FCC-hh overview

17.06.2021 Future Colliders @ DESY Meeting

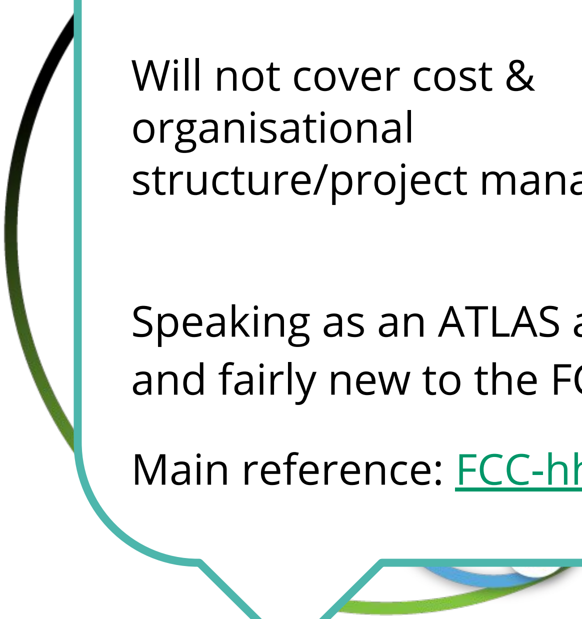
Birgit Stapf

What is FCC? (A sales pitch)

- FCC project: Future circular collider with ~100km circumference
- With options
  - FCC-ee : Presented last meeting
  - FCC-hh: In this presentation
  - FCC-eh: Next meeting
- .. provides the broadest perspective to shed light on new physics and serves as a powerful research tool till the end of the 21st century *
  - FCC-hh at the energy frontier, a discovery machine

According to this summary report

What is FCC? (A sales pitch)



Overview of the FCC-hh project for *pp*-collisions @ 100 TeV

Will not cover cost & organisational structure/project management

Speaking as an ATLAS analyst and fairly new to the FCC effort

Main reference: FCC-hh CDR

- FCC project: Future circular collider with ~100km circumference
- With options
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- .. provides the broadest perspective to shed light on new physics and serves as a powerful research tool till the end of the 21st century *
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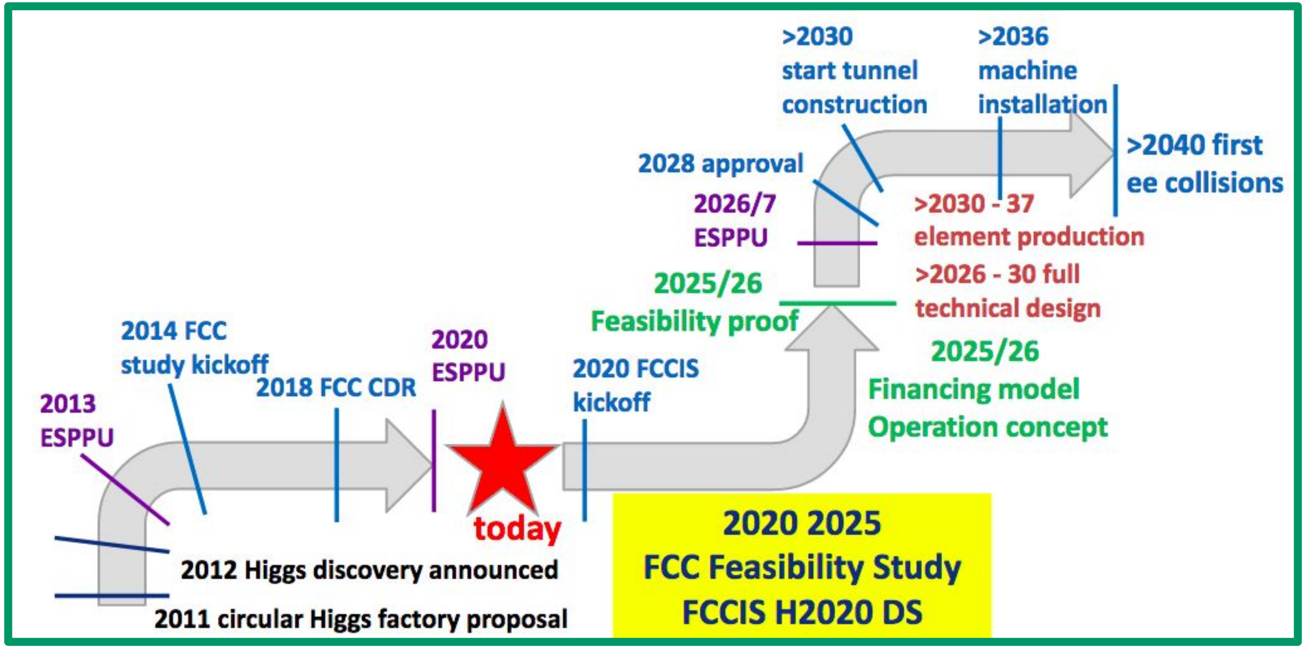
**According to this summary report*

FCC timelines

Roadmap to FCC stage 1 (with FCC-ee integrated program)



Source: M.Benedikt

FCC operation timeline (with FCC-ee integrated program)

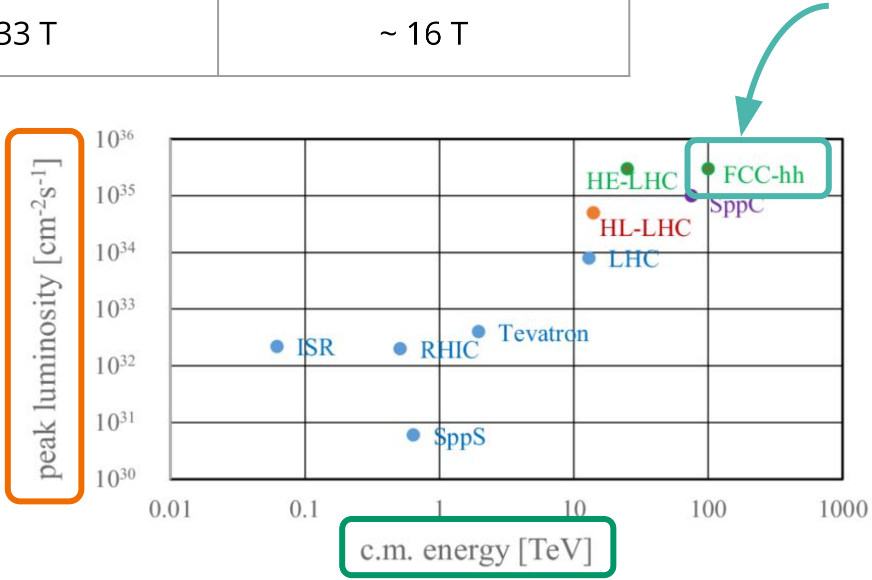
FCC-ee

FCC-ee

Collider design: Key parameters

Parameter	(HL)-LHC	FCC-hh
E_{CM}	14 TeV	100 TeV
Peak inst. lumi.	(1 - 5) x 10^{34} cm^{-2} s^{-1}	(5 - 30) x 10^{34} cm^{-2} s^{-1}
Circumference	26.7 km	97.75 km
Dipole field strength	8.33 T	~ 16 T

- FCC-hh 6-7 x energy and lumi. than HL-LHC
- Energy increase achieved by larger circumference and higher *B*-field
  - E_b [GeV] = 0.3 (B ρ) [Tm]
- Linear increase of luminosity natural due to shrinking beam size when other beam parameters stay the same
  - Further increase possible from decreasing β* functions at IP



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Dipole field strength	8.33 T	~ 16 T
Goal int. lumi.	3 ab^{-1}	30 ab^{-1}

- Total of >= 30 ab^{-1} during operation time of 25 years
  - Between two experiments and two phases:
    - 10 years w. initial values collecting 5 ab^{-1}
    - 15 years w. nominal values collecting 15 ab^{-1}
    - Required upgrade between phases: Crab cavities
- Possible to gradually evolve beam parameters, following progress of detector developments to deal with pile-up + high rates

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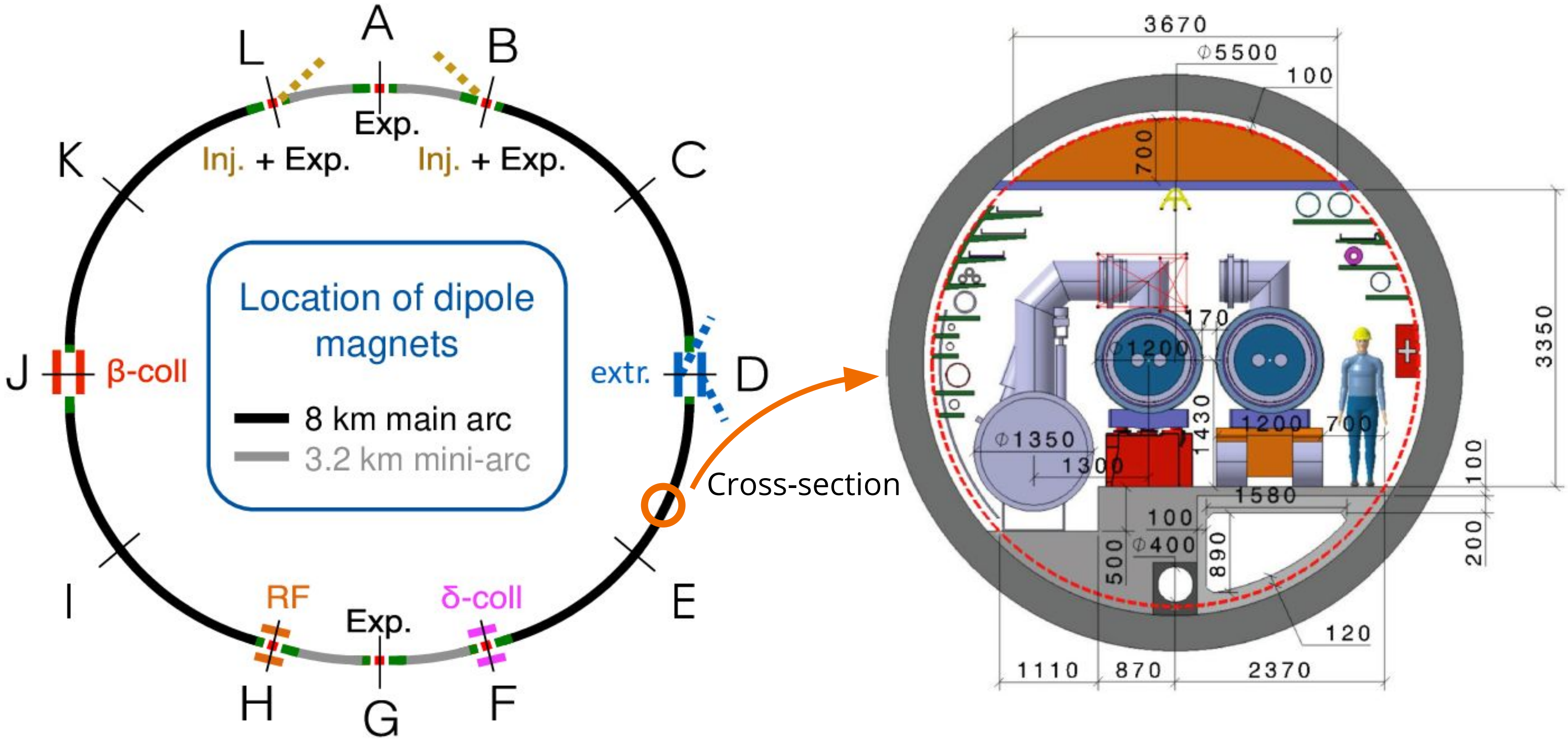
Events/crossing	O(10-100)	Max. 1000
Stored energy/beam	0.4 - 0.7 GJ	8.3 GJ
SR power loss/beam	< 0.01 MW	2.4 MW

Challenges

- Pile-up could be reduced by alternative bunch spacings from the accelerator side
- Losses due to synchrotron radiation become sizeable, first at a hadron collider
  - Proportional to E^4

Collider design: Components

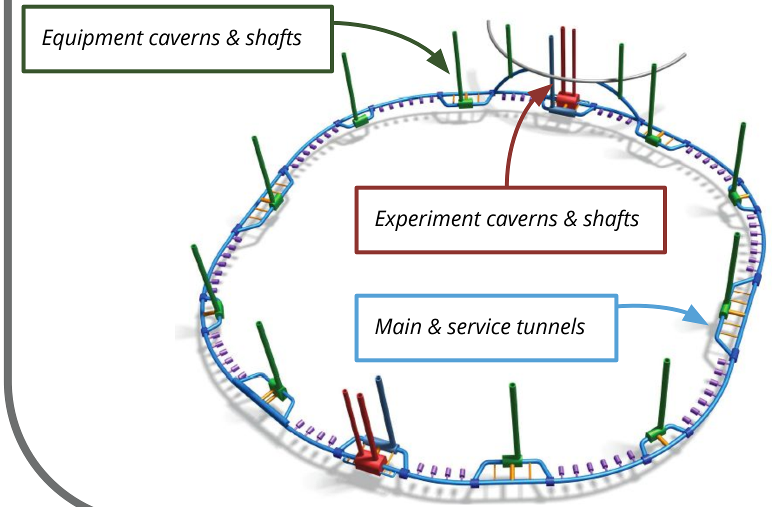
Or: Wir bauen uns einen Teilchenbeschleuniger

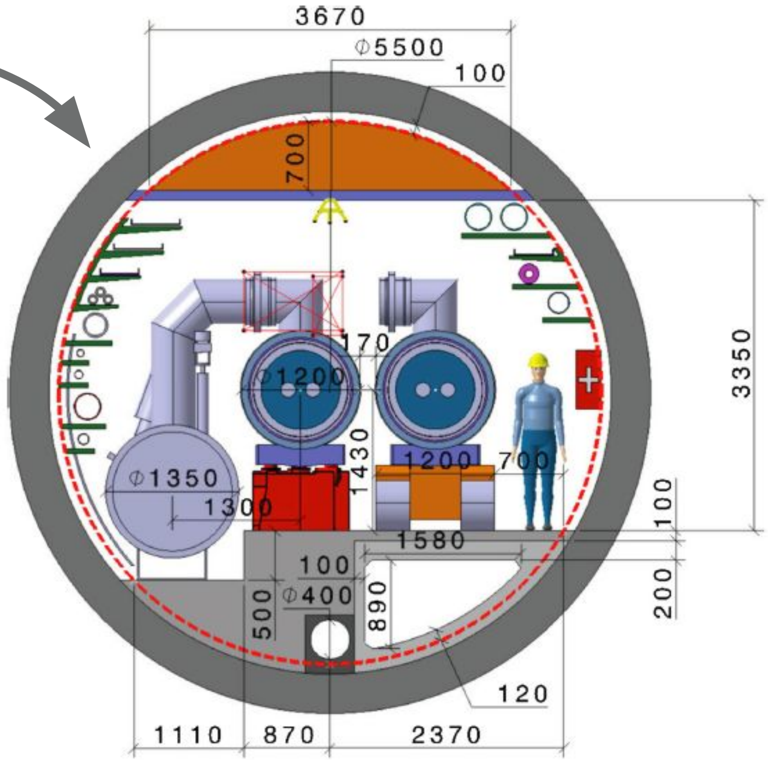


Collider design: Components

Tunnel+ civil engineering:

- 97.75 km long tunnel, 5.5 m internal diameter
    - + caverns, access shafts, by-passes, surface sites





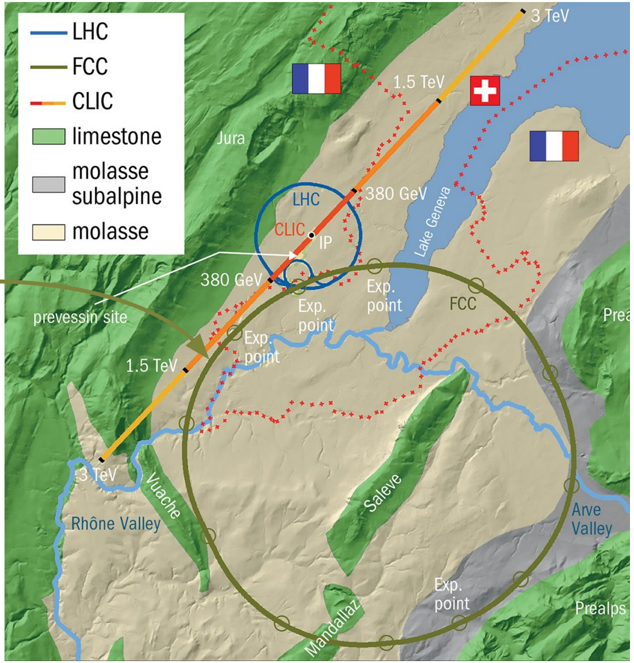
Collider design: Components

Tunnel+ civil engineering:

- 97.75 km long tunnel, 5.5 m internal diameter
  - + caverns, access shafts, by-passes, surface sites
- Construction key factor of project feasibility
  - Administratively challenging
- Location optimized w.r.t many factors, e.g. geology, shaft depth, distance to existing infrastructure, location of surface sites ...

➡ Achievable, construction time ~7 years, but ground + site studies to be done

FCC optimum location

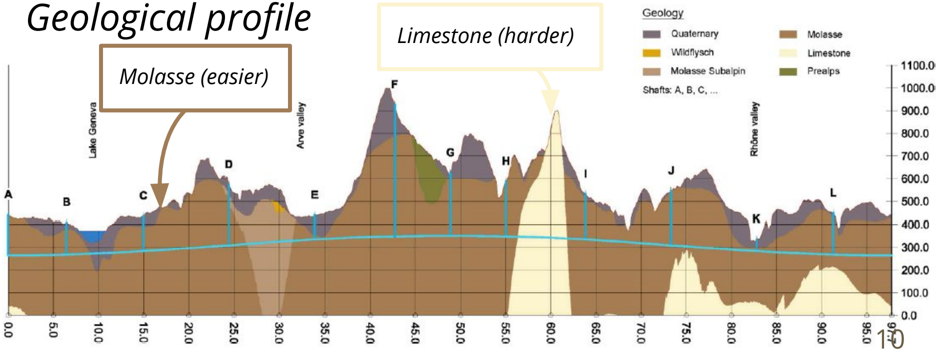


Source & more details

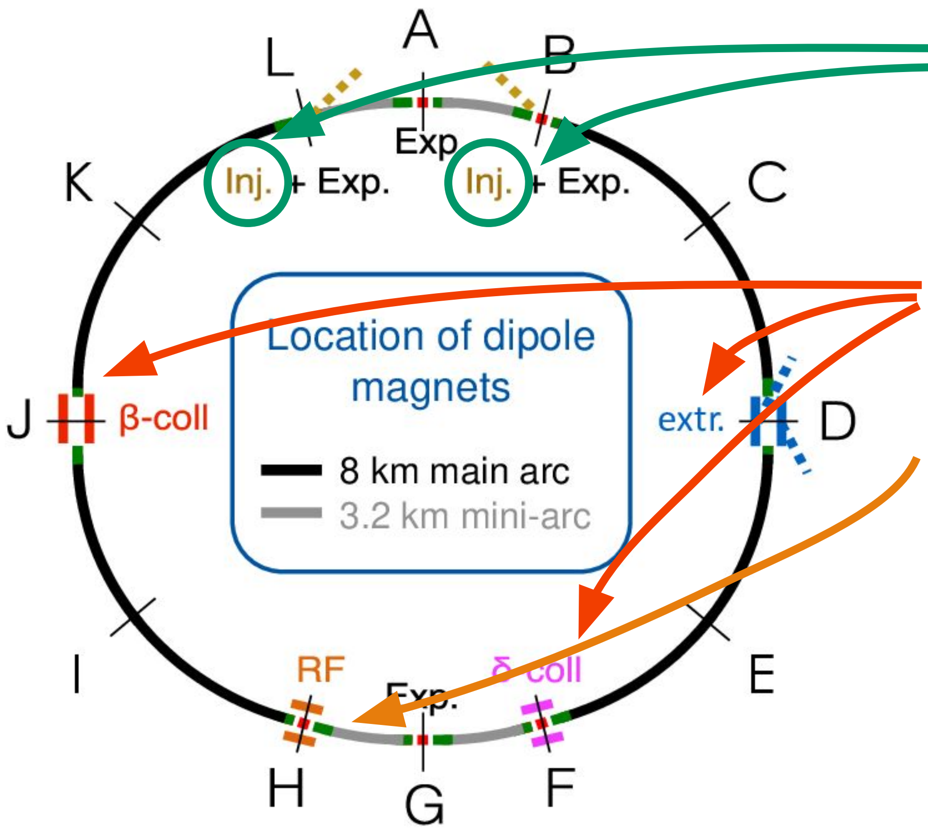
Geological profile

Molasse (easier)

Limestone (harder)



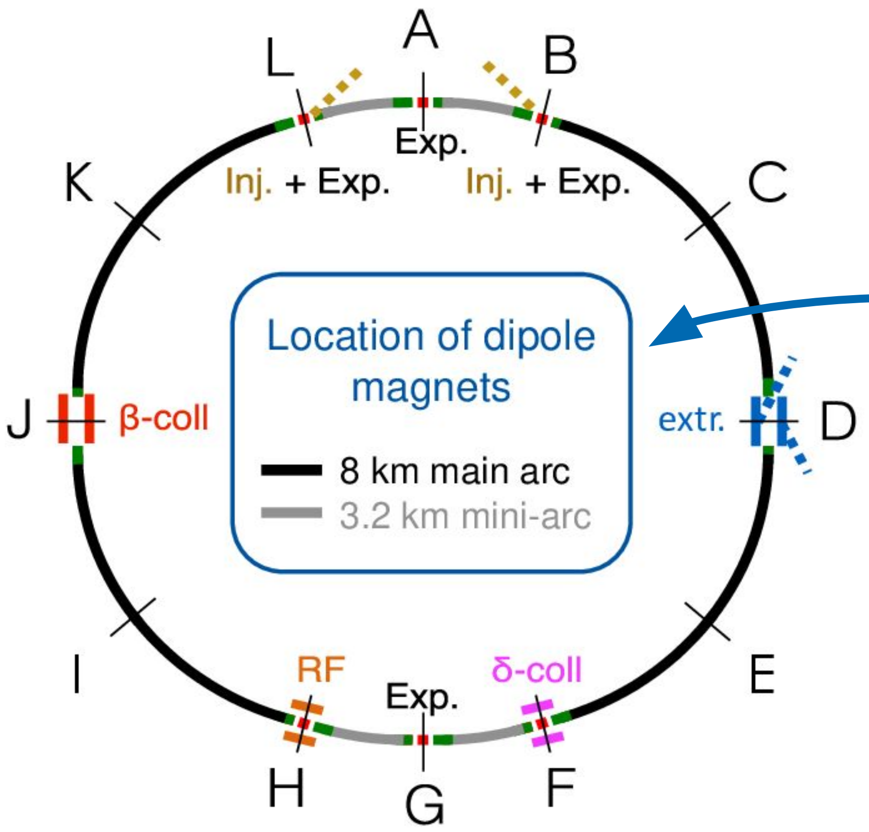
Collider design: Components



Beam injection, collimation, extraction systems & the RF system all achievable with current or expected future technologies with focused R&D

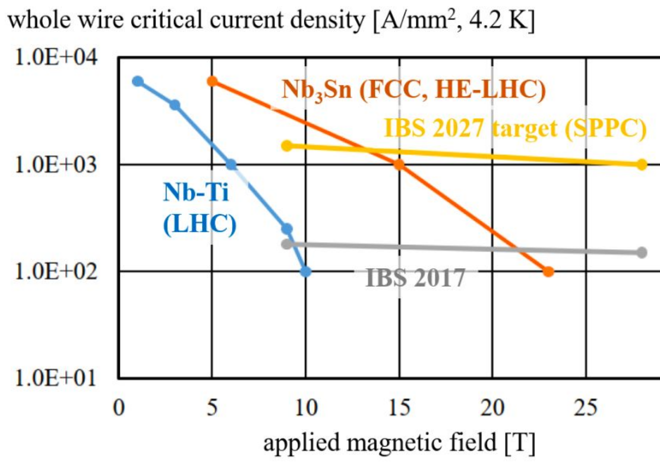
➡ No concerns for feasibility

Collider design: Components



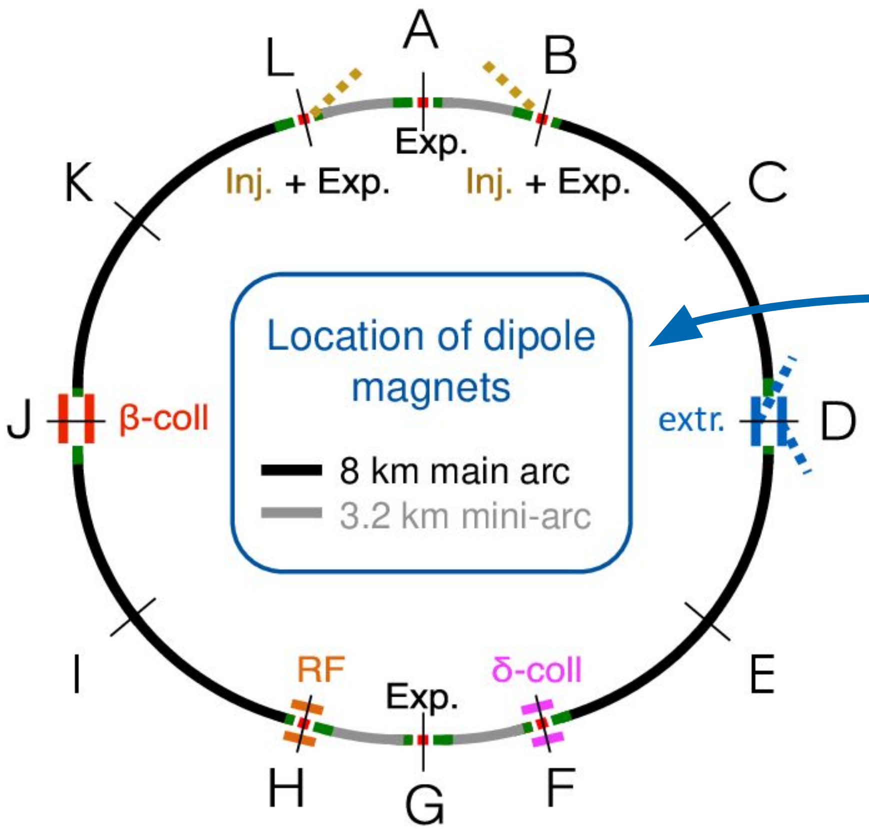
Magnet system:

- High-field magnets key R&D effort
- Similar system to LHC, but require 4 x more magnets with ~2 times the field strength (16 T)
- Nb-Ti as used at LHC limited to ~10 T, use Nb_3Sn



Source

Collider design: Components



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- High-field magnets key R&D effort
- Similar system to LHC, but require 4 x more magnets with ~2 times the field strength (16 T)
- Nb-Ti as used at LHC limited to ~10 T, use Nb_3Sn
  - Will be used for HL-LHC
  - 15 T field dipole test

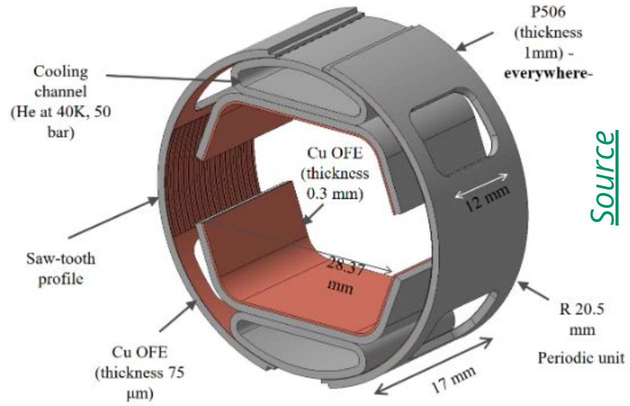
➡ R&D progressing, but associated with uncertainties, e.g. affordability of superconducting wires?

➡ Investigating also High Temperature Superconducting magnets (EuCard2, WP10)

Collider design: Components

Cryogenic & beam vacuum system:

- Synchrotron radiation from the 50 TeV beams relevant (~5 MW)
    - Novel beam screen design



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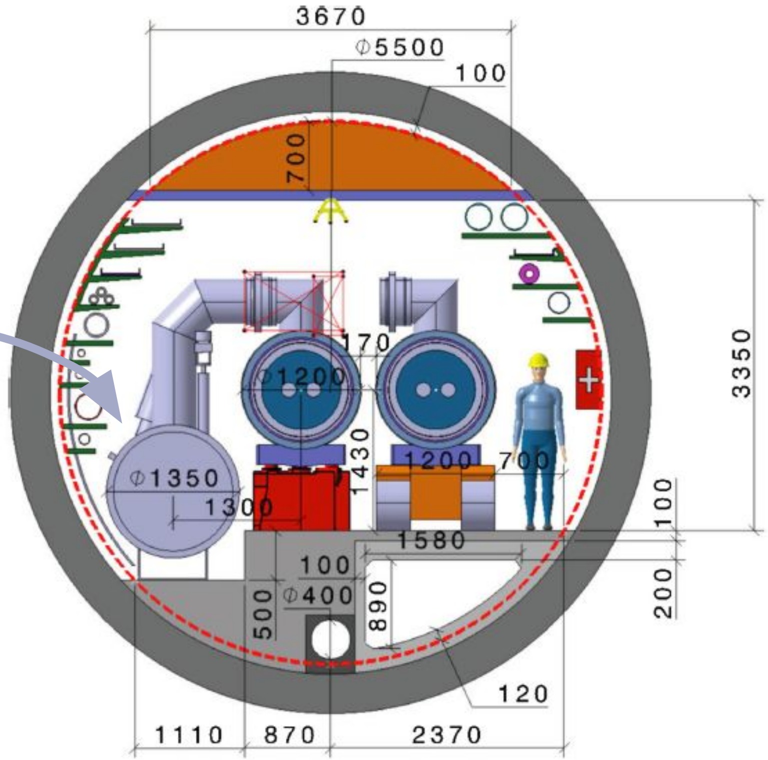
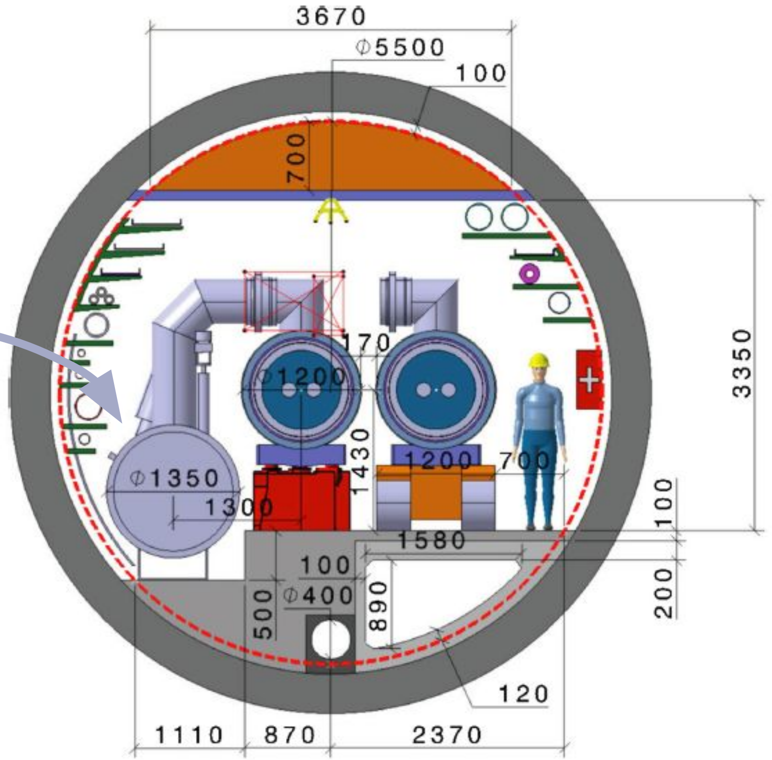


Collider design: Components

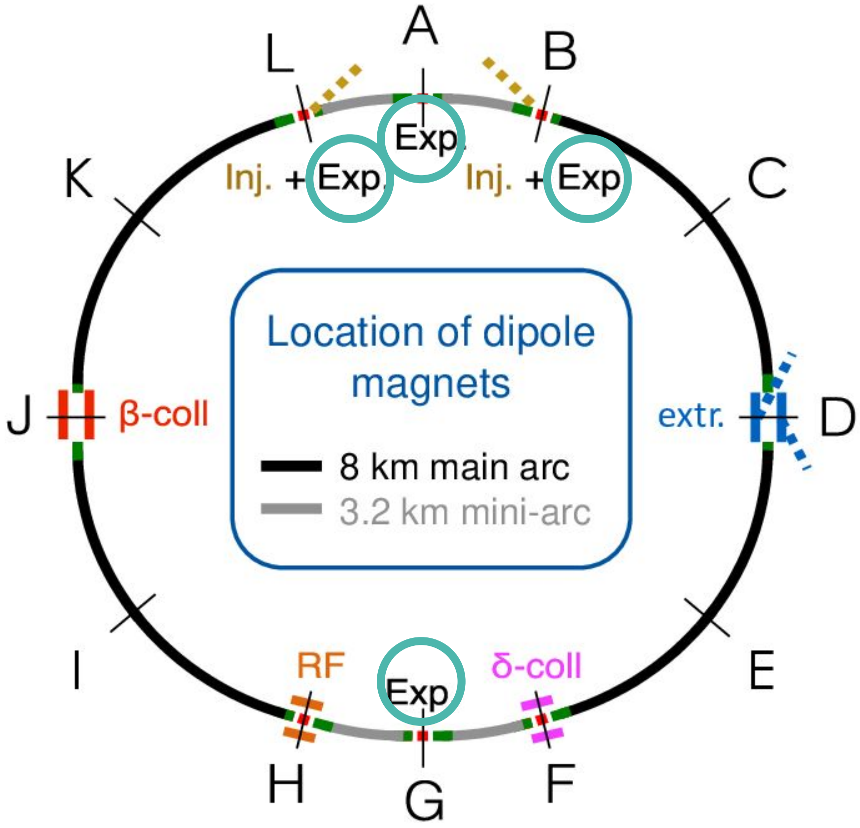
<u>Cryogenic & beam vacuum system:</u>

- Synchrotron radiation from the 50 TeV beams relevant (~5 MW)
  - Novel beam screen design
  - Operates @ 50 K
  - [Prototype tested at KIT]
- Magnets operating at T < 2 T in such a large scale project requires unprecedented cryogenic refrigeration
  - R&D programme to use neon-helium mixture

→ Another of the main challenges, and energy+cost heavy

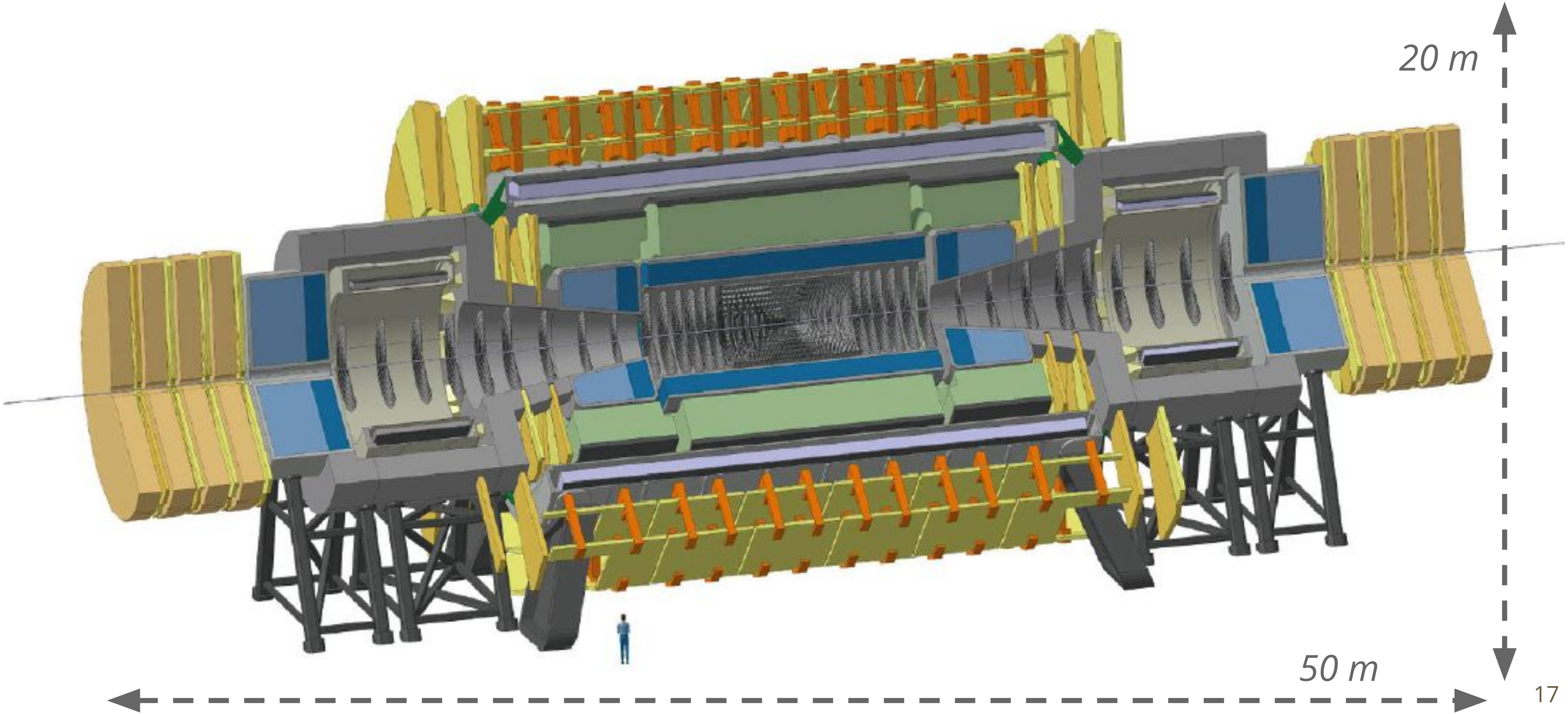


Experiments



- Four interaction points:
  - 2 x high luminosity
  - 2 x lower luminosity
- Focussing on *pp*-collisions here:
- (SM) physics more forward + boosted @ 100 TeV
  - Precision up to $|\eta|$ ~ 4 , VBF jets up to $|\eta|$ ~ 6
  - High granularity e.g. resolve products of highly boosted tau
  - Contain multi-TeV jets
- Other challenges due to the much higher collision rates w.r.t. HL-LHC:
  - Radiation hardness
  - Pile-up
  - Huge data rates

Reference detector



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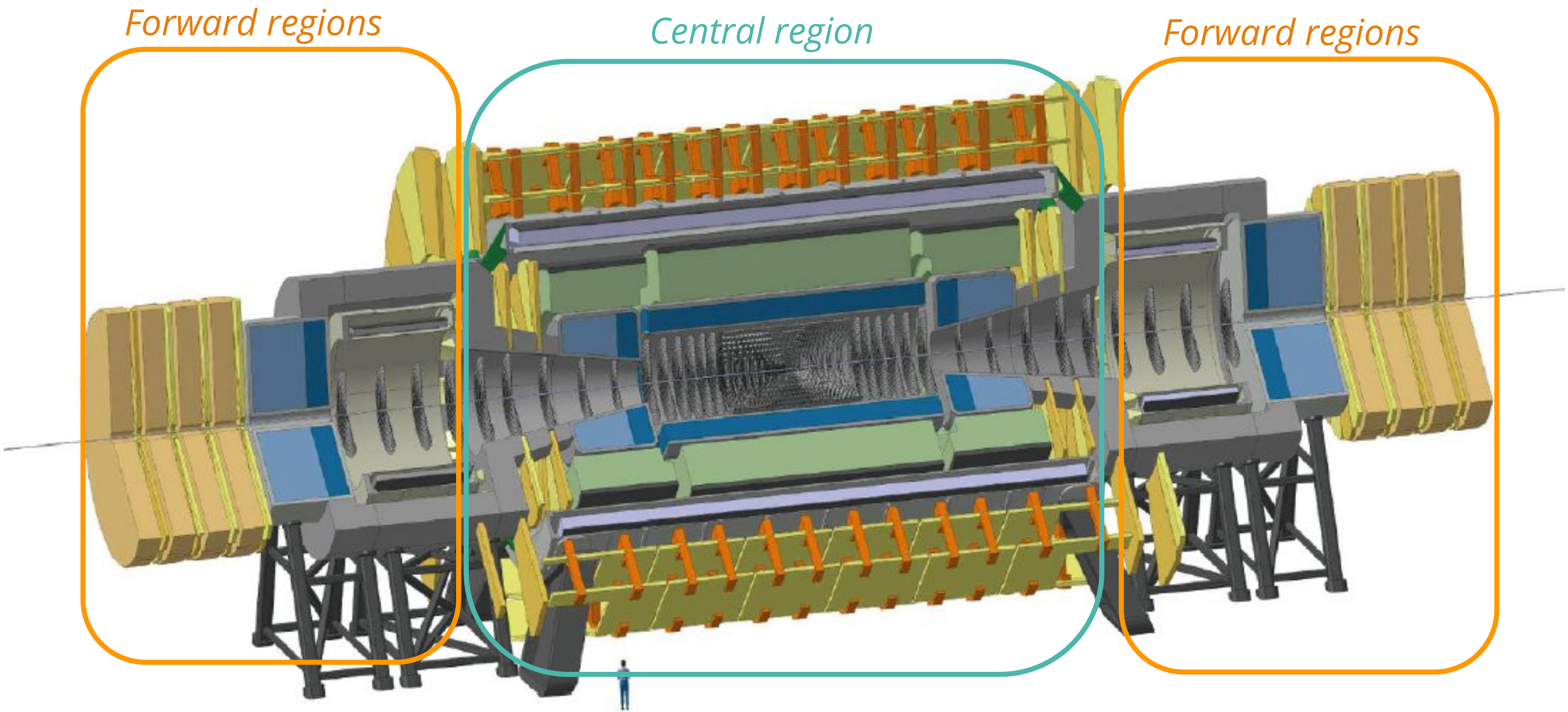

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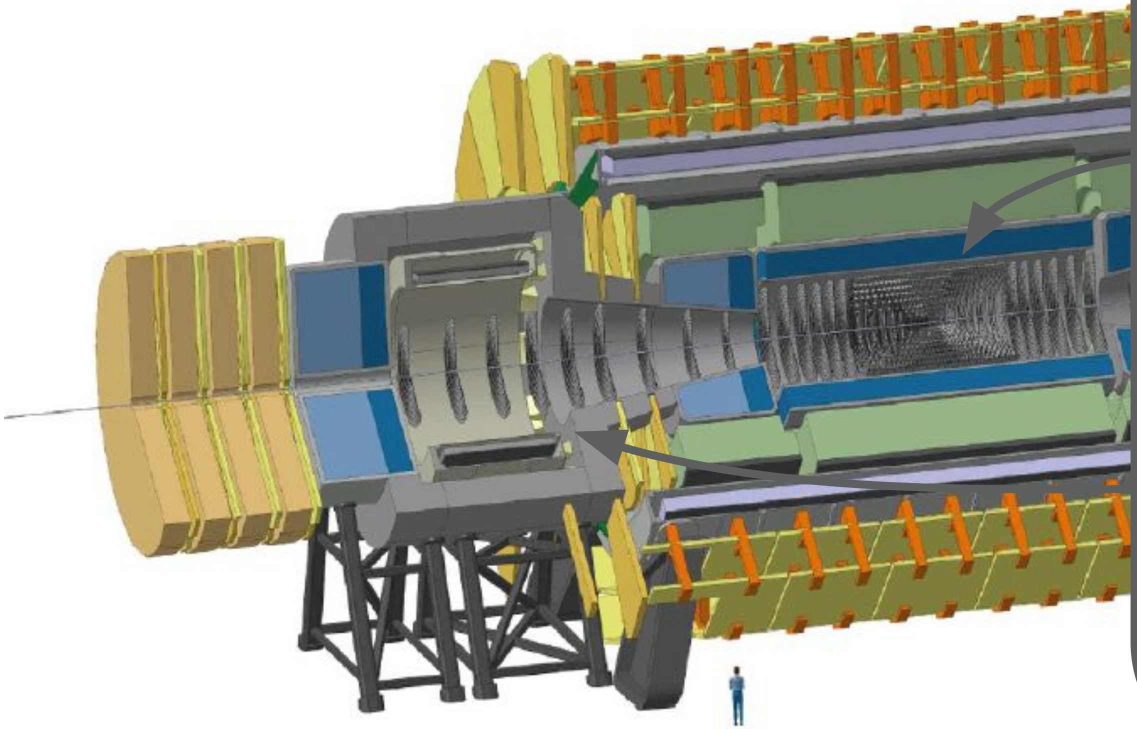
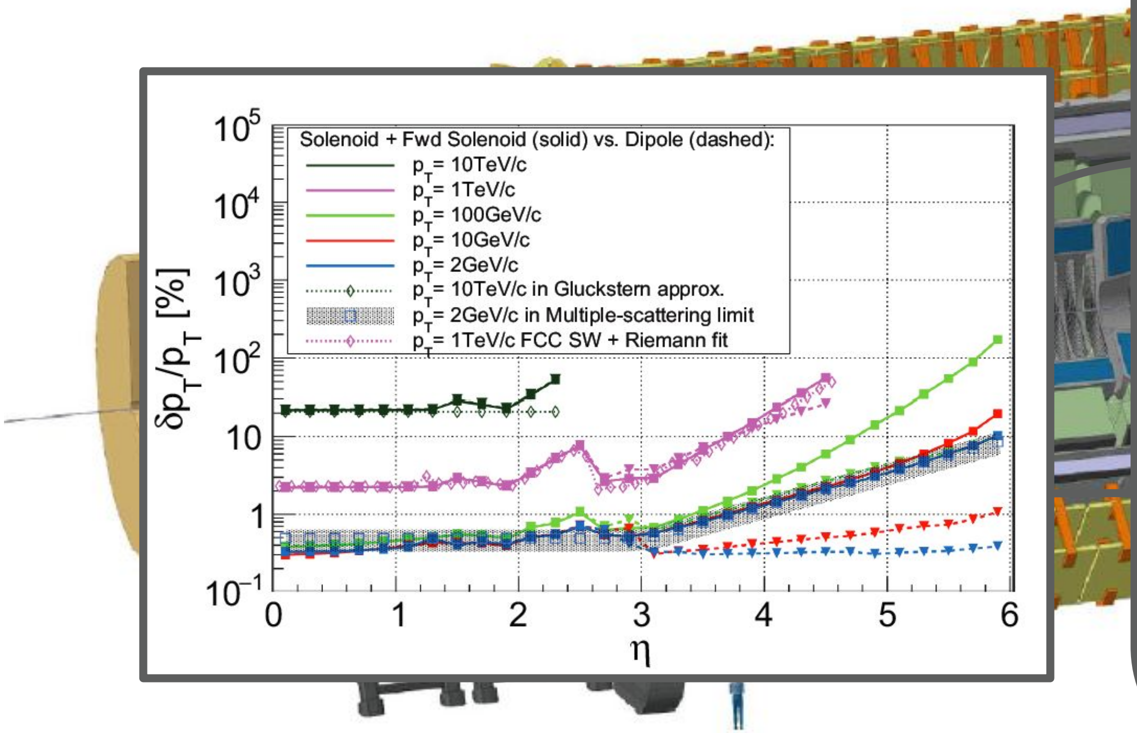


Tracking

- Si-Trackers using (macro-)pixels & strips
- Central tracker < 5m from IP, forward tracker < 16 m
  - Challenge: Alignment!
- Aim: ~20% res. at 10 TeV
  - 10 μm single point
- Central in 4 T solenoid, two options for forward
  - Two solenoids
  - Two dipoles

Reference detector



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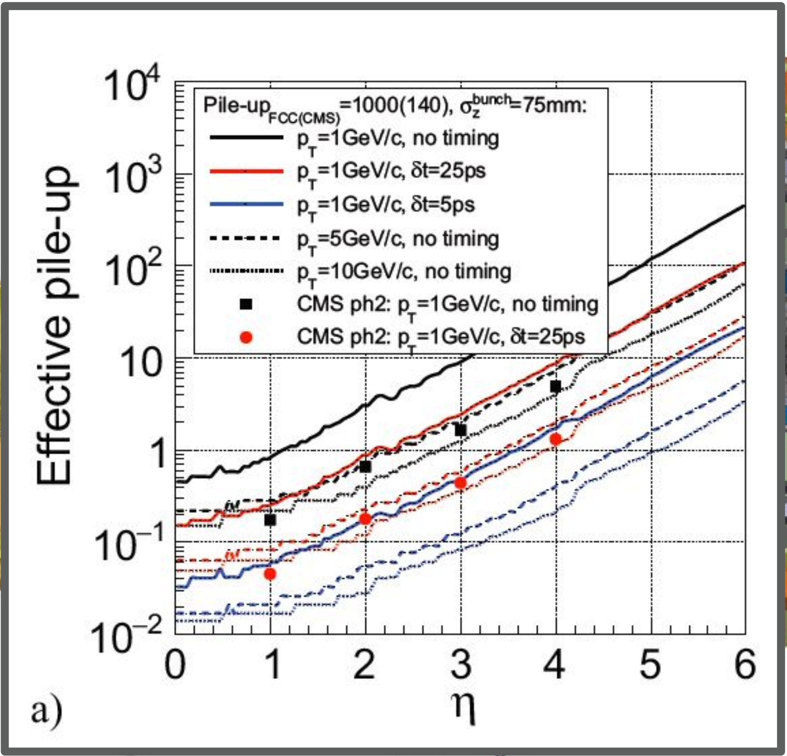

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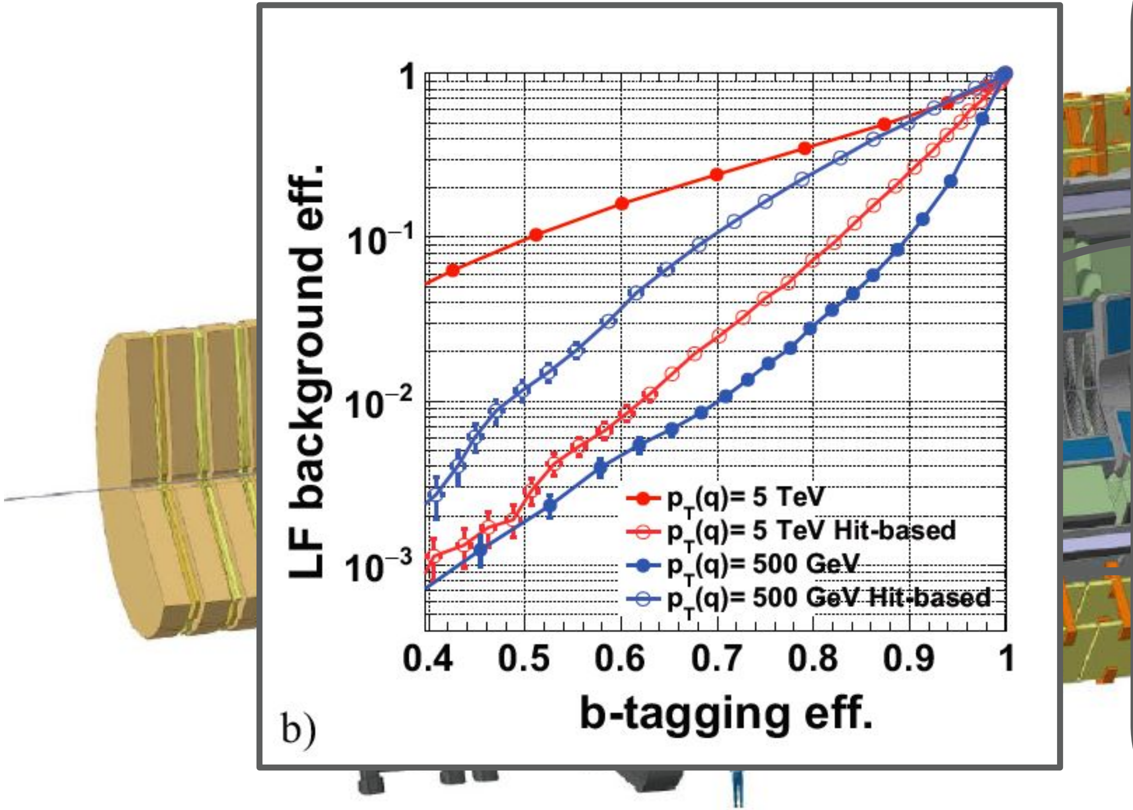

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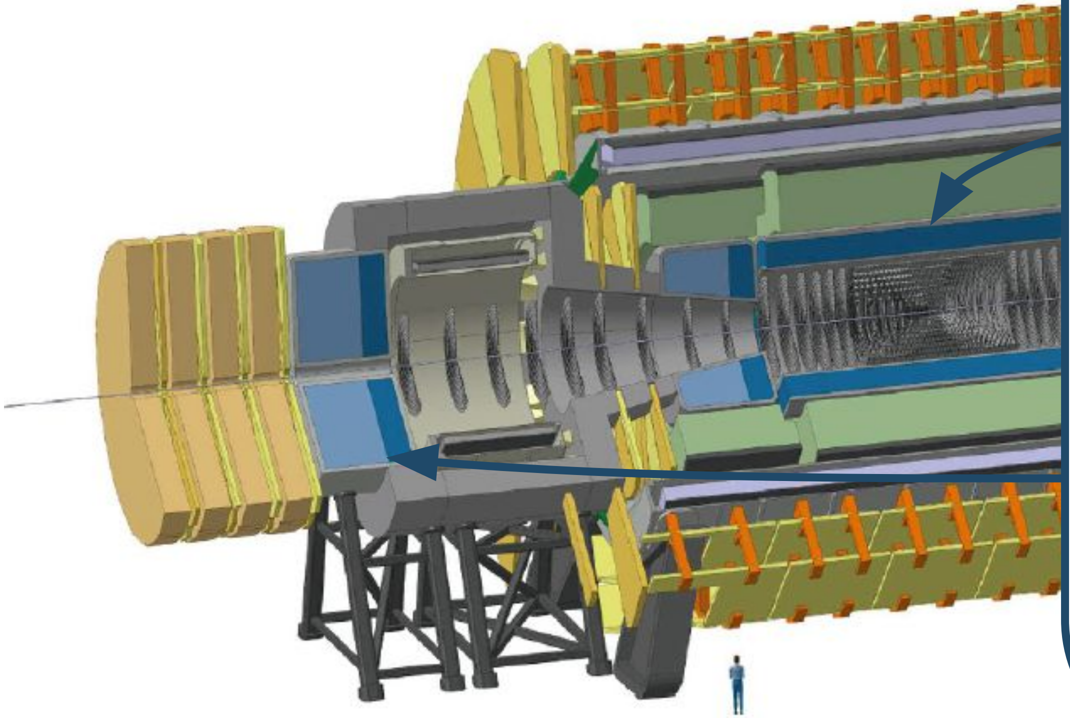
- Central in 4 T solenoid, two options for forward
- Exploit timing information for vertex reco in high PU?
- Issue for e.g. b-tagging: Dense environment in jets + displaced vertices outside acceptance
  - "Trackless" b-tagging

Reference detector



Calorimetry

- (Mostly) Inspired by ATLAS calorimetry, but finer segmentation & optimized for particle flow + PU suppression
  - ECAL: LAr & Pb (Cu)
  - HCAL: Scintillating tiles & Fe/Pb in barrel, LAr on endcaps + forward

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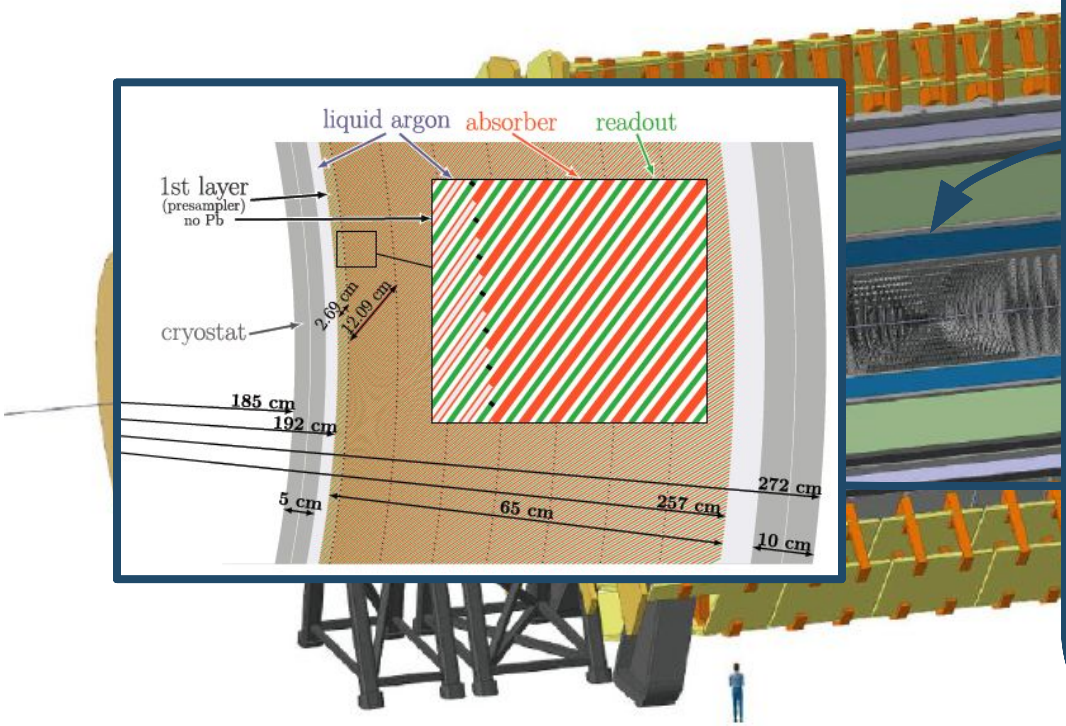

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- Barrel ECAL geometry new concept

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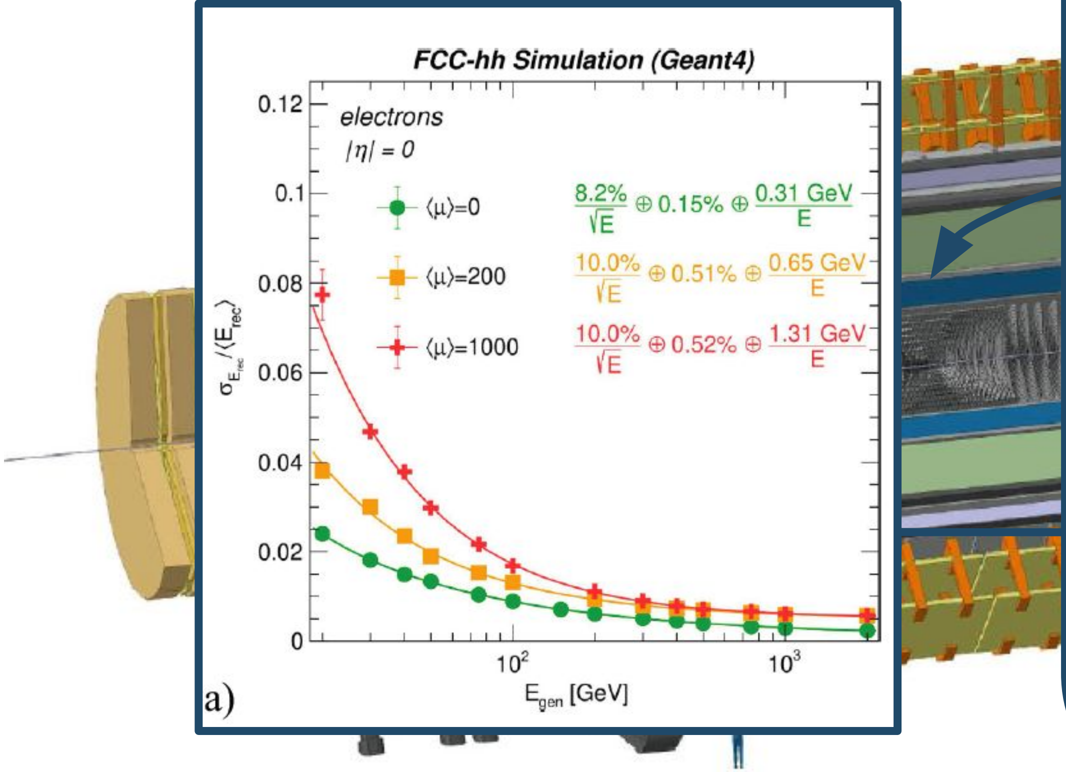

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- ECAL ~30 X_0, $\boldsymbol{\sigma}_E/E$ ~ 10%/√E
- HCal ~ 10.5 $\boldsymbol{\lambda}$, $\boldsymbol{\sigma}_E/E$ ~ 50%/√E

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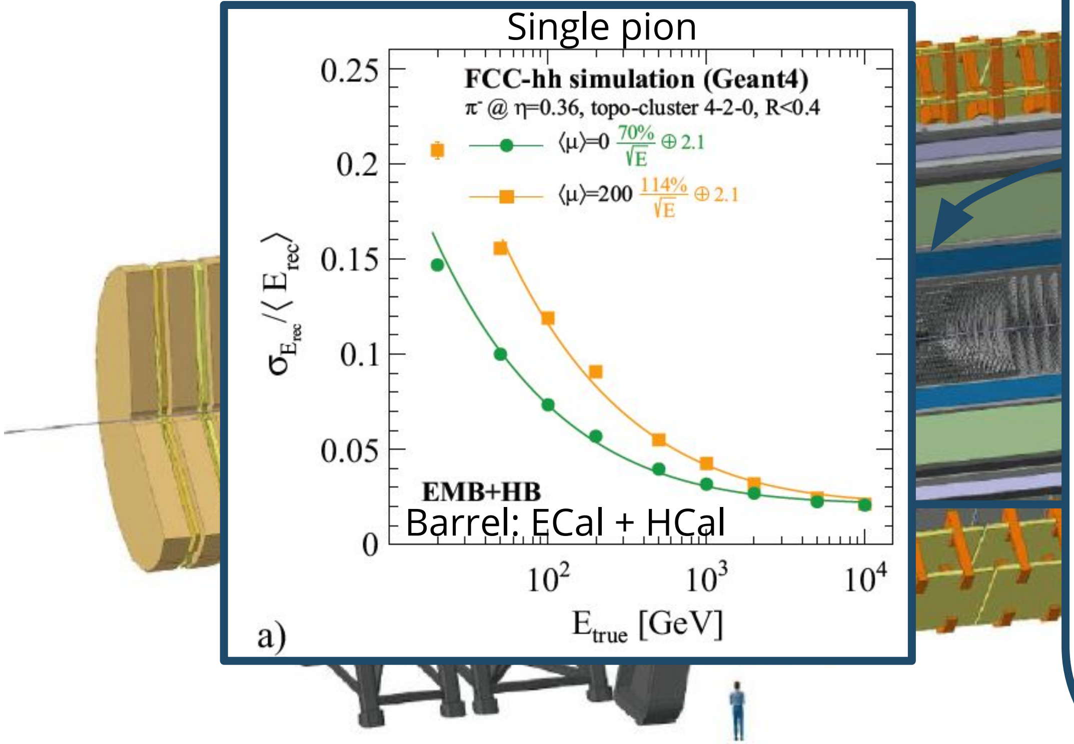

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- ECAL ~30 X_0, σ_E/E ~ 10%/√E
- HCal ~ 10.5 λ, σ_E/E ~ 50%/√E
- PU degrades energy resolution significantly

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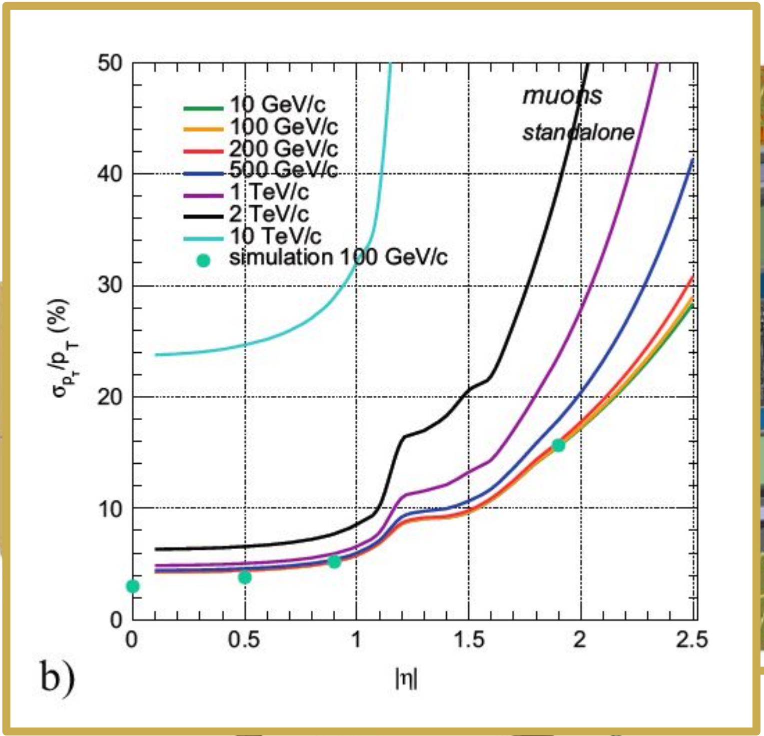

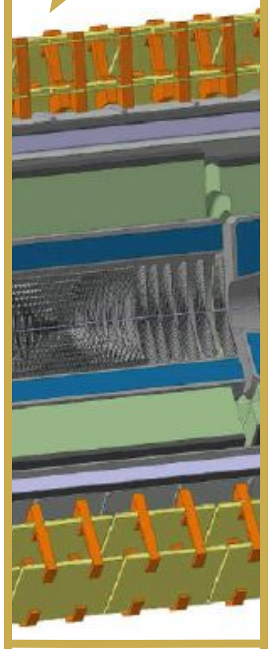

Muon systems

- Proposal: Combine drift tubes (sMDTs) & RPCs
- Mainly for muon identification + trigger, less focus on muon stand-alone precision
  - Forward MS can only provide trigger with the 2 dipole design!

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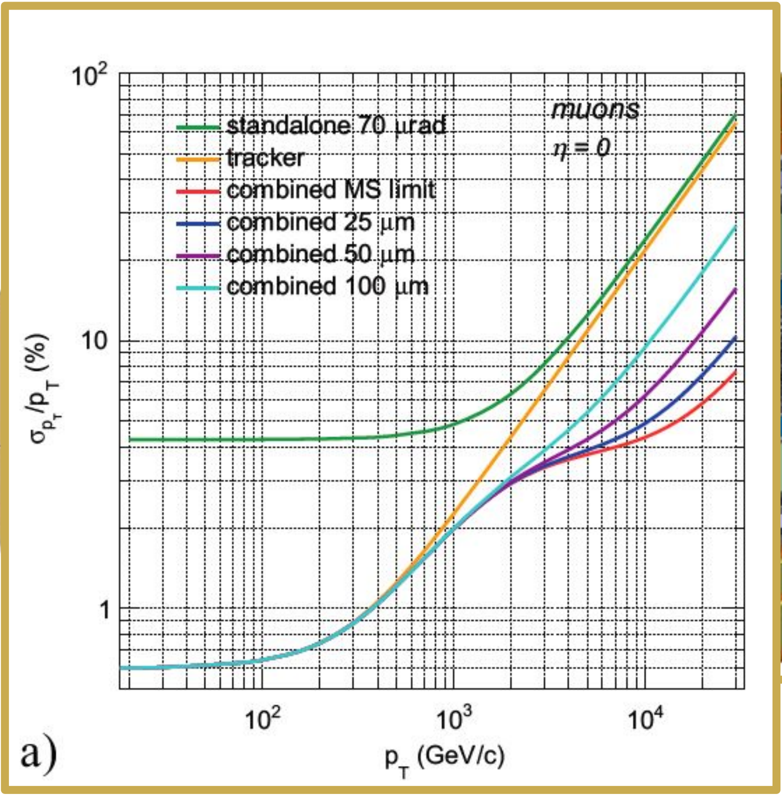

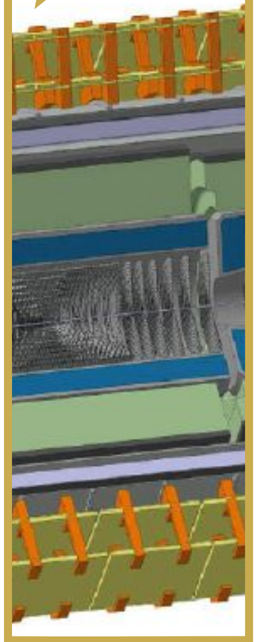

Muon systems

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  - Forward MS can only provide trigger with the 2 dipole design!
- Achieve combined muon resolution of 5% with MS precision of 50 μm

Software for FCC-hh physics studies

Event generator

↓

Detector simulation

↓

Samples

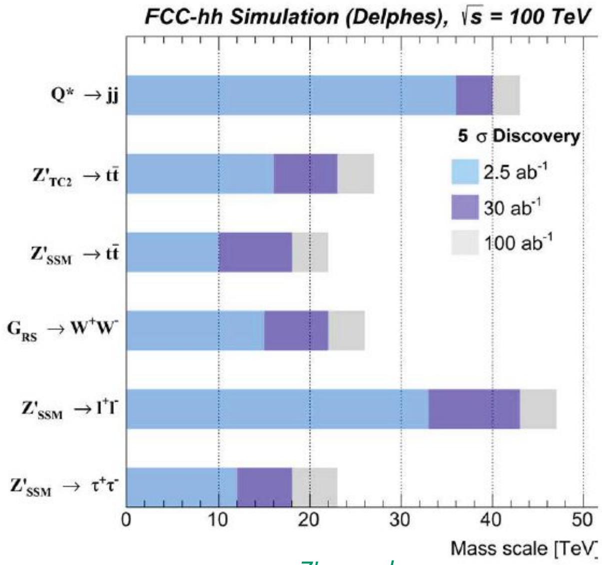
↓

Physics analysis

- Simulation chain employs idea to use common tools shared between different future projects (e.g. FCC, ILC..)
  - Ensure code is well-maintained, well-documented and easy to adapt to specific usecase
- FCCSW now with key4hep project: "turnkey system"
  - Physics studies: Detector simulation with Delphes
    - Parametrized response as fast, simplified simulation
    - Full simulations of separate subdetectors used for the design studies only
  - Samples in EDM4HEP format: shared language between all SW components
  - k4SimDelphes: Full production chain in one setup
- Analysis tools available in FCCAnalyses

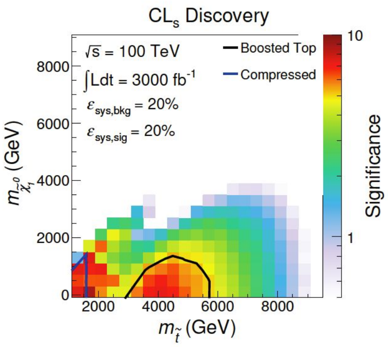
Physics: Direct BSM mass reach

- FCC-hh is a discovery machine at the energy frontier ..
  - Collecting 20-30 ab^{-1} extends mass reach by factor ~ 7 ($\boldsymbol{\sigma}(M) \sim 1/M^2$)
- Discovery potential in many models: SUSY, (WIMP) DM, Z', .. significantly extended
  - [CDR report]

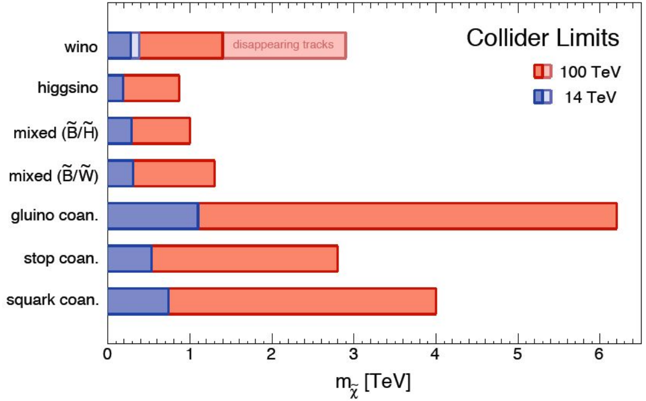


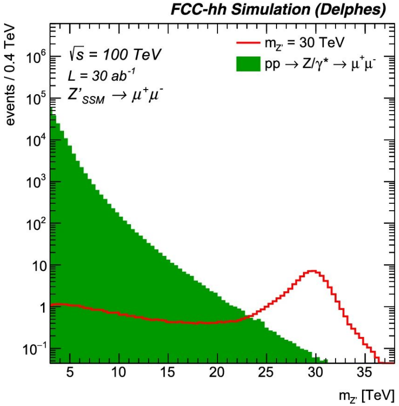
Z' search

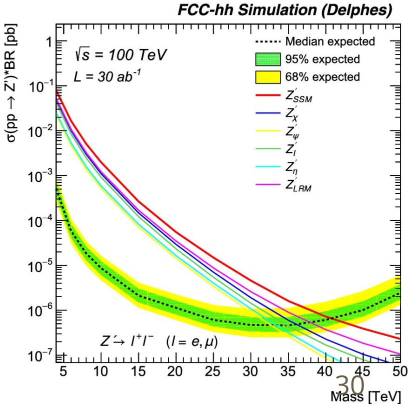
Search for $\tilde{t} \to t\tilde{\chi}_1^0$



WIMP DM with SM mediators







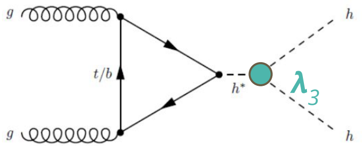
Physics: Higgs measurements

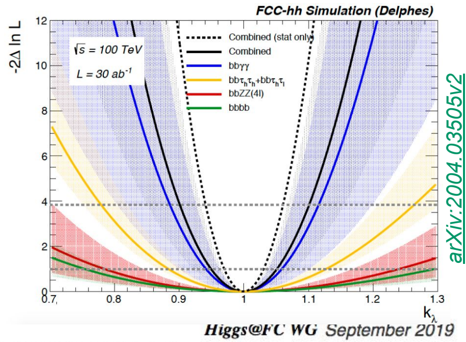
Self-coupling measurement: key benchmark!

- … and also a precision machine!
- E.g. > 10^{10} Higgs bosons

	ggF	VBF	ttH	VH
σ(100TeV)(pb)	802	69	33	27
σ(100TeV)/σ(14TeV)(pb)	16	16	52	11
N($\sqrt{s}$ = 100 TeV, 30 ab^{-1})	25 $\times 10^9$	2.5 $\times 10^9$	10^9	7.5 $\times 10^8$

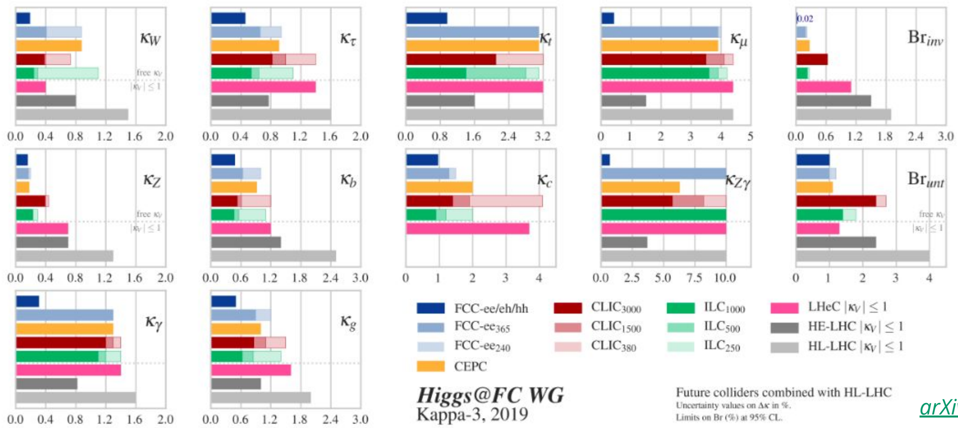
- Precisely measure rare channels (even in high pT regime), H-top coupling …
    - CDR report, Granada report, di-Higgs, Zh (..)

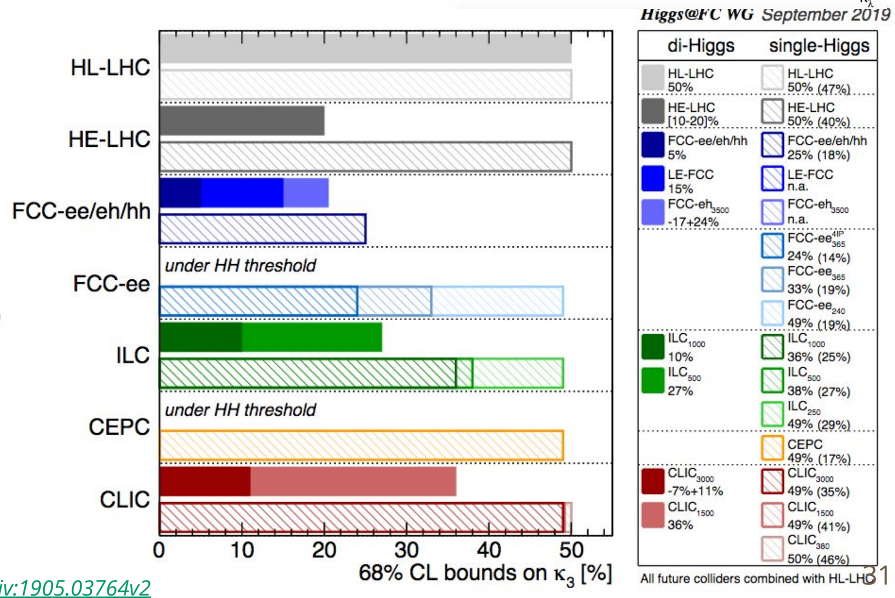




arXiv:2004.03505v2

Precision of k parameters





arXiv:1905.03764v2

Summary

- FCC-hh provides very ample perspectives to bring answers to questions which might remain open after HL-LHC and aiming to collect 30 ab^{-1} of data over 25 years it is not only a discovery machine at energy frontier, but also at the precision frontier
- Baseline design is a 100 km collider with 100 TeV *pp*-collisions
  - Highest energy hadron collider considered feasible from today's view
  - Main challenges of technical feasibility are the need for 16 T magnets and cryogenic system
- Reference detector conceptualised
  - Main challenges for the detector are boosted+forward physics, high radiation & pile-up
- Physics potential well established: Direct BSM mass reach extends to O(10) TeV, Higgs (and other SM) precision measurements
  - FCC-hh will bring 5% precision of Higgs self-coupling
- It is far ahead in our future, but if (when) it gets realized FCC it will be ***the*** project until the end of the 21st century
- FCC-week 2021 : 28.06. - 02.07.2021

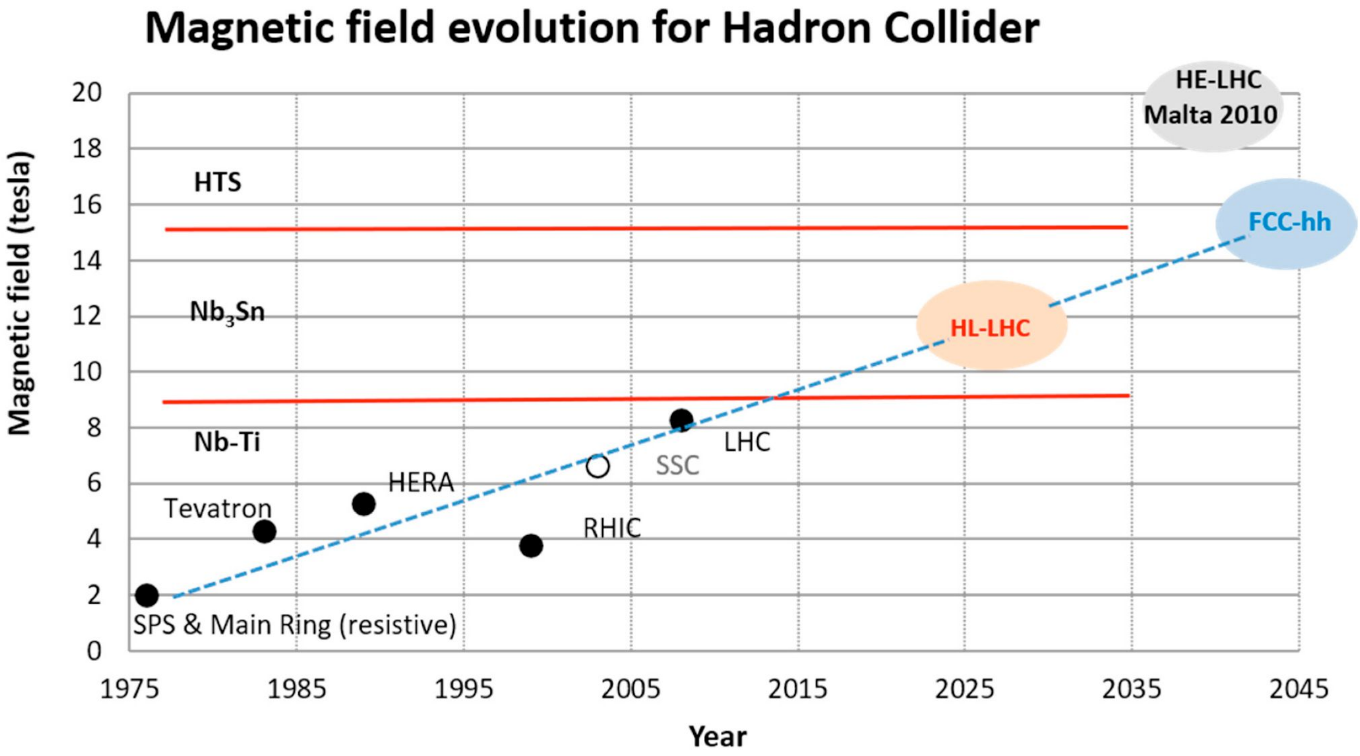
Bonus

Collider design: Parameters of magnet system

Parameter	(HL)-LHC	FCC-hh
Peak dipole field (T)	8.33	~16
# Long arcs w. dipoles	8	8
Length arc (km)	3	8
# Dipoles/arc	154	438
# main dipoles	1232	4668
Tot. energy stored in dipoles (GJ)	8.8	108 - 176

140 GJ ~ 35 tons of TNT

Reaching 16 T magnets: Historical view



Source

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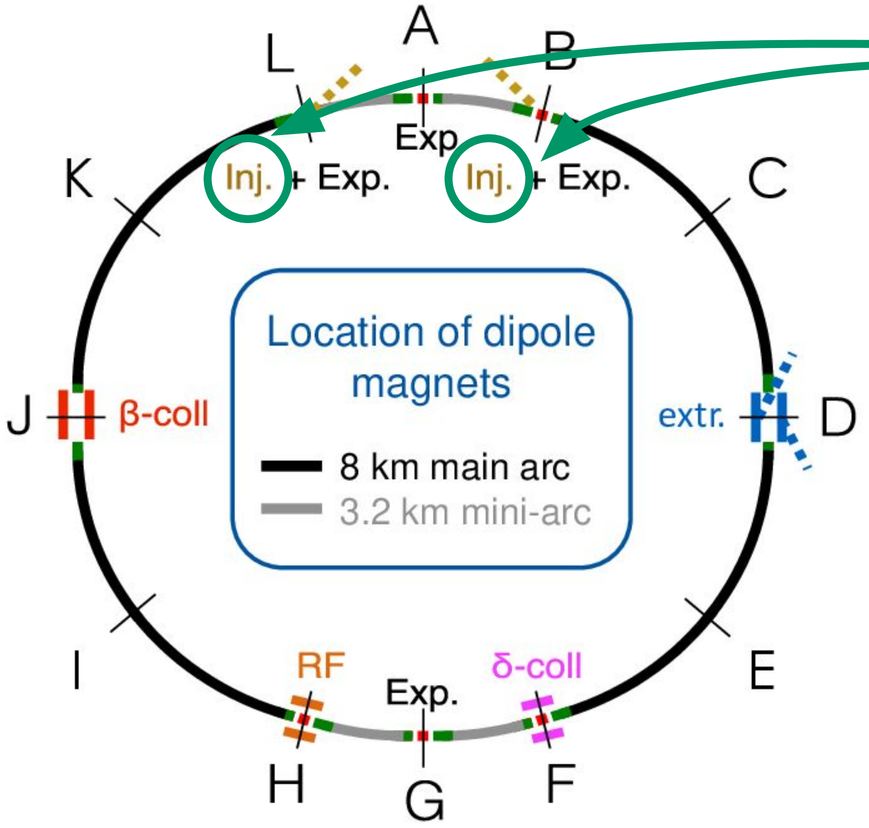
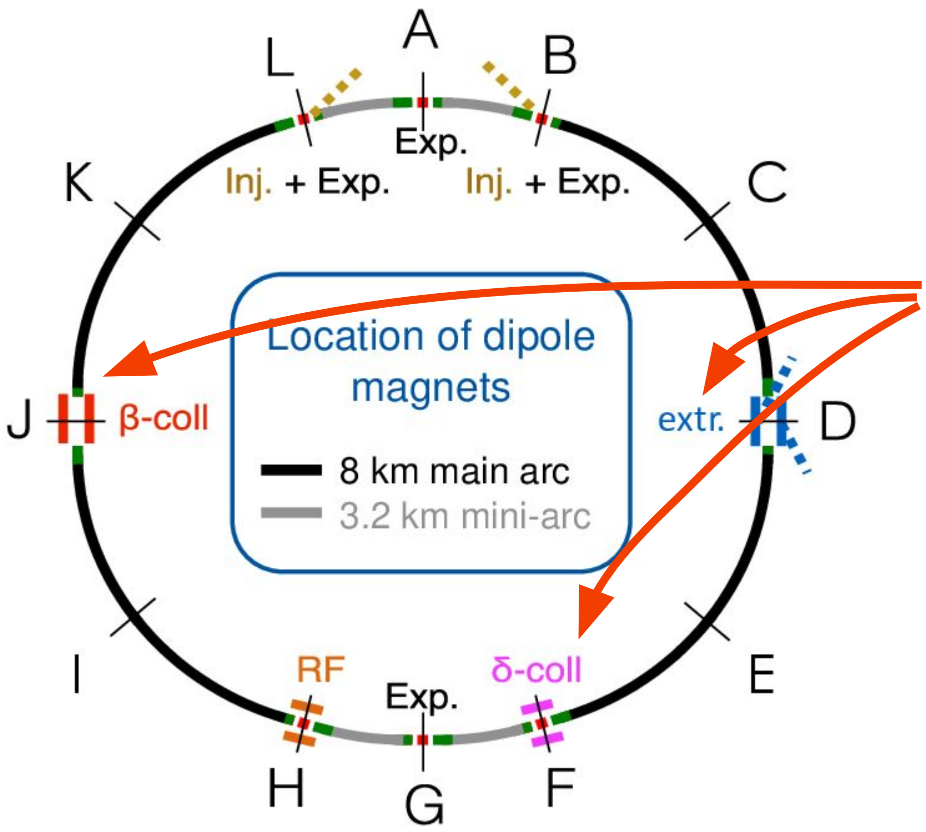


<u>Beam injection</u>:

- Reuse existing LHC injector chain (Linac4, PS, PSB) + High Energy Booster
- Two scenarios: (superconducting)SPS or LHC @ 3.3 TeV
- Transfer line with 1.8 T (SPS) or 7 T (LHC) magnets

➡ All necessary modifications studied & feasible!

Collider design: Components

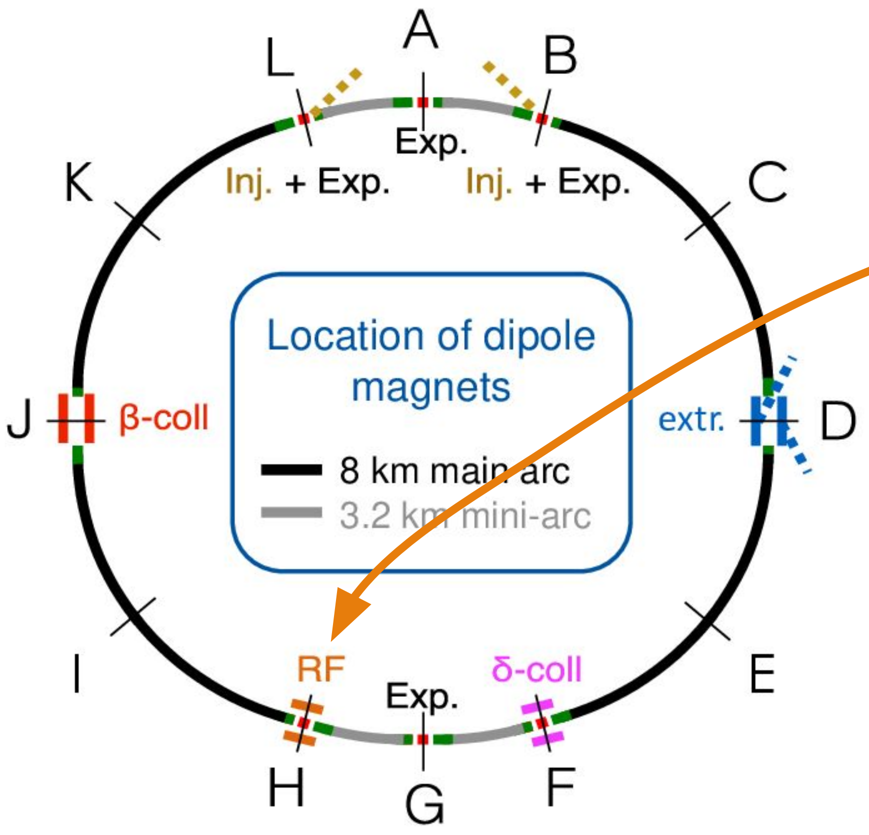


<u>Beam collimation & extraction:</u>

- Protects machine from energy stored in beams
    - 8,3 GJ, > 20 x higher than at LHC
- Scaled-up & optimized version of the LHCs collimation system
- Required superconducting magnets for extraction under development

➡ Feasible with technology available today

Collider design: Components



<u>RF system:</u>

- Similar to LHC system
  - 24 single-cell Nb/Cu cavities, operating at 400 MHz and 4.5K, but with 48 MV
    - 3x LHC voltage
- R&D ongoing to operate at higher gradients and/or temperatures (shared w. FCC-ee)

➡ No concerns about feasibility

Forward physics

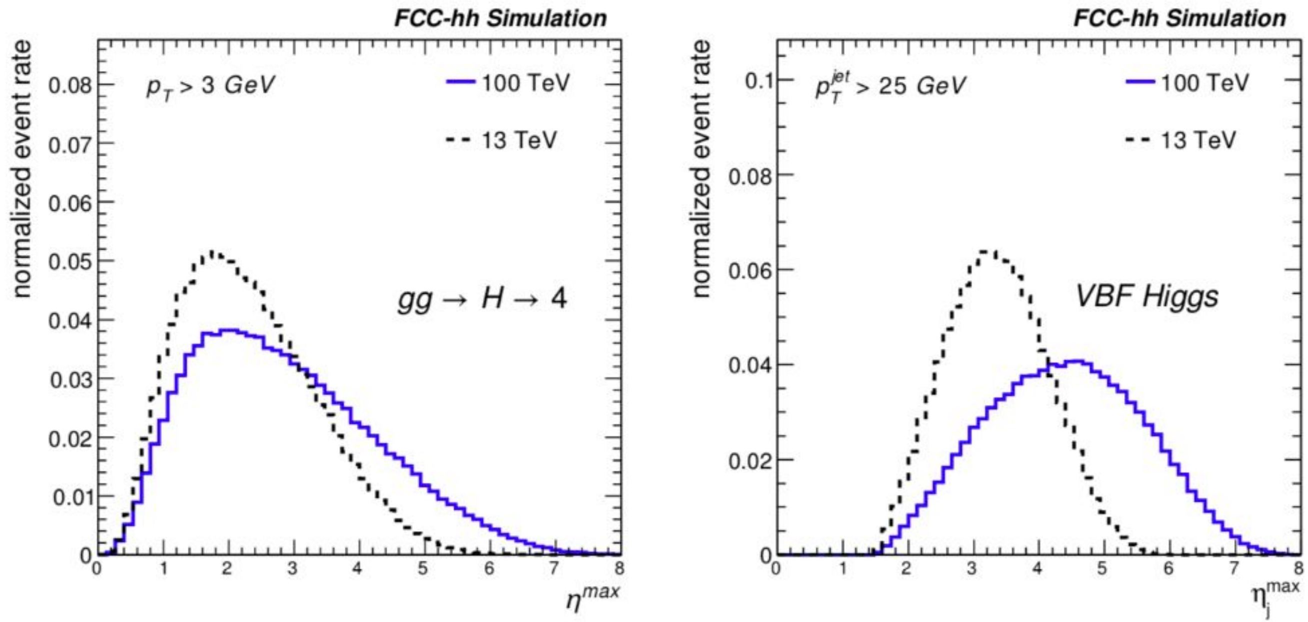


Fig. 2.2: highest lepton pseudo-rapidity for gluon-gluon fusion Higgs decaying to 4 leptons (left) and maximum jet pseudo-rapidity for vector-boson fusion Higgs (right)

Reference detector

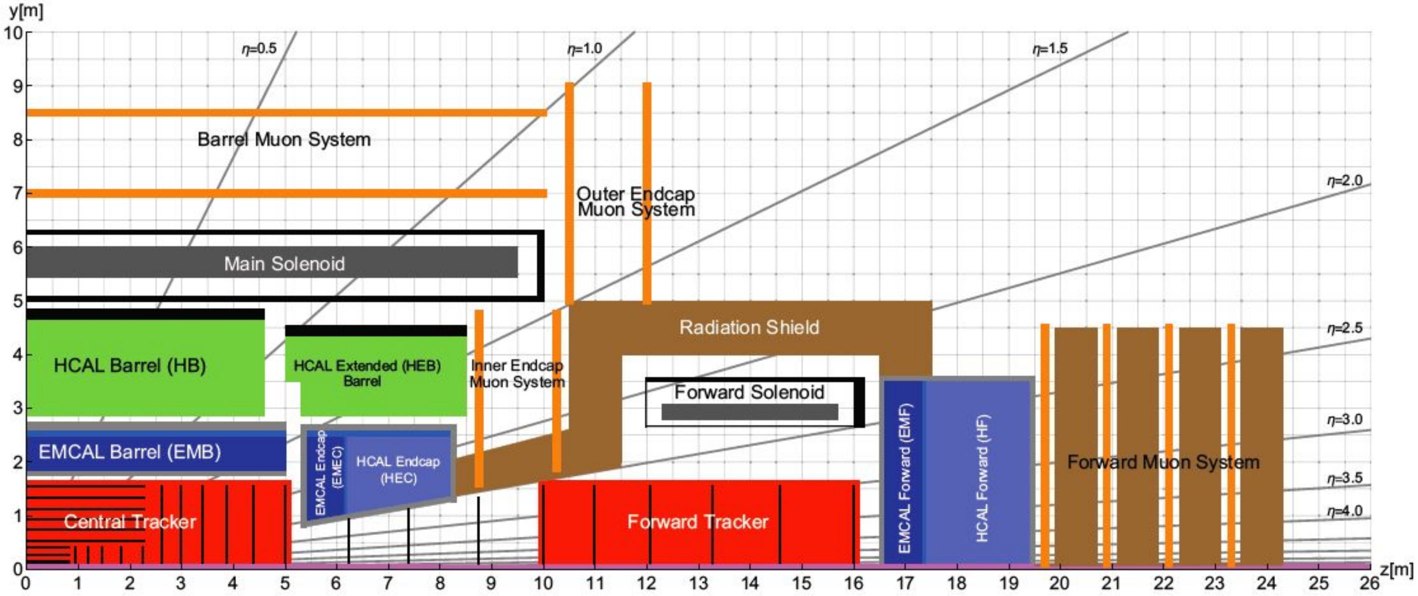
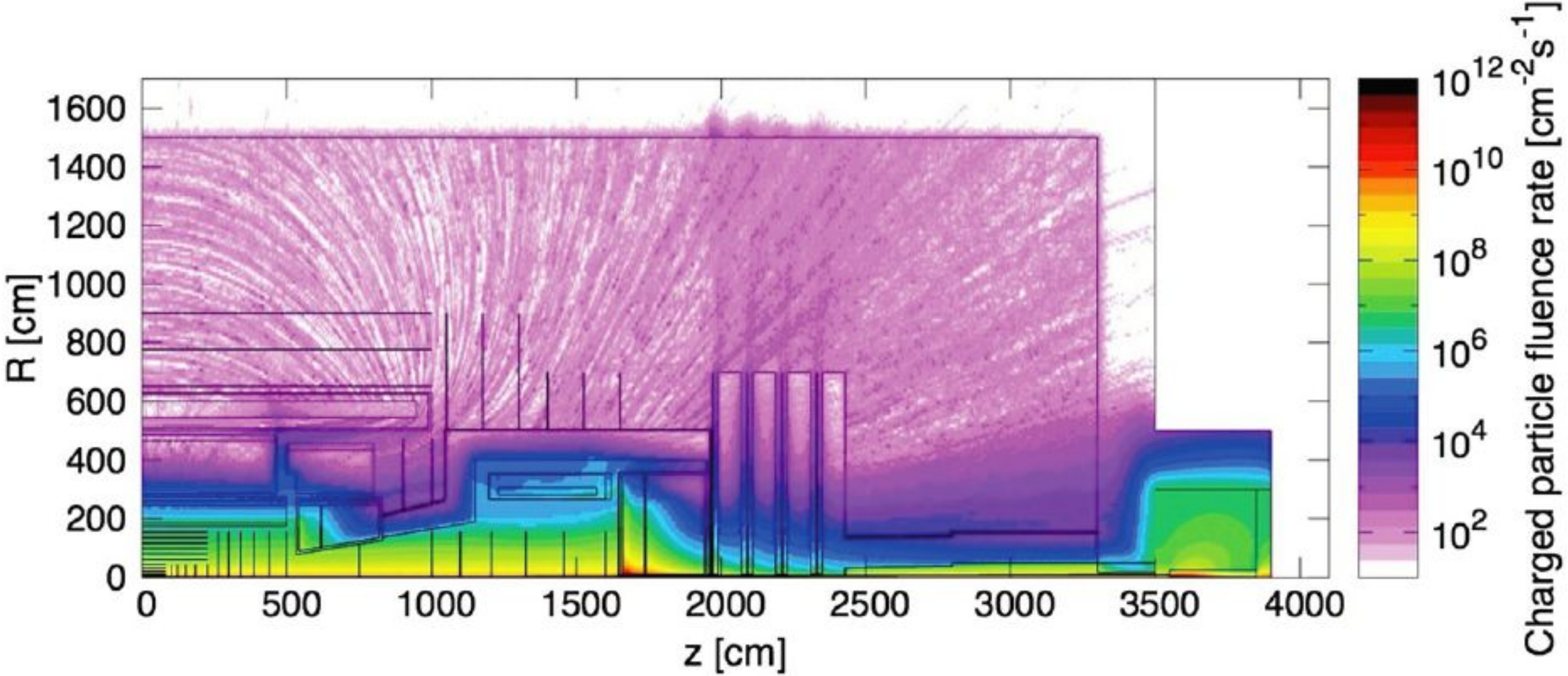


Fig. 7.2. Longitudinal cross-section of the FCC-hh reference detector. The installation and opening scenario for the detector requires a cavern length of 66 m, which is compatible with the baseline assumption of $L^* = 40\,\mathrm{m}$ for the FCC-hh machine.

Detector: Radiation environment



Detector: Magnet system

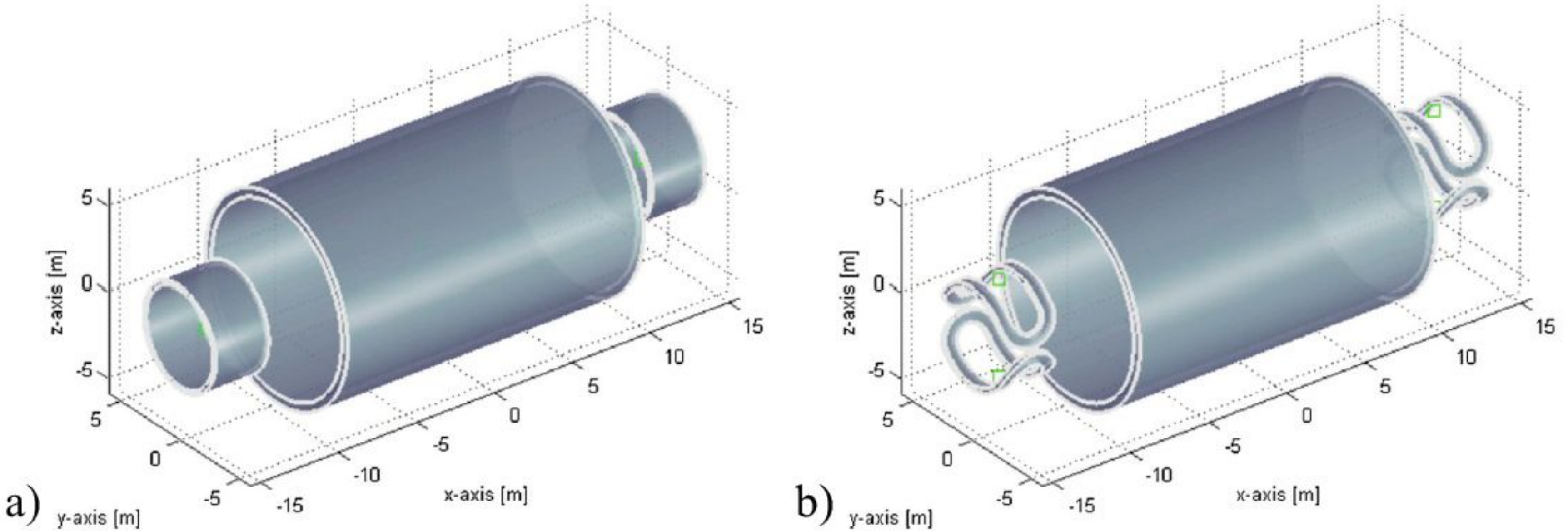
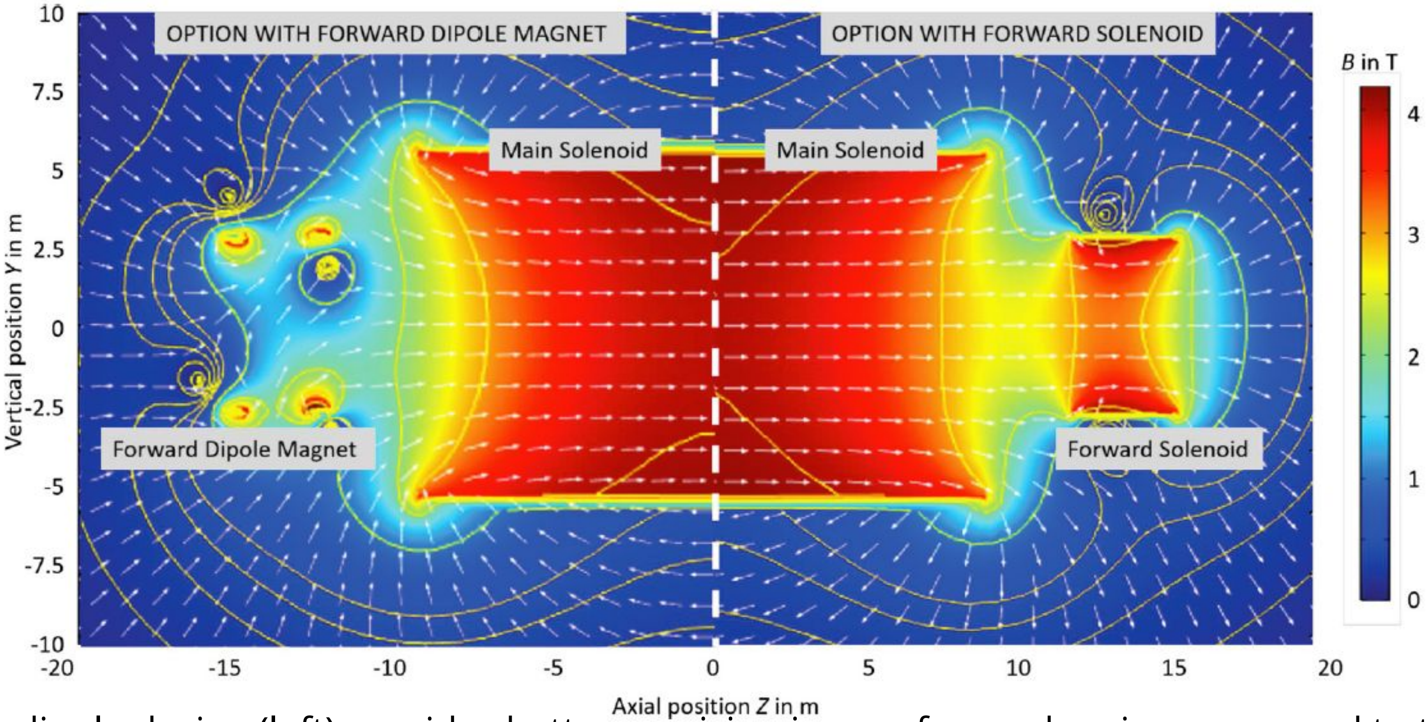


Fig. 7.6. (a) Cold mass for a central solenoid of 4 T with two forward solenoids and (b) a central solenoid of 4 T and two forward dipole magnets with field integral of 4 Tm.

Detector: Magnet system



- Twin dipole design (left) provides better precision in very forward region compared to twin solenoid design (right), but rotational symmetry is lost

Detector: Tracker layout

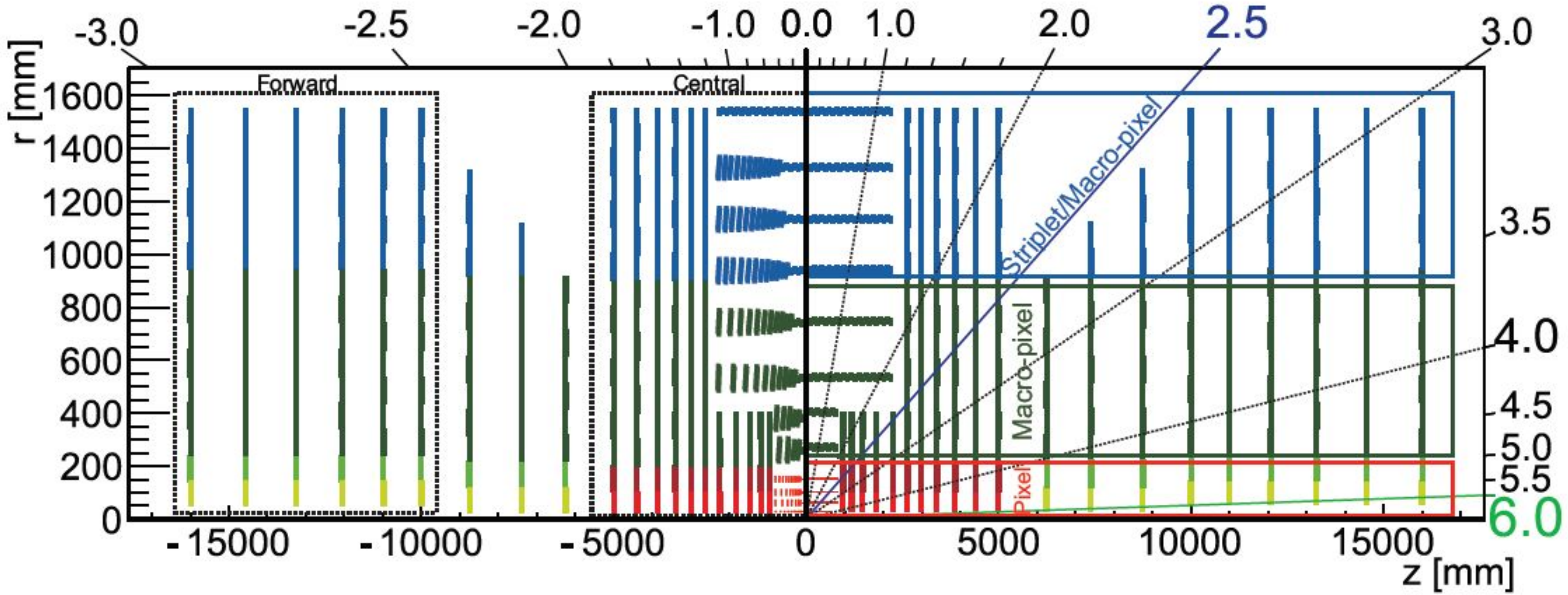


Fig. 7.11. Tracker layout using the so called "tilted geometry" (left) and "flat geometry" (right).

Detector: Tracker layout

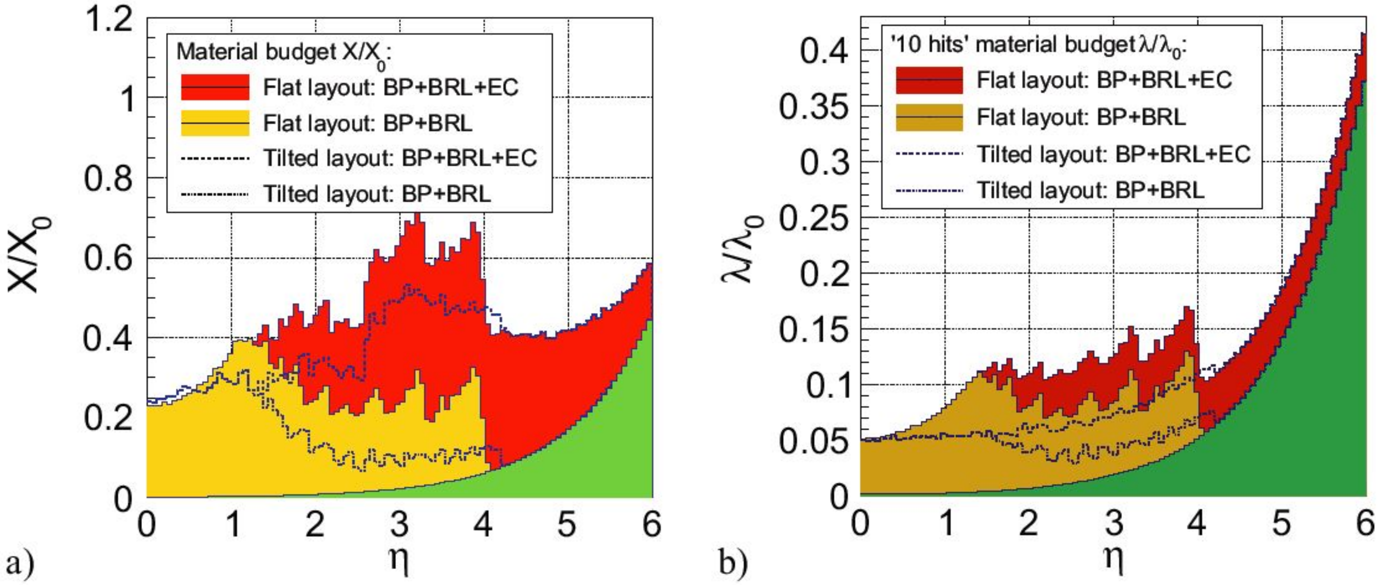


Fig. 7.14. (a) Material budget in units of radiation length for the flat and tilted tracker geometries. (b) Material budget in units of nuclear interaction length for the flat and tilted tracker geometries, assuming a limit of 10 hits on the track.