36th International Conference on High Energy Physics
4 – 11 July 2012
Melbourne Convention and Exhibition Centre
ICHEP2012 Melbourne

The Large Hadron electron Collider Detector Design Concept

A. Polini

(for the LHeC Study Group)

Outline:

- Experiment requirements and accelerator boundaries (Physics, Machine, Interaction Region and Detector)
- Present Detector Design
- Future and Outlook

The LHeC at ICHEP 2012

Thu 10:15 [abs: 597] Claudia Glasman:
Partons, QCD and Low x Physics at the Large Hadron electron Collider

Fri 13:00 [abs: 603] Paul Newman:
Electron-Ion Collisions at a Large Hadron electron Collider

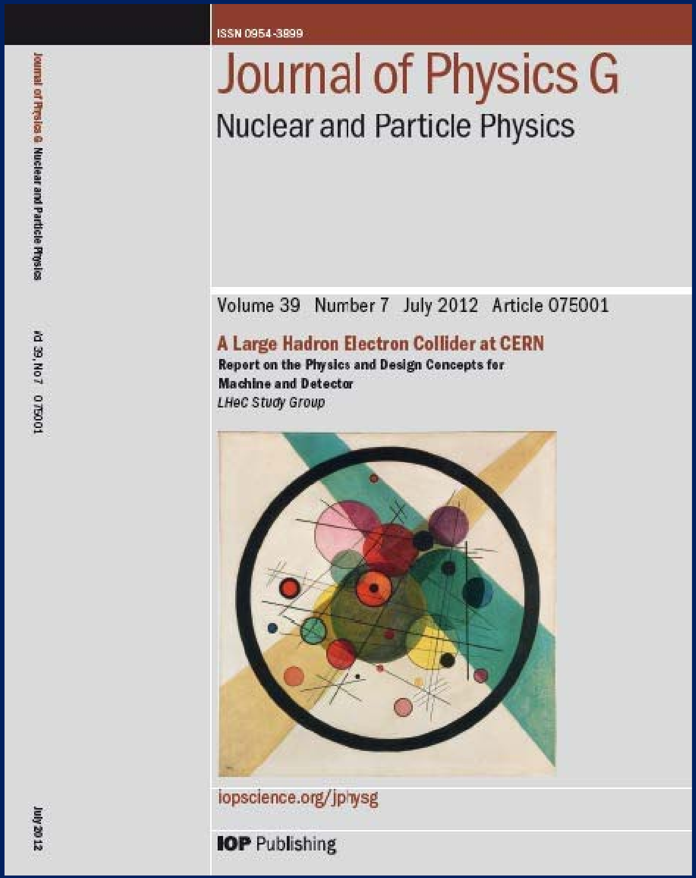
Sat 11:30 [abs: 595] Max Klein:
Design Concepts for a Large Hadron Electron Collider

Sat 15:15 [abs: 605] Alessandro Polini:
The Large Hadron electron Collider Detector Design Concept

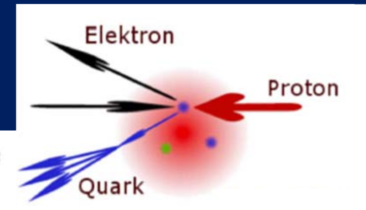
Sat 17:00 [abs: 607] Uta Klein:
Prospects for Higgs Physics at a Large Hadron Electron Collider

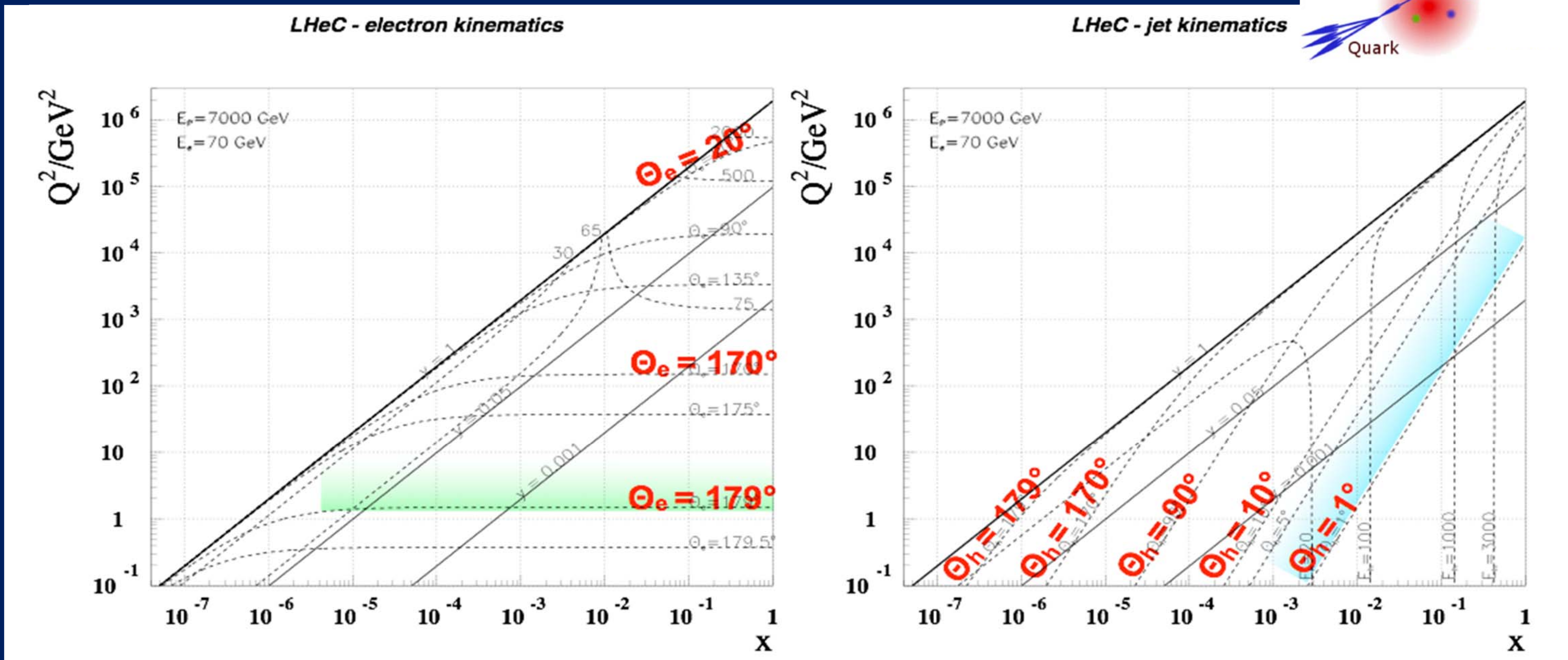
http://cern.ch/lhec

CDR: A Large Hadron Electron Collider at CERN
LHeC Study Group
arXiv:1206.2913
J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001



LHeC Kinematics





- High x and high Q^2: few TeV HFS scattered forward:

➔ Need forward calorimeter of few TeV energy range down to 10^o and below

Mandatory for charged currents where the outgoing electron is missing

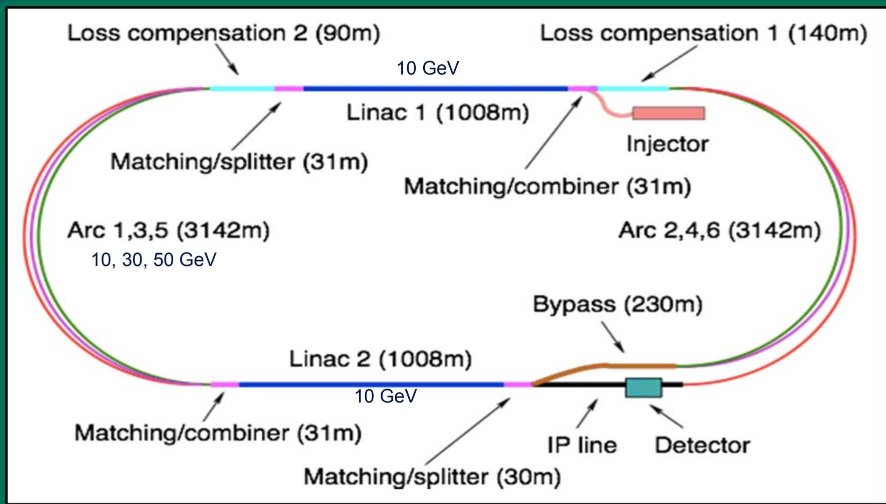
- Scattered electron:

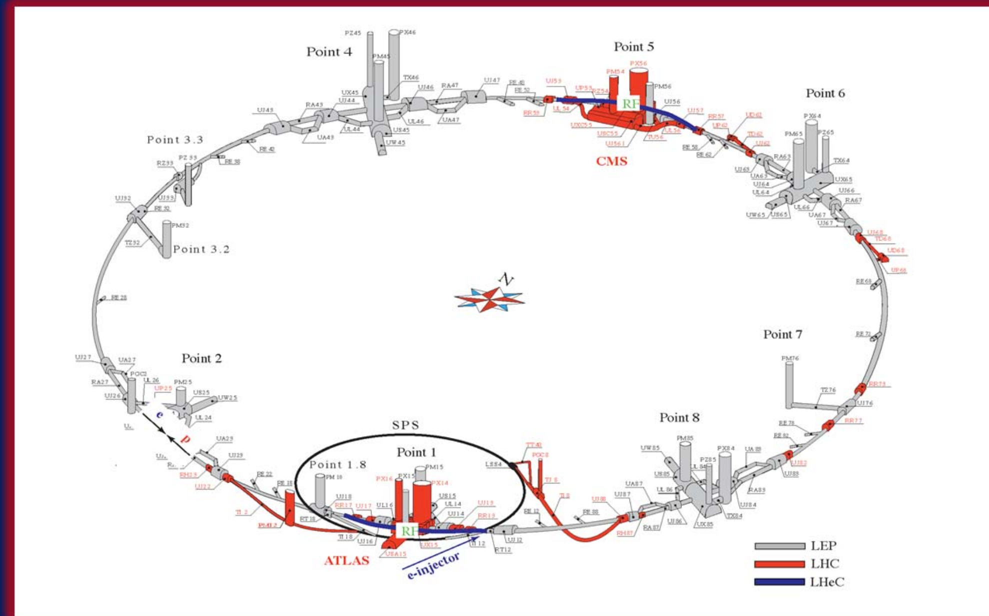
➔ Need very bwd angle acceptance for accessing the low Q^2 and high y region

Design Approach

- Provide a baseline design which satisfies the Physics requirements along with the constraints from the machine and interaction region for running during the PHASE II of LHC
- Having to run along with the LHC, the detector needs to be designed and constructed in about 10 years from now to be able to run concurrently with the other LHC experiments designed for *pp* and *AA* studies in the *ep*/*eA* mode, respectively.
- While avoiding large R&D programs, the final LHeC detector can profit from the technologies used nowadays at the LHC and the related developments and upgrades
- Modular and flexible accommodating upgrade programs; Detector assembly above ground; Detector maintenance (shutdown)
- Affordable - comparatively reasonable cost.
- More refined studies are required and will follow with the TDR and once a LHeC collaboration has been founded

Two Alternative Designs



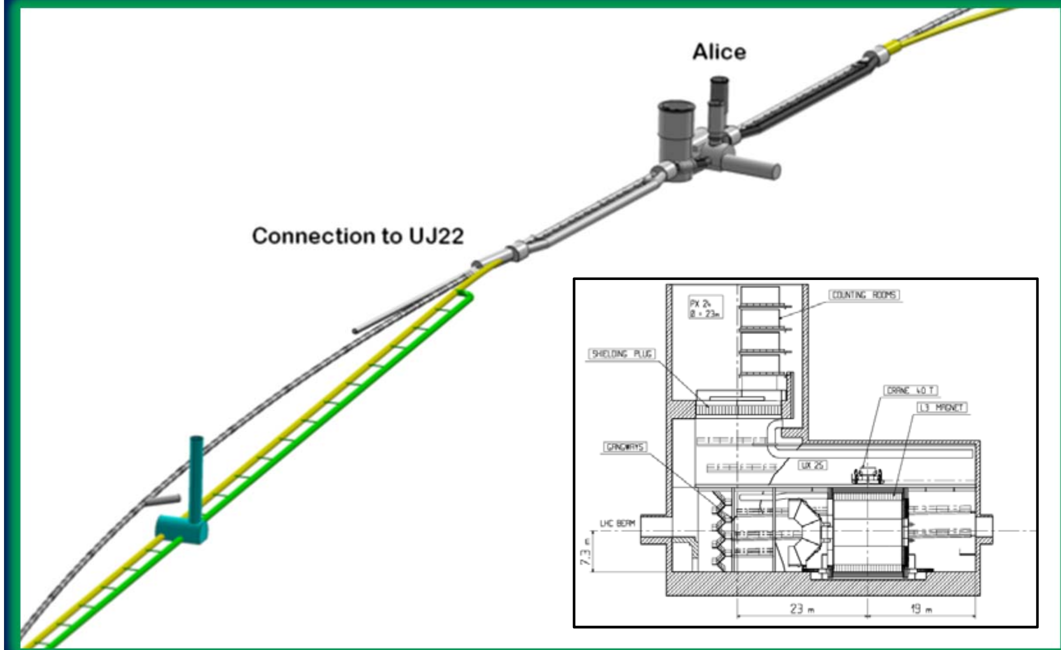


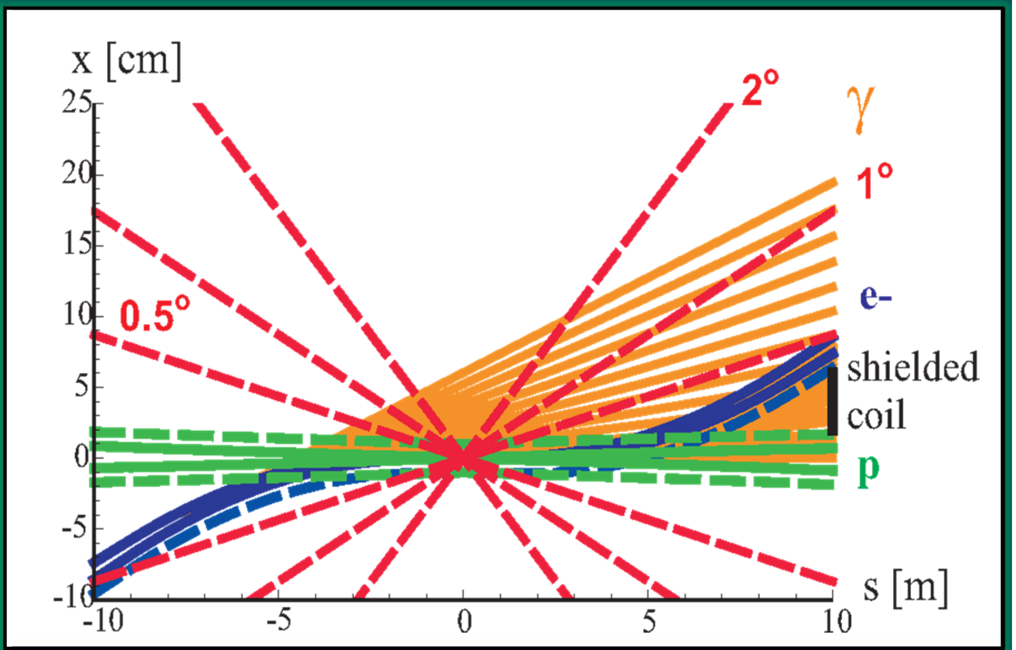
- Ring-Ring
  - e-p and e-A (A=Pb, Au, …) collisions
  - More "conventional" solution, like HERA, no difficulties of principle - at first sight - but constrained by existing LHC in tunnel
  - polarization 40% with realistic misalignment assumptions
- Linac-Ring
  - e-p and e-A (A=Pb, Au, …) collisions, polarized *e* from source, somewhat less Luminosity/Power
  - New collider type of this scale

Linac Ring: Favored Option

Linac-Ring:

- Reduced impact on the LHC schedule
- New Accelerator Design (Energy Recovery Linac)
- Dipole Field along the whole interaction region
- LHC Interaction Point P2





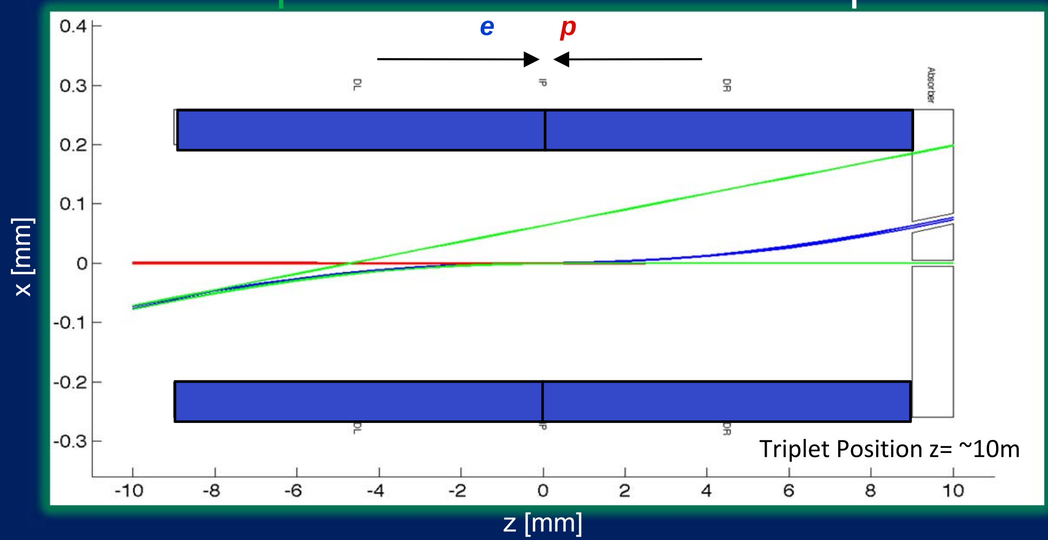
LR Interaction Region

Dipole Field along the full interaction region needed

B = ±0 .3 Tesla
for z = [–9m , +9m]

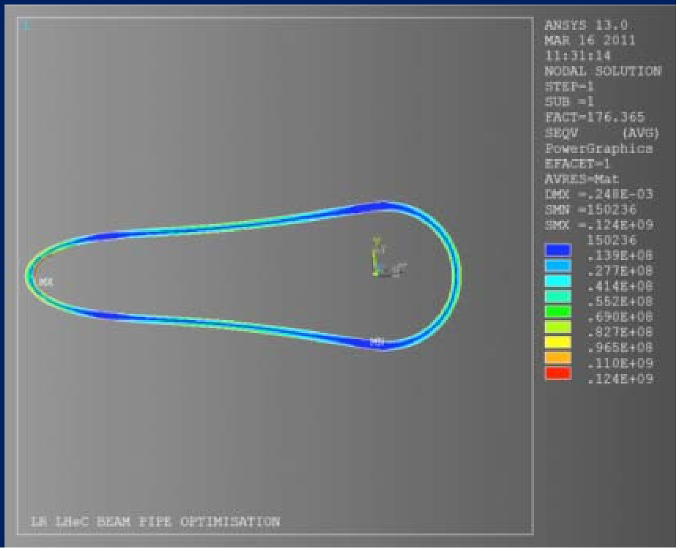
SR Fan growth with z

LR Option - Beam & Fan Envelopes



Linac-Ring - Inner Dimensions

Circular(x)=2.2cm; Elliptical(-x)=-10., y=2.2cm



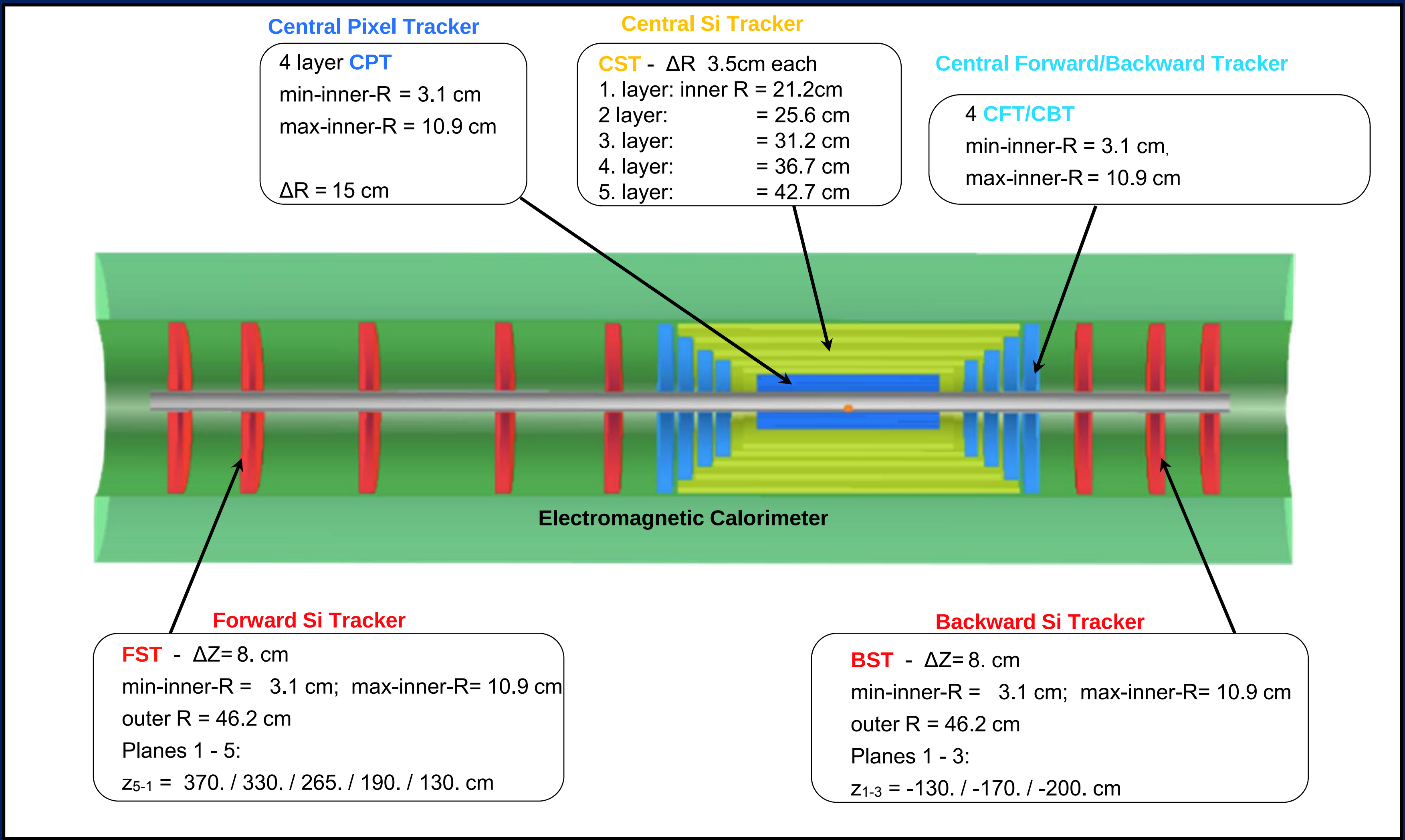
Requirements from Physics

- High resolution tracking system
  - excellent primary vertex resolution
  - resolution of secondary vertices down to small angles in forward direction for high x heavy flavor physics and searches
  - precise p_t measurement matching to calorimeter signals (high granularity), calibrated and aligned to 1 mrad accuracy
- The calorimeters
  - electron energy to about 10%/ $\sqrt{E}$ calibrated using the kinematic peak and double angle method, to permille level

    Tagging of γ's and backward scattered electrons - precise measurement of luminosity and photo-production physics
  - hadronic part 40%/$\sqrt{E}$ calibrated with p_{t_e} /p_{t_h} to 1% accuracy
    - Tagging of forward scattered proton, neutron and deuteron - diffractive and deuteron physics
- Muon system, very forward detectors, luminosity measurements

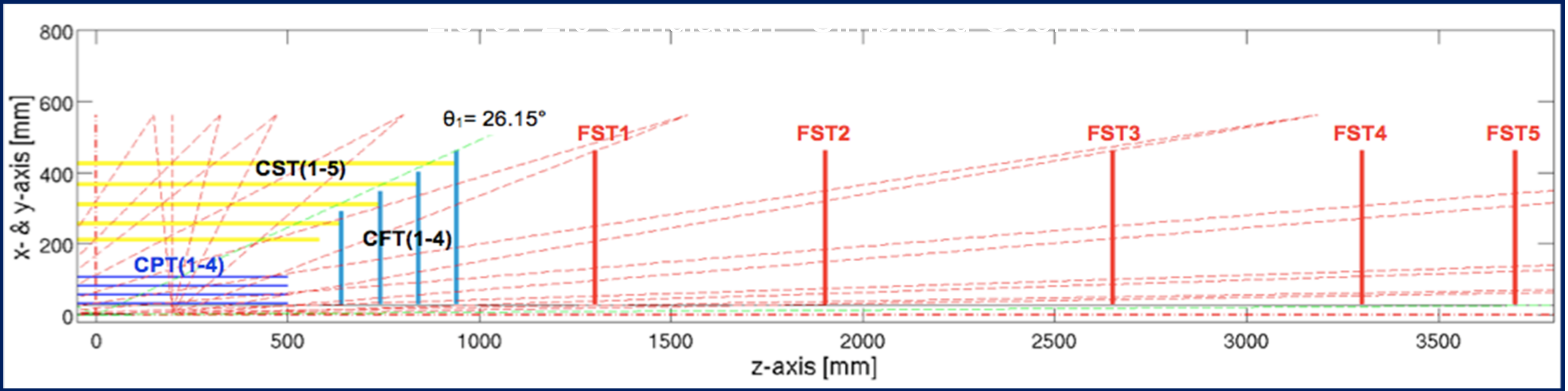
Tracking - High Acceptance

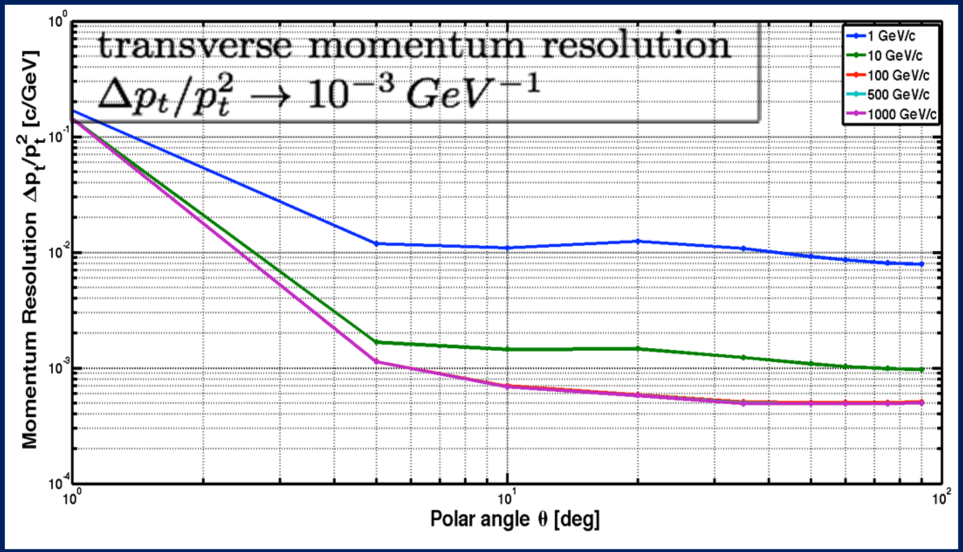
Dominant forward production of dense jets; backward measurements relaxed

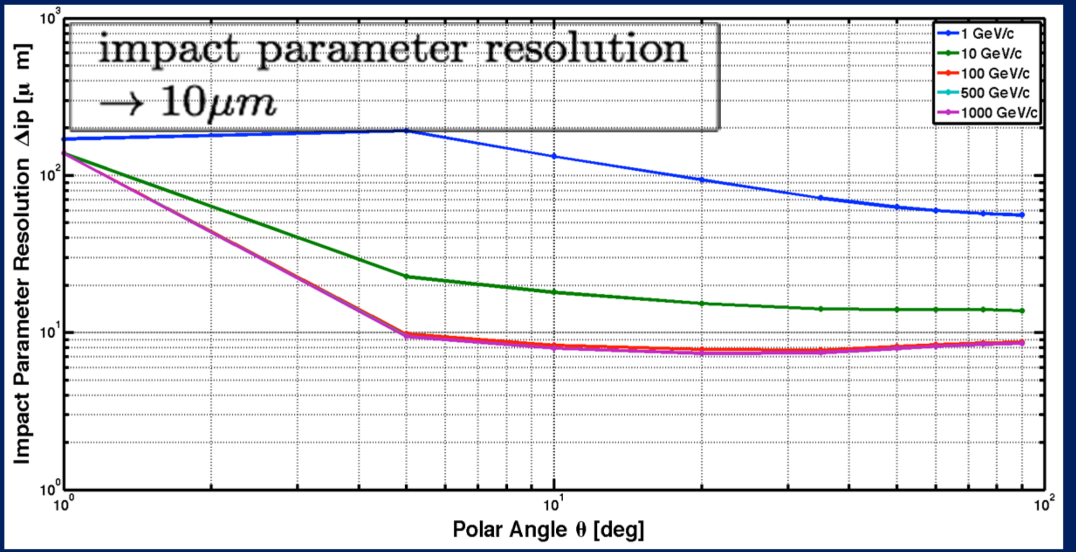


Tracker Simulation

http://wwwhephy.oeaw.ac.at/p3w/ilc/lictoy/UserGuide_20.pdf

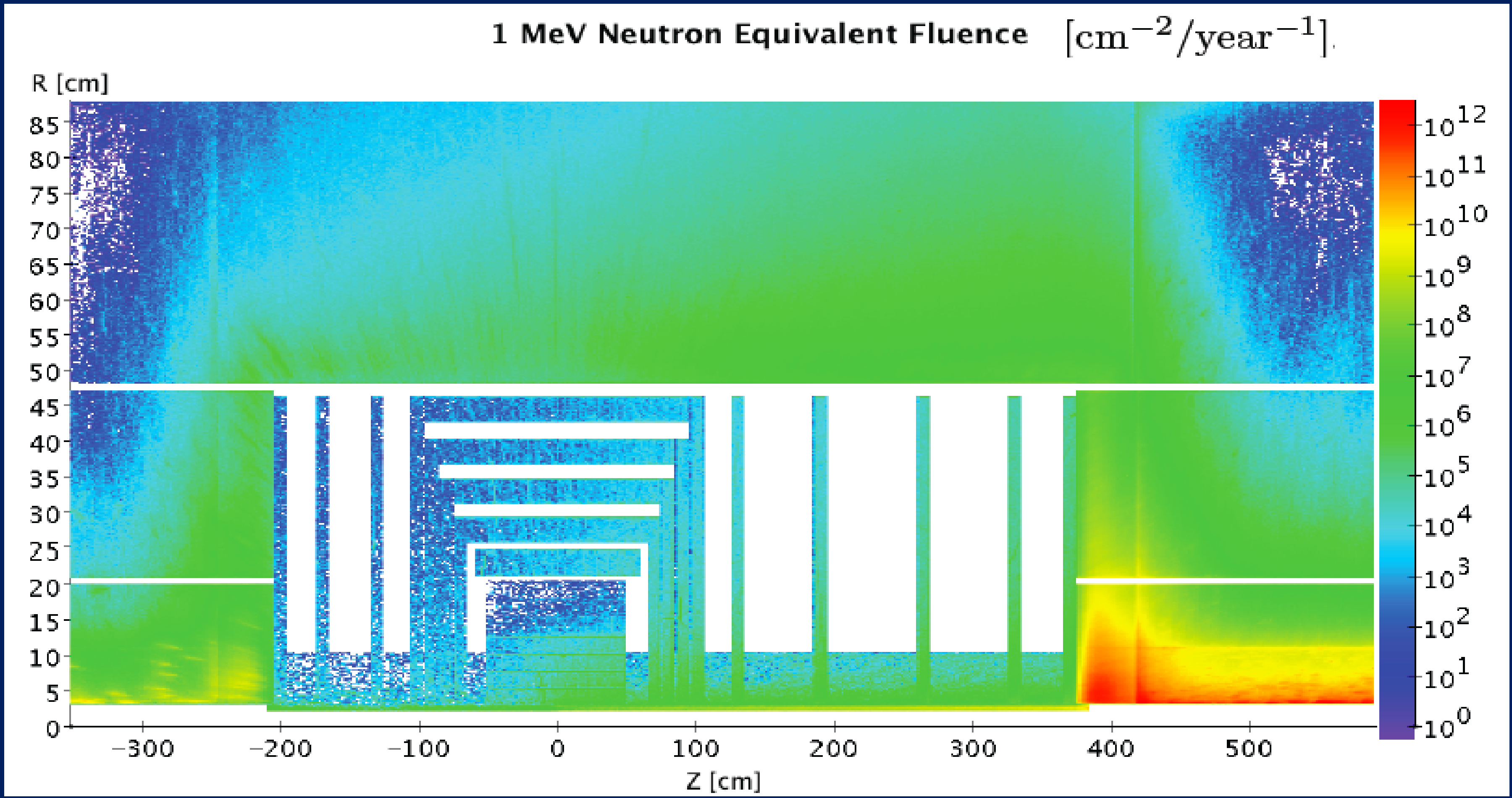






- Silicon: compact design, low budget material, radiation hard

GEANT4 - Fluences



- Similar studies being done with FLUKA
- Most critical the forward region
- Rates far lower than LHC (LHC ~5 x 10^{14})

Services and Infrastructure

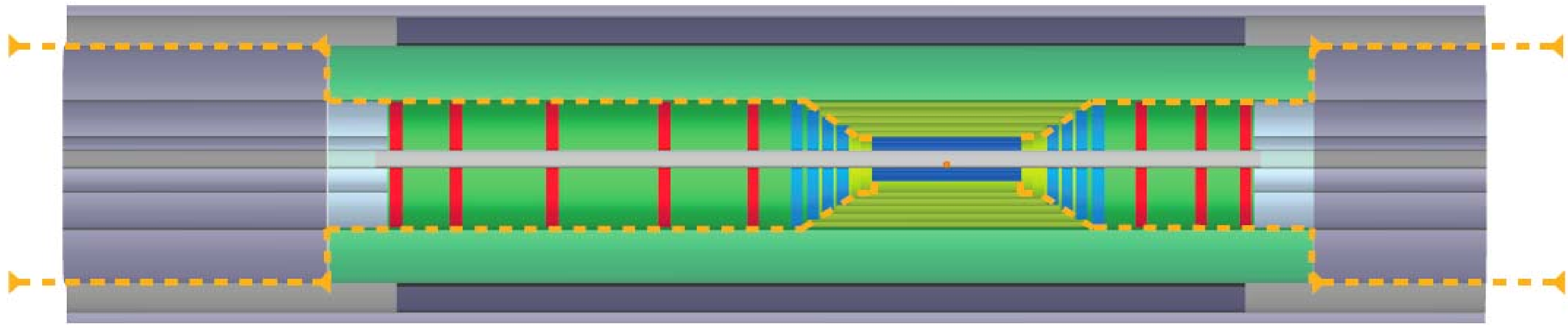
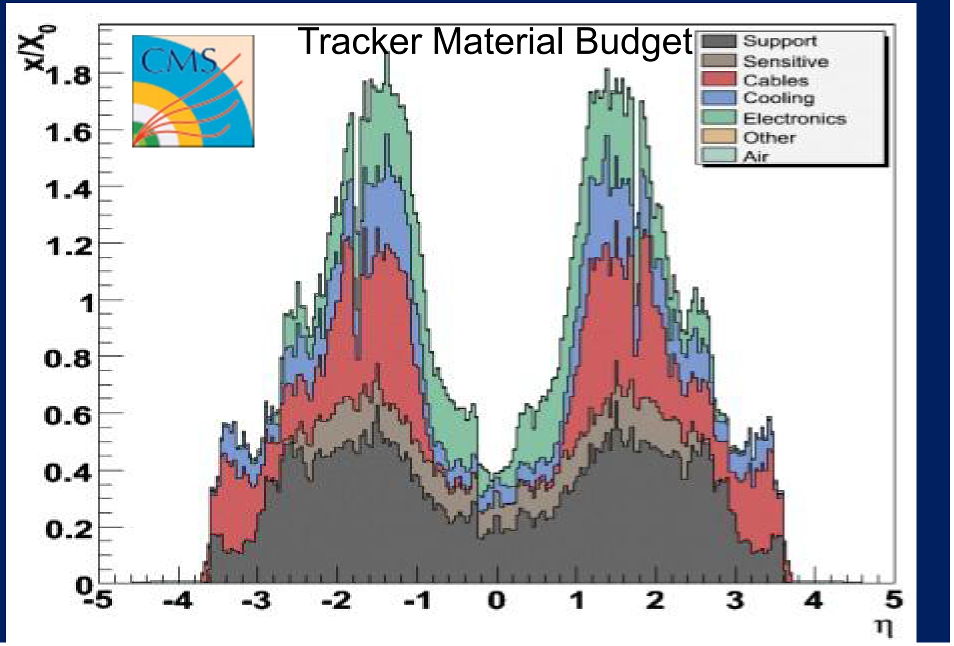


Figure 13.29: Path of services for all tracking detectors (shown in orange). The services are integrated into support structures whenever possible

- Detector of very compact design;
  It might be necessary to open places/grooves/tunnels for services affecting the aperture of the detector;
  Optimum between costs and detector acceptance needs to be found.
- Service and Infrastructure need very careful design being the main contributor to Material Budget ➔



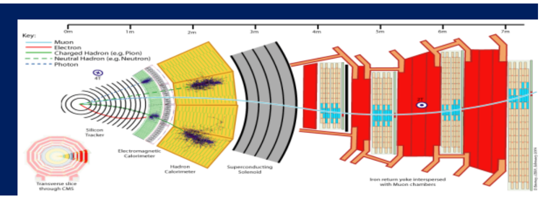
A. Polini

Solenoid Options

Large Coil

- Large Solenoid containing the Calorimeter
- 3.5 T Solenoid of similar to CMS/ILC
- Precise Muon measurement
- Large return flux either enclosed with Iron or

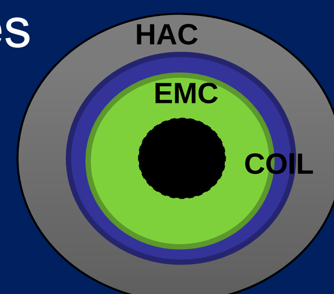
  Option of active B shielding with 2^{nd} solenoid

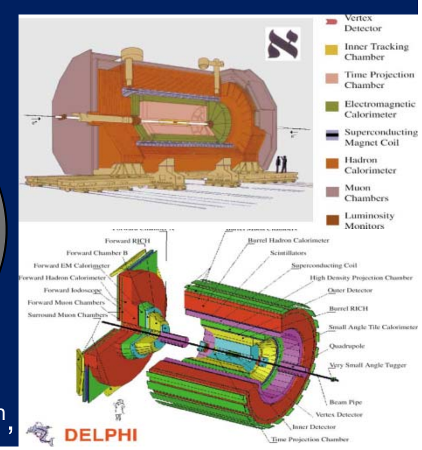


General parameters	
Magnetic length	12.5 m
Free bore diameter	6.3 m
Central magnetic induction	4 T
Total Ampere-turns	41.7 MA-t
Nominal current	19.14 kA
Inductance	14.2 H
Stored energy	2.6 GJ
Cold mass	
Layout	Five modu coupled
Radial thickness of cold mass	312 mm
Radiation thickness of cold mass	3.9 X_0
Weight of cold mass	220 t
Maximum induction on conductor	4.6 T
Temperature margin wrt operating temperature	1.8 K
Stored energy/unit cold mass	11.6 kJ/kg
Iron yoke	
Outer diameter of the iron flats	14 m
Length of barrel	13 m
Thickness of the iron layers in barrel	300, 630 a
Mass of iron in barrel	6000 t
Thickness of iron disks in endcaps	250, 600 a
Mass of iron in each endcap	2000 t
Total mass of iron in return yoke	10 000 t

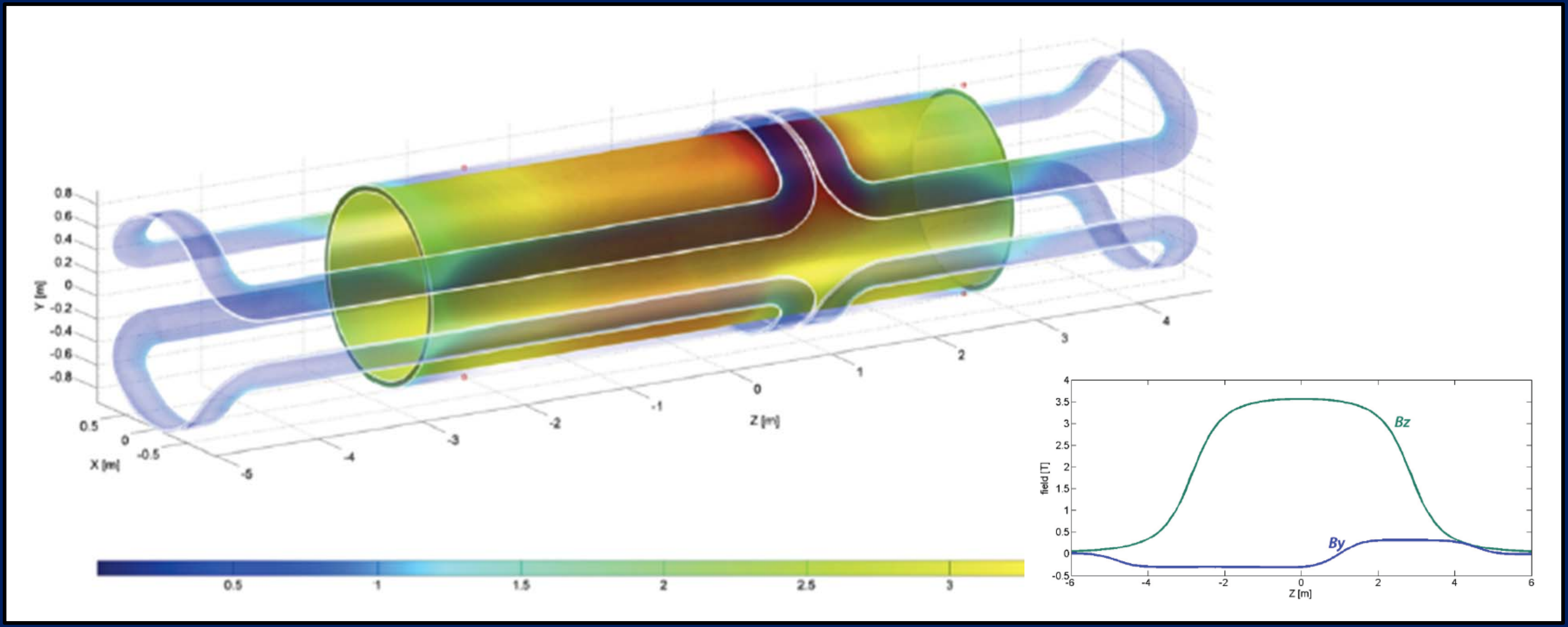
Small Coil

- Smaller Solenoid placed between EMC and HAC
- Cheaper option
- Convenient displacement of Solenoid and Dipoles in same cold vacuum vessel (Linac-Ring only)
- Smaller return flux (less iron required)
- Muon p, p_t measurement compromised





Magnets

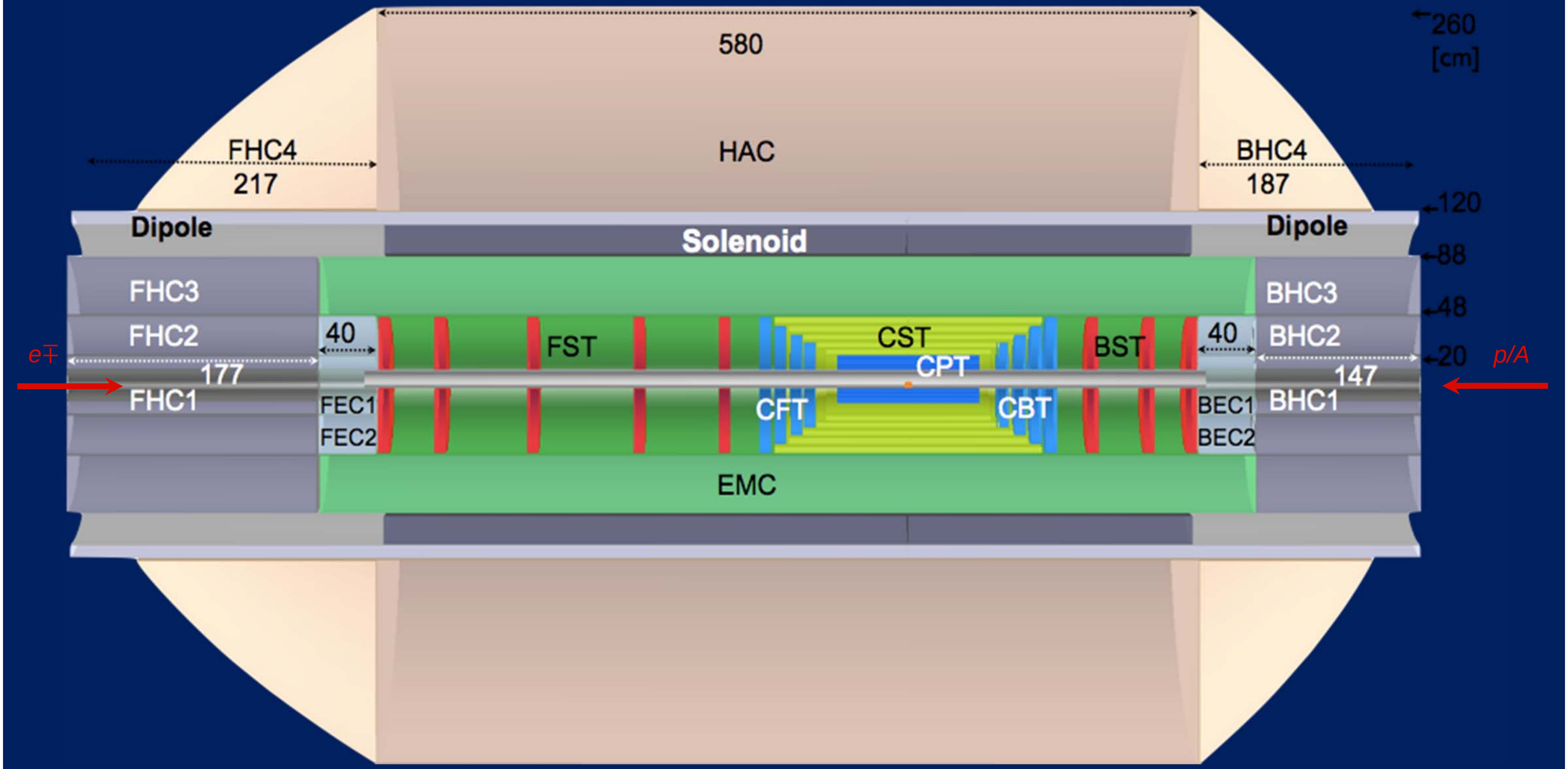


Baseline Solution:

- Solenoid (3.5 T) + dual dipole 0.3 T (Linac-Ring Option)
- Magnets (may be) embedded into EMC LAr Cryogenic System

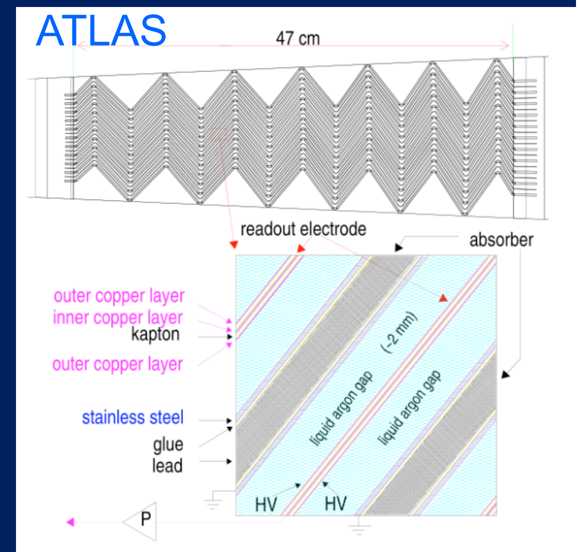
➔ Need of study the Calorimeter Performance and impact of dead material between EMC and HAC sections; it might be possible placing the magnet system even in front of the EMC - at even lower radius at just outside of the tracking system

Baseline Detector

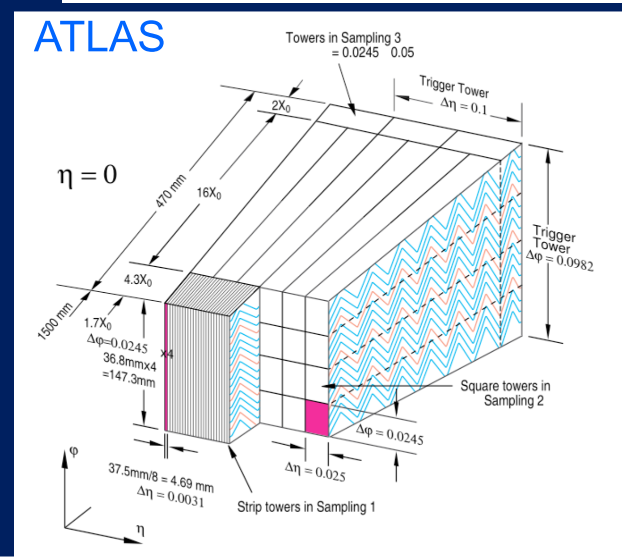


Electromagnetic Calorimeter (i)

- Baseline Electromagnetic Calorimeter
- LAr for barrel EMC calorimetry - ATLAS (~25-30 X_0)

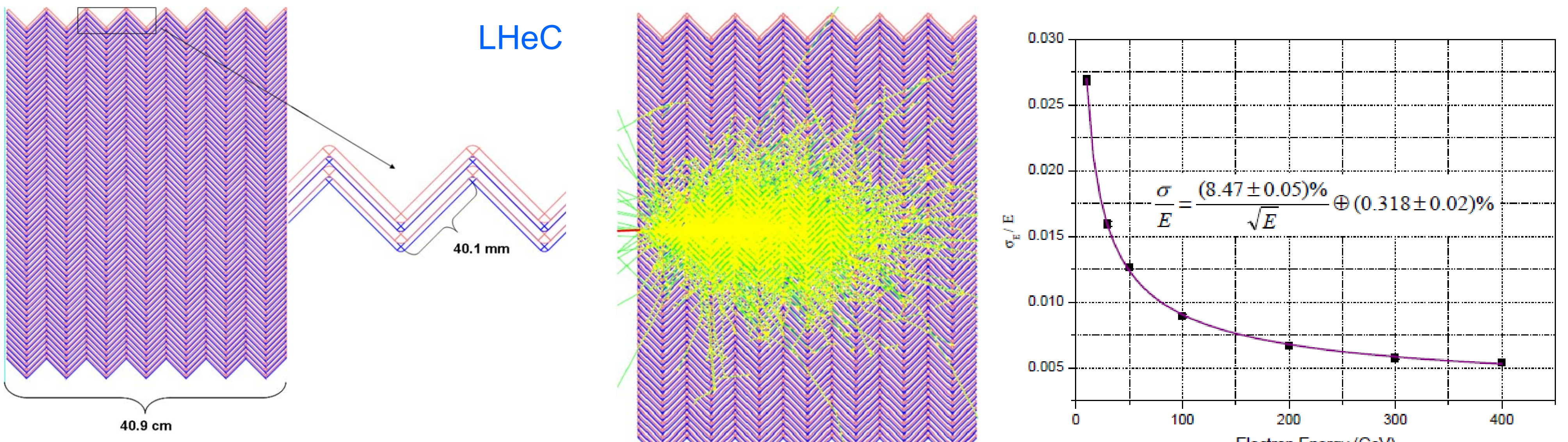


  - Advantage: same cryostat used for solenoid and dipoles
  - GEANT4 simulation (*)
  - Simulation results compatible with ATLAS
  - barrel cryostat being carefully optimized
    pre-sampler optimal
  - 3 different granularity sections longitudinally



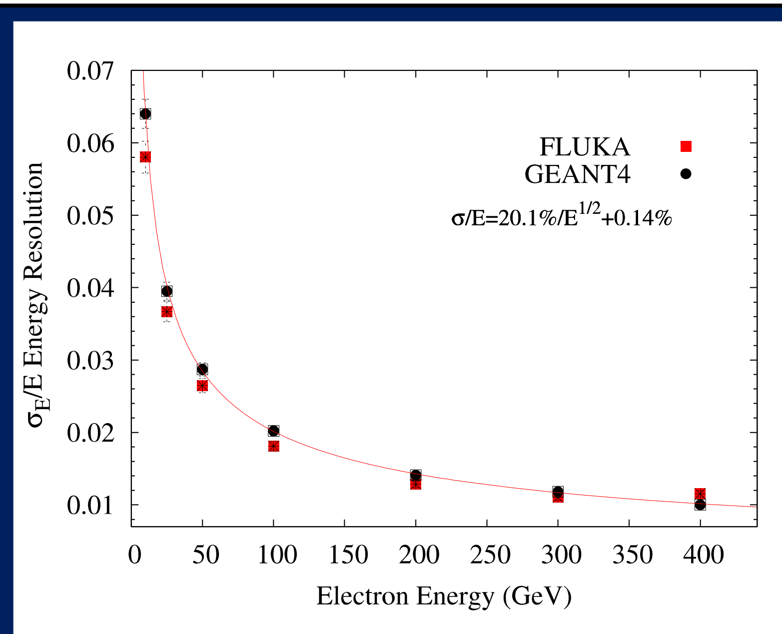
(*) F. Kocak, I. Tapan Uludag Univ.

Electromagnetic Calorimeter (ii)



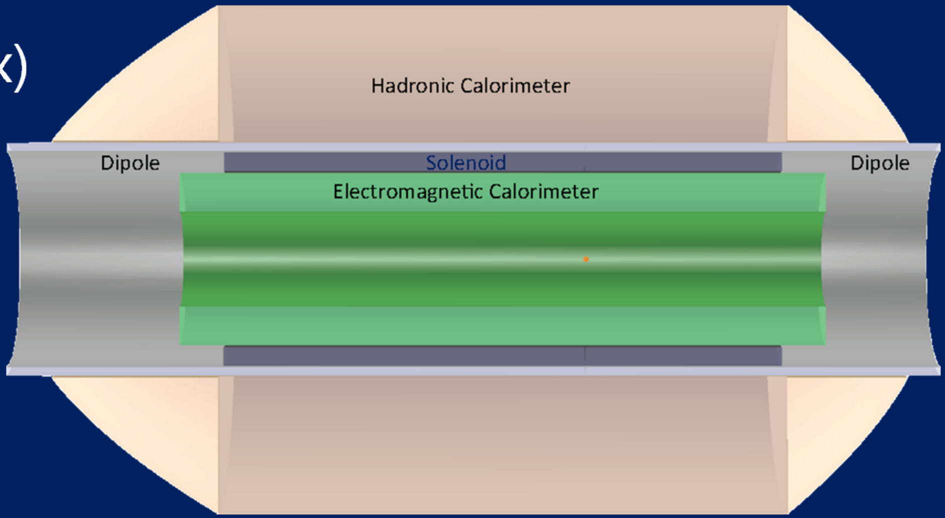
F. Kocak, I. Tapan Uludag Univ.

- Simulation with simplified design w.r.t.Atlas
- LAr Calorimeter : good energy resolution, stable performance
- Simulation results compatible with ATLAS
- Warm (Pb/Sci) option also investigated
- $30X_0$ (X_0(Pb)=0.56 cm; 20 layers) →



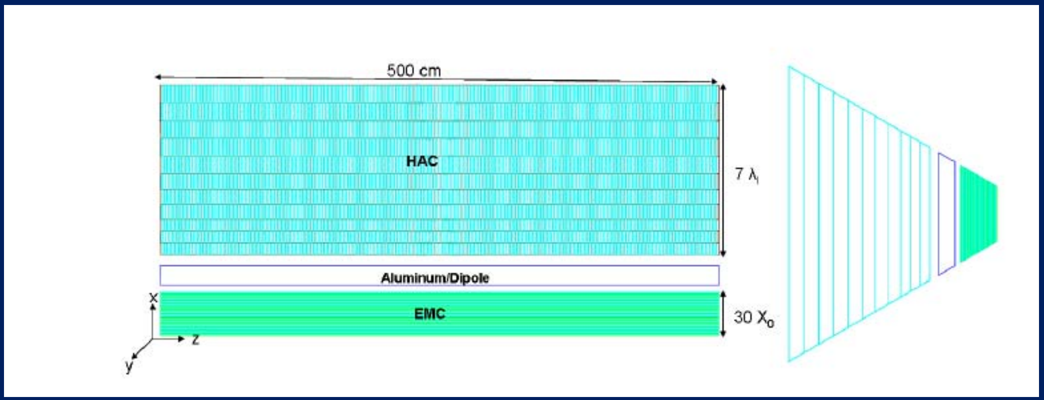
Hadronic Calorimeter (i)

- Baseline Design
  - HAC iron absorber (magnet return flux)
  - scintillating plates
    (similar to ATLAS TILE CAL)
  - Interaction Length: ~7-9 λ_I



- Setup:

Tile Rows	Height of Tiles in Radial Direction	Scintillator Thickness
1-3	97mm	3mm
4-6	127mm	3mm
7-11	147mm	3mm



- GEANT4 + FLUKA simulations
- performance optimization:
  - containment, resolution, combined HAC & EMC response
  - solenoid/dipoles/cryostat in between

Hadronic Calorimeter (ii)

- Preliminary studies on impact of the magnet system on calorimetric measurements (GEANT4 & FLUKA *)
- Energy resolutions
- Shower profiles

*) F.Kocak, I.Tapan, A.Kilic, E.Pilicer Uludag Univ.; E.Arikan, H.Aksakal Nigde Univ.

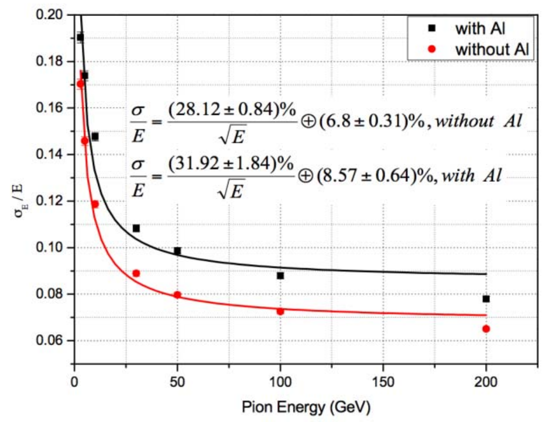


Figure 12.37: Combined LAr Accordion and Tile Calorimeter energy resolution for pions with and without 14 cm Al block (**GEANT4**)

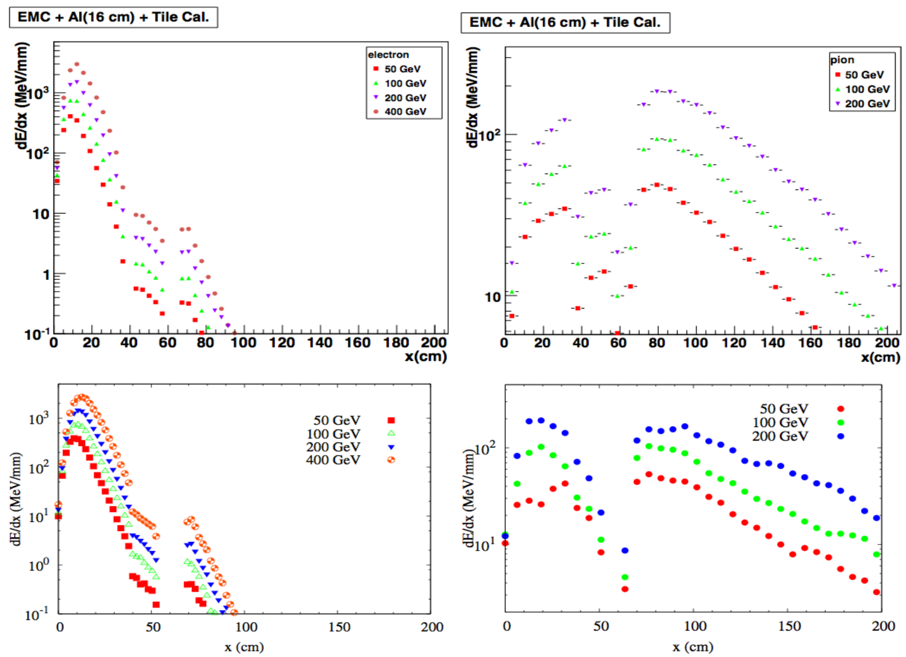


Figure 12.41: Electron (left) and Pion (right) longitudinal shower profile for the EMC_{Pb-Sc} / solenoid-dipole-system (Al-block) / HAC at various energies (**GEANT4** (top) and **FLUKA** (bottom)).

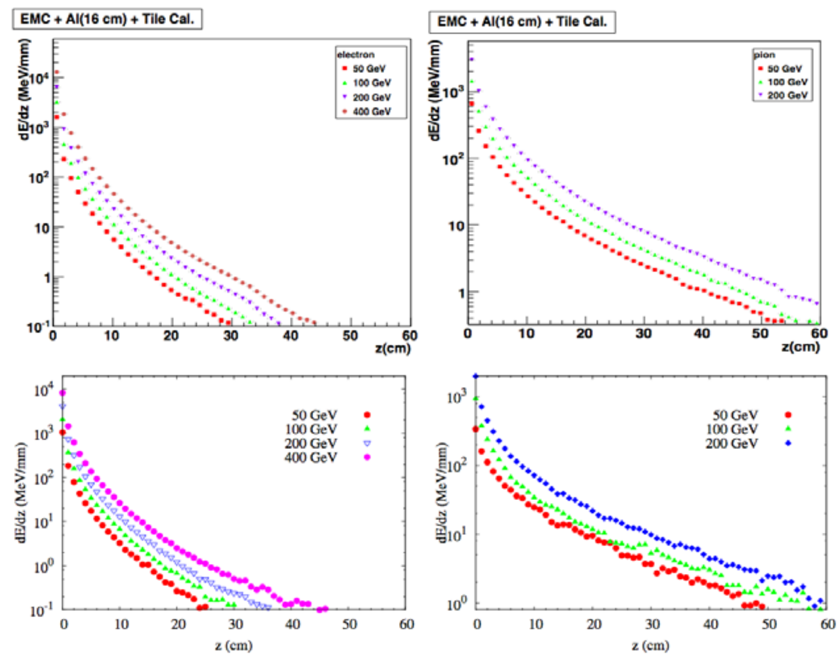


Figure 12.42: Energy deposit and transverse shower profiles for electron (left) and pion (right) - both for the EMC_{Pb-Sc} stack (**GEANT4** (top) and **FLUKA** (bottom)).

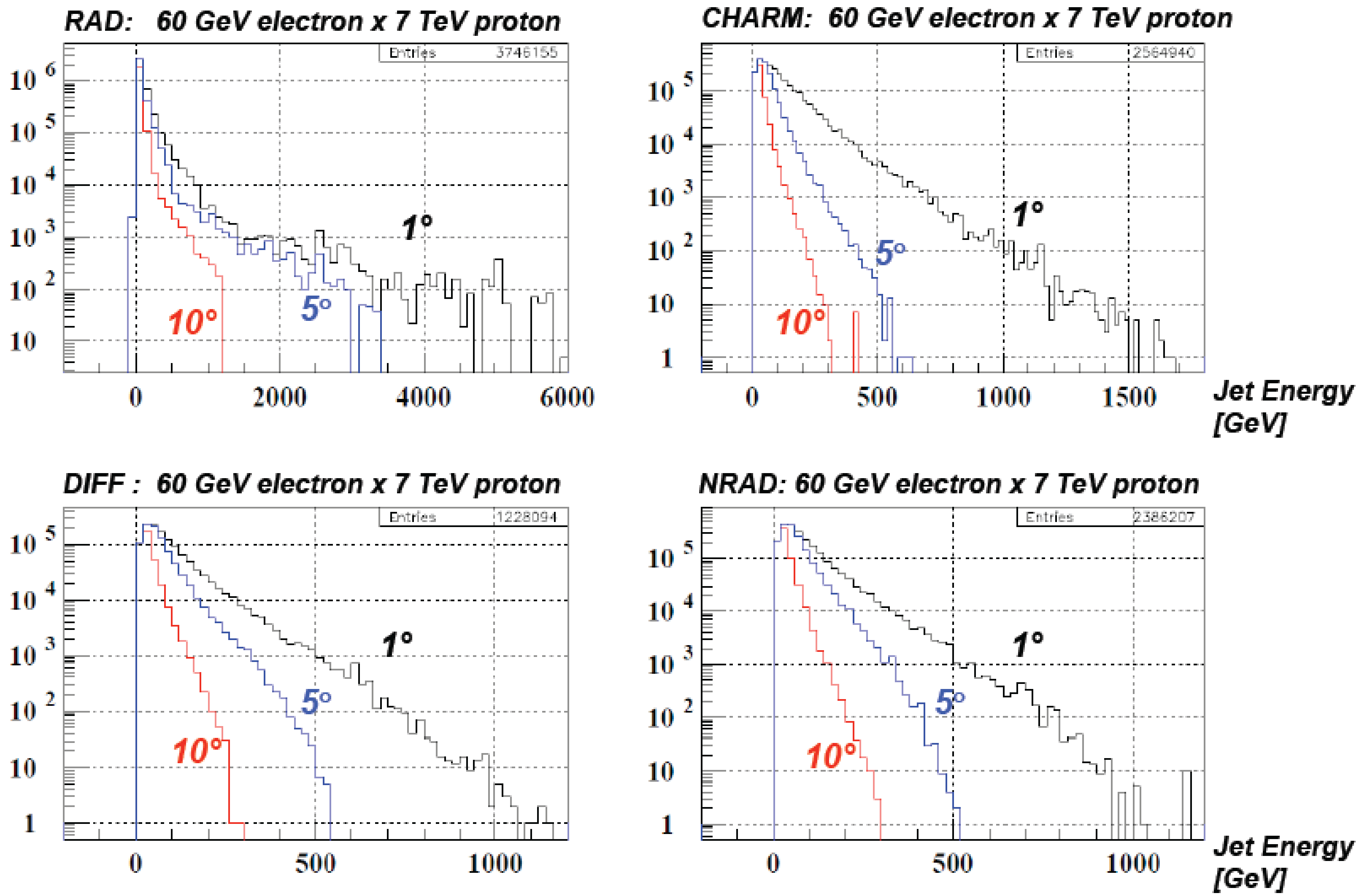
Forward Energy and Acceptance

RAPGAP-3.2 (H.Jung et.al.- http://www.desy.de/~jung/rapgap.html)

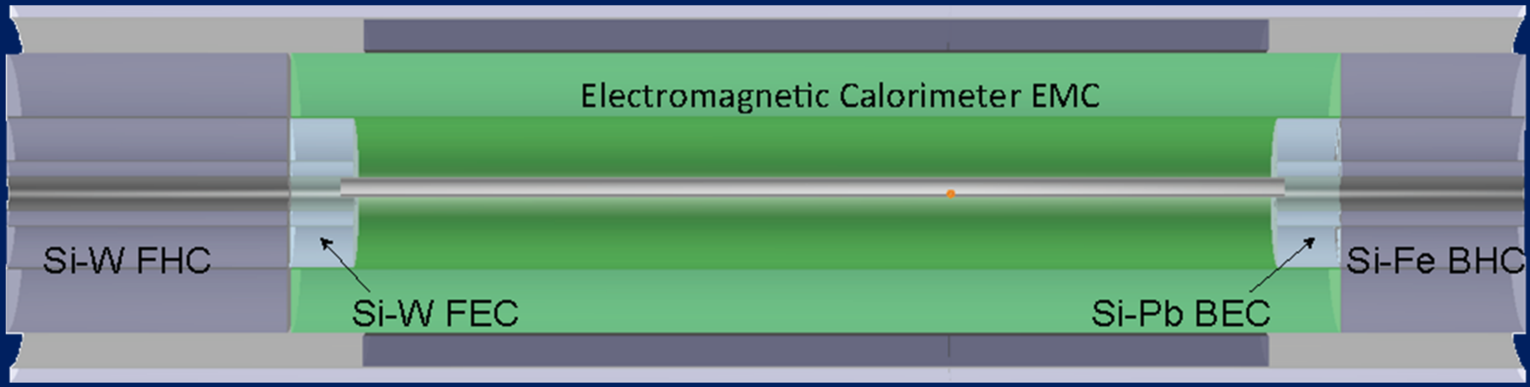
HzTooL-4.2 (H.Jung et.al. - http://projects.hepforge.org/hztool/)

selection: q^2.gt.5

→ Highest acceptance desirable

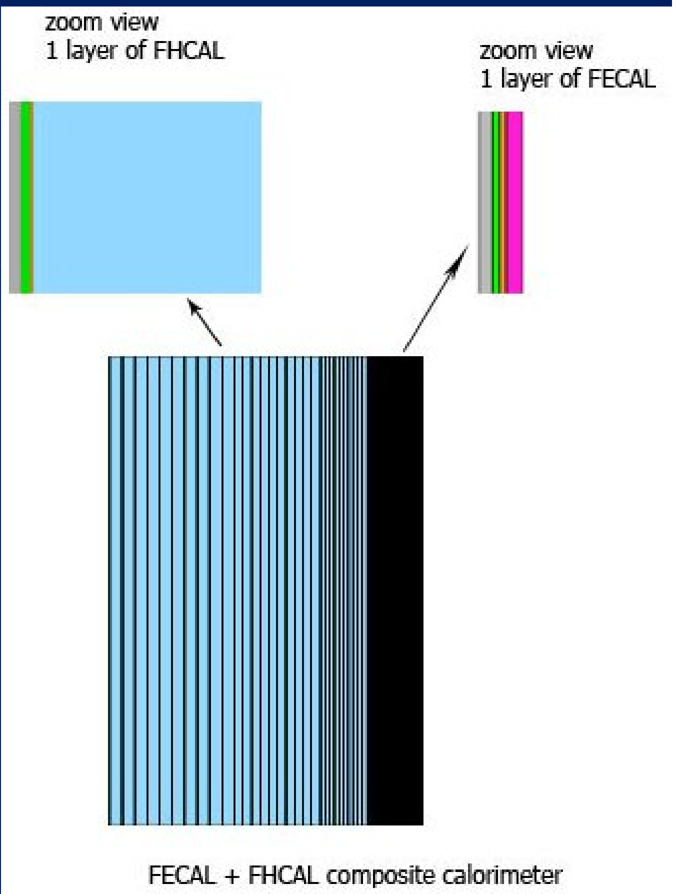


Forward/Backward Calorimeters (i)



Forward/Backward Calorimeters

- Forward FEC + FHC:
  - tungsten high granularity
  - Si (rad-hard)
  - high energy jet resolution
  - FEC: ~30X_0; FHC: ~8-10 λ_I
- Backward BEC + BHC:
  - need precise electron tagging
  - Si-Pb, Si-Fe/Cu (~25X_0, 6-8 λ_I)
- GEANT4 simulation *
  - containment, multi-track resolution (forward)
  - $e^{\pm}$ tagging/E measurement (backwards)

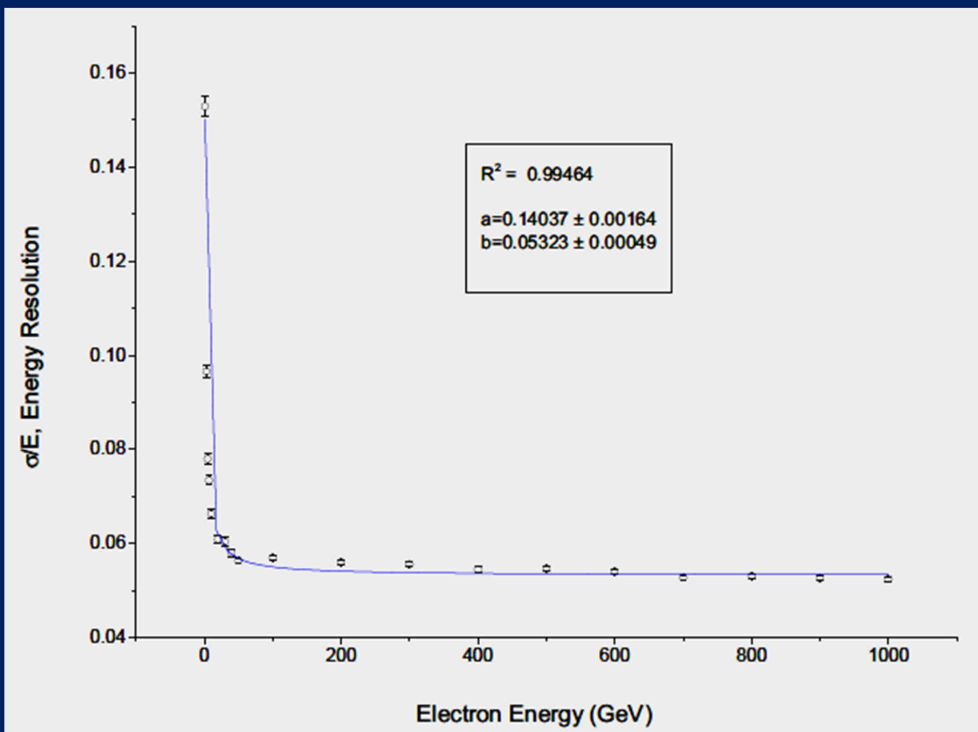


* A. Kilic, I. Tapan - Uludag University

Forward/Backward Calorimeters (ii)

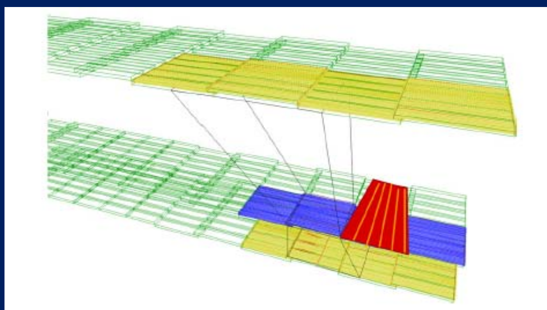
- Highest energies in forward region
- Radiation hard
- High Granularity
- Linearity

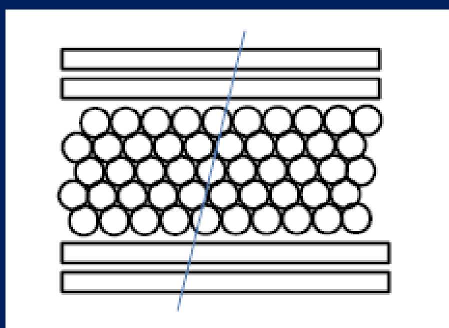
Calorimeter Module	Layer	Absorber	Thickness	Instrumented Gap	Total Depth
FEC(W-Si) 30x0	1-25 26-50	1.4 mm 2.8 mm	16 cm 19.5 cm	5 mm	35.5 cm
FHC (W-Si)	1-15 16-31 32-46	1.2 cm 1.6 cm 3.8 cm	39 cm 48 cm 78 cm	14 mm	165 cm
FHC (Cu-Si)	1-10 11-20 21-30	2.5 cm 5 cm 7.5 cm	30 cm 55 cm 80 cm	5 mm	165 cm
BEC (Pb-Si)	1-25 26-50	1.8 mm 3.8 mm	17 cm 22 cm	5 mm	39 cm
BHC(Cu-Si) 7.9	1-15 16-27 28-39	2.0 cm 3.5 cm 4.0 cm	39.75 cm 49.8 cm 55.8 cm	6.5 mm	145.35cm

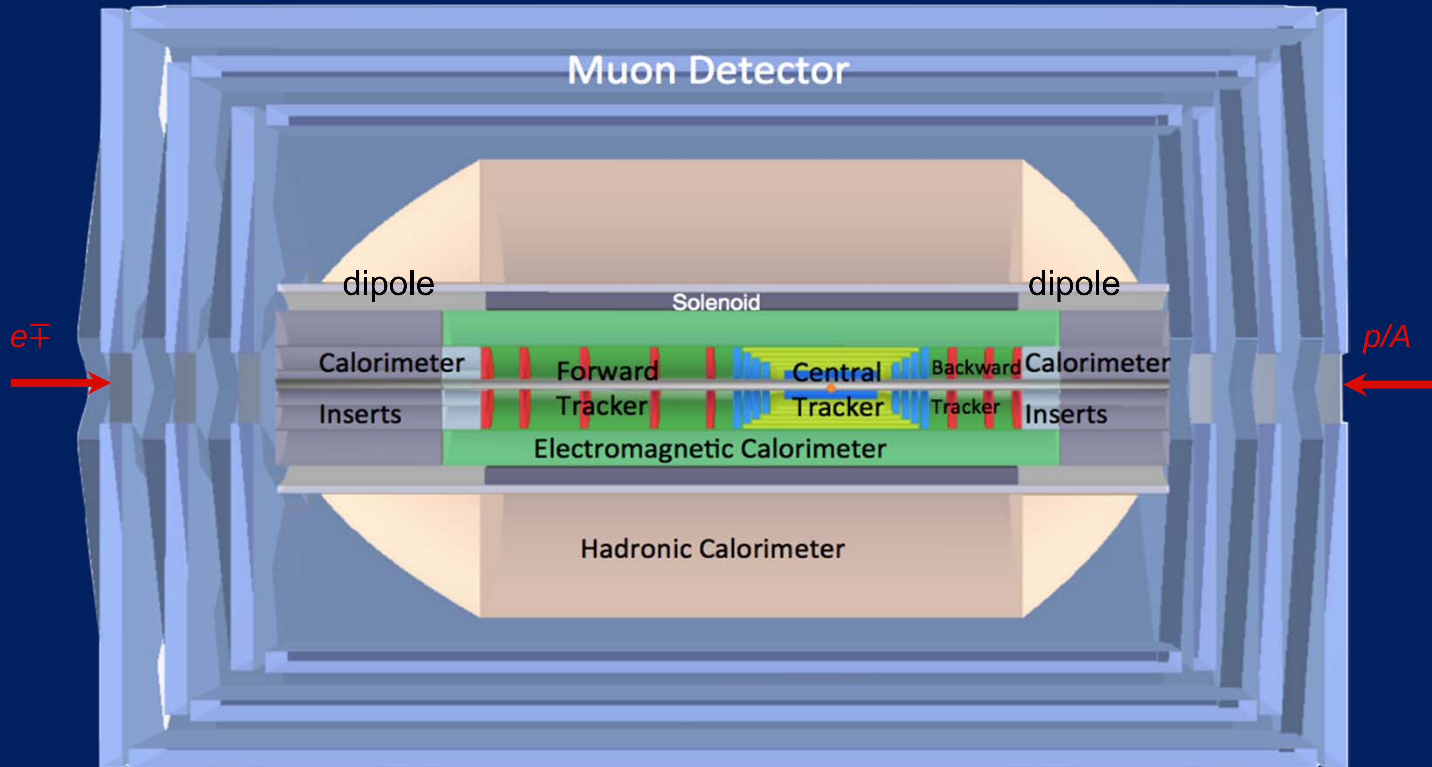


Calorimeter Module (Composition)	Parameterized Energy Resolution
Electromagnetic Response	
$\mathrm{FEC}_{(\mathbf{W-Si})}$	$\frac{\sigma_E}{E} = \frac{(14.0 \pm 0.16)\%}{\sqrt{E}} \oplus (5.3 \pm 0.049)\%$
$\mathrm{BEC}_{(\mathbf{Pb-Si})}$	$\frac{\sigma_E}{E} = \frac{(11.4 \pm 0.5)\%}{\sqrt{E}} \oplus (6.3 \pm 0.1)\%$
Hadronic Response	
$\mathrm{FEC}_{(\mathbf{W-Si})}$ & $\mathrm{FHC}_{(\mathbf{W-Si})}$	$\frac{\sigma_E}{E} = \frac{(45.4 \pm 1.7)\%}{\sqrt{E}} \oplus (4.8 \pm 0.086)\%$
$\mathrm{FEC}_{(\mathbf{W-Si})}$ & $\mathrm{FHC}_{(\mathbf{Cu-Si})}$	$\frac{\sigma_E}{E} = \frac{(46.0 \pm 1.7)\%}{\sqrt{E}} \oplus 6.1 \pm 0.073)\%$
$\mathrm{BEC}_{(\mathbf{Pb-Si})}$ & $\mathrm{BHC}_{(\mathbf{Cu-Si})}$	$\frac{\sigma_E}{E} = \frac{(21.6 \pm 1.9)\%}{\sqrt{E}} \oplus (9.7 \pm 0.4)\%$

Muon System Baseline







Baseline Solution:

- Muon system providing tagging, no independent momentum measurement
- Momentum measurement done in combination with inner tracking
- Present technologies in use in LHC exp. sufficient (RPC, MDT, TGC)

Summary and Outlook

Status

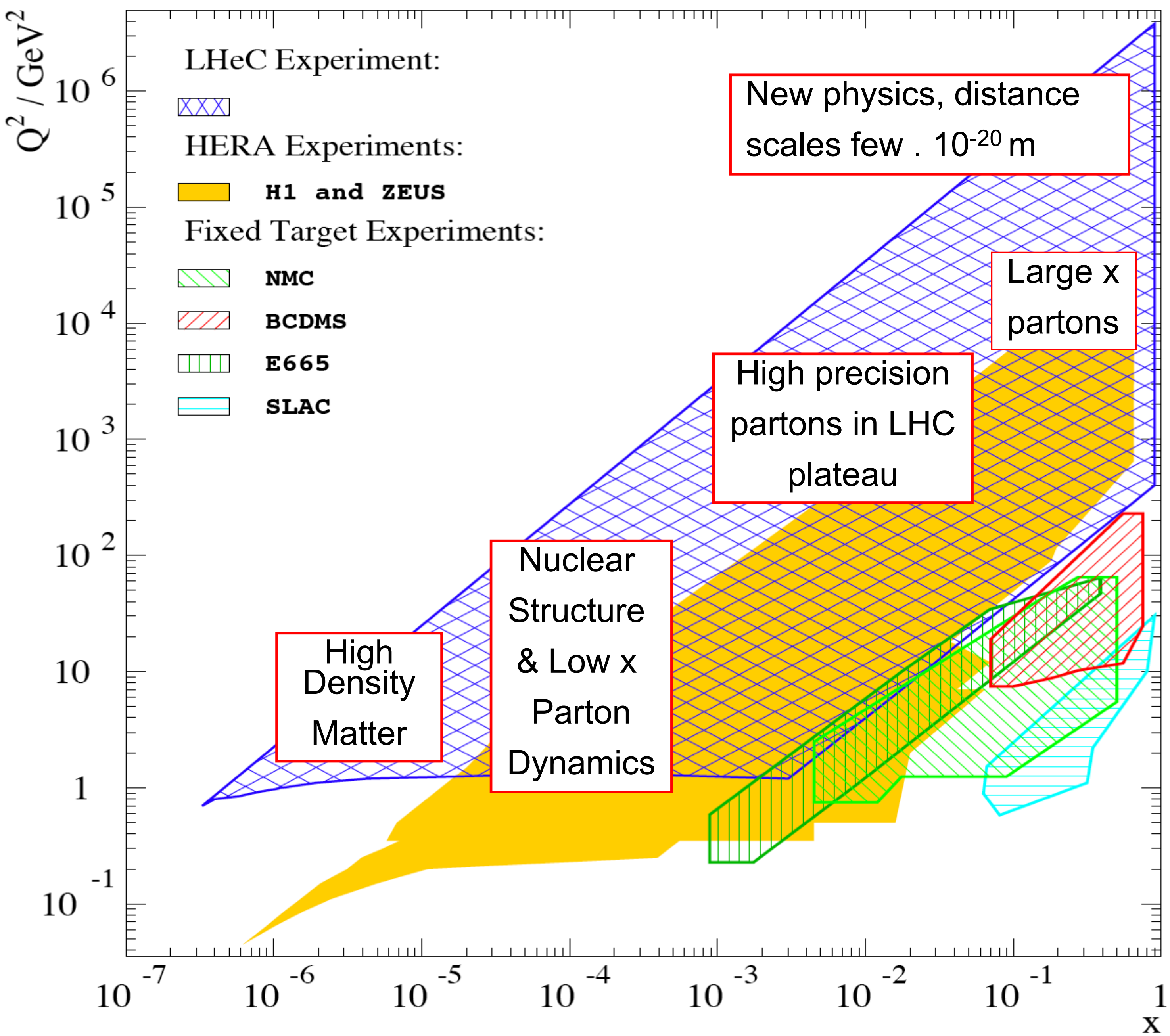
- A LHeC baseline detector concept has been presented
- The design depends heavily on the constraints from the machine and interaction region
- For all cases a feasible and affordable concept which fulfills the physics requirements has been presented
- As a baseline many improvements available. A more precise design will follow from more detailed simulations, engineering and the knowledge of the machine constraints

The Future

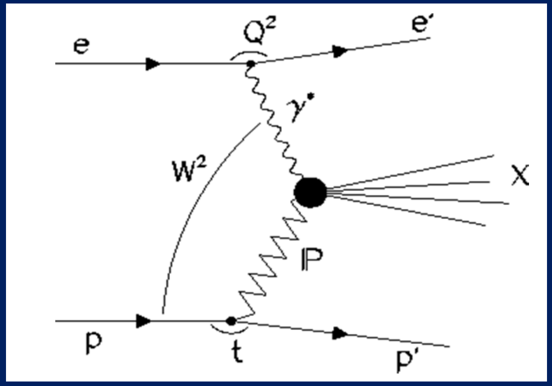
- Start a new phase in detector design
- Collect people, experience, information
- Identify and address critical items, discuss the timeline for realization
- Build a collaboration and move next steps towards a Technical Design

Backup

Kinematics & Motivation (60 GeV x 7 TeV *ep*)



$\sqrt{s}$= 1.4 TeV

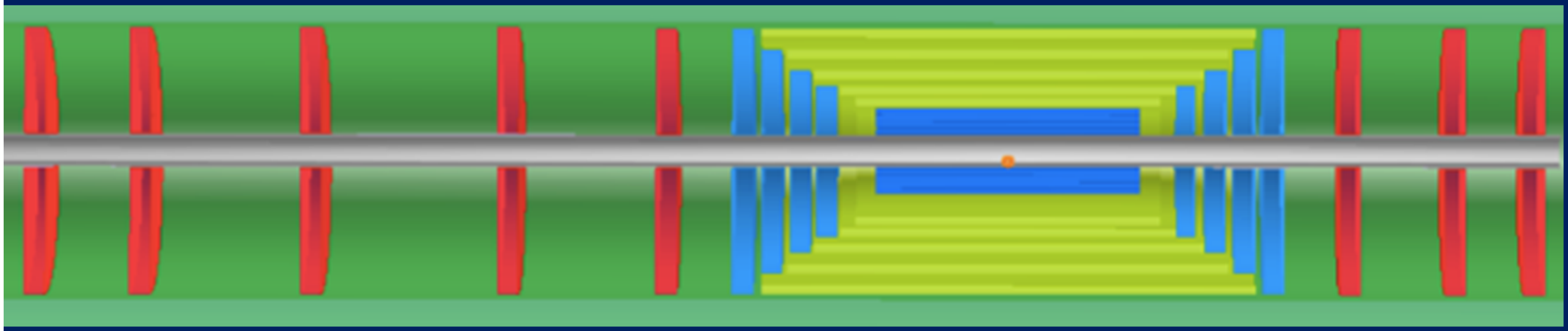


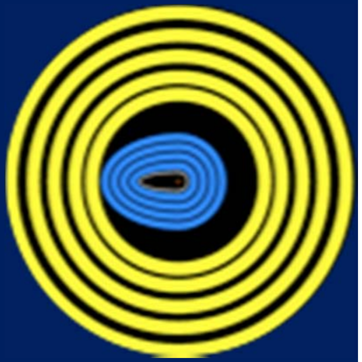
- High mass (M_{eq},Q^2) frontier
- EW & Higgs
- Q^2 lever-arm at moderate & high x → PDFs
- Low x frontier [x below 10^{-6} at Q^2 ~ 1 GeV^2]

→ novel QCD …

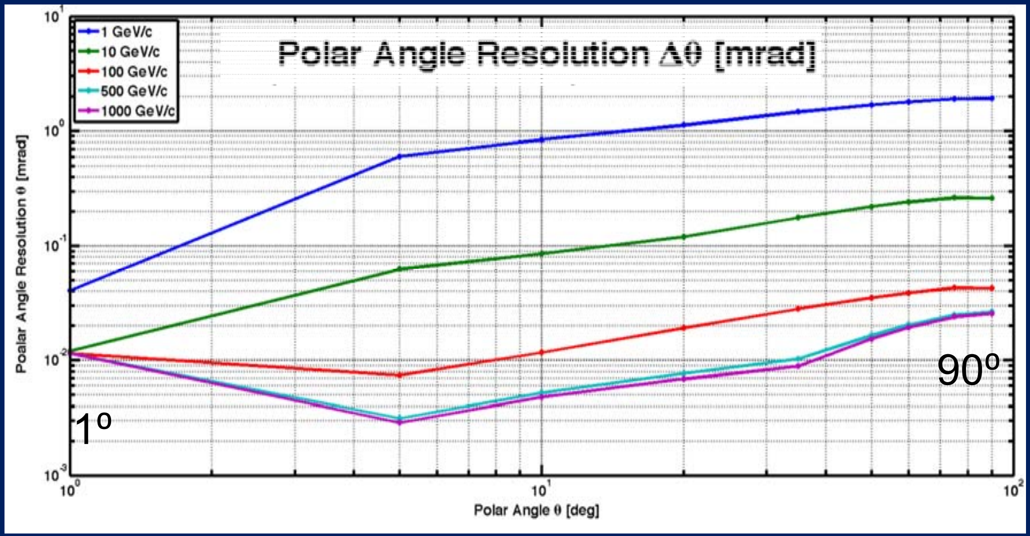
Tracker Detector Technology

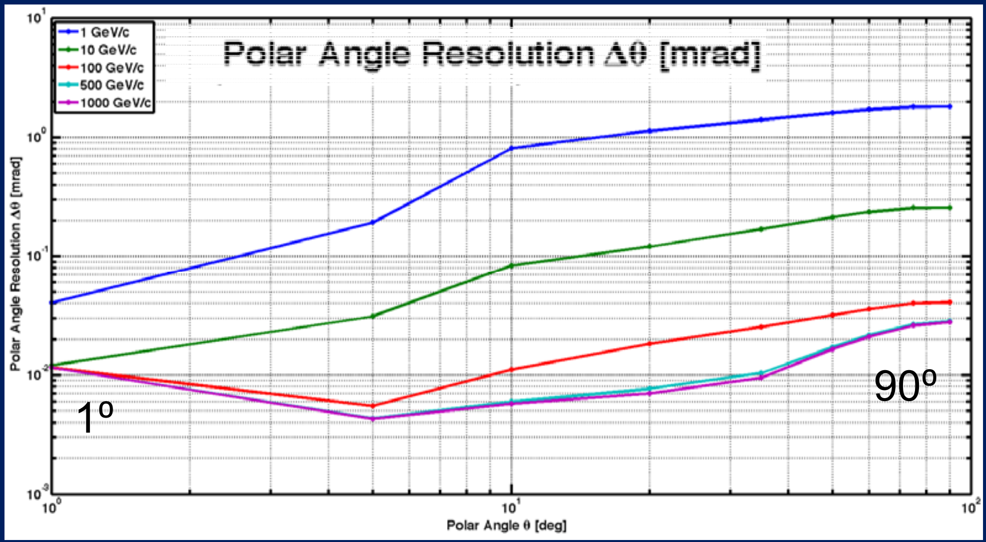
- Choose among available technologies
  n-in-p (sLHC) or n^+-in-n (ATLAS/CMS/LHCb)
- Radiation hardness in LHeC not as challenging as in LHC
- Silicon Pixel, Strixel, Strips
- Detailed simulation to best understand the needs and implications
- Readout/Trigger, Services, # silicon layers
- Analog/Digital Readout
- Modular structure for best replacement / maintenance and detector adoption: RR high luminosity / high acceptance running
- Pixel Detector*) (barrel CPT 1-4 and inner forward/backward FST/BST)

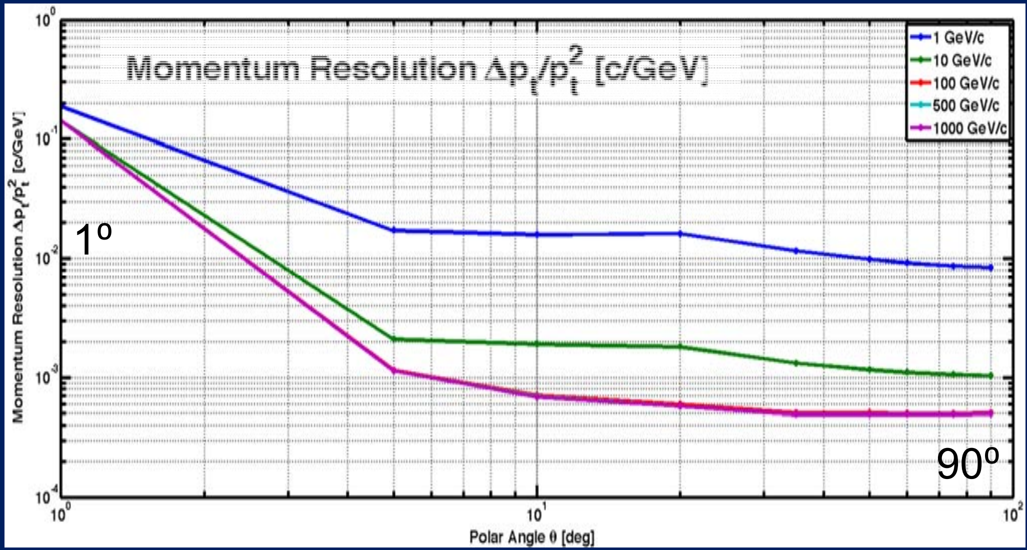


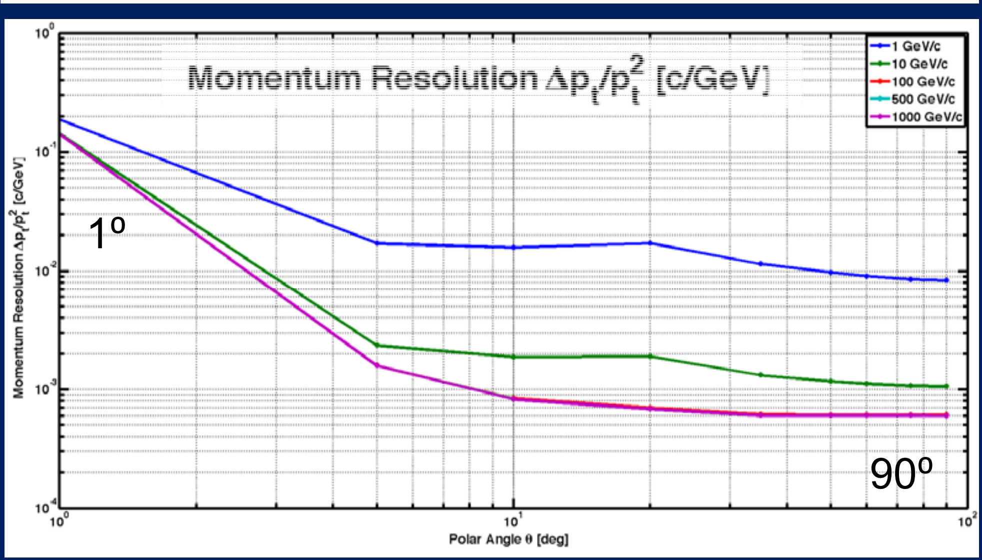


Tracker Simulation (ii)



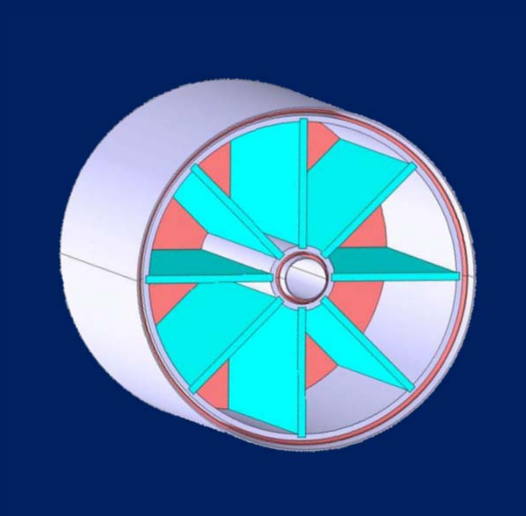


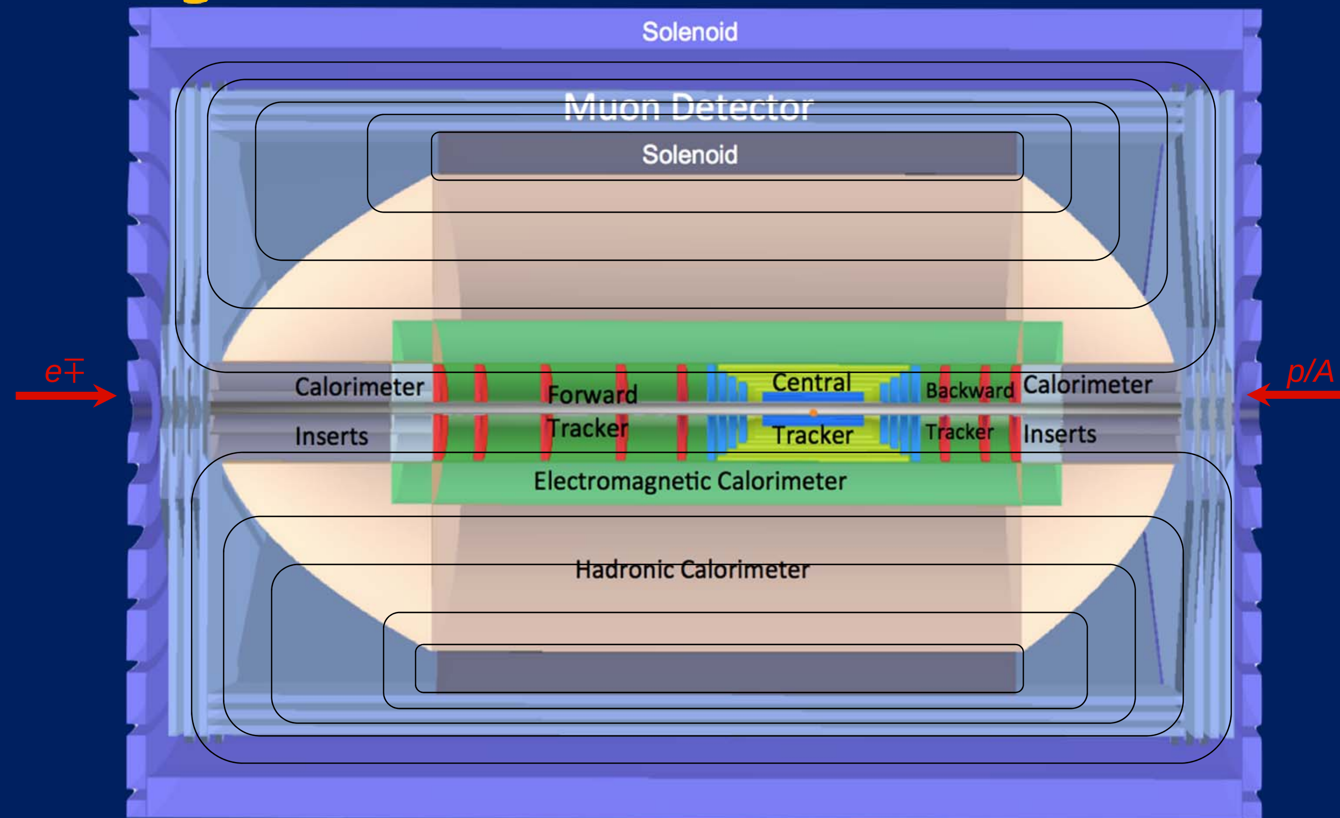




- Same plots (left) and (small) deterioration in case of innermost barrel layer failure (right)

Muon System Extensions





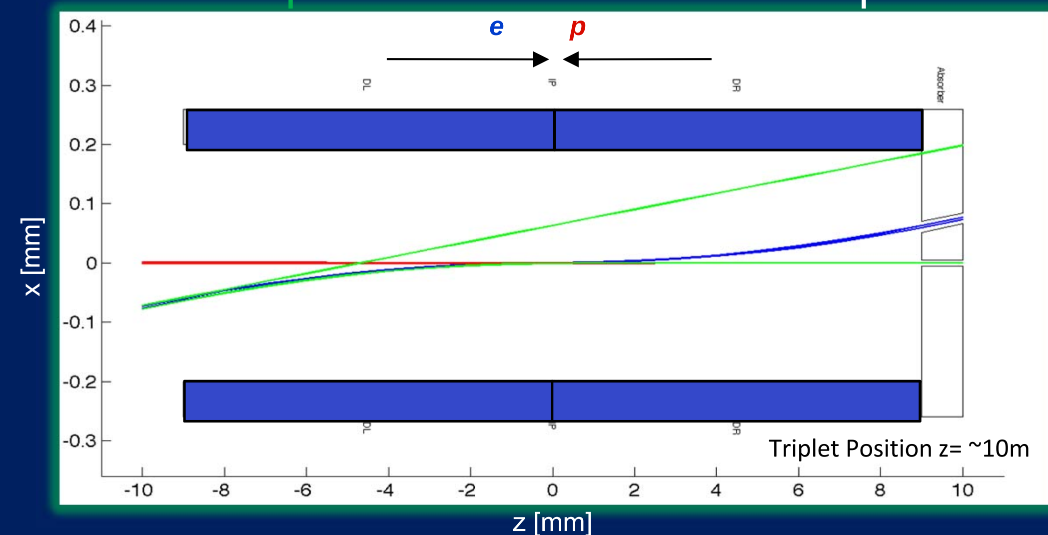
Extensions:

- Independent momentum measurement
- Large solenoid (incompatible with LR dipoles)
- Dual Coil System (homogeneous return field)
- Forward Toroid System

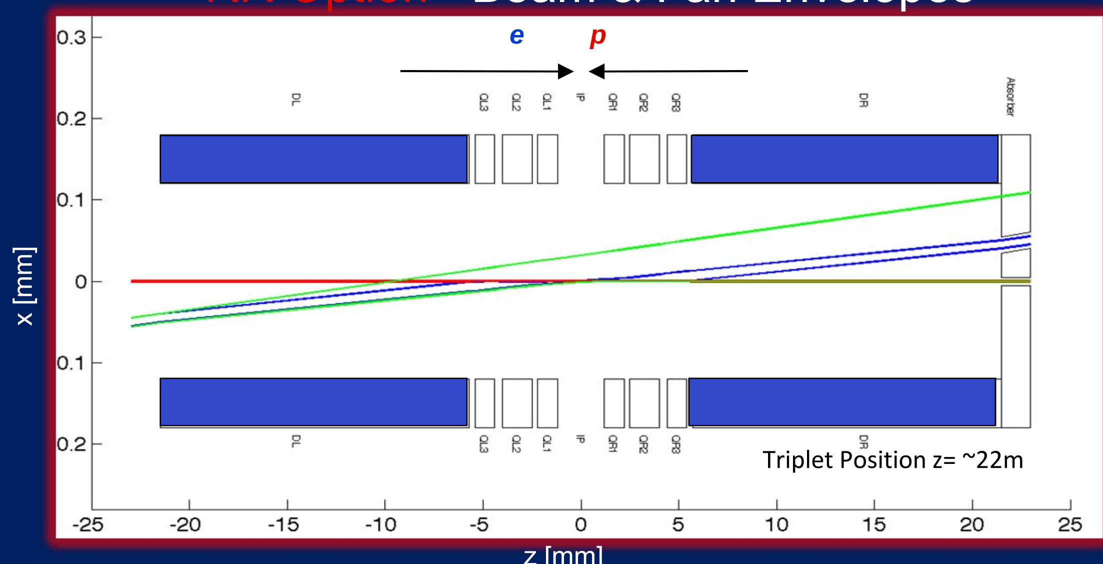
LR, RR option - Beam & SR

SR Fan growth with z

LR Option - Beam & Fan Envelopes



RR Option - Beam & Fan Envelopes



Legend : Dipole

SR Fan growth with z

(high luminosity case)

LR Interaction Region

- Special attention is required to the interaction region design, which comprises beam bending (in/out), direct and secondary synchrotron radiation, vacuum and beam pipe

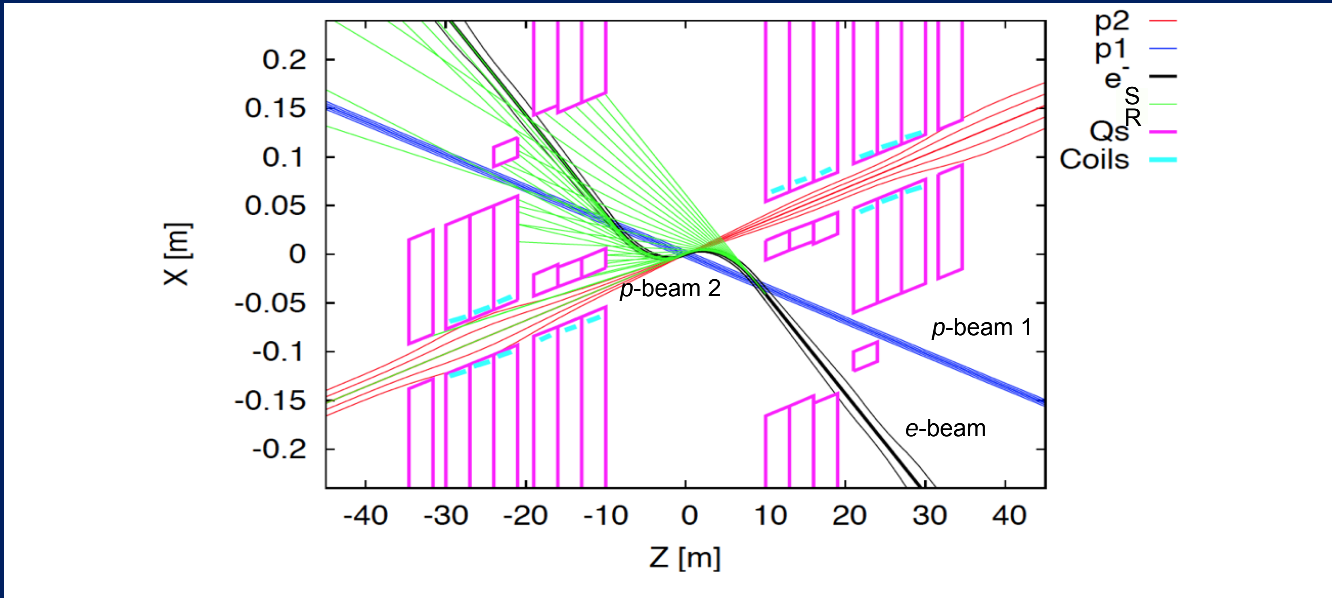
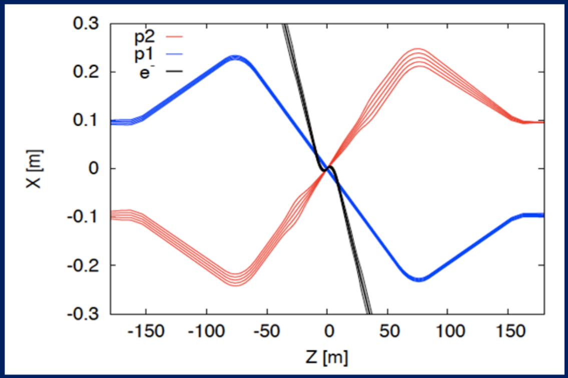
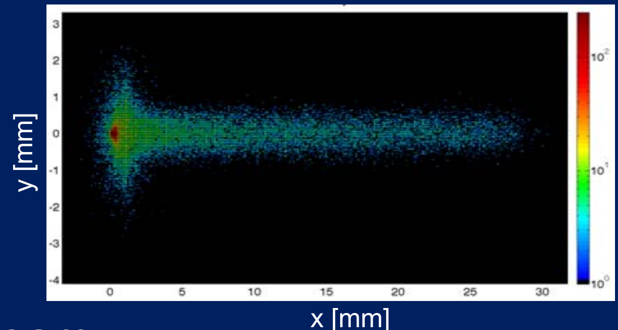


Figure 9.14: LHeC interaction region with a schematic view of synchrotron radiation. Beam trajectories with 5σ and 10σ envelopes are shown.

3 beams, head-on collisions



Photon Number Density at the IP



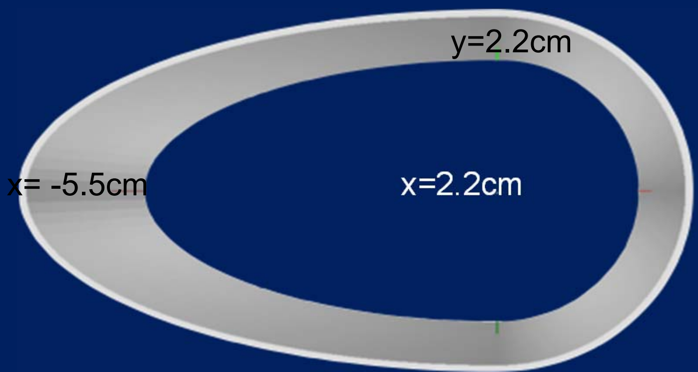
- Dipoles around the IP (2 x 9m, 0.3T) for making electrons collide head-on with *p-beam 2* & safely extract the disrupted electron beam.
- Simulation of Synchrotron Radiation (SR) load in the IR and design of absorbers / masks shielding SR from backscattering into the detector & from propagating with $e^{\pm}$ beam.
- Beam pipe design - space for SR fan - tracking/calorimetry close to the IP / beam line (goal: 1° - 179°)

Beam Pipe / Profile - SR Fan

Ring-Ring - Inner dimensions (masks at 6, 5, 4m - primary SR shield)

Circular(x)=2.2cm (LHC upgrade); Elliptical(-x)=-5.5, y=2.2cm

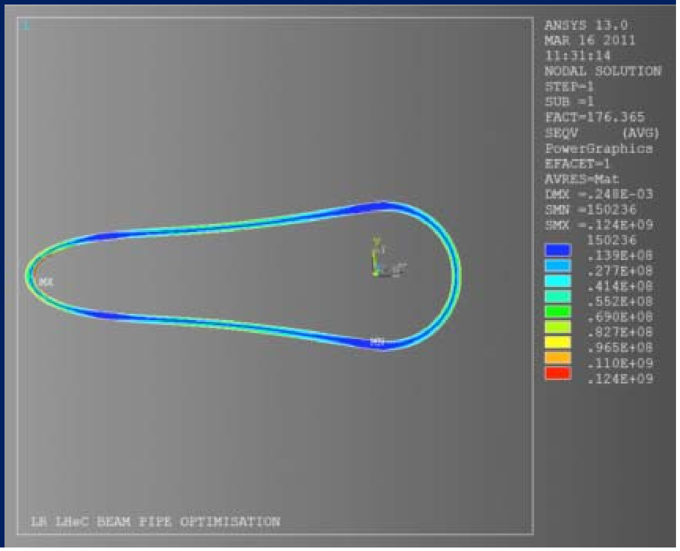
beam pipe dimensions reduced - using static / movable masks;



housing beam/SR envelopes
+ 1cm safety margin

Linac-Ring - Inner Dimensions

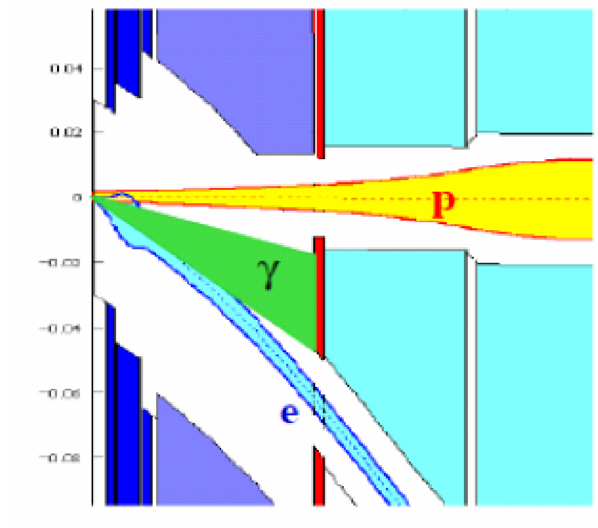
Circular(x)=2.2cm; Elliptical(-x)=-10., y=2.2cm



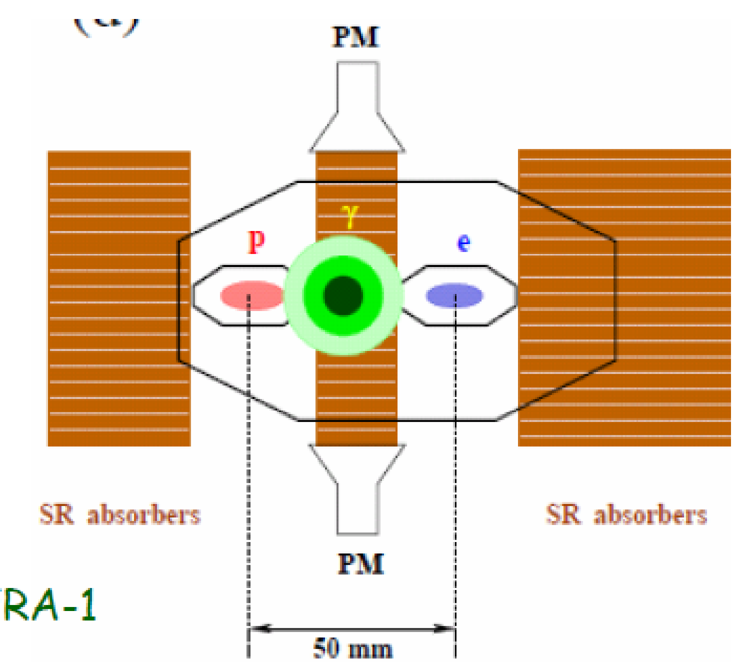
Luminosity measurement: Bethe-Heitler (ep→eγp)

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

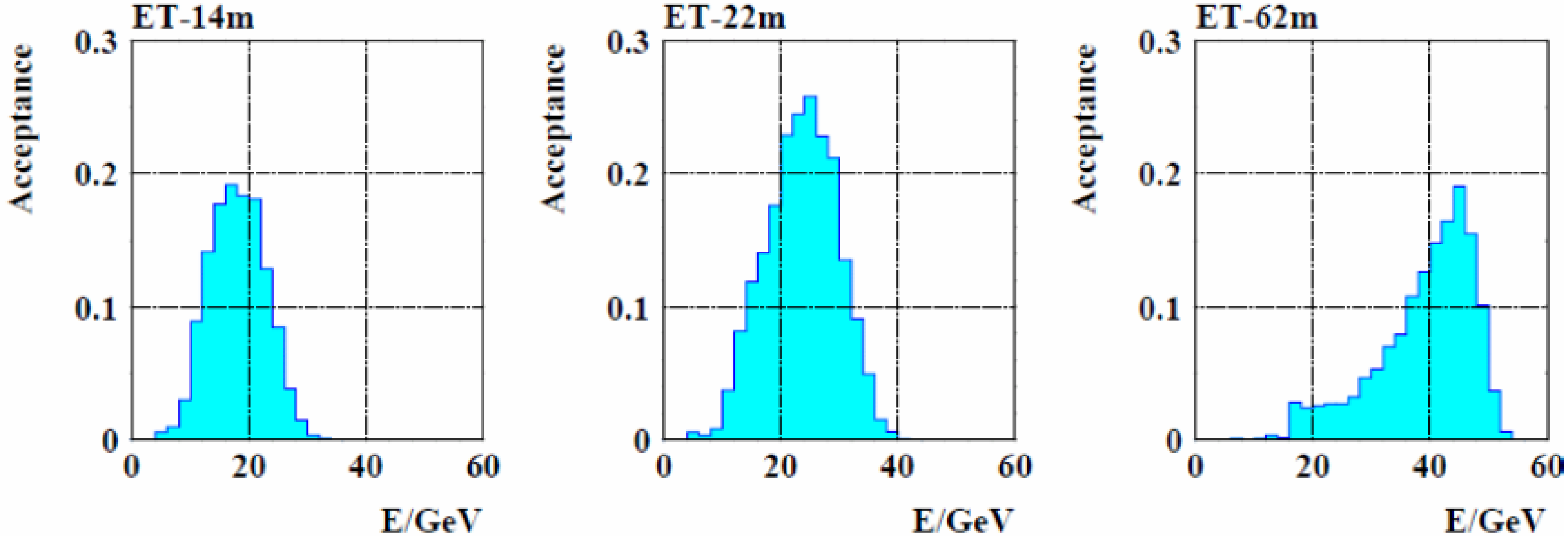
* Water Čerenkov detector was successfully used in H1 during HERA-1

Electron tagger

detect scattered electron from Bethe-Heitler (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 is preferable - less SR, more space. Next step- 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)

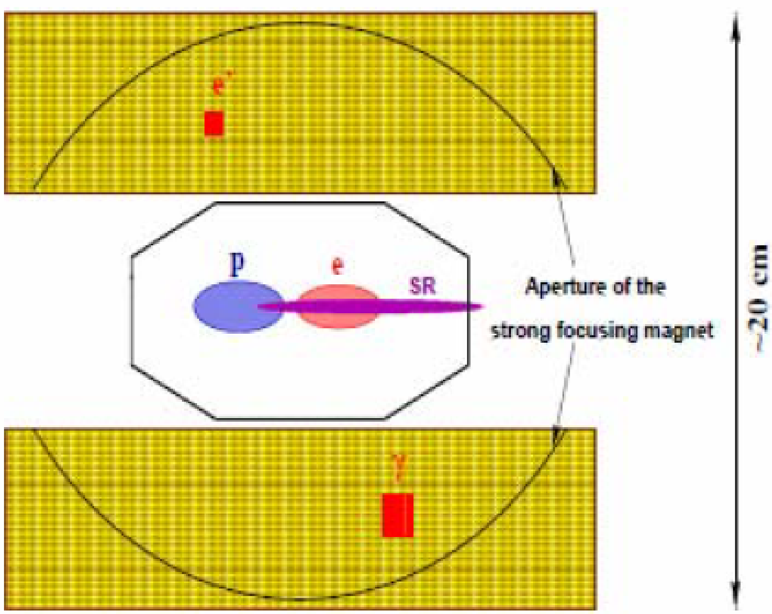
Luminosity measurement: QED Compton

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

σ_{vis} ~3.5nb (low Q^2 setup); 0.03nb (high Q^2 setup)

Install additional 'QEDC tagger' at z≈-6m → increase visible cross section for QEDC up to ~3-4 nb

→ 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 of QEDC tagger

-good energy resolution,linearity in 10-60 GeV range

-small amount of dead material in front (and well known/simulated)

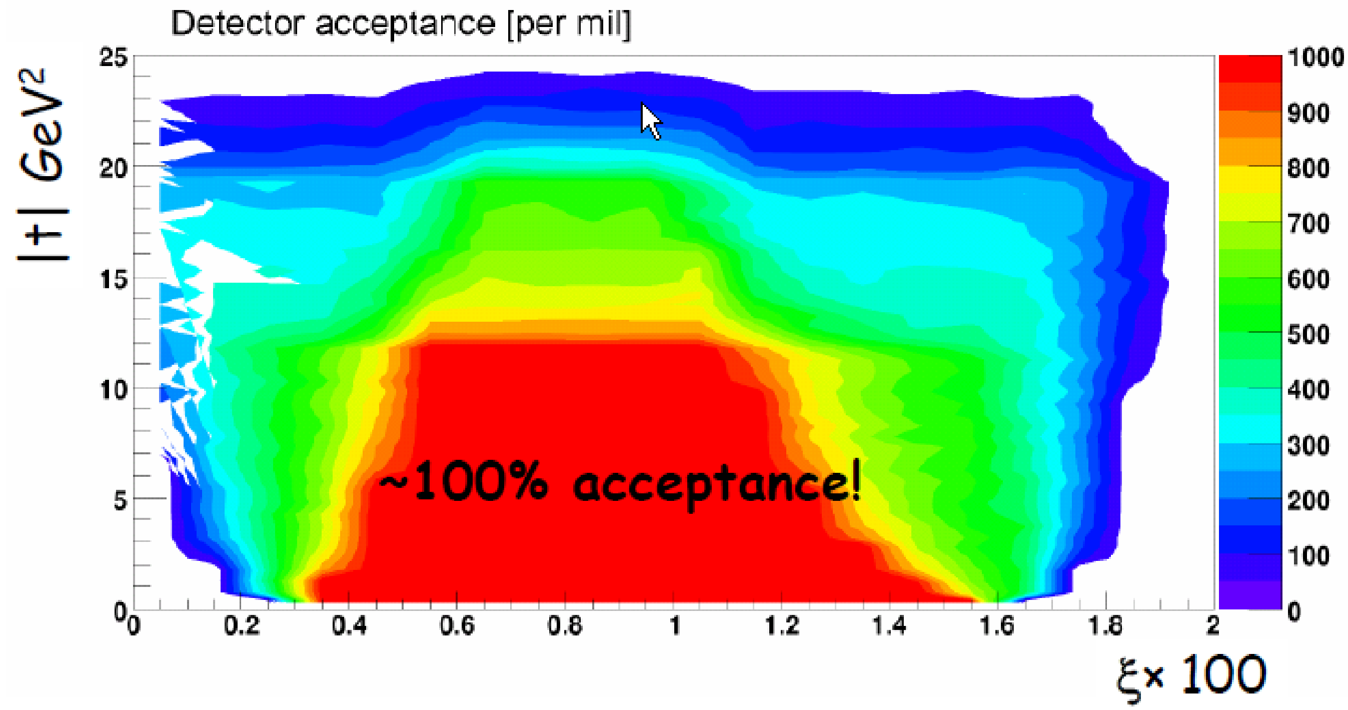
-efficient e/γ separation → a small silicon tracker in front of calorimeter modules (this also allows z-vertex determination)

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 $0.002<\xi<0.013$

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.

LHeC Beampipe Timescale

A tentative timescale (months)............

CDR

Typical Be solution (3-4 yrs)

12? vac studies	12? vac tests					
eng, layouts, integration						
composite studies 24?	prototypes 24?	eng design 6	approval 3	tender 12	manu 12-24	coating 3

Low Z materials R&D (C. Garion)

LEB WG (M. Galillee)

Additional manpower is necessary to advance on LHeC eng & vacuum

A. Polini

Alternative Beam Pipe Solutions

CHAMBER COST

½ cylinder, ½ ellipse tapering

Variable wall thickness

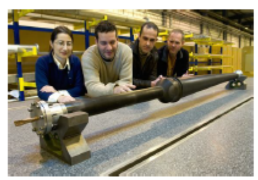
½ cylinder, ½ ellipse

Ellipse

Racetrack

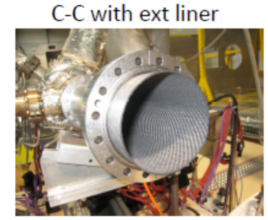
Cone

Cylinder



LHCb UX85/1
Bi-conical Be

C-C with ext liner

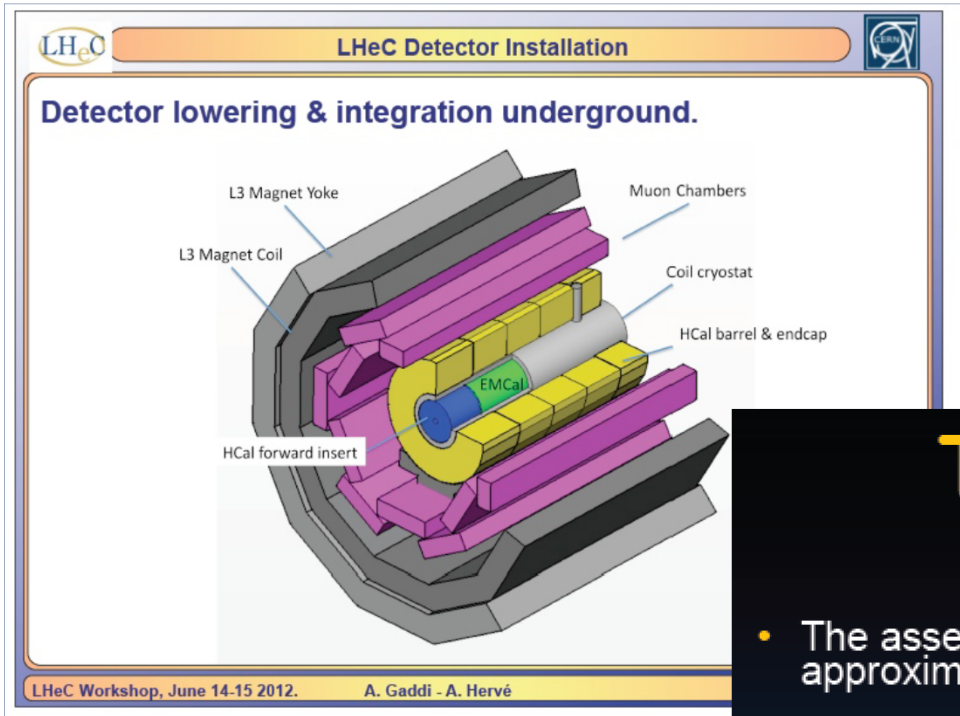


Carbon-fibre, Carbon-Carbon
Sandwich structures, Glassy carbon

Beryllium — Composites

EXECUTION TIME, RISK

P. Cruikshank



Timeline - Installation

- The assembly on surface of the main detector elements as approximately 16 months
- The Coil system commissioning on site three additional month, preparation for lowering one month and lowering one week per piece
- Underground completion of the integration of the main detector elements inside the L3 Magnet would require about two months, cabling and connection to services
- Some six months, in parallel with the installation of Muons Tracker and the EMCal
- The total estimated time, is thus 30 months.
- The field map would take one extra month.
- Some contingency is foreseen between the lowering (8 weeks) and integration inside the L3 Magnet of the same elements (2 months).
- Tight but doable

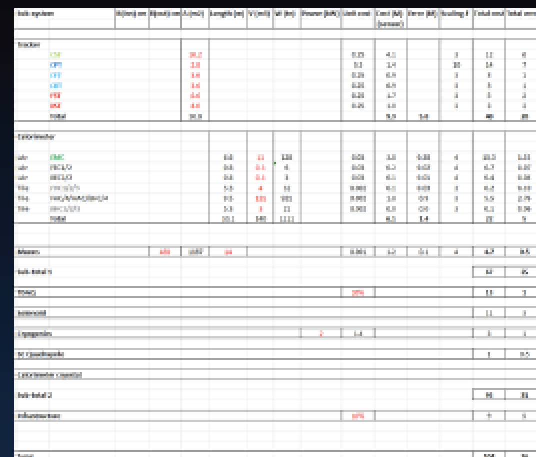
1st-order Cost Estimates of LHeC Detector

NuPECc WS Chavannes, June 15, 2012

Max Klein/Univ. of Liverpool
Peter Kostka/DESY
Alessandro Polini/Univ. of Bologna
Markus Nordberg/CERN

Detector materials, components, electronics, DAQ, computing etc..

CORE



- LHeC 1st-order cost estimates based on ATLAS-CORE numbers, with an error bar reflecting current costs
  - 104 +/- 36 MCHF
- It is assumed ATLAS-numbers scale downwards
- Solenoid costs follow the “A. Herve/ A. Gaddi-equation”

  …which is also consistent with the experimental observation that magnet system ~ 25% of the total (CORE) cost