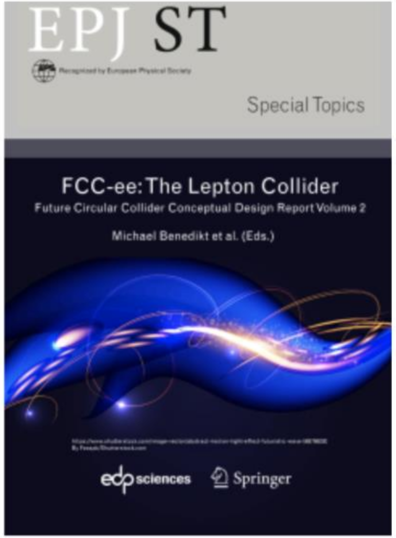
FCC-hh Detector

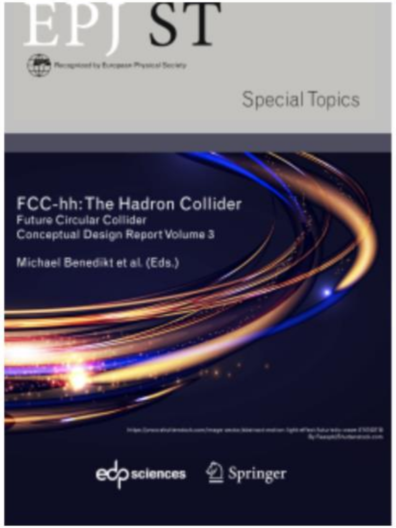
FCC CDR summary report, Status of detailed report

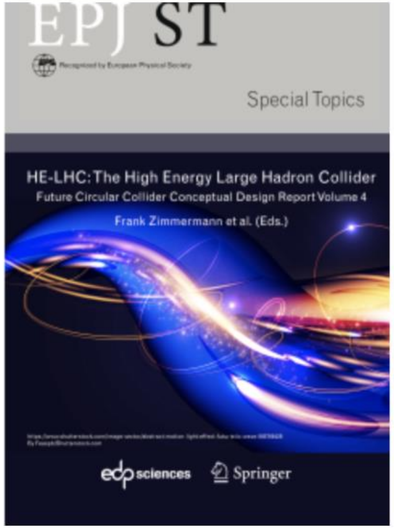
W. Riegler

for the FCC-hh detector study group

FCC week Brussels, June 26th 2019







Following the FCC week in Amsterdam in 2018, we wrote up the Chapter 7 of the FCC-hh volume (Volume 3).

Preface

The 2013 Update of the European Strategy for Particle Physics (ESPPU) [1] stated, inter alia, that "... *Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update*" and that "*CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide*".

In response to this recommendation, the Future Circular Collider (FCC) study was launched [2] as a world-wide international collaboration under the auspices of the European Committee for Future Accelerators (ECFA). The FCC study was mandated to deliver a Conceptual Design Report (CDR) in time for the following update of the European Strategy for Particle Physics.

European studies of post-LHC circular energy-frontier accelerators at CERN had actually started a few years earlier, in 2010–2013, for both hadron [3–5] and lepton colliders [6, 7], at the time called HE-LHC/VHE-LHC and LEP3/DLEP/TLEP, respectively. In response to the 2013 ESPPU, in early 2014 these efforts were combined and expanded into the FCC effort.

Since its inception, the international FCC collaboration has been working on the design of a hadron collider (FCC-hh) for proton-proton collisions at the centre-of-mass energy of 100 TeV that would offer the broadest discovery potential at the energy frontier. The FCC-hh physics programme also has the potential to be expanded to include heavy-ion, electron-proton and electron-ion collisions.

Five years of intense work and a steadily growing international collaboration have resulted in the present Conceptual Design Report, consisting of four volumes covering the physics opportunities, technical challenges, cost and schedule of several different circular colliders, some of which could be part of an integrated programme extending until the end of the 21st century.

Geneva, December 2018

Rolf Heuer
CERN Director-General 2009–2015

Fabiola Gianotti
CERN Director-General since 2016

Experiment and Detectors, 27 pages

Strategic R&D

The R&D programme for technologies for future experiments described in a dedicated document and 2 R&D workshops were held in 2018.

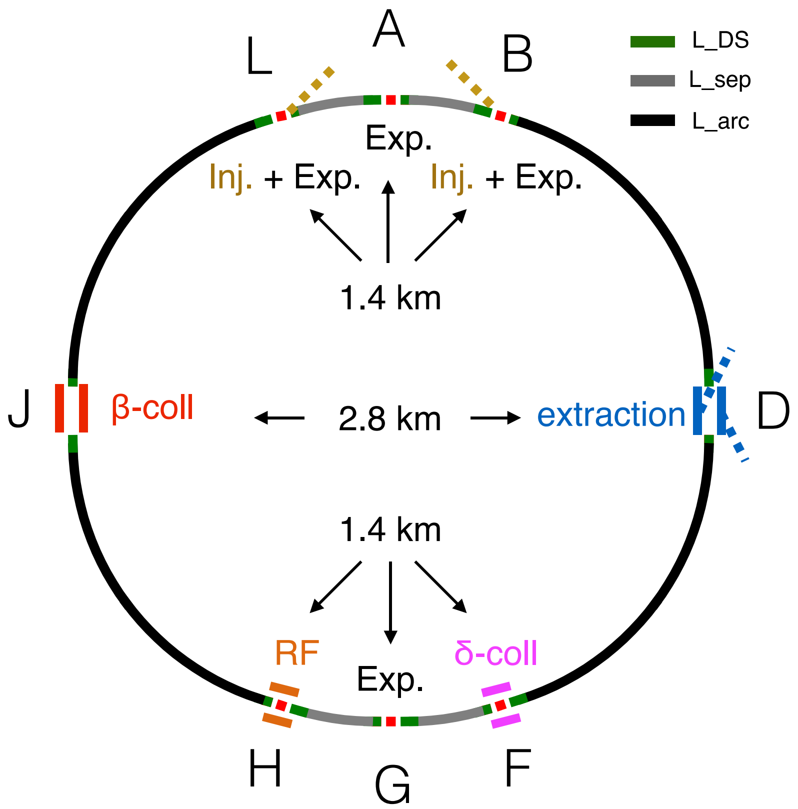
These developments will take place

- inside LHC experiment upgrade programs
- Inside existing CERN experiments and support groups
- in existing R&D collaborations
- possibly in new R&D collaborations
- in ‘informal’ collaborations

https://ep-dep.web.cern.ch/rd-experimental-technologies

https://cds.cern.ch/record/2649646

Experiment and Detector(s)



Two main IP's in A, G for both machines

Two High Luminosity IPs A/G

Two Lower Luminosity IPs L/B

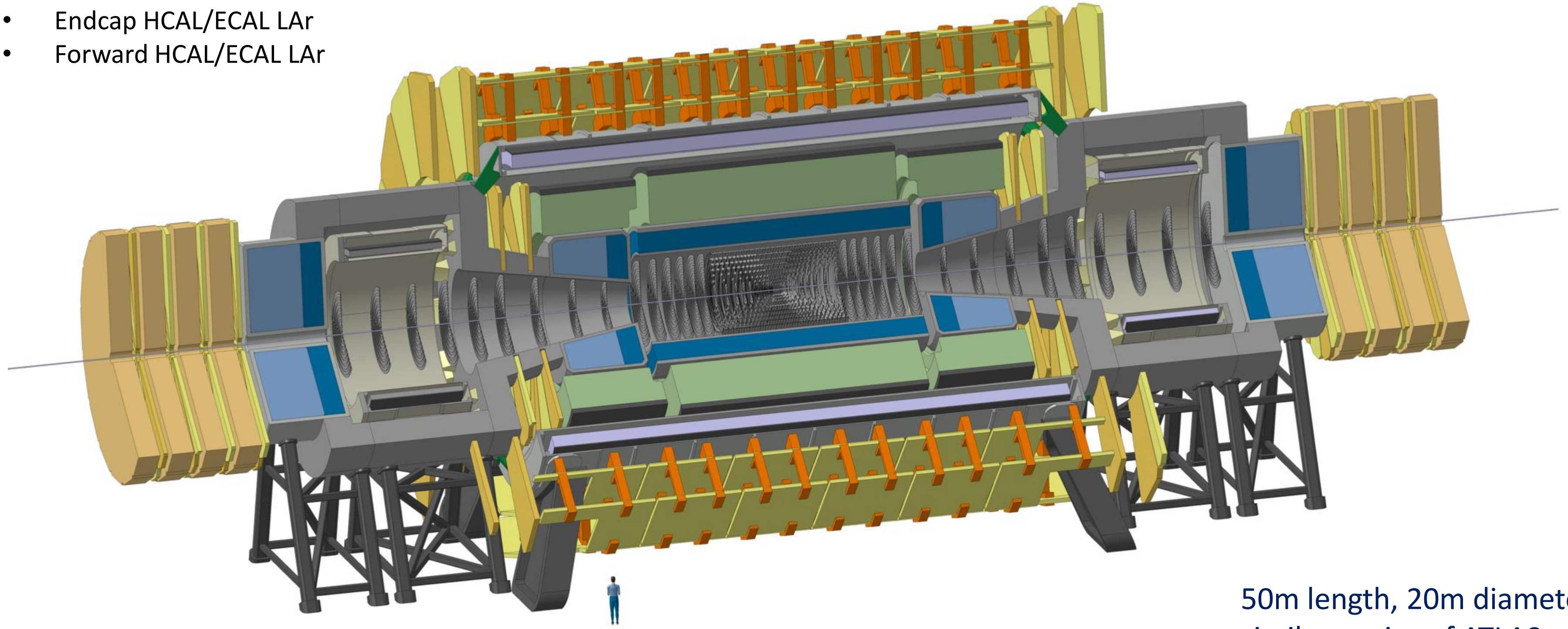
Similar to layout at LHC

→ We decided to work out one general purpose reference detector concept.

→ Simulated performance of the subsystems was used for Physics Studies (DELPHES)

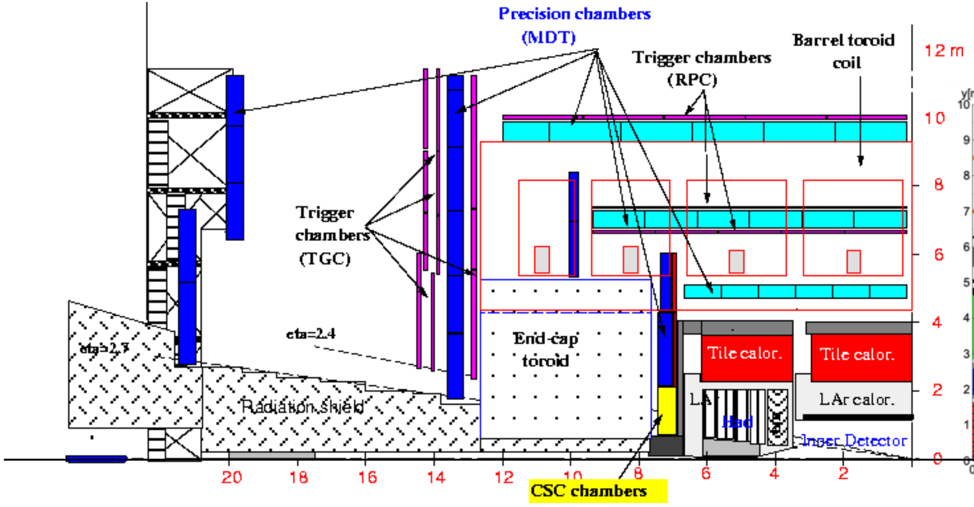
FCC-hh Reference Detector

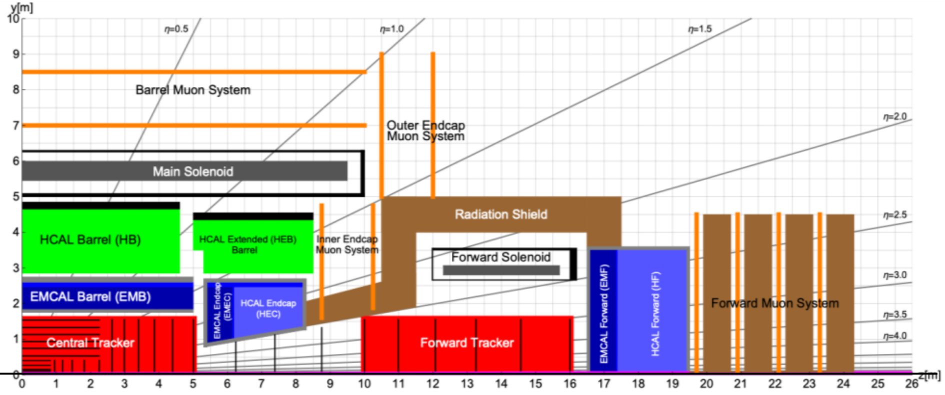
- 4T, 10m solenoid, unshielded
- Forward solenoids, unshielded
- Silicon tracker
- Barrel ECAL LAr
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

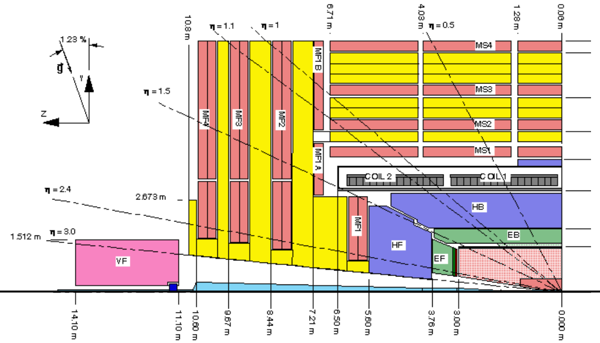


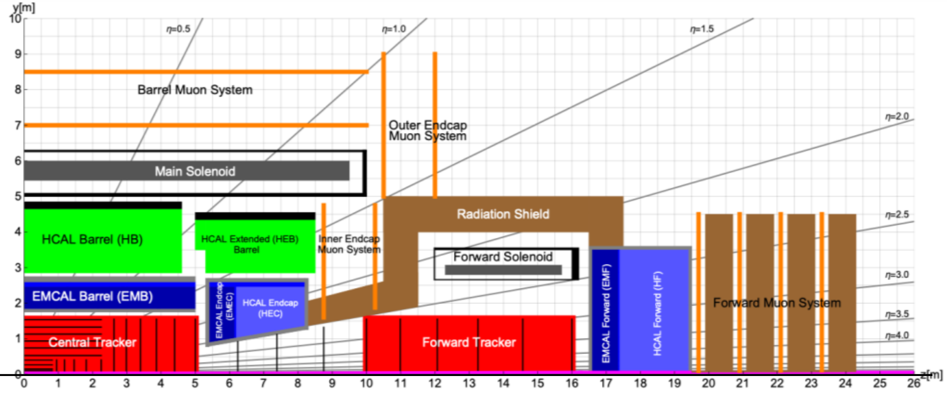
50m length, 20m diameter
similar to size of ATLAS

Comparison to ATLAS & CMS









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)	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	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
$dN_{ch}/d\eta\|_{\eta=0}$ [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
$\langle p_T \rangle$ [331]	GeV/c	0.56	0.56	0.6	0.7
Bending radius for $\langle p_T \rangle$ at B=4 T	cm	47	47	49	59
Total number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm, est.(FLUKA)	$\mathrm{GHz\,cm}^{-2}$	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est.(FLUKA)	$10^{16}\,\mathrm{cm}^{-2}$	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% $H \to 4l$ [332]	$\|\eta\|<$	3.8	3.8	4.1	4.8
$b\bar{b}$ cross-section	mb	0.5	0.5	1	2.5
$b\bar{b}$ rate	MHz	5	25	250	750
$b\bar{b}$ $p_T^b > 30$ GeV/c cross-section	µb	1.6	1.6	4.3	28
$b\bar{b}$ $p_T^b > 30$ GeV/c rate	MHz	0.02	0.08	1	8
Jets $p_T^{jet} > 50$ GeV/c cross-section [331]	µb	21	21	56	300
Jets $p_T^{jet} > 50$ GeV/c rate	MHz	0.2	1.1	14	90
$W^+ + W^-$ cross-section [333]	µb	0.2	0.2	0.4	1.3
$W^+ + W^-$ rate	kHz	2	10	100	390
$W^+ \to l + \nu$ cross-section [333]	nb	12	12	23	77
$W^+ \to l + \nu$ rate	kHz	0.12	0.6	5.8	23
$W^- \to l + \nu$ cross-section [333]	nb	9	9	18	63
$W^- \to l + \nu$ rate	kHz	0.1	0.5	4.5	19
Z cross-section [333]	nb	60	60	100	400
Z rate	kHz	0.6	3	25	120
$Z \to ll$ cross-section [333]	nb	2	2	4	14
$Z \to ll$ rate	kHz	0.02	0.1	1	4.2
$t\bar{t}$ cross-section [333]	nb	1	1	4	35
$t\bar{t}$ rate	kHz	0.01	0.05	1	11

… to define the specifications and requirement for such a detector.

… to relate the challenges for detectors at the between LHC/HL-LHC/HE-LHC and FCC-hh.

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31 GHz of pp collisions

Pile-up 1000

4 THz of tracks

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First tracking layer:

10GHz/cm^2 charged particles

10^{18} hadrons/cm^2 for 30ab^{-1}

Increased Boost at 100TeV ‘spreads out’ light SM physics by 1-1.5 units of rapidity.

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$t\bar{t}$ rate	kHz	0.01	0.05	1	11

100MHz of jets p_T>50GeV

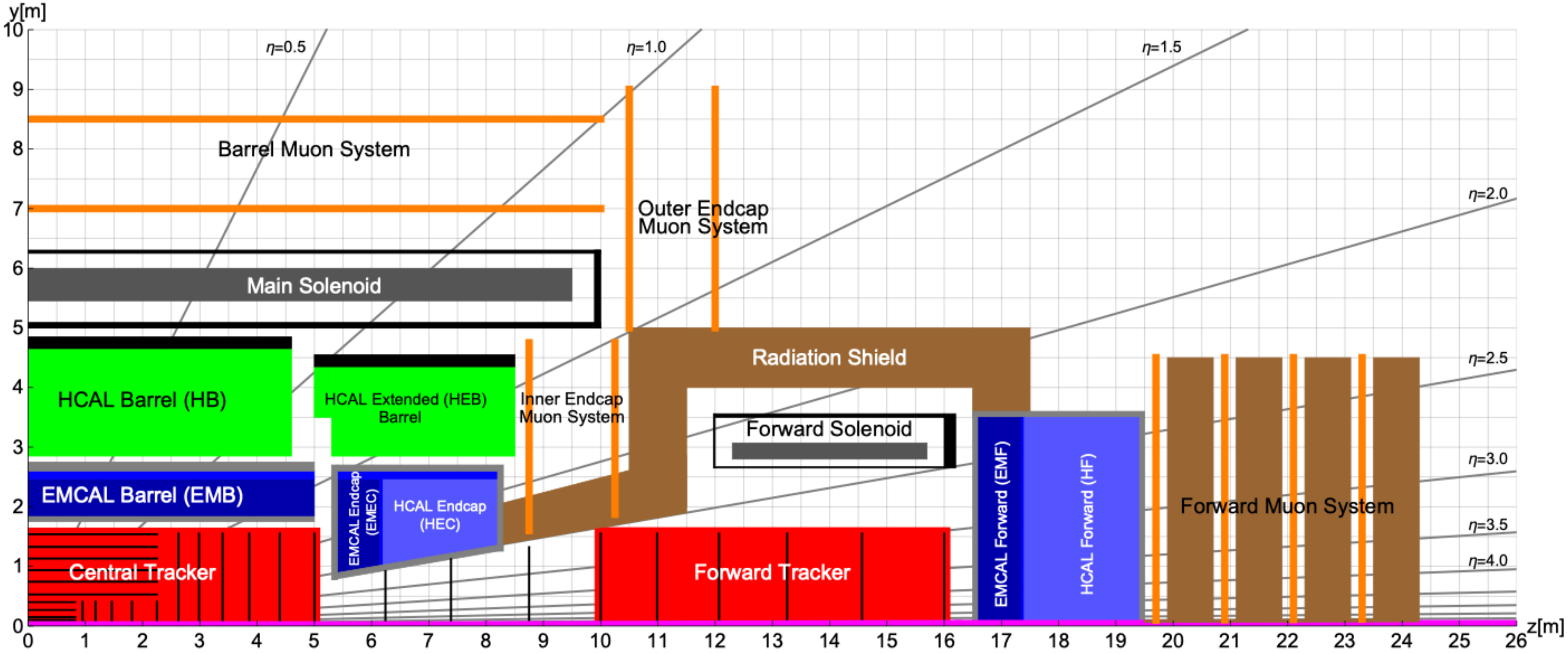
400kHz of Ws

120kHz of Zs

11kHz of Top

FCC-hh Reference Detector

50m long, 20m diameter
Cavern length 66m
L* of FCC 40m.



90% of 'heavy' physics will take place in η<2.5.

Increase of acceptance for precision spectroscopy and calorimetry from 2.5 at LHC to 3.8-4 for SM physics.

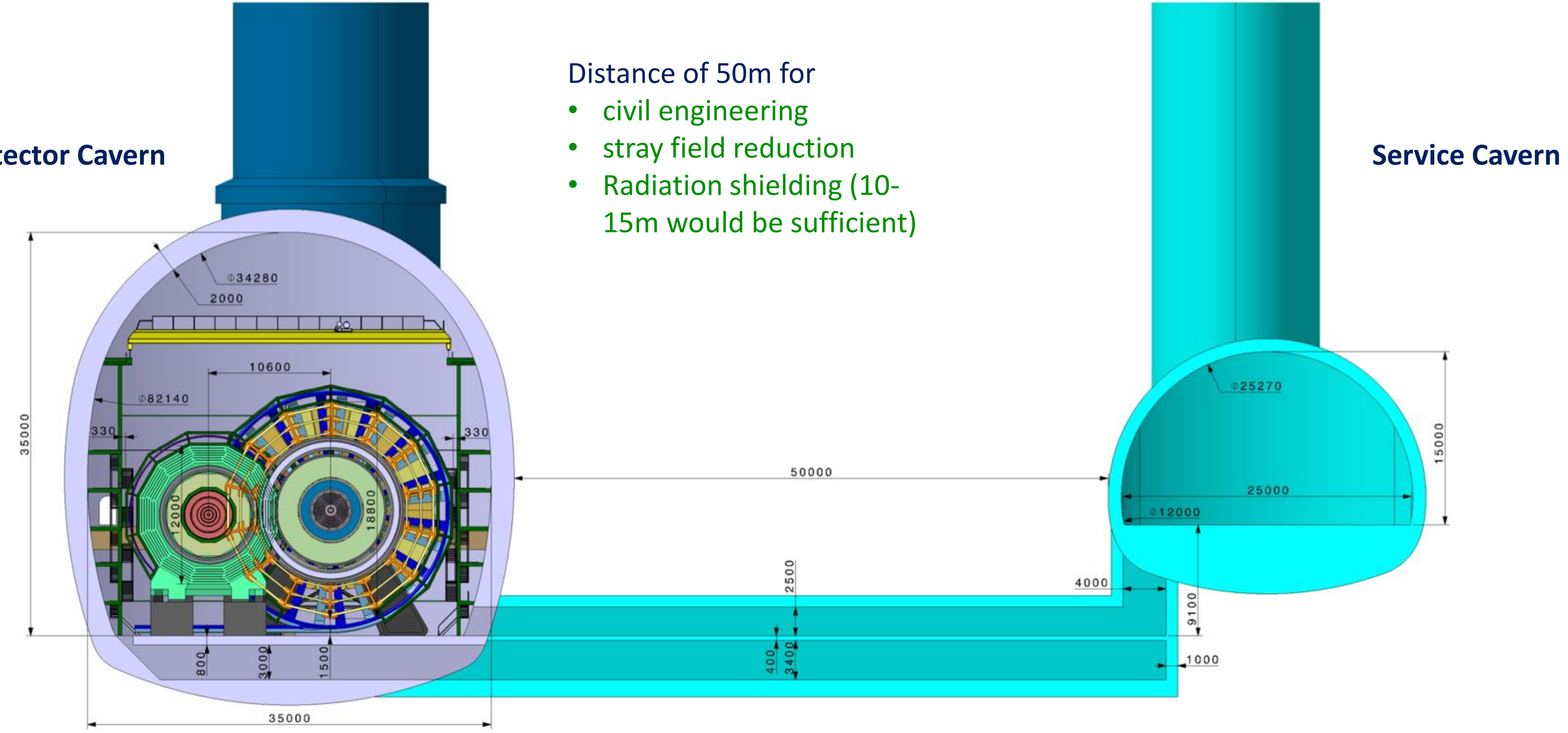
FCC-hh Reference Detector Cavern

Distance of 50m for

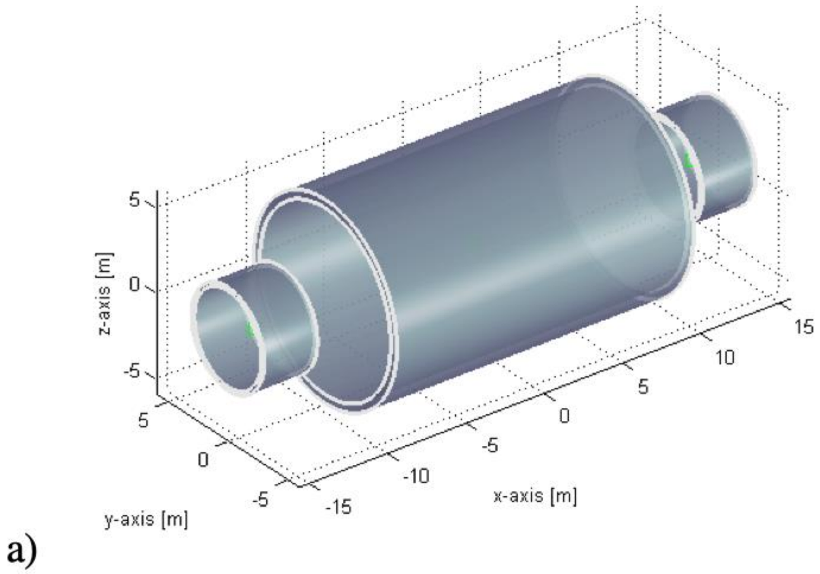
- civil engineering
- stray field reduction
- Radiation shielding (10-15m would be sufficient)

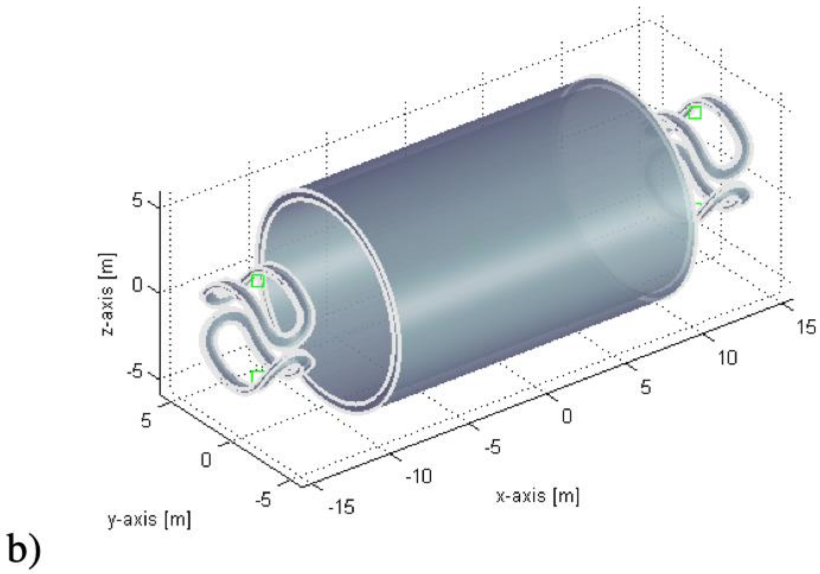
Detector Cavern

Service Cavern



Magnet System

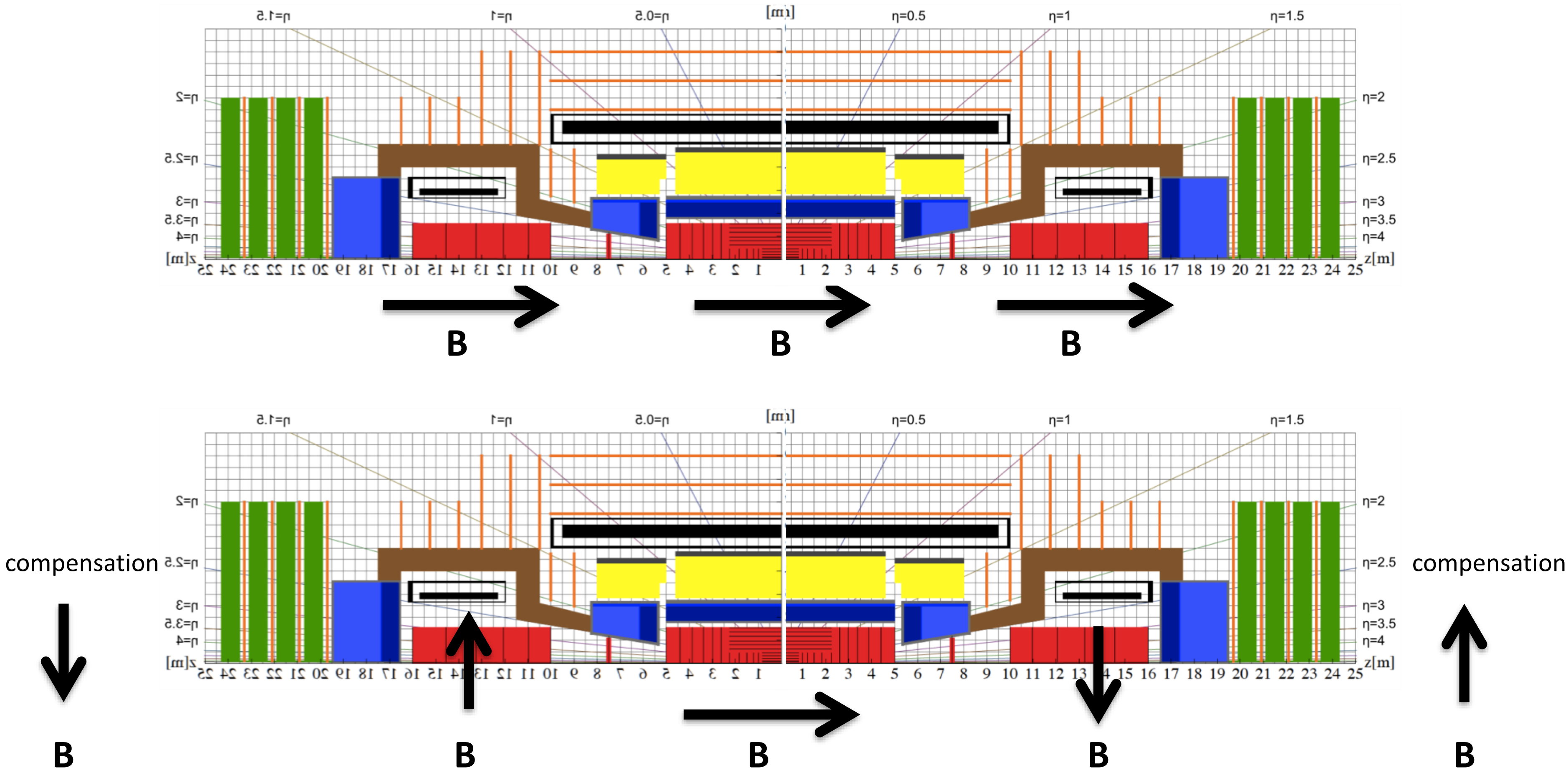




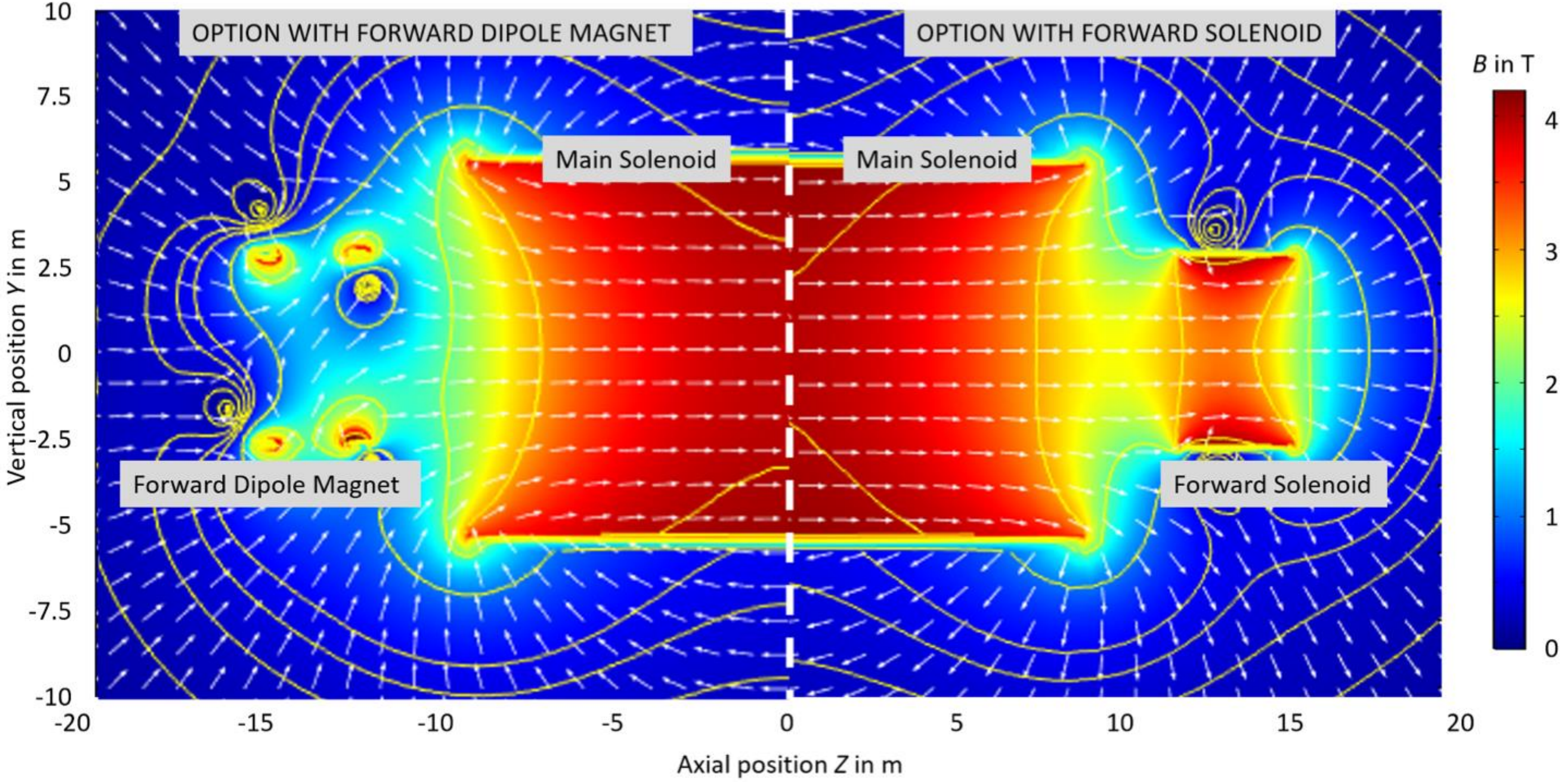
Central Solenoid + 2 Forward Solenoids

Central Solenoid + 2 Forward Dipoles

Magnet System



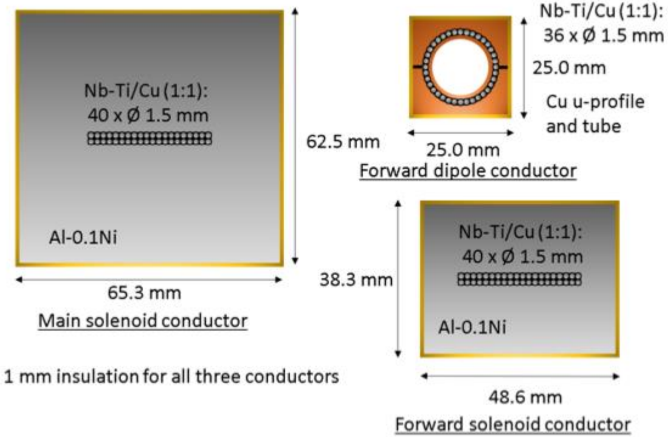
Magnet System



Magnet System Parameters

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

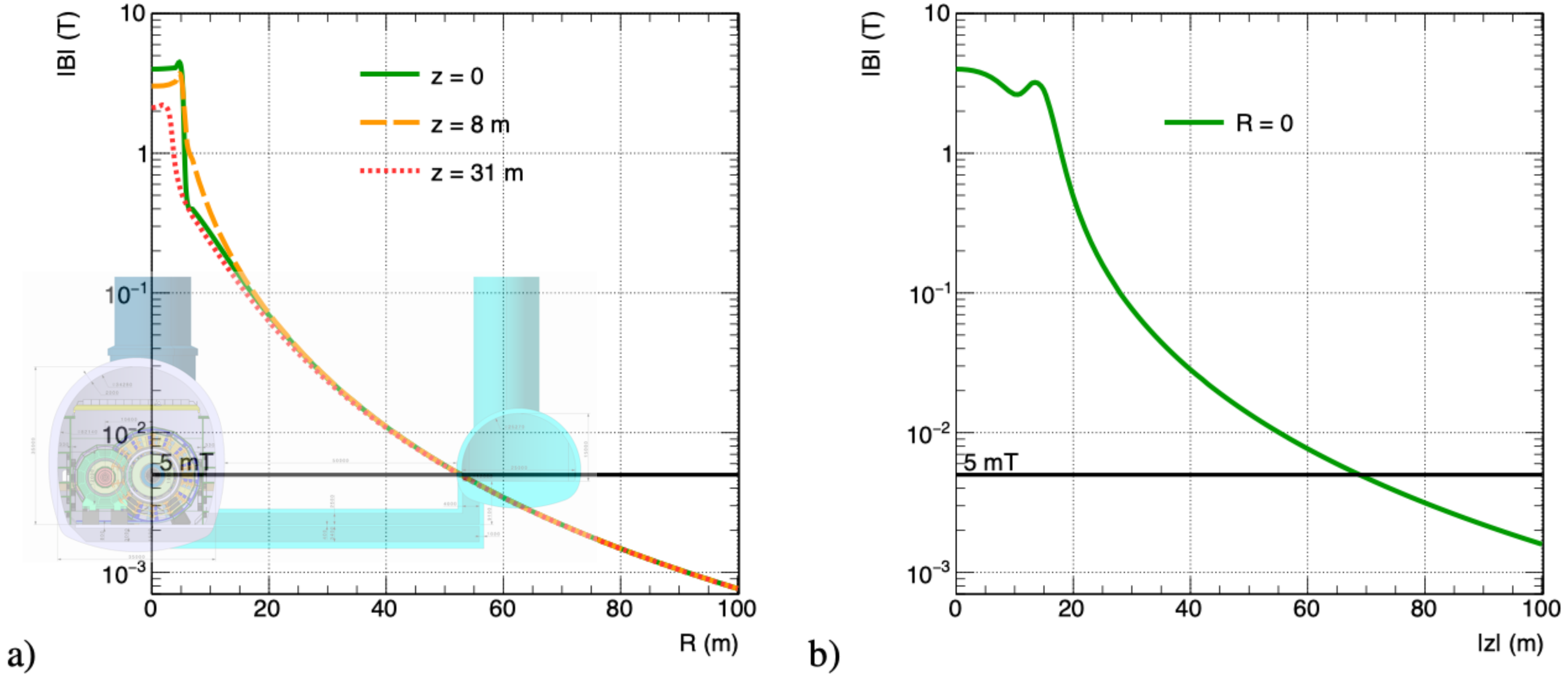
	Unit	Main solenoid	Forward solenoid	Forward dipole
Operating current	kA	30	30	16
Stored energy	GJ	12.5	0.43	0.20
Self-inductance	H	27.9	0.96	1.54
Current density	A/mm^2	7.3	16.1	25.6
Peak field on conductor	T	4.5	4.5	5.9
Operating temperature	K	4.5	4.5	4.5
Current sharing temp.	K	6.5	6.5	6.2
Temperature 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 2.7GJ
CMS Magnet System 1.6 GJ

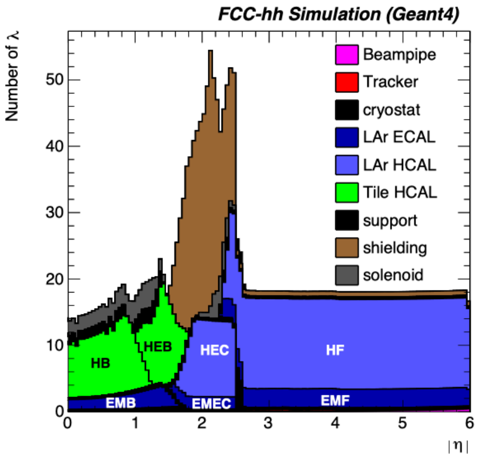
Cold Mass + Cryostat around 2000 tons.

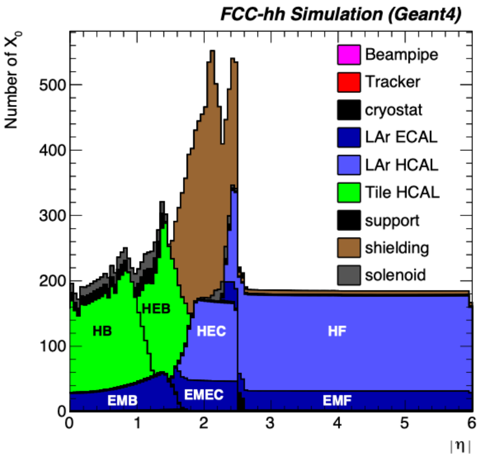
Stray Field

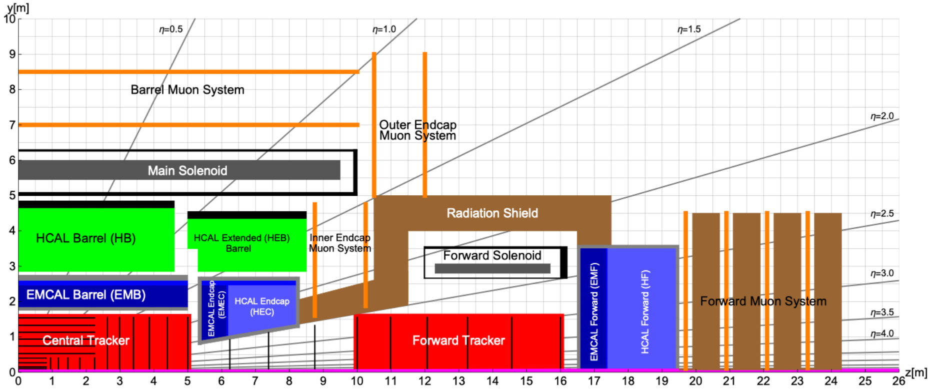


Less than 5mT in the Service Cavern, 200-300mT outside the detector.

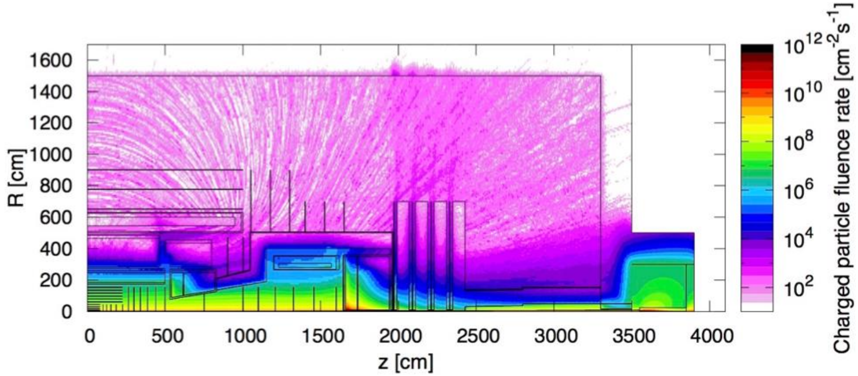
Material Distribution





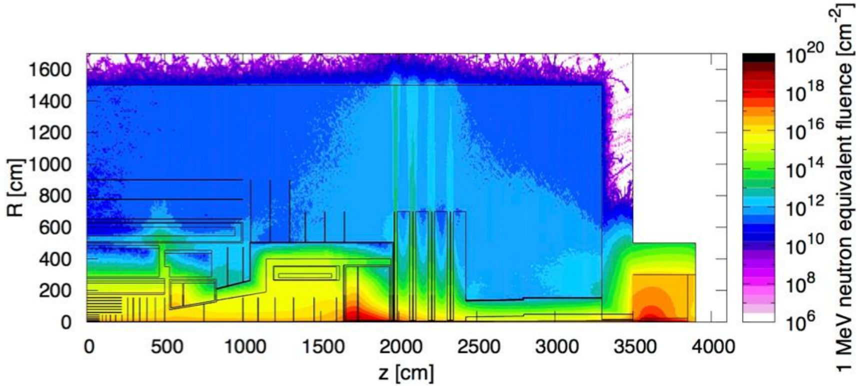


Radiation Studies for L=3×10^{36} $cm^{-2}s^{-1}$ and 30ab^{-1}



Maximum of 10kHz/cm^2 of charged particle rate in the Barrel and Forward Muon System, similar to HL-LHC Muon Systems.

In the tracker volume the charged particle rate is just a function of distance from the beampipe with rather small dependence on z.

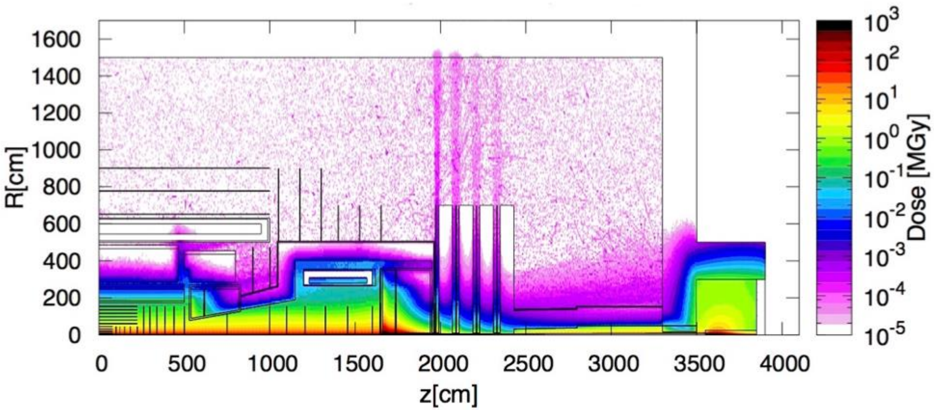


Hadron fluence in the order of 10^{18} /cm^2 close to the beampipe and 10^{15} -10^{16} /cm^2 (HL-LHC levels) for r>40cm.

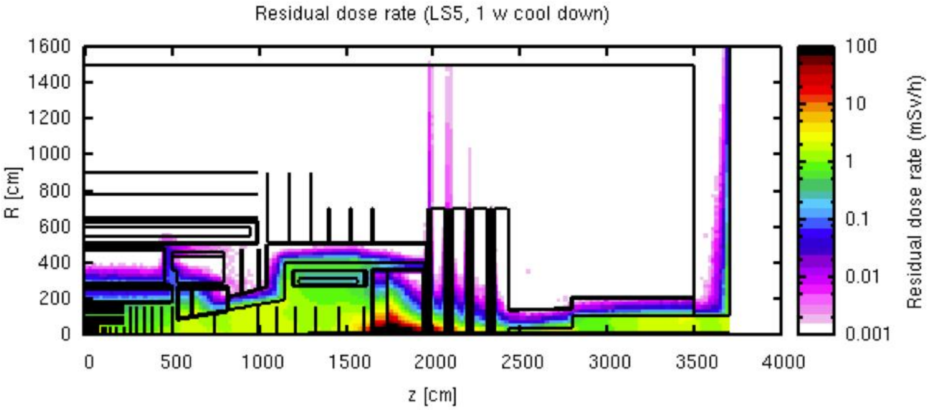
Extreme fluences in the forward calorimeter …

Triplet (z=40m), Triplet shielding TAS (z=35m) and related radiation are nicely 'burried' inside the tunnel.

Radiation Studies for L=$3x10^{36}$ $cm^{-2}s^{-1}$ and $30ab^{-1}$



Dose of 300MGy in the first tracker layers.
<10kGy in HCAL barrel and extended barrel.



Dose from activation towards the end of FCC operation, 1 week of cooldown, so significant decrease for 1month, 1 year.

Tracker Layout

Silicon tracker, two options studied, ‘tilted’ and ‘’flat’ layout’.

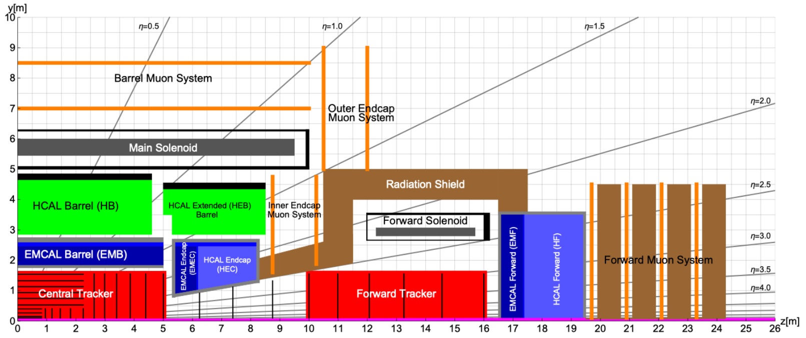
390m^2 of silicon for tilted layout and 430m^2 for flat layout.

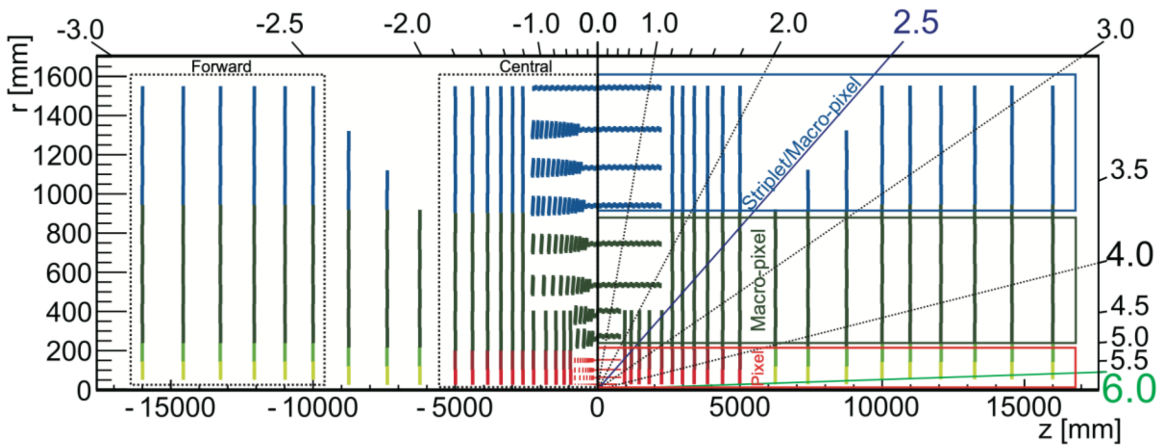
ATLAS CMS Phase-II silicon trackers have around 250m^2.

25-33.3µm x 50-400µm pixels for r < 200 mm
33µm x 400µm pixels for 200 mm < r < 900 mm
33µm x 2-50mm strips for 900 mm < r < 1600 mm

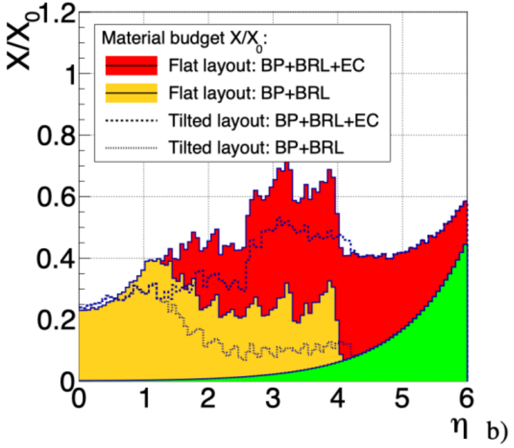
This represents and r-phi resolution of 7.5-9.5µm per detector layer

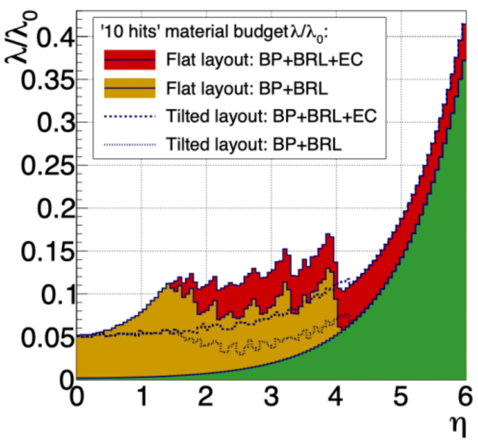
16 x 10^9 channels vs. 6 x 10^9 and 2.2 x 10^9 for ATLAS/CMS Phase-II trackers

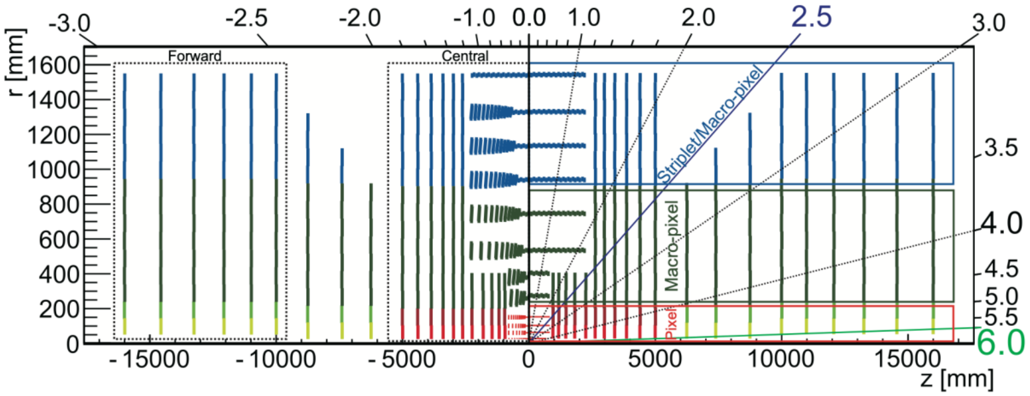




Tracker Material Budget



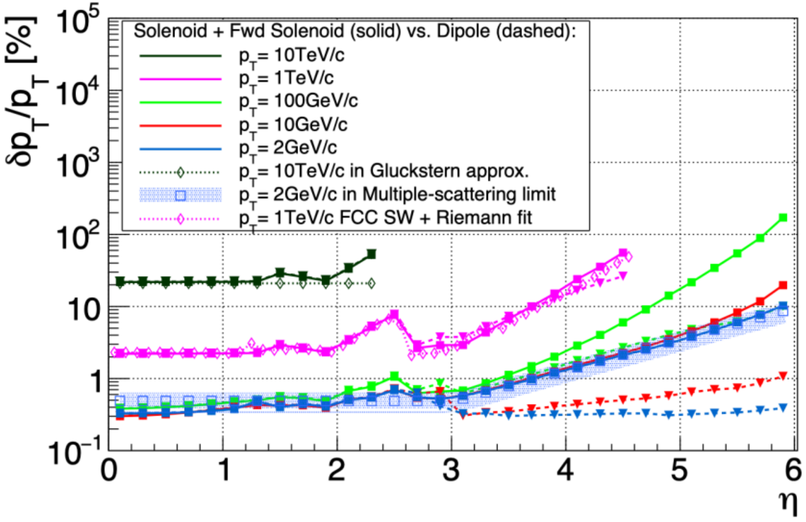


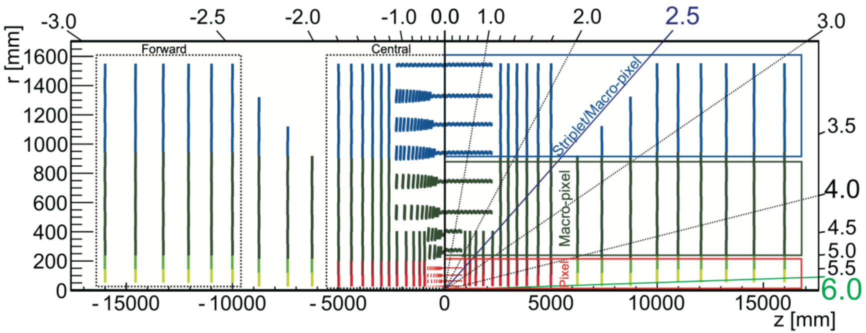


A key advantage of the tilted layout is the reduced amount of material in the 'transition' region around $\eta = 2\text{-}3$.

This results in a reduced probability for hadronic interactions and, together with the reduced propagation distance between layers, therefore in a higher reconstruction efficiency.

Tracker Momentum Resolution





The momentum resolution is around 20% for p_T = 10TeV/c in the central region.

The resolution limit due to multiple scattering is around 0.5% in the central region.

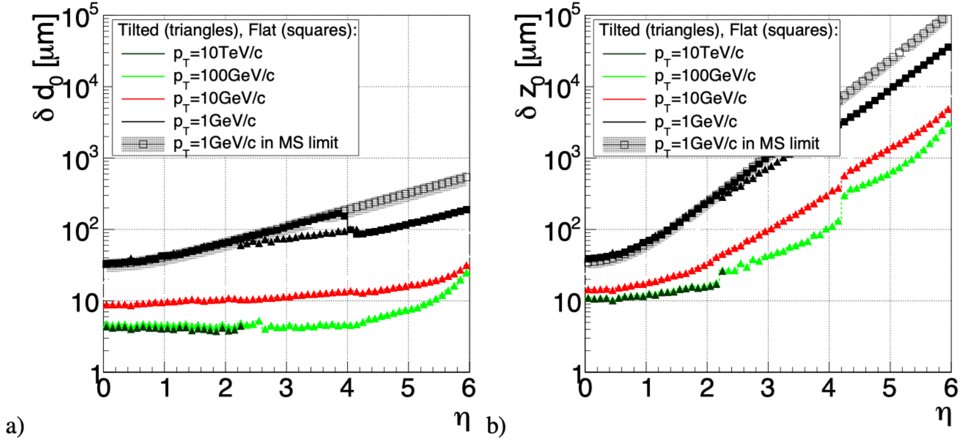
The material dominates the resolution up to p_T = 250GeV/c.

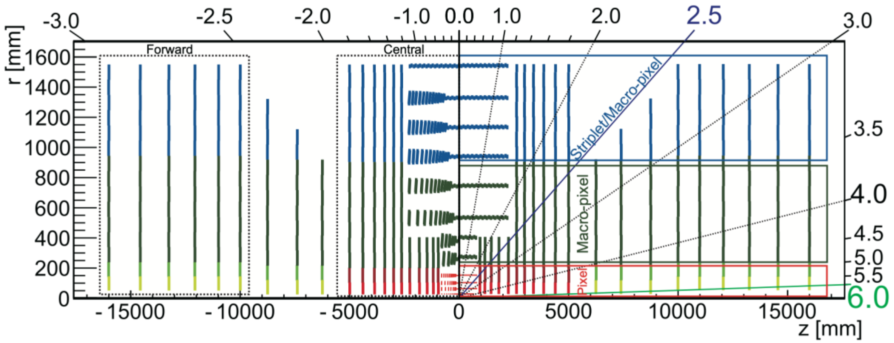
In the forward region beyond η = 3.5 the momentum resolution deteriorates due to the 'loss of lever arm' in the solenoid field.

Using dipole magnets in the forward region the momentum resolution can be kept below 1% even up to η = 6.

The resolution curves for the solenoid field can be reproduced with the standard 'pocket' formulas.

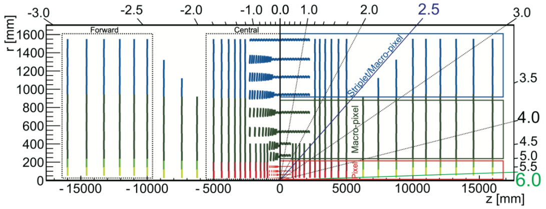
Vertex Resolution

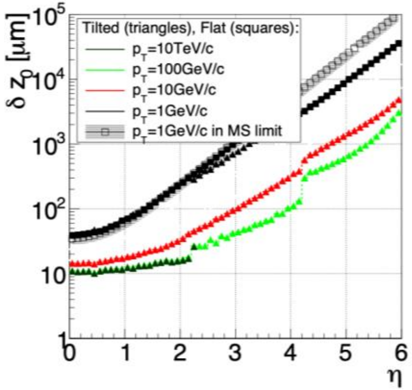


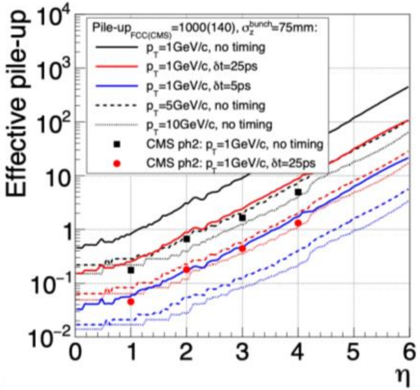


d_0 and z_0 resolution of 30μm at η = 0 for p_T = 1GeV/c, limited by multiple scattering.

Pileup, Timing, Tagging







Average distance between vertices at z=0:

1mm for HL-LHC (140 pileup)
125um for FCC-hh (1000 pileup)

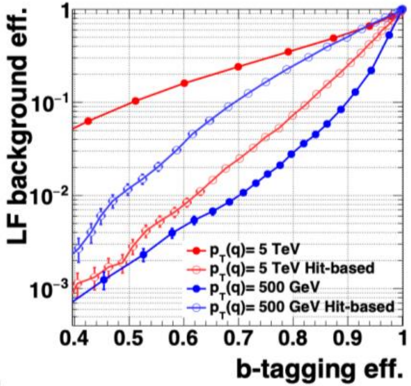
As for HL-LHC, timing can help for vertex identification:

Effective pileup:
Number of vertices that a track of a given p_T is compatible with at 95% CL.

For a time resolution of 25ps, CMS can get to an effective pileup of 1 for 1 GeV/c tracks at η = 4.

For an FCC detector the time resolution has to be at a level of 5ps to get to similar numbers.

The impact of pileup on a given physics analysis depends very much on the specific channels.



B-tagging studies:

B-Mesons with very high p_T travel far into the tracker and have a highly collimated decay tracks.

Traditional taggers have difficulty in identifying the decay vertex.

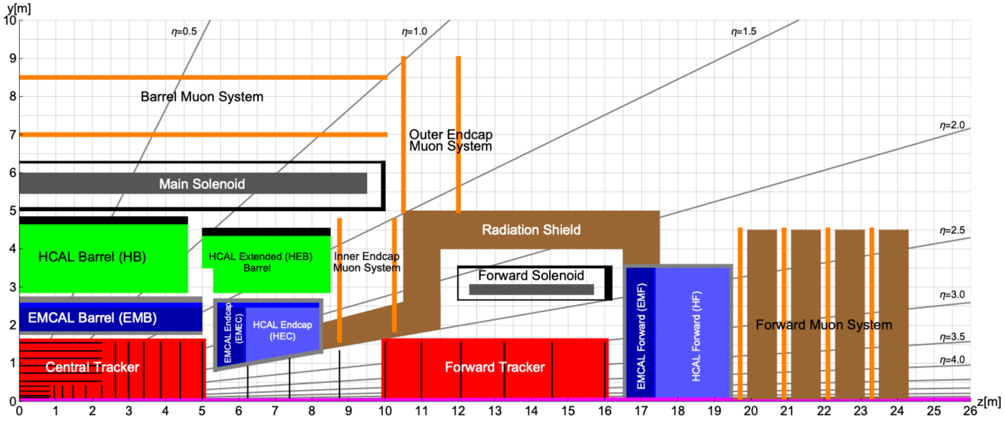
Using the ‘multiplicity jump’ between tracking layers due to a b decay can significantly improve the tagging performance.

Calorimetry

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

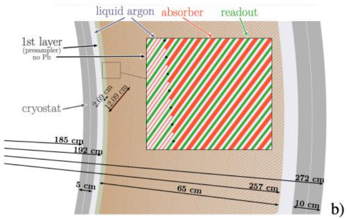
LAr and Fe/Pb/Sci are used as reference technologies. Silicon calorimetry will be extensively 'evaluated' in the CMS Phase-II upgrade.

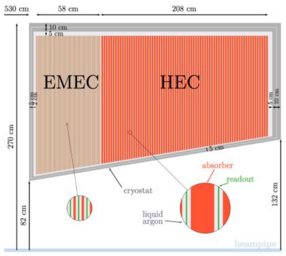
	η_{min}	η_{max}	a	c	$\Delta\eta$	$\Delta\phi$	Fluence	Dose	Material	Mix	Seg.
Unit			$\%\sqrt{\text{GeV}}$	%			cm^{-2}	MGy			
EMB	0	1.5	10	0.7	0.01	0.009	5×10^{15}	0.1	LAr/Pb/PCB	1/0.47/0.28	8
EMEC	1.5	2.5	10	0.7	0.01	0.009	3×10^{16}	1	LAr/Pb/PCB	1/0.75/0.6	6
EMF	2.5	4	10	0.7	0.025	0.025			LAr/Cu/PCB	1/50/6	6
	4	6	30	1	0.025	0.025	5×10^{18}	5000	LAr/Cu/PCB	1/50/6	6
HB	0	1.26	50	3	0.025	0.025	3×10^{14}	0.006	Sci/Pb/Fe	1/1.3/3.3	10
HEB	0.94	1.81	50	3	0.025	0.025	3×10^{14}	0.008	Sci/Pb/Fe	1/1.3/3.3	8
HEC	1.5	2.5	60	3	0.025	0.025	2×10^{16}	1	LAr/Cu/PCB	1/5/0.3	6
HF	2.5	4	60	3	0.05	0.05	5×10^{18}	5000	LAr/Cu/PCB	1/200/6	6
	4	6	100	10	0.05	0.05	5×10^{18}	5000	LAr/Cu/PCB	1/200/6	6

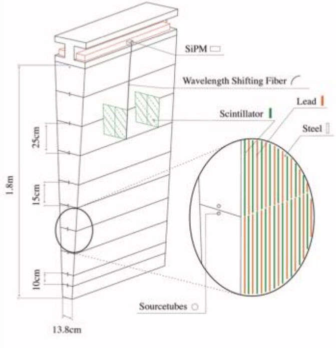


The calorimeter system is 'inspired' by ATLAS (LAr, TileCal), with increased granularity and with the forward for (η > 2.5) moved to z=16.5m to make space for the forward tracker und to achieve coverage up to η = 6.

For the EMCAL Barrel, the demand for increased granularity motivated a deviation from the ATLAS 'accordion' structure to a geometry with inclined plates.





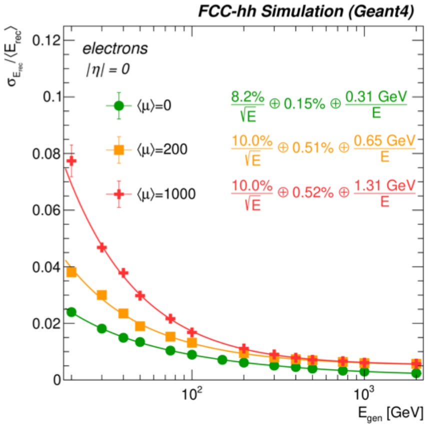


HCAL Barrel

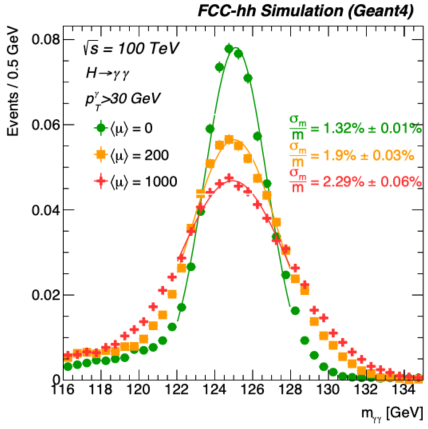
EMCAL

The Higgs mass resolution decreases from 1.3% to 2.3% when going from pile-up zero to pile-up 1000.

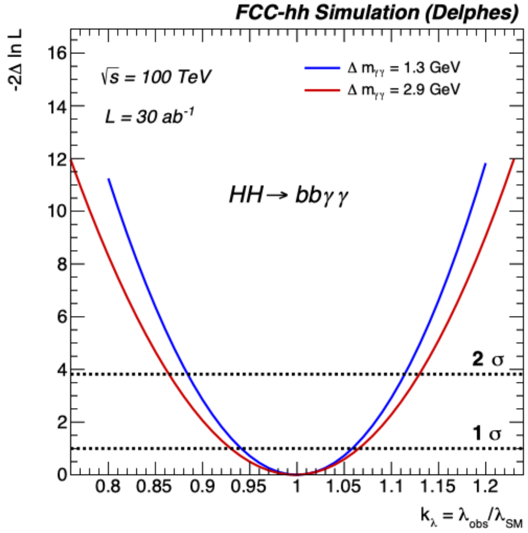
These number do however not use any tracking information that can reduce the pileup effect.

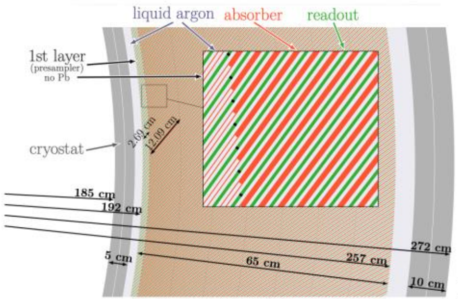


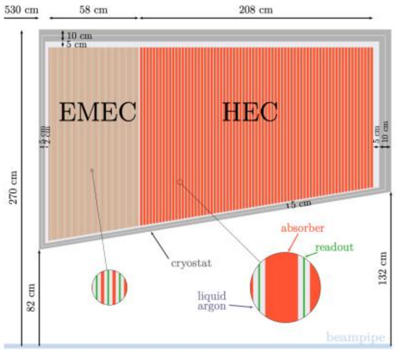
a)



b)

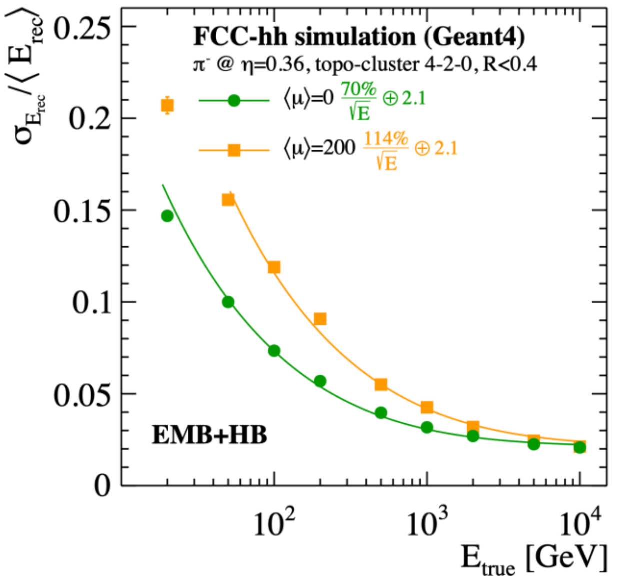






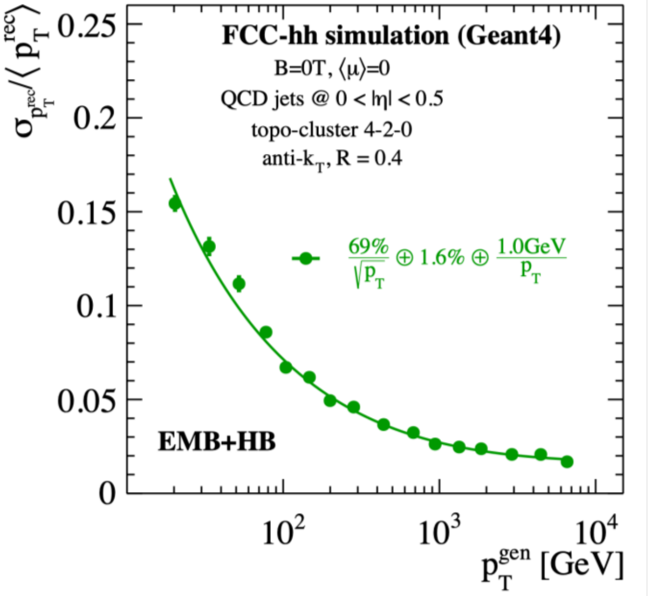
b)

HCAL



b)

Single pion resolution of the Barrel Calorimetry wo/o pileup



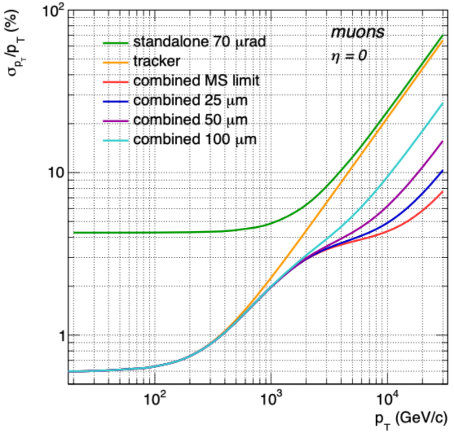
Jet p_T resolution assuming zero magnetic field.

With the 4T B-field, about 15% of the charged particles within jets of momenta <100GeV/c are not reaching the calorimeters.

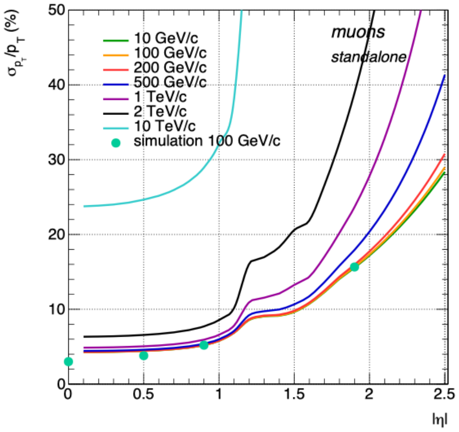
For jets with p_T > 1TeV/c the resolution is not degraded by the field.

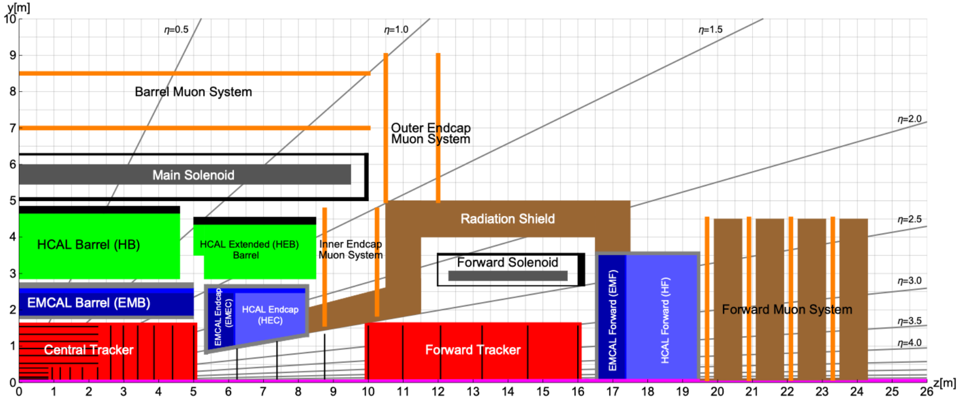
Studies on combined tracker/calorimeter performance have to be done next …

Muon Systems



b)





'Standalone' muon performance is not any more a very important criterion. Future detectors rely on a combined tracker/muon system performance.

The task of the muon system is triggering and muon identification.

4-5% standalone momentum resolution can be achieved in at η=0, 30% at η=2.5 by simply measuring the angle at which the muon exits the calorimeters.

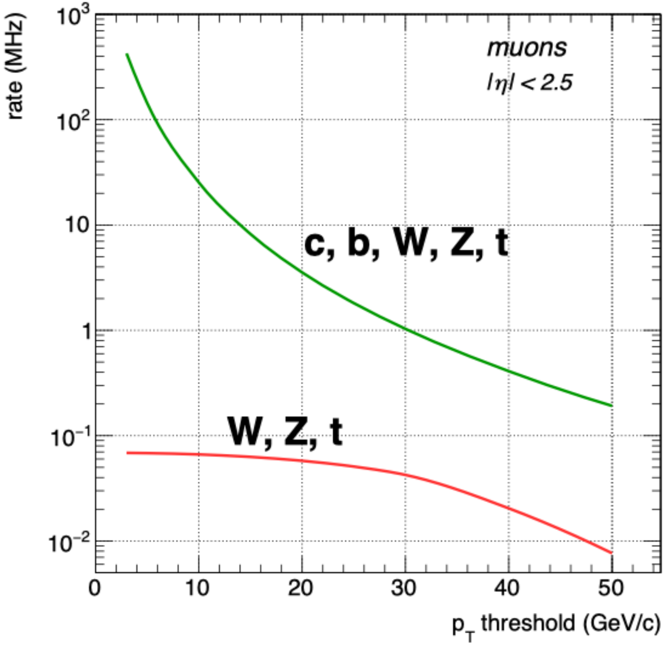
In the forward muon system, standalone momentum measurement and triggering can only be achieved when using a forward dipole (like ALICE, LHCb).

The combined muon momentum resolution (tracker + muon system) can better than 10% even for momenta of 20TeV/c at η=0.

Gas detectors similar to the ones employed for HL-LHC are good candidates for the muon systems.

Muon Systems

Rate of muons for L=3x10^{35} cm^{-2}s^{-1}



The muon rate is dominated by c and b decays.

In contrast to leptonic decays from W, Z, t (→W→l) these muons are not isolated but accompanied by particles that are seen in the calorimeters.

'Isolation' by using calorimeter information in addition the the muon system is key for W/Z/t triggering.

Trigger/DAQ

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

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
$b\bar{b}$ cross-section	mb	0.5	0.5	1	2.5
$b\bar{b}$ rate	MHz	5	25	250	750
$b\bar{b}$ $p_T^b > 30$ GeV/c cross-section	µb	1.6	1.6	4.3	28
$b\bar{b}$ $p_T^b > 30$ GeV/c rate	MHz	0.02	0.08	1	8
Jets $p_T^{jet} > 50$ GeV/c cross-section [331]	µb	21	21	56	300
Jets $p_T^{jet} > 50$ GeV/c rate	MHz	0.2	1.1	14	90
$W^+ + W^-$ cross-section [333]	µb	0.2	0.2	0.4	1.3
$W^+ + W^-$ rate	kHz	2	10	100	390
$W^+ \rightarrow l + \nu$ cross-section [333]	nb	12	12	23	77
$W^+ \rightarrow l + \nu$ rate	kHz	0.12	0.6	5.8	23
$W^- \rightarrow l + \nu$ cross-section [333]	nb	9	9	18	63
$W^- \rightarrow l + \nu$ rate	kHz	0.1	0.5	4.5	19
Z cross-section [333]	nb	60	60	100	400
Z rate	kHz	0.6	3	25	120
$Z \rightarrow ll$ cross-section [333]	nb	2	2	4	14
$Z \rightarrow ll$ rate	kHz	0.02	0.1	1	4.2
$t\bar{t}$ cross-section [333]	nb	1	1	4	35
$t\bar{t}$ rate	kHz	0.01	0.05	1	11

100MHz of jets p_T>50GeV

400kHz of Ws

120kHz of Zs

11kHz of Tops

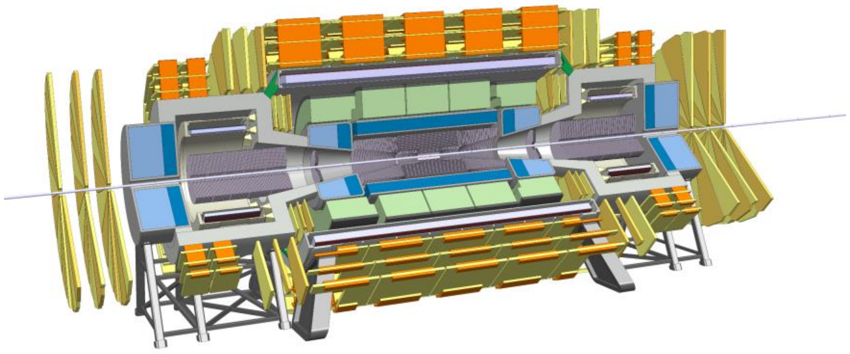
Trigger/DAQ

Example: ATLAS Phase2 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 at about 10us latency.

Muon system will also be read out at 40MHz to produce a L1 Trigger.

Reading out the FCC detector calorimetry and muon system at 40MHz will result in **200-300 TByte/s**, which seems feasible.

40MHz readout of the tracker would produce about **1000 TByte/s.**



Question:

Can the L1 Calo+Muon Trigger have enough selectivity to allow readout of the tracker at a reasonable rate of e.g. 1MHz ?

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.

Heavy Ions

Table 7.4: Key parameters defining the detector requirements for PbPb collisions.

Parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm} per nucleon	TeV	5.5	5.5	10.6	39.4
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$	10^{27} cm^{-2}s^{-1}	1	6.5	15-50	320
Bunch spacing	ns	100	50	50	50
Number of bunches		1232	1232	1232	5400
Goal $\int \mathcal{L}$	nb^{-1}	1	10	10/month	110/month
σ_{inel}	b	7.8	7.8	8	9
σ_{tot}	b	515	515	530	597
BC rate	MHz	13.8	13.8	13.8	16.6
Peak PbPb collision rate	kHz	7.8	50.7	400	2880
RMS luminous region σ_z	mm	50-70	50-70	35-70	30-60
$dN_{ch}/d\eta\|_{\eta=0}$		500	500	610	900
Charged tracks per collision N_{ch}		5800	5800	7500	12500
Rate of charged tracks	GHz	0.05	0.3	3	36
$< p_T >$	GeV/c	0.47	0.47	0.49	0.55
Bending radius for $< p_T >$ at B=4T	cm	39	39	41	46

The general purpose detector will also be able to perform well for PbPb collisions at the predicted Luminosities.

Continuous readout, PID from TOF with the timing detectors are good features for Heavy Ion Physics.

Operating at a lower field than 4T would of course be desirable (calibration questions to be worked out …)

The significantly lower radiation requirement allows of course optimized detector solutions that can outperform a general purpose detector.

We definitely have to keep the door open for a dedicated HI experiment setup.

Summary

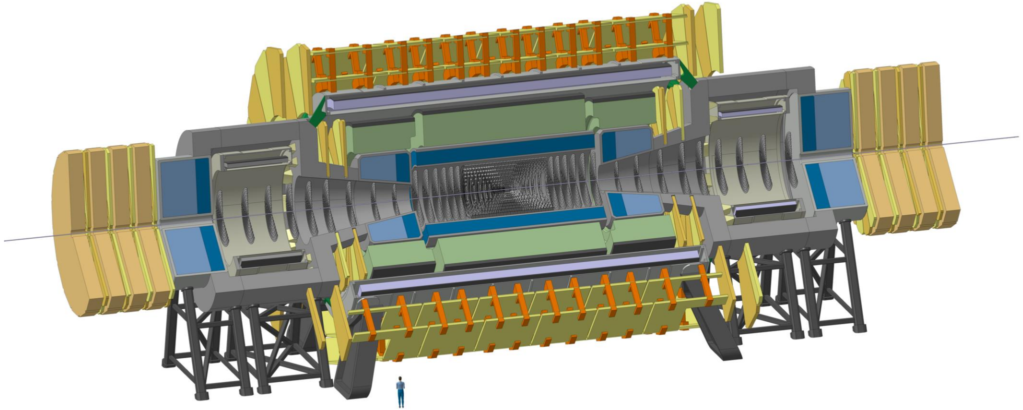
We have developed a general purpose reference detector concept for an FCC-hh collider. The detector and the performance for some benchmark channels is summarized in the FCC-hh CDR (30 pages).

The concepts for the subsystems are simulated and parametrized to a level of detail that allowed serious physics studies to be performed.

At this moment we are working on the detailed write-up of the work.

The development of ultra-radiation hard silicon sensors, low power radiation hard optical links, high granularity Liquid Argon calorimetry as well as high precision timing detectors are key detector R&D items.

A next round of detector performance studies will have to look at combined performance of tracker & calorimetry as well as general pattern recognition issues in the pile-up = 1000 environment.



Detailed Report

A 260 page draft version of the detailed report on the FCC-hh detector and experiments exists.

We want to publish this document as a yellow report, independent of the the other detailed FCC reports.

In principle we wanted this document to be ready for this FCC week, but some of the editors where slightly overwhelmed with other activities, so we try to finish the report over the summer.

The responsibilities for the different chapters are clearly defined – it's just work.