OVERVIEW FUTURE ACCELERATORS & DETECTORS

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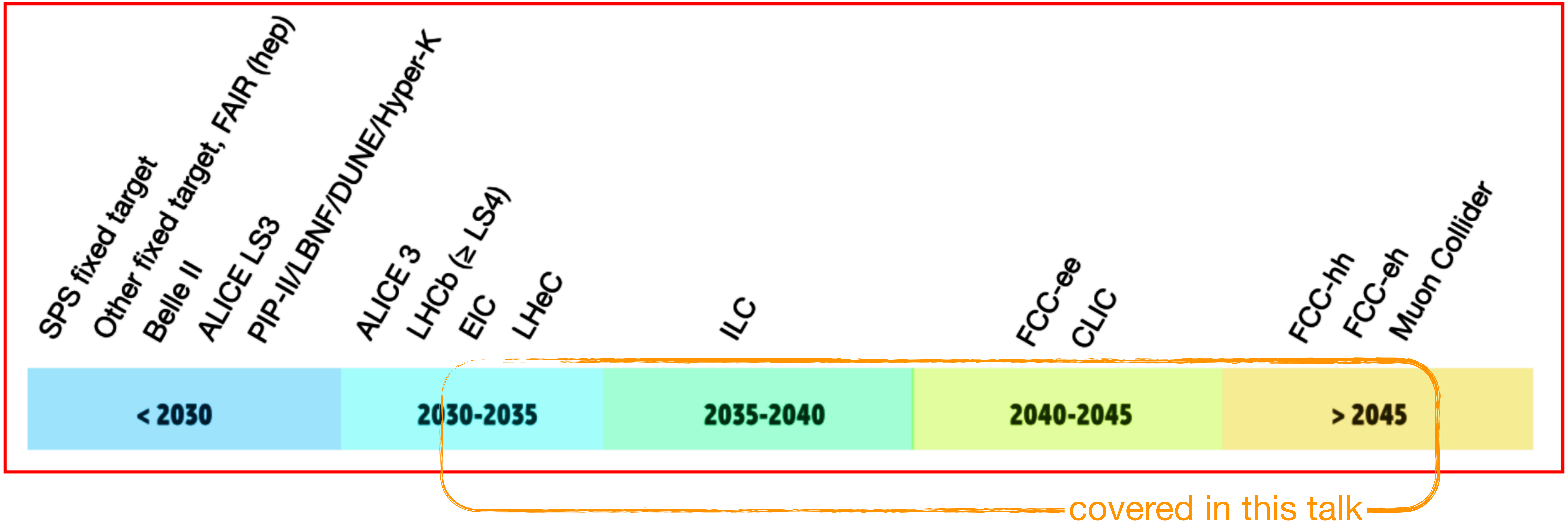
Pomeriggio tematico su iniziativa ECFA per Future Accelerators - INFN Roma 17 Gennaio 2023

INFN
Istituto Nazionale di Fisica Nucleare

HEAD NOTE AND OUTLINE

- **it is not** a refined and complete review, but just a **brief collection** of information on future **collider facilities** and **conceptual reference detectors** proposed for it
- meant as a **reference for terminology & concepts** treated in the specific presentations and for the discussion that follow
- will touch only some of the future colliders projects: no fixed target, no detectors upgrades proposed for HL_LHC after LS4 …

FUTURE FACILITIES

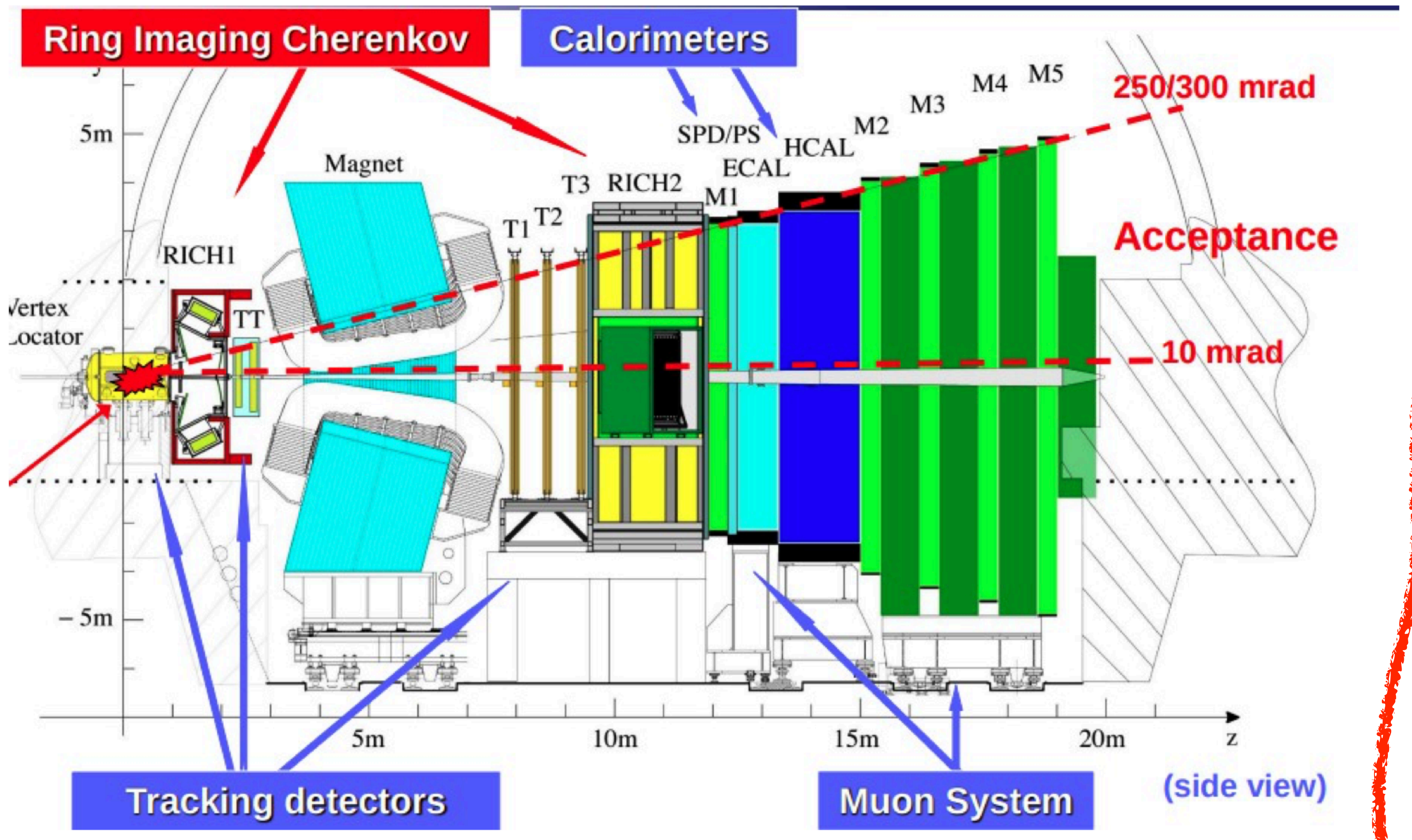


Timeline: low precision - earliest “feasible start date”

includes steps for approval/development/machine civil engineering&construction

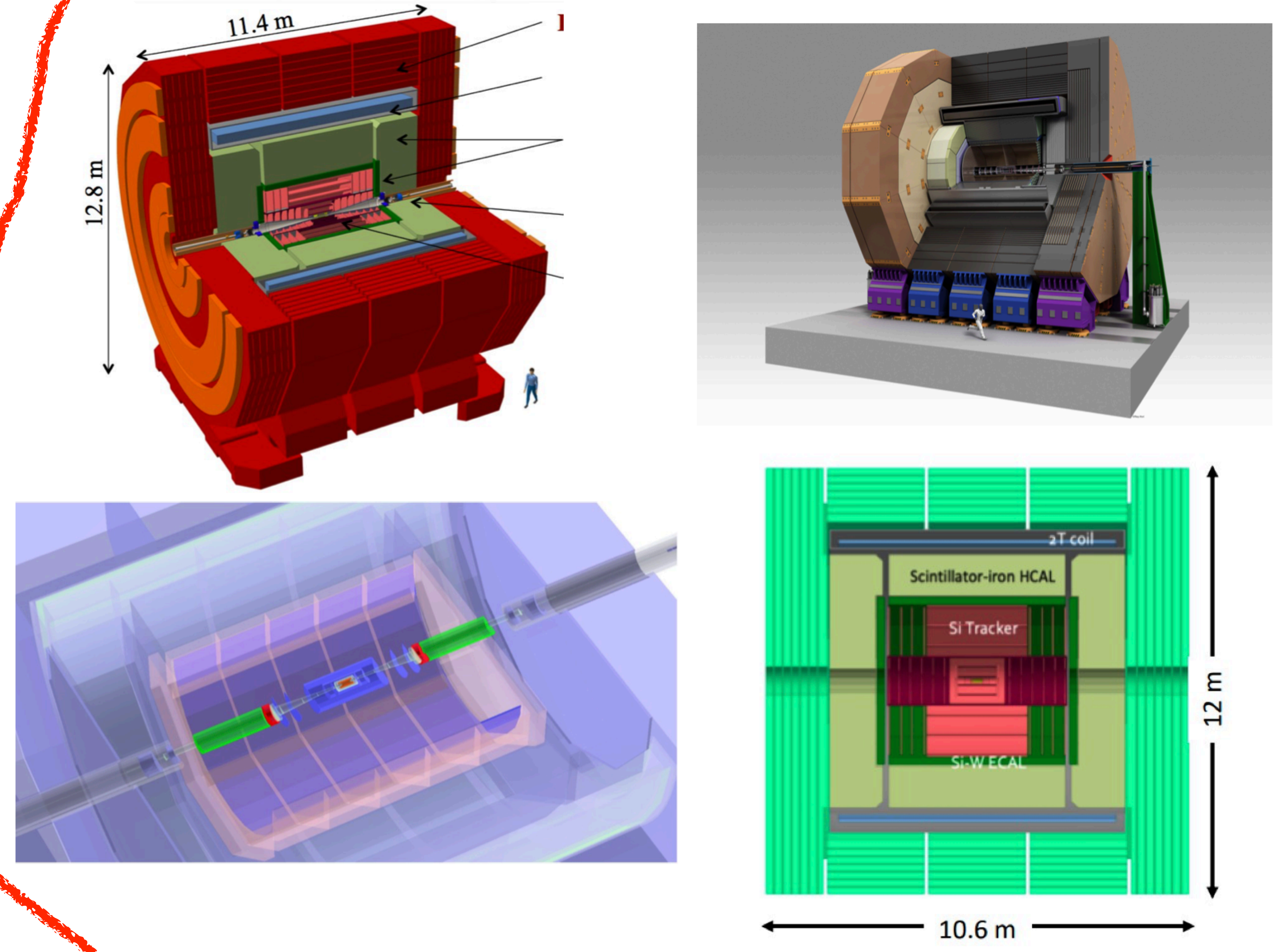
TARGET CONCEPTUAL DETECTORS OF ECFA DRD

HL-LHC after LS4

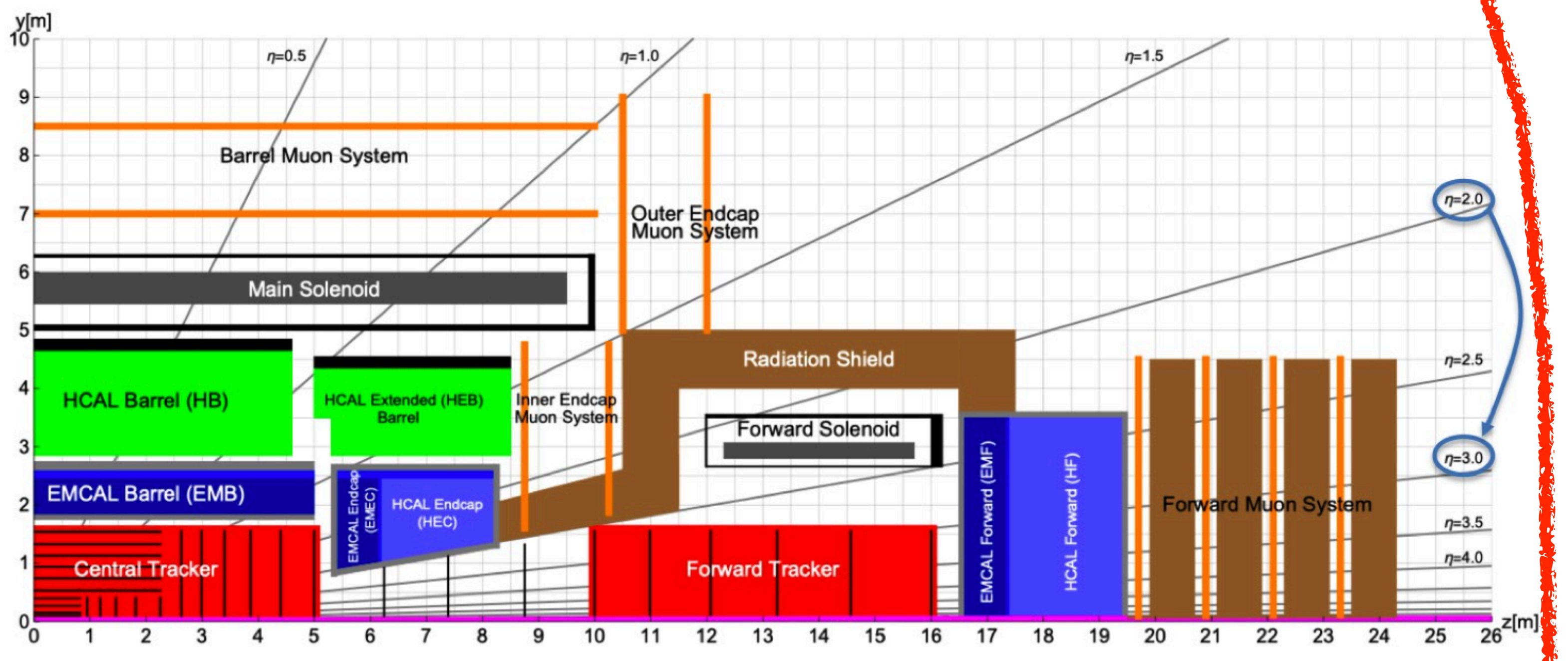


Higgs Factories

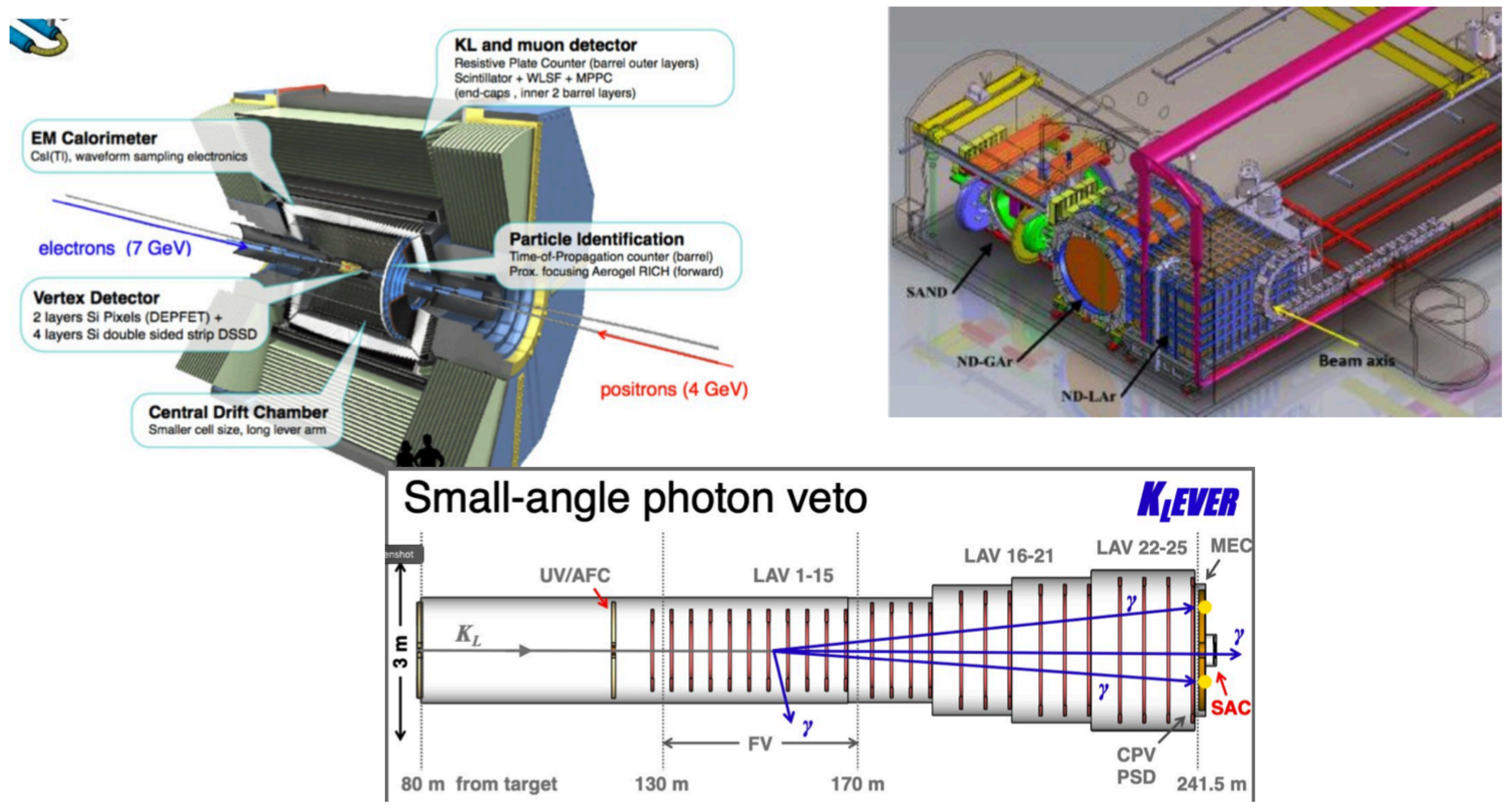
eg e+e- LC & CC



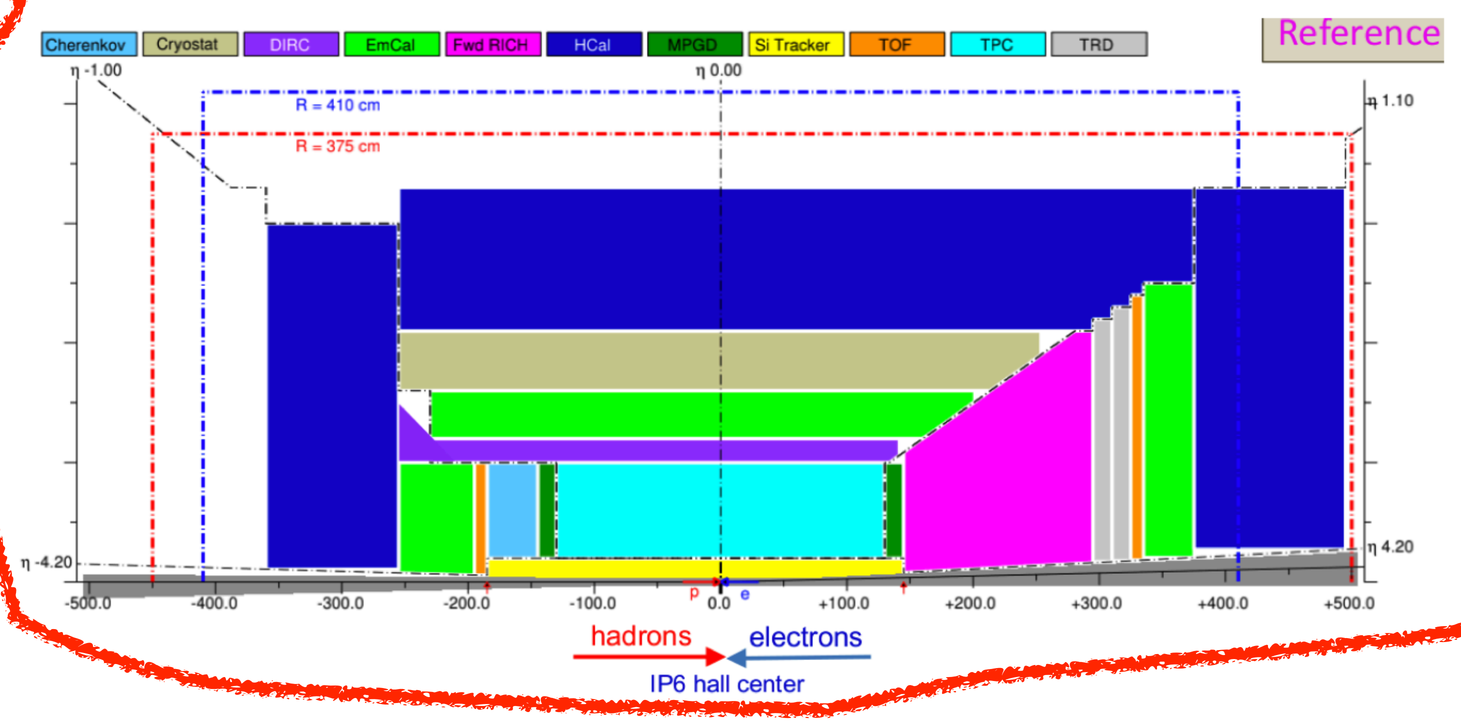
Future hadron colliders (including eh colliders)



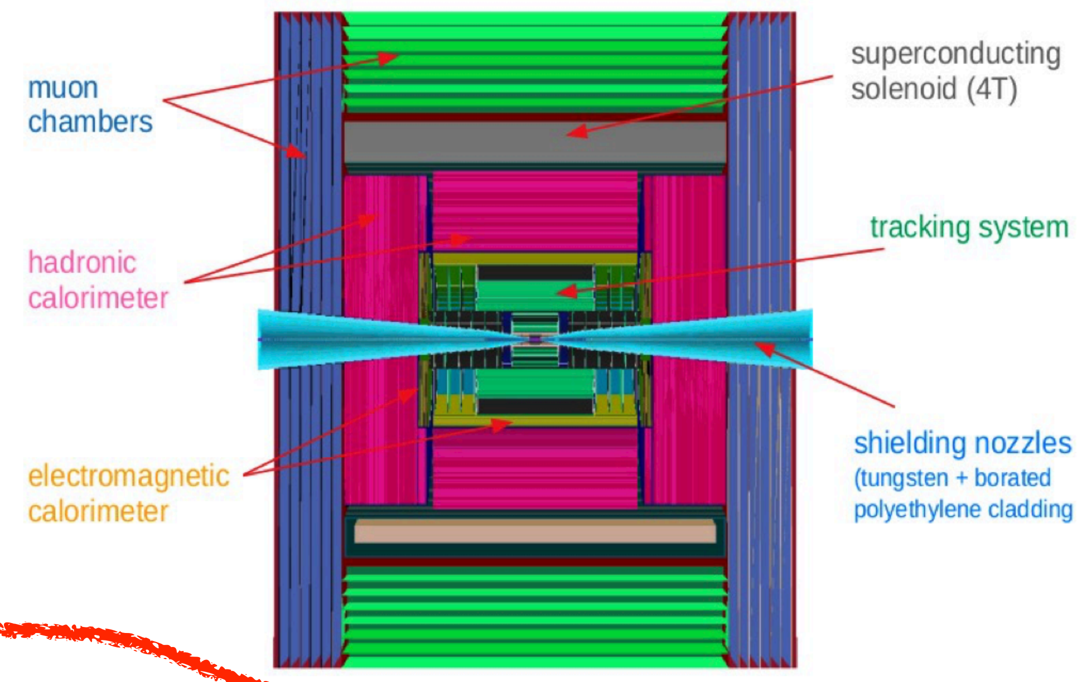
SuperKEKB, DUNE ND and Fixed Target



EiC

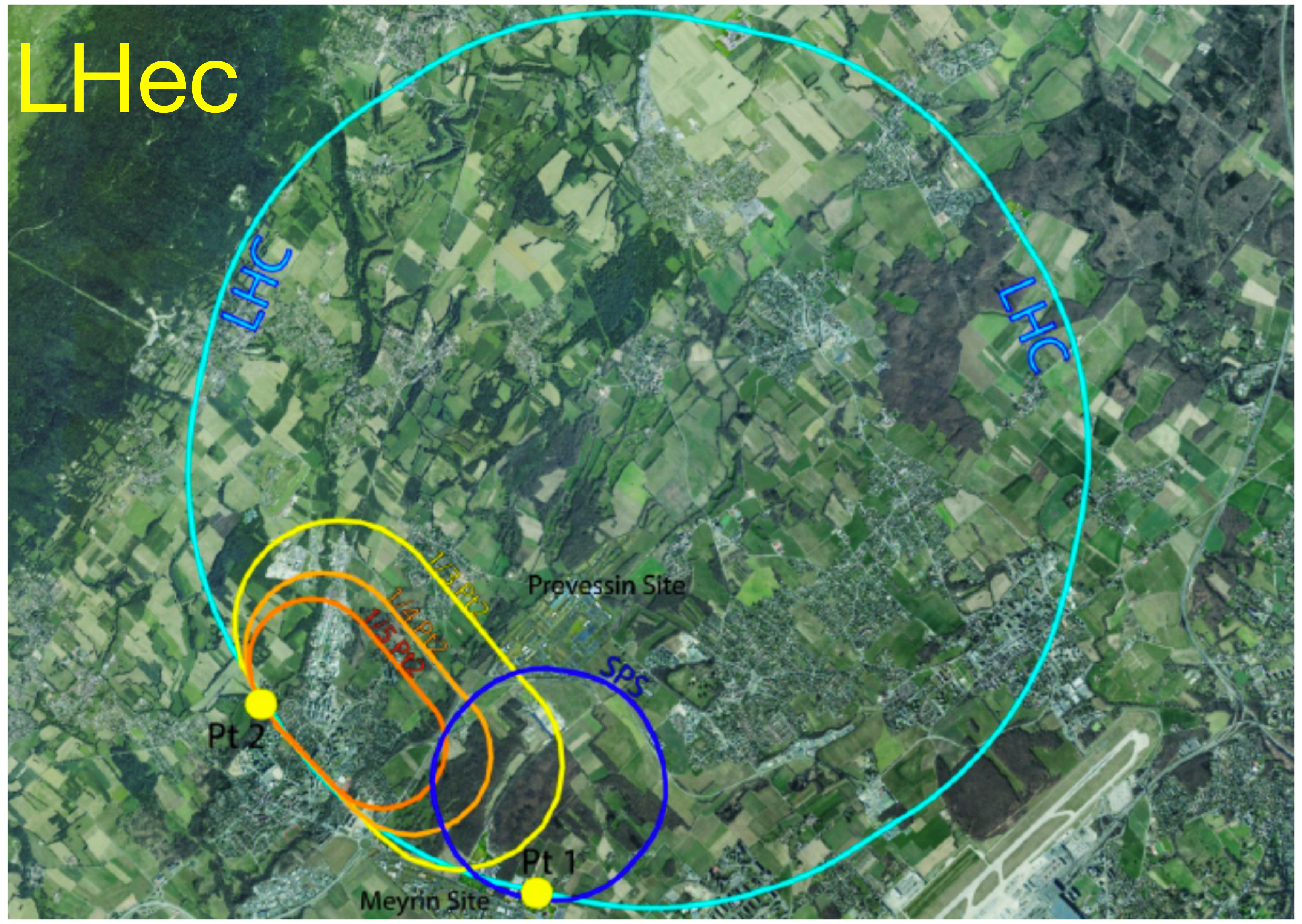


Muon Collider



STRONG INTERACTION EXPERIMENTS @ FC

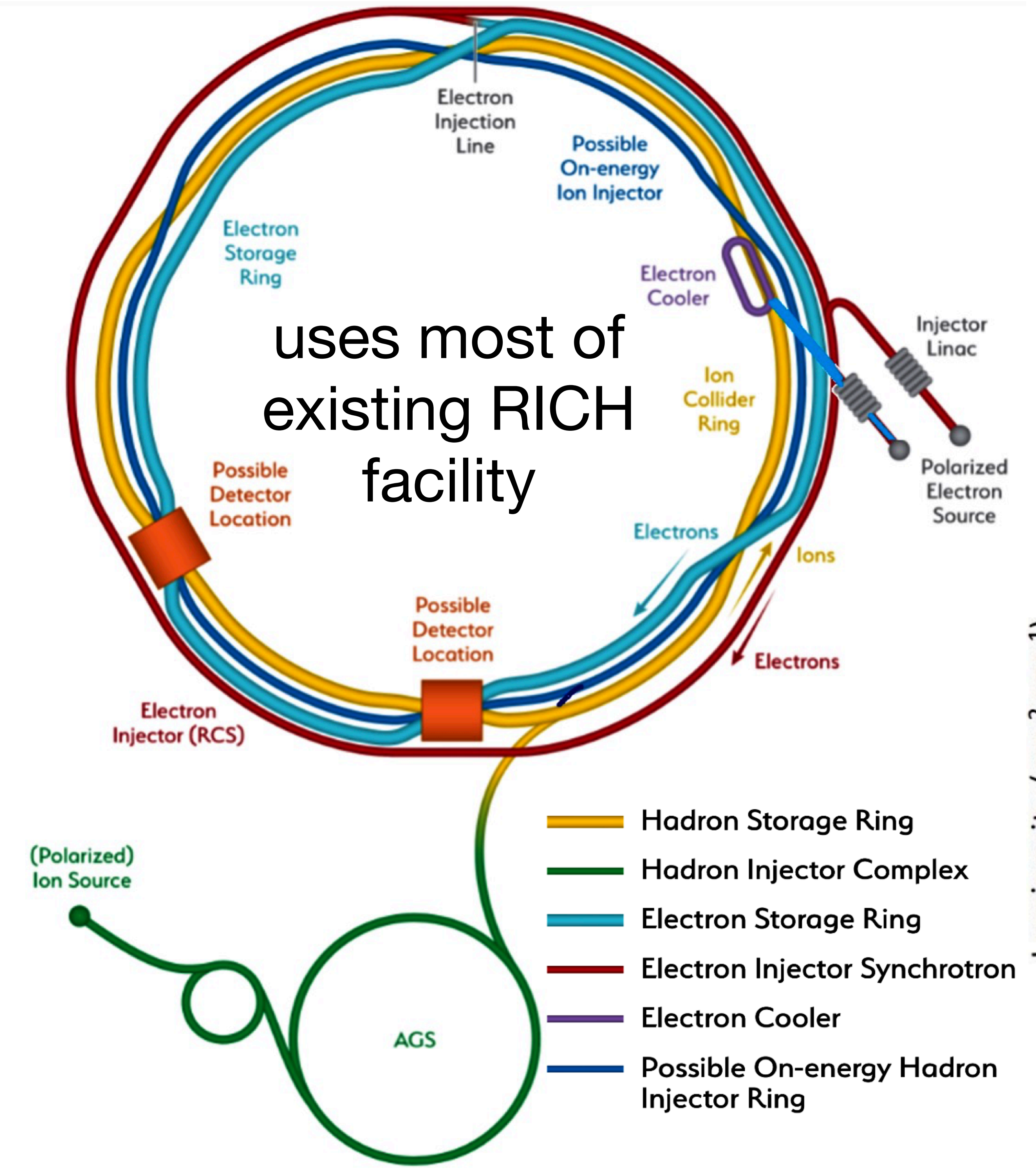
- several proposals and study ongoing with earliest starting times 2030-ish (ALICE 3 for RUN-5+ of HL-LHC, Electron-Ion Collider) and beyond (LHec, FCC-eh)



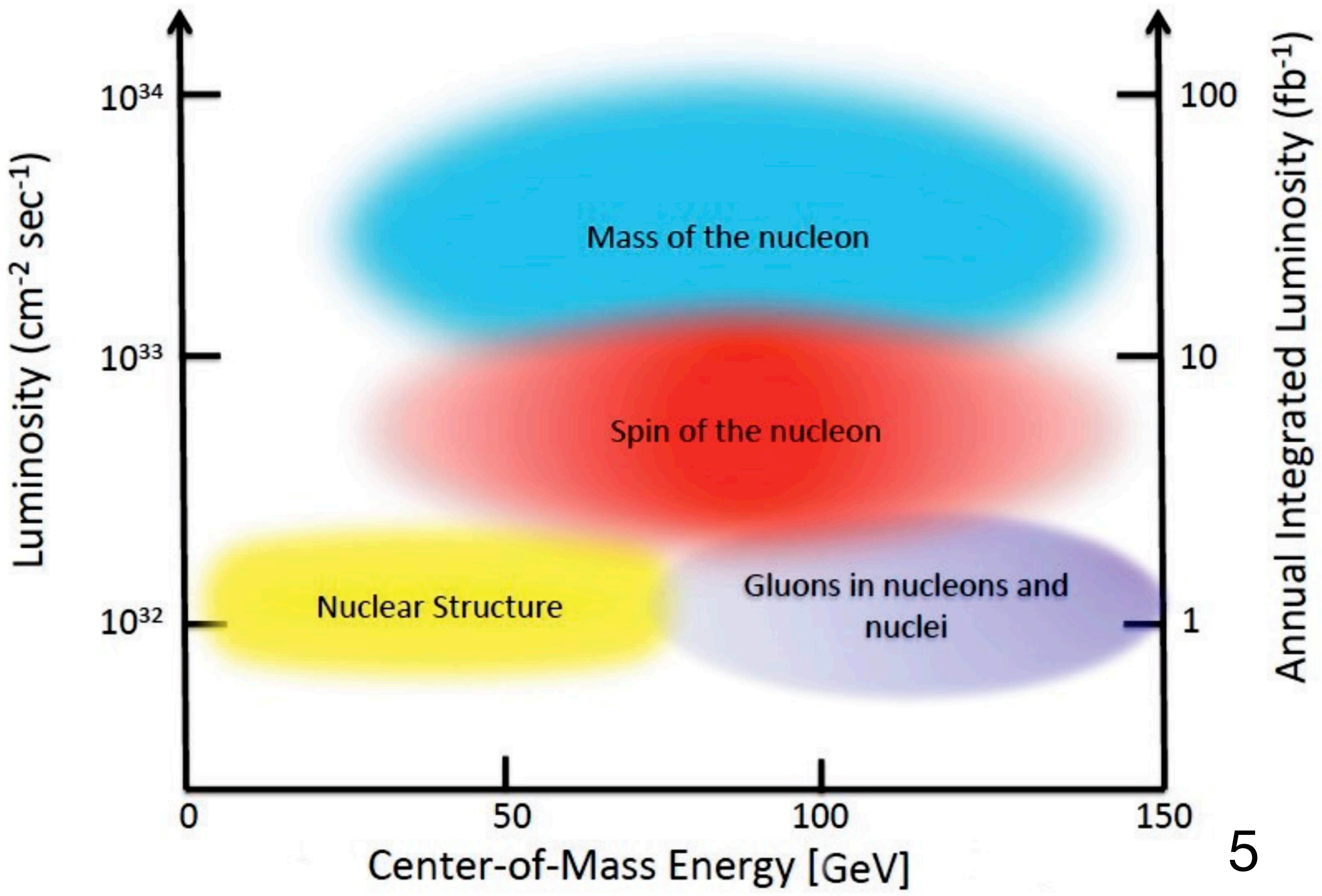
DIS to the energy and intensity frontier

- LHec: 50 GeV x 7 TeV: 1.2 TeV ep collider
  - operation: 2035+, cost O(1) BCHF
- FCC-eh: 60 GeV x 50 TeV: 3.5 TeV ep collider
  - operation: 2050+, cost O(1-2) BCHF + FCC-hh

EIC @Brookhaven

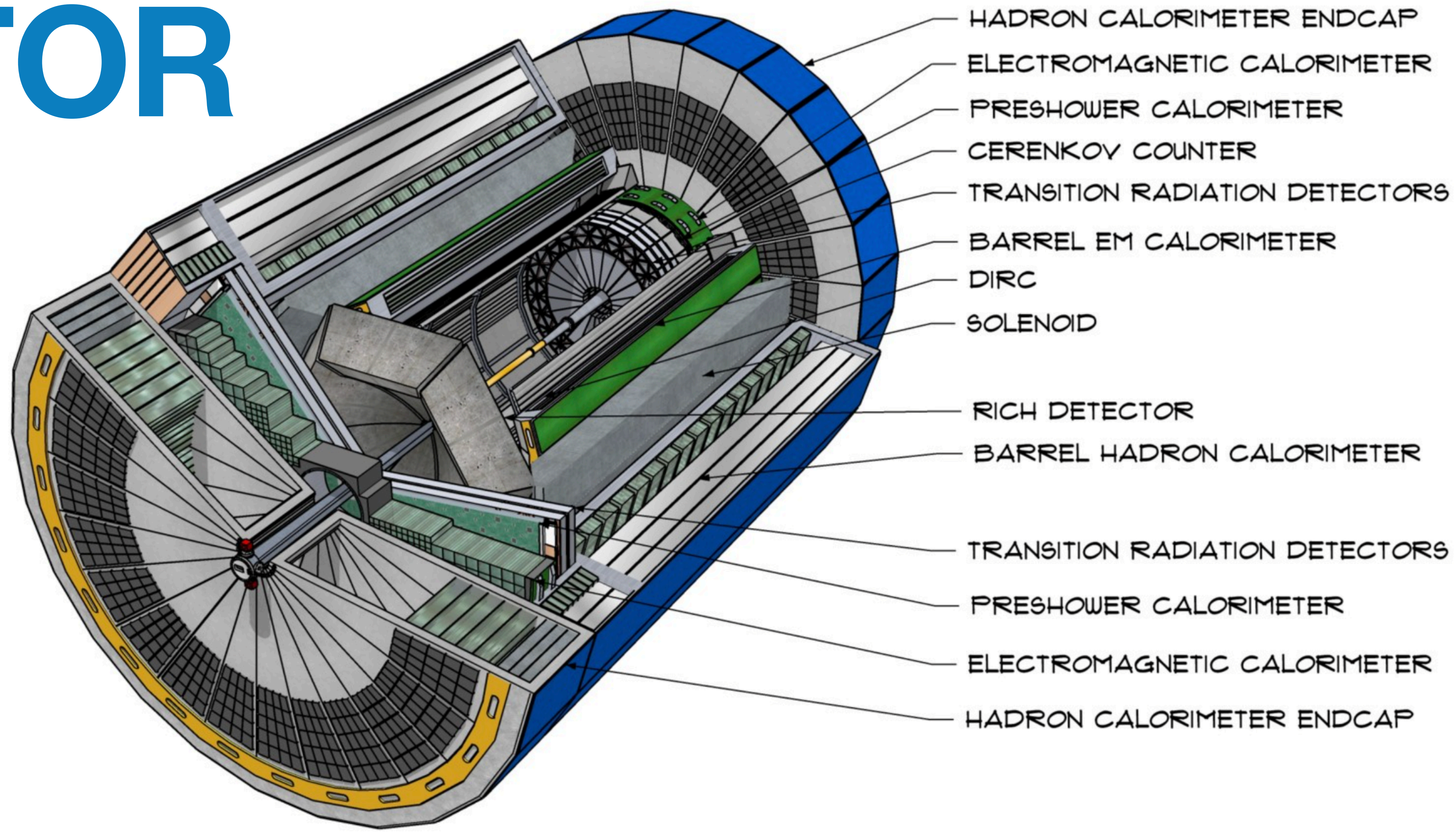


Center of Mass Energies:	20GeV - 140GeV
Luminosity:	10^{33} - 10^{34} $cm^{-2}s^{-1}$ / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!



http://www.eicug.org

EIC REFERENCE DETECTOR

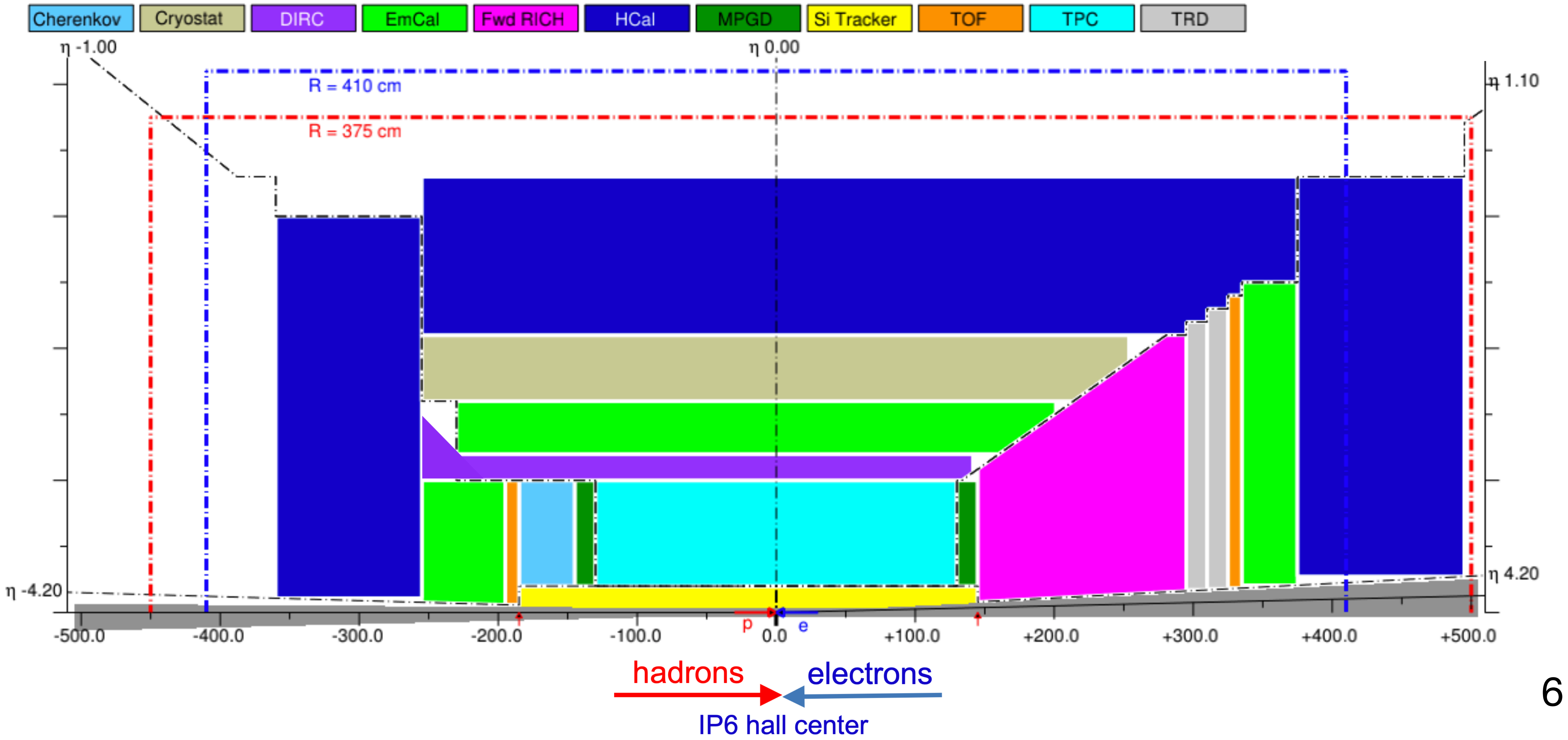


General requirements

- Large rapidity (-4 < η < 4) coverage;
  and far beyond in especially far-forward detector regions
- High precision low mass tracking
  - small (μ-vertex) and large radius tracking
- Electromagnetic and Hadronic Calorimetry
  - equal coverage of tracking and EM-calorimetry
- High performance PID to separate π, K, p on track level
  - also need good e/π separation for scattered electron

main challenges: PID and EMCal at $< 2\%/\sqrt{E}$

different detectors for different regions (barrel, forward, backward, vertex …)
- tracking: MAPS + TPC
- ecal:
  - Barrel: Pb/Sc Shashlyk
  - Foward: W powder/ScFi
  - Backward: PbWO4 + SciGlass
- PID: RICH, DIRC, Aerogel, TPC dE/dx, TOF, …



FCC-ee & -hh

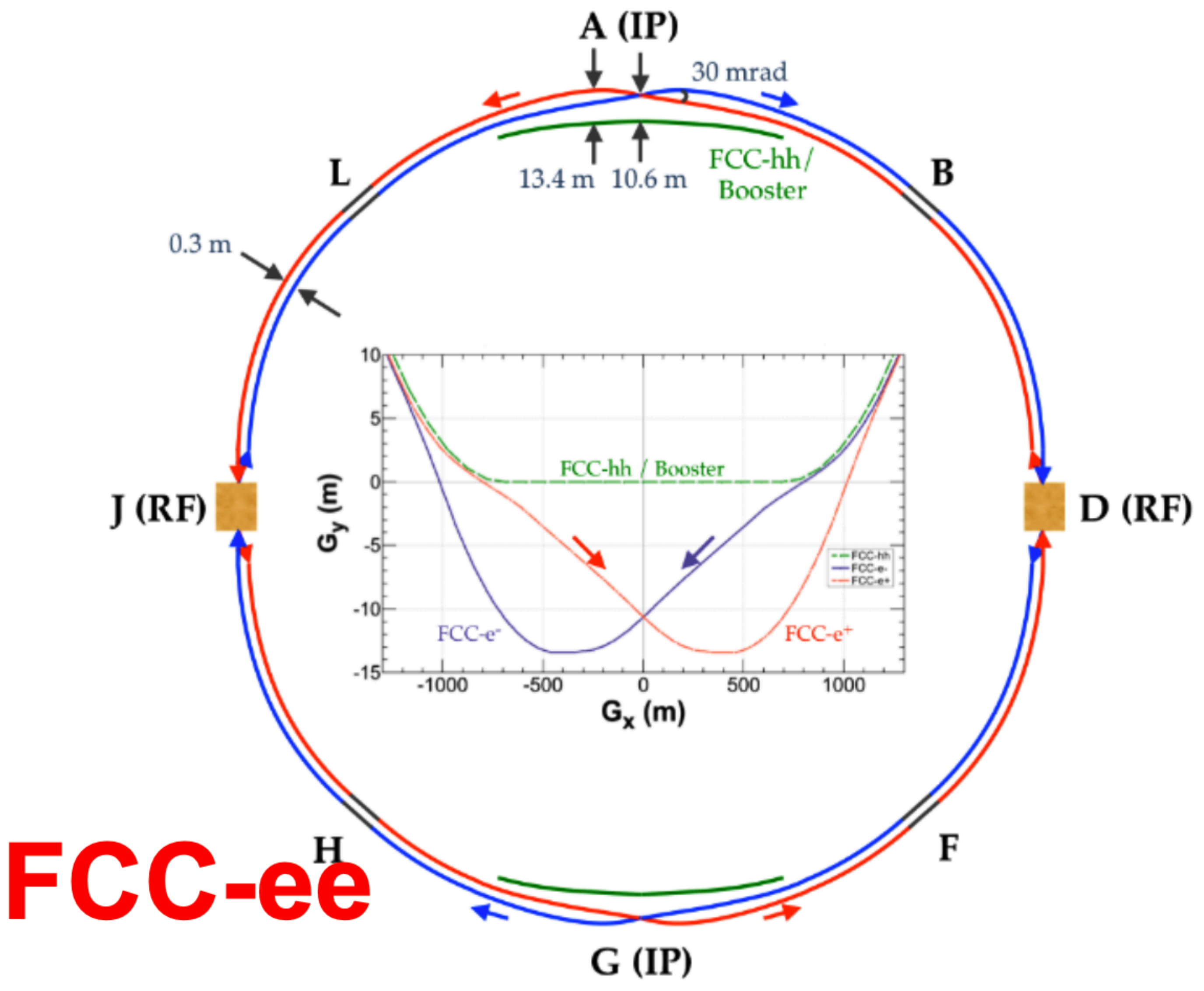
FCC CDRs: https://link.springer.com/article/10.1140/epjst/e2019-900045-4
https://link.springer.com/article/10.1140/epjst/e2019-900087-0

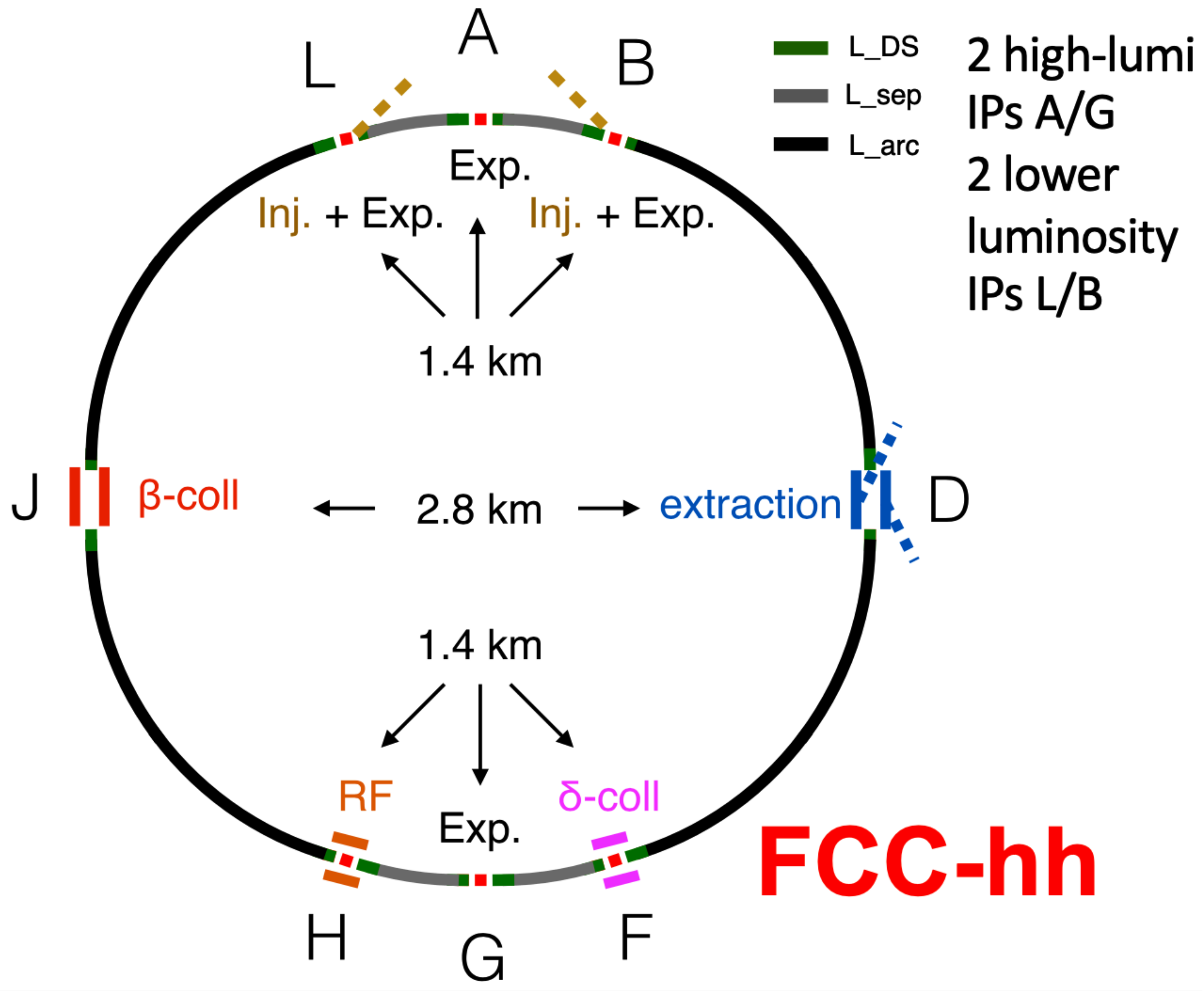
original study requested by ESPP in 2013, started in 2014 as main way to guarantee research continuity in HEP at CERN in the post HL-LHC era

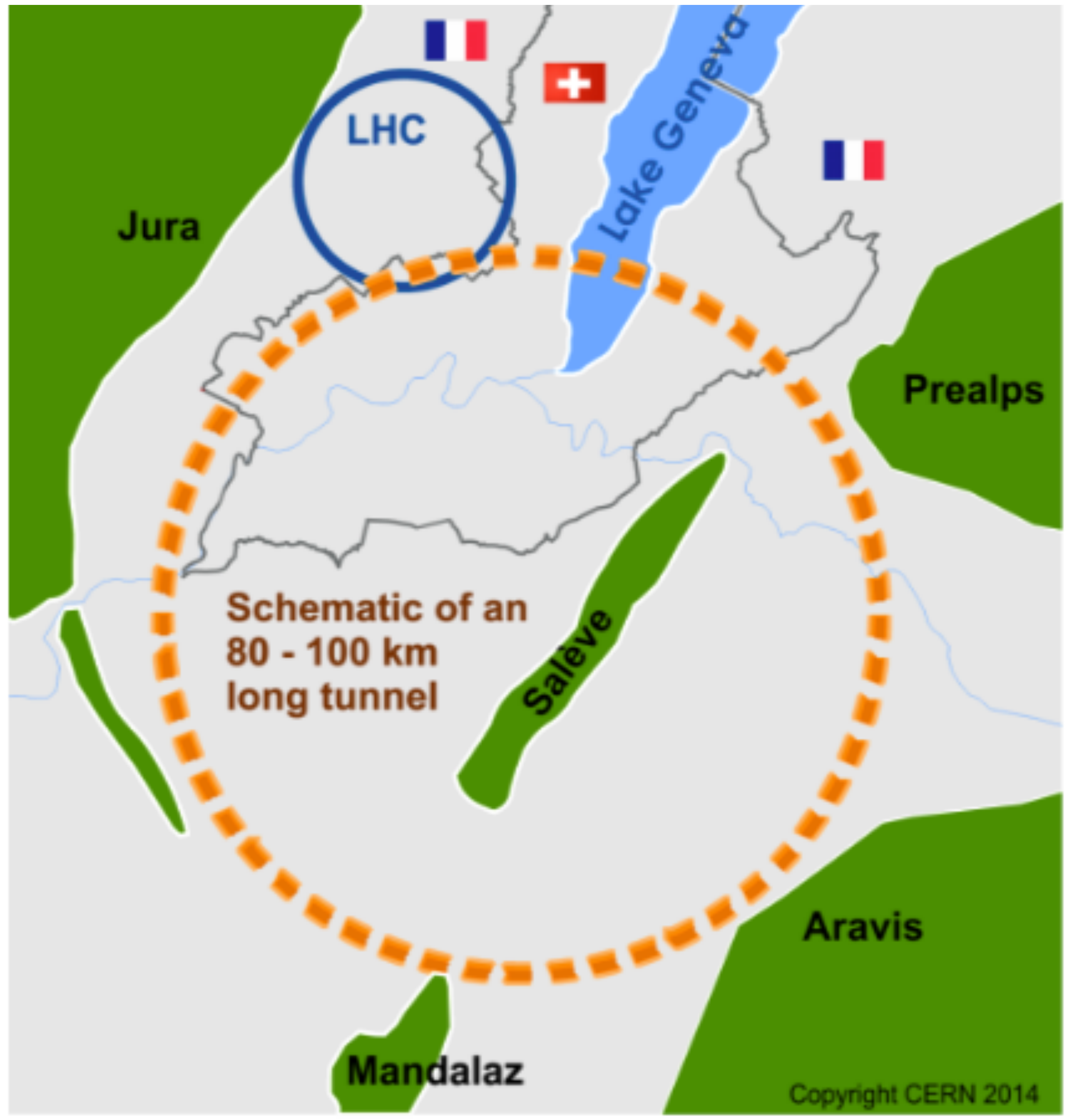
integrated project in two consecutive phases:

- stage 1: FCC-ee - ~90-400 GeV e^+e^- collider as Higgs, EW and top factory at the maximal achievable luminosity
- stage 2: FCC-hh - ~100 TeV hadron collider at the energy frontier + optional ions/eh machines

complementary physics goals & common infrastructures and civil engineering

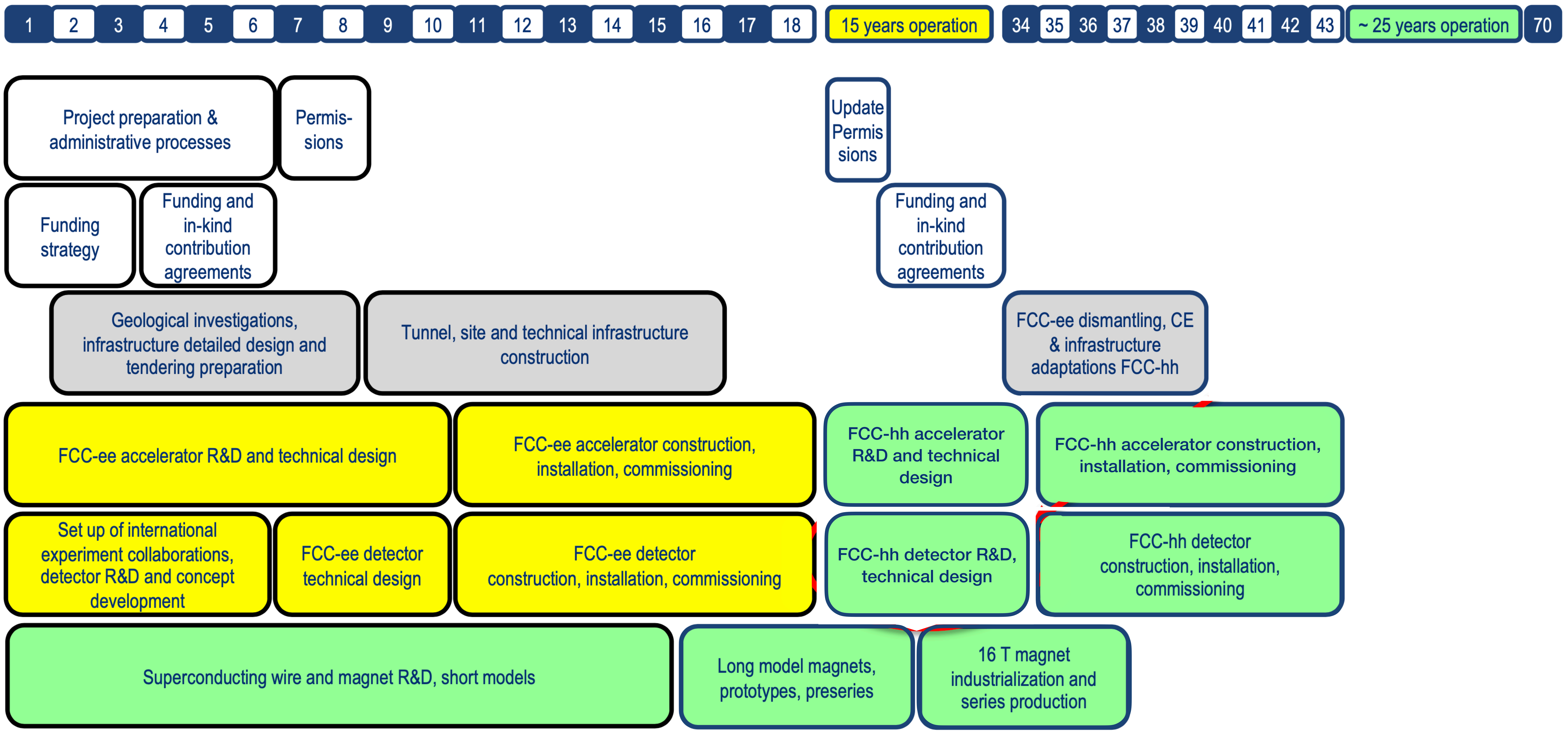




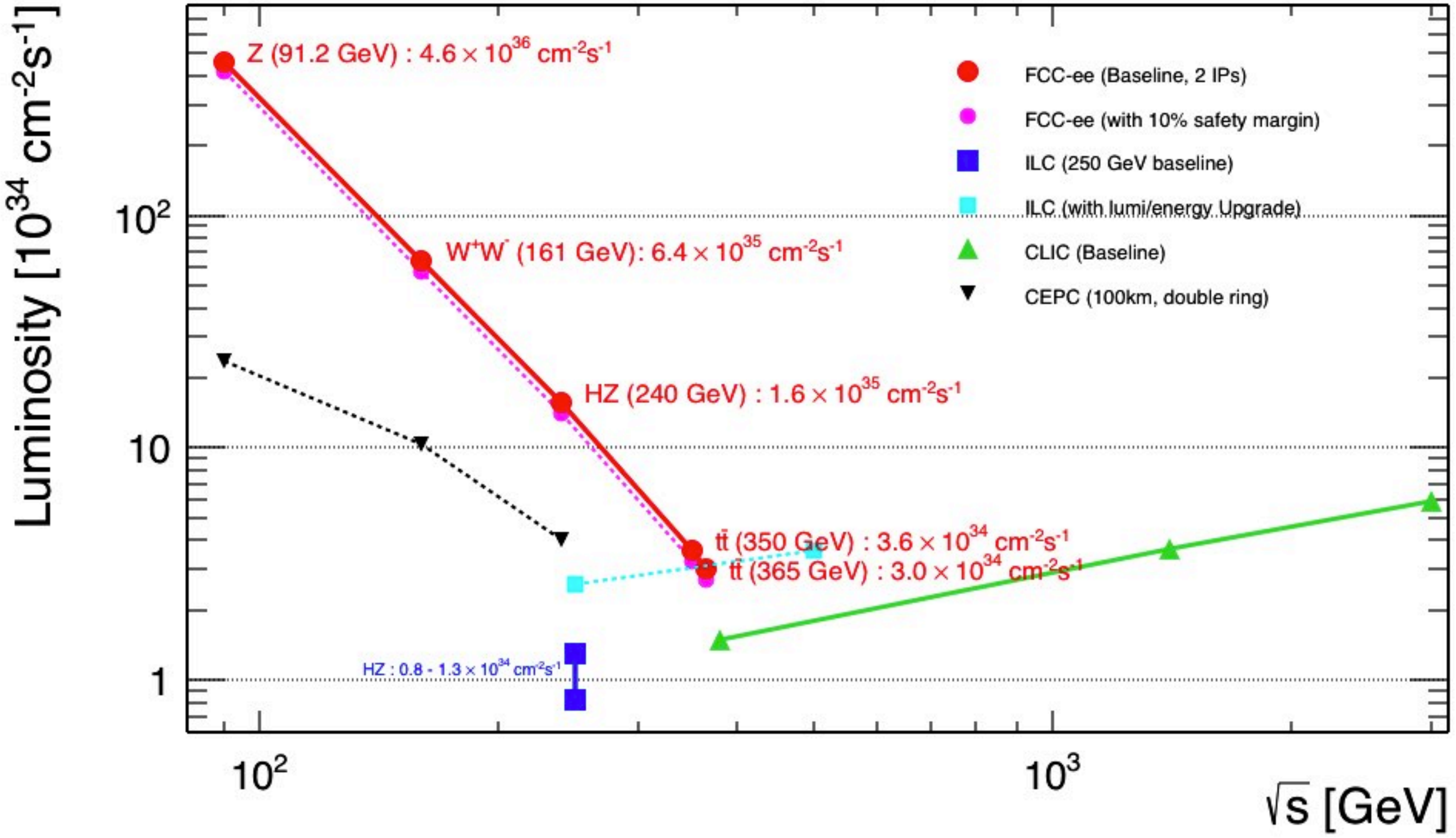


FCC INTEGRATED PROJECT SCHEDULE

FCC-ee: 18 years construction: 8 preparation + 10 construction



FCC-ee LUMINOSITY



- 100 000 Z / second
  - 1 Z / second at LEP
- 10 000 W / hour
  - 20 000 W in 5 years at LEP
- 1 500 Higgs bosons / day
  - 10-20 times more than ILC
- 1 500 top quarks / day

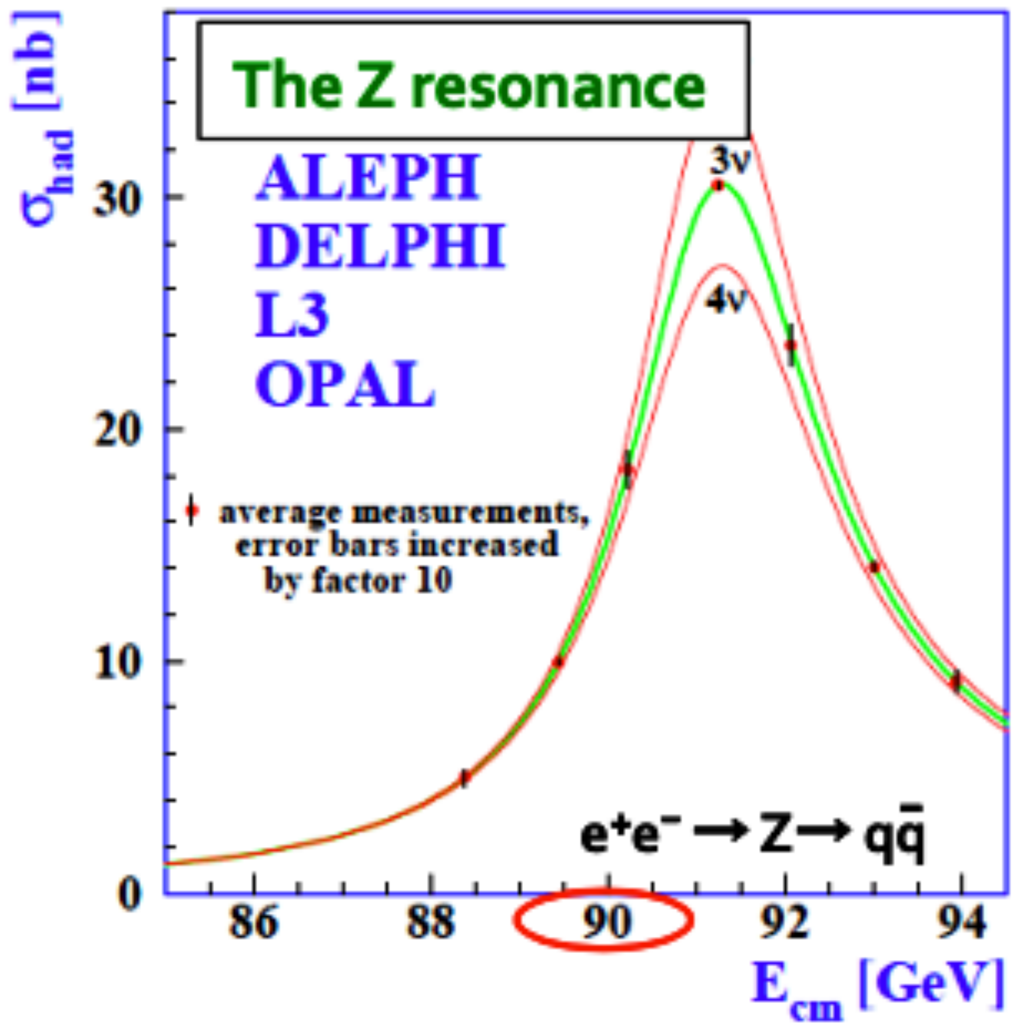
$$\int Ldt \sim 1 - 40\,\mathrm{ab}^{-1}/\mathrm{year}$$

HZ Z

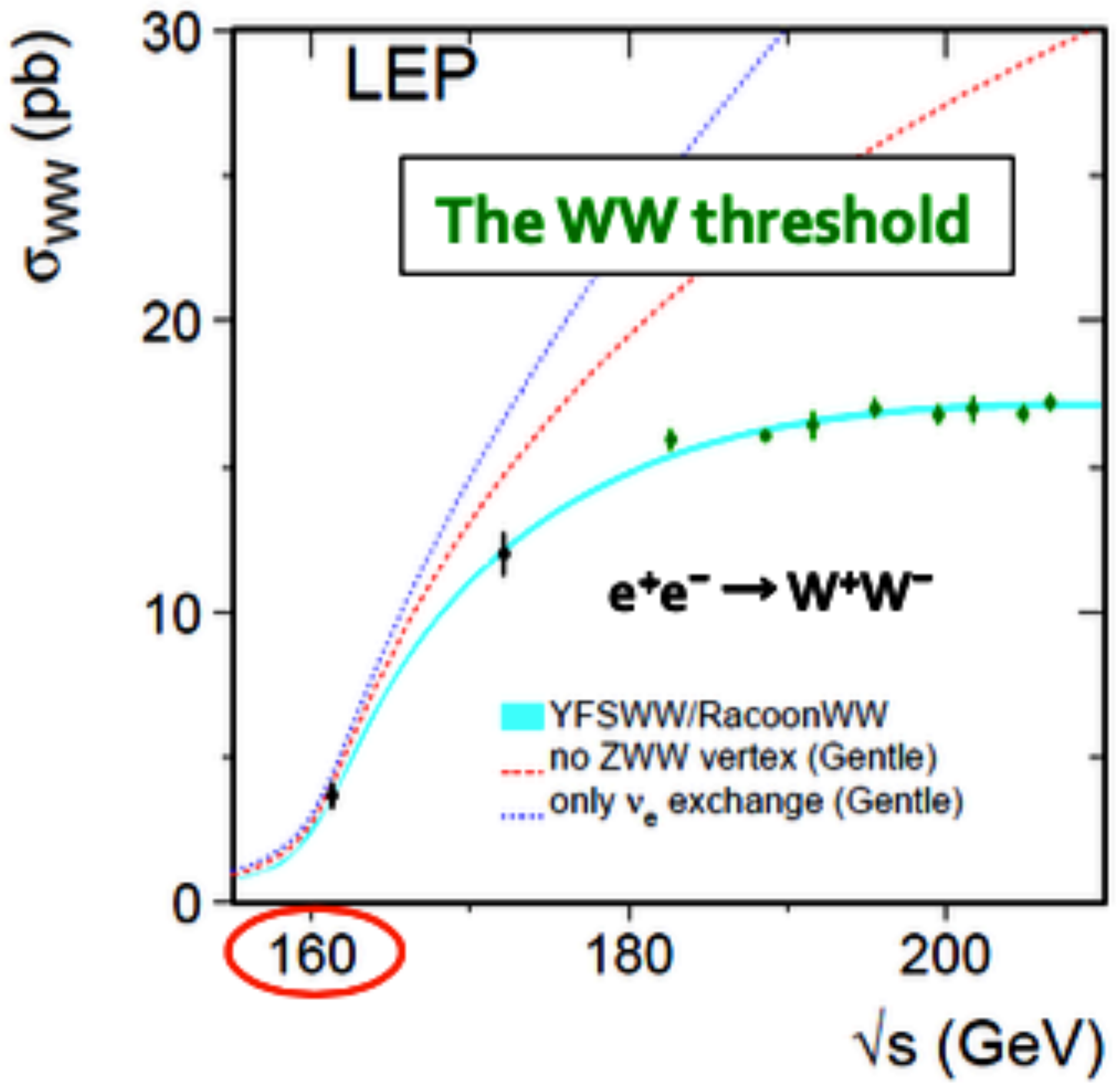
luminosity x$10^{3\div5}$ LEP thanks to the use of techniques developed for B-factories
- independent rings for e^+ and e^-: more bunches, higher currents w/o parasitic collisions
- crab waist and asymmetric IP, and continuous injection
- parameters optimised to keep same totale power for synchrotron radiation at all CM energies (100 MW)
  - total consumption with 50% of the klystrons active is 200 MW (compare with LHC: 210 MW and HL-LHC: 260 MW)

FCC-ee CM ENERGY

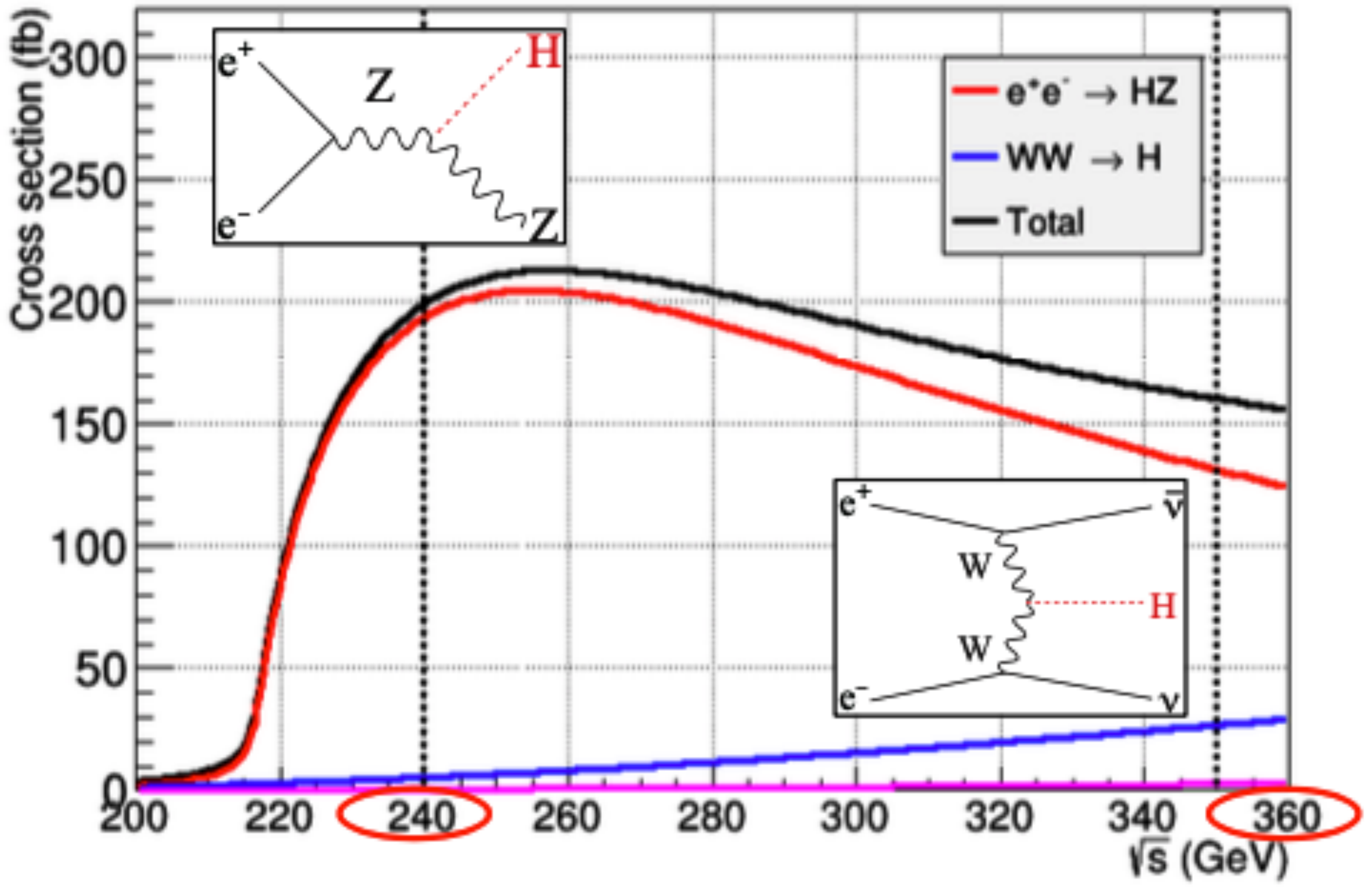
15 years physics: 4 (Z) + 2 (WW) + 3 (H) + 1 LS + 5 (tt) not necessarily in this order …



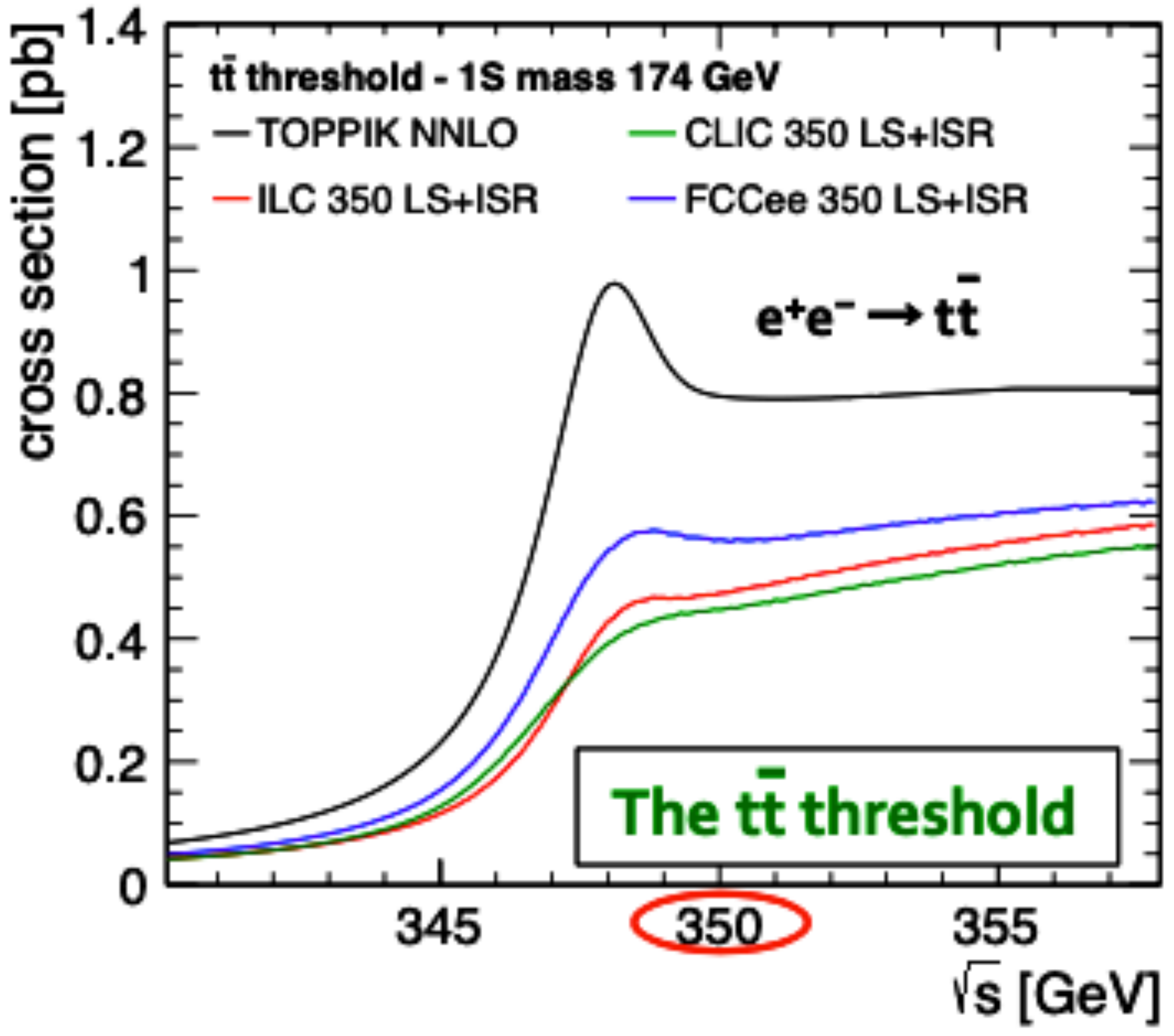
Z



WW

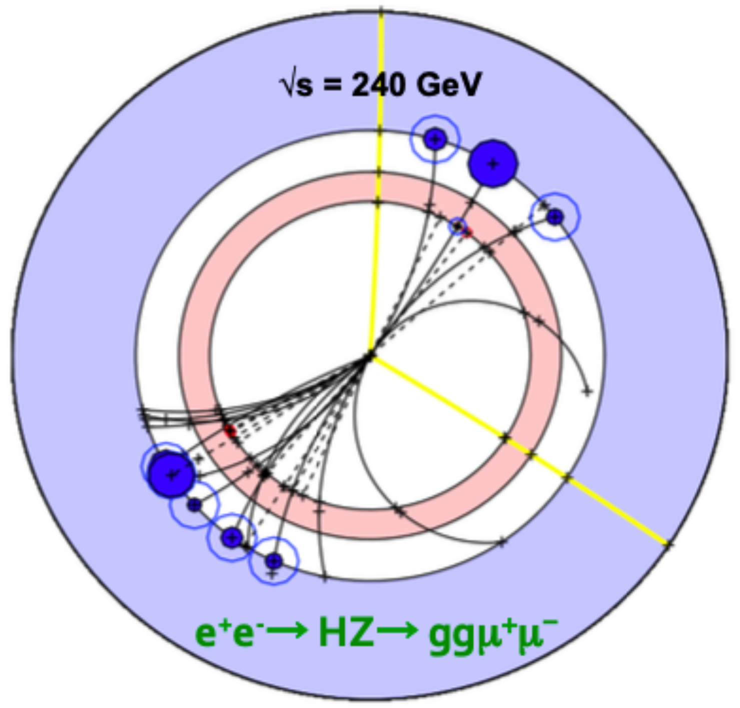


ZH e VBF-H

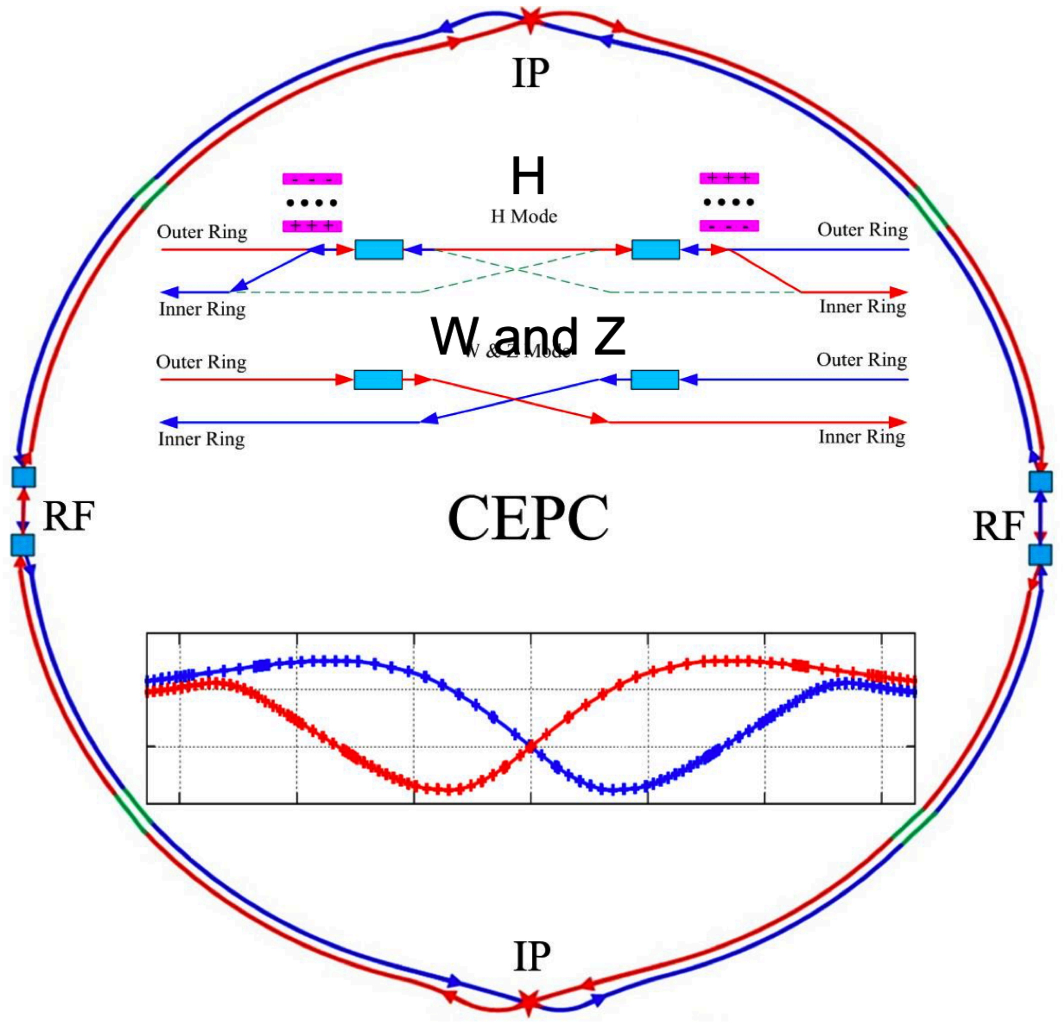


$t\bar{t}$

- physics at the Z pole allows study of light fermions (τ and b - factory)
- clean environment and substantial yields open the possibility to study the properties of gluons in higgs decays: $e^+e^- \to HZ \to gg\mu^+\mu^-$



CEPC: SCHEDULE



CEPC collider ring (100km)

CEPC Site Selections

1) Qinhuangdao, Hebei Province（Completed in 2014）
2) Huangling, Shanxi Province（Completed in 2017)
3) Shenshan, Guangdong Province(Completed in 2016)
4) Huzhou, Zhejiang Province (Started in March 2018)
5) Chuangchun, Jilin Province (Started in May 2018)
6) Changsha, Hunan Province (Started in Dec. 2018)

2023	2024	2025	2026	2027	2028	2029	2030

51 months (including project preparation) — 2023.1~2027.3 TBM excavation

63 months — 2023.1~2028.3 Drilling & Blasting excavation

Construction duration of civil engineering
63 months **2023.1~2028.3**

Critical path of the physical equipment installation

First-stage control network setting and survey (12 months) + physical equipment alignment and installation (30 months) + Overall alignment and commissioning (6 months) = Total duration (48 months)

2027.1~2030.12

Total duration of CEPC project
96 months **2023.1~2030.12**

- 2027.1~2027.12 First-stage Control network construction and survey — 12months
- 2027.10~2028.9 Second-stage Control network construction and survey — 12months
- 2028.1~2029.6 Support installation and alignment — 18 months
- 2028.3~2029.8 Dipole magnets installation — 18 months
- 2029.9~2030.6 Installation of other equipment — 10 months
- 2030.7~2030.12 Overall alignment and commissioning — 6 months

optimisation post-CDR: now very similar to FCC-ee

FCC-ee DETECTOR REQUIREMENTS

- stronger constraints on the interaction point due to luminosity maximisation:
  - quadrupoles, sextuples and compensation solenoid extremely close to the IP
    - reduced space for luminosity detectors (a factor 2 closer to IP compared to LEP experiments)
    - detector $B \leq 2$ T
- sophisticated shielding of beam pipe to minimise synchrotron radiation adverse effects: Machine Detector Interface complex and crucial
- “continuous” beam (no bunch trains) w/ bunch spacing between 20 ns (Z) and 7 μs (tt):
  - fast detectors response (< 1 μs) and fast RE electronic and DAQ (@Z pole: ~70 KHz Z + ~100 KHz LumiCal rate)
  - highly segmented silicon detectors to cope with occupancy due to SR and $\gamma\gamma \to e^+e^-$

- With 100,000 Z / second / detector, expect more than 2×10^{12} Z / year
  - Statistical accuracies on cross sections, asymmetries, etc. of 10^{-5} or better
    - Experimental uncertainties must be controlled at this level too
      - ➠ Demands state-of-the-art performance for all detector subsystems
- Vertex detector
  - Excellent b- and c-tagging capabilities : few μm precision for charged particle origin
    - Small pitch, thin layers, limited cooling, first layer as close as possible from IP
- Tracker
  - State-of-the-art momentum and angular resolution for charged particles.
    - Typically $\sigma(1/p) \sim 2-3\times10^{-5}$ GeV^{-1} and $\sigma(\theta,\phi) \sim 0.1$ mrad for 45 GeV muons
    - Almost transparent to particles (as little material as possible)
  - Particle ID is a valuable additional ability
- Calorimeters
  - Good particle-flow capabilities and energy resolution
    - Transverse segmentation ~ cm : separate clusters from different particles in jets
    - Longitudinal segmentation : identify or even track electron/photon and hadron showers
    - $\sigma(E) \sim 10\%\sqrt{E}$ for e, γ and ~$30\%\sqrt{E}$ for pions
    - Inside solenoid coil, or alternatively, extremely thin coil
- Instrumented return yoke OR large tracking volume outside the calorimeters
  - Muon identification and long-lived particle reconstruction

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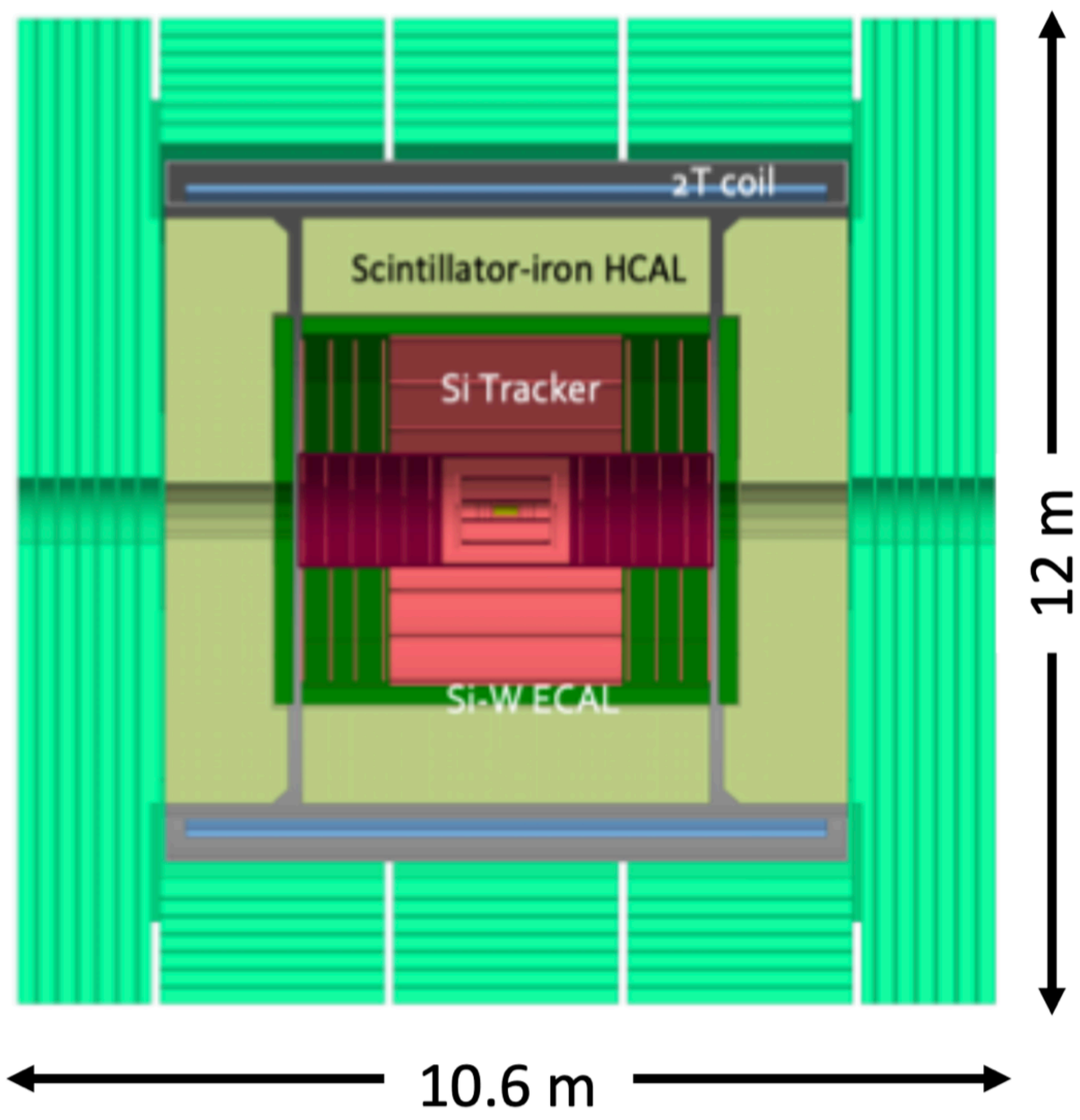
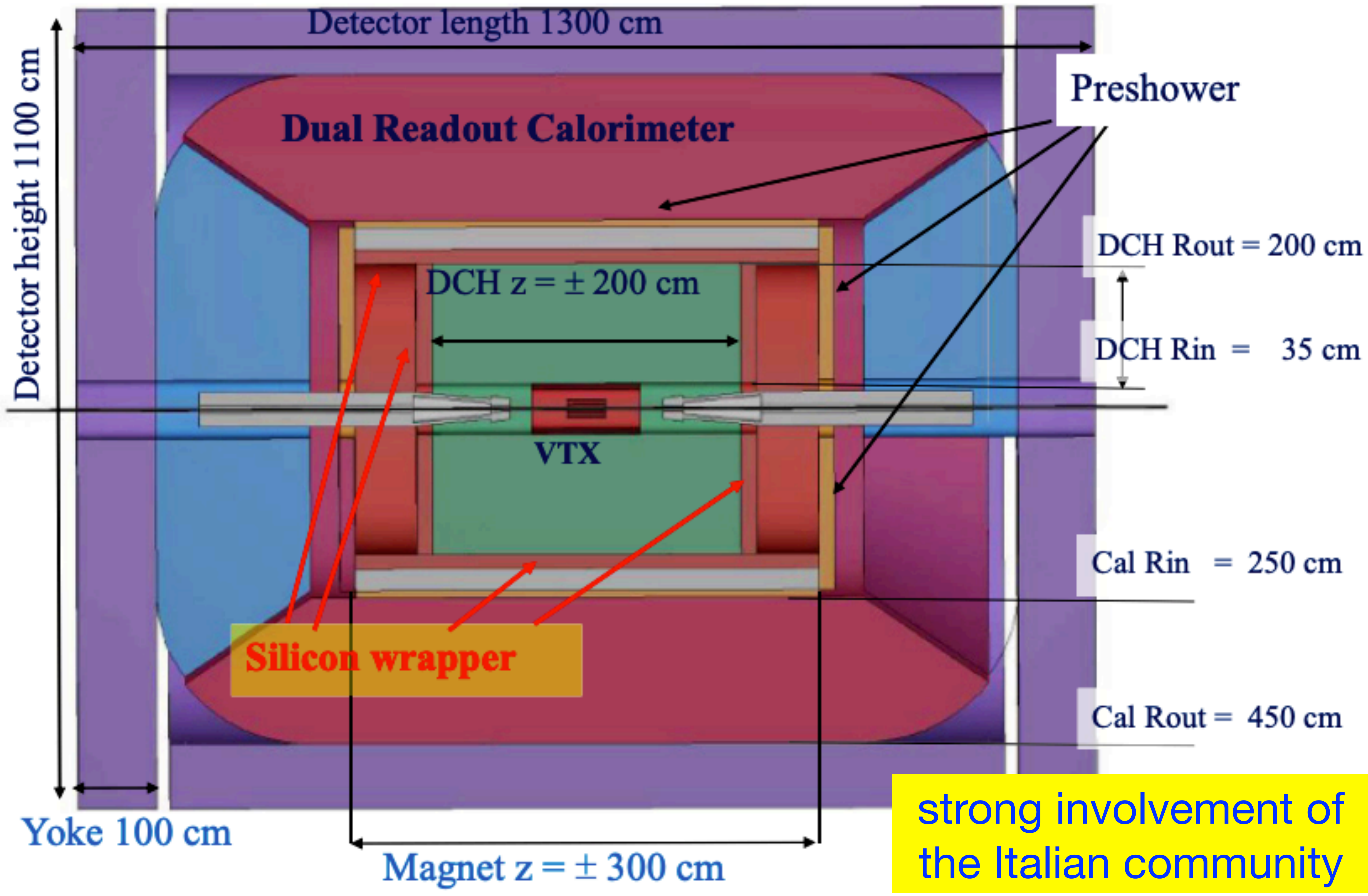
FCC-ee CONCEPTUAL REFERENCE DETECTORS

Clic-Like Detector: adapted from CLIC design



- 2T B-field (CMS-style)
- Silicon ID (pixel + tracker)
- 3D imaging Silicon-tungsten ECAL
- Scintillator + FE HCAL
- MS: steel yoke instrumented with RPCs

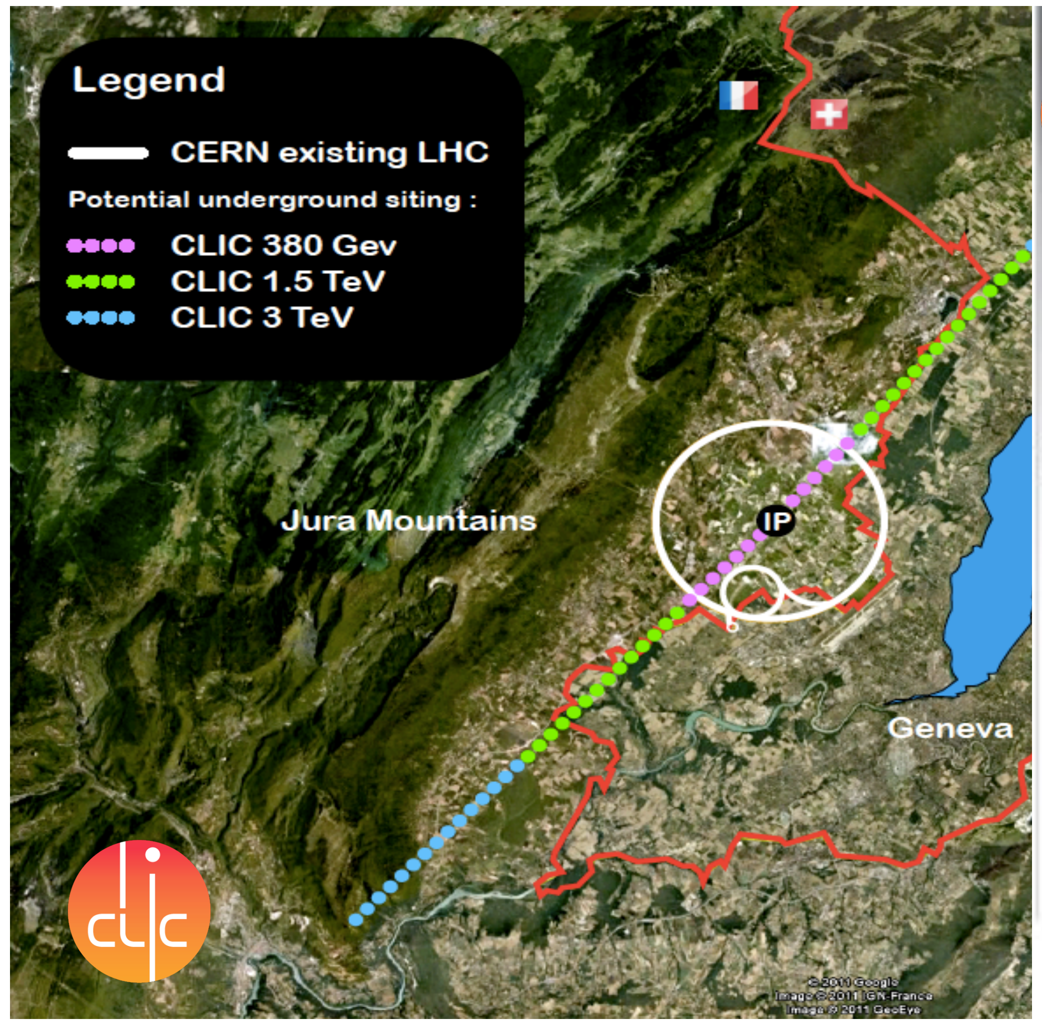
International Detector for Electron-positron Accelerators: specific design for FCC-ee / CepC

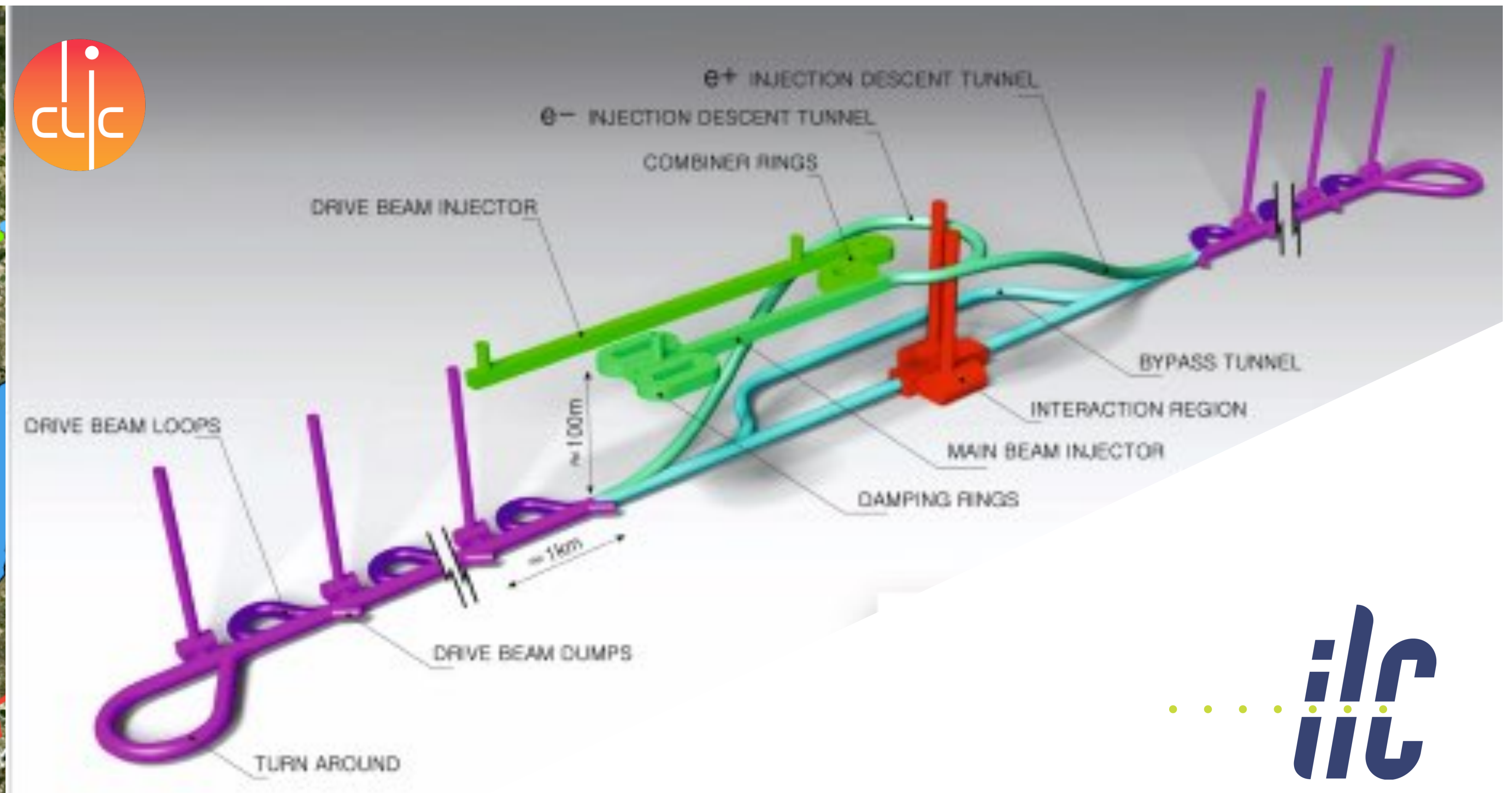


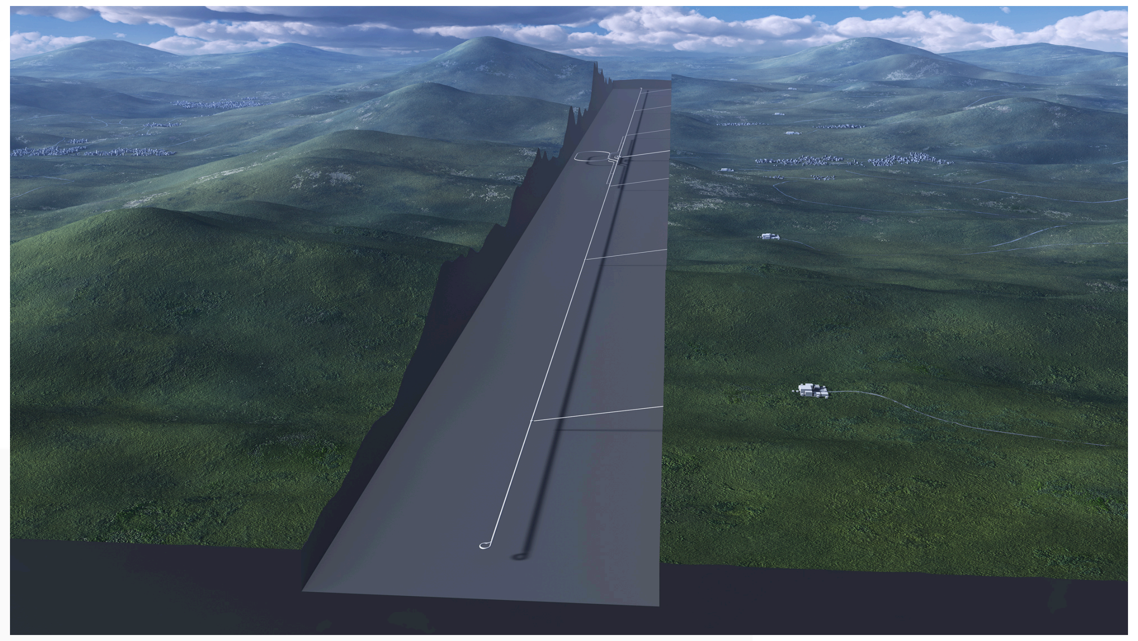
strong involvement of the Italian community

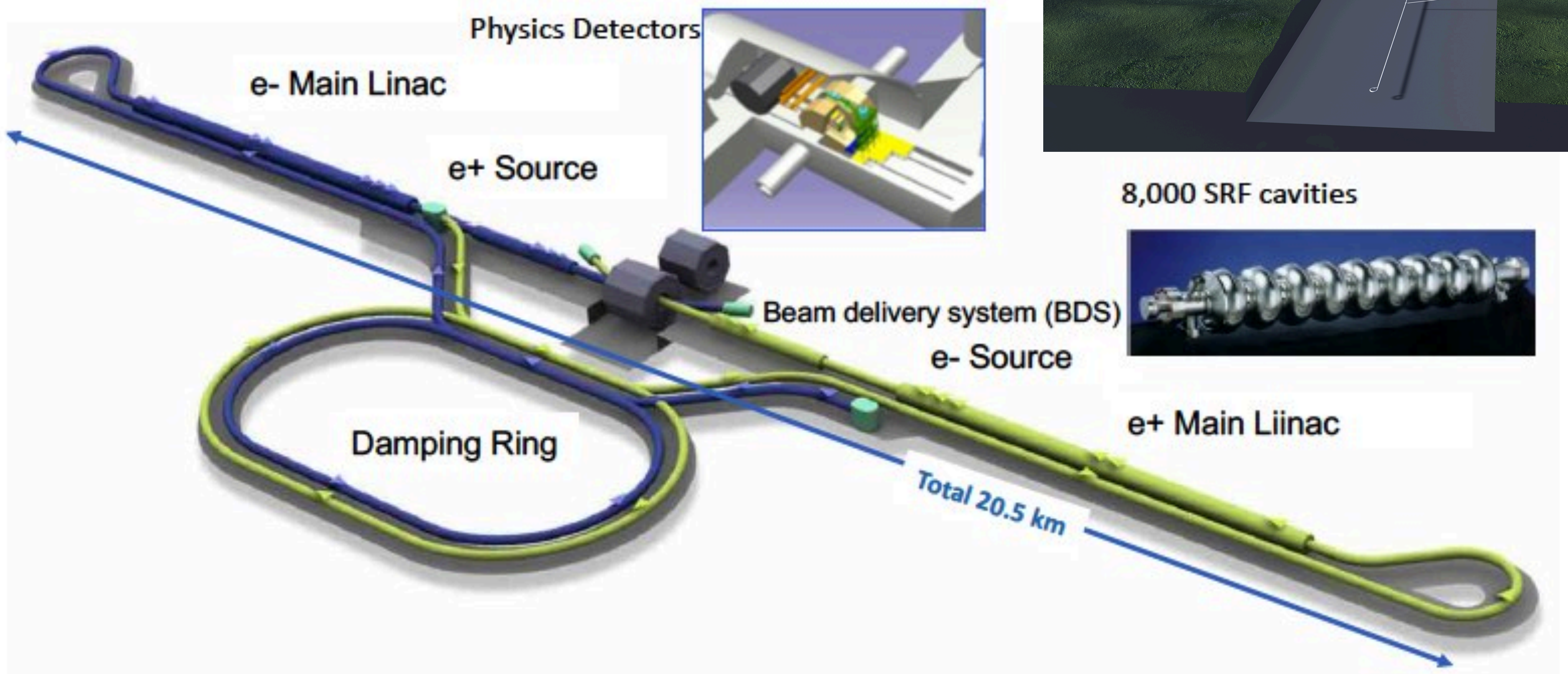
- 2T SC solenoid 2T ultra-thin and transparent before calorimeters
- Silicon vertex detector + short-drift, ultra-light wire chamber
- Silicon wrapper pre-shower/timing counter
- Dual-readout calorimeter + possibly coupled with a crystal ECAL
- MS: thin iron yoke equipped with RPCs

ILC & CLIC









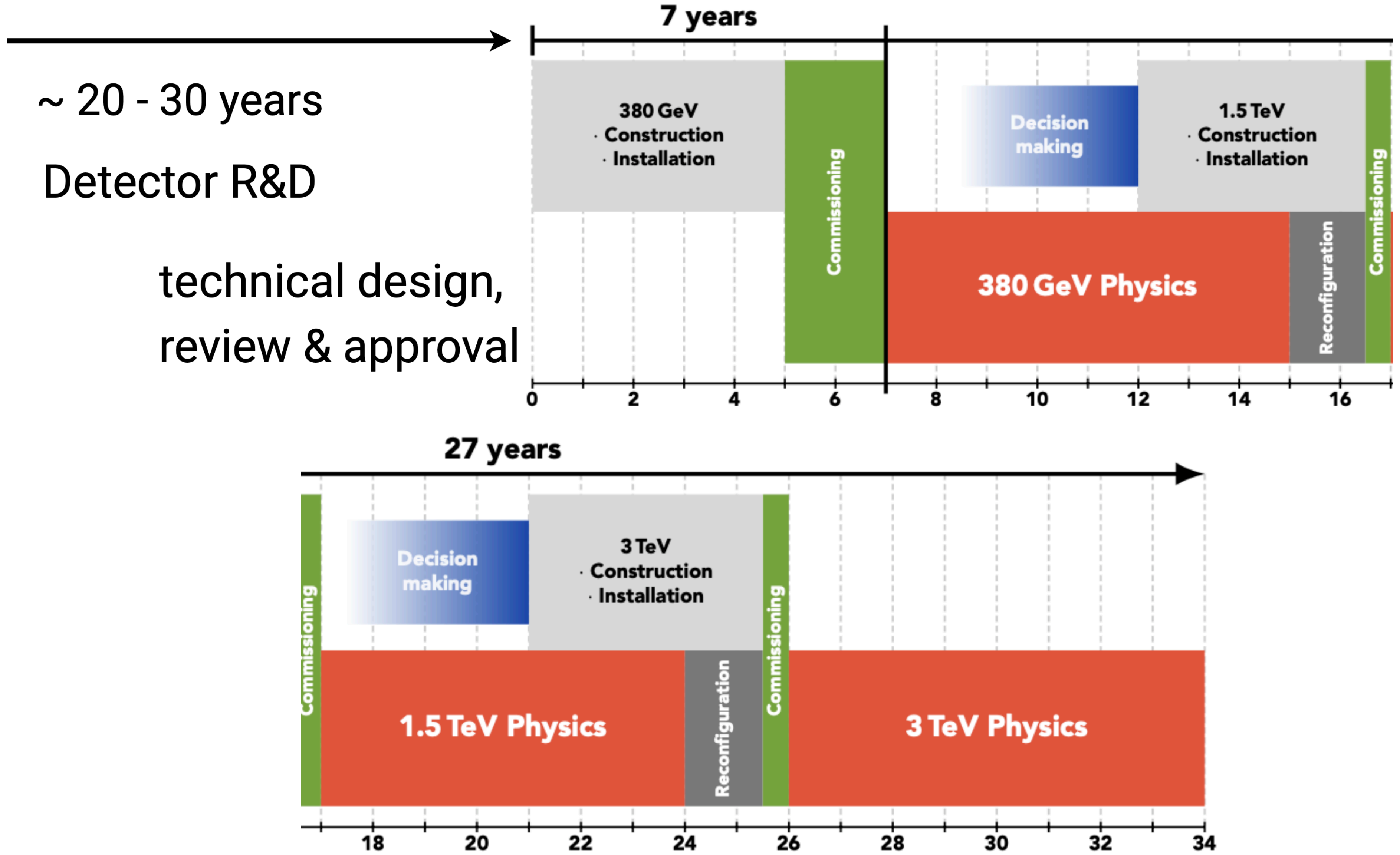
International Linear Collider ILC

- Superconducting Cavities, 1.3GHz, 31.5 (35) MV/m
- Klystrons
- 250GeV CME, upgradeable to 500, 1000GeV
- L = 1.35x10^{34} cm^{-2}s^{-1} (at initial 250GeV)
- 20km length, in Tohoku / Japan
- Polarisation 80%(e-), 30%(e+)

Compact Linear Collider CLIC

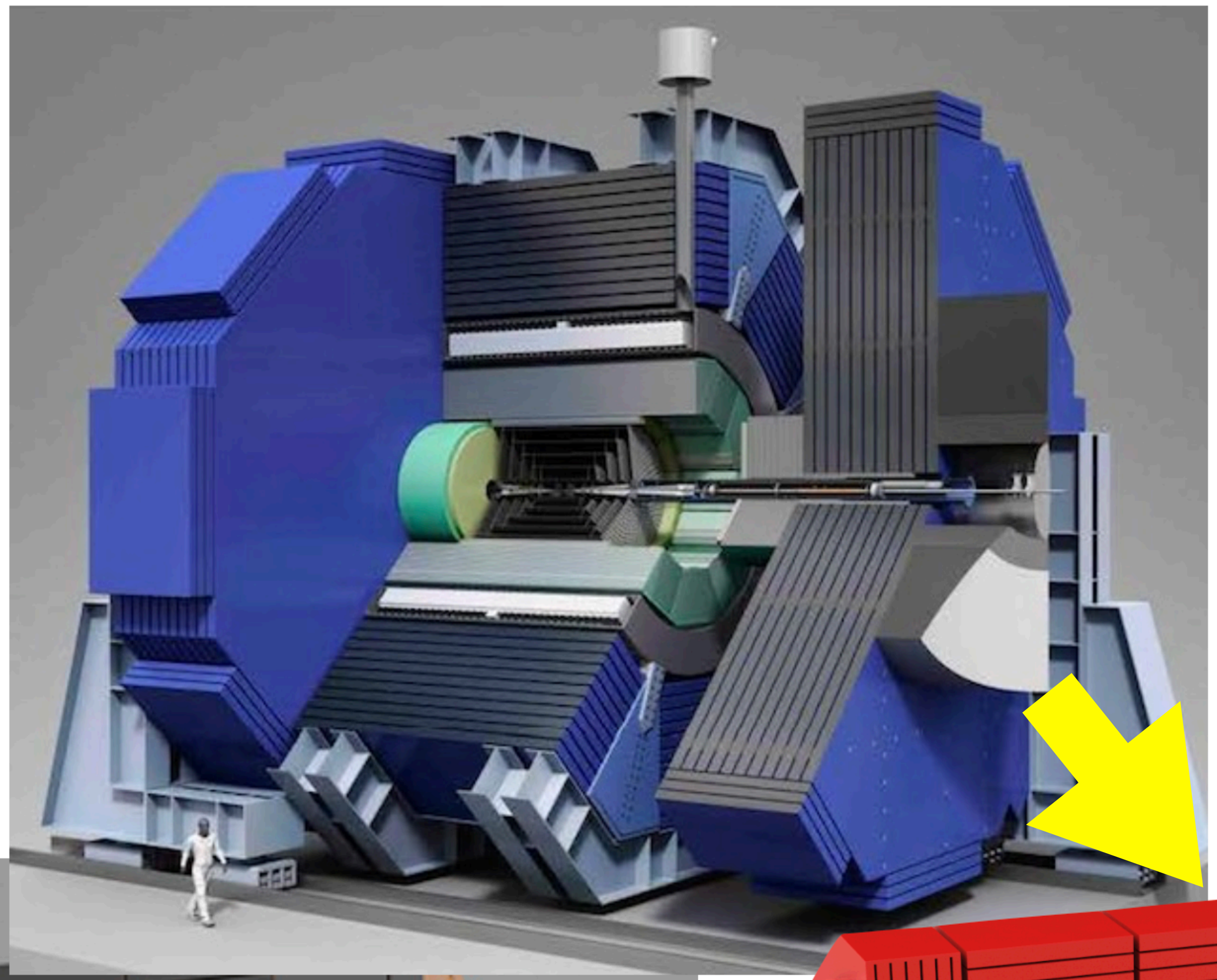
- NC Copper Cavities, 12.0GHz, 72 – 100 MV/m
- Two-beam acceleration (Klystrons)
- 380GeV CME, upgradeable to 1500, 3000GeV
- L = 1.50x10^{34} cm^{-2}s^{-1} (at initial 380GeV)
- 11.4km long, at CERN / France & Switzerland
- Polarisation 80% (e-)

"feasible start-date"
2035-2040 (ILC) - 2040-2045 (CLIC)

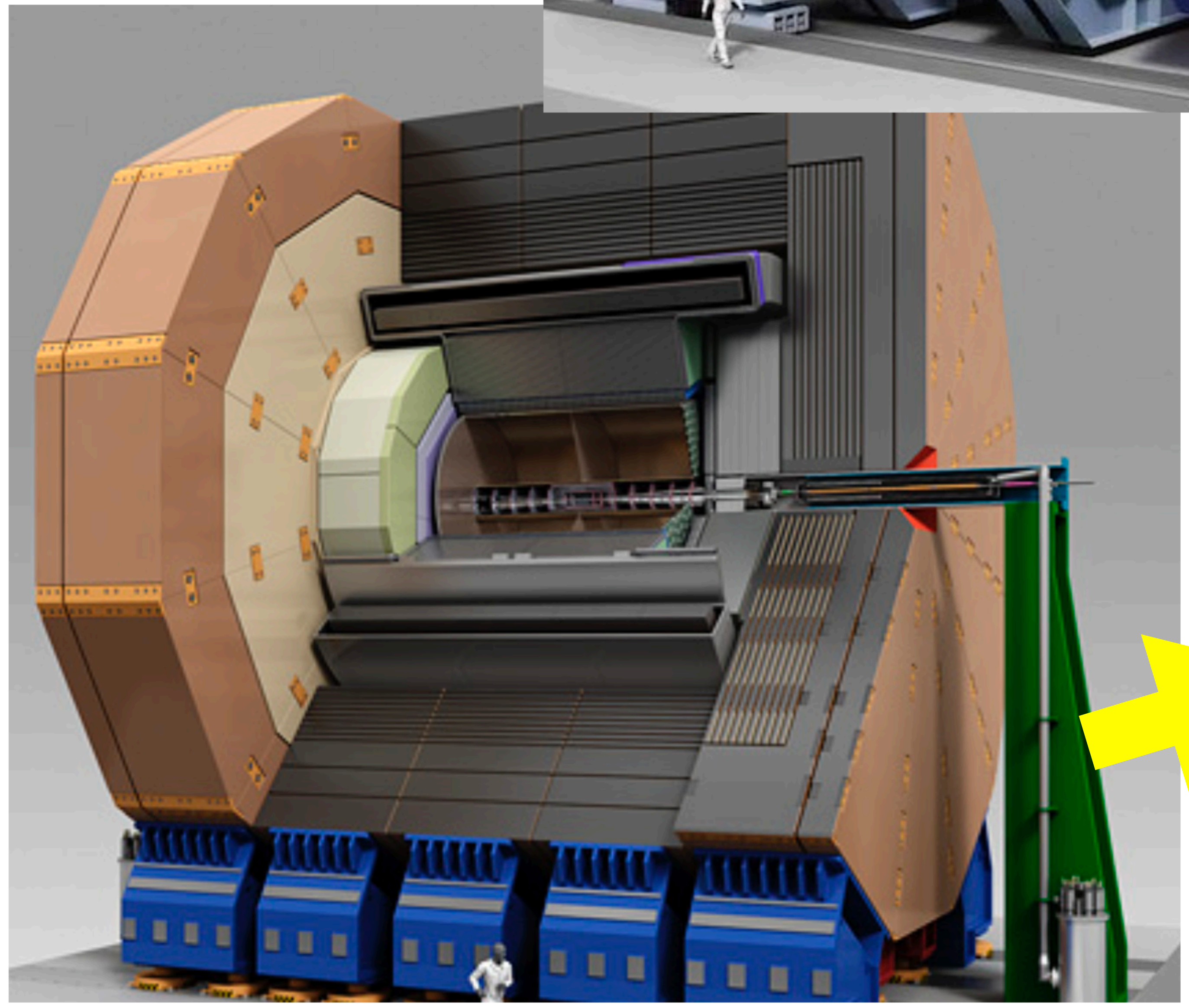


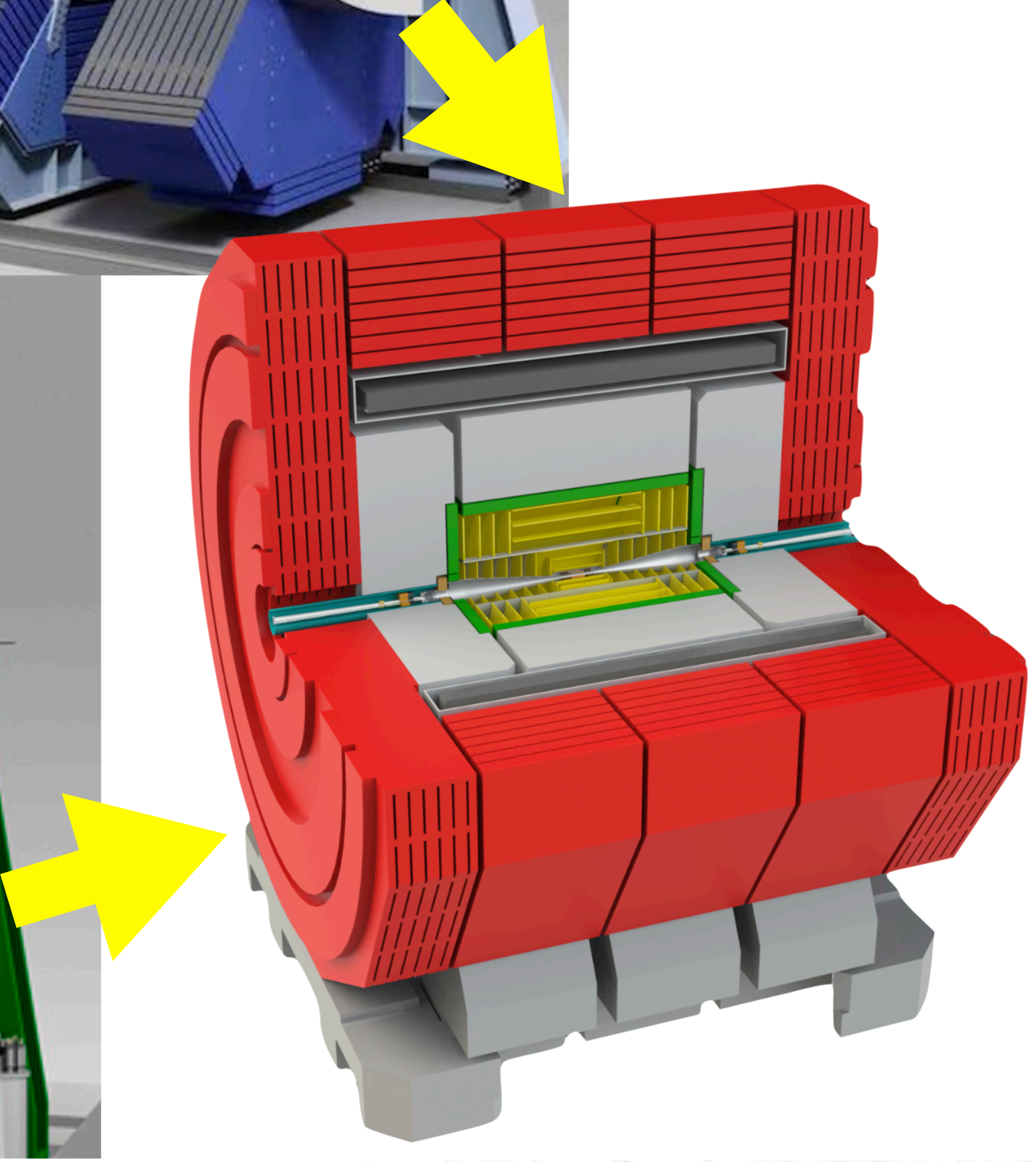
LC DETECTORS

SiD
more compact all-Si



ILD
larger volume Si+TPC



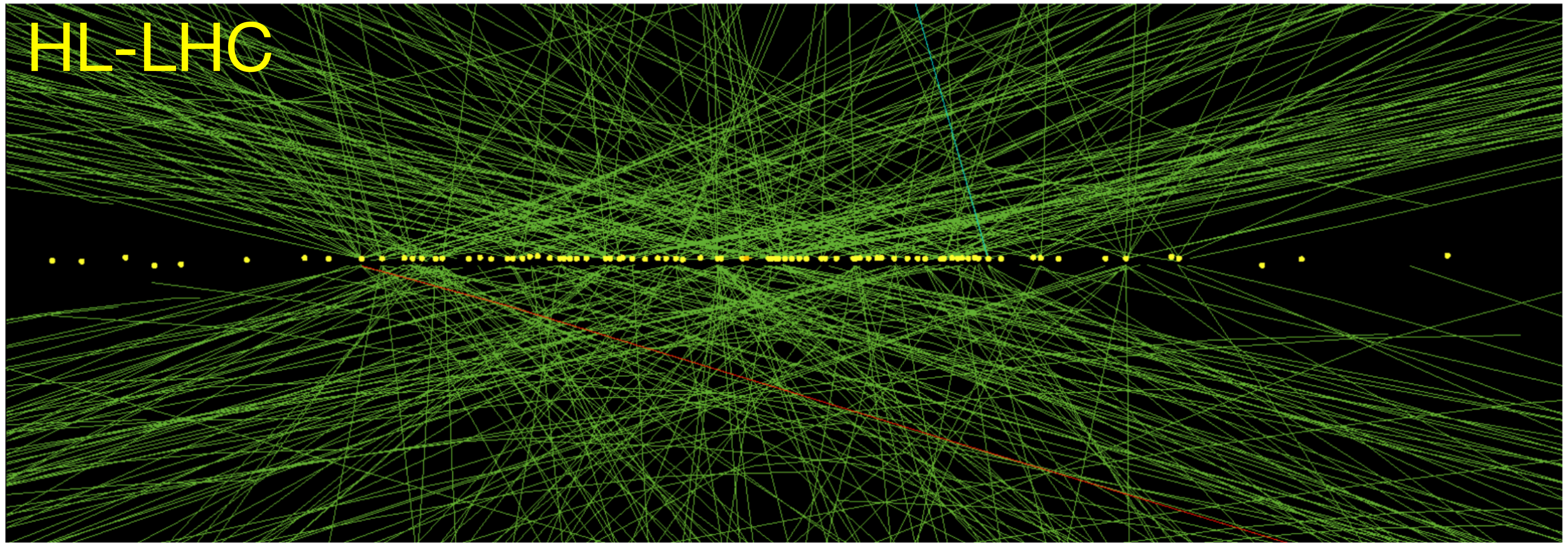


- A **large-volume solenoid** 3.5 - 5 T, enclosing calorimeters and tracking
- **Highly granular calorimeter systems**, optimised for particle flow reconstruction, best jet energy resolution *[Si, Scint + SiPMs, RPCs]*
- **Low-mass main tracker**, for excellent momentum resolution at high energies *[Si, TPC + Si]*
- **Forward calorimeters,** for low-angle electron measurements, luminosity *[Si, GaAs]*
- **Vertex detector**, lowest possible mass, smallest possible radius *[MAPS, thinned hybrid detectors]*
- **Triggerless readout** of main detector systems

CLIC detectors VS FCCee detectors
- higher energy → larger calorimeter depth
- lower luminosity → higher solenoidal fields
- higher fields → increase yoke thickness, smaller tracker radius
- higher background from e^+e^- → hadrons → larger VTX radius

FCC-hh DETECTORS

- main challenges: achieve state of the art in physics object ID and momentum/energy resolution with a pileup of <μ>=1000!
  - granularity and timing are a must
  - radiation hardness and stability also crucial (1 MeV neutron equivalent fluence ~20÷30 × HL-LHC)

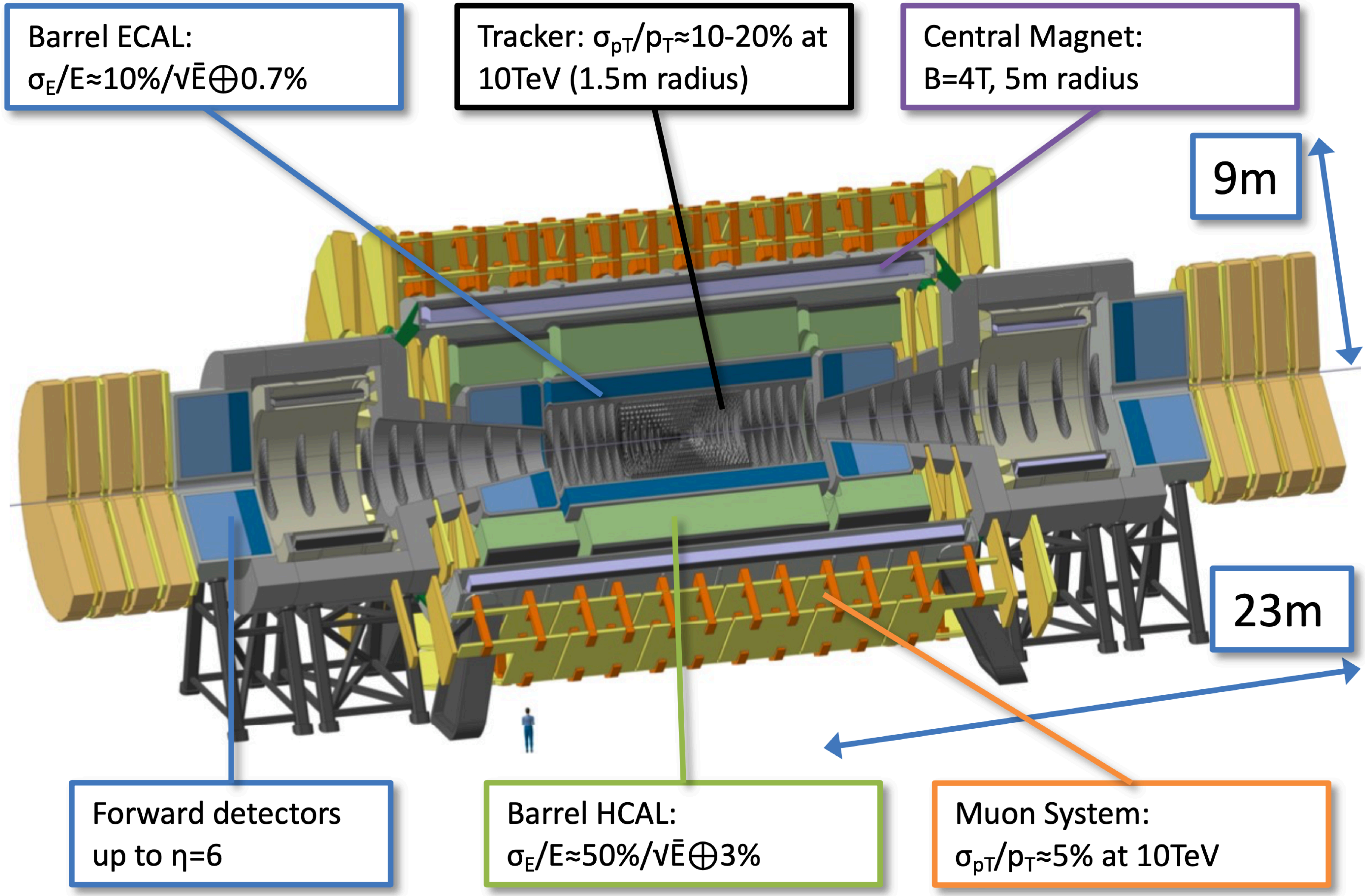


HL-LHC max pileup <μ>=200
average distance between vertices at z=0:
Δd~1mm and Δt~3 ps

@FCC-hh at <μ>=1000: Δd~120 μm and Δt~0.4 ps

Multiple scattering in the beam pipe: even w/ a perfect tracking detector the error due to MS is significant

LHC-hh REFERENCE DETECTOR DESIGN



just one example experiment
other choice possibile and very likely
a lot of room for new ideas, concepts
and different technologies

FCC-hh CDR

https://muoncollider.web.cern.ch/

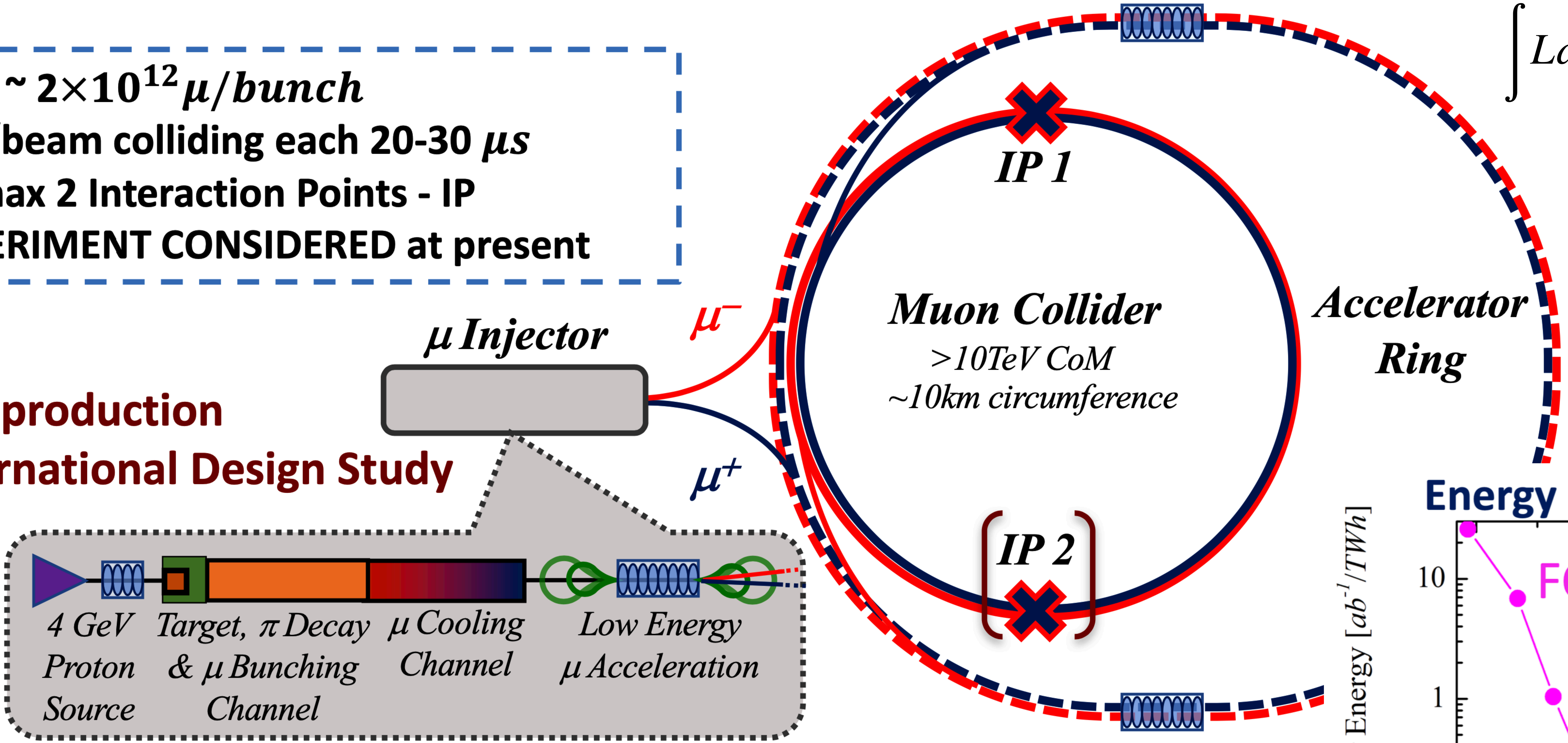
MUON COLLIDER

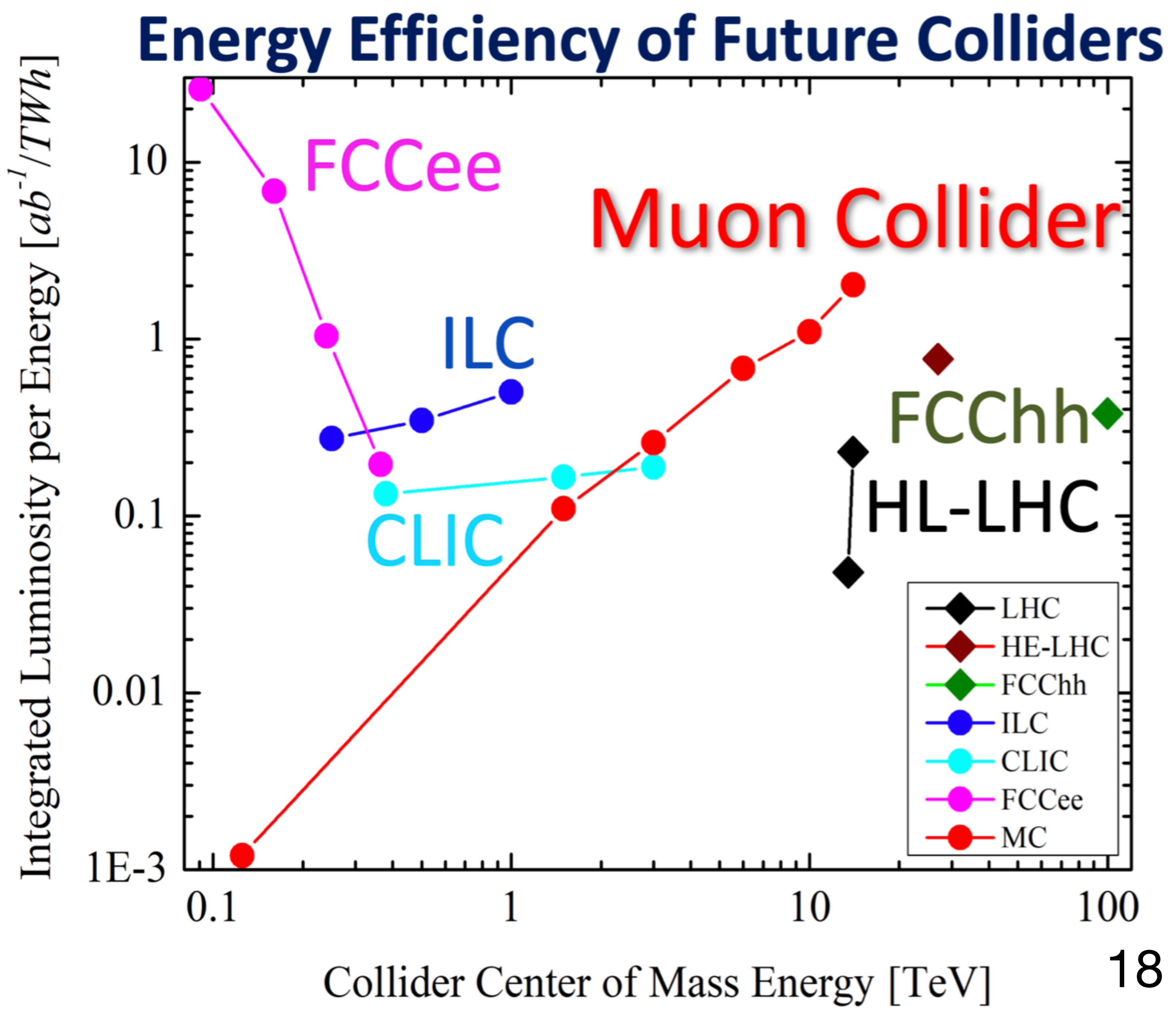
$$L = 2 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1} @ 10\ \mathrm{TeV}$$

$$\int L dt = \left(\frac{E_{CM}}{10\ \mathrm{TeV}} \right)^2 \times 10\ \mathrm{ab}^{-1}/5\mathrm{y}$$

$\sim 2\times10^{12} \mu/bunch$
1 bunch/beam colliding each 20-30 μs
➔ max 2 Interaction Points - IP
ONLY 1 EXPERIMENT CONSIDERED at present

Proton driver μ production
Baseline @ International Design Study





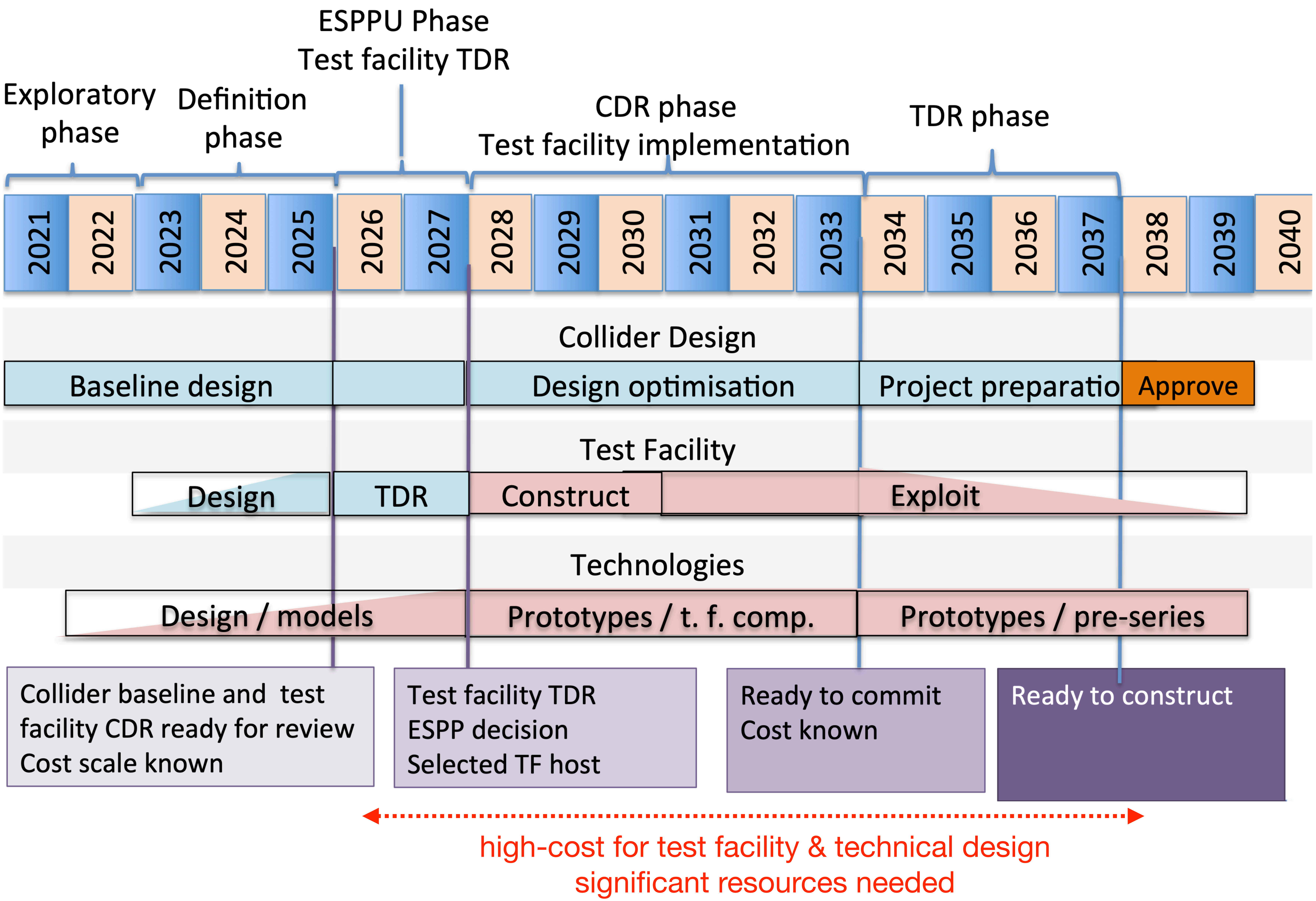
Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled by ionisation cooling in matter

Acceleration to collision energy

Pions decay into muons that can be captured

TECHNICALLY LIMITED LONG-TERM TIMELINE



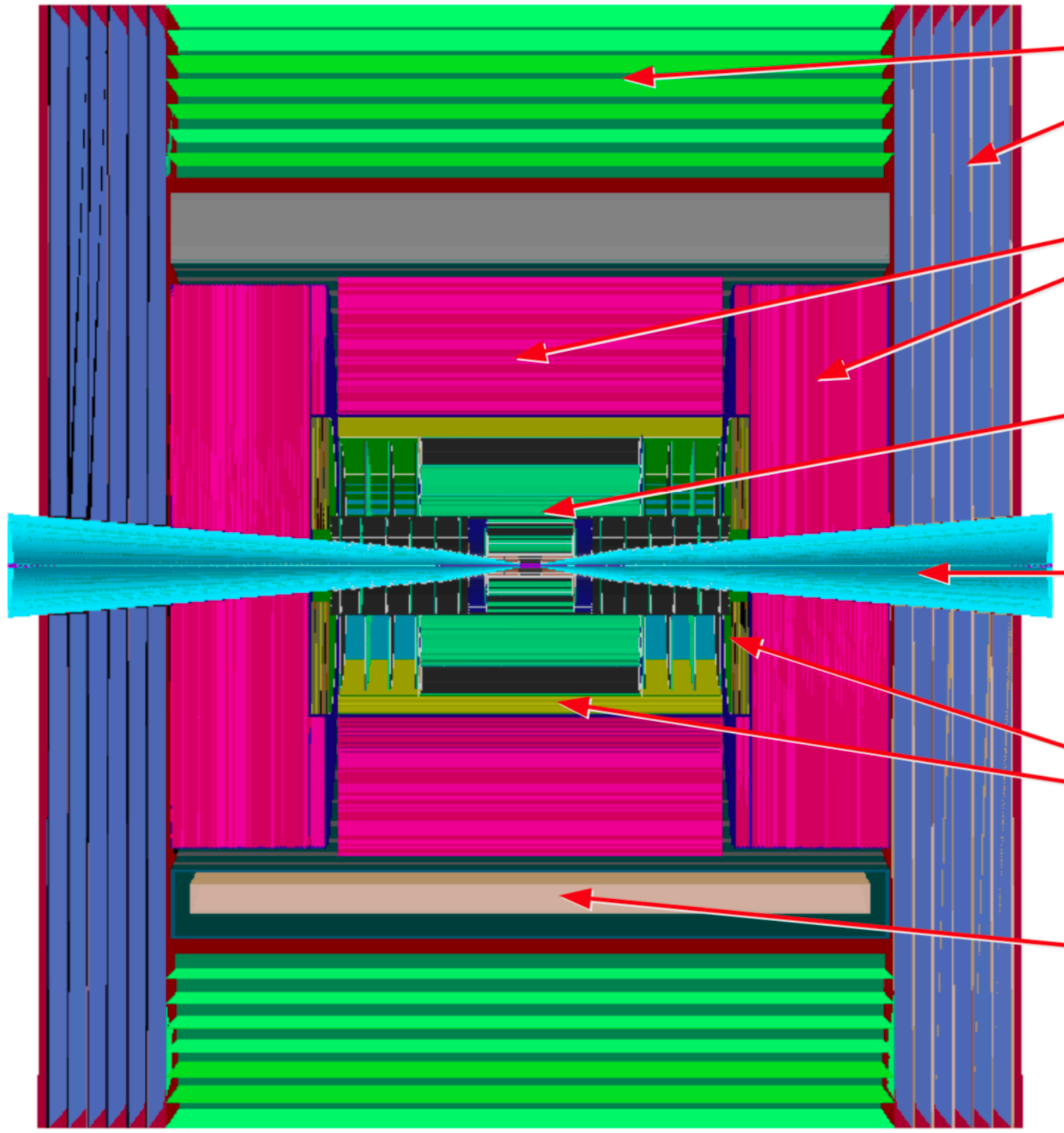
REFERENCE DETECTOR @MUON COLLIDER

- GOAL: explore multi-TeV energy domain beyond reach of ee-colliders
  - precision measurements (e.g. higgs potential)
  - discovery searches

$$V = \frac{1}{2} m_h^2 h^2 + (1+k_3)\lambda_{hhh}^{SM} \nu h^3 + (1+k_4)\lambda_{hhhh}^{SM} h^4$$

sensitivity ~3% with 20 ab-1 @10 TeV
(wrt FCC combined ~5%)

sensitivity ~few 10% with 30 ab^{-1} @10 TeV
(significantly better than what expected at FCC-hh)



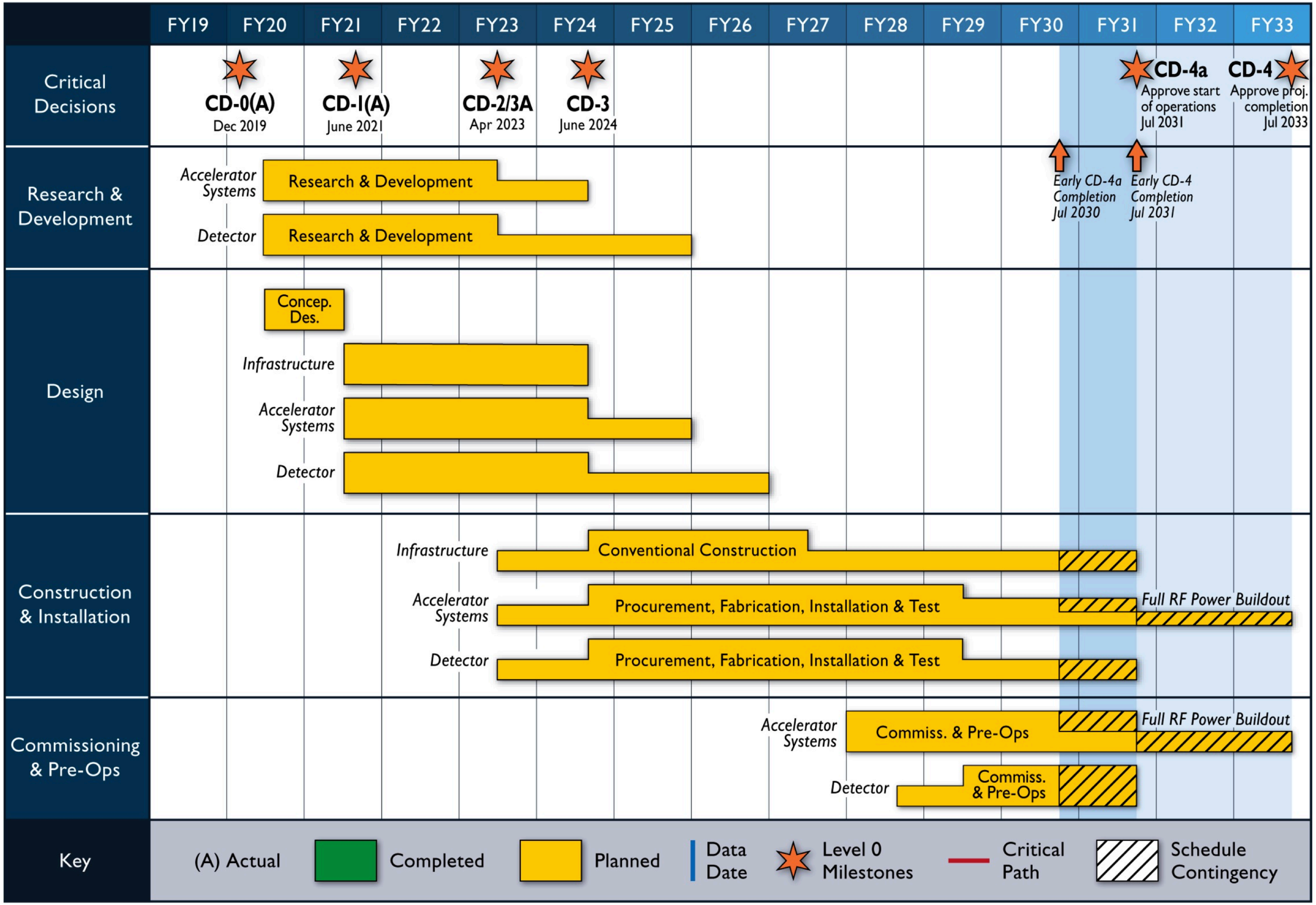
- detector concept based on CLIC detector model + MDI and Vertex detector designed by MAP

- most tracker and calorimeter hits originate from BIB
- occupancy in VTX detector ~×10 CMS pixels @HL-LHC
- large bandwidth needed to send data off the detector (data rates ~50 Gbps)
- multi-stage filtering with complex data reconstruction

- bunch crossing large ~10-20 μs → possibly a triggerless DAQ systems

ADDITIONAL MATERIAL

EIC



Reference schedule @10/2021

EIC REFERENCE DETECTOR

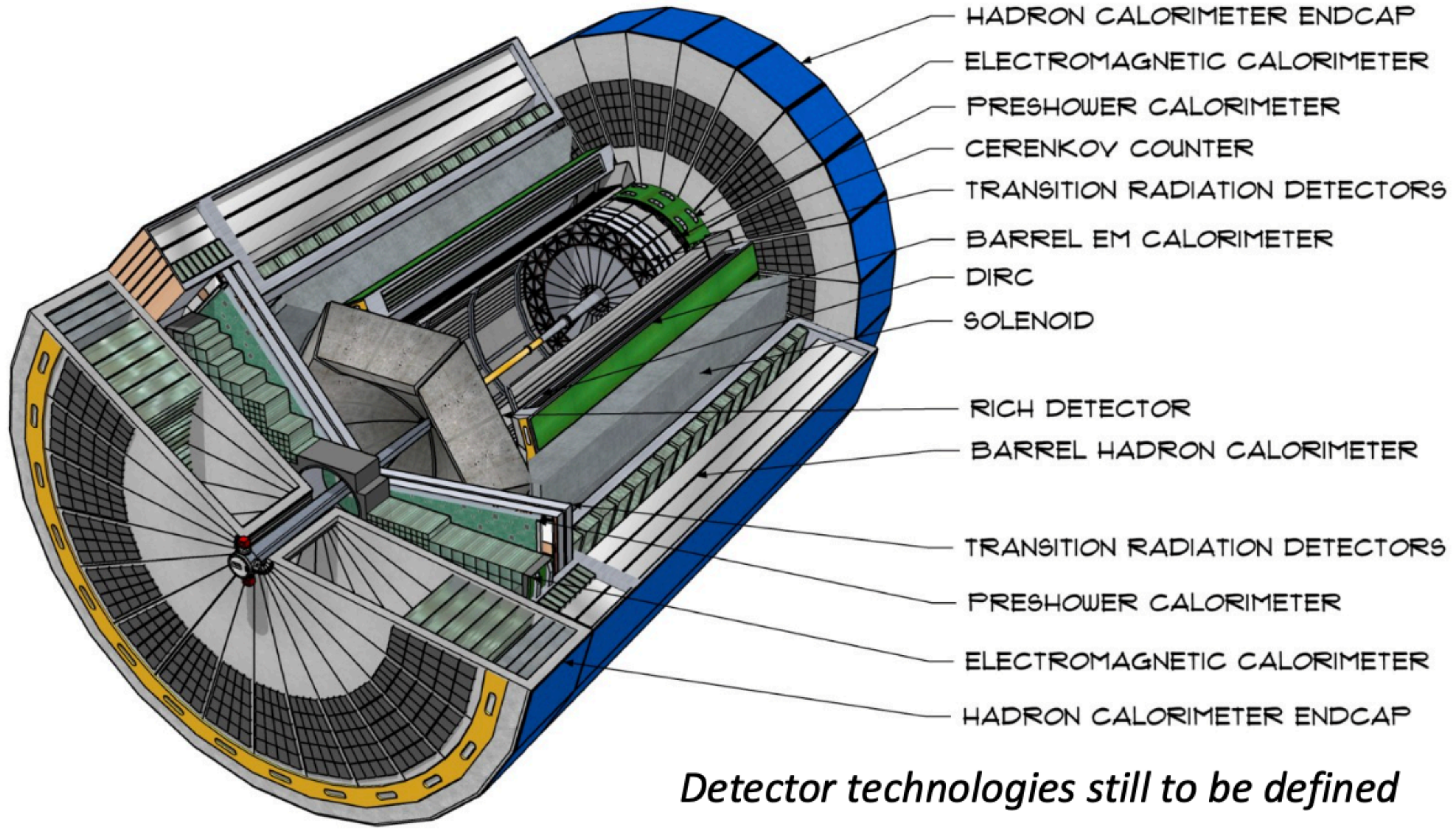
Electron Ion Collider

Detector General Requirements

- Large rapidity ($-4 < \eta < 4$) coverage;
  and far beyond in especially far-forward detector regions
- High precision low mass tracking
  - small (μ-vertex) and large radius tracking
- Electromagnetic and Hadronic Calorimetry
  - equal coverage of tracking and EM-calorimetry
- High performance PID to separate π, K, p on track level
  - also need good e/π separation for scattered electron
- Large acceptance for diffraction, tagging, neutrons from nuclear breakup: critical for physics program
  - Many ancillary detector integrated in the beam line: low-Q^2 tagger, Roman Pots, Zero-Degree Calorimeter, ….
- High control of systematics
  - luminosity monitor, electron & hadron Polarimetry

Not further discussed here

Integration into Interaction Region is critical



Detector technologies still to be defined

Low pile-up, low multiplicity, data rate
~500kHz (full lumi)
Moderate radiation hardness

Main Challenges
- PID
- EMCal at < 2%/ $\sqrt{E}$

EIC – Possible Detector Tehnologies

Possible detector technologies for the Main Detector fulfilling the physics requirements

Note: **setup used for CD1** – **many decisions still open** ⇨ will be decided by the Collaboration

system	system components	reference detectors	detectors, alternative options considered by the community		
tracking	vertex	MAPS, 20 um pitch	MAPS, 10 um pitch		
	barrel	TPC	TPC [a]	MAPS, 20 um pitch	MICROMEGAS [b]
	forward & backward	MAPS, 20 um pitch	GEMs with Cr electrodes		
ECal	barrel	Pb/Sc Shashlyk	SciGlass	W powder/ScFi	W/Sc Shashlyk
	forward	W powder/ScFi	SciGlass	Pb/Sc Shashlyk	W/Sc Shashlyk
	backward, inner	$PbWO_4$	SciGlass		
	backward, outer	SciGlass	PbWO4	W powder/ScFi	W/Sc Shashlyk [c]
h-PID	barrel	High performance DIRC & dE/dx (TPC)	reuse of BABAR DIRC bars	fine resolution TOF	
	forward, high p	fluorocarbon gaseous RICH	double RICH combining	high pressure Ar RICH	
	forward, medium p	aerogel	aerogel and fluorocarbon		
	forward, low p	TOF	dE/dx		
	backward	modular RICH (aerogel)			
e/h separation at low p	forward	TOF & areogel & gaseous RICH	adding TRD		
	backward	modular RICH & TRD	Hadron Blind Detector		
HCal	barrel	Fe/Sc	RPC/DHCAL	Pb/Sc	
	forward	Fe/Sc	RPC/DHCAL	Pb/Sc	
	backward	Fe/Sc	RPC/DHCAL	Pb/Sc	

[a] TPC surrounded by a micro-RWELL tracker
[b] set of coaxial cylindrical MICROMEGAS
[c] also Pb/Sc Shashlyk

Source: *EIC CDR Experimental Equipment, Nov 2020, Table 8.4*

EIC – performance of reference detector

Source: *EIC CDR Experimental Equipment, November 2020*

η	θ	Nomenclature			Tracking						Electrons and Photons			π/K/p		HCAL		Muons
					Resolution	Relative Momentum	Allowed X/X_0	Minimum-pT	Transverse Pointing Res.	Longitudinal Pointing Res.	Resolution σ_E/E	PID	Min E Photon	p-Range (GeV/c)	Separation	Resolution σ_E/E	Energy	
< -4.6		↓ p/A	Far Backward Detectors	low-Q2 tagger														
-4.6 to -4.0					Not Accessible													
-4.0 to -3.5						Reduced Performance												Muons useful for bkg, improve resolution
-3.5 to -3.0			Central Detector	Backward Detector		σ_p/p ~0.2%×p⊕5%	~5% or less X	70-150 MeV/c (B=1.5 T)			1%/E ⊕ 2.5%/√E ⊕ 1%	π suppression up to 1:1E-4	20 MeV	≤ 10 GeV/c	≥ 3 σ	50%/√E⊕10%	~500MeV	
-3.0 to -2.5																		
-2.5 to -2.0						σ_p/p~0.04%×p⊕2%												
-2.0 to -1.5									dca(xy) ~ 40/pT µm ⊕ 10 µm	dca(z) ~ 100/pT µm ⊕ 20 µm	2%/E ⊕(4-8)%/√E ⊕ 2%	π suppression up to 1:(1E-3 - 1E-2)	50 MeV					
-1.5 to -1.0																		
-1.0 to -0.5				Barrel		σ_p/p ~0.04%×p⊕1%		200 MeV/c	dca(xy) ~ 30/pT µm ⊕ 5 µm	dca(z) ~ 30/pT µm ⊕ 5 µm	2%/E ⊕(12-14)%/√E ⊕ (2-3)%	π suppression up to 1:1E-2	100 MeV	≤ 6 GeV/c		100%/√E+10%		
-0.5 to 0.0																		
0.0 to 0.5																		
0.5 to 1.0																		
1.0 to 1.5				Forward Detectors		σ_p/p ~0.04%×p⊕2%		70 - 150 MeV/c (B = 1.5 T)	dca(xy) ~ 40/pT µm ⊕ 10 µm	dca(z) ~ 100/pT µm ⊕ 20 µm	2%/E ⊕ (4*-12)%/√E ⊕ 2%	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c		50%/√E+10%		
1.5 to 2.0																		
2.0 to 2.5																		
2.5 to 3.0																		
3.0 to 3.5						σ_p/p ~0.2%×p⊕5%												
3.5 to 4.0		↑ e		Instrumentation to separate charged particles from photons		Reduced Performance												
4.0 to 4.5					Not Accessible													
> 4.6			Far Forward Detectors	Proton Spectrometer; Zero Degree Neutral Detection														

Interactvie version of this matrix ➪ Yellow Report Physics Working Group Wiki page: https://physdiv.jlab.org/DetectorMatrix/

ALICE 3: a next generation HI detector for Run 5+

Fast and ultra-thin detector with precise tracking and timing

- **Ultra-lightweight** silicon tracker with excellent vertexing
- **Fast** to profit from higher luminosity (also with nuclei lighter than Pb): 50-100x Run 3/4
- **Large acceptance** ➪ barrel + end caps $\Delta\eta = 8$
- **Particle Identification**: TOF determination (≲20 ps time resolution), Cherenkov, pre-shower/calorimetry
- **Kinematic range** down to very low p_T: ≲ 50 MeV/c (central barrel), ≈ 10 MeV/c forward (dedicated detector)

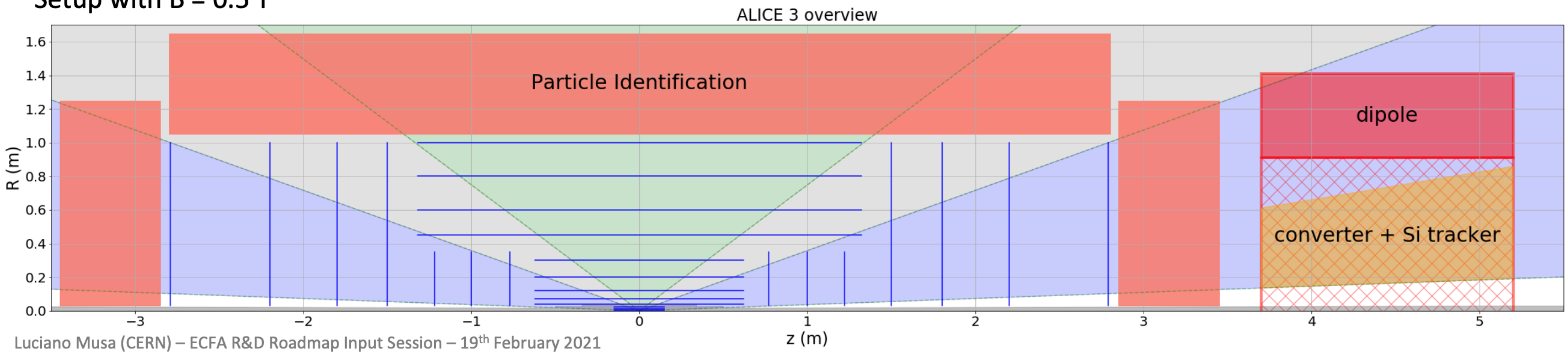
~12 tracking barrel layers + disks based on CMOS Active Pixel Sensors

Particle identification based on TOF, Cherenkov, em. shower

Dedicated forward detector for soft photons (conversion + Si tracker)

Further detectors under study (e.g. muon ID)

Setup with B = 0.5 T



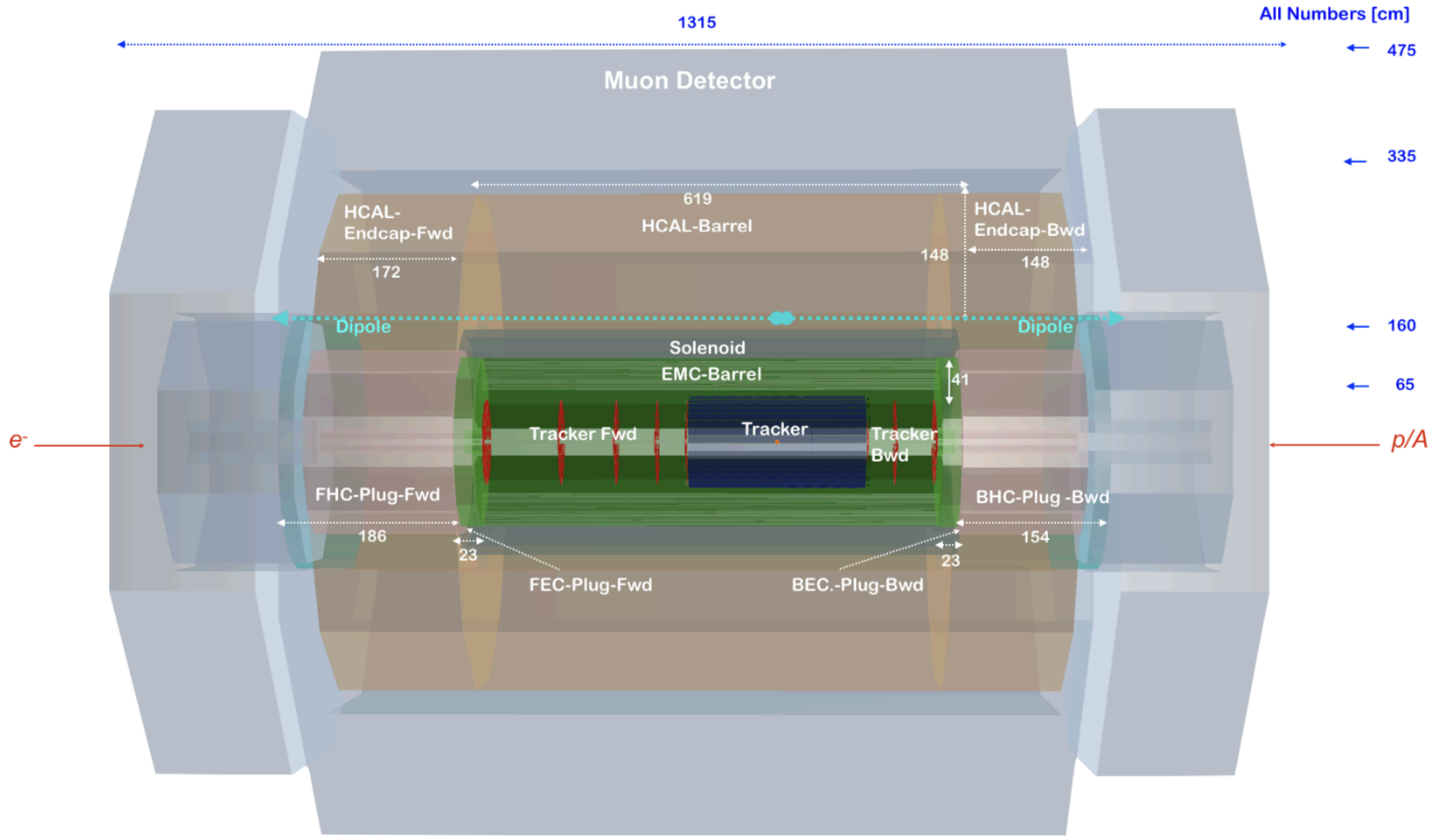
ALICE 3: a next generation HI detector for Run 5+

Possible detector technologies

System	System component	Reference detector	Alternative options		Physics channel
Tracking	Central - Inner Tracker	MAPS, < 10µm pitch	-		Multi-charmed baryons, dielectrons (HF rejection)
	Central - Outer Tracker	MAPS, ~ 20µm pitch	-		Multi-charmed baryons
	Forward & Backward	MAPS, ~ 20µm pitch	-		HF correlations, low-momentum dileptons and photons
h-PID	Central	TOF + RICH (aerogel)	TOF + DIRC	fine resolution TOF (5ps)	Multi-charmed baryons
	Forward & Backward	RICH (aerogel) + TOF	RICH (gas) + TOF?	fine resolution TOF (5 ps)	Low p_T pions: chiral production
e-h separation	Central	TOF + RICH (aerogel)	TOF + preshower/ECAL		Di-electrons, quarkonia, X(3872)
	Forward & Backward	RICH (aerogel) + TOF	Preshower/ECAL + TOF?		Very low mass di-electrons
low-energy photons	Forward	Converter + Si-tracker	High-resolution ECal		Soft theorems
Ecal	Barrel	Sci-Crystal + Sci-Glass (long. segmentation)	metal-scint		Photons, jets
	Forward & backward	Sci-Glass	metal-scint		
Muons	Barrel	Iron absorber + chambers			New quarkonia, X(3872)

Hadron-Electron Collisions at the LHC and FCC

LHeC Detector Design 7/2020



Current design leans heavily on HL-LHC technologies
But they are over-spec'ed for radiation hardness

General detector requirements

- **High-resolution tracking system**
  - primary and secondary vertex resolution down to small angles
  - precise p_T measurement and matching to calorimeter
- **Full coverage calorimetry**
  - Electron energy 10%/√E calibr. 0.1%
  - Hadronic energy 10%/√E calibr. 1%
  - Tagging of backward scattered electrons and photons
  - Tagging of forward scattered photons, neutrons and deuterons
- **Full coverage muon system**
  - Tagging and combination with tracking, no independent p measurement

FCC-ee PARAMETRI DI PROGETTO

	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
arc cell optics	60/60	90/90	90/90	90/90
emittance hor/vert [nm]/[pm]	0.27/1.0	0.28/1.0	0.63/1.3	1.45/2.7
β* horiz/vertical [m]/[mm]	**0.15/.8**	**0.2/1**	**0.3/1**	**1/2**
SR energy loss / turn (GeV)	0.036	0.34	1.72	9.21
total RF voltage [GV]	**0.10**	**0.44**	**2.0**	**10.9**
energy acceptance [%]	1.3	1.3	1.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.15 / 0.20
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.5 / 3.3
bunch intensity [10^{11}]	1.7	1.5	1.5	2.8
no. of bunches / beam	**16640**	**2000**	**393**	**39**
beam current [mA]	**1390**	**147**	**29**	**5.4**
SR total power [MW]	**100**	**100**	**100**	**100**
luminosity [10^{34} cm^{-2}s^{-1}]	**230**	**32**	**7.8**	**1.5**
luminosity lifetime [min]	70	50	42	44
allowable asymmetry [%]	±5	±3	±3	±3

- parametri scelti in modo da avere la stessa potenza totale per radiazione di sincrotrone a tutte le energie (100 MW)
- permette di ottimizzare le correnti dei fasci a più bassa energia

NOTA: 100 MW con 50% dei klystron efficienti significa 200 MW
LHC: 210 MW, HL-LHC: 260 MW

FCC-ee PHYSICS PROGRAM

”Higgs Factory” Programme

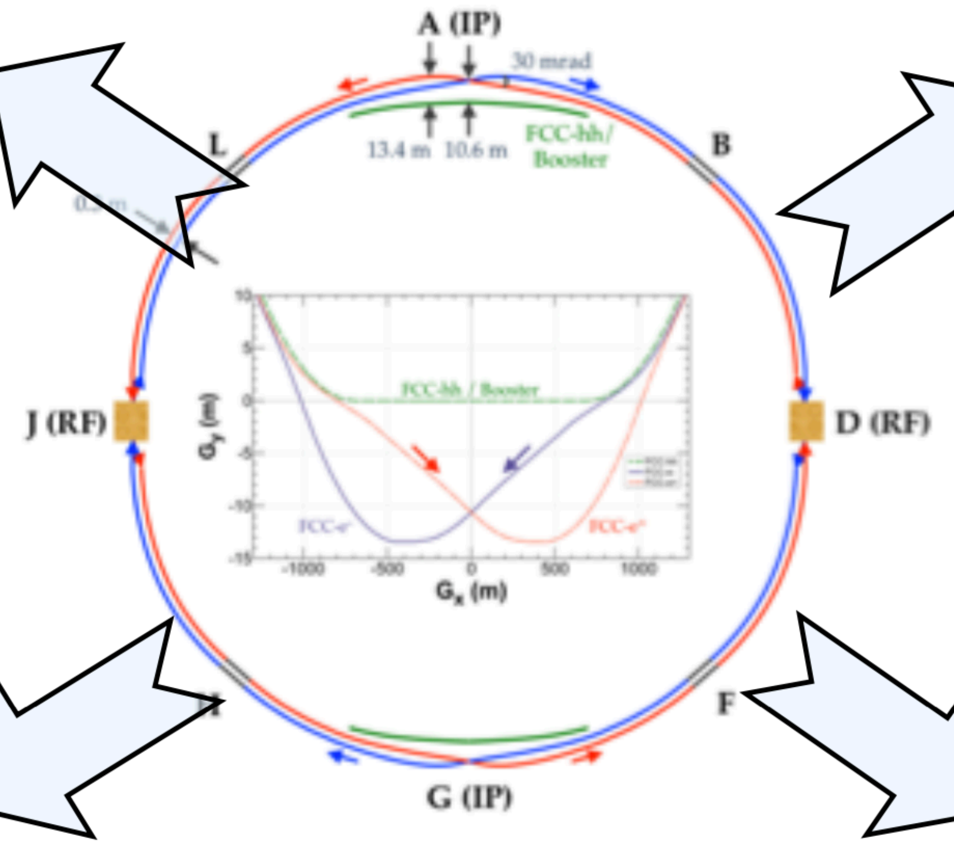
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \to H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 5×10^{12} Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W…
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; 1.7×10^{11} ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, ”flavour anomaly” studies, e.g. b → sττ, rare decays, cLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z:

- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes - LLPs

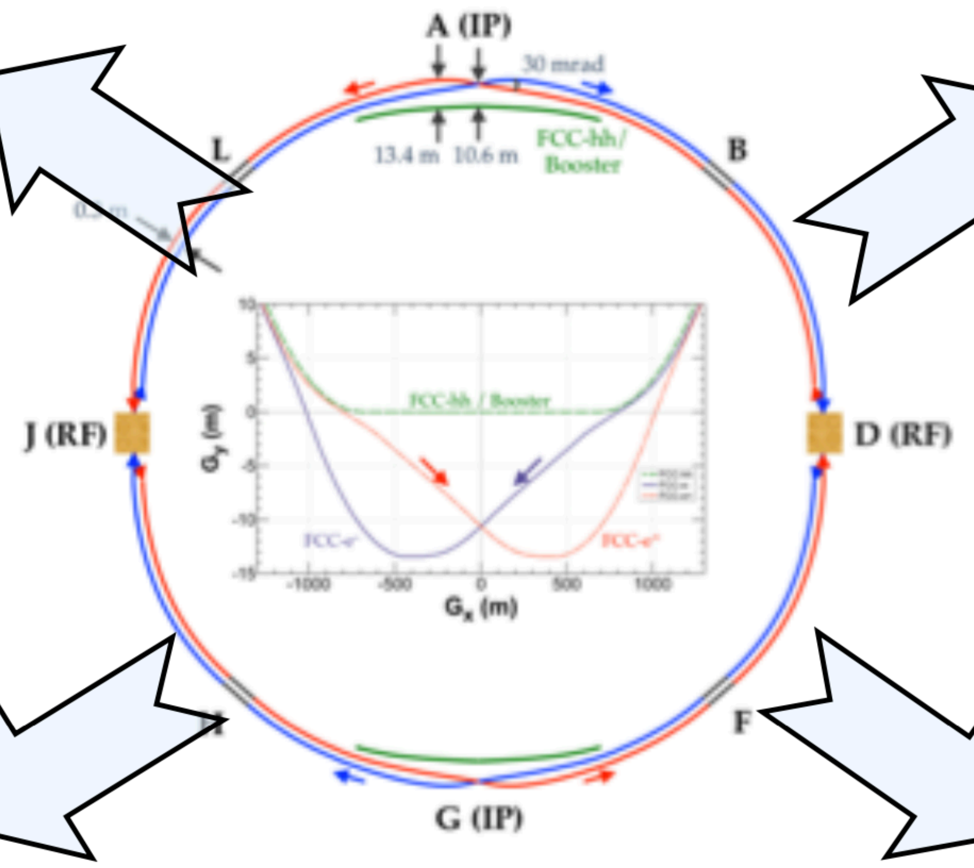
FCC-ee DETECTOR REQUIREMENTS

"Higgs Factory" Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$ commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

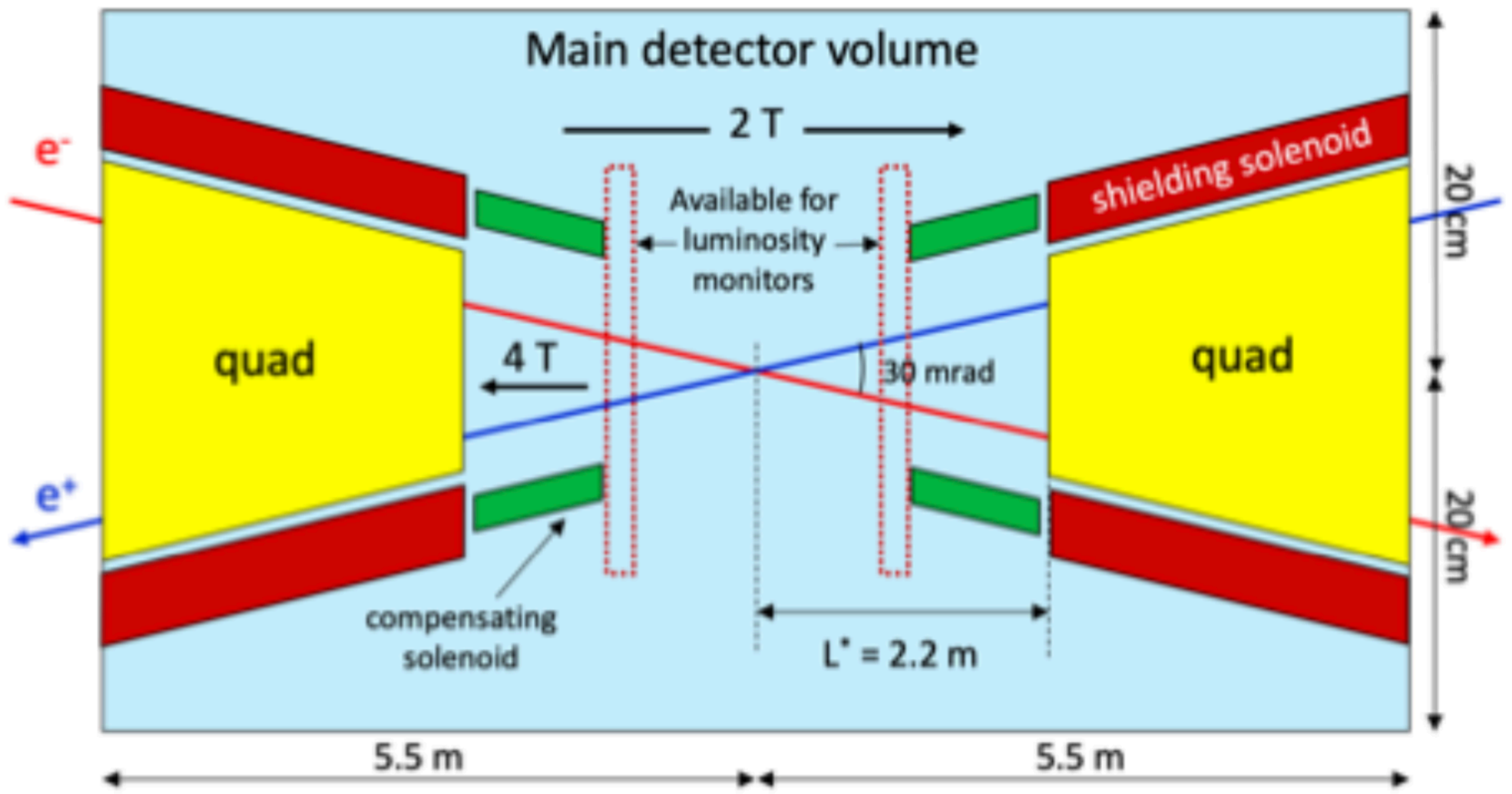
Benchmark signature: Z → νN, with N decaying late

- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Hermeticity

FCC-ee EXPERIMENTAL CHALLENGES

- 30 mrad beam crossing angle
  - Detector B-field limited to 2 Tesla at Z-peak operation
  - Very complex and tightly packed MDI (Machine Detector Interface)
- "Continuous" beams (no bunch trains); bunch spacing down to 20 ns
  - Power management and cooling (no power pulsing)
- Extremely high luminosities
  - High statistical precision – control of systematics down to 10^{-5} level
  - Online and offline handling of $\mathcal{O}(10^{13})$ events for precision physics: "Big Data"
- Physics events at up to 100 kHz
  - Fast detector response ($\lesssim$ 1 μs) to minimise dead-time and event overlaps (pile-up)
  - Strong requirements on sub-detector front-end electronics and DAQ systems
    - At the same time, keep low material budget: minimise mass of electronics, cables, cooling, …

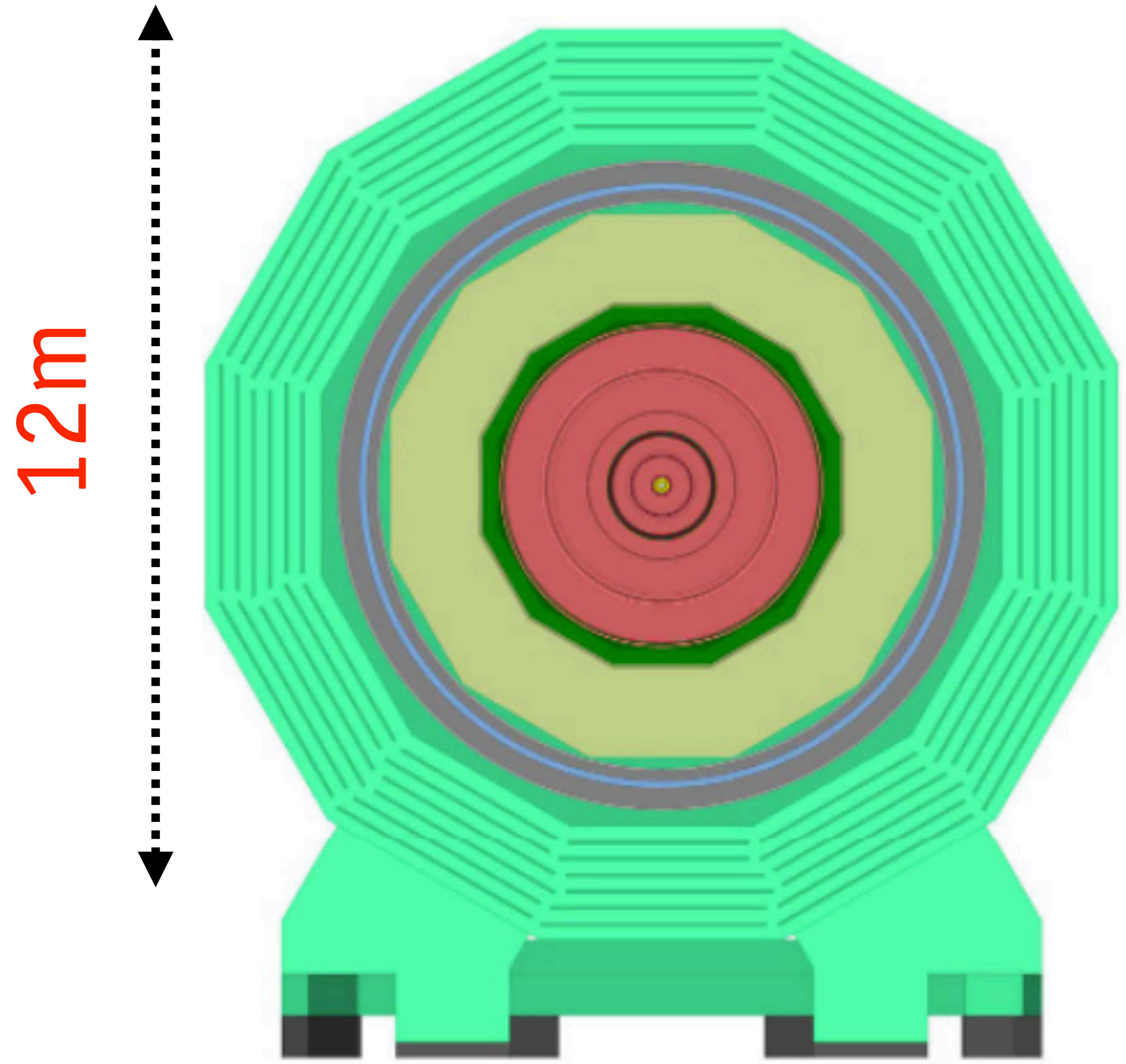
Central part of detector volume – top view

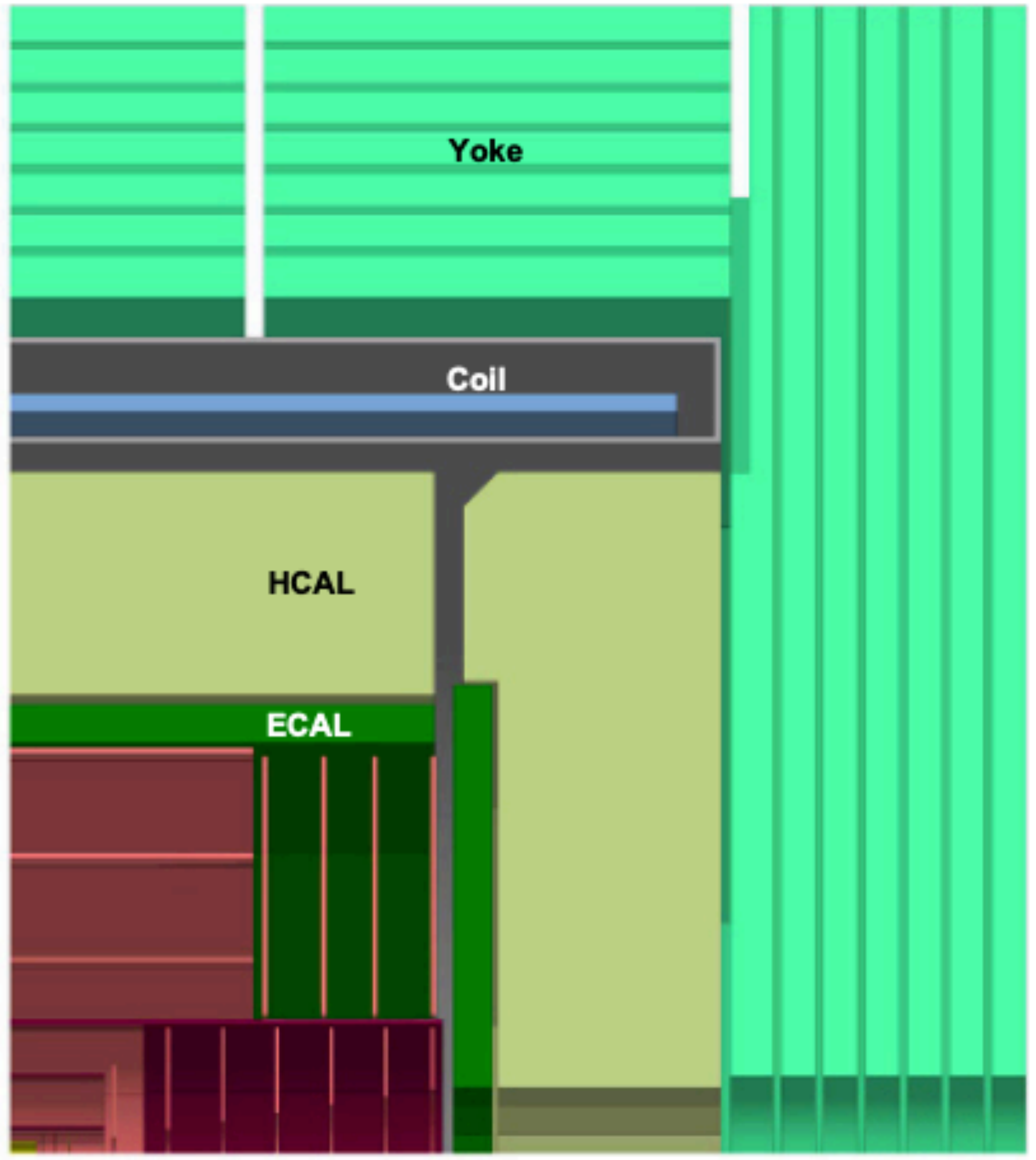


- More physics challenges
  - Luminosity measurement to 10^{-4} – luminometer acceptance to 1 μm level
  - Detector acceptance to ~10^{-5} – acceptance definition to few 10s of μm, hermeticity (no cracks!)
  - Stability of momentum measurement – stability of magnetic field wrt E_{cm} (10^{-6})
  - Impact parameters, detached vertices – Higgs physics (b/c/g jets); flavour and τ physics, life-time measurements
  - Particle identification (π/K/p) without ruining detector hermeticity – flavour and τ physics (and rare processes)

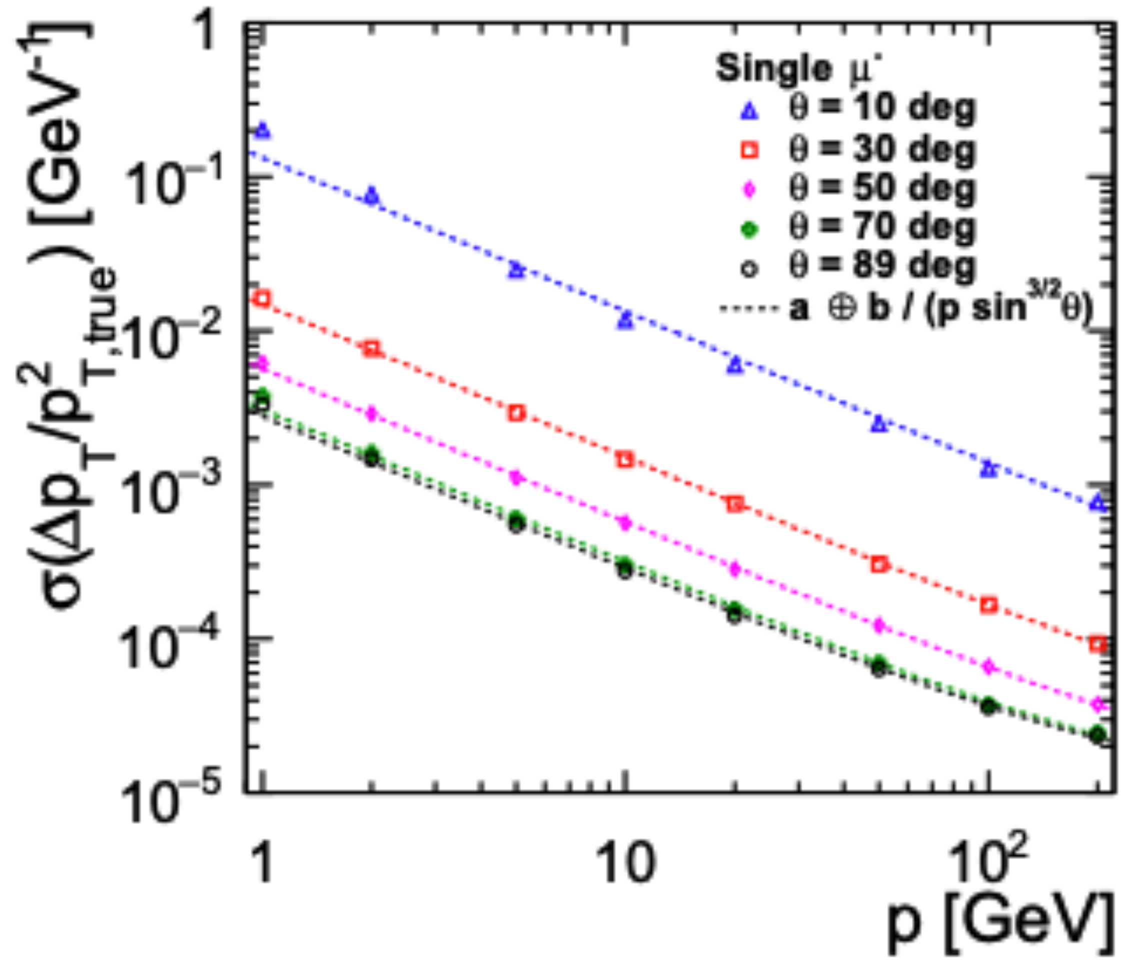
DETECTOR CONCEPTUAL DESIGN #1: CLD

CLIC-Like Detector: adattato dal disegno fatto per CLIC per soddisfare le specifiche FCC-ee

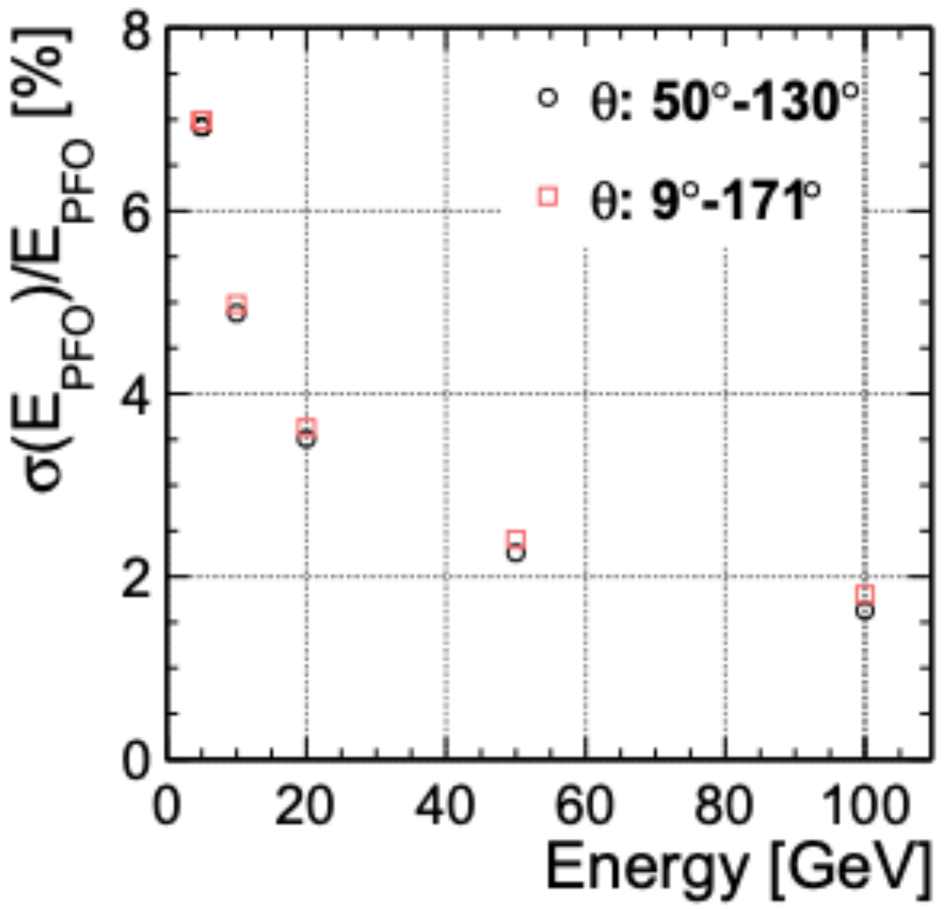




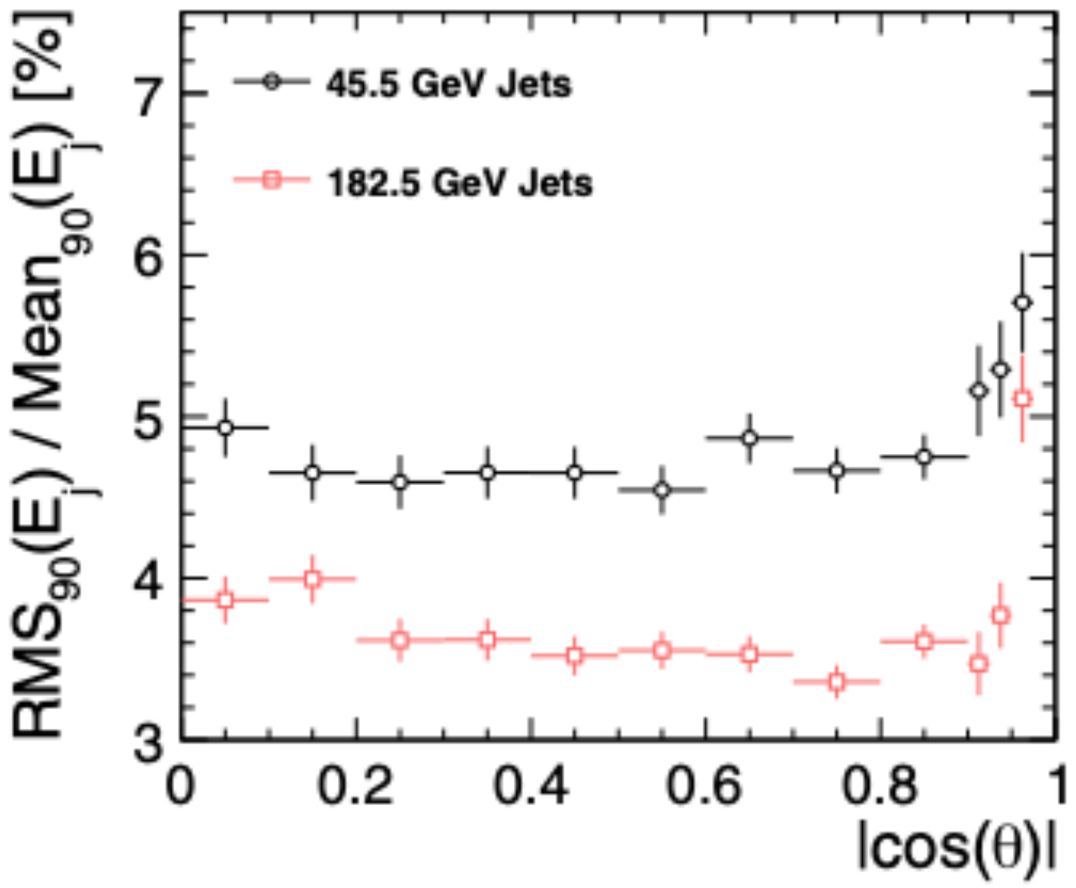
- 2T B-field (CMS-style)
- Silicon ID (pixel + tracker)
- 3D imaging Silicon-tungsten ECAL
- Scintillatore+FE HCAL
- MS: giogo in acciaio strumentato con RPC



μ



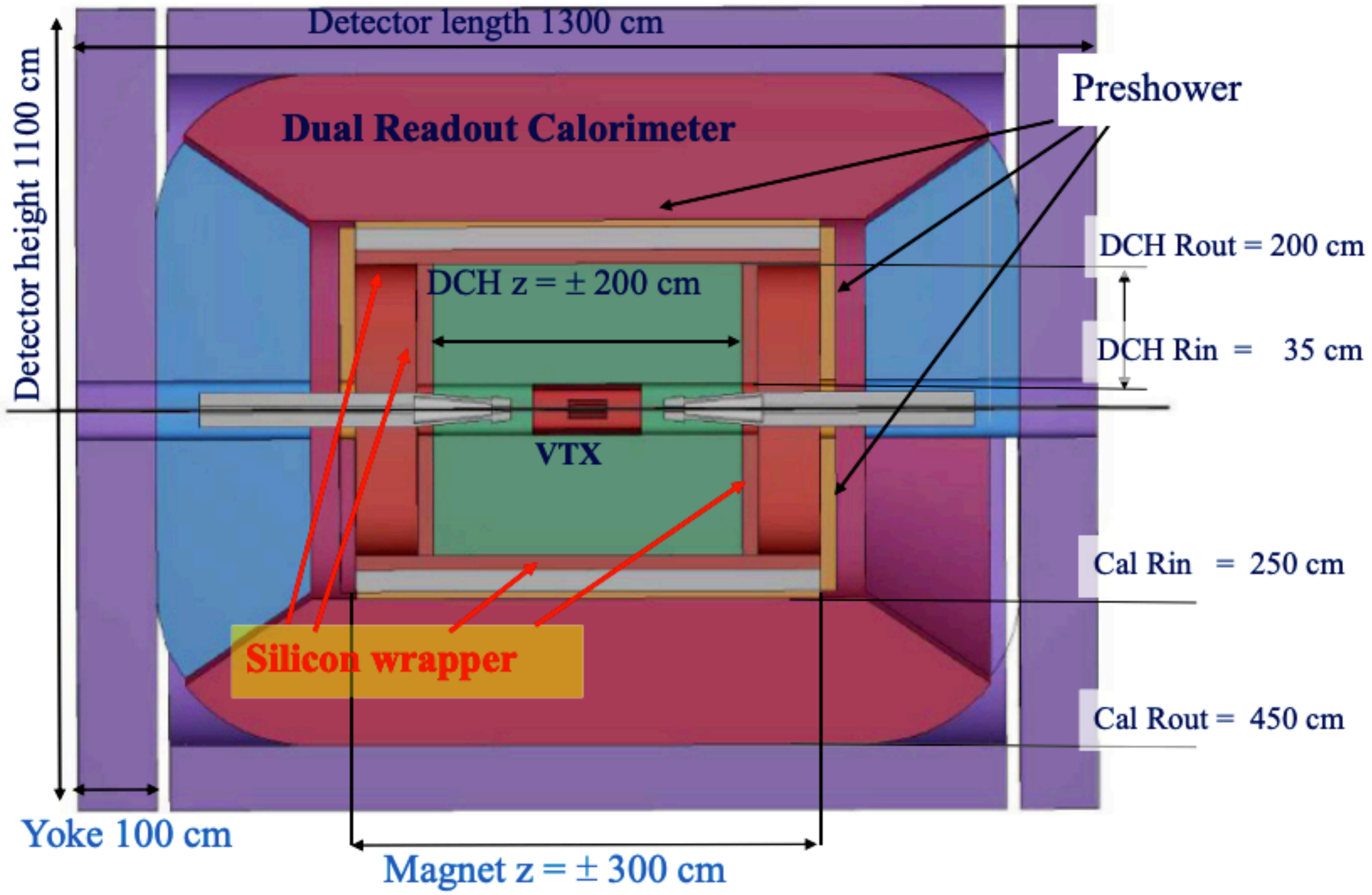
PF-γ



PF-Jets

DETECTOR CONCEPTUAL DESIGN #2: IDEA

International Detector for Electron-positron Accelerators: design specifico per FCC-ee, con forte coinvolgimento della comunità Italiana



- Vertex Si detector
  - With light MAPS technology
  - 7 layers, up to 35cm radius
- Ultra light wire drift chamber
  - 4m long, 2 m radius, 0.4% X_0
  - 112 layers with Particle ID
- One Si layer for acceptance determination
  - Precise tracking with large lever arm
    - ➨ Barrel and end-caps
- Ultra-thin 20-30cm solenoid (2T)
  - Acts as preshower ($1X_0$)
  - Or $1X_0$ Pb if magnet outside calo
- Two μ-RWell layers
  - Active preshower measurement
- Dual readout fibre calorimeter
  - 2m thick, longitudinal segmentation
- Instrumented return yoke

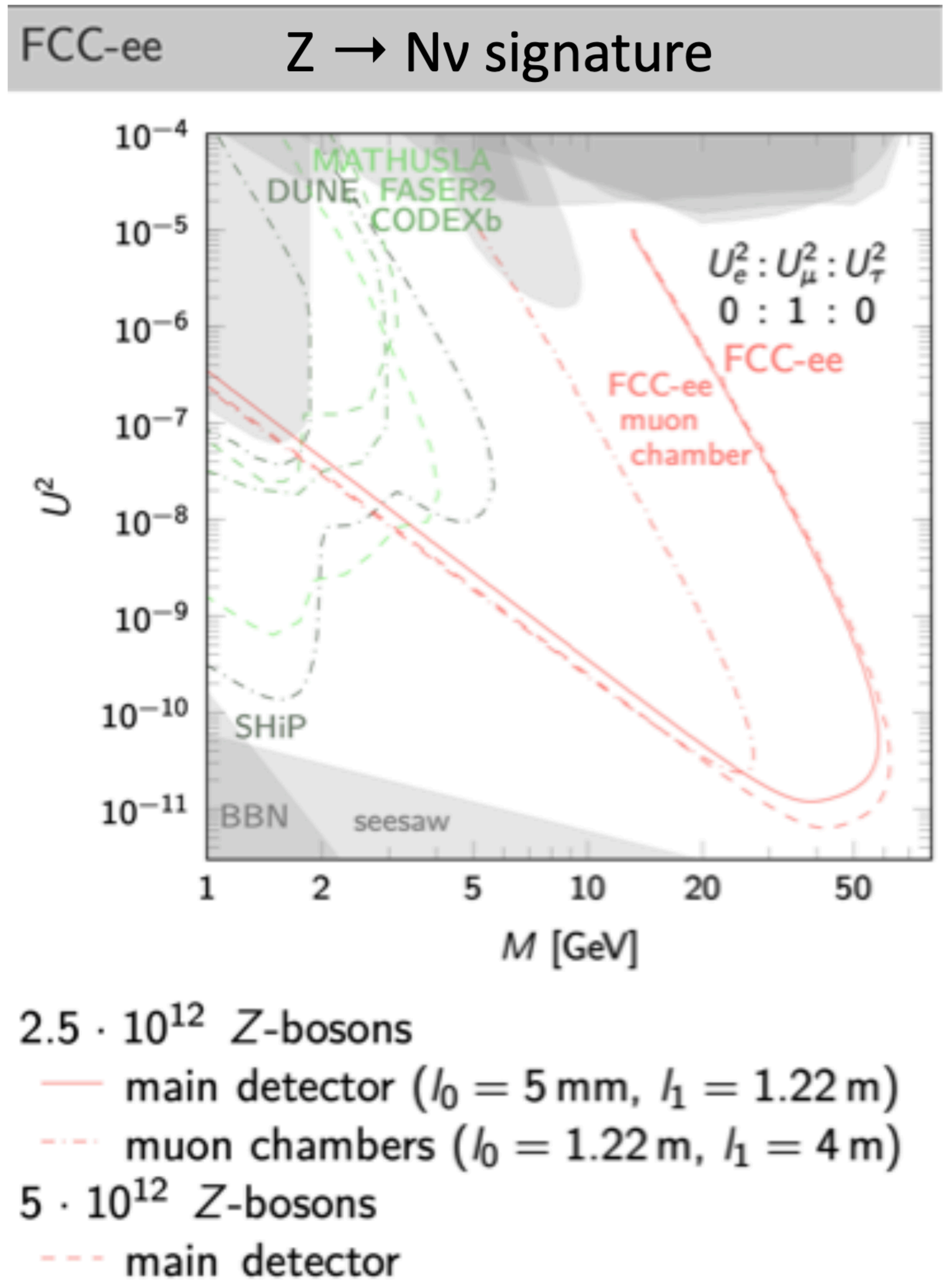
- solenoide SC da 2T ultra-sottile e trasparente davanti ai calorimetri
- iron yoke sottile equipaggiato con RPC che funziona da MS

FCC-ee READOUT/DAQ/DATA HANDLING

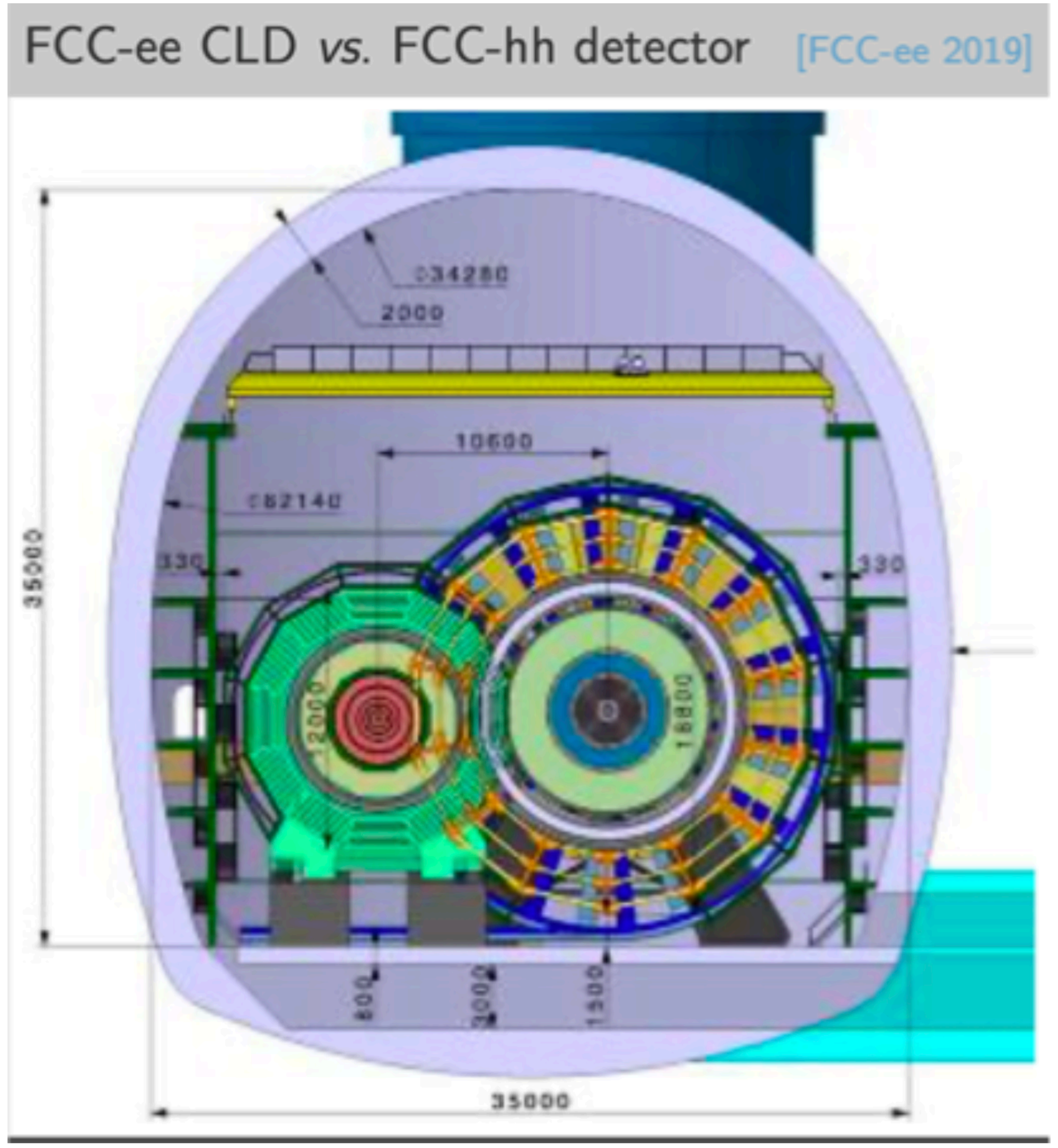
- In particular at Z-peak, challenging conditions
  - 50 MHz BX rate
  - 70 kHz Z rate + ~100 kHz LumiCal rate
  - Absolute normalisation goal 10^{-4}
    - In comparison, "pileup" parameter for LumiCal is ~2×10^{-3}
- Different sub-detectors tend to prefer different integration times
  - Silicon VTX/tracker sensors: $\mathcal{O}$(μs) [also to save power]
    - Time-stamping probably needed
  - LumiCal: Probably preferential at ~BX frequency (20 ns)
    - Avoid additional event pileup
- How to organize readout?
  - Need a "hardware" trigger with latency buffering a la LHC
    - Which detector element provides the trigger ?
  - Free streaming of self-triggering sub-detectors, event building based on precise timing information
    - Need careful treatment of relative normalisation of sub-detectors
- Need to consider DAQ issues (trigger vs. streaming) when designing detectors and their readout
- Off-line handling of $\mathcal{O}(10^{13})$ events for precision physics
  - … and Monte Carlo

FCC-ee VERY LARGE TRACKING VOLUME FOR LLP

FCC-ee "standard" detector



Instrument cavern as huge decay volume

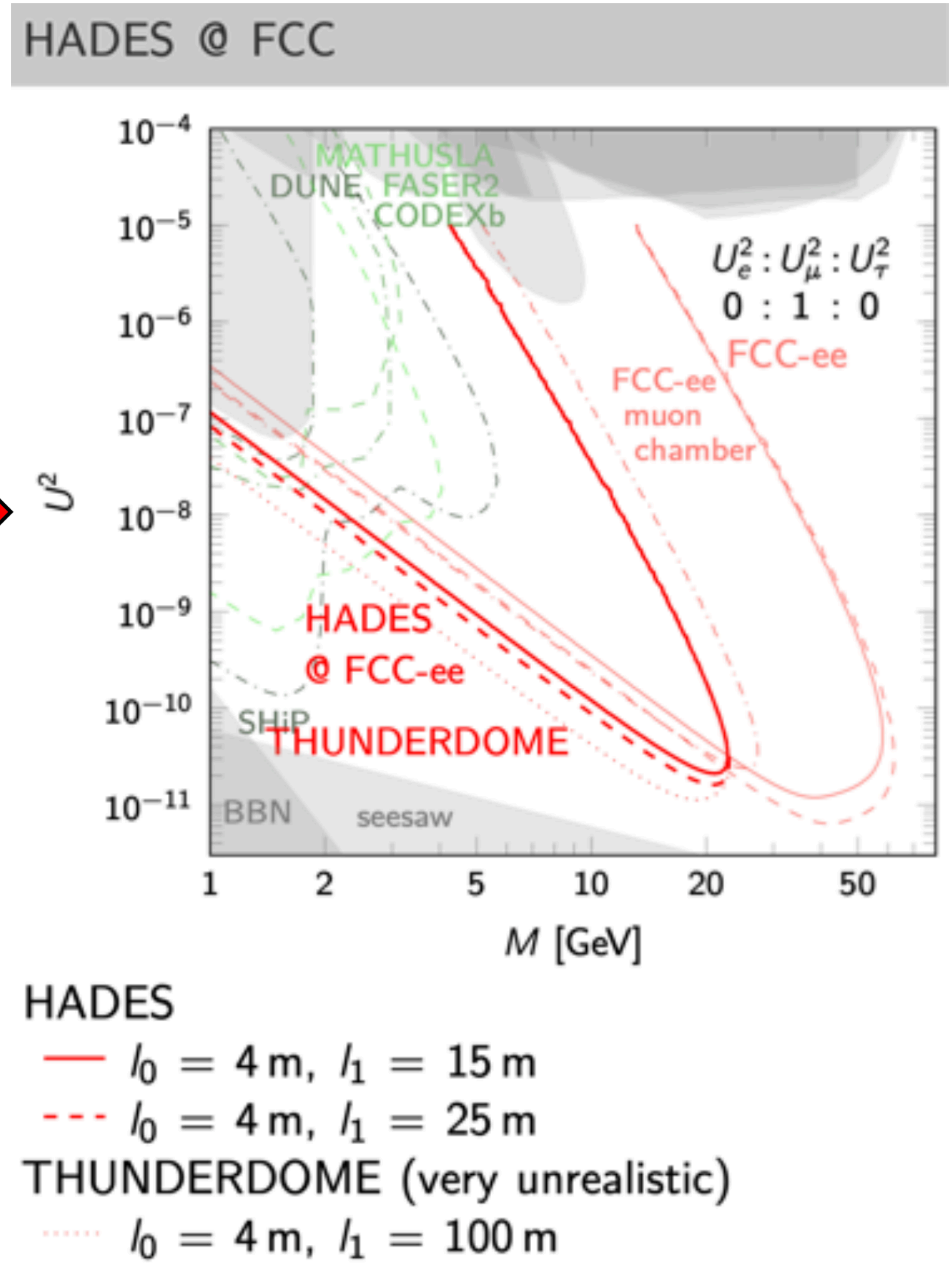


Scintillators

RPCs

…

Half a magnitude sensitivity gain in U^2



J. Hajer,
4th FCC Physics and Experiments workshop, Nov. 2020

FCC-ee DETECTORS R&D ISSUES

High duty-cycle detectors [TF7, TF8]

a) Low-power readout electronics and low-mass cooling

Silicon sensors – VTX, tracker, calorimeters [TF3]

b) High spatial resolution (3-5 μm), timing (at least 20 ns for BX assignment), low material budget, low power consumption

Drift chamber [TF1]

c) Prototypes: full length (few cells) to verify wire stability and electronics issues; portions of full-scale end-plate
d) Investigate possibility to save material going from metal wires to metal-coated carbon monofilaments
   - Wire production line need to be engineered
e) Experimental verification of dN/dx method for PID
   - Need test beams, e, μ, π, K, p in range ≳ 100 MeV to 50 GeV

Calorimetry [TF6, TF4, TF7]

f) Optimisation for each technology including choice of materials and segmentation
g) Dual Readout: SiPM/FE electronix, had-shower-size prototype

Coil design/placement [TF8]

h) Quantititive study of impact of ”early” coil on phys. perf.

PID (other than specific ionisation) [TF4, TF3]

i) Precise timing, gaseous RICH

Muon system [TF1, TF4]

j) Technology choice for very large area detectors
   - RPC, scintillator, μRWell,…

Readout & DAQ [TF7, TF8]

k) Design of DAQ architecture: triggered or free streaming
l) Sub-detector readout to be designed correspondingly

Normalisation issues [TF6, TF7]

m) LumiCal: micron level mechanical precision; fast, low-power read-out electronics
n) Definition of geometrical acceptance of main detector to 10s of μm precision (dedicated low-angle (pre-shower) device?)

Large detector volume for LLPs [TF1, TF4, TF6]

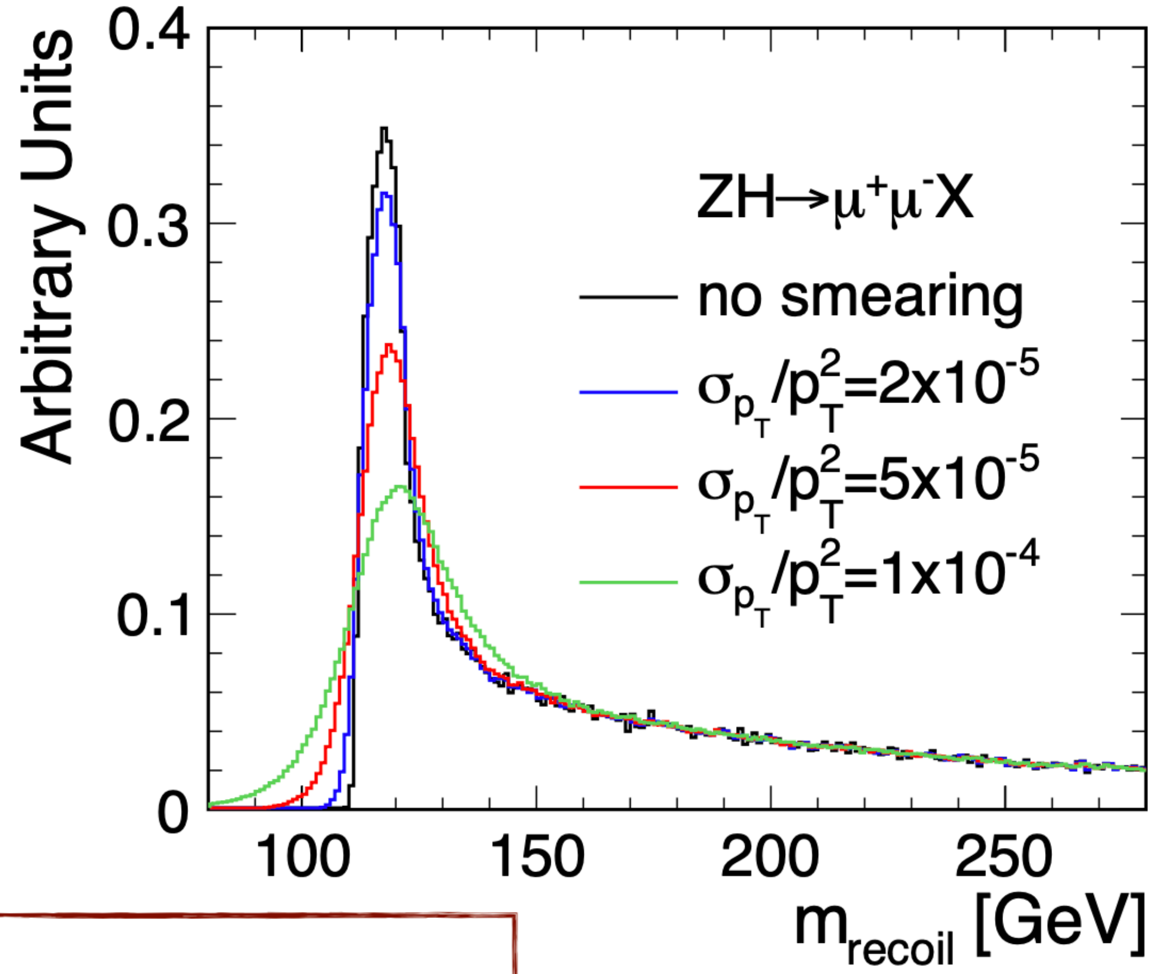
o) Optimization of calorimeter and muon system for late decaying particles
p) Possibility of large instrumented decay volume in surrounding cavern

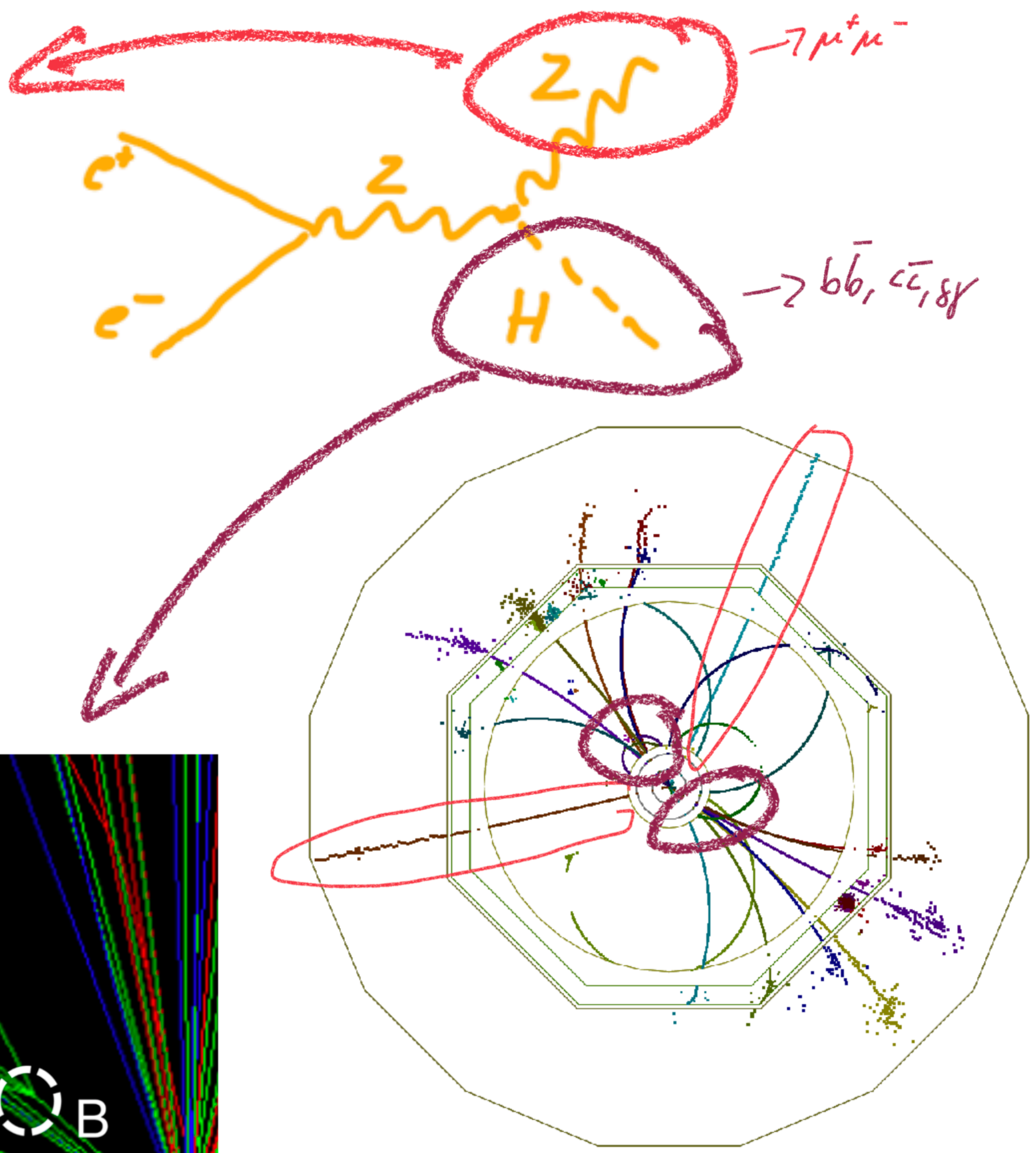
LC DETECTOR PERFORMANCE GOALS: TRACKING

- ***Momentum resolution***
  Higgs recoil measurement, H -> μμ, BSM decays with leptons

  $\sigma(p_T) / p_T^2 \sim 2 \times 10^{-5}$ / GeV

  precise and highly efficient tracking, extending to 100+ GeV



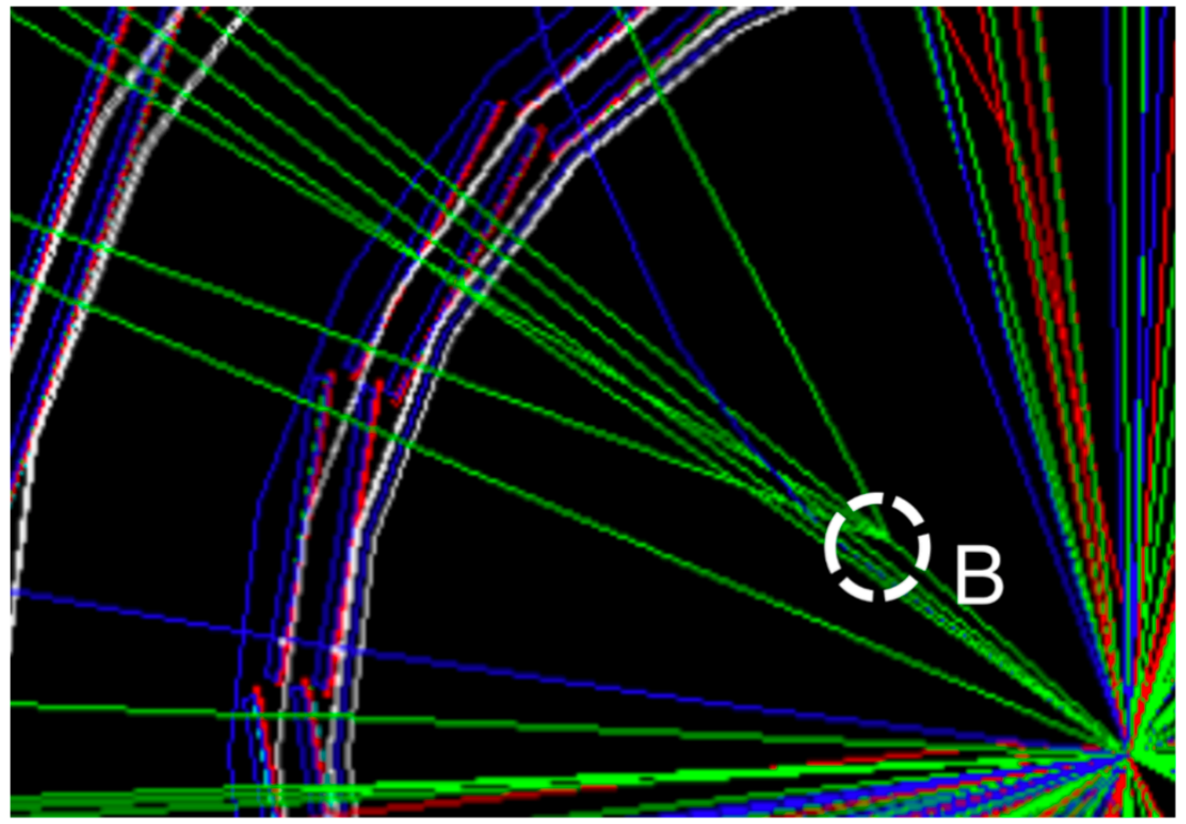


low mass, good resolution:
for Si tracker ~ 1-2% X_0 per layer, 7 μm point resolution

- ***Impact parameter resolution,*** *vertex charge*
  Flavour tagging: b/c/light tagging in Higgs decays, top physics, …

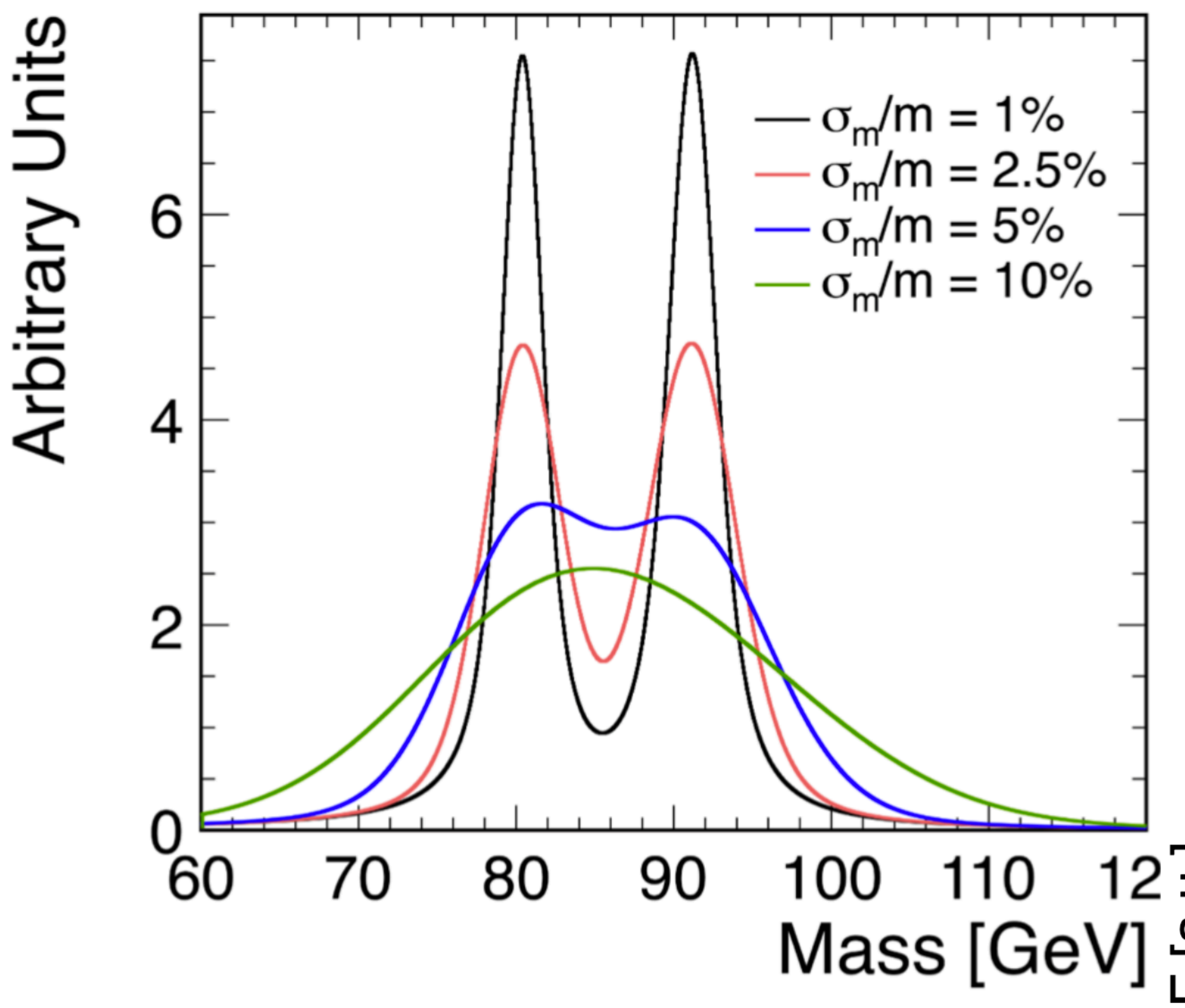
  $$\sigma(d_0) \sim [5 \oplus (10 - 15)/p\sin^{3/2}\theta]\ \mu m$$

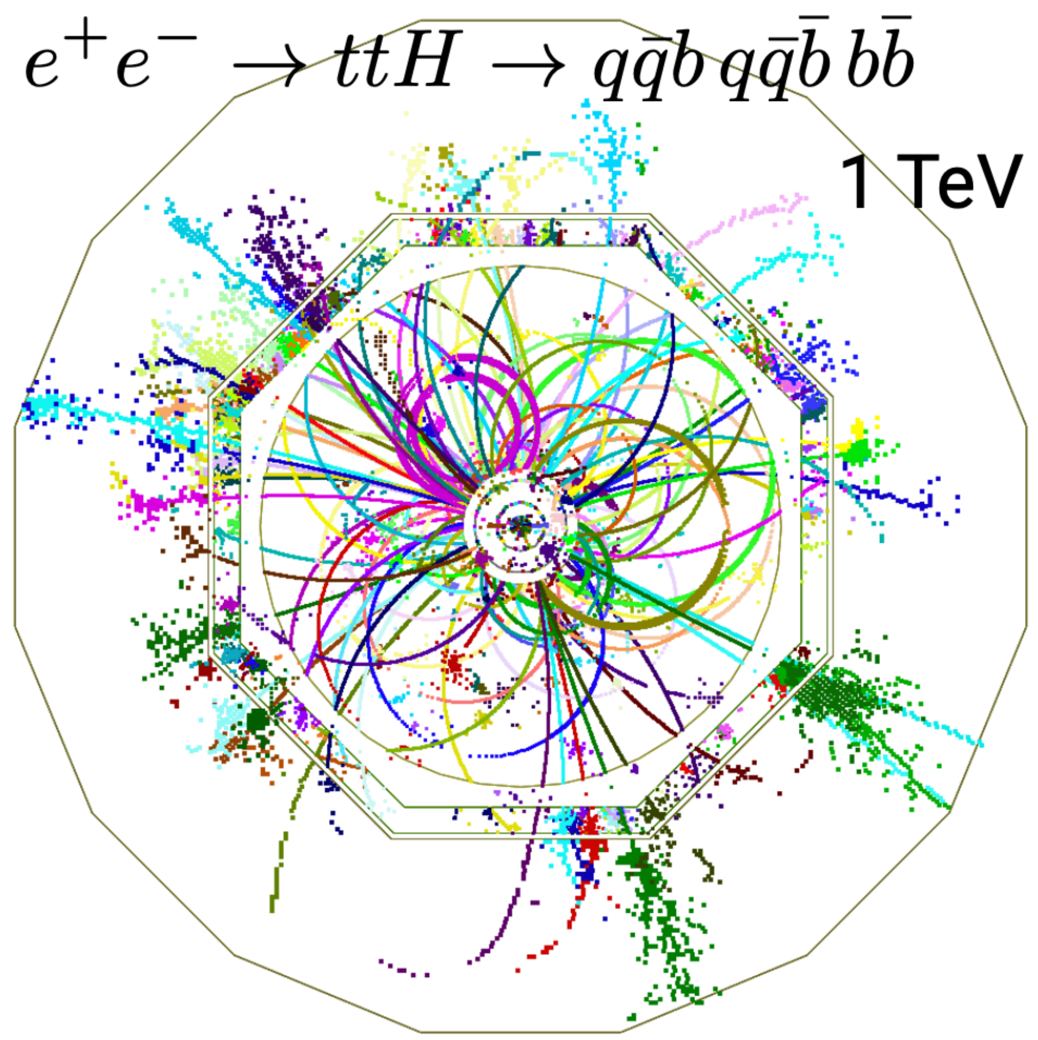
single point resolution in vertex detector ~3 μm
< 0.2 X_0 per layer

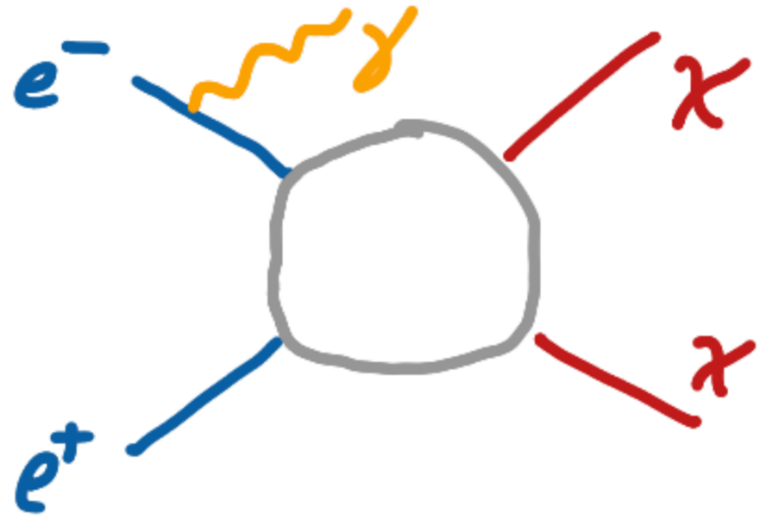


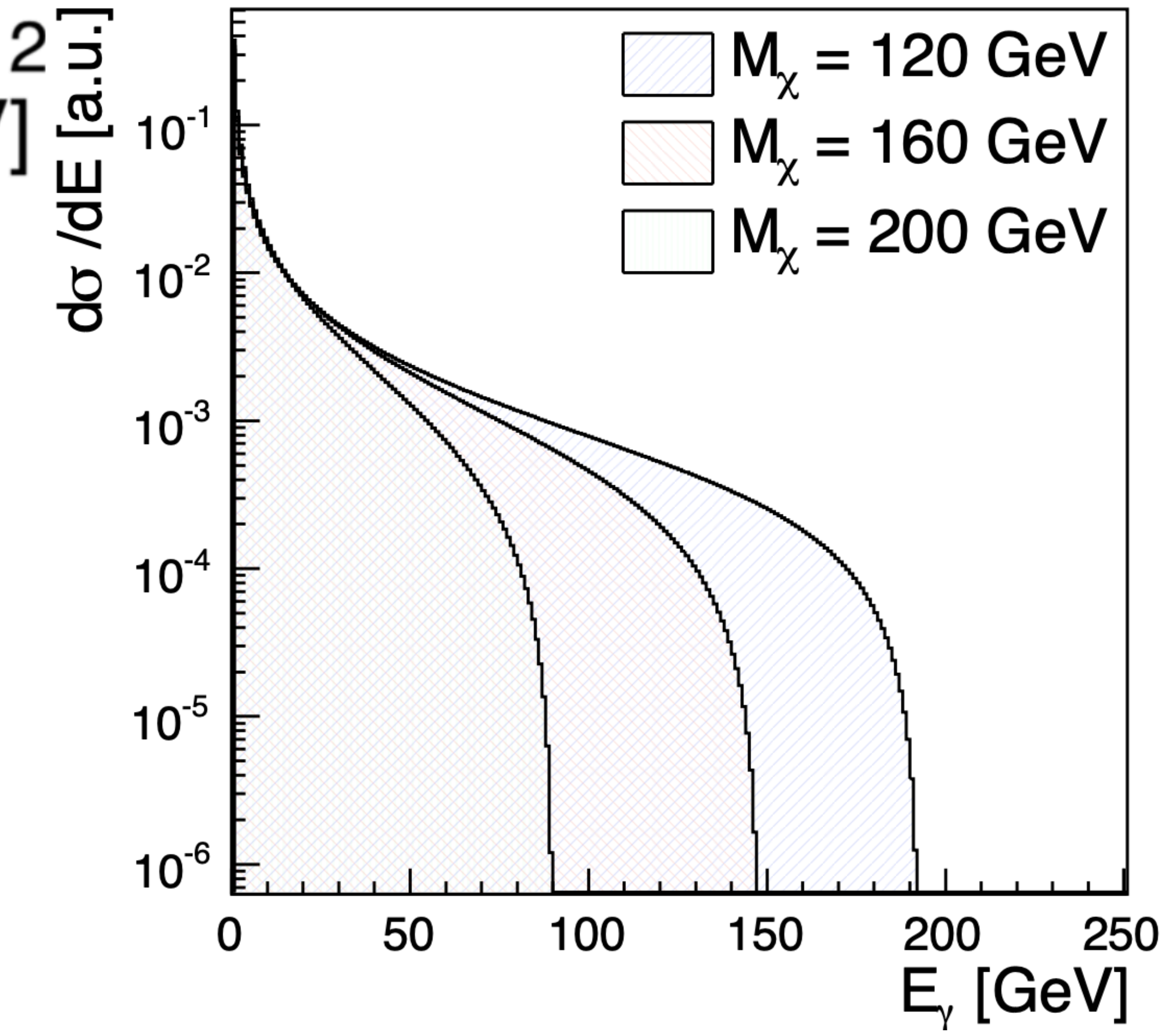
LC DETECTOR PERFORMANCE GOALS: JETS/PHOTONS/PID

- ***Jet energy resolution***
  Recoil measurements with hadronic Z decays, separation of W, Z, H bosons, …
  $\sigma(E_{jet}) / E_{jet}$ ~ 3% - 5% **for E_{jet} > 45 GeV**
  reconstruction of complex multi-jet final states.
- ***Photons***
  Resolution not in the focus: ~ 15 - 20%/√E
  Worth another look ?
  Coverage to 100s of GeV important
- ***Particle ID***
  Clean identification of e, μ up to highest energies
- PID of hadrons to improve tagging, jets,…
- ***Hermetic coverage***
  Dark matter searches in mono-photon events, …
  N.B.: Achievable limits do not depend strongly on $\sigma(E_\gamma)$

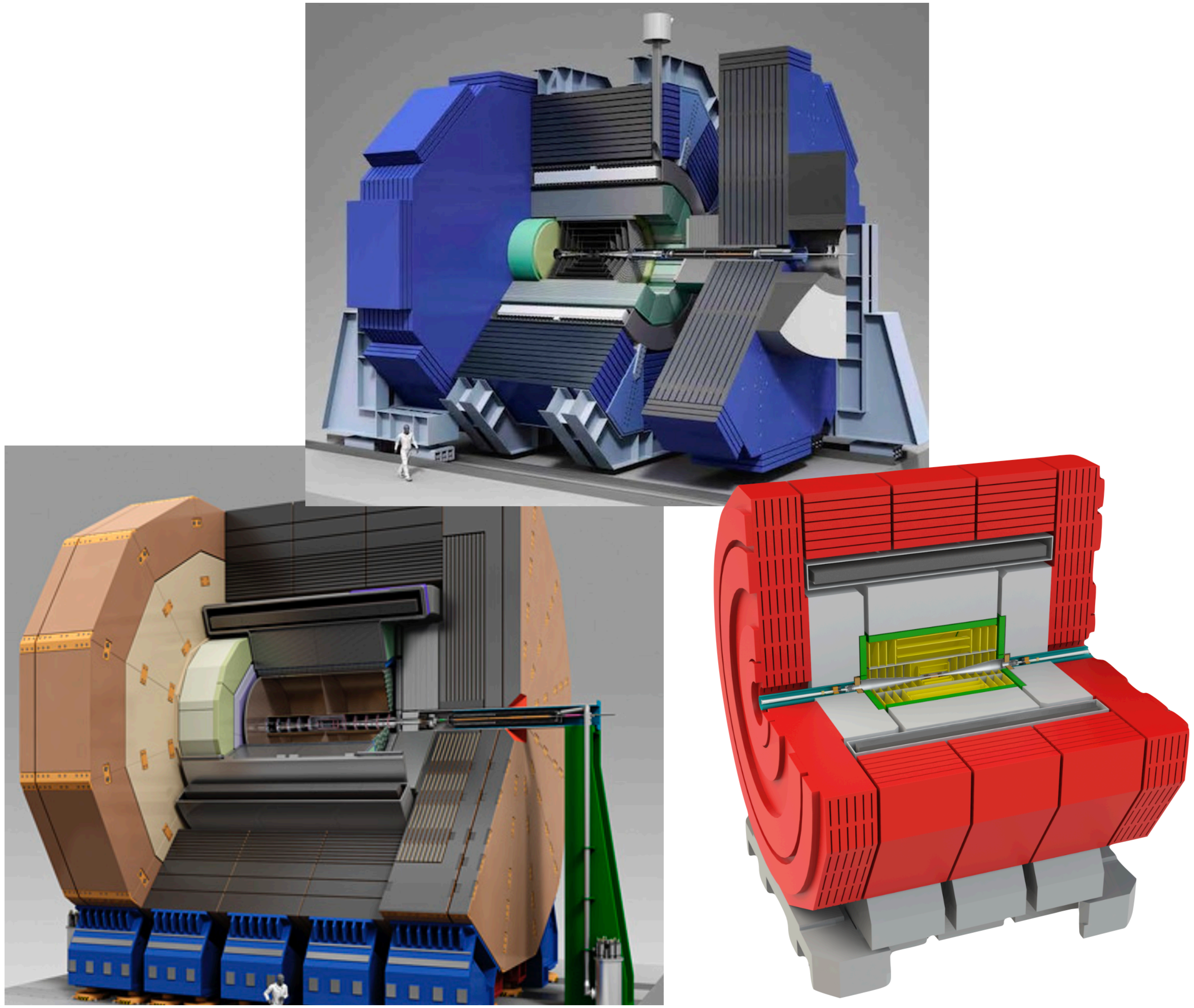








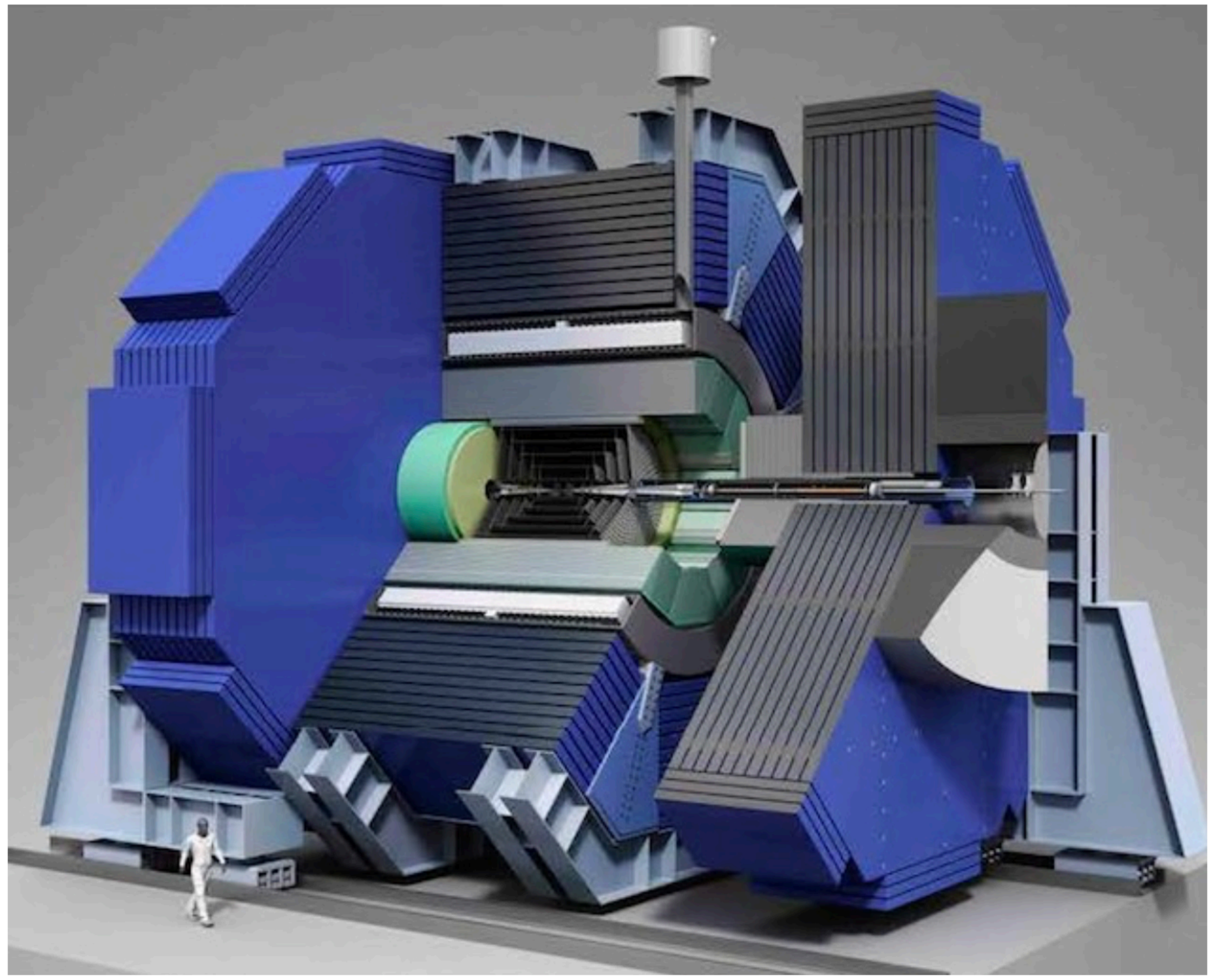
LC DETECTORS: MAIN FEATURES

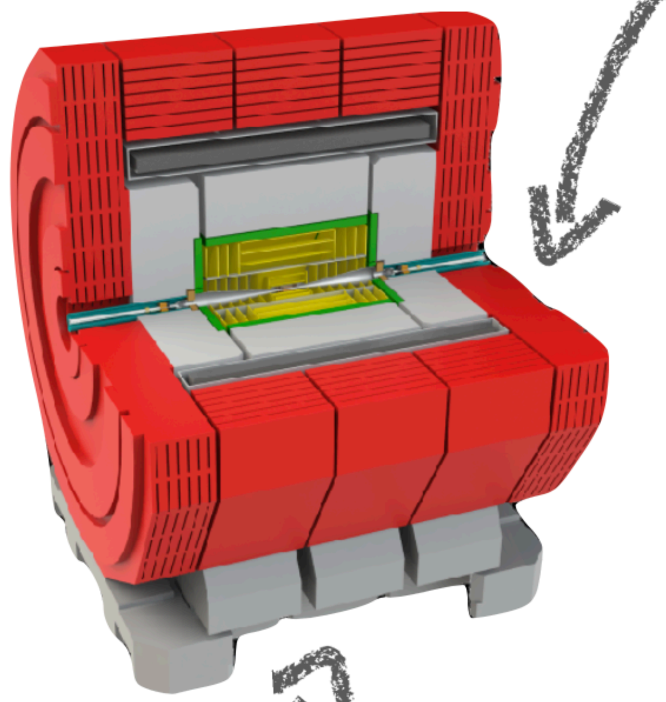


- A **large-volume solenoid** 3.5 - 5 T, enclosing calorimeters and tracking
- **Highly granular calorimeter systems**, optimised for particle flow reconstruction, best jet energy resolution *[Si, Scint + SiPMs, RPCs]*
- **Low-mass main tracker**, for excellent momentum resolution at high energies *[Si, TPC + Si]*
- **Forward calorimeters,** for low-angle electron measurements, luminosity *[Si, GaAs]*
- **Vertex detector**, lowest possible mass, smallest possible radius *[MAPS, thinned hybrid detectors]*
- **Triggerless readout** of main detector systems

LC REFERENCE DETECTORS

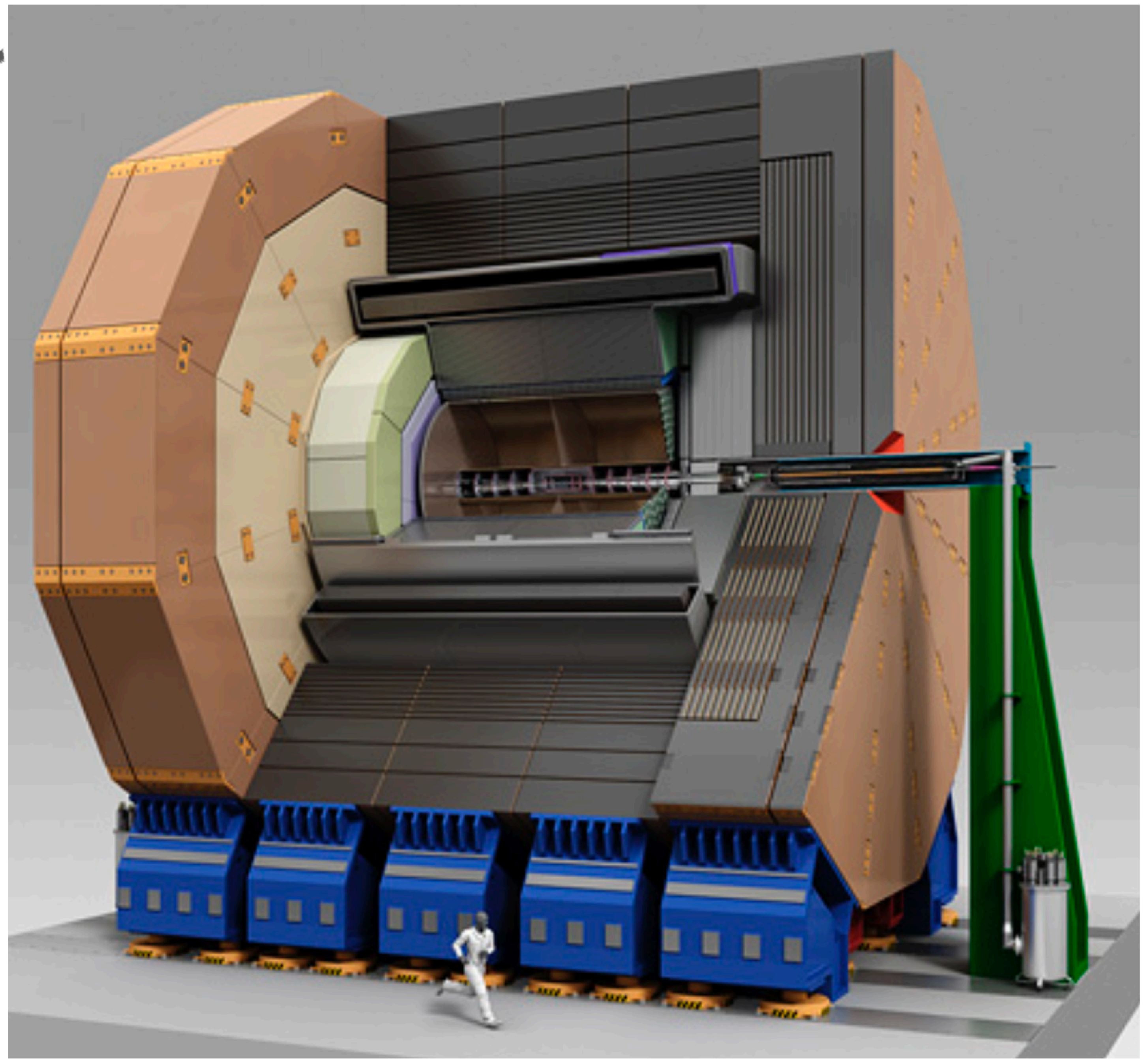
- Two detector concepts for ILC: SiD, ILD - with somewhat different optimisation





larger volume

more compact

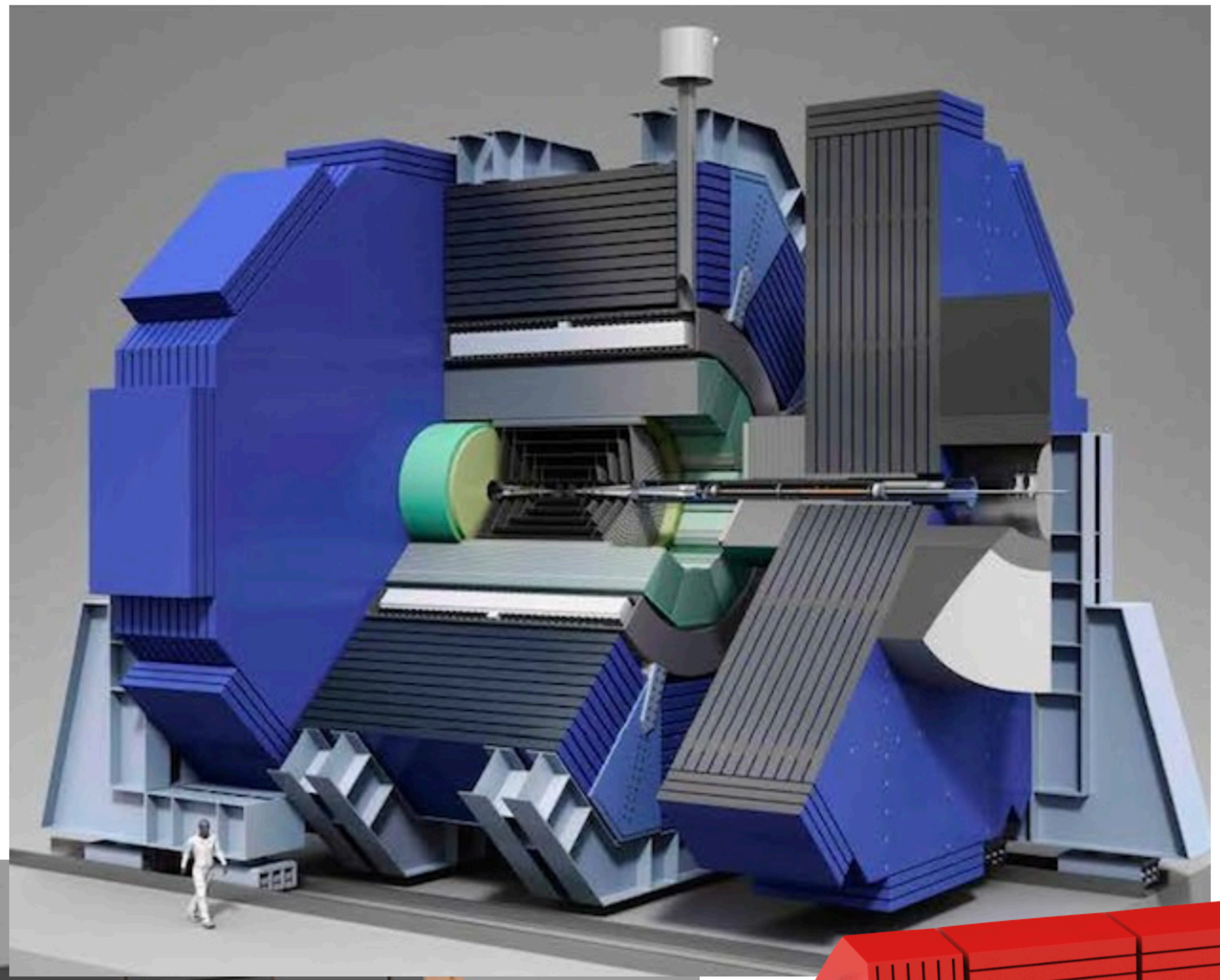


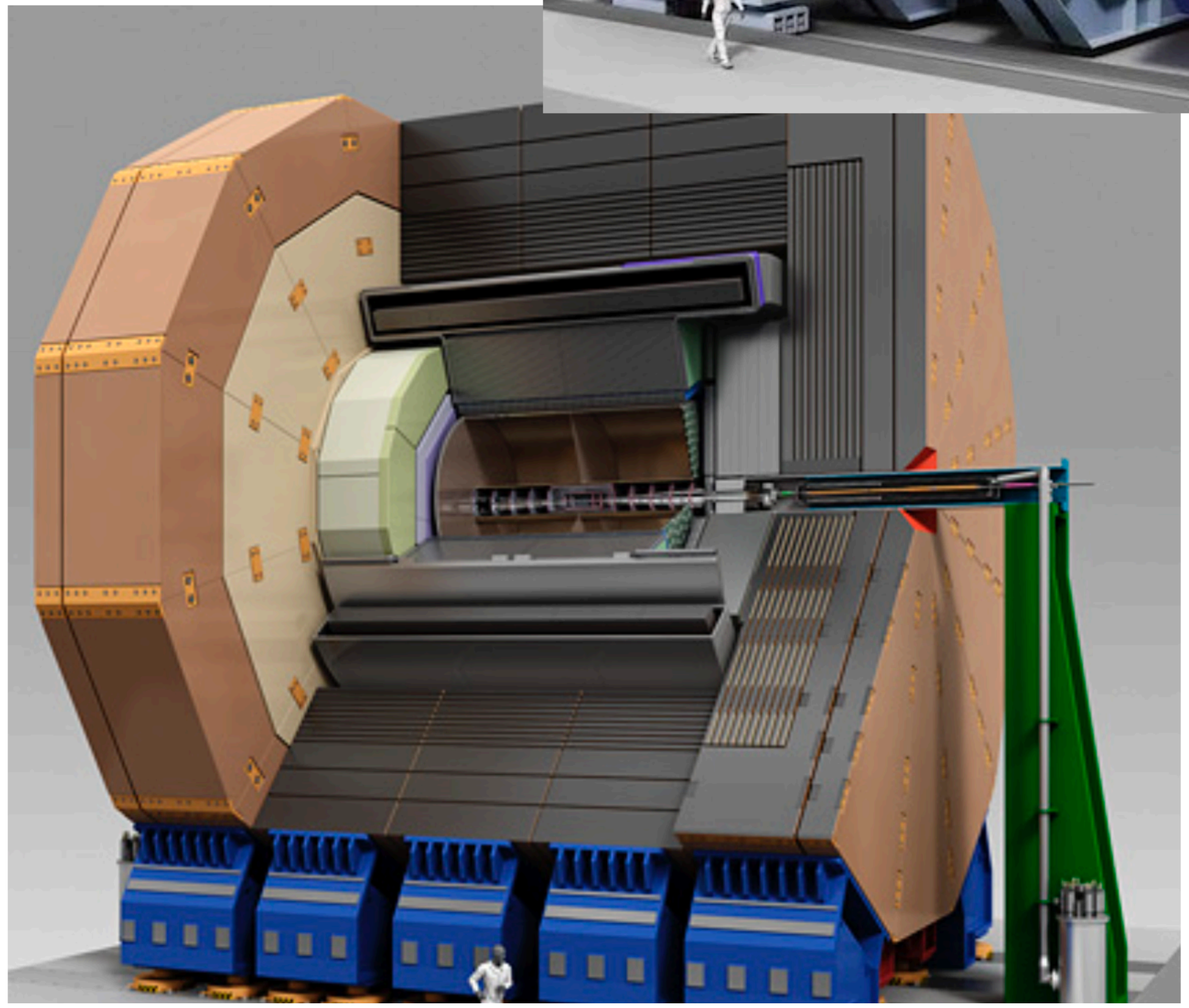
For ILD: 2 versions (large / small) under study

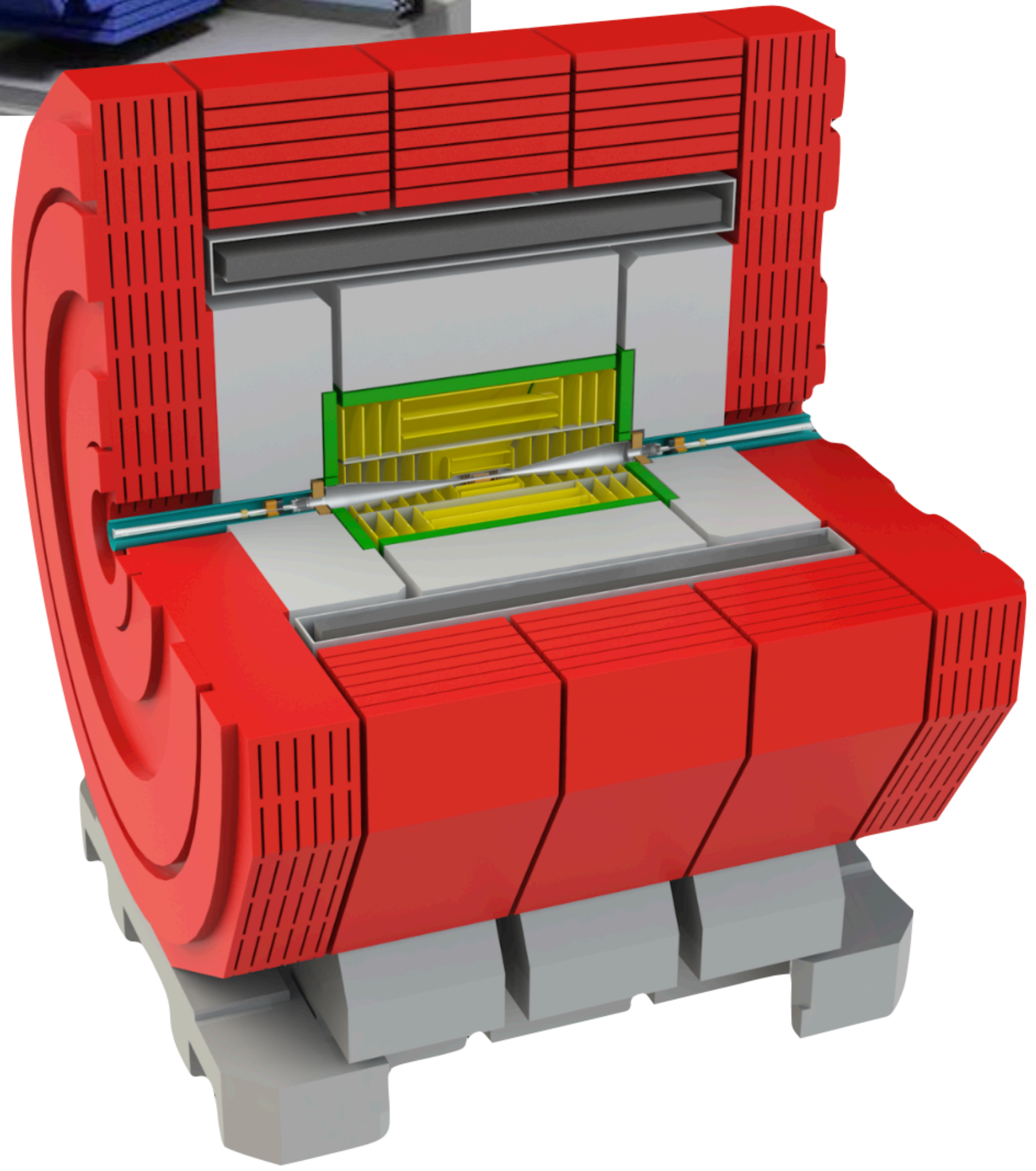
5T field
all-Si tracker with outer radius of 1.2 m
VTX inner radius 14 mm
4.5 λ_I HCAL

- 3.5T / 4T field
- TPC as main tracker, supplemented by outer Si envelope radius 1.77 m / 1.43 m
- VTX inner radius 16 mm
- 6 λ_I HCAL

LC BEYOND BASELINE IDEAS …







particle ID systems - improved flavour tagging with better π/K separation via TOF or other means

added readout dimensions in calorimetry: highly granular dual readout, new optical materials

exploiting ps timing capabilities in calorimeters and trackers

highly pixelated sensors throughout all silicon systems of the detectors

New radiation hard sensor materials for forward instrumentation

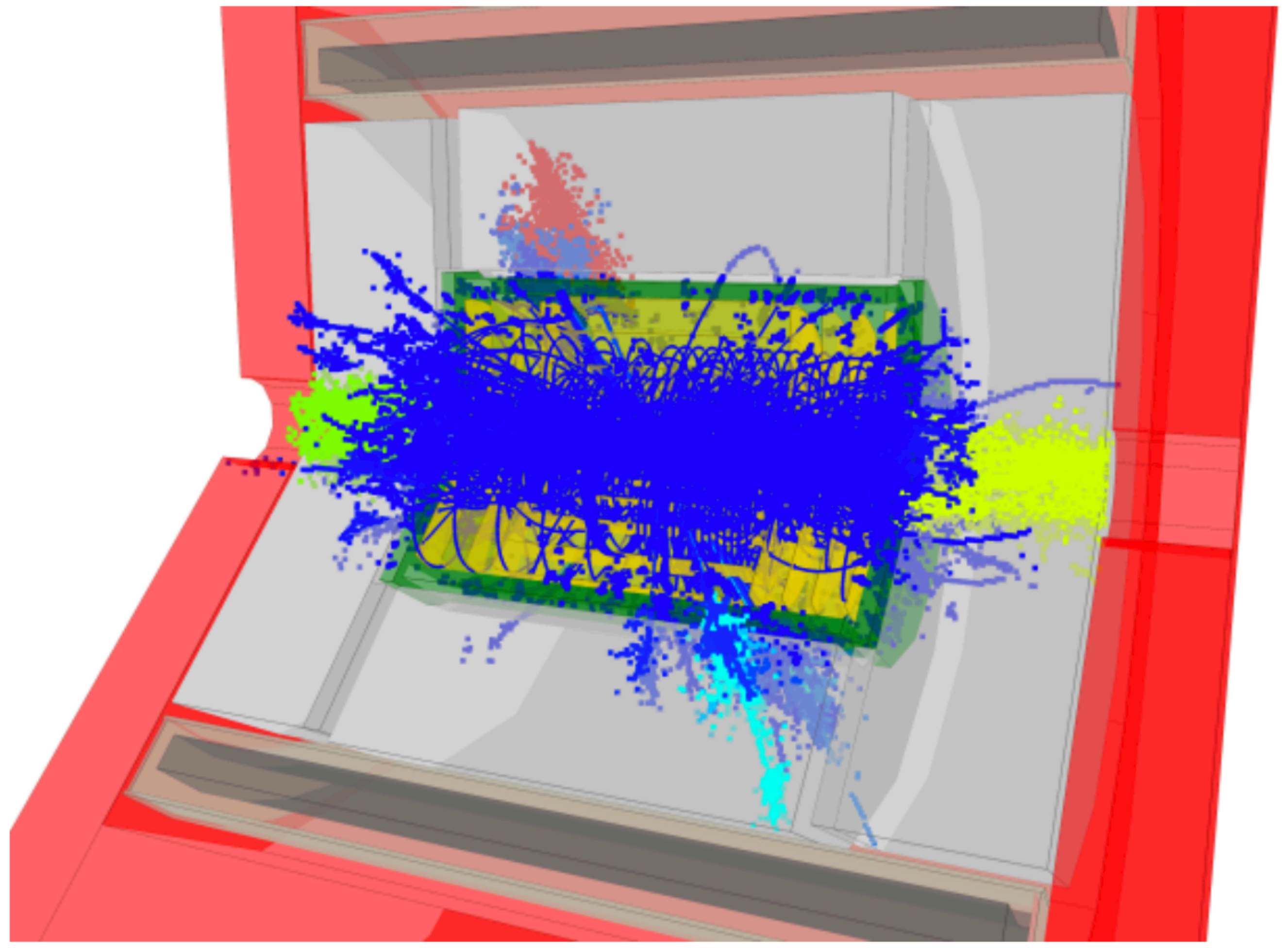
Ultra-low mass mechanics, ultra-low mass & ultra-low power interfaces and services

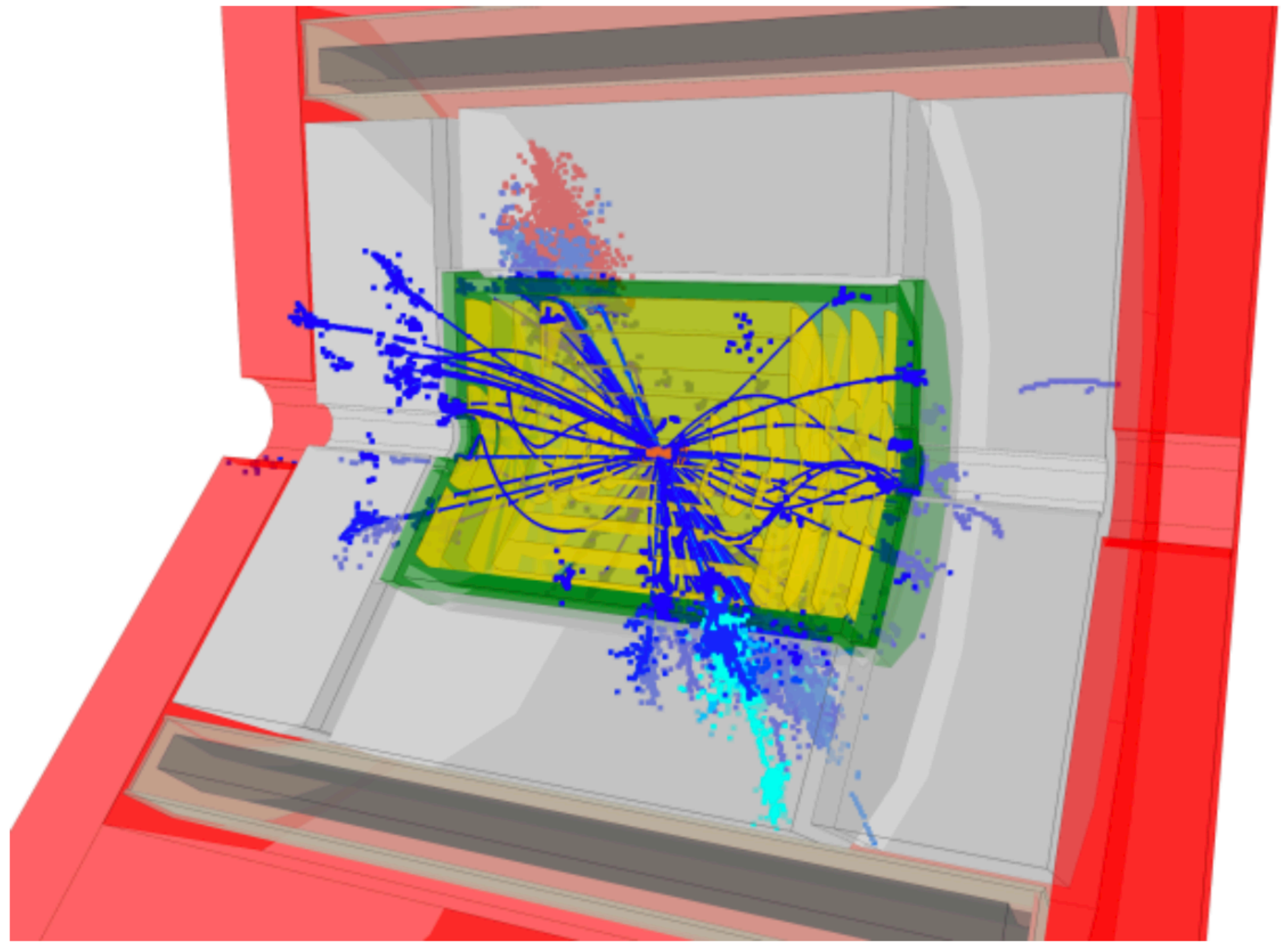
LC DETECTOR PARAMETERS

	ILD (IDR_L/IDR_S)	SiD	CLICdet	CLD	IDEA	CEPC baseline
Vertex technology	Silicon	Silicon	Silicon	Silicon	Silicon	Silicon
Vertex inner radius	1.6 cm	1.4 cm	3.1 cm	1.75 cm	1.7 cm	1.6 cm
Tracker technololy	TPC + Silicon	Silicon	Silicon	Silicon	Drift chamber + Si	TPC + Silicon
Tracker outer radius	1.77 m / 1.43 m	1.22 m	1.5 m	2.1 m	2.0 m	1.8 m
Calorimeter	PFA	PFA	PFA	PFA	Dual readout	PFA
(ECAL) inner radius	1.8 m / 1.46 m	1.27 m	1.5 m	2.15 m	2.5 m	1.8 m
ECAL technology	Silicon	Silicon	Silicon	Silicon	-	Silicon
ECAL absorber	W	W	W	W	-	W
ECAL thickness	24 X_0 (30 layers)	26 X_0 (30 layers)	22 X_0 (40 layers)	22 X_0 (40 layers)	-	24 X_0 (30 layers)
HCAL technology	Scintillator	Scintillator	Scintillator	Scintillator	-	RPC
HCAL absorber	Fe	Fe	Fe	Fe	-	Fe
HCAL thickness	5.9 λ_I (48 layers)	4.5 λ_I	7.5 λ_I (60 layers)	5.5 λ_I (44 layers)	8 λ_I (2 m)	4.9 λ_I (40 layers)
(HCAL) outer radius	3.34 m / 3.0 m	2.5 m	3.25 m	3.57 m	≤4.5 m	3.3 m
Solenoid field	3.5 T / 4 T	5 T	4 T	2 T	2 T	3 T
Solenoid length	7.9 m	6.1 m	8.3 m	7.4 m	6.0 m	8.0 m
Sol. inner radius	3.42 m / 3.08 m	2.6 m	3.5 m	3.7 m	2.1 m	3.4 m

LC DETECTOR CONSTRAINTS FROM MACHINE CONDITIONS

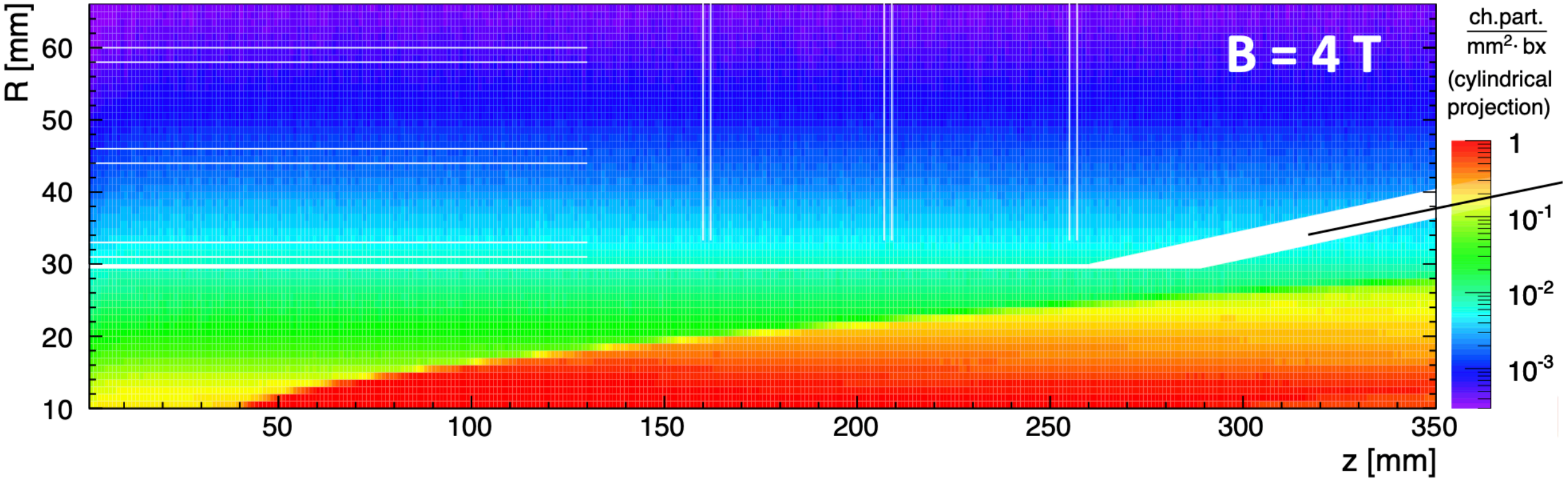
- Backgrounds - a key driver at CLIC:
  γγ -> hadrons results in significant backgrounds in the full acceptance of the detector





3 TeV tt event at CLIC, with background overlaid, and removed by reconstruction

➯ Requires timing on the ns level, high segmentation and powerful reconstruction techniques



- Significant background from e^+e^- pairs - imposes constraints on beam pipe radius, vertex detector location:

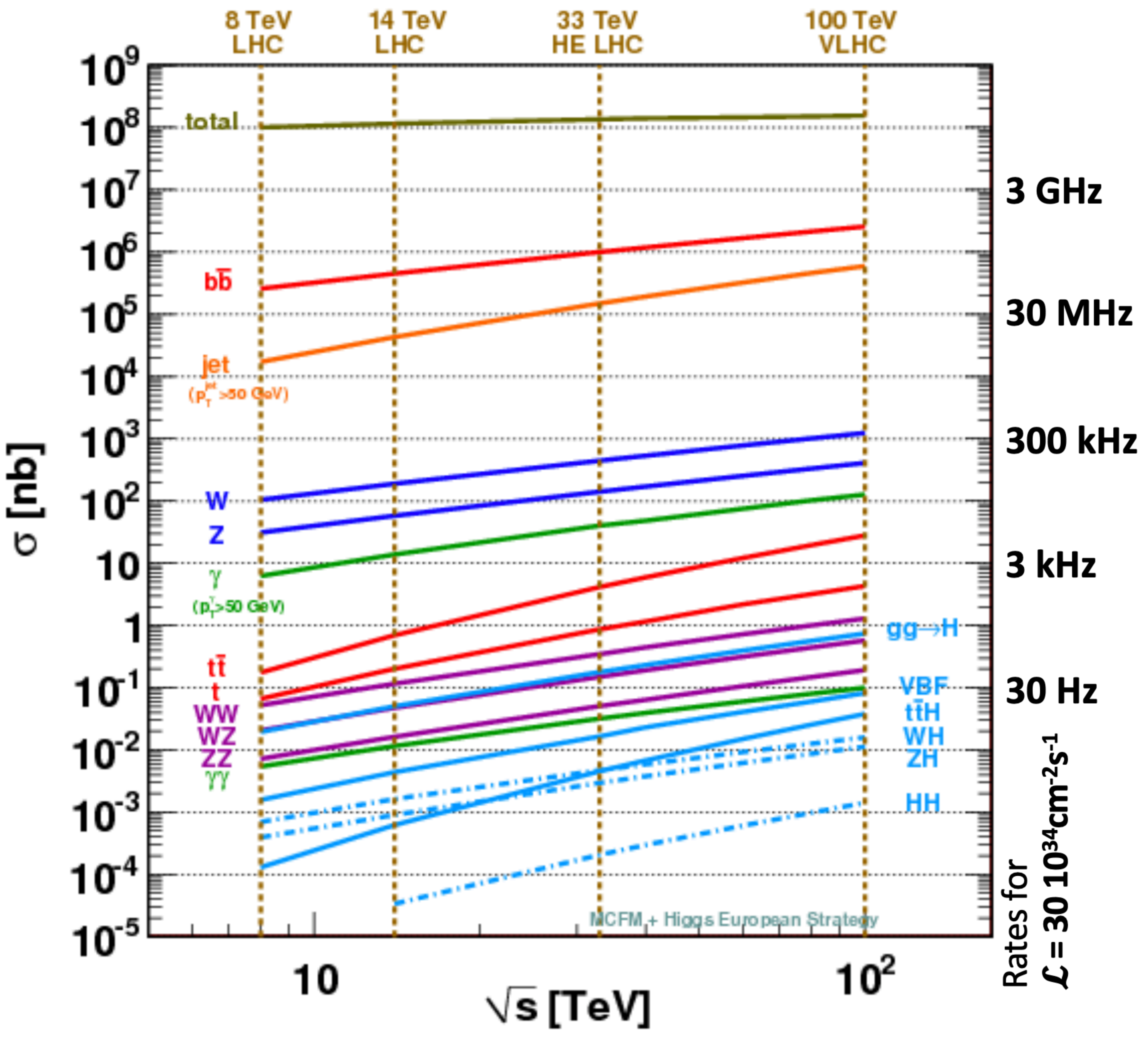
➯ High magnetic field to enable small radius

TECHNOLOGIES FOR DETECTORS AT LC/FCC…

Key technologies for linear collider detector baselines have been developed and demonstrated in prototypes and test beams - many, but not all central requirements met [but there is always potential for improvement!]

+ activities in different R&D initiatives and consortia, such as EU funded projects EUDET, AIDA, AIDA-2020

CROSS SECTIONS FOR KEY PROCESSES @FCC-hh



- **Total cross-section and Minimum Bias Multiplicity** show only a **modest increase** from LHC to FCC-hh.
- The **cross-sections for interesting processes, however, increase significantly** (e.g. HH x 50!)!
- Higher luminosity to increase statistics → pileup of 140 at HL-LHC to **pileup of 1000** at FCC-hh → **challenge for triggering and reconstruction**
- **$\mathcal{L}$ = 30x10^{34}cm^{-2}s^{-1}:**
  - 100MHz of jets p_T>50GeV,
  - 400kHz of Ws,
  - 120kHz of Zs,
  - 11kHz of ttbars
  - 200Hz of gg→H

FCC-hh PARAMETER TABLE

Table 7.1: Key numbers relating the detector challenges at the different accelerators.

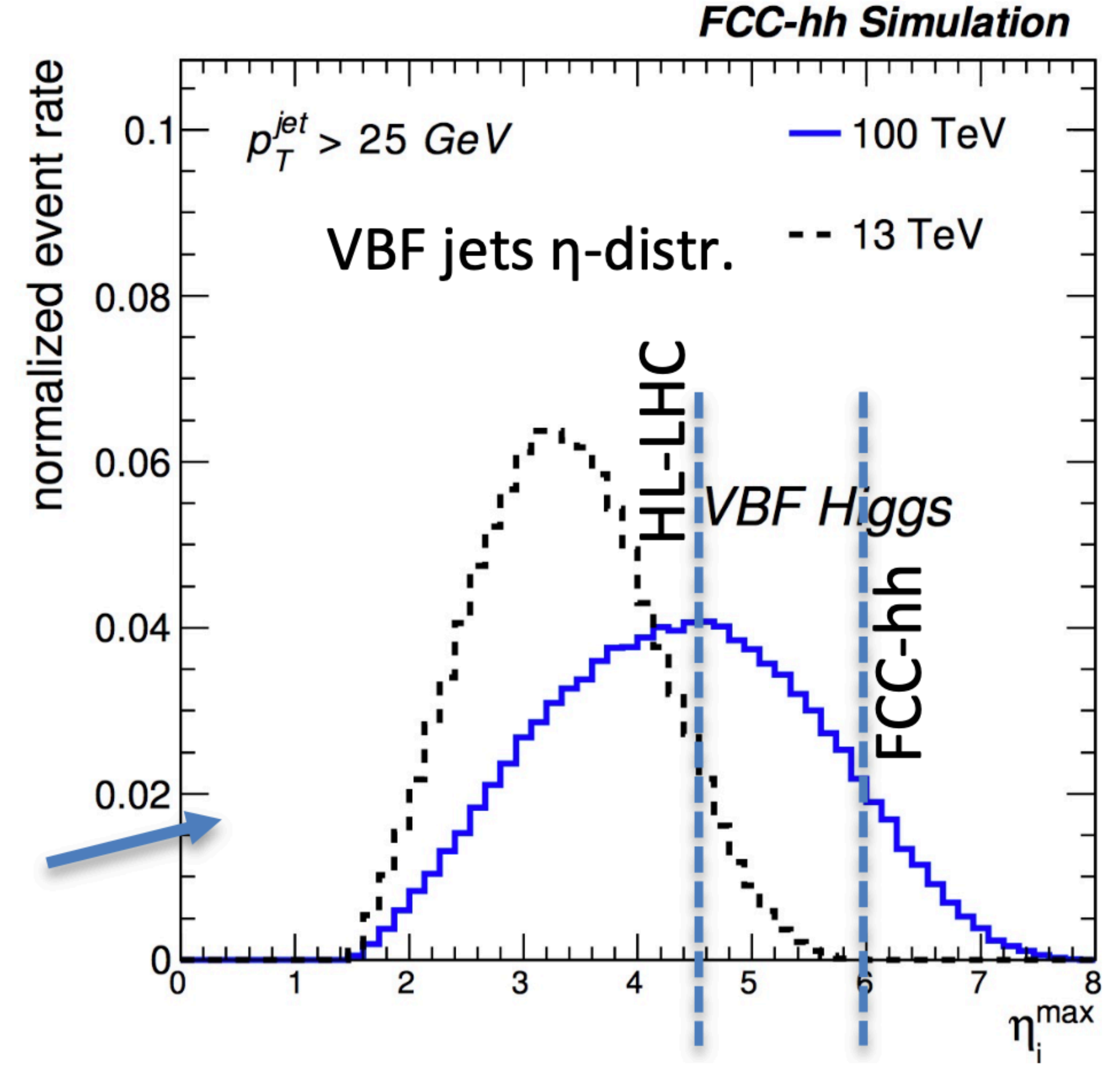
Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10600
Goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel} [331]	mb	80	80	86	103
σ_{tot} [331]	mb	108	108	120	150
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.8	4	14	31
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950
Rms luminous region σ_z	mm	45	57	57	49
Line PU density	mm^{-1}	0.2	1.0	3.2	8.1
Time PU density	ps^{-1}	0.1	0.29	0.97	2.43
$dN_{ch}/d\eta\vert_{\eta=0}$ [331]		6.0	6.0	7.2	10.2
Charged tracks per collision N_{ch} [331]		70	70	85	122
Rate of charged tracks	GHz	59	297	1234	3942
$<p_T>$ [331]	GeV/c	0.56	0.56	0.6	0.7
Bending radius for $<p_T>$ at B=4 T	cm	47	47	49	59

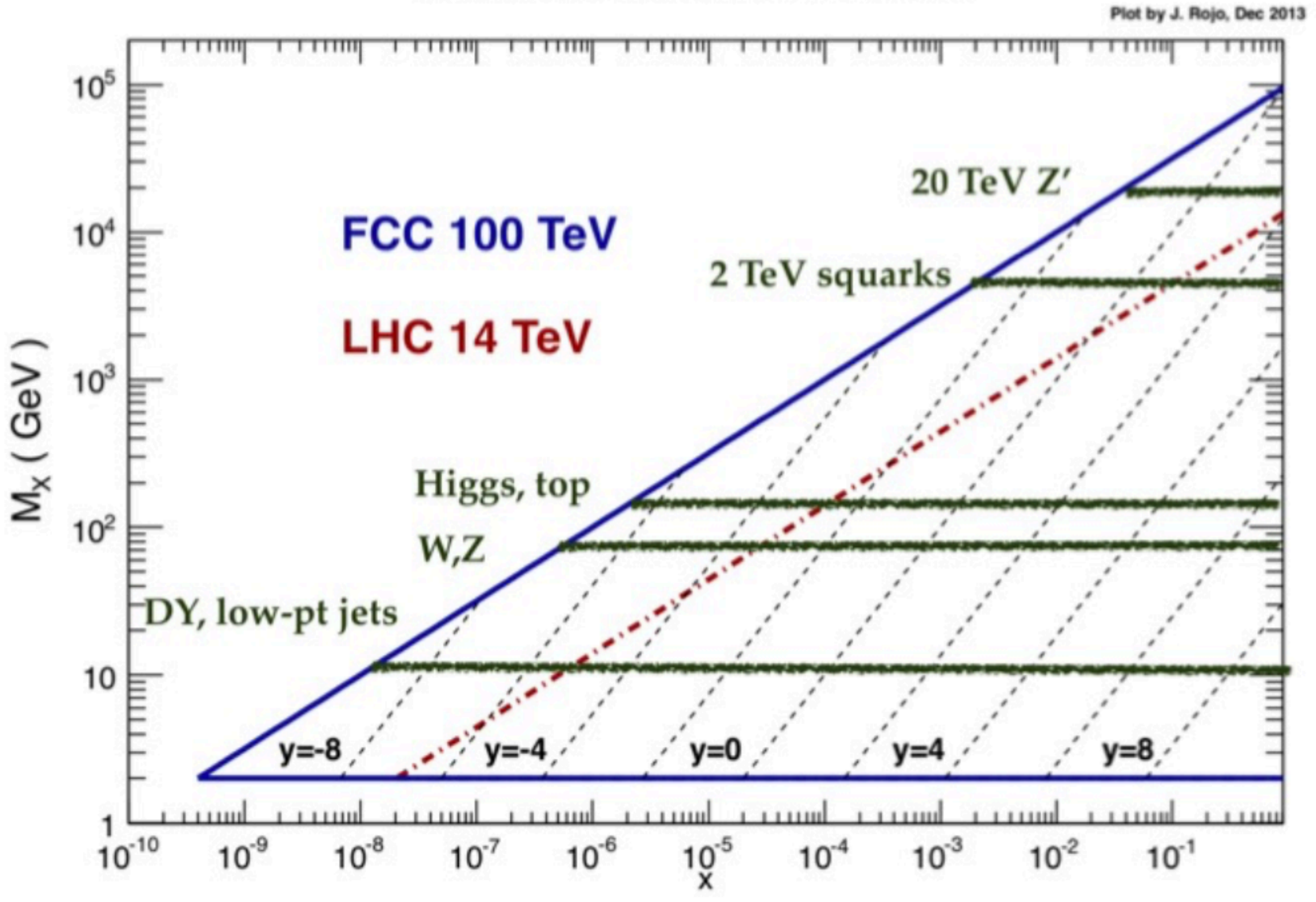
- E_{cm} = 100 TeV
- ~100 km circumference
- $\mathcal{L} = 30 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
- $\int\mathcal{L} = 30\ \text{ab}^{-1}$
- 31 GHz pp collisions
- Pile-up <μ> ≈ 1000
- 4 THz of charged tracks

FCC-hh PARAMETER TABLE

Table 7.1: Key numbers relating the detector challenges at the different accelerators.

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
Total number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm, est.(FLUKA)	GHz cm^{-2}	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est.(FLUKA)	10^{16} cm^{-2}	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm, est.(FLUKA)	MGy	1.3	13	54	270 (300)
$dE/d\eta\|_{\eta=5}$ [331]	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0
90% $b\bar{b}$ $p_T^b > 30$ GeV/c [332]	$\|\eta\|<$	3	3	3.3	4.5
VBF jet peak [332]	$\|\eta\|$	3.4	3.4	3.7	4.4
90% VBF jets [332]	$\|\eta\|<$	4.5	4.5	5.0	6.0
90% $H \rightarrow 4l$ [332]	$\|\eta\|<$	3.8	3.8	4.1	4.8





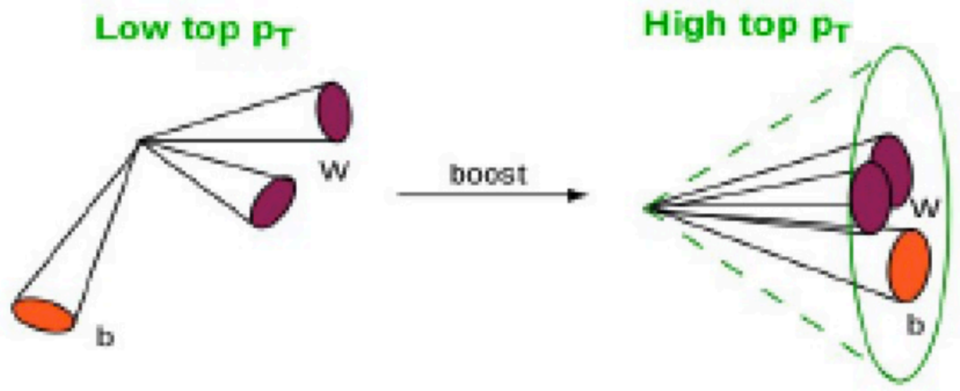
Unprecedented particle flux and radiation levels

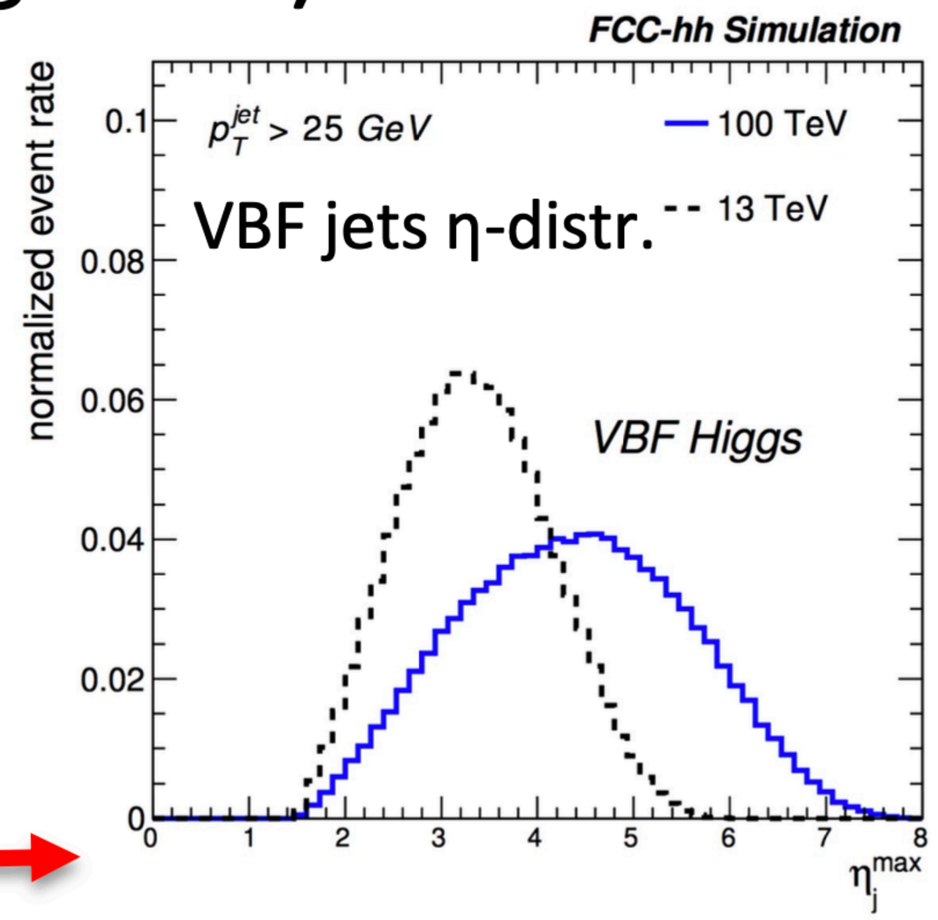
- **10 GHz/cm² charged particles**
- **≈ 10^{18} cm^{-2} 1 MeV-n.eq. fluence for 30ab^{-1} (first tracker layer, fwd calo)**
- **"Light" SM particles produced with increased forward boost**
  - **→ spreads out particles by 1-1.5 units of rapidity**

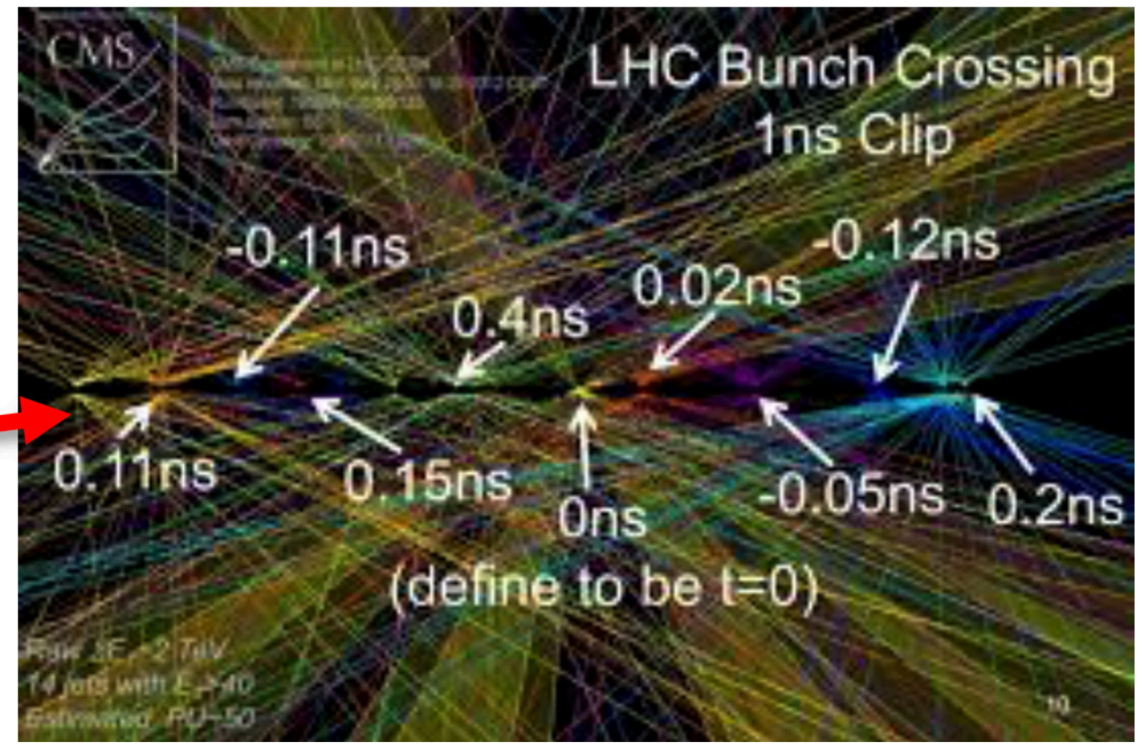
FCC-hh DETECTORS REQUIREMENTS

Used in Delphes physics simulations

- **ID tracking target**: achieve σ_{pT} / p_T = 10-20% @ 10 TeV
- **Muon target**: σ_{pT} / p_T = 5% @ 10 TeV
- Keep **calorimeter constant** term as small as possible (and good sampling term)
  - Constant term of <1% for the EM calorimeter and <2-3% for the HCAL
- **High efficiency vertex reconstruction, b-tagging, τ-tagging, particle ID**!
  - Pile-up of <μ>=1000 → 120μm mean vertex separation
- **High granularity** in tracker and calos (boosted obj.)
- **Pseudorapidity (η) coverage**:
  - Precision muon measurement up to |η|<4
  - Precision calorimetry up to |η|<6
- **→ Achieve all that at a pile-up of 1000! → Granularity & Timing!**
- **On top of that radiation hardness and stability!**



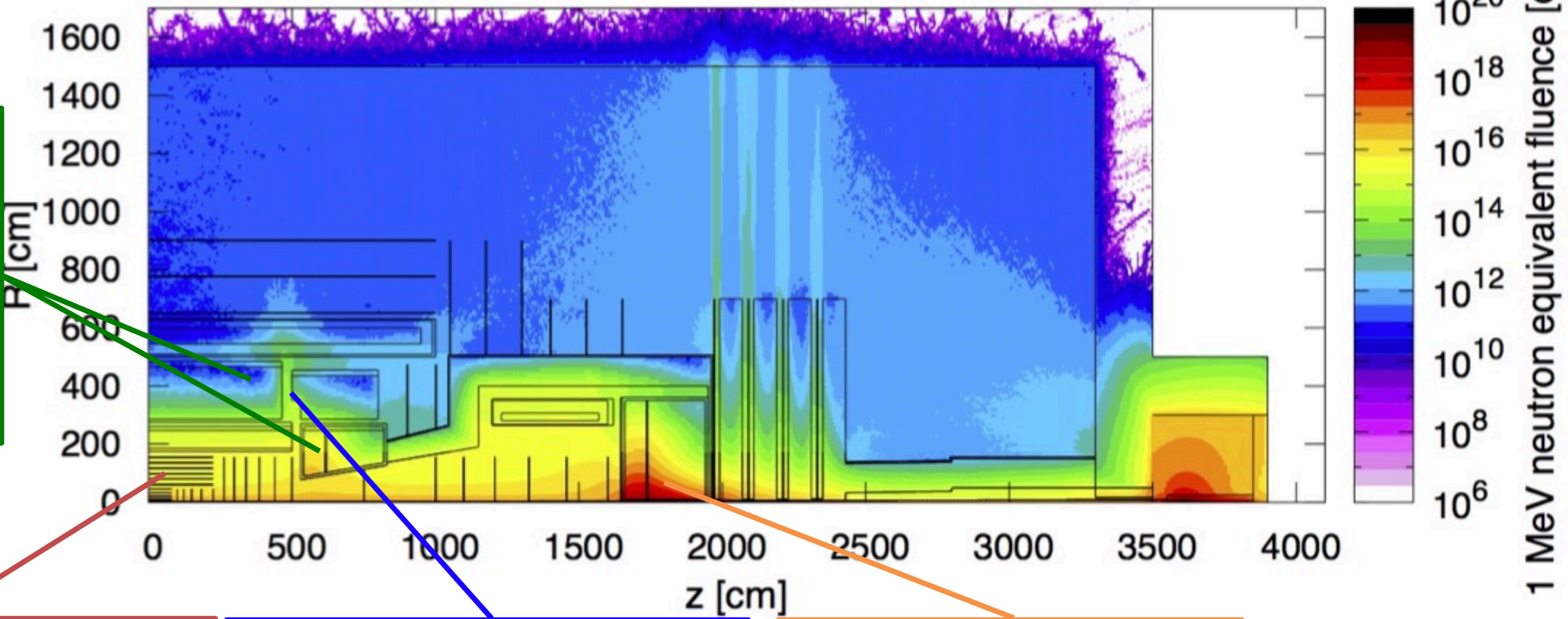




1 MeV NEUTRON EQUIVALENT FULENCE FOR 30 ab^{-1} AT FCC-hh

Generally ~10-30 times worse than HL-LHC

Exception: Forward calorimeter goes to higher η → bigger factor



Barrel calorimeter:
EM-calo: 4 10^{15} cm^{-2}
HAD-calo: 4 10^{14} cm^{-2}

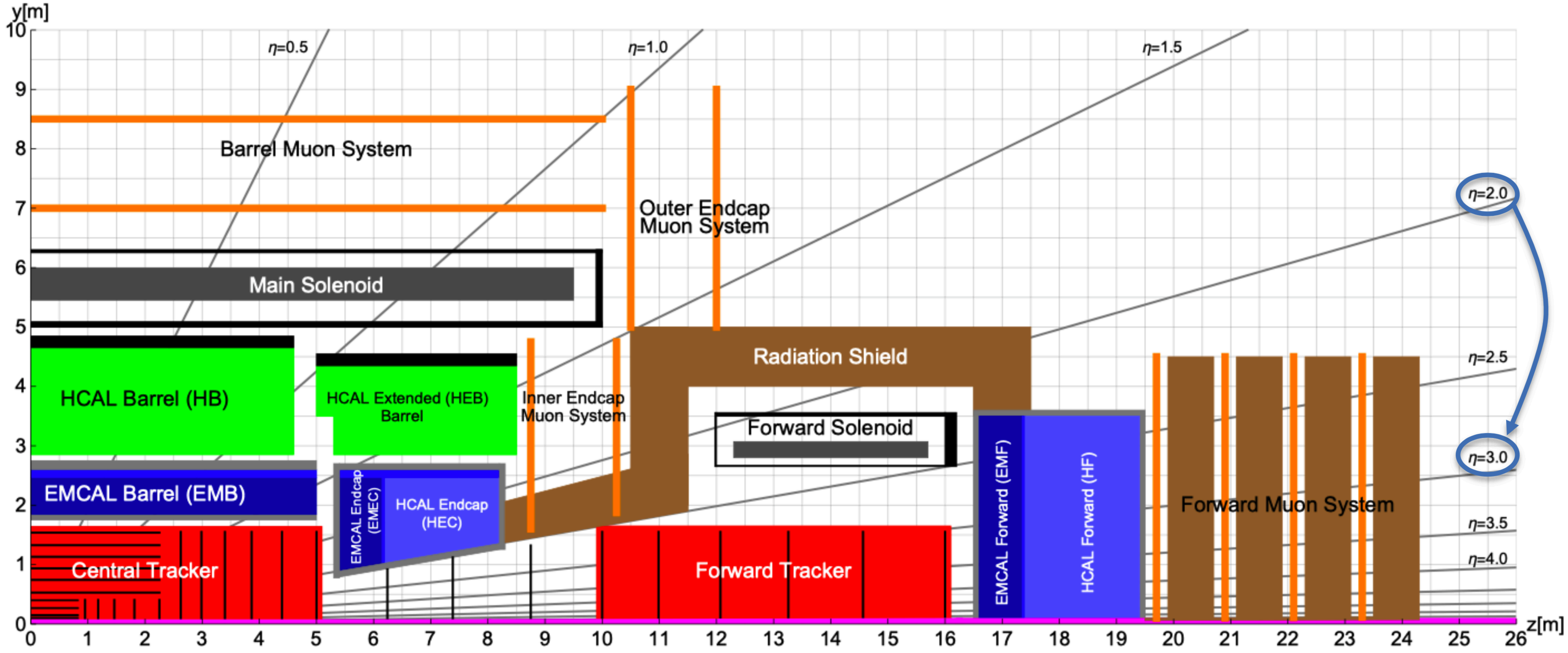
End-cap calorimeter:
EM-calo: 2.5 10^{16} cm^{-2}
HAD-calo: 1.5 10^{16} cm^{-2}

Central tracker:
- first IB layer (2.5 cm): ~5-6 10^{17} cm^{-2}
- external part: ~5 10^{15} cm^{-2}

Calorimeter gap:
from 10^{16} cm^{-2} to 10^{14} cm^{-2}

Forward calorimeters:
~5 10^{18} cm^{-2} for both the EM and the HAD-calo

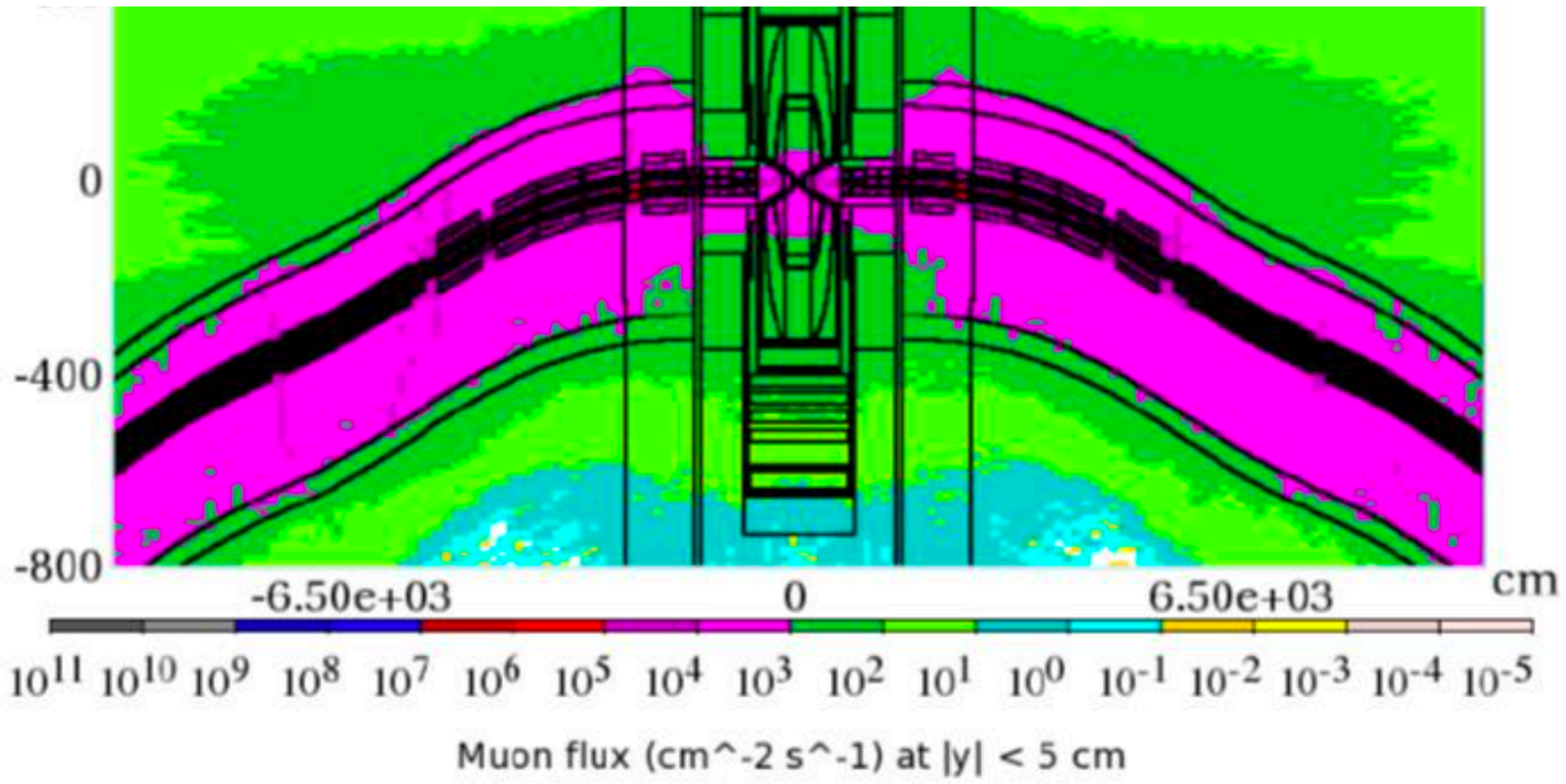
FCC-hh REFERENCE DETECTOR



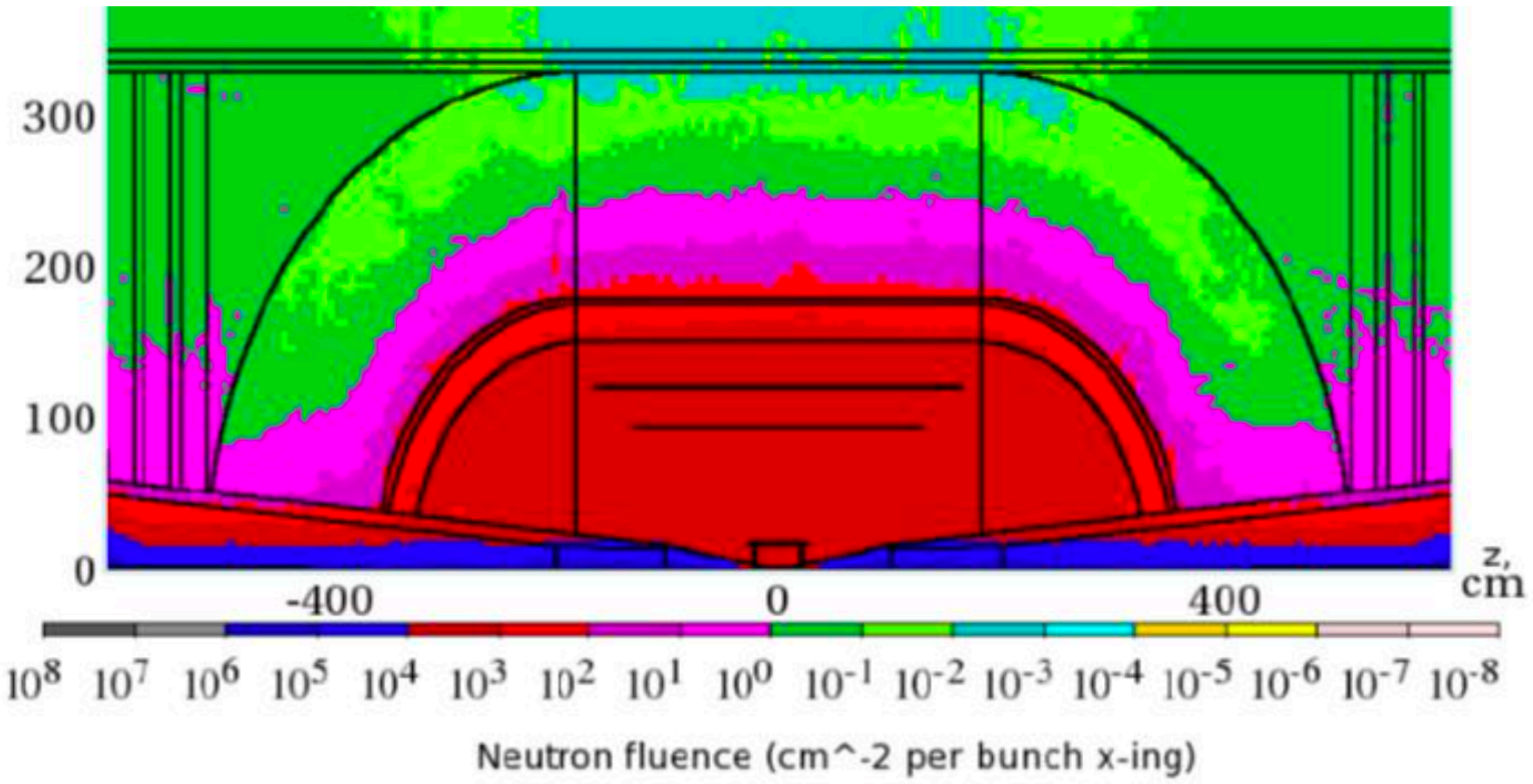
Forward solenoid adds about 1 unit of η with full lever-arm

Forward solenoid requires additional radiation shield to connect endcap and forward calorimeter

MUON COLLIDER: MUON & NEUTRON FLUENCES AT 1.5 TeV



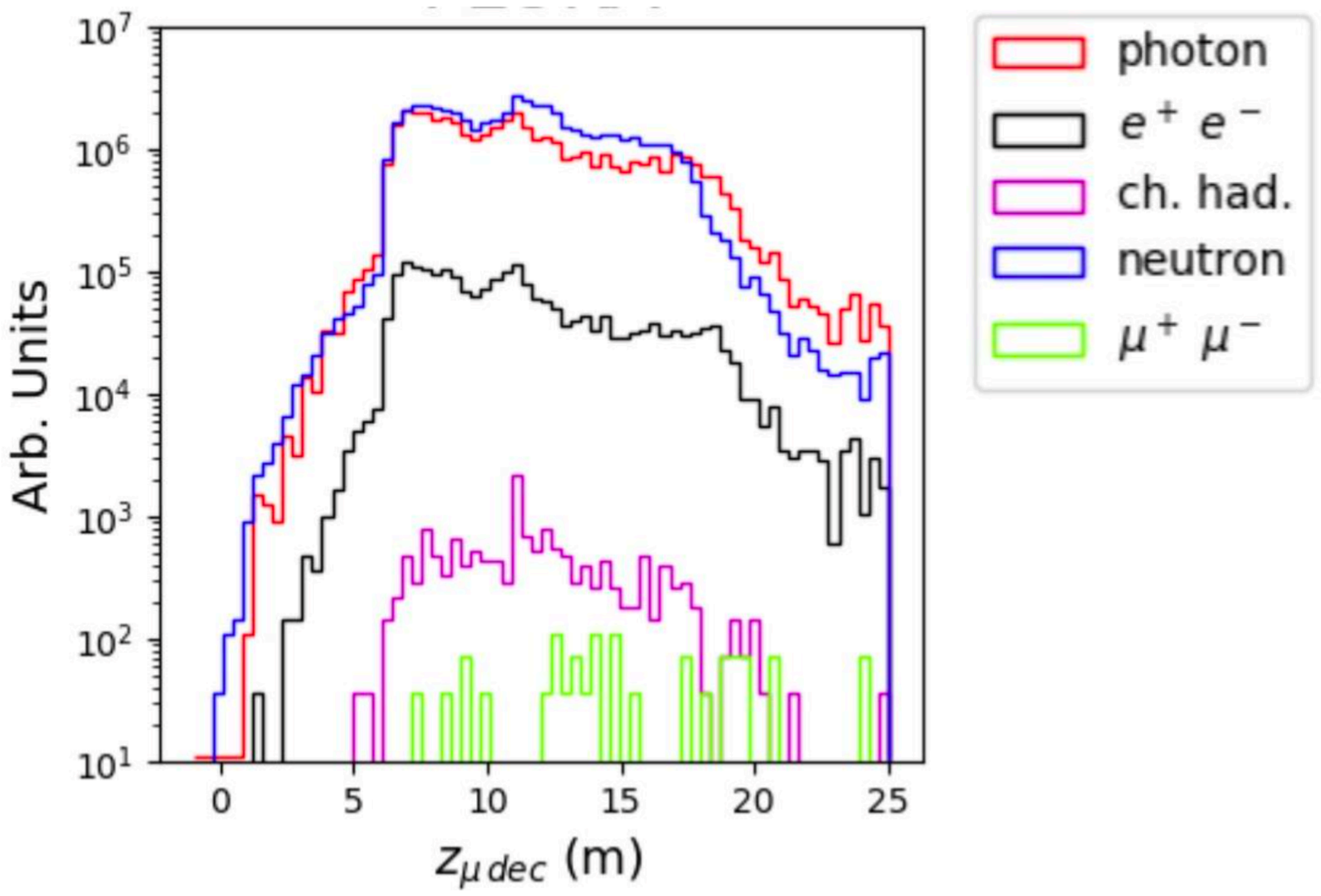
Muon flux map in IR.
Muons – with energy of tens and hundreds GeV – illuminate the whole detector. They are produced as Bethe-Heitler pairs by energetic photons in EMS originated by decay electrons in lattice components.



Neutron fluence map inside the detector.
Maximum neutron fluence and absorbed dose in the innermost layer of the Si tracker for a one-year operation are at a 10% level of that in the LHC detectors at the nominal luminosity. High fluences of photons and electrons in the tracker and calorimeter exceed those at LHC, and need more work to suppress them.

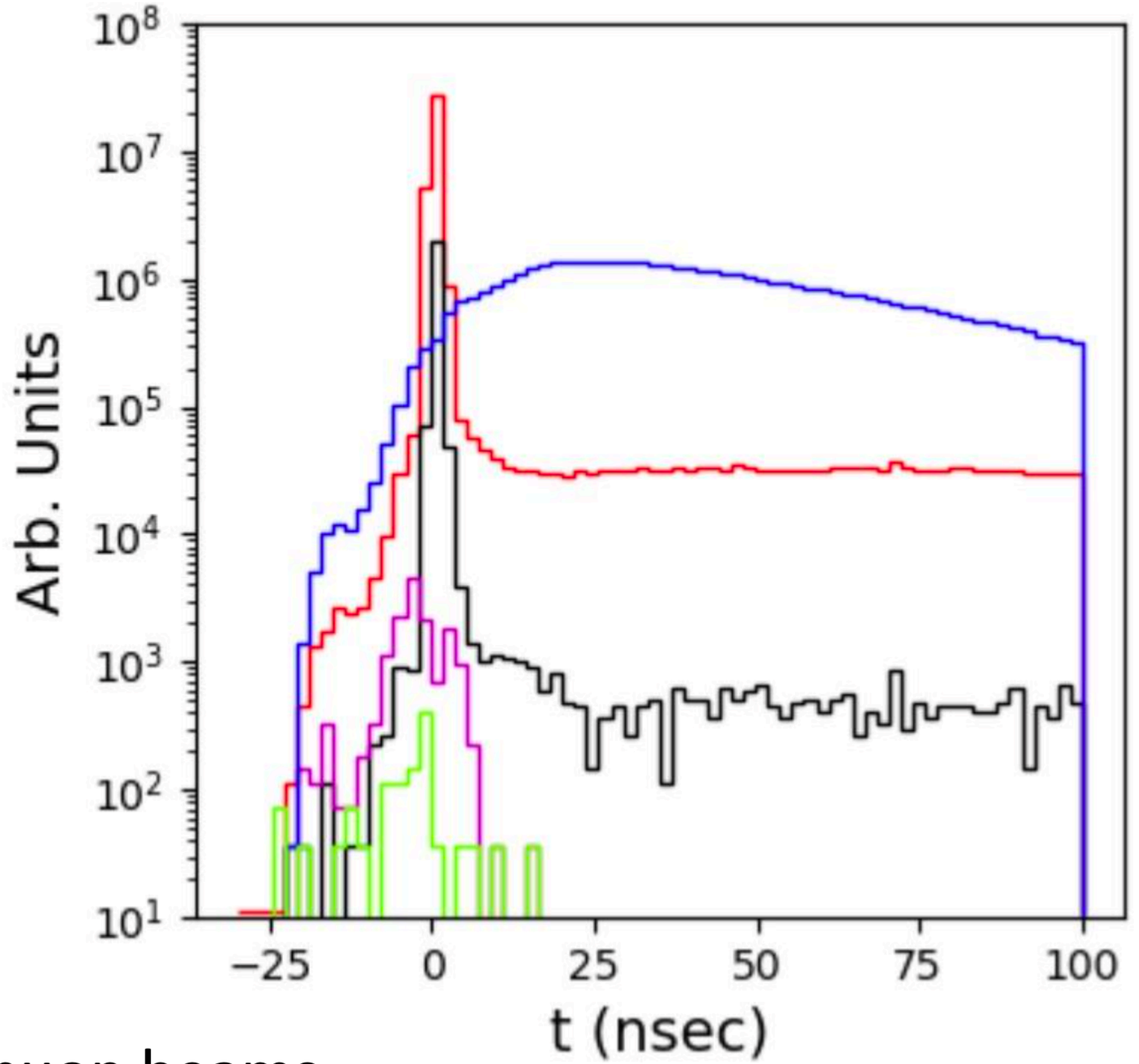
Expected fluence < HL-LHC HL-LHC < Expected dose < FCC-hh
Still expecting radiation hardness
to play a significant role, but unlikely to be a major problem
Leaves more flexibility in adapting detector design to such requirements

MUON COLLIDER: BIB AT 1.5 TeV



Particle (E_{th}, MeV)	MARS15	FLUKA
Photon (0.2)	$8.3\ 10^7$	$4.29\ 10^7$
Neutron (0.1)	$2.44\ 10^7$	$5.37\ 10^7$
Electron/positron (0.2)	$7.23\ 10^5$	$2.2\ 10^6$
Ch. Hadron (1)	$3.07\ 10^4$	$1.52\ 10^4$
Muon (1)	$1.47\ 10^3$	$1.22\ 10^3$

Donatella Lucchesi et al.



muon beams
@ **0.75 TeV** with **2×10^{12}muons/bunch** ➔
4×10^5 muon decays/m single bx
JINST 13 (2018), P09004
***JINST* 15 (2020) 05, P05001**

BIB @ 10 TeV only general consideration

- Not expected to dramatically change compared to lower energies
- BIB timing distributions to be verified

4

MUON COLLIDER: BIB PROPERTIES

BIB has several characteristic features → crucial for its effective suppression

1. Predominantly very soft particles (p << 250 MeV) except for neutrons

fairly uniform distribution in the detector → no isolated signal-like deposits
↳ conceptually different from pile-up contributions at the LHC

2. Significant spread in time (few ns + long tails up to a few μs)

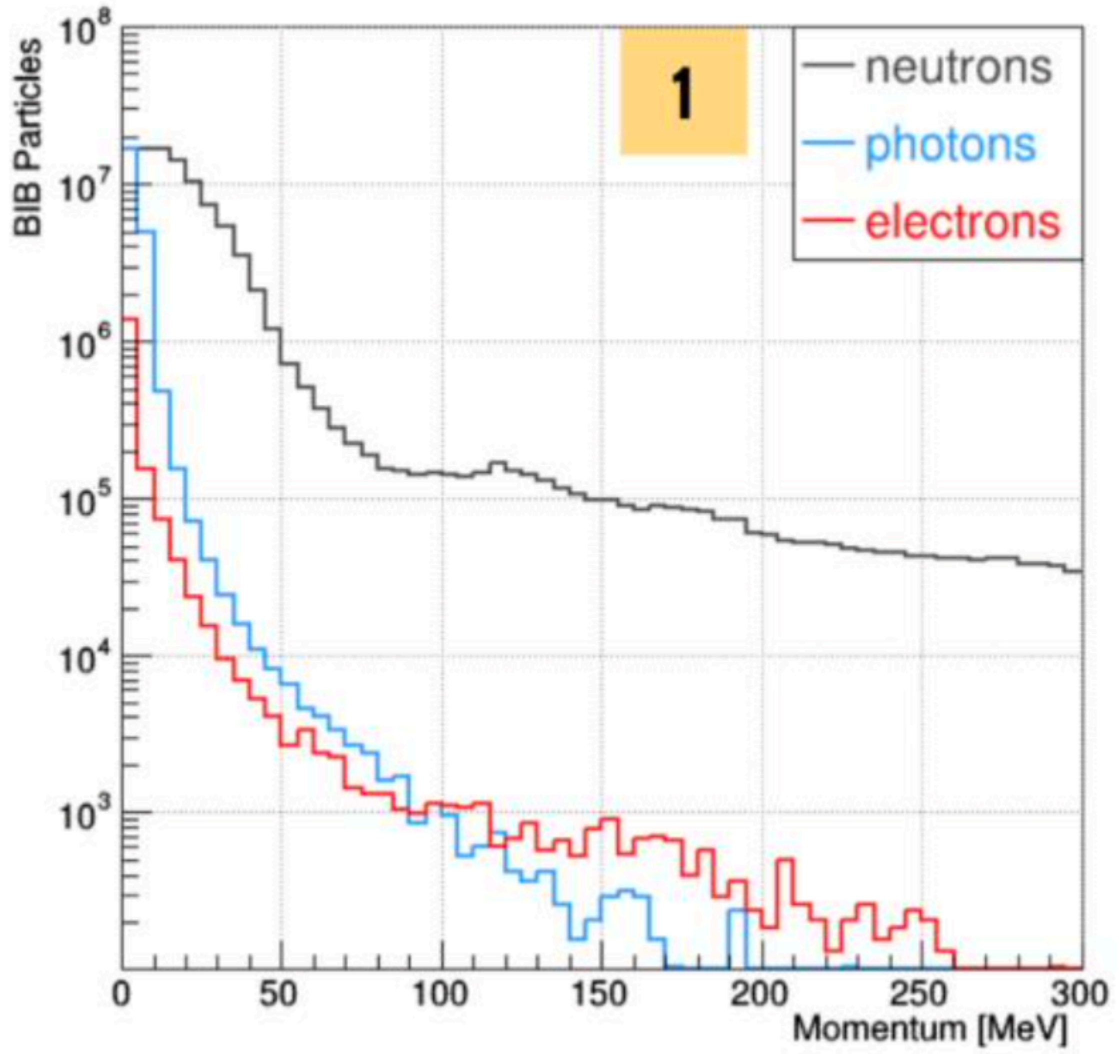
$\mu^+\mu^-$ collision time spread: ~30ps (defined by the muon-beam properties)
↳ strong handle on the BIB → requires state-of-the-art timing capabilities

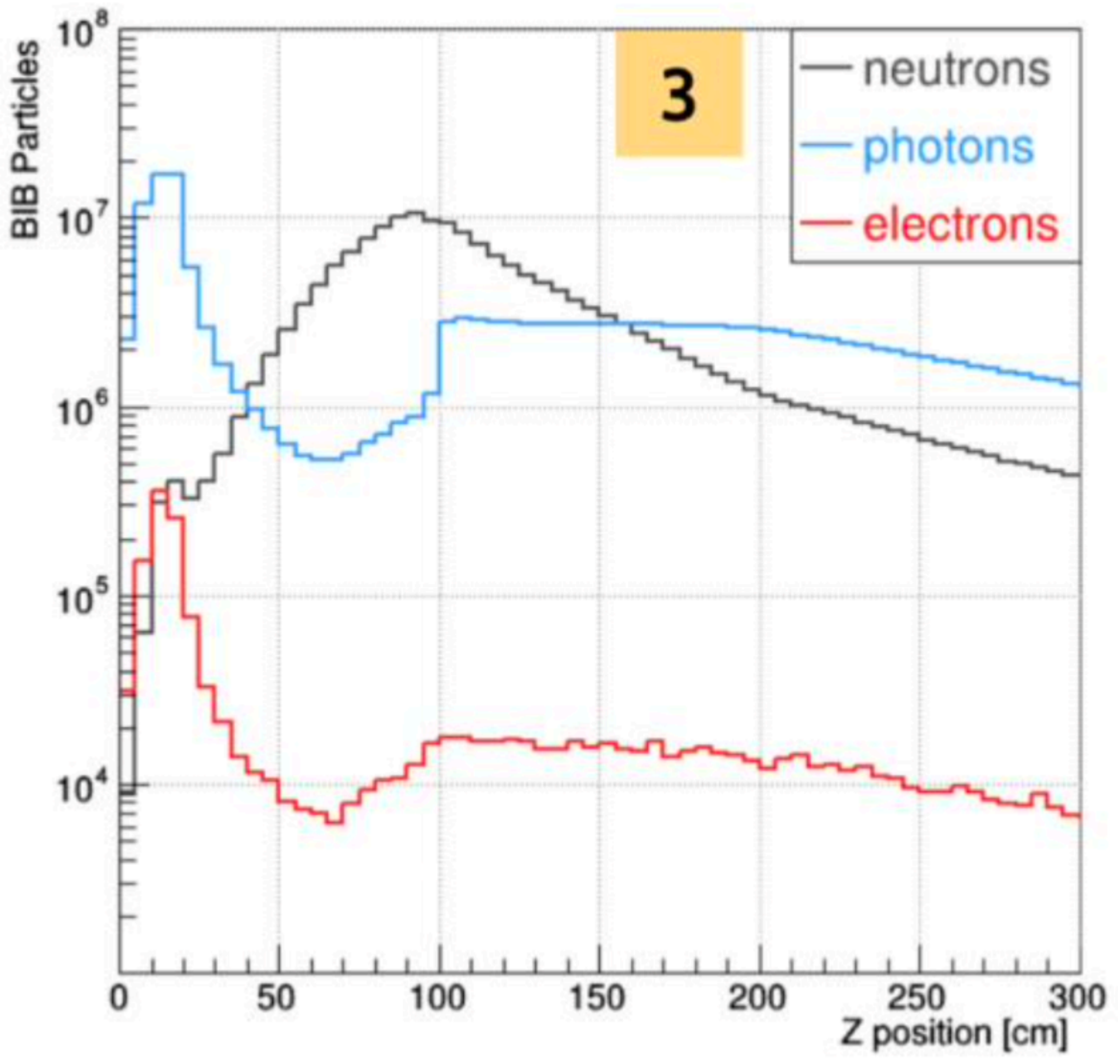
3. Large spread of the origin along the beam

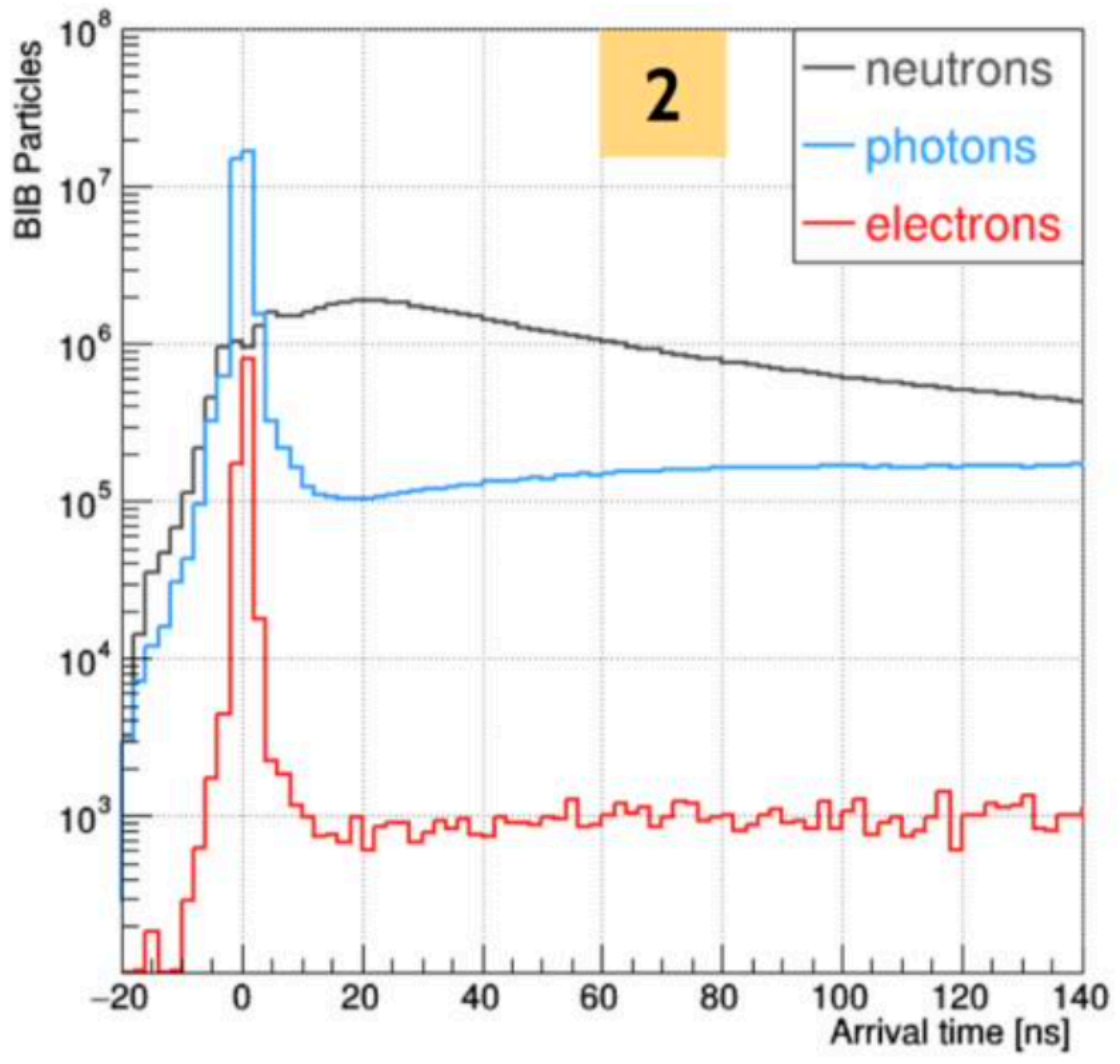
different azimuthal angle wrt the detector surface
+ affecting the time of flight to the detector

Sophisticated detector technologies and event-reconstruction strategies required to exploit these features

4D coordinates of the Interaction Point (IP) define the reference to 2 and 3







MUON COLLIDER: GENERAL REQUIREMENTS FOR DETECTOR

- ✓ Track efficiency and momentum resolution – for feasibility and precision of many physics studies e.g. final states with leptons
- ✓ Good ECAL energy and position resolution for e/gamma reconstruction
- ✓ Good jet energy resolution
- ✓ Efficient identification of a secondary vertex for heavy quark tagging
- ✓ Other considerations (Missing Energy/MET, taus, substructure)

- ✓ Many ILC or CLIC considerations apply to Muon Collider detectors, although beam background conditions are different and much more challenging requiring a dedicated design for Muon Collider experiment: vertex/tracking – calorimetry – triggerless DAQ
- ✓ Detector design considerations should be driven by physics requirements and BIB considerations
- ✓ **Optimal design will very likely be different for different collision energies**

MUON COLLIDER: DET. KEY CONSIDERATIONS

- ✓ **Most tracker hits and calorimeter clusters produced in the detector originate from BIB**
- ✓ Example: inner layers of the vertex tracker detector have occupancy ~x10 larger than CMS pixels in HL-LHC
  - Requires **large bandwidth for sending data off the detector**
  - High complexity of data reconstruction
- ✓ Applying filtering at various stages of data processing (both on and off the detector) is important
- ✓ Explore characteristics of the BIB that are different from the hard scatter:
  - Position, Time, Energy, Particle ID, Correlations of the above
- ✓ Higher bandwidth requires power, filtering on detector requires power

- ✓ Considering large bunch crossing intervals at the muon collider (~10-20 us), it is probably best to consider a triggerless DAQ system
- ✓ **Bunch crossing time is ~20-30 ps, defines natural time resolution**

MUON COLLIDER: DET. READOUT CONSIDERATIONS

- Per module, occupancy is significantly higher in the inner tracker layers than at the HL-LHC

➔ Requires on-detector logic (timing, double-layers) or higher bandwidth (more material, power)

- Total data rates at 1.5 TeV assumed to be tracker dominated and are ~30 Tb with **1 ns readout window (conservative)**
- Similar to total bandwidth of the LHCb triggerless DAQ. LHCb has smaller per event data volumes (~8800 5Gbps links) but operates at 40MHz (vs **100kHz for the Muon Collider**)
- Triggerless readout could probably work for this configuration. Total data rates do not look crazy even with today's commercial technology
- Studies are needed to understand system requirements at higher collider energies (different BIB) and larger readout windows (if needed for slow, heavy particles)

➔ Feasibility of triggerless readout for such scenarios need to be investigated.

Note, time between bunch crossings is very important

- Data => bandwidth => power

MUON COLLIDER: EXAMPLE DET. READOUT REQ.

- Assuming module size of 20 cm^2
- With 50x50 microns pixel size, get ~800k pixels per module
- With 1% occupancy, this is 8k hits per module
- 32 bits to encode x/y/amp/time
- Data rates: 8000 * 32 bit * 100 kHz * 2(safety factor) ~ 50 Gbps
- This number is factor of ~5-10 higher than HL-LHC
- Not obvious that the technology will get us there in ~10-20 years
- More handles should be explored:

Data compression, some front-end clustering, pT-module based suppression (preliminary estimates indicate more than x5)