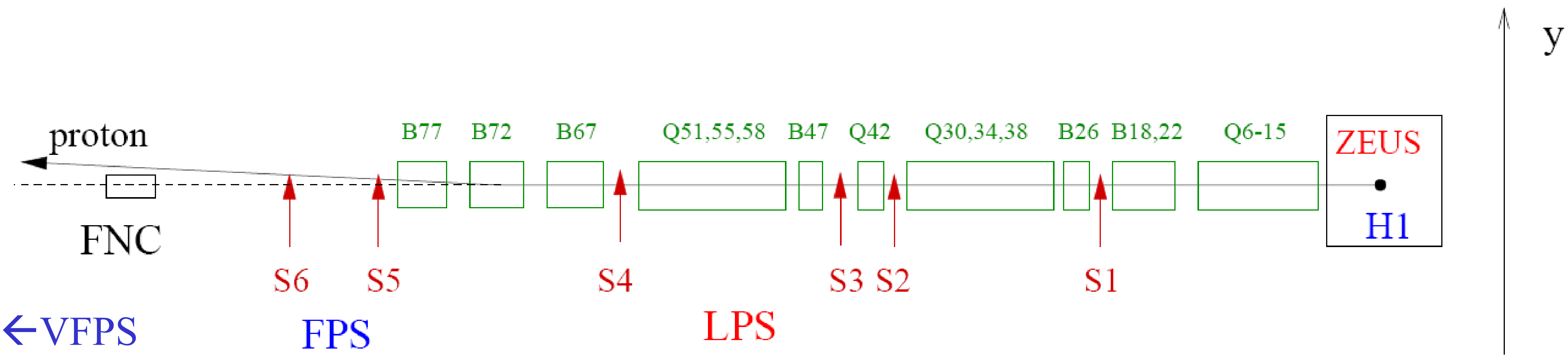
HERA collider- 27.6 GeV electrons (or positrons) collide with 920 GeV protons (also 820, 460 and 575 GeV)
Total CM energy of collision- up to 320 GeV

Leading forward particles are produced at a very small angles from the proton fragmentation or from the exchange mechanism (Pomeron, Reggeon, π^+,π^0…)





Forward detectors at HERA



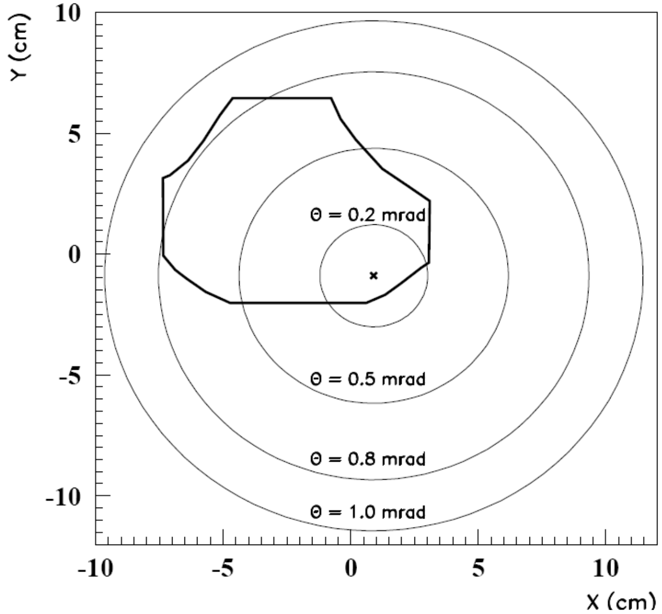
- FPS/VFPS (H1); LPS (ZEUS) – forward proton spectrometers (Roman Pots) , at z=24…220m from interaction point; measure scattered protons with x_L=E/Ep = ~0.4÷0.9 (vertical pots), ~0.85÷1 (horizontal pots)

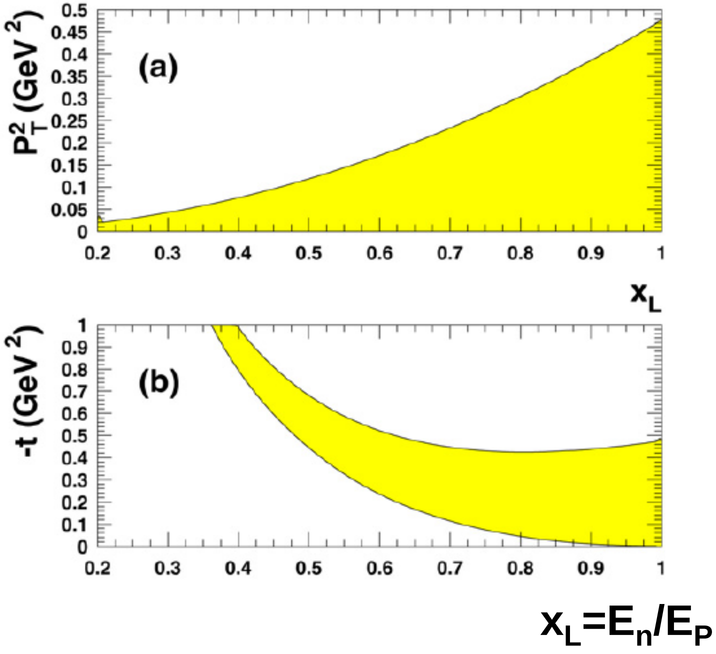
- FNC – forward neutron calorimeters- 105m from interaction point. Neutral particles (neutrons, photons) scattered at angle <0.8mrad are within the FNC acceptance

Size and weight of FNC defined by the space available in the HERA tunnel:

- position– 105m from the interaction point,
- size ~ 70 x 70 x 200cm^3, weight <10t

- geometrical acceptance is limited by beam-line elements <0.8mrad





Structure of H1-FNC

Longitudinal segmentation: 'Preshower' + 4 modules of 'Main' calorimeter

Material	Depth (mm)	Nuclear interaction lengths λ_I
e/m part		
PbSb4	7.5 × 12	0.52
scintillator	2.6 × 13	0.04
Tyvek paper	0.3 × 12	0.00
air	1.2 × 12	0.00
total e/m part	142	0.56
hadron part		
PbSb4	14. × 12	0.98
scintillator	5.2 × 12	0.07
Tyvek paper	0.3 × 12	0.00
air	0.6 × 12	0.00
total hadr.part	251	1.05
total	393	1.6

'Preshower'

- 26 x 26 x 38.6 cm^3 (1.6λ)
- 12 x-layers, 12 y-layers, each layer has 9 readout strips
- ~40% of hadronic shower is deposited in Preshower
- allows separation of e/m and hadronic showers

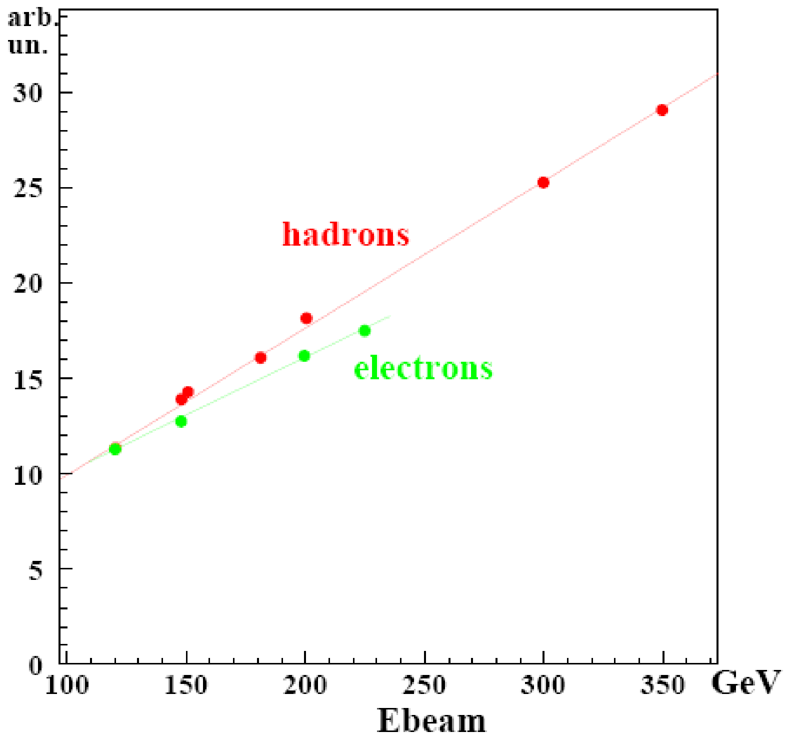
Material	Depth (mm)	Nuclear interaction lengths λ_I
PbSb4	14 × 100	8.20
scintillator	3.0 × 100	0.34
Tyvek paper	0.3 × 100	0.00
steel	0.6 × 100	0.36
air	2.0 × 100	0.00
total	2000	8.9

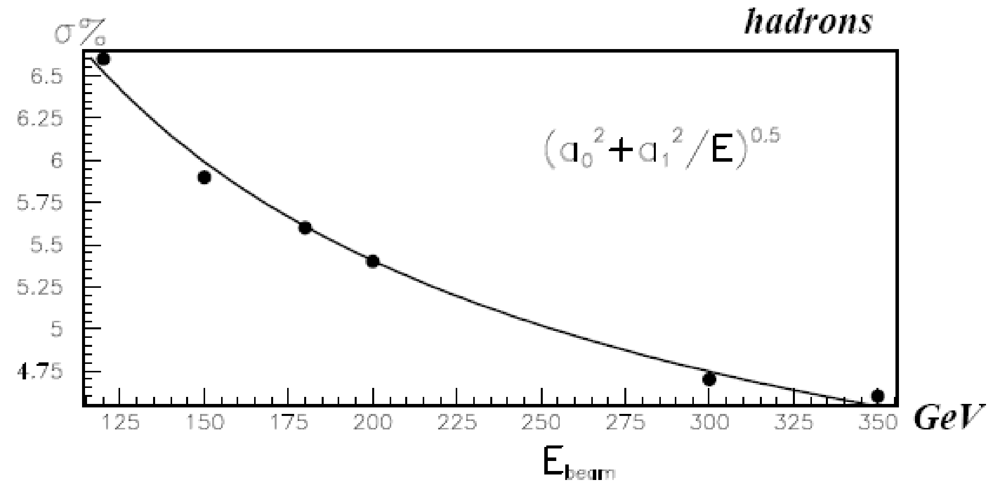
'Main' calorimeter

- 4 modules, each 60 x 70 x 50 cm^3 (2.2λ)
- 8 readout towers for each module

the H1-FNC energy response

test-beam calibration at CERN with hadrons (Ebeam=120-350 GeV) and electrons (Ebeam=120-225 GeV)





Energy resolution:

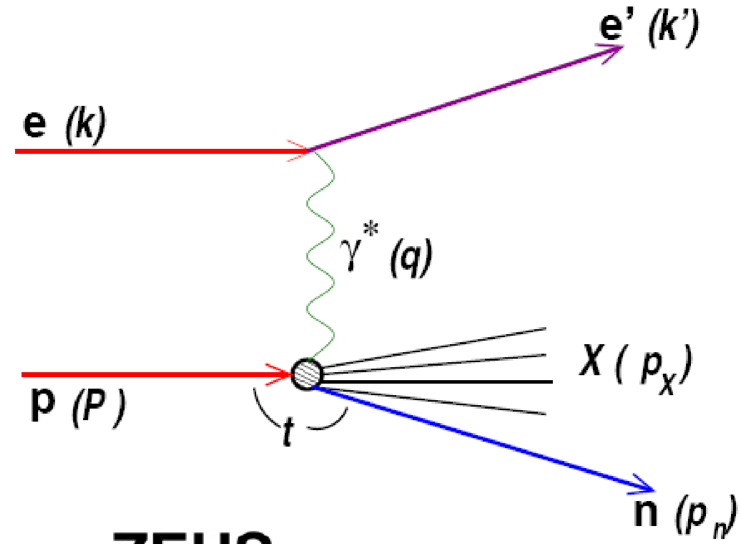
hadrons: $$\frac{\sigma_E}{E} = \frac{63.4 \pm 4.7}{\sqrt{E[GeV]}} \oplus (3.0 \pm 0.4)\%$$

e/m: $$\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E[GeV]}} \oplus 2\%$$

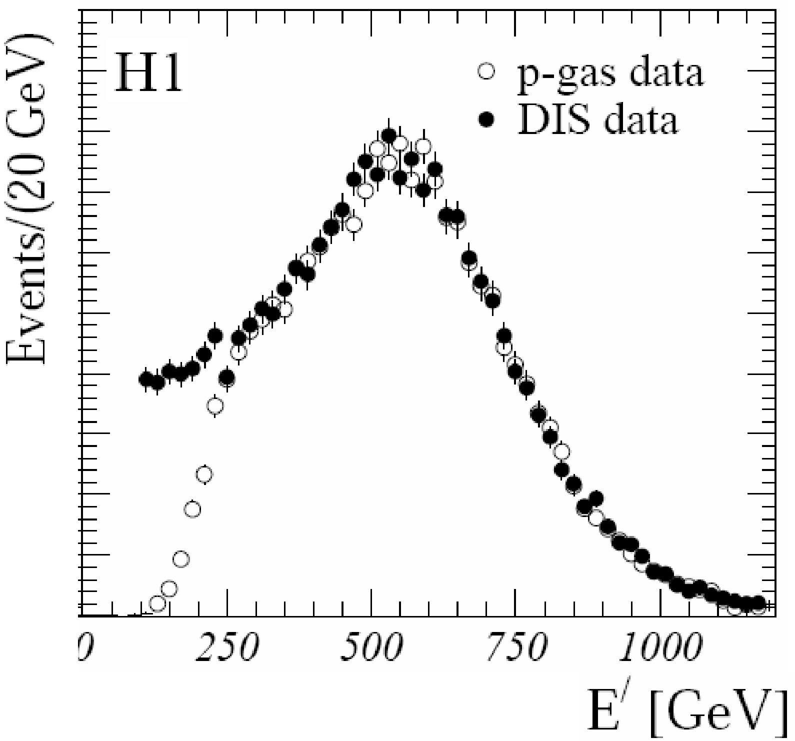
Position resolution in Preshower – better than 3mm

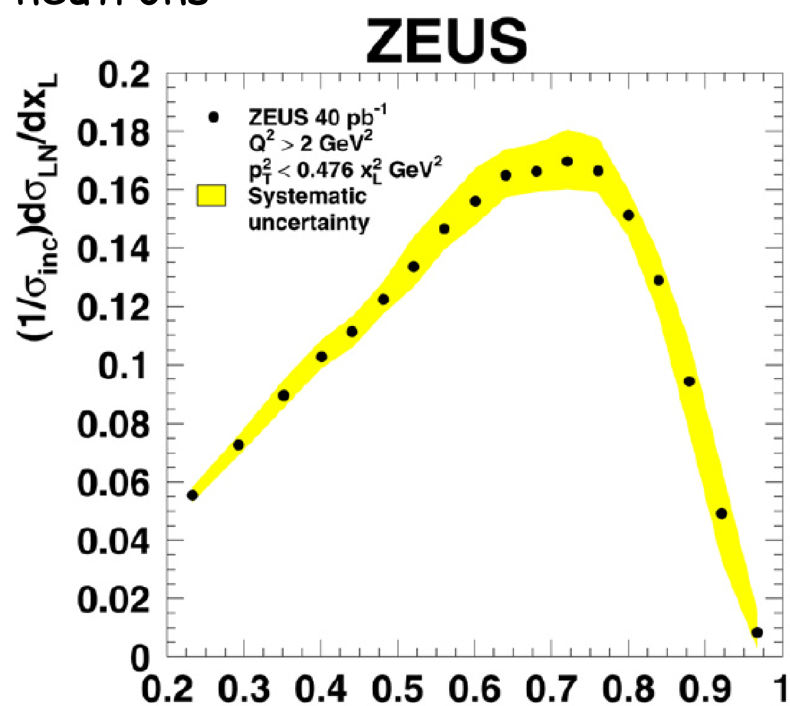
Main goal of FNC calorimeter is to measure the energy and angles of fast neutrons from reaction

$ep \rightarrow e' + X + n$



energy distributions of the forward neutrons



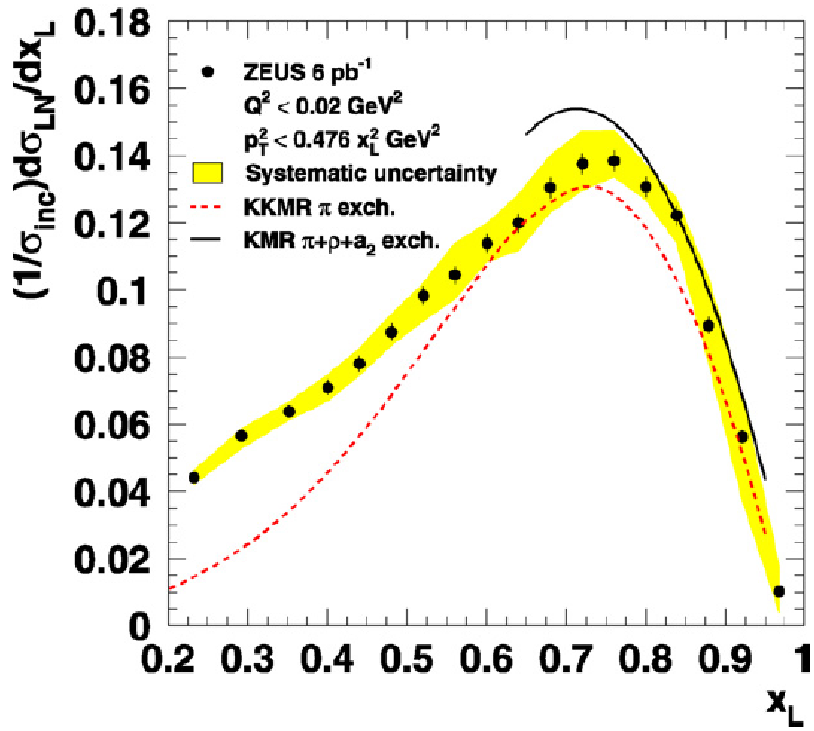


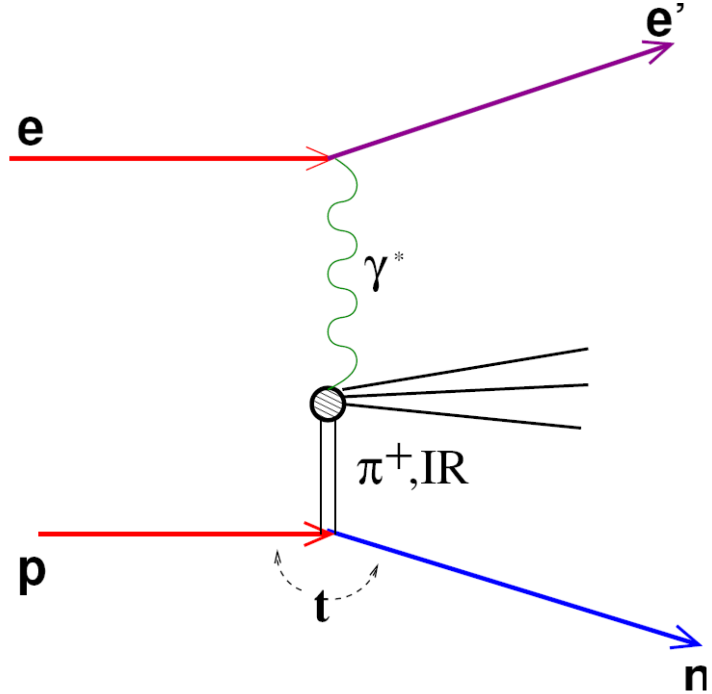
$x_L = E_n/E_{p\ beam}$

Physics with Forward Neutron Calorimeter

Many results are published by H1 and ZEUS Collaborations on leading neutron production in DIS, photoproduction, events containing jets or D* in the final state (more details in e.g. talk by B.Schmidke in this workshop).

Several theory analyses suggest that at high x_L ($\equiv E_n/E_{p\text{-beam}}$) and low p_T the dominant mechanism of forward neutron production is the π^+- exchange. HERA results can be successfully interpreted within this approach.

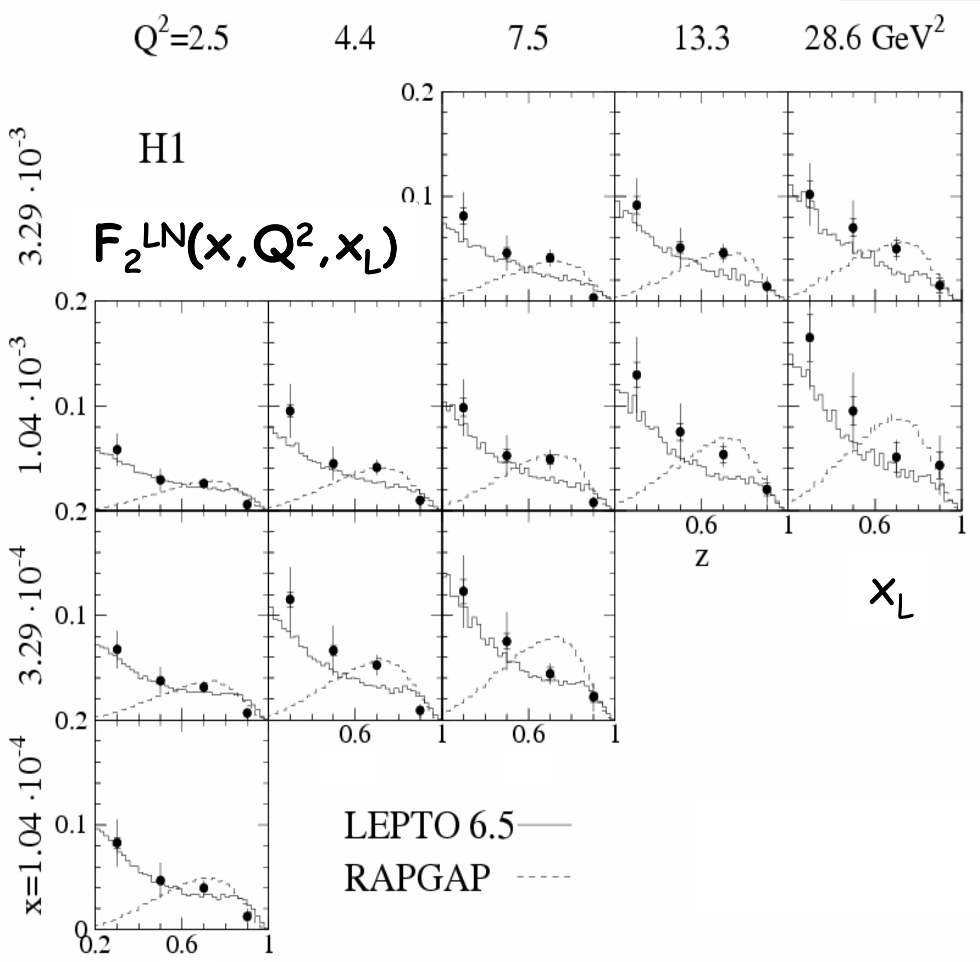


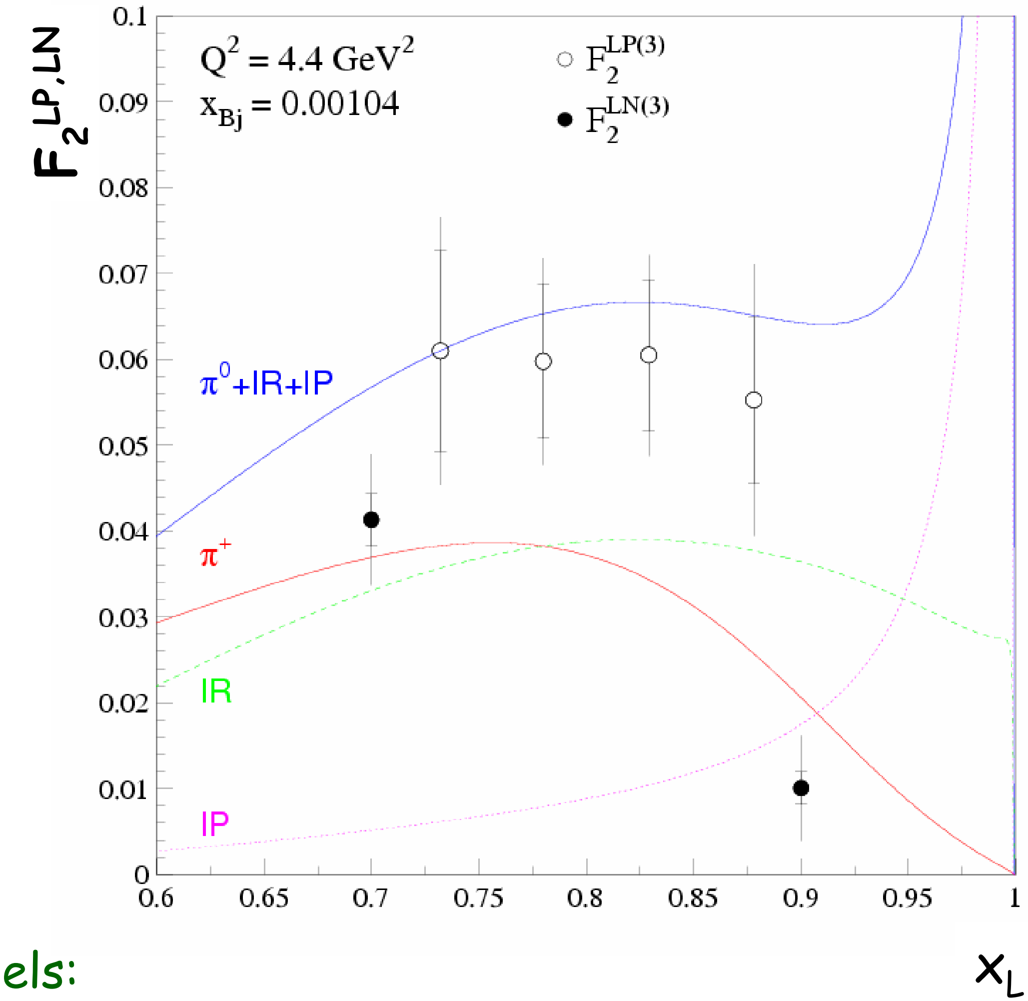


Semi-inclusive cross-sections F_2^{LN}, F_2^{LP}

Measure cross section for deep inelastic scattering with leading proton or neutron as a function of Q^2, x_{Bj} and x_L ($\equiv z$)

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



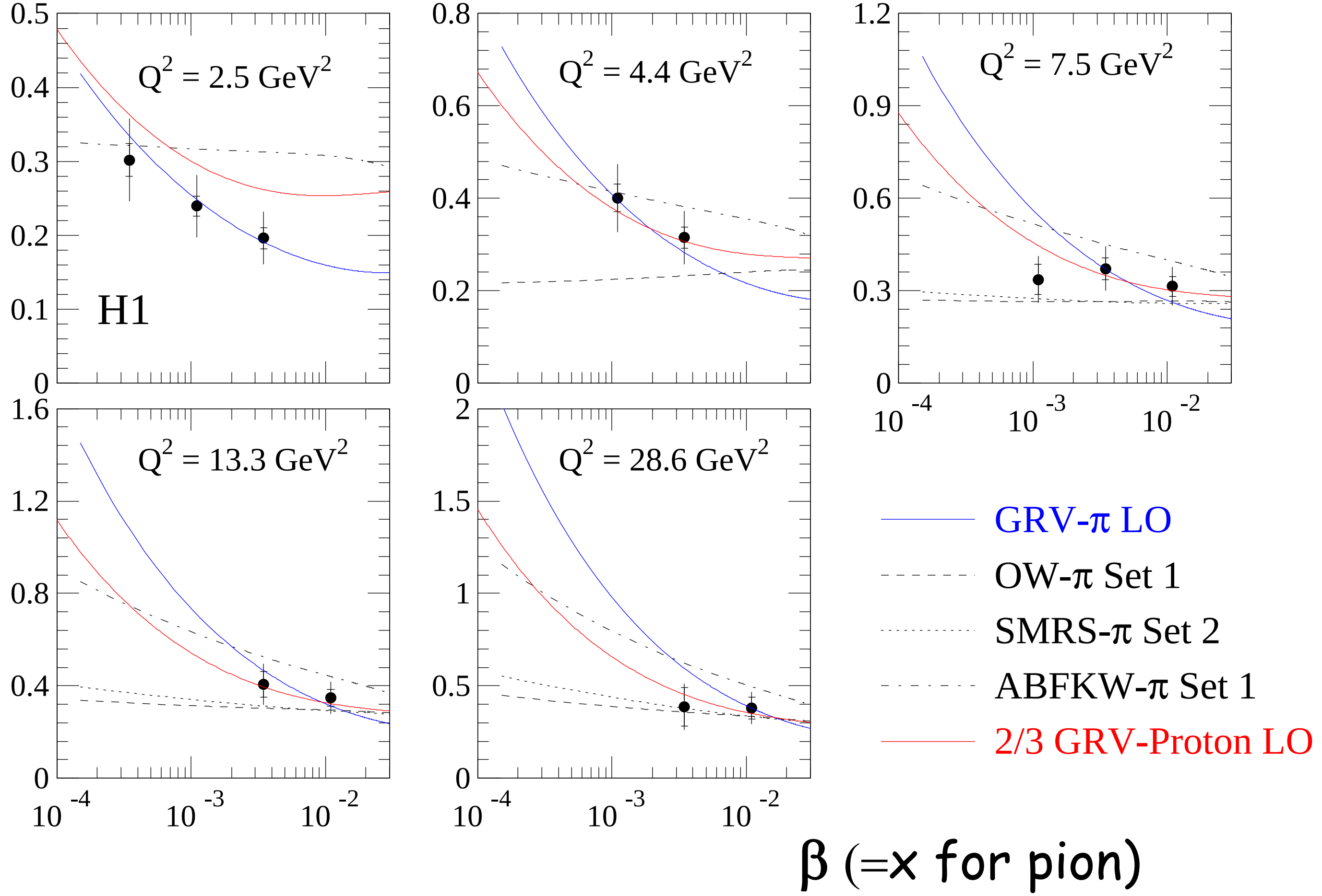


Good agreement with particle exchange models:
leading neutrons – π+ exchange, leading protons - π^0+Pomeron+Reggeon

Extraction of pion structure function

$$\frac{F_2^{LN}(x_L=0.7)}{\Gamma_\pi}$$

Γ_π =(integrated pion flux)

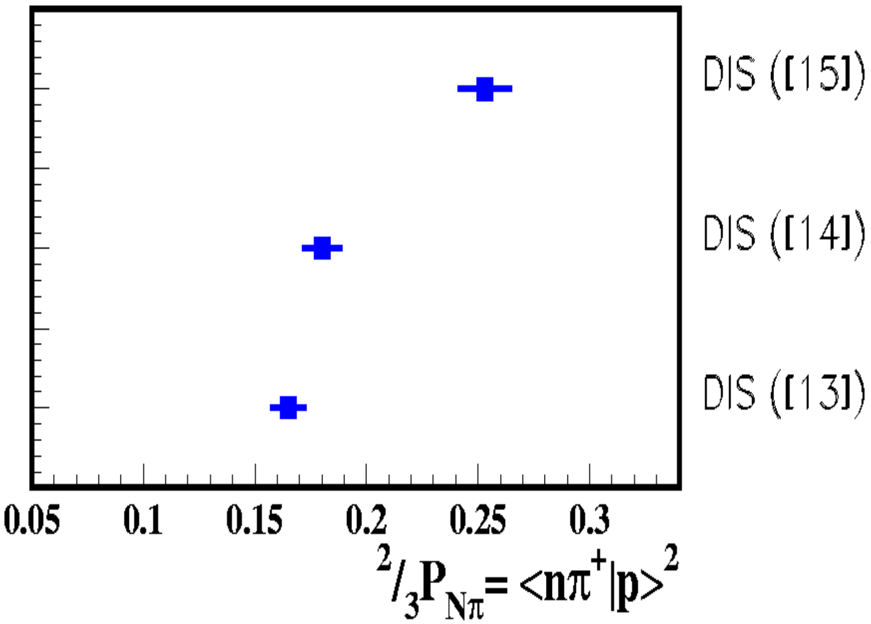


Within the π-exchange model for 0.7<x_L<0.9 $F_2^{LN}(x,Q^2,x_L)$ is related to $F_2^{\pi}(x,Q^2)$

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

Leading neutron production: probability of $p \to p\pi^0, n\pi^+$ fluctuation

Estimation of the probability of the $p \to N\pi$ from the neutron rate in DIS and extrapolating to the full energy range (for three parameterisations different pion fluxes)

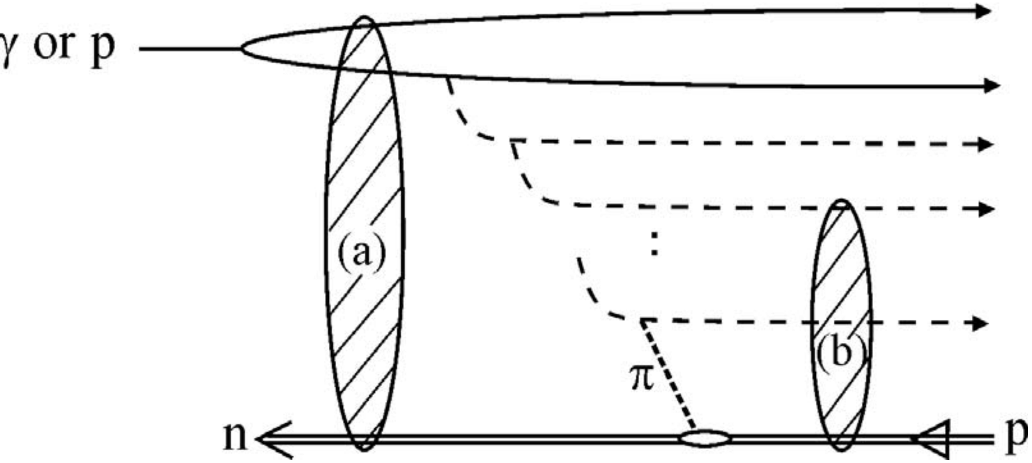


Total probability of $p \to p\pi^0, n\pi^+$ fluctuation ~16-25% (depending on choice of π-flux [13,14,15]-different flux parameterisations

A.B., B.Povh Eur.Phys.J. A27, 359 (2006)

Leading neutron production: absorptive corrections

Absorptive corrections: important ingredient to interpret the results in terms of pion exchange



talk A.Martin 'HERA-LHC workshop 2006'

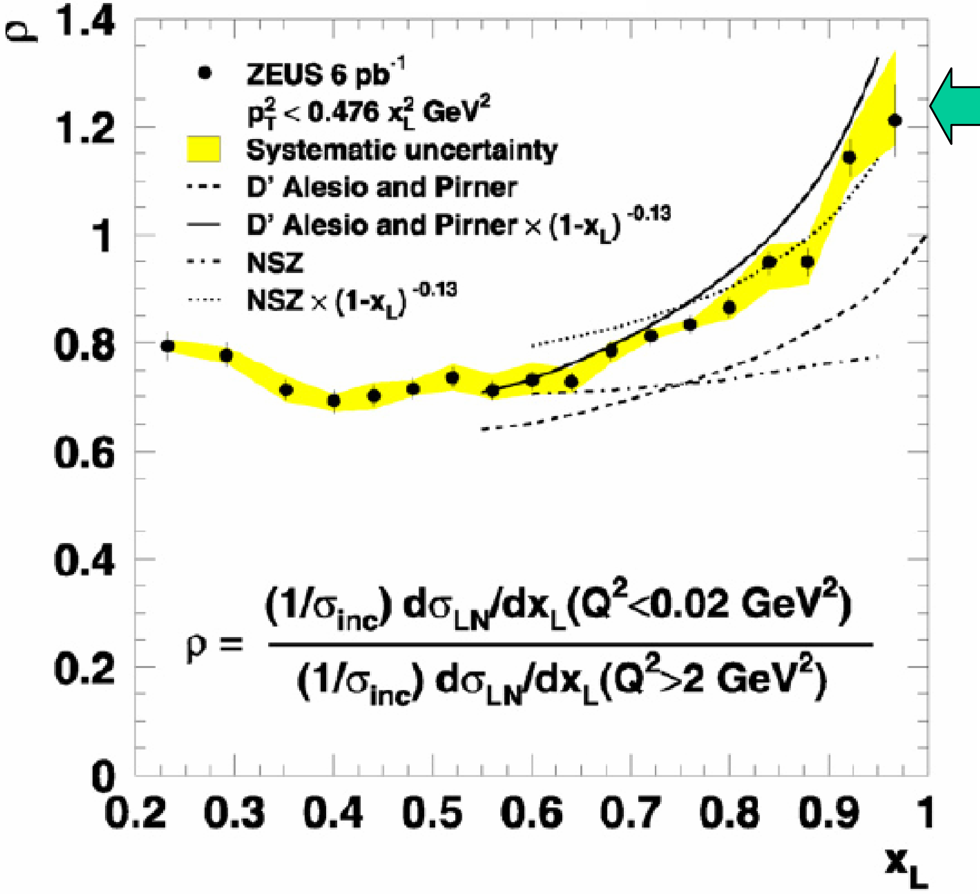
- In DIS the virtual photon γ^* is a small object,

- in photoproduction (Q^2~0), photon is almost real, i.e. it is an extended object like a hadron→ neutron rescattering may occur ➔
-neutron breaks up or
-is kicked to lower x_L,higher p_T and escapes detector acceptance

Similar in pp interactions

Effects of absorption and migration estimated:
D'Alesio,Pirner Eur.Phys.J. A7 (2000) 109
Nikolaev,Speth,Zakharov hep-ph/9708290
Kaidalov,Khoze,Martn,Ryskin Eur.Phys.J. C47 (2006) 385

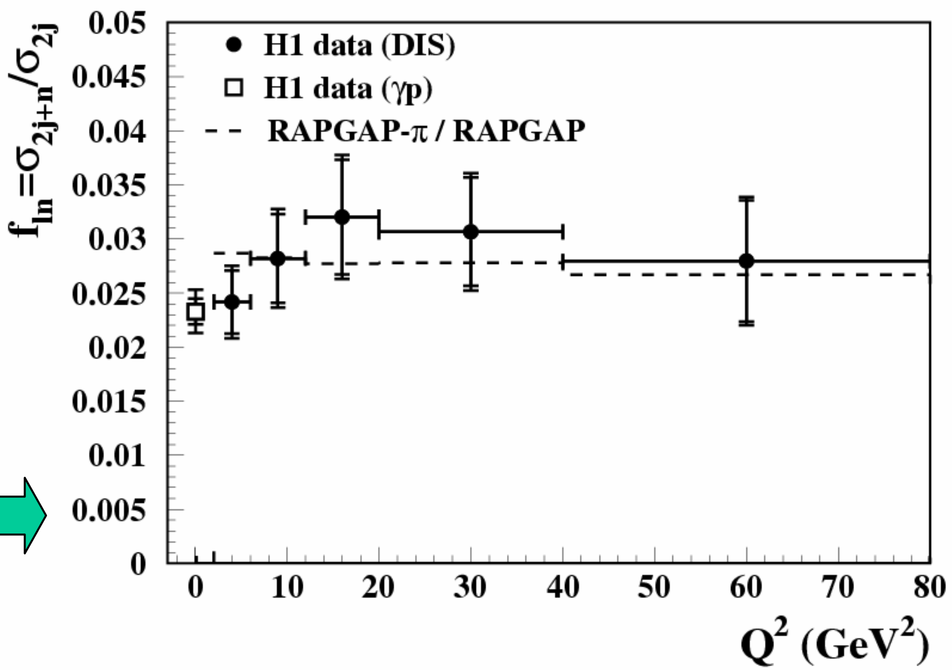
Leading neutron production: experimental indication of absorption



ratio of normalized photoproduction to DIS cross sections
ρ ~70% at mid-x_L, rising to 1 at x_L>0.9

➔violation of vertex factorization
➔qualitative agreement with the models

normalised cross sections of dijet production with leading neutrons vs Q^2:
➔ sign of Q^2 dependence



Leading neutron production: experimental indication of absorption

Comparison of LN production rates for different processes (ZEUS)

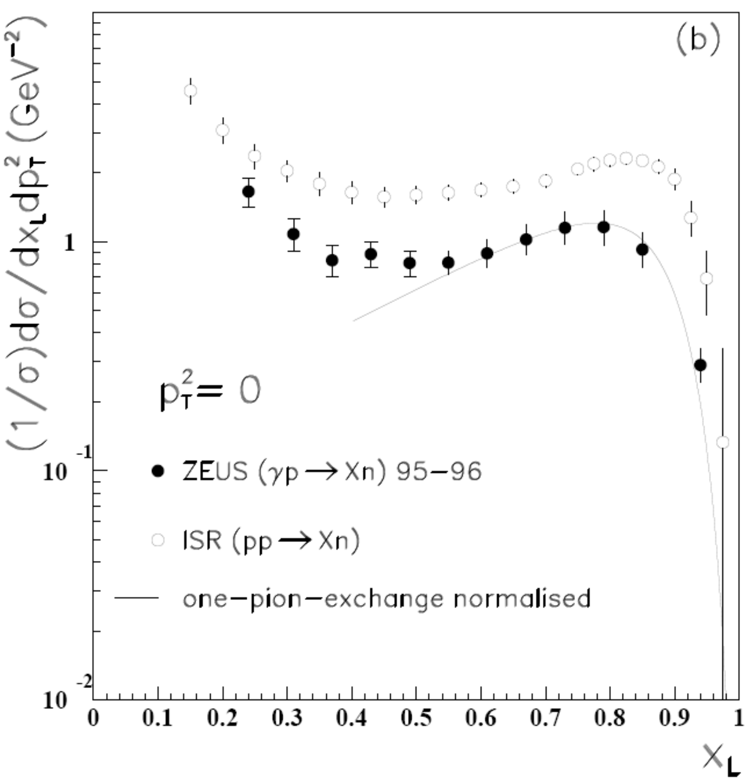
$$r^{D^*}(x_L > 0.49) = 6.55 \pm 0.76(\mathrm{stat.})^{+0.35}_{-0.45}(\mathrm{syst.})\%$$

$$r^{\mathrm{DIS}}(x_L > 0.49) = 5.8 \pm 0.3\%,$$

$$r^{jj}(x_L > 0.49) = 4.9 \pm 0.4\%,$$

$$r^{\gamma p}(x_L > 0.49) = 4.3 \pm 0.3\%.$$

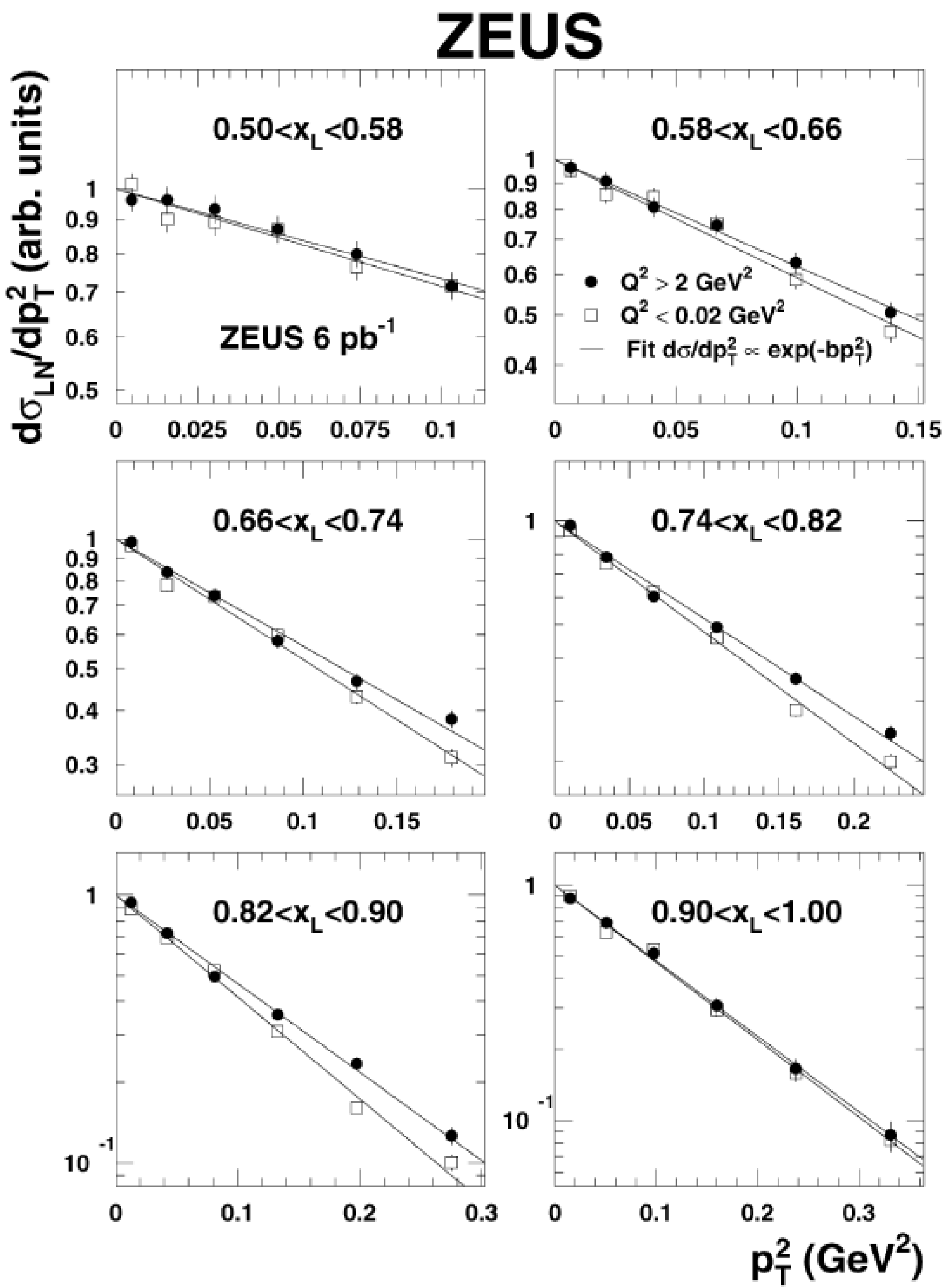
compatible with rescattering hypothesis:
harder interaction → larger yield of LN



The normalised cross sections:
compare $\gamma p \to Xn$ ($p_T^2=0$) and $pp \to Xn$ (ISR).

average number of neutrons per event at HERA is ~2 times less than at ISR pp

LN production: comparison p_T^2 distributions DIS vs photoproduction

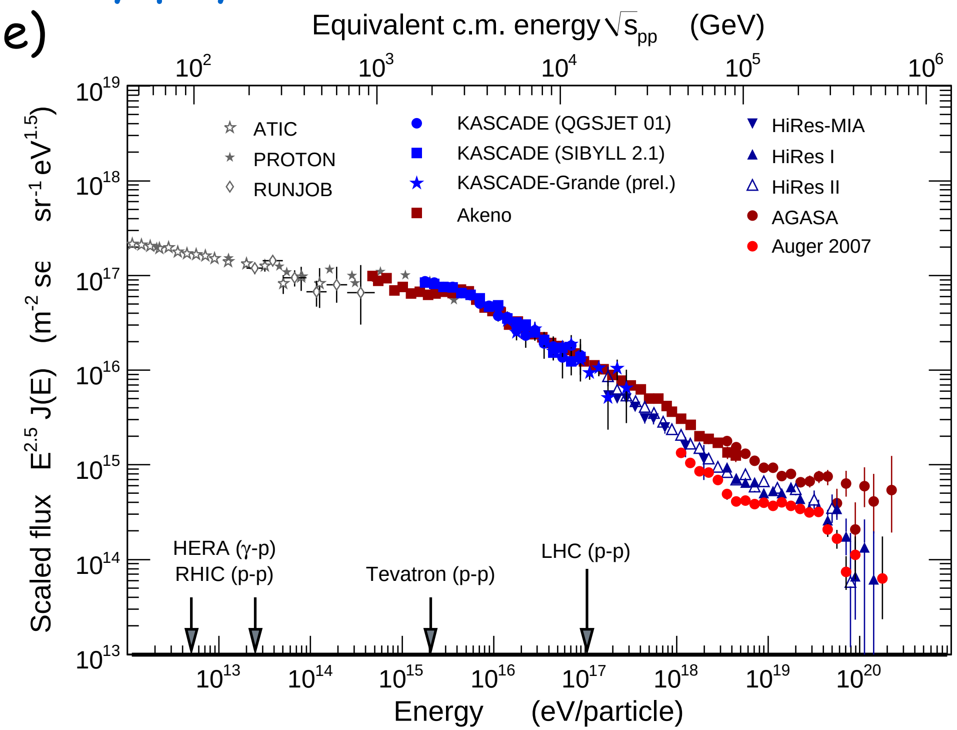


p_T^2 slope in photoproduction steeper than for DIS

➔suggests the violation of vertex factorization due to absorption

How the measurement of leading particles at HERA (or any accelerator) can be related to the ultra high energy cosmic ray physics ?

(Energy ranges differ by orders of magnitude)



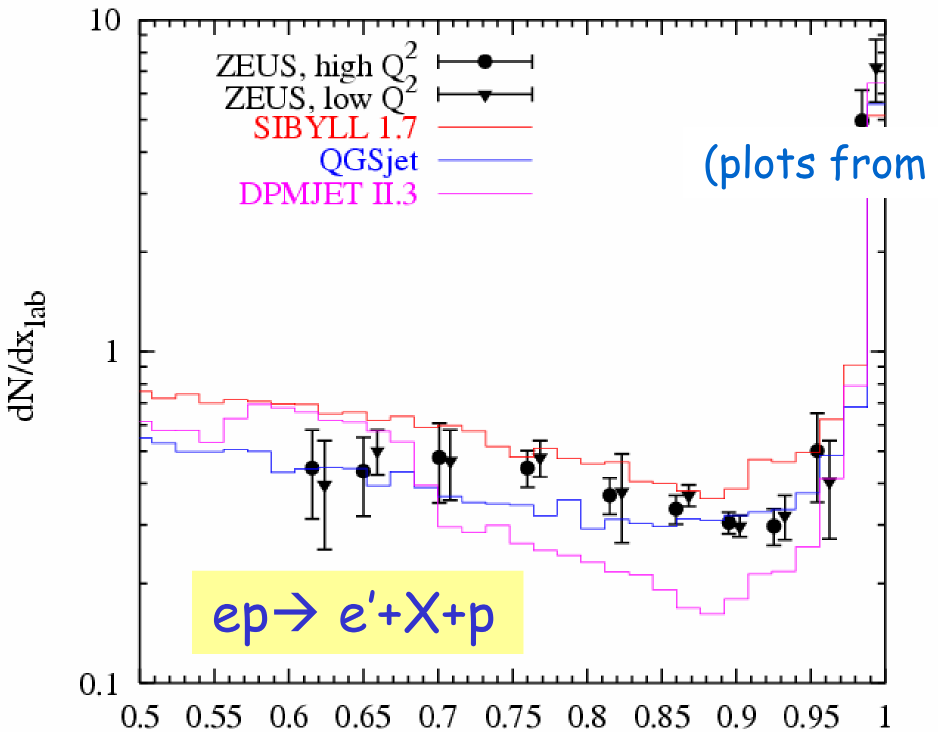
High energy cosmic ray experiments use MC models to estimate the primary energy of cosmic ray. In accelerator experiments the incoming particle energy is known, the hadron production in the proton fragmentation region is assumed to be almost independent of the type of interacting particle, e.g. of the photon virtuality Q^2 for ep scattering (factorization/limiting fragmentation)

➔ These models can make predictions for the accelerator energies, which can be compared to the measurements.

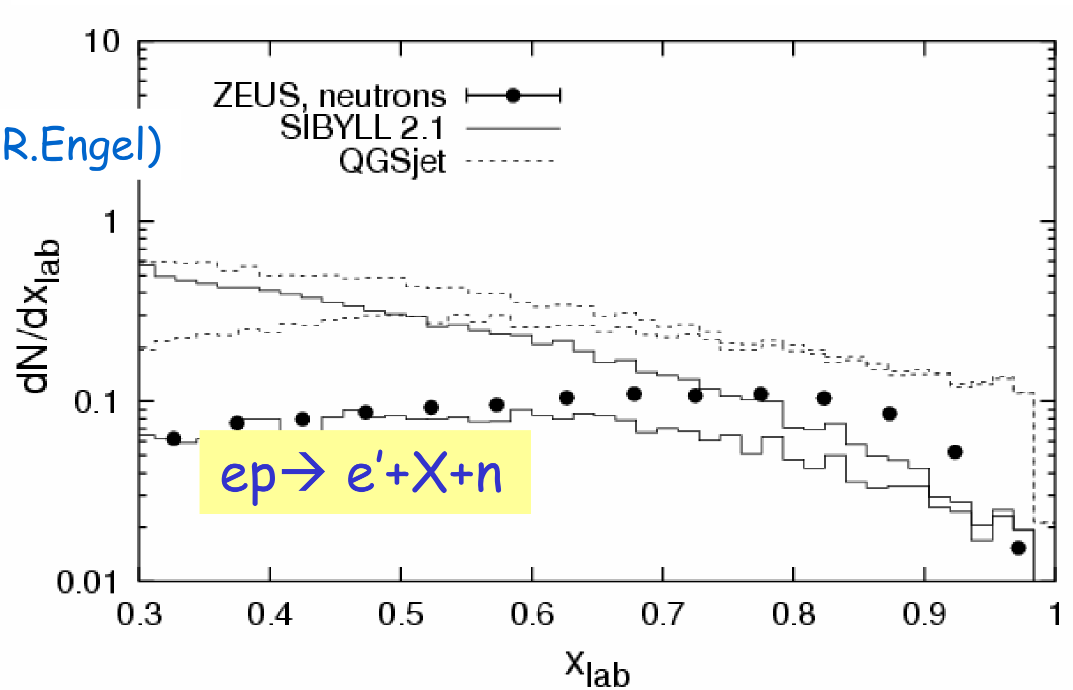
Forward particles at HERA and models for cosmic rays

Important observable for shower development: 'elasticity' – ratio between the energy of leading particle to that of incoming particle Elead/E

In a model with Feynman scaling in forward region elasticity does not depend on energy



(plots from R.Engel)



x_{lab} =energy fraction carried by the leading proton or neutron

Comparison of HERA data with the MC models used for cosmic ray physics:

-For leading protons- reasonable agreement between the measurements and the models - the HERA data discriminate between the models

-For leading neutrons – none of models describe the data

→ room for improvement, common effort from CR and HERA needed

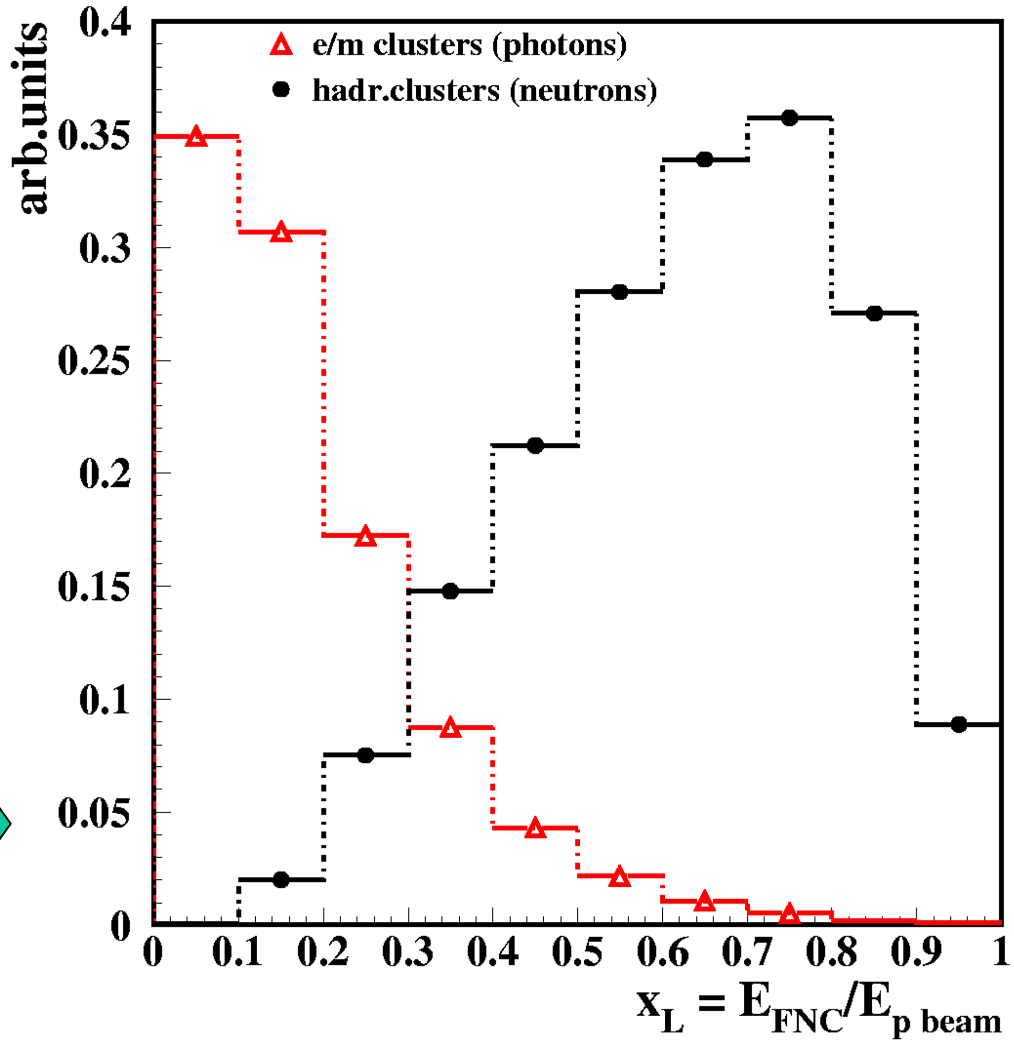
Neutral Particle measurements in the FNC (H1)

Can we (HERA) contribute to the understanding of high energy cosmic rays?

The longitudinal segmentation of H1-FNC allows to separate electromagnetic and hadronic showers. We can measure the differential distributions of x_L and p_t for photons and for neutrons, in the photoproduction (Q^2~0) and DIS regimes (similar for ZEUS-FNC)

The model for cosmic rays can make predictions for these measurements and tuned correspondingly

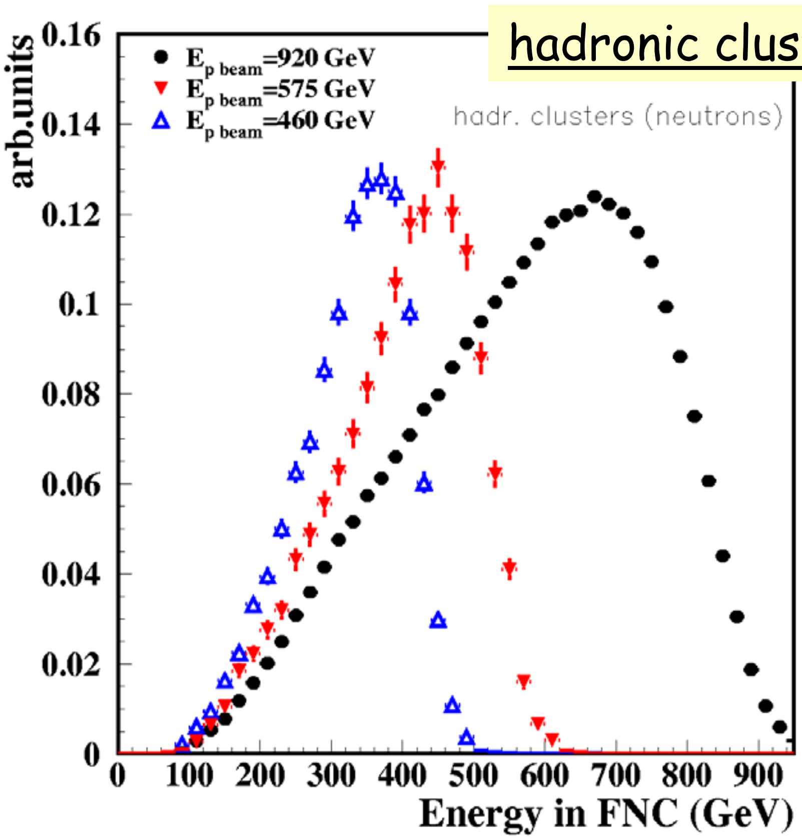
x_L distribution of electromagnetic (photons) and hadronic (neutron) clusters in H1-FNC

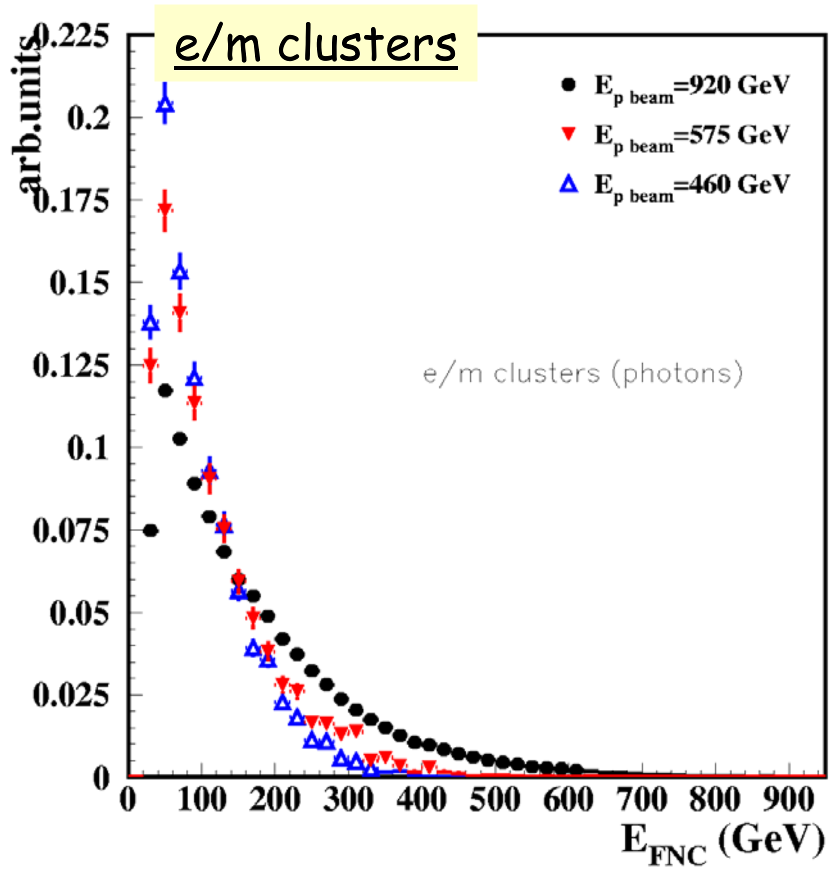


Neutral Particles in the FNC

The measurements can be made also as a function of proton beam energy
(The last 3 months HERA was running with 460 GeV and 575 GeV protons.)

Energy distributions of electromagnetic (photons) and hadronic (neutron) clusters in H1-FNC at tree different proton beam energies (920, 575 and 460 GeV).





Summary

The HERA experiments provide a wealth of measurements of leading baryon production. These measurements provide an important input for an improved theoretical understanding of the proton fragmentation. mechanism.

The HERA results support the theory predictions that the interactions with the pion fluctuations in the proton are the dominant mechanism of leading neutron production in the region of high x_L and low p_t ;
the HERA results show several indications of neutron rescattering/absorption

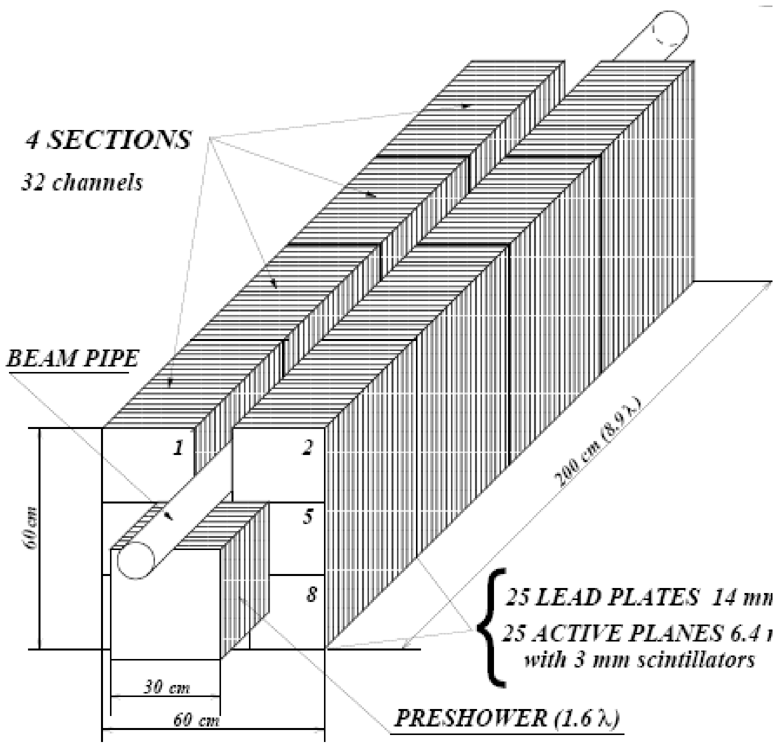
HERA data on leading neutron and photon production can help to reduce the uncertainty in the model predictions for very high energy cosmic ray air showers. HERA data have the highest available energy for the time being.

We, HERA and Cosmic Ray experiments, need to combine our efforts !

Forward Neutron Calorimeter

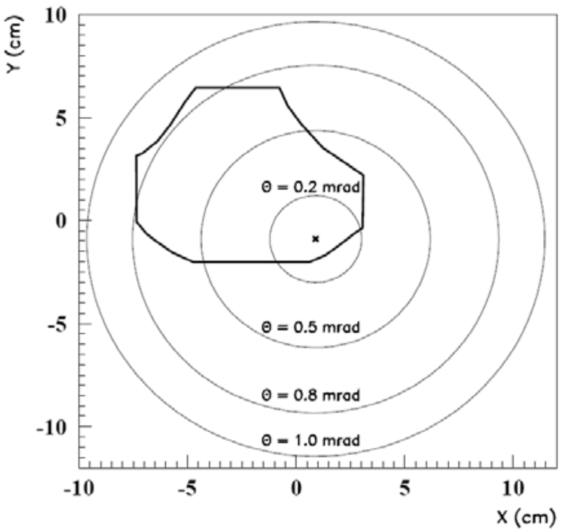
H1-FNC

- position– 105m from the interaction point,
- size ~ 70 x 70 x 200cm^3, weight <10t

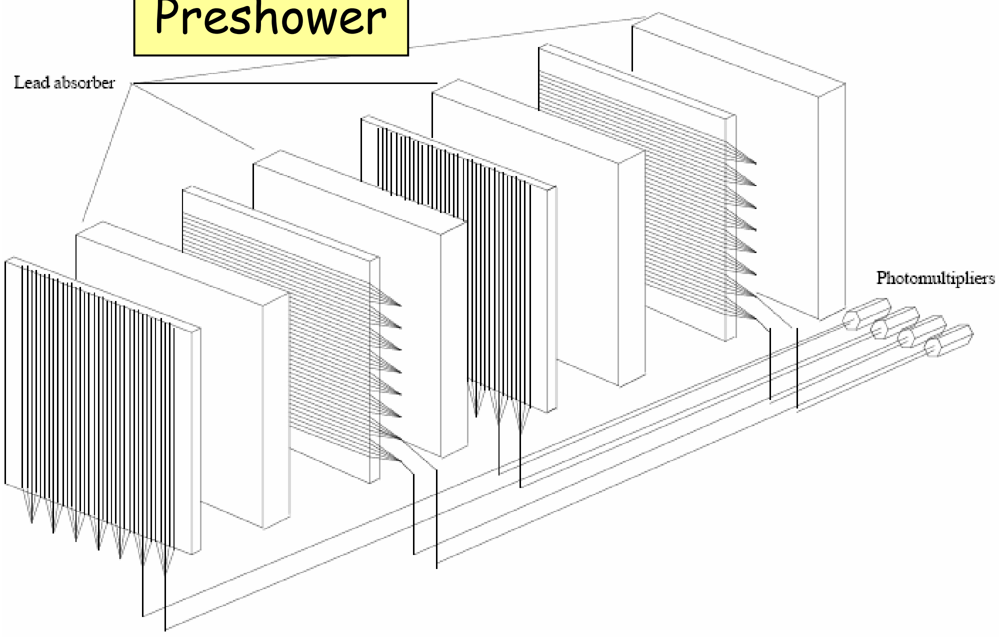


- Preshower + 4 Sections
- each Section consists of 8 Towers
- each Tower is 25 Scintillator tiles

- geometrical acceptance is limited by beam-line elements <0.8mrad

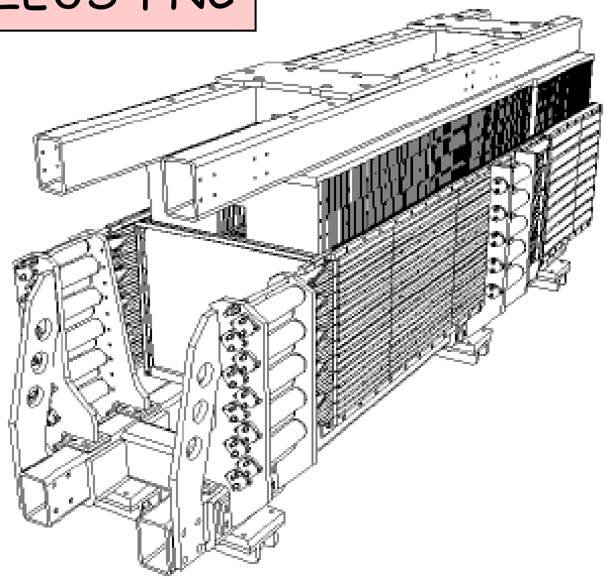


Preshower



Forward Neutron Calorimeter

ZEUS-FNC



- S.Bhadra et al., *NIM A394 (1997) 121*
- sampling calorimeter, $e/h \sim 0.96$
- 134 layers 1.25cm Pb and 0.26cm scintillator, readout by WLS from both sides,
- front section (7λ) -14 towers, rear section 3λ,
- e/h separation using transverse width of shower
- $\sigma_E/E = 0.65\%/\sqrt{E\ [GeV]}$
- Forward Neutron Tracker (since 1998)
  17×15 X-Y strips, 1.2cm each,
  installed 1λ inside the calorimeter
  position resolution 0.23cm