A Future Hadron Collider in Europe
FCC-hh

Martin Aleksa

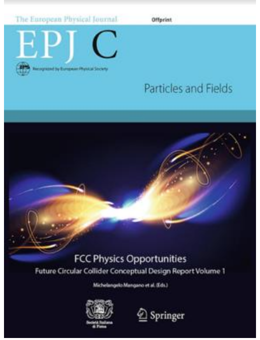
Based on material from:

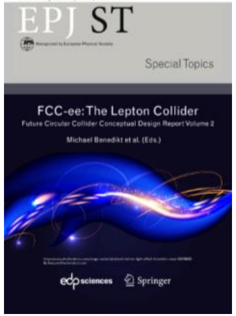
FCC Week Vienna 2025: https://indico.cern.ch/event/1408515/
FCC Feasibility Study Report 2025: https://indico.cern.ch/event/1534205/
FCC CDR Summary Volumes: https://fcc-cdr.web.cern.ch/, EPJ ST 228, 4 (2019) 755-1107

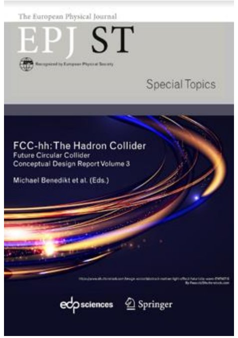
Introduction

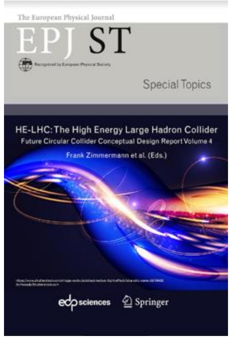
ESPPU 2019/20 and Start of FCC FS

FCC Collaboration delivered 4 volumes Conceptual Design Reports as input to ESPPU 2019/20









Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC

CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 ,

EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

2020 Update of European Strategy for Particle Physics:

"Europe, together with its international partners, should investigate technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage."

➔ Launch of the FCC Feasibility Study (FS) mid 2021

Feasibility Study Report Published in March 2025

Structure:Three Volumes

- ***Vol. 1:*** *Physics, Experiments and Detectors*
- ***Vol. 2:*** *Accelerators, Technical Infrastructures, Safety Concepts*
- ***Vol. 3:*** *Civil Engineering, Implementation & Sustainability*

Input for the Update of European Strategy for Particle Physics

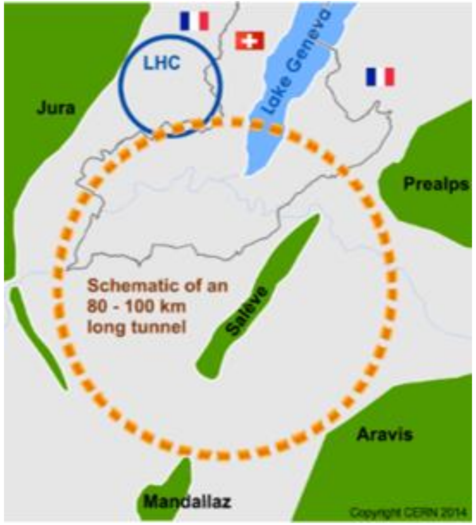
Three FSR volumes & other FCC-related input to 2025/26 European Strategy Update posted at https://indico.cern.ch/event/1534205/

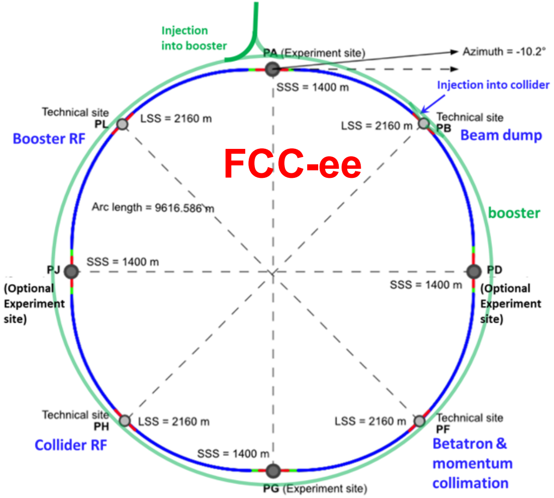
prepared with Overleaf submitted for publication to EPJ (Springer-Nature) – FCCIS members

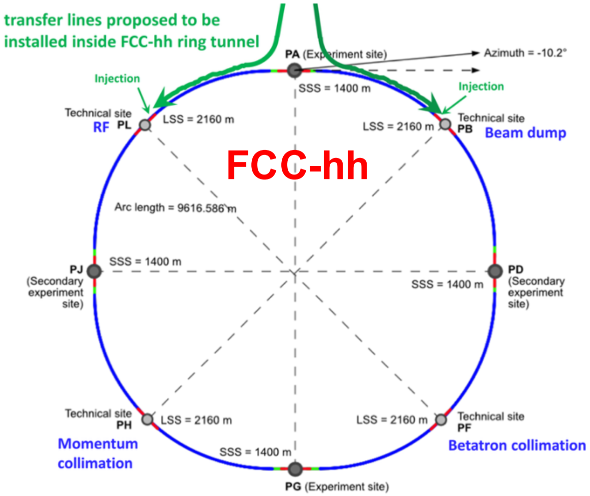
Overleaf FUTURE CIRCULAR COLLIDER Innovation Study EPJ.org your physics journal SPRINGER NATURE

FCC Integrated Program – Scope and Timeline

- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; eh option**
- Highly synergetic and complementary programme maximising the physics opportunities
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows start of a new, major facility at CERN within a few years of the end of HL-LHC







2020 - 2045 | 2045 - 2065 | 2070 - 2100

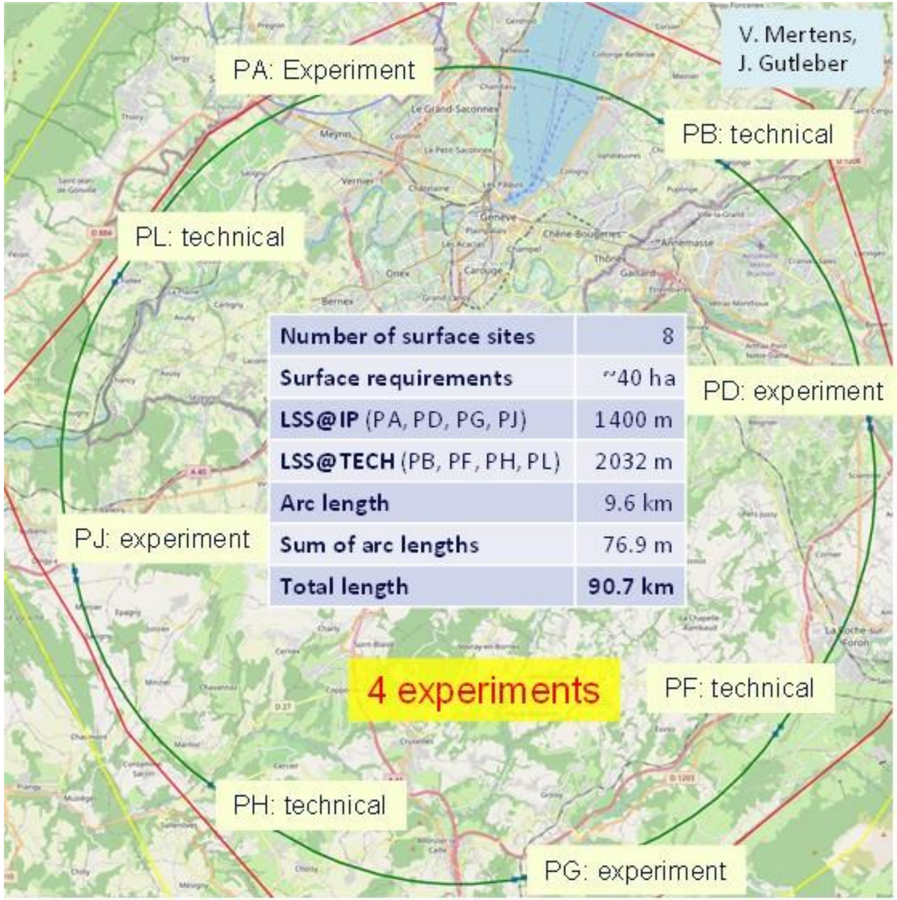
Reference Layout and Implementation: 90.7 km

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

Overall lowest-risk baseline:
90.7 km ring, 8 surface points,
4-fold symmetry

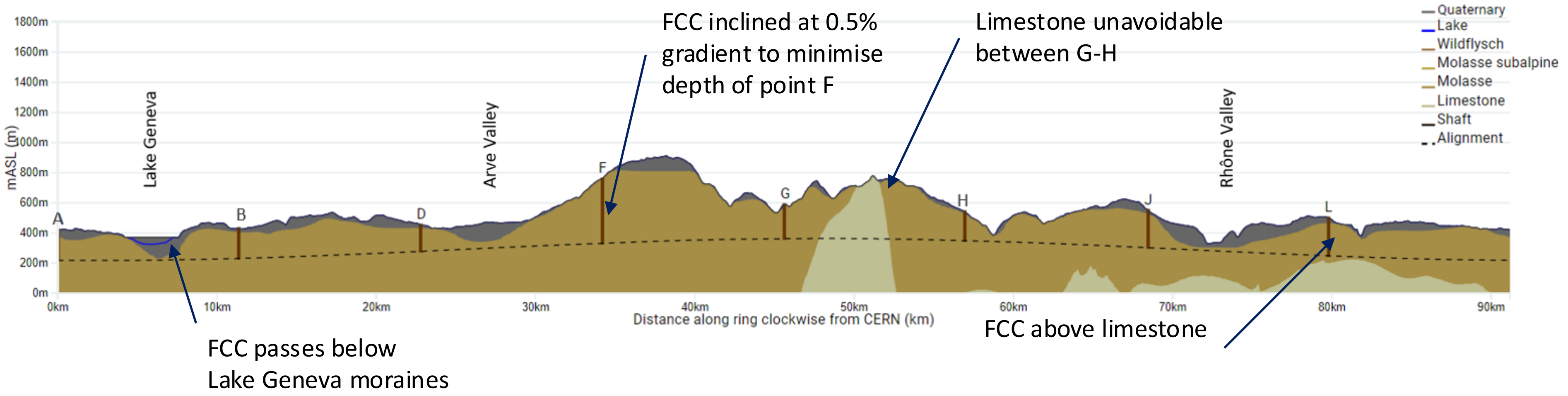
Reference layout was the basis for:

- **Surface sites optimisation** and **land reservation** with host states CH and FR
- **Environmental initial-state study**



Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

Optimum Placement of FCC Tunnel and Geology



Tunneling mainly in moraine layer (soft rock), well suited for fast, low-risk TBM construction.

6 million m^3 excavated volume → 8.5 million m^3 excavation material on surface

CE Designs of all underground structures developed

Average shaft depths ~240 m

To fix the vertical position of the tunnel, interfaces between geological layers have to be known

Future Hadron Collider – FCC-hh

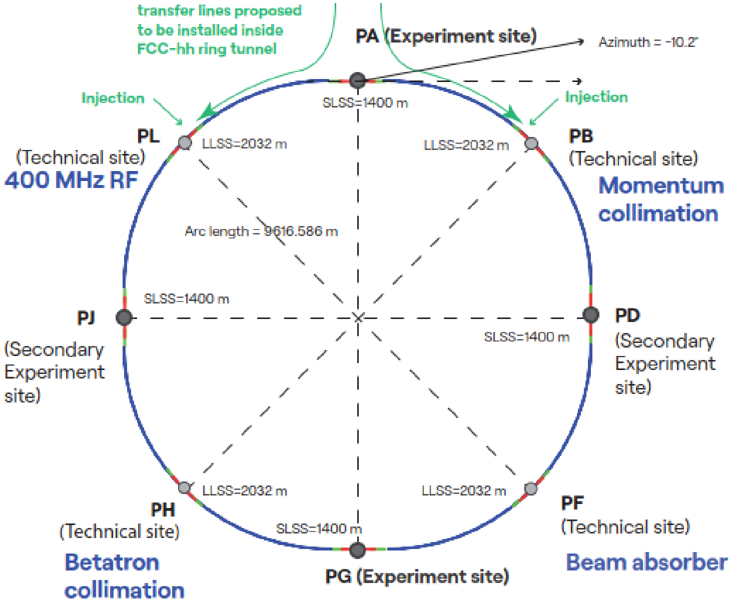
Hadron Collider FCC-hh

- Parameter optimization to lower electricity consumption (~max. consumption of FCC-ee)
- Magnetic field considered realistic with today's technologies (Nb_3Sn, ~14T, 1.9 K)

Main parameters FSR 2025

Parameter	FCC-hh	FCC-hh CDR	HL-LHC
Collision energy cms [TeV]	85	100	14
Dipole field [T]	14	16	8.33
Circumference [km]	90.7	97.8	26.7
Beam current [A]	0.5	0.5	1.1
Synchr. rad. per ring [kW]	1200	2400	7.3
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	30	30	5 (lev.)
Events/bunch crossing	1000	1000	132
Stored energy/beam [GJ]	6.5	8.3	0.7
Integr. luminosity / IP [fb^{-1}]	20000	20000	3000

FCC-hh functional layout



New FCC-hh Baseline and Power Consumption

Technical system choices and areas for optimisation:

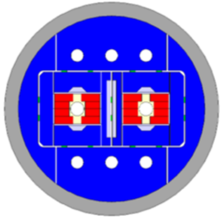
- Accelerator optics design to increase arc dipole filling factor and maximize beam energy
- Cold mass either at 1.9 K with superfluid He (studied in CDR, cf. LHC) or with 4.5 K with forced flow
- Temperature of beam vacuum system (beam screen)
- Cryogenics eco mode during shutdowns

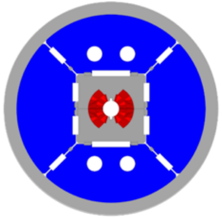
	FCC-hh 90.7km Nb_3Sn 14T	FCC-hh 90.7km Nb_3Sn 14T
Magnet temperature	**1.9 K**	4.5 K
Yearly electricity consumption	**< 2.5 TWh**	< 2.0 TWh

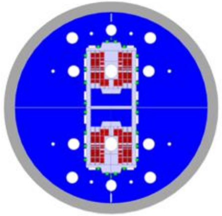
- **Significant reduction of electrical power consumption (close to factor 2!) compared to CDR version 2019 (CDR value: ~4TWh, current CERN consumption: 1.2TWh)**
- **Potential for further reduction with design optimisation and R&D on 4.5 K operation**
- **Long term R&D towards accelerator magnets based on high-temperature superconductor materials, targeting higher fields and reduced electricity consumption**

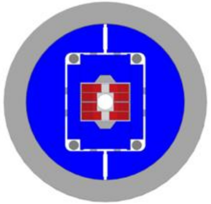
FCC-hh High-Field Magnet Nb_3Sn and HTS R&D

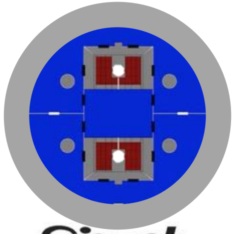
Nb_3Sn:
- 12- and 14-T short demonstrators
- Different coil geometries
- Tests scheduled for 2026
- Hybrid Nb_3Sn/NbTi for 14T (reduced cost)







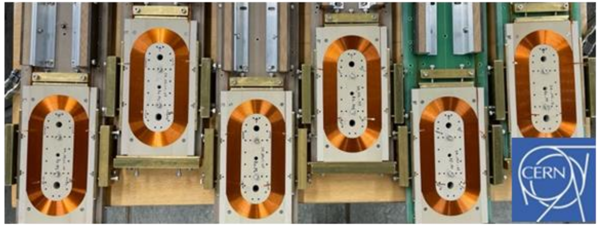




HTS R&D in various domains:
- REBCO and IBS Conductor R&D
- Racetrack coil developments
- Hybrid Nb_3Sn/HTS up to 16T

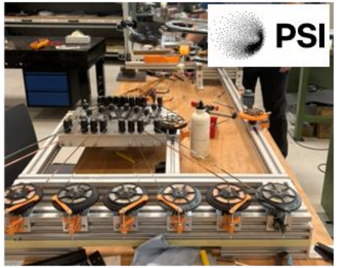
See next talk by L. Bottura

REBCO coated-conductor R&D line at KIT.



Insulated tape-stack coils for assembly in common-coil config at CERN.

Iron-based SC powder synthesis and R&D tape fabrication at CNR SPIN



Fabrication of racetrack from solder-impregnated tape-stack cable at PSI.

CEA process development for metal-insulated racetrack coils.

FCC-hh Scenarios & Possible Parameter Range

With present layout of the FCC, after optimization, the following energies can be reached as a function of the dipole field:

Dipole field [T]	c.m. energy	Comment
12	72	not far above peak field of HL-LHC Nb_3Sn quadrupoles
14	84	Nb_3Sn or HTS
17	102	HTS
20	120	HTS

Increasing the c.m. energy beyond ~100 TeV, **we will assume that the synchrotron-radiation power could not increase, beyond a total of about 4 MW** (which must be removed from inside the cold magnets) → **F17** and **F20**

On the other hand, **when decreasing the beam energy, one can hold either the synchrotron-radiation power** (increasing current up to HL-LHC values, **F12HL**) **or the beam current constant (F12LL)**. Also, the **pile-up might need to be limited, e.g. to ~1000 events/crossing (F12PU)**. We thus consider three scenarios for 12 T: 0.5 A (**F12LL**) and 1.12 A (**F12HL**) beam current, the latter without or with pile-up levelling (**F12PU**).

Finally, **further overall lowering the synchrotron radiation power, by reducing the number of bunches, in order to restrict the total power consumption of the future FCC-hh, would decrease peak and integrated luminosity by the same factor.**

Scenarios (90.7km ring)

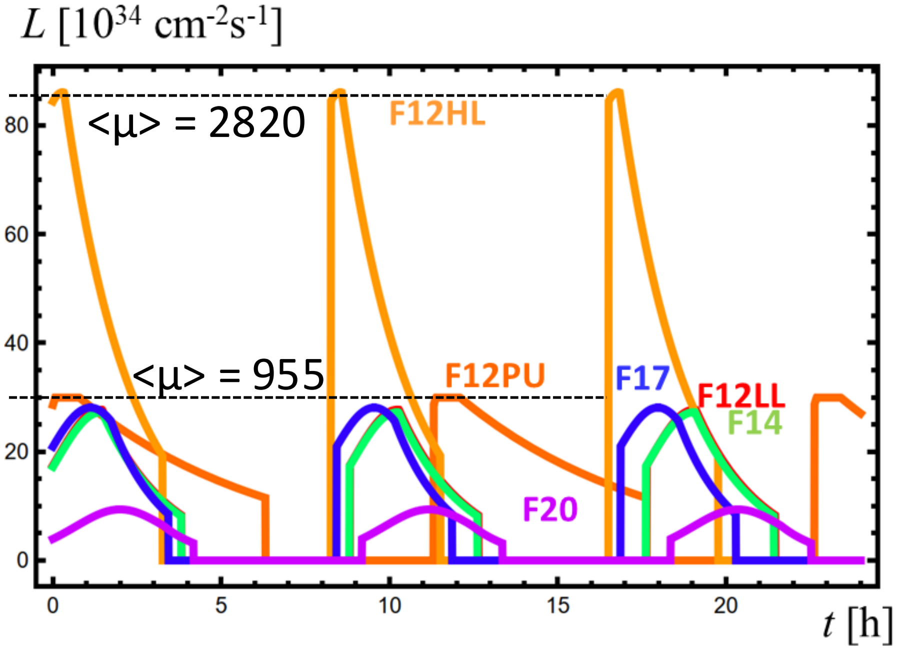
Courtesy F. Zimmermann (link)

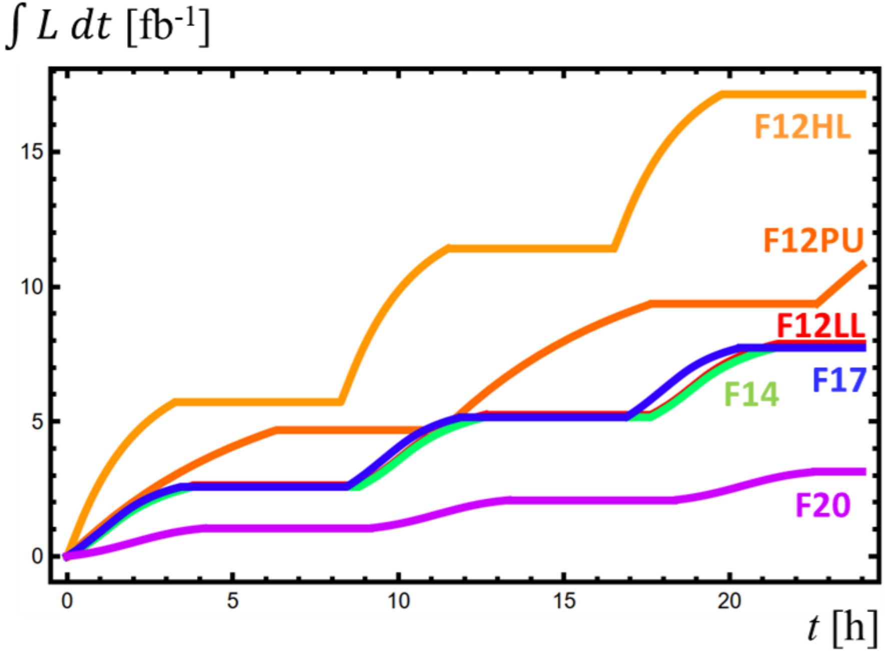
Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
c.m. energy	TeV	72	72	72	84	102	120	14
dipole field	T	12	12	12	14	17	20	8.33
beam current	A	0.5	1.12	1.12	0.5	0.5	0.2	(1.12) 0.58
bunch popul.	10^{11}	1.0	2.2	2.2	1.0	1.0	0.4	(2.2) 1.15
bunches/beam		9500	9500	9500	9500	9500	9500	(2760) 2808
rf voltage	MV	30	30	30	35	43	50	(16) 16
longit. emit.	eVs	6.9	6.9	6.9	8.1	9.7	11.4	2.5
norm. tr. emit.	μm	2.5	2.5	2.5	2.5	2.5	2.5	(2.5) 3.75
IP beta*	m	0.22	0.22	0.65	0.26	0.31	0.37	(0.15) 0.55
initial σ*	μm	3.8	3.8	6.5	3.8	3.8	3.8	(7.1 min) 16.7
initial L	$nb^{-1}s^{-1}$	175	845	286	172	209	39	(50, lev'd) 10
initial pile up		580	2820	955	590	732	141	(135) 27
ΔE / turn	MeV	1.3	1.3	1.3	2.4	5.3	10.1	0.0067
SR power/beam	kW	650	1450	1450	1200	2670	2020	(7.3) 3.6
tr.ε damp'g time	h	0.68	0.68	0.68	0.43	0.24	0.15	25.8
init p-burnoff time	h	5.1	2.3	6.9	5.1	4.0	8.4	(15) 40

Instantaneous and Integrated Luminosity

Simulation incl. beam-beam effects and optimal fill length for 5 hours interfill (F. Zimmermann)

Courtesy F. Zimmermann (link)



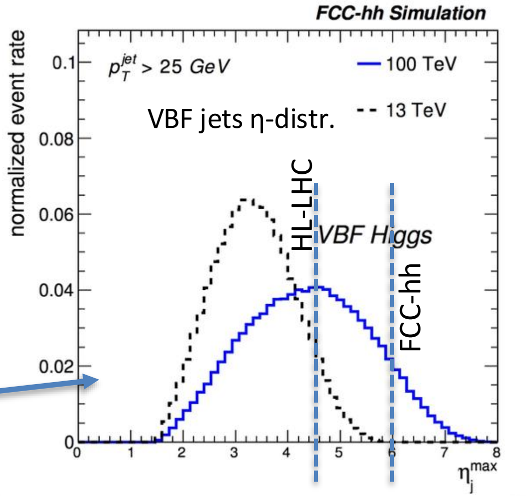


Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
ideal $\int L\, dt$ /day	fb^{-1}	7.9	17.1	10.8	7.7	7.7	3,1	(1.9) 0.4
$\int L\, dt$ / year	fb^{-1}	950	2000	1300	920	920	370	(240) 55

CDR Parameter Table (100km, 100TeV)

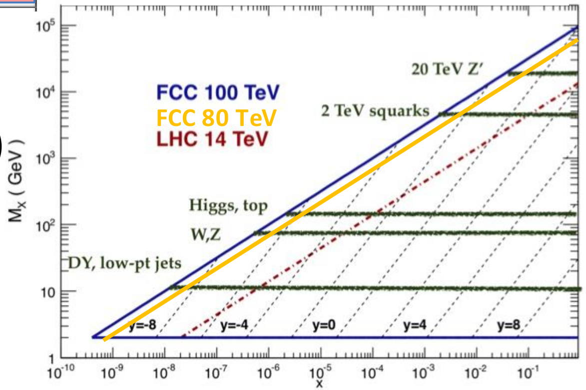
Table 7.1: Key numbers relating the detector challenges at the different accelerators.

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



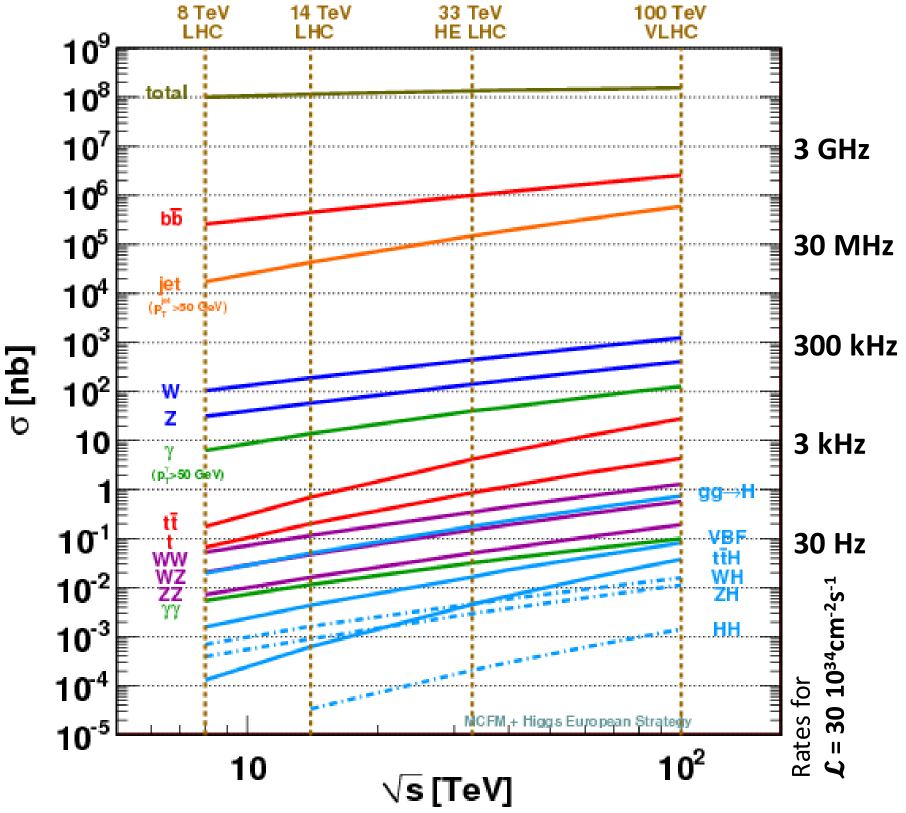
Unprecedented particle flux and radiation levels

- 10 GHz/cm^2 charged particles at 2.5cm
- ≈ 10^{18} cm^{-2} 1 MeV-n.eq. fluence for 30ab^{-1} (1st tracker layer, fwd calo)
- "Light" SM particles produced with increased forward boost
  - → spreads out particles by 1-1.5 units of rapidity



Parameters shown for the scenario presented in the FCC CDR
→ Minimal changes only for 80TeV, but fluxes scale with luminosity!

Cross-Sections for Key Processes



- **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

HH cross-section down by ~30% for 80 TeV compared to 100 TeV!

FCC-hh Detector

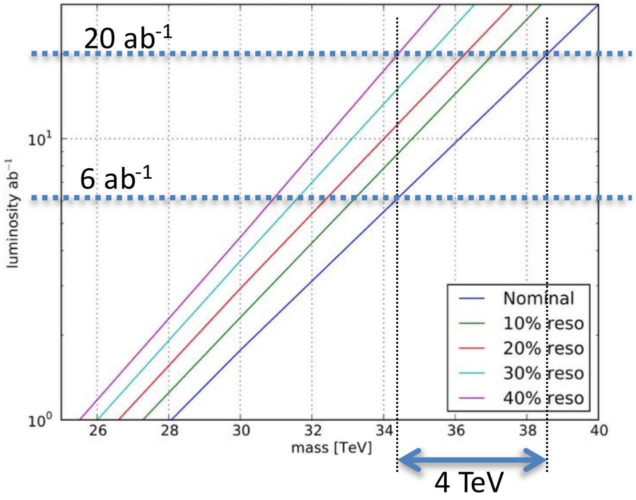
Physics Benchmarks – Detector Requirements

Physics at the $\mathcal{L}\sigma$-limit

Exploration potential through higher energy, increased statistics, increased precision

Example: Z'_{SSM} discovery

luminosity versus mass for a 5σ discovery



Muon momentum resolution:

- **O(5%) at 10TeV.**
- **Compare to 10% at 1TeV spec. at LHC**

Tracking – Resolution degrading with higher momentum!

$$\frac{\Delta p}{p} \propto \frac{\sigma_{\text{pos}} \cdot p}{BL^2}$$

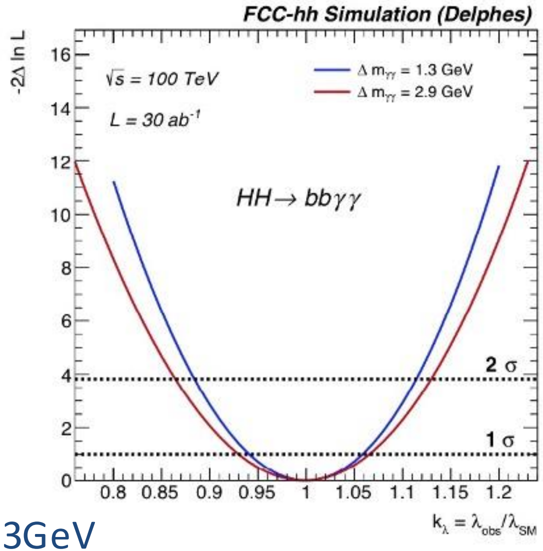
→ Have to improve on

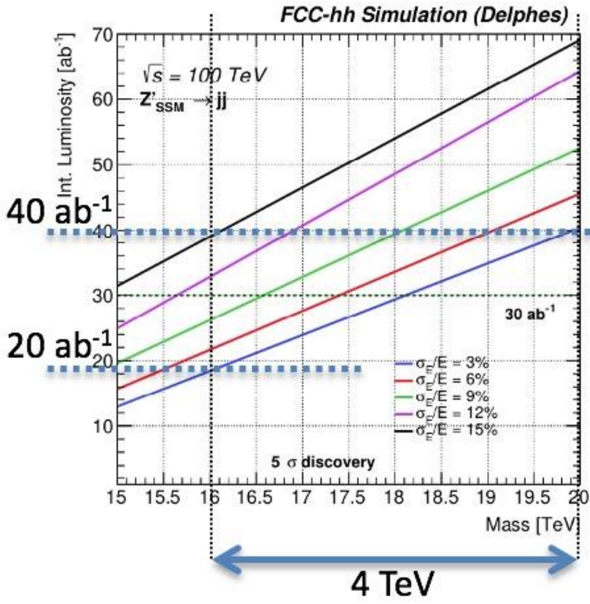
- σ_{pos}: difficult
- Magnetic field B: go from 2T (ATLAS) to 4T (FCC-hh)
- Lever arm L: magnet cost scales with ≈ volume$^{2/3}$ → very quickly very expensive

Physics Benchmarks – Detector Requirements

Calorimetry – Improving resolution with higher energy!

$$\frac{\sigma_E}{E} \approx \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$





Higgs self-coupling $\delta\lambda/\lambda$ = 7% for $\Delta m_{\gamma\gamma} < 3$GeV

- → **EM-calorimeter resolution**
  sampl. term *a* ≈ *10%* and noise term *b* < *1.5GeV* (including pile-up)!

Di-jet resonances: HCAL constant term of *c* = 3% instead of 15%**:** extend discovery potential by 4TeV (or same disc. pot. for 50% lumi)

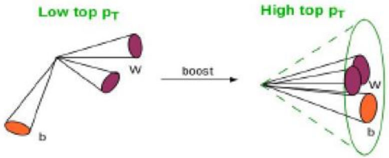
- → **full shower containment is mandatory!**
- → Large **HCAL depth (~ 12 λ_{int})!**

Better detector performance could compensate decreased HH statistics at 80 TeV

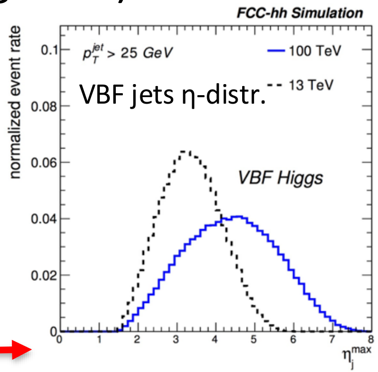
Requirements for FCC-hh Detector

Used in Delphes physics simulations

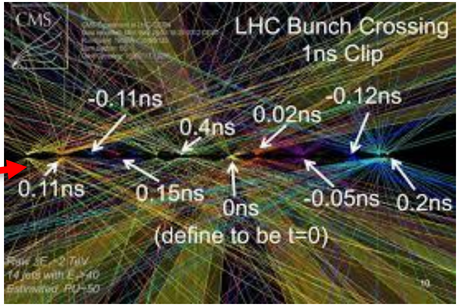
- **ID tracking target**: achieve σ_{p_T} / p_T = 10-20% @ 10 TeV
- **Muon target**: σ_{p_T} / p_T = 5% @ 10 TeV
- Keep **calorimeter constant** term as small as possible (and good sampling term)
  - Constant term of <1% for the EM calorimeter and <2-3% for the HCAL
- **High efficiency vertex reconstruction, b-tagging, τ-tagging, particle ID**!
  - Pile-up of <μ>=1000 → 120μm mean vertex separation
- **High granularity** in tracker and calos (boosted obj.)



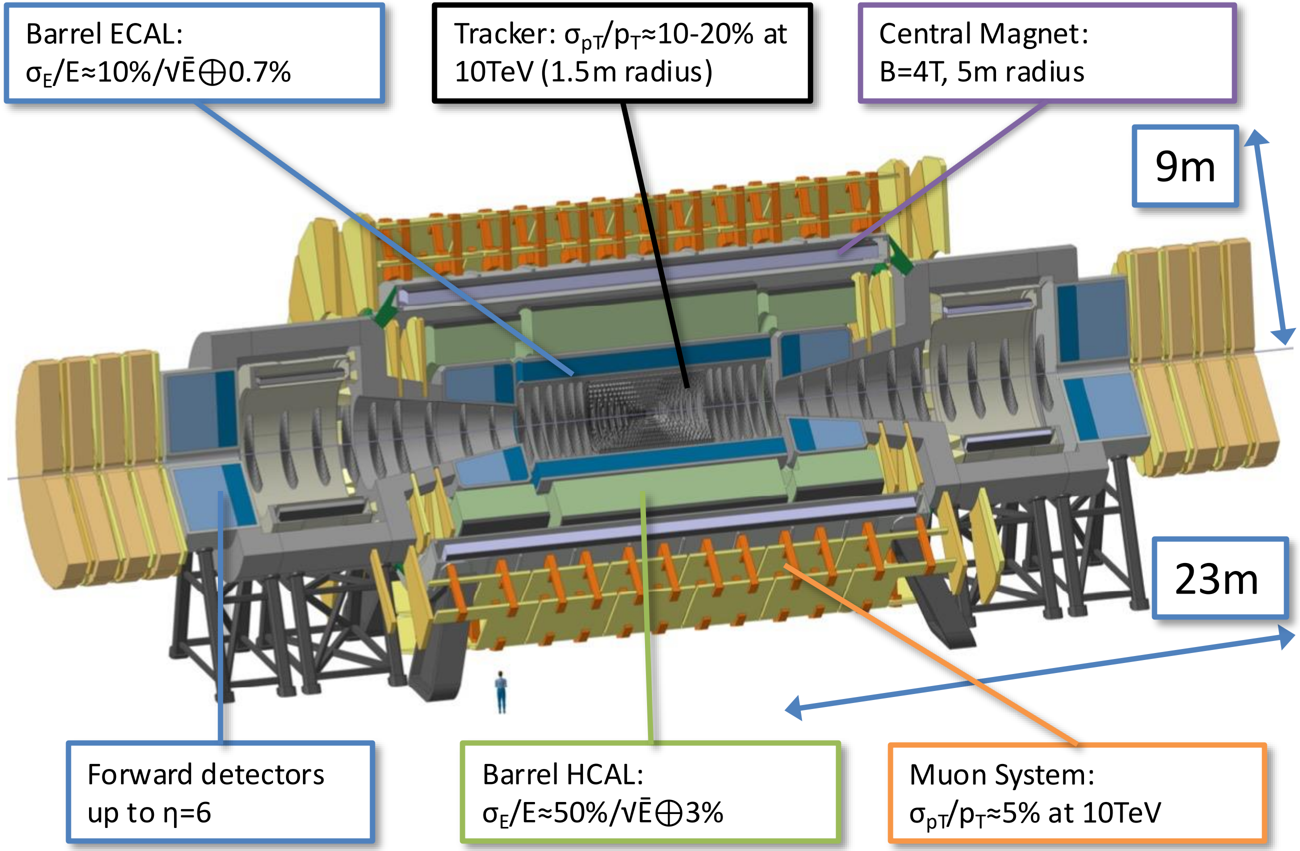
- **Pseudorapidity (η) coverage**:
  - Precision muon measurement up to |η|<4
  - Precision calorimetry up to |η|<6



- → **Achieve all that at a pile-up of 1000! → Granularity & Timing!**
- **On top of that radiation hardness and stability!**

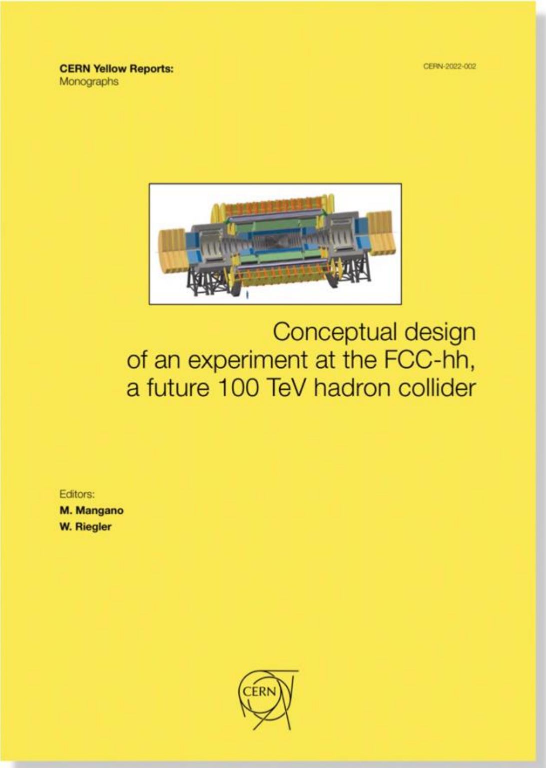


A Possible FCC-hh Detector – Reference Design for CDR



- Converged on **reference design for an FCC-hh experiment for the FCC CDR**
- Goal was to demonstrate, that an **experiment** exploiting the **full FCC-hh physics potential** is **technically feasible**
  - **Input for Delphes physics simulations**
  - **Radiation simulations**
- This is one example experiment, other choices are possible and very likely → A lot of **room for other ideas, other concepts and different technologies**

Documentation



FCC CDR (link) & Yellow report (link)

Volume editors:
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Editors: H. Gray, C. Helsens, F. Moortgat, M. Selvaggi

Experiment, detector requirements from environment
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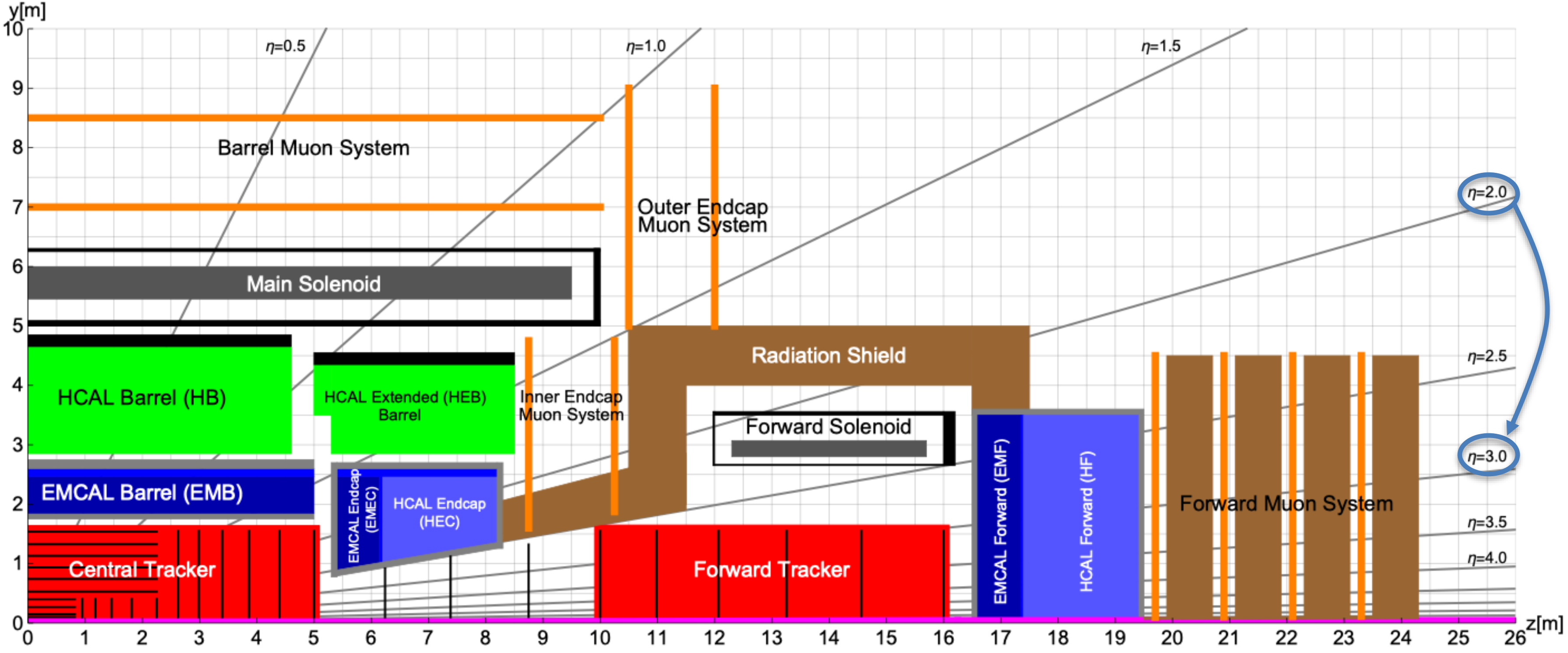
Reference Design for CDR

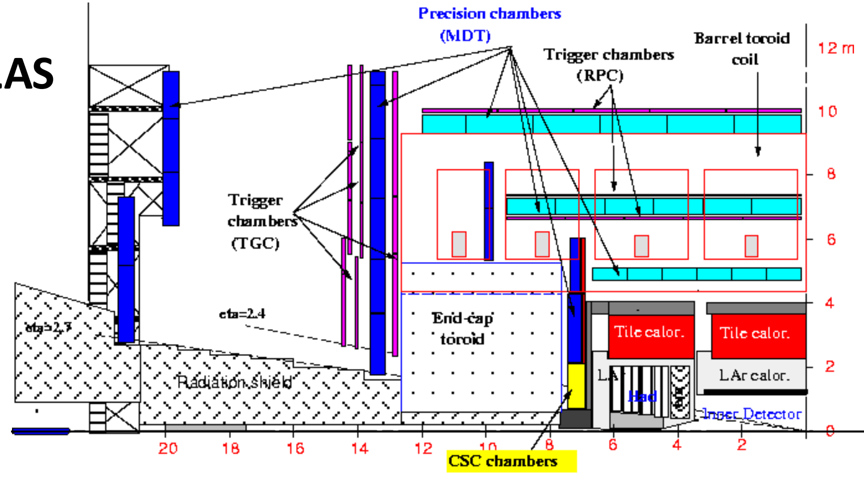


Forward solenoid adds about 1 unit of η with full lever-arm

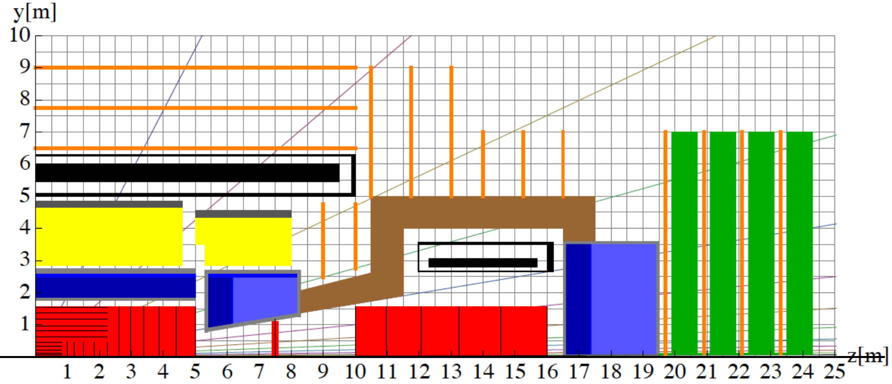
Forward solenoid requires additional radiation shield to connect endcap and forward calorimeter

FCC-hh Detector: Comparison to ATLAS & CMS

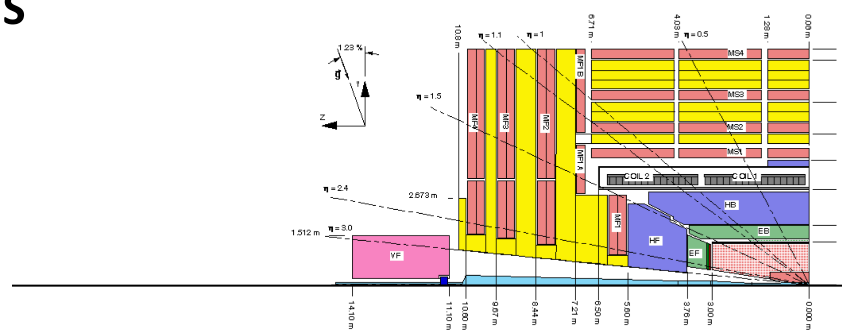
ATLAS

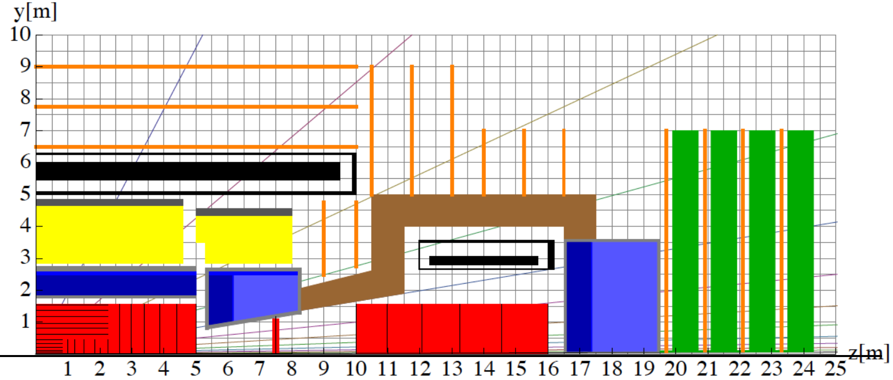


FCC-hh Reference Detector

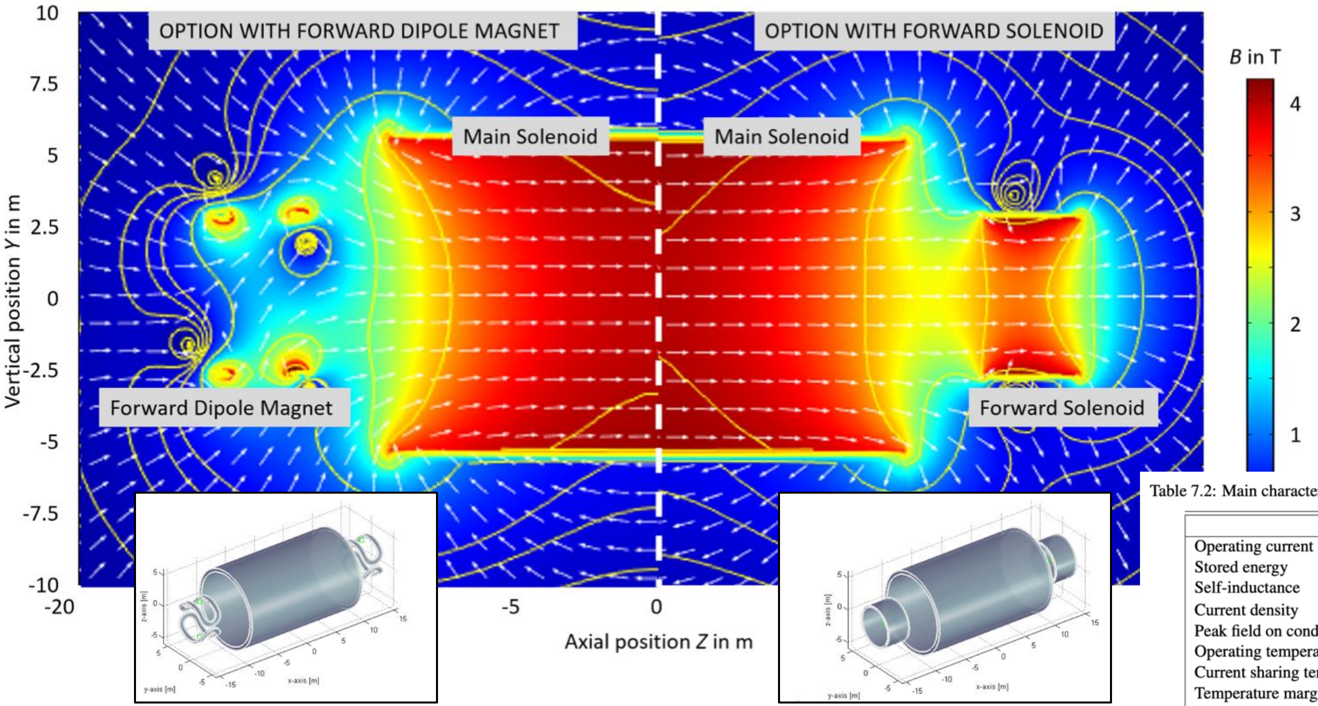


CMS





FCC-hh Magnet System



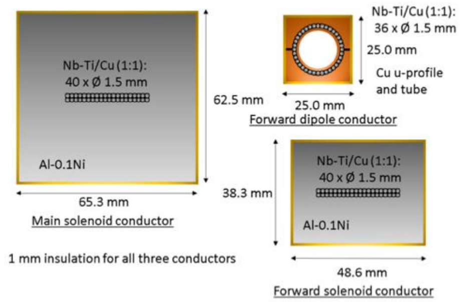


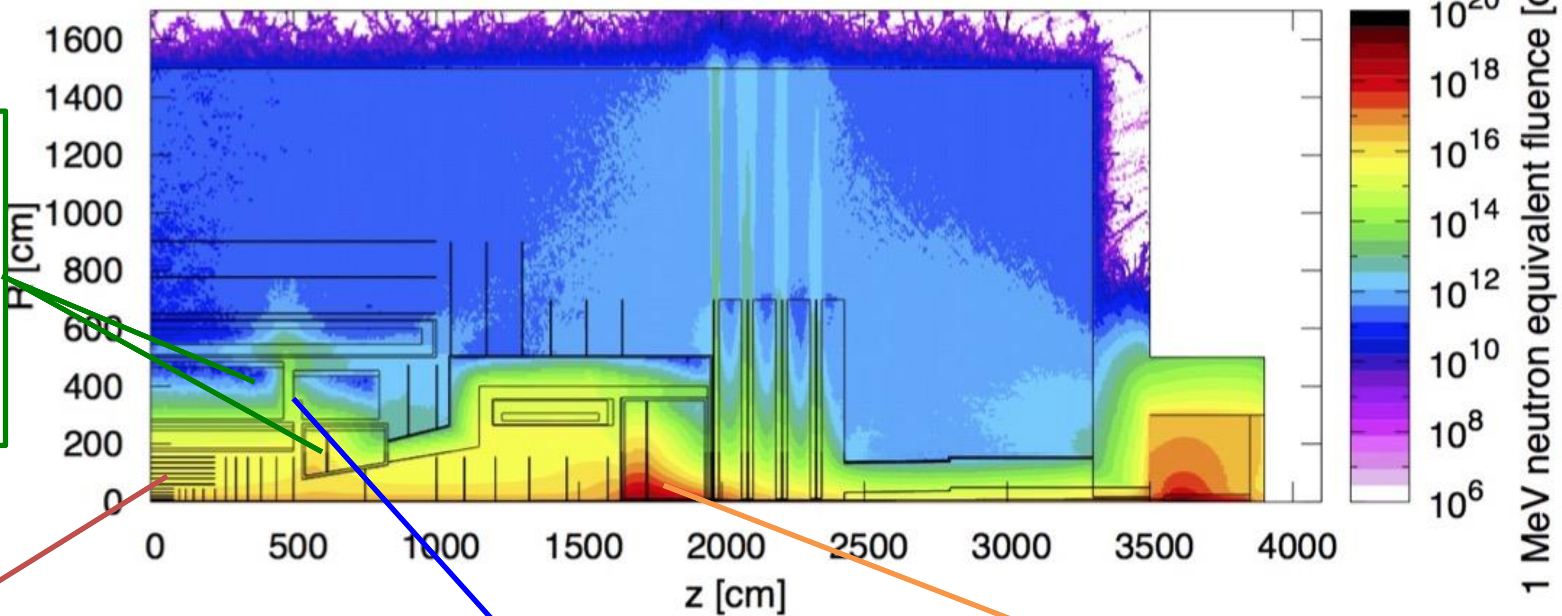
Table 7.2: Main characteristics of the central solenoid, a forward solenoid and a forward dipole magnet.

	Unit	Main solenoid	Forward solenoid	Forward dipole
Operating current	kA	30	30	16
Stored energy	GJ	12.5	0.43	0.20
Self-inductance	H	27.9	0.96	1.54
Current density	A/mm^2	7.3	16.1	25.6
Peak field on conductor	T	4.5	4.5	5.9
Operating temperature	K	4.5	4.5	4.5
Current sharing temp.	K	6.5	6.5	6.2
Temperature margin	K	2.0	2.0	1.7
Heat load cold mass	W	286	37	50
Heat load thermal shield	W	5140	843	1500
Cold mass	t	1070	48	114
Vacuum vessel	t	875	32	48
Conductor length	km	84	16	23

ATLAS Magnet System 2.7 GJ
CMS Magnet System 1.6 GJ
FCC-hh: ~13 GJ, cold mass + cryostat around 2000 tons.
Possible alternative solutions: Ultra-thin solenoid positioned inside the calorimeter (difficulty: muon measurement!)

1 MeV Neutron Equivalent Fluence for 30ab^{-1}

Generally ~10-30 times worse than HL-LHC
Exception: Forward calorimeter goes to higher η → bigger factor



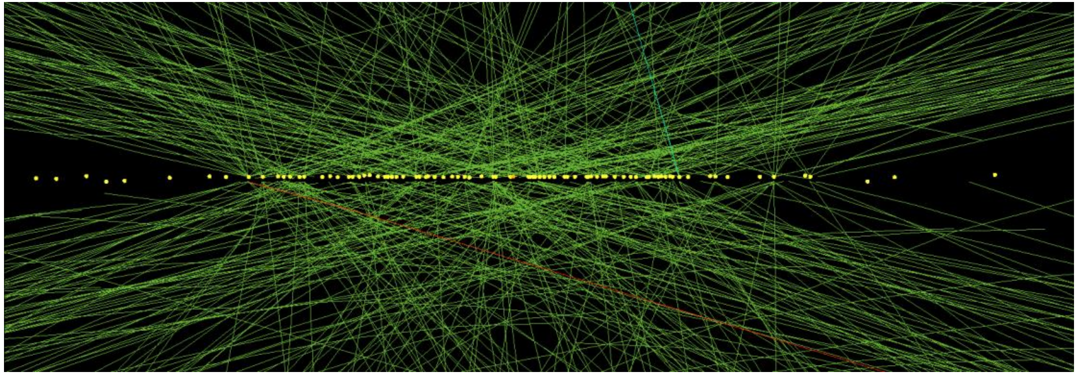
Barrel calorimeter:
EM-calo: 4 10^{15} cm^{-2}
HAD-calo: 4 10^{14} cm^{-2}
End-cap calorimeter:
EM-calo: 2.5 10^{16} cm^{-2}
HAD-calo: 1.5 10^{16} cm^{-2}

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

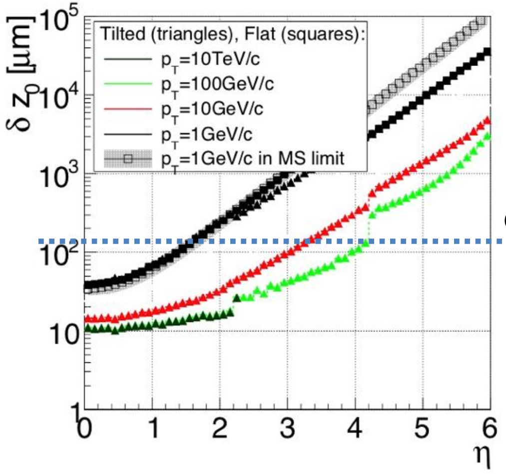
Calorimeter gap:
from 10^{16} cm^{-2} to 10^{14} cm^{-2}

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

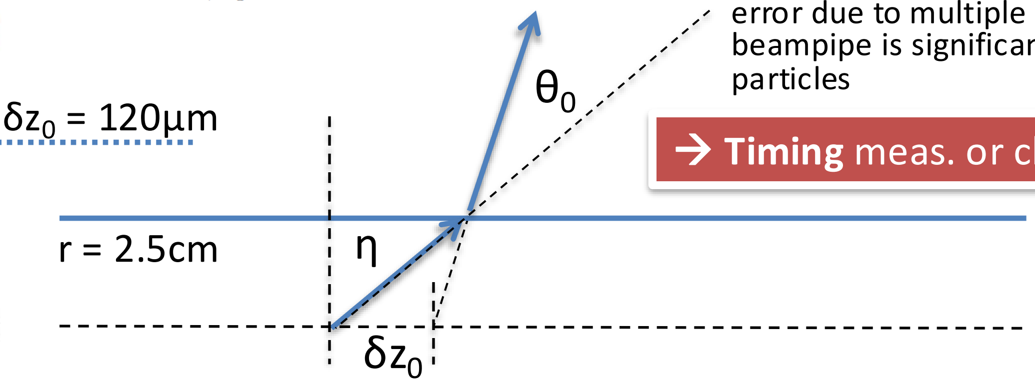
The Challenge of <μ> = 1000 Pile-Up



- HL-LHC average distance between vertices at z=0 is
  - ≈ **1mm in space and 3ps in time.**
- → For 6 times higher luminosity and higher c.m. energy at FCC-hh:
  - ≈ **120 μm in space and 0.4ps in time**
- **→ Future trackers will need to use both, position resolution and timing to identify the correct vertex!**



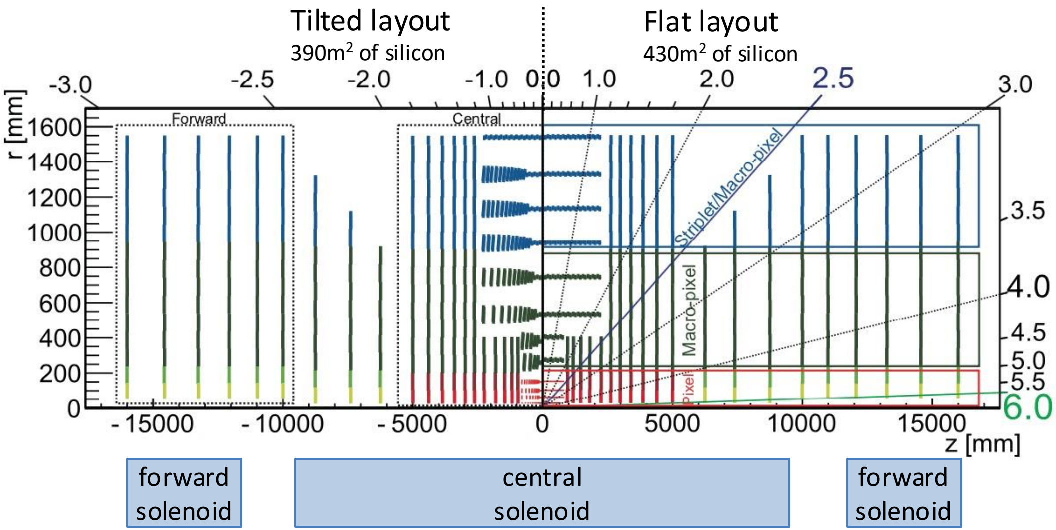
$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

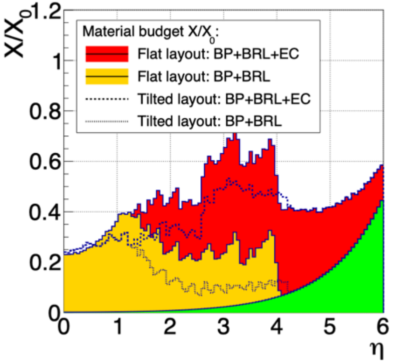


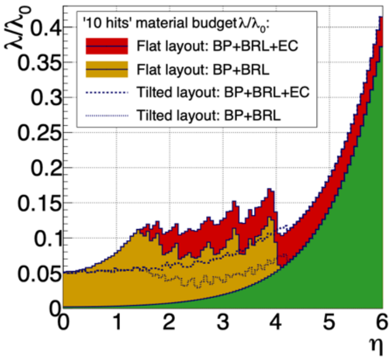
Multiple scattering in the beam pipe:
→ Even with a perfect tracking detector, the error due to multiple scattering in the beampipe is significant for low energetic particles

→ Timing meas. or clever new ideas …

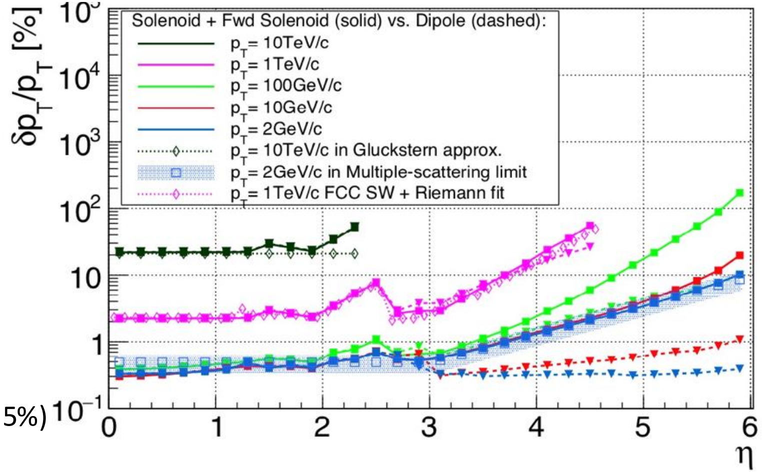
FCC-hh Tracker







Tilted layout:		
$25 \times 50\,\mu m^2$ (1–4th BRL)	$33.3 \times 400\,\mu m^2$	$33.3\,\mu m \times 1.75\,mm$ (BRL)
$25 \times 50\,\mu m^2$ (1st EC ring)		$33.3\,\mu m \times 1.75\,mm$ (EC)
$33.3 \times 100\,\mu m^2$ (2nd EC ring)		$33.3\,\mu m \times 50\,mm$ (12th BRL layer)
$33.3 \times 400\,\mu m^2$ (3–4th EC ring)		



Assuming an r-phi resolution of 7.5-9.5µm per detector layer
$\delta p_T/p_T \leq 10\%$ for

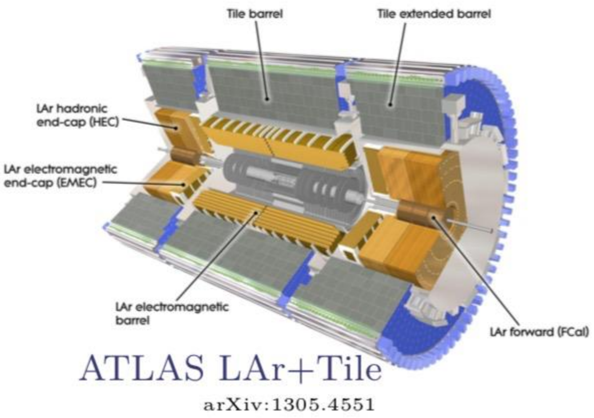
- $\leq$ 10 GeV/c and $\eta \leq 5.8$
- $\leq$ 1 TeV/c and $\eta \leq 4.0$

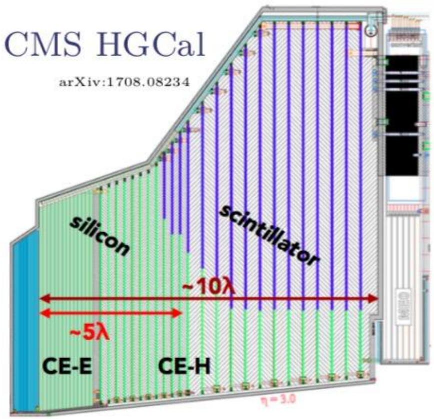
$\delta p_T/p_T$ = 20% for 10 TeV/c in the central region

Momentum resolution dominated by **multiple scattering** up to 250GeV (limit at $\delta p_T/p_T$ = 0.5%)

→ **low material tracker**!!

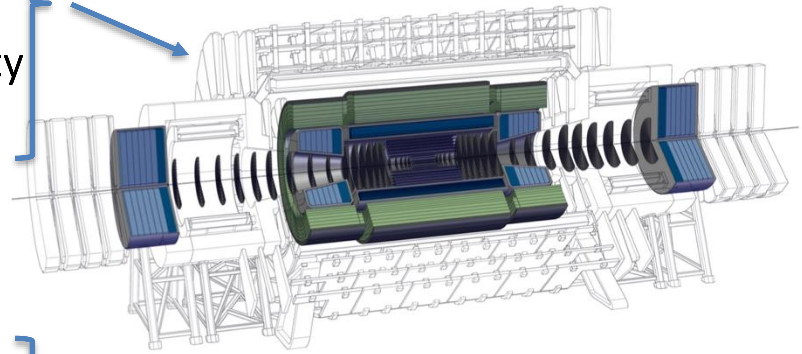
FCC-hh Calorimetry





- Good intrinsic energy resolution
- Radiation hardness
- High stability
- Linearity and uniformity
- Easy to calibrate

FCC-hh Calorimetry
„conventional calorimetry“ optimized for particle flow

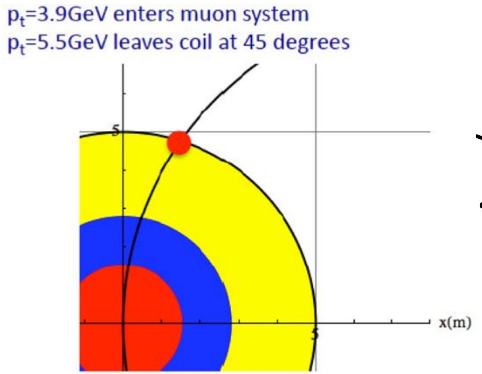


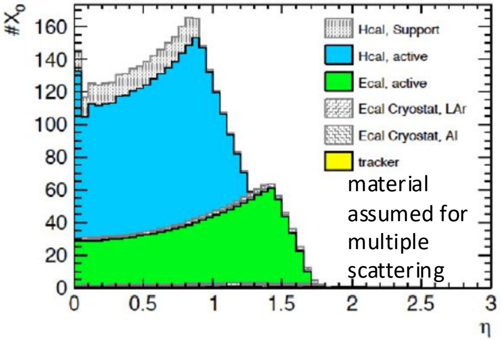
- High granularity
  - → Pile-up rejection
  - → Particle flow
  - → 3D/4D/5D imaging

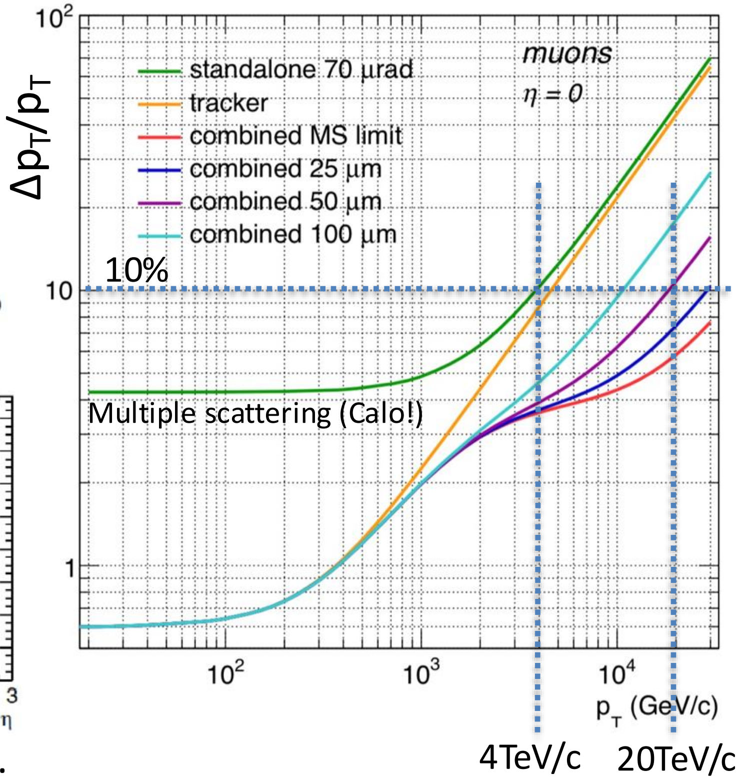
→ Proposed:
Highly granular LAr/Pb ECAL
Scintillator/Steel HCAL

FCC-hh Calorimetry studies have been published at https://arxiv.org/abs/1912.09962

FCC-hh Muon System





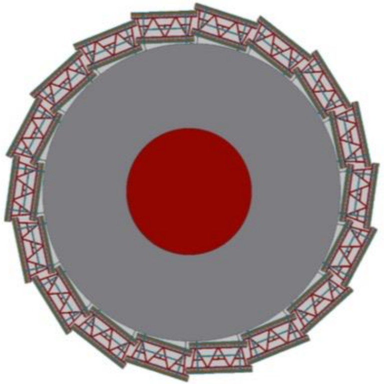


With 50μm position resolution and 70μrad angular resolution we find (η=0):

- ≤10% $\Delta p_T/p_T$ standalone up to 4TeV/c
- ≤10% $\Delta p_T/p_T$ combined up to 20TeV/c

Standalone muon performance not relevant, the task of muon system is **triggering and muon identification!**

Muon rate dominated by c and b decays → isolation is crucial for triggering W, Z, t!



Muon barrel: Rates of up to ~500Hz/cm^2 expected

Muon detection in forward region:

Excpected rates up to 500kHz for r > 1m

→ **HL-LHC muon system gas detector technology will work for most of the FCC detector area**

Conclusions

- **Feasibility Study Report published in March 2025**
  - Presents FCC reference layout and implementation for 90.7 km tunnel
  - Assuming 14T dipole magnets that leads to a c.o.m. energy of FCC-hh of 85 TeV
  - → Reduction of power needs by almost a factor 2 with respect to the CDR parameters
  - → Other scenarios under study assuming 16T (Nb_3Sn, HTS) or higher field (HTS) magnets
- **Detector Requirements for Future High-Energy Hadron Colliders extremely challenging!**
- An **FCC-hh Reference Detector** has been introduced that could fulfill physics requirements, but intense detector R&D necessary to achieve very ambituous design goals
- **Main challenges:**
  Radiation hardness, precision timing, huge data rates, low-power read-out electronics and links, low material for support structures, power and cooling
- **Expecting to profit from R&D for HL-LHC**
- **Detector R&D collaborations have been set-up to address these challenges, see arXiv:2408.17094v1!**
- **Join in and contribute!**

Thank You for Your Attention!

Back-Up

From ESPPU 2020 Document

Under "3. High-priority future initiatives":

"Europe, together with its international partners, should investigate the **technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.** Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

Under "4. Other essential scientific activities for particle physics":

"**Detector R&D programmes and associated infrastructures** should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should **define a global detector R&D roadmap** that should be used to support proposals at the European and national levels."

https://europeanstrategyupdate.web.cern.ch/resources

Future Circular Collider
Feasibility Study Report

627 Pages

Volume 2

Accelerators, Technical Infrastructure and Safety

March 31, 2025

arXiv:2505.00274

Submitted to the European Physics Journal ST, a joint publication of EDP Sciences, Springer Science+Business Media, and the Società Italiana di Fisica.

FCCee: 498 pages

Estimated investment costs in 2024 Swiss Francs.

Domain	Cost [MCHF]
FCC-ee total, including four experiments	15 320

The investments are distributed over a time frame of about 15 years.

FCChh: 57 pages

Domain	Cost [MCHF]
FCC-hh total	18 880

The investments are distributed over a time frame of about 15 years.

CDR: FCC-hh Parameter Table (100km, 100TeV)

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

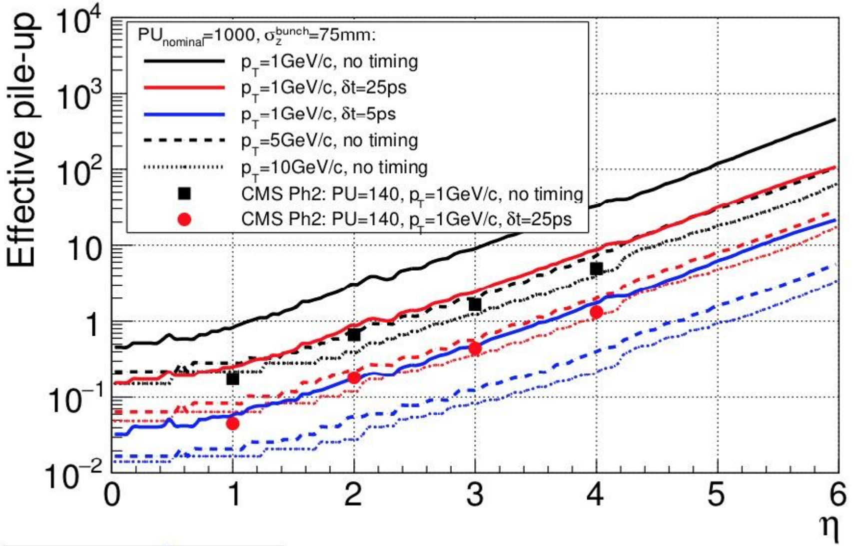
Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10600
Goal $\int \mathcal{L}$	ab^{-1}	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

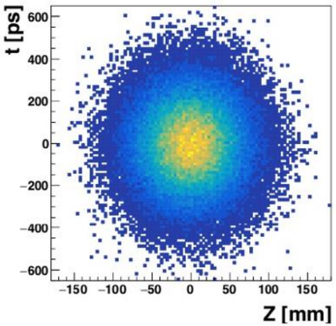
- E_{cm} = 100 TeV
- ~100 km circumference
- $\mathcal{L} = 30 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\int\mathcal{L} = 30\ \mathrm{ab}^{-1}$
- 31 GHz pp collisions
- Pile-up <μ> ≈ 1000
- 4 THz of charged tracks

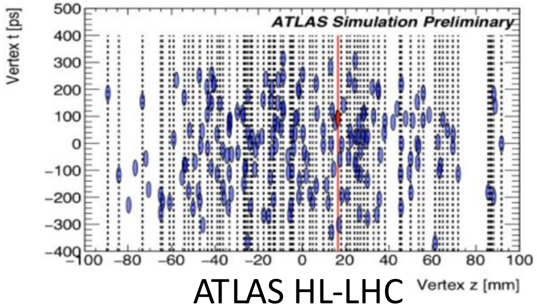
Parameters for the scenario presented in the **FCC CDR**
As shown before now there are **several different scenarios**
Exact values will **depend on the chosen scenario**

Timing Information for Vertex Reconstruction

- **Goal is to identify the primary vertex!**
- **Effective pile-up:** number of vertices compatible with reconstructed tracks (95%CL)
  - Eff. pile-up = 1: Indication for unambiguous primary vertex identification
- **Example:** eff. pile-up = 1 for p_T = 5GeV:
  - η < |2| without timing (---)
  - η < |3.5| with 25ps timing accuracy (---)
  - η < |4.5| with 5ps timing accuracy (---)
- → **Very challenging!**



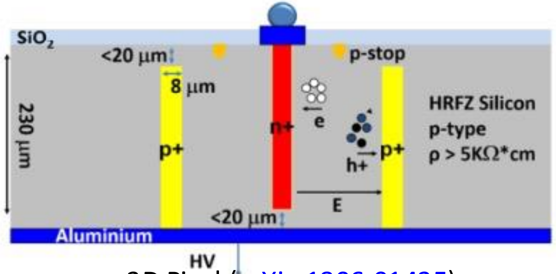




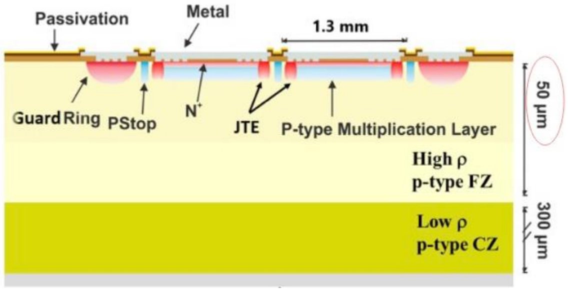
ATLAS HL-LHC

Challenges for the Tracker – R&D Needs

- **Radiation hardness:**
  - **Radius > 30cm: Existing technologies are applicable**
  - **Radius < 30cm: Radiation challenge has to be solved**
    - Ultra-rad. hardness of sensors and chip: up to 10^{18}cm^{-2} 1 MeV n.eq. fluence, TID of 300MGy
- **Timing** of tracks at the <10ps level
  - Either timing measurement of each pixel or dedicated timing layers
  - LGAD for timing O(30ps) achieved, ultra-thin LGADs ≤ 10ps
    - Improve rad. tolerance, now up to 2×10^{15} n/cm^2 (esp. gain layer, admixture of doping elements)
    - Limited to relatively large cells due to inefficient collection at pad edges → smaller cell sizes
  - 3D Pixel technology → radiation tolerance up to 3×10^{16} neutrons/cm^2 demonstrated, timing O(30ps)
  - R&D on new technologies to achieve <10ps timing resolution
- **Low material**
  - **Monolithic designs with integrated sensor and readout** (e.g. MAPS)
    - → R&D on improving radiation hardness to make it compatible with **outer layers** of future tracker.
  - **Outer layers:** waver scale CMOS sensors (potential to reduce power consumption and low-material)
- **Integration problems to be solved**:
  - Huge amount of data produced (1000TByte/s)
  - Power needs of sensors, FE-chips and optical links critical
  - Low-mass detector system integration: integrated services, power management, cooling, data flow, and multiplexing.
- **New sensor materials?** E.g. to work at room temperature?
- **Far future:** R&D on mass-minimized, or irreducible-mass tracker → mass budget is reduced to the active mass of the sensor



3D Pixel (arXiv:1806.01435)

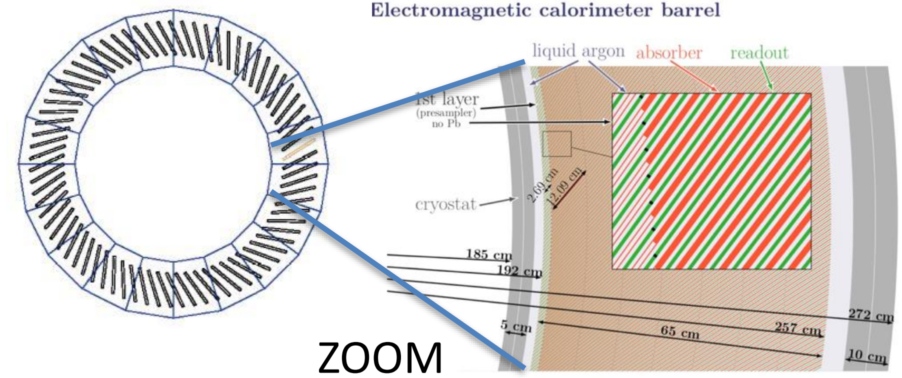


LGAD

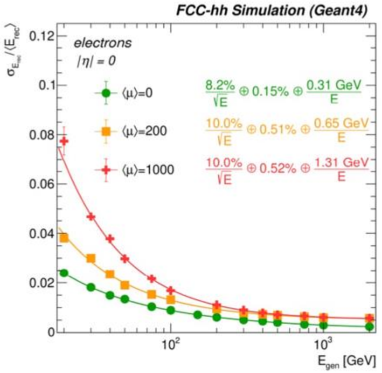
Challenges for the Magnet System – R&D Needs

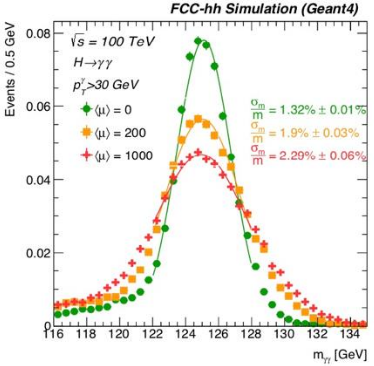
- New orders of magnitude of **stored energy**!
- **R&D needs (4T, r = 5m, length ≈ 20m):** Conductor development, powering and quench protection, coil windings pre-stressing, conduction cooling techniques and force transfer to cryostat and neighbouring systems.
- **R&D needs** for the ultra-thin and radiation transparent solenoids: Study the limits of high yield strength Al stabilized NbTi/Cu conductor and its cold mass technology affecting the feasibility of the concept of such a challenging magnet.
- **Low material cryostats**, Al-alloy honeycomb or composite material (carbon-fibre)

Electromagnetic Calorimeter (ECAL)

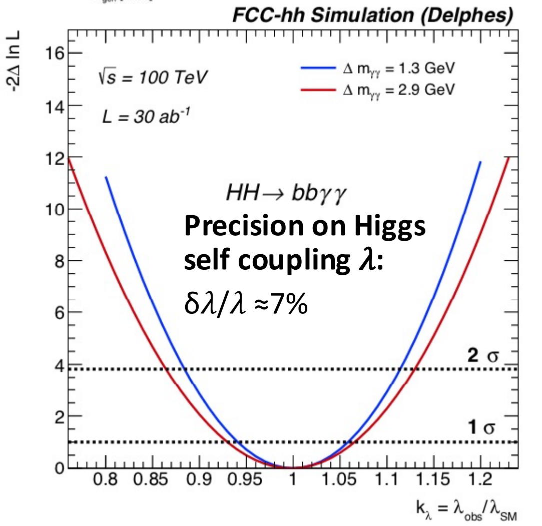


- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;





- **CDR Reference Detector: Performance & radiation considerations → LAr ECAL, Pb absorbers**
  - Options: LKr as active material, absorbers: W, Cu (for endcap HCAL and forward calorimeter)
- **Optimized for particle flow: larger longitudinal and transversal granularity** compared to ATLAS
  - 8-10 longitudinal layers, fine lateral granularity ($\Delta\eta$ x $\Delta\phi$ = 0.01 x 0.01, first layer $\Delta\eta$=0.0025),
  - → ~2.5M read-out channels
- Possible only with **straight multilayer electrodes**
  - Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
  - Baseline: warm electronics sitting outside the cryostat (radiation, maintainability, upgradeability),
    - Radiation hard cold electronics could be an alternative option
- **Required energy resolution achieved**
  - Sampling term ≤ 10%/√Ē, only ≈300 MeV electronics noise despite multilayer electrodes
  - Impact of in-time pile-up at <μ> = 1000 of ≈ 1.3GeV pile-up noise (no in-time pile-up suppression)
  - →Efficient in-time pile-up suppression will be crucial (using the tracker and timing information)



Hadronic Calorimeter (HCAL)

Barrel HCAL:

- **ATLAS type TileCal optimized for particle flow**
  - Scintillator tiles – steel,
  - Read-out via wavelength shifting fibres and SiPMs
- **Higher granularity** than ATLAS
  - Δη x Δϕ = 0.025 x 0.025
  - 10 instead of 3 longitudinal layers
  - Steel –> stainless Steel absorber (Calorimeters inside magnetic field)
- SiPM readout → faster, less noise, less space
- Total of 0.3M channels

Combined pion resolution (w/o tracker!):

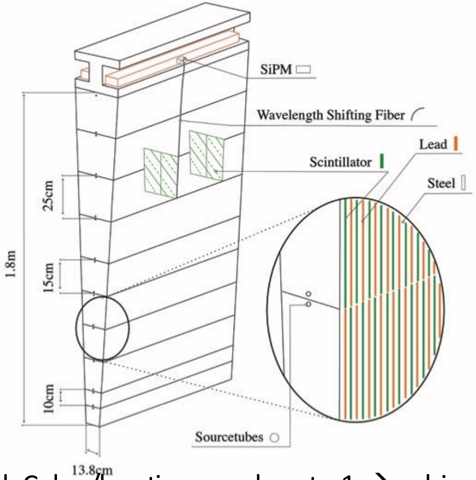
- Simple calibration: 44%/√Ē to 48%/√Ē
- Calibration using neural network (calo only):
  - Sampling term of 37%/√Ē

Jet resolution:

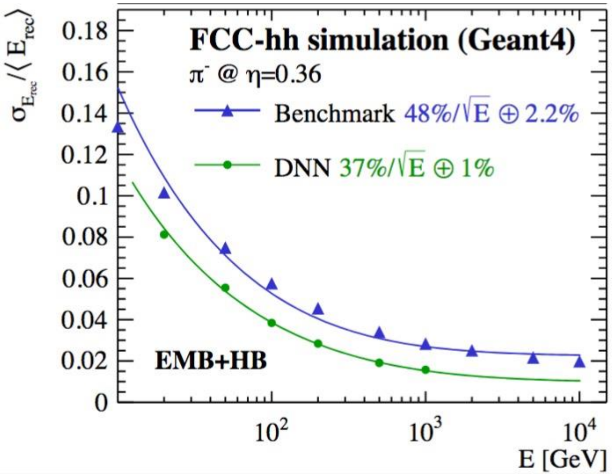
- Jet reconstruction impossible without the tracker @ 4T → particle flow.

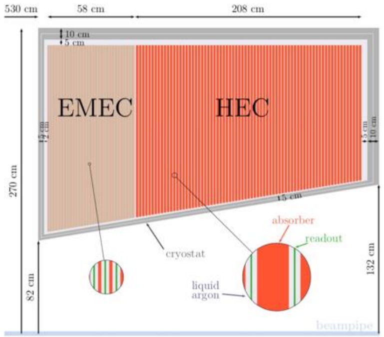
Endcap HCAL and forward calorimeter:

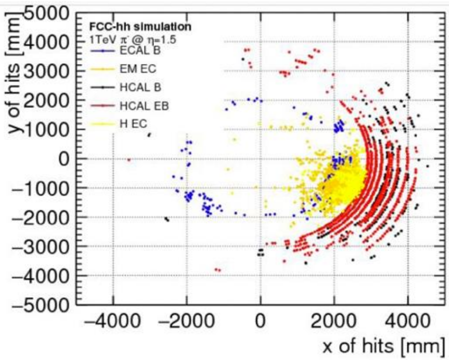
- Radiation hardness!
- LAr/Cu, LAr/W



TileCal: e/h ratio very close to 1 → achieved using steel absorbers and lead spacers (high Z material)







Challenges for Calorimetry – R&D Needs

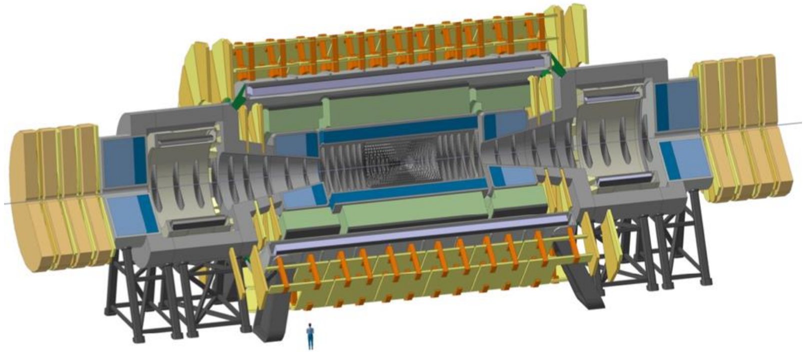
- **Radiation hardness:**
  - **Forward calo:** 5 10^{18} n_{eq}/cm^2, 5000MGy
    - Noble liquid calorimetry – intrinsic radiation hardness (of active material), other components (e.g. read-out electrodes!) need to be well chosen and tested. Electronics well shielded behind calorimeter outside the cryostat.
  - **Barrel and endcap ECAL:** 2.5 10^{16} n_{eq}/cm^2
    - Noble liquid calorimetry,
    - Si as active material maybe possible in the barrel ECAL → need to increase radiation tolerance by factor 3-5
    - Inorganic crystal scintillators: e.g. Cerium doped LYSO
    - SPACAL-type calorimeter with crystal fibres (e.g. YAG or GAGG) → need to increase radiation tolerance by factor 5
  - **Barrel HCAL:** 4 10^{14} n_{eq}/cm^2, <10kGy
    - Organic scintillator/steel possible in the barrel HCAL (R&D on radiation tolerance) → read-out by SiPMs or wavelenght shifting fibres + SiPMs
    - Many other existing technologies would also be applicable
- **Possible technologies – R&D needs**
  - **Noble liquid calorimetry:** Development of highly granular read-out electrodes and low-noise read-out, high-density signal feedthroughs, low-material cryostats (composite or Al-alloy honeycomb)
  - **Scintillator based calorimetry:** Radiation hardness of scintillators and SiPMs. R&D on radiation hard inorganic scintillators, crystal fibres (SPACAL type)
  - **Si-based calorimetry:** Radiation hardness, cost- and material reduction through monolithic designs with integrated sensor and readout
  - **For all technologies:** Timing resolution at the O(25ps) level or better would help to reduce pile-up

Challenges for Calorimetry – R&D Needs

- **High granularity** (lateral cell sizes of ≤2cm, like for the proposed reference detector LAr calorimeter)
  - **Particle flow (measure each particle where it can be best measured)**
  - **5D calorimetry (imaging calorimetry, including timing) → use of MVA based reconstruction (Neural Networks, …)**
  - **Pile-up rejection**
    - Efficient combined reconstruction together with the tracker
- **Timing for pile-up rejection, 5D calorimetry:**
  - O(25ps) to reduce pile-up by factor 5 (<μ> = 1000 → 200) → LGADs, 3D pixel sensors → R&D on pad sizes and rad. hardness
  - O(5ps) to reduce pile-up by factor 25 (<μ> = 1000 → 40) → ultra-fast inorganic scintillators, ultra-thin LGADs
- **Data rates – Triggering**
  - Noble-liquid calorimetry + scintillator/Fe HCAL: O(3M) channels 200 – 300TB/s
  - Si option: many more channels, zero suppression on-detector necessary
- **Crazy ideas for the future:** Possible "maximal information" calorimeter: divided into small detection volumes (voxels) that measure ionization, time, and Cherenkov and scintillation light simultaneously – e.g. noble liquid calorimetry

Reading Out Such a Detector → Trigger/DAQ

- **Example ATLAS**:
  - ATLAS Phase II calorimetry will be digitized at 40MHz and sent via optical fibers to L1 electronics outside the cavern at 25TByte/s to create the L1 Trigger.
  - Muon system will also be read out at 40MHz to produce a L1 Trigger.
- **FCC-hh detector**:
  - calorimetry and muon system at 40MHz will result in 200-300 TByte/s, which seems feasible.
  - 40MHz readout of the tracker (using zero-suppression) would produce about 800TByte/s.



- **FCC-hh trigger strategy question:**
  - Can the L1 Calo+Muon Trigger have enough selectivity to allow readout of the tracker at a reasonable rate of e.g. 1MHz?
    - Difficult: 400kHz of W's and 100MHz of jets (p_T > 50GeV)
  - Or: un-triggered readout of the detector at 40MHz would result in 1000-1500TByte/s over optical links to the underground service cavern and/or a HLT computing farm on the surface.

Challenges for Read-Out Electronics & Trigger

- **Huge amounts of data produced** (e.g. O(1000TByte/s ≈ 10Pbps) for zero-suppr. tracker)
  - **Streaming:**
    - Read-out everything → need fast low power radiation hard optical links
    - Alternative: summarize received data by higher-level quantities and only transmit and store those
  - **Triggered:** Read-out interesting events → challenge to achieve a data reduction of factor O(10) (HL-LHC aims for factor 40) with much higher pile-up
    - → need efficient triggering – intelligent decision as close to the sensor as possible (ML or AI on front-end, programmable ASICs, FPGAs?)
    - → radiation hard buffering/storage
- **→ High bandwidth, low power, radiation hard data links**
  - Industry at link speeds of 400Gbps, need to be adapted to radiation hardness, low power, low material and distributed data sources
  - Rad. hard link R&D targeting 25Gbps has started at CERN, but will need 50-100Gbps links to fulfil FCC-hh requirements
  - Low-power: 10Pbps = 1 million lpGBTs (~500mW) → 500kW for the links alone!
    - Cooling needs cause large amounts of dead material → minimize cooling needs
  - New technologies: CMOS with integrated photonics (Silicon Photonics)

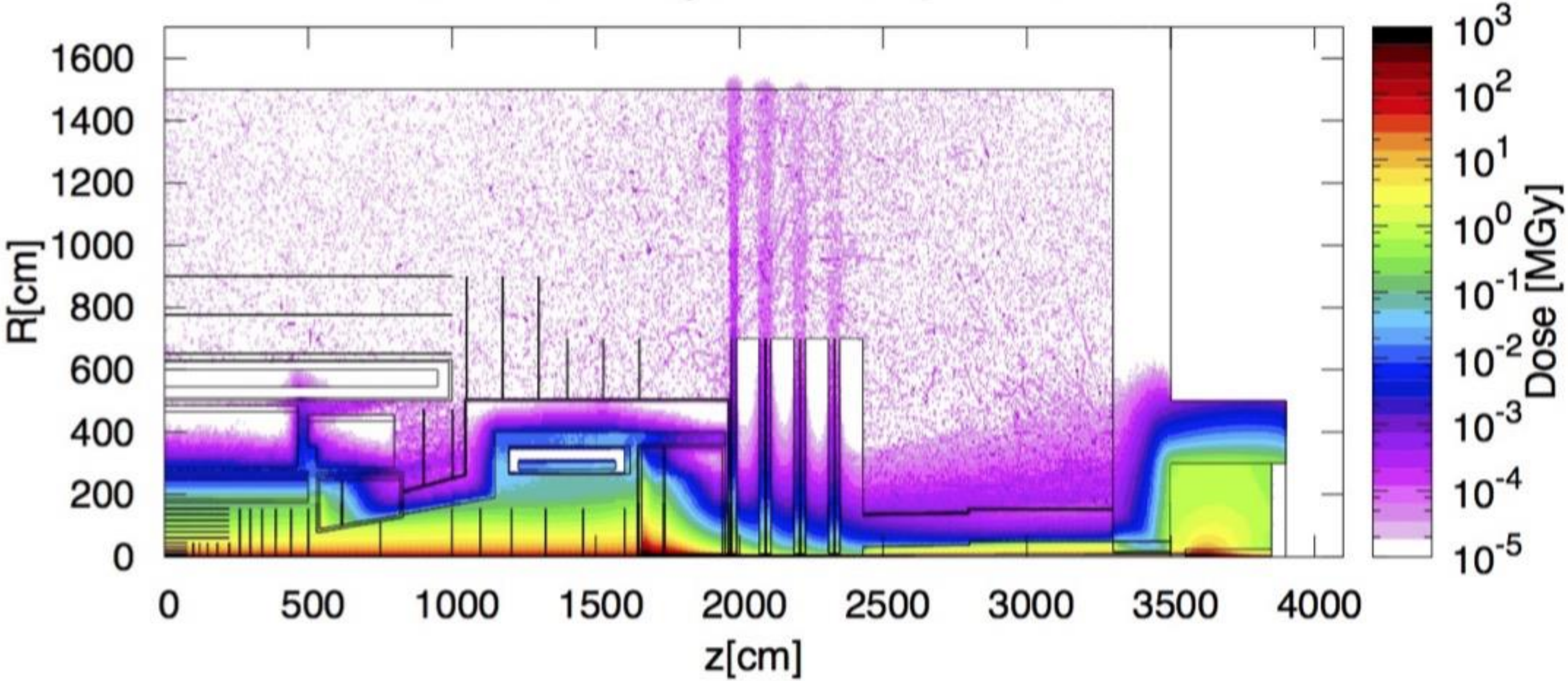
Challenges for Read-Out Electronics & Trigger

- **Wireless read-out systems:**
  - Potential to reduce material – interesting if wireless transmission can fulfil the low-power requirement
  - But main material contribution coming from power and cooling needs (and not from optical fibers)
- **Analogue to digital conversion** will be located at the front-end
  - Already the case for all HL-LHC upgrades, e.g. analogue calorimeter trigger Run1 and Run2 → digitization at the front-end for Run 3 and HL-LHC
  - Advantages: low noise, standardised and efficient digital transmission
  - But needs radiation hard and low-power ADCs and ASICs (300MGy, 10^{18}neutrons/cm^2)
    - For comparison: HL-LHC factor 30 less, 65nm ok up to O(3MGy)
- Develop **radiation hard power management blocks** (DC/DC converters, regulators)
- Develop **precision clock and timing circuits** (PLL, DLL, Timing Discriminators, Delay Lines, Picosecond TDCs)
  - Timing distribution with pico-second synchronization

Total Ionizing Dose for 30ab^{-1}

Dose of 300 MGy (30 Grad) in the first tracker layers.

< 10 kGy in HCAL barrel and extended barrel.



DRD Collaborations

arXiv:2408.17094v1

- European Strategy for Particle Physics (ESPP, link) encouraged the community to define a **Detector R&D Roadmap** identifying the most important technological developments in the domain of particle detectors required to reach the goals defined in the ESPP
- In autumn 2022, CERN SPC endorsed the **Detector Roadmap Implementation Plan** which foresees the formation of **Detector R&D Collaborations hosted at CERN**
- **DRD Collaborations** have been set-up and started working (approvals in Dec. 2023 and June 2024)