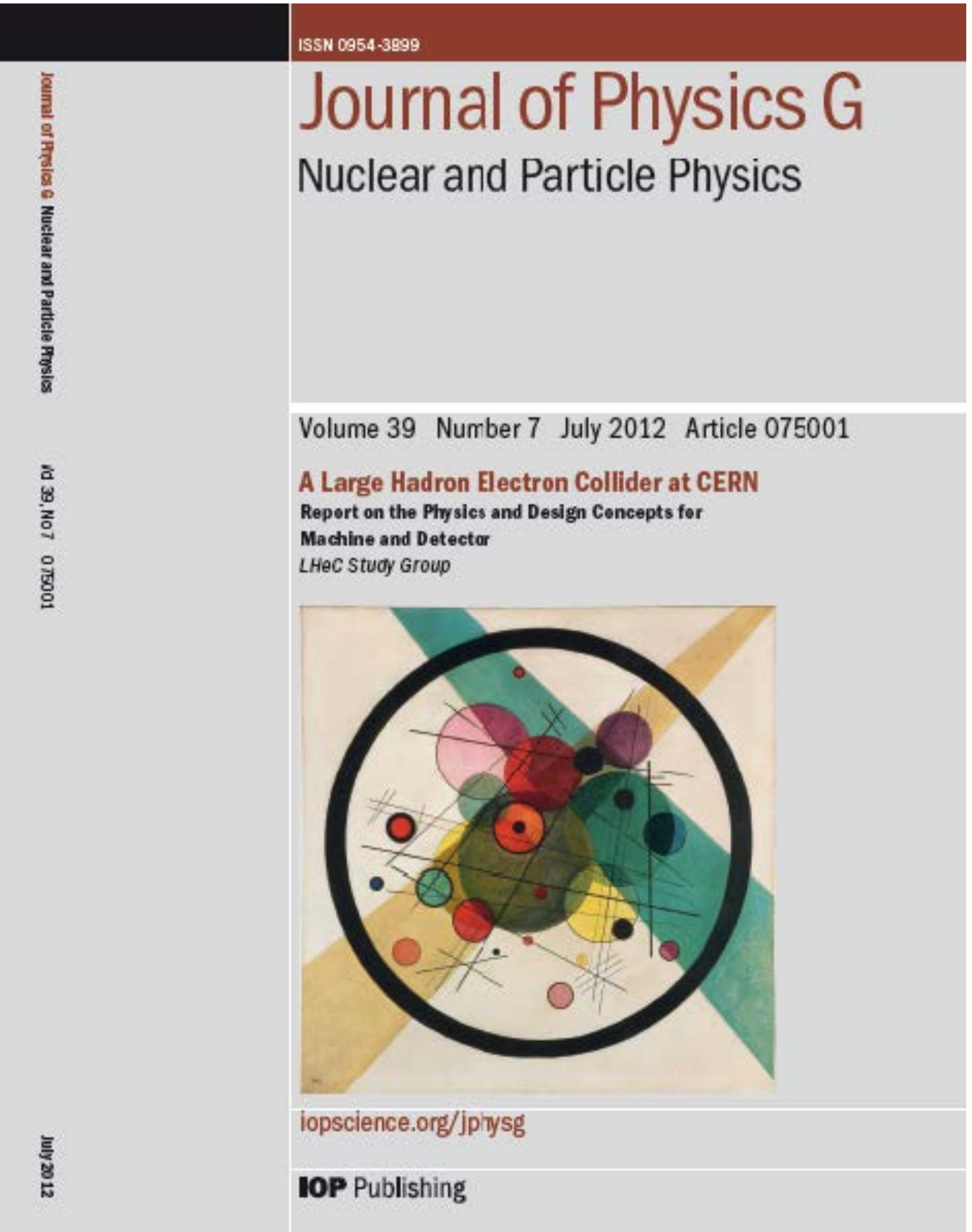
FCC-he Conceptual Detector Design
CDR Plan and Status

eh Baseline
IR
Kinematics
Detector Structure
Software Status
Remarks, CDR Guideline

Peter Kostka, Max Klein, Alessandro Polini
For the LHeC/FCC-eh Study Group

From LHeC to FCC-he CDR



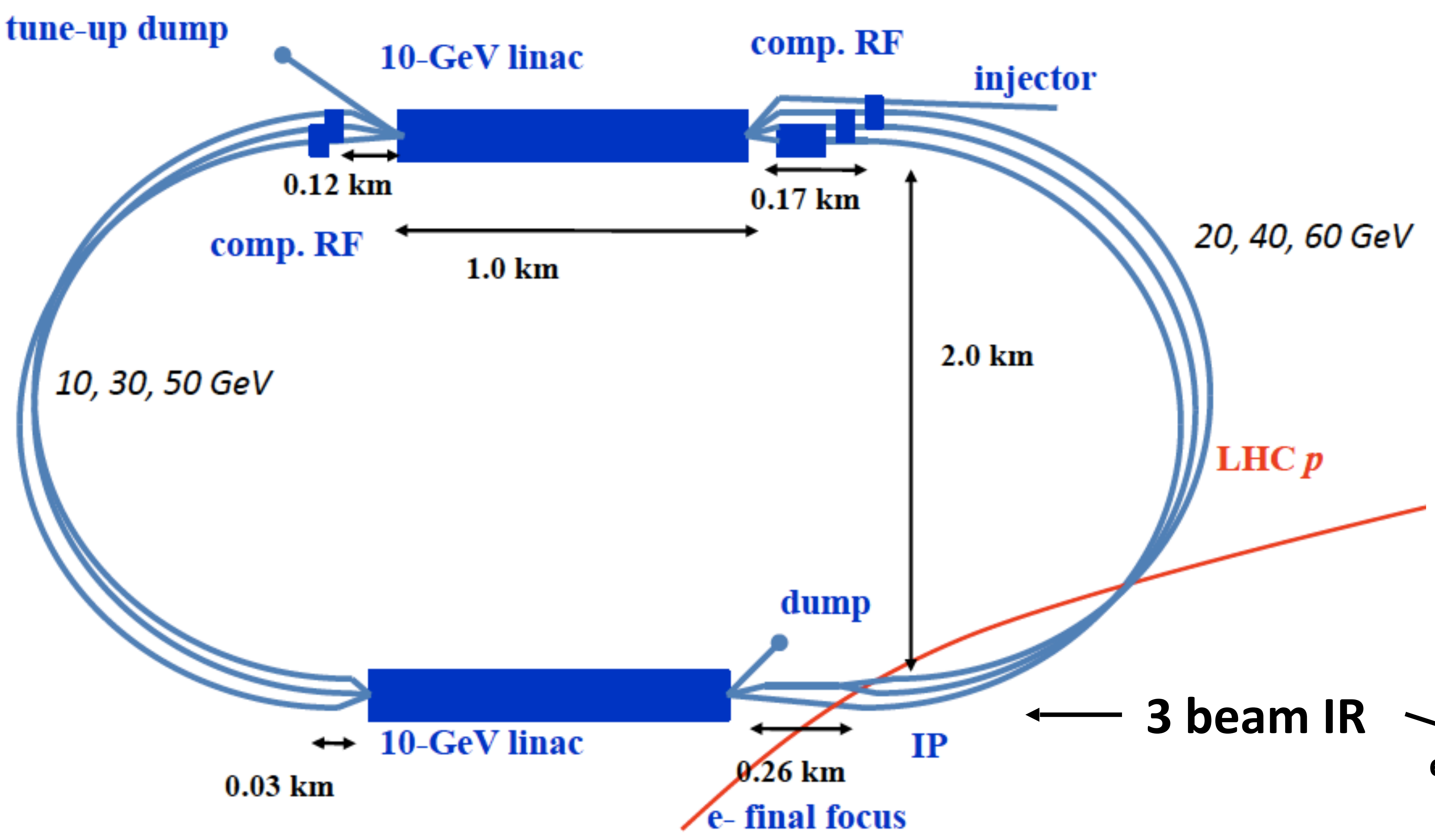
Shortly after publishing the LHeC CDR the Higgs was discovered. For any FCC detector under discussion the Higgs is a key benchmark. Discussed in detail by Uta Klein later in this session.

The FCC-he is a full featured, alternative device for Higgs related measurements of high quality / sensitivity, with special strength for the forward boosted Higgs production
By construction the detector is taking into account additionally the asymmetric eh/eA kinematic (unbalanced beam energies).

The FCC-he detector must be a 'general' purpose detector with very large η acceptance and very high granularity.

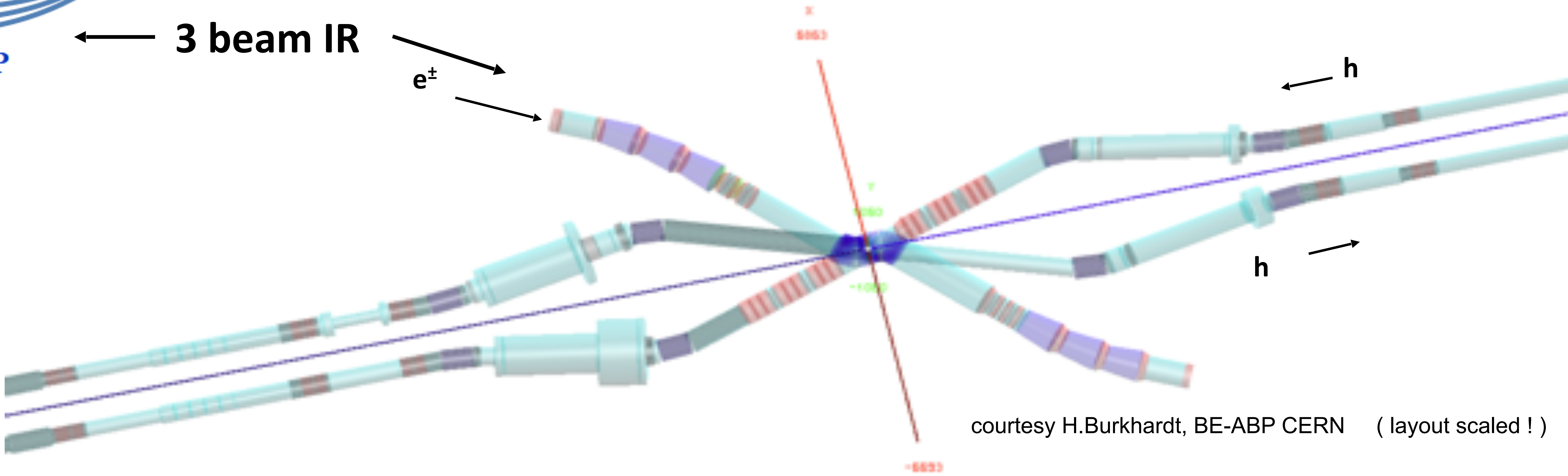
Baseline Electron Beam Configuration*

* LHeC CDR, arXiv:1206.291



Operation in parallel with LHC/HE-LHC

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



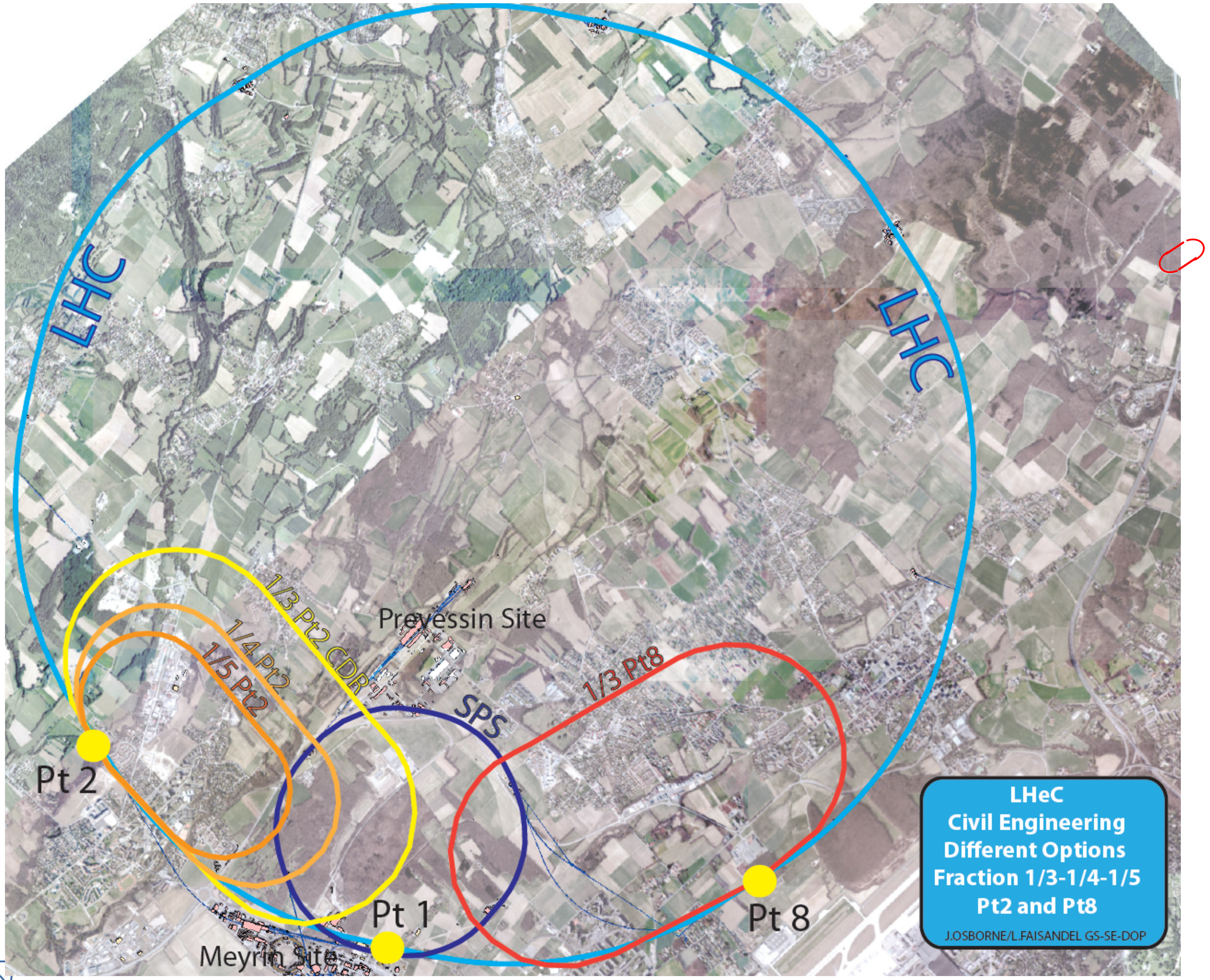
courtesy H.Burkhardt, BE-ABP CERN (layout scaled !)

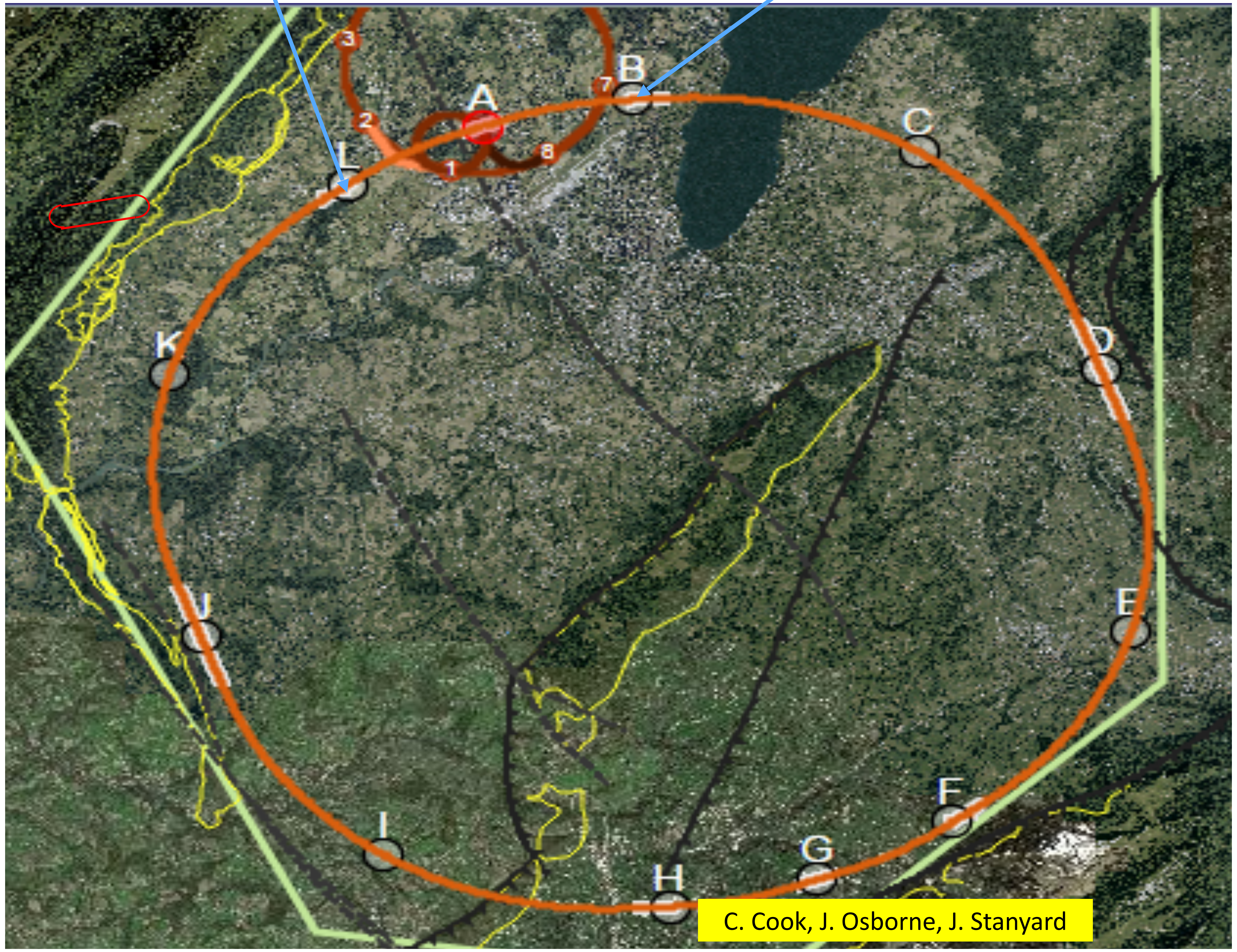
Configurations of Future ep Colliders at CERN

LHeC/HE-LHeC
machine variants

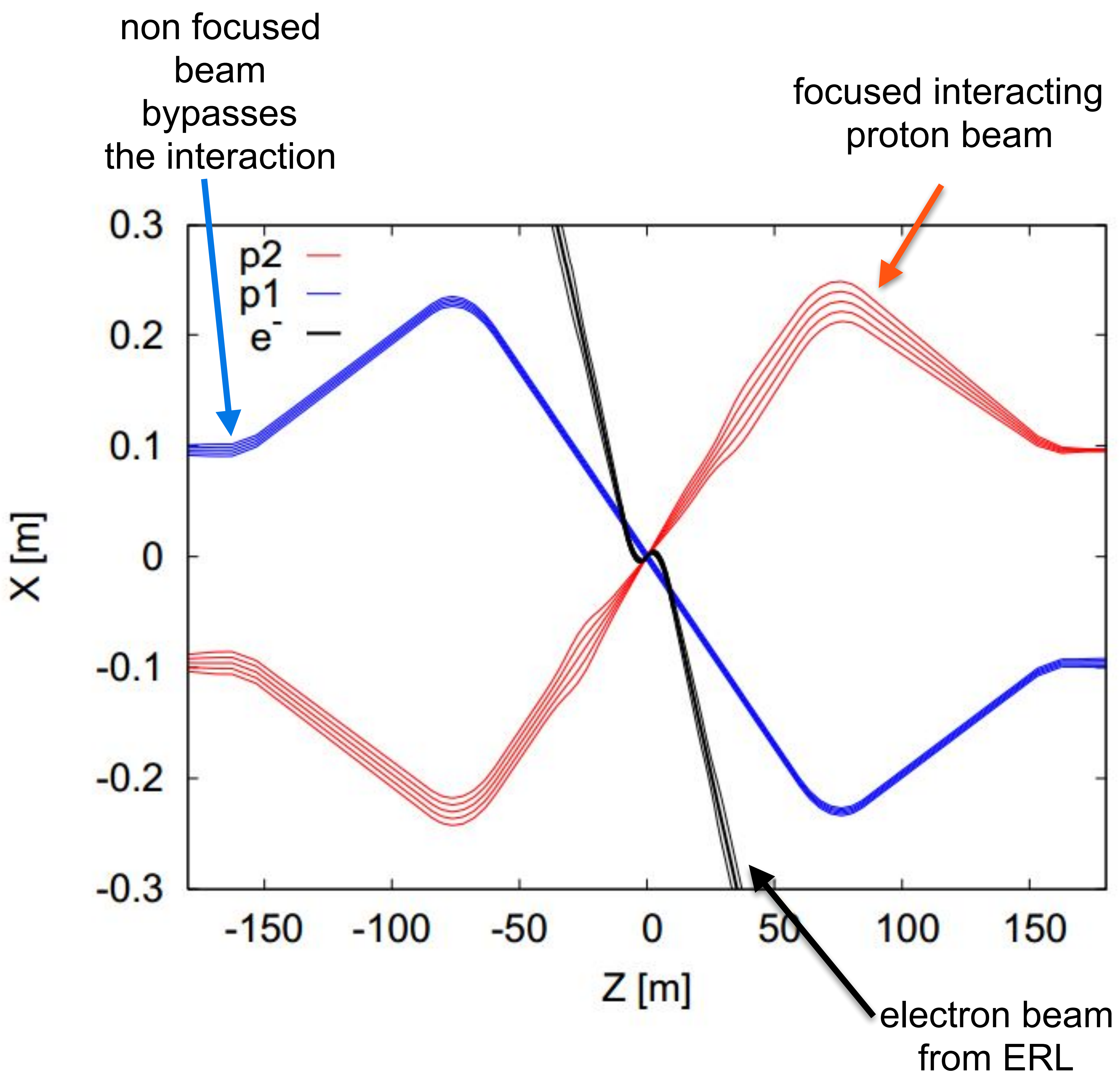
independent FCC-he
Point L, F, H or B

(HE-)LHeC / FCC-he
LHC P8 & FCC PB



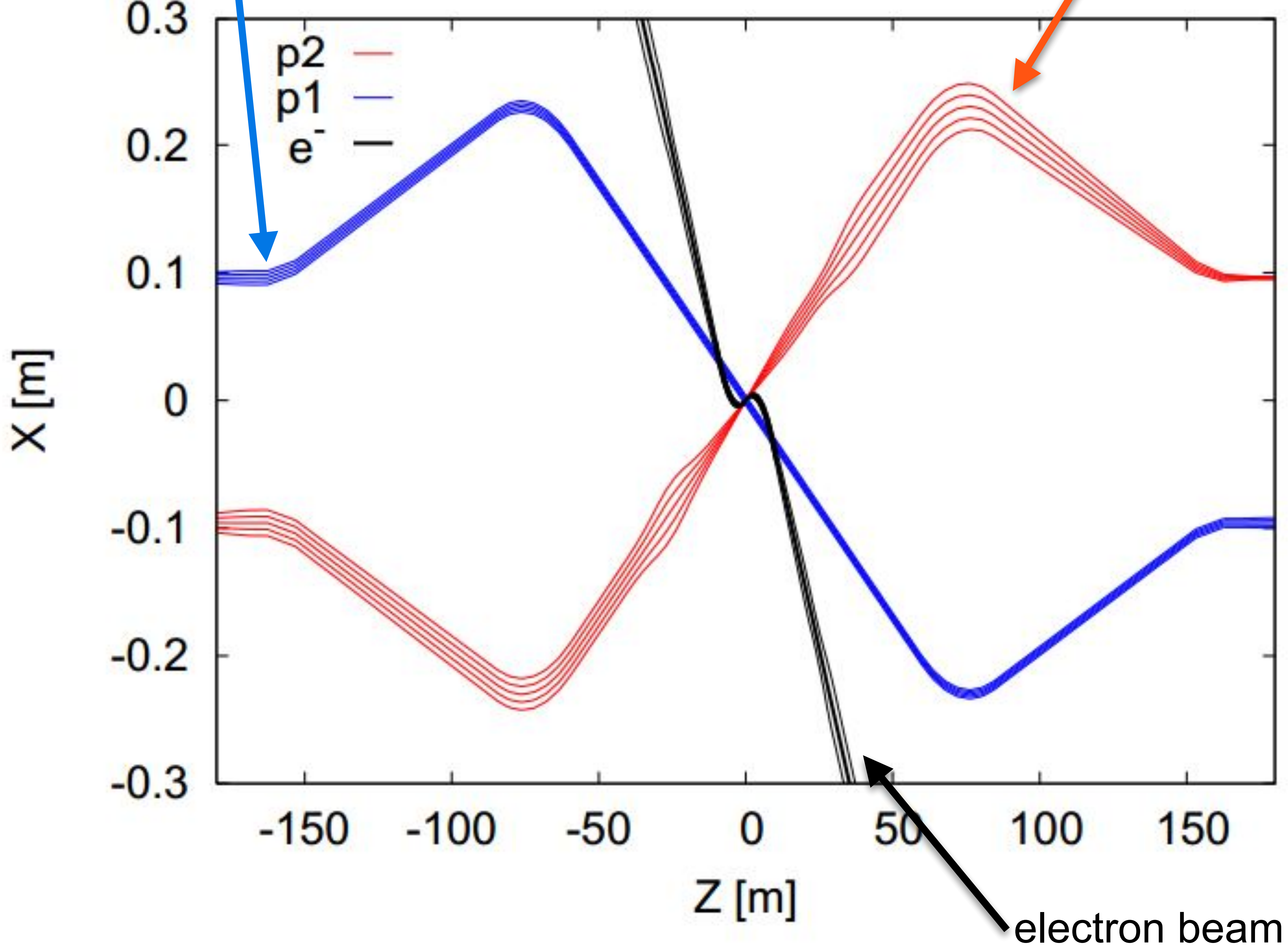


LHeC/FCC-eh interaction region

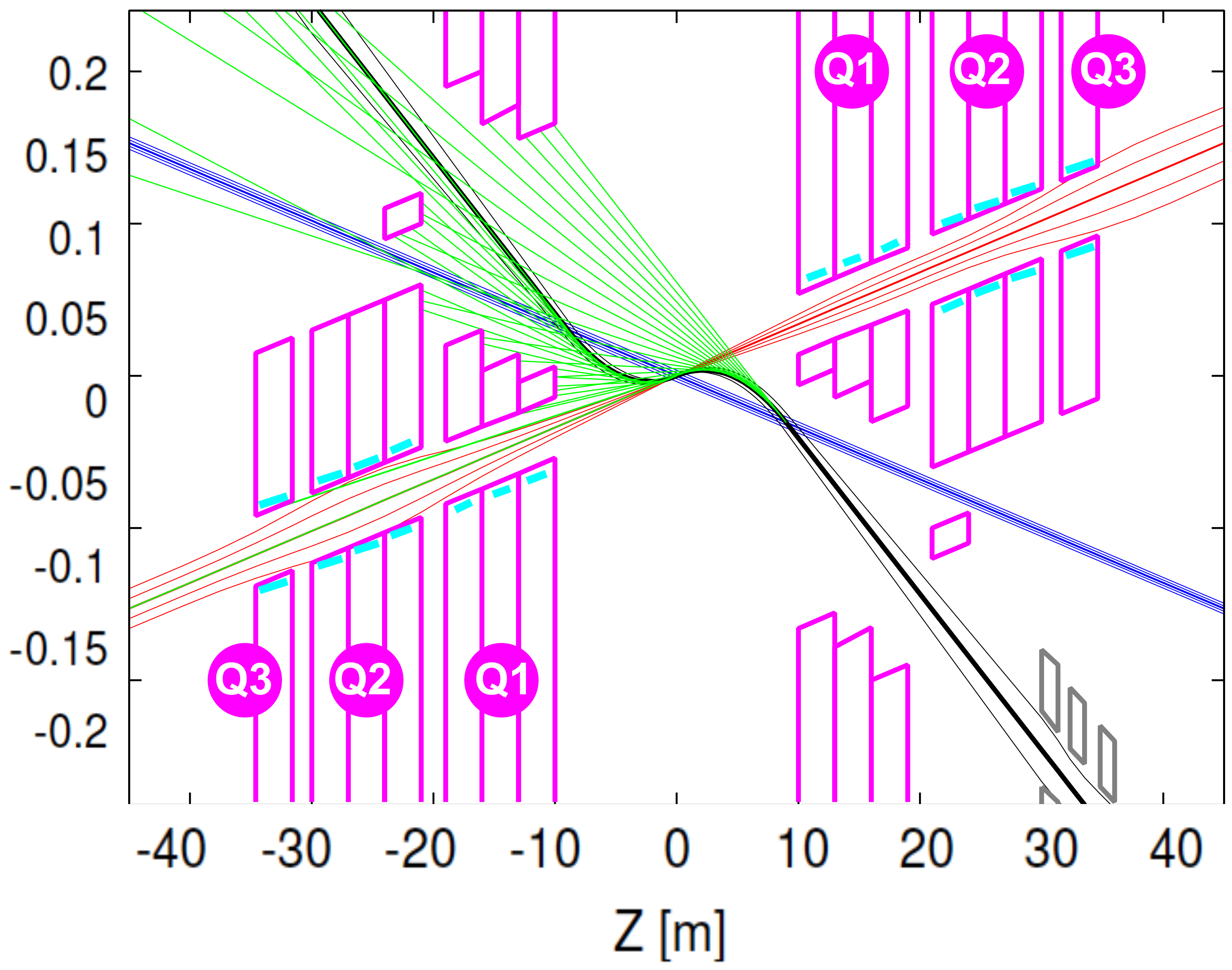


E. Cruz, R. Tomas, F. Zimmermann et al.

LHeC/FCC-eh interaction region



Synchrotron Radiation and various beams



Tentative: ε_p=2μm, β*=20cm → σ_p=3μm ≈σ_e matched! ε_e=5μm ..

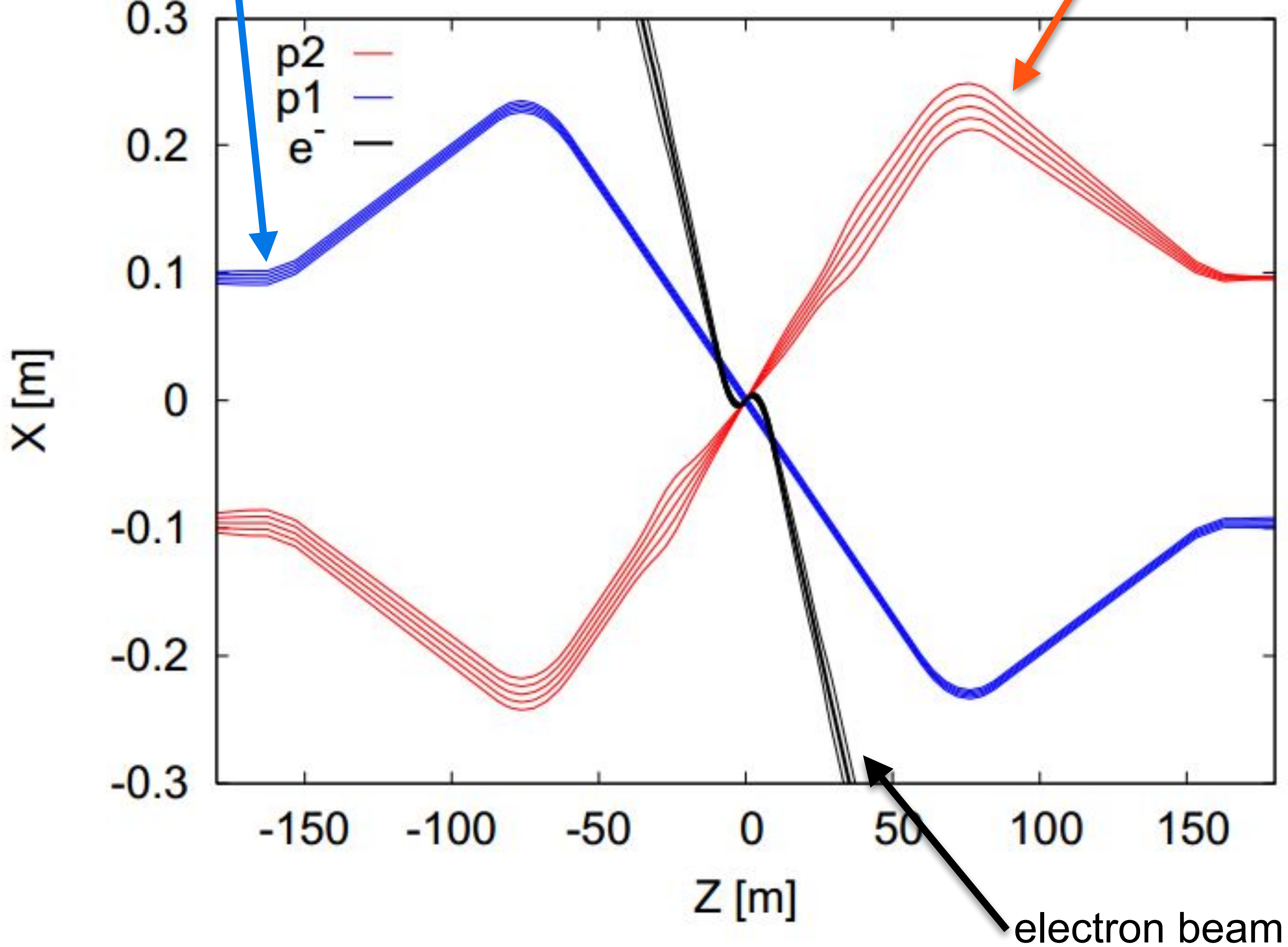
electron proton beams well matched!

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

LHeC/FCC-eh interaction region

non focused beam bypasses the interaction

focused interacting proton beam

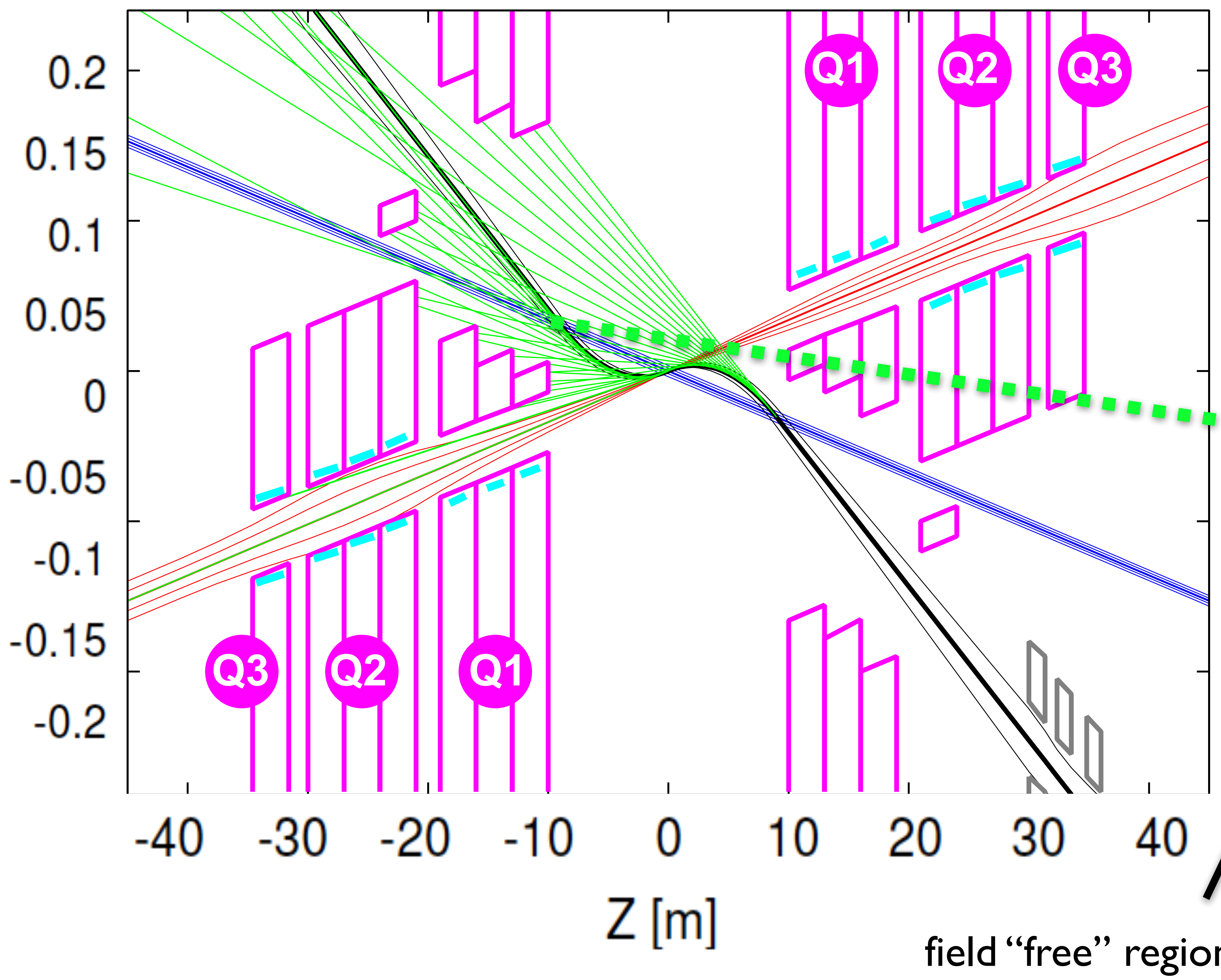


electron beam from ERL

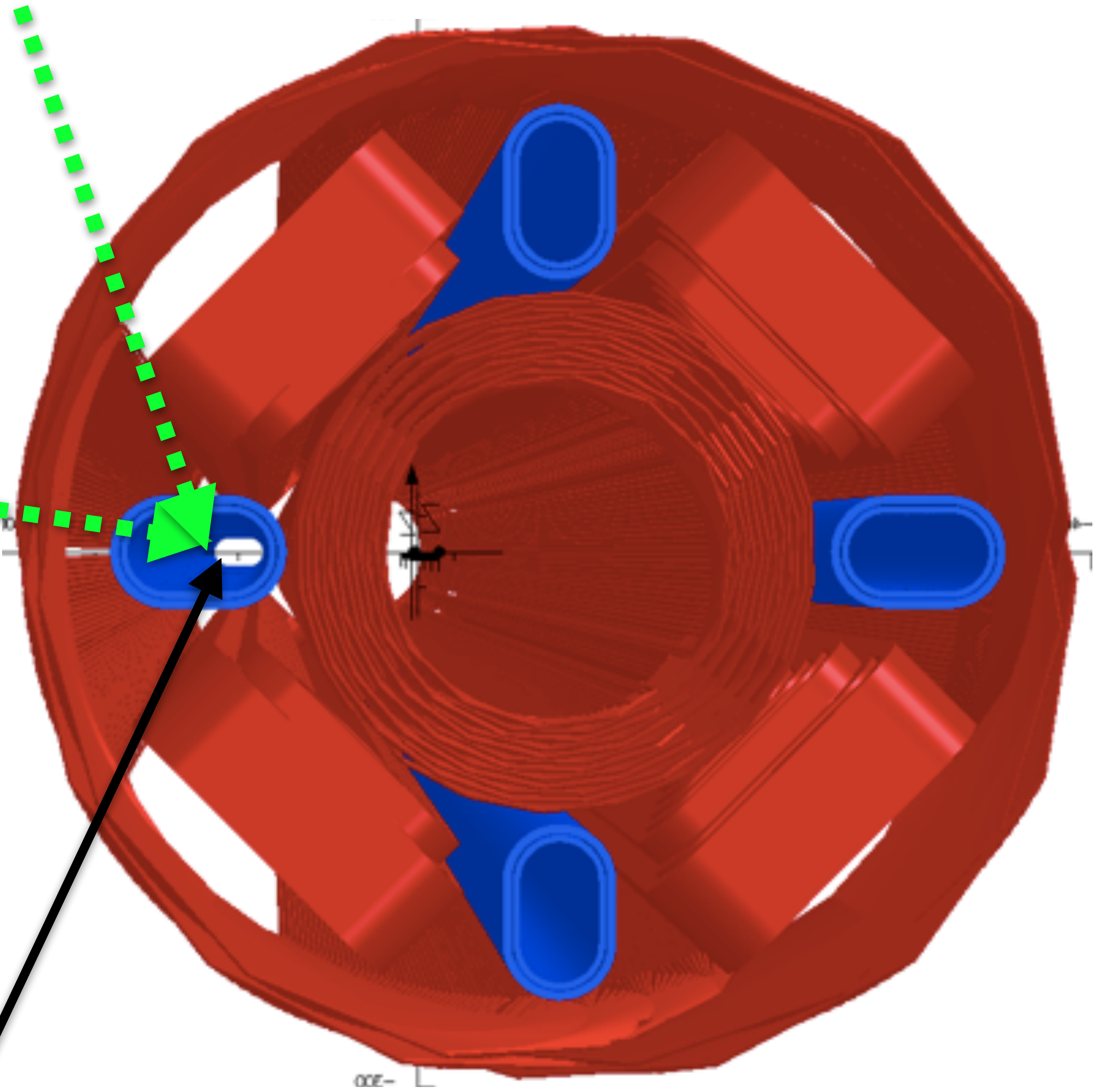
Synchrotron Radiation and various beams

SR fan

exit hole - electrons and non-colliding protons



Final quadrupole magnet Q1 example design "sweet spot"



field "free" region

Tentative: ε_p=2µm, β*=20cm → σ_p=3µm ≈σ_e matched! ε_e=5µm ..

electron proton beams well matched!

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

B. Parker, S. Russenschuck et al.

Baseline Parameters of ep at LHC and FCC

Baseline parameters of future electron-positron collider configurations based on the ERL electron linac

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

The Higgs discovery has raised the L(ep) goal to 10^{34}. The pile-up is O(1) at FCC-eh

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017,
"A Baseline for the FCC-he"

Oliver Brüning, John Jowett, Max Klein, Dario Pellegrini,
Daniel Schulte, Frank Zimmermann
see talk F. Zimmermann: https://indico.cern.ch/event/556692/contributions/2483407/

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LHeC-ERL added to LHC, HL-LHC, HE-LHC, FCC-eh,…

➔ high-energy high luminosity *ep* and *eA* collisions

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With the Higgs discovery and measured cross section σ ~ 200fb there is a striking option to make the LHeC a clean Higgs factory with maximum luminosity and even more the FCC-he

The Higgs discovery has raised the L(ep) goal to 10^{34}. The pile-up is O(1) at FCC-eh

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Interaction-Region Design for ep/eA at LHC and FCC

Machine-detector interface
- dipoles inside detector volume - (e-beam head-on p/A)

Final quadrupole magnets (Brett Parker's talk given by Oliver Bruning)

Synchrotron-Radiation inside detector
- avoid / mask / shield

Detailed integration study depends on location
- IP choice for FCC not fixed, IP tentatively FCC point L

25ns or 5ns/12.5ns FCC bunch timing operation?

…..

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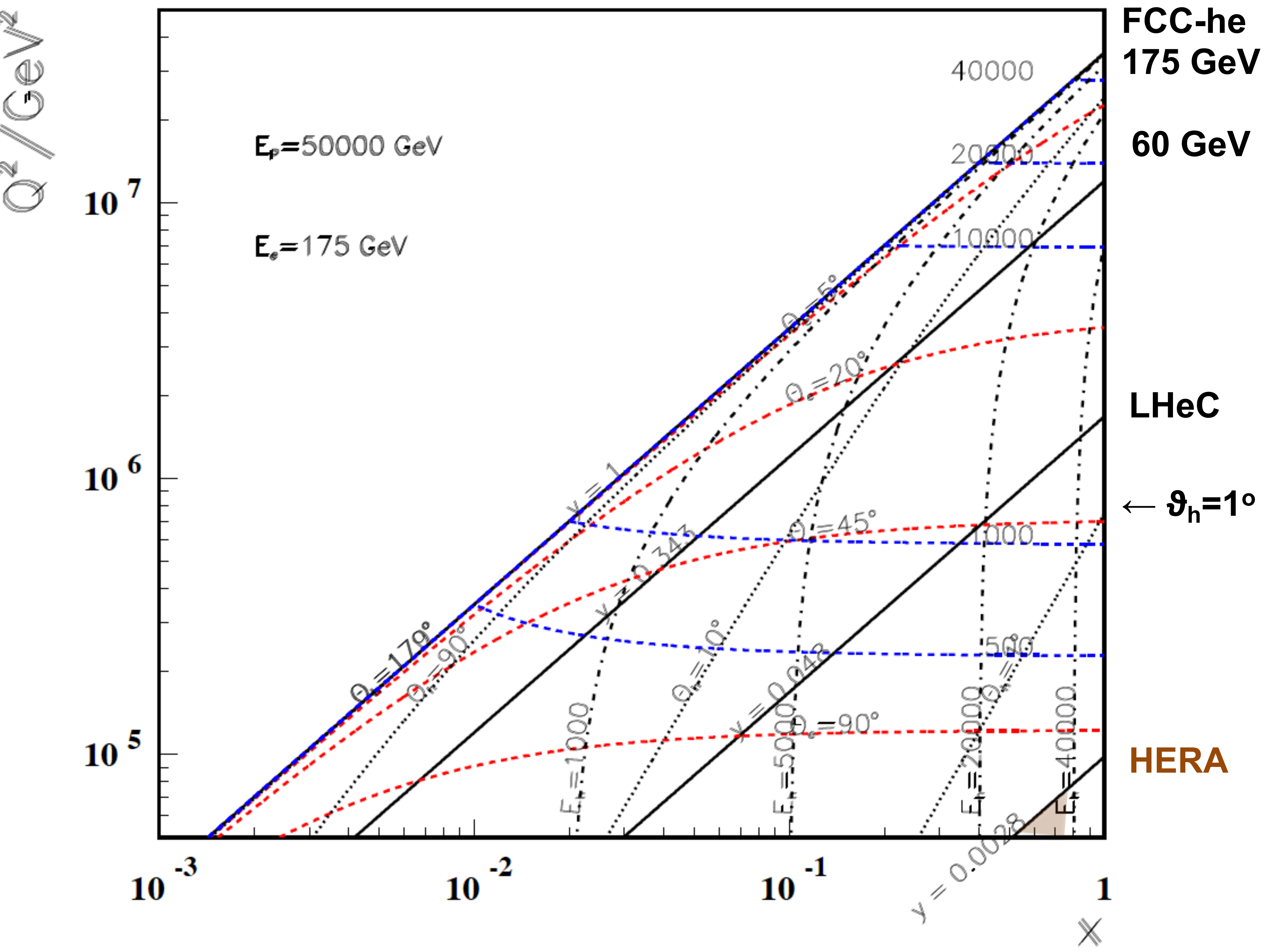
see talk F. Zimmermann: https://indico.cern.ch/event/556692/contributions/2483407/

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

courtesy Max Klein

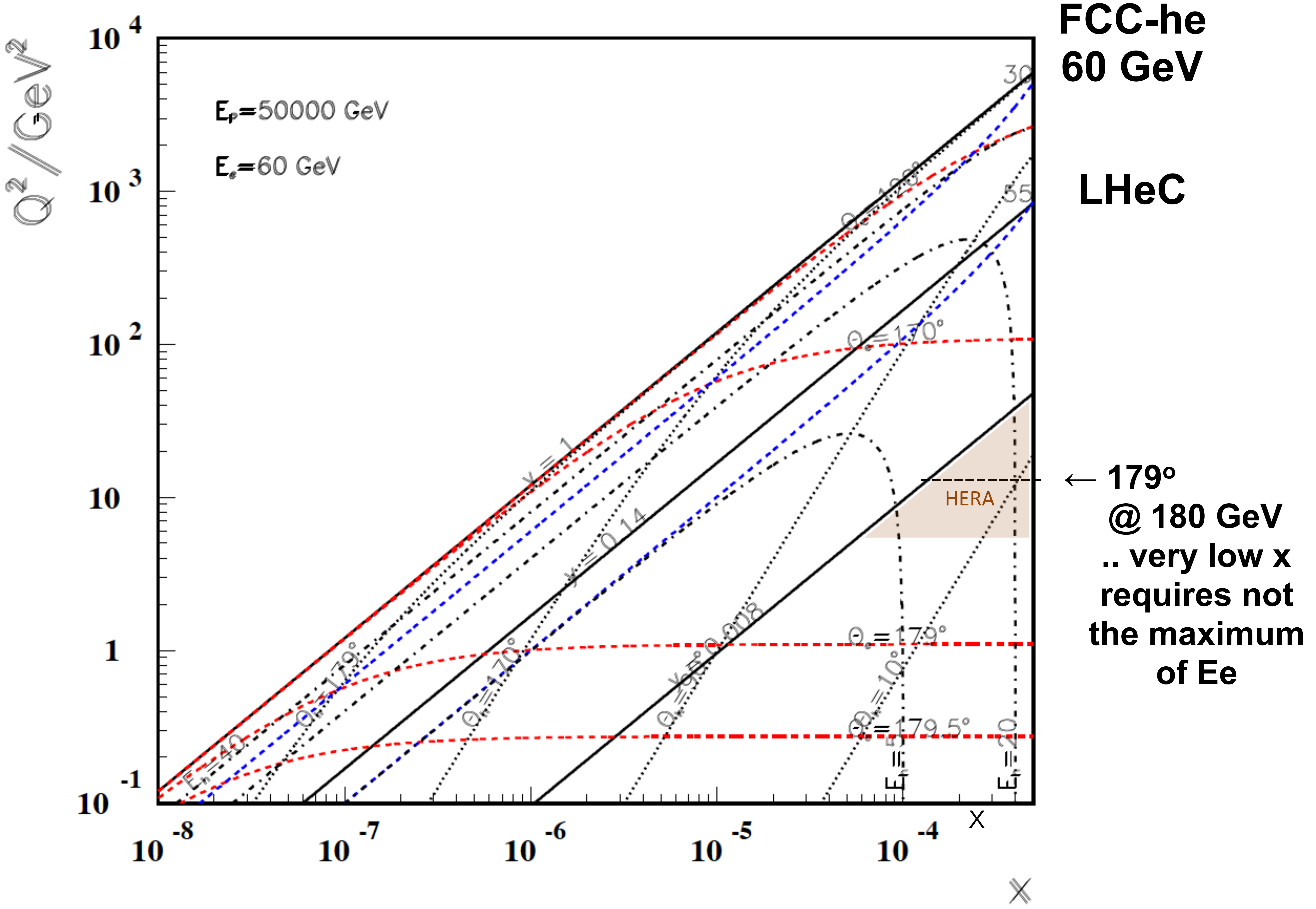
High Q^2

Rutherford backscattering
of dozens of TeV e- energy



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

Low x



Very low x reaches direct range of UHE neutrino physics

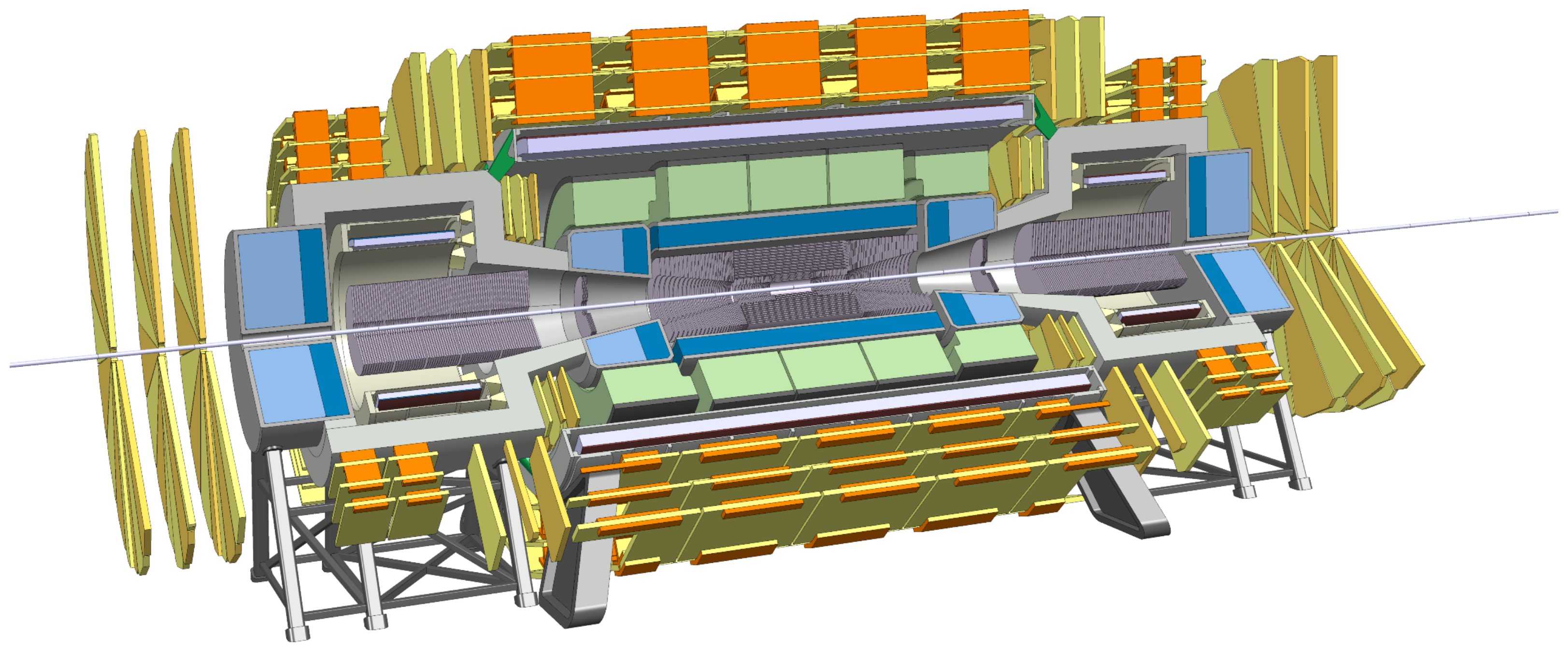
Forward calorimeter containment up to few 10thTeV down to 1° θ
~doubling the calorimeter depth compared to LHeC

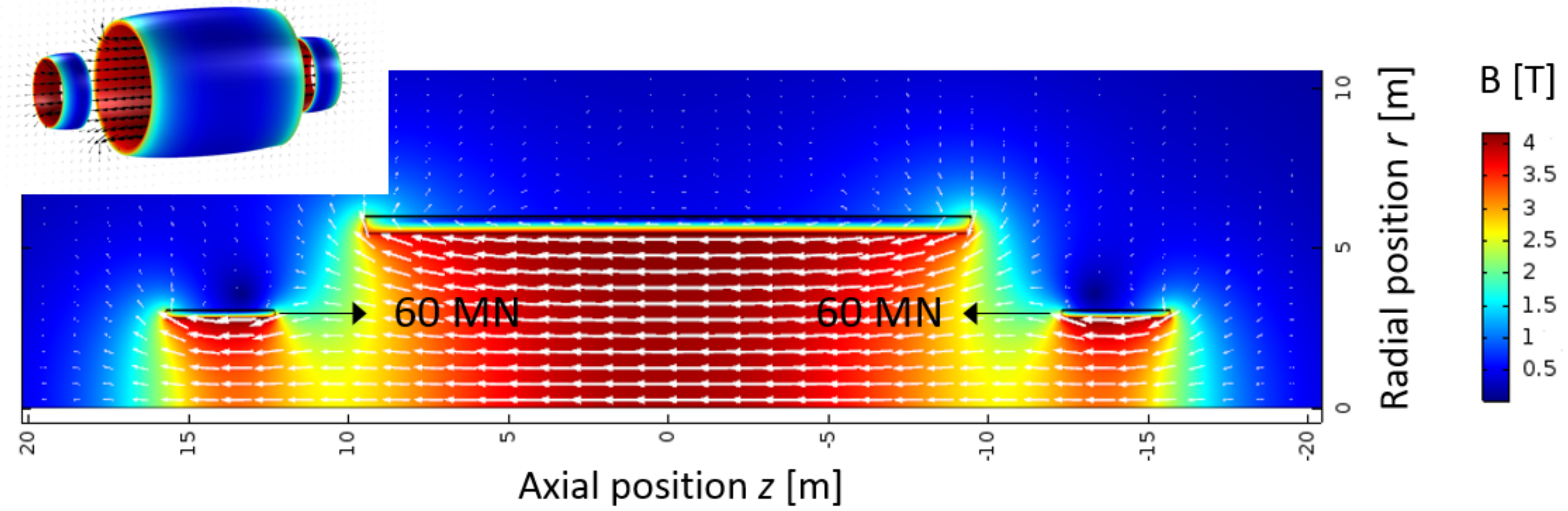
Detector Considerations from the LHeC to the FCC

Pictures W.Riegler on Monday
talk of Herman ten Kate, Matthias Mentink
https://indico.cern.ch/event/556692/contributions/2465157/

- **Interaction region:**
  - **Assume similar interaction region as for LHeC**
    - **FCC-hh bunch spacing? 25 ns no showstopper,**
    - **5 ns, 12.5ns to be looked at → stronger dipole field?**
  - **dipole field across the whole detector**
  - **$e^{\pm}$ syn radiation → elliptical beam-pipe**
- **Detector:**
  - **Higher momenta/energies → Larger BL^2**
  - **Larger transverse calorimetry (up to 12 λ_I in the fwd region)**
  - **Large acceptance over η**
  - **Bunch spacing (25ns → 12.5ns → 5ns)**
  - **Pile-up no problem in ep than for LHC/FCC-hh**
- **Beam Pipe Design**
  - **low X_0, λ_I material (Be), stable, capable for 1° tracks**
  - **allowing low p_T particle measurement**
- **Magnets**
  - **Use the solenoid option as proposed for FCC-hh + balanced conical solenoid.**
  - **Strong field in the fwd/bwd region to allow for tracking over a wide range of η - down 1^0 θ-angle.**
  - **The concept is attractive and could be adjusted.**

New Reference Design FCC-hh

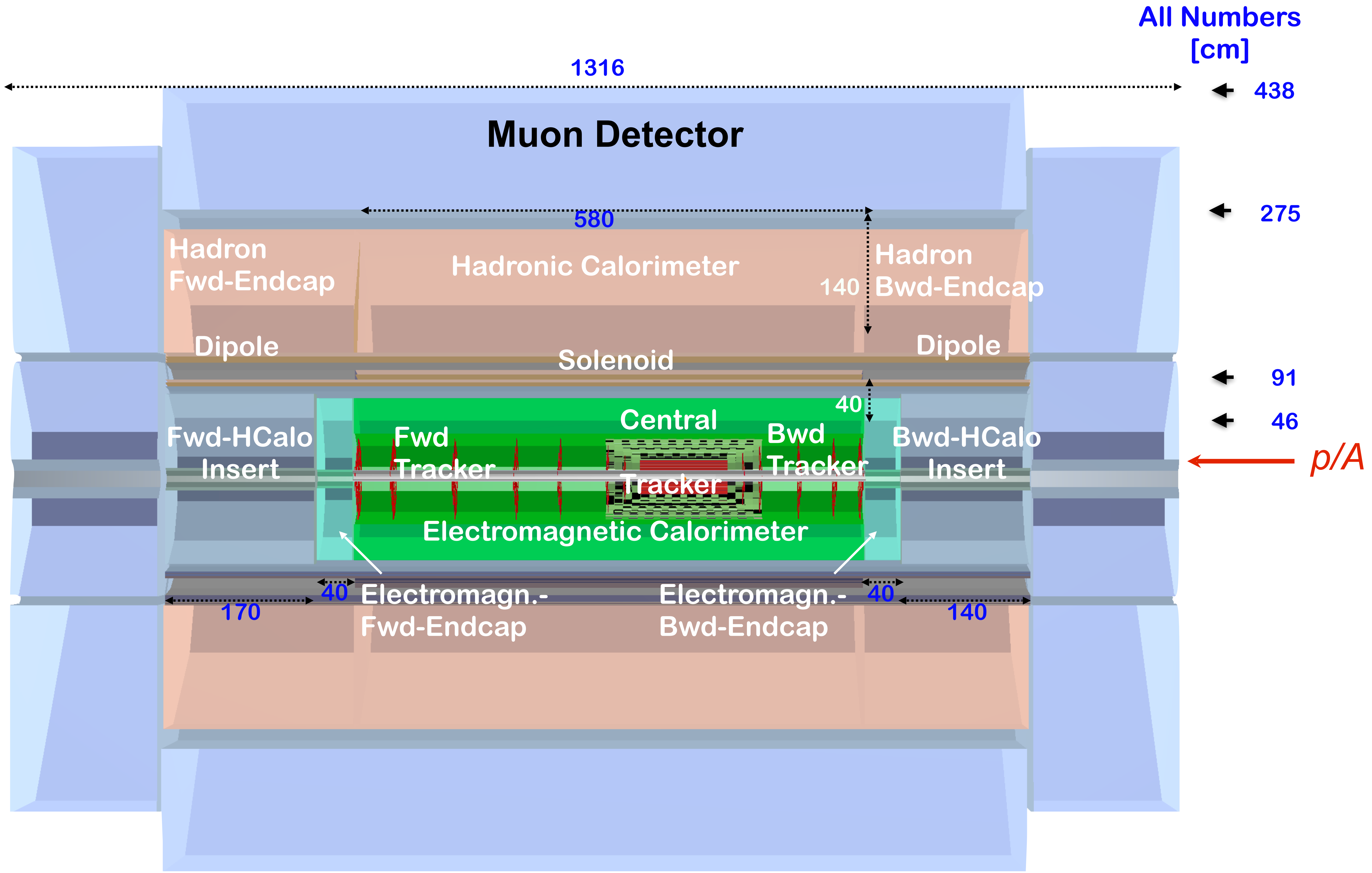




LHeC Detector Basic Layout

Detailed report and study in LHeC CDR (150 pages).
Includes taggers (fwd,bwd)
Basic change for FCC_eh:
extension of forward dimensions by factor log(50/7), backward ~ similar

No studies of very fwd, bwd Taggers for FCC-he yet



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

"On the Relation of the LHeC and the LHC" [arXiv:1211.5102]

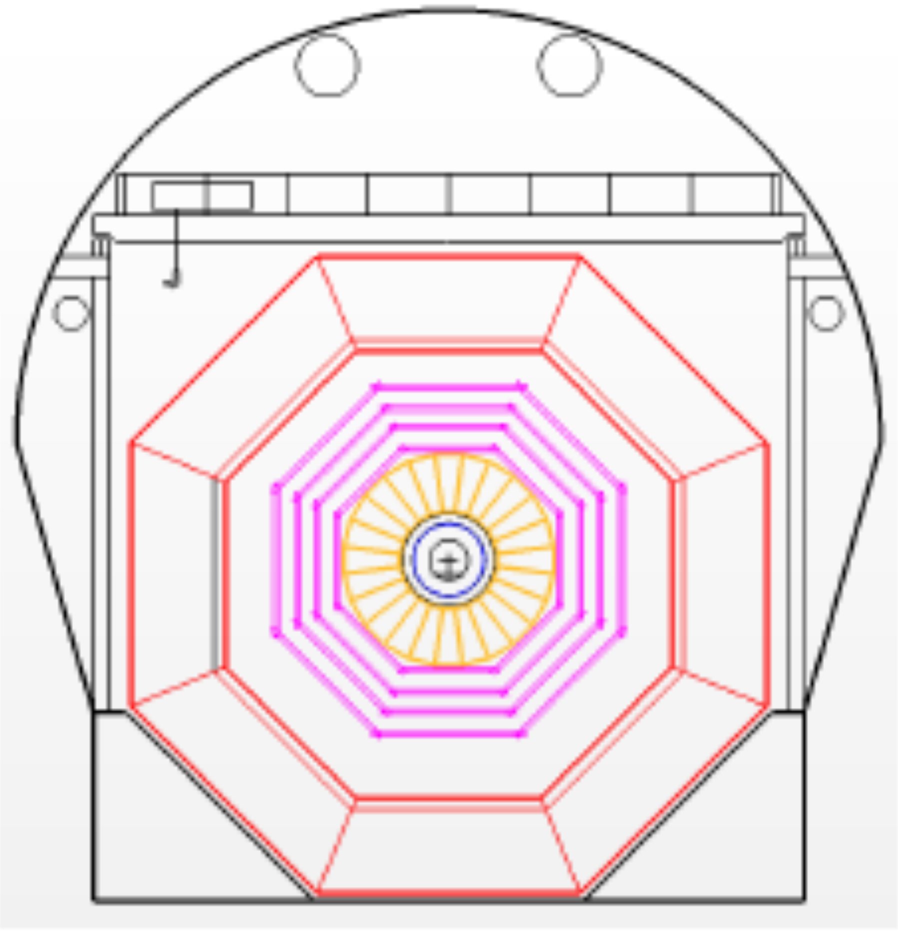
Forward/backward asymmetry in energy deposited and thus in geometry and technology

Present dimensions: LxD = 14x9m^2 [CMS 21x15m^2 , ATLAS 45x25m^2]

Taggers at ~62m (e), 100m (γ,LR), -22.4 (γ,RR), +100m (n), +420m (p)

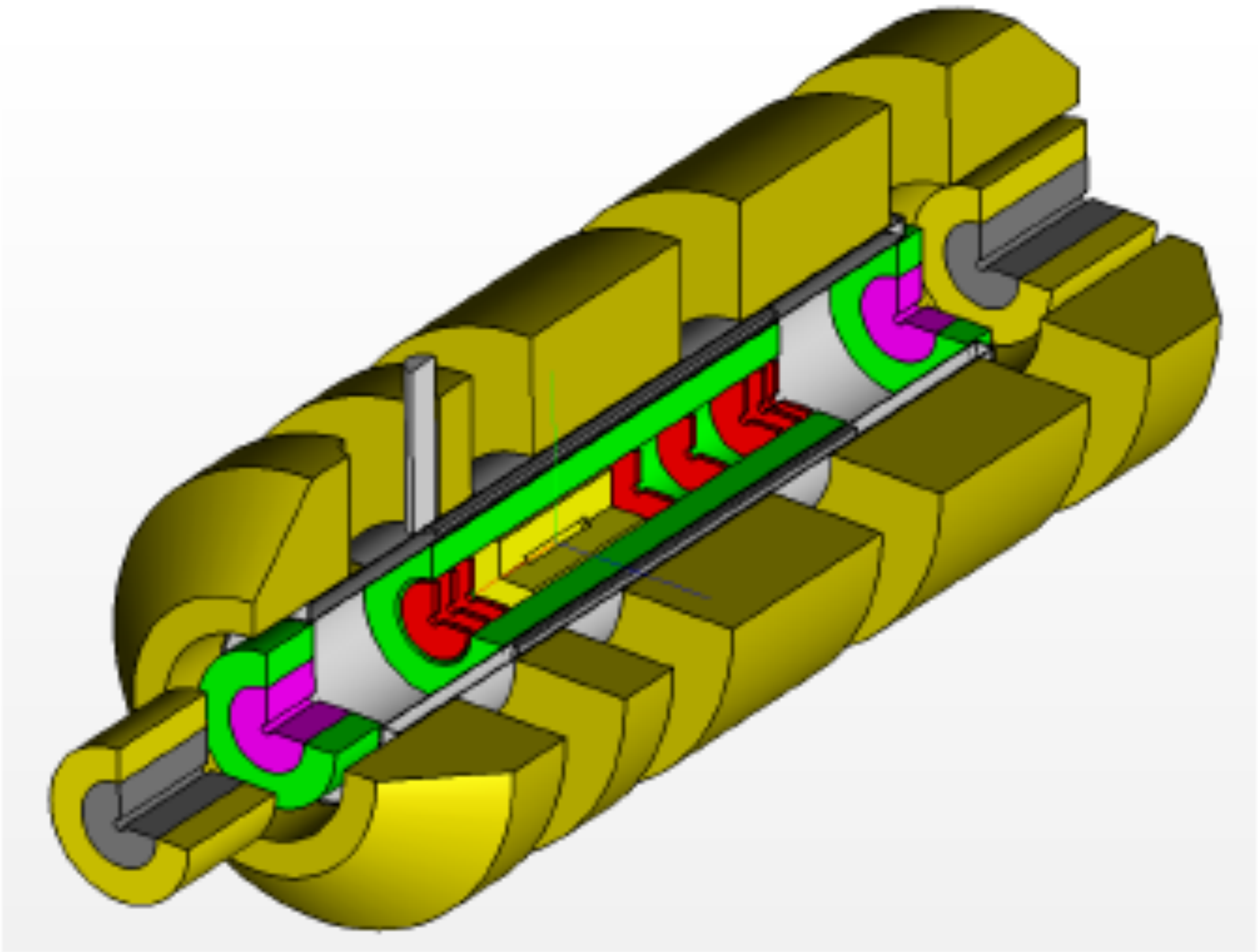
LHeC:
detector installation with removal of current detector on IP2 can be done within 2 years,
which is compatible with typical LHC shutdowns.

For FCC-eh (and HE-LHC) that constraint can be lifted.



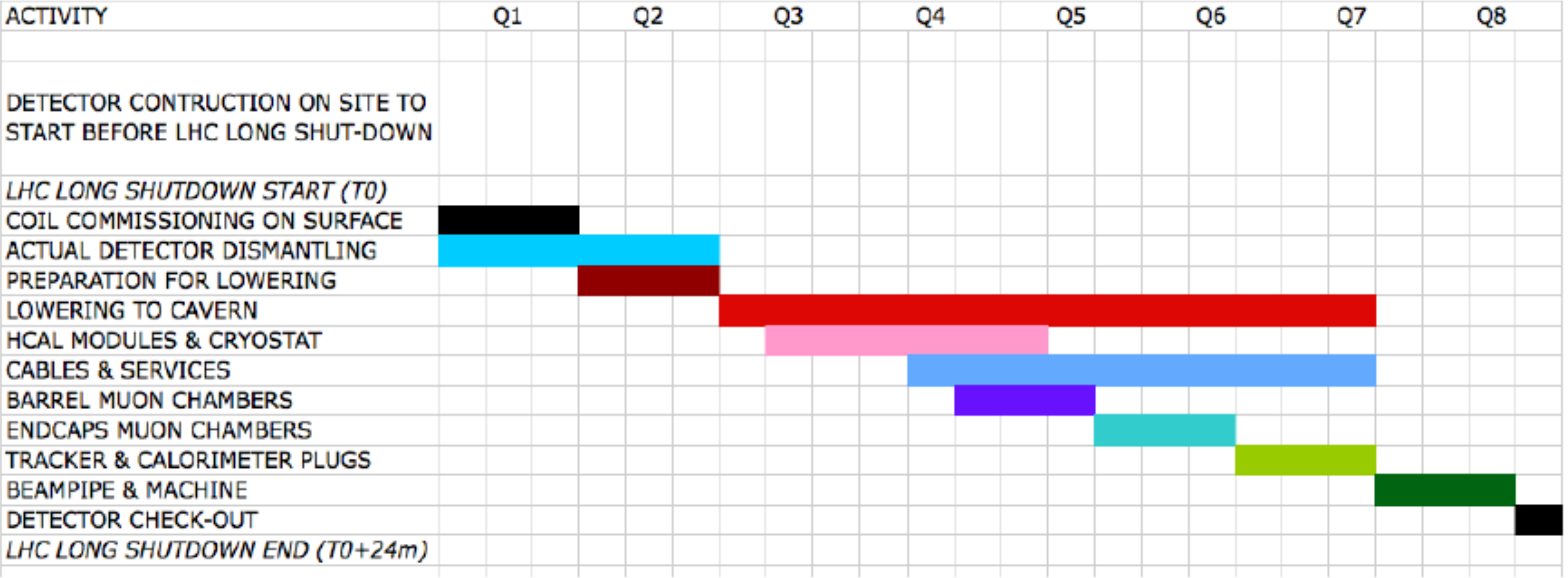
Detector fits in L3 magnet support

Installation Study



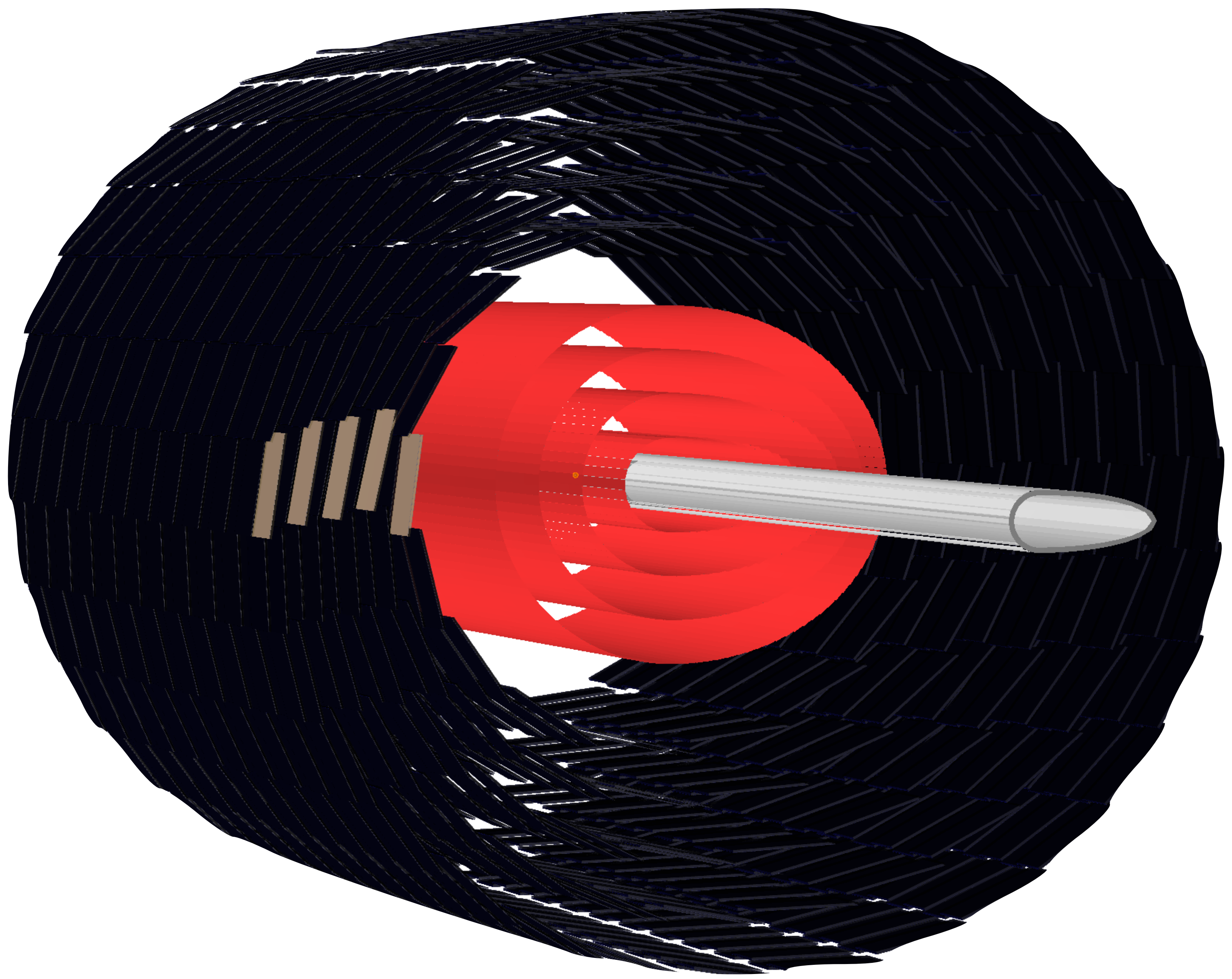
Modular structure

LHeC INSTALLATION SCHEDULE



see talk A. Gaddi
https://indico.cern.ch/event/356714/contributions/844883/attachments/709255/973648/LHeC-Workshop-2015_ag_v6.pdf

Detector Layout - Beampipe & Central Tracker

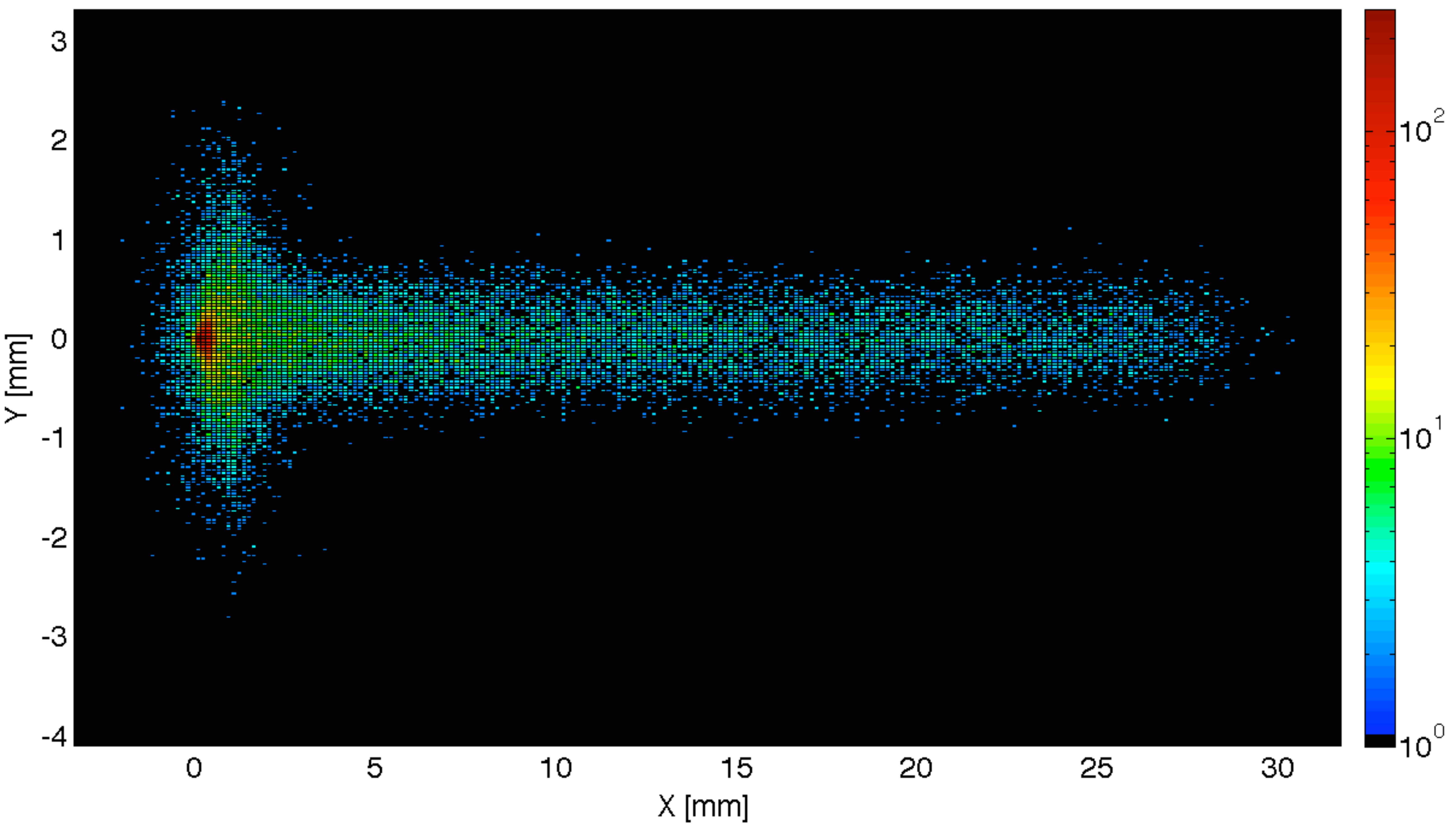


Central Tracker
circular-elliptical beam pipe
4 layers Si-pixel (ALICE+ type)
5 layers Si-strixel

(see Table of Detector Dimensions/Parameters)

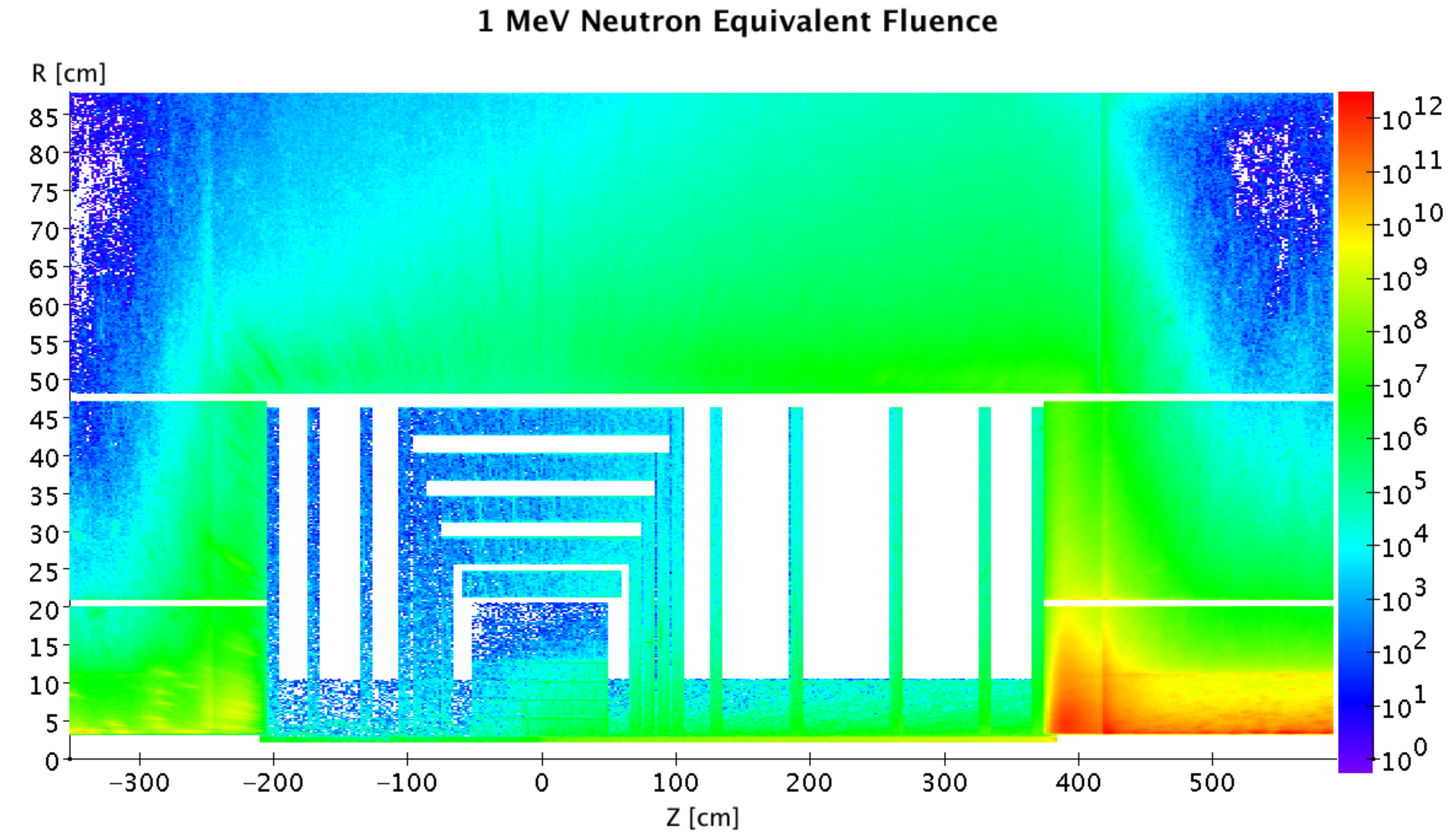
Synchrotron Radiation Fan at IP

Photon Number Density at Z = 0 m



GEANT4 has been used - special treatment enabled

LHeC - Radiation Load - Tracker (prel.)



Central Barrel			
Region	$\Delta Z [cm]$	R_{min} [cm]	Fluence $[\frac{N}{cm^2 yr}]$
CPT1	100	3.1	1.38×10^{10}
CPT2	100	5.6	9.99×10^{9}
CPT3	100	8.1	8.26×10^{9}
CPT4	100	10.6	7.25×10^{9}
CST1	116	21.2	6×10^{9}
CST2	128	25.6	5.66×10^{9}
CST3	148	31.2	5.38×10^{9}
CST4	168	36.7	5.25×10^{9}
CST5	188	42.7	5.16×10^{9}

Central Endcaps			
Region	Z [cm]	ΔR [cm]	Fluence $[\frac{N}{cm^2 yr}]$
CFT1	70	26	8×10^{9}
CFT2	80	31.6	7.42×10^{9}
CFT3	90	37.1	7.08×10^{9}
CFT4	101	43.1	6.93×10^{9}
CBT1	-70	26	2.77×10^{9}
CBT2	-80	31.6	2.48×10^{9}
CBT3	-90	37.1	2.26×10^{9}
CBT4	-101	43.1	2.09×10^{9}

Fwd/Bwd Planes			
Region	Z [cm]	ΔR [cm]	Fluence $[\frac{N}{cm^2 yr}]$
FST1	130	43.1	8.2×10^{9}
FST2	190	43.1	1.14×10^{10}
FST3	265	43.1	1.63×10^{10}
FST4	330	43.1	2.29×10^{10}
FST5	370	43.1	2.75×10^{10}
BST1	-130	43.1	1.96×10^{9}
BST2	-170	43.1	1.91×10^{9}
BST3	-200	43.1	1.99×10^{9}

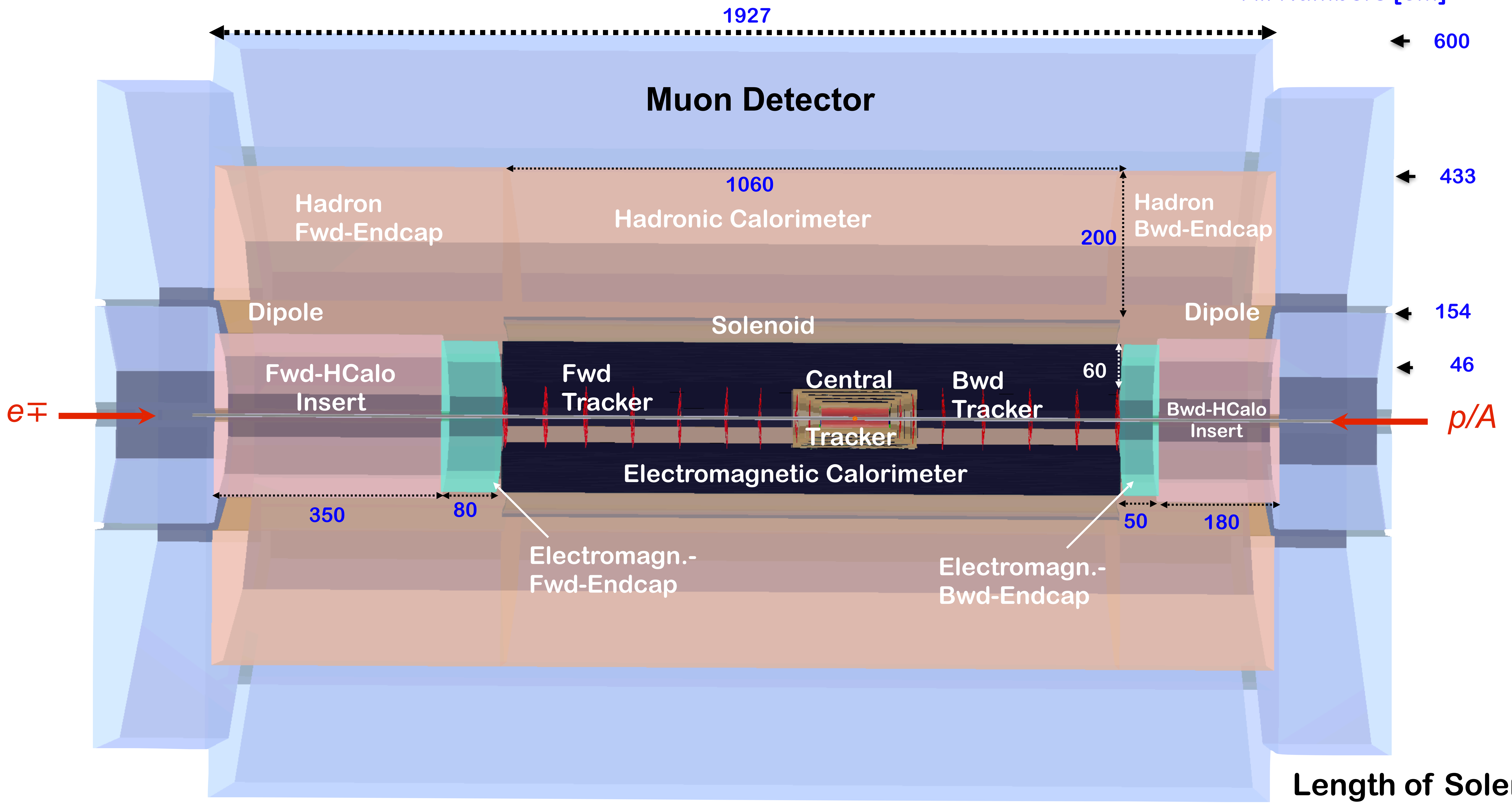
Expected radiation load defined/influenced by:
interaction rate, luminosity, particle rate per angle interval, fluence n_{eq} and ionisation dose.

Impact of radiation on
tracker wheels, calorimeter inserts and the inner tracker-barrel layer.

prel. Geant4-Event-Simulations (Pythia6):
→ no indication for extremely high radiation load in the detectors adjacent to the beam pipe. The expected levels are far below what the LHC experiments have to withstand.

FCC-he Detector Basic Layout

All Numbers [cm]



Length of Solenoid 10m

Based on the LHeC design; figure shows the version using a single solenoid system; Solenoid&Dipoles between Electromagnetic Calorimeter and Hadronic Calorimeter.

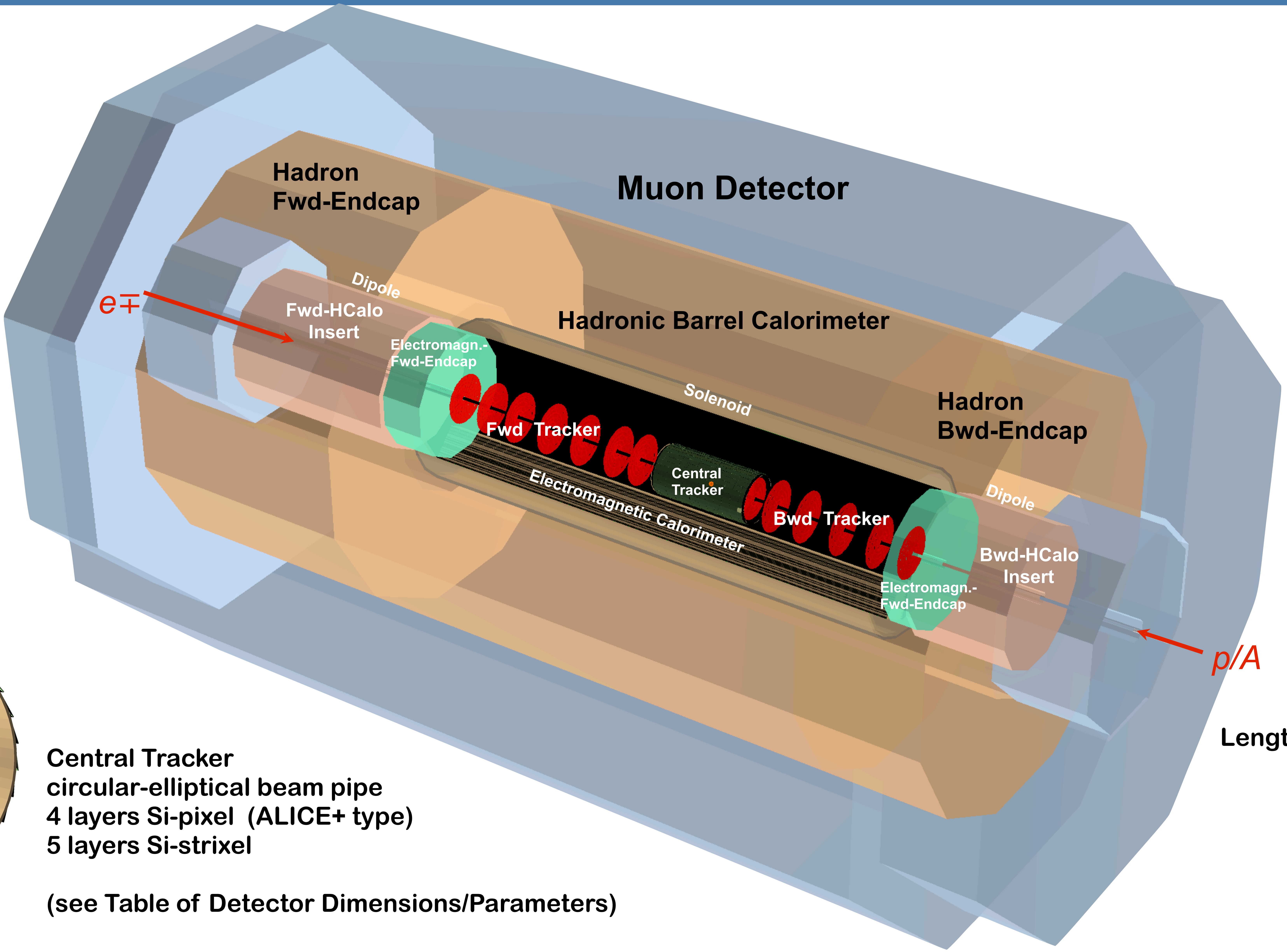
FCC-he Detector Layout - Inner Dipoles and Solenoid

3 beams:

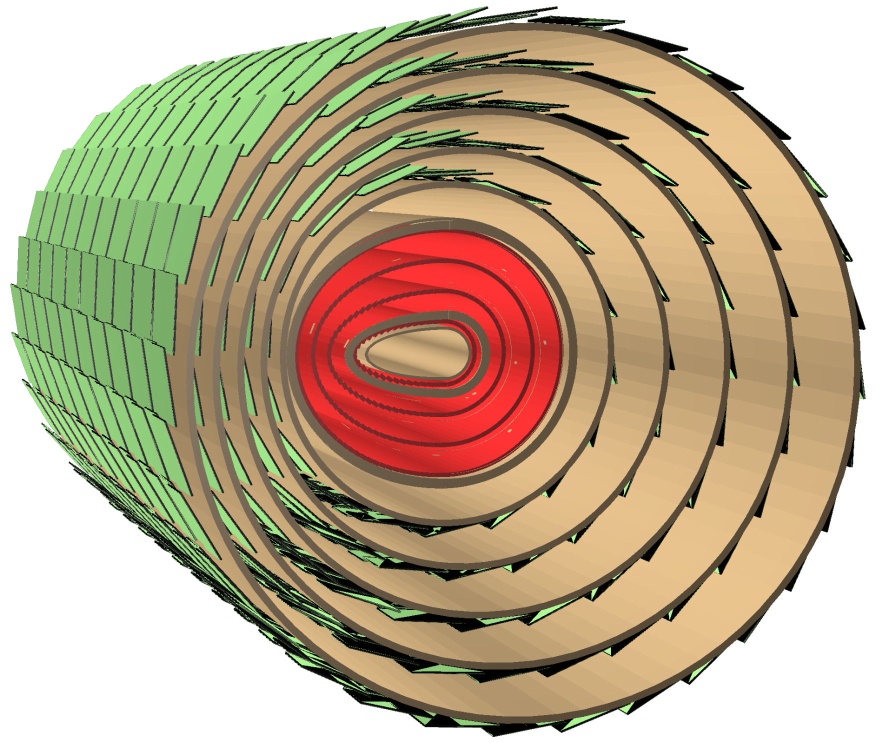
e∓ + proton1 + proton2
(or heavy ions A)

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

0.3 T dipoles (transverse) field
along 2 x 9 m (internal shown only)



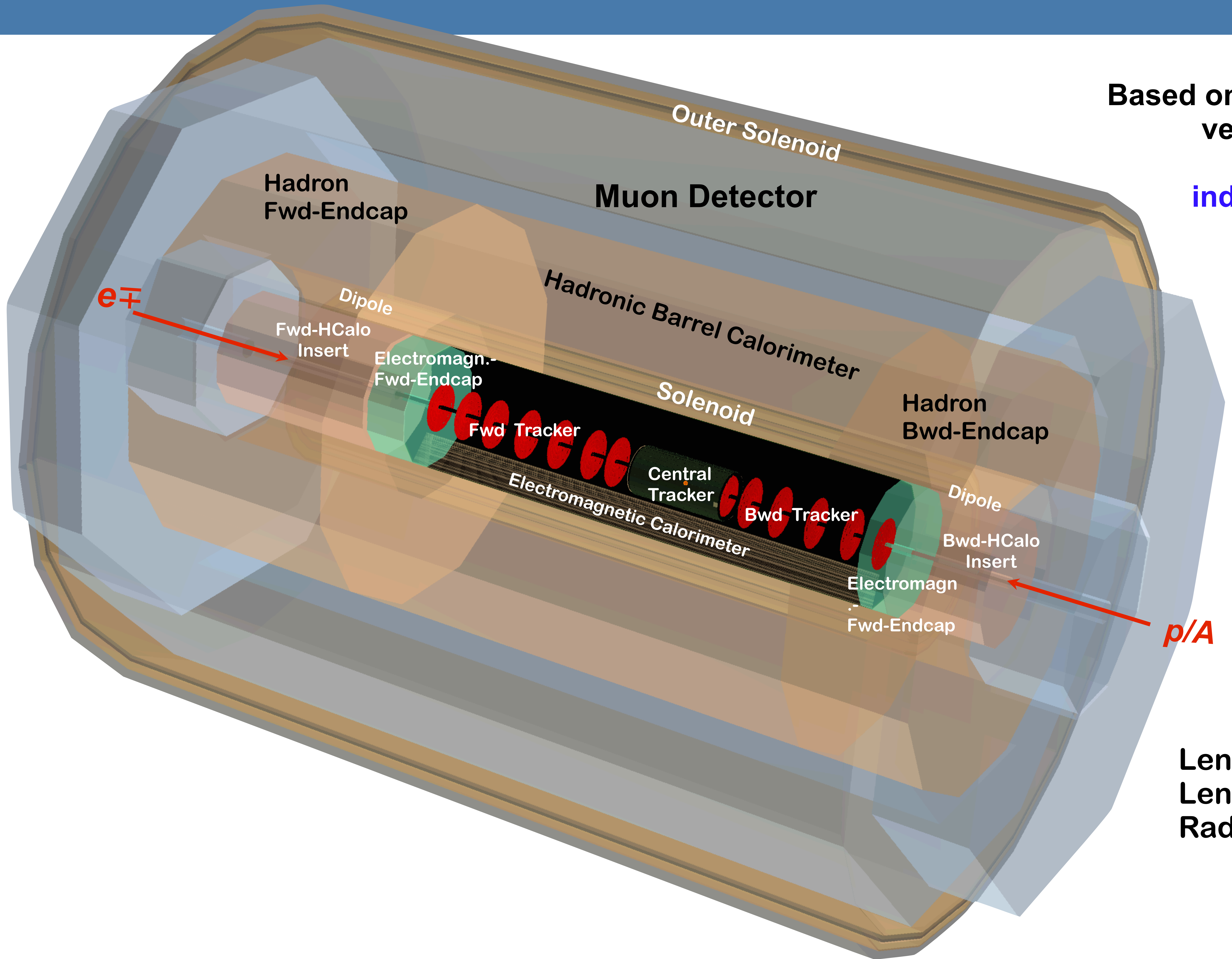
Length of Solenoid ~10m



Central Tracker
circular-elliptical beam pipe
4 layers Si-pixel (ALICE+ type)
5 layers Si-strixel

(see Table of Detector Dimensions/Parameters)

FCC-he Detector Layout - Inner Dipoles and Solenoid + Outer Solenoid



Based on the LHeC design; figure shows the version using a twin solenoid system; Solenoid_2 outside of Muon-Det.: independent momentum measurement - hadrons, min. interacting leptons.

Length of Inner Solenoid ~10m
Length of Outer Solenoid ~19m
Radius " ~6m

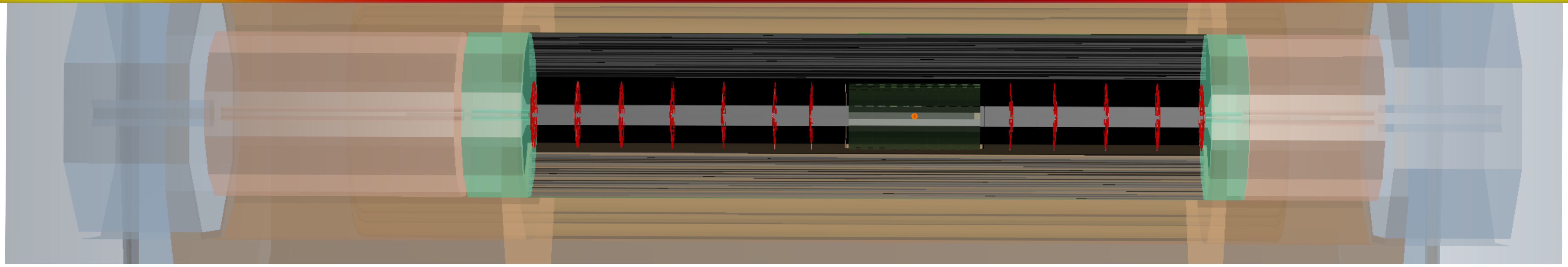
FCC-he Detector + FCC-hh Magnet Concept

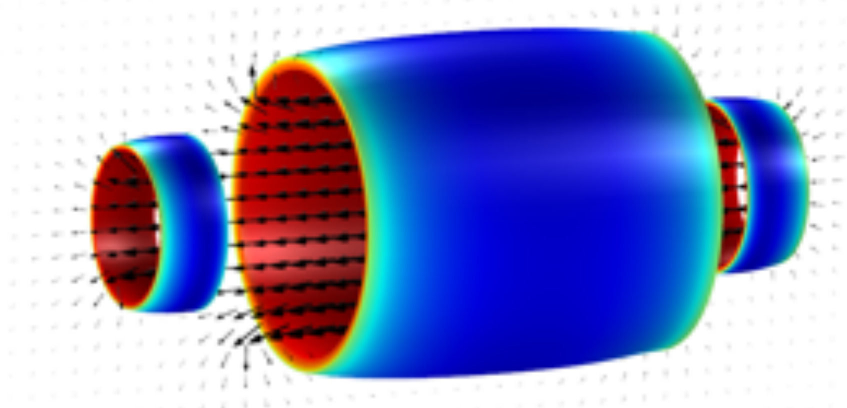
Numbers [m]

FCC-he Detector + FCC-hh Magnet Concept

Numbers [m]

FCC-he Detector + FCC-hh Magnet Concept

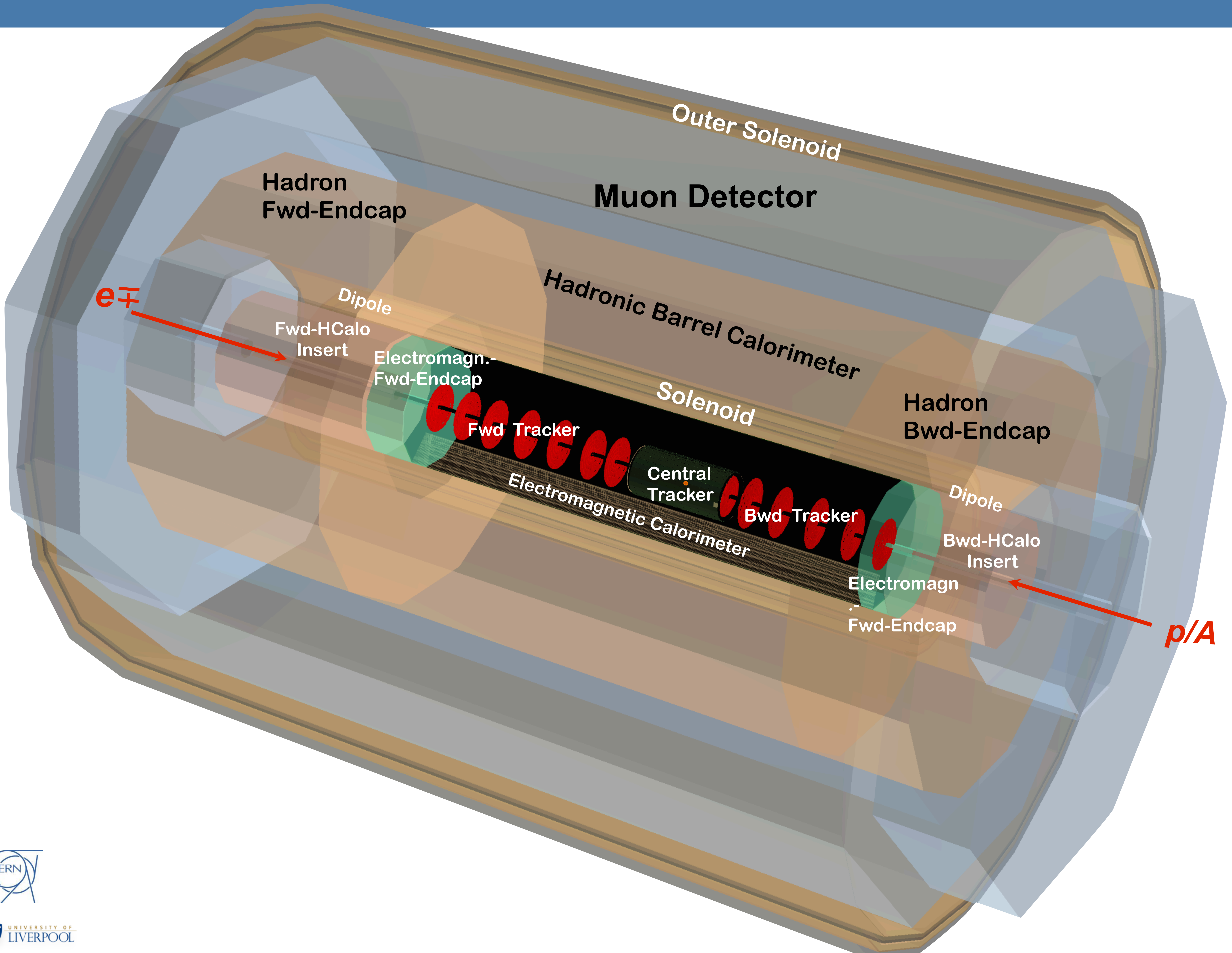




This magnet concept may enlarge the acceptance in η and improve the resolution in fwd/bwd regions - an example for hh-eh possible detector collaboration

Numbers [m]

Detector Concepts for the CDR

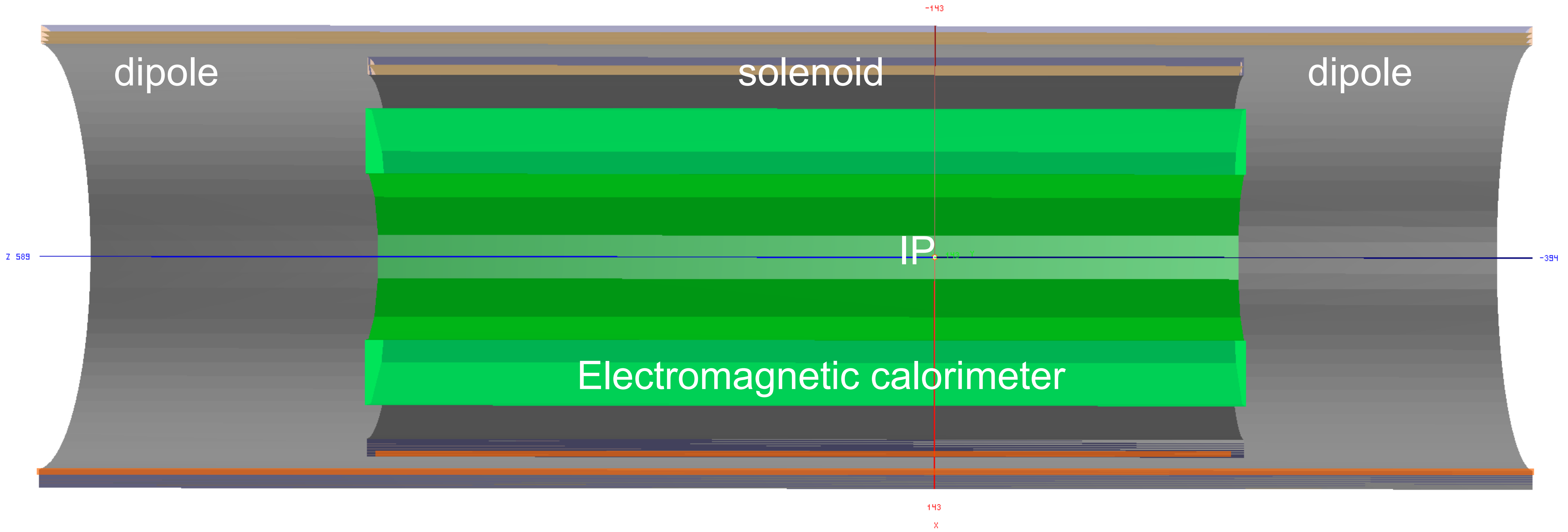


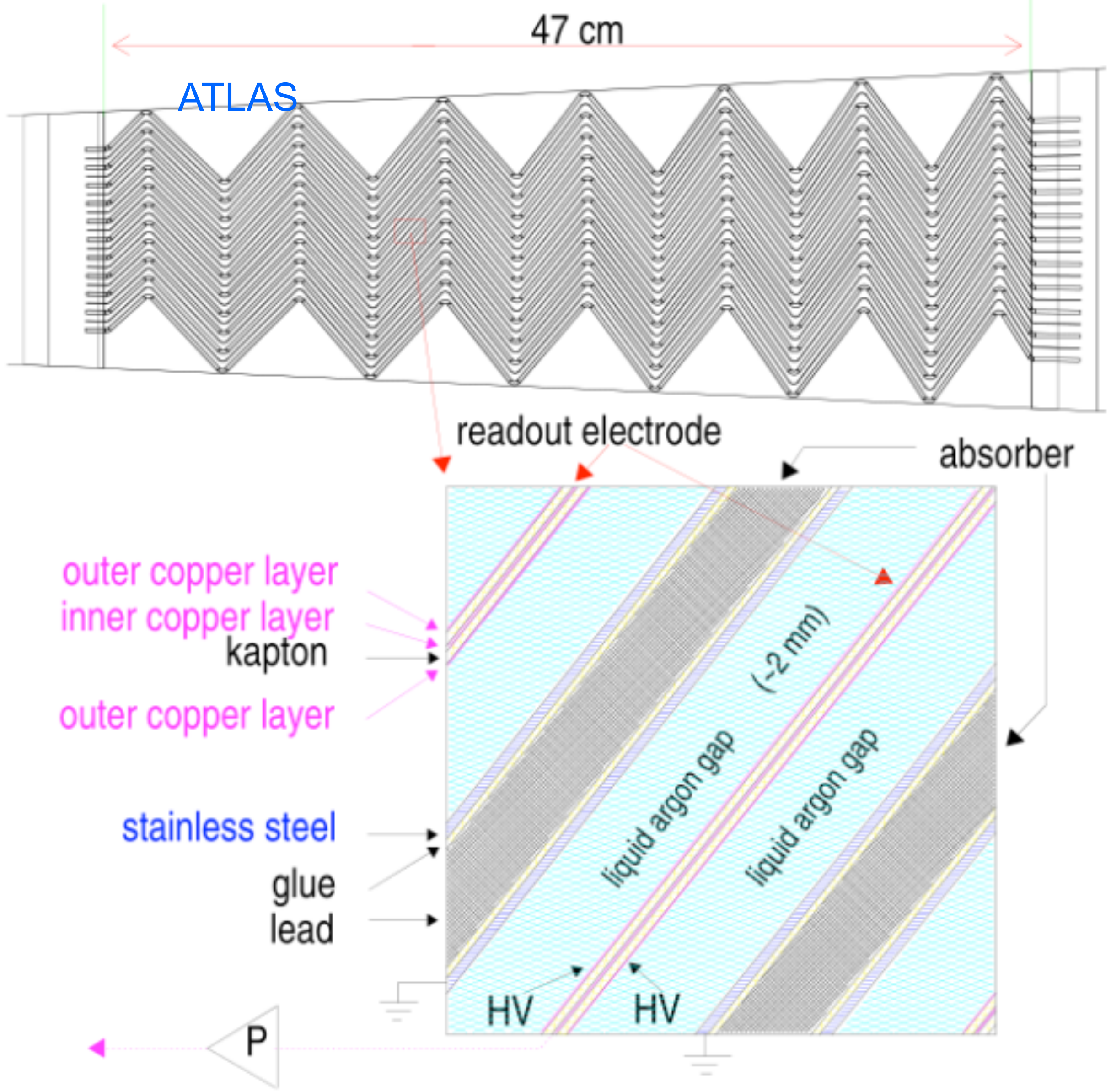
Silicon tracker	
Barrel ECAL	SciPb / LAr
Barrel HCAL	SciFe / LAr
Endcap HCAL/ECAL	SciFe/SciPb / LAr
Forward HCAL/ECAL	SiW/SiW / LAr
Backward HCAL/ECAL	SiFe/SiPb / LAr

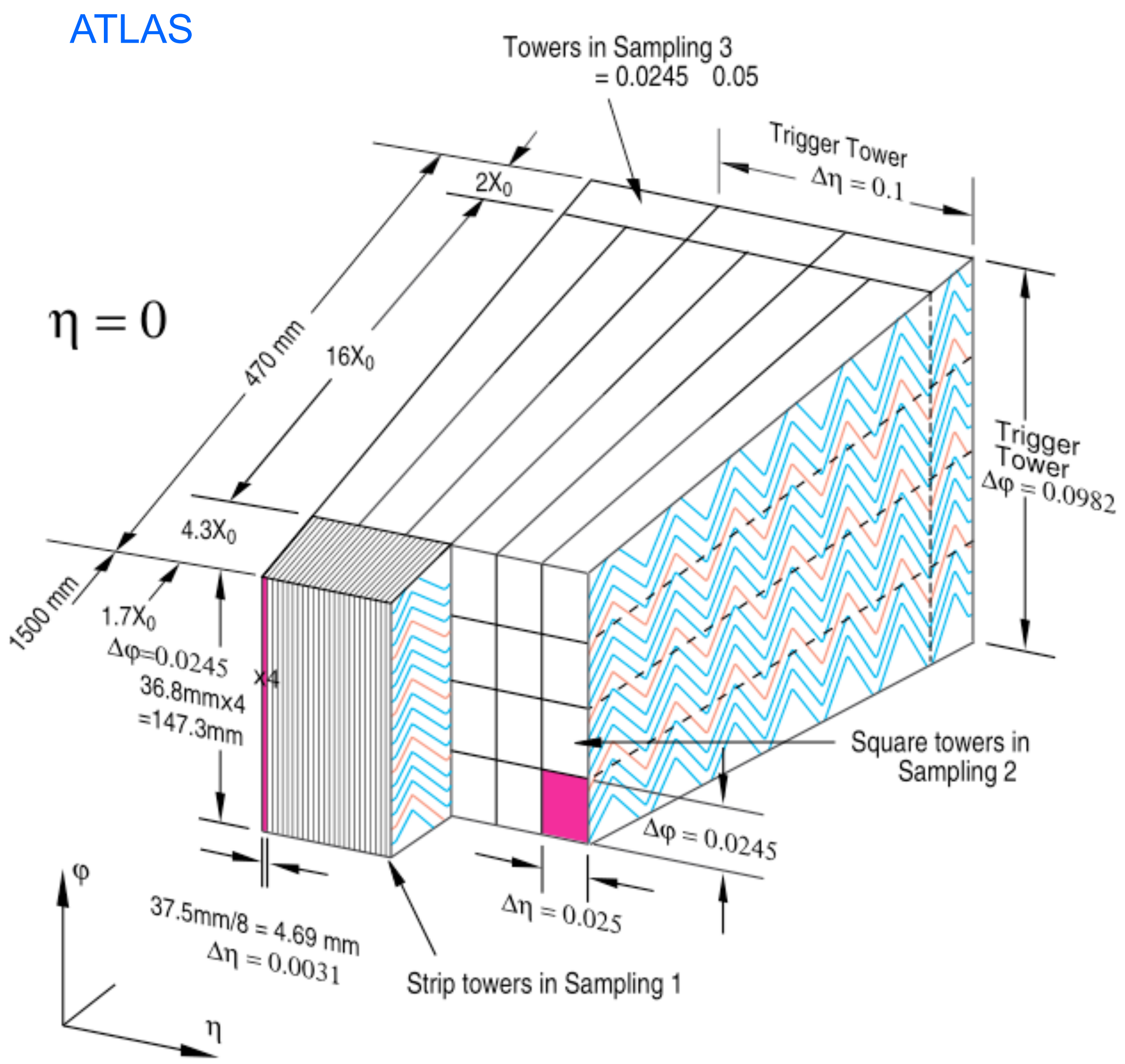
3.5T inner Solenoid ~10m
-1.5T outer Solenoid ~19m
bore " ~6m
OR
4T 10m solenoid +
Fwd/Bwd solenoids (FCC-hh)

dual dipoles ±0.3 T to steer the e-beam

ECAL Barrel







- L-Ar for barrel EMCal – ATLAS (28-30 X_0)
- Same cryostat used for inner solenoid and dipoles
- Simulation results compatible with ATLAS
- 3 different granularity sections longitudinally
- Warm (Pb/Sci) option also investigated $30X_0$ (X_0(Pb)=0.56 cm; 20 layers)

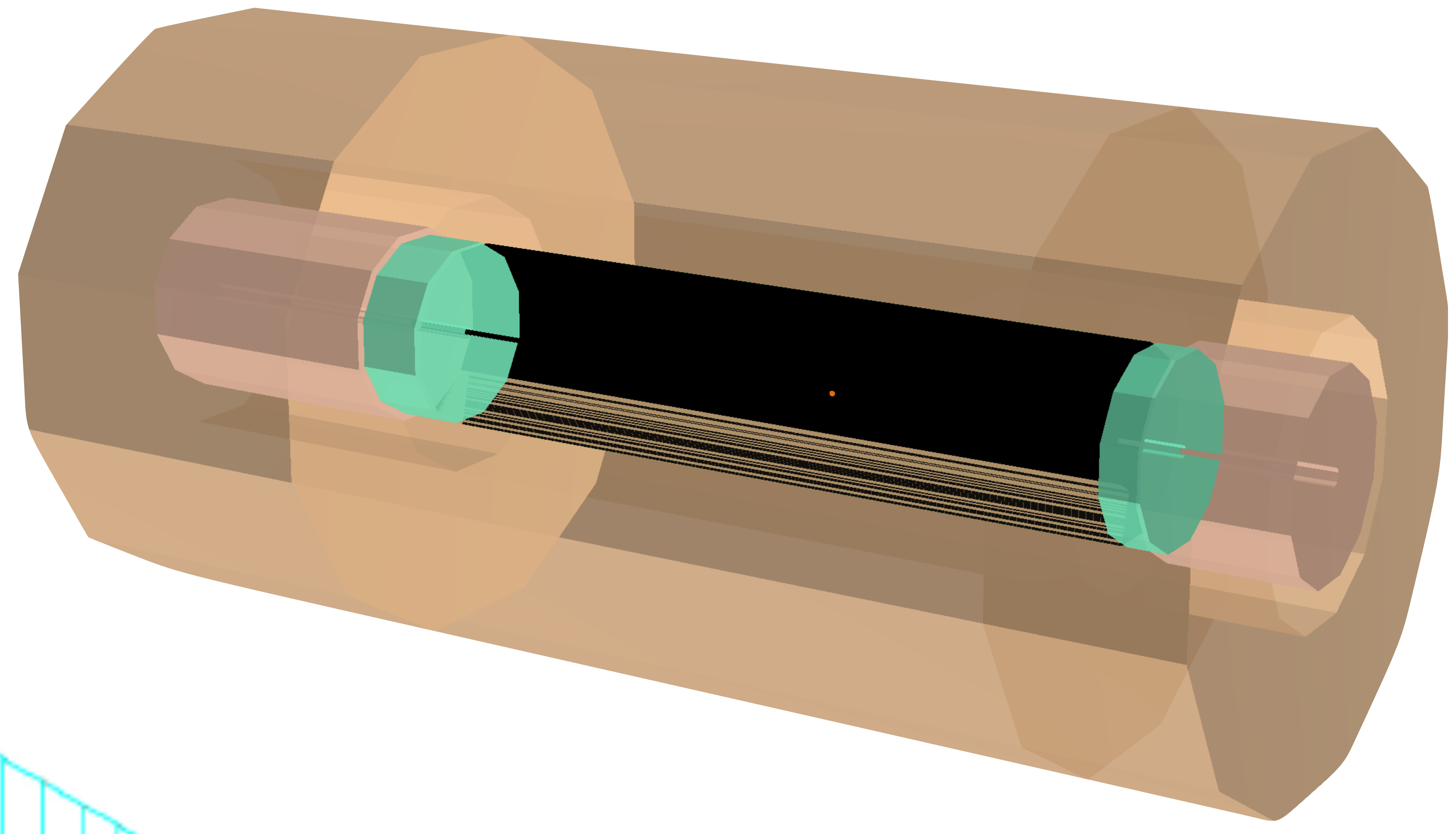
HCAL Barrel

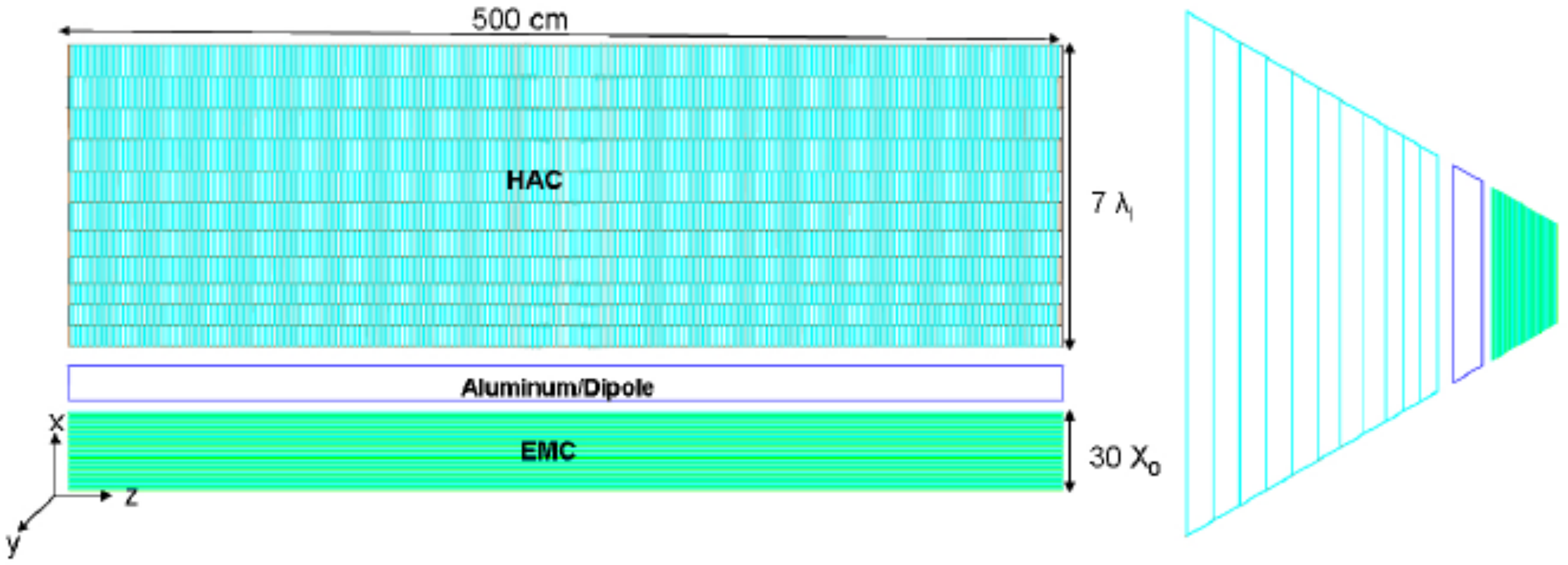
HAC iron absorber (magnet return flux)

Scintillating plates (similar to ATLAS TILE CAL)

Interaction Length: ~7-12 λ_I

Geant4 Simulation done with structure:





30 X_0

FCC-he Detector Basic Elements Layout

Tracker	FST_{pix}	FST_{strix}	CFT_{pix}	CPT_{pix}	CST_{strix}	CBT_{pix}	BST_{strix}	BST_{pix}
#Wheels	7		2	–	–	2	5	
#Rings/Wheel	2_{inner}	3_{outer}	3/4	–	–	3/4	3_{outer}	2_{inner}
#Layers	–	–	–	4	5	–	–	–
$\theta_{min/max}$ $[^0]$	0.5	3.8	3.6	5.1	24/155	176.4	173.1	179.3
$\eta_{max/min}$	5.4	3.4	3.5	±3.1	±1.4	-3.5	-2.8	-5.2
Pitch $[\mu m]$	30 x 30	37.5 x 1750	30 x 30	30 x 30	37.5 x 1750	30 x 30	37.5 x 1750	30 x 30
ReadOut-Pitch $[\mu m]$	30	75	30	30	75	30	75	30
X_0 per layer [%]	0.3	0.8	0.3	0.3	0.8	0.3	0.8	0.3
$Si_{pix/strix}$ $[m^2]$	9.7	13.3	2.8	5.4	33.7	2.8	9.7	6.9
Sum-Si $[m^2]$	84.3 double layers taken into account							

Calo	FHC_{SiW}	FEC_{SiW}	$EMC_{SciPb/LAr}$	HAC_{SciFe}	BEC_{SiPb}	BHC_{SiFe}
$\theta_{min/max}$ $[^0]$	0.3	0.4	5.6/173.4	8.6/167	179.4	179.6
$\eta_{max/min}$	6.0	5.6	3.0/-2.7	2.5/-2.2	-5.3	-5.6
ReadOut-Pitch $[mm]$	20 x 20	10 x 10			20 x 20	20 x 20
Volume $[m^3]$	13.2	3.1	28.8	407	1.98	7.0
Sum-Si $[m^2]$	461					

FCC-he Detector Dimensions/Parameters

Very high energy ≥ 10 TeV in forward direction: resolution terms less relevant vs constant term

e-p allows stringent cross calibration of calorimeters (HERA)

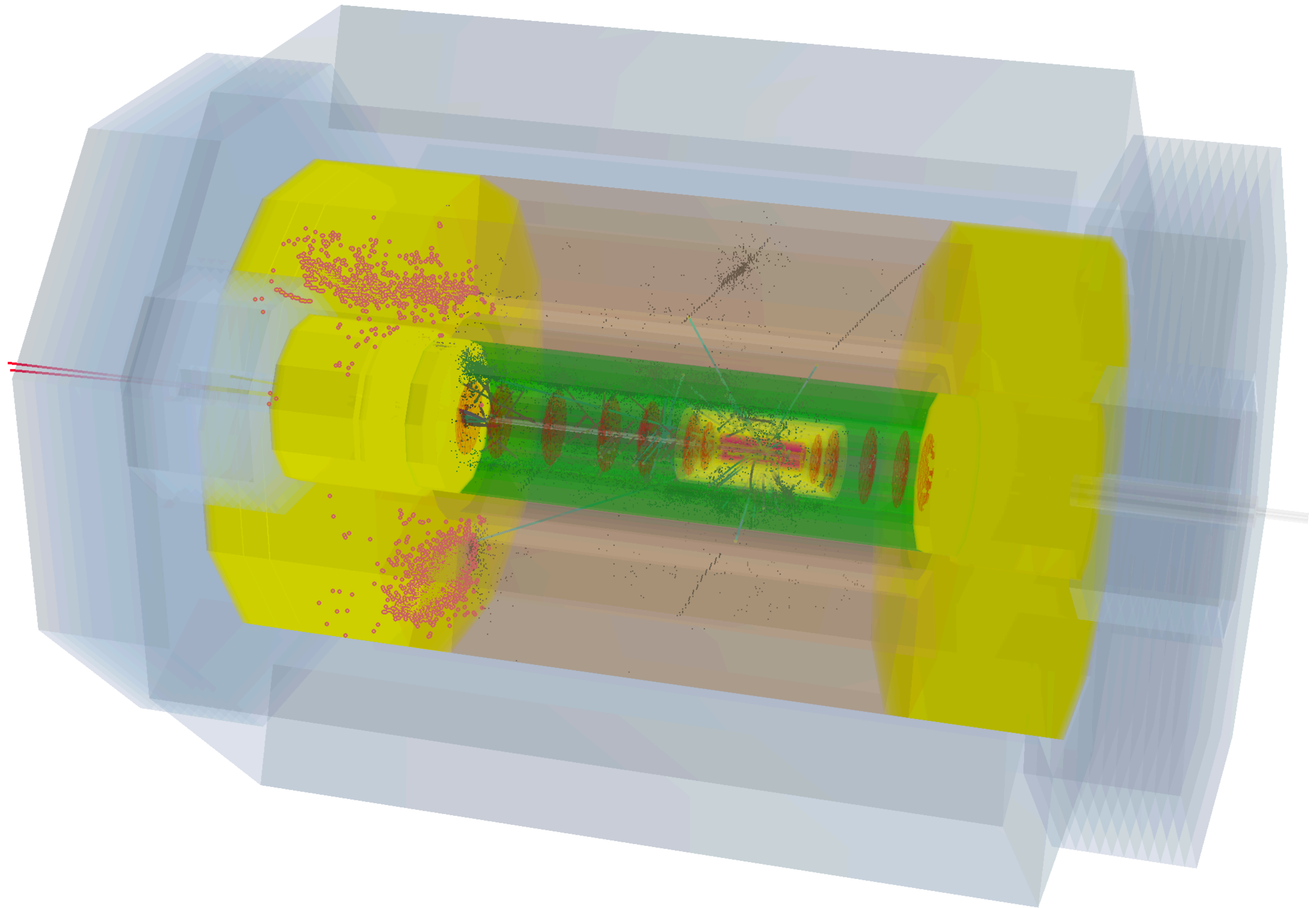
see
On the cross calibration of calorimeters at e-p colliders
J. Blumlein, M. Klein (DESY, Zeuthen). Nov 1992. 9 pp. Published in Nucl.Instrum.Meth. A329 (1993) 112-116 DESY-92-148

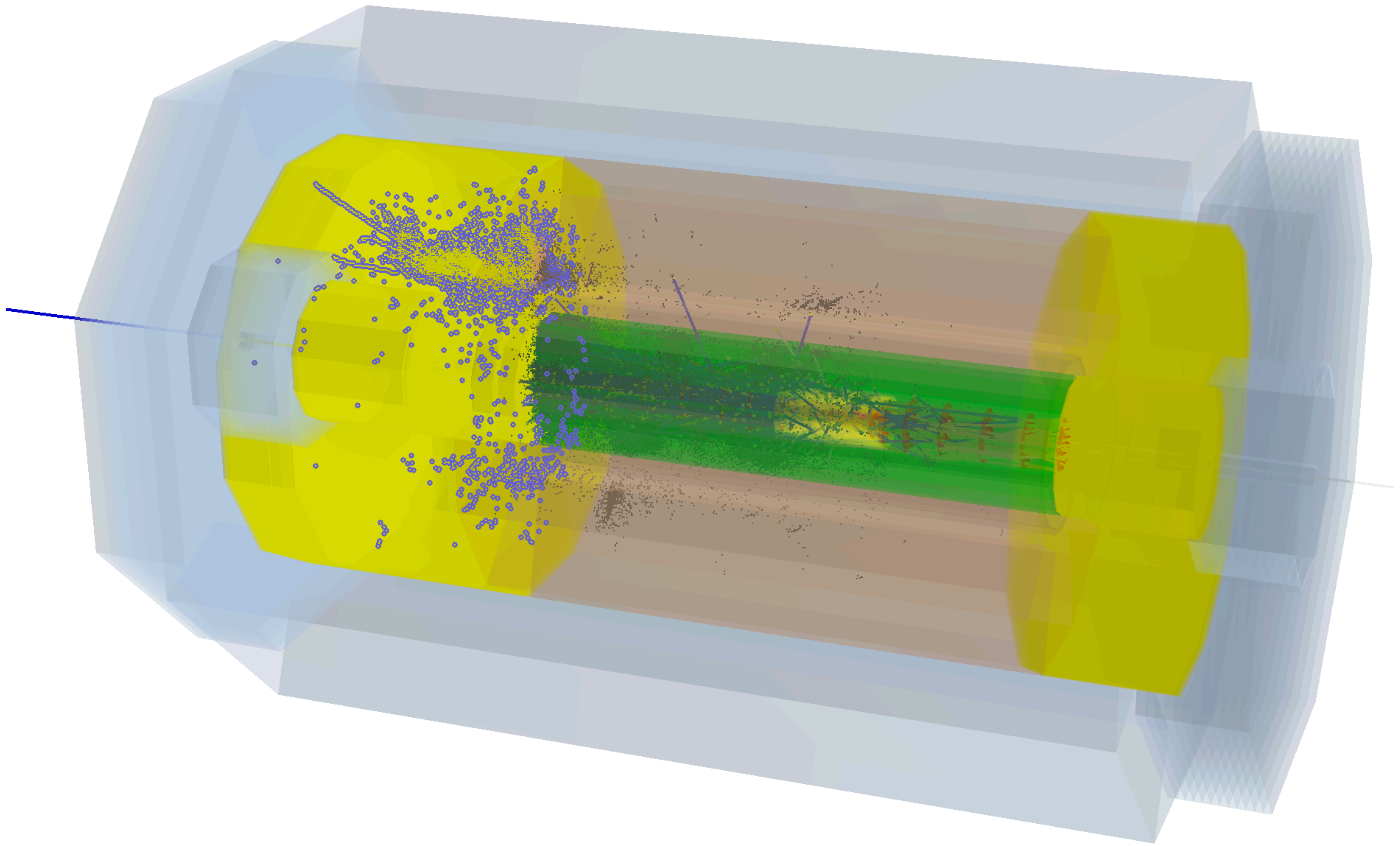
Tracker	FST_{pix}	FST_{strix}	CFT_{pix}	CPT_{pix}	CST_{strix}	CBT_{pix}	BST_{strix}	BST_{pix}
#Wheels	7		2	–	–	2	5	
#Rings/Wheel	2_{inner}	3_{outer}	3/4	–	–	3/4	3_{outer}	2_{inner}
#Layers	–	–	–	4	5	–	–	–
$\theta_{min/max}$ [^{0}]	0.5	3.8	3.6	5.1	24/155	176.4	173.1	179.3
$\eta_{max/min}$	5.4	3.4	3.5	±3.1	±1.4	-3.5	-2.8	-5.2
Pitch [μm]	30 x 30	37.5 x 1750	30 x 30	30 x 30	37.5 x 1750	30 x 30	37.5 x 1750	30 x 30
ReadOut-Pitch [μm]	30	75	30	30	75	30	75	30
pix-σ^{point} [μm]	≤14		≤14	≤14		≤14		≤14
strix-$\sigma^{r-\phi}$ [μm]		~5			~5		~5	
strix-σ^{z} [mm]		~5			~5		~5	
Vertexing-σ	$5\mu m \times 20\mu m/(p \times \sin^{3/2}\theta)$ solenoid and dipole field							
Tracking-σ [μm]	$\Delta(p_T/p_T^2) = 5 \times 10^{-5}$							
X_0 per layer [%]	0.3	0.8	0.3	0.3	0.8	0.3	0.8	0.3
$Si_{pix/strix}$ [m^2]	9.7	13.3	2.8	5.4	33.7	2.8	9.7	6.9
Sum-Si [m^2]	84.3 double layers taken into account							

Calo	FHC_{SiW}	FEC_{SiW}	$EMC_{SciPb/LAr}$	HAC_{SciFe}	BEC_{SiPb}	BHC_{SiFe}
$\theta_{min/max}$ [^{0}]	0.3	0.4	5.6/173.4	8.6/167	179.4	179.6
$\eta_{max/min}$	6.0	5.6	3.0/-2.7	2.5/-2.2	-5.3	-5.6
R/O-Pitch [mm]	20 x 20	10 x 10			20 x 20	20 x 20
$\sigma_E/E \approx$	$0.4/\sqrt{E}+0.02$	$0.1/\sqrt{E}+0.01$	$0.09/\sqrt{E}+0.02$	$0.4/\sqrt{E}+0.02$	$0.1/\sqrt{E}+0.01$	$0.4/\sqrt{E}+0.04$
E-Flow	$\sigma_{E_{jet}}/E_{jet} = 0.03$ (at lower energies $25\%/\sqrt{E}$; sampling ~55 ; $\sigma_{jet} \sim 3\%$)					
Λ_I / X_0	$\Lambda_I \geq 12$	$X_0 \geq 28$	$X_0 \geq 28$	$\Lambda_I \geq 12$	$X_0 \geq 25$	$\Lambda_I \geq 10$
Volume [m^3]	13.2	3.1	28.8	407	1.98	7.0
Sum-Si [m^2]	461					

Double Higgs in LHeC & FCC-he Detector

courtesy U. Klein - Generator input files for simulation





Software DD4Hep/DDG4 based Detector Design / Simulation / Reconstruction Environment
Software for LHeC and FCC detector - DD4hep xml-description adopted only
All calorimeters here set to "warm" option (no LAr)

SW Transfer DD4hep/DDG4 to FCCSW

DD4hep/DDG4 - driven by ILC/CLIC based developers - pre-release software

- **LCIO event data model (EDM)**
- **LCIO - connecting all modules in DD4hep/DDG4**
- **Generator data import into the framework - root, stdhep- and hepmc2-file formats**

- **Python, C++ int./ext.**
  - **LHeC/FCC detector geometry (being optimised), material description, R/O description as needed, segmentations and surfaces - ingredients for reconstruction**
  - **DDEve - event display tool for quality judgment and control …**

Switch DD4hep/DDG4 framework to FCCSW - "speaking the same language"
In progress: xml-descriptions - naming conventions; factory module rewriting

- **Common efforts to be organised, e.g. forward region calorimetry - dense jets of very high energy**
- **ALICE$^+$ tracker: lightweight, faster R/O (but low power) - cooling, ….**
- **Collaboration with experts of other experiments**
- **Hardware optimisation according to latest R&D (HL-LHC …)**

Remarks

Based on HERA, LHC, ILC R&D there exist clear concepts for an eh detector which will be fun to work on.

Experimental demands are lighter than for pp - reduced radiation level,
no pileup concern and a cleaner final state

Redundant DIS kinematics allows cross calibration & very high precision, such as 0.1% electron energy scale calibration.

Modern technology is being developed in HEP, enabling high precision tracking and high energy, O(10) TeV, forward particle and jet reconstruction also in ep. R&D for even higher energies ongoing.

Specific eh demands are the 3-beam IR for synchronous ep and pp operation and the need to bend the e beam for head-on collision with the p beam.

The Higgs and top studies pose a higher demand on the fwd acceptance and spatial and energy jet resolutions which leads the current developments beyond the 2012 LHeC CDR.
After the Higgs discovery, LHeC + FCC-he designs upgraded to $O(10^{34})$ luminosity
→ ep precision Higgs facilities (see talk by U.Klein, next session)

FCC-he Detector CDR - Guideline

FCC-he: utilize the LHeC design study to describe baseline ep/A option.

- emphasis: multi TeV physics; IR and detector; synchronous ep-pp operation.
- open to other configurations and new physics developments
- caveats:
  - interaction region not yet well defined
    - need specifications/simulations to allow for detector concept / design
    - optics, beam-pipe, B Fields, masks, synchrotron radiation estimations

- practical approach
  - start from LHeC CDR design
  - adapt existing detector (structures, resolutions) to larger beam energies (larger c.m.s. energy, larger forward boost, wider kinematic space) and the physics reach and scope
  - final choice of technology considered for CDR, consultations with FCC-hh (and ECFA detector panel)

- aim at an update of the CDR (LHeC+ FCC-he) by 2018
  - establish interaction region/ machine detector interface
  - focus on Software simulations
  - key aspect: enlarge person power base and synergy with hh+ee detector studies

Backup

LHeC/FCC-eh workshop 2017

CERN, September 11-13

https://indico.cern.ch/event/639067/

http://lhec.web.cern.ch/

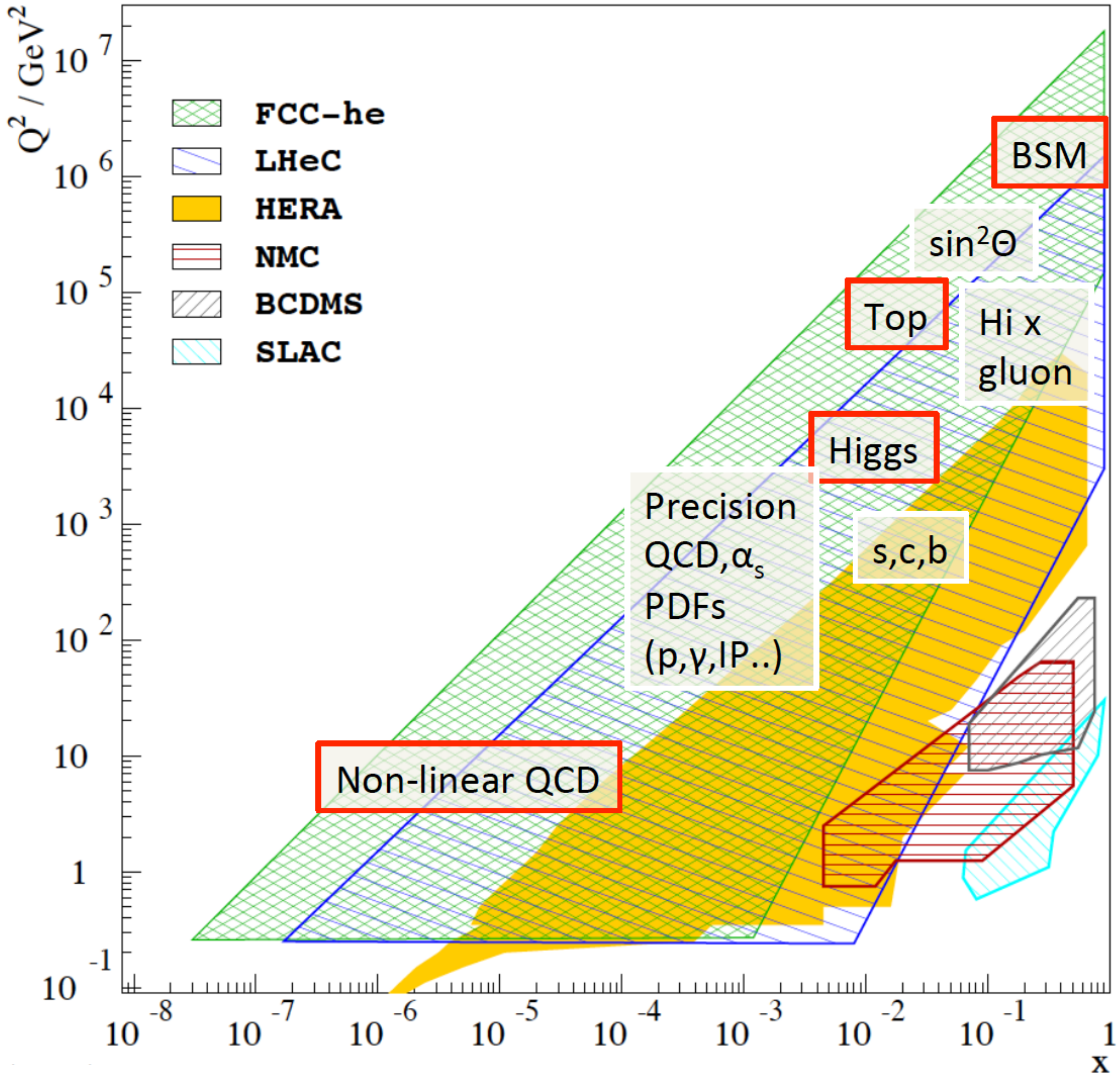
Supported in part by the European Commission under the HORIZON2020 Integrating Activity project ARIES, grant agreement 730871.

2017 workshop discusses the **LHeC/HE-LHeC/FCC-eh physics, accelerator, test facility and detector developments**, in view of the documents to be prepared on the LHeC (“LHeC Book”) and the FCC-eh (FCC CDR), which will be input to the deliberations of the forthcoming European and global strategy debates

see talk F. Zimmermann:
https://indico.cern.ch/event/556692/contributions/2483407/

Nestor Armesto, Oliver Brüning, Max Klein, Herwig Schopper, Achille Stocchi and Colleagues, with Celine Le Bon

Summary of ep Physics



see talks at this FCC week

M. Klein https://indico.cern.ch/event/556692/contributions/2483419/

D,Britzger https://indico.cern.ch/event/556692/contributions/2510777/

U.Klein https://indico.cern.ch/event/556692/contributions/2510778/

O.Cakir https://indico.cern.ch/event/556692/contributions/2510779/

K.Wang https://indico.cern.ch/event/556692/contributions/2510782/

ep/eA Luminosities

Nominal case: 60 GeV ERL electron beam against the hadron beams.

e-p (as of March 2016):

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	15	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.9	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.2	1
ϵ_p [μm]	3.7	2	2	2.2
electrons per bunch [10^9]	1	2.3	2.3	2.3
electron current [mA]	6.4	15	15	15
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
luminosity [10^{33}cm^{-2}s^{-1}]	1.3	10.1	15.1	9.2

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017, "A Baseline for the FCC-he"
Oliver Brüning, John Jowett, Max Klein, Dario Pellegrini, Daniel Schulte, Frank Zimmermann

LHeC e-Pb:

- N_{Pb}=7×10^7/bunch (2012 values) ⇒ ~0.1 fb^{-1}/month
  - L_{eN} = 9 x 10^{31} cm^{-2} s^{-1} (Nominal Pb) (Pb numbers ~ 3 times higher with updated Pb parameters)
  - L_{eN} = 1.6 x 10^{32} cm^{-2} s^{-1} (Ultimate Pb)
  - L_{eD} = 3 x 10^{31} cm^{-2} s^{-1} (eD)

FCC-he:

- Crude estimates: (N_{Pb}=2×10^8/bunch - 2016 values) and rescaling hadron parameters only ➔ L_{eN}=3×10^{33} cm^{-2}s^{-1} ~4 fb^{-1} /month (J. Jowett).

From LHeC to FCC

Beam Energies:
- 7 TeV p vs 60 GeV $e^{\pm}$ (LHeC(ERL))
- 50 TeV p vs 60 GeV $e^{\pm}$ (FCC-h vs LHeC(ERL))
- 50 TeV p vs 50-175 GeV $e^{\pm}$ (FCC-h vs FCC-e)

Data Taking:
- Concurrent running with FCC-hh (pp)
- i.e. 3 beams interaction region:
  $e^{\pm}$p plus counter-rotating spectator p beam

Bunch Spacing:
- LHeC: 25 ns (LHC) bunch spacing
- FCC-hh: 25 ns (5 ns?)
  - 25 ns: similar constraints (electron head-on steering)
  - 5 ns: problematic for parasitic interactions (higher B field required)

Instantaneous Luminosity:
- LHeC: up to 10^{34} cm^{-2}s^{-1} (i.e pileup ~ 0.2)
- FCC-he: O(10^{34}) cm^{-2}s^{-1} (i.e. max pileup ~1)

FCC-hh collider parameters — **FCC Study Status and Plans** Michael Benedikt

parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.12	1.12	0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.20	0.55
normalized emittance [μm]	2.2 (0.4)		2.5 (0.5)	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	25	5	1
events/bunch crossing	170	1k (200)	~800 (160)	135	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

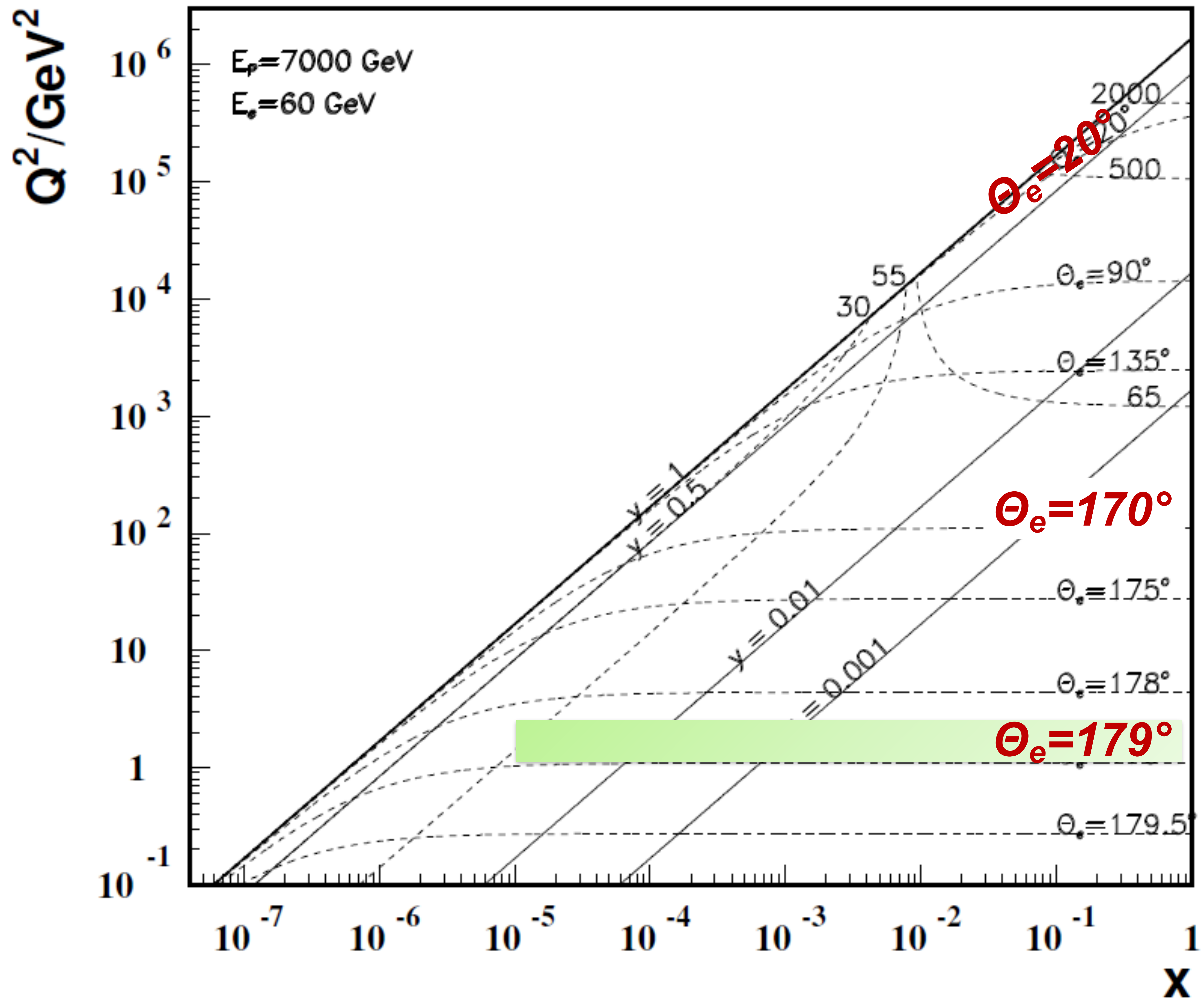
FCC-ee collider parameters

Parameter	FCC-ee				LEP2
physics working point	Z	WW	ZH	$t\bar{t}_{bar}$	
energy/beam [GeV]	~45.6	~80.5	~120	~175	~105
bunches/beam	70760	7280	826	64	4
bunch spacing [ns]	3.0	40	400	5000	22000
bunch population [10^{11}]	0.4	0.4	0.7	2.1	4.2
beam current [mA]	1400	150	30	6.4	3
luminosity/IP x 10^{34}cm^{-2}s^{-1}	137	16.5	4.9	1.4	0.0012
energy loss/turn [GeV]	0.036	0.34	1.71	7.72	3.34
synchrotron power [MW]	100				22
RF voltage [GV]	0.25	0.8	3.0	9.5	3.5
√s spread SR [%]	0.04	0.07	0.10	0.15	0.11
√s spread SR+BS [%]	0.07	0.07	0.11	0.19	0.11

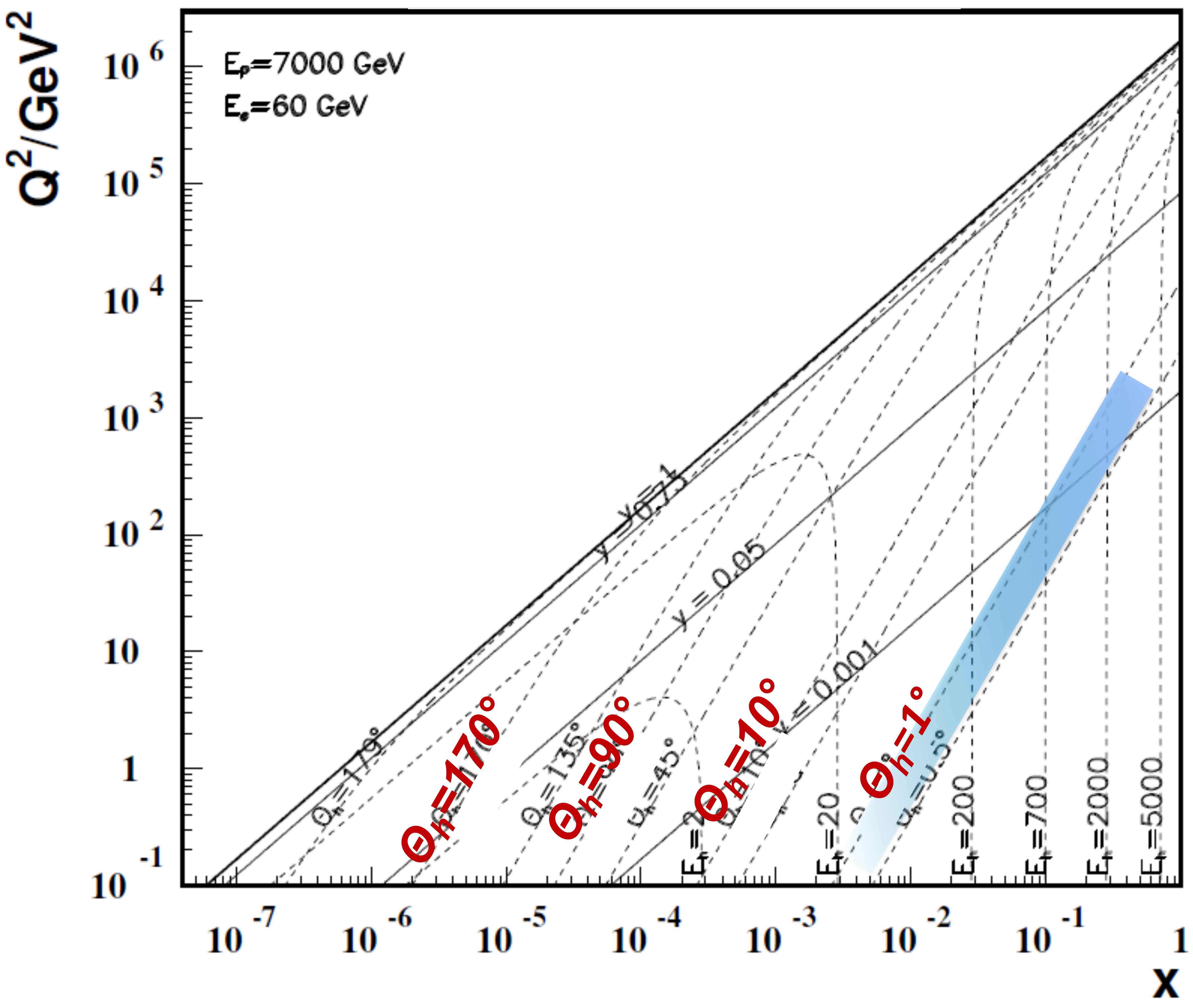
FCC-ee review: Physics and Experiments Patrick Janot
J. Wenninger et al. FCC-ACC-SPC-003 Revision 4.0

LHec Kinematic Range (low x; high Q^2)

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

LHeC Detector Basic Element Layout

LHeC

Tracker	FST_{pix}	FST_{strix}	CFT_{pix}	CPT_{pix}	CST_{strix}	CBT_{pix}	BST_{strix}	BST_{pix}
#Wheels	5		2	–	–	2	3	
#Rings/Wheel	2_{inner}	3_{outer}	3/4	–	–	3/4	3_{outer}	2_{inner}
#Layers	–	–	–	4	5	–	–	–
$\theta_{min/max}$ $[^0]$	0.7	3.8	3.0	5.1	24/155	177.8	173.1	178.7
$\eta_{max/min}$	5.1	3.4	3.6	±3.1	±1.4	-3.6	-2.8	-4.5
$Si_{pix/strix}$ $[m^2]$	6.9	9.5	2.8	5.4	33.7	2.8	5.7	4.1
Sum-Si $[m^2]$	70.9 double layers taken into account							

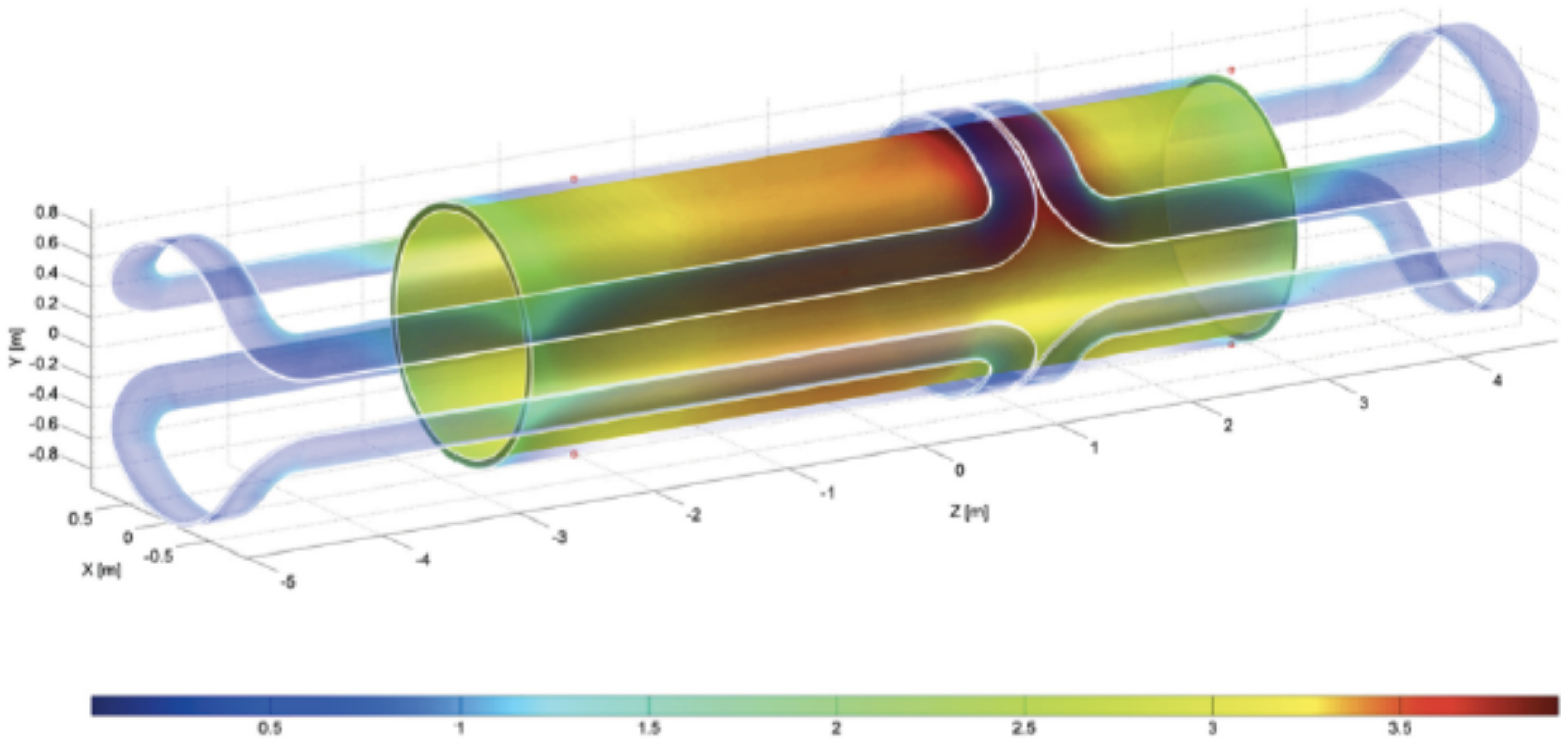
Calo	FHC_{SiW}	FEC_{SiW}	$EMC_{SciPb/LAr}$	HAC_{SciFe}	BEC_{SiPb}	BHC_{SiFe}
$\theta_{min/max}$ $[^0]$	0.61	0.68	8/166	14.2/160	178.7	178.9
$\eta_{max/min}$	5.2	5.1	2.7/-2.1	2.1/-1.7	-4.5	-4.7
Volume $[m^3]$	6.7	1.6	15.1	165	1.6	5.8
Sum-Si $[m^2]$	197.4					

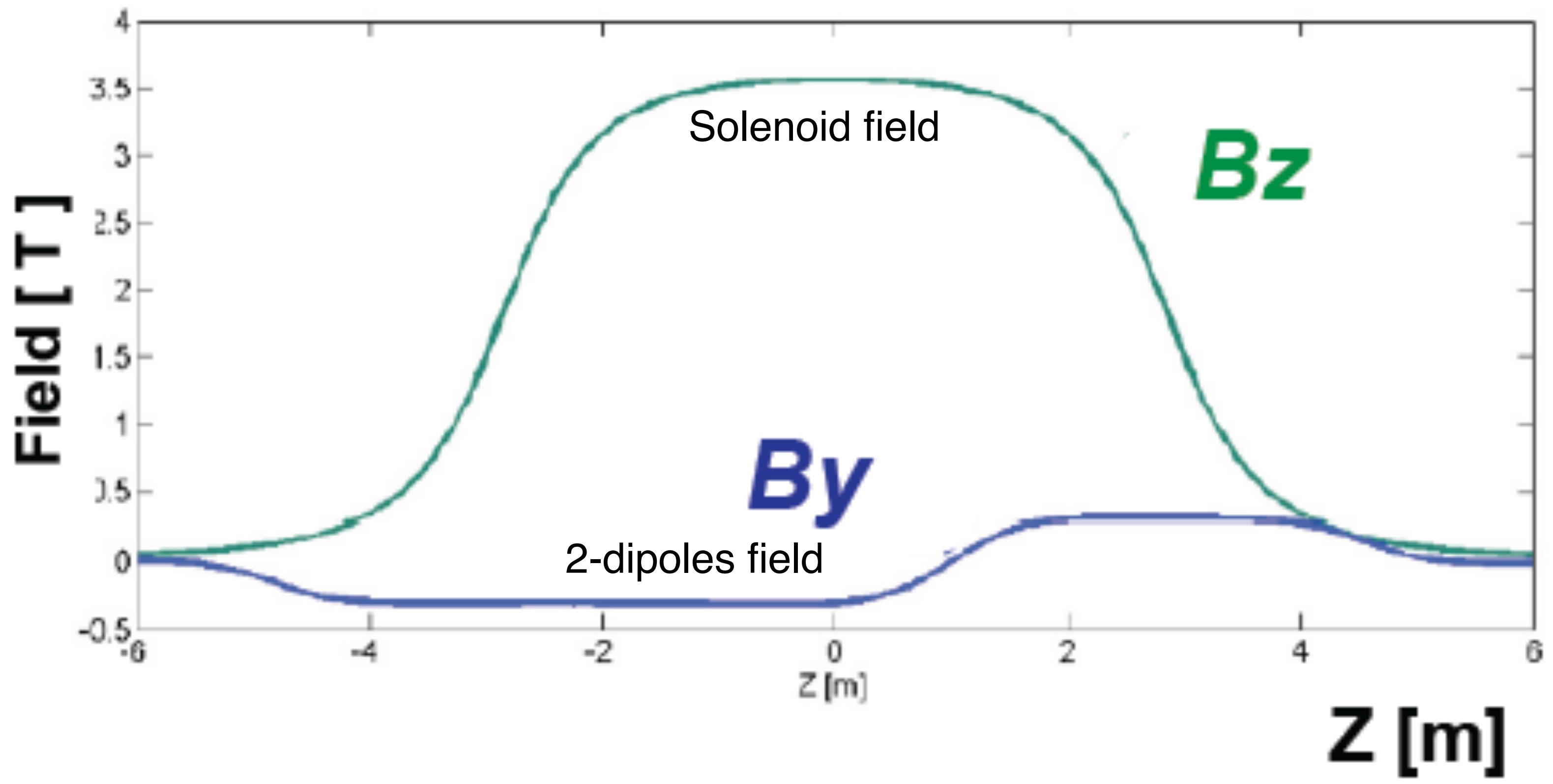
Detector Magnets: Solenoid and Dipoles

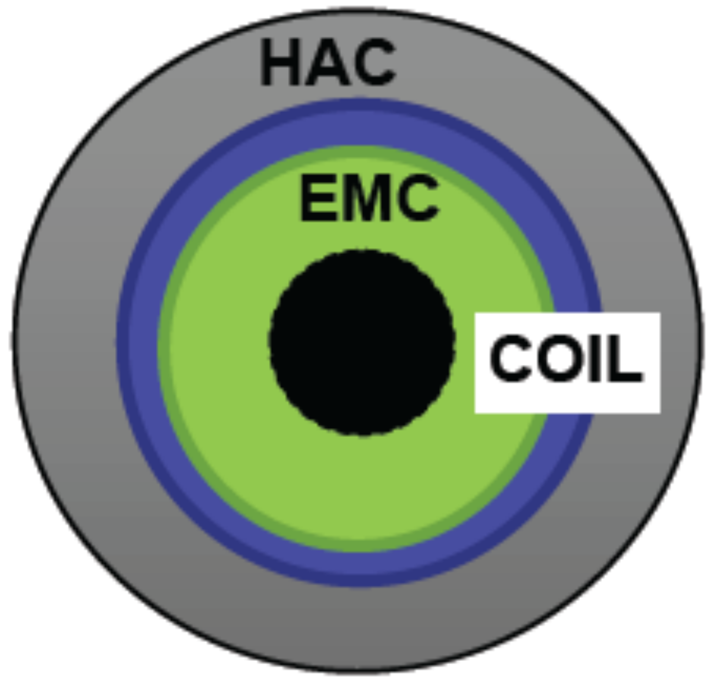
courtesy Herman ten Kate and Alexey Dudarev

- Baseline: Solenoid (3.5 T) + dual dipole 0.3 T (Linac-Ring Option)
  - Large coils (double solenoid): Containing full calorimeter, precise muon measurement, large return flux

- Small coil: Cheaper, less iron for return flux, solenoid and dipoles conveniently within the same cold vacuum vessel, but no muon measurement





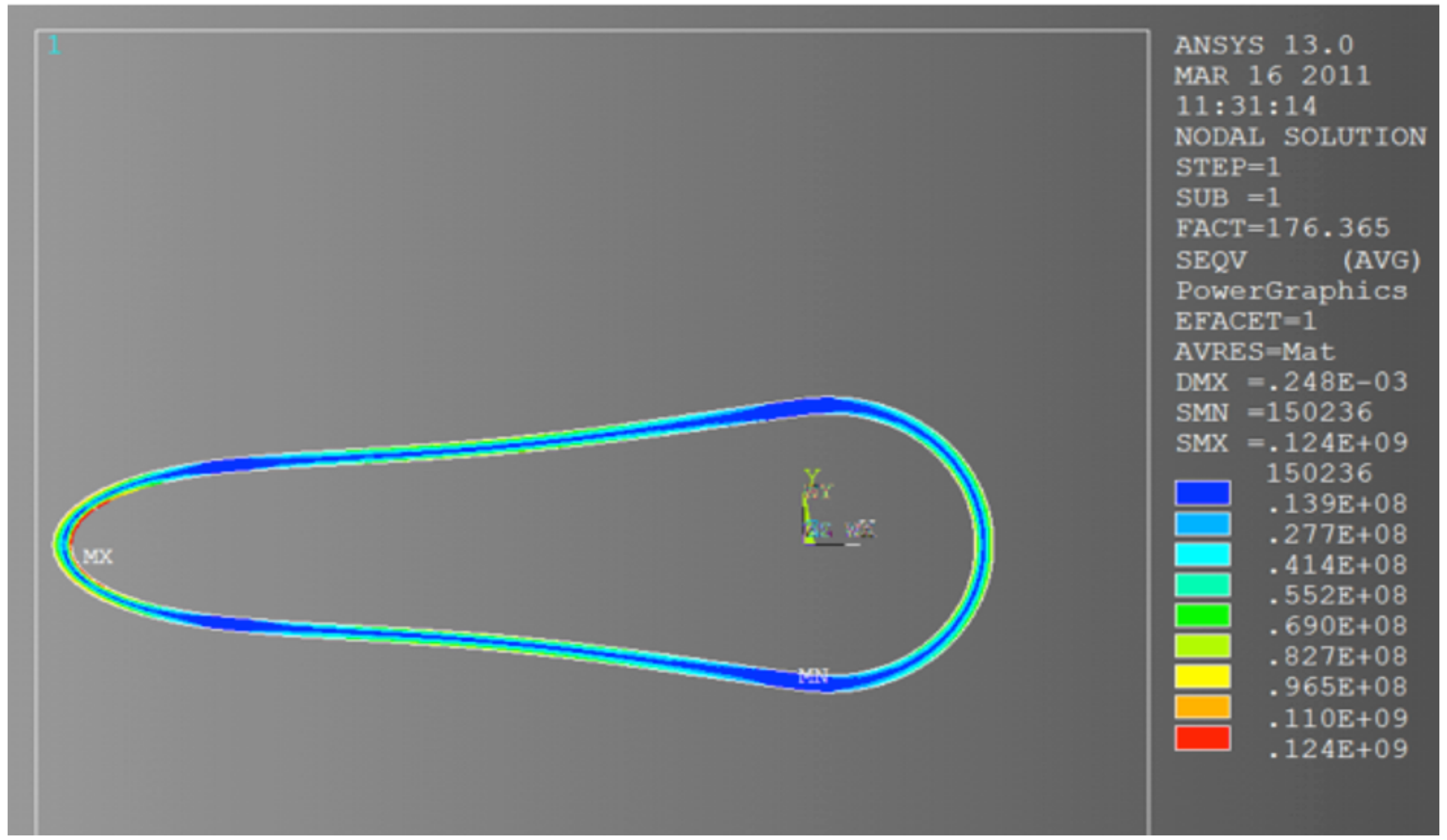


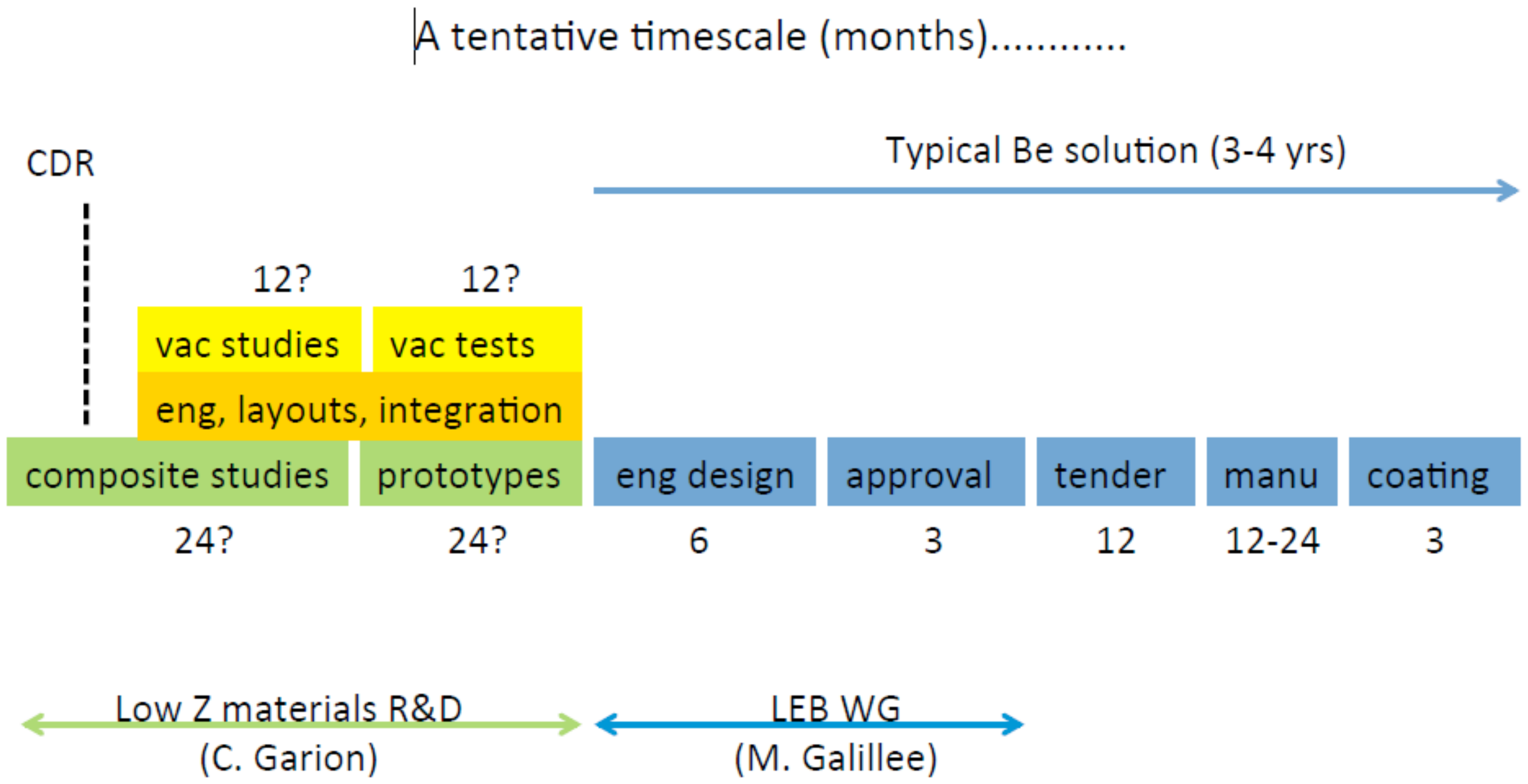
LHeC Detector Magnet system, Herman ten Kate
LHeC Workshop Chavannes, Jan 21, 2014

Beam Pipe Considerations

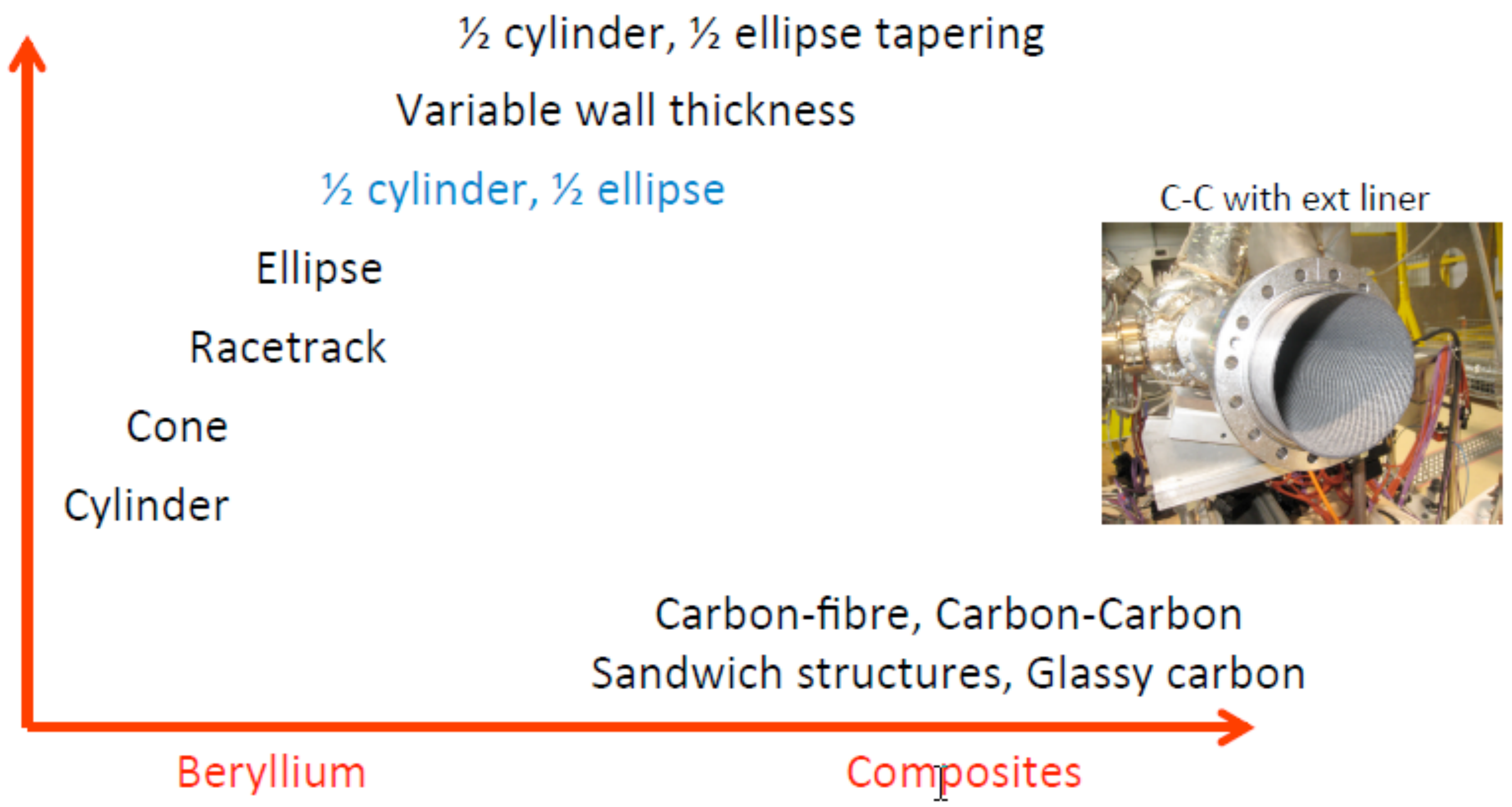
courtesy Paul Cruikshank, CERN

https://indico.cern.ch/event/183282/session/12/contribution/54/material/slides/1.pdf
https://indico.cern.ch/event/278903/session/13/contribution/56/material/slides/1.pdf



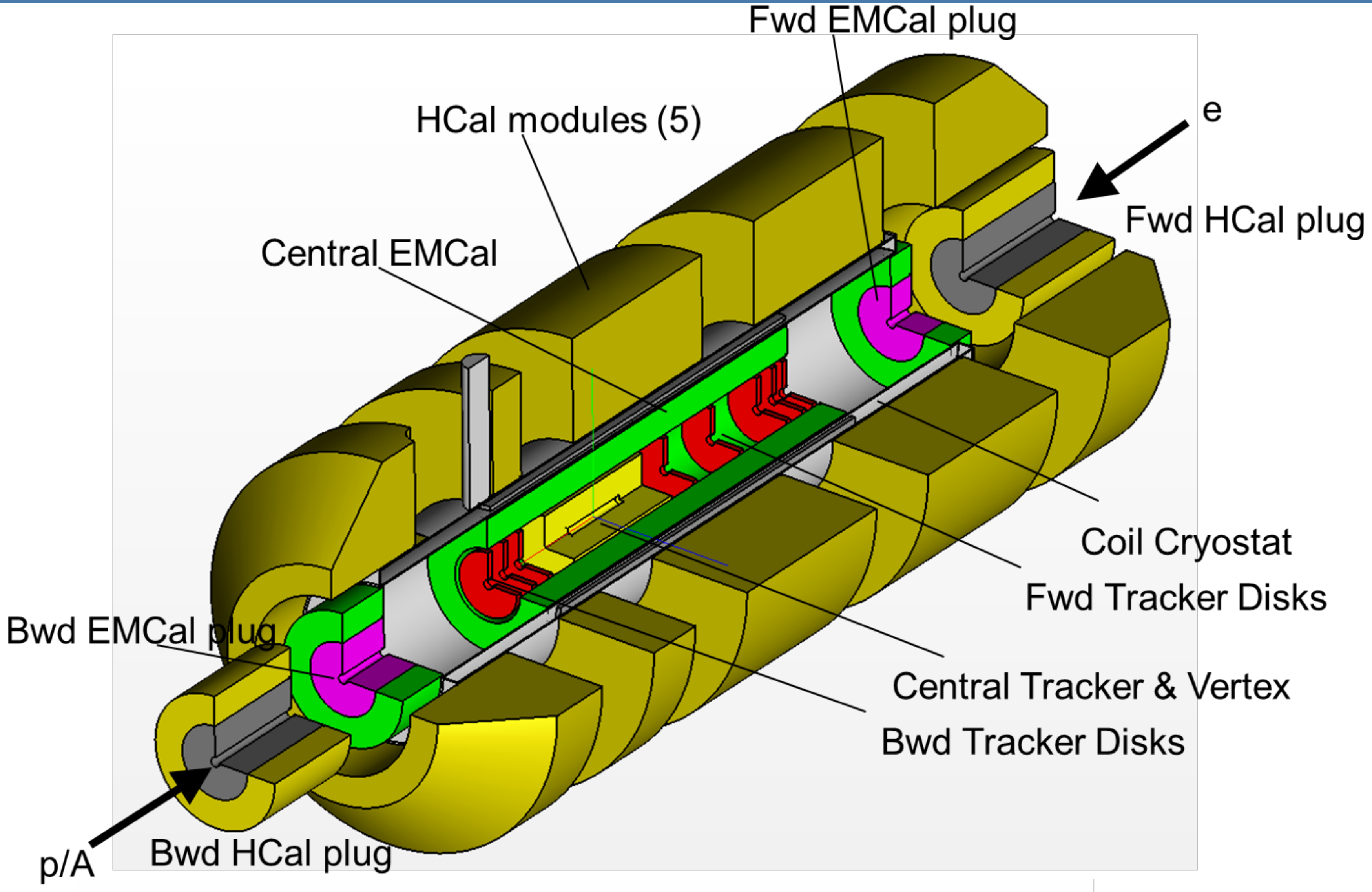


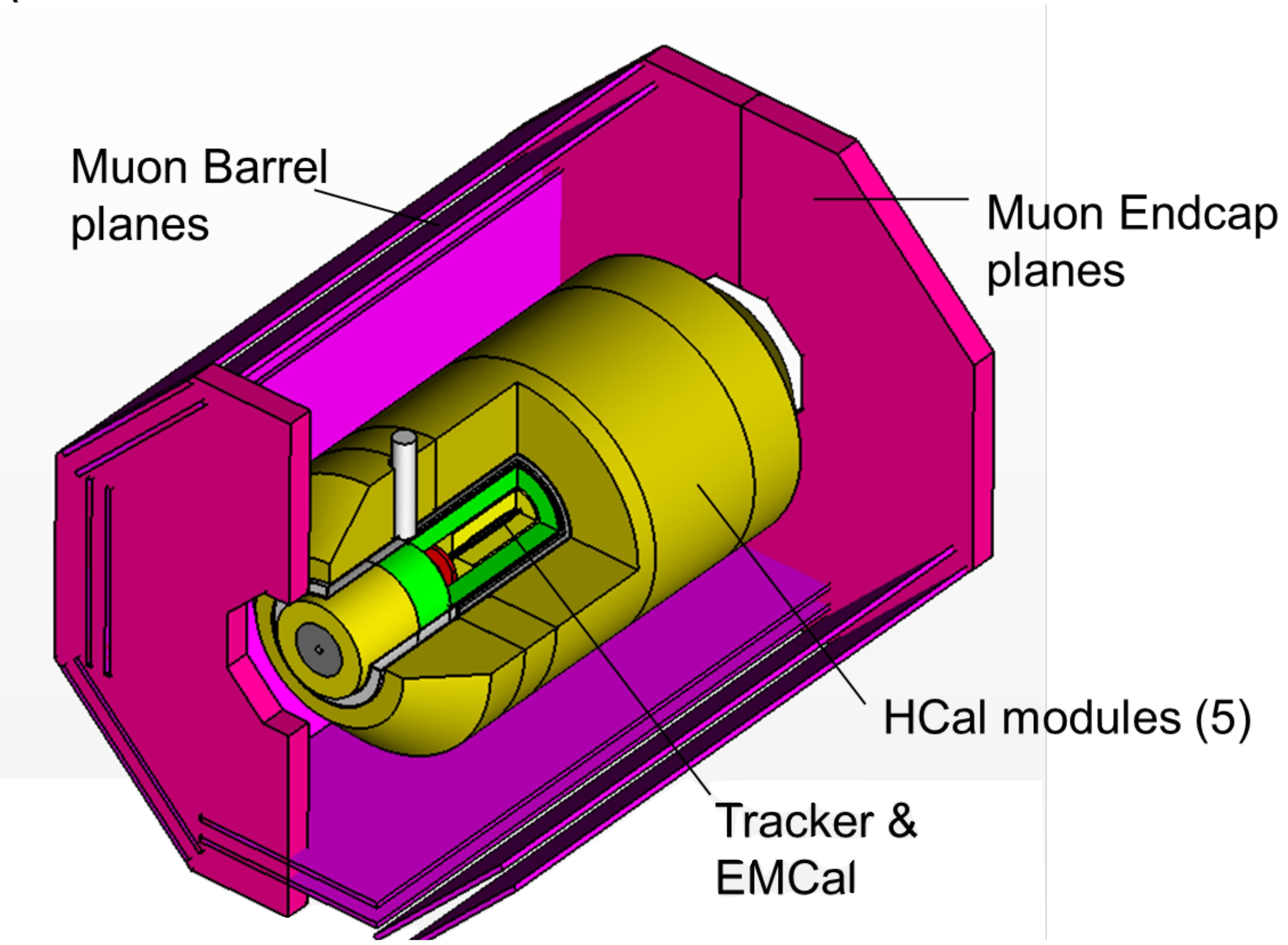
Additional manpower is necessary to advance on LHeC eng & vacuum physics issues



- **Circular-Elliptical beam-pipe design**
  - **Beryllium 2.5-3.0 mm wall thickness**
  - **Central beam pipe ~ 6 meters**
  - **TiZrV NEG coated**
  - **Wall protected from primary SR (upstream masks)**
  - **Minimised end flanges, minimised supports**
  - **optimisation needed - R&D**

FCC-he Detector Segmenting/CMS-like-Install

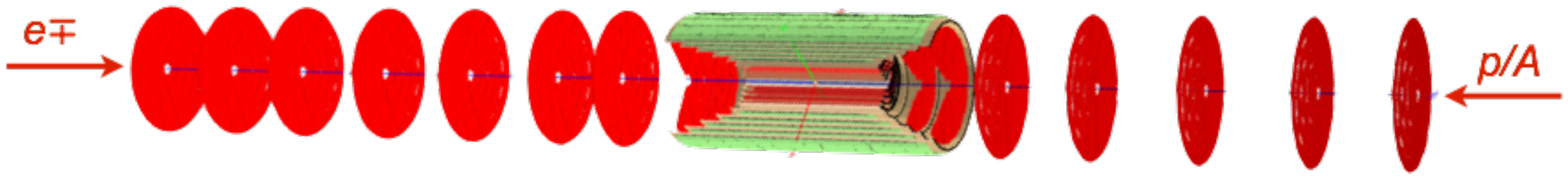


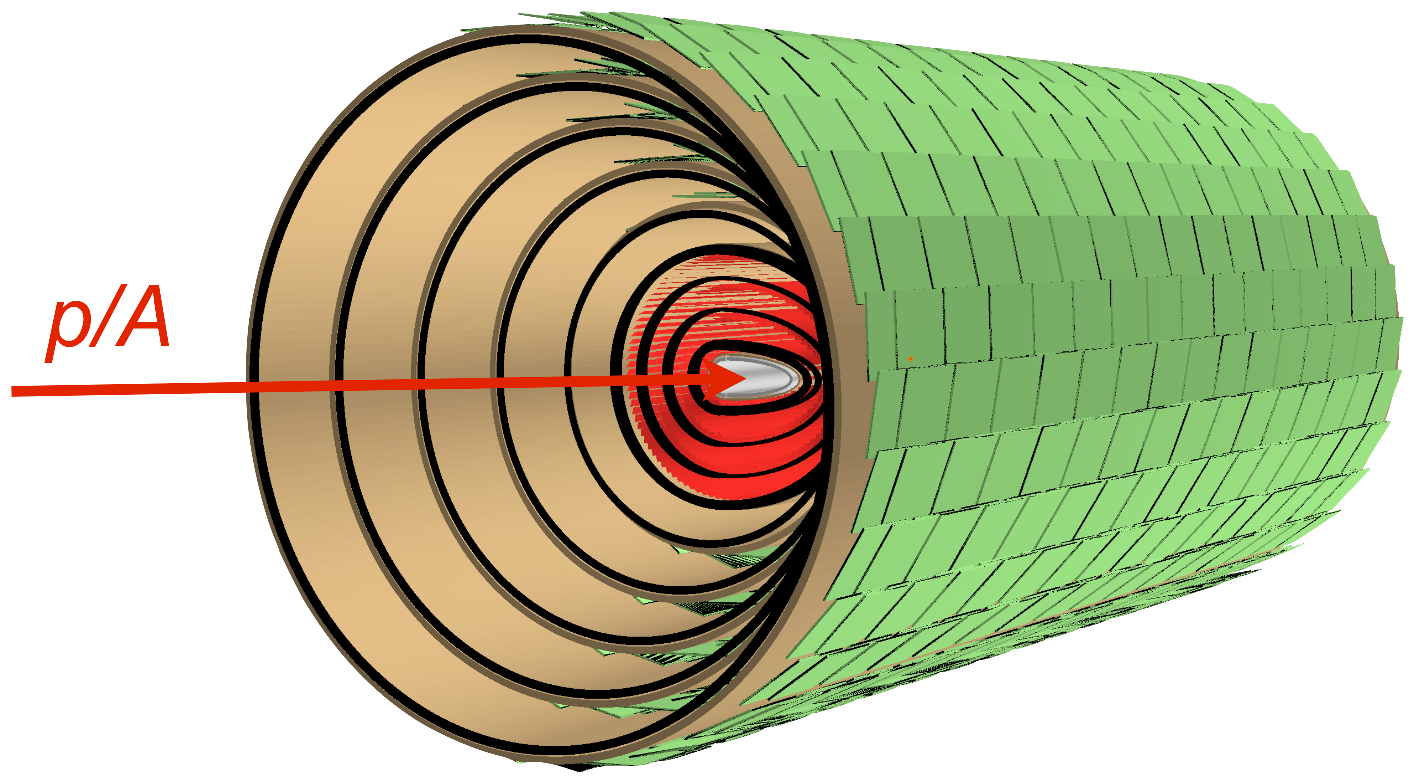


- First studies for the realization of the LHeC detector and perform its installation during a LHC Long Shutdown
- Preliminary installation and maintenance scenarios using LHC P2 interaction region
- Pre-mounting of detector and commissioning of the coil system on surface, lowering and commissioning of the detector underground. At IP2
- mount detector inside L3 magnet support structure.
- Time for field map of solenoid and beam-pipe bake out & vacuum pumping.
- Estimated total time is about compliant with LHC shutdown durations.

see talk A. Gaddi
https://indico.cern.ch/event/356714/contributions/844883/attachments/709255/973648/LHeC-Workshop-2015_ag_v6.pdf

Tracker





Interaction region design - Impact of Synchrotron Radiation

Circular-Elliptical Beam Pipe and Vertex Pixel Detector placement around

1st version describes sensitive / passive elements
(sensors / support structure / I-O elements)
Many details to be solved

LHeC/FCC-he design differ in fwd/bwd wheels placement only (currently)

Challenges

- The ep configuration uniquely selects the WW-H and ZZ-H vertices for production
  - ep → vH(bb)X: O(1)% precision on H-bb couplings with matching theoretical uncertainty

- FCC-he reaches the H→μμ decay, with O(1000) events
  - μ measurement essential - magnet placement!

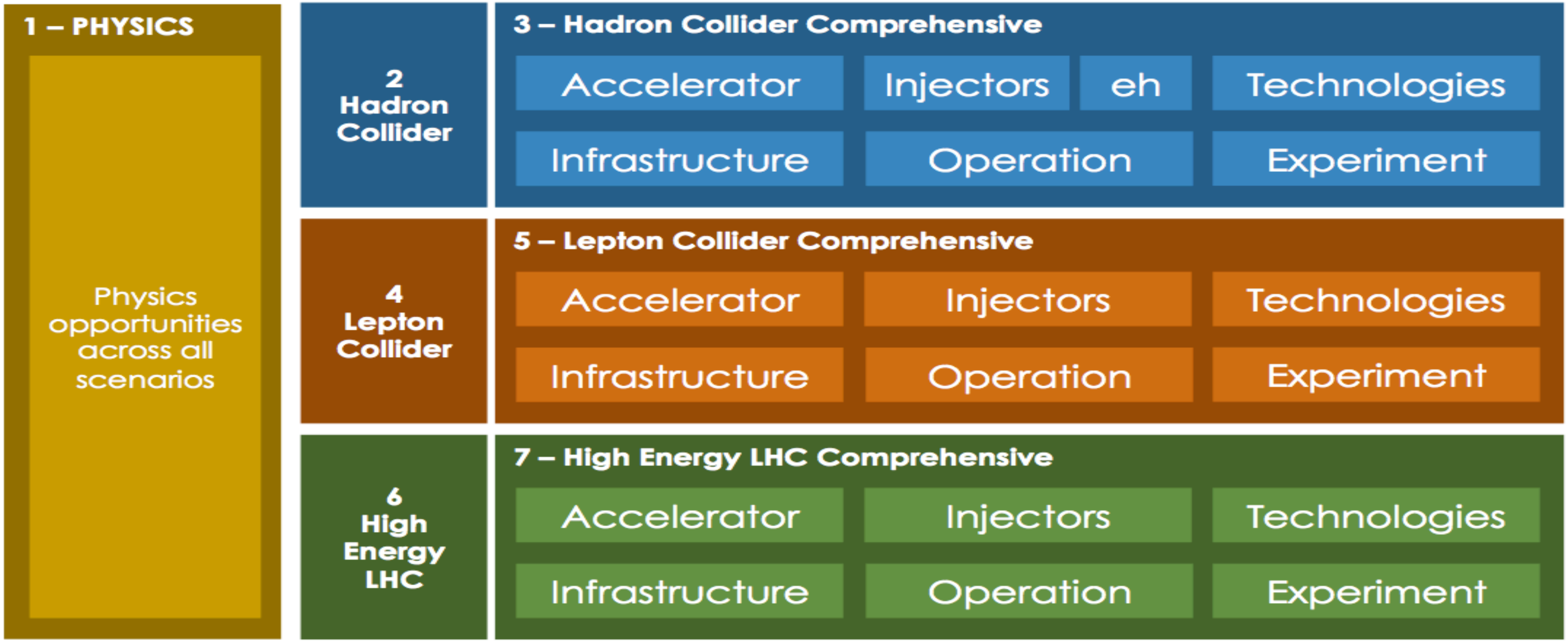
- Very demanding and being studied in detail e.g.:
  - ep → vHHX ep produces the Higgs from WW → double Higgs

- FCC-he will be a Higgs factory and the consequences are to be studied
  - desire to measure also rare decays,
  - maximum coverage for all kinds of decays

- Extrapolation from LHeC:
  the FCC-he detector is feasible, the design will benefit from coming technology progress
  (sensors, magnets, low power consumption, cooling, mechanical systems, electronics …)

FCC-he Contribution to CDR

FCC-he Physics, Experiments and Detector will be incorporated into Vol. 2



FCC-he Contribution to CDR

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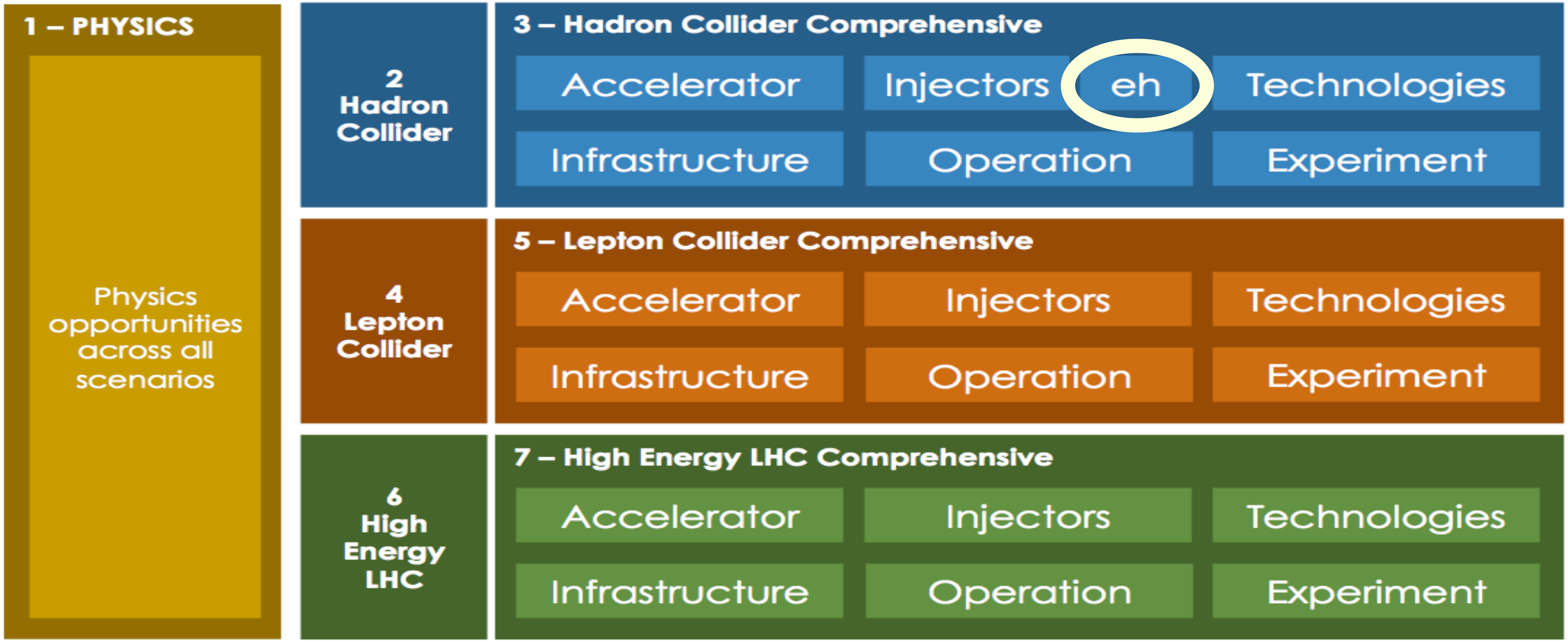

FCC-eh & HE-LHeC eA baselines

parameter [unit]	LHeC (HL-LHC)	eA at HE-LHC	FCC-he
E_{Pb} [PeV]	0.574	1.03	4.1
E_e [GeV]	60	60	60
$\sqrt{s_{eN}}$ electron-nucleon [TeV]	0.8	1.1	2.2
bunch spacing [ns]	50	50	100
no. of bunches	1200	1200	2072
ions per bunch [10^8]	1.8	1.8	1.8
$\gamma\epsilon_A$ [μm]	1.5	1.0	0.9
electrons per bunch [10^9]	4.67	6.2	12.5
electron current [mA]	15	20	20
IP beta function β_A^* [cm]	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3
bunch filling H_{coll}	0.8	0.8	0.8
luminosity [$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	7	18	54

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017,
"A Baseline for the FCC-he"

John Jowett, F.Z.

simulated FCC-eh performance

Parameter	Unit	Protons	Electrons
Beam energy	GeV	50000	60
Normalised emittance	μm	$2.2 \to 1.1$	10
IP betafunction	mm	150	$42 \to 52$
Nominal RMS beam size	μm	$2.5 \to 1.8$	$1.9 \to 2.1$
Waist shift	mm	0	$65 \to 70$
Bunch population	10^{10}	$10 \to 5$	0.31
Bunch spacing	ns	25	25
Luminosity	$10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$18.3 \to 14.3$	
Int. luminosity per 10 years	$[\mathrm{ab}^{-1}]$	1.2	

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Daniel Schulte

FCC-eh & HE-LHeC eA baselines

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