POETIC IV
Physics Opportunities at an Electron-Ion Collider
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Measuring very forward (backward) at the LHeC

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Detectors located outside of the main detector
(~ 10 ÷ 100m from the Interaction Point)

Goals:
- Instantaneous luminosity
- Tag photo-production (Q^2~0)
  - Luminosity Detectors, Electron Tagger
- Very forward nucleons
  - Zero Degree Calorimeter, Forward Proton Spectrometer

CDR, arXiv:2306.2913, 1211.4831, 1211.5102; http://cern.ch/lhec

Luminosity measurement

Goals:

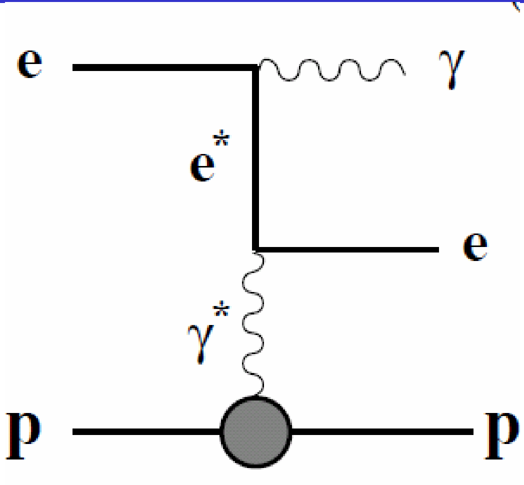
- Integrated luminosity with precision $\delta L \sim 1\%$
- Fast beam monitoring for optimisation of *ep*-collisions (1%/sec) and control of mid-term variations of instantaneous luminosity

Need to prepare several 'alternative' methods for luminosity determination

Requirements to physics process (visible cross sections)

fast monitoring	(δL=1%/sec	→ 10kHz)	σ_{vis}>100μb
mid-term control	(δL=0.5%/hour	→ 10Hz)	σ_{vis}>100nb
physics normalisation	(δL=0.5%/week	→ 0.1Hz)	σ_{vis}>1nb

The studies presented in CDR consider both LR and RR options



Bremsstrahlung ep→ eγp

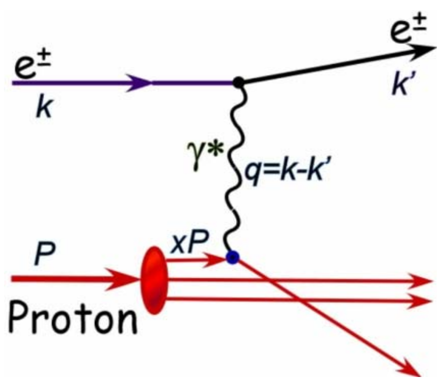
Bethe-Heitler (collinear emission):

- very high rate of 'zero angle' photons and electrons, but
- sensitive to the details of beam optics at IP
- requires precise knowledge of geometrical acceptance
- suffers from synchrotron radiation
- aperture limitation
- pile-up

QED Compton (wide angle bremsstrahlung):

- lower rate, but
- stable and well known acceptance of central detector

➔ **Methods are complementary, different systematics**



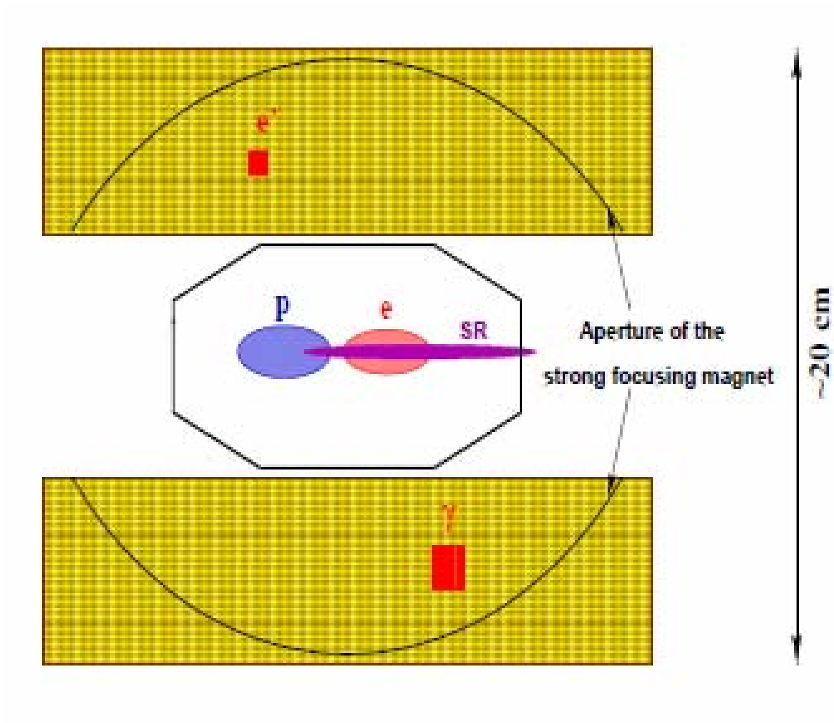
NC DIS in (x,Q^2) range where F_2 is known to $O(1\%)$
for relative normalisation and mid-term yield control

Luminosity measurement: QED Compton

electron and photon measured in the main detector (backward calorimeter)

σ_{vis} ~3.5 nb (low Q^2 setup)

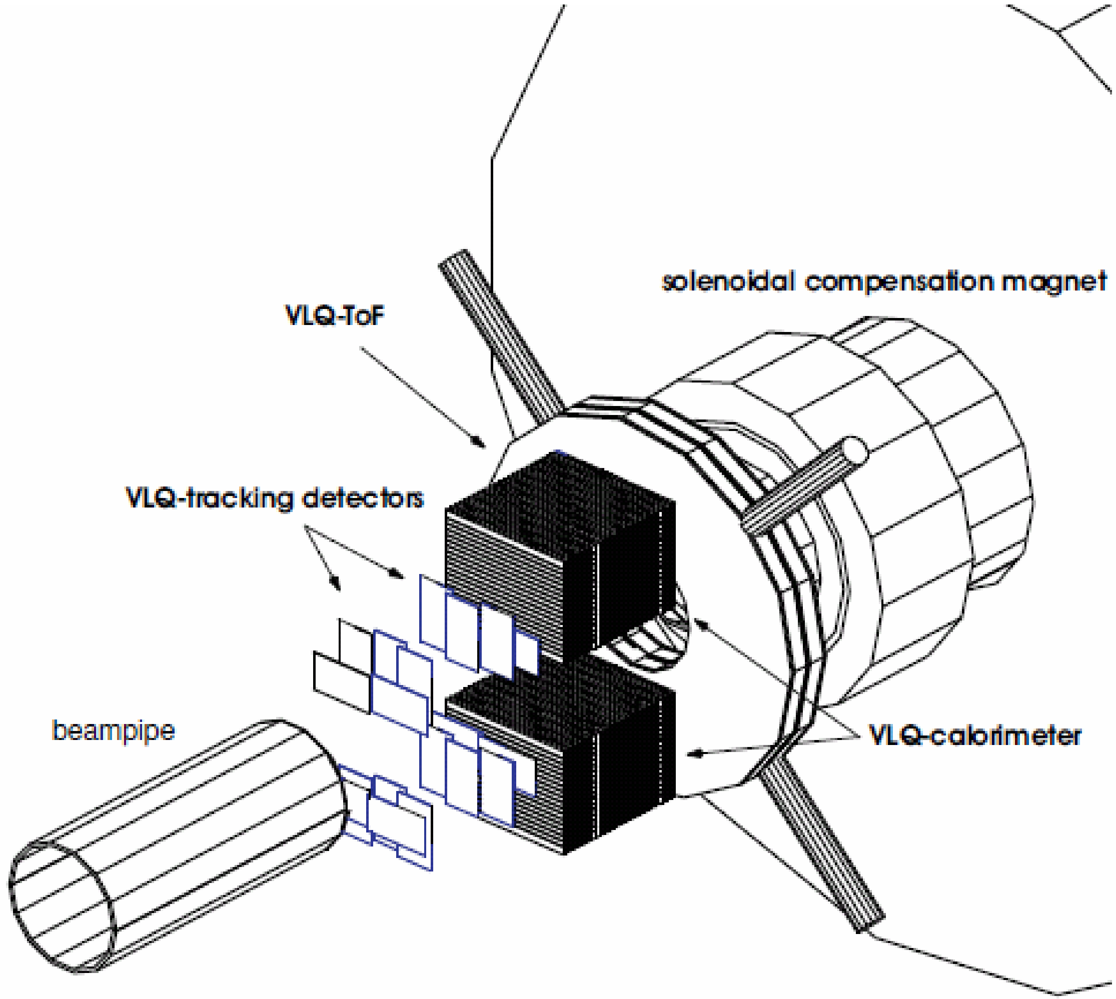
visible cross section for QEDC can be increased up to ~3-4 nb with additional 'QEDC tagger' at z≈-6m →→ e.g. two moveable sections approaching the beam-pipe from top and bottom (assume angular acceptance $\theta \approx 0.5 \div 1^o$)



Detector requirements:

- good position measurement, resolution, alignment for the movable sections
- good energy resolution, linearity
- small (and well known and simulated) amount of dead material in front
- efficient e/γ separation → a small silicon tracker in front of calorimeter modules (this also allows z-vertex determination)

An example for QEDC tagger: H1 VLQ calorimeter



Luminosity measurement: QED Compton - uncertainty

HERA (H1) σ_{vis} ≈ 50 pb; <L> = 1.5e+31cm^{-2}s^{-1} → 0.75e-3 Hz
LHeC ~2000 pb; <L> = 4.0e+32cm^{-2}s^{-1} → 0.80 Hz (1000 x HERA !)

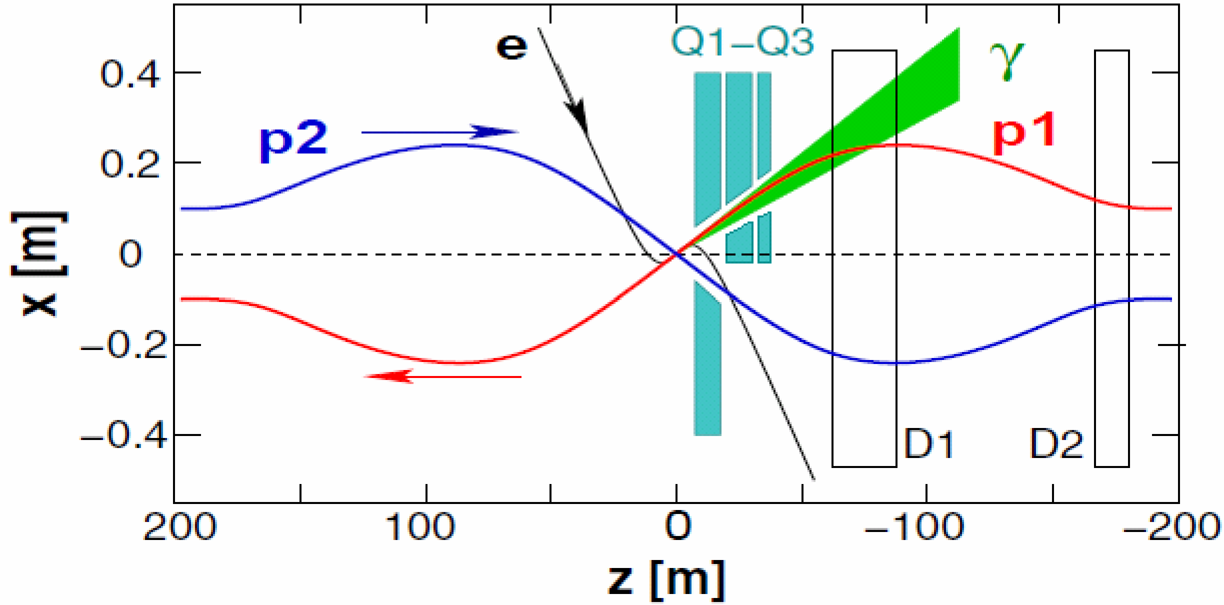
Stat.error: H1 ~ 4.50% /month (0.8% for full HERA2 sample)
LHeC ~ 0.15% /month

This allows much harder cuts against background → smaller syst.error

	H1(2004-2007)	LHeC/month
syst.error		
experimental	1.4%	0.8% (improved E-scale and E-resolution)
background	1.2%	0.4% (harder cuts, esp. on acoplanarity)
theory	1.1%	0.6% (improved higher order corrections)
stat.error	0.8%	0.2% (bigger acceptance, Luminosity)
total error	2.3%	1.1%

Luminosity measurement: Bethe-Heitler ($ep \rightarrow e\gamma p$)

For **LR** option (zero crossing angle) the photons travel along the proton beam direction and can be detected at z≈-120m, after the proton bending dipole.
→ Place the photon detector in the median plane next to interacting proton beam



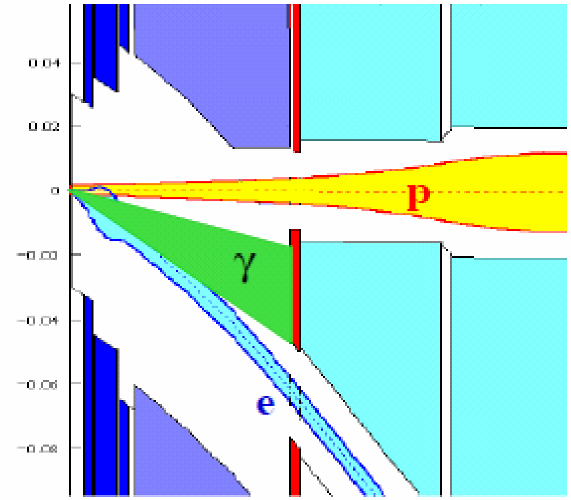
Main limitation – geometrical acceptance, defined by the aperture of Q1-Q3.
May be need to split dipole D1 to provide escape path for photons.
Geometrical acceptance of 95% is possible, total luminosity error δL≈1%.

- need to clarify and calculate acceptance and its variations due to beam optics; (this is essentially HERA setup, so we can use similar detectors/methods)

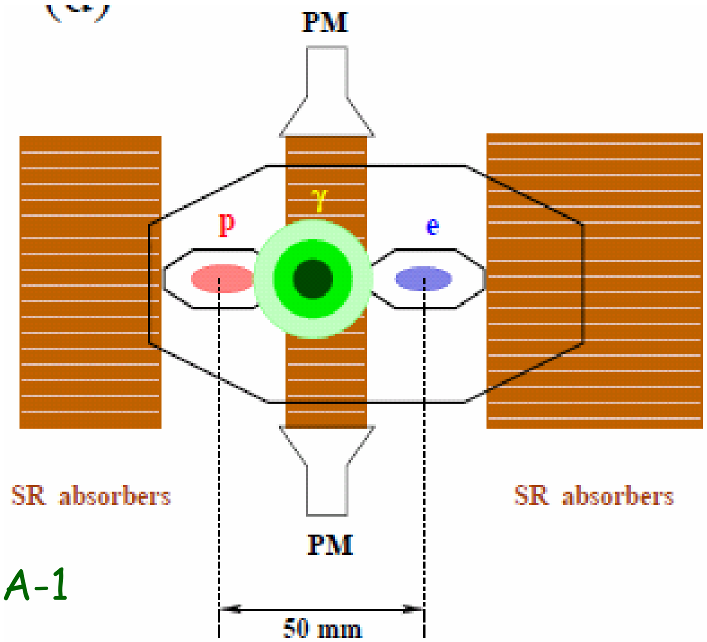
Luminosity measurement: Bethe-Heitler ($ep \rightarrow e\gamma p$)

For **RR** option (1mrad crossing angle) the dominant part of photons will end up at z≈-22m, between *e* and *p* beampipes

→ **very high synchrotron radiation !**



Idea is to use the cooling water of SR absorber as active media for Čerenkov calorimeter; r/o two PMs:
- radiation hard
- insensitive to SR



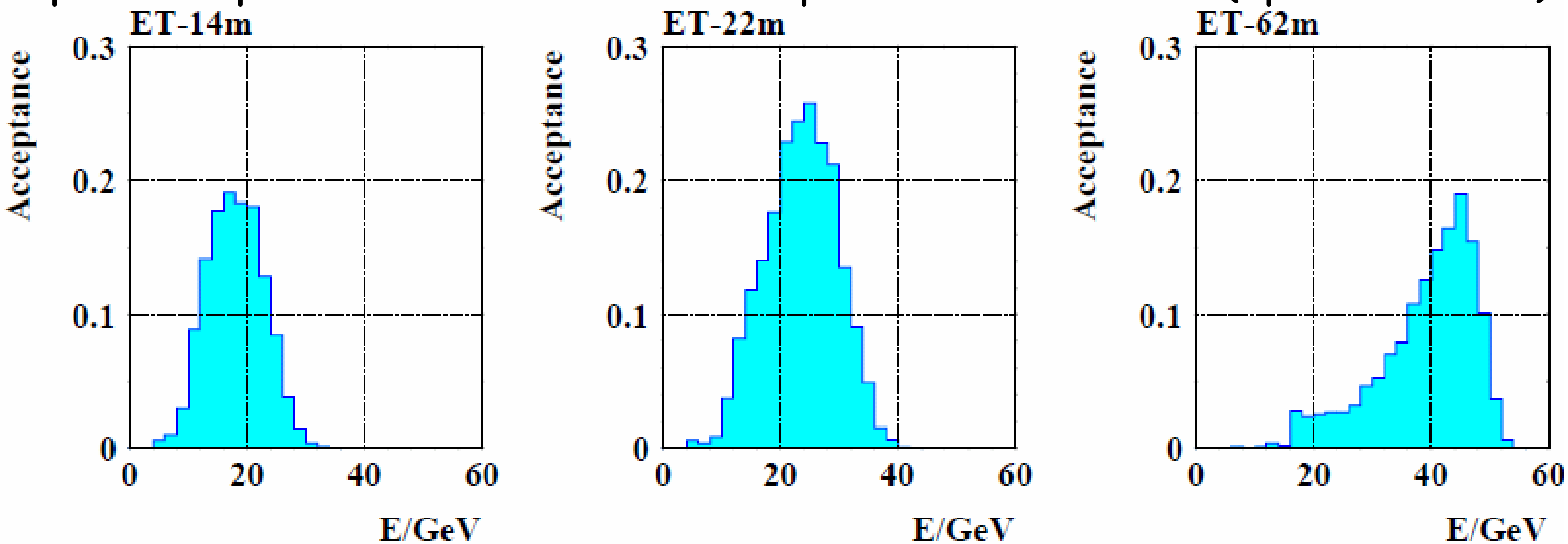
Geometrical acceptance of ~90% allows fast and reliable luminosity determination with 3÷5% systematic uncertainty

* Water Čerenkov detector was successfully used in H1 during HERA-1

Electron tagger

detect scattered electron from BH (also good for photoproduction physics and for control of γp background to DIS)

Clean sample – background from e-gas can be estimated using pilot bunches.
Three possible positions simulated→ acceptances reasonable (up to 20÷25%)



62m – less SR, more space. Need detailed calculation of acceptance and variations due to optics (beam-tilt, trajectory offset) and etagger position measurement and stability

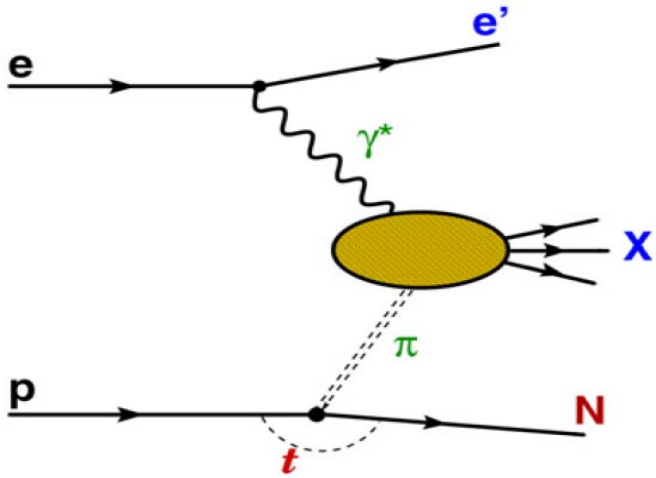
Need a precise monitoring of beam optics and accurate position measurement of the etagger to control geometrical acceptance to a sufficient precision (e.g. 20μm instability in the horizontal trajectory offset at IP leads to 5% systematic uncertainty in the σ_{vis})

Main experimental difficulty would be good absolute calibration and resolution (leakage over the detector boundary)

Zero Degree Calorimeter (ZDC): physics potential

Measure neutrons and photons scattered at ~0°.

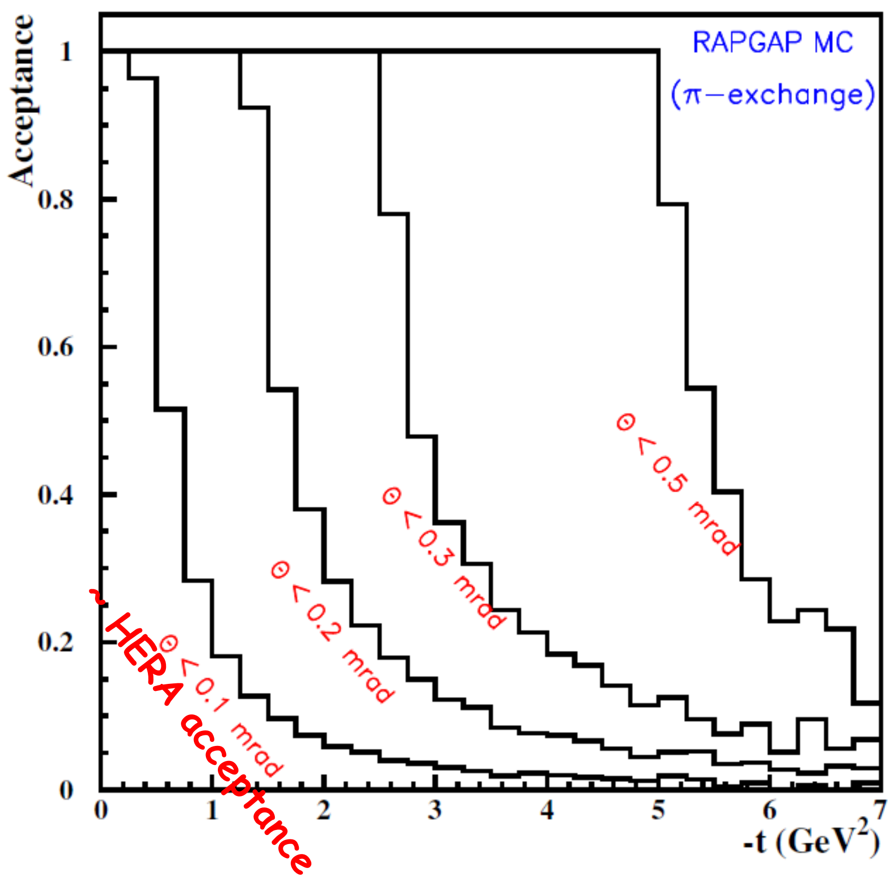
- tag pion exchange process, pion structure, absorptive /gap survival effects
- colour single exchange, diffractive scattering
- tag spectator neutron in ed scattering, distinguish spectator and scattered neutrons
- Crucial in diffractive eA, to distinguish coherent from incoherent diffraction
- Measurements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

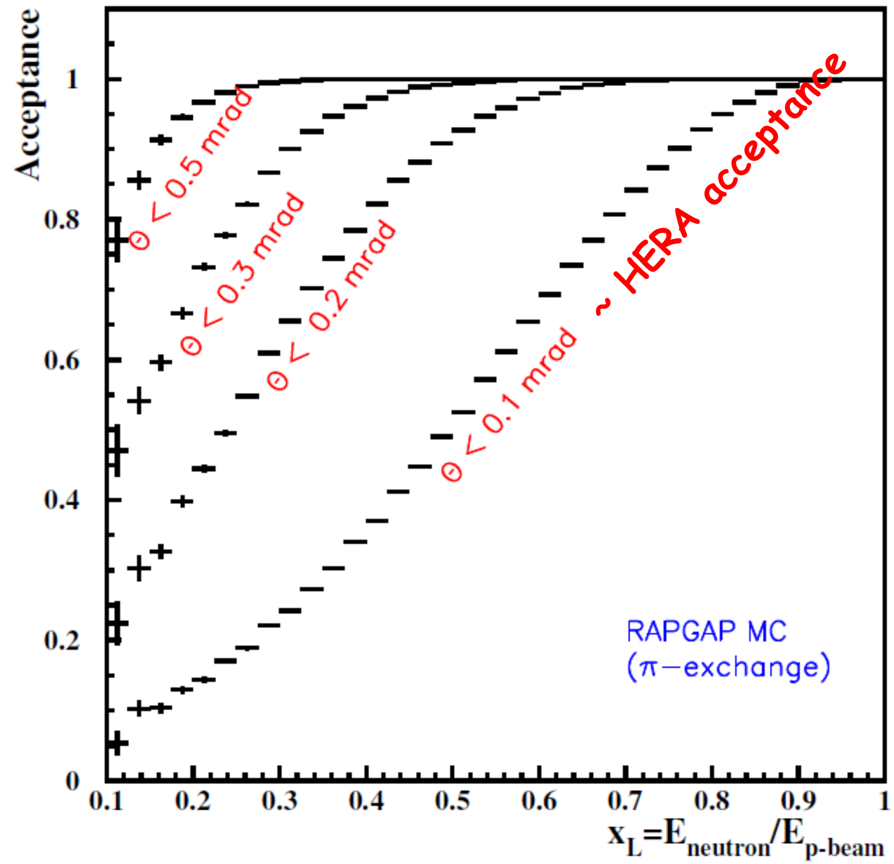


At HERA, both experiments had Forward Neutron Calorimeters (FNC)
The LHC experiments- Alice, ATLAS, CMS and LHCf- have ZDC.

Acceptance for forward neutrons vs energy for LHeC (7000 GeV x 70 GeV)

Study acceptance for neutrons vs x_L=En/Ep and t, depending on angular range
(assume neutron calorimeter at ~100m: 1mrad is ±10cm ; 0.1mrad is ±1cm ;



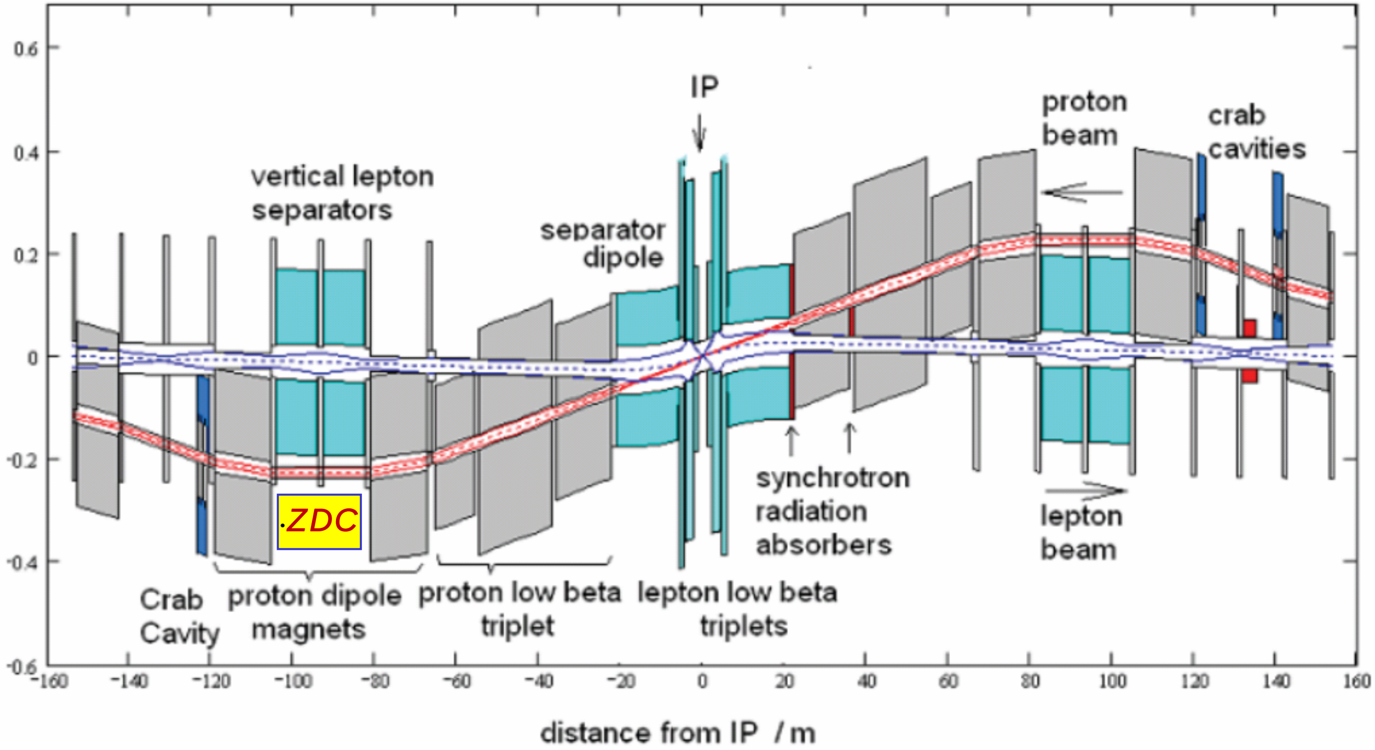


At HERA the FNC acceptance was limited by beam aperture to θ < 0.8 mrad. 0.8 mrad acceptance cut at HERA corresponds to ~0.1 mrad at LHeC !
With ~ ±3cm we can get quite reasonable acceptance, >90% for x_L>0.3, |t|<3 GeV^2

Zero Degree Calorimeter

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

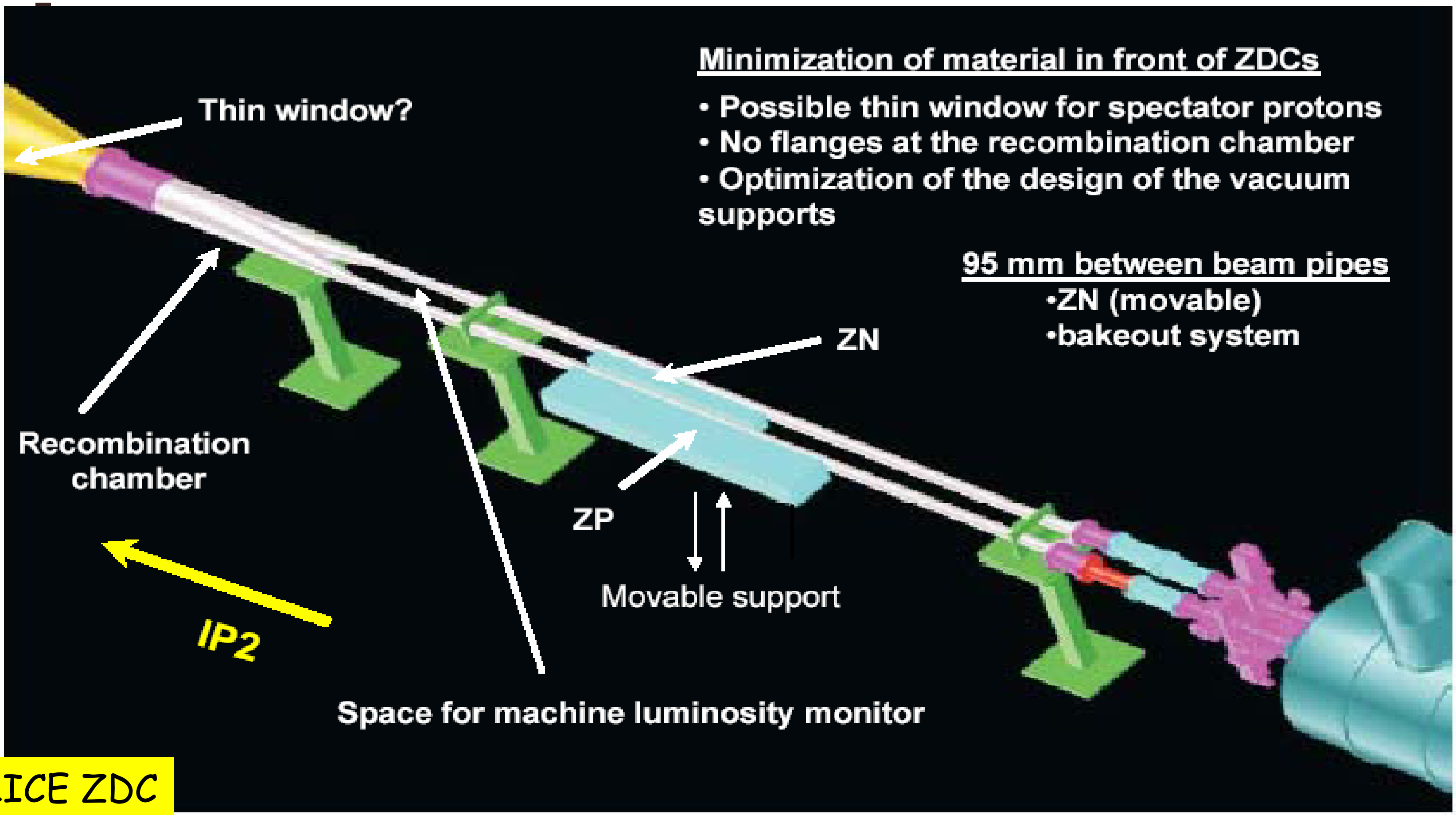
→need detailed info/simulation of beam-line



We consider also the ZDC for the measurement of spectator protons from eD or eA scattering (positioned external to proton beam as done for ALICE)

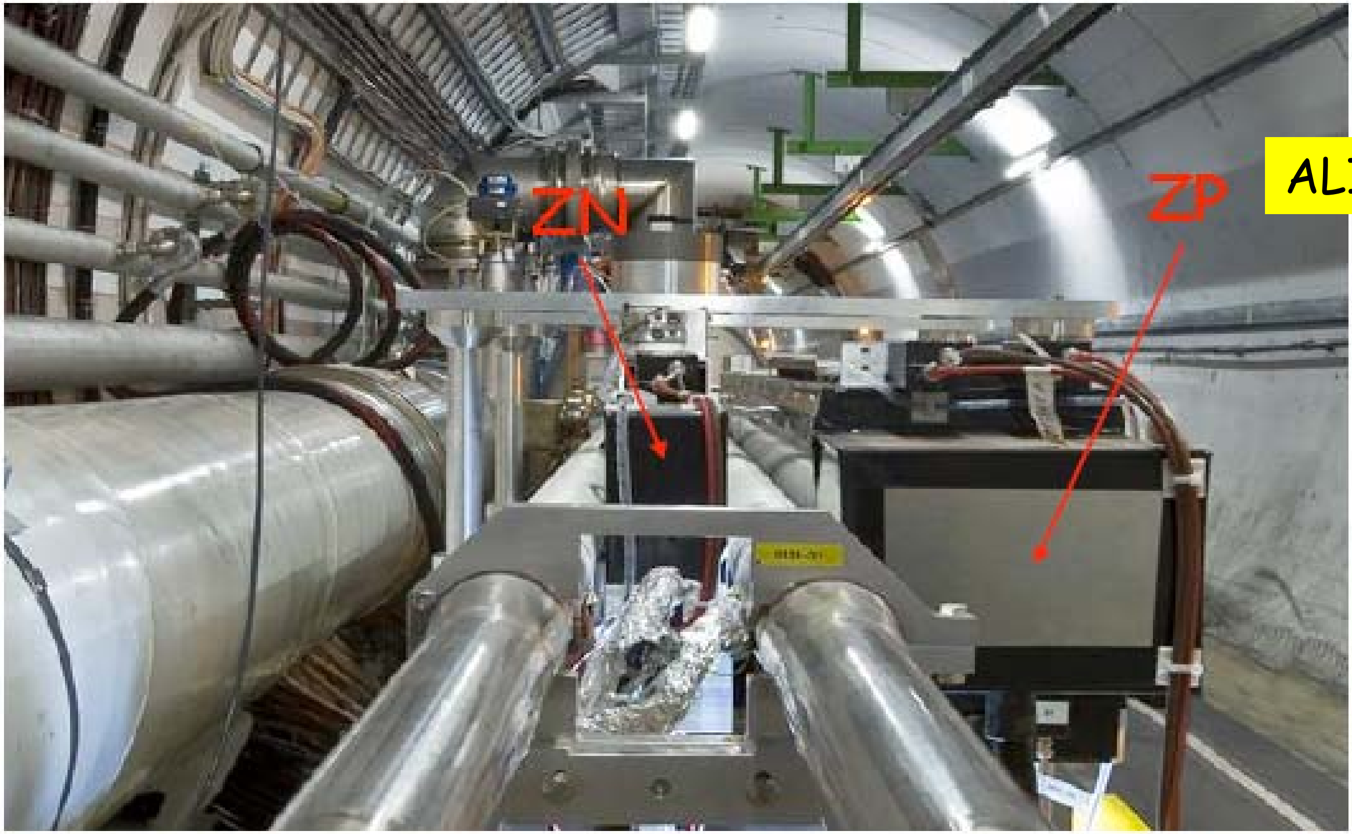
Zero Degree Calorimeter for the LHeC

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

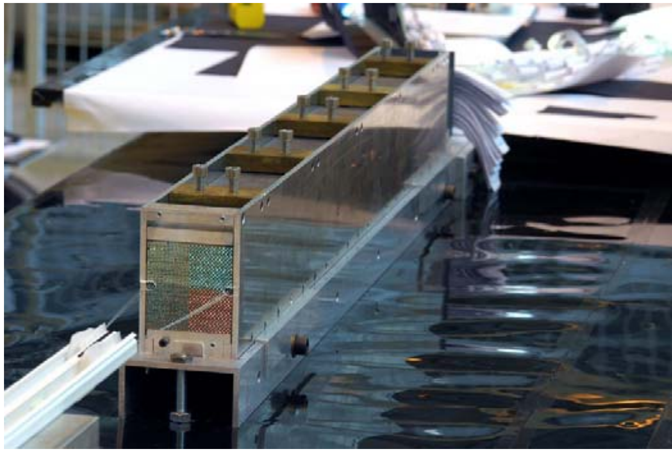


ALICE ZDC

Zero Degree Calorimeter



ALICE ZDC



ZDC for the LHeC - general considerations

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

- Requirement to the calorimeter: 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

- position sensitive: control beam position and beam spot during data taking

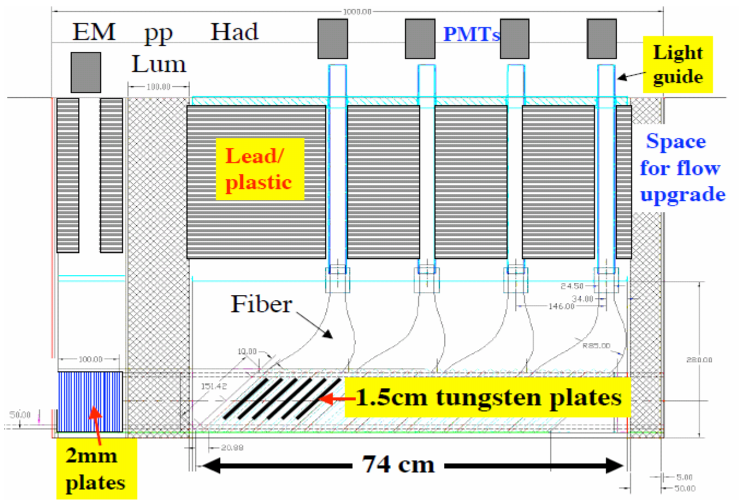
ZDC for the LHeC – possible solutions

- 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

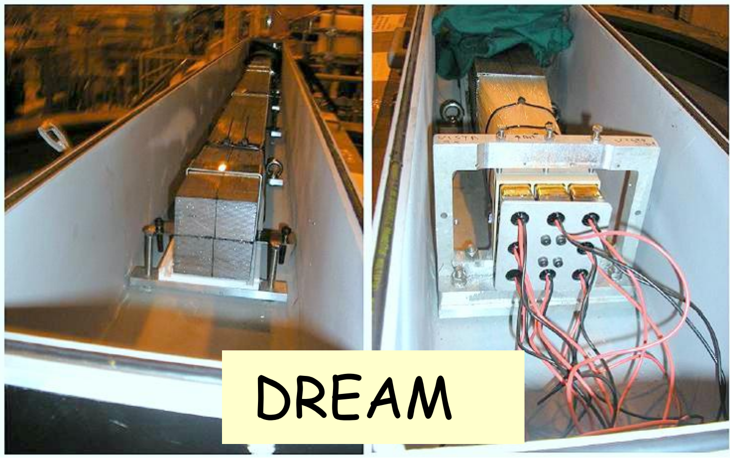
Experience from the LHC, RHIC – sampling hadron calorimeter: absorber-W plates, active media – quartz fibers (W/Čerenkov detectors are fast, rad. hard, narrow visible showers)

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

- 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 and lateral shower profile
(R.Wigmans, RD52/DREAM project, EPS 2013)



CMS ZDC


DREAM

<u>Proton calorimeter</u> – similar technique as for neutron detector, at about same distance from IP; can be smaller- few cm small size of spectator proton spot, but sufficient to obtain shower containment

(R.Wigmans, RD52/DREAM project, EPS 2013)

Dual readout fibre calorimeter

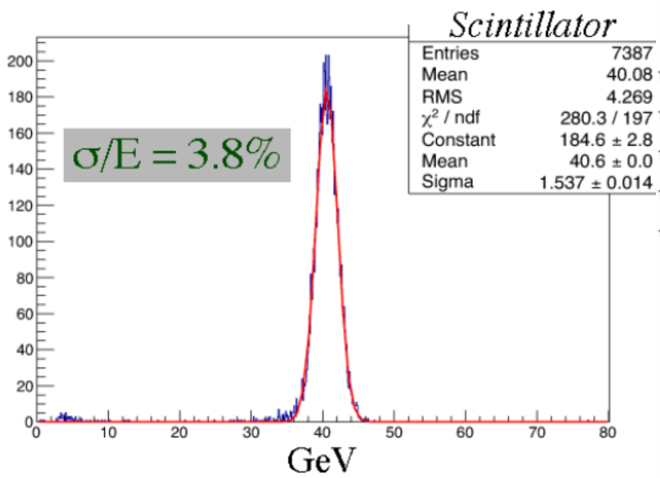
- eliminate f_{em} fluctuations
- improve stochastic fluctuations

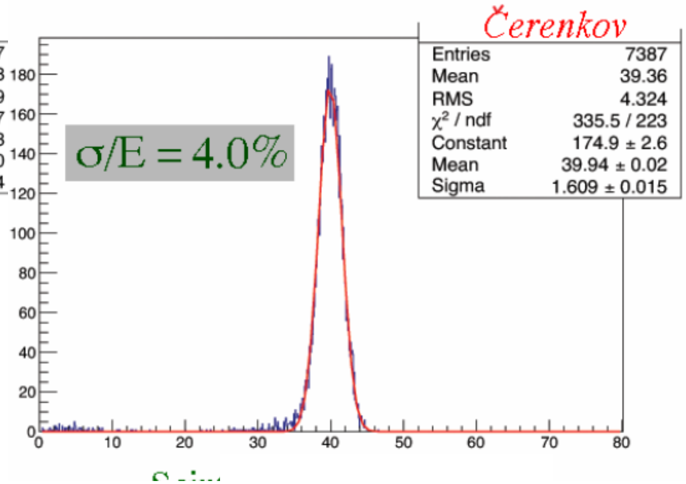
9 modules (36 towers, 72 signals), 1.4 tonnes Pb/fiber + 2 modules Cu/fiber
20 leakage modules (500 kg plastic scintillator)

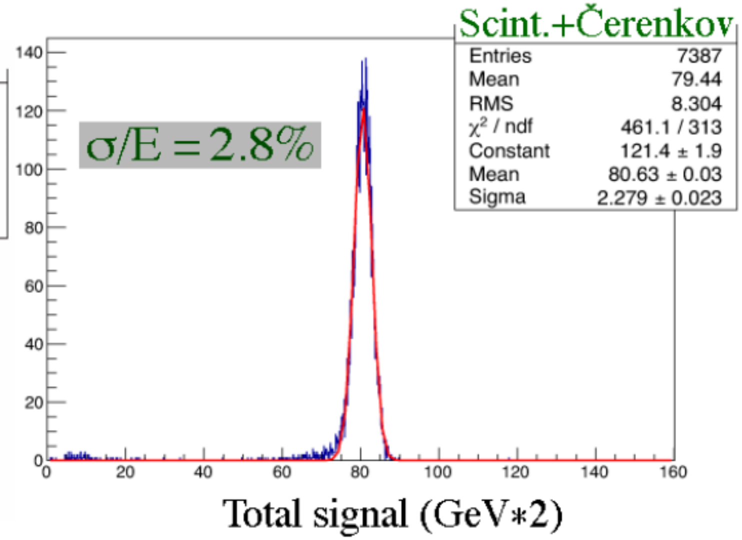
SuperDREAM may consider to investigate option with Tungsten, test SiPM readout on fibres

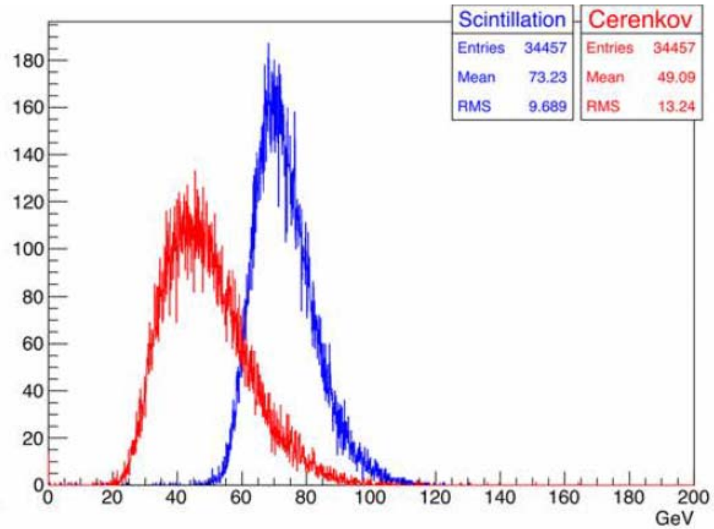
Independent Scintillator and Cherenkov readout; Resolution improved by combining

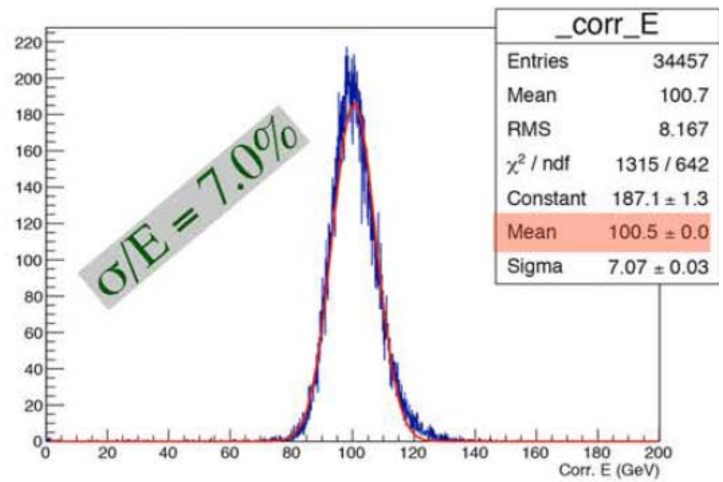
40 GeV e-









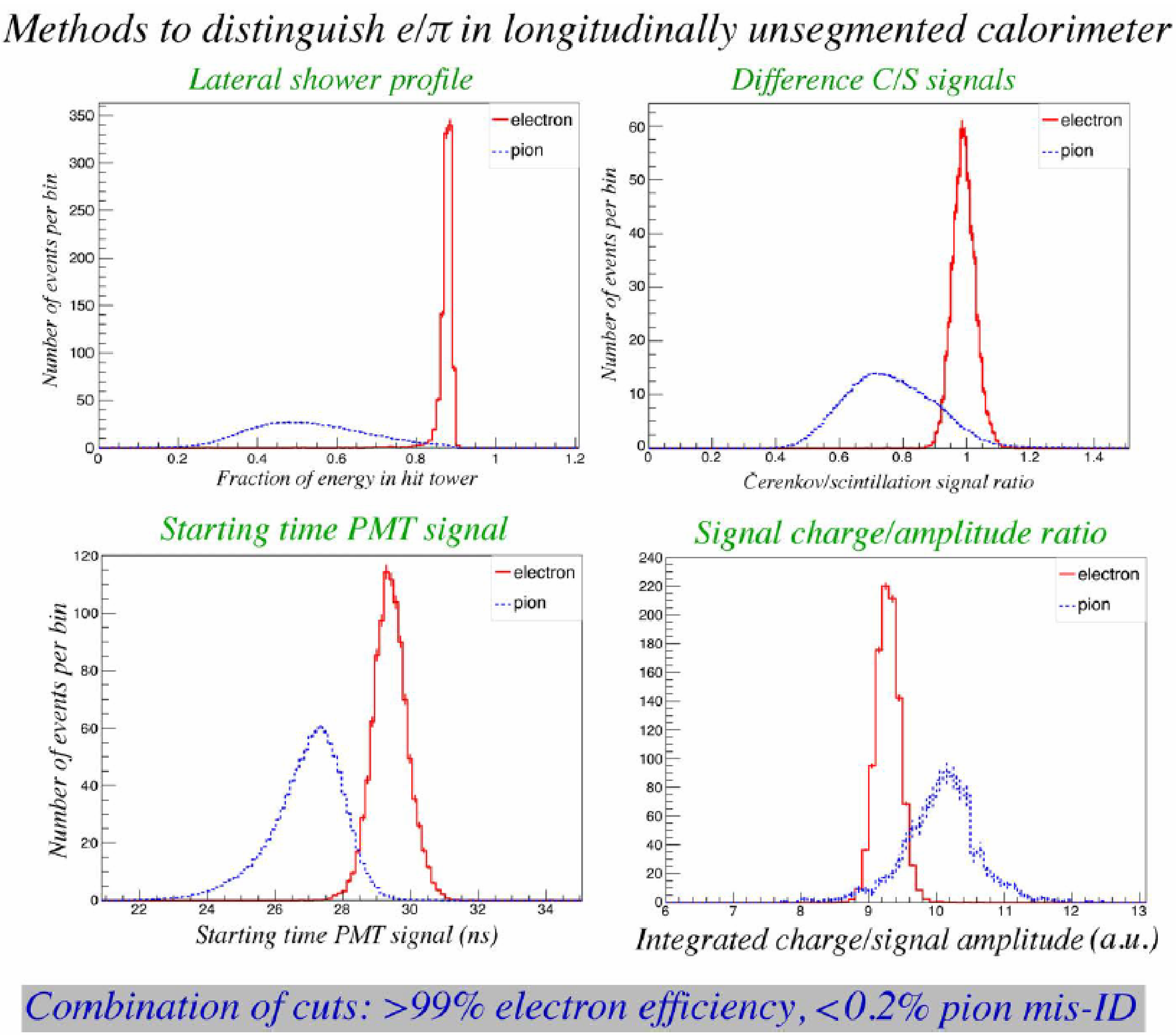


100 GeV π-

(R.Wigmans, RD52/DREAM project, EPS 2013)

- different methods available

(R.Wigmans, RD52/DREAM project, EPS 2013)



ZDC calibration and monitoring

Need on-line gain monitoring, relative and absolute calibration

- Stability of the photomultiplier gain and radiation damage in fibres can be monitored using laser or LED light pulse.

-In the dual-readout approach, make readout from both sides of fibres – control of radiation damage

- Stability of absolute calibration using neutron spectra from beam-gas interaction.

- Invariant masses $\pi^0 \rightarrow 2\gamma$, $\Lambda,\Delta \rightarrow n\pi^0$ (Need to reconstruct several particles in ZDC within same event)

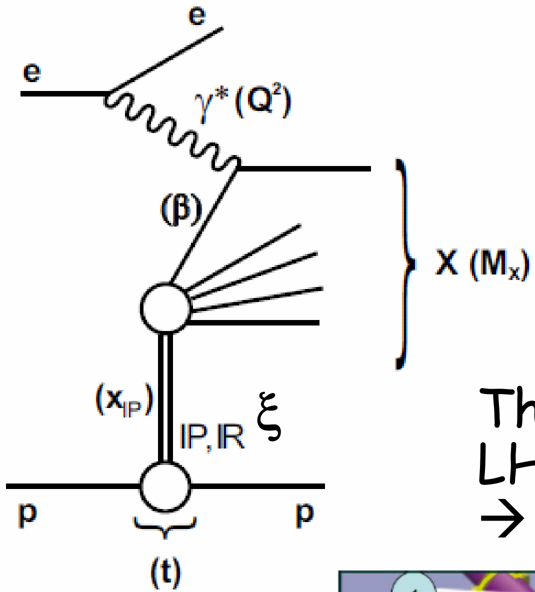
also need to care about

-Background rate (beam-gas), pileup

-How large (and how well known) is the proton beam spread and 0^0 direction at IP ?

-Beam emittance, divergence → limitation for t (p_T) resolution

Forward Proton Detection

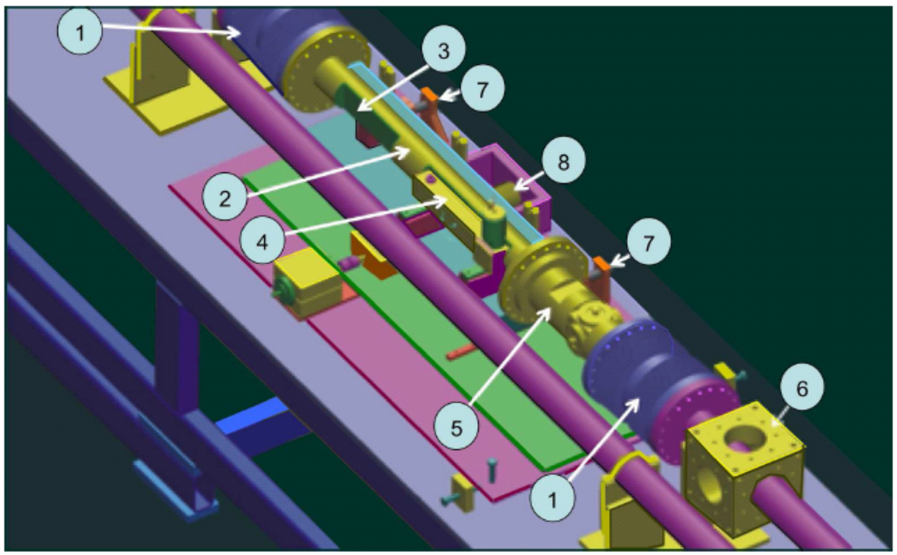


ep→ eXp' diffractive scattering

(proton survives a collision and scatters at a low angle along the beam-line)

$\xi \approx 1 - E_{p'}/E_p \sim 1\%$

The feasibility to install forward proton detectors along the LHC beamline investigated at the ATLAS and CMS
→ the results of R&D studies are relevant for LHeC



(from ATLAS AFP Project)

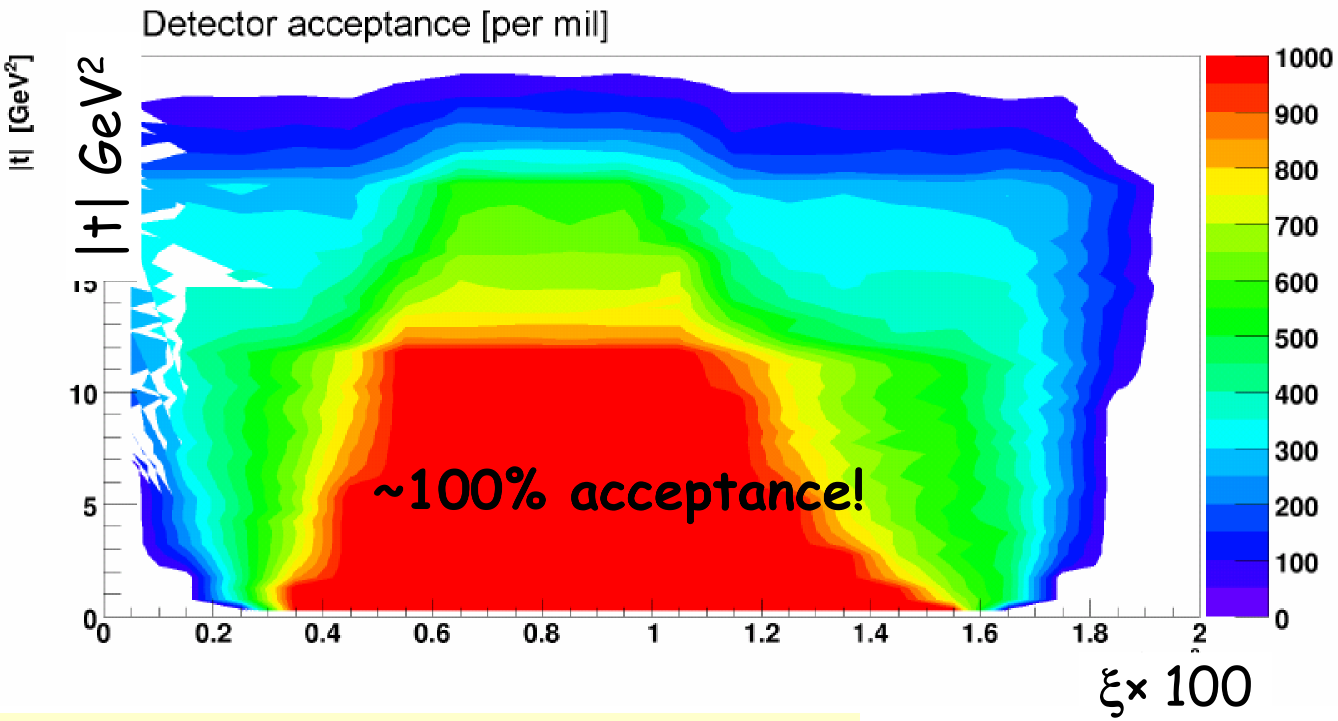
Figure 3.2: Top view of one detector section: bellows (1), moving pipe (2), Si-detector pocket (3), timing detector (4), moving BPM (5), fixed BPM (6), LVDT position measurement system (7), emergency spring system (8).

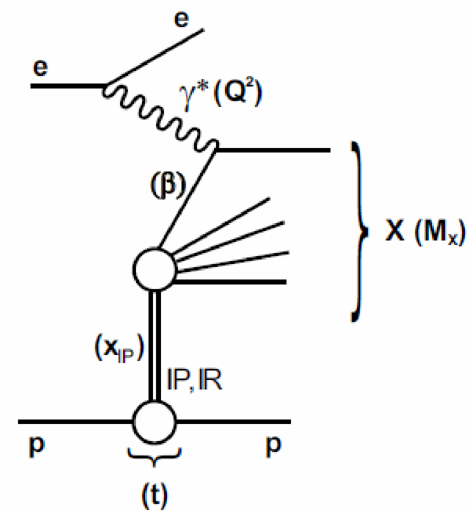
Acceptance for forward protons at LHeC

- Scattered protons are separated in space from the nominal beam:
  ($x_{offset}=D_x \times \xi$; D_x - energy dispersion function)

- Acceptance window is determined by the closest approach of proton detectors to the beam, and by the size of beam-pipe walls

Assume closest approach $12\sigma_{beam}$ (σ_{beam}=250μm at 420m), $R_{beampipe}\approx$2cm, $D_x\approx$ 1.5m

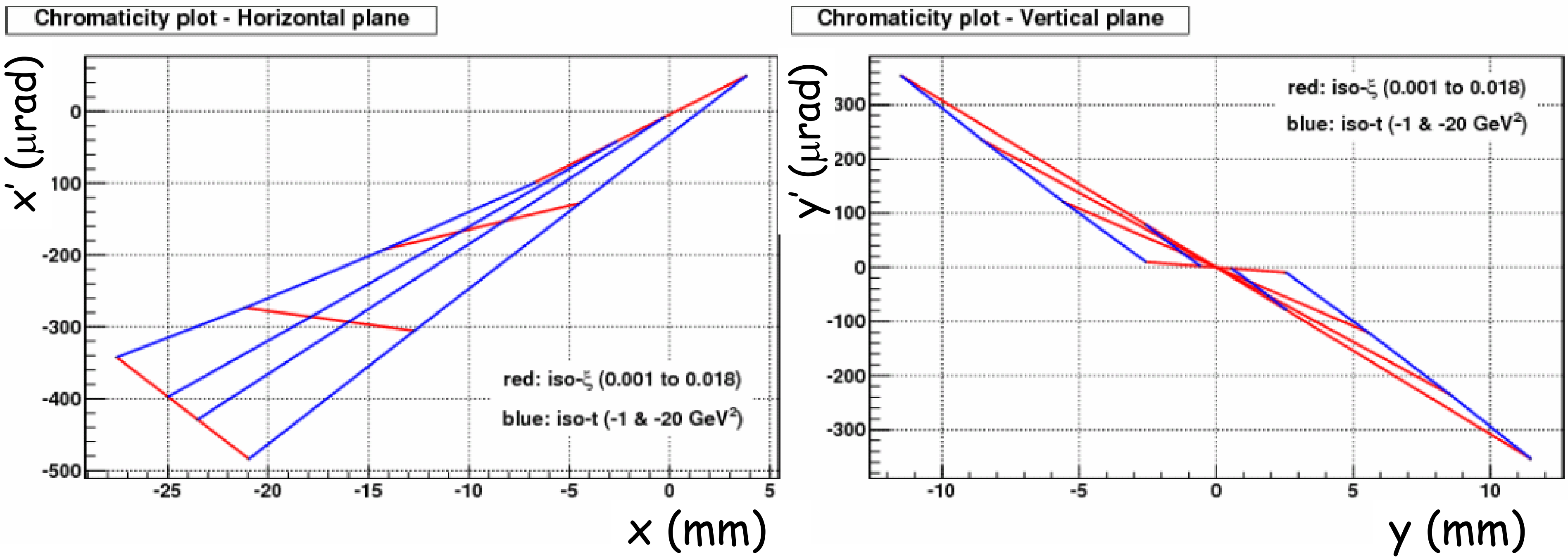




Good acceptance for 0.002<ξ<0.013

Forward protons: Reconstruction of event kinematics

The event kinematics ξ and $t \approx (1-\xi)E_{beam}\theta^2$ can be determined from the measurement of proton position and angle w.r.t. nominal beam



Relation between position and angle w.r.t. nominal beam and the t and ξ

Resolution limited due to beam divergence and width: typically 0.5‰ for ξ and 0.2μrad for θ.

Forward protons: alignment

Alignment of FPS - crucial: detector position with respect to the beam direction is not constant

➔ need to align (and monitor) detector position for each luminosity fill

- kinematic peak method - cross section maximal for forward scattering;
- use exclusive system, with well defined kinematics (e.g. $ep \rightarrow e' + \rho + p'$, ρ-meson reconstructed in the central tracker)

→ Need detailed studies

Conclusions

Forward and backward 'tunnel' detectors – important parts of the future ep (ed,eA) experiment

Ideas for the luminosity detectors, electron tagger, ZDC and FPS detectors described in the LHeC CDR

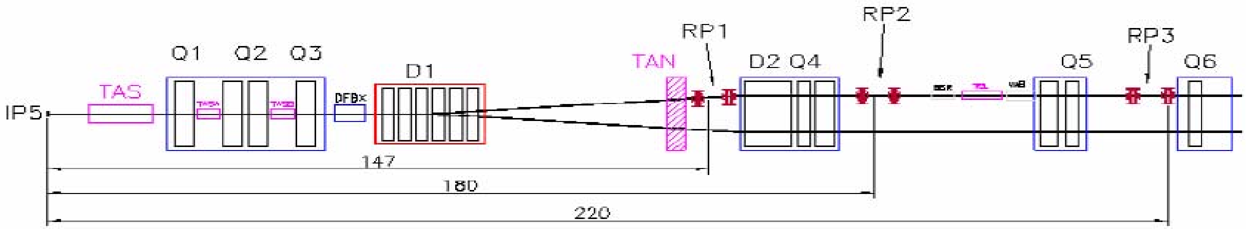
For TDR: clarify the geometrical constraints; investigate the possible design options in details

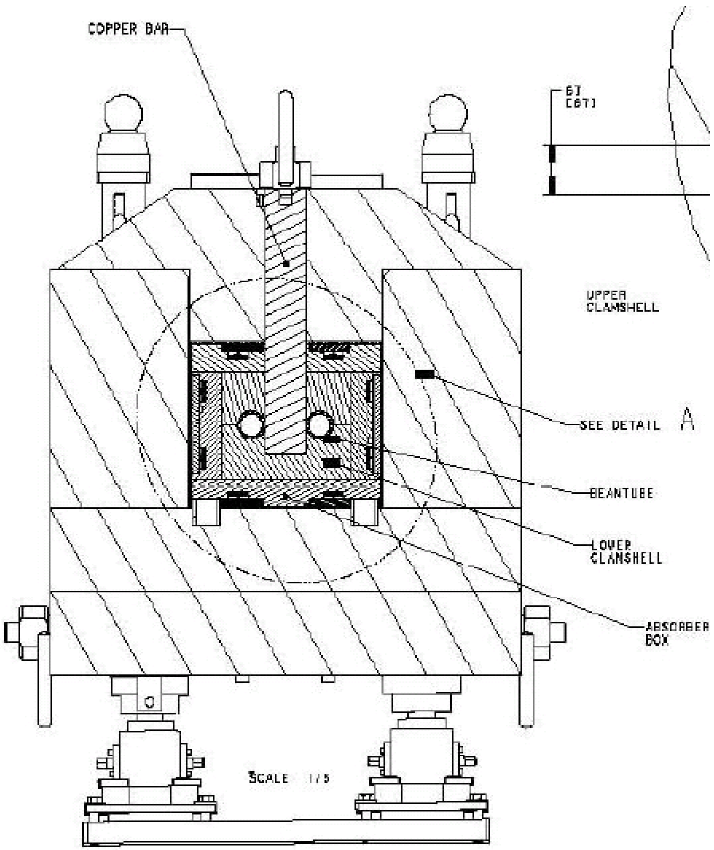
Design of detectors – challenging task !
- Use the experiences from HERA, LHC, RHIC,...
- Explore novel particle detector methods.


THANKS FOR AN ENJOYABLE WORKSHOP !!!

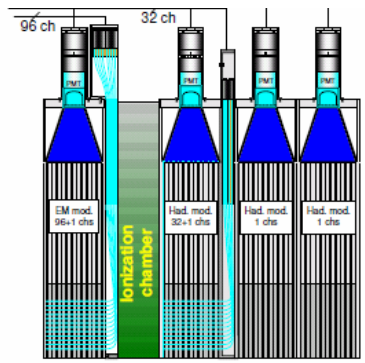
backup

ZDC at the LHC detectors

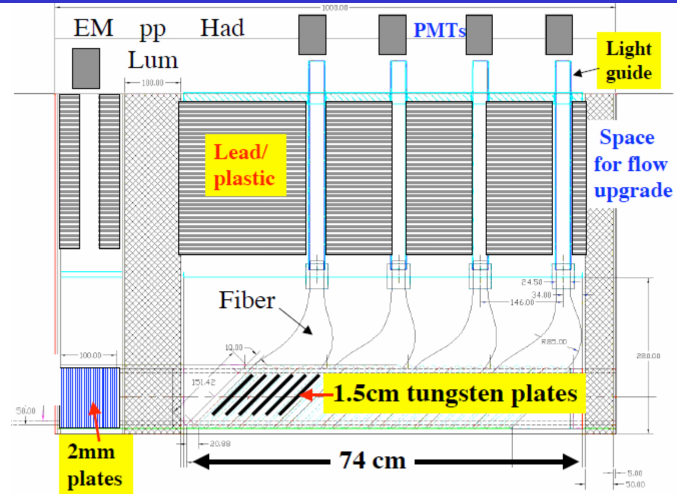




ZDC within TAN absorber

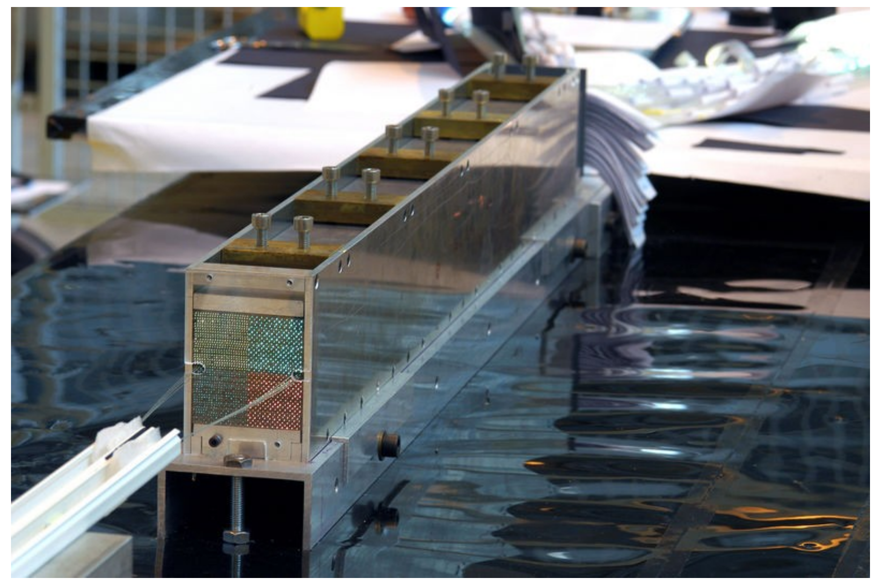


ATLAS

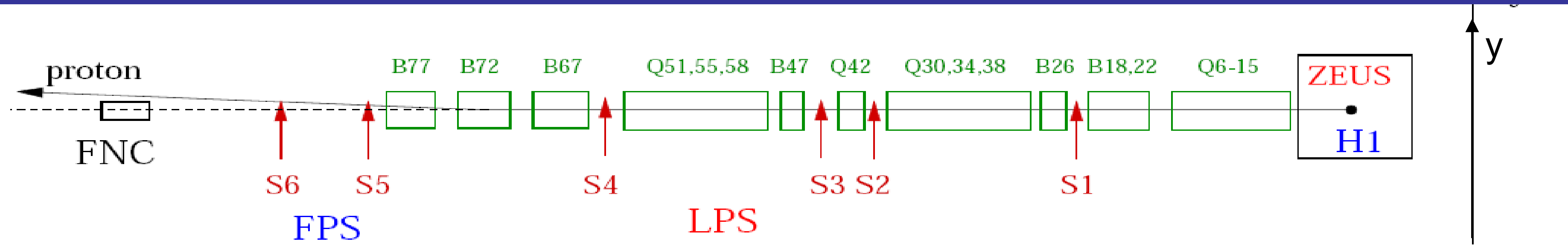


CMS

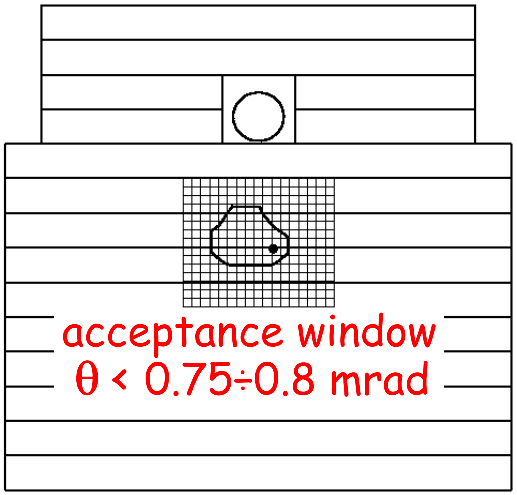
ALICE



H1 and ZEUS detectors for forward neutrons



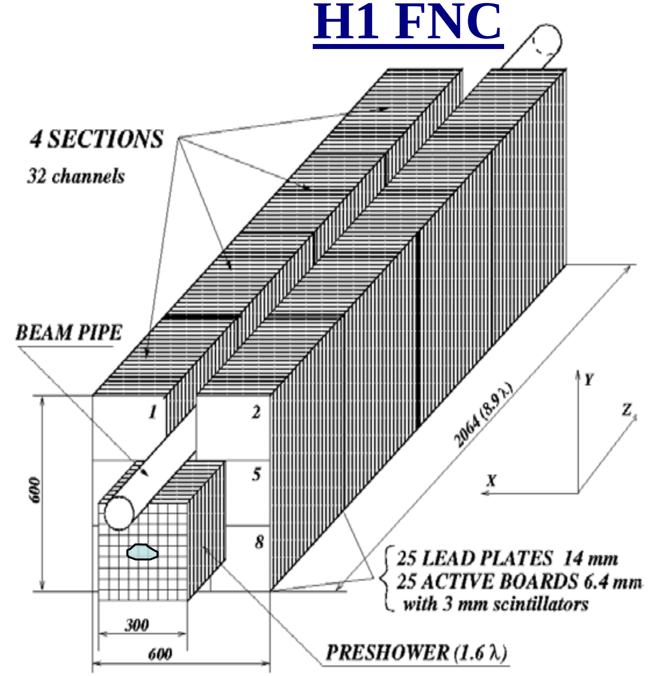
ZEUS FNC+FNT



position resolution 2-3mm

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

H1 FNC

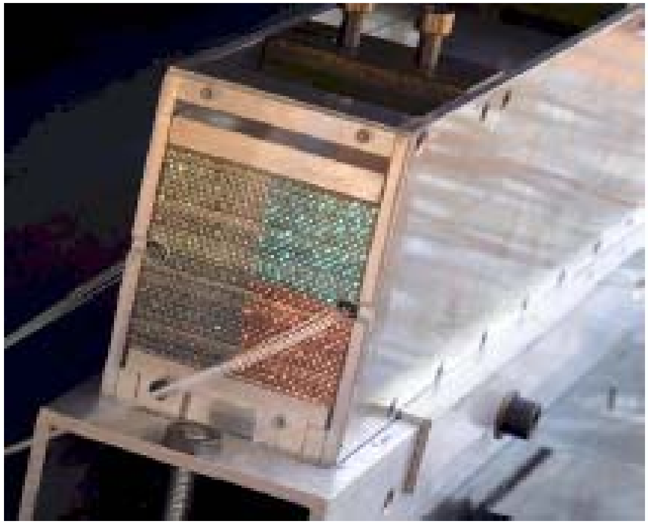


$\sigma_E/E \approx 0.63/\sqrt{E} \oplus 2\%$

Acceptance limited by beam apertures to θ<0.75-0.8 mrad, asymmetric in ϕ
p_T resolution is dominated by p_T spread of proton beam (50-100 MeV)

ZDC for ALICE

ZDCs are sampling Quartz-Fiber-Calorimeters *(Čerenkov),* with silica optical fibers, as active material, embedded in a dense absorber

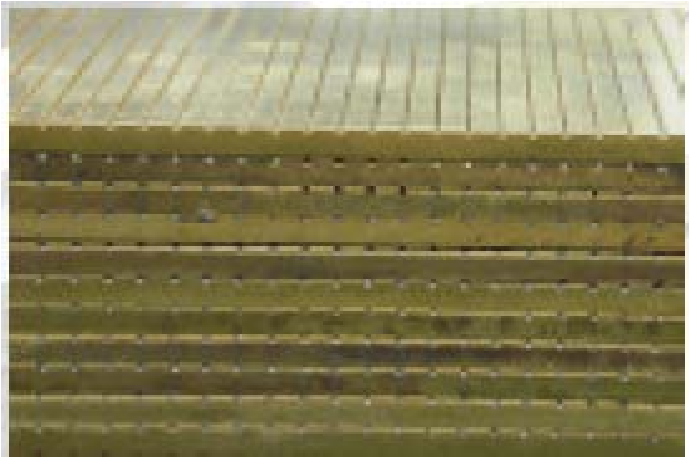


The Neutron ZDC (ZN)

44 grooved W-alloy slabs (ρ=17.6 g/cm^3), each of them 1.6 mm thick, stacked to form a parallelepiped (7.2 x 7.2 x 100 cm^3, 8.5 λ_I)

1936 quartz fibers ($\varnothing$ 365μm), embedded in the absorber with a pitch of 1.6 mm

Energy resolution for 2.7 TeV neutrons: σ/E ~ 11.4%



The Proton ZDC (ZP)

30 grooved brass slabs (ρ=8.48 g/cm^3), each of them 4 mm thick, stacked to form a parallelepiped (22.8 x 12 x 150 cm^3, 8.4 λ_I)

1680 quartz fibers ($\varnothing$ 550μm), embedded in the absorber with a pitch of 4 mm

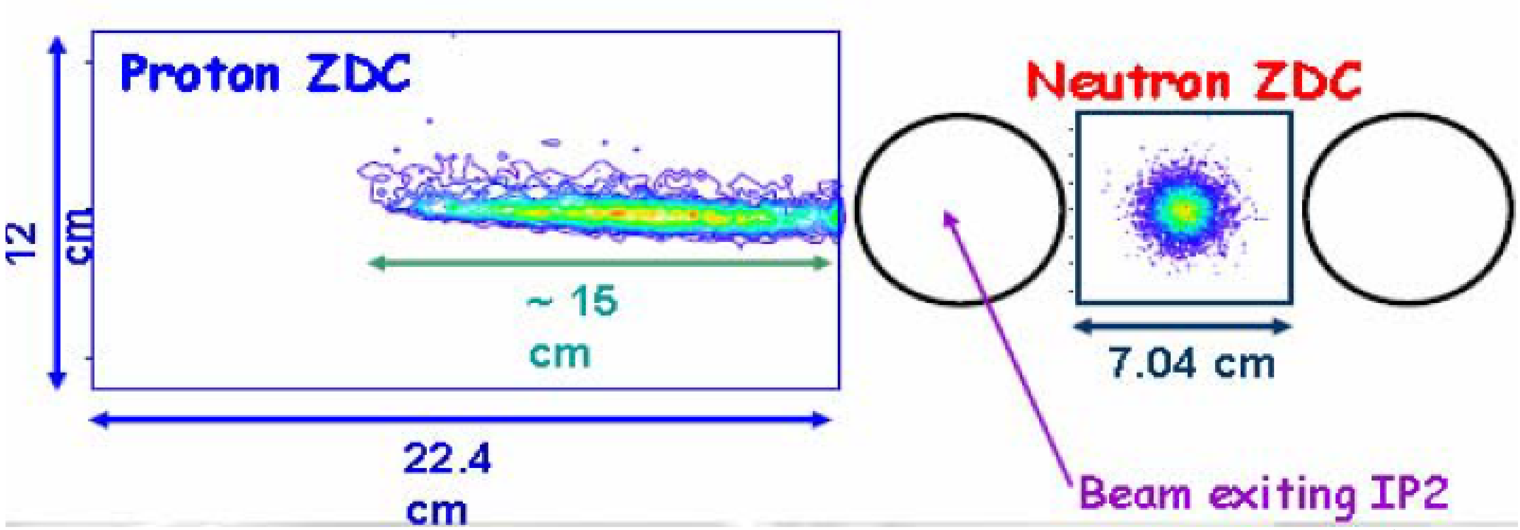
Energy resolution for 2.7 TeV protons: σ/E ~ 13%

(from talk R.Arnaldi)

ZDC acceptances (ALICE)

Due to Fermi motion and Lorentz boost, the spread of the longitudinal momentum of spectators is about 500 GeV → Spectator protons are spread over the horizontal coordinate by the separator dipole; over ZP front face cover an area ~12.6 x 2.8 cm^2

For the spectator neutrons only the transverse component of Fermi momentum plays a role in determining the size of the spot at the ZDC face, which is of the order 6x6mm^2



(from talk R.Arnaldi)

Measurement of electron beam Polarisation

Based on 'Compton scattering' (as at HERA and SLC):

- γ–beam from laser scatters off the electron beam;
- scattered γ (and electron) measured in the calorimeters
- longitudinal polarisation from a fit to the scattered γ and e energy spectra

γ and e-measurements are complementary and improve the precision

Polarisation from the scattered photons:

- the single and few scattered photons regime

- extract the polarisation from a fit to the scattered γ energy spectrum;
- *in situ* calibration to the kinematical edge of the energy spectra;

- the multi-photon regime

- extract the polarisation from an asymmetry between the average scattered energies corresponding to a circularly left and right laser beam polarisations;
- negligible background but no energy calibration *in situ*

With a very stable pulsed laser beam, with adjustable energy and operating in different regimes, one can calibrate the calorimeter and optimise the dynamical regime to improve the uncertainty on the polarisation

Polarisation from the scattered electrons

implement a dedicated electron spectrometer and a segmented electron detector to measure the electron angular distribution, related to the energy spectrum.