Detector R&D Requirements for Future High-Energy Hadron Colliders

Martin Aleksa

on behalf of the FCC-hh Detector Group

Based on material from:

- FCC CDR Summary Volumes:
  - https://fcc-cdr.web.cern.ch/, EPJ ST 228, 4 (2019) 755-1107, talk by W. Riegler at https://indico.cern.ch/event/789349/
- European Strategy Physics Briefing Book (https://arxiv.org/abs/1910.11775)
- DOE BRN Study on High Energy Physics Detector Research and Development (https://science.osti.gov/hep/Community-Resources/Reports)
- FCC-hh Calorimetry studies have been published at https://arxiv.org/abs/1912.09962

With thanks to W. Riegler for the valuable discussions and inputs!

Some Considerations – Outline

- I was asked to summarize **detector R&D requirements for future high-energy (HE) hadron colliders**

- **In order to identify the detector R&D requirements** one has to answer the following questions first:
  - How would such a future HE hadron collider look like? Which parameters?
  - What would be the physics program of such a future HE hadron collider?
  - What are the benchmark measurements that define detector requirements?
  - What are possible experiment layouts? Which detector technologies could be used to fulfil these requirements?

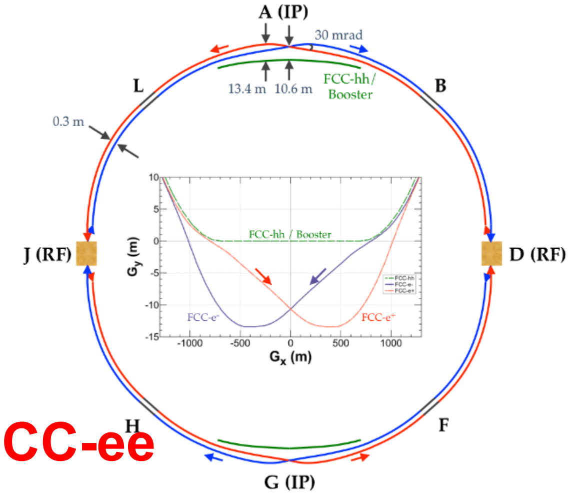
  Let us **answer these questions and identify the areas where further R&D is necessary** and/or beneficial to maximise the physics reach

- **A lot of work on the first four items was done for the FCC-hh CDR →** in this talk I will closely follow the lines of the FCC-hh CDR, but FCC-hh and its reference detector should serve here as one example how such an experiment could look like. Alternative solutions are possible and even likely! I will try point to possible alternatives during the presentation.

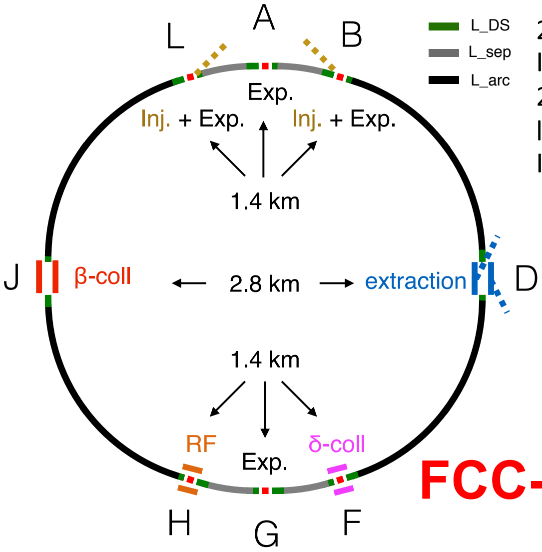
- **Outline of this talk:**
  - Introduction: A Future High-Energy Hadron Collider – Example: FCC-hh
  - Challenges of the FCC-hh Environment
  - Future High-Energy Hadron Collider Reference Detector
  - Necessary R&D – Challenges
  - Conclusions & Outlook

FCC Integrated Program

- **Comprehensive cost-effective program maximizing physics opportunities**
  - **Stage 1: FCC-ee (Z, W, H, ttbar) as Higgs factory, electroweak & and top factory at highest luminosities**
  - **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
  - Complementary physics
  - Common civil engineering and technical infrastructures
  - Building on and reusing CERN's existing infrastructure
  - FCC integrated project allows seamless continuation of HEP after HL-LHC



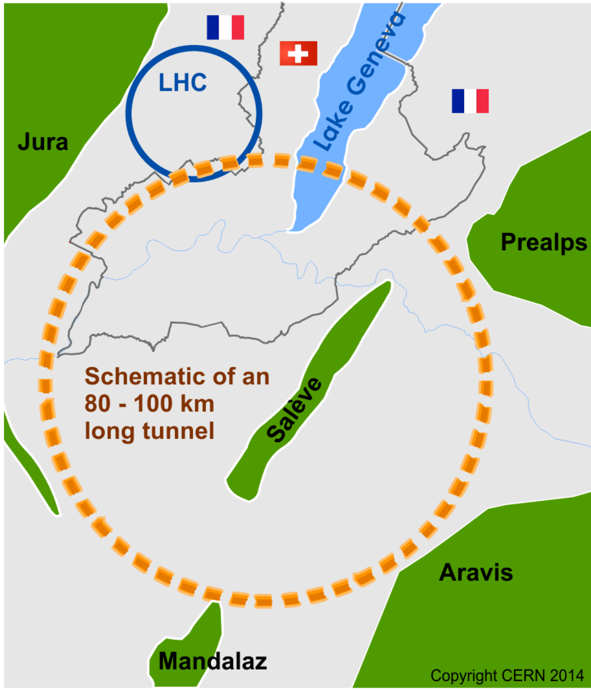
FCC-ee



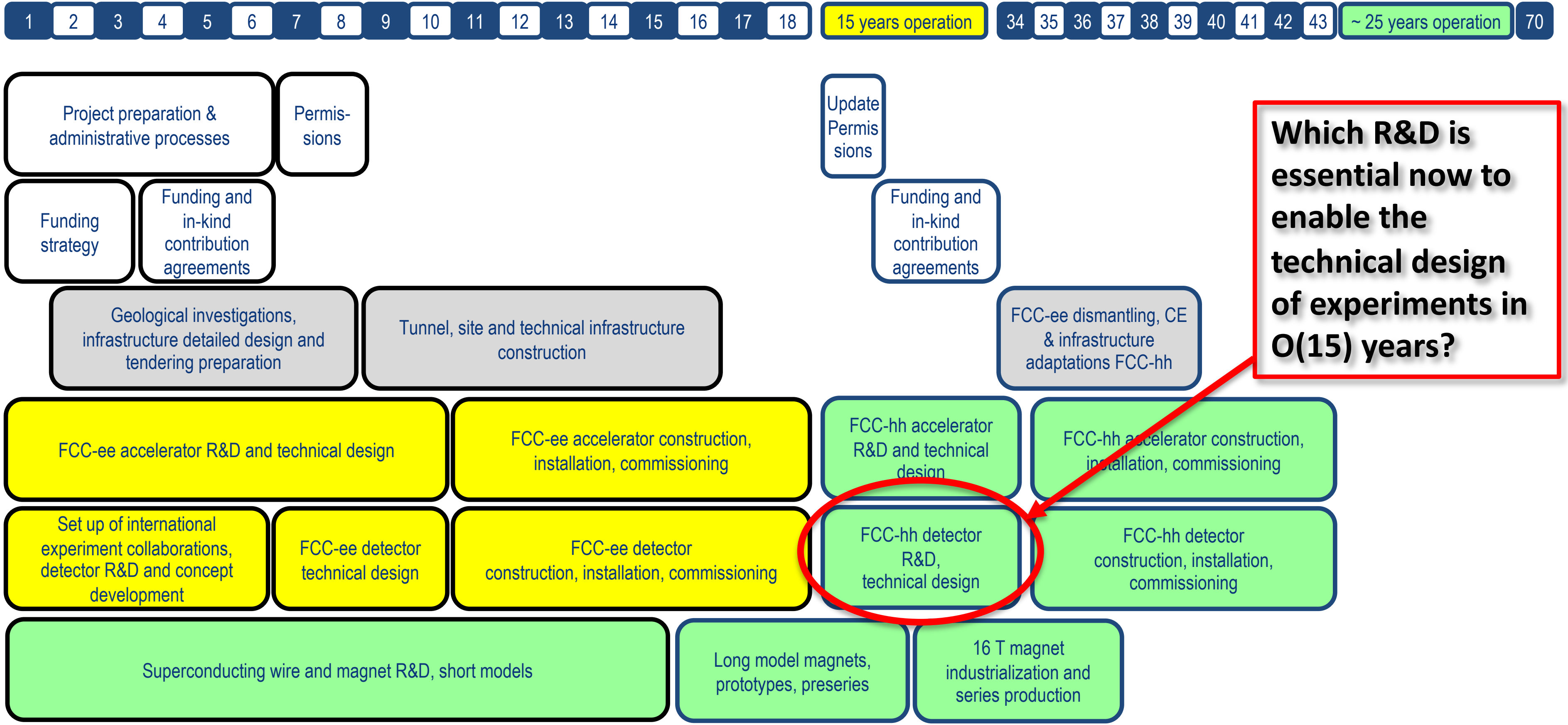
2 high-lumi IPs A/G

2 lower luminosity IPs L/B

FCC-hh



FCC Integrated Project Schedule



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 | 15 years operation | 34 35 36 37 38 39 40 41 42 43 | ~ 25 years operation | 70

Project preparation & administrative processes

Permis-sions

Update Permis sions

Funding strategy

Funding and in-kind contribution agreements

Funding and in-kind contribution agreements

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Set up of international experiment collaborations, detector R&D and concept development

FCC-ee detector technical design

FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

Superconducting wire and magnet R&D, short models

Long model magnets, prototypes, preseries

16 T magnet industrialization and series production

Which R&D is essential now to enable the technical design of experiments in O(15) years?

FCC-hh Parameter Table

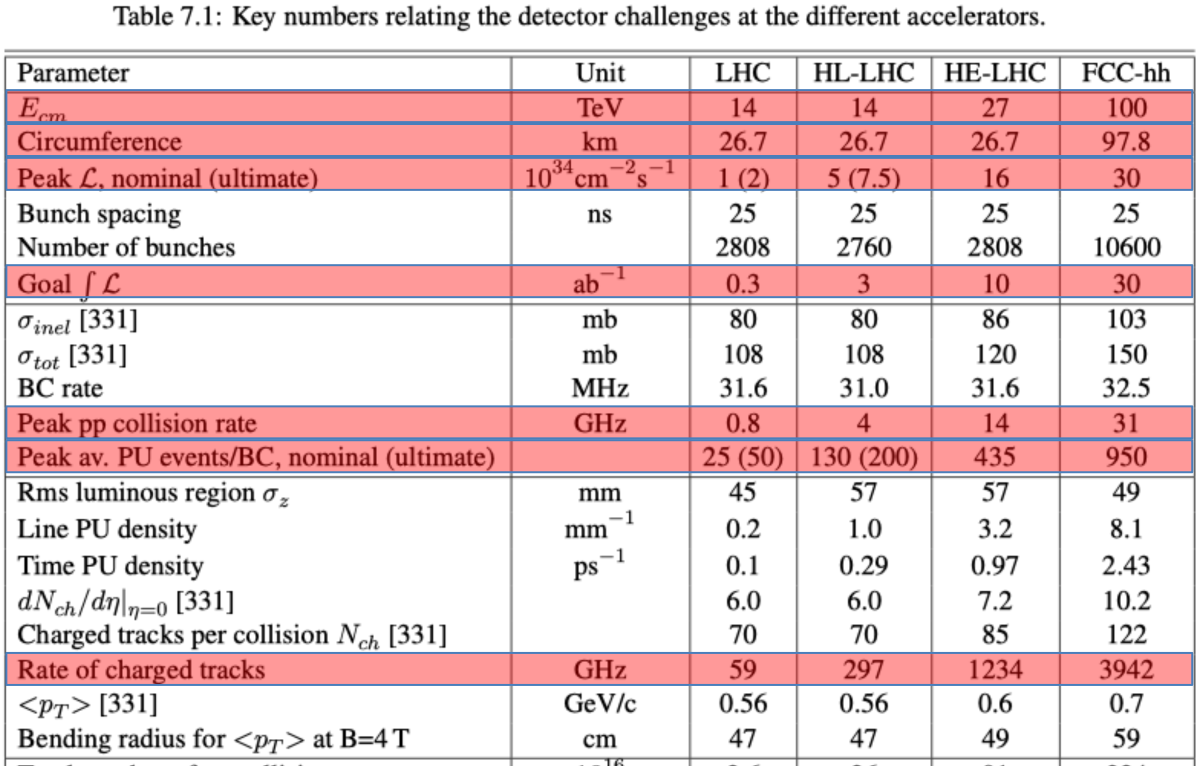


Table 7.1: Key numbers relating the detector challenges at the different accelerators.

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	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

Parameter Table

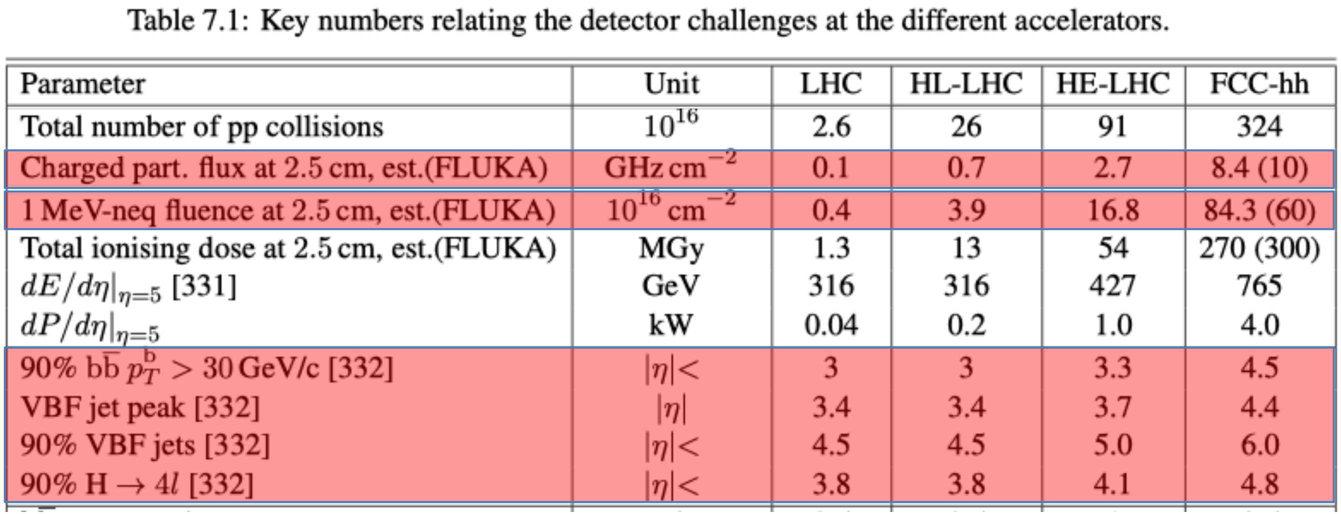
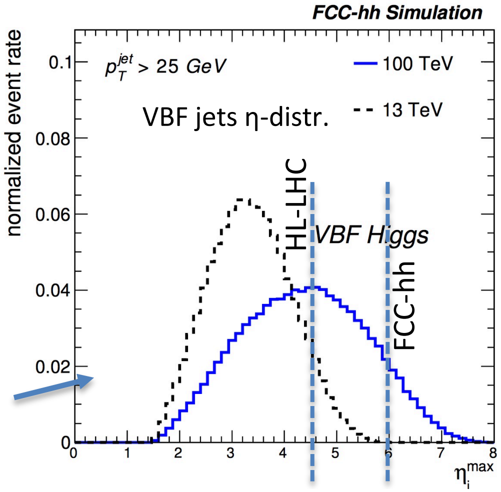


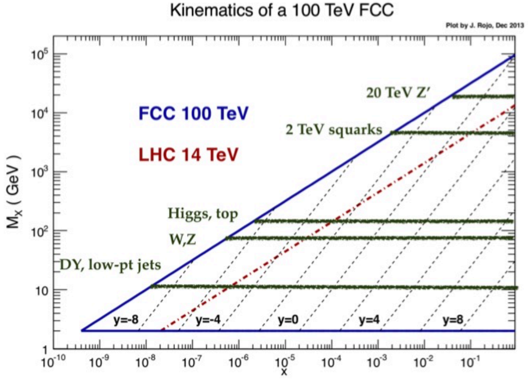
Table 7.1: Key numbers relating the detector challenges at the different accelerators.

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

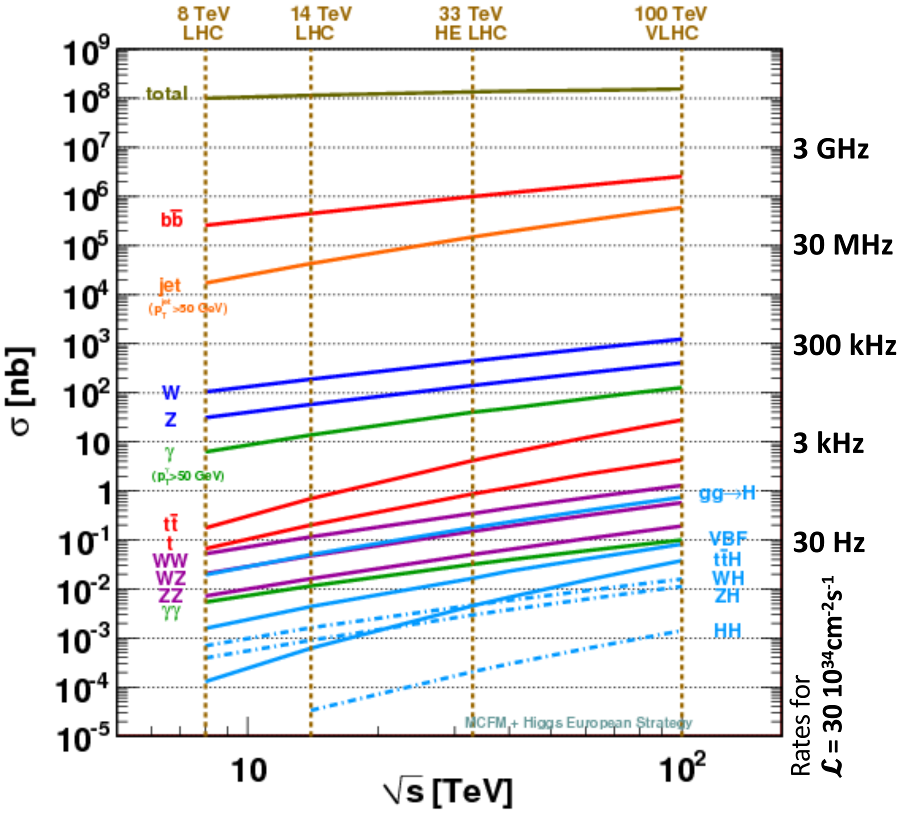


Unprecedented particle flux and radiation levels

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



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

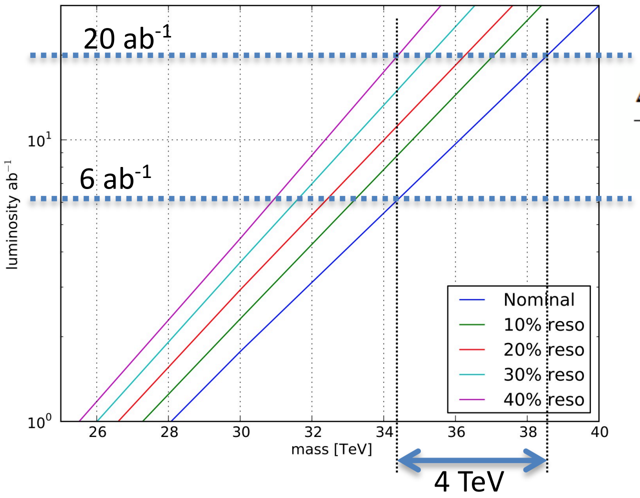
Physics Benchmarks – Detector Requirements

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

Exploration potential through higher energy, increased statistics, increased precision

Example: Z’$_{SSM}$ discovery

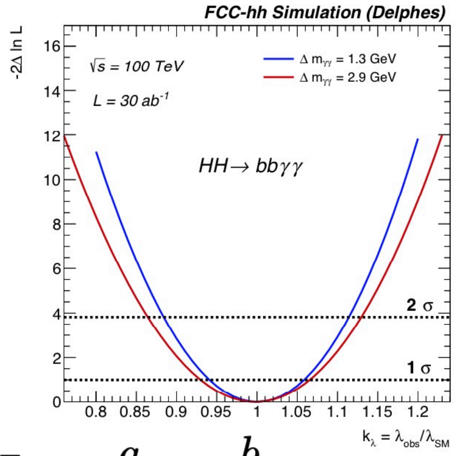
luminosity versus mass for a 5σ discovery

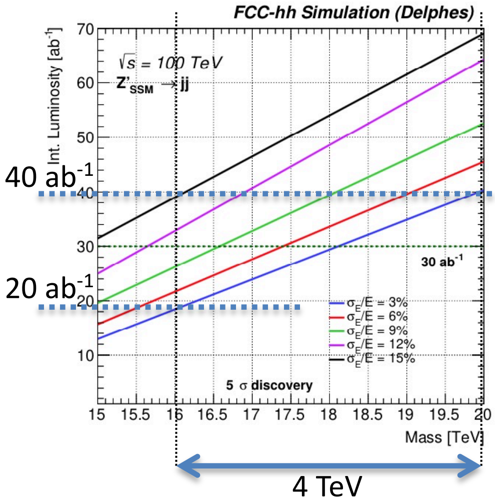


$$\frac{\Delta p}{p} \propto \frac{p}{BL^2}$$

Muon momentum resolution:

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





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

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)!

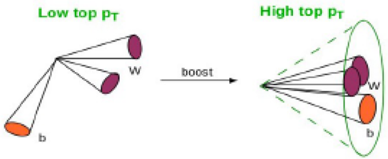
Di-jet resonances: HCAL constant term of *c* = 3% instead of 15%: extend discovery potential by 4TeV (or same disc. pot. for 50% lumi)

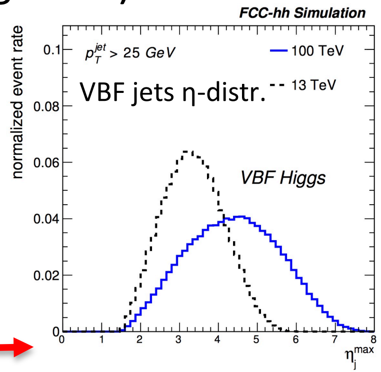
- → **full shower containment is mandatory !**
- → Large **HCAL depth (~ 12 λ$_{int}$)!**

Requirements for FCC-hh Detector

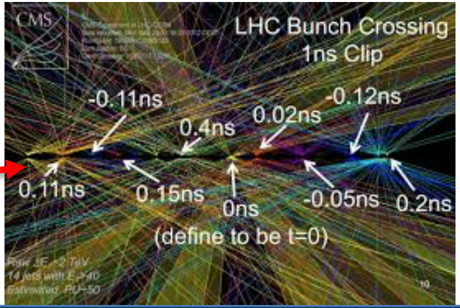
Used in Delphes physics simulations

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



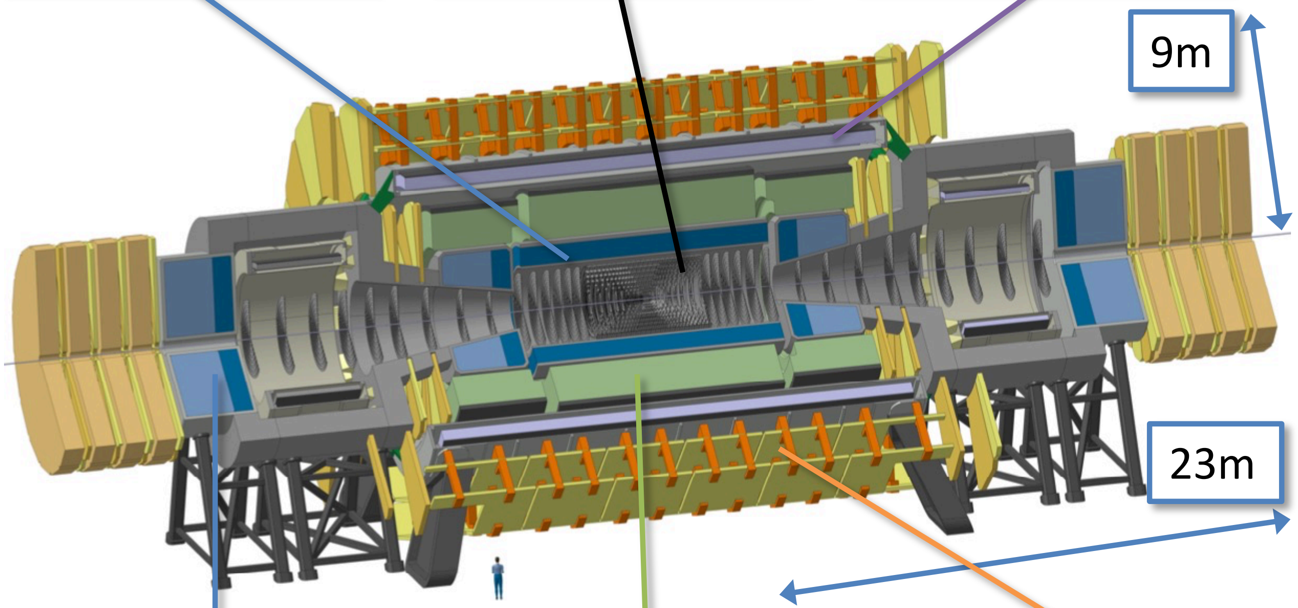


- **High granularity** in tracker and calos (boosted obj.)
- **Pseudorapidity (η) coverage**:
  - Precision muon measurement up to |η|<4
  - Precision calorimetry up to |η|<6



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

A Possible FCC-hh Detector – Reference Design for CDR



Barrel ECAL:
$\sigma_E/E \approx 10\%/\sqrt{E} \oplus 0.7\%$

Tracker: $\sigma_{p_T}/p_T \approx 10\text{-}20\%$ at 10TeV (1.5m radius)

Central Magnet:
B=4T, 5m radius

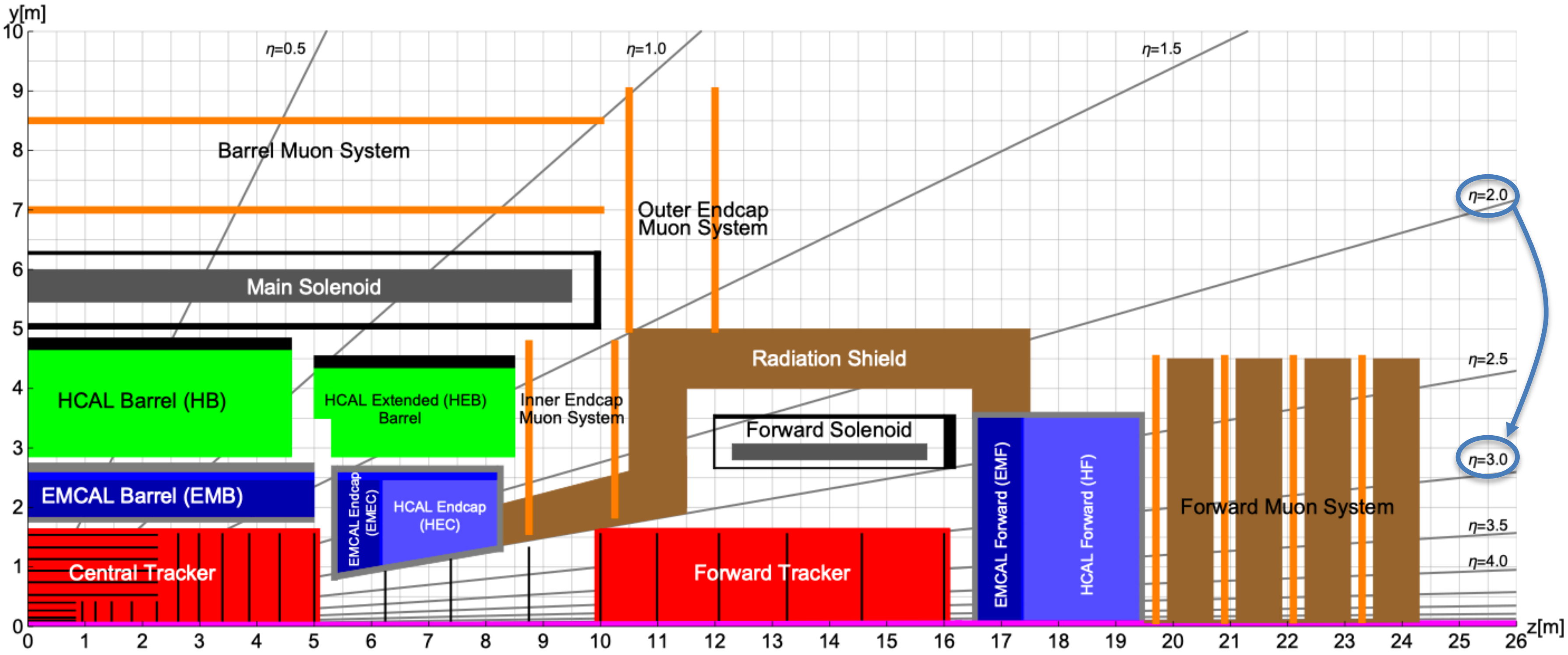
Forward detectors
up to $\eta=6$

Barrel HCAL:
$\sigma_E/E \approx 50\%/\sqrt{E} \oplus 3\%$

Muon System:
$\sigma_{p_T}/p_T \approx 5\%$ at 10TeV

- Converged on **reference design for an FCC-hh experiment for 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**
- However, this is one example experiment, other choices are possible and very likely → A lot of **room for other ideas, other concepts and different technologies**
- **In the following I will demonstrate the challenges for such an experiment – mostly independent of detector technologies chosen**

Reference Design for CDR



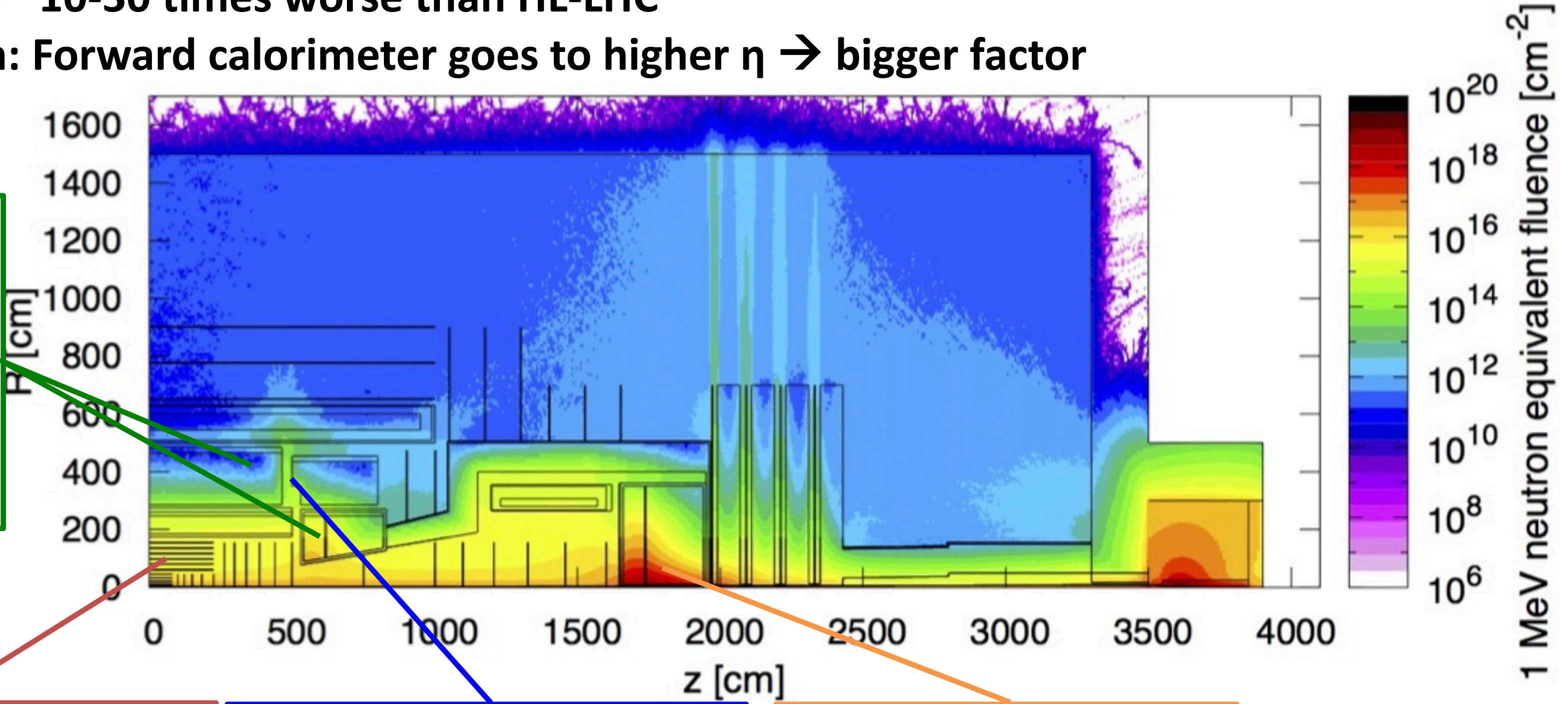
Forward solenoid adds about 1 unit of η with full lever-arm

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

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:

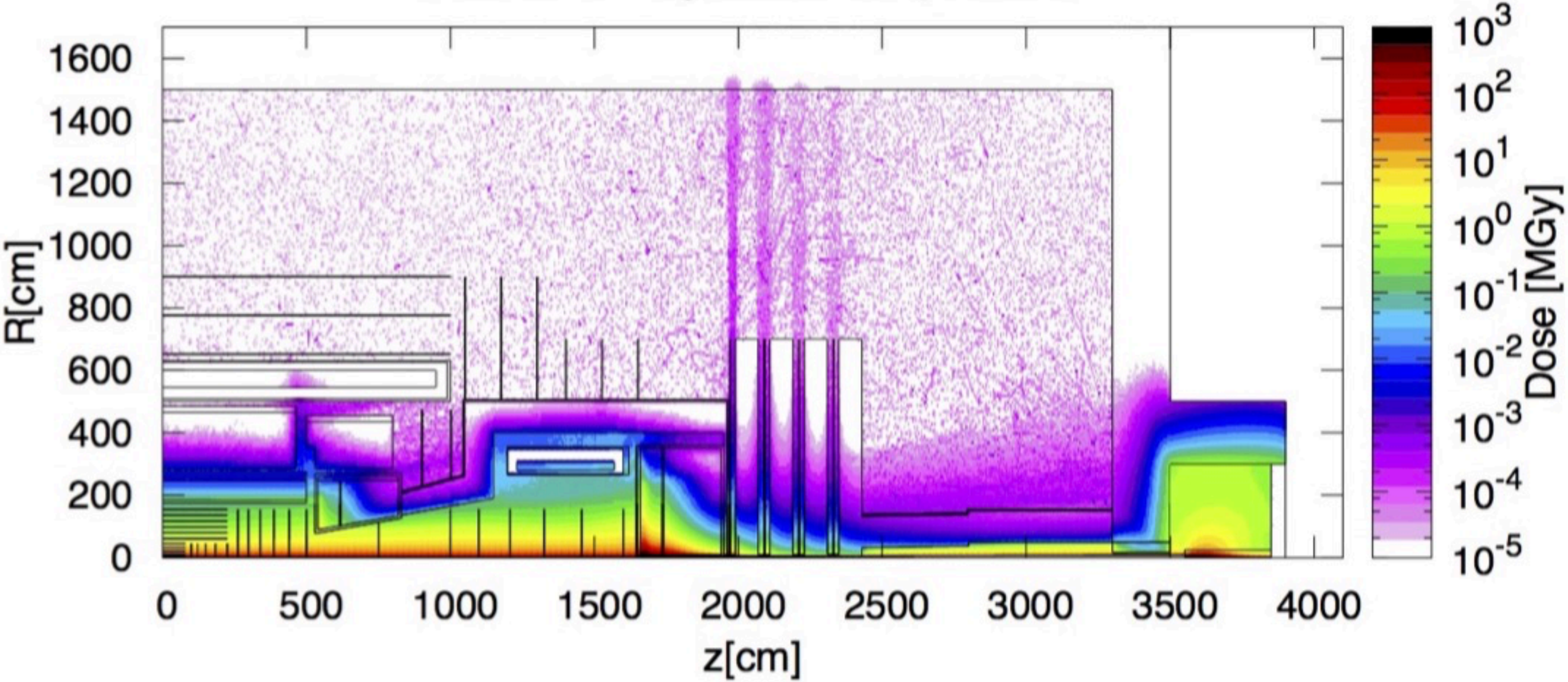
from 10^{16} cm^{-2} to 10^{14} cm^{-2}

Forward calorimeters:

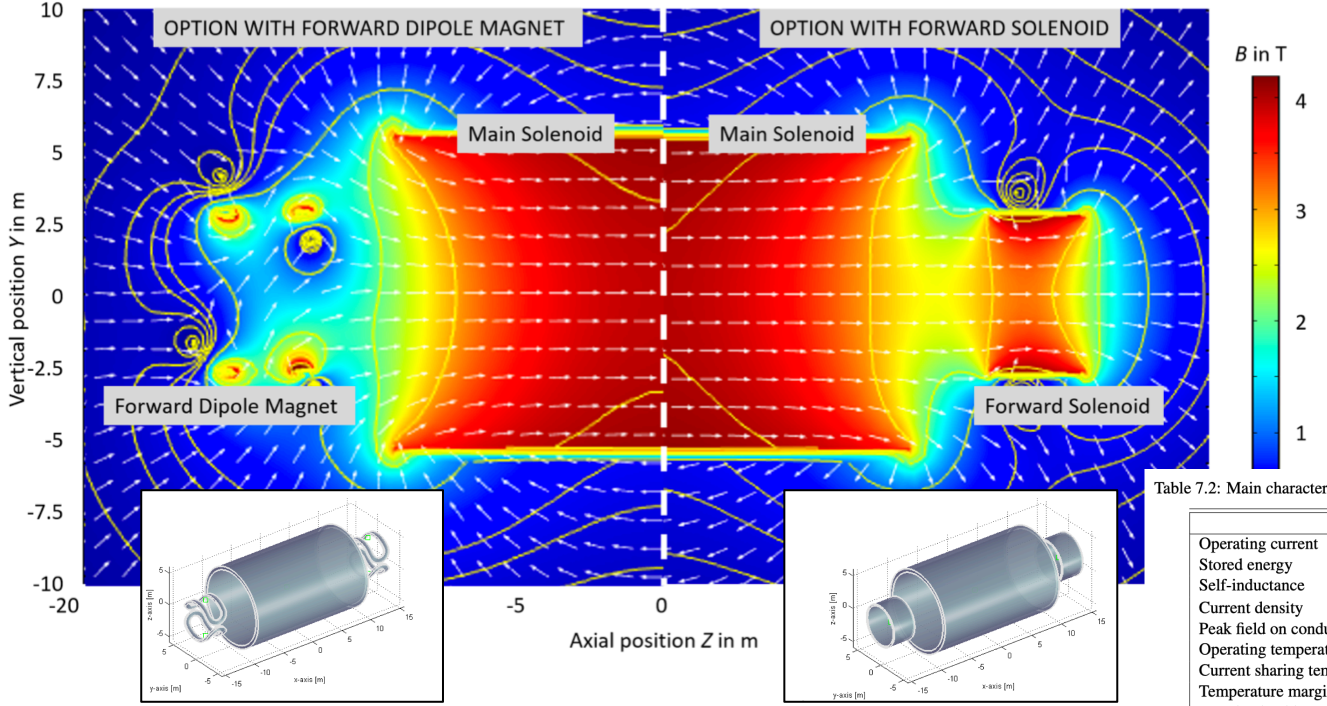
~5 10^{18} cm^{-2} for both the EM and the HAD-calo

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.



FCC-hh Magnet System



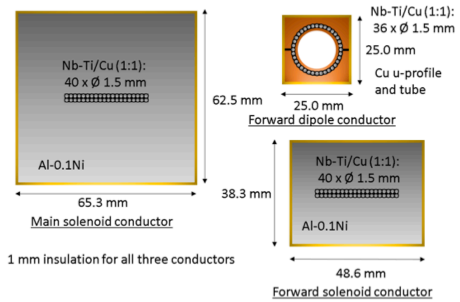


Table 7.2: Main characteristics of the central solenoid, a forward solenoid and a forward dipole magnet.

	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

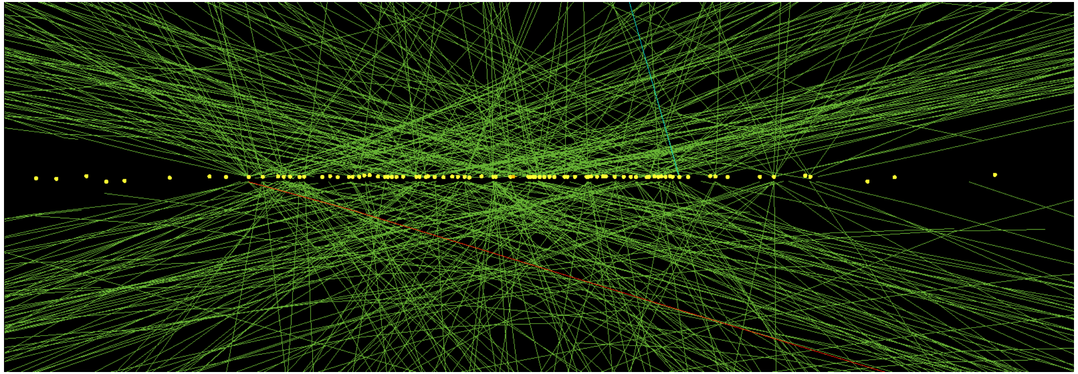
FCC-hh: ~13 GJ, cold mass + cryostat around 2000 tons.

Possible alternative solutions: Ultra-thin solenoid positioned inside the calorimeter (difficulty: muon measurement!)

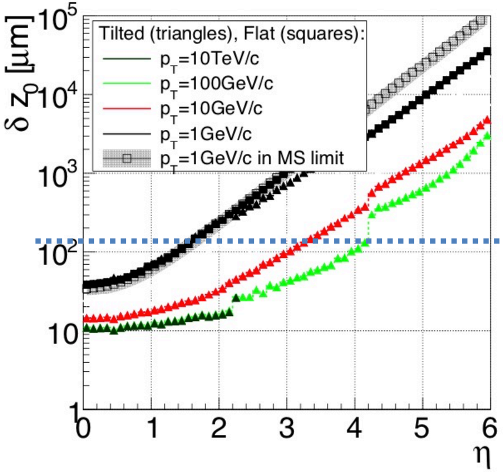
Challenges for the Magnet System – R&D Needs (TF8)

- 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 neighboring 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)

The Challenge of <μ> = 1000 Pile-Up



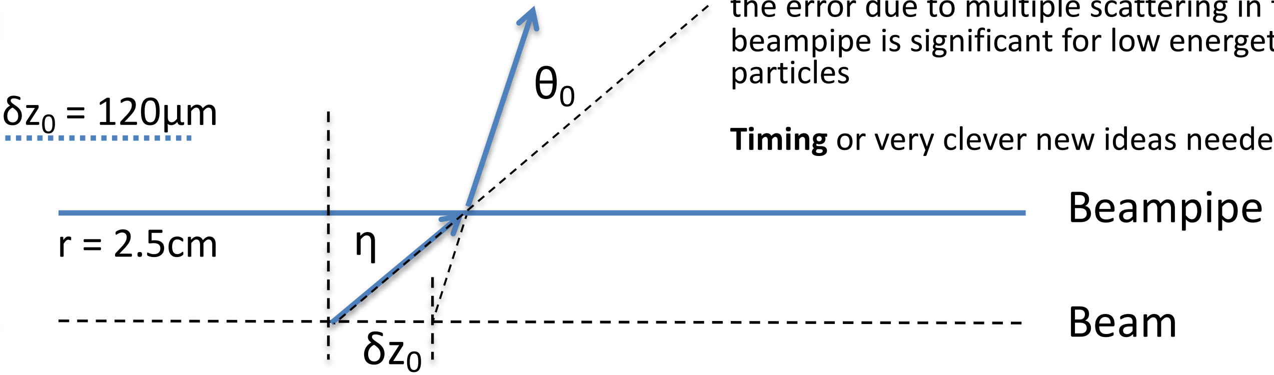
- HL-LHC average distance between vertices at z=0 is
  - ≈ **1mm in space and 3ps in time.**
- → For 6 times higher luminosity and higher c.m. energy at FCC-hh:
  - ≈ **120 μm in space and 0.4ps in time**
- **→ Future trackers will need to use both, position resolution and timing to identify the correct 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 having a perfect tracking detector, the error due to multiple scattering in the beampipe is significant for low energetic particles

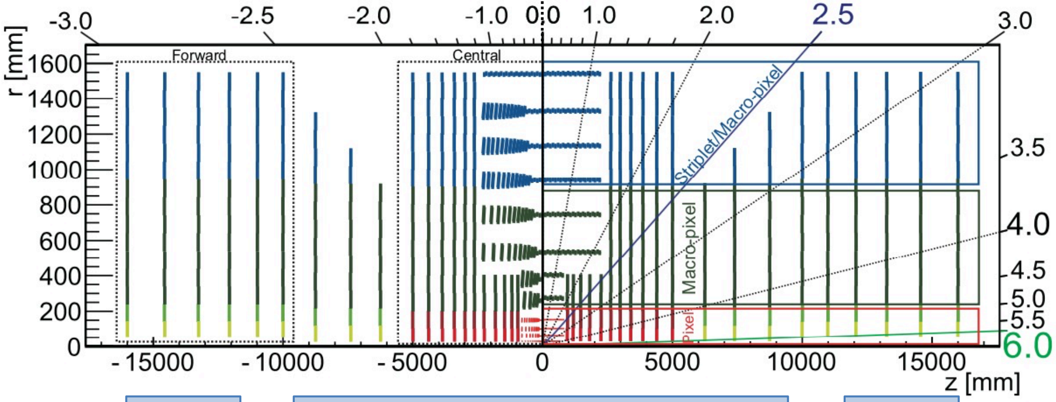
Timing or very clever new ideas needed …



FCC-hh Tracker

Tilted layout
390m² of silicon

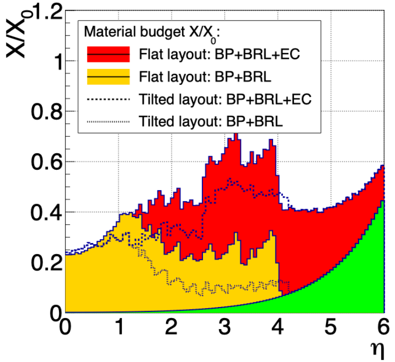
Flat layout
430m² of silicon

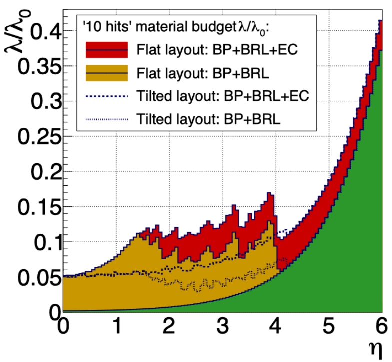


forward solenoid

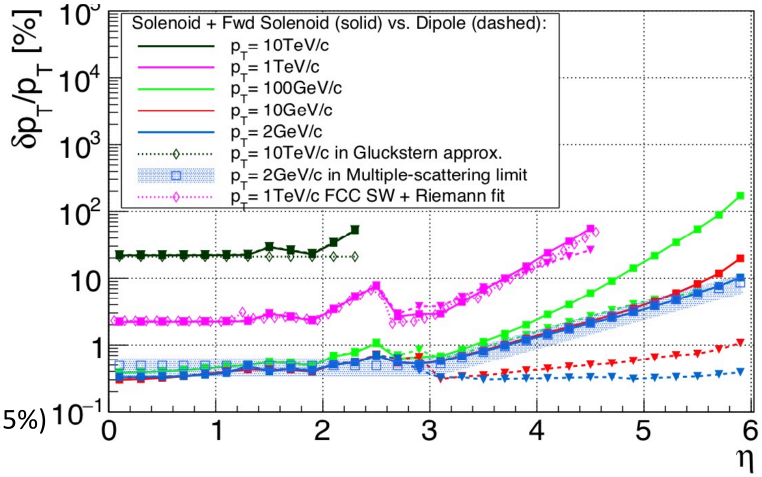
central solenoid

forward solenoid





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

- ≤ 10 GeV/c and η ≤ 5.8
- ≤ 1 TeV/c and η ≤ 4.0

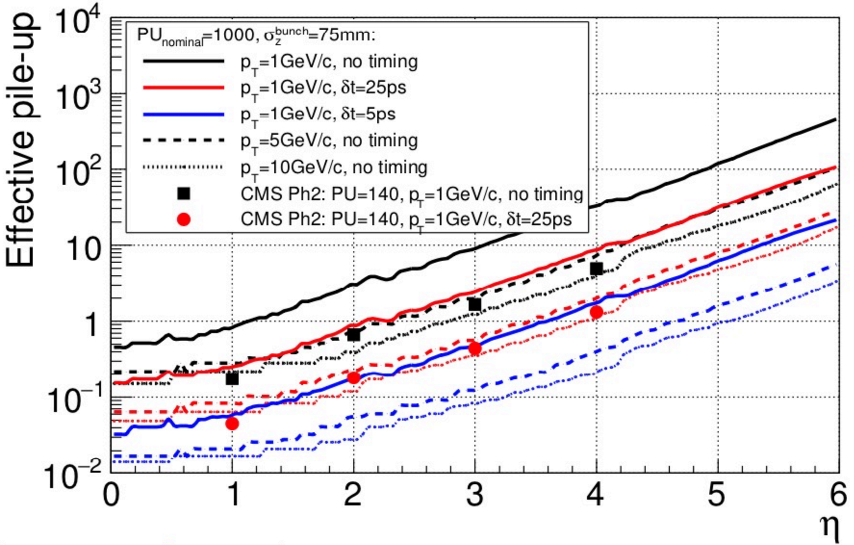
$\delta p_T/p_T = 20\%$ for 10 TeV/c in the central region

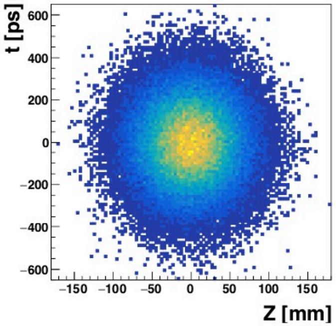
Momentum resolution dominated by **multiple scattering** up to 250GeV (limit at $\delta p_T/p_T = 0.5\%$)

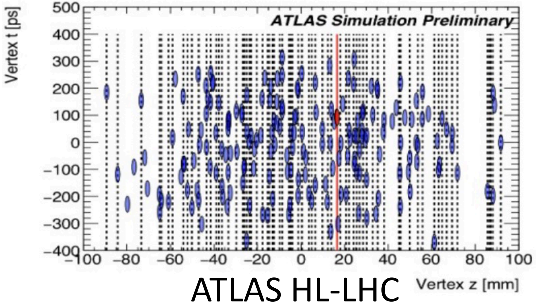
→ **low material tracker**!!

Timing Information for Vertex Reconstruction

- **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!**



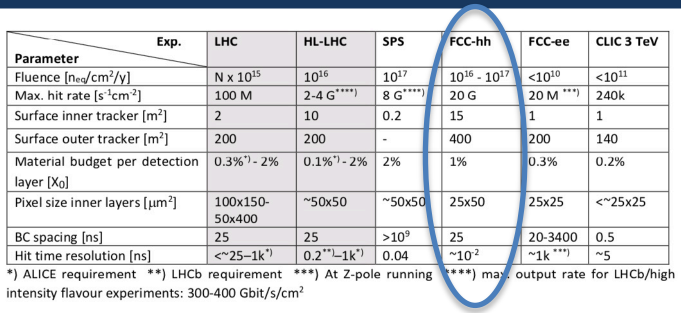




ATLAS HL-LHC

Challenges for the Tracker – R&D Needs (TF3)

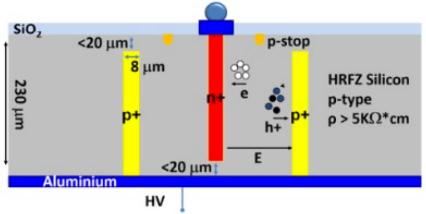
- **Radiation hardness:**
  - **Radius > 30cm: Existing technologies are applicable**
  - **Radius < 30cm: Radiation challenge has to be solved**
    - Ultra-radiation hardness of sensors and read-out chip
    - Up to 10^{18}cm^{-2} 1 MeV n.eq. fluence, TID of 300MGy
- **Timing** of tracks at the <10ps 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 have the potential to reduce power consumption and fulfill low-material budget requirement
- **Integration problems to be solved (TF7, TF8, TF3)**:
  - Huge amount of data produced (1000TByte/s)
  - Power needs of sensors, FE-chips and optical links critical
    - → keep material for power lines and cooling under control
  - Low-mass detector system integration: This includes 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, namely, a tracker which mass budget is reduced to the active mass of the sensor



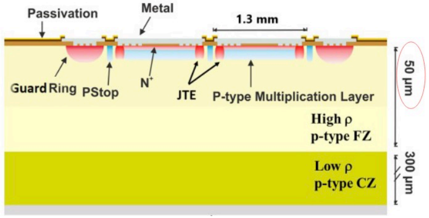
Parameter \ Exp.	LHC	HL-LHC	SPS	FCC-hh	FCC-ee	CLIC 3 TeV
Fluence [n_{eq}/cm^2/y]	N x 10^{15}	10^{16}	10^{17}	10^{16} - 10^{17}	<10^{10}	<10^{11}
Max. hit rate [s^{-1}cm^{-2}]	100 M	2-4 G****)	8 G****)	20 G	20 M ***)	240k
Surface inner tracker [m^2]	2	10	0.2	15	1	1
Surface outer tracker [m^2]	200	200	-	400	200	140
Material budget per detection layer [X_0]	0.3%*) - 2%	0.1%*) - 2%	2%	1%	0.3%	0.2%
Pixel size inner layers [μm^2]	100x150-50x400	~50x50	~50x50	25x50	25x25	<~25x25
BC spacing [ns]	25	25	>10^9	25	20-3400	0.5
Hit time resolution [ns]	<~25–1k*)	0.2**)–1k*)	0.04	~10^{-2}	~1k ***)	~5

*) ALICE requirement **) LHCb requirement ***) At Z-pole running ****) max. output rate for LHCb/high intensity flavour experiments: 300-400 Gbit/s/cm^2

Table from EP R&D Final Report (CERN-OPEN-2018-006)

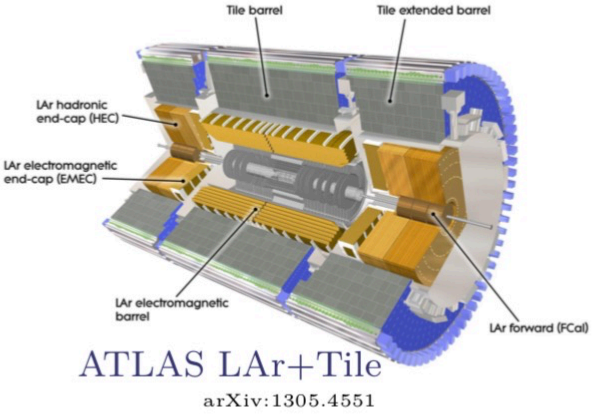


3D Pixel (arXiv:1806.01435)



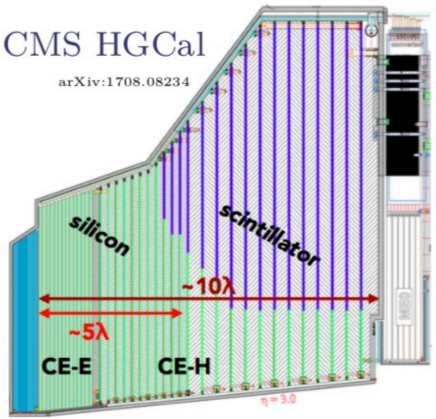
LGAD, see e.g. talk by S. Grinstein

FCC-hh Calorimetry



ATLAS LAr+Tile

arXiv:1305.4551



CMS HGCal

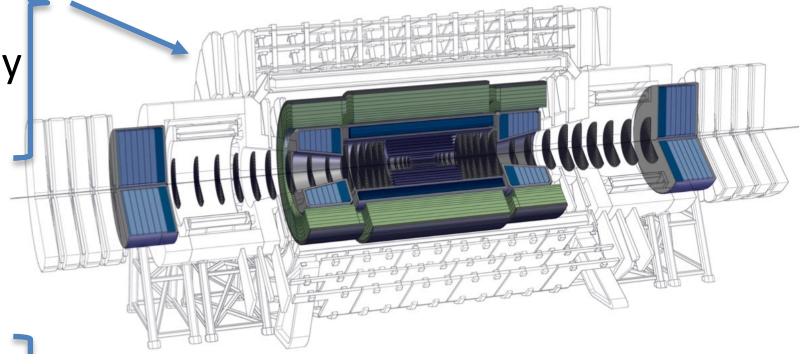
arXiv:1708.08234

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

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

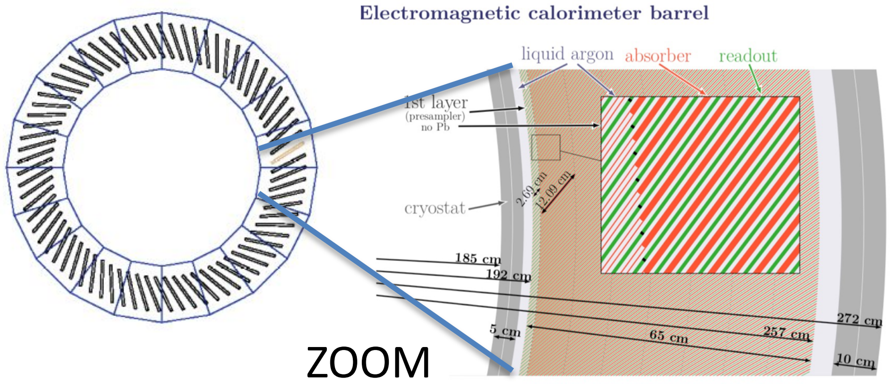
FCC-hh Calorimetry

„conventional calorimetry“
optimized for particle flow

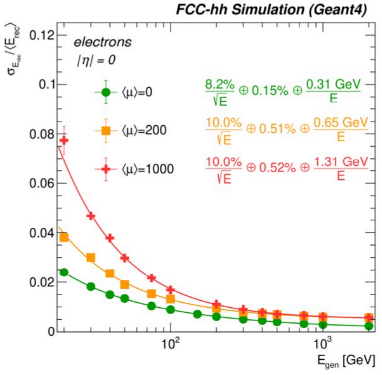


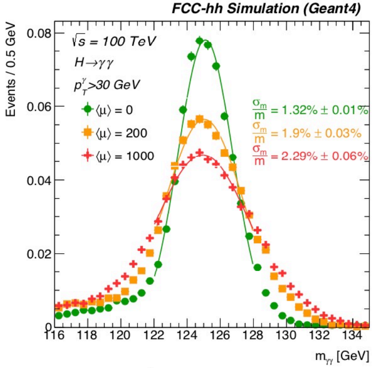
FCC-hh Calorimetry studies have been published at https://arxiv.org/abs/1912.09962

Electromagnetic Calorimeter (ECAL)

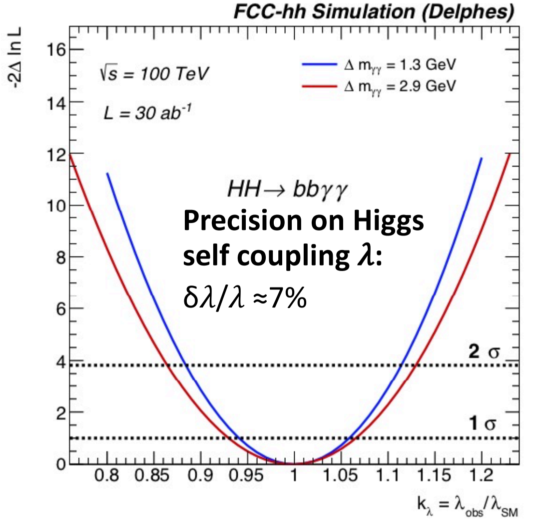


- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;





- **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 ($\Delta\eta \times \Delta\phi = 0.01 \times 0.01$, 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)



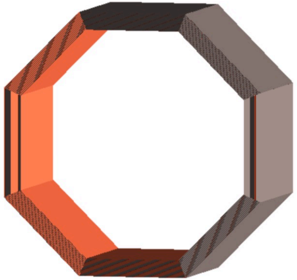
Precision on Higgs self coupling λ:

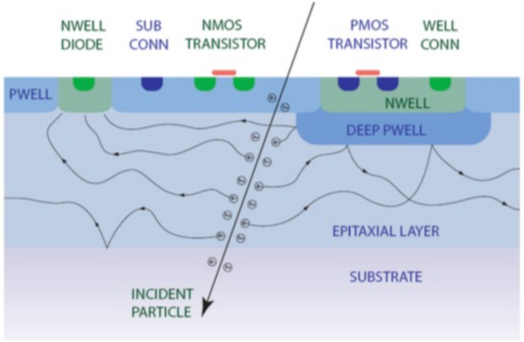
$\delta\lambda/\lambda \approx 7\%$

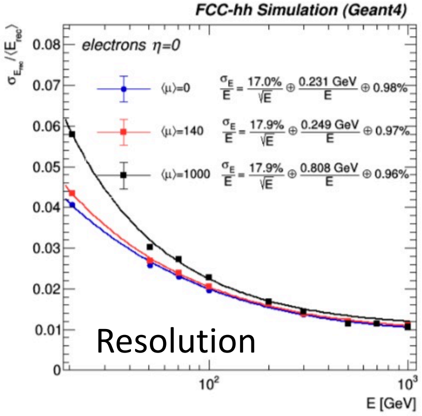
Barrel ECAL – Other Options

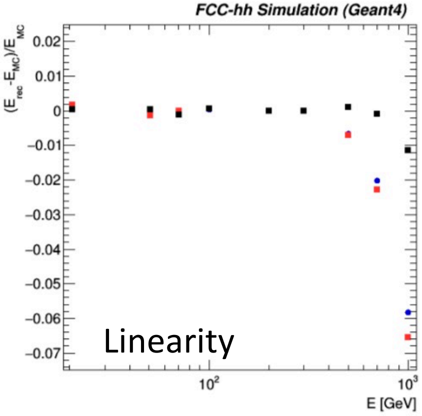
Other options considered for ECAL Barrel:

- **Digital Si/W DECal (MAPS):**
  - 18µm epitaxial thickness, on a substrate of 300µm.
  - 50×50 µm² pitch pixels are summed into 5×5 mm²
  - 2.1 mm thick tungsten absorber is located directly after the two silicon layers, followed by a 3 mm air gap (space foreseen for services, cooling,…)
  - Threshold at $6\sigma_{noise} = 480e^-$
  - MIP signal in 18µm Si: $1400e^-$
  - **Non-linearity for E > 300GeV due to multiple particles traversing single pixel → corrections necessary**
- **Option: Analog Si/W:** Will profit from experience of CMS HGCal









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
  - $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$
  - 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!):

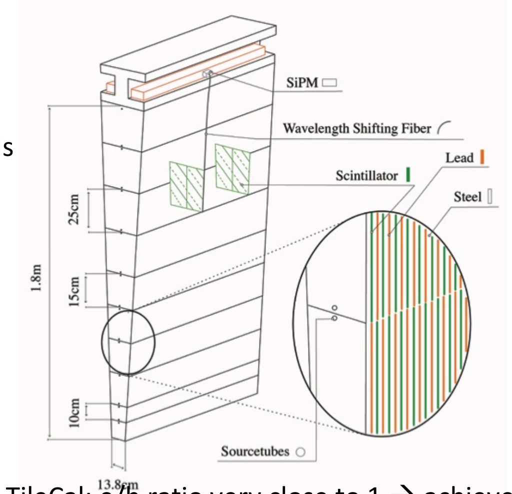
- Simple calibration: $44\%/\sqrt{\bar{E}}$ to $48\%/\sqrt{\bar{E}}$
- Calibration using neural network (calo only):
  - Sampling term of $37\%/\sqrt{\bar{E}}$

Jet resolution:

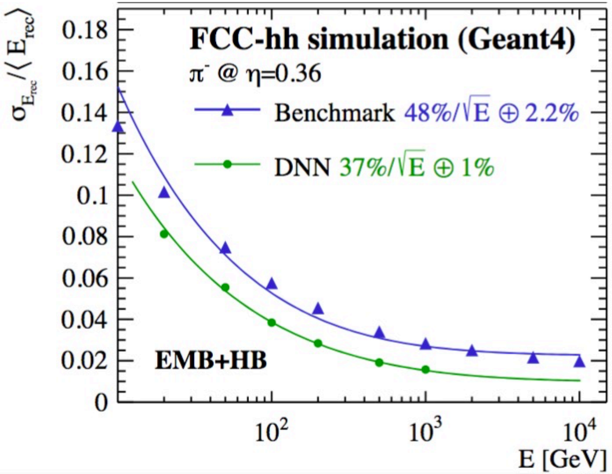
- Jet reconstruction impossible without the tracker @ 4T → particle flow.

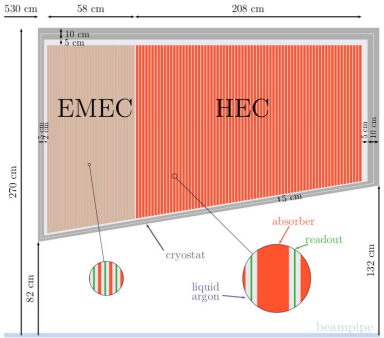
Endcap HCAL and forward calorimeter:

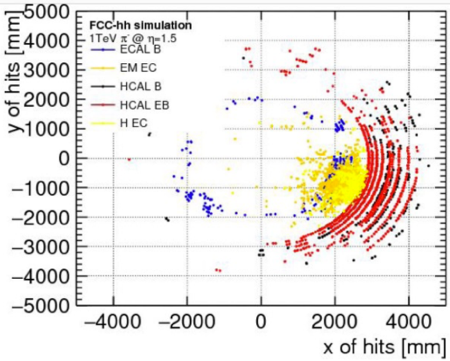
- Radiation hardness!
- LAr/Cu, LAr/W



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







Challenges for Calorimetry – R&D Needs (TF6)

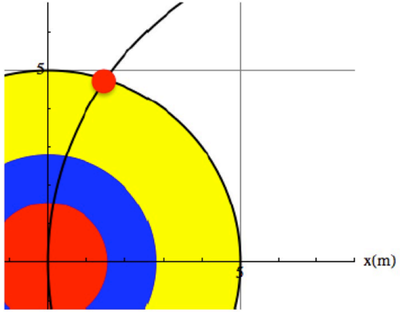
- **Radiation hardness:**
  - **Forward calo:** 5 10^{18} n_{eq}/cm^2, 5000MGy
    - Noble liquid calorimetry – intrinsic radiation hardness (of active material), other components (e.g. read-out electrodes!) need to be well chosen and tested. Electronics well shielded behind calorimeter outside the cryostat.
  - **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) (TF6)
  - **Scintillator based calorimetry:** Radiation hardness of scintillators and SiPMs (TF4). 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 (TF3)
  - **For all technologies:** Timing resolution at the O(25ps) level or better would help to reduce pile-up

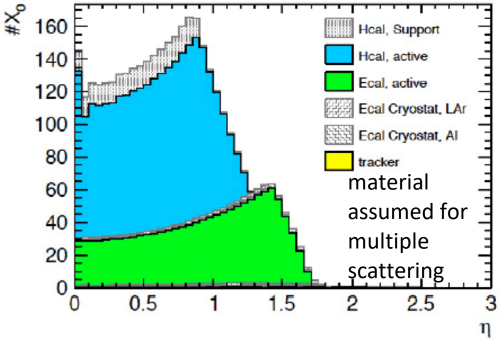
Challenges for Calorimetry – R&D Needs (TF6)

- **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 → further R&D on pad sizes and radiation 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 → full read-out at 40MHz (like ATLAS in HL-LHC)
  - Si option: many more channels, zero suppression on-detector necessary
  - → 100Gbps data links, off-detector real-time event processing with advanced hardware (GPUs, FPGAs)
  - → on-detector processing with radiation tolerant processing
- **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

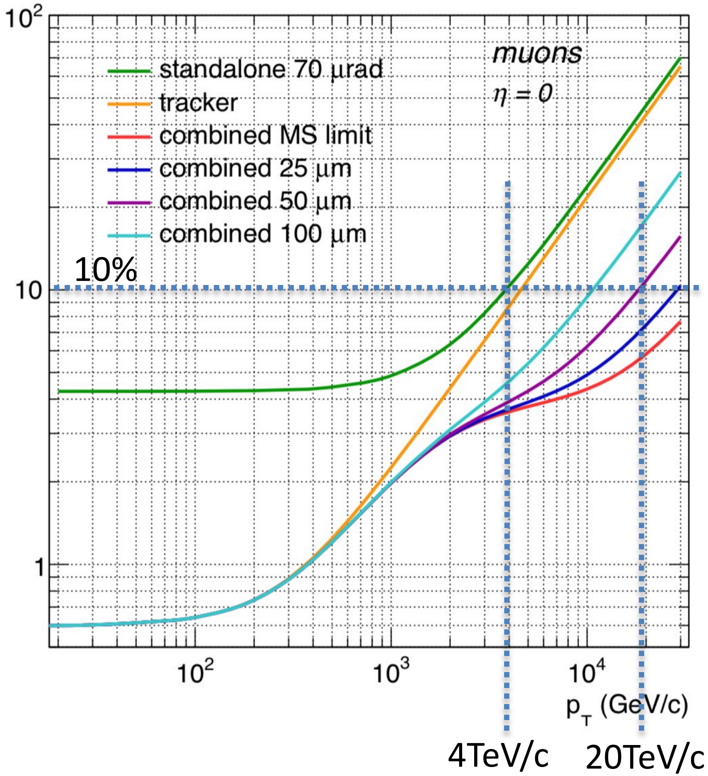
FCC-hh Muon System

p_t=3.9GeV enters muon system
p_t=5.5GeV leaves coil at 45 degrees





material assumed for multiple scattering

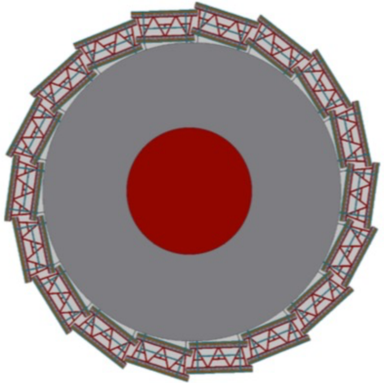


With 50µm position resolution and 70µrad angular resolution we find (η=0):

- ≤10% standalone momentum resolution up to 4TeV/c
- ≤10% combined momentum resolution 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

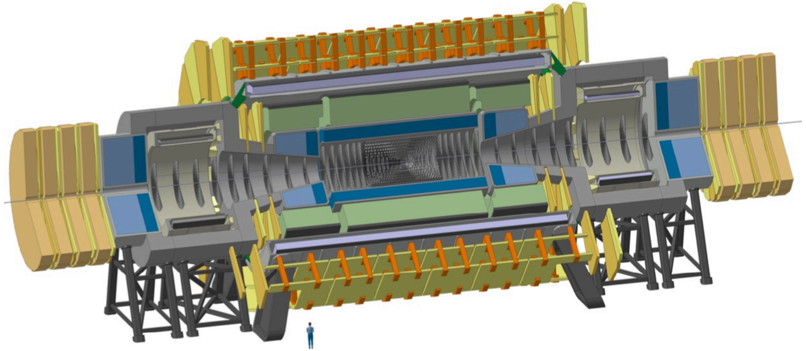
Muon detection in forward region:

Excpected rates up to 500kHz for r > 1m

→ HL-LHC muon system gas detector technology will work for most of the FCC detector area (TF1)

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 (TF7)

- **Huge amounts of data produced** (e.g. O(1000TByte/s) = O(10Pbps) for zero-suppressed 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)
    - DOE Instrumentation BRN: “The presently used data link architecture in which front-end ASICs communicate electrically to optical converters does not scale to arbitrary data rates…. New architectures will need to be explored to solve this problem. In terms of ASIC technology, industry predicts that photonics will be integrated with CMOS processes within 5 to 10 years.”

Challenges for Read-Out Electronics & Trigger (TF7)

- **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 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

Conclusions

- **Detector Requirements for Future High-Energy Hadron Colliders extremely challenging!**
- **Main challenges:**
  - Radiation hardness
  - Precision timing
  - Power & cooling for huge data rates
- Hadron collider experiments' **technical design will start in O(15) years**
- **Needs for such an experiment** have been described here and areas of **necessary R&D have been identified**
- **Expecting to profit from R&D for HL-LHC**
  - **Phase II Upgrades and future pixel inner layer replacements for ATLAS & CMS, future LHCb and ALICE upgrades**
- **Also some overlapping requirements with lepton collider experiments**
  - → **Will profit from detector R&D** performed now **for those experiments**
  - **Exception:** radiation hardness, which is only an issue for hadron collider experiments, but also more extreme requirements in other areas, e.g. for timing detectors and data links
  - **Only in some cases move (lepton collider → hadron collider experiment) will be incremental, in many areas new technologies will be necessary**
  - → **Need to start/continue strategic R&D in these areas!**

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":

"C/ 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

Global FCC Collaboration

Increasing international collaboration as a prerequisite for success: Links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

141
Institutes

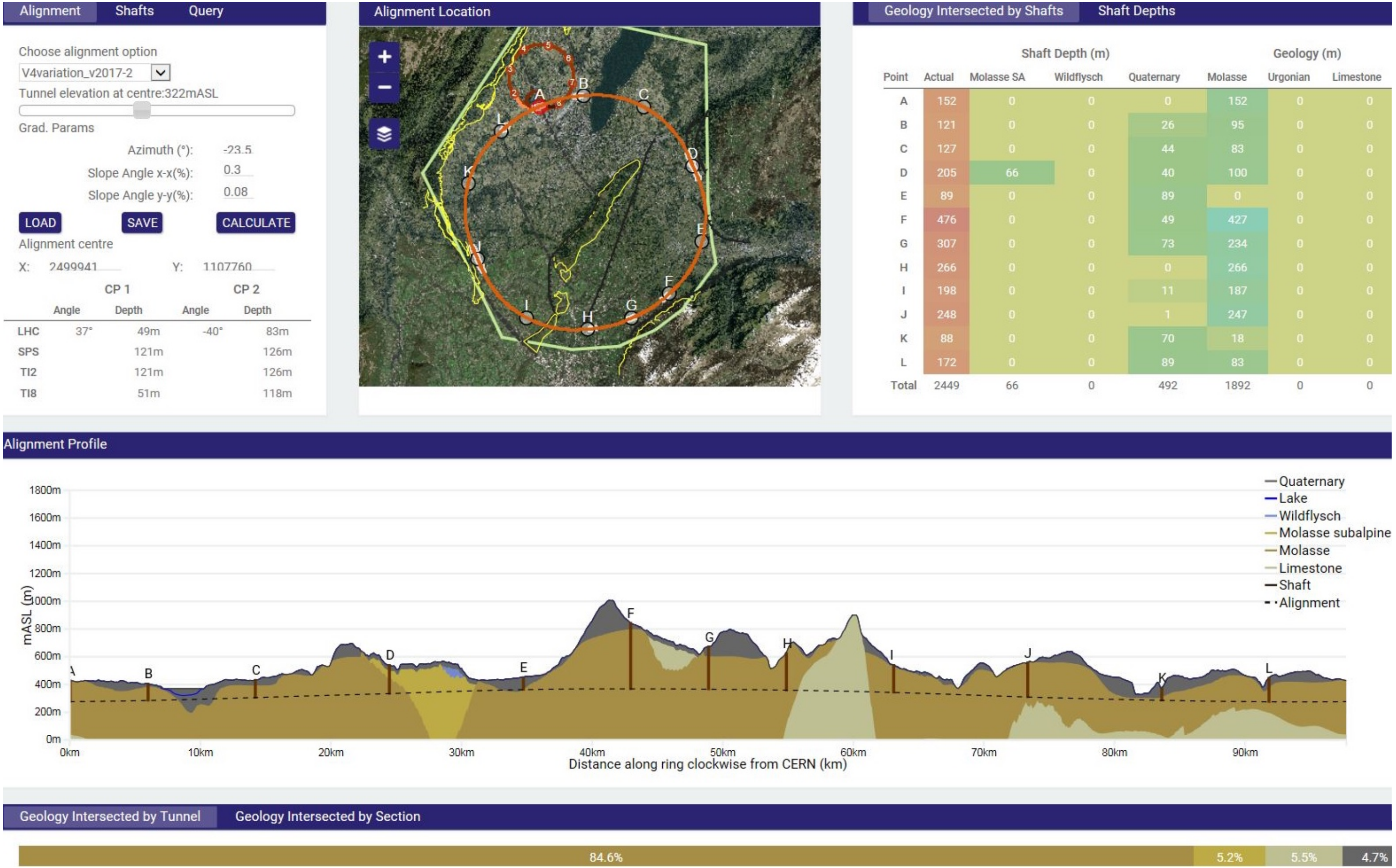
30
Companies

34
Countries

EC
H2020

FCC Tunnel

Civil Engineering – Tunnel Implementation Study



Choose alignment option

V4variation_v2017-2

Tunnel elevation at centre:322mASL

Grad. Params

Azimuth (°): -23.5

Slope Angle x-x(%): 0.3

Slope Angle y-y(%): 0.08

Alignment centre

X: 2499941 Y: 1107760

	CP 1		CP 2	
	Angle	Depth	Angle	Depth
LHC	37°	49m	-40°	83m
SPS		121m		126m
TI2		121m		126m
TI8		51m		118m

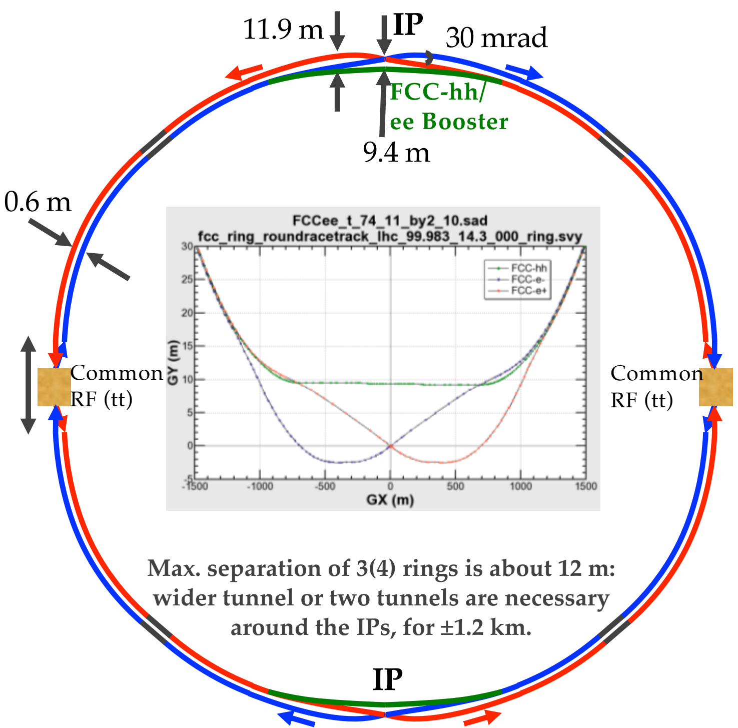
		Shaft Depth (m)			Geology (m)		
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Limestone
A	152	0	0	0	152	0	0
B	121	0	0	26	95	0	0
C	127	0	0	44	83	0	0
D	205	66	0	40	100	0	0
E	89	0	0	89	0	0	0
F	476	0	0	49	427	0	0
G	307	0	0	73	234	0	0
H	266	0	0	0	266	0	0
I	198	0	0	11	187	0	0
J	248	0	0	1	247	0	0
K	88	0	0	70	18	0	0
L	172	0	0	89	83	0	0
Total	2449	66	0	492	1892	0	0

Optimisation criteria:
- Tunneling rock type,
- Shaft depth accessibility
- Surface points, etc.
- Lowest risk for construction,
- Schedule & cost

Tunneling:
- Molasse 90%,
- Limestone 5%,
- Moraines 5%

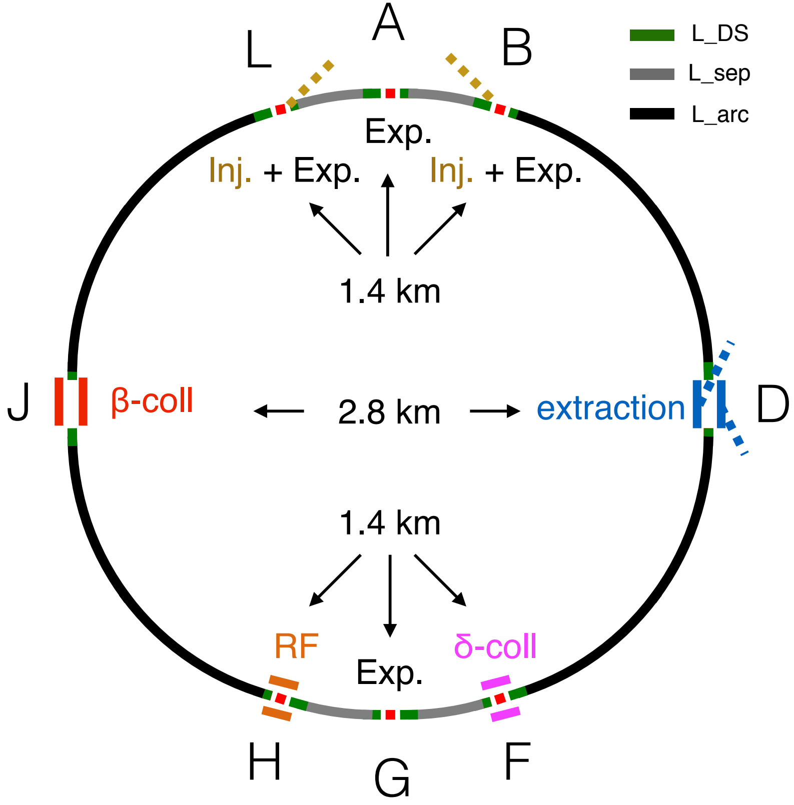
Implementation:
- 90-100 km fits well geological situation in Geneva basin
- Connected with LHC or SPS

Same Tunnel for FCC-ee and FCC-hh



Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.

Two separate rings for e^+ and e^- (# bunches)
A booster for continuous top-up (lifetime)
Asymmetric interaction region (SR)
Crossing angle 30 mrad

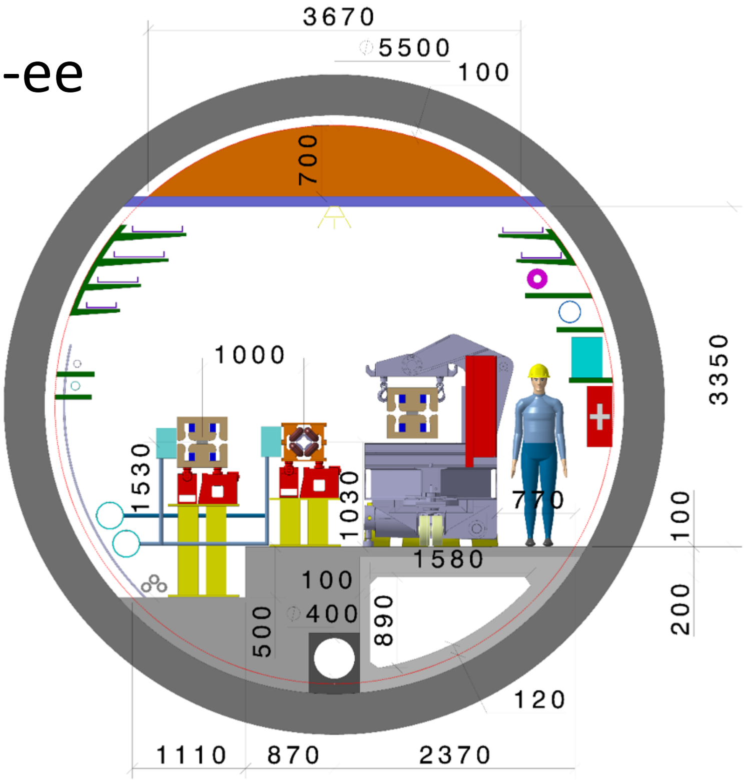


Two main IP's in A, G for both machines

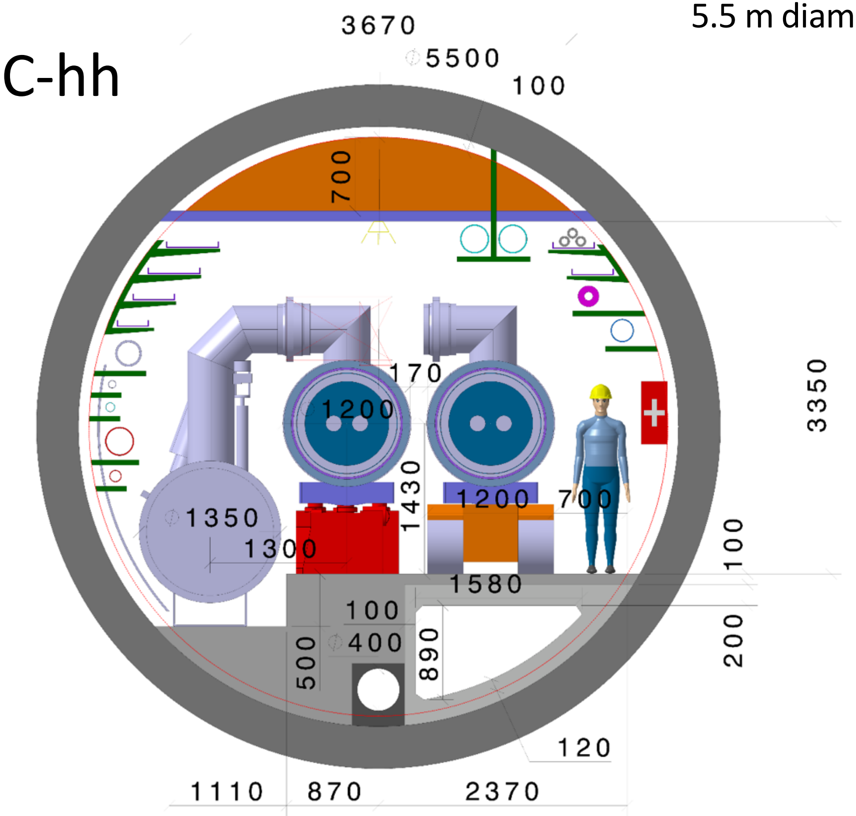
FCC Tunnel Integration

5.5 m diameter

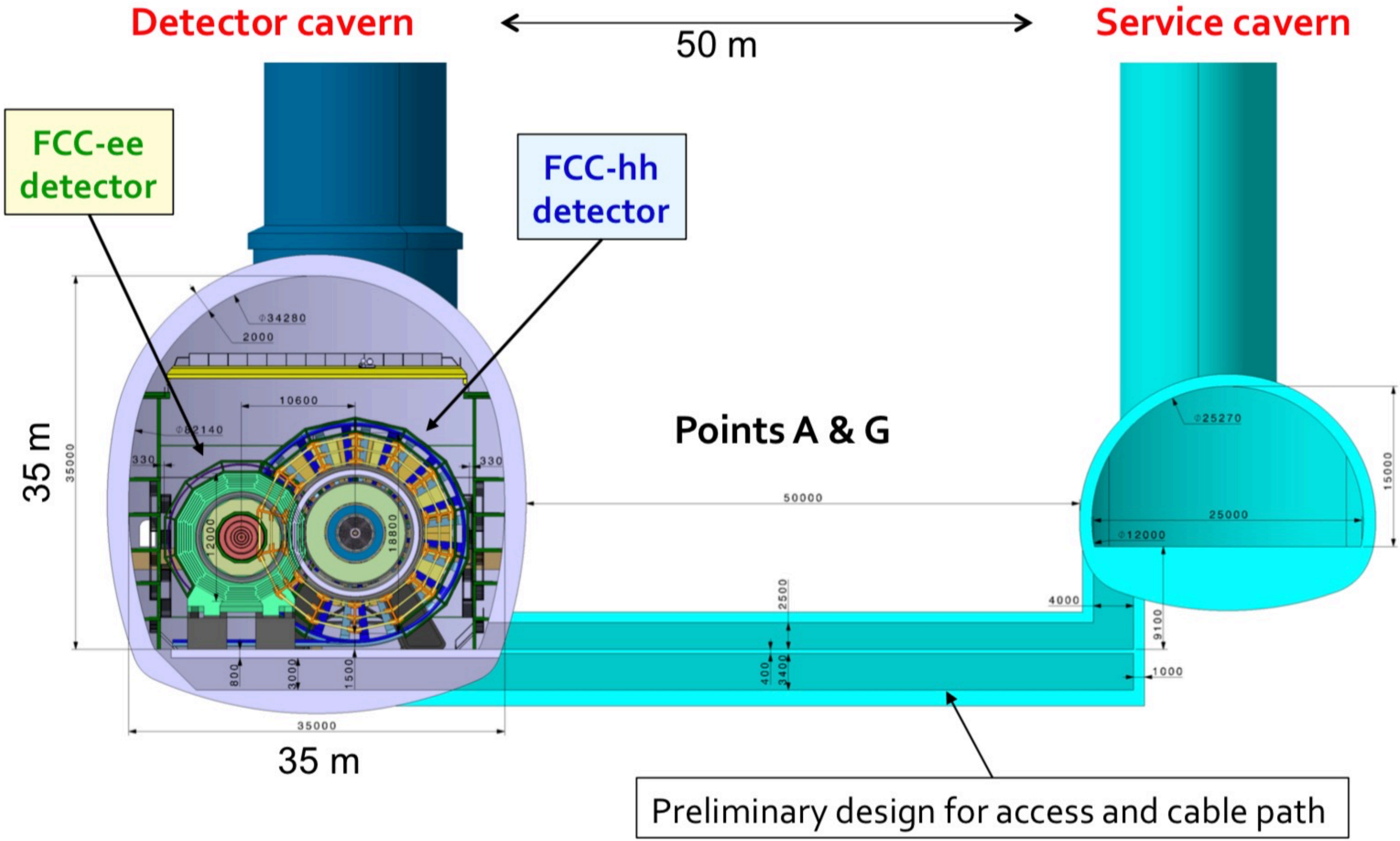
FCC-ee



FCC-hh



Sharing the Same Experimental Caverns



Detector cavern

50 m

Service cavern

FCC-ee detector

FCC-hh detector

Points A & G

35 m

35 m

Preliminary design for access and cable path

FCC-hh

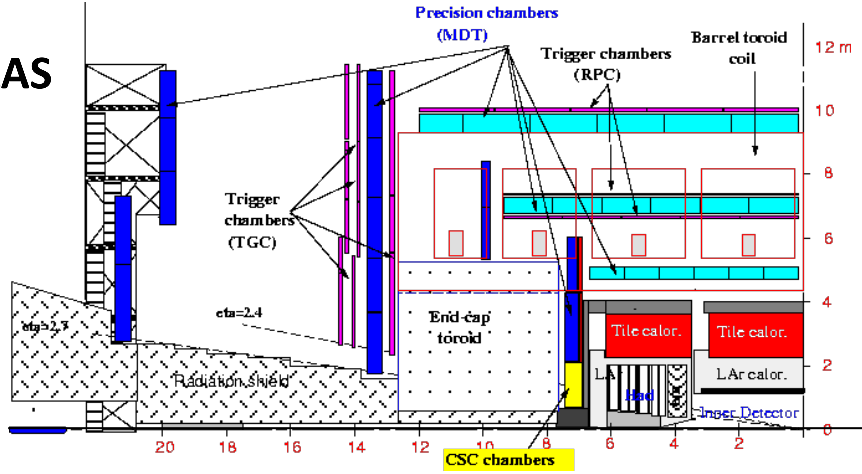
FCC-hh (pp) Collider Parameters

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

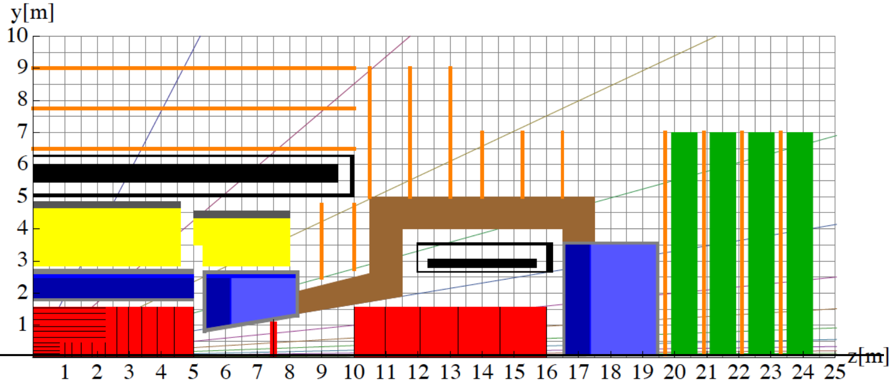
FCC-hh Detector

FCC-hh Detector: Comparison to ATLAS & CMS

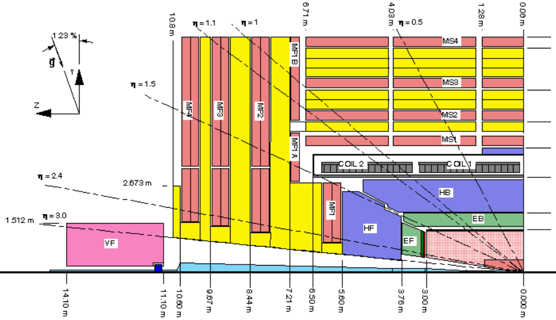
ATLAS

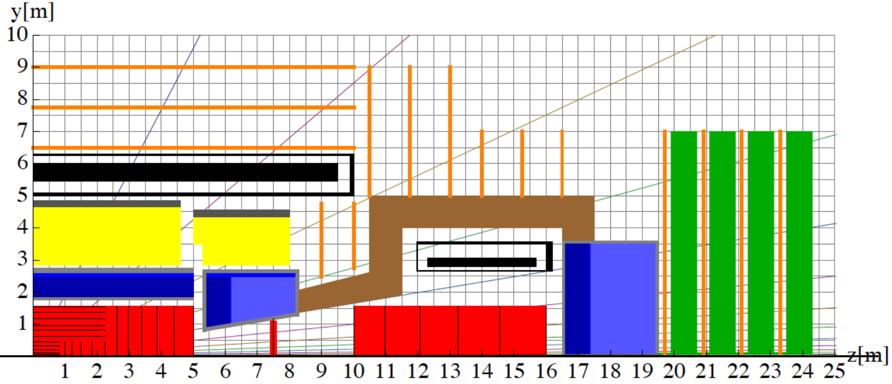


FCC-hh Reference Detector

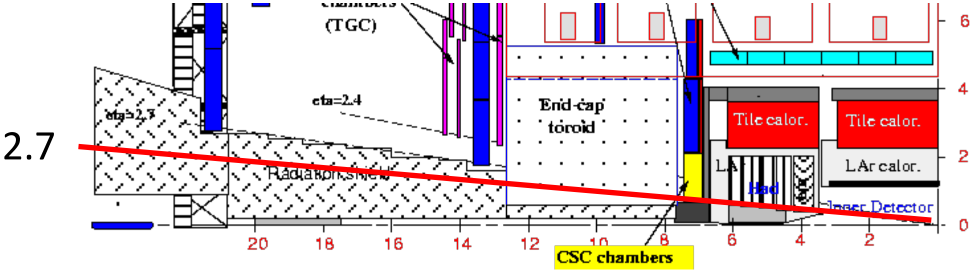


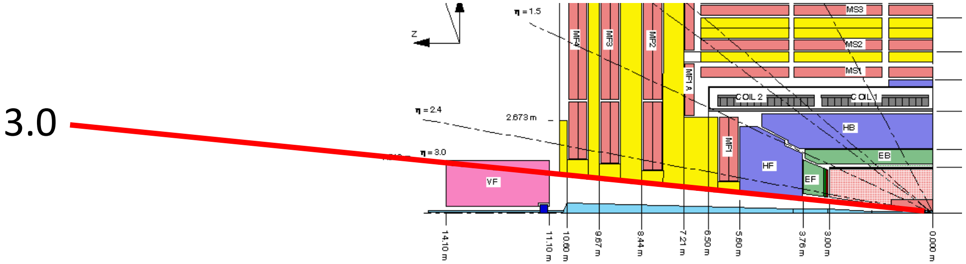
CMS

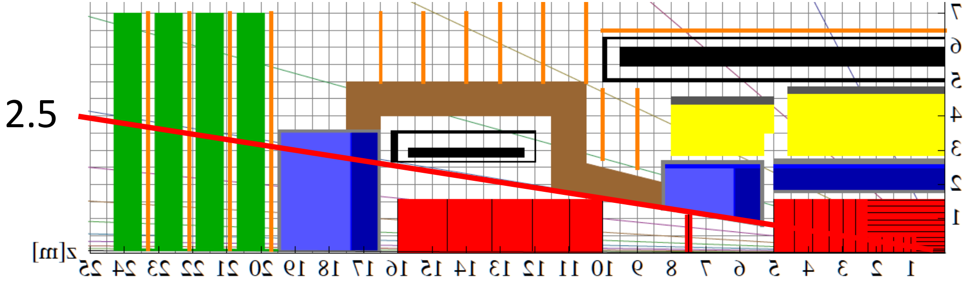




Radiation: Comparison to ATLAS & CMS





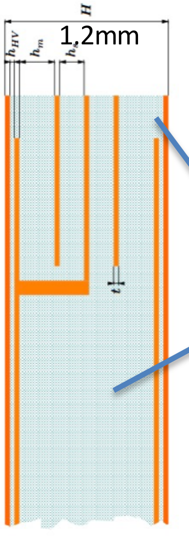


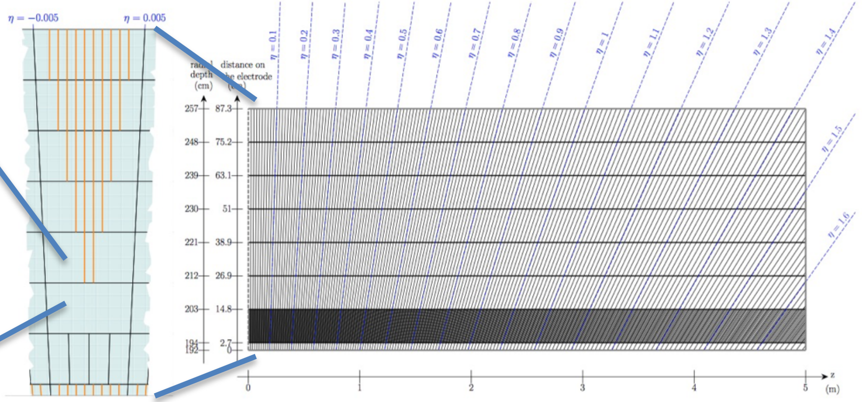
- The forward calorimeters are a very large source of radiation (diffuse neutron source).
- In ATLAS the forward calorimeter is inside the endcap calorimeter, in CMS the forward calorimeter is enclosed by the return Yoke.
- For the FCC, the forward calorimeter is moved far out in order to reduce the radiation load and increase granularity.
- → A shielding arrangement is needed to stop the neutrons to escaping into the cavern hall and the muon system.

LAr Calorimeter: How to Achieve High Granularity?

Realize electrodes as multi-layer PCBs (1.2mm thick), 7 layers

- HV and read-out
- Signal traces (width w_t) in dedicated signal layer connected with vias to the signal pads
- Traces shielded by ground-shields (width w_s) forming 25Ω – 50Ω transmission lines
- → capacitance between shields and signal pads C_s will add to the detector capacitance via the gap C_d
- → $C_{cell} = C_s + C_d \approx 25 – 1000$pF
- The higher the granularity the more shields are necessary → C_s increases, C_d decreases (smaller cells)

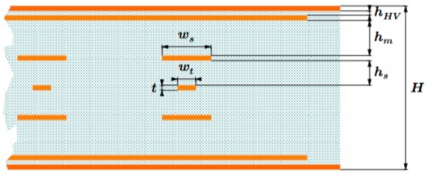




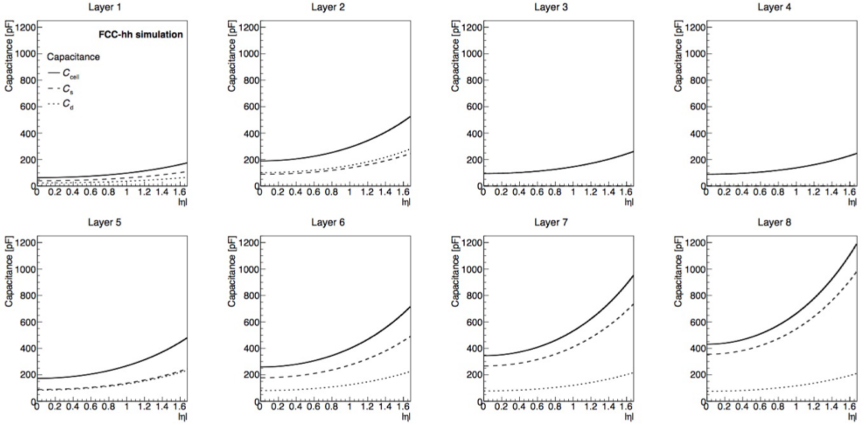
→ Serial noise contribution proportional to capacitance C_{cell}

→ 0.5 – 40MeV noise per read-out channel assuming ATLAS-like electronics

→ ≤ 0.1 MeV possible with cold preamplifiers



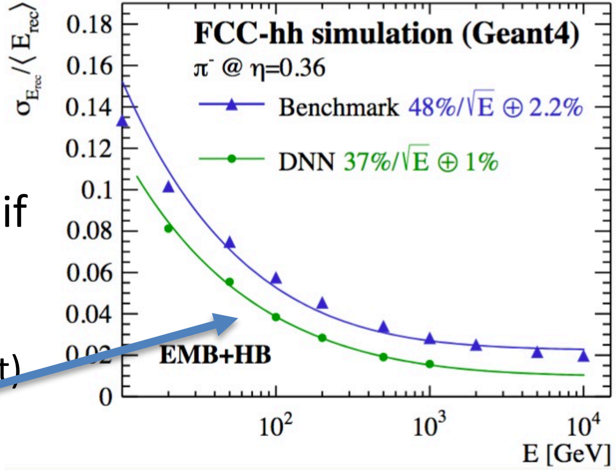
Hadronic showers:
Energy sums over O(500-10000) cells

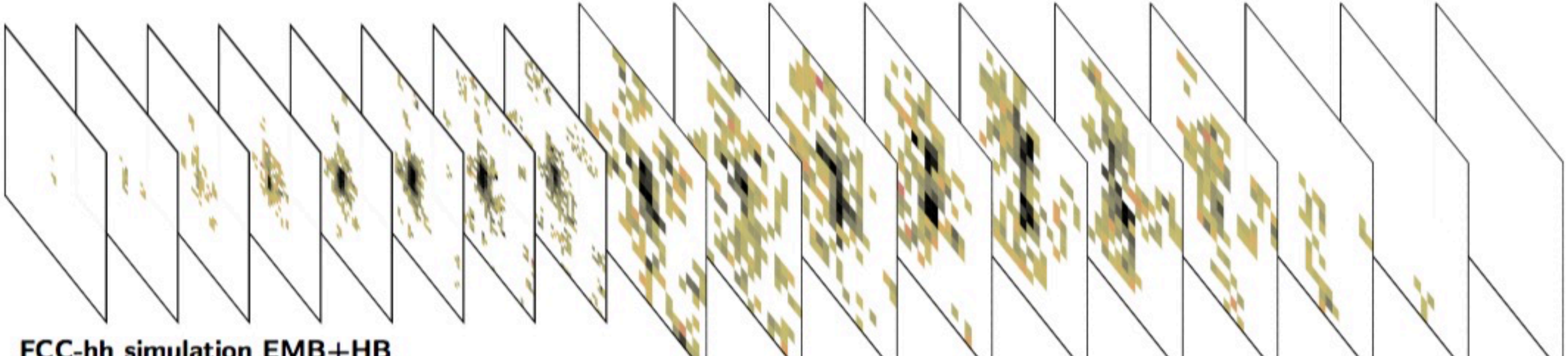


Plots A. Zaborowska, J. Faltova

Combined Performance for Hadrons

- **FCC-hh calorimetry: High granularity of EM and HCal**
- → Ideal for particle flow techniques (but not yet implemented in SW)
- → Which resolution can be achieved with calorimetry only, if using the full shower-imaging information?
- **First results** obtained using a **convolutional neural network**
  - Training with 8M events (without electronics noise for the moment)
  - Excellent results obtained → **Sampling term of 37%/√Ē (!!!)**



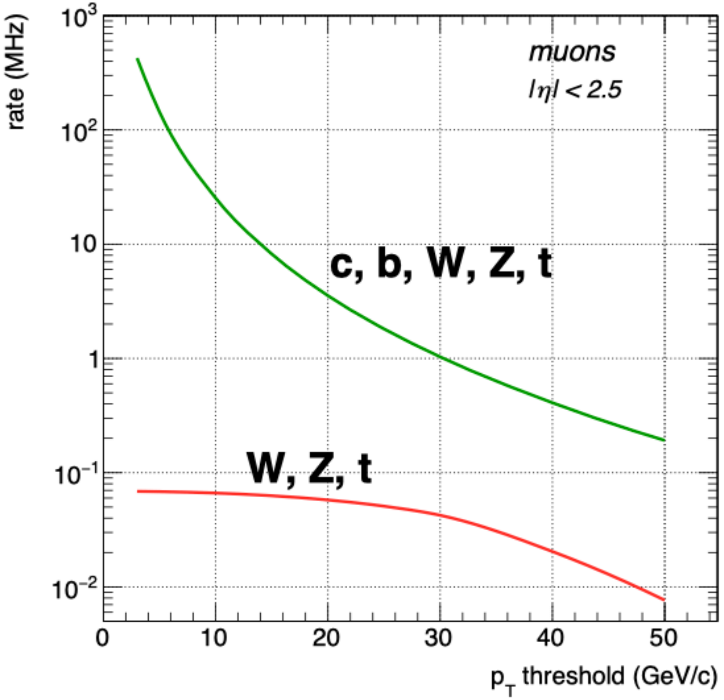


FCC-hh simulation EMB+HB

100 GeV π^- @ $\eta = 0.36$, topo-cluster 4-2-0 PU0

Plots C. Neubüser, J. Kieseler

Challenges for Muon System



- **Task: Triggering and muon identification**
- 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 to the muon system is key for W/Z/t triggering.
- Overall expected rates similar to HL-LHC
- **→ Gas detectors similar to those used for HL-LHC are a good option**