DESY, 5.4.2012

Measurements of Very Forward Neutral Particles in ep Collisions

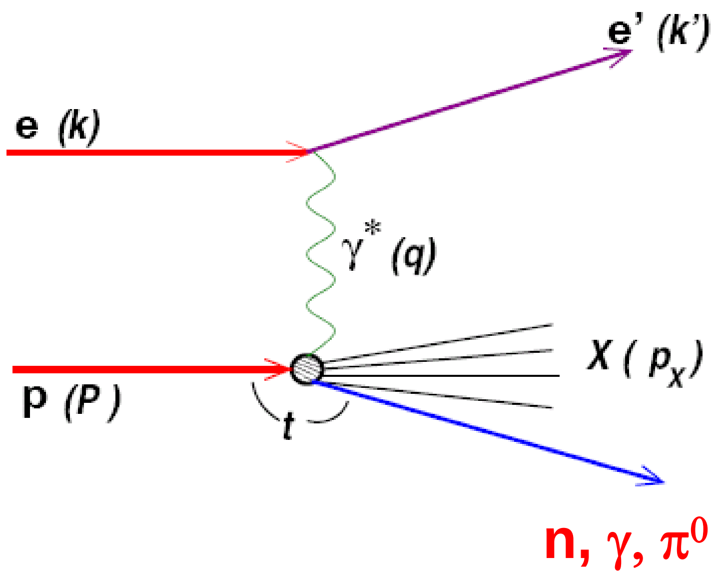
Armen Buniatyan

Outline:

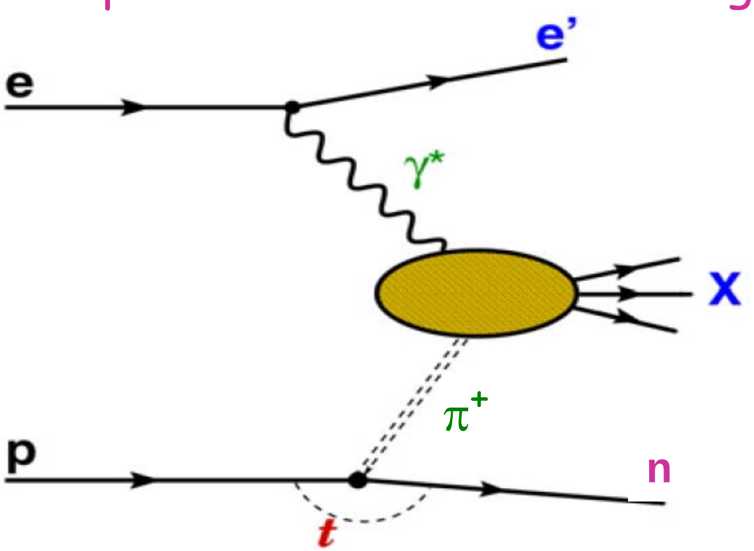
- Introduction:
  Why measure forward neutrals?
- How we measure? -Forward Neutron Calorimeter (FNC)
- H1 FNC: construction, calibration, operation
- Selected physics results with the FNC
- Zero Degree Calorimeters at the future ep collider
- Conclusions

Why measure very forward neutrons/photons ? (very forward = almost parallel to the proton beam)

- Understanding proton fragmentation
- MC model tuning - in particular important for the hadronic interaction models of cosmic rays, since the shower development is dominated by forward, soft interactions
- Study more sophisticated scenarios: e.g. exchange of virtual pion
  → study pion structure, interactions with the pion target



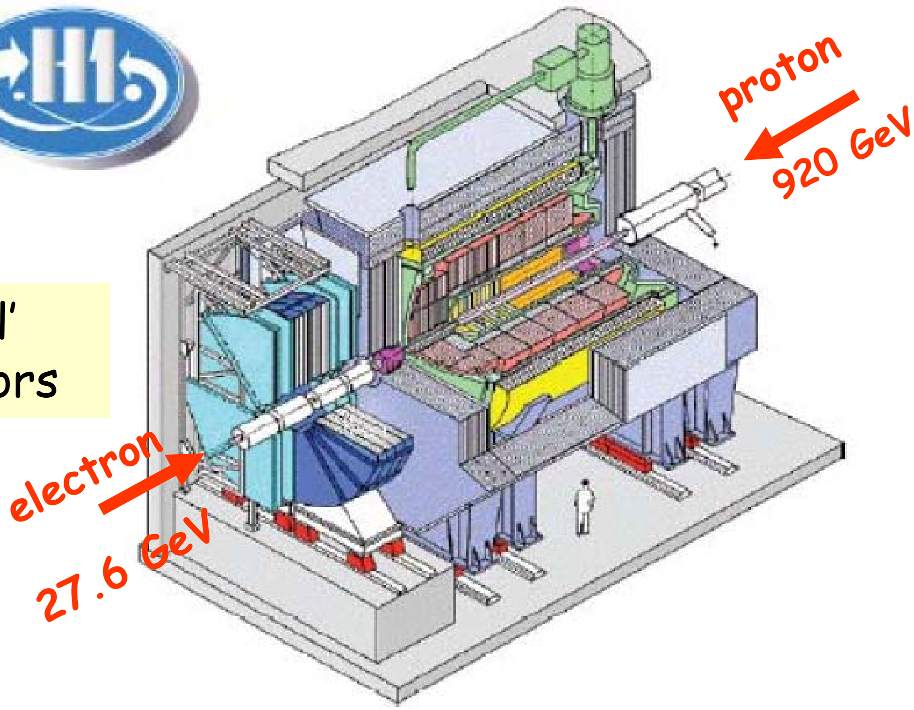
neutron production via π+- exchange

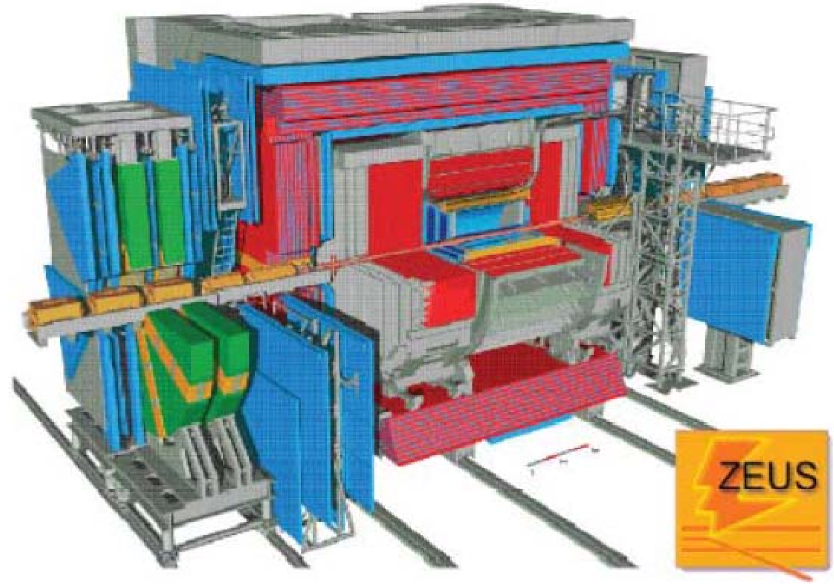


~5% of DIS events at HERA contain very forward neutron or photon in the 'forward neutron calorimeter'

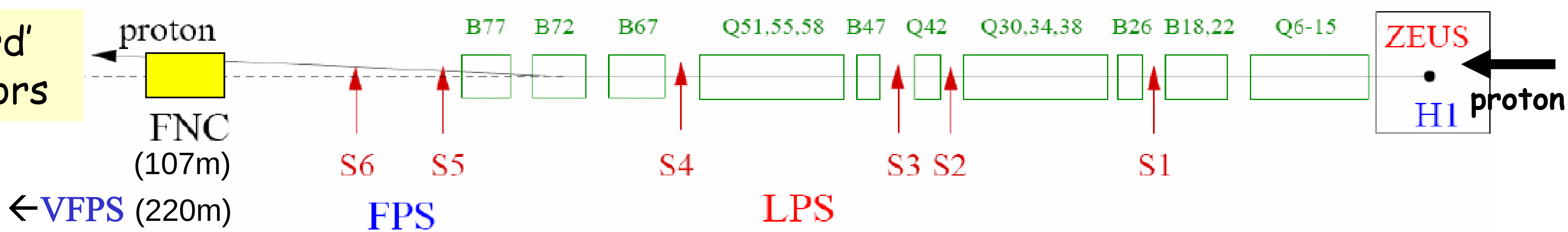
H1 and ZEUS experiments at HERA

'Central' detectors



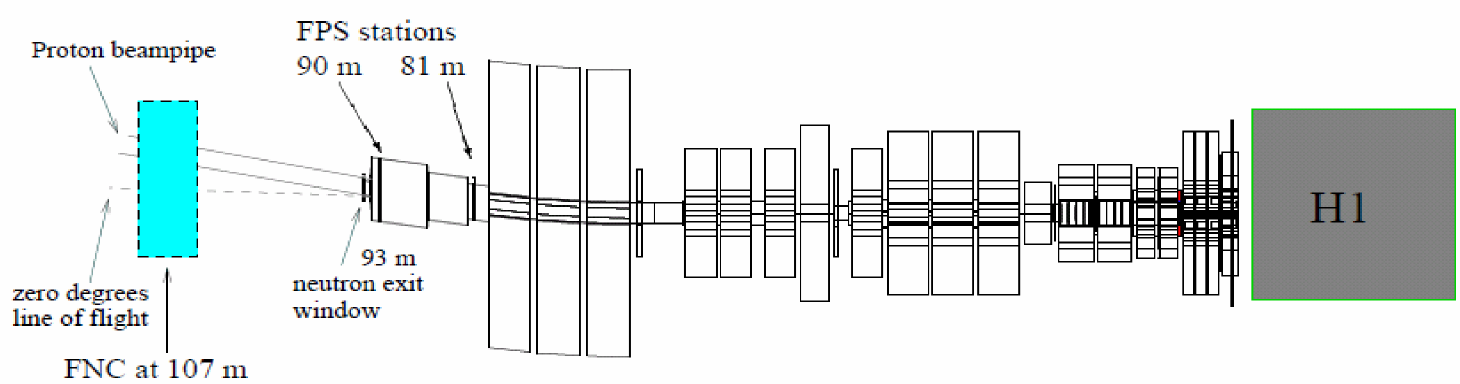


'Forward' detectors

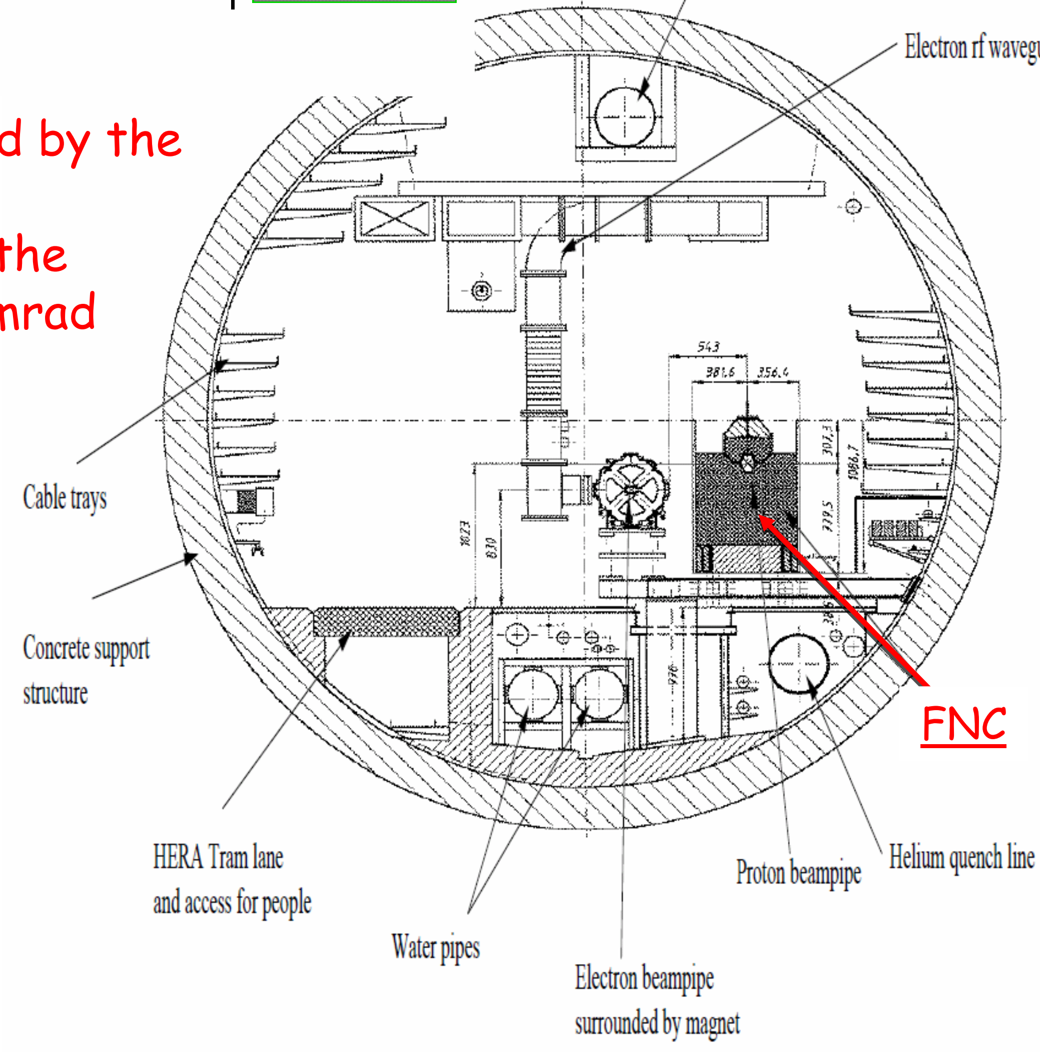


- FPS/VFPS(H1) and LPS (ZEUS)– proton spectrometers, 24…220m from IP; measure scattered protons with $E_{p'}/E_p = 0.4 \div 1$.

- <u>**FNC**</u> – <u>forward neutron calorimeters</u> -106m from IP, measure neutral particles (neutrons, photons) scattered at angle <0.8mrad

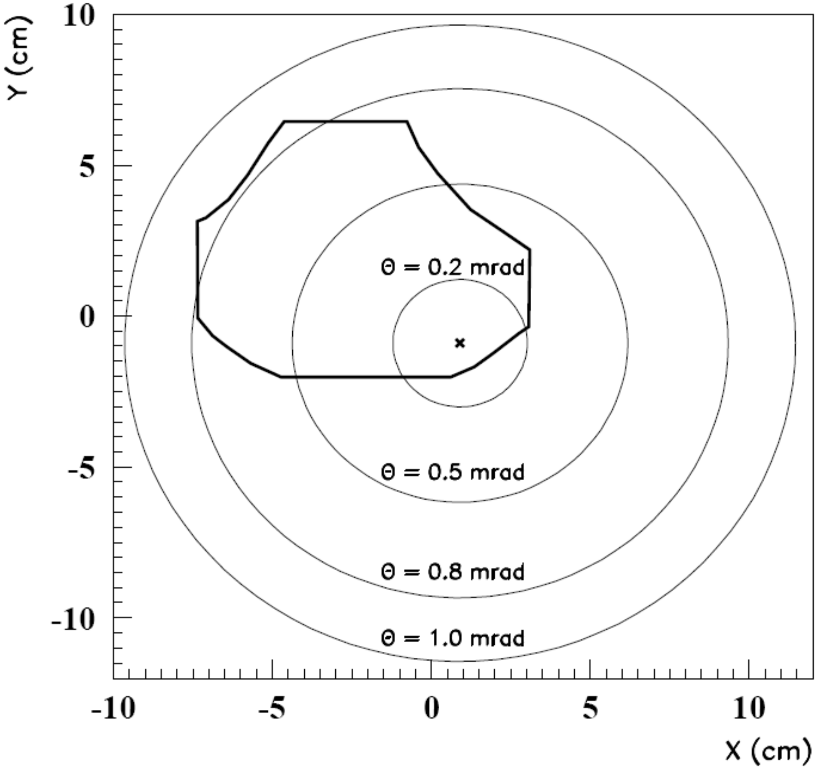


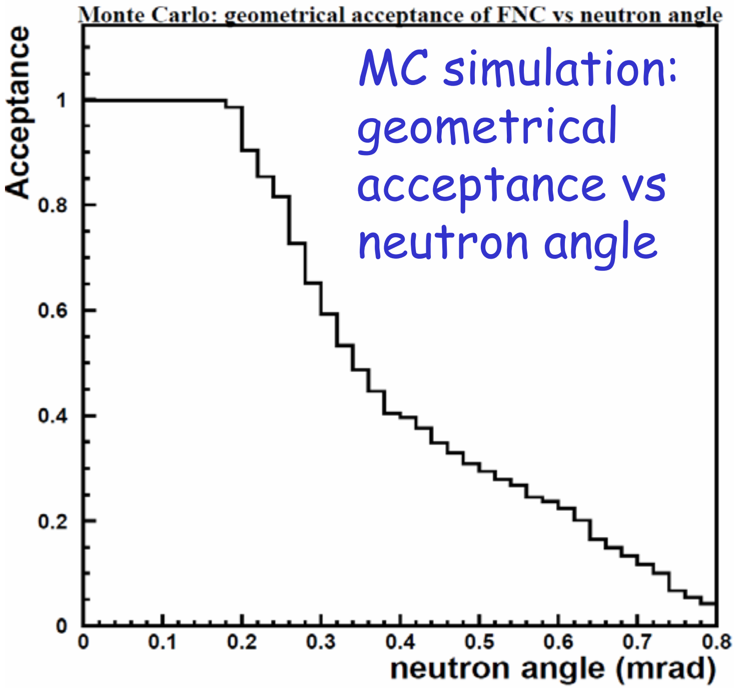
Position, size and weight of the FNC defined by the space available in the HERA tunnel:
~106m from the interaction point, between the e-beam line and the tunnel wall, after the 6mrad upward bend of the protons:
size ~ 70 x 70 x 200cm^3, weight <10t



Forward Neutron Calorimeter (FNC)

geometrical acceptance is limited by beamline elements <0.8mrad. In average acceptance ~30%

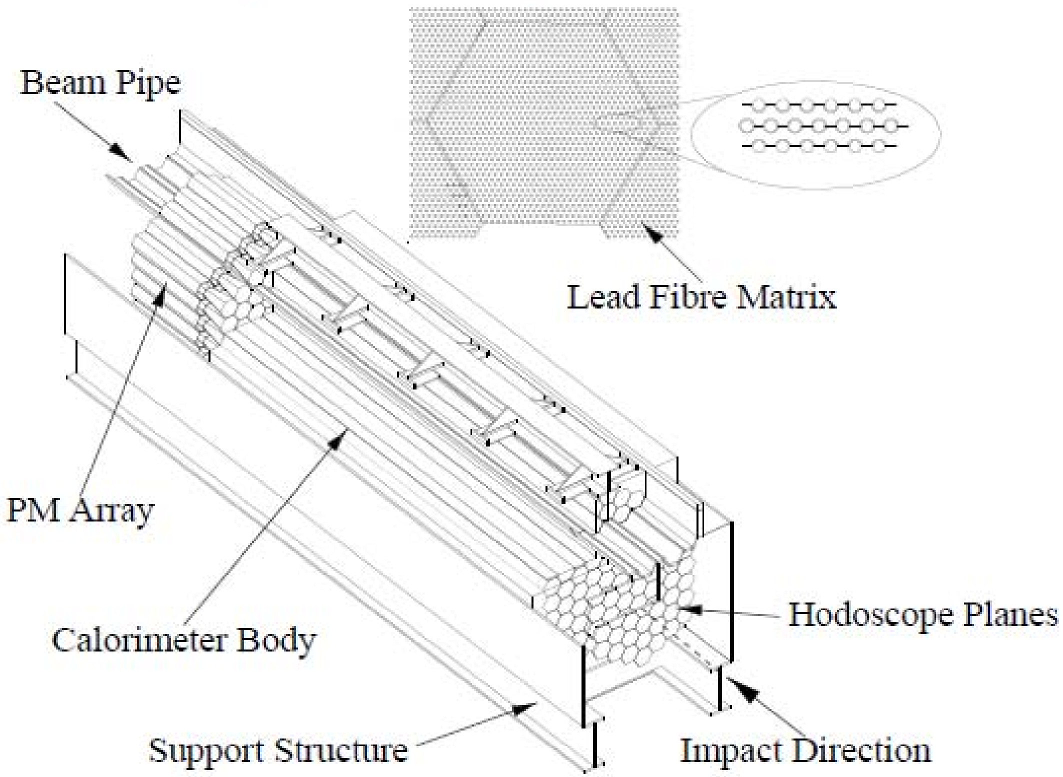




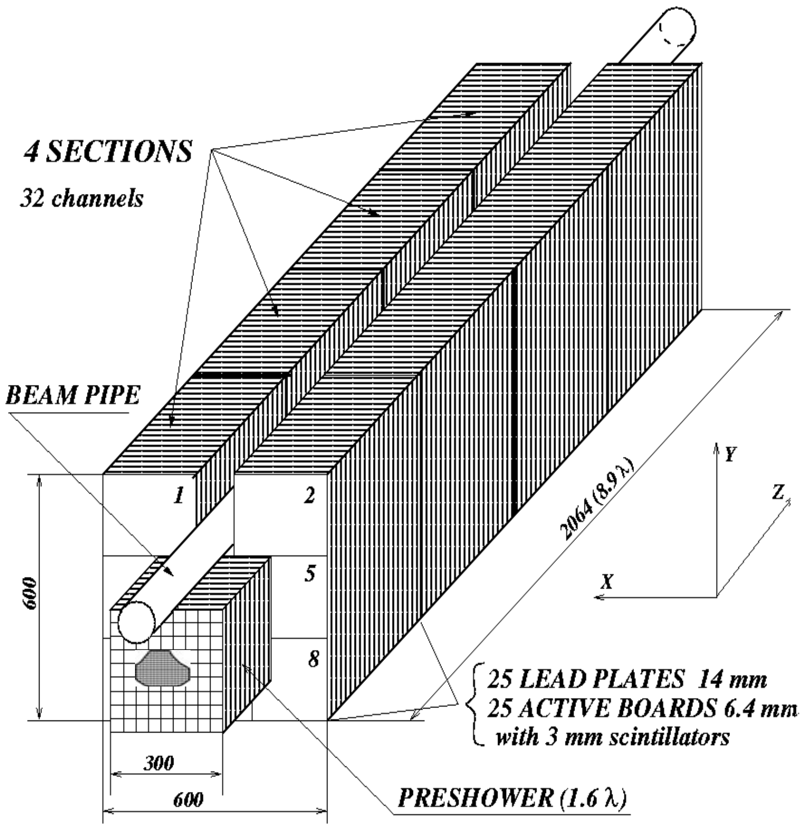
MC simulation: geometrical acceptance vs neutron angle

H1 Forward Neutron Calorimeter (H1-FNC)

HERA-1 (1996-2000)



HERA-2 (2002-2007)



- SpaCal (was initially built for CERN/LAA project, used in WA89 experiment)
- 75 modules (1141 fibres in each)
– $\sigma_E/E \sim 20\%$ in the range E~300÷900 GeV
- σ_{xy} = 5.13cm / √E + 0.22cm

H1 Collab., Eur.Phys.J. C6 (1999) 687

Lead-Scintillator sandwich; 5 Sections

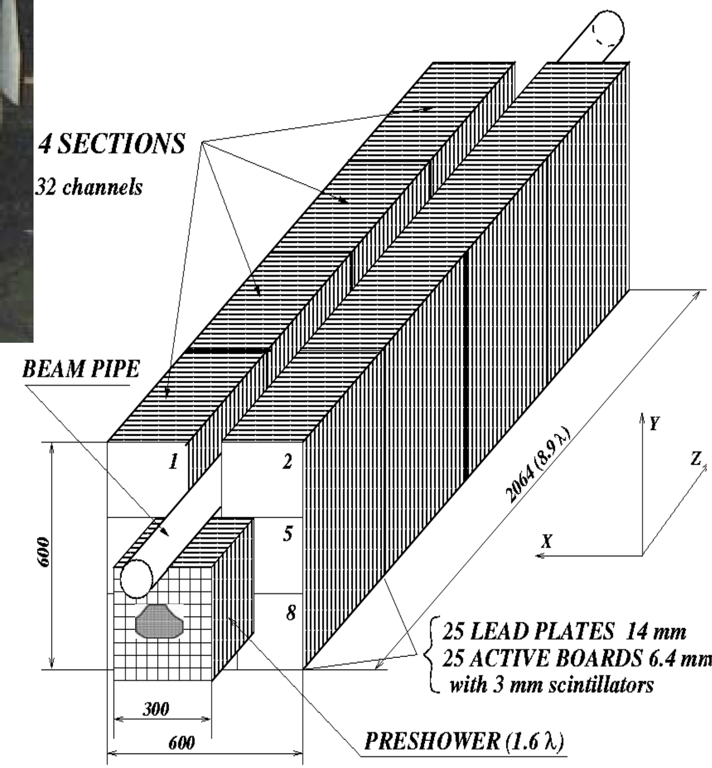
- Main Calorimeter: 4 sections x 8 modules
- Preshower : 9x, 9y strips

H1 Collab., Eur.Phys.J. C68 (2010) 381; C71 (2011) 1771

http://www-h1.desy.de/h1det/calo/fnc/psfiles/fnc_note2002.pdf

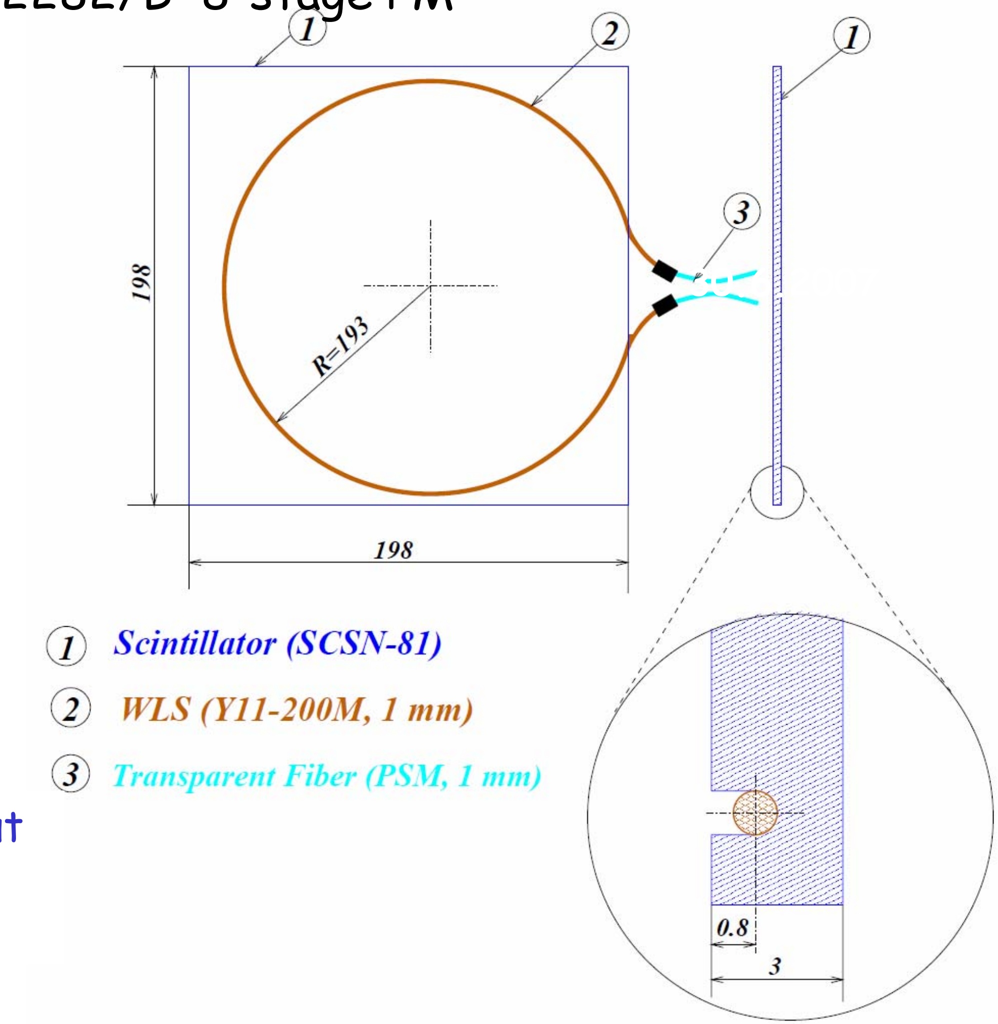
Structure of H1-FNC

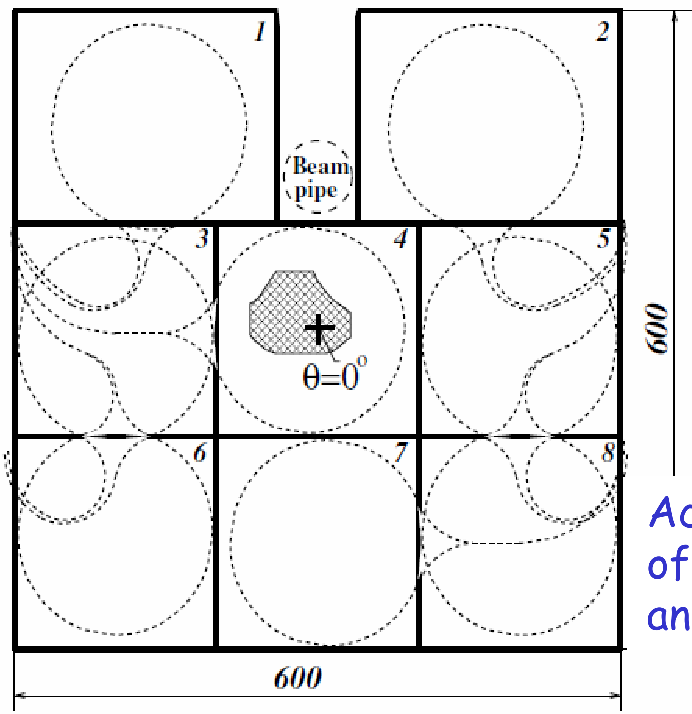
Longitudinal segmentation: 'Preshower' + 4 modules of 'Main' calorimeter



H1 FNC: Structure of 'Main' modules

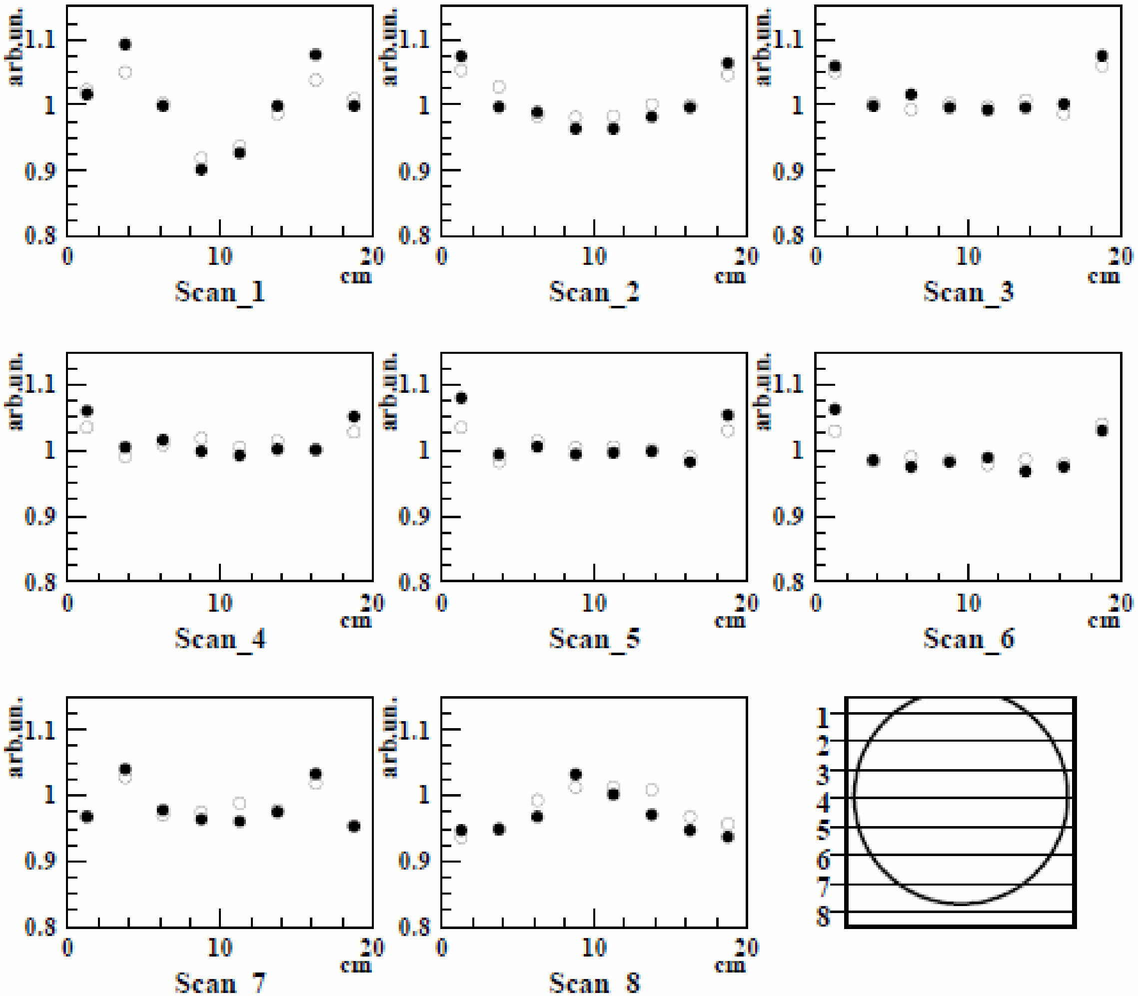
- 4 identical modules   60×60×51.6 cm³ (2.2λ_I)
- 25 Pb/Scintillator layers (14mm/3mm)
- each active layer - 8 tiles (20×20 cm² and 20x26 cm²)
- 8x25 tiles of each module combined into 8 r/o *towers*
- 50 transparent fibres from one tower connected to Philips XP2282/B 8-stage PM

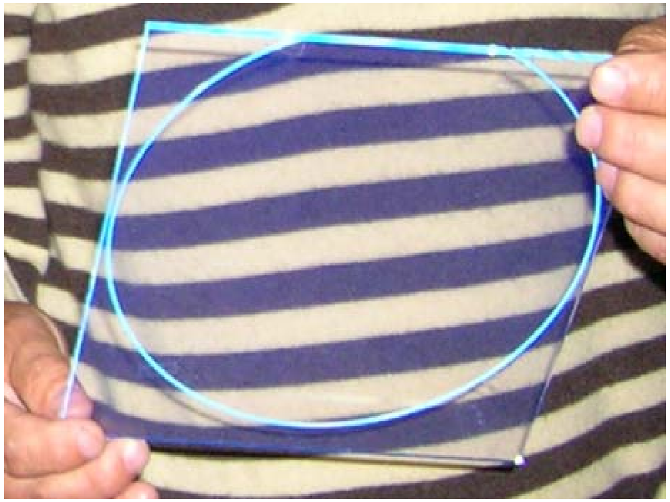




Active board: layout of scintillator tiles and fibres

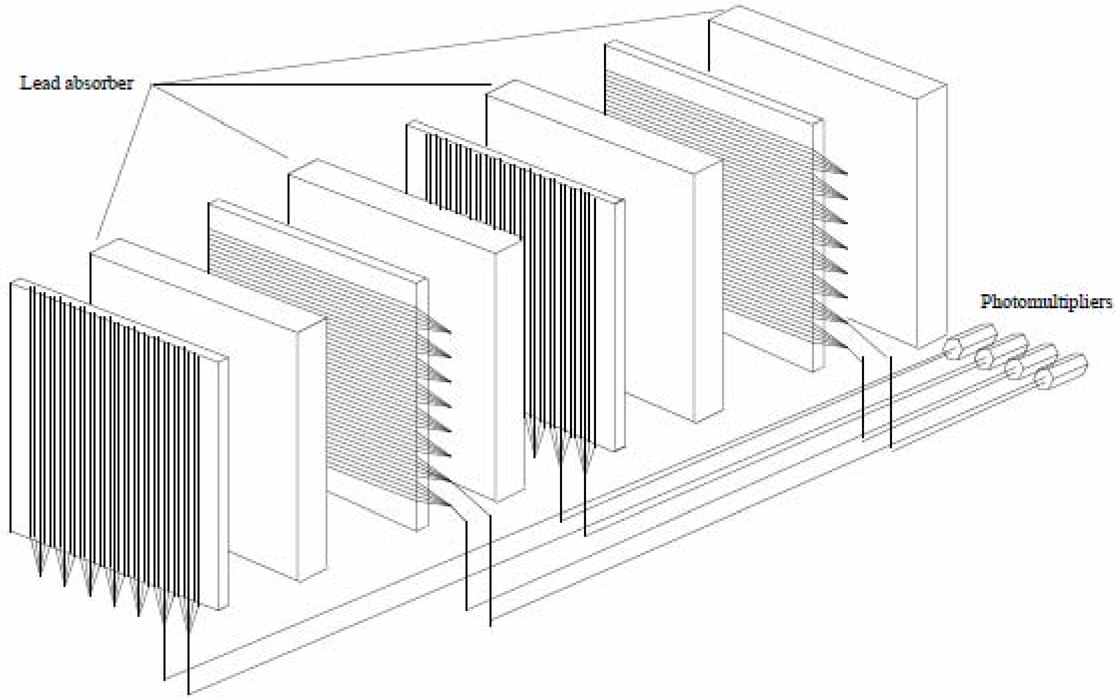
Horizontal scan of scintillator in 25mm steps with radioactive source

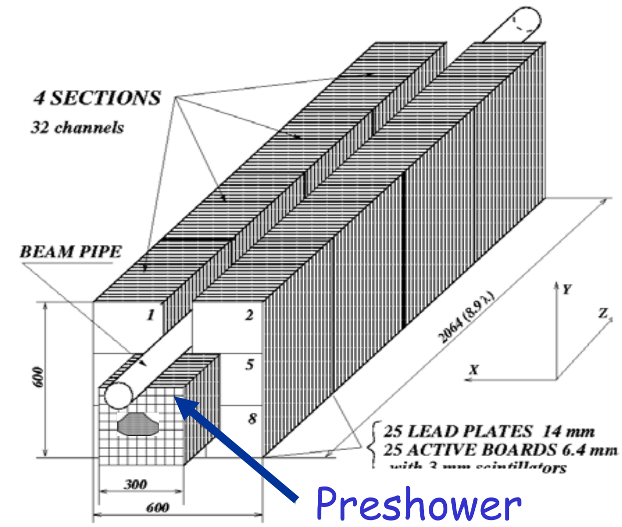




● Data
○ MC

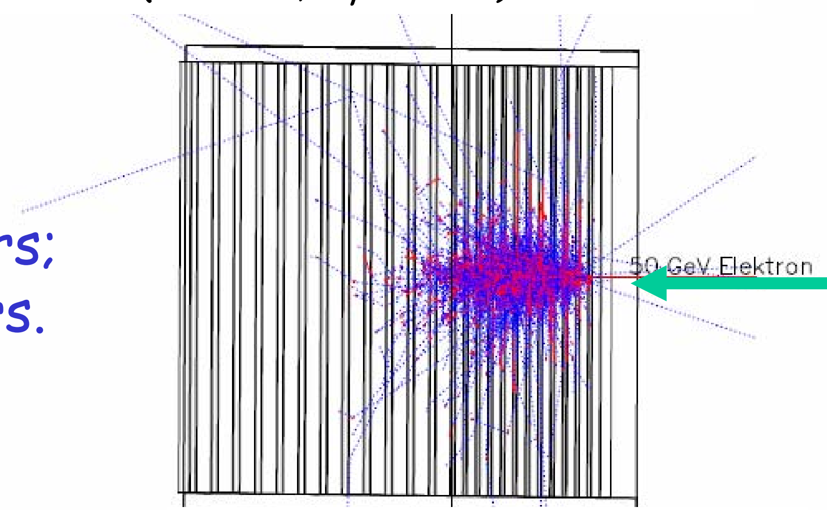
H1 FNC: Structure of Preshower





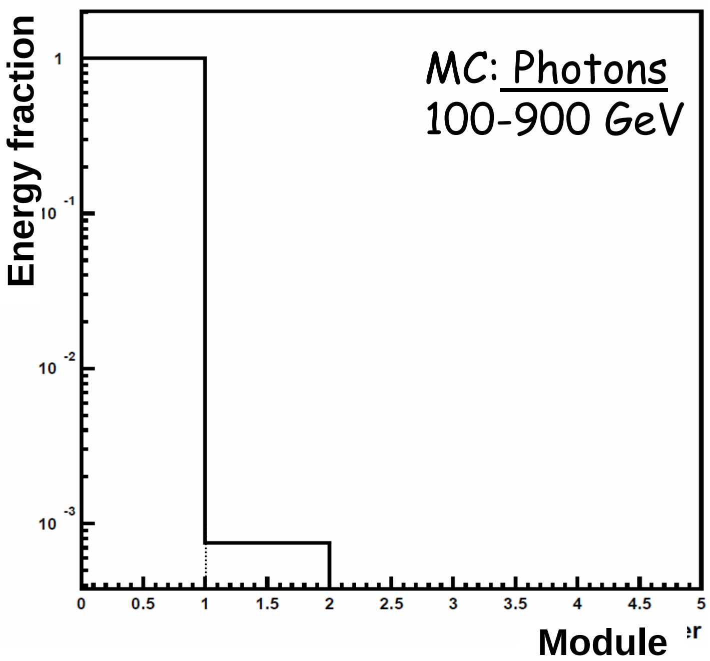
- $26 \times 26 \times 38.6$ cm³ ($60X_0$, $1.6\lambda_I$)
- 24 Pb/Scintillator layers
- layers 1-12 : 7.6mm Pb/ 2.6mm scintillators;
  layers 13-24: 14mm Pb/ 5.2mm scintillators.
- each scintillator plate has 45 1.2mm WLS combined into 9 readout *strips*, readout by Philips XP2282/B 8-stage PMs
- 9 x-strips, 9 y-strips

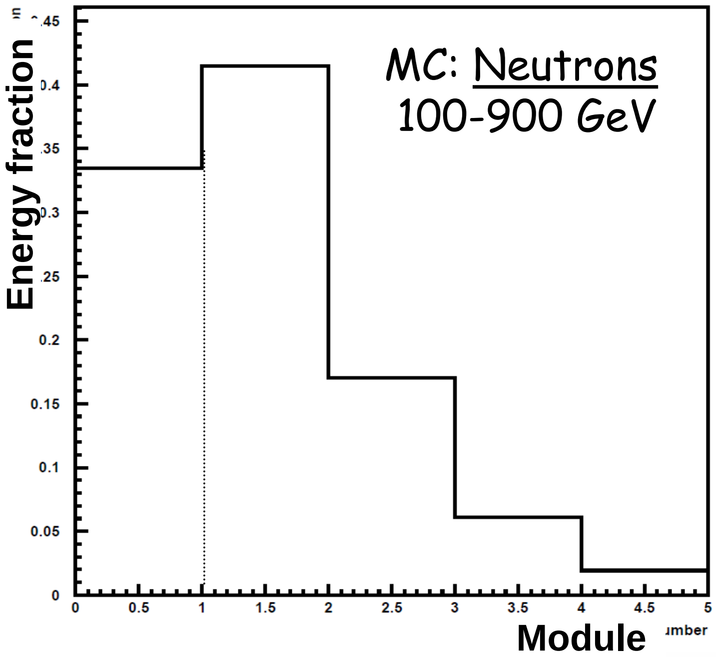
(M.Kreuz, dipl.thesis)



24………layer ……………. 1

Preshower: γ/n separation

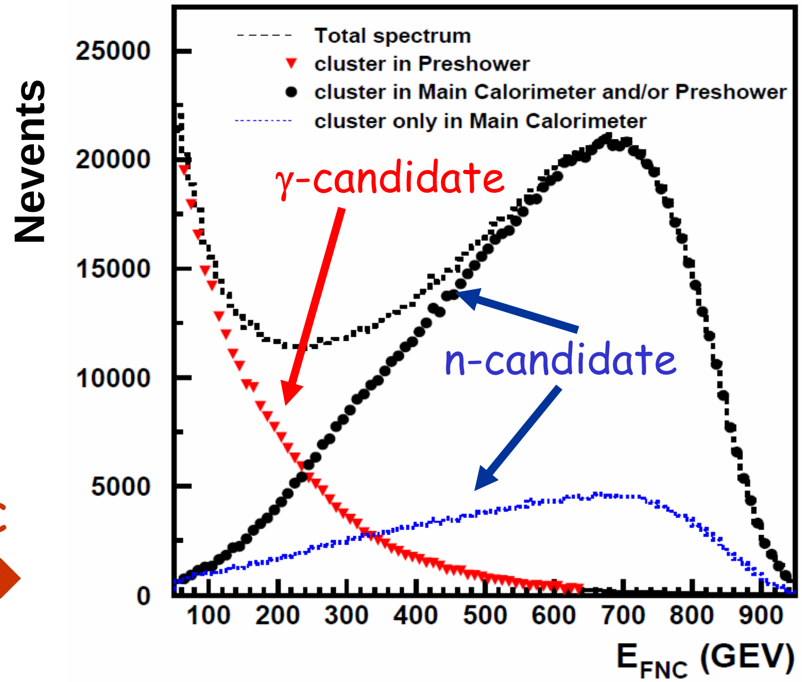




Fraction of energy deposited in FNC modules (Preshower=module 1)

- e/m showers fully contained in Preshower
- neutrons deposit in Preshower ~35% of energy

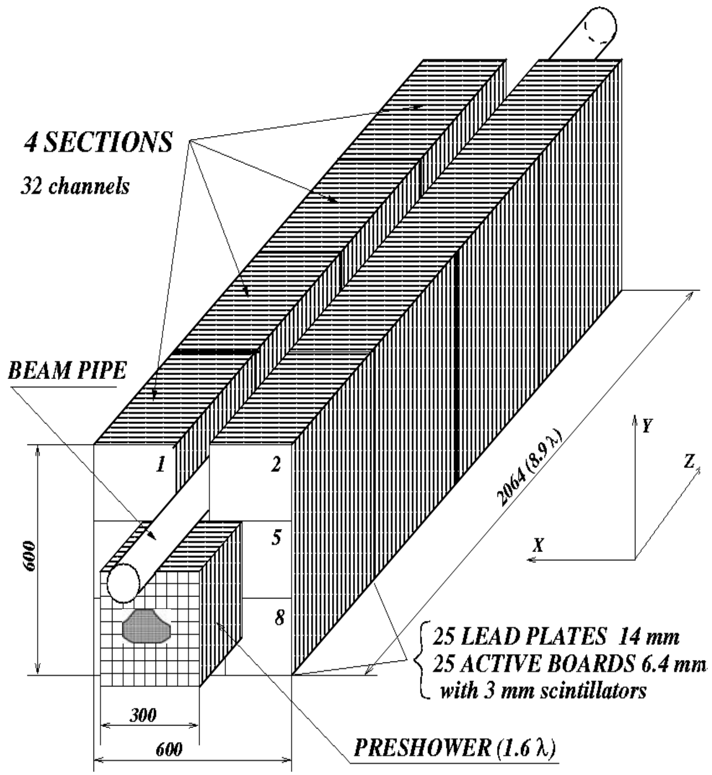
→ unambiguous separation of e/m and hadronic showers ➔



Structure of H1 FNC

The structure of the main FNC calorimeter

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



The structure of the Preshower

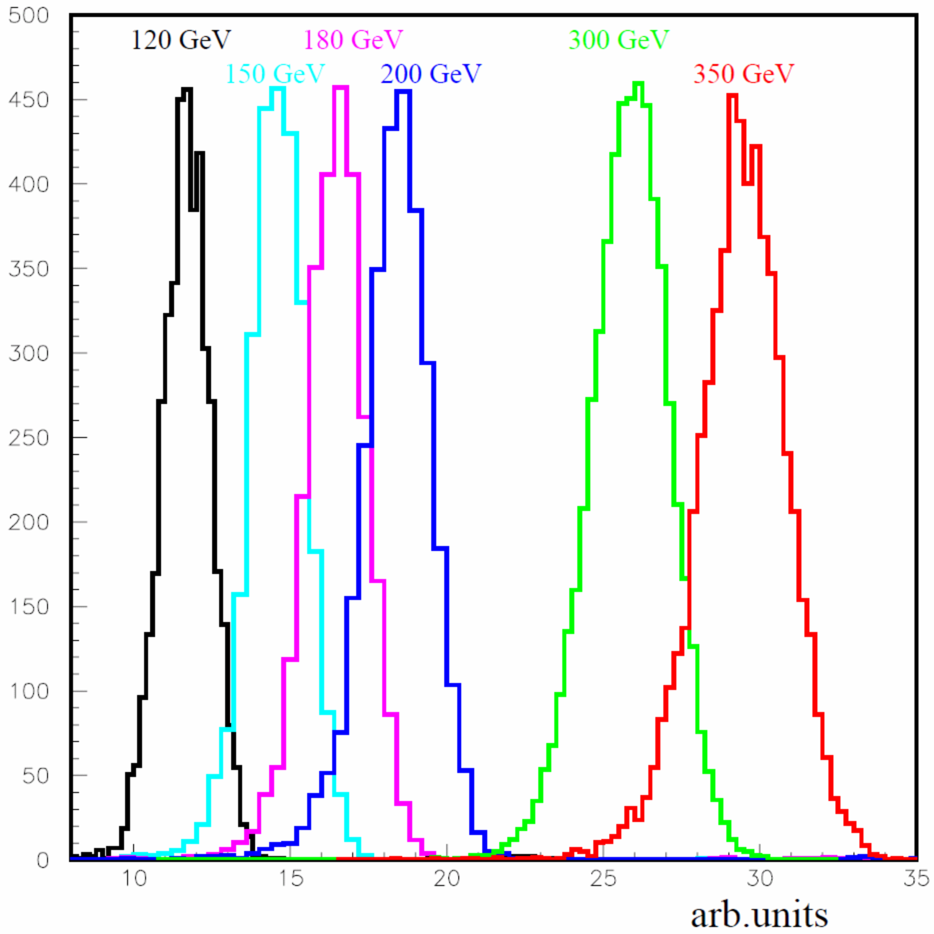
Material	Depth (mm)	Nuclear interaction lengths λ_I
e/m part		
PbSb4	7.5 $\times$ 12	0.52
scintillator	2.6 $\times$ 13	0.04
Tyvek paper	0.3 $\times$ 12	0.00
air	1.2 $\times$ 12	0.00
total e/m part	142	0.56
hadron part		
PbSb4	14. $\times$ 12	0.98
scintillator	5.2 $\times$ 12	0.07
Tyvek paper	0.3 $\times$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

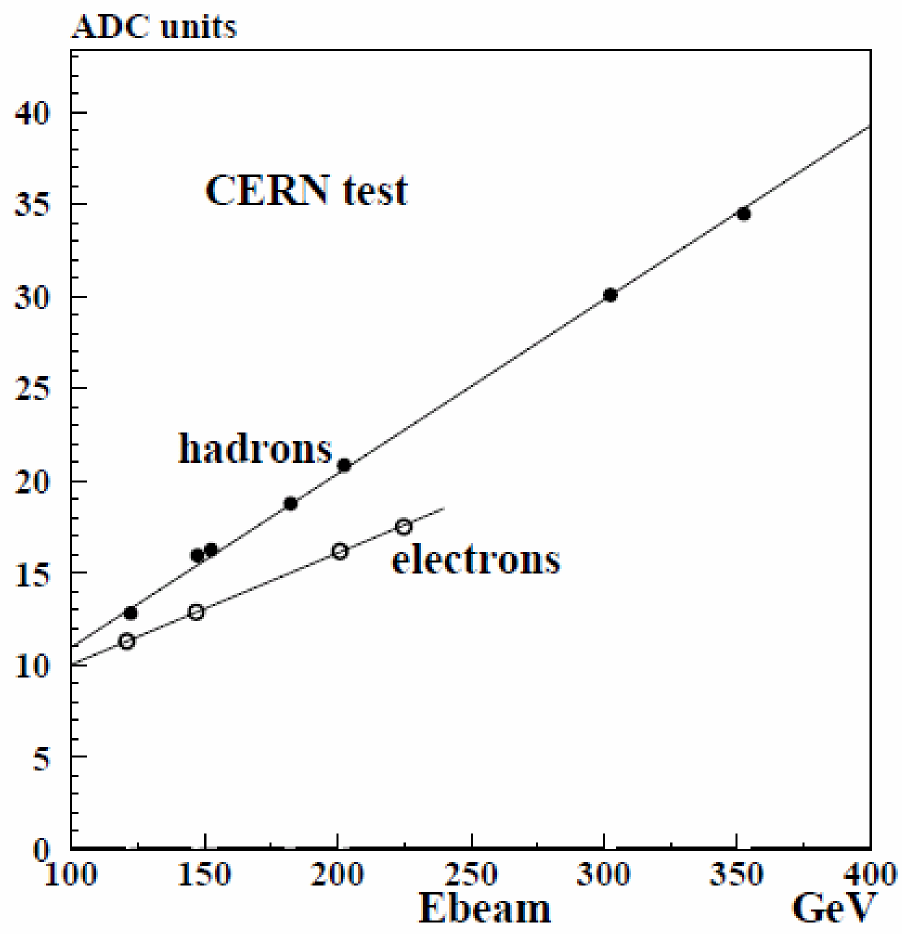
In total 50 readout channels:
9 x-strips, 9 y-strips, 4x8 towers

Installed in HERA tunnel in 2001
The H1-FNC was proposed, designed, assembled and operated by the teams of MPI-Heidelberg and ITEP-Moscow.

After the assembling the FNC was calibrated with the test-beam at CERN SPS (H4 and H6) with hadrons (Ebeam=120-350 GeV) and electrons (Ebeam=120-225 GeV)

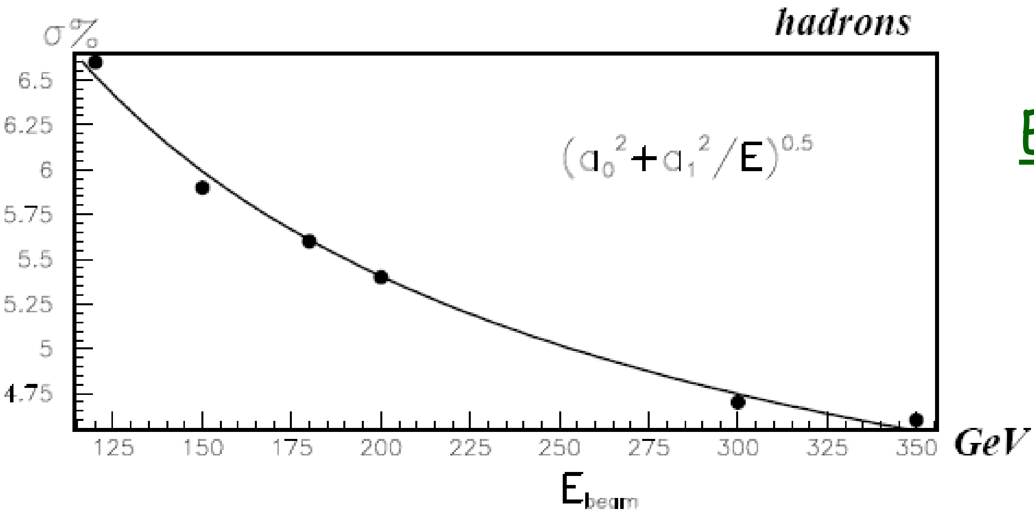
The H1 FNC energy response from CERN test-beam data





The H1-FNC energy resolution

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



Energy resolution

hadrons:

$$\boxed{\frac{\sigma_E}{E} \approx \frac{(63.4 \pm 4.7)\%}{\sqrt{E[GeV]}} \oplus (3 \pm 0.4)\%}$$

e/m: $$\boxed{\frac{\sigma_E}{E} \approx \frac{20\%}{\sqrt{E[GeV]}} \oplus 2\%}$$

Position resolution

Preshower: $\sigma(x,y) \approx 2\mathrm{mm}$,

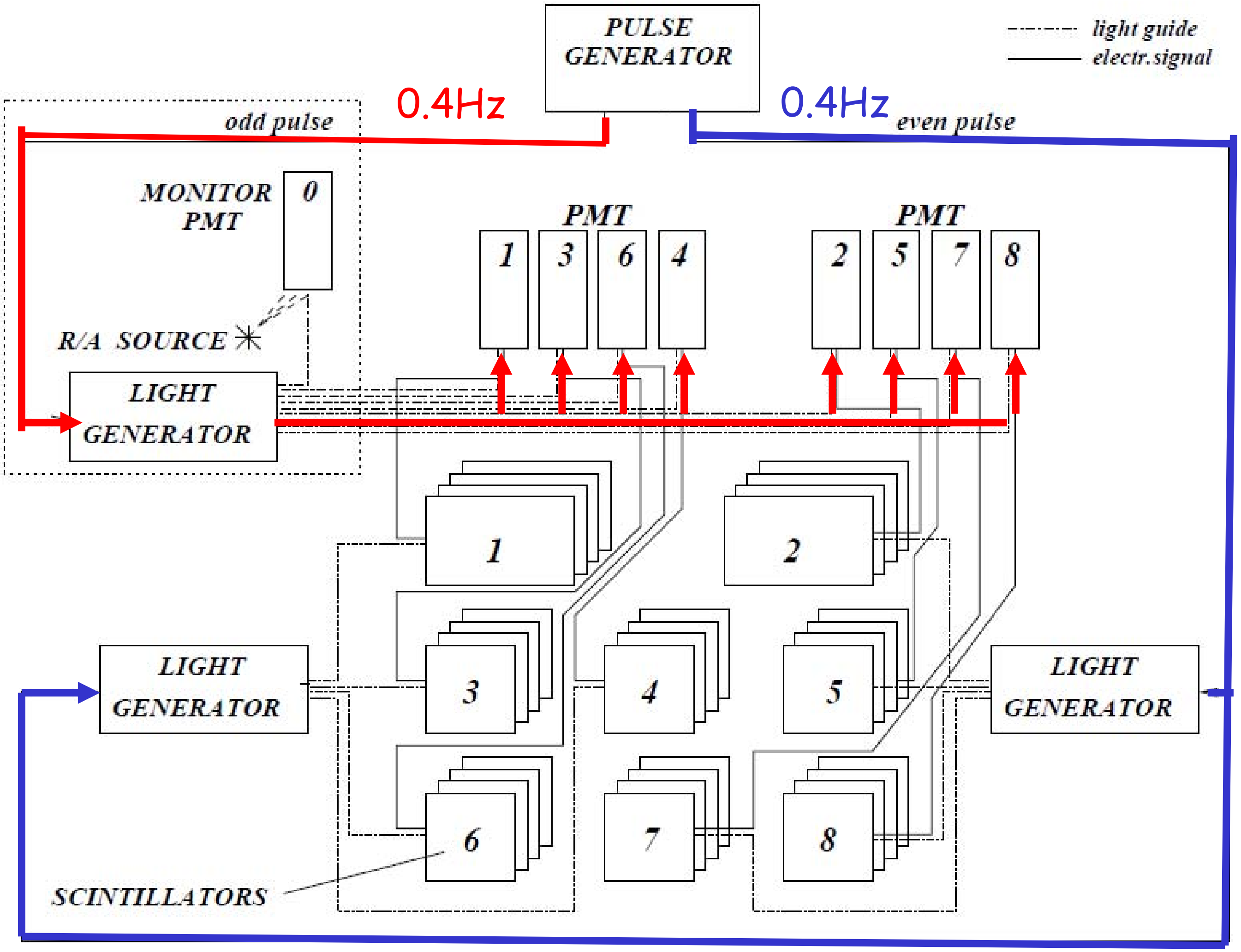
Main Calorimeter:

$$\sigma(x,y) \approx \frac{10\mathrm{cm}}{\sqrt{E[GeV]}} \oplus 0.6\mathrm{cm}$$

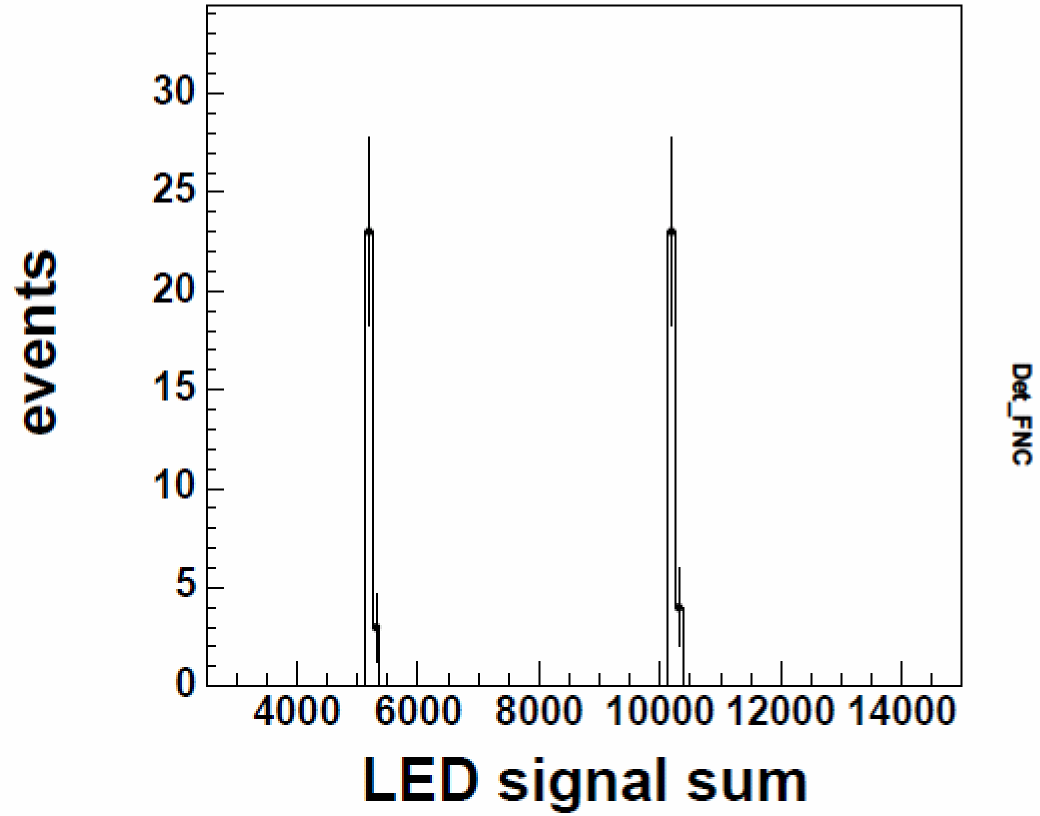
Control of energy calibration: gain monitoring

The gain variation of PMs and the light yield of scintillators and WLS monitored by <u>two</u> LED systems:

- LED pulses transferred to all PMs at 0.4 Hz (empty bunch)→ monitor PM gain
- LED pulses from two LEDs per module are injected into all scintillators of each 5-th layer at 0.4 Hz → monitor the whole chain: the optical connections and radiation damage
- LED stability monitored by comparing signals from LED and from the r/a source (Am^{241})



An example: L4/DQ histogram: stability of LED responses



LED summary signal. Sum of responses of all FNC channel to monitoring LED pulses. We have two different LED pulses, which is seen in the figure.

The averaged LED signal responses were used to provide offline energy corrections applied during the reconstruction.

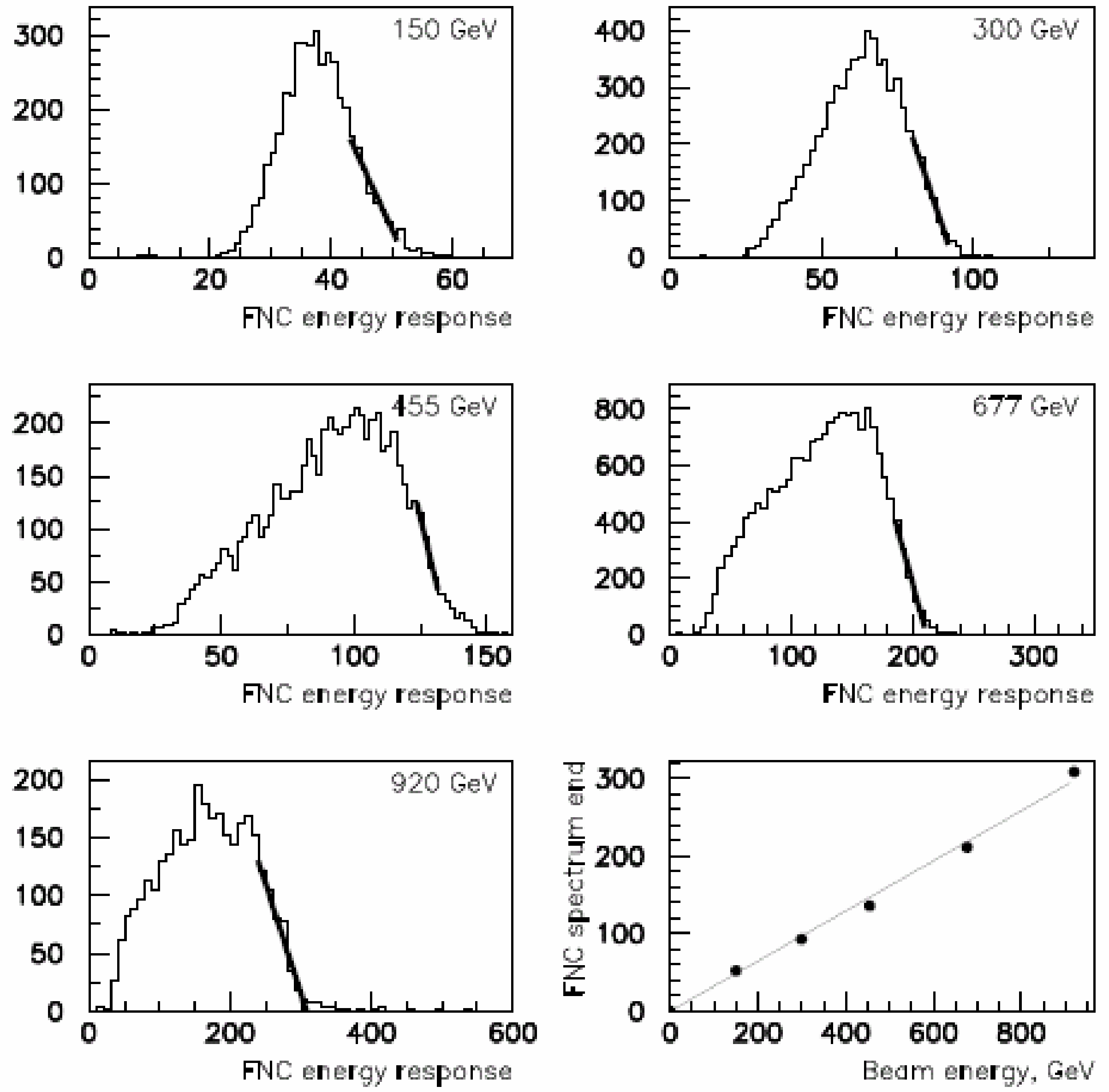
Control of energy calibration

The stability of calibration constants during data taking was monitored using interaction between the proton beam with residual gas in the beam-pipe.

Special 'FNC beam-gas runs' were regularly taken during the beam injection, when the proton beam has been already accelerated, but the electrons were not yet injected. Collect ~100.000 events in ~20min → sufficient to have a good energy spectrum, and compare the peak position and the high energy part of energy distribution with the expectation from the pion exchange MC simulation.

Linearity check with HERA data

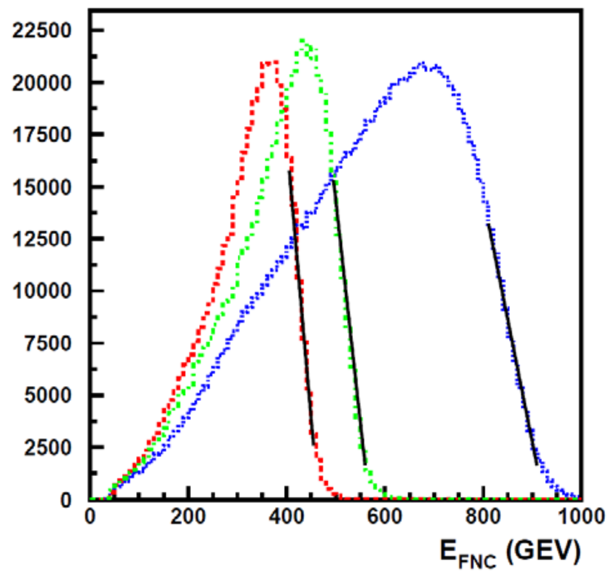
Proton beam ramp data: beam-gas

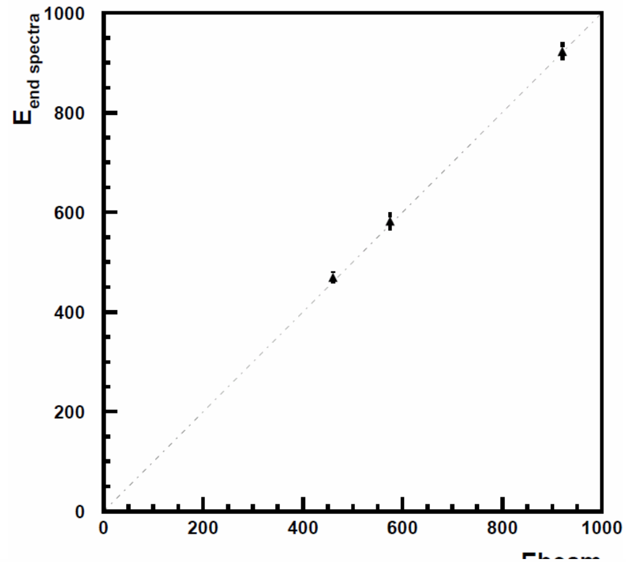


Control of energy calibration and linearity check

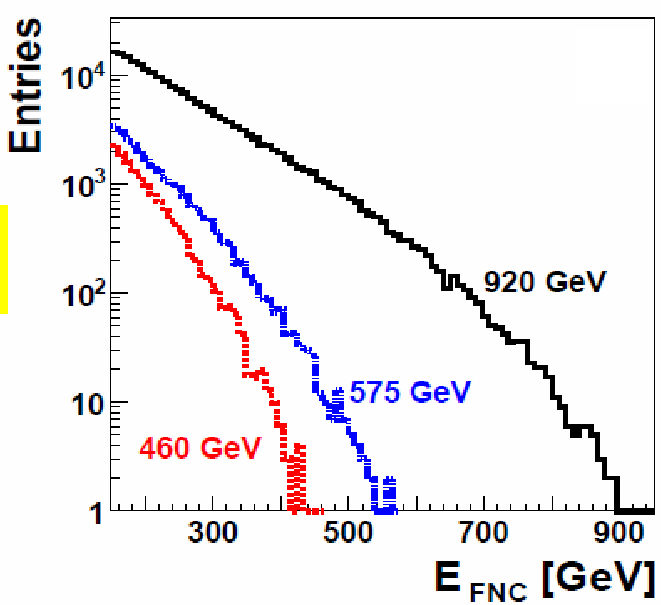
HERA ep data: LER (460 GeV), MER (575 GeV), HER (920 GeV)

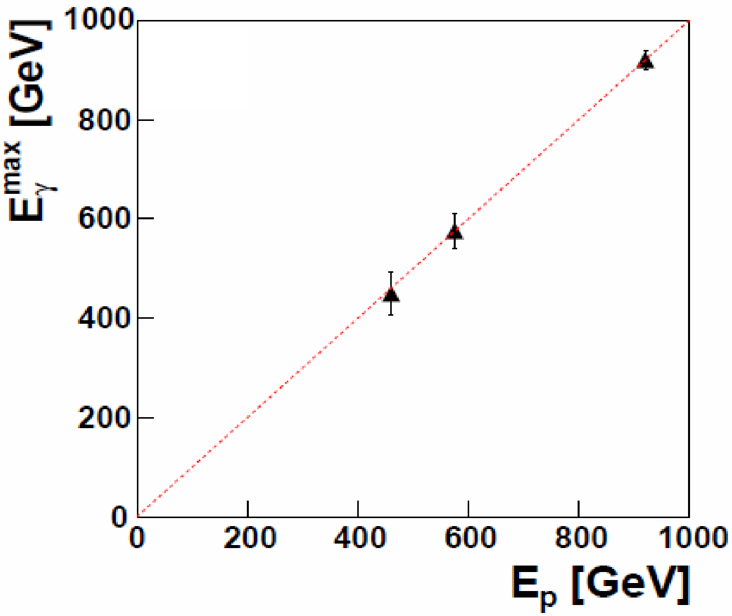
n



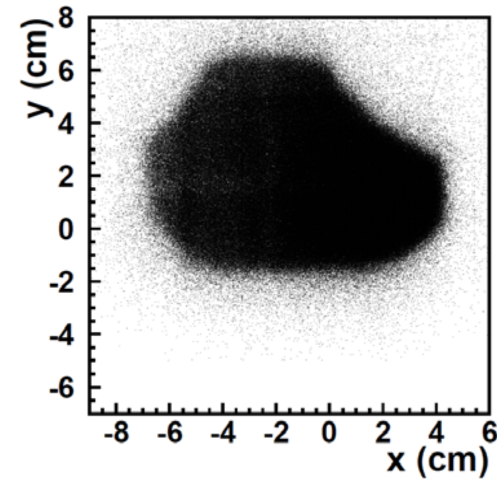


γ



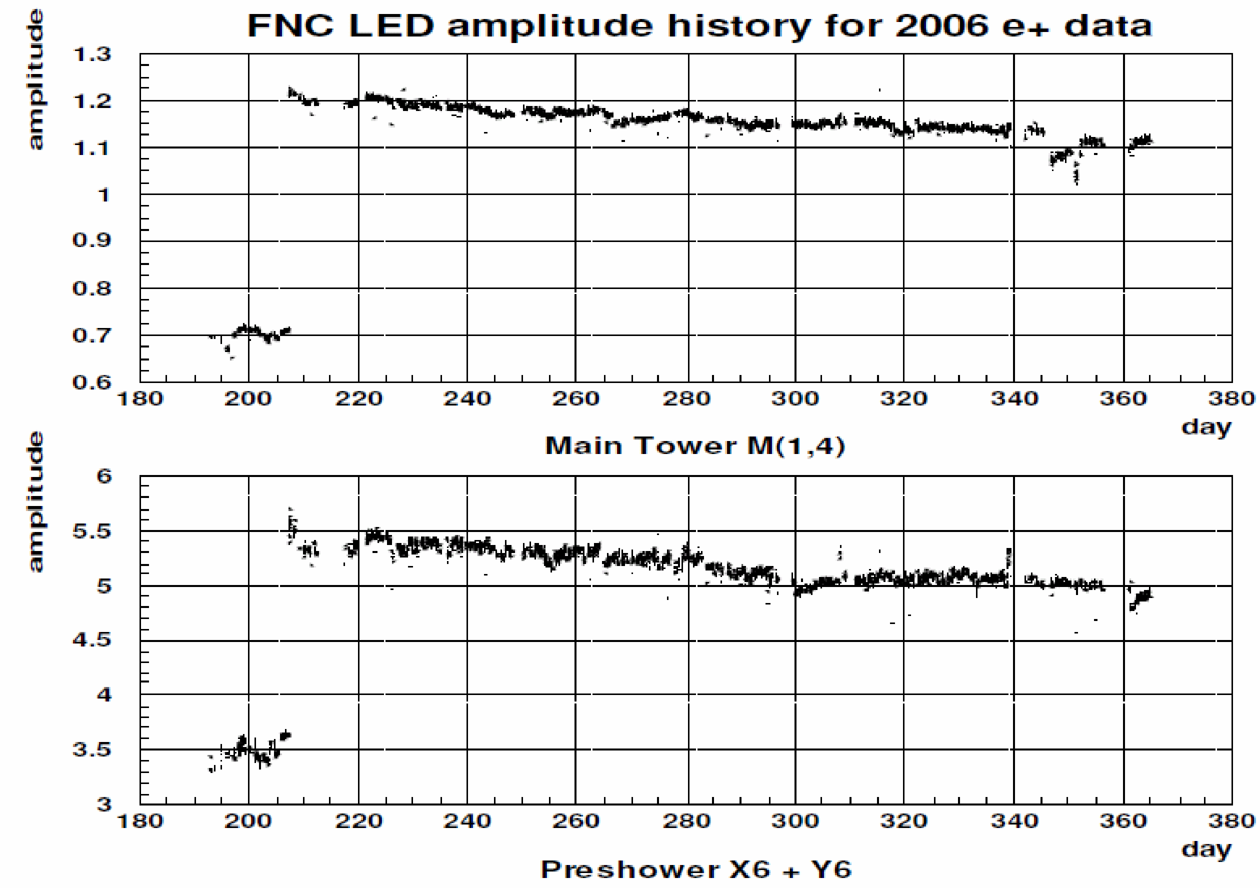


Neutron impact point distribution



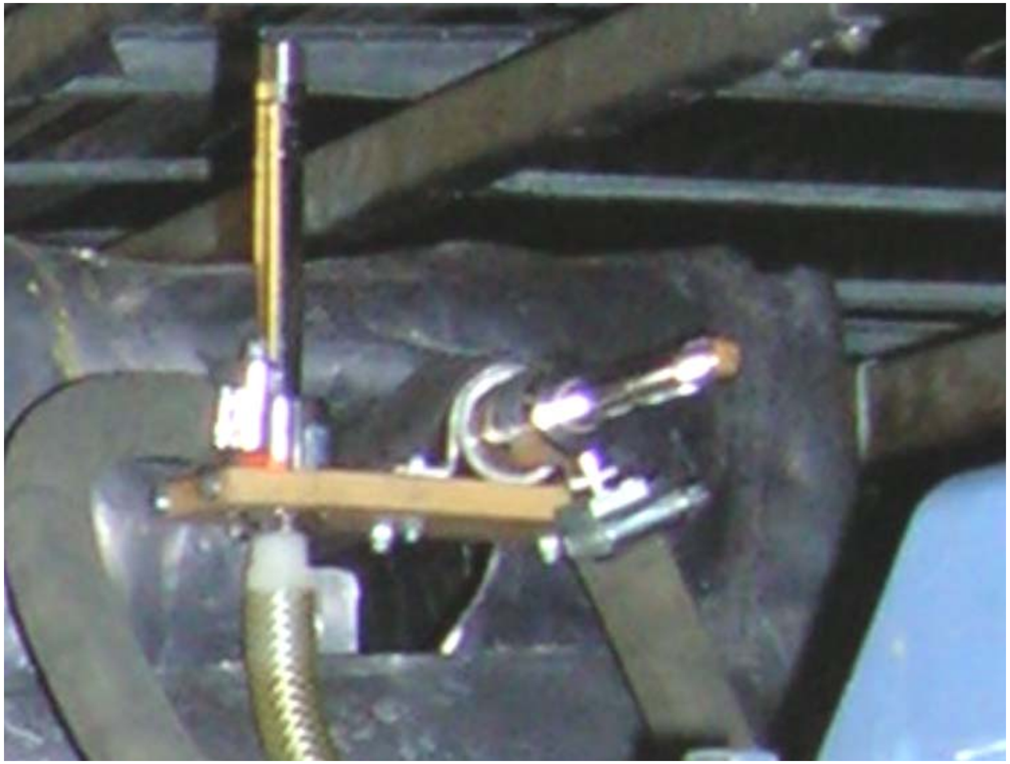
Overall smooth operation over the full running period (2002-2007)

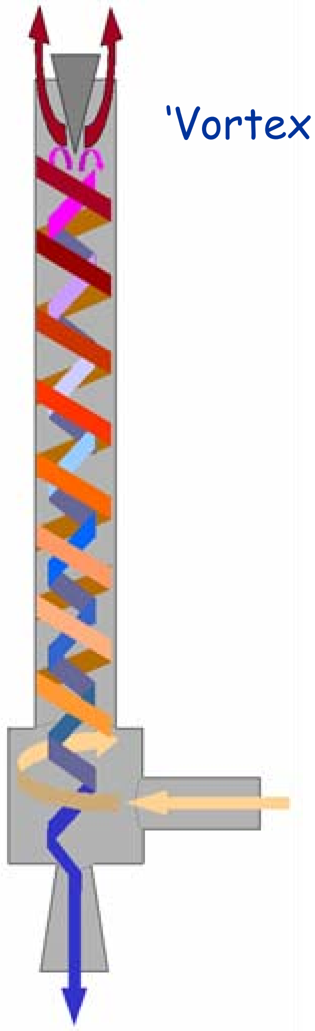
Detector control and maintenance included permanent control of the total energy, impact point distribution, PM gain stability, signal shape, L4 histograms



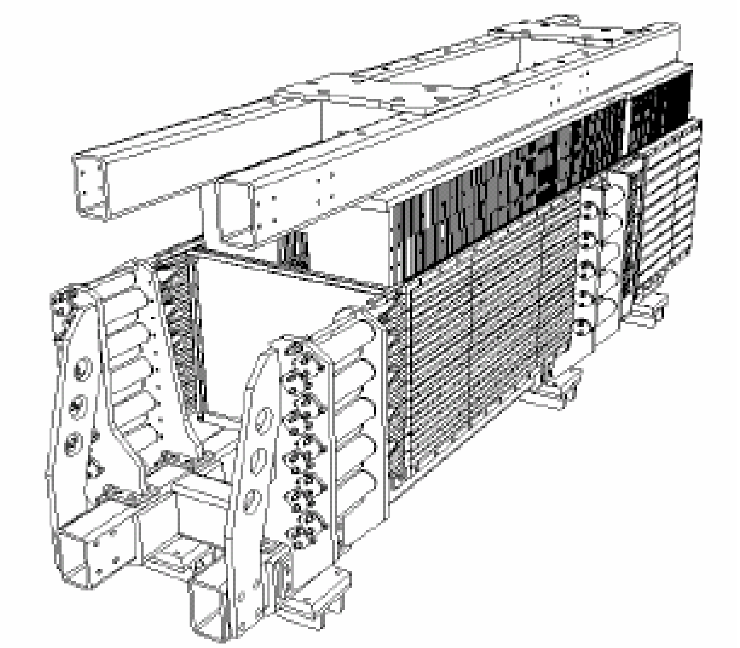
A problem was observed with PM gain degradation due to overheating

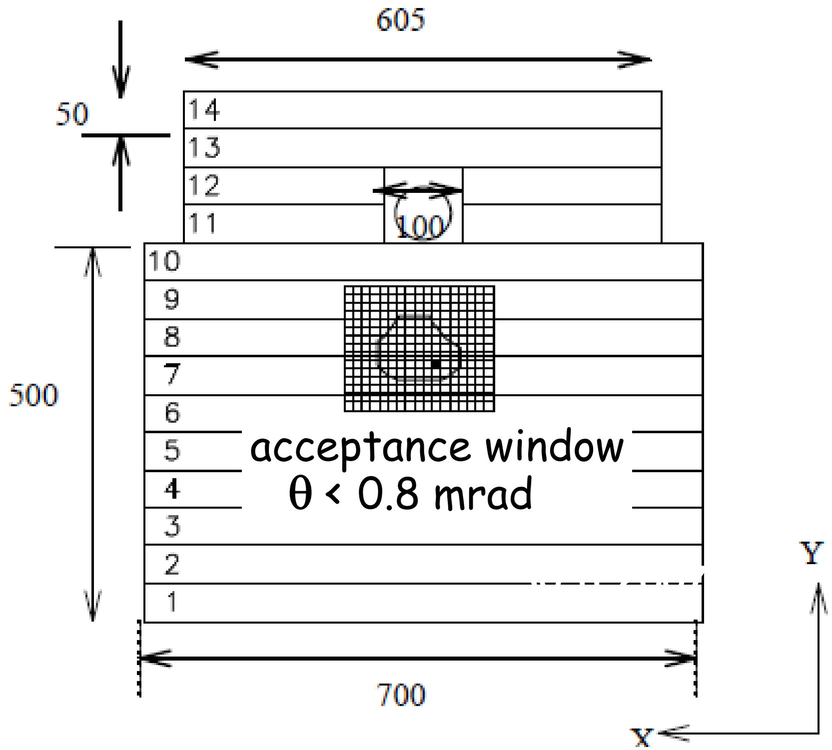
Problem with overheating of PMs – temperature was often above 50° (cooling air in the tunnel was hot)→ degradation of PM gain. Installed 'Vortex tubes' to cool down the cooling air

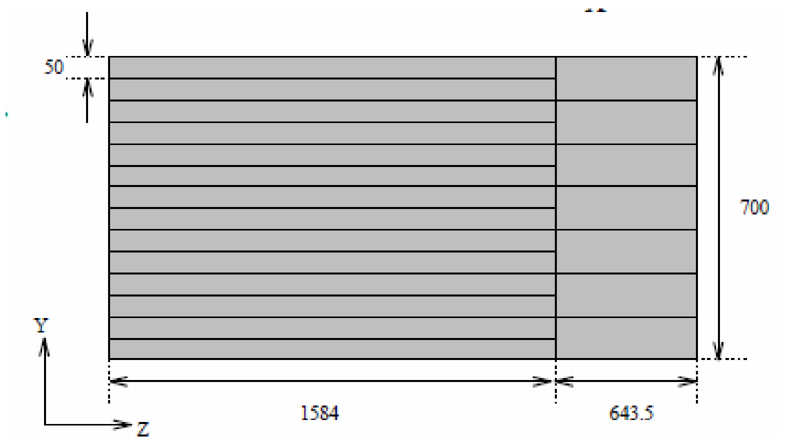




ZEUS FNC







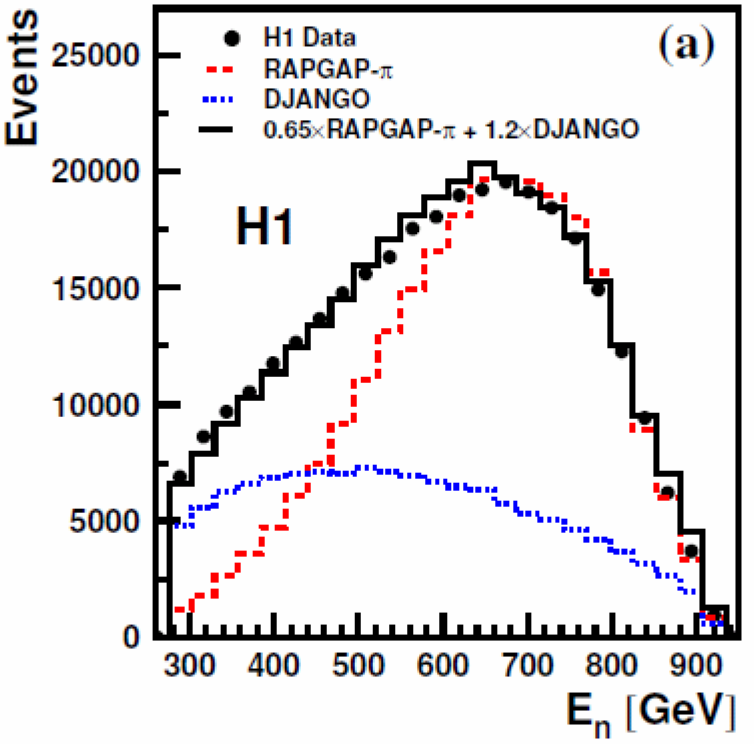
- Sampling calorimeter; 134 layers
  1.25cm Pb/ 0.26cm scintillators readout by WLS from both sides
- Front section ($7\lambda_I$) – 14 towers, rear section $3\lambda_I$
- e/h separation using transverse width of shower
- $\sigma_E/E \sim 70\%/\sqrt{E(\mathrm{GeV})}$
- 'Forward Neutron Tracker'
  scintillator hodoscope, 17x15 x-y strips, 1.2cm each
  Installed $1\lambda_I$ inside the calorimeter
  Position resolution 2.3mm

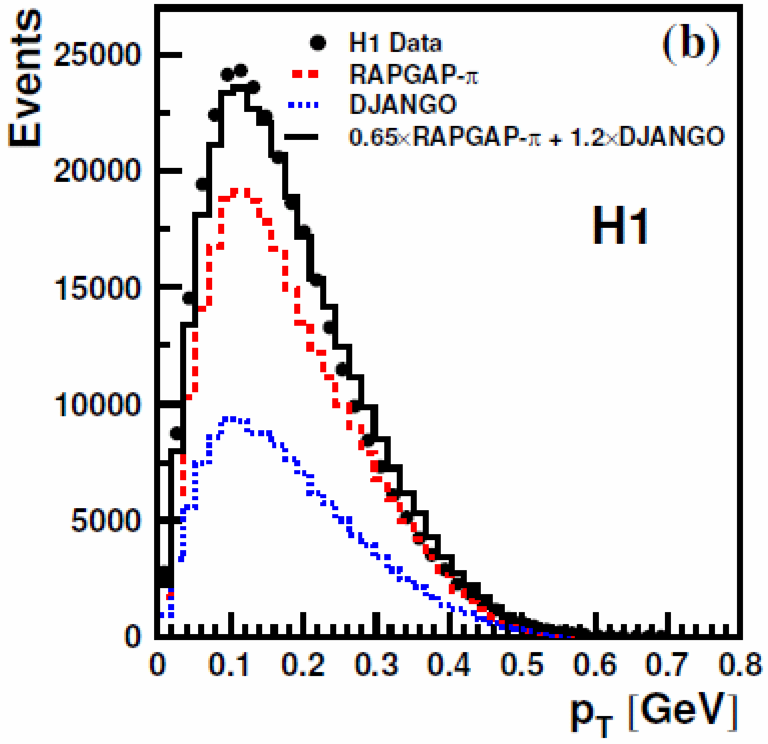
S.Bhadra et al., NIM A394 (1997) 121;
ZEUS Collab., Nucl. Phys. B776 (2007) 1

- measurements with forward neutrons
- measurements with forward photons

Leading neutron energy and p_T distributions measured by the FNC

Eur.Phys.J.C68 (2010) 381





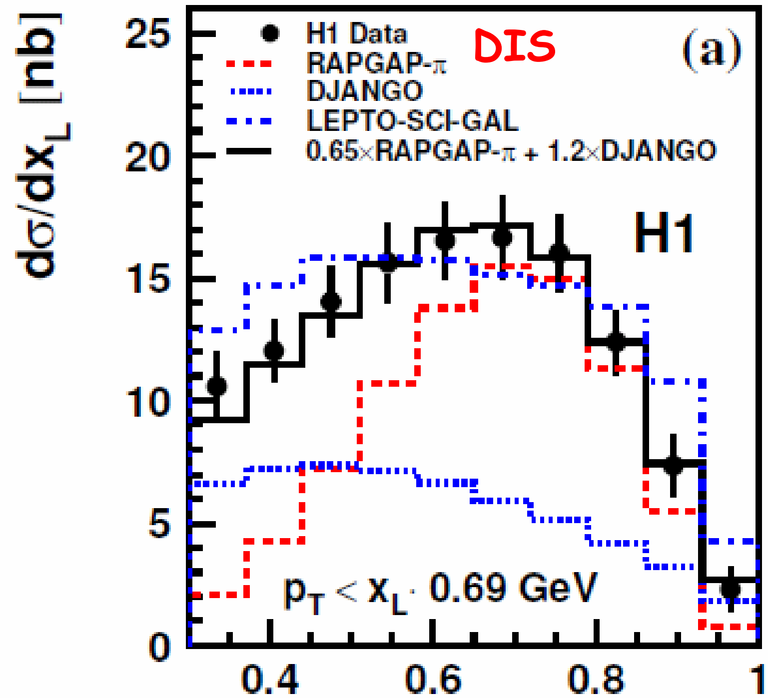
- the MC model with standard fragmentation (DJANGO-CDM) can not describe the neutron energy distribution at high E_n
- RAPGAP-π MC, where neutrons are produced from the exchange of virtual pion ($p \rightarrow n+\pi^+$) describes data well for E_n>650 GeV, underestimate data at E_n<600 GeV.

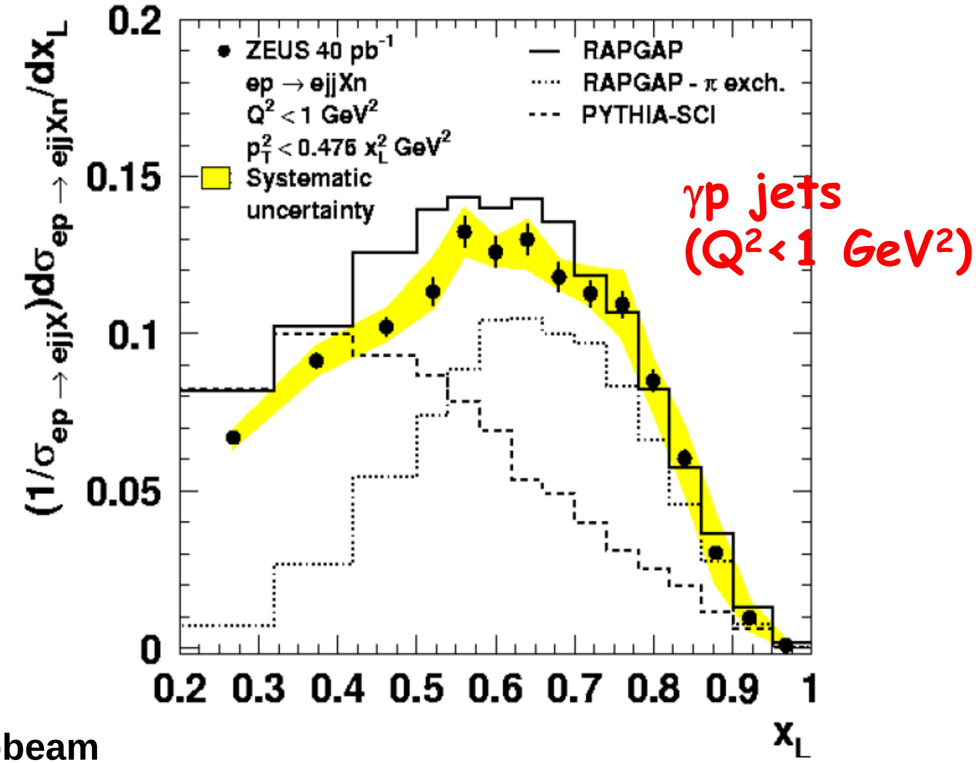
- The best description of data gives a mixture of RAPGAP-π-exchange and DJANGO Monte Carlo simulations

Forward neutron cross section vs x_L: DIS and γp jets

Eur.Phys.J.C68 (2010) 381

ZEUS Nucl.Phys.B827 (2010) 1



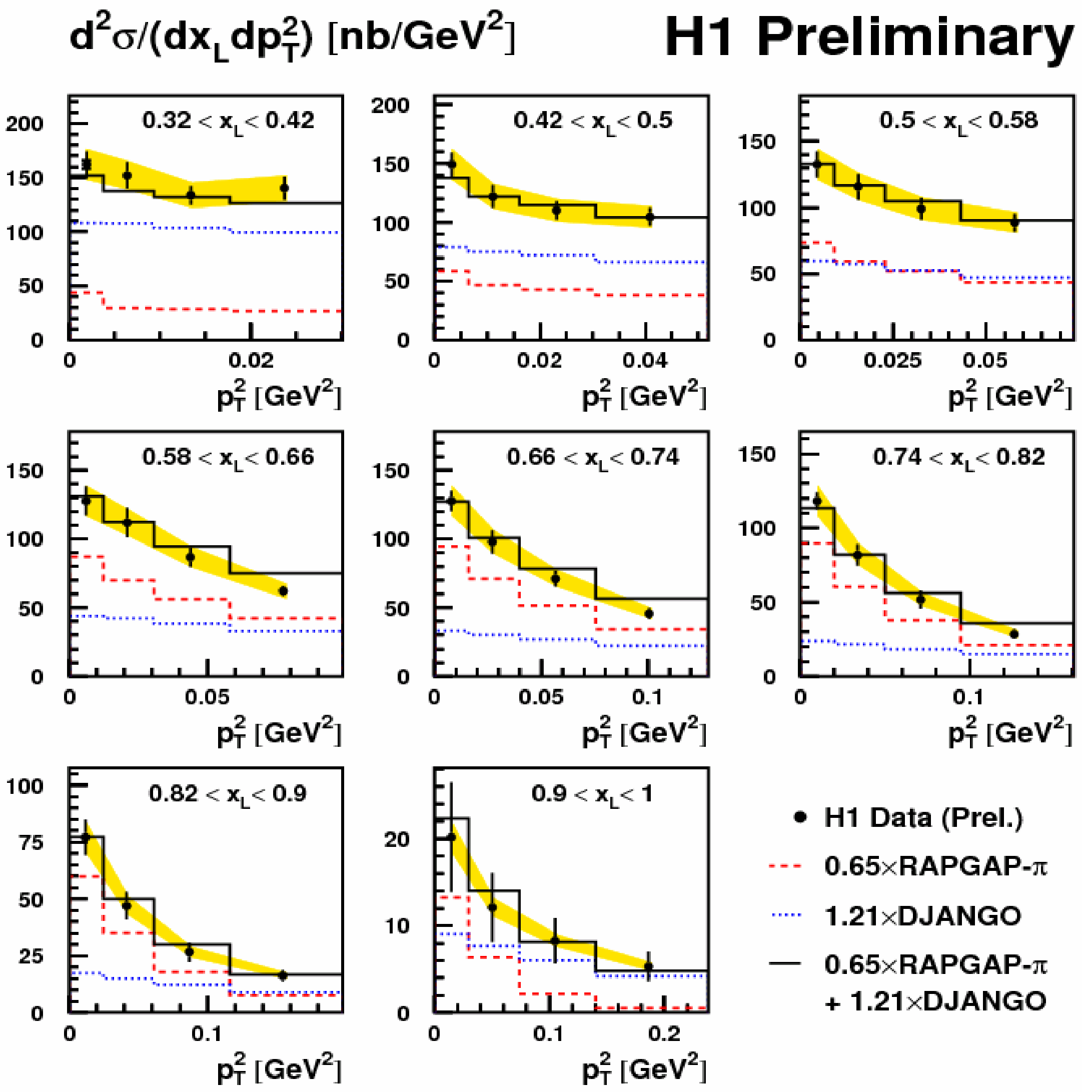


- Data described by a combination of standard fragmentation and π^+-exchange (RAPGAP-π) MC models over the full range
- 'Standard' fragmentation models (DJANGO, RAPGAP) don't describe the shape at high x_L
- π^+-exchange model describes the shape of data distribution well for x_L>0.7

➔ **pion exchange- the dominant mechanism of neutron production at high x_L**

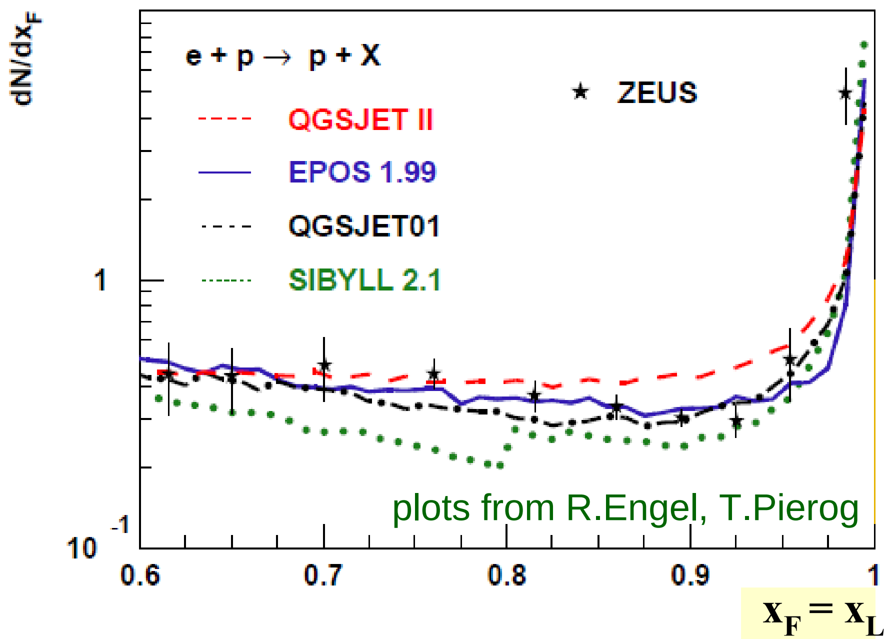
Extend the measurement differentially in transverse momentum of neutron p_T

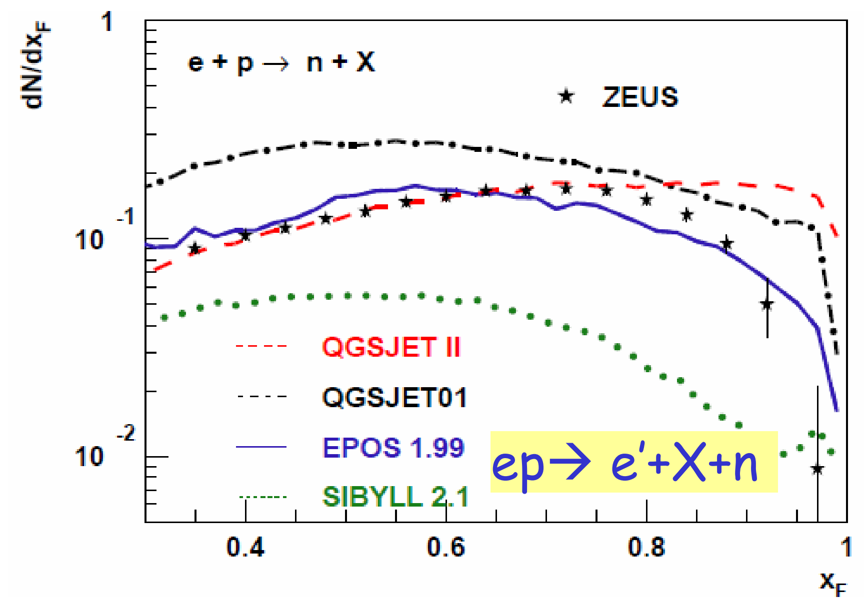
H1prelim-10-113



Combination of RAPGAP-π and DJANGO describes well the p_T^2 distributions the forward measurements (baryons, π^0 , γ) are of the greatest importance for the model tuning

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





EPOS 1.9: *(Pierog,Werner),*

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

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

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

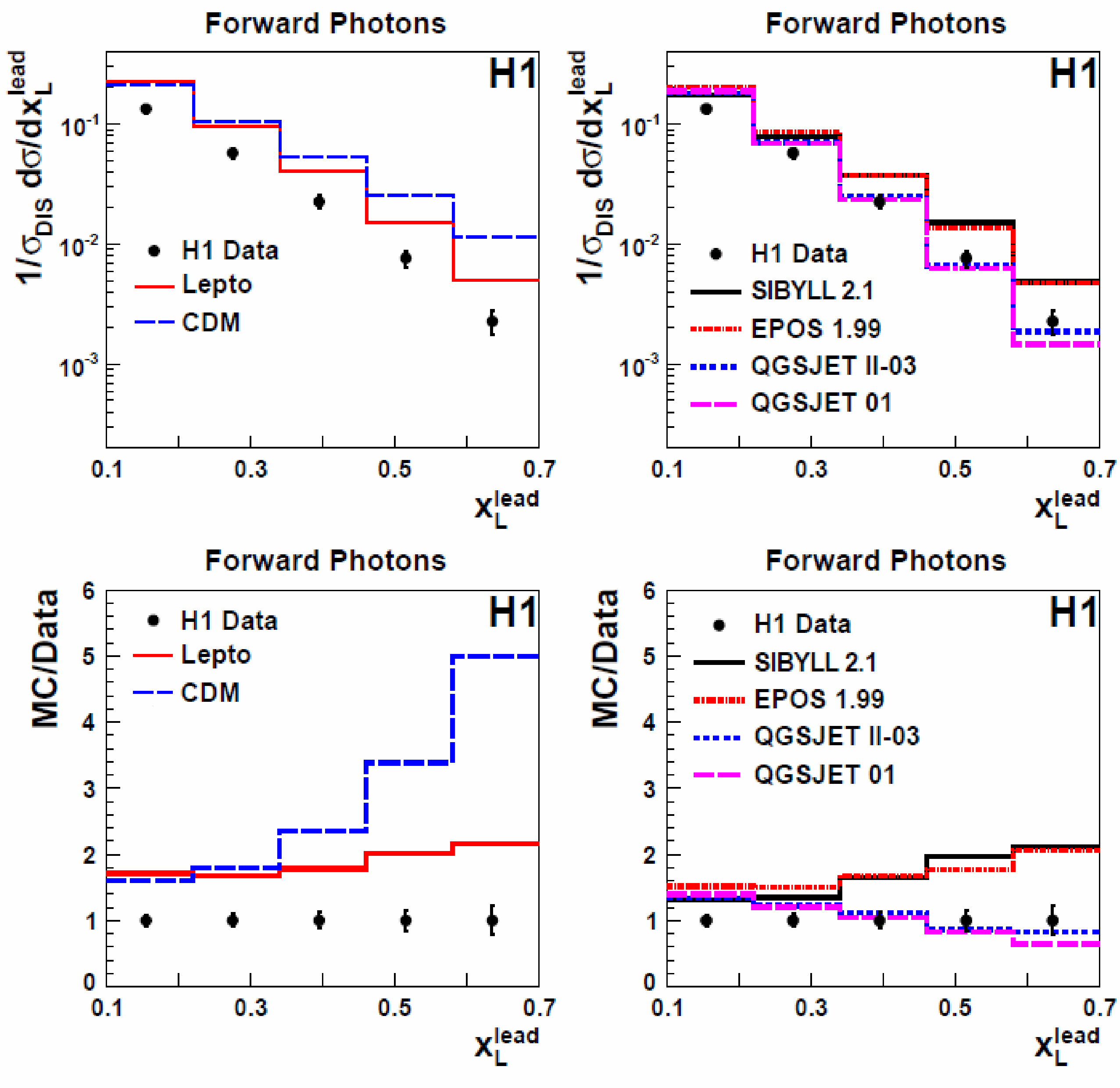
Forward photon production cross sections

Eur.Phys.J.C71 (2011) 1771

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

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

None of cosmic ray interaction models can describe the data



Summary of physics measurements

Neutron measurements:

- precise measurements of forward neutron x_L and p_T^2 in DIS and in dijet events
- the measurements well described by the combination of 'standard' fragmentation models and models with pion exchange
- provide constraints of pion PDFs and pion flux

Photon measurements:

- 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
- Useful input for models of cosmic ray interactions with matter

Future of ep physics – LHeC ?

- Collide LHC proton beam with electrons/positrons (Ring-Ring or Linac-Ring options)
- Lepton energy ≥ 60 GeV
- No interference with pp physics

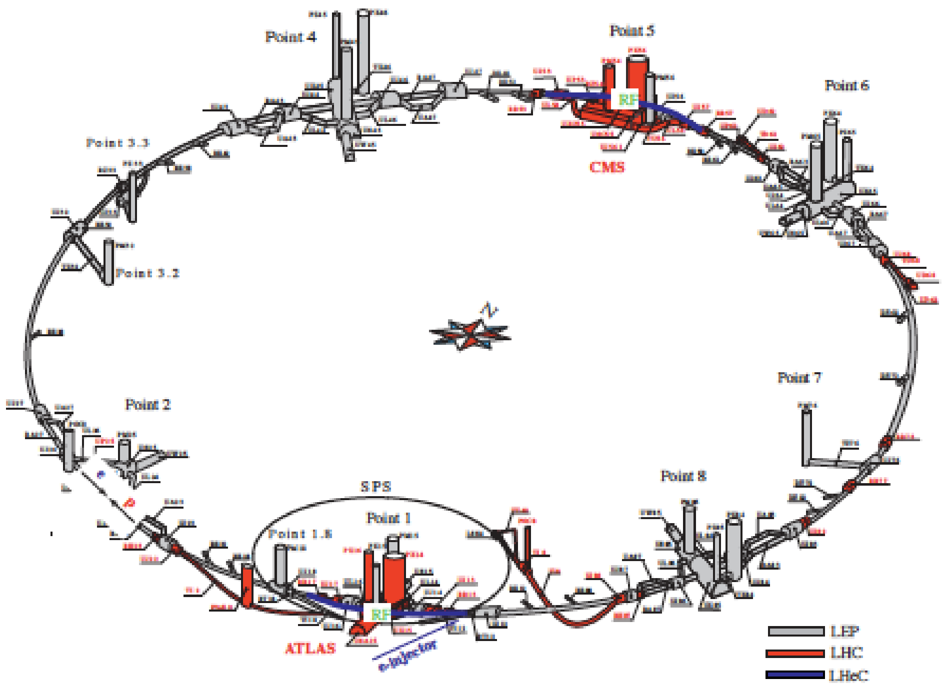


Figure 1: Schematic Layout of the LHC (grey/red) with the bypasses of CMS and ATLAS for the ring electron beam (blue) in the RR version. The e injector is a 10 GeV superconducting linac in triple racetrack configuration which is considered to reach the ring via the bypass around ATLAS.

DRAFT 1.0
Geneva, August 5, 2011
CERN report
ECFA report
NuPECC report
LHeC-Note-2011-001 GEN

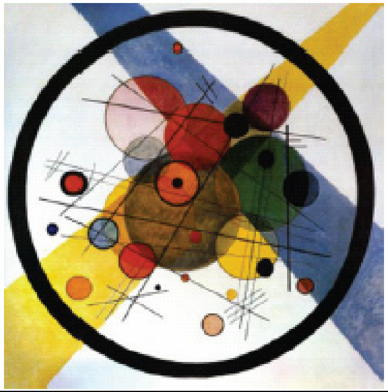
CERN

LHeC

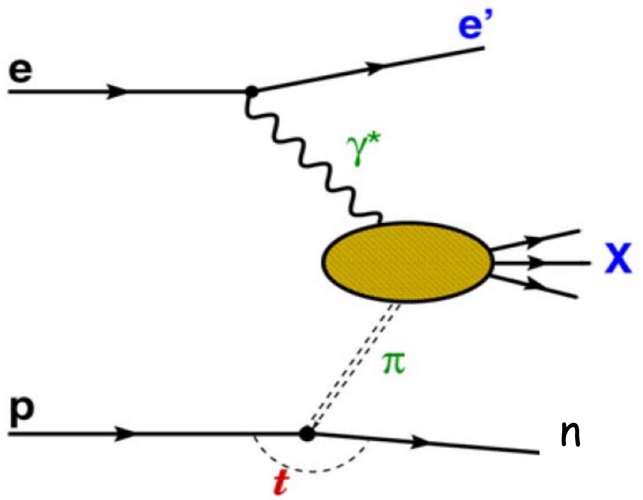
A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group
THIS IS THE VERSION FOR REFEREEING, NOT FOR DISTRIBUTION



Measure neutrons and photons scattered at ~0°

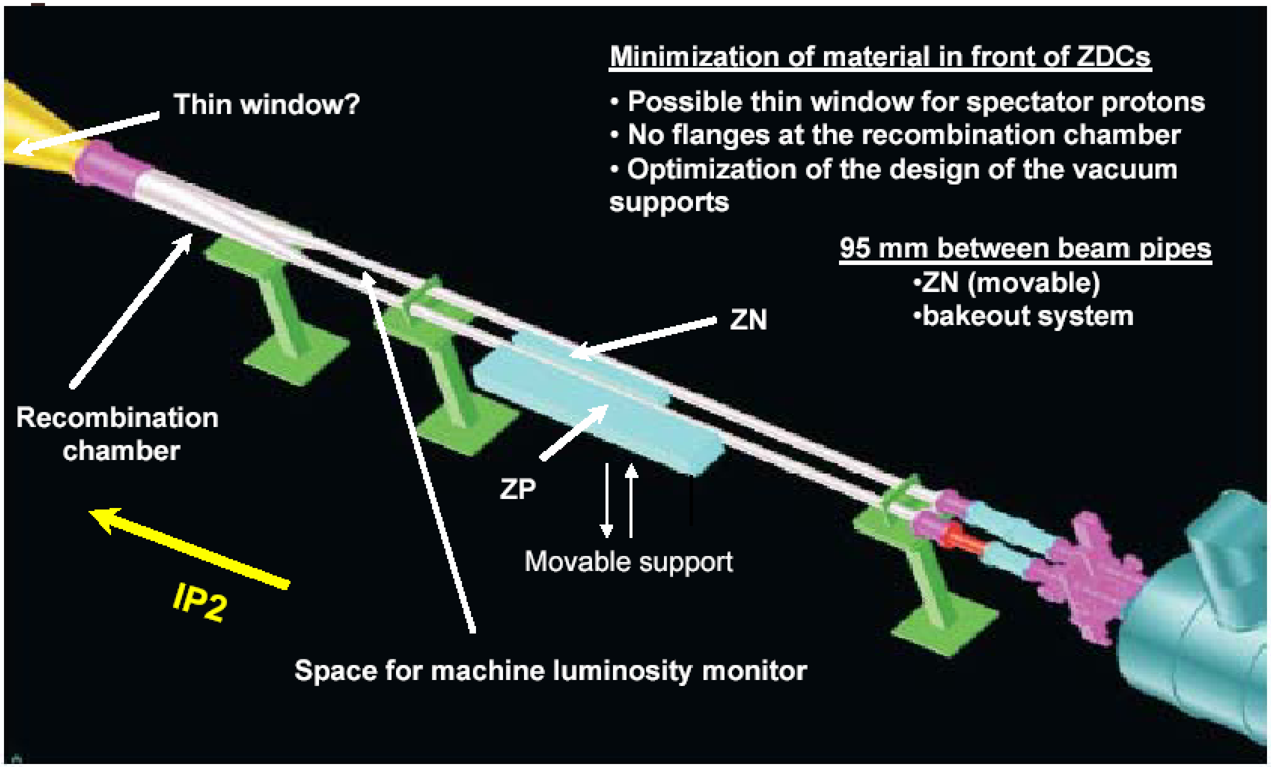


- tag pion exchange process, pion structure, absorptive /gap survival effects
- colour single exchange, diffractive scattering
- Crucial in ed-scattering to tag spectator neutron, distinguish spectator and scattered neutrons
- Crucial in diffractive eA, to distinguish coherent from incoherent diffraction
- Measurements for cosmic ray data analysis proton fragmentation, forward energy and particle flows…
- New forward physics phenomena
- …

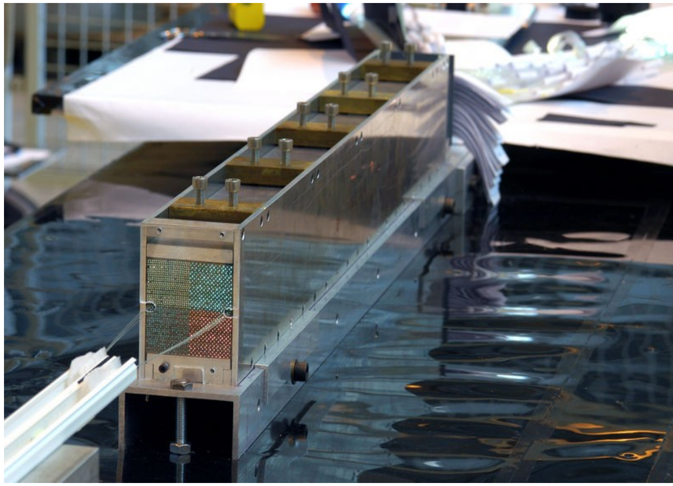
The LHC experiments ATLAS, CMS, ALICE and LHCf experiments have ZDC

Zero Degree Calorimeter for the LHeC

The position of ZDC in the tunnel and the overall dimensions will depend mainly on the space available for installation (~90mm space between two beampipes at z~ 90÷100m)

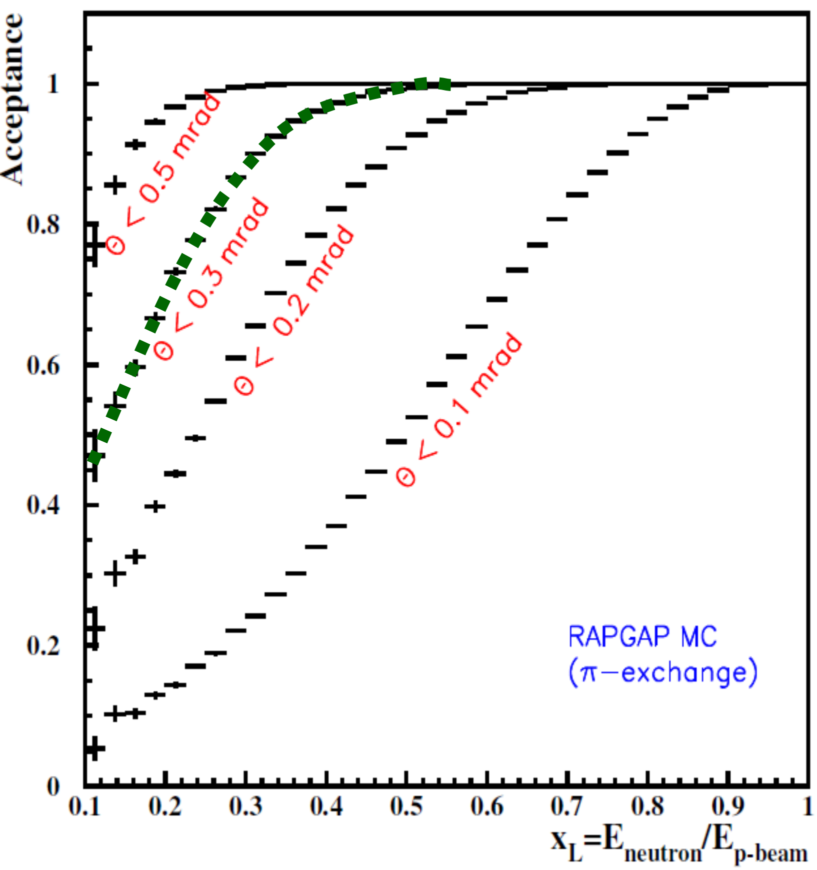


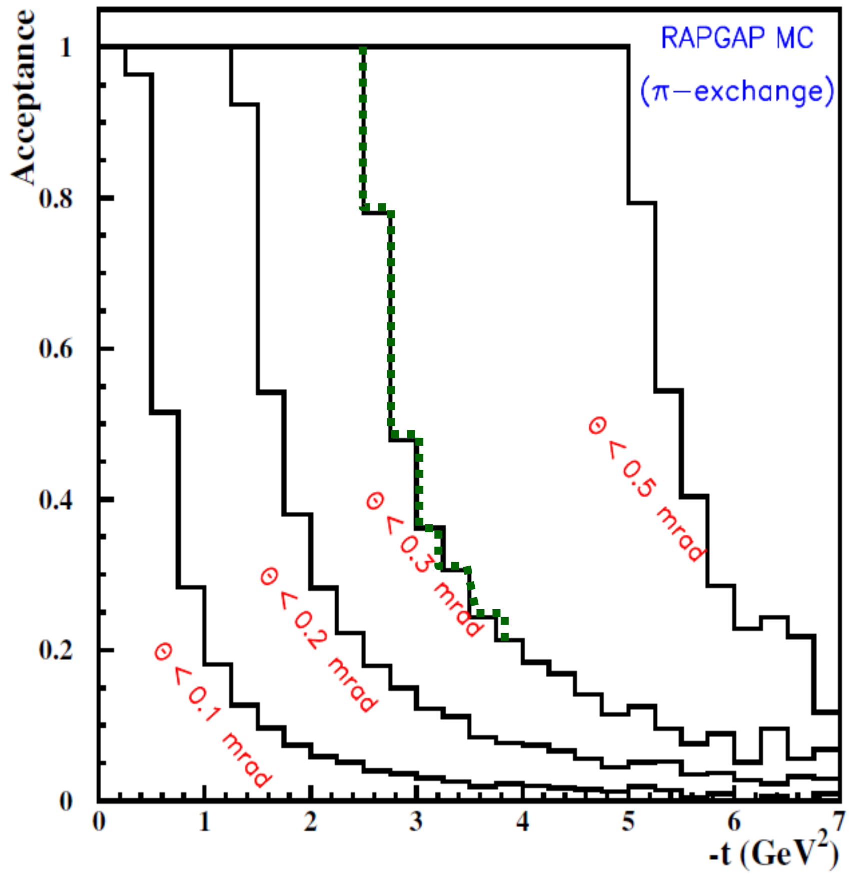
ALICE ZDC



Zero Degree Calorimeter for the LHeC

For θ<0.3mrad quite reasonable gemetrical acceptance, >90% for x_L>0.3, |t|<3GeV²





ZDC for the LHeC - general considerations

- Geometric constraints- depends on the available space and angular aperture

- Requirement to the <u>calorimeter</u>: detect neutral particles with θ<0.3mrad and E~O(100) GeV to 7 TeV with a reasonable resolution of few percent

- identify γ (π^0), n; measure energy and position of n and γ with reasonable resolution; reconstruct >1 particles, evtl. reconstruct $\pi^0 \rightarrow 2\gamma$; $\Lambda,\Delta \rightarrow n\pi^0$

- radiation resistant

- monitor the stability of PM gain and radiation damage (laser or LED), absolute calibration

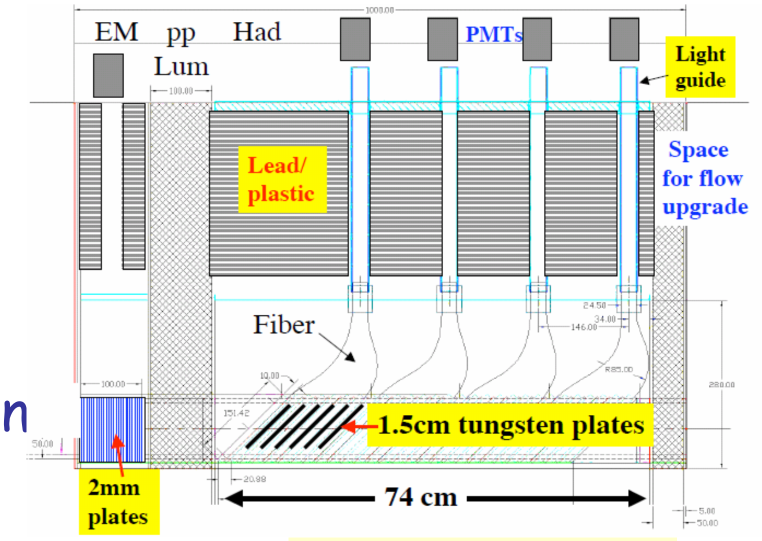
- control beam position and beam spot during data taking

ZDC for the LHeC – possible solutions

- Longitudinally segmented calorimeter: e/m (~1.5λ_I, fine granularity to reconstruct impact point) and hadronic (~7-8λ_I) sections, transverse size ~3λ_I, long. segmentation to control radiation damage

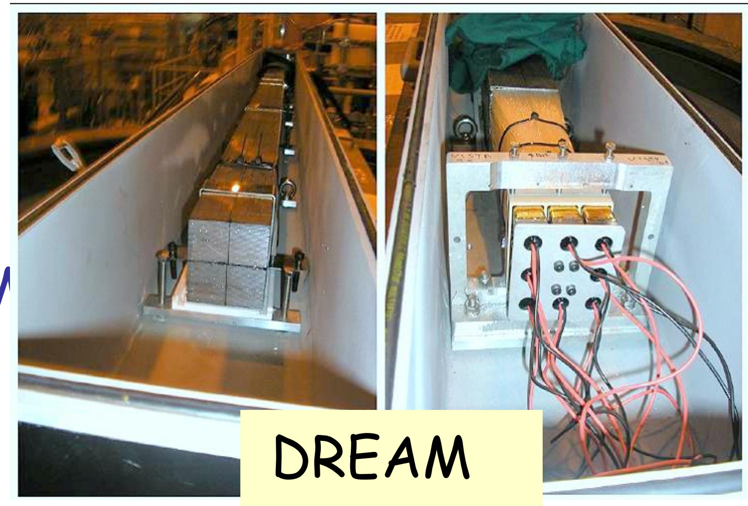
Experience from the LHC, RHIC – sampling hadron calorimeter: absorber-W plates, active media – quartz fibers (W/Čerenkov detectors are fast, rad. hard, narrow visible showers)

(One can also consider THGEM as an active media *O.Grachov, V.Kryshkin, et al.*)



CMS ZDC

- Make use of recent developments: e.g. Dual Readout (DREAM); Tungsten absorber with both Čerenkov and scintillators fibres, SiPM readout; γ/n separation using time structure



(G.Gaudio and R.Wigmans, DREAM Collaboration (RD52), Progress report June 2011)

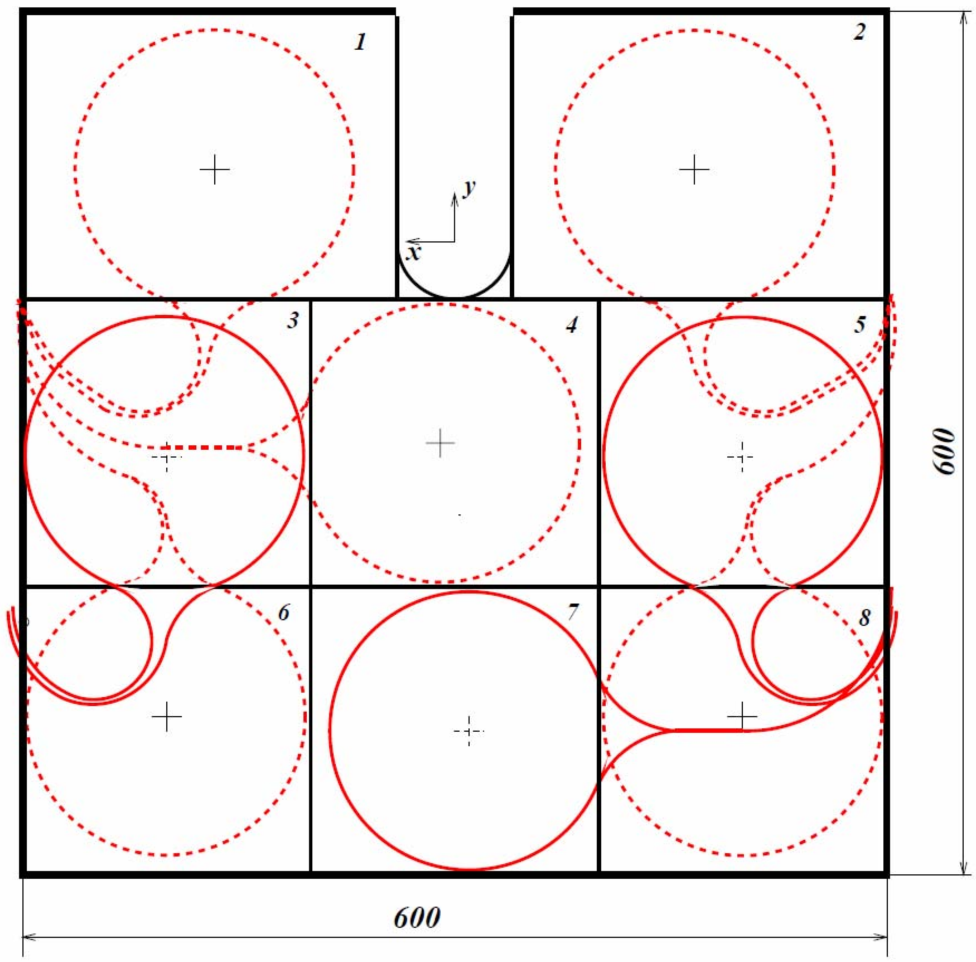
Conclusions

The Forward Neutron Calorimeters were valuable additions to both HERA experiments.
They provided many useful, interesting and unique data for physics analyses.

The concepts chosen for the construction of neutron calorimeters, design parameters and performance satisfied the requirements defined by physics program.

Zero Degree Calorimeter will be an important part of the future ep (ed,eA) experiment. Some ideas presented in the LHeC CDR.
Next steps: clarify the geometrical constraints, investigate the possible design options in details: use the experience from HERA, LHC… , explore novel particle detector concepts

Thank you for your attention !


1
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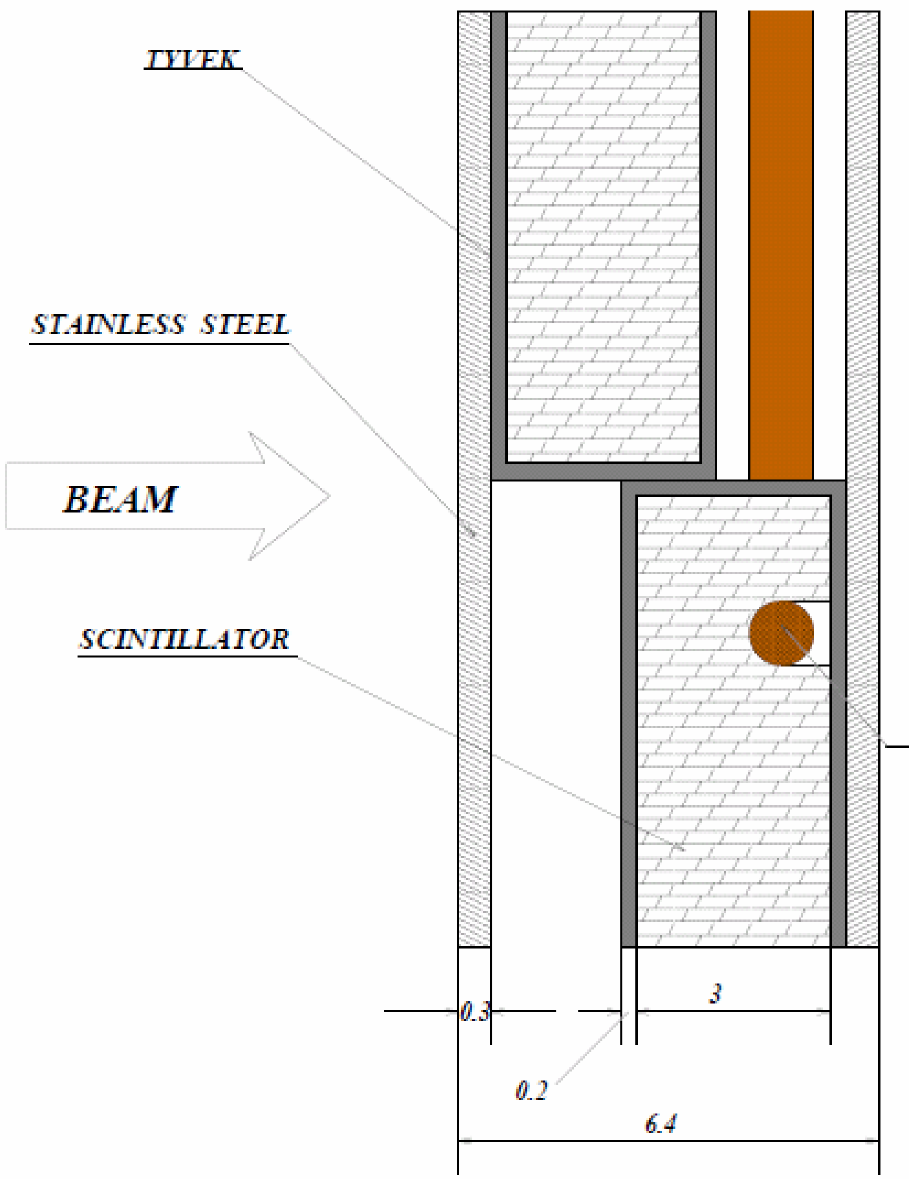

TYVEK
STAINLESS STEEL
BEAM
SCINTILLATOR
0.3
3
0.2
6.4

Control of energy calibration

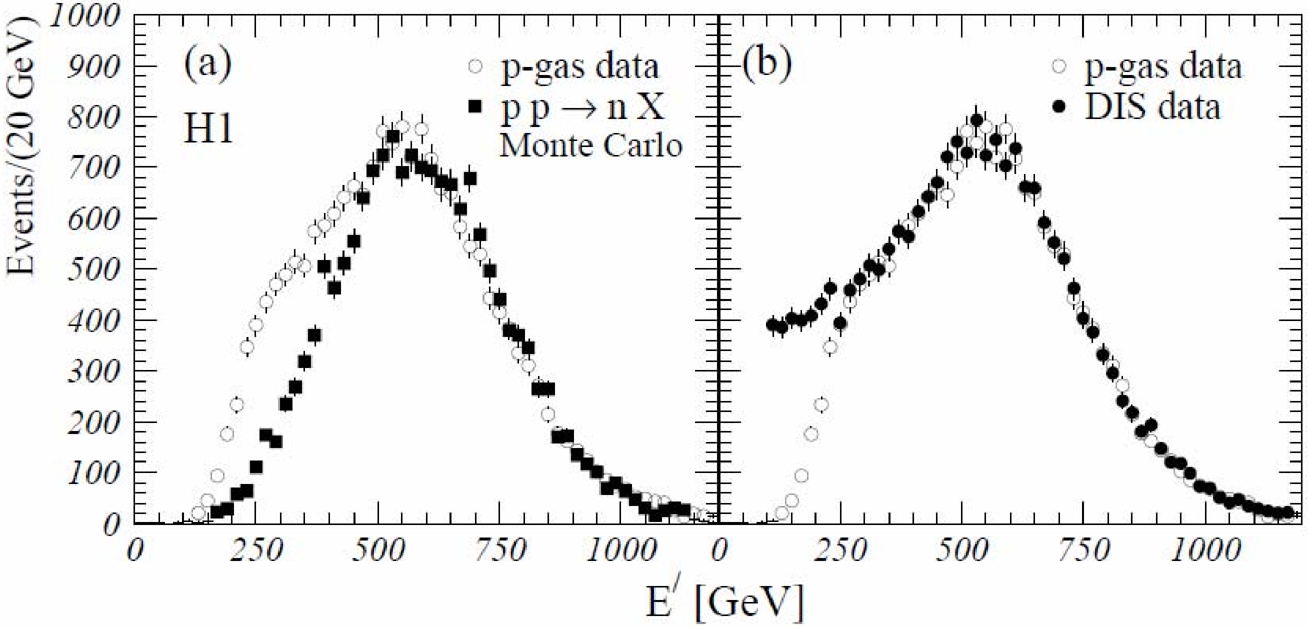


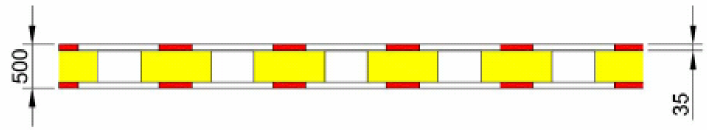
Figure 3: (a) The observed neutron energy spectrum in proton beam–gas interactions compared to the results of a $pp \to nX$ Monte Carlo simulation based upon pion exchange. The Monte Carlo simulates the acceptance and response of the FNC. (b) The same proton beam–gas energy spectrum compared to the neutron energy distribution observed in DIS interactions. The proton beam–gas energy spectrum has not been corrected for the trigger effi ciency which is less than 100% below 300 GeV. All distributions are normalized to the number of events with $E' \geq 500$ GeV.

ZDC for LHeC - general considerations

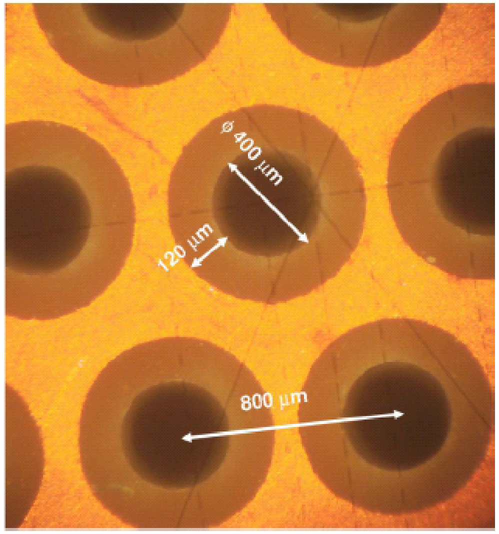
O.Grachov, V.Kryshkin, et al.

Another proposal: sampling calorimeter: absorber – Tungsten (~10 mm), active media – multilayer THGEM (thick gas electron multiplier) with gas mixture of Ar:CO_2 (70:30)

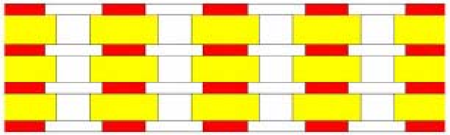
Schematic view of the THGEM.



The cross section of the THGEM – PCB 0.5 mm thick covered with 0.035 mm cop-per from both sides



Microscope photograph of the THGEM electrode



Fragment of the three layers THGEM electrode

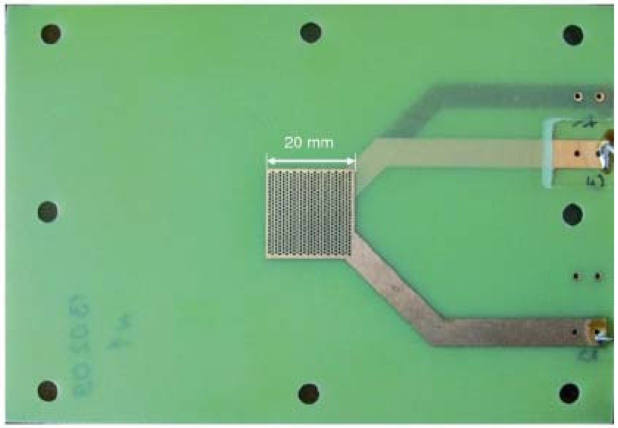
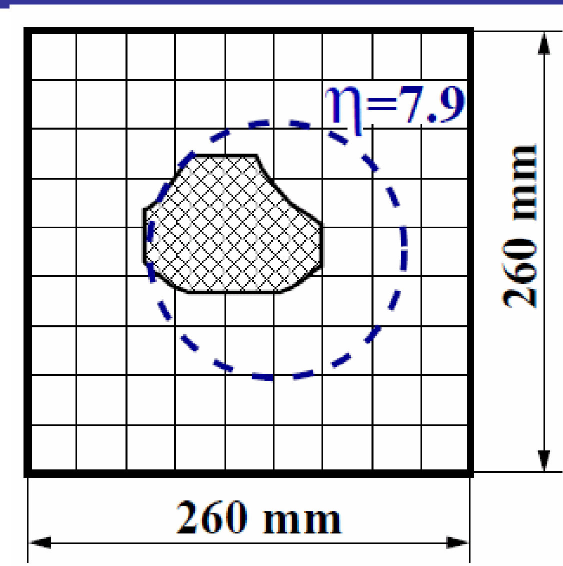


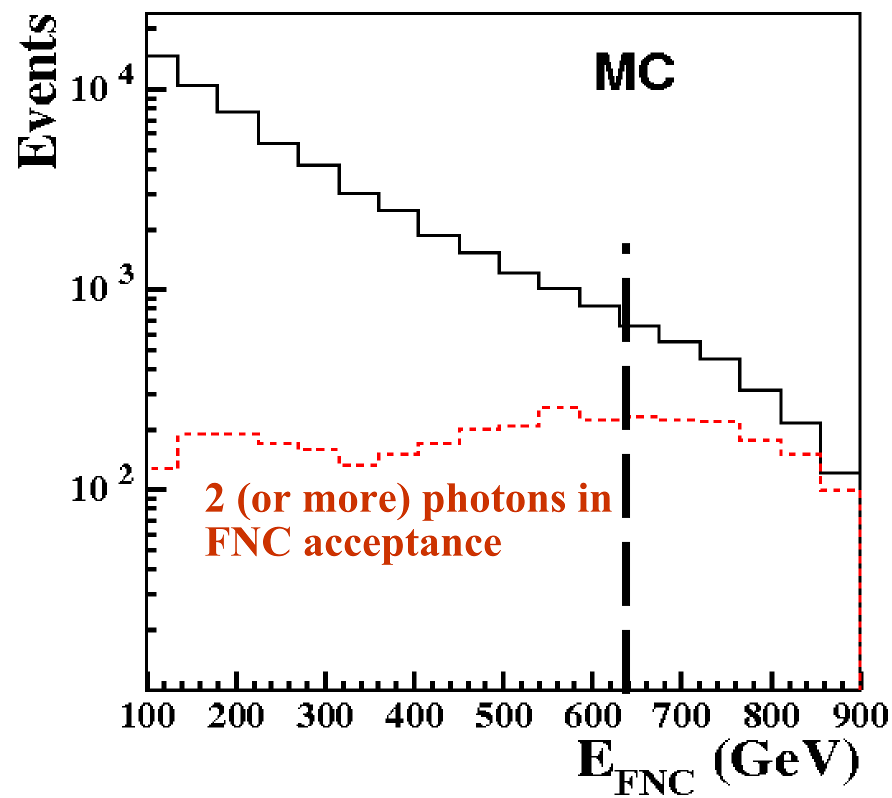
Photo of the three layers THGEM electrode The thickness of the electrode was 1 mm. If the cathode and anode plates have thickness 1 mm (to serve as the outer protective covers) then the total thickness of the chamber will be 7 mm and it can be easily inserted into W absorber of ZDC.

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 (η>7.9).

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



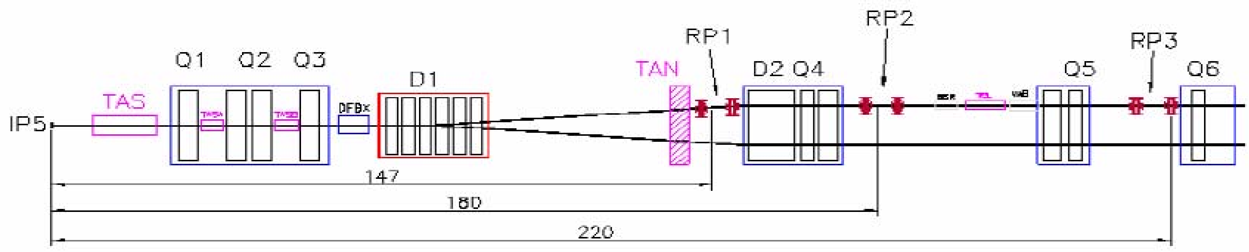


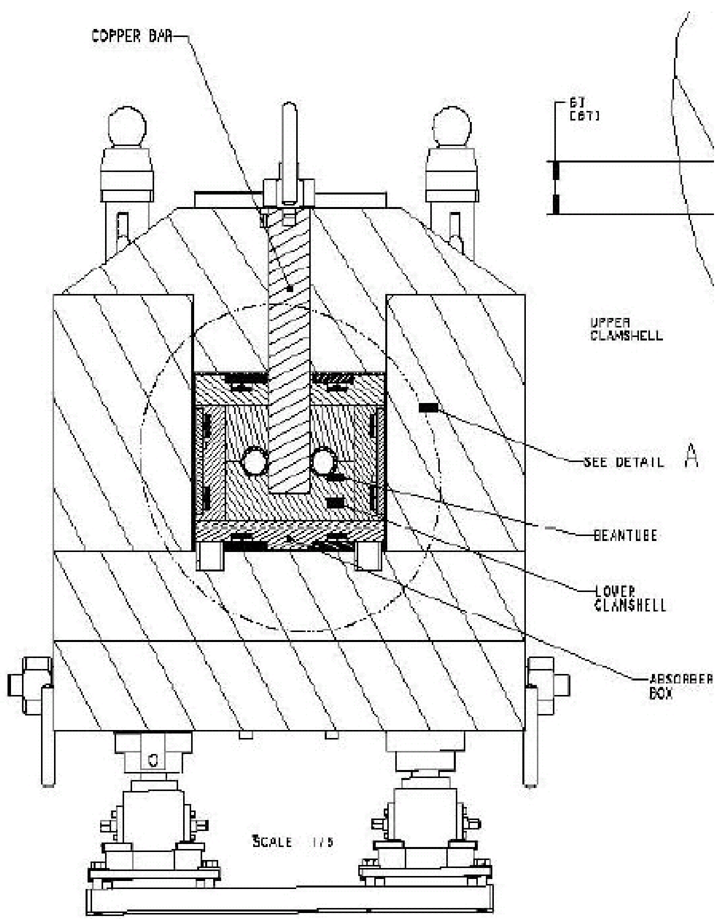
For photons with η>7.9 provide cross sections:

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

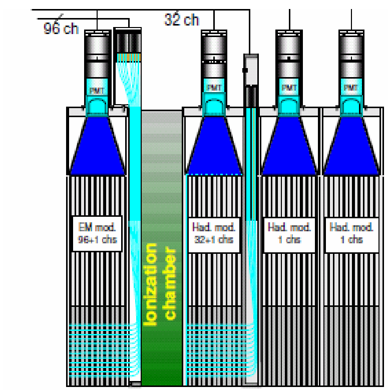
- x_L of sum of all photons

ZDC at the LHC detectors

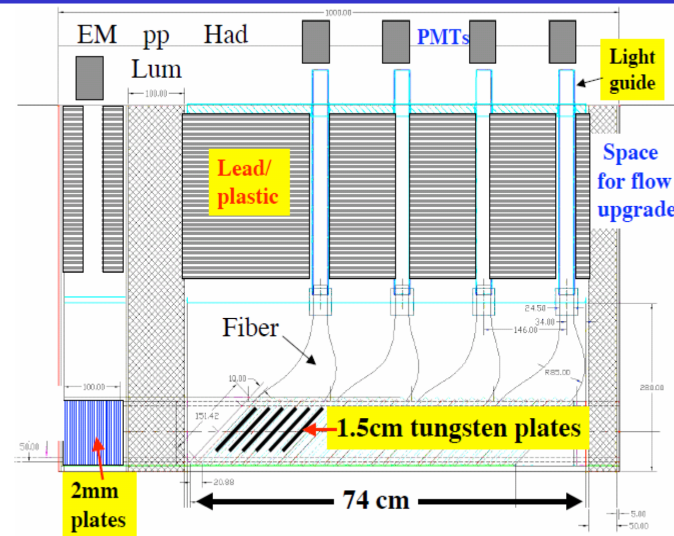




ZDC within TAN absorber



ATLAS



CMS

ALICE