FCC-hh detector concept

Anna Zaborowska
on behalf of the FCC-hh detector group

6th FCC Physics Workshop,
January 24th 2023

Conceptual design of an experiment at the FCC-hh, a future 100 TeV hadron collider

FCC-HH: THE HADRON COLLIDER

Recognizing that circular proton-proton colliders are the main, and possibly only, experimental tool available in the coming decades for directly exploring particle physics in the energy range of tens of TeV, the FCC study prepares for a 100 TeV hadron collider (FCC-hh) as the next step. FCC-hh will increase the mass reach by almost an order of magnitude and the integrated luminosity by a factor of 50 with respect to the LHC thus being able to access a large range of new physics opportunities.

Together with a heavy ion operation programme and the possibility of integrating a lepton-hadron interaction point (FCC-he), it provides the amplest perspectives for research at the energy frontier.

Cite as: *Future Circular Collider Study. Volume 3: The Hadron Collider (FCC-hh) Conceptual Design Report, preprint edited by M. Benedikt et al. CERN accelerator reports, CERN-ACC-2018-0058, Geneva, December 2018. Published in Eur. Phys. J. ST.*

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doi:10.1140/epjst/e2019-900087-0

Study of the FCC-hh detector concept is summarised in Vol 3 of the FCC CDR, published in 2019.

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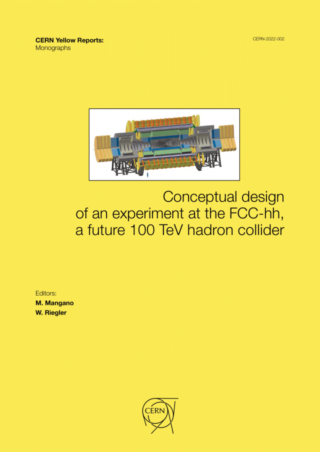
Summary could not cover all the activities within the FCC-hh detector group.

A detailed report was prepared at the same time and has finally been published in 2022.

Conceptual design of an experiment at the FCC-hh, a future 100 TeV hadron collider

doi:10.23731/CYRM-2022-002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Conceptual design
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Editors:
M. Mangano
W. Riegler

CERN

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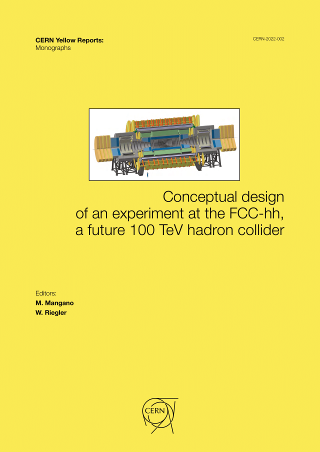
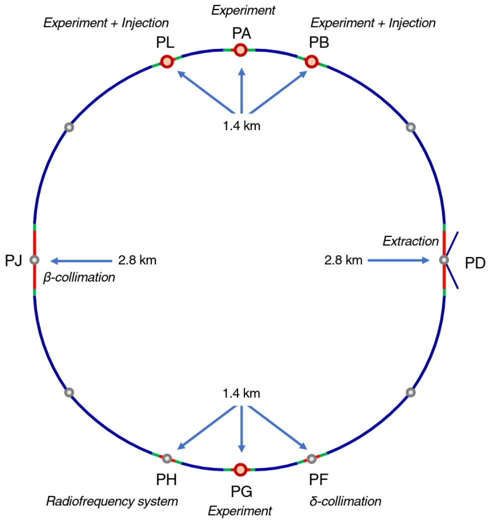


Detailed summary of work on a design of **general purpose detector**.
A reference layout has been studied in terms of performance, discussed, and parameterised.
Parameterisation is used to evaluate **key benchmark physics topics**.

Contents

FCC collider



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- Similar layout to LHC
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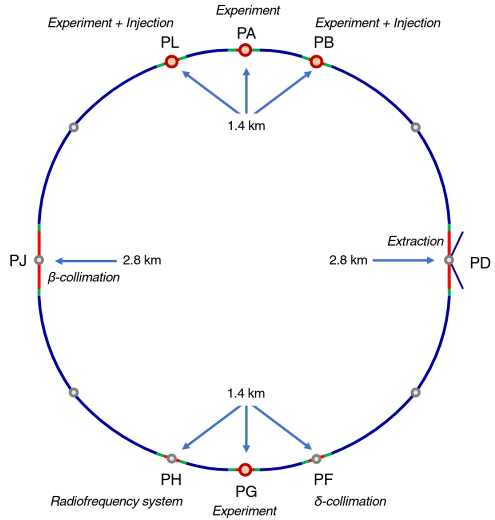
- Two lower luminosity points (PL, PB)

FCC collider



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FCC-hh experiment: we decided to demonstrate a single general purpose detector

Key baseline parameters

Parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14		27	100
Circumference	km	26.7			97.8
Peak luminosity, nominal (ultimate)	$\times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$	1 (2)	5(7.5)	16	30
bunch spacing	ns	25			
Number of bunches		2808	2760	2808	10600
Goal integrated luminosity	ab^{-1}	0.3	3	10	30
σ_{inel}	mbarn	80		86	103
σ_{tot}	mbarn	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 avg PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950
RMS luminous region σ_z	mm	45	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
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$\langle p_{\mathrm{T}} \rangle$	GeV/c	0.6		0.7	0.76
Bending radius for $\langle p_{\mathrm{T}} \rangle$ at B=4 T	cm	47	47	49	59

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FCC-hh an extremely high luminosity machine.

- huge particle/data rates
- significantly higher radiation level (especially in inner/forward detector)

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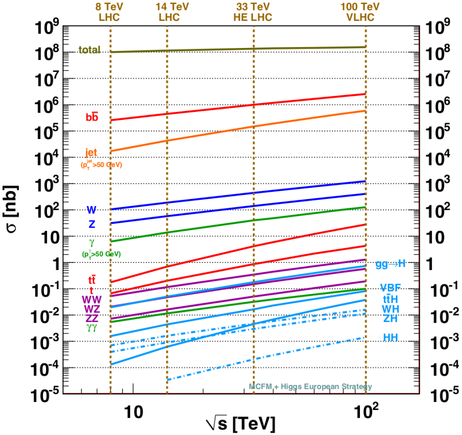
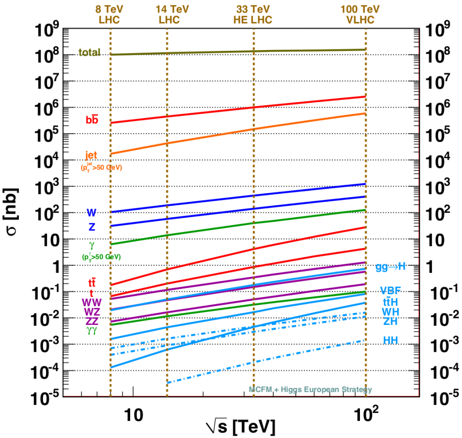
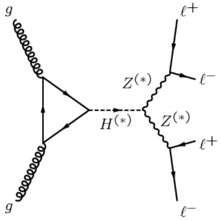


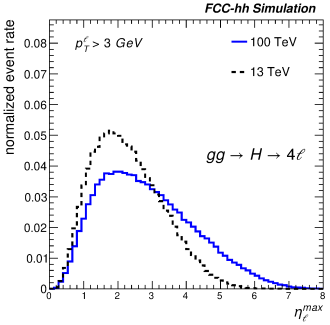
Physics requirements

More forward physics → large acceptance

- precision momentum spectroscopy and energy measurements up to $|\eta| < 4$







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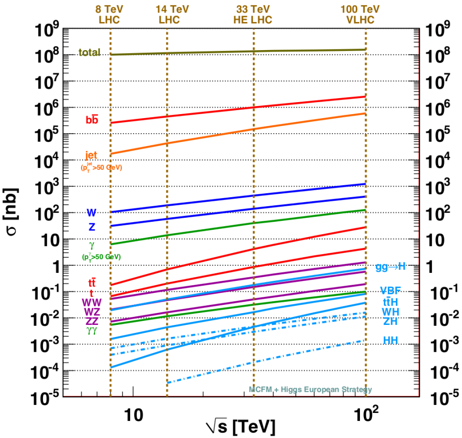
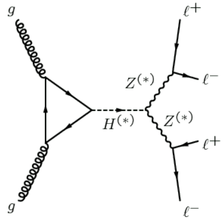
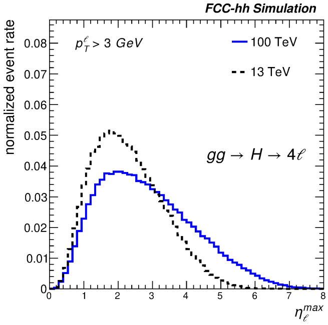
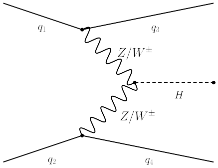
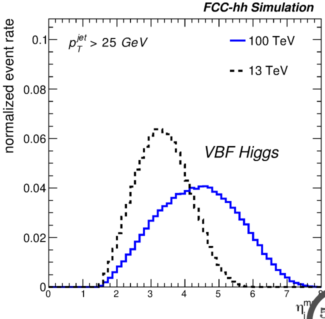
- tracking and calorimetry up to $|\eta| < 6$







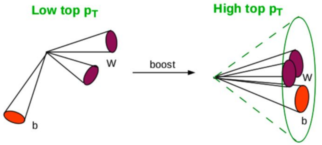




Physics requirements

Physics objects will be more boosted

Requirement of high granularity (both in tracker and calorimeters)



e.g.: W(p_T=10 TeV) will have decay products separated by $\Delta R = 0.01$.

Long-lived particles live longer:

- 5 TeV tau lepton can travel 10 cm before decaying
- 5 TeV b-hadron can travel 50 cm before decaying

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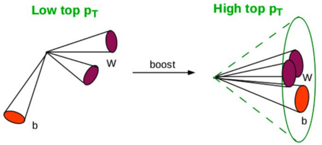

Tracking

- granularity defined by
  - occupancy
  - double track separation
  - pattern recognition
  - vertex/momentum resolution
- target $\sigma_{p_T}/p_T = (10 - 20)\%$ @ 10 TeV (10% @ 1 TeV at LHC)
- $\sigma_{p_T}/p_T < 1\%$ @ low-p_T tracks (multiple scattering limit)

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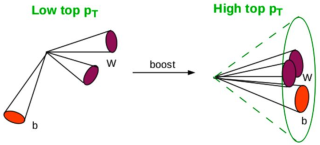

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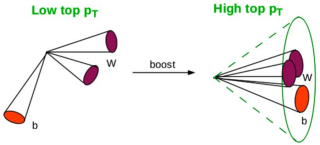

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Calorimeter:

- keep constant term as small as possible
- target $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$ for electrons/photons
- target $\sigma_E/E = (50-60)\%/\sqrt{E} \oplus 3\%$ for jets
- transverse granularity x4 better than ATLAS or CMS

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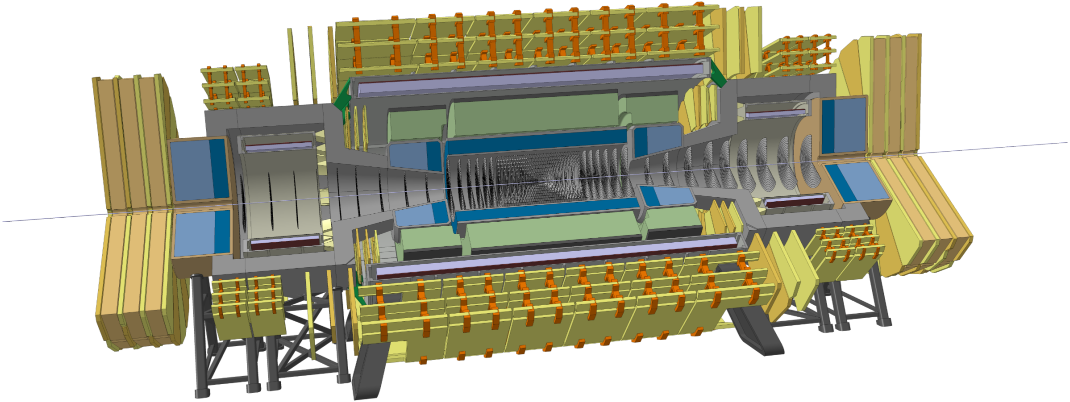
FCC-hh reference detector layout



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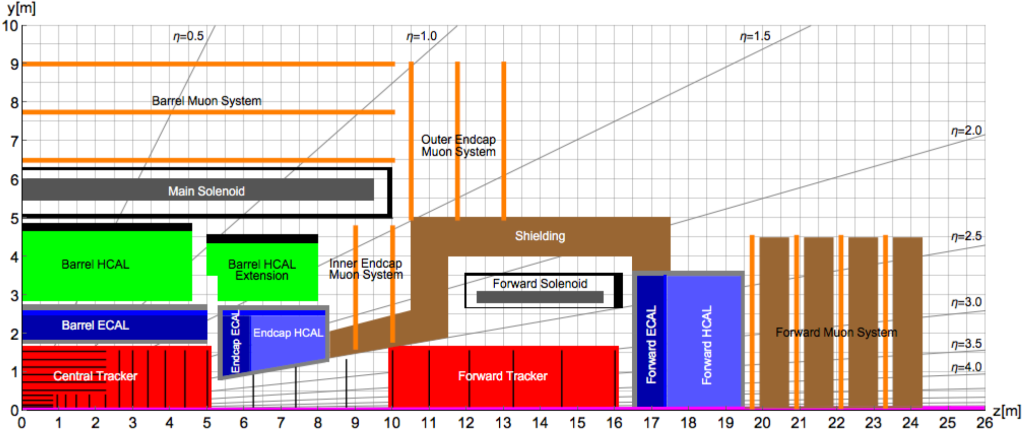
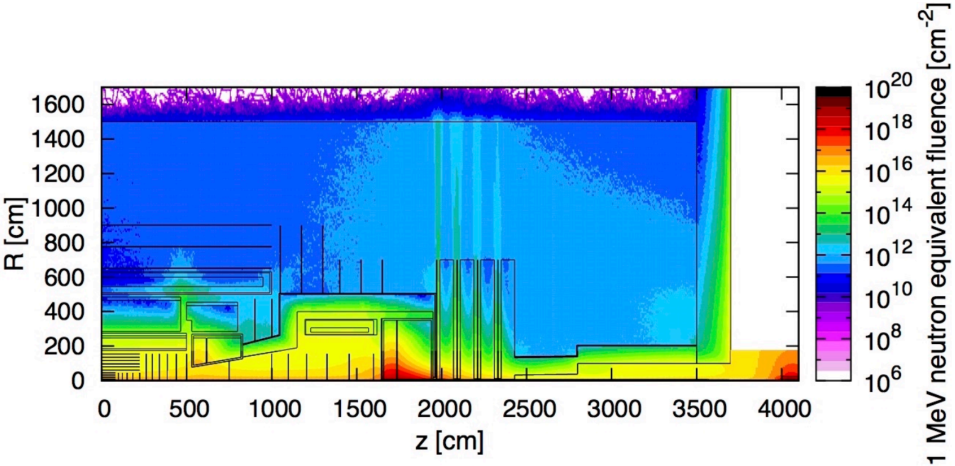


- 50 m long, 20 m diameter
- cavern length 66 m
- L^* of FCC 40 m

1 MeV neutron equivalent fluence for 30 ab^{-1}



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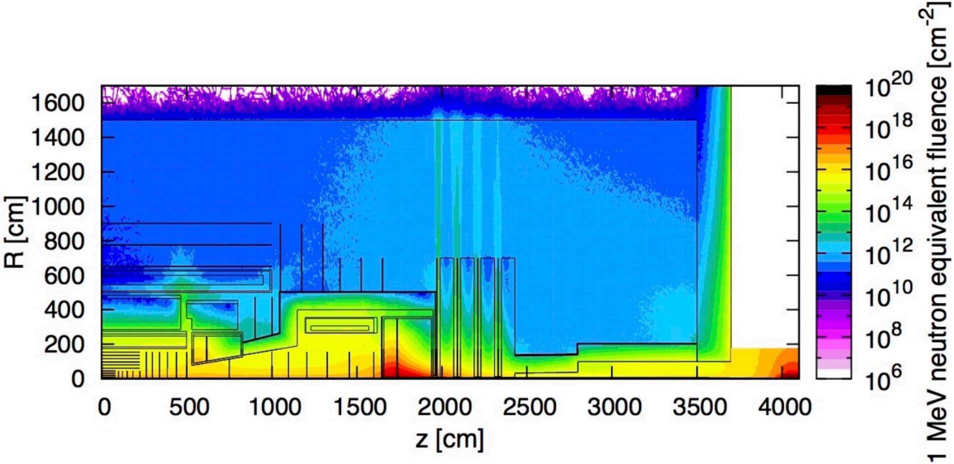
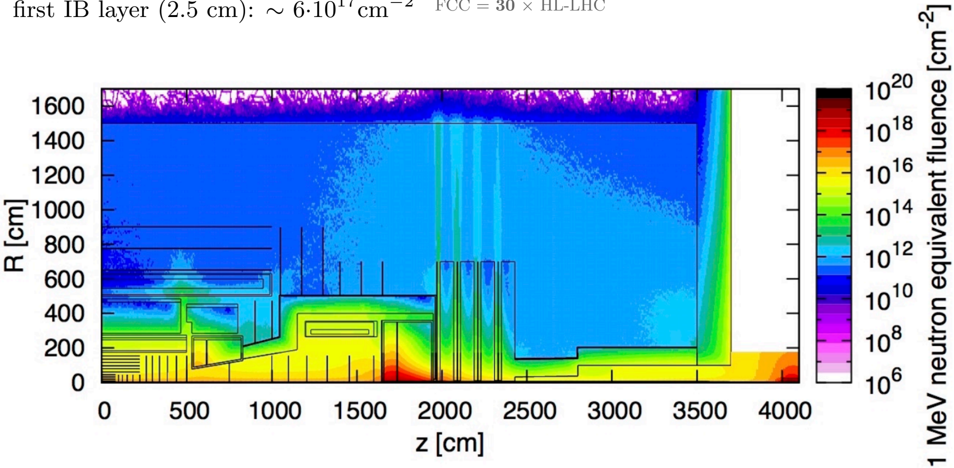


Forward calorimetry:
maximum at $\sim 10^{18}$ cm^{-2}

1 MeV neutron equivalent fluence for 30 ab^{-1}

Tracker:
first IB layer (2.5 cm): $\sim 6{\cdot}10^{17}\text{cm}^{-2}$

HL-LHC = **20**× LHC
FCC = **30** × HL-LHC



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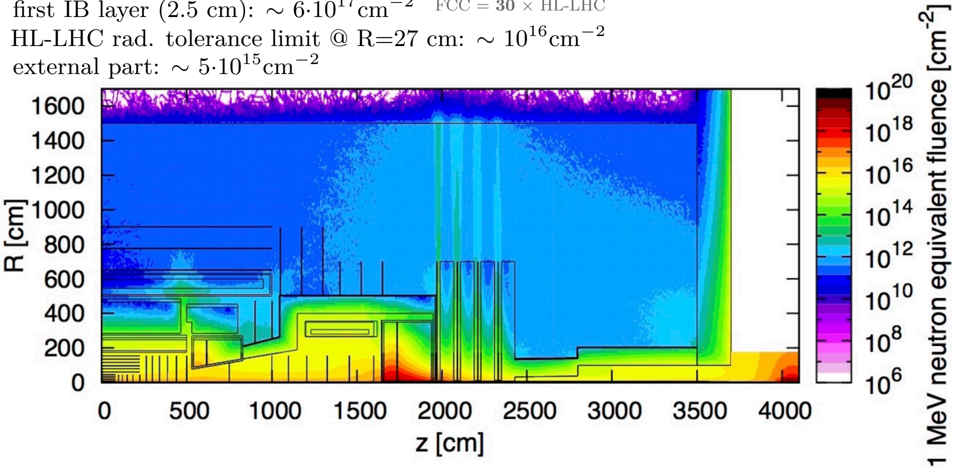
HL-LHC rad. tolerance limit @ R=27 cm: $\sim 10^{16}\text{cm}^{-2}$

external part: $\sim 5{\cdot}10^{15}\text{cm}^{-2}$

HL-LHC = **20**× LHC
FCC = **30** × HL-LHC



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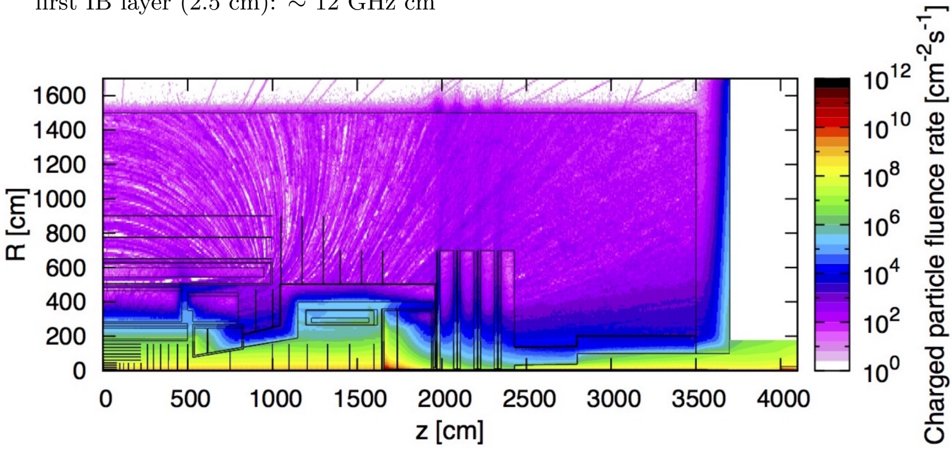

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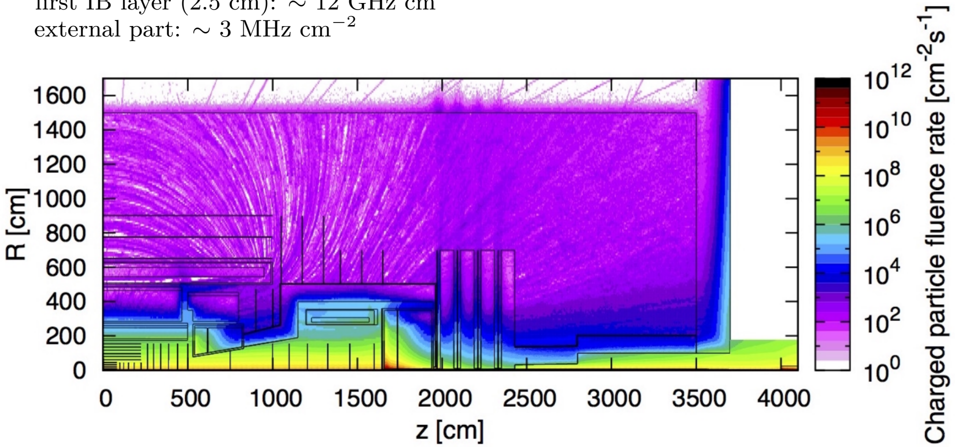

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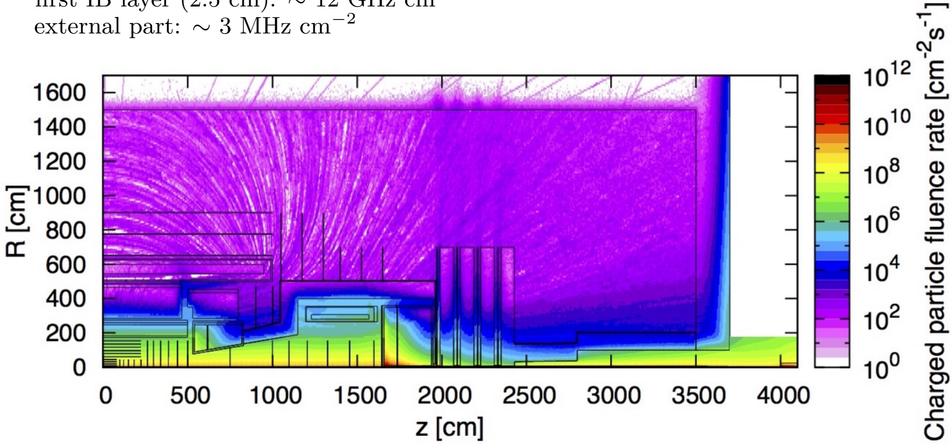

Barrel & outer endcap muon chambers:
$<$0.5 kHz cm^{-2}

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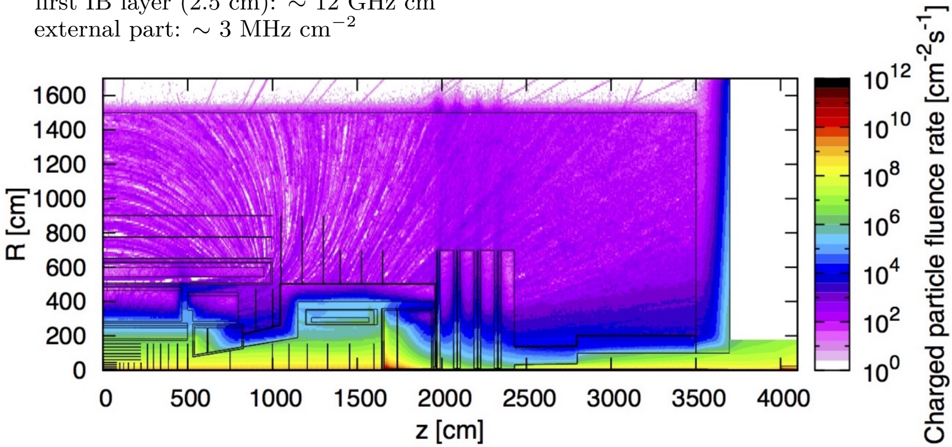
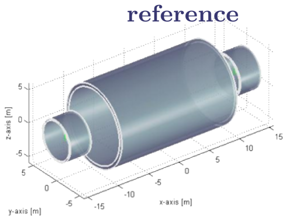
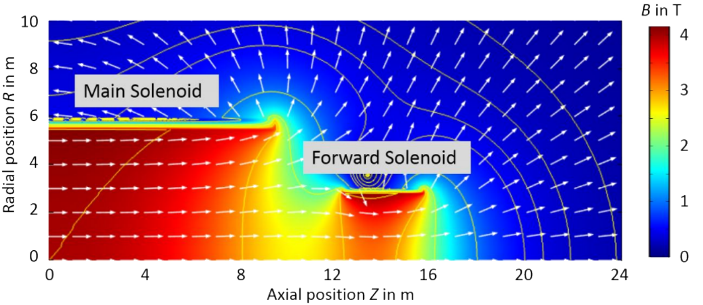


Barrel & outer endcap muon chambers:
<0.5 kHz cm^{-2}

Inner endcap muon chambers:
~ 10 kHz cm^{-2} similar to HL-LHC

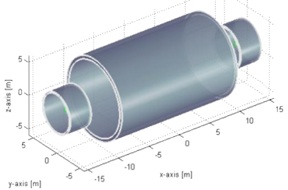
Magnet

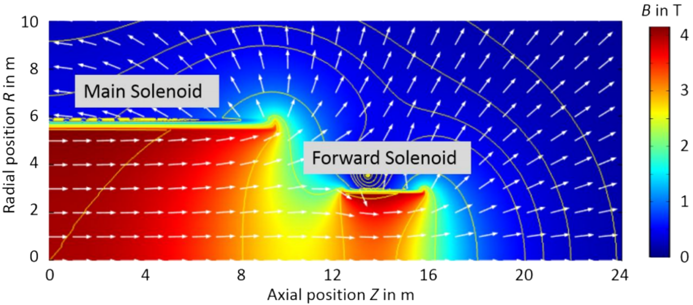

reference
z-axis [m]
y-axis [m]
x-axis [m]


Main Solenoid
Forward Solenoid
Radial position R in m
Axial position Z in m
B in T

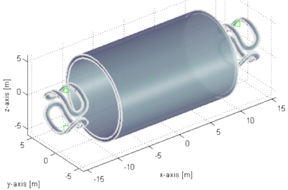
Magnet

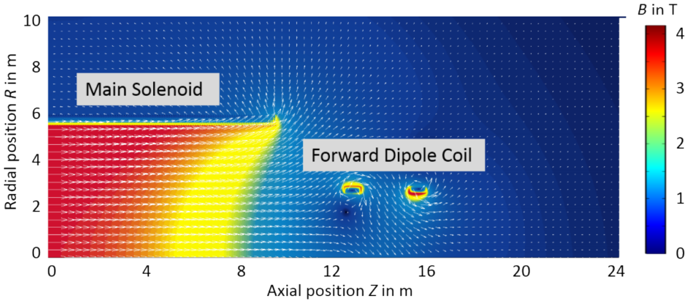
reference





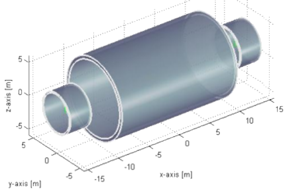
alternative

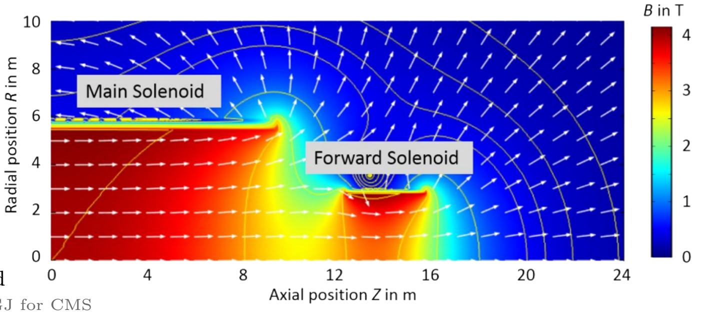




Magnet

reference



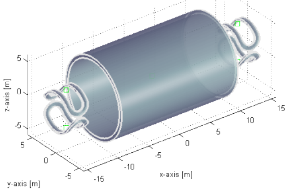


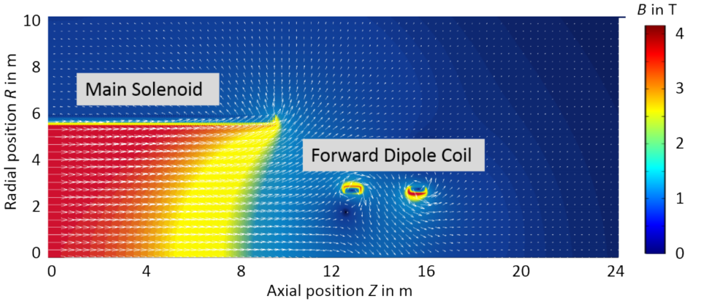
12.5 GJ stored energy in main solenoid

2.7 GJ for ATLAS, 1.6 GJ for CMS

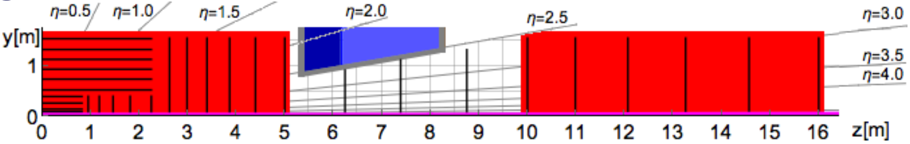
cold mass + cryostat ≈ 2000 tons

alternative





Magnet: track momentum resolution



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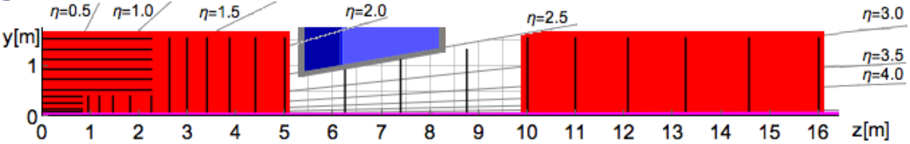

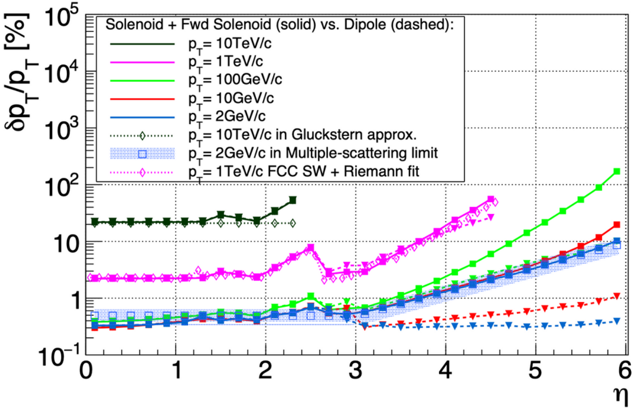

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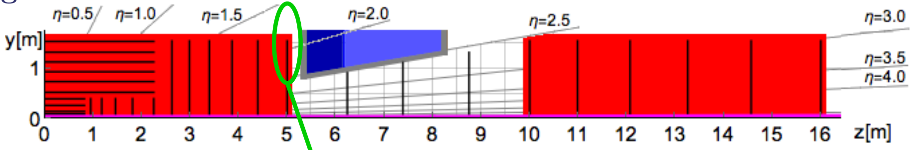

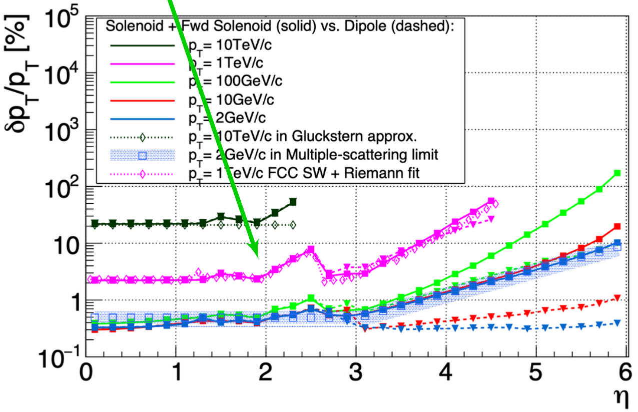

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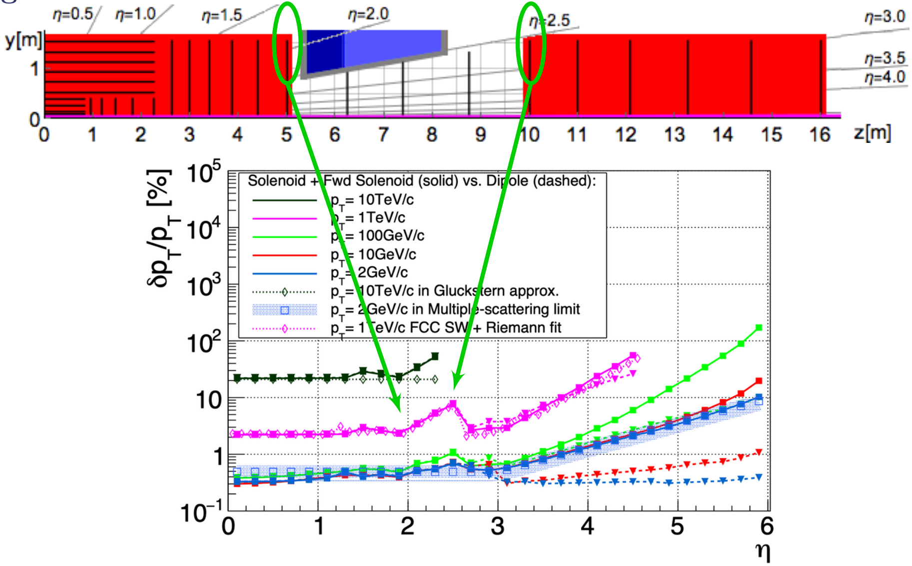

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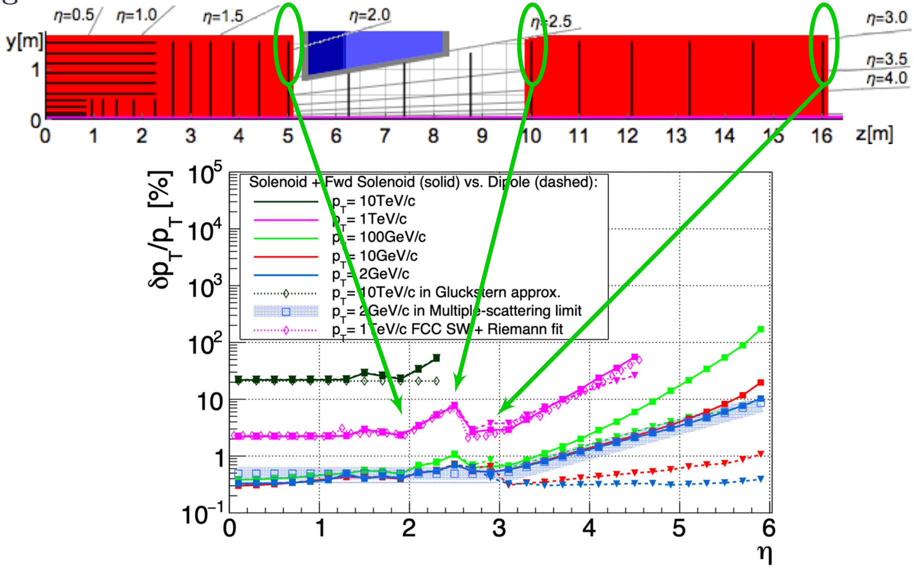

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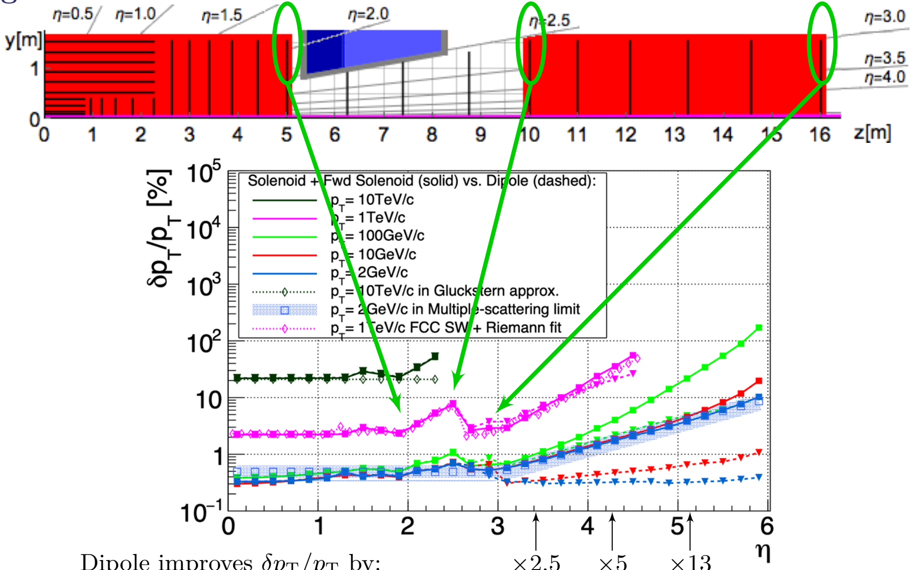
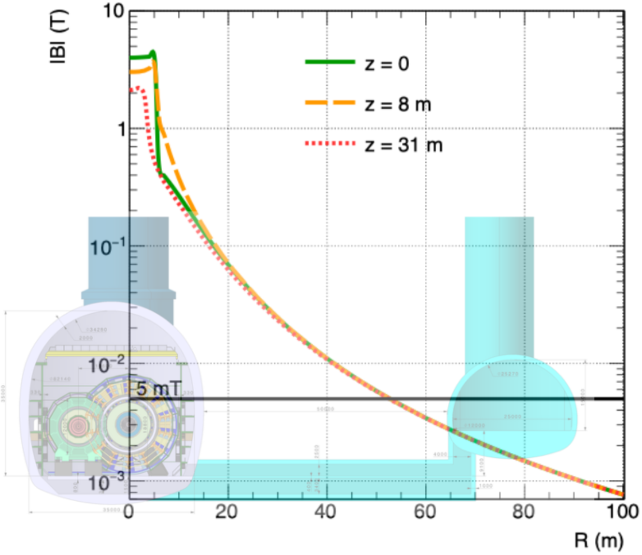
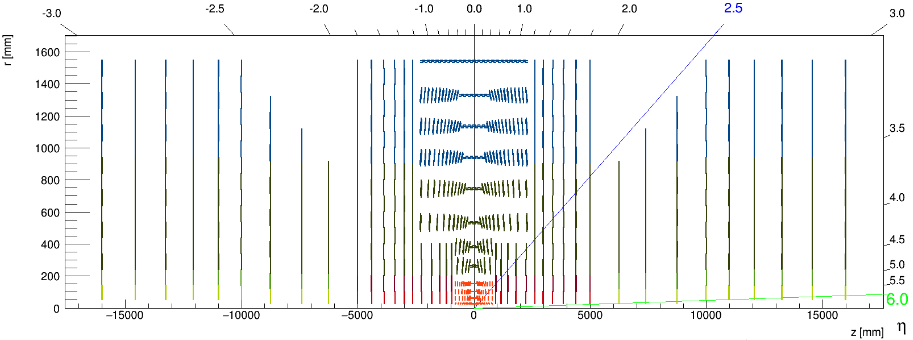


Dipole improves $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ by: ×2.5 ×5 ×13

Stray field and service cavern



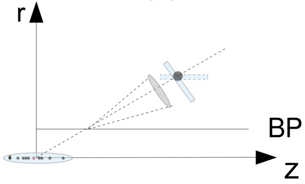
Tracker



- Minimization of the effect of multiple scattering (material budget).
- Optimised by the pattern recognition and vertexing.

→ Inclined tracker modules.

- $390\,\mathrm{m}^2$ of silicon ($430\,\mathrm{m}^2$ for flat layout) $250\,\mathrm{m}^2$ for ATLAS/CMS Phase-II
- 16 × 109 channels 6 × 109 and 2.2 × 109 for ATLAS/CMS Phase-II



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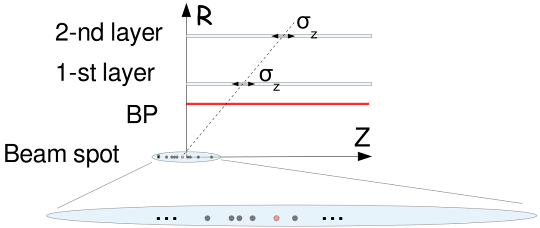
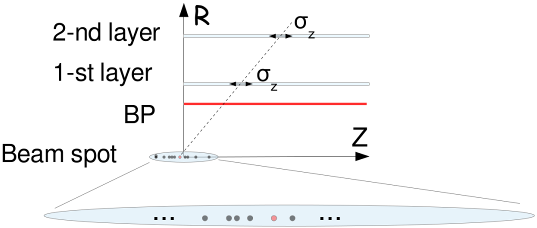
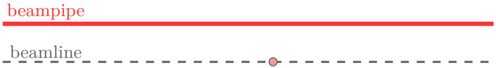


Average distance between vertices at z=0:
$\sim 120\,\mu$ m in space and 0.4 s in time
For HL-LHC it is ∼1 mm and 3 ps

Tracker





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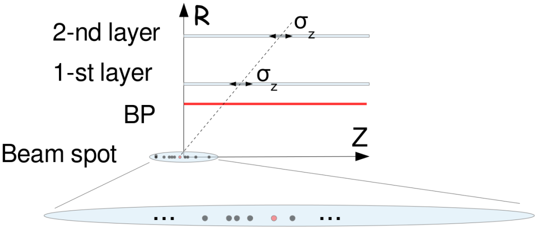
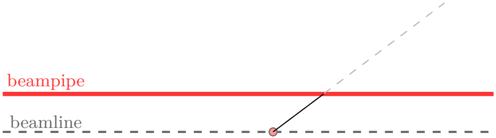
Tracker





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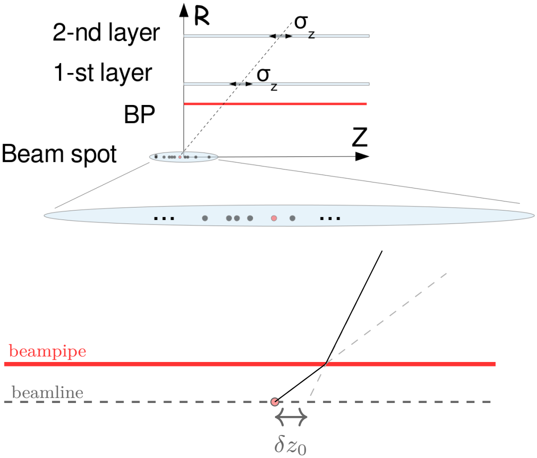

Average distance between vertices at z=0:
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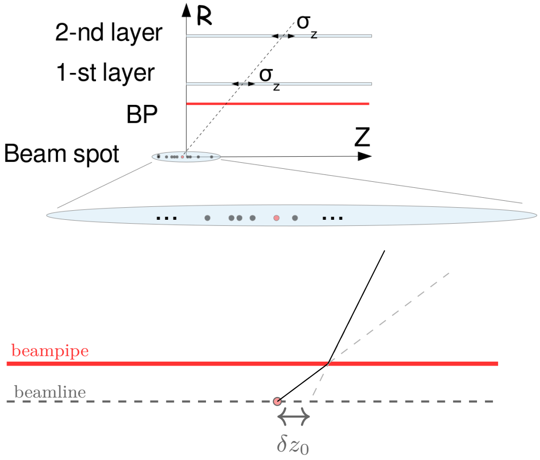
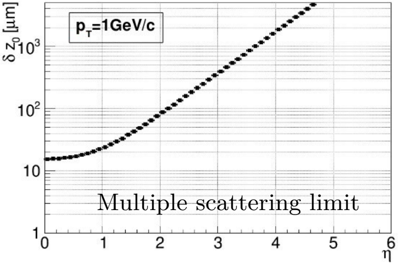
For HL-LHC it is ~1 mm and 3 ps

Tracker





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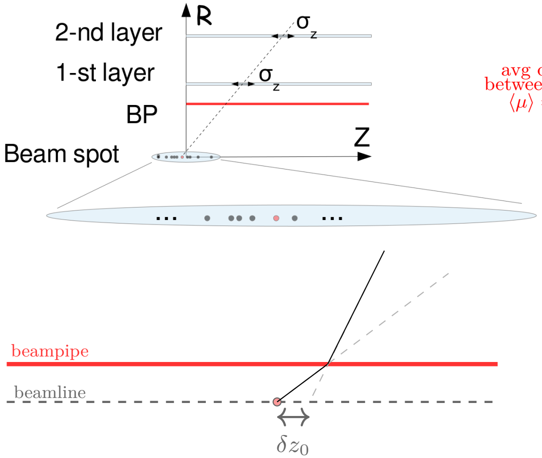

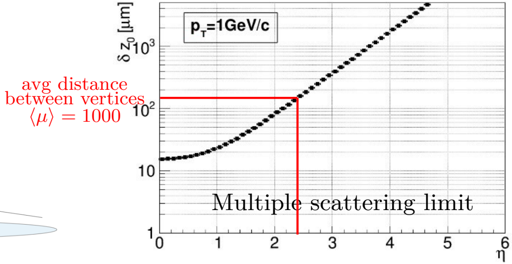

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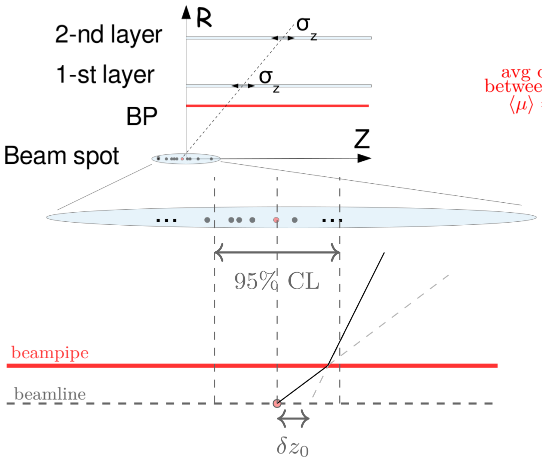

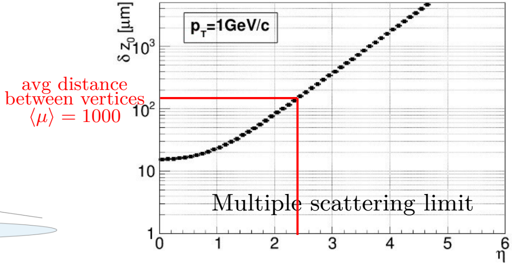

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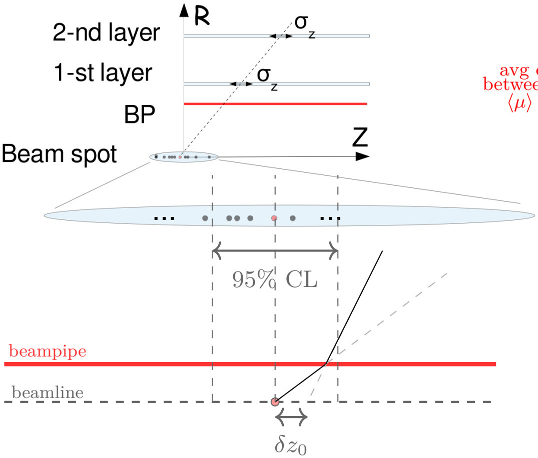
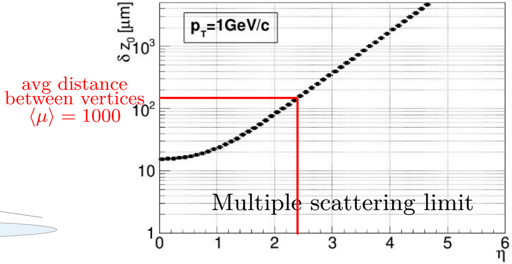
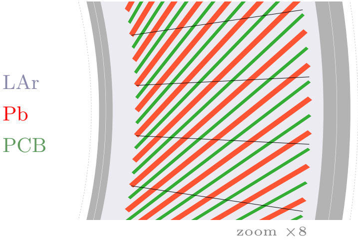




Effective pile-up for 1 GeV/c at $\eta = 4$:
- w/o timing: **20**
- 25 ps: **8**
- 5 ps: **2**

Average distance between vertices at z=0:
$\sim 120\,\mu$ m in space and 0.4 s in time
For HL-LHC it is ~1 mm and 3 ps

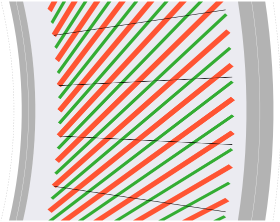
LAr electromagnetic calorimeter



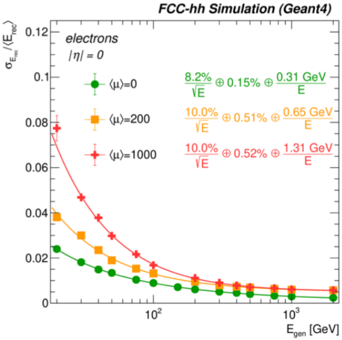
- Much more granular than ATLAS calorimeter (×10).
- High longitudinal and lateral segmentation possible with straight, multilayer electrodes.

LAr electromagnetic calorimeter

LAr
Pb
PCB



zoom ×8



- Much more granular than ATLAS calorimeter ($\times 10$).
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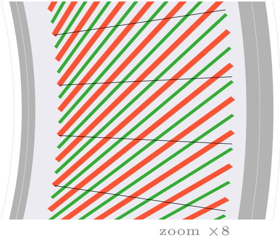
LAr electromagnetic calorimeter



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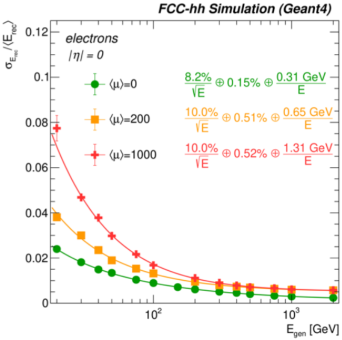
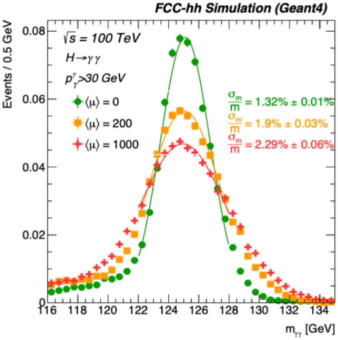
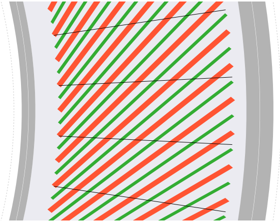
- Huge impact of pile-up in calorimeter standalone measurements - need to subtract pile-up using pile-up track identification.





LAr electromagnetic calorimeter

LAr
Pb
PCB



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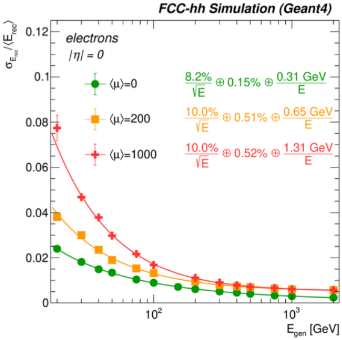
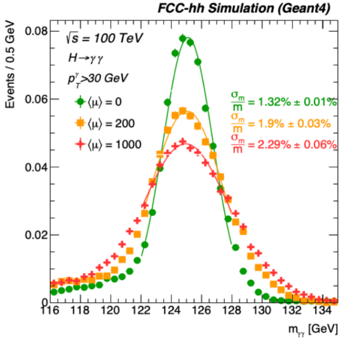
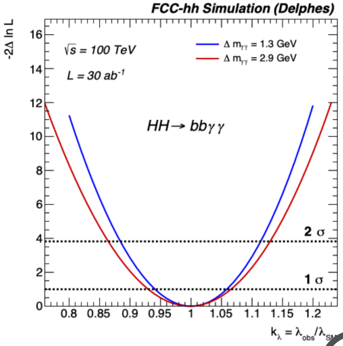
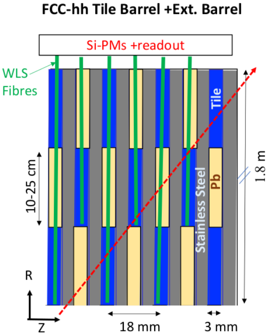




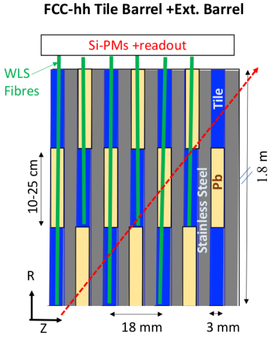


Hadronic barrel calorimeter



- ATLAS-like tile calorimeter with scintillating tiles/WLS fibres + stainless steel and lead (1:3.3:1.3)
- SiPM readout: faster, less noise, less space
- 3-4 times higher granularity in $\Delta\eta\Delta\varphi = 0.025 \times 0.025$ and 10 layers
- For containment of multi-TeV jets (98%): ECAL + HCAL depth $\sim 11\lambda$ at $\eta = 0$.

Hadronic barrel calorimeter



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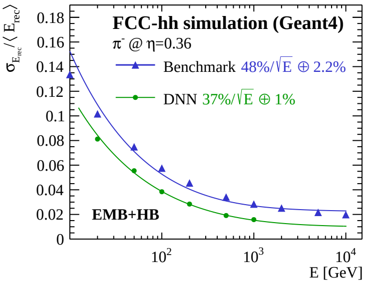
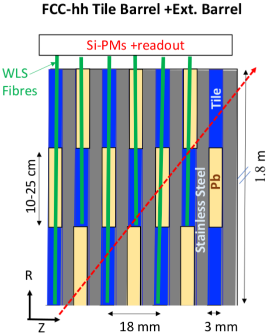


Preliminary no-noise (PU) studies

Hadronic barrel calorimeter



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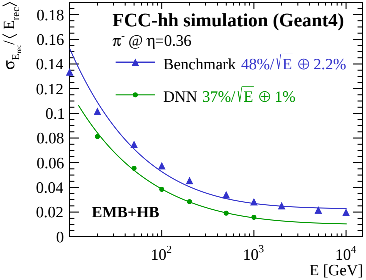

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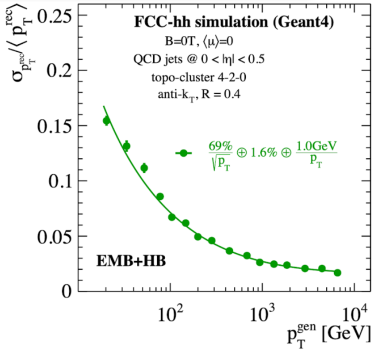
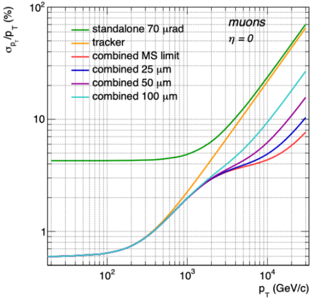


Combined (tracker) studies vital for jets in B field

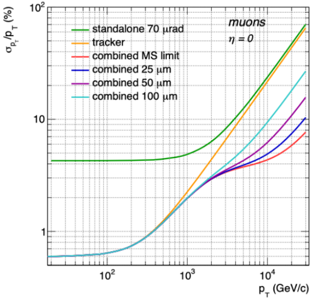
Muon system



- Combined tracker/muon system performance is important, not standalone muon performance

- Combined muon momentum resolution can achieve 10% even for momenta of 20 TeV/c at $\eta = 0$.

Muon system



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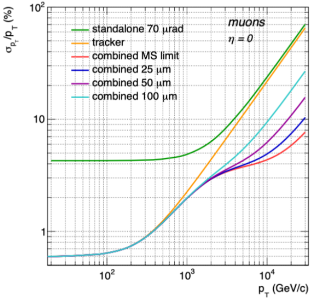
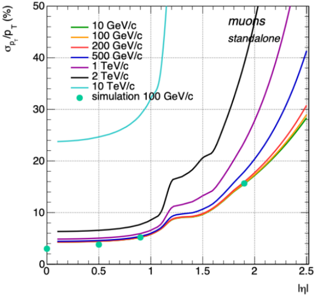
Muon system





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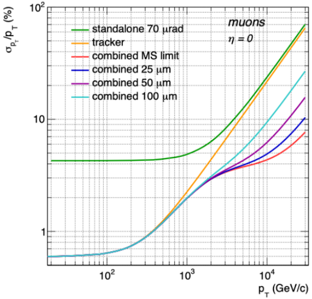
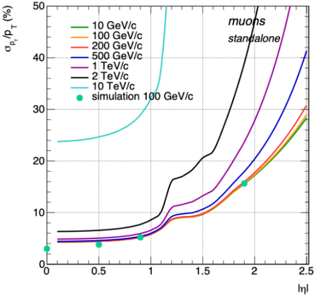
Muon system





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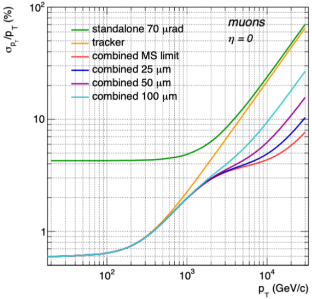
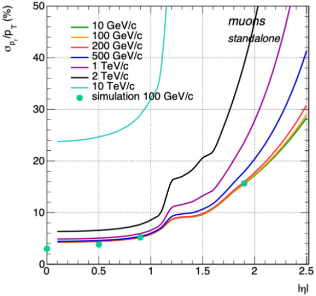
Muon system





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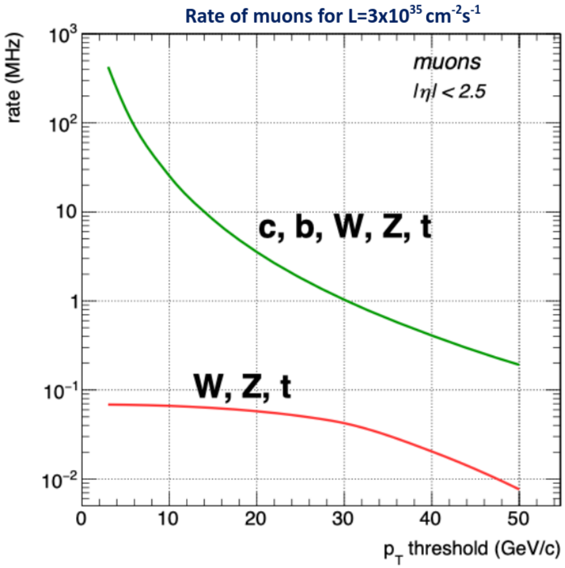
- In forward muon system, standalone momentum measurement and triggering can only be achieved when using a forward dipole (like ALICE, LHCb).
- Gas detectors similar to the ones employed for HL-LHC are good candidates for the muon systems.

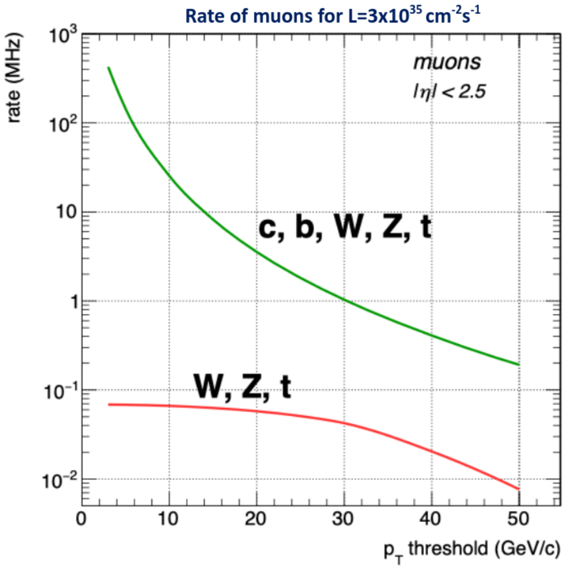
Muon system



Rate of muons for L=3x10^35 cm^-2s^-1
rate (MHz)
muons
|η| < 2.5
c, b, W, Z, t
W, Z, t
p_T threshold (GeV/c)
10^3
10^2
10
1
10^-1
10^-2
0
10
20
30
40
50

Muon system

- Muon rate dominated by c and b decays
- In contrast to leptonic decays from W, Z, t these muons are not isolated but accompanied by particles seen in calorimeters
- Isolation with calorimeter information is key for W/Z/t triggering.



Trigger

Taking as an example ATLAS phase-II trigger:

- Calorimetry will be digitized at 40 MHz and sent via optical fibers to L1 electronics outside the cavern at **25 TByte/s** to create the L1 Trigger at about 10 μs latency.

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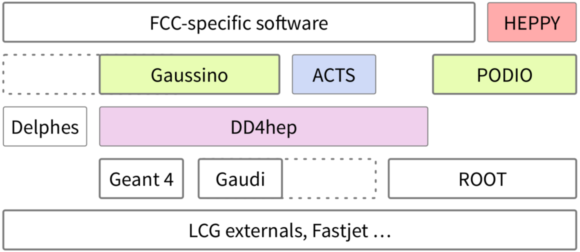
- Un-triggered readout of the detector at 40MHz would result in **3000 TByte/s** over optical links to the underground service cavern and/or a HLT computing farm on the surface.

FCC Common Software



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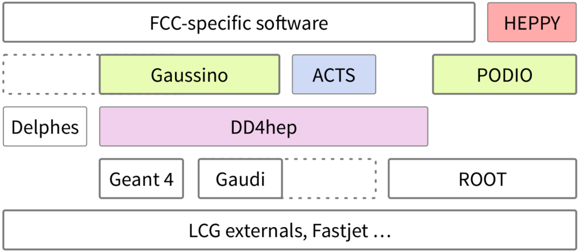

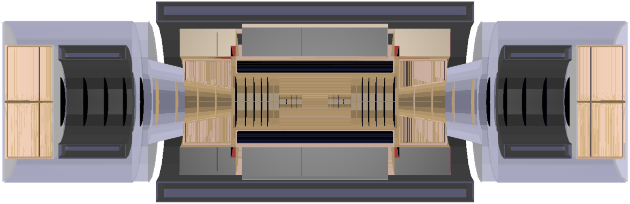

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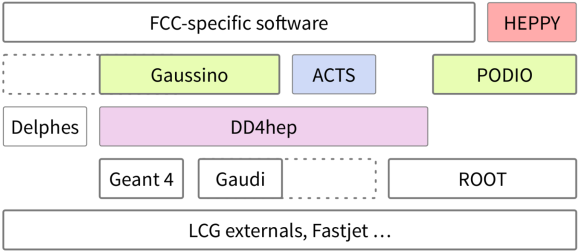
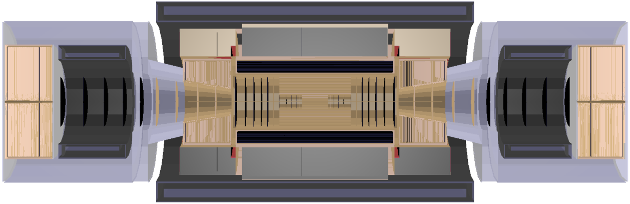
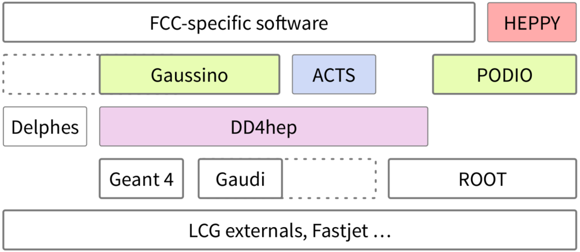
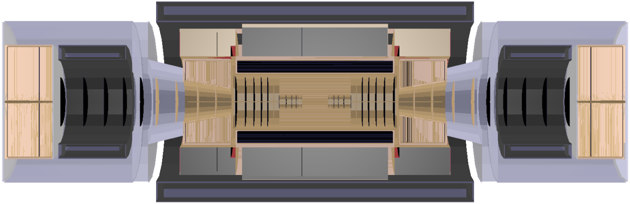


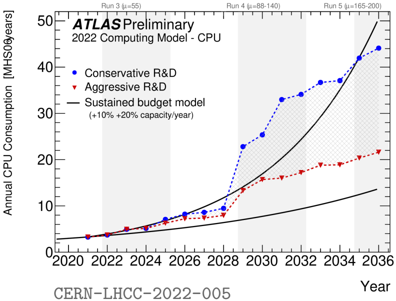


- FCC Software is shared between FCC-hh and FCC-ee
- Recent changes base on key4HEP (arXiv:2111.09874)

FCC Common Software







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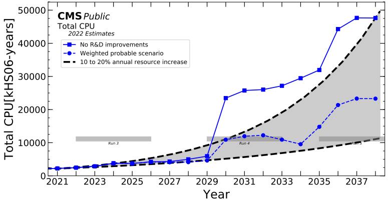
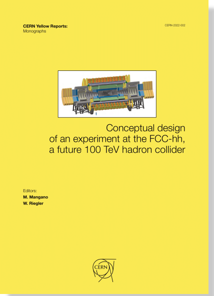


CMS NOTE 2022/008

- FCC Software is shared between FCC-hh and FCC-ee
- Recent changes base on key4HEP (arXiv:2111.09874)
- Many R&D topics relevant already for HL-LHC

Summary

- Feasability study of general purpose detector for FCC-hh has been concluded and described in:



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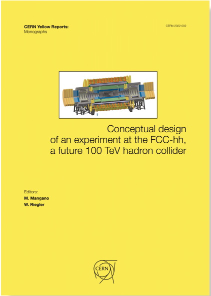

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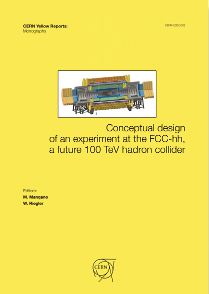
  - efficient software.



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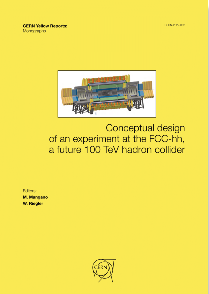
- Key R&D items have been identified:
  - ultra-radiation hard silicon sensors,
  - high precision timing detectors,
  - low power radiation hard optical links,
  - high granularity liquid argon calorimetry,
  - efficient software.
- If 100 TeV pp collider like FCC-hh is to be built, we can build detector that fully exploits the physics potential, as long as multiple identified R&D studies are carried out.



Thank you!

Special thanks to Werner Riegler and Martin Aleksa for their help with preparation of this talk.

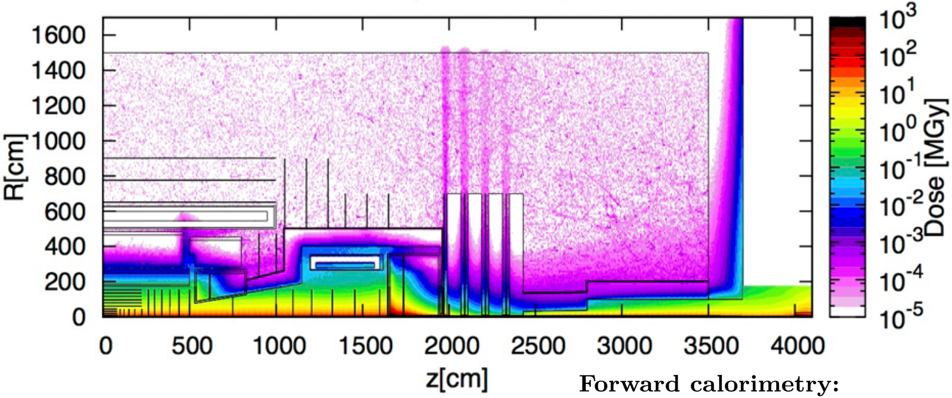
Backup

Dose for 30 ab^{-1}

Central tracker:

first IB layer (2.5 cm): $\sim$ 400 MGy

external part: $\sim$ 0.1 MGy

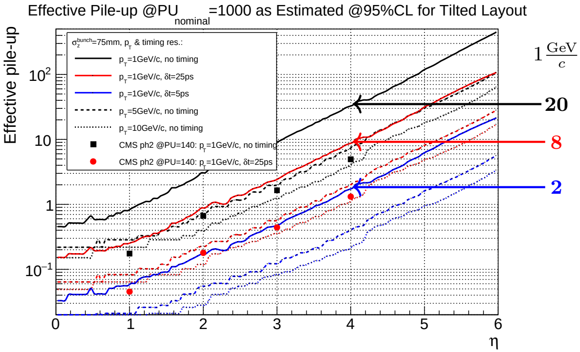


Forward calorimetry:

ECal at $\sim$5 GGy

HCal at $\sim$1 GGy

Effective pile-up



$1\,\frac{\text{GeV}}{c}$

no timing

δt=25 ps

δt=5 ps

Trigger

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
$W^+ \to l + \nu$ 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

- 100 MHz of jets $p_T > 50$ GeV

  $= 100 \times$ HL–LHC
- 400 kHz of W^+W^-

  $= 40 \times$ HL–LHC
- 120 kHz of Zs

  $= 40 \times$ HL–LHC
- 11 kHz of $t\bar{t}$

  $= 200 \times$ HL–LHC