Detector Design for LHeC / lowE-FCCeh / FCCeh

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on behalf of the LHeC/FCCeh Study Group

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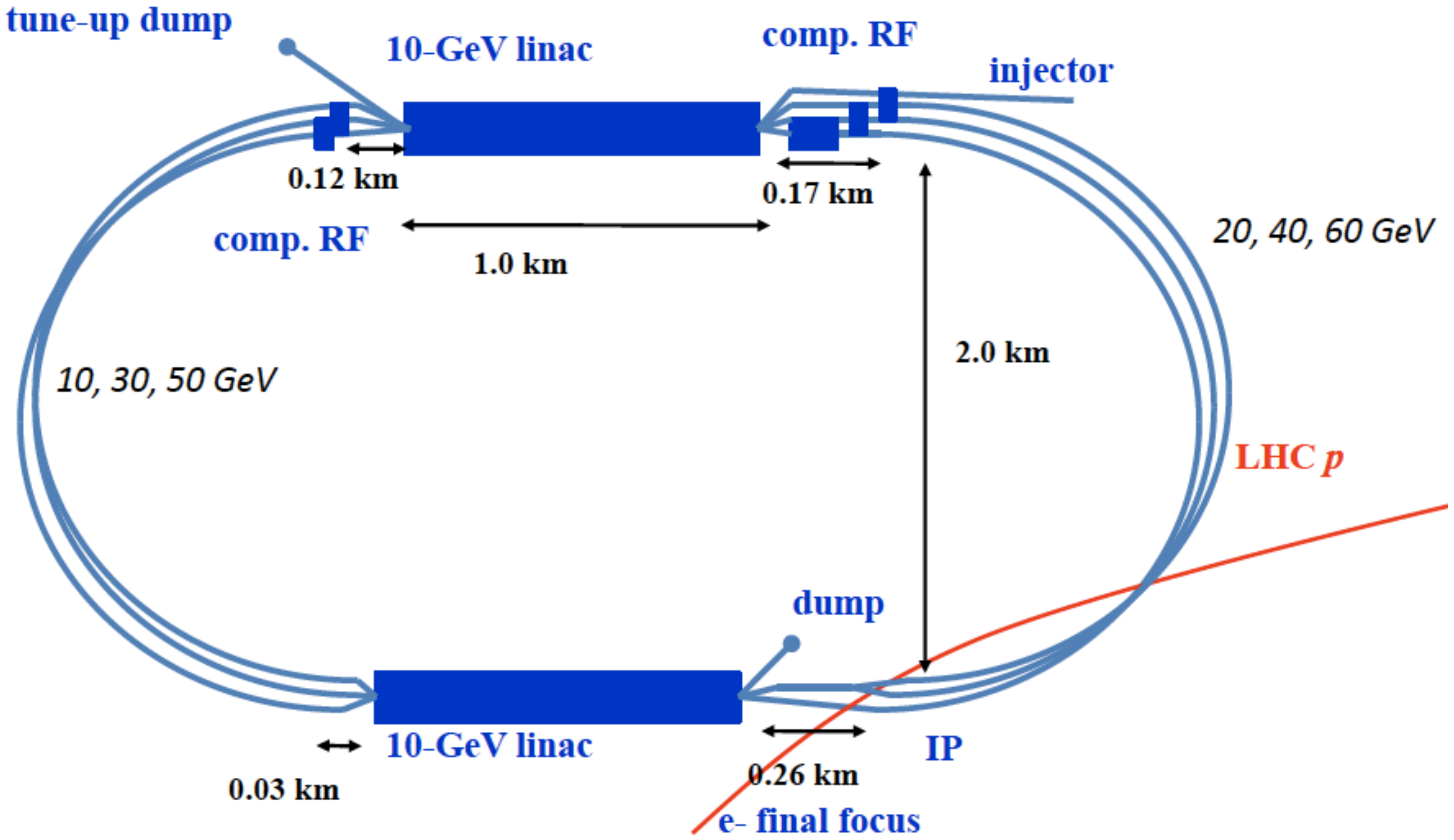
ERL - Electron Beam Configuration



Interaction Point - LHC-P2

Operation in parallel with LHC(/ lowE-FCC / FCC) experiments around the ring

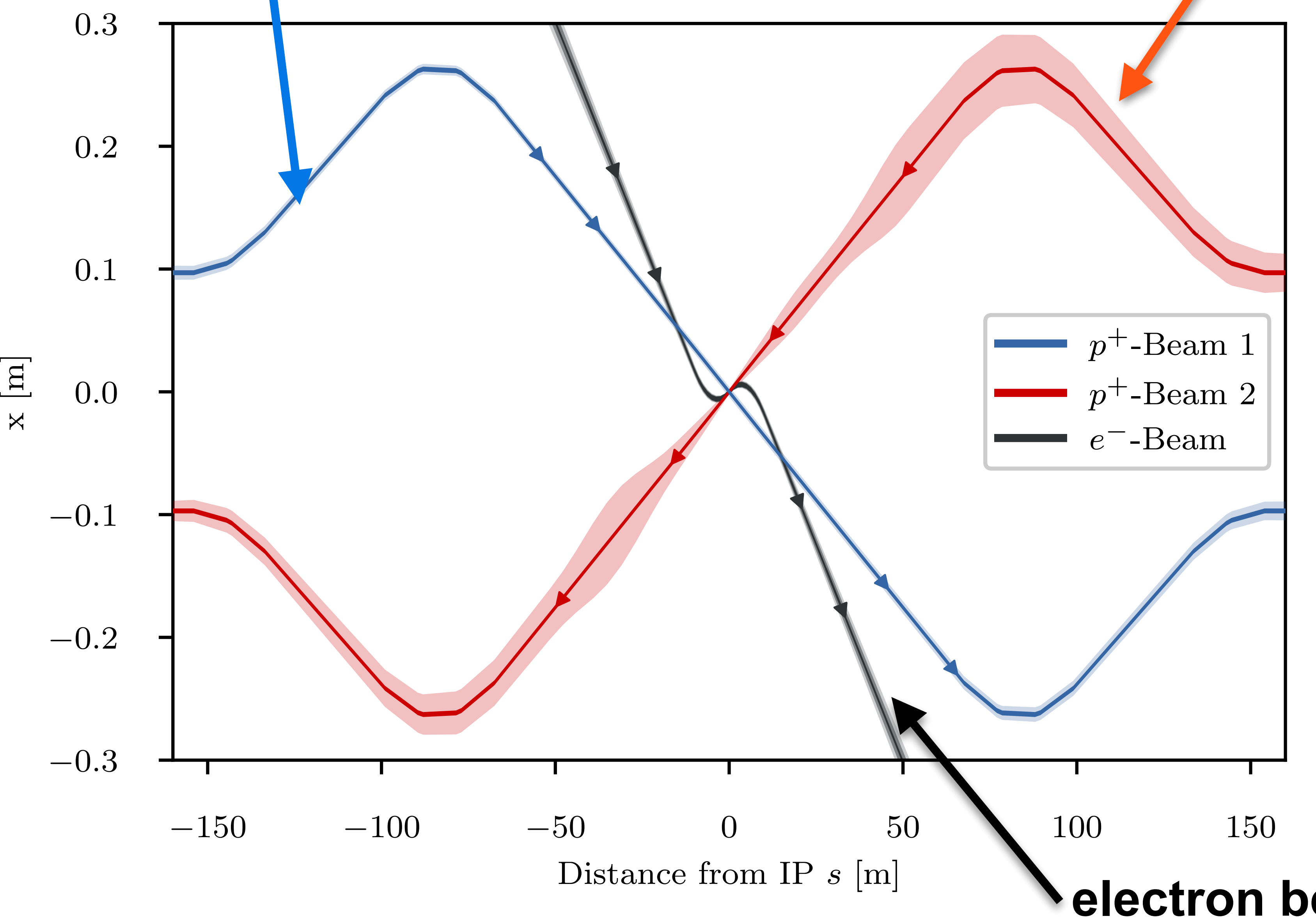
- TeV scale collision energy
  - ➔ 50-150 GeV beam energy
- power consumption < 100 MW
  - ➔ 50 GeV beam energy
- int. luminosity > 100 * HERA
- peak luminosity L > 10^{34} $cm^{-2}s^{-1}$ - precision physics

Some Requirements & Consequences

1. eh Interaction Setup - IR Design

non focused beam bypasses the interaction

focused interacting proton beam

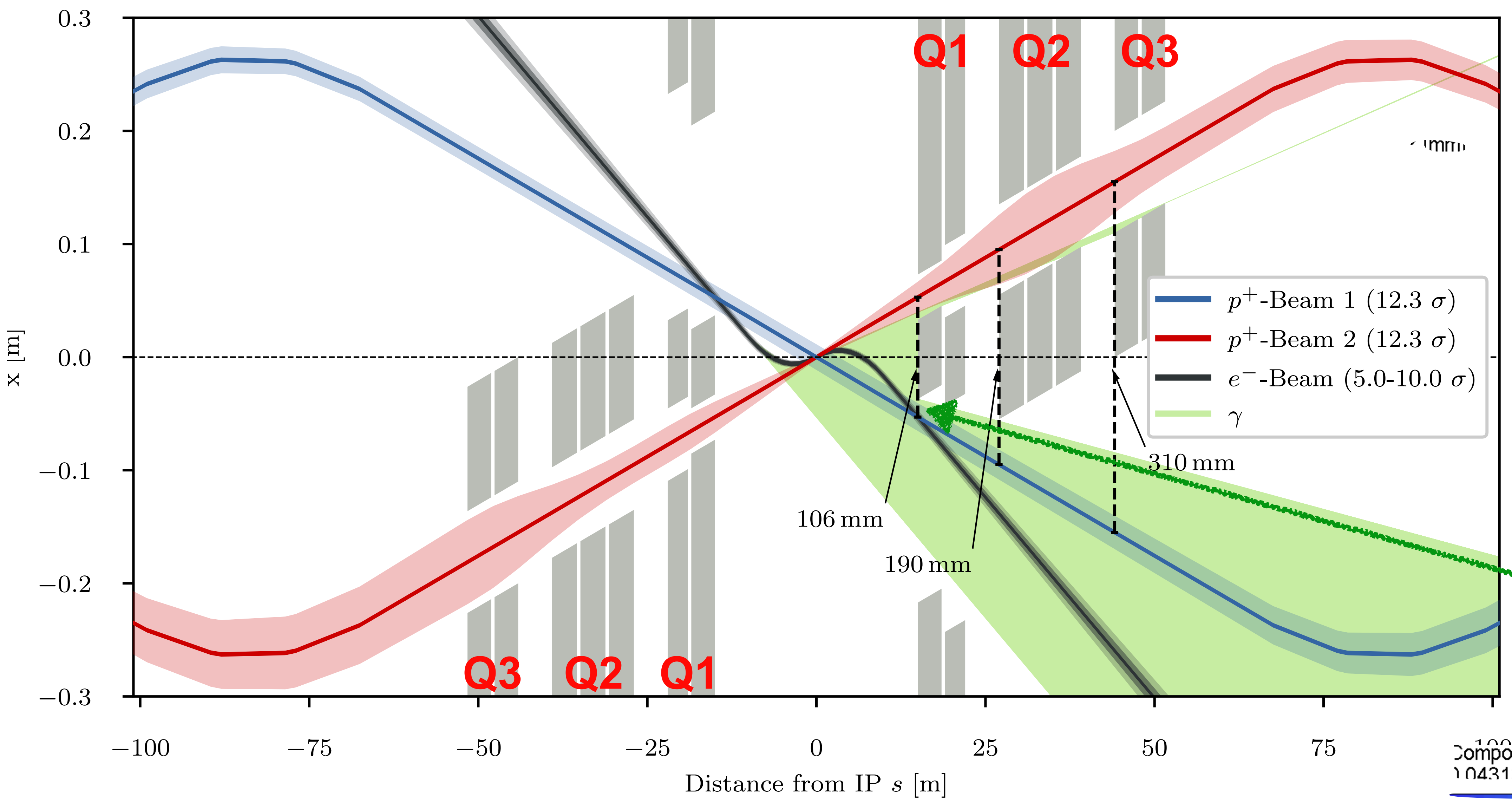


electron beam from ERL

E. Cruz, R. Tomas, F. Zimmermann et al.

Synchrotron Radiation and various beams

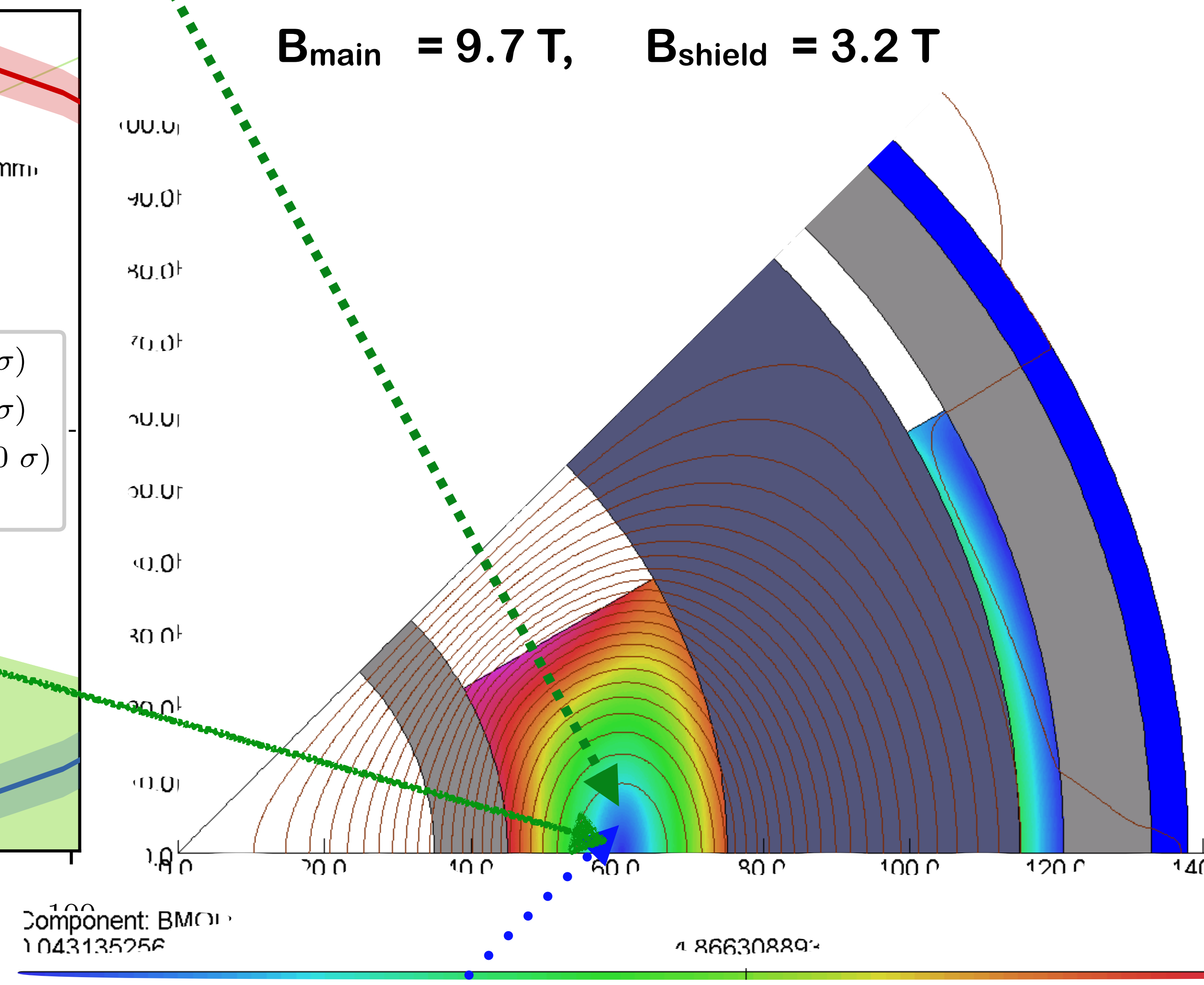
SR fan



Geometry of the interaction region with 10σ envelopes
- electron proton beams well matched
R.Martin

Final quadrupole magnet
Q1 actively shielded quad

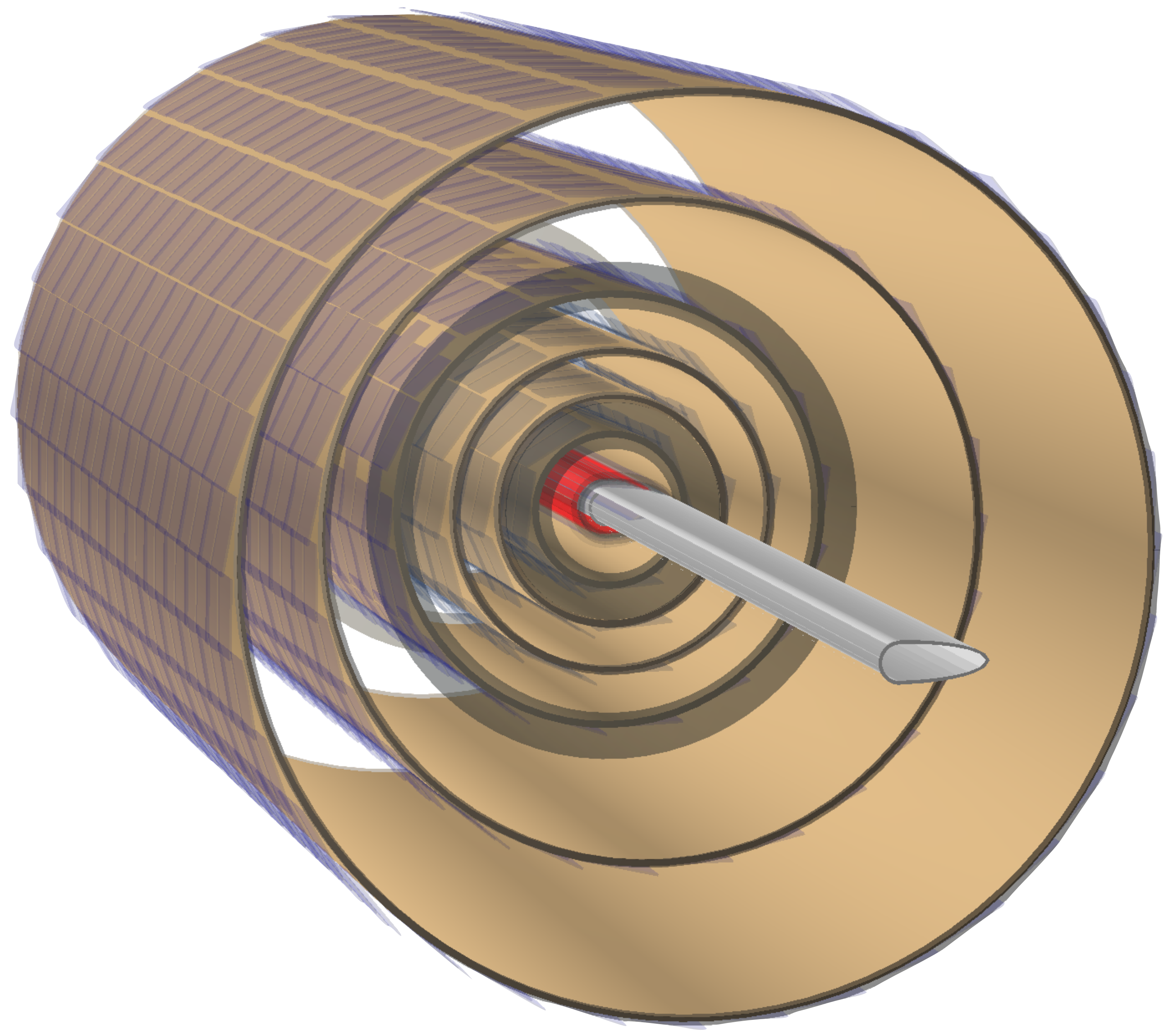
exit - electrons and non-colliding protons



field "free" region

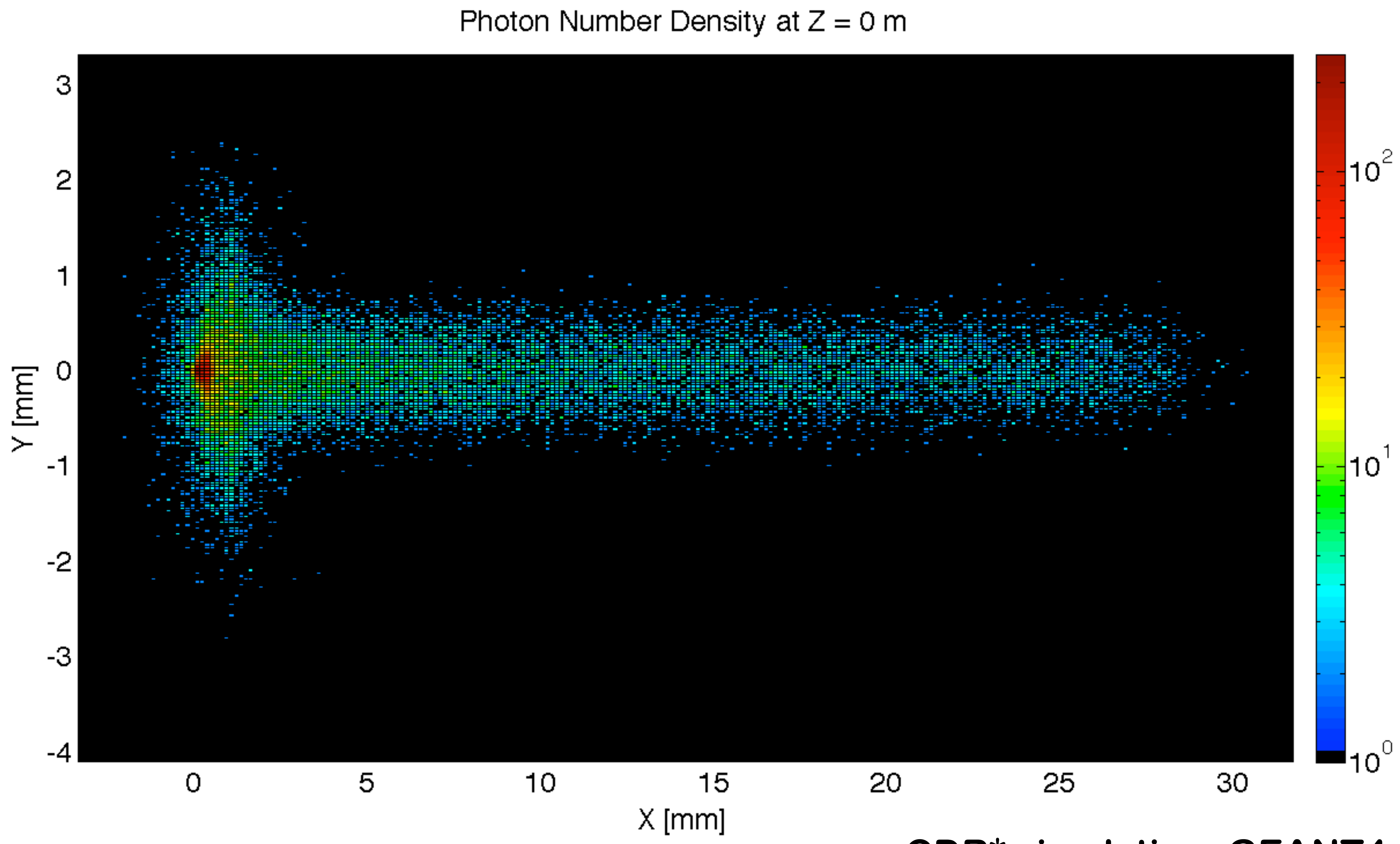
B. Parker, S. Russenschuck et al.

2. Consequences: Beampipe & Central Tracker
Asymmetry of Tracking

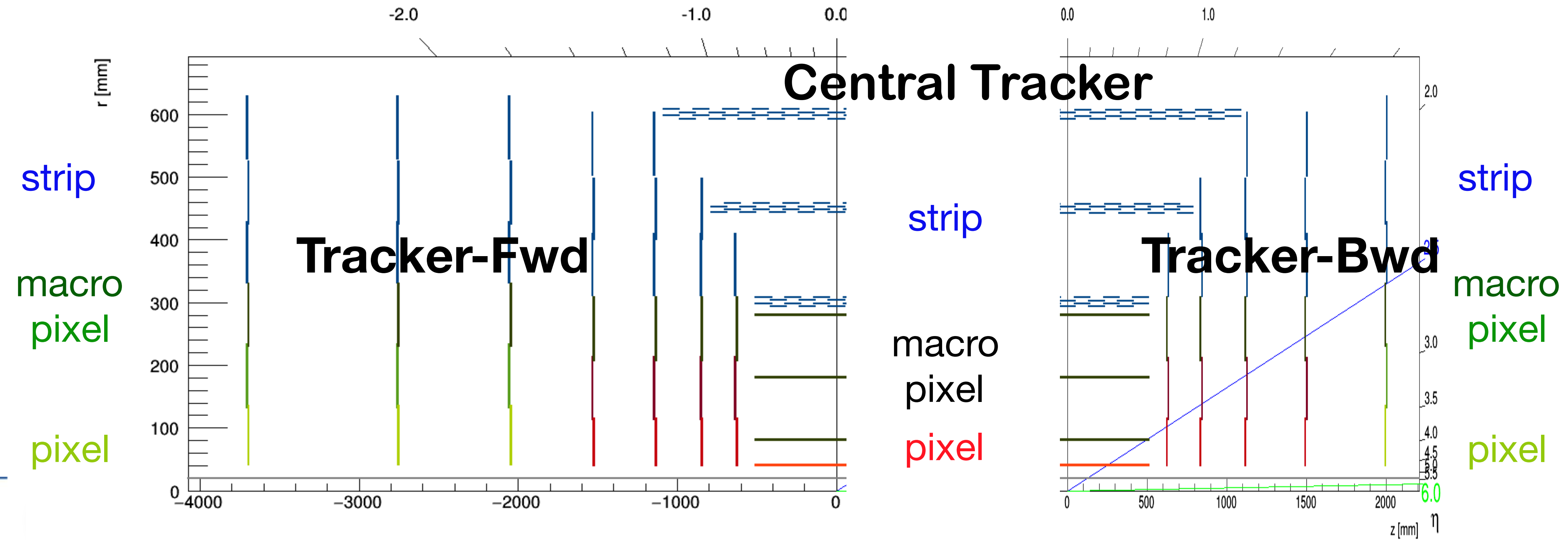


Central Tracker Barrel
circular-elliptical beam pipe

Synchrotron Radiation Fan at IP



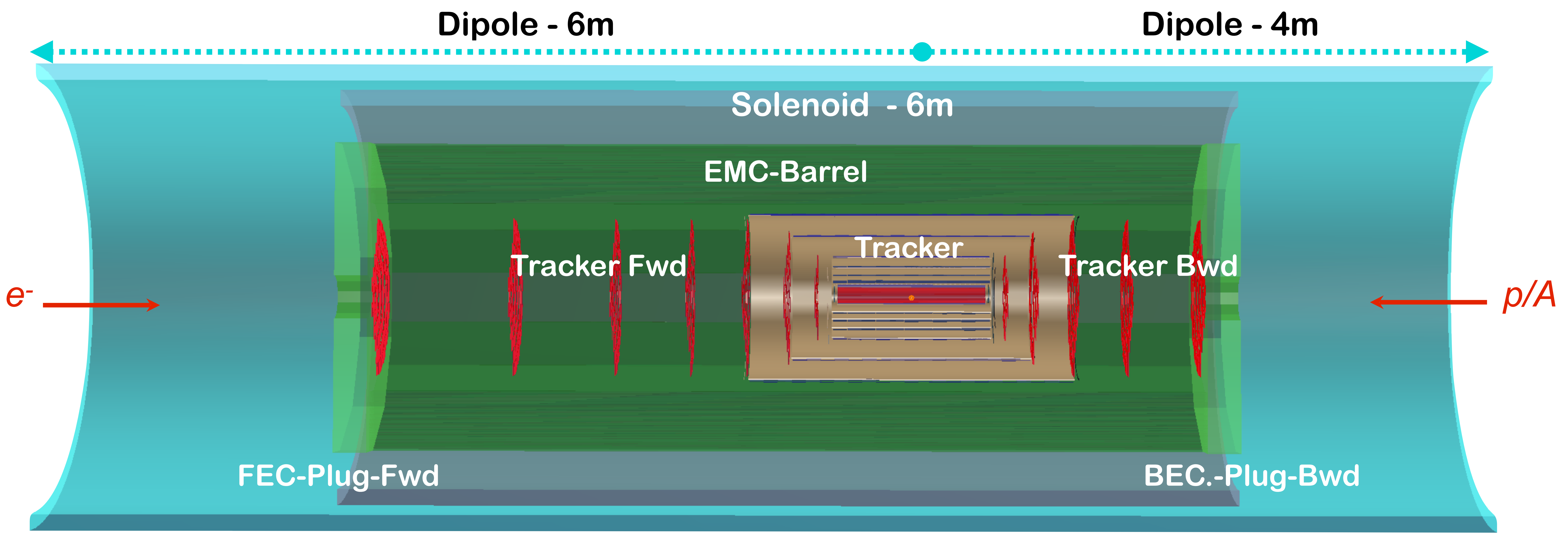
CDR* simulation: GEANT4



Si-technology choices dictated by
- availability
- cost
- minimizing the number of R/O channels

compromising also the material impact - X_0, λ_I
main material contributor is the BP thickness

3. Consequence: Placement of Dipoles, Solenoid

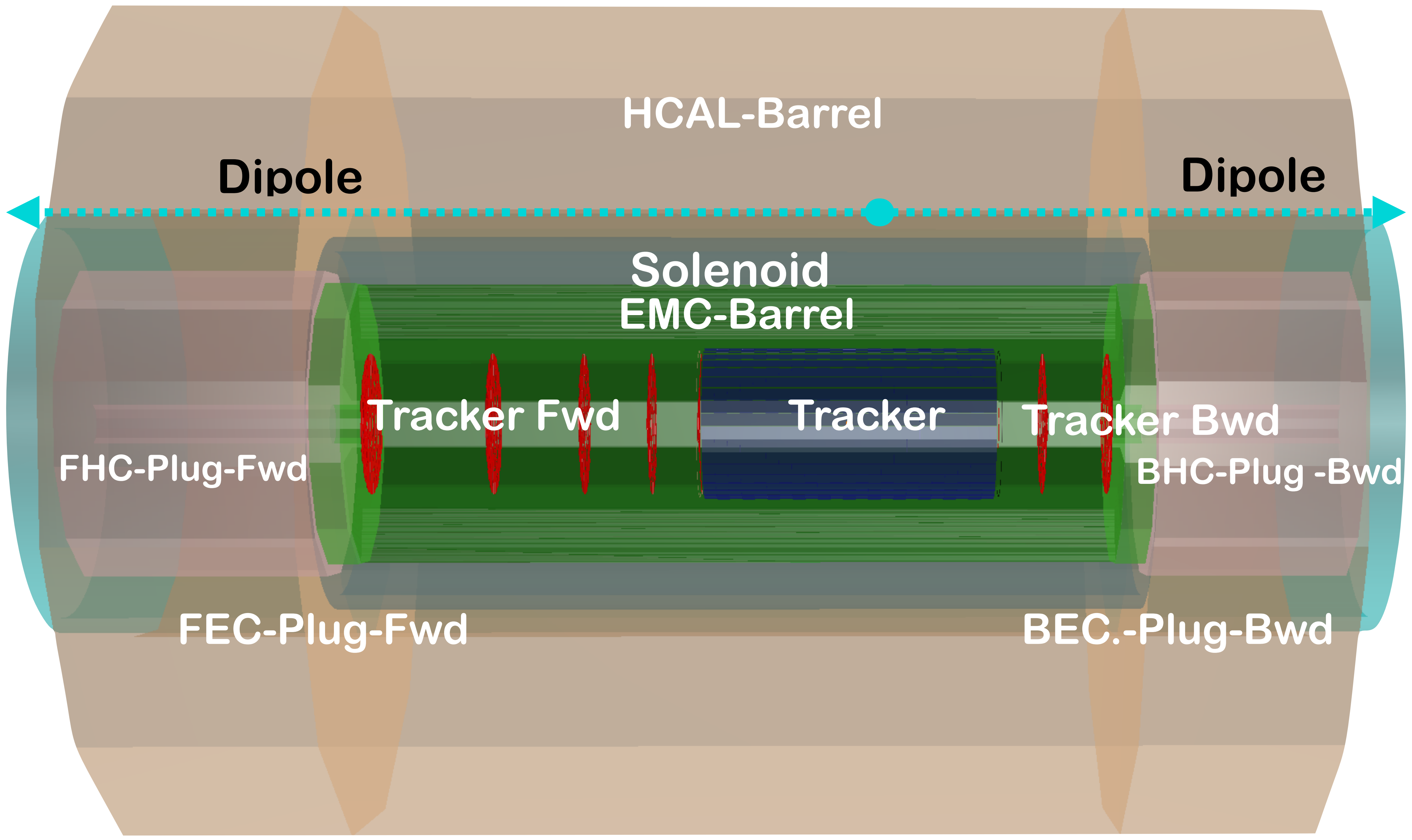


- Solenoid (3.5T) placed between the ECAL-Barrel and Hadronic-Barrel calorimeter (not shown)
  - common cryostat with
    weak electron beam bending dipole (0.21T) steering for head-on collisions with colliding proton beam
    and after the interaction point a dipole with opposite polarity separates the orbits of the electron and proton beam

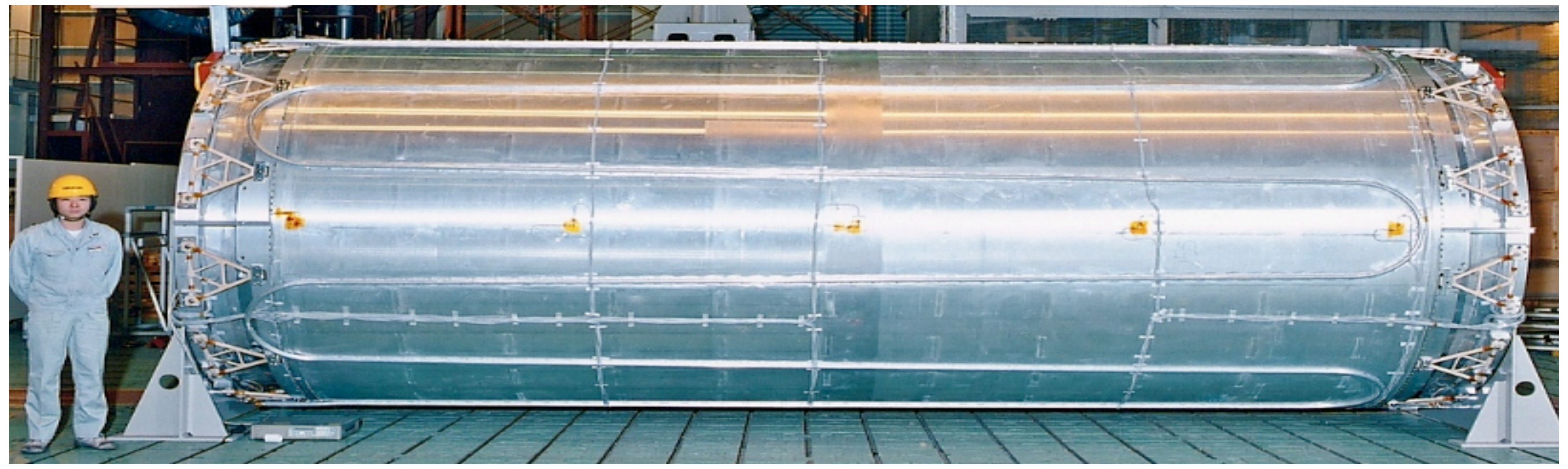
crucial:

- the strength/dynamical development of SR-fan has to be known (as best as possible) beforehand
  -> geometry of beam pipe, placement of masks, collimators, absorbers - shielding of machine elements / detector
  hope: less elongated elliptical part of BP in proton direction (+z) - but: injection/lumi-setup scenario unclear yet

4. Consequence: Construction of Solenoid

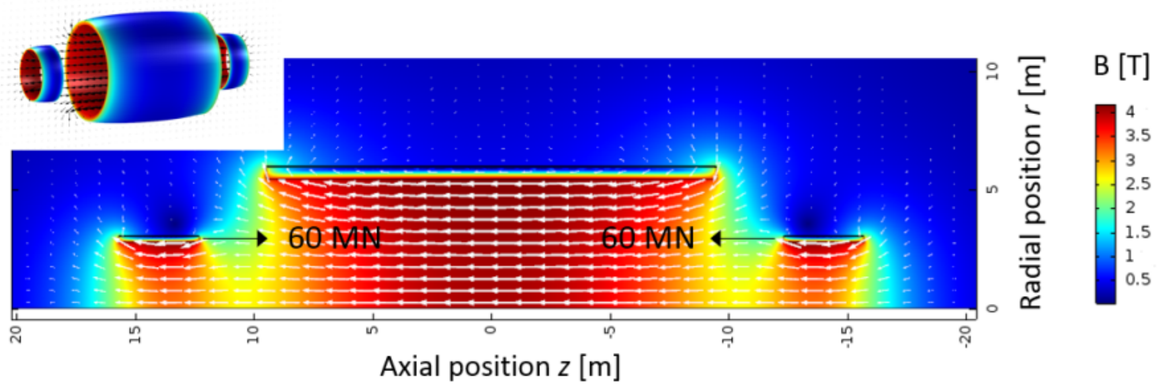


LHeC Solenoid/Dipole Cryostat



Herman ten Kate & Alexey Dudarev

Solenoid (3.5T) placed between the EMC-Barrel and Hadronic-Barrel.
HCAL-Barrel - sampling calorimeter using steel and scintillating tiles as absorber and active material, respectively.
Provides the mechanical stability for the Magnet/Dipole cryostat
(and the LAr cryostat in a cold EMC version) along with the iron required for the return flux of the solenoidal field.
Alternative for the FCC-detector: setup using fwd/bwd solenoids additionally, as for FCC-hh



Herman ten Kate & Matthias Mentink

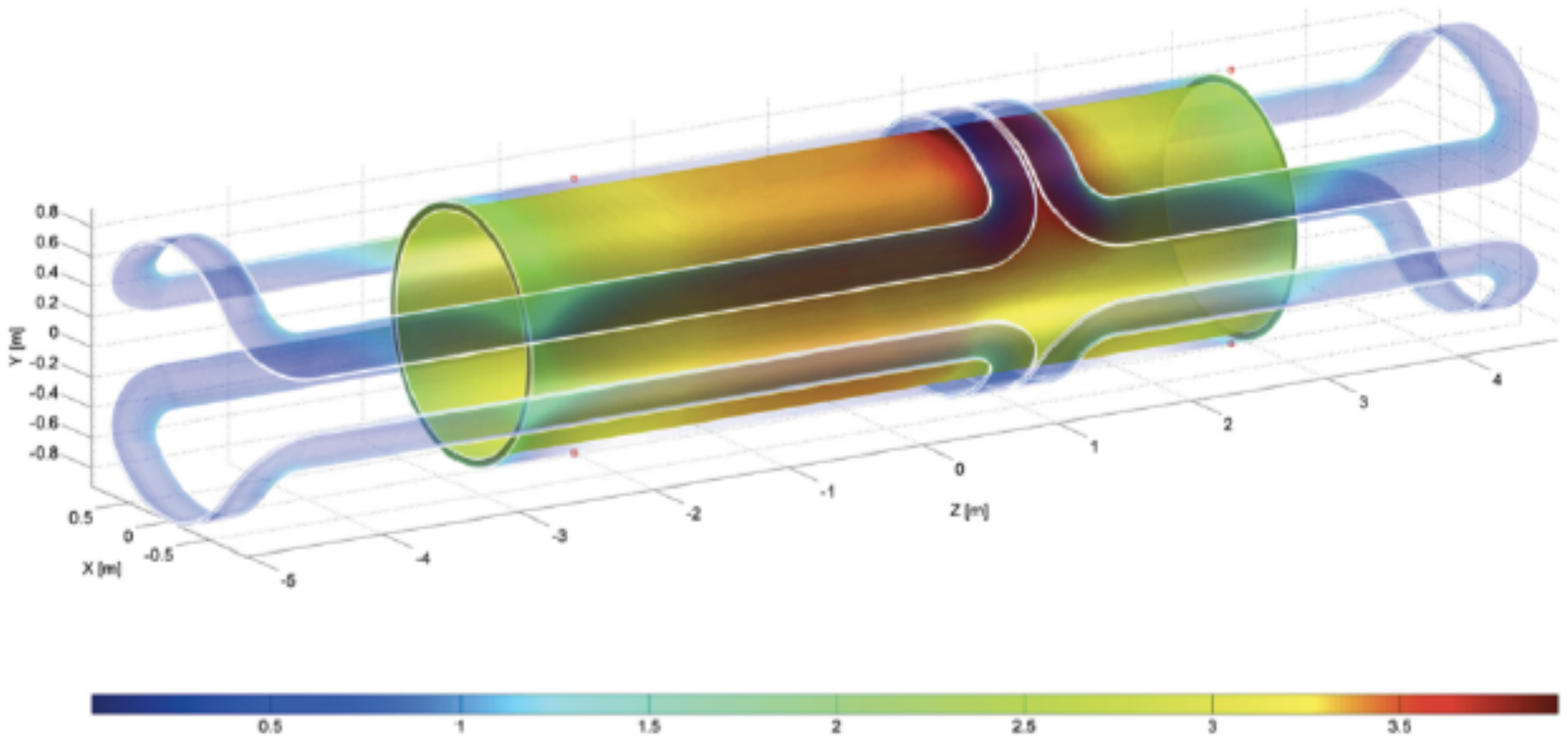
Detector Magnets: Solenoid and Dipoles

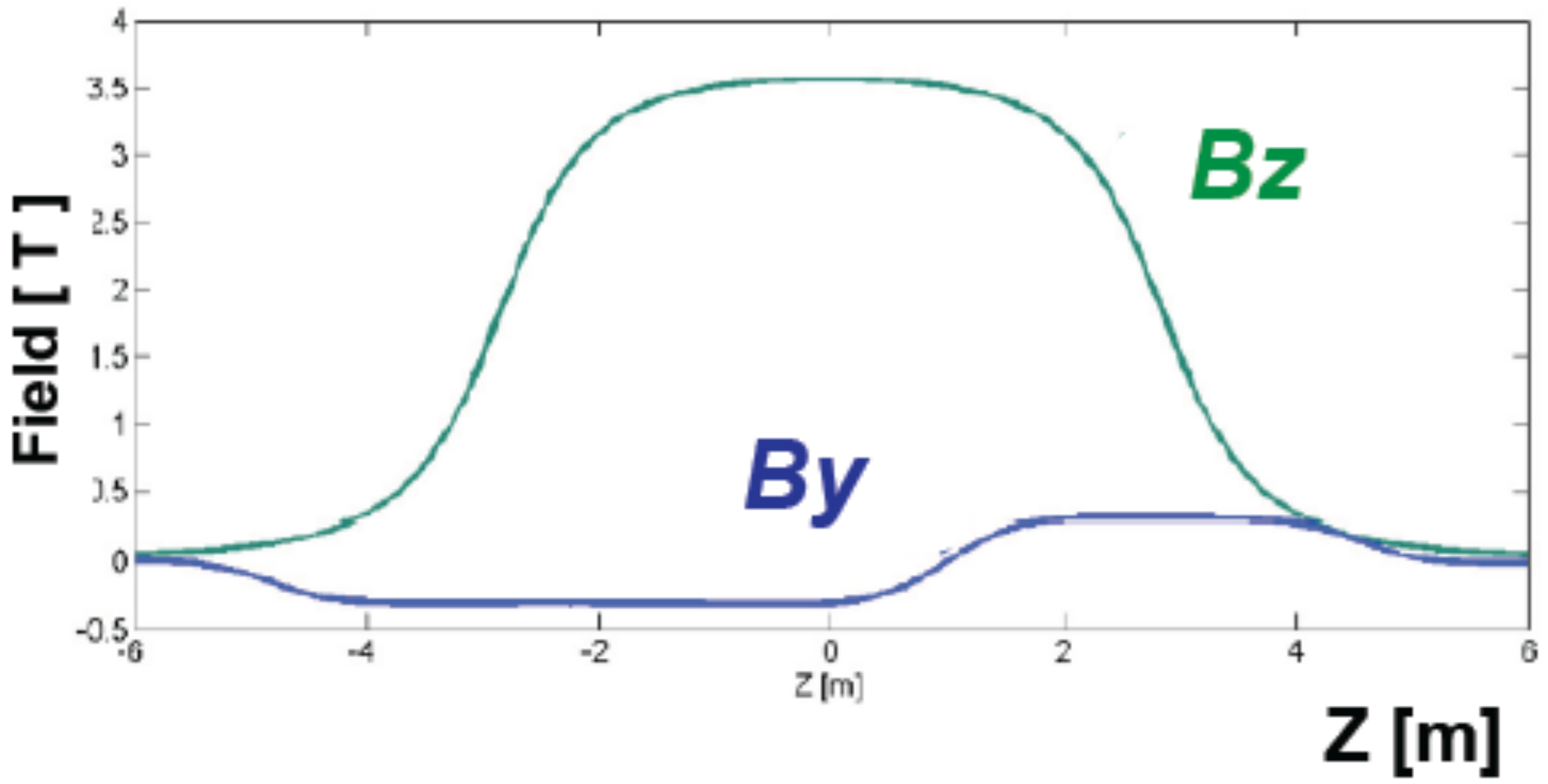
courtesy Herman ten Kate and Alexey Dudarev

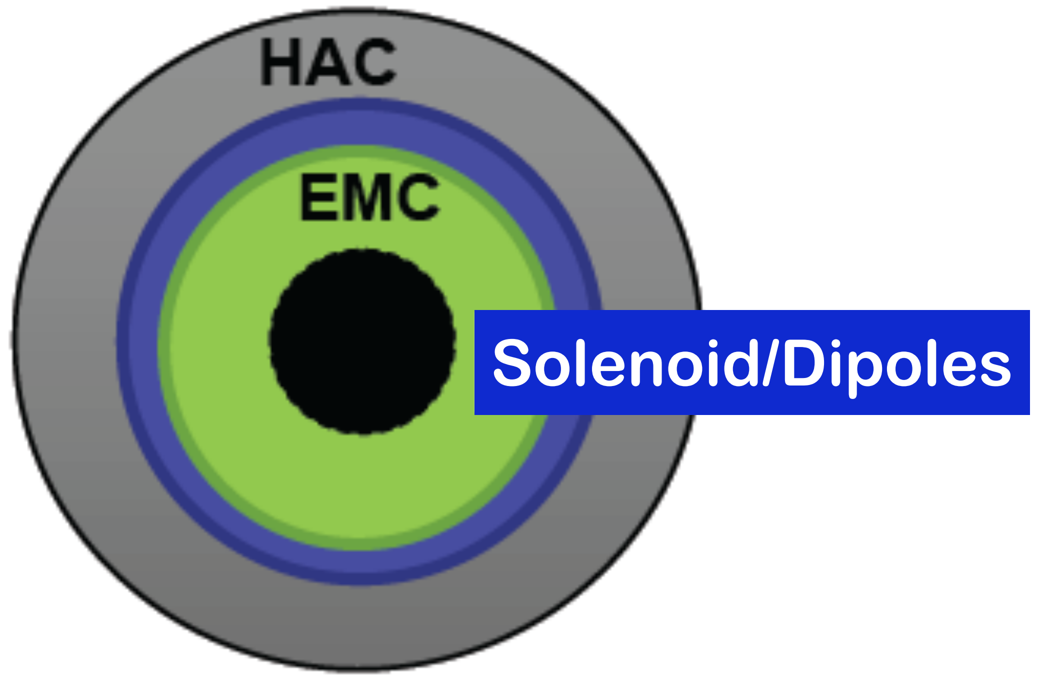
Baseline: Solenoid (3.5 T) + dual dipole 0.21 T
Inner solenoid: containing full Tracker & EMC-Barrel, HCAL-Barrel & Muon-Det. outside

Small coil: Cheaper & less iron for return flux, solenoid and dipoles (& EMC-Barrel—LAr?) within the same cold vacuum vessel, but no muon measurement

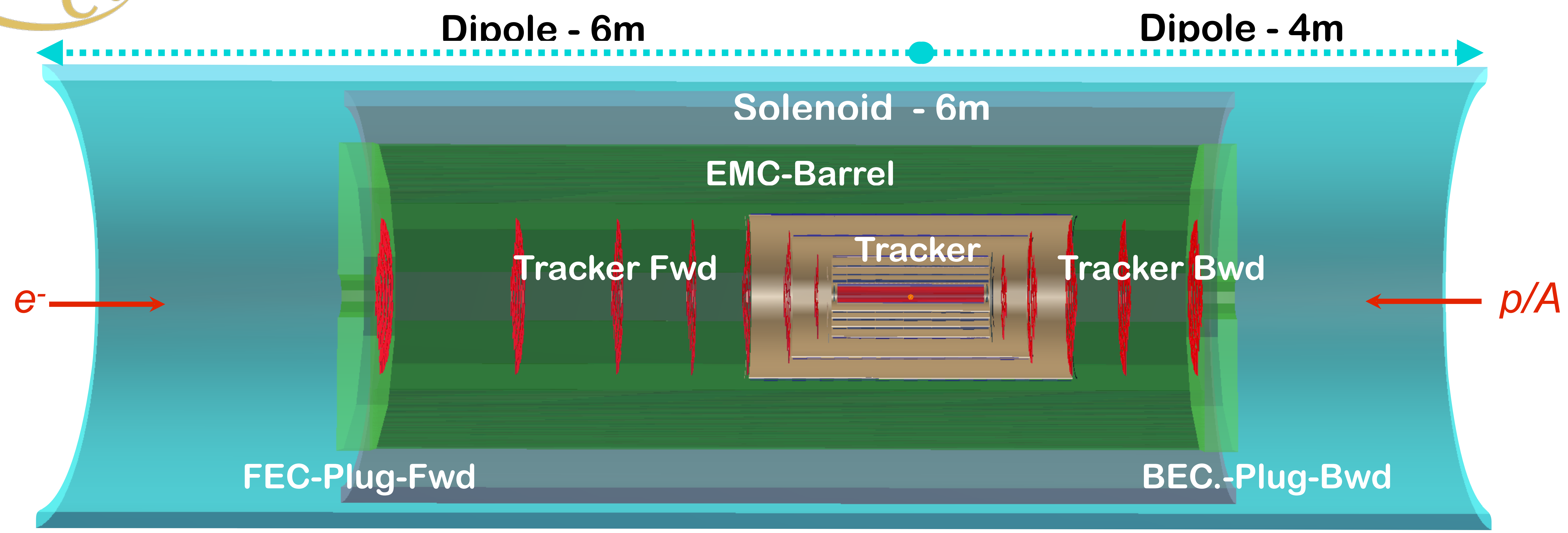
OR: Solenoid system - FCC-hh style (H.t.Kate)

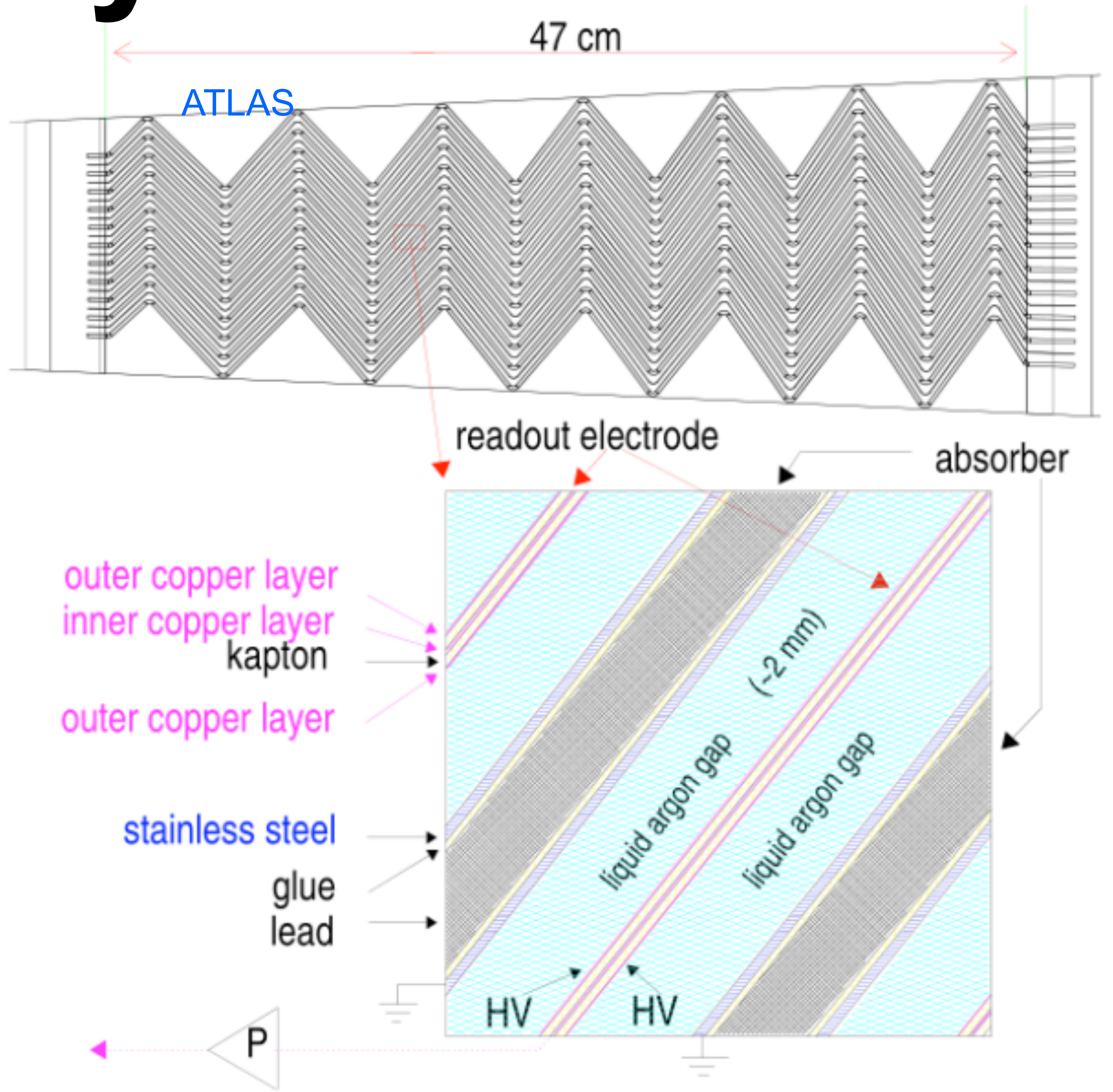




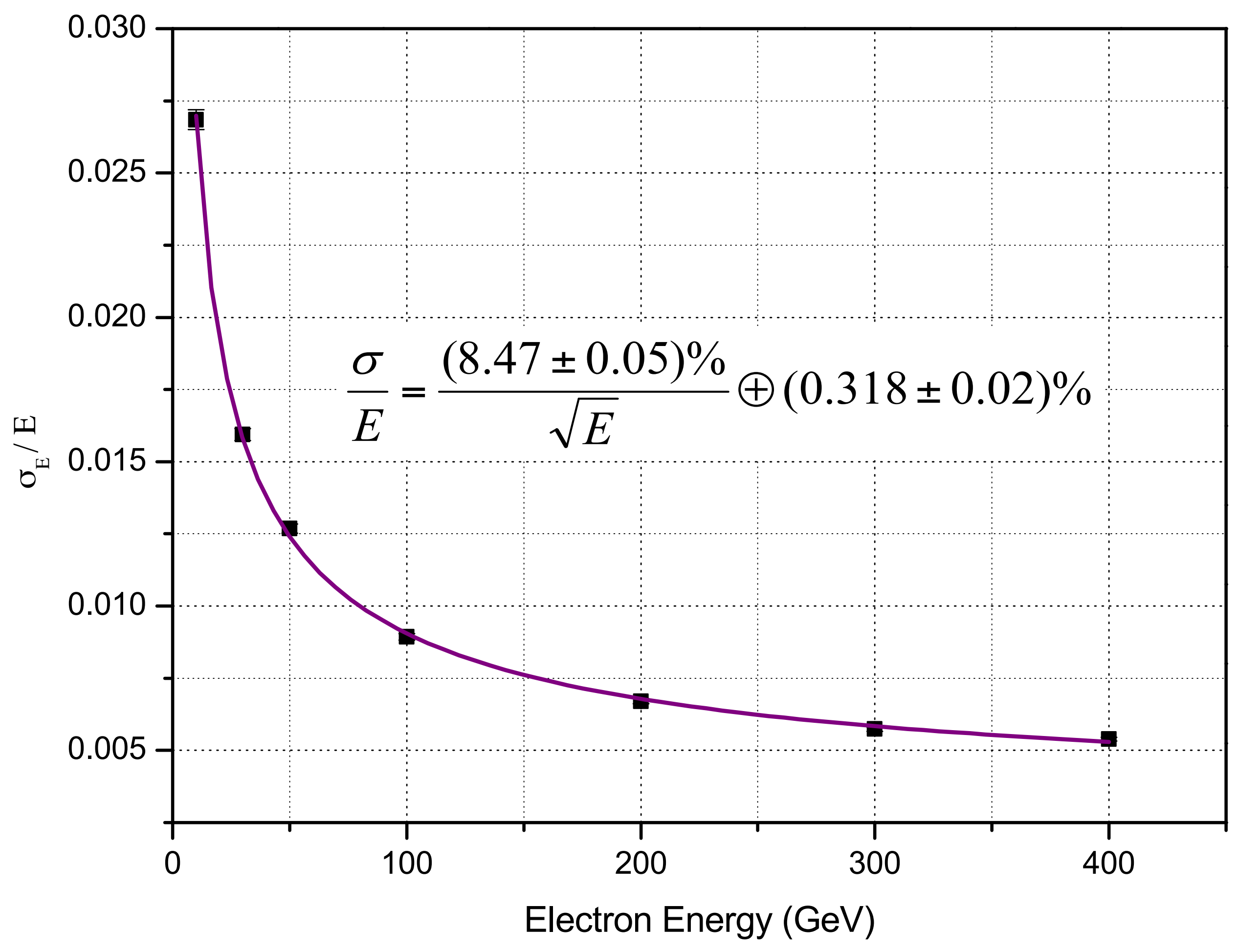


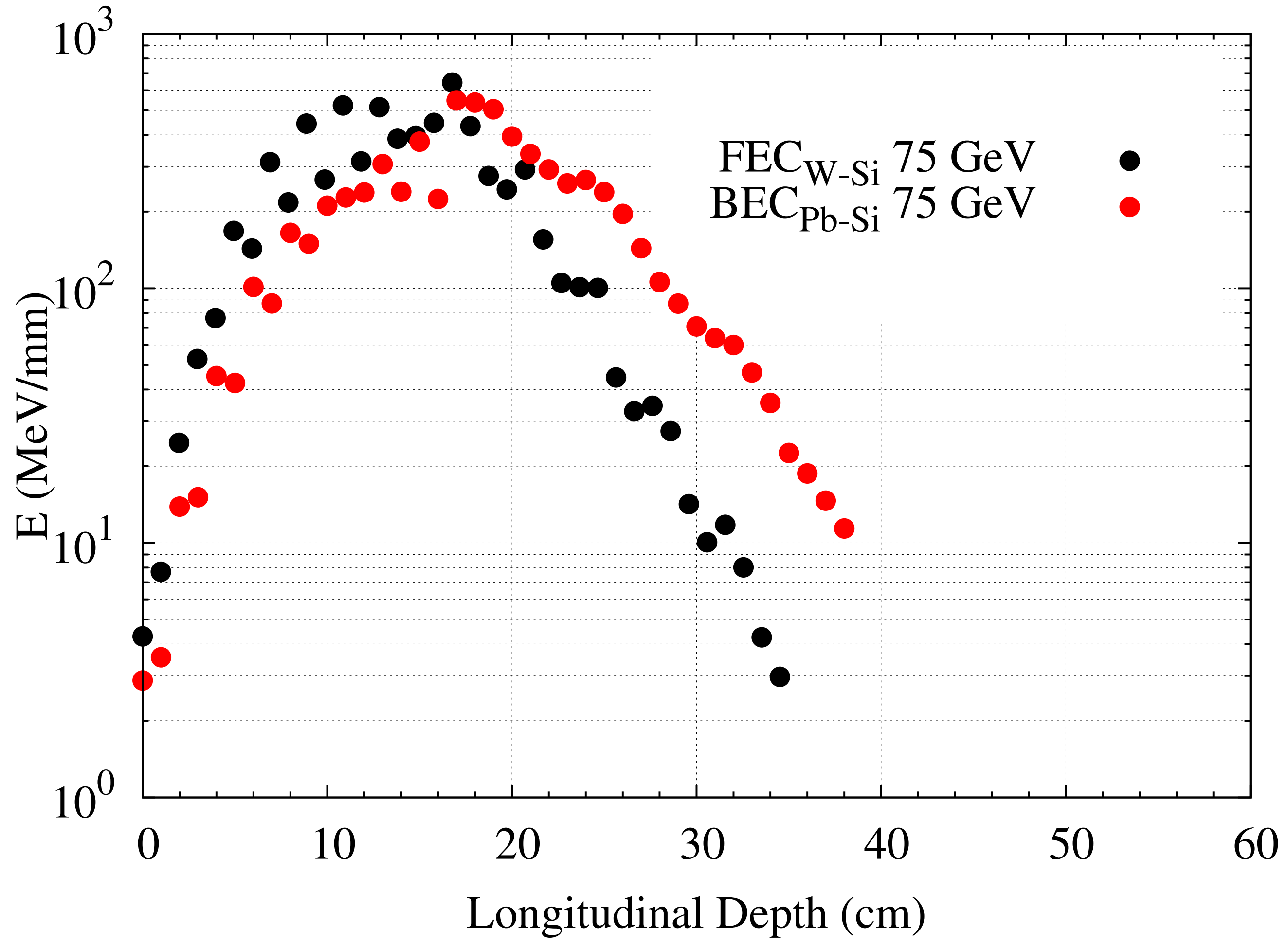
EMC-LAr Barrel - LHeC Study

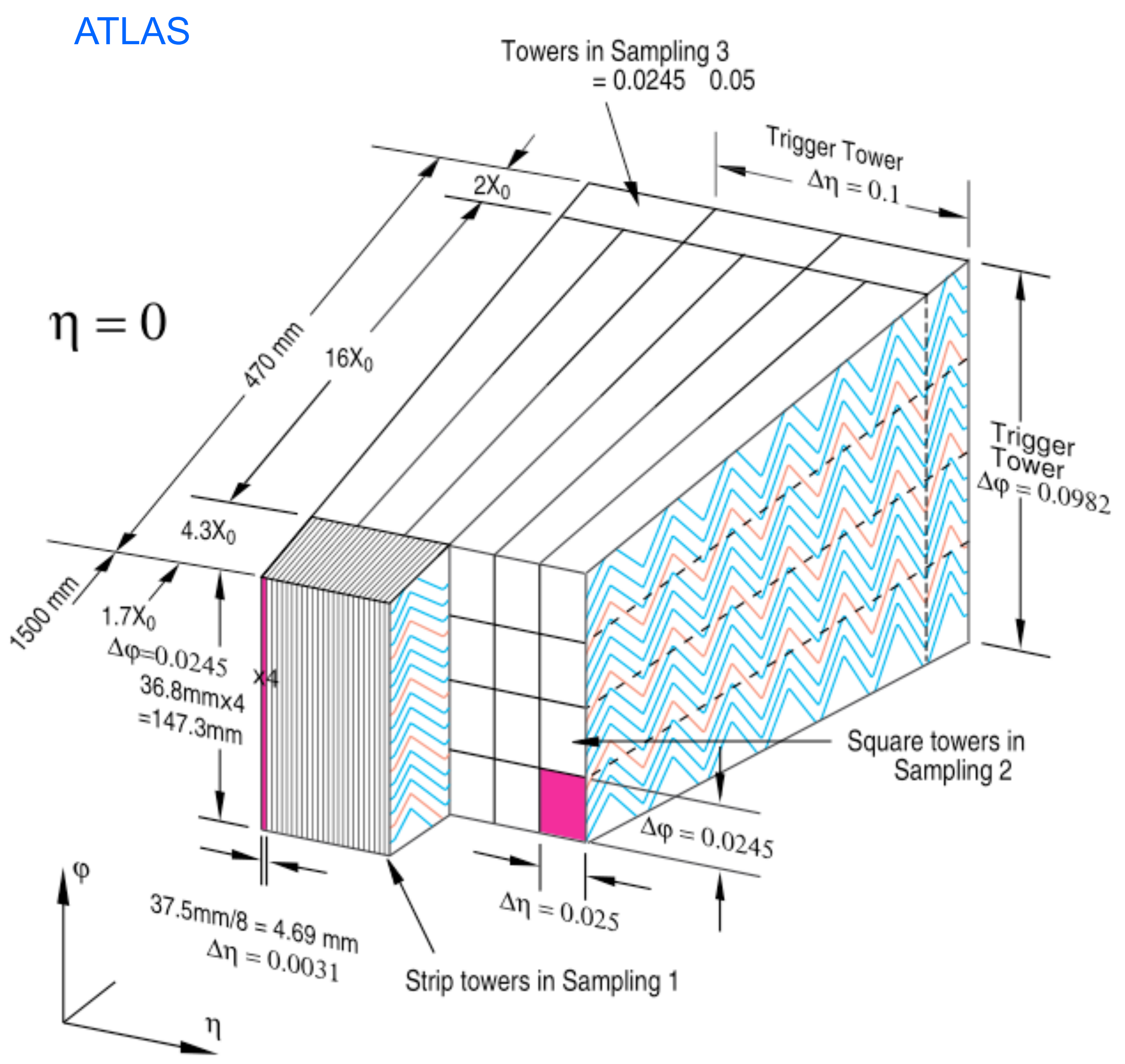




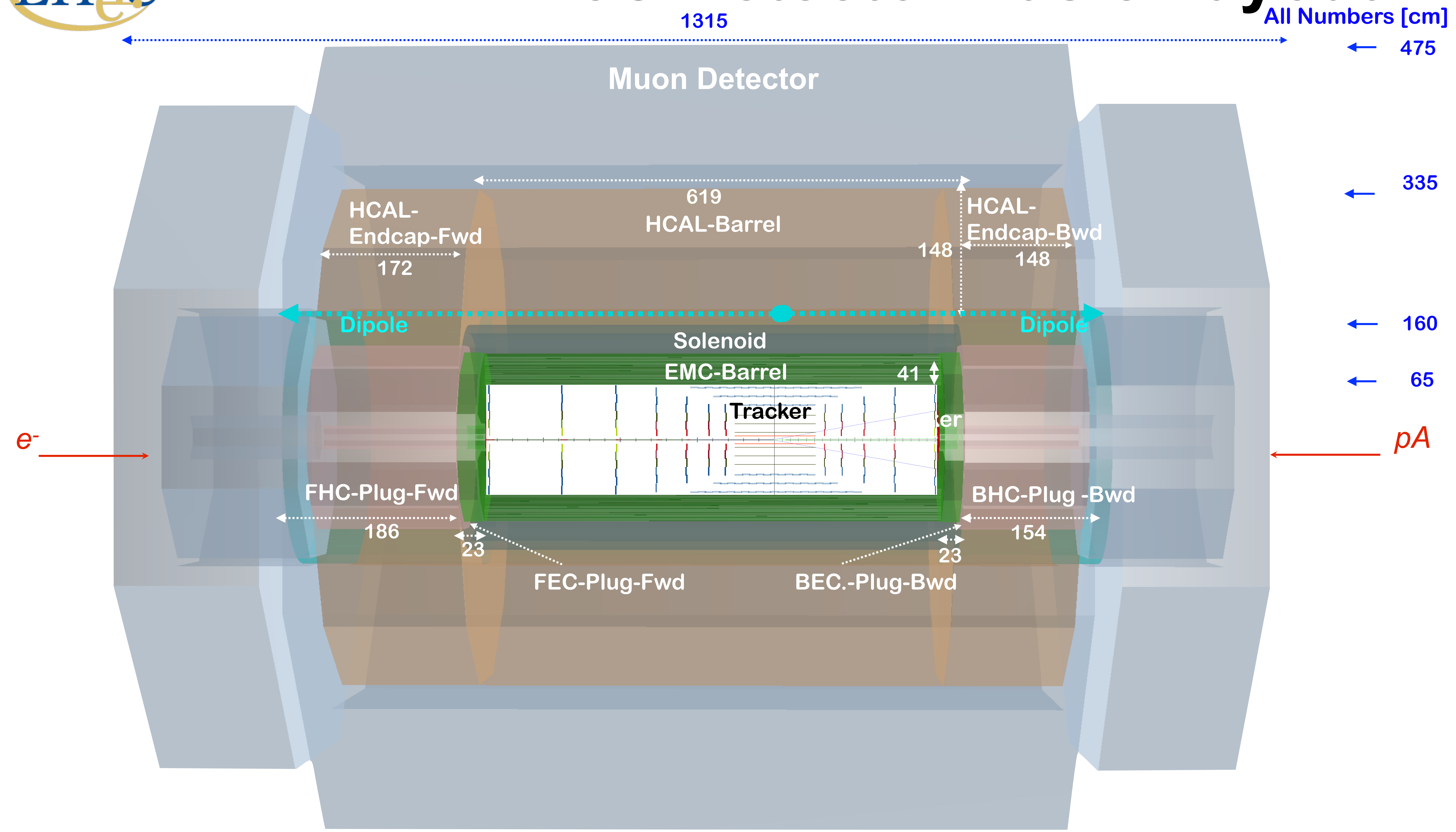
- LAr for barrel EMCal – ATLAS Type (28-30 X_0)
- Same cryostat used for inner solenoid and dipoles
- Simulation results compatible with ATLAS
- 3 different granularity sections longitudinally



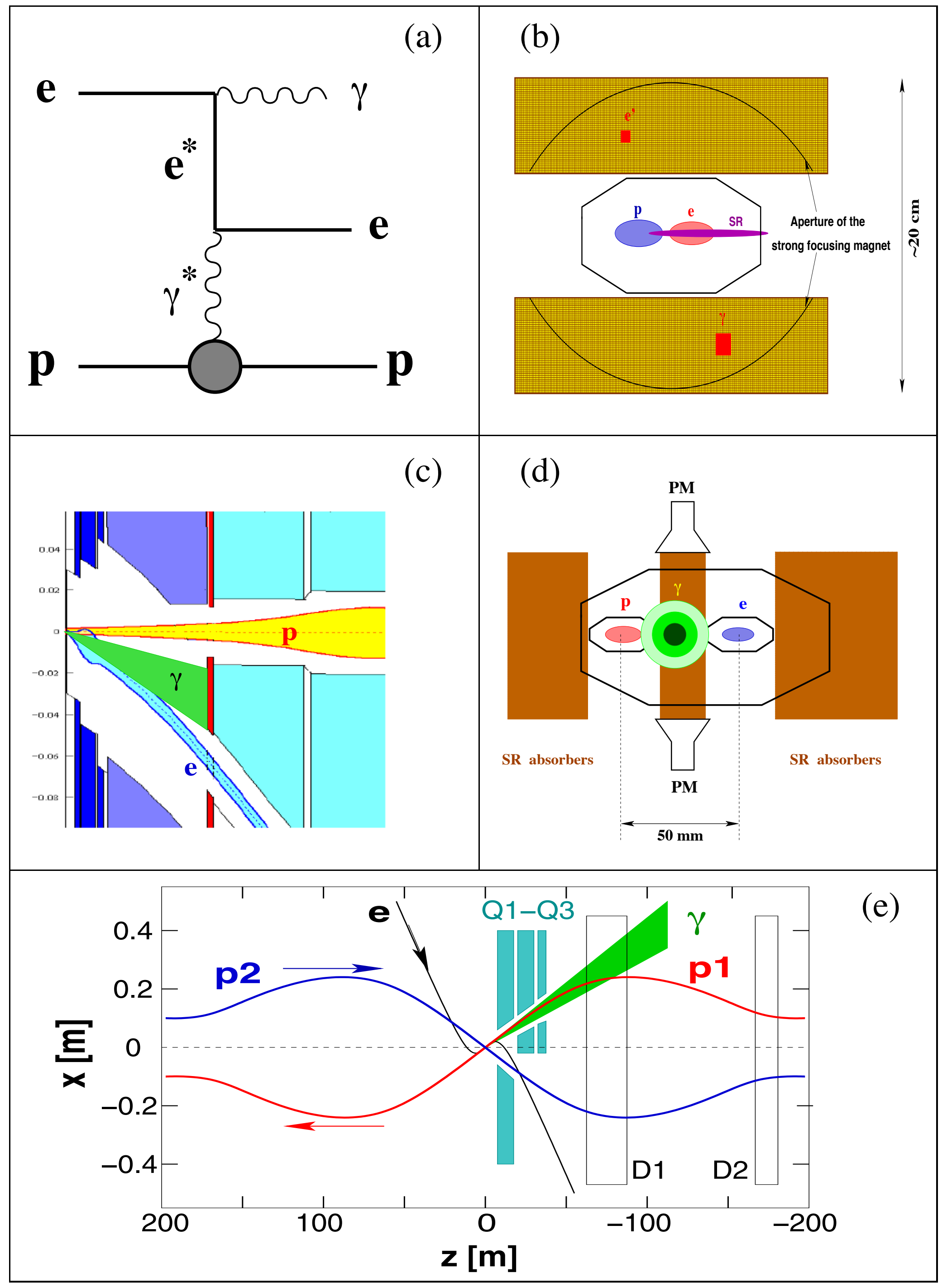




LHeC Detector Basic Layout



Based on detailed report and study in LHeC CDR* (150 pages). Includes fwd/bwd taggers at ~62m (e), -100m (γ,LR), +100m (n), +420m (p)



Options for the luminosity monitoring at the LHeC

Solenoid & beam steering dipoles between EMC-Barrel and HCAL-Barrel Calorimeters. Length of Solenoid ~6.2m. HCAL of ATLAS type detectors. The Muon Detector builds an envelope of all other parts of the main LHeC detector - tagging functionality (not discussed here). Detector layout in [DD4hep-framework](). Si-based tracker optimised using the [tkayout-light program]().

see also following talk of Yuji Yamazaki

*LHeC CDR, arXiv:1206.2913

LHeC Detector Layout

3 beams:

e^- + proton1 + proton2
(or heavy ions A)

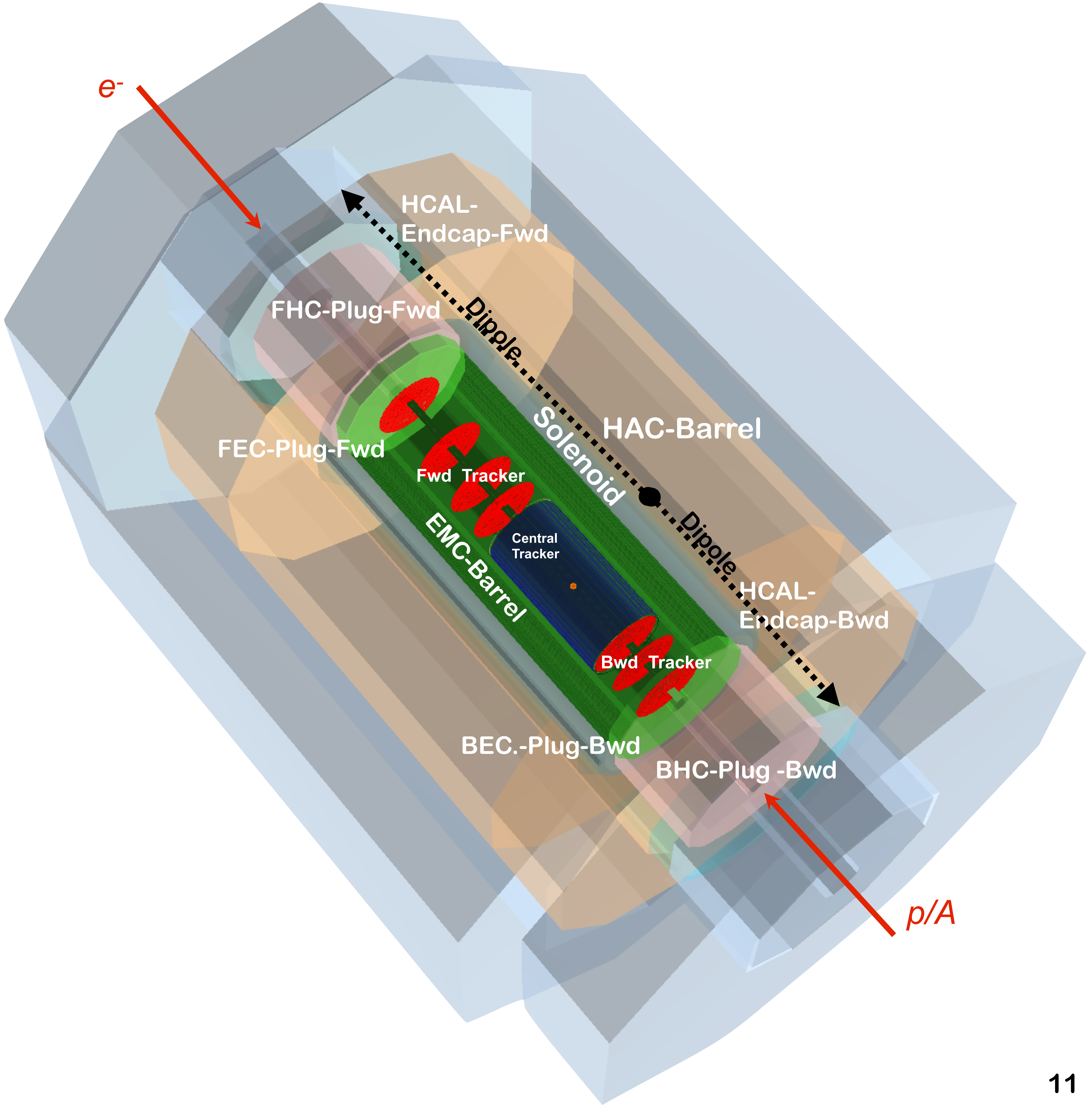
Dipole magnets to guide
the e-beam in and out,
for making electrons to collide head-on with p-beam1

± 0.214T (LHeC) dipoles
± 0.12T (FCCeh - prel.)
field along 2 x ~9 m (in Fig. inner dipoles only)
- final layout of solenoid/dipoles to be defined

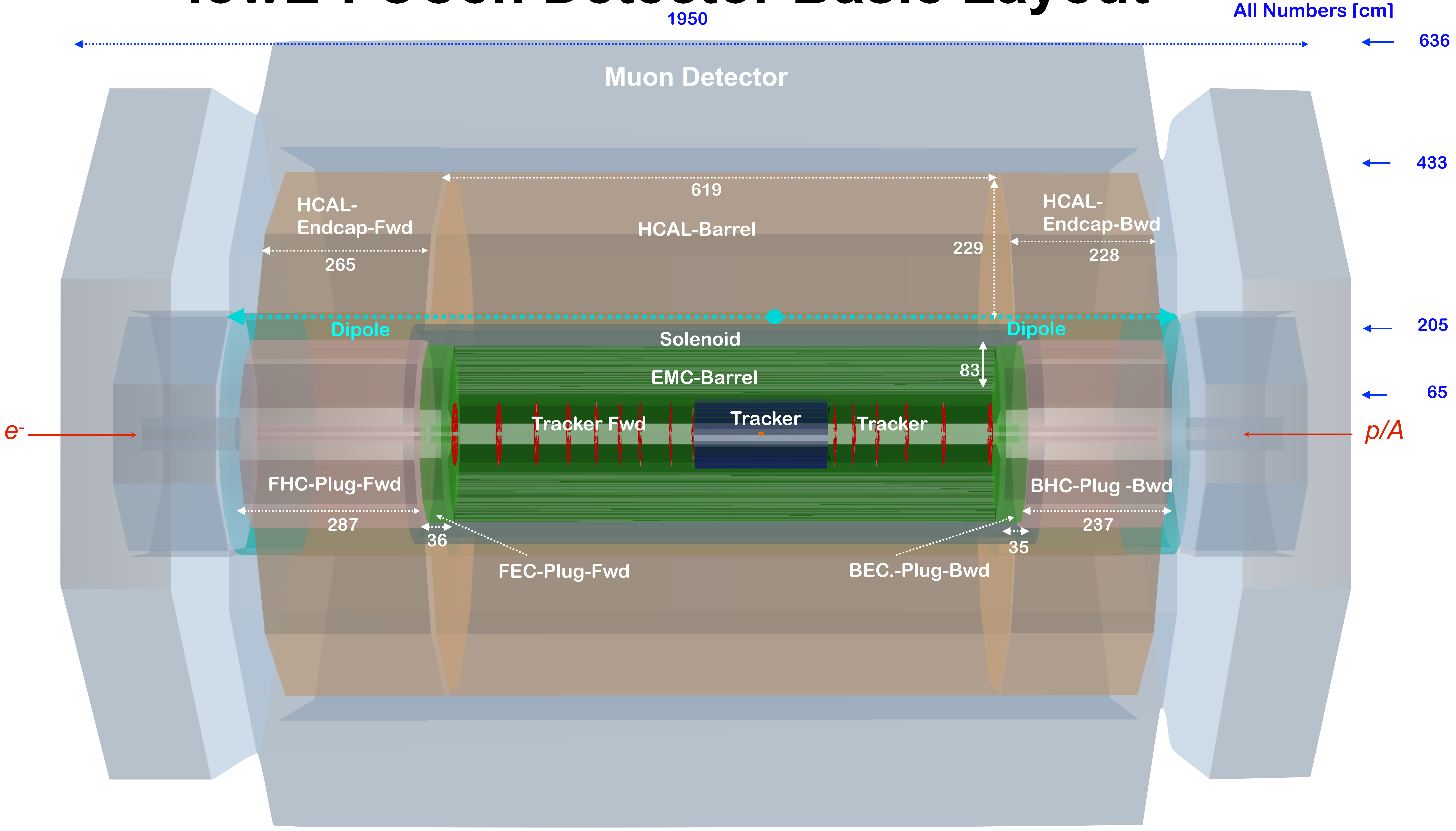
Length of Solenoid for the LHeC detector: 6.2m
Solenoid light-weighted

Basic change for LHeC → lowE-FCCeh

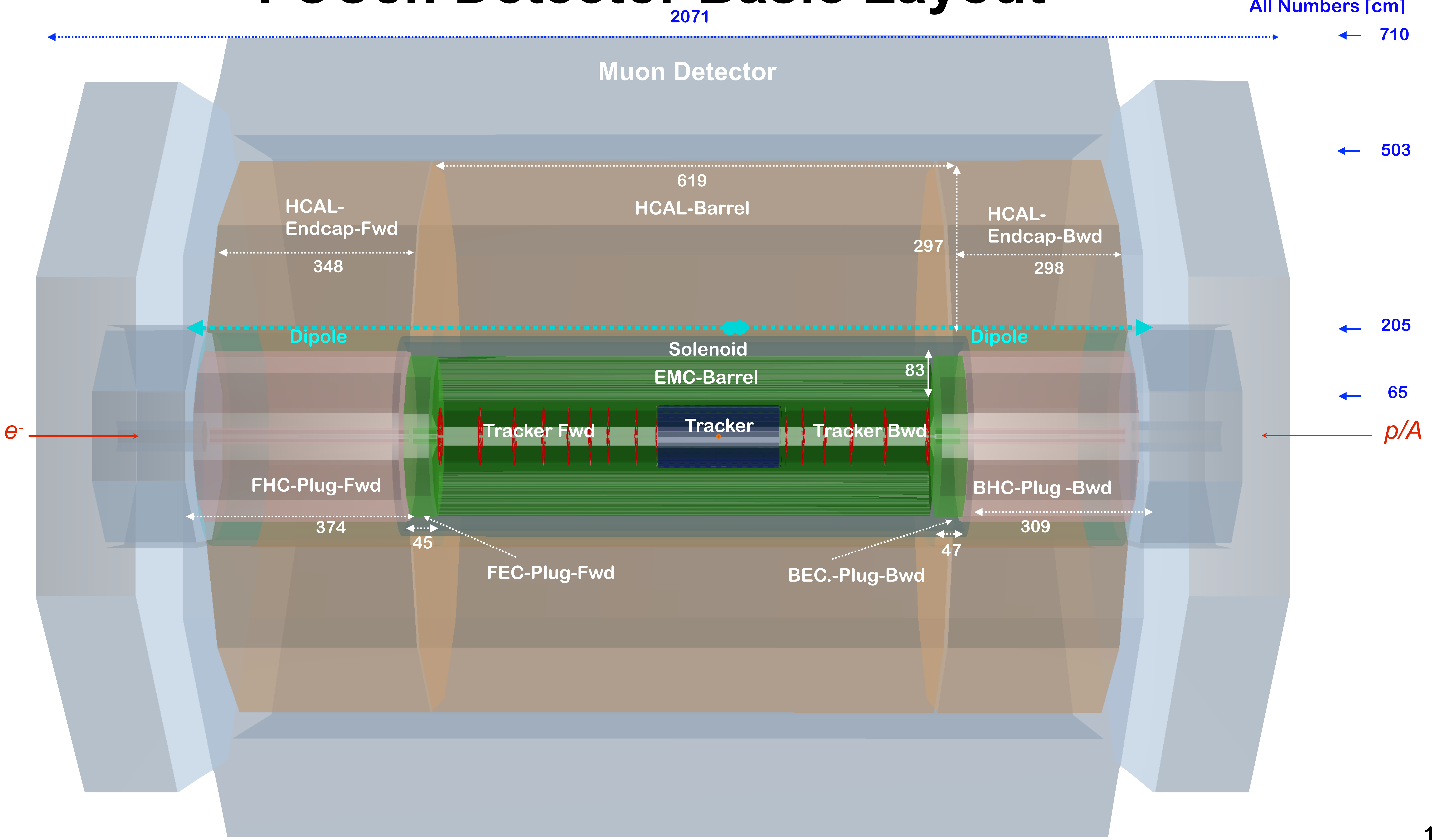
scaling of calorimeter dimensions & FCCeh tracker/solenoid/
dipole/Ecal-Barrel design (upgrade compatibility)



lowE-FCCeh Detector Basic Layout

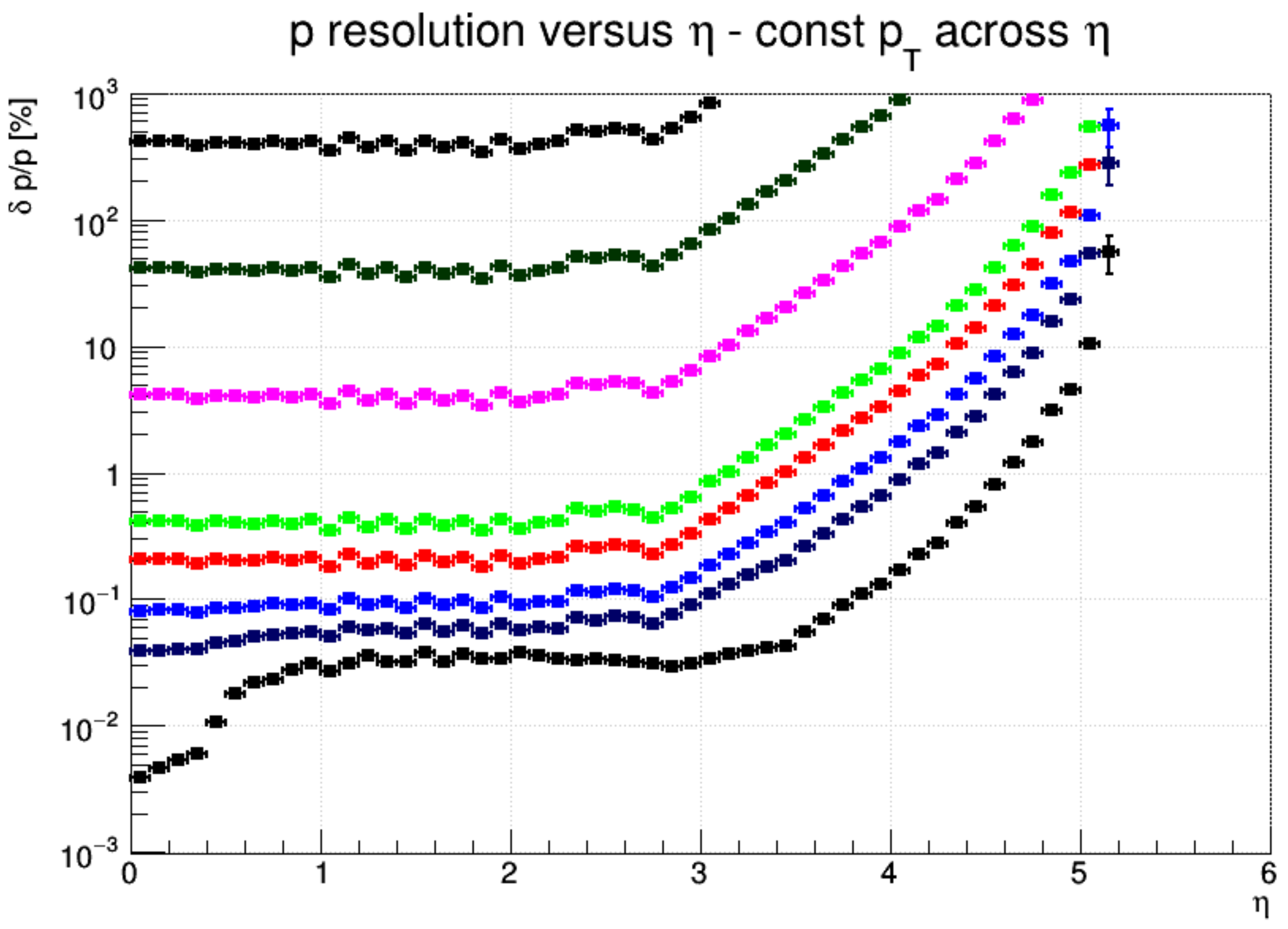


FCCeh Detector Basic Layout

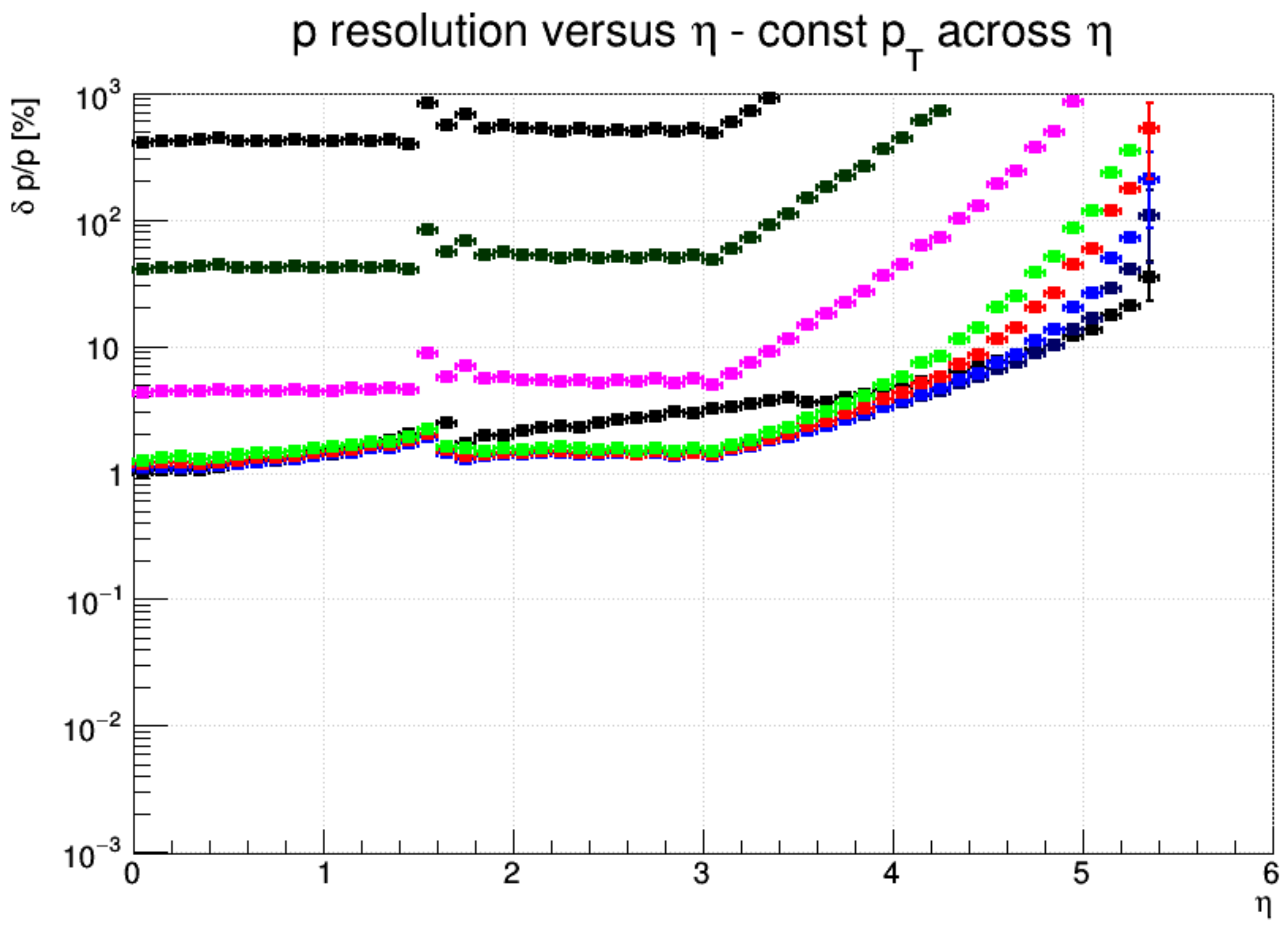


lowE-FCCeh Tracker - p Resolution (const p_T)

preliminary



No Material & No Services



BeamPipe (3.5mm) & Active Material

Particle momenta in GeV: 0.2 (Black), 1 (DarkBlue), 2 (Blue), 5 (Red), 10 (Green), 100 (Magenta), 1000 (DarkGreen), 10000 (Black).

Crucial: measurement length's of tracks (small tracker radius- extended from 40 to 60cm) & measurement at large η limit the resolution of high energy track momentum

LHeC / lowE-FCCeh / FCCeh Tracker Characteristic

LHeC

$Tracker_{LHeC}$ Part	Inner Barrel		ECAP Barrel	Forward Tracker		Backward Tracker	
	Pix	Strix	Pix	Pix	Strix	Pix	Strix
#Layers/Wheels	4_{inner}	3_{outer}	4	3		2	
#Mods/Ring/Wheel	max 12^{flat}	max 24^{tilt}	2	2_{inner}	2_{outer}	2_{inner}	2_{outer}
#Modules	6010			648		432	
$\eta_{max/min}$	±1.5		±2.5	2.5 – 5.1		-2.5 – -4.8	
$\sigma^{r-\phi}$ [μm]	5-7.5	7-9.5	5-7.5	5-7.5	7-9.5	5-7.5	7-9.5
σ^{z} [μm]	15	15	15	15	30	15	30
X_0/Λ_I [%]	9.42 / 2.92			2.27 / 0.71		1.52 / 0.47	
Sum-Si [m^2]	17.			3.3		2.2	

lowE-FCCeh/ FCCeh

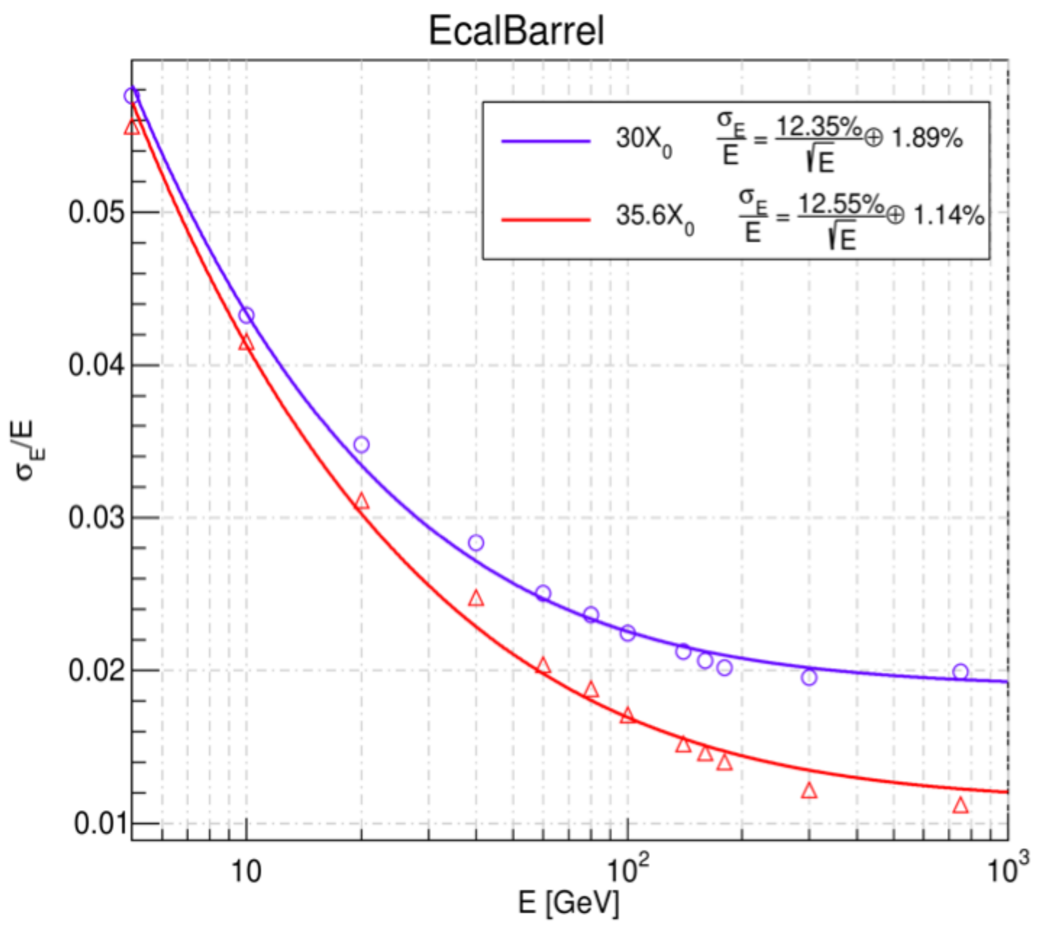
$Tracker_{FCCeh}$ Part	Inner Barrel		ECAP Barrel	Forward Tracker		Backward Tracker	
	Pix	Strix	Pix	Pix	Strix	Pix	Strix
#Layers/Wheels	4_{inner}	3_{outer}	4	7		5	
#Mods/Ring/Wheel	max 12^{flat}	max 24^{tilt}	2	2_{inner}	2_{outer}	2_{inner}	2_{outer}
#Modules	5794			1512		1080	
$\eta_{max/min}$	±1.5		±2.5	2.5 – 6.0		-2.5 – -6.0	
$\sigma^{r-\phi}$ [μm]	5-7.5	7-9.5	5-7.5	5-7.5	7-9.5	5-7.5	7-9.5
σ^{z} [μm]	15	15	15	15	30	15	30
X_0/Λ_I [%]	9.51 / 2.95			5.31 / 1.65		3.79 / 1.18	
Sum-Si [m^2]	15.8			7.7		5.5	

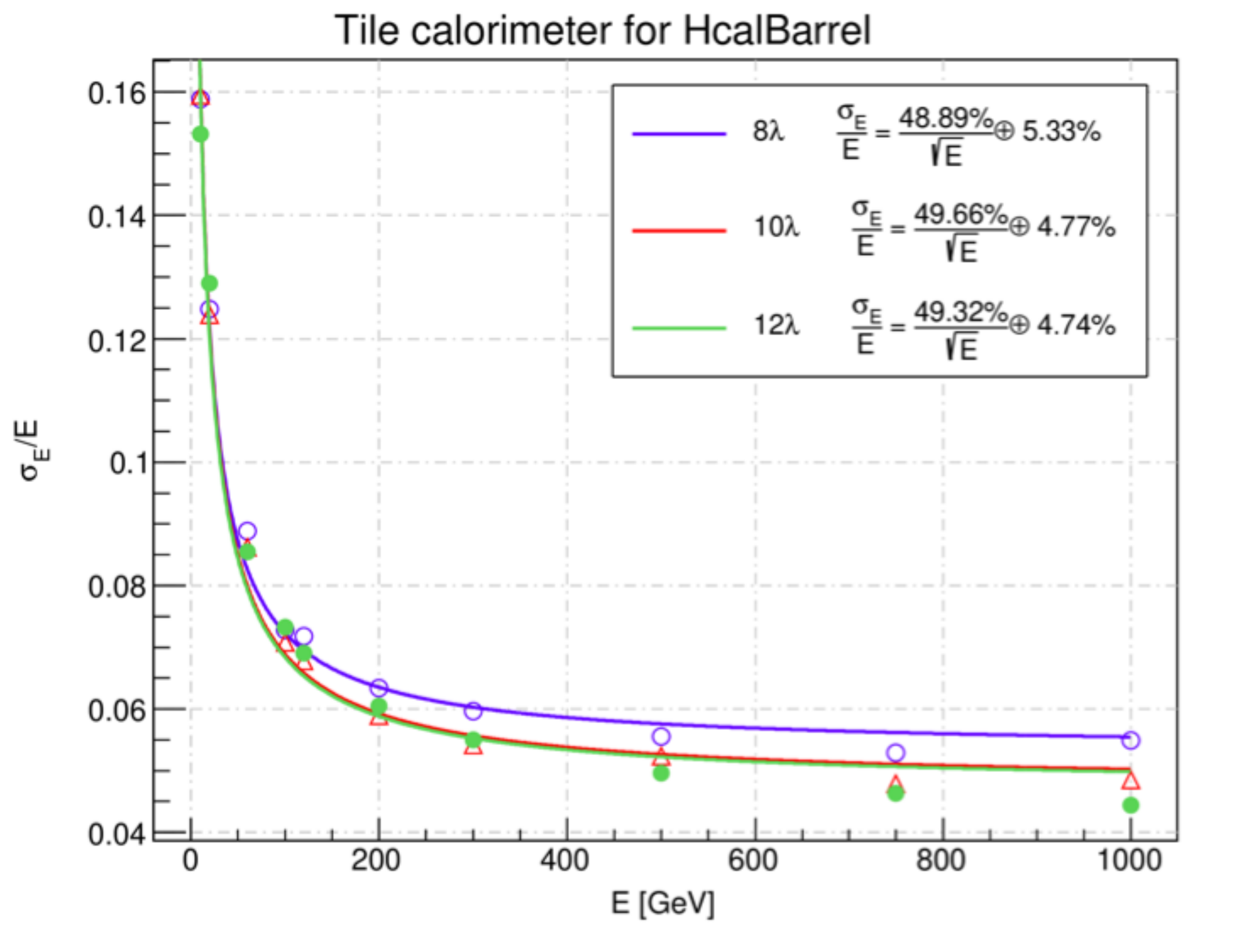
tables partly outdated

X_0, λ_I Calorimeter Characteristic

$Calo_{LHeC}$ [Readout, Absorber]	FHC [Si,W] Plug Fwd	FEC [Si,W] Plug Fwd	EMC [Sci,Pb] Barrel	HCAL [Sci,Fe] Ecap Fwd	HCAL Barrel	HCAL Ecap Bwd	BEC [Si,Pb] Plug Bwd	BHC [Si,Cu] Plug Bwd
1) σ_E/E [%] $= \mathbf{a}/\sqrt{E} \oplus \mathbf{b}$	51.8/5.4	17.8/1.4	12.4/1.9	49.3/4.7	48.9/5.3	49.9/4.8	14.4/2.8	49.5/7.9
Λ_I / X_0	$\Lambda_I = 9.6$	$X_0 = 48.8$	$X_0 = 30.2$	$\Lambda_I = 10.0$	$\Lambda_I = 8.6$	$\Lambda_I = 8.7$	$X_0 = 30.8$	$\Lambda_I = 9.2$

1) GEANT4 simulation based fits using crystal ball function

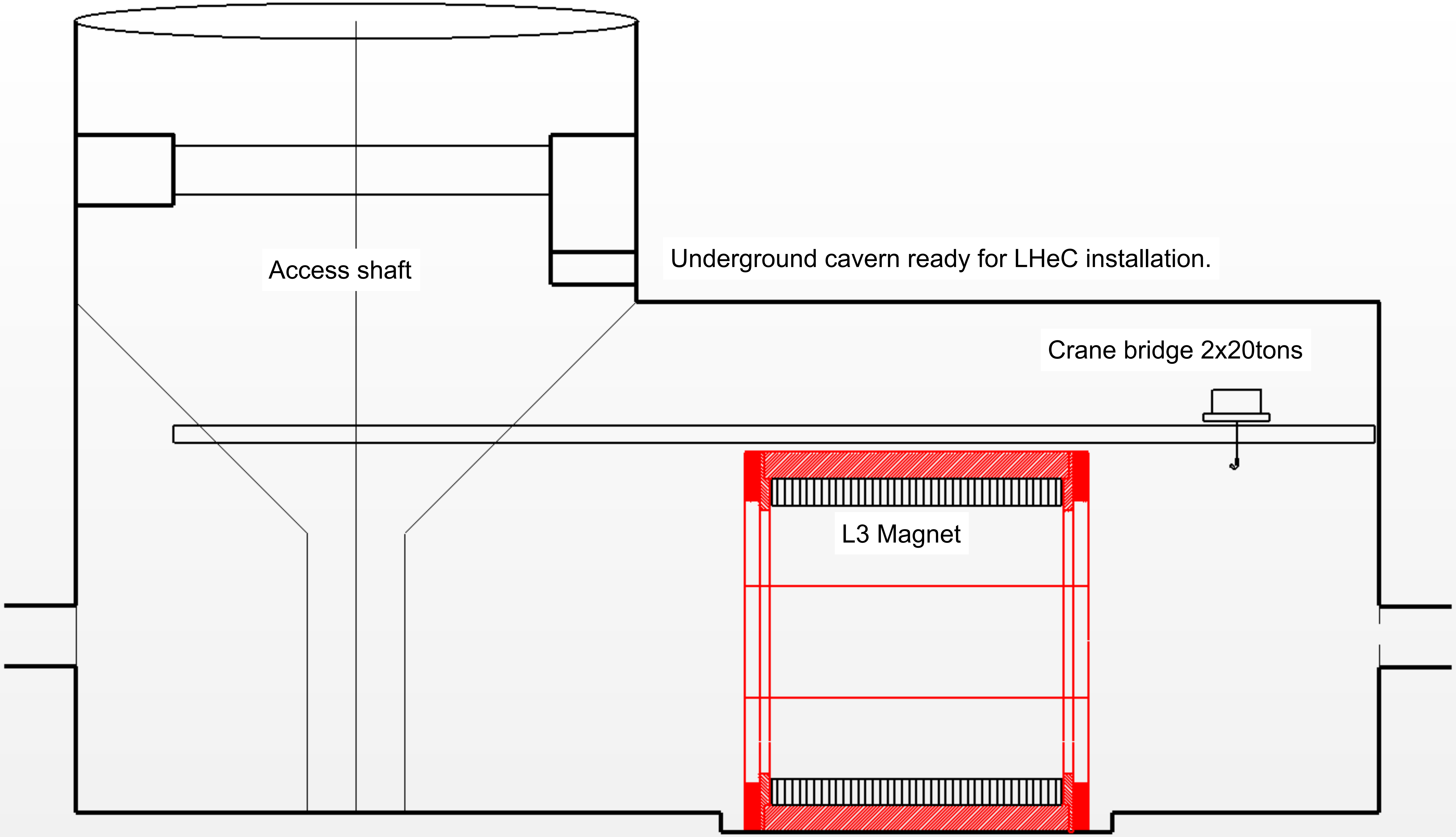




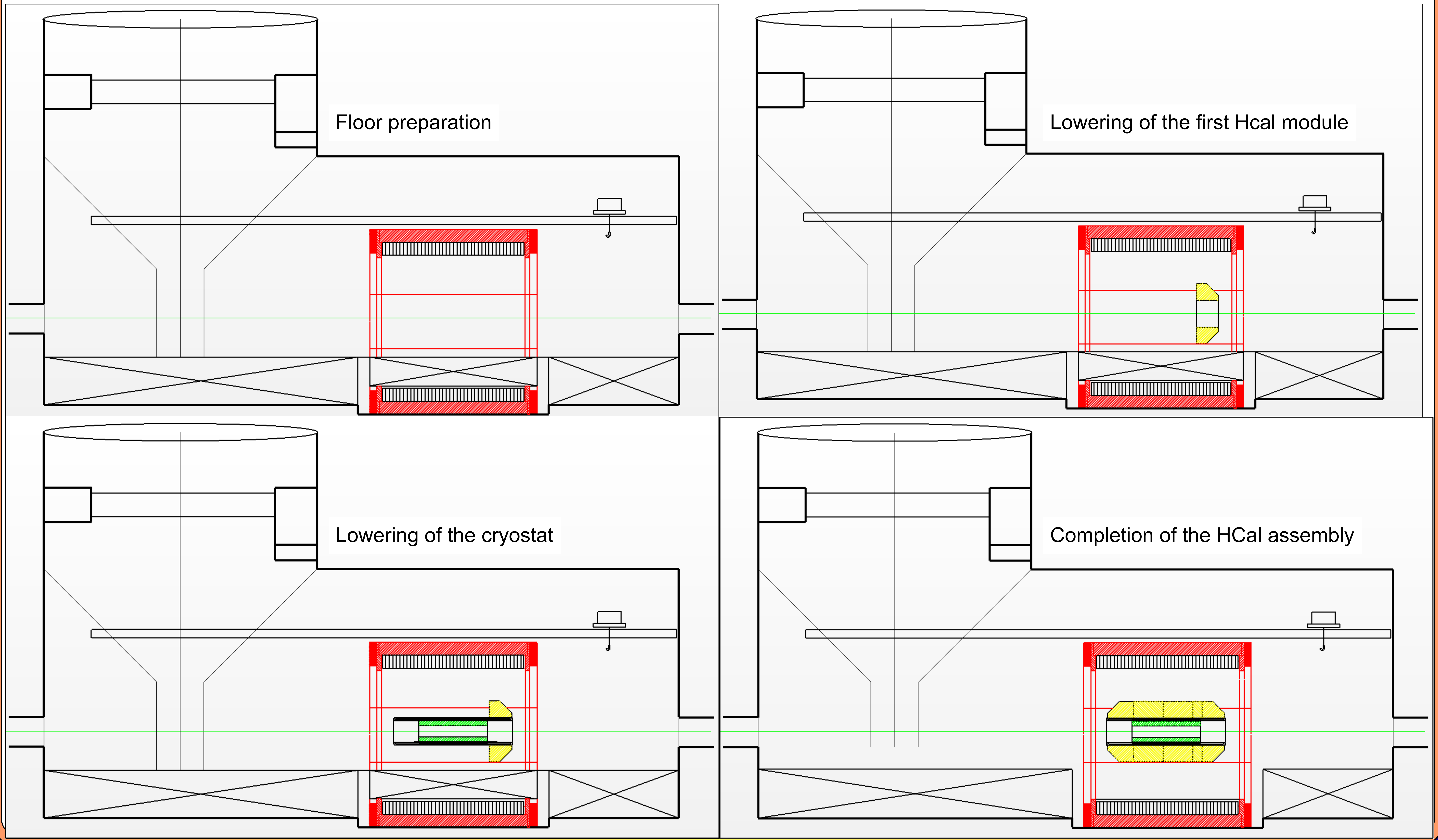
$Calo_{lowE-FCC-eh}$ [Readout, Absorber]	FHC [Si,W] Plug Fwd	FEC [Si,W] Plug Fwd	EMC [Sci,Pb] Barrel	HCAL [Sci,Fe] Ecap Fwd	HCAL Barrel	HCAL Ecap Bwd	BEC [Si,Pb] Plug Bwd	BHC [Si,Cu] Plug Bwd
Λ_I / X_0	$\Lambda_I = 15.5$	$X_0 = 84.7$	$X_0 = 66.2$	$\Lambda_I = 15.4$	$\Lambda_I = 13.3$	$\Lambda_I = 13.3$	$X_0 = 50.2$	$\Lambda_I = 14.6$

$Calo_{FCC-eh}$ [Readout, Absorber]	FHC [Si,W] Plug Fwd	FEC [Si,W] Plug Fwd	EMC [Sci,Pb] Barrel	HCAL [Sci,Fe] Ecap Fwd	HCAL Barrel	HCAL Ecap Bwd	BEC [Si,Pb] Plug Bwd	BHC [Si,Cu] Plug Bwd
Λ_I / X_0	$\Lambda_I = 20.5$	$X_0 = 112.0$	$X_0 = 66.2$	$\Lambda_I = 20.2$	$\Lambda_I = 17.2$	$\Lambda_I = 16.8$	$X_0 = 69.6$	$\Lambda_I = 19.3$

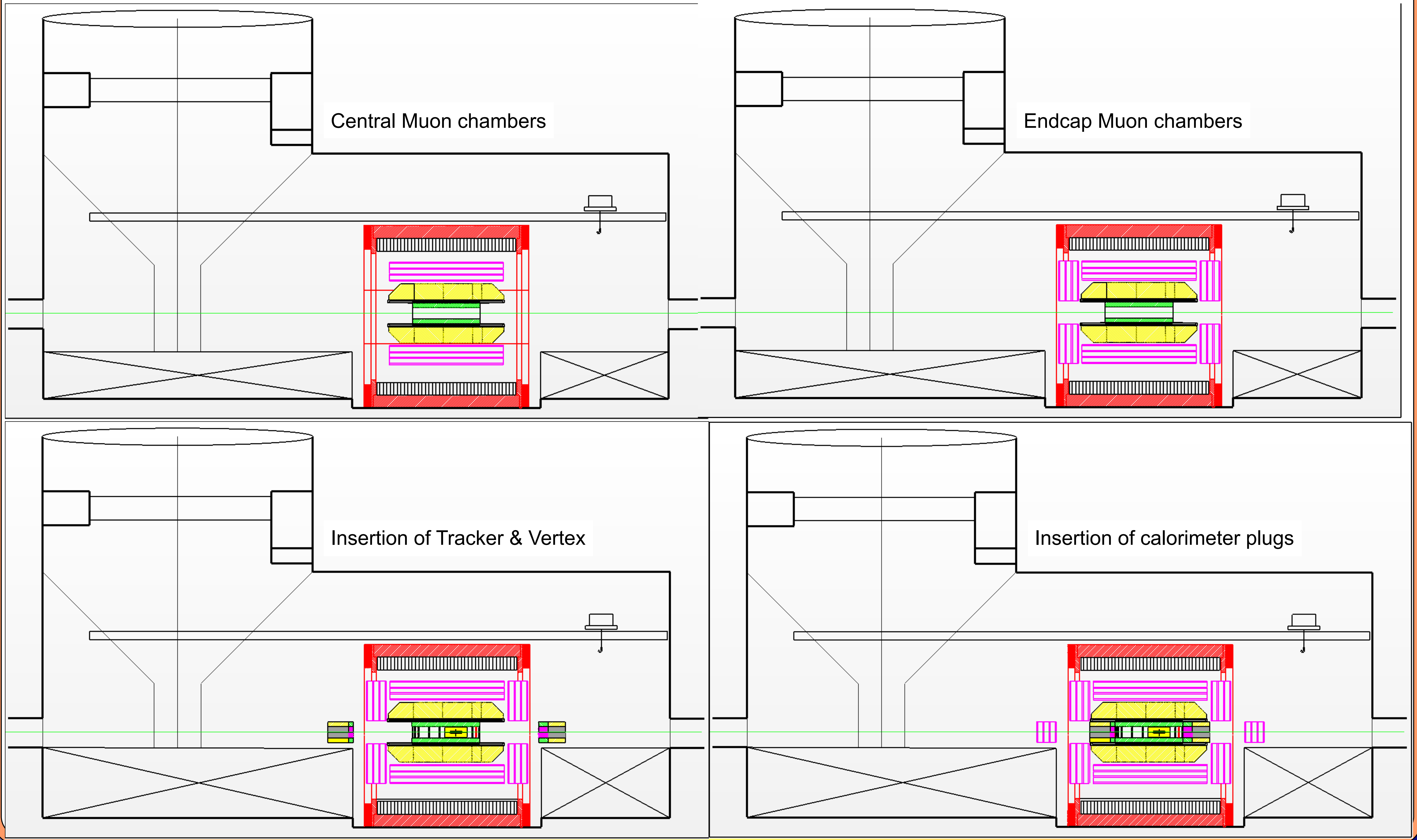
Detector lowering & integration underground (1).



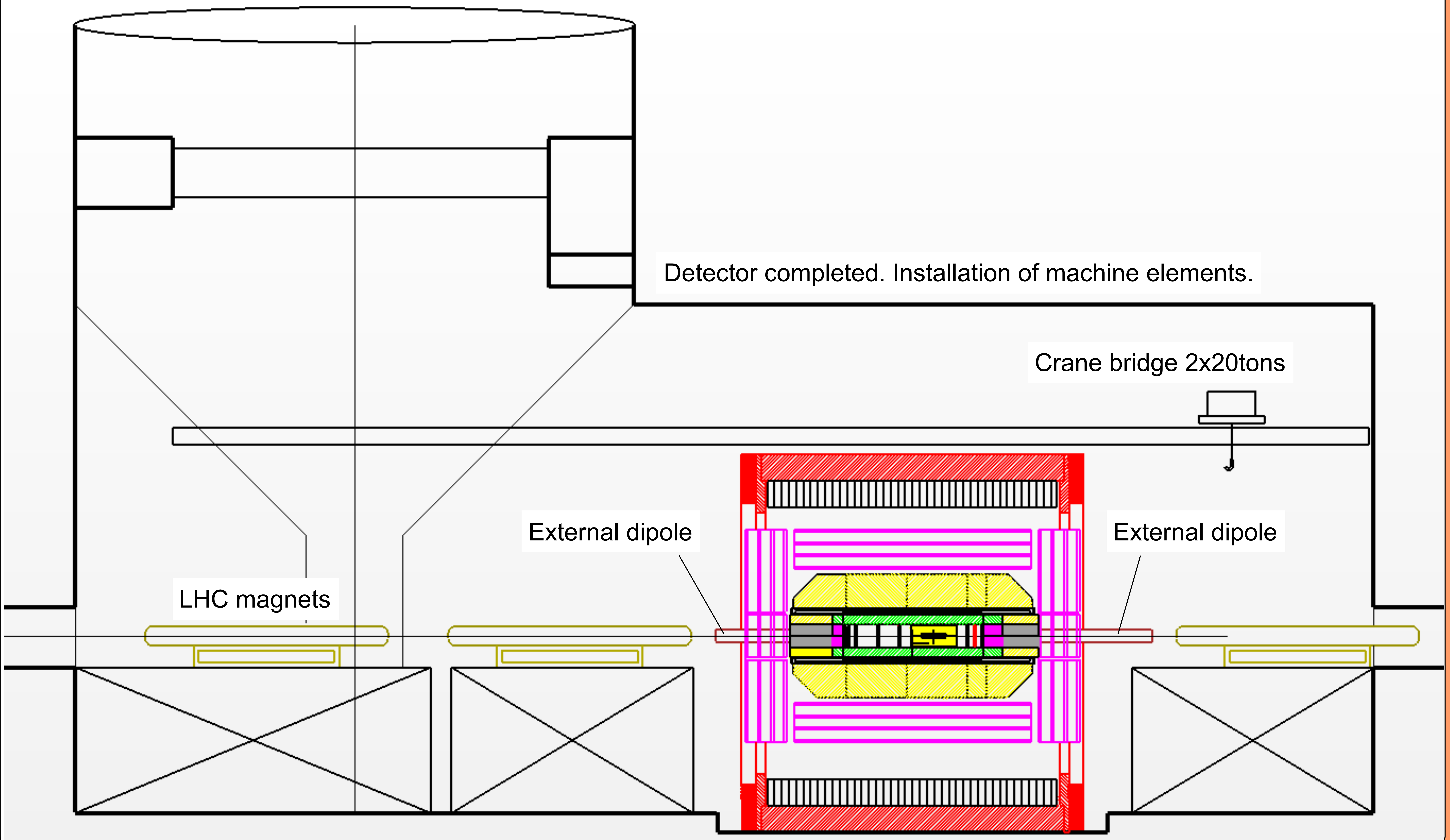
Detector lowering & integration underground (2).



Detector lowering & integration underground (3).

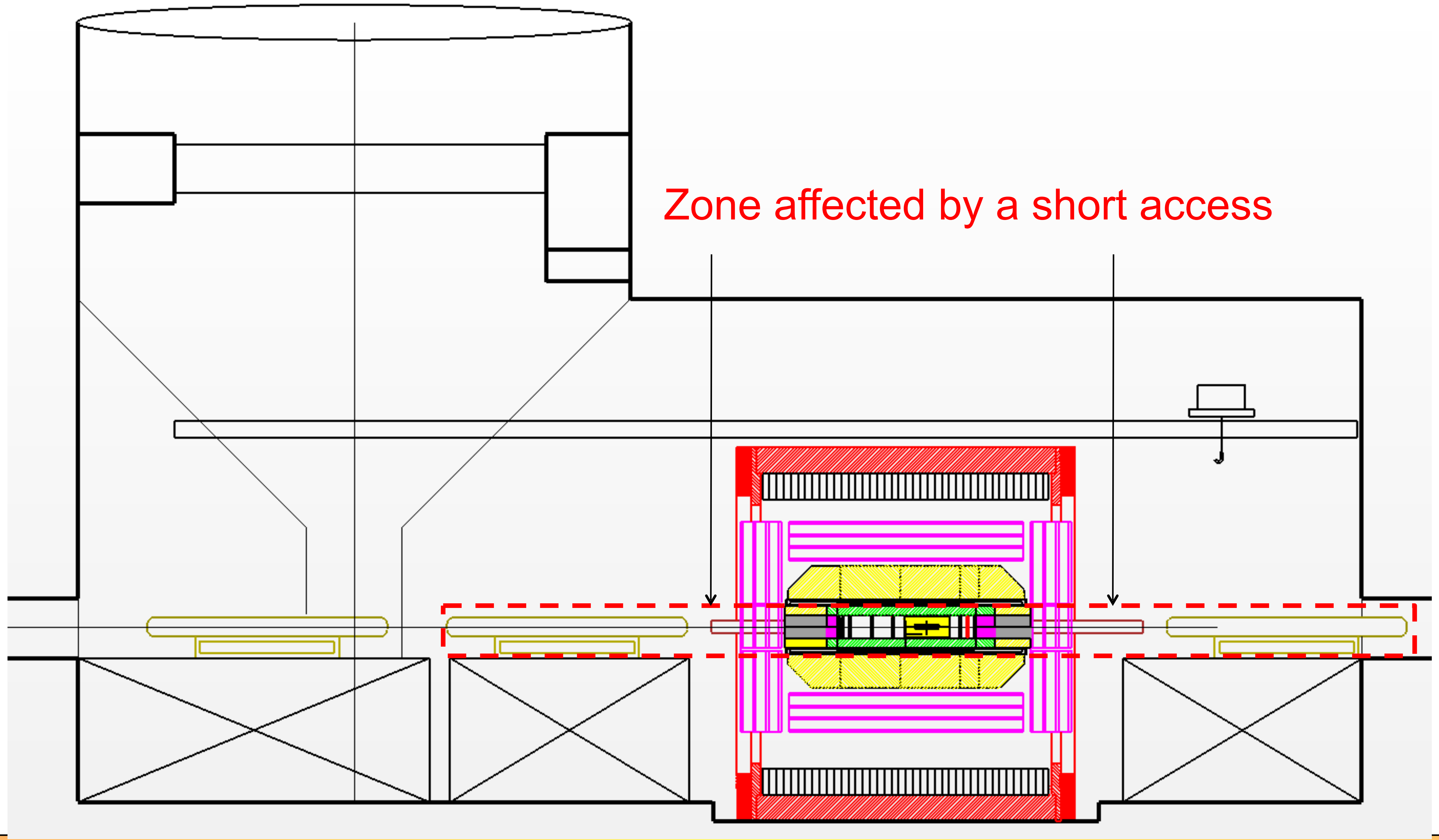


Detector lowering & integration underground (4).

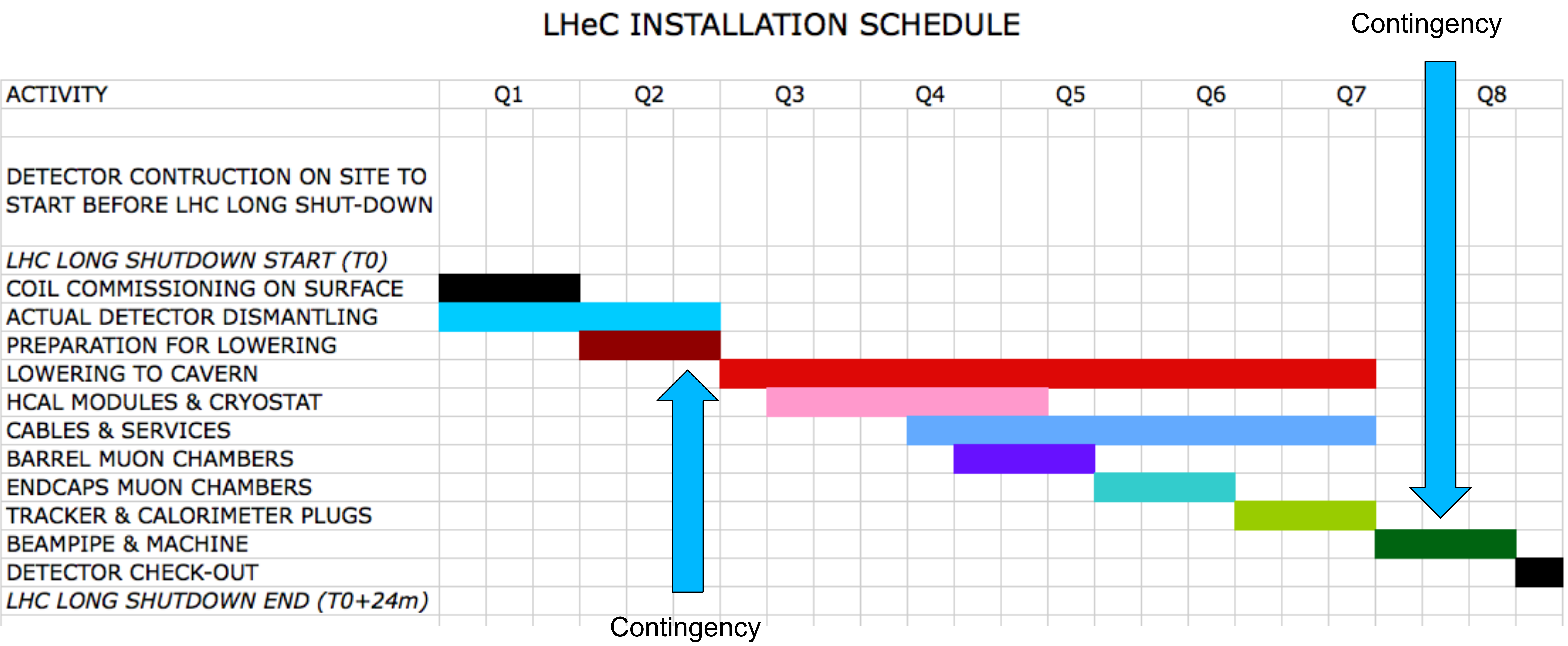


Maintenance & opening scenario.

A minimal maintenance scenario has been analysed. This foresees the possibility of opening the detector to get access to the Central Tracker & the Vertex. To allow this, the two heavy HCal inserts have to be removed from inside the cryostat and moved along z on the platform that supports the last machine elements, in particular the external dipoles. These elements have to be previously disconnected from the beam-pipe and moved away on the same platform along x. To avoid disconnecting the HCal inserts form the main services, cable-chains will accomodate extra-lengths of cables, fibres and services.
More time is needed to better define a reliable detector maintenance scenario.



Tentative schedule.



Summary

ERL-based designs for LHeC / FCCeh are taking shape. It could installed within a 24 month shutdown.

Specific eh demands are the 3-beam IR for synchronous ep/eA and pp/pA operation and
the need to bend the e-beam for head-on collision with the p/A beam.
The detector has to tolerate the additional dipole magnet system inside the IR!

The IR region design passed some corner stones - work on IR-magnet,
Optics are (p & e) being worked on - Synchrotron Radiation load, critical Energy (!) and Luminosity optimised
- detailed investigation (MDISim, Geant4) - some missing still

Detector serving for rich physics program -
different options, e.g. calorimeter warm ↔ cold (LAr based),
detector magnet design, dimensions of detector parts
Modern technology → high precision tracking,
high energy forward particle & jet reconstruction in ep
Porting the LHeC / lowE-FCCeh / FCCeh detector descriptions into FCCSW ?
Or following the DD4hep Ansatz?

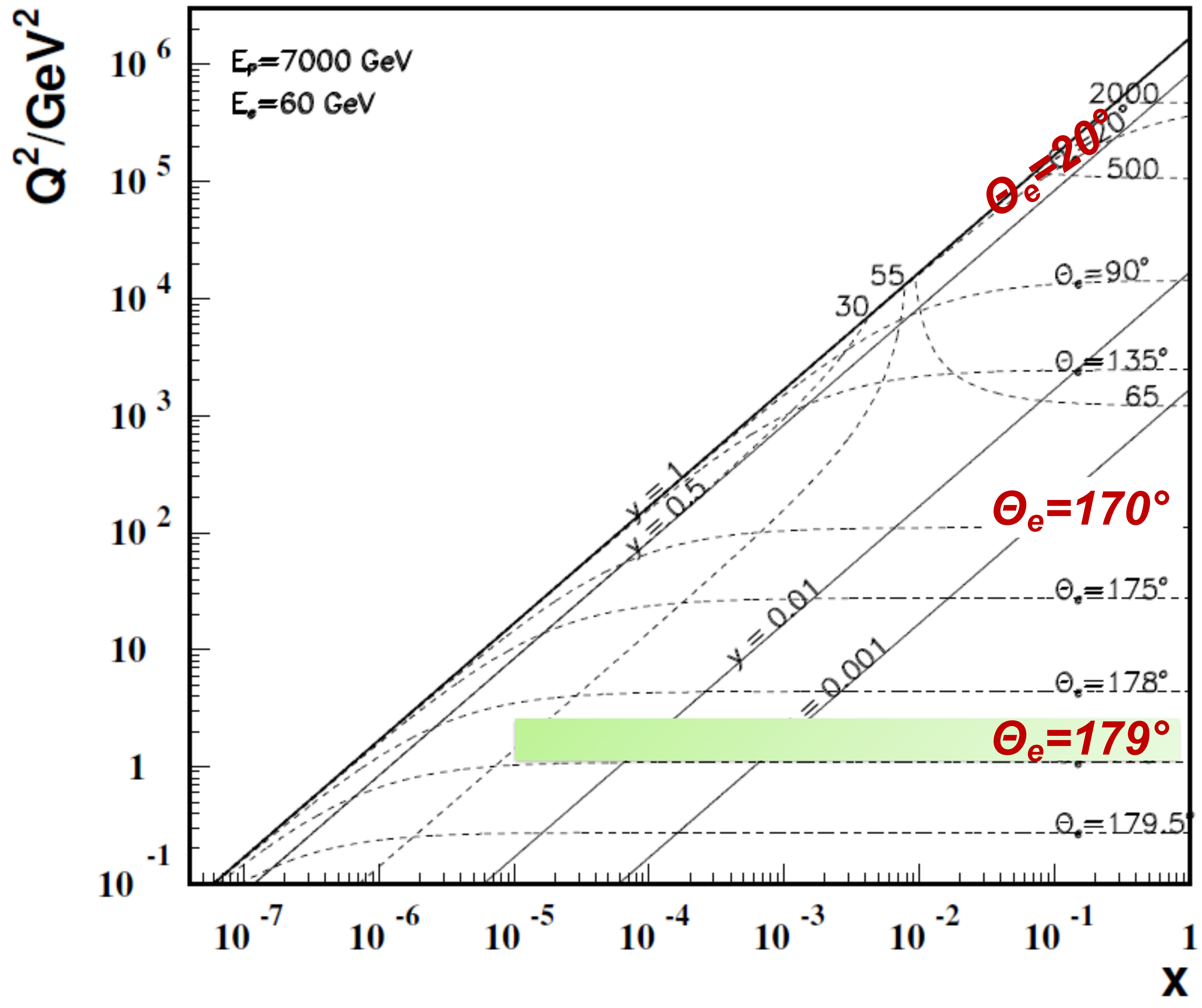
Benchmark channels - detailed definition & tests pending
Some examples of detector performance given - in DD4hep/DDG4 environment

Add On

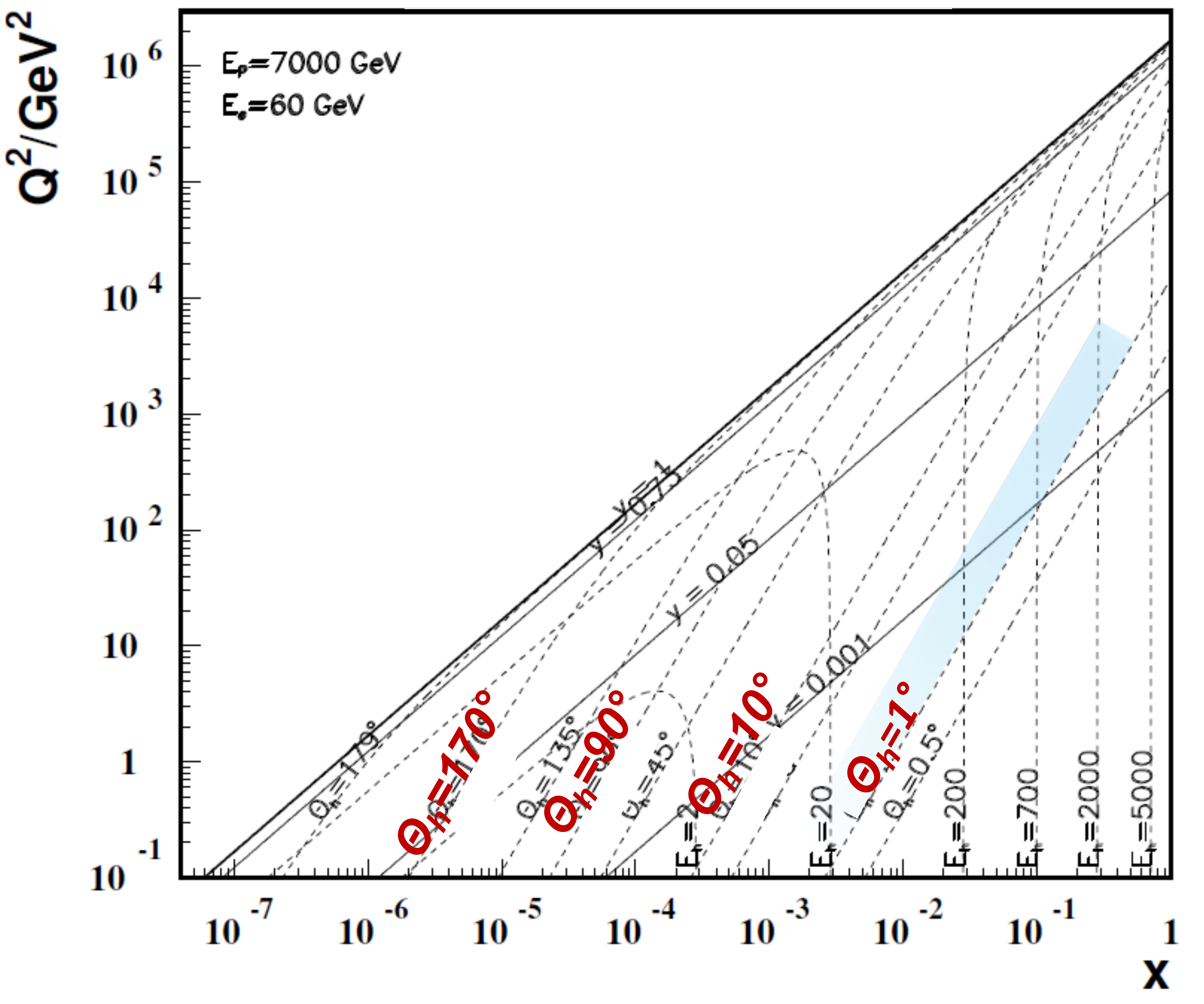
LHeC Kinematic Range (low x; high Q2)

courtesy Max Klein

LHeC – electron kinematics



LHeC – jet kinematics

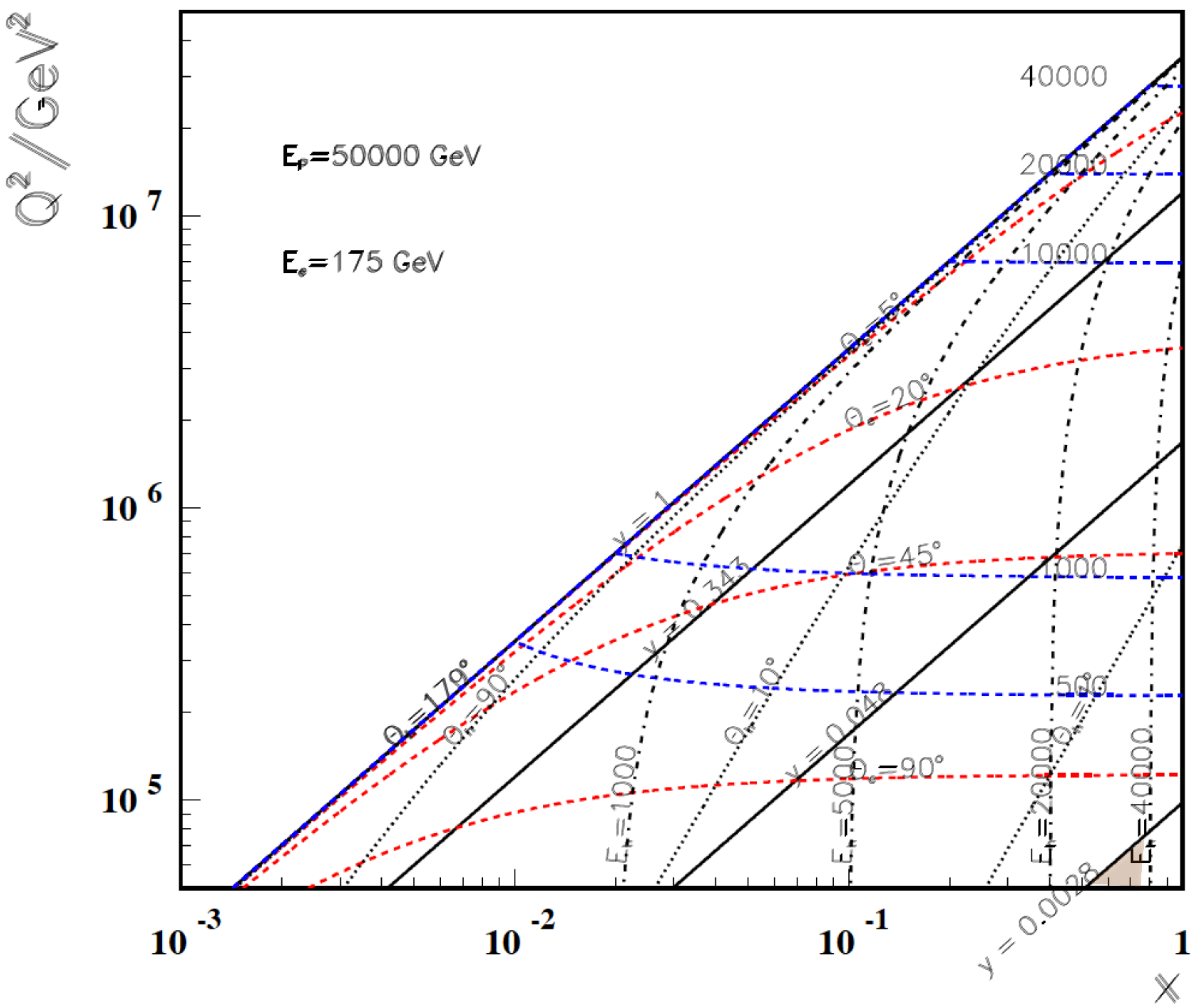


- High x and high Q^2: few TeV HFS scattered forward: Need forward calorimeter of few TeV energy range down to 1^0
  - Mandatory for charged currents where the outgoing electron is missing
- Scattered electron: Need very bwd angle acceptance for accessing the low Q^2 and high y region

FCC-eh Kinematic Range (low x; high Q^2)

courtesy Max Klein

Rutherford backscattering of dozens of TeV e- energy



FCCeh 175 GeV

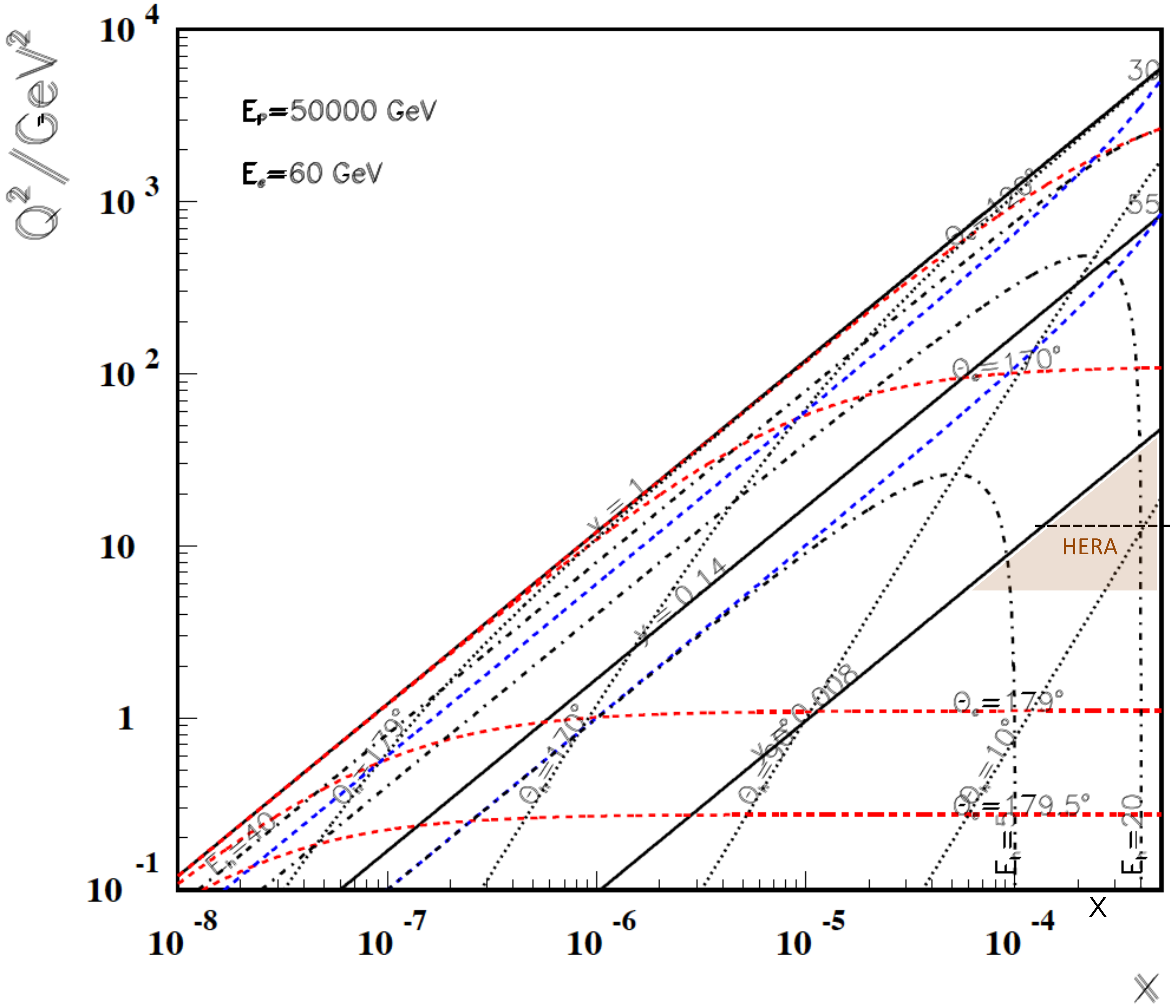
60 GeV

LHeC

← ϑ_h=1°

HERA

Low x



FCCeh 60 GeV

LHeC

← 179° @ 180 GeV .. very low x requires not the maximum of E_e

Large imbalance of e and p energies is surprisingly tolerable for the high Q^2, x kinematics,
LHeC to bridge from HERA to FCC

Very low x reaches direct range of UHE neutrino physics

Forward calorimeter containment up to few 10th TeV down to 1° θ ~doubling the calorimeter depth compared to LHeC

Backward region, low x is governed solely by E_e

FCCeh Physics Benchmarks e.g.

Uta & Max Klein, Contribution to FCC Workshop, 16.1.2018, preliminary

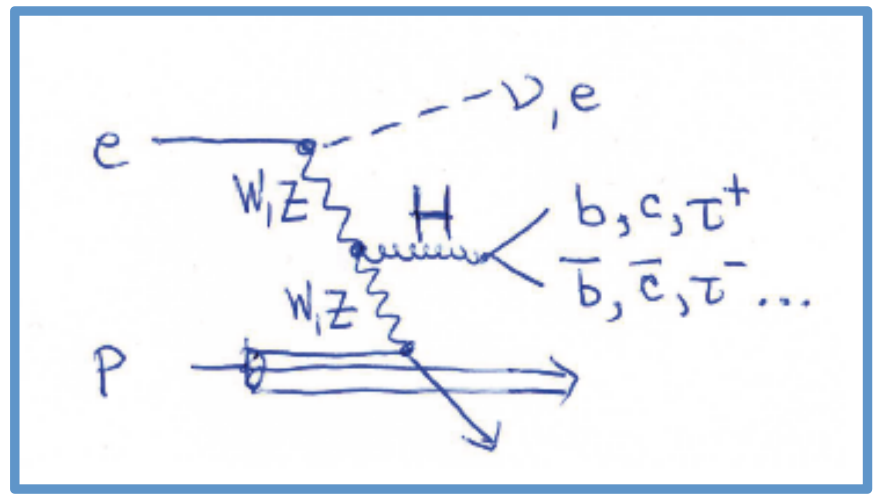
CC DIS WWH → H

FCC-he L=2 ab^{-1}

	bb	WW	gg	ττ	cc	ZZ	γγ
BR	**0.577**	**0.215**	**0.086**	**0.0632**	**0.0291**	**0.0264**	**0.00228**
δBR_{theory}	3.2%	4.2%	10.1%	5.7%	12.2%	4.2%	5.0%
N	**$1.15\ 10^6$**	**$4.3\ 10^5$**	**$1.72\ 10^5$**	**$1.26\ 10^5$**	**$5.8\ 10^4$**	**$5.2\ 10^4$**	**4600**
f	$2.86_{\ BDT}$	16	7.4	5.9	$5.6_{\ BDT}$	8.9	3.23
δμ/μ [%]	**0.27**	**2.45**	**1.78**	**1.65**	**2.36**	**3.94**	**3.23**
$\delta\kappa = \frac{1}{2}\frac{\delta\mu}{\mu}$	0.14	0.61*	0.89	0.83	1.18	1.97	2.37

bb/cc

both vertex tagging demanding somewhere between 5-10μm resolution required; accompanied by excellent calorimeter measurement



→ Sum of first 6 branching fractions that could be measured

LHeC : 0.9964 +- 0.02

FCChe: 0.9964 +- 0.01

pp: < 0.99 → cc? gg?

Further coupling constraints to be explored:

$$\sigma(WW \to H \to WW) \propto \kappa^4(HWW)$$

$$\sigma(WW \to H \to bb) \propto \kappa^2(HWW) \bullet \kappa^2(Hbb)$$

$$\sigma(WW \to H \to \tau\tau) \propto \kappa^2(HWW) \bullet \kappa^2(H\tau\tau)$$

$$\sigma(WW \to H \to gg) \propto \kappa^2(HWW) \bullet \kappa^2(Hgg)$$

$$\sigma(WW \to H \to cc) \propto \kappa^2(HWW) \bullet \kappa^2(Hcc)$$

$$\sigma(WW \to H \to ZZ) \propto \kappa^2(HWW) \bullet \kappa^2(HZZ)$$

$$Note: \sigma(ZZ \to H \to WW) \propto \kappa^2(HZZ) \bullet \kappa^2(HWW)$$

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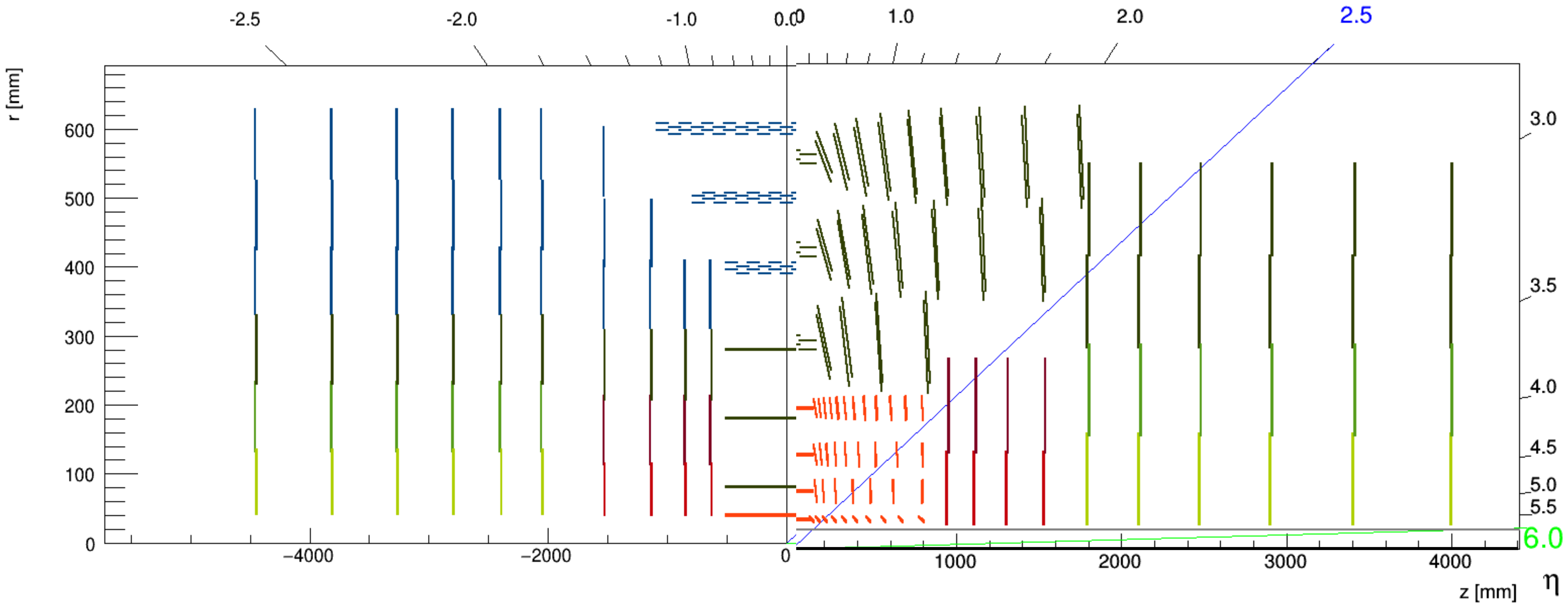
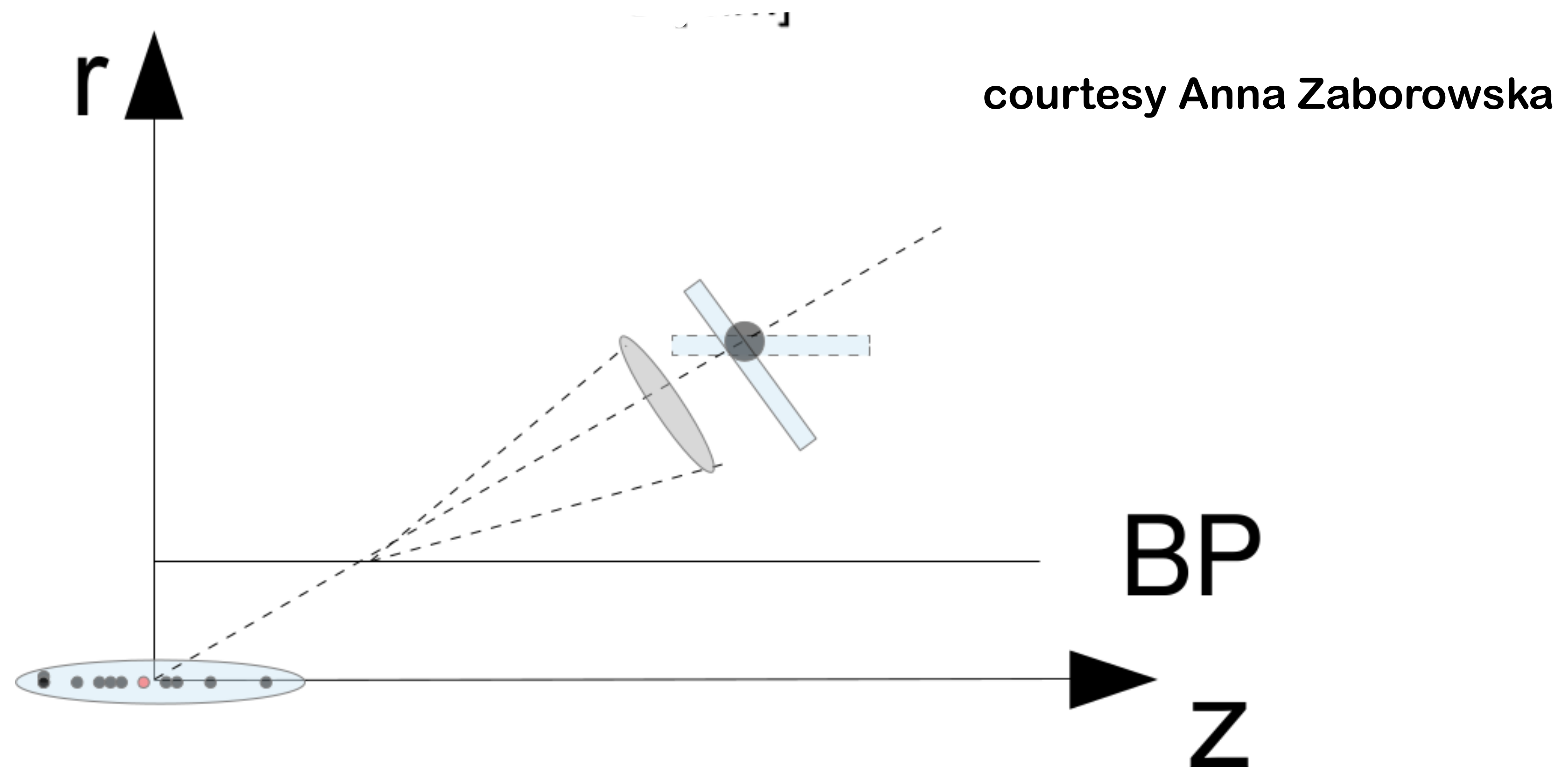
Alternative FCC-eh / lowE-FCC-eh Tracker Layout



bwd - planar design

fwd - tilted design

Going from planar design to Inclined inner tracker modules minimising material budget

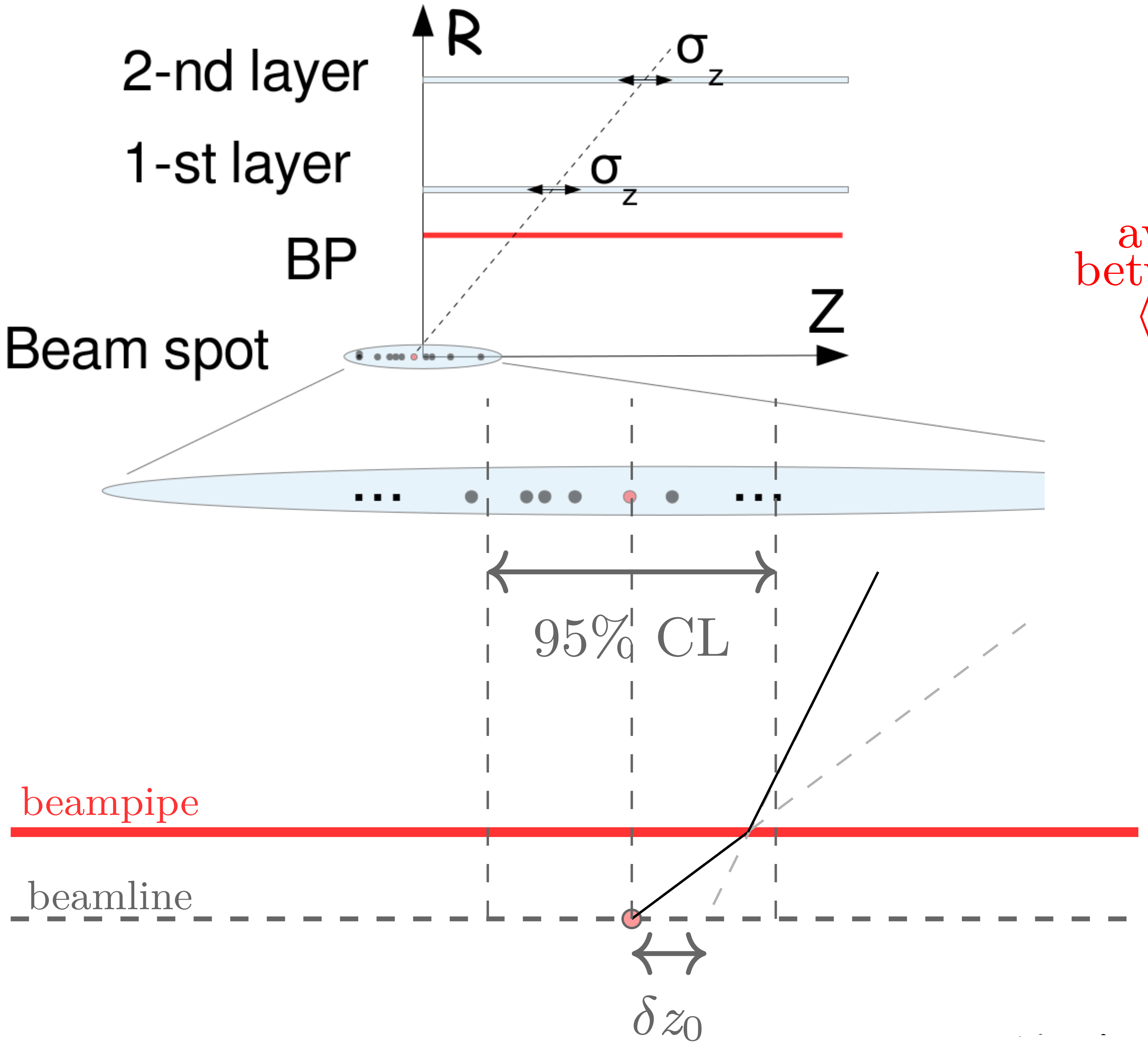


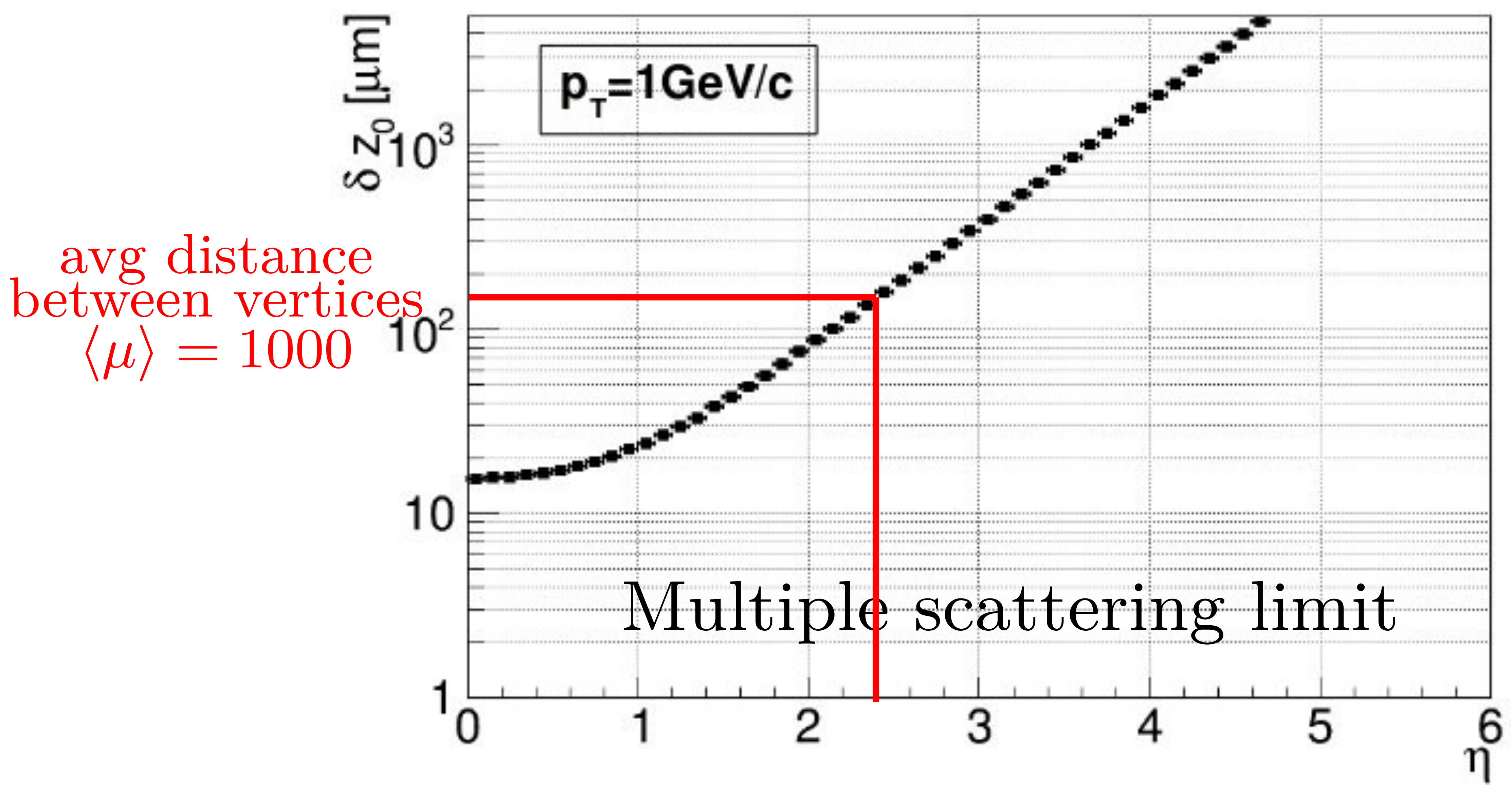
Very compact layout
Forward/backward boosted jet-/particle-flow
The physics requirements dictates final dimensions
Higher accuracy / larger lever arms (radius, z-extension) needed? ... radius extension within limits

Optimised by pattern recognition and vertexing
3.5mm beam pipe thickness
3.5T solenoidal field
NO pile-up

Zbyněk Drásal:
https://github.com/drasal/tkLayout/tree/masterLite

LHeC / lowE-FCCeh / FCCeh Track-Detector - Vertex Resolution





FCC-hh picture

courtesy Anna Zaborowska

NO pileup for LHeC / lowE-FCCeh / FCCeh

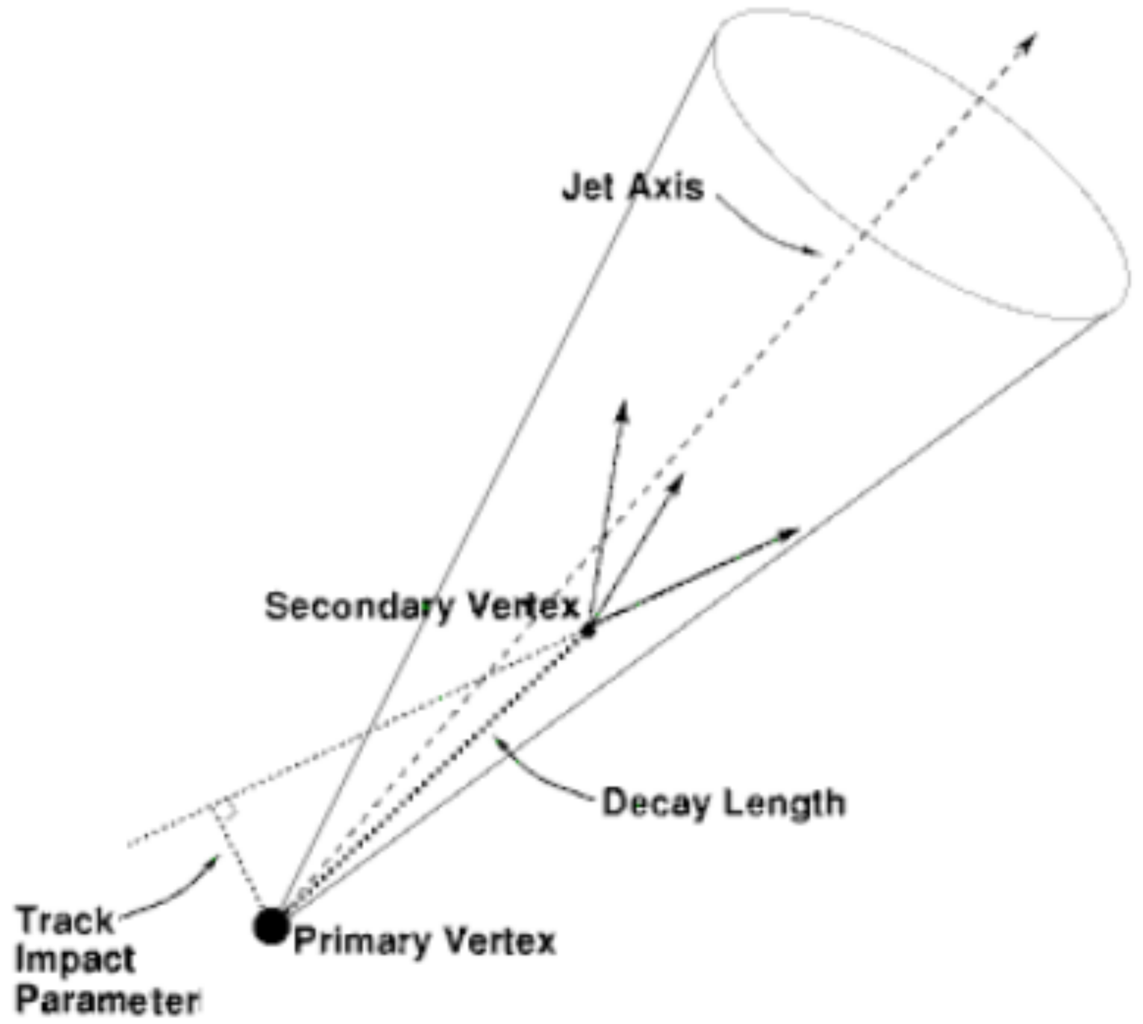
- effects of thicker BP compared to FCC-hh - to be investigated

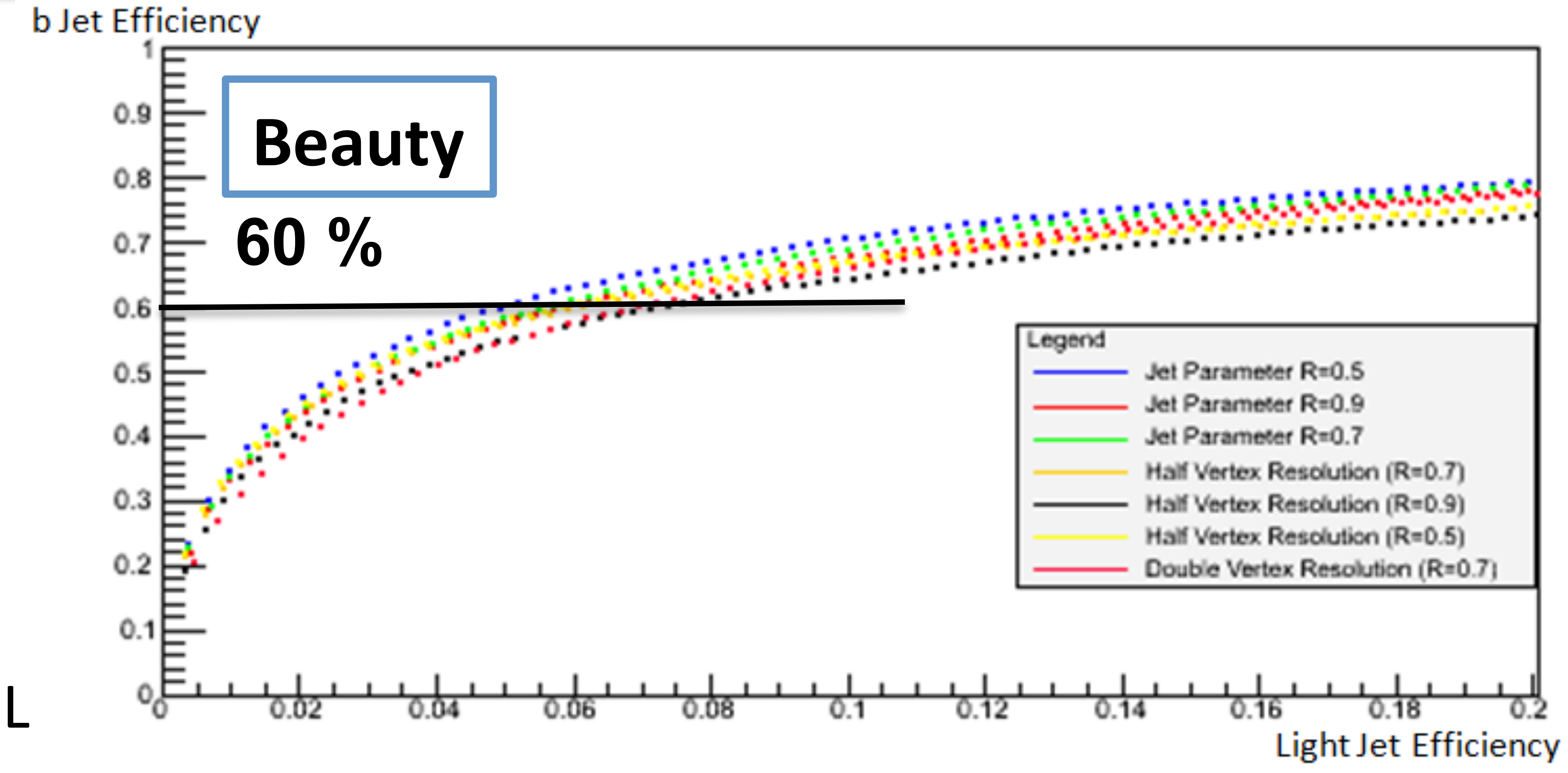
- resolution of displaced vertices, secondary vertices, boosted daughters

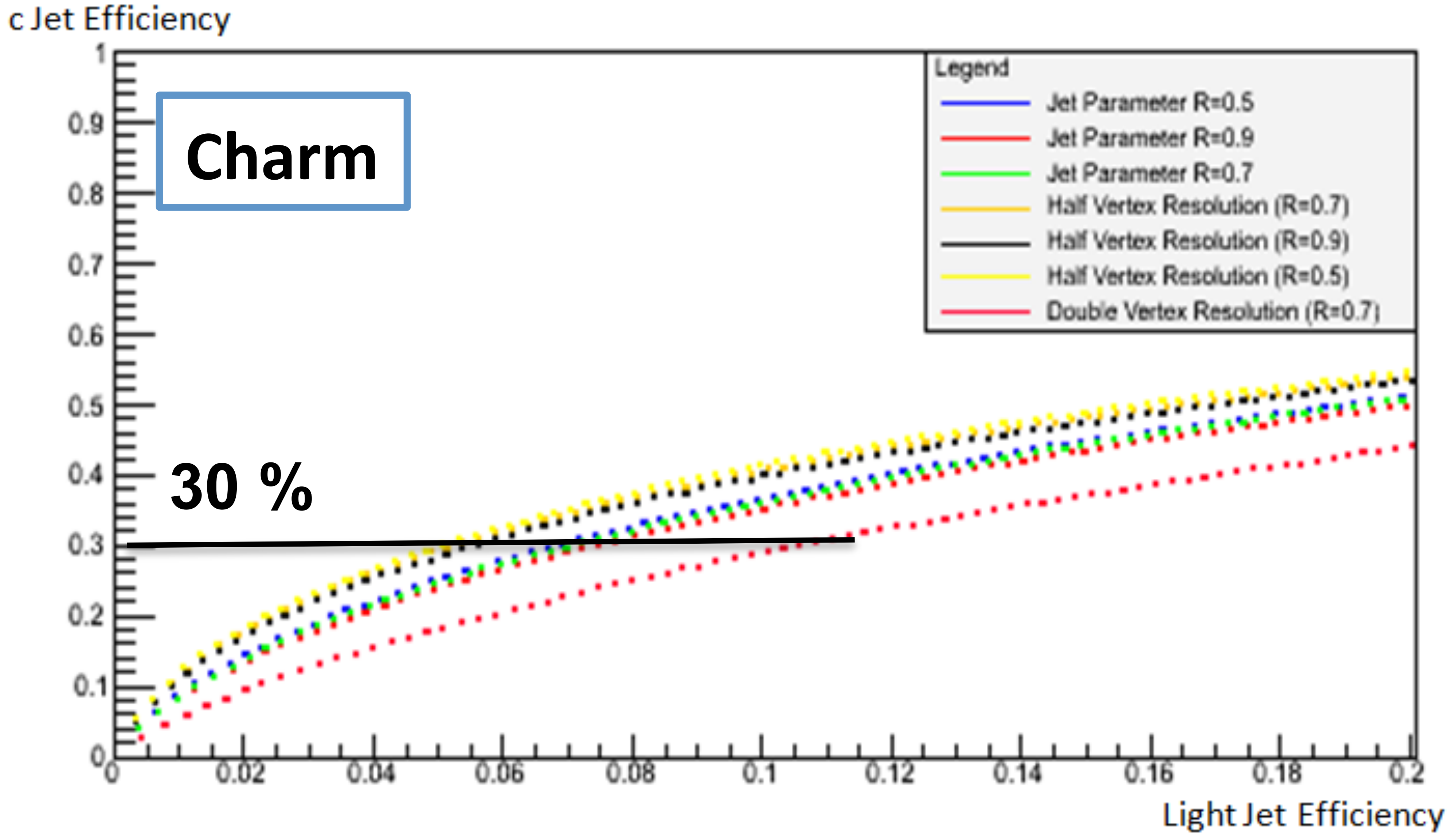
Secondary Vertex Tagging

HFL Tagging

Uta Klein &
Daniel Hampson







- → Realistic and conservative HFL tagging within Delphes realised, and dependence on vertex resolution (nominal 10 µm) and anti-kt jet radius studied
- → Light jet rejection very conservative, i.e. factor 10 worse than ATLAS
- → **used in full LHeC analysis and for FCC-eh extrapolations**

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