Detector Options for Future pp Colliders

PISA school on future colliders, Sept. 18th, 2018

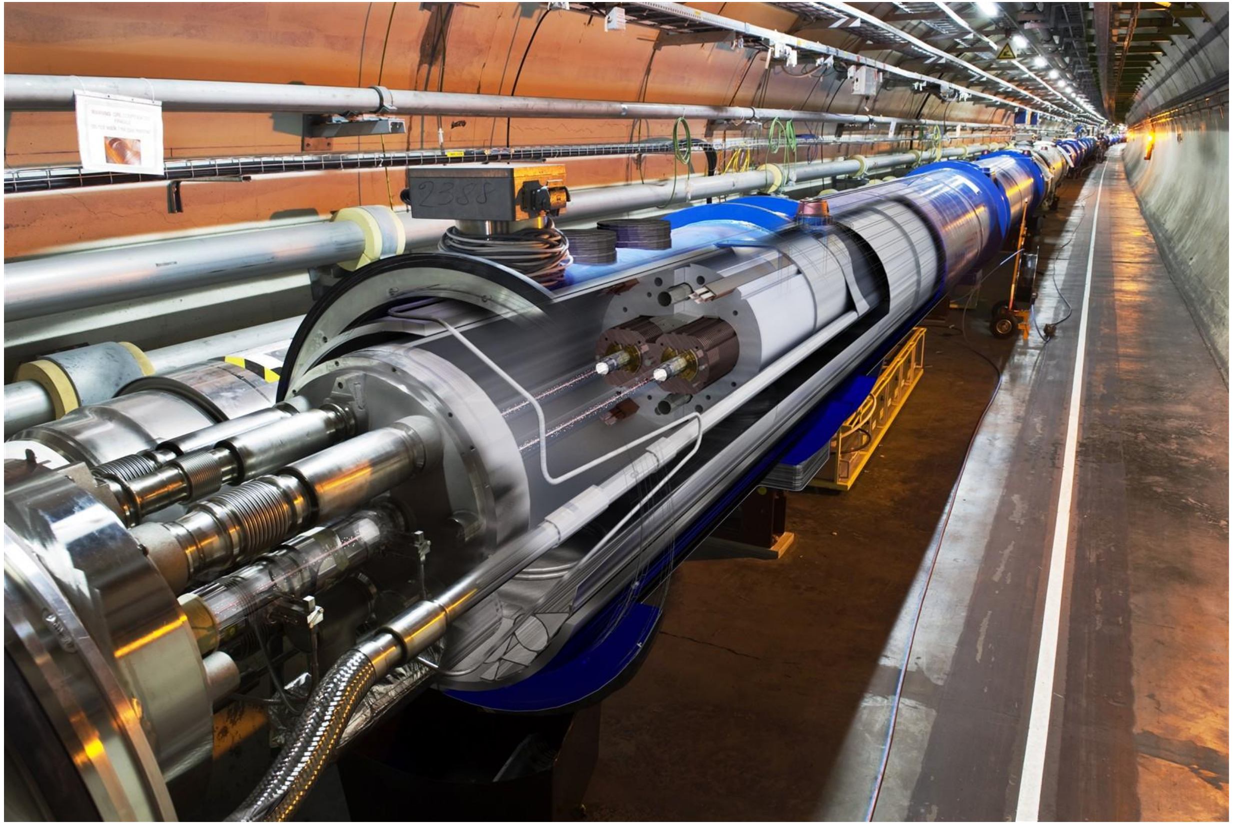
W. Riegler, CERN

Large Hadron Collider at CERN, Geneva, 14TeV pp collisions

27km
8.3T dipoles
p=0.3xRxB=10.7TeV

1983 First concept
2009 First physics
2025 Luminosity upgrade
2035 End of exploitation

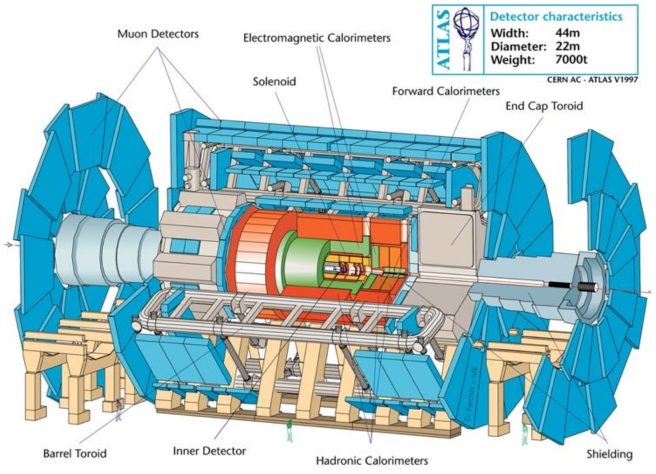
Large Hadron Collider at CERN, Geneva, 14TeV pp collisions

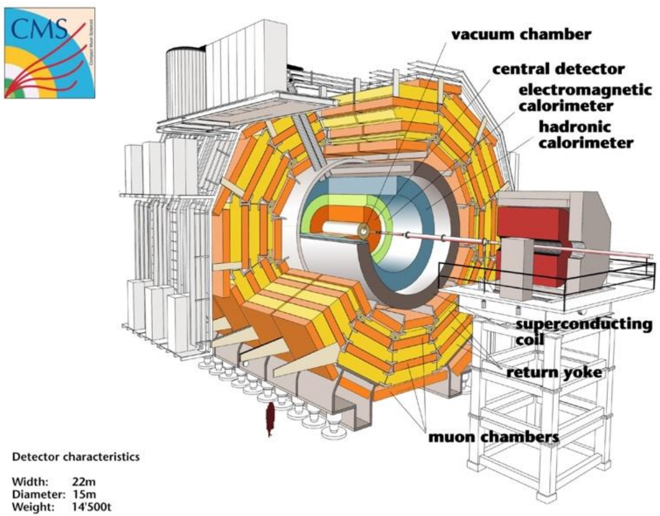


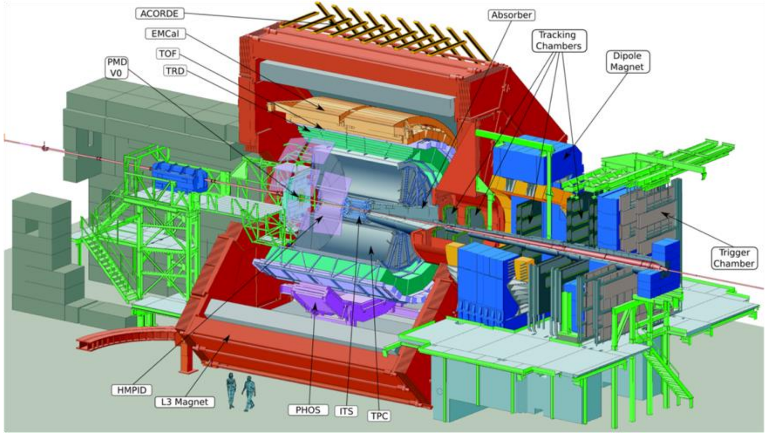
27km

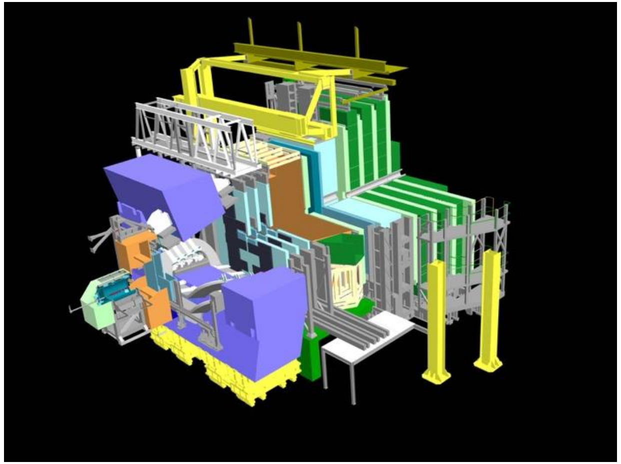
8.3T Dipoles

ATLAS, CMS, ALICE, LHCb

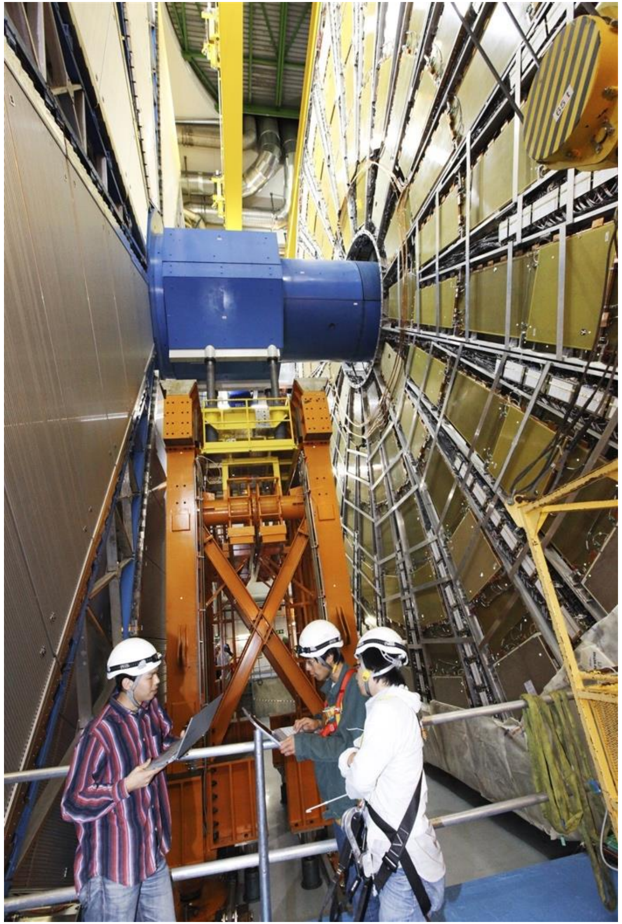


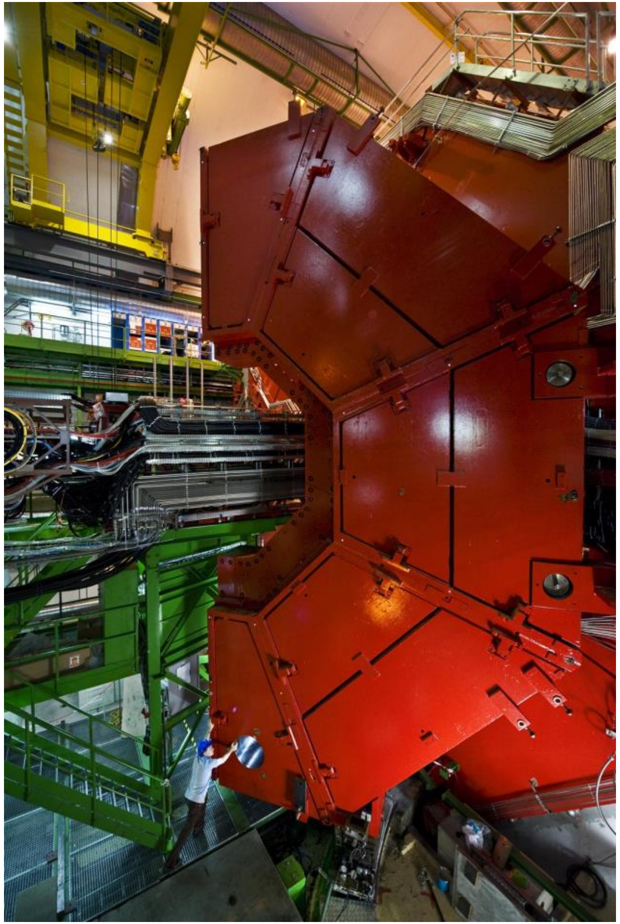




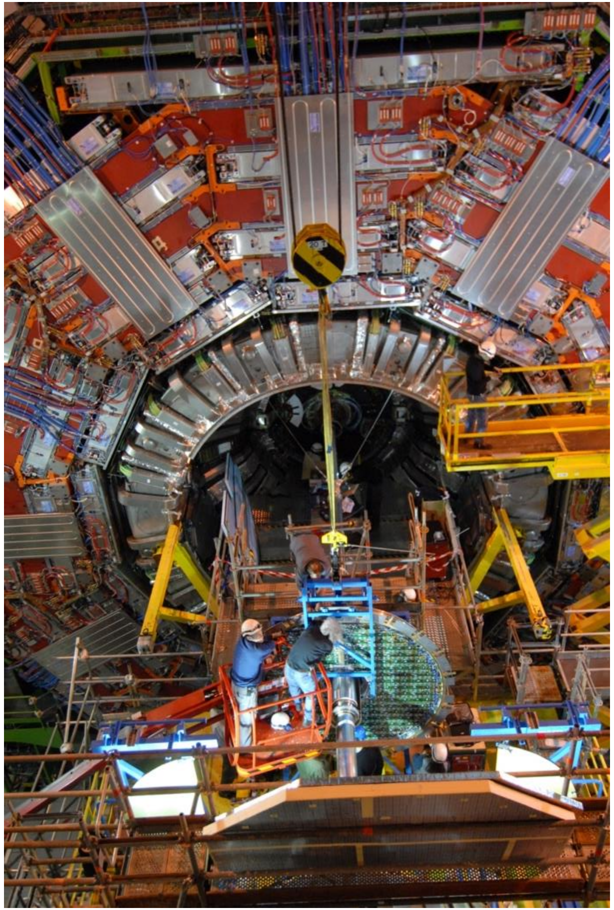


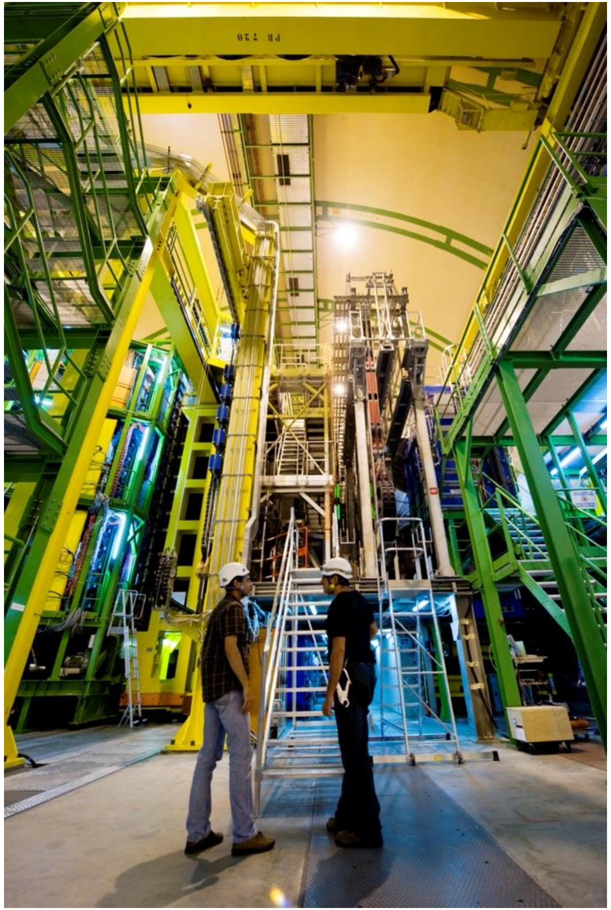
ATLAS, ALICE





CMS, LHCb





July 4th 2012

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

ARTICLE INFO

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ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

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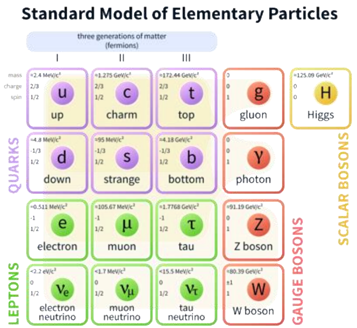
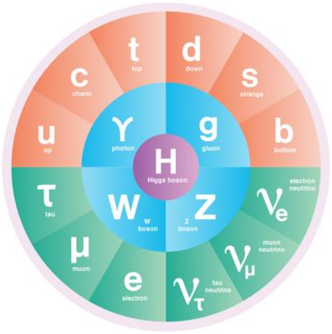
ABSTRACT

Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

The Standard Model of Particle Physics



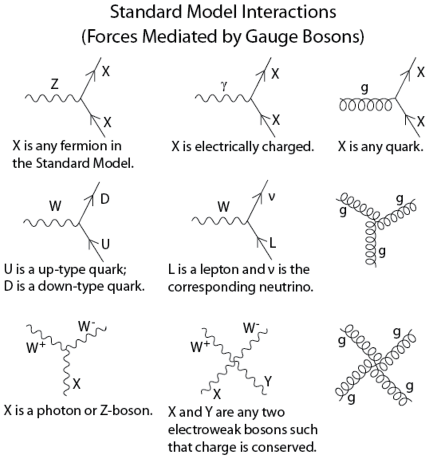


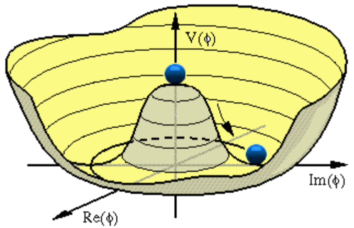
$$U(1) \times SU(2) \times SU(3)$$

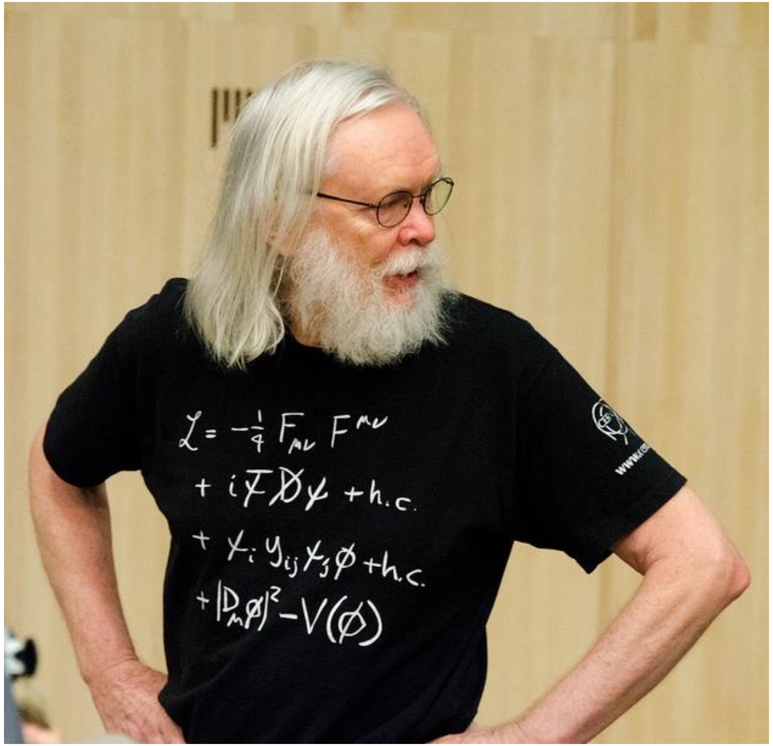
1 hypercharge

2 left-handed isospin charges

3 colour charges







Some very biased statistics from an experimentalist

91 Persons got Nobel Prices related to the development of the Standard Model

59 Experiment

33 for Standard Model Experiments

13 for Standard Model Instrumentation and Experiments

3 for Particle Physics Instrumentation

1 for Relativity Experiment (Michelson)

9 for Quantum Mechanics Experiments

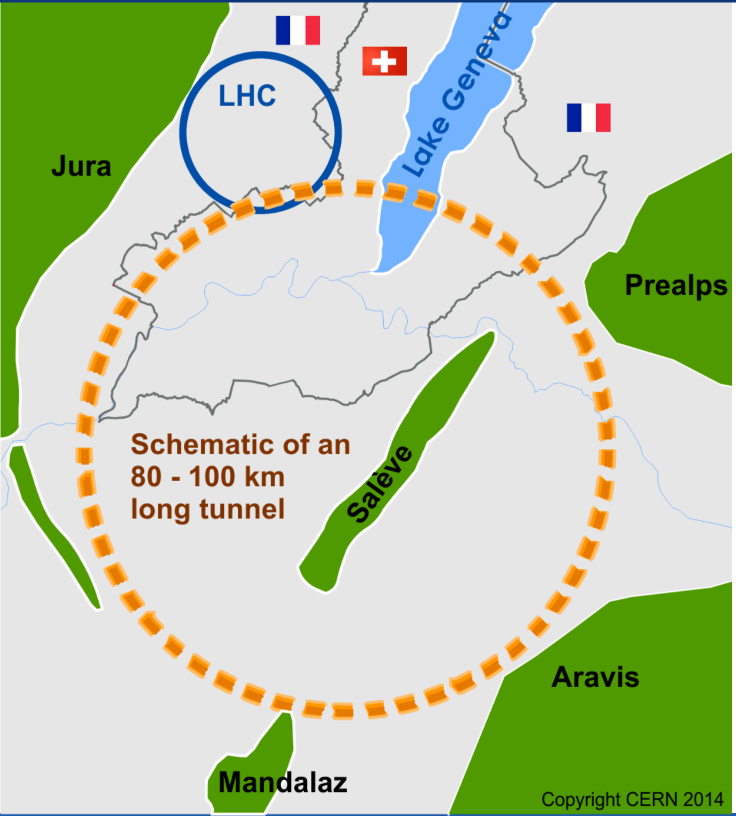
32 Theory

23 for Standard Model Theory

9 for Quantum Mechanics Theory

What next ?

Future Circular Collider Study



International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  - main emphasis, defining infrastructure requirement
  - **~16 T ⇒ 100 TeV *pp* in 100 k**
  - **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*)** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, e from ERL
- **High Energy LHC (HE-LHC)** with *FCC-hh* technology
- (LHC Ring 8→16T, 14→28TeV)

The rationale underlying the interest in FCC

- HEP has two priorities:
  - explore the origin of known departures from the SM (DM, neutrino masses, baryon asymmetry of the universe)
  - explore the physics of electroweak symmetry breaking:
    - experimentally, via the measurement of Higgs properties, Higgs interactions and selfinteractions, couplings of gauge bosons, flavour phenomena, etc
    - theoretically, to understand the nature of the hierarchy problem and identify possible natural solutions (to be subjected to exptl test)

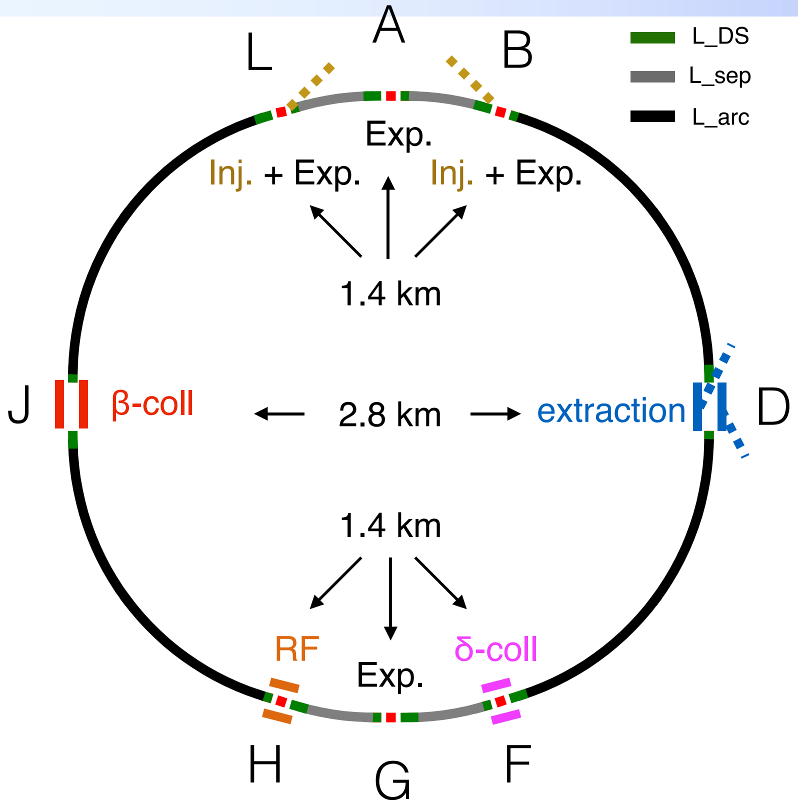
The physics case of FCC project (ee, hh and eh) builds on the belief that these two directions are deeply intertwined

Conceptual Design Report

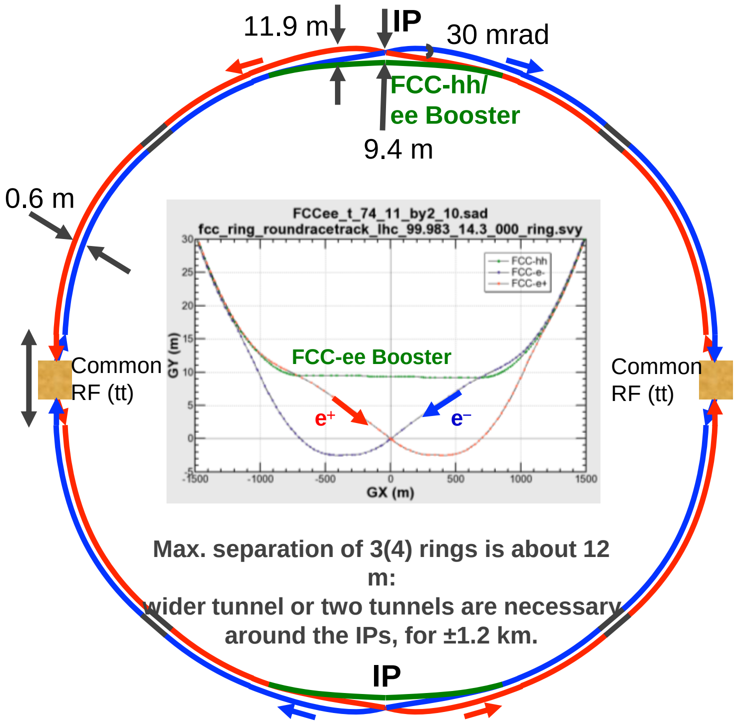
1 – PHYSICS	2 Hadron Collider Summary	3 – Hadron Collider Comprehensive
Physics opportunities across all scenarios		Accelerator, Injectors, Technologies, Infrastructure, Operation, Experiment, eh
	4 Lepton Collider Summary	5 – Lepton Collider Comprehensive: Accelerator, Injectors, Technologies, Infrastructure, Operation, Experiment
	6 High Energy LHC Summary	7 – High Energy LHC Comprehensive: Accelerator, Injectors, Infrastructure; *Refs to FCC-hh, HL-LHC, LHeC*

- **Required for end 2018, as input for European Strategy Update**
- **Common physics summary volume**
- **Three detailed volumes FCChh, FCCee, HE-LHC**
- **Three summary volumes FCChh, FCCee, HE-LHC**

Same home for ee and hh

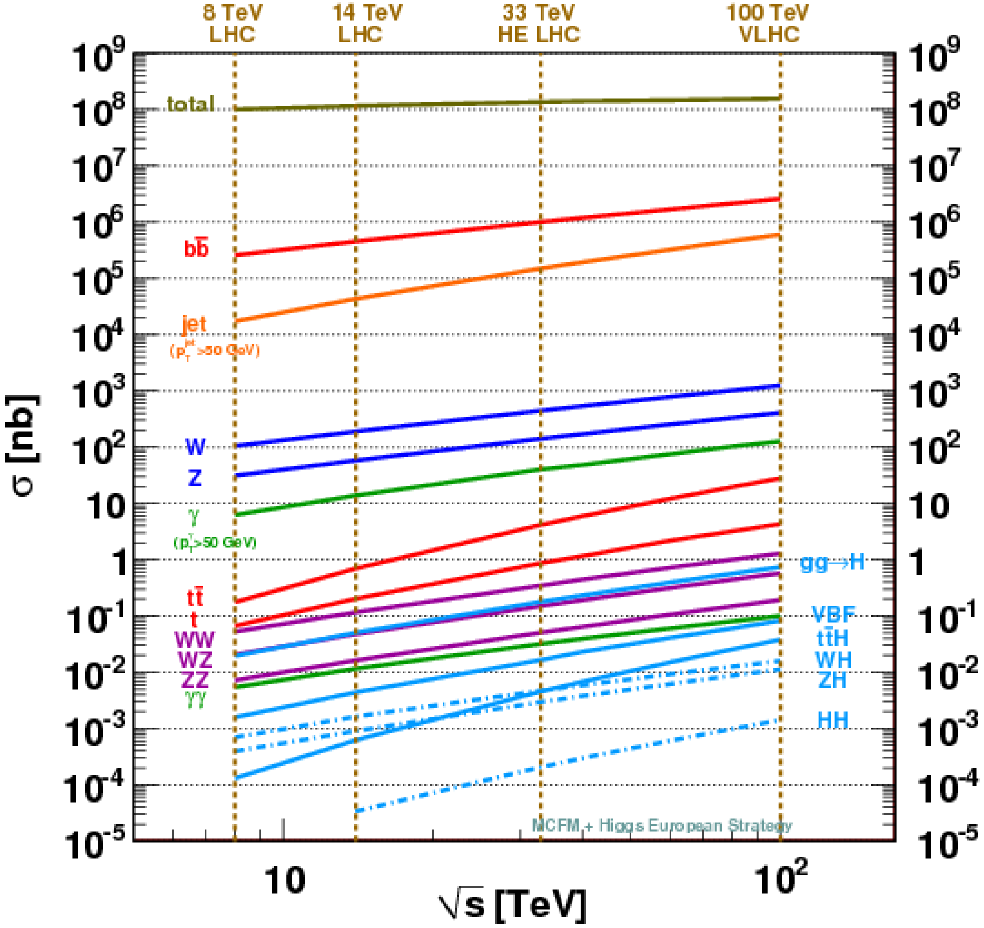


Two main IP's in A, G for both machines



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

Crossections for key processes



Total crossection and Minimum Bias Multiplicity show only a modest increase from LHC to FCC-hh.

The crossection for interesting processes shows however significant increase !

→ **Interesting stuff is sticking out more !!**

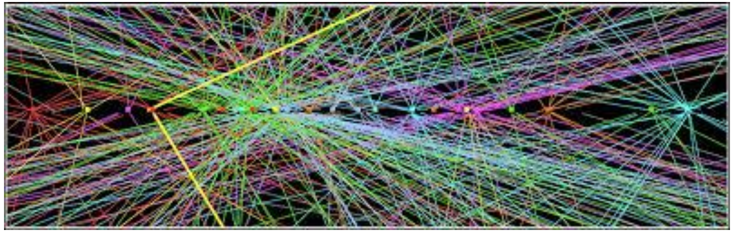
Going from pileup of 140 at HL-LHC to pileup of 1000 at FCC does however reduced this possible advantage for triggering.

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 $\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	1	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}	mb	85	85	91	108
σ_{tot}	mb	111	111	126	153
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.85	4.25	15.6	32.4
Peak av. PU events/BC		27	137	461	996
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
$dN_{ch}/d\eta\|_{\eta=0}$		6.0	6.0	7.2	9.6
Charged tracks per collision N_{ch}		70	70	85	122
Rate of charged tracks	GHz	59	297	1234	3942
$<p_T>$	GeV/c	0.47	0.47	0.49	0.55
Bending radius for $<p_T>$ at B=4 T	cm	39	39	41	46

Parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
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 (12)
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 (400)
$dE/d\eta\|_{\eta=5}$	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	$\|\eta\|<$	3	3	3.3	4.5
VBF jet peak	η	3.4	3.4	3.7	4.4
90% VBF jets	$\|\eta\|<$	4.5	4.5	5.0	6.0
90% $H \rightarrow 4l$	$\|\eta\|<$	3.8	3.8	4.1	4.8

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	μb	21	21	56	300
Jets $p_T^{jet} > 50$ GeV/c rate	MHz	0.2	1.1	14	90
$W^+ + W^-$ cross-section	μb	0.2	0.2	0.4	1.3
$W^+ + W^-$ rate	kHz	2	10	100	390
$W^+ \to l + \nu$ cross-section	nb	12	12	23	77
$W^+ \to l + \nu$ rate	kHz	0.12	0.6	5.8	23
$W^- \to l + \nu$ cross-section	nb	9	9	18	63
$W^- \to l + \nu$ rate	kHz	0.1	0.5	4.5	19
Z cross-section	nb	60	60	100	400
Z rate	kHz	0.6	3	25	120
$Z \to ll$ cross-section	nb	2	2	4	14
$Z \to ll$ rate	kHz	0.02	0.1	1	4.2
$t\bar{t}$ cross-section	nb	1	1	4	35
$t\bar{t}$ rate	kHz	0.01	0.05	1	11

Pileup, number of pp collisions per bunchcrossing

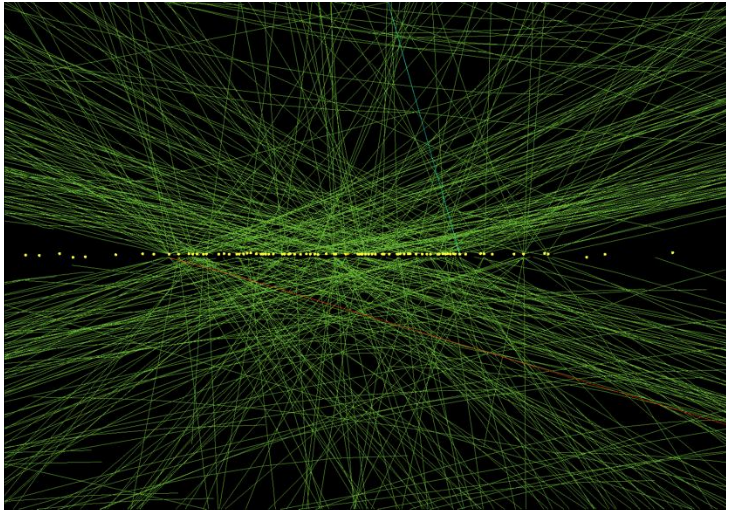


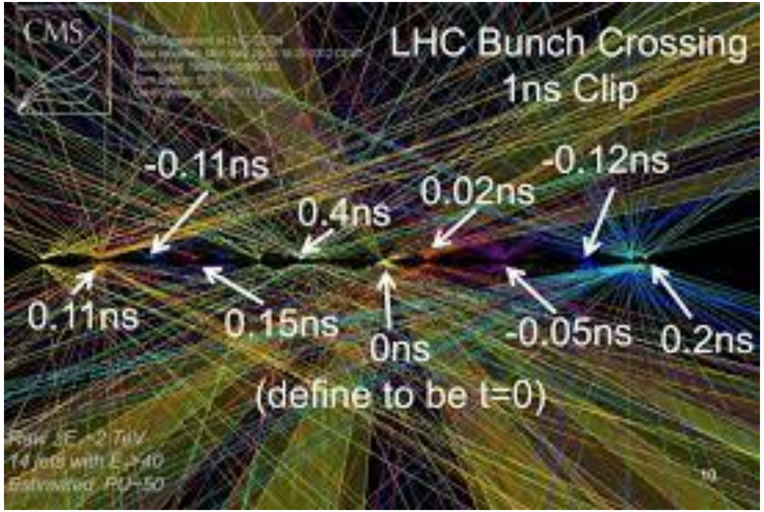
LHC: 30

HL-LHC: 140

FCC-hh: 1000

Small time differences between the individual collisions in one BC allow identification with detectors having order 10-20ps time resolution.





Physics at a 100 TeV Hadron Collider

Exploration + Higgs as a tool for discovery

How to specify detectors for such a machine ?

ATLAS and CMS are general purpose detectors that were benchmarked with the 'hypothetical' Higgs in different mass regions with tracking up to $\eta=2.5$.

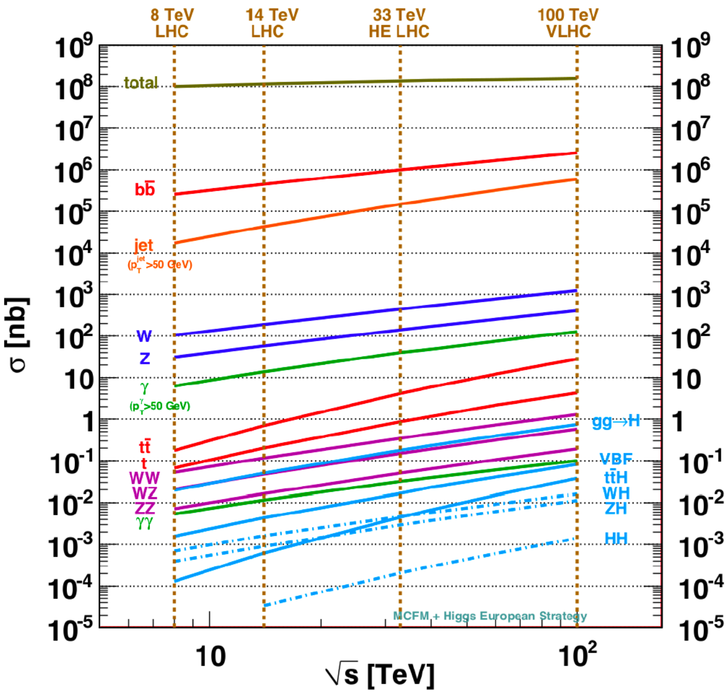
The Higgs is also key benchmark for the FCC detectors, with highly forward boosted features (100TeV, 125GeV Higgs)

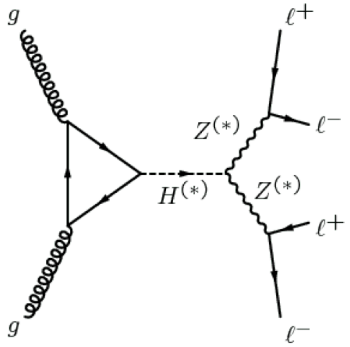
FCC detectors must be 'general general' purpose detectors with very large η acceptance and extreme granularity.

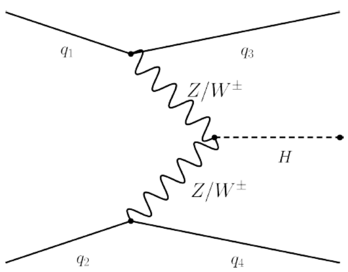
Physics requirements

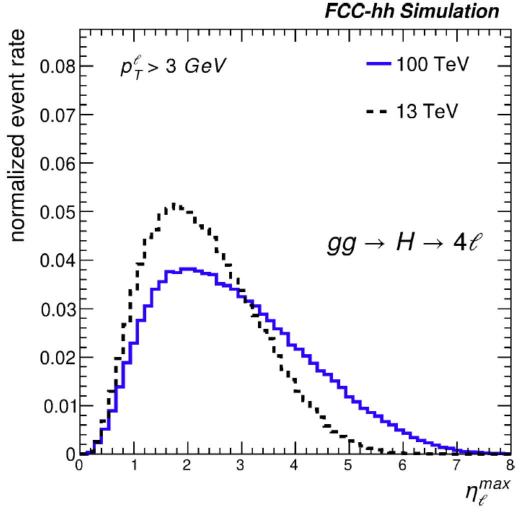
More forward physics → large acceptance

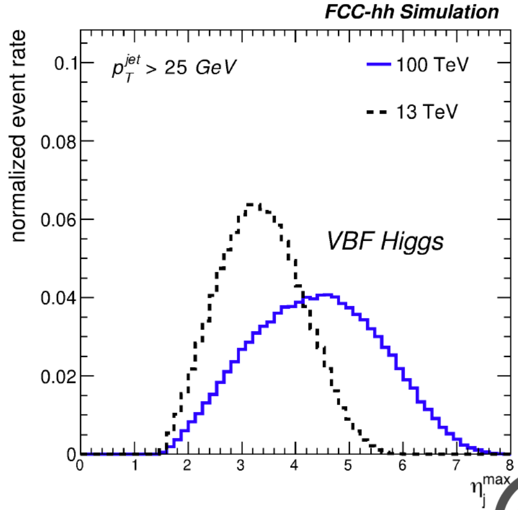
- precision momentum spectroscopy and energy measurements up to $|\eta| < 4$
- tracking and calorimetry up to $|\eta| < 6$









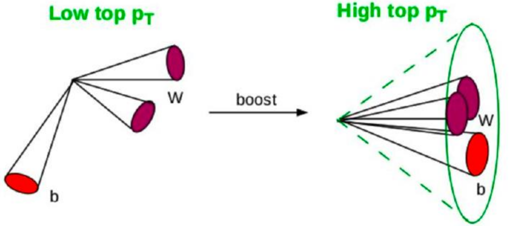


Physics at a 100 TeV Hadron Collider

- ## Ultimate discovery machine
  - **directly** probe new physics up to **unprecendented** scale [1606.00947]
  - discover/exclude:
    - heavy resonances "strong" m(q*) ≈ 50 TeV,
      "weak" m(Z') ≈ 30TeV,
    - SUSY m(gluino) ≈ 10 TeV,
      m(stop). ≈ 5 TeV
- ## Precision machine
  - probe Higgs **self-coupling** to few % level, and %-level precision for top yukawa and rare decays [1606.09408]
  - measure **SM parameters** with high precision
  - **complementary** to e^+e^- by probing **high dim.operators** in **extreme kinematic** regimes

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 $\Delta R = 0.01$.

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)

Muons target: $\sigma_p/p = 5\%$ @ 10 TeV ($\eta \sim 0$)

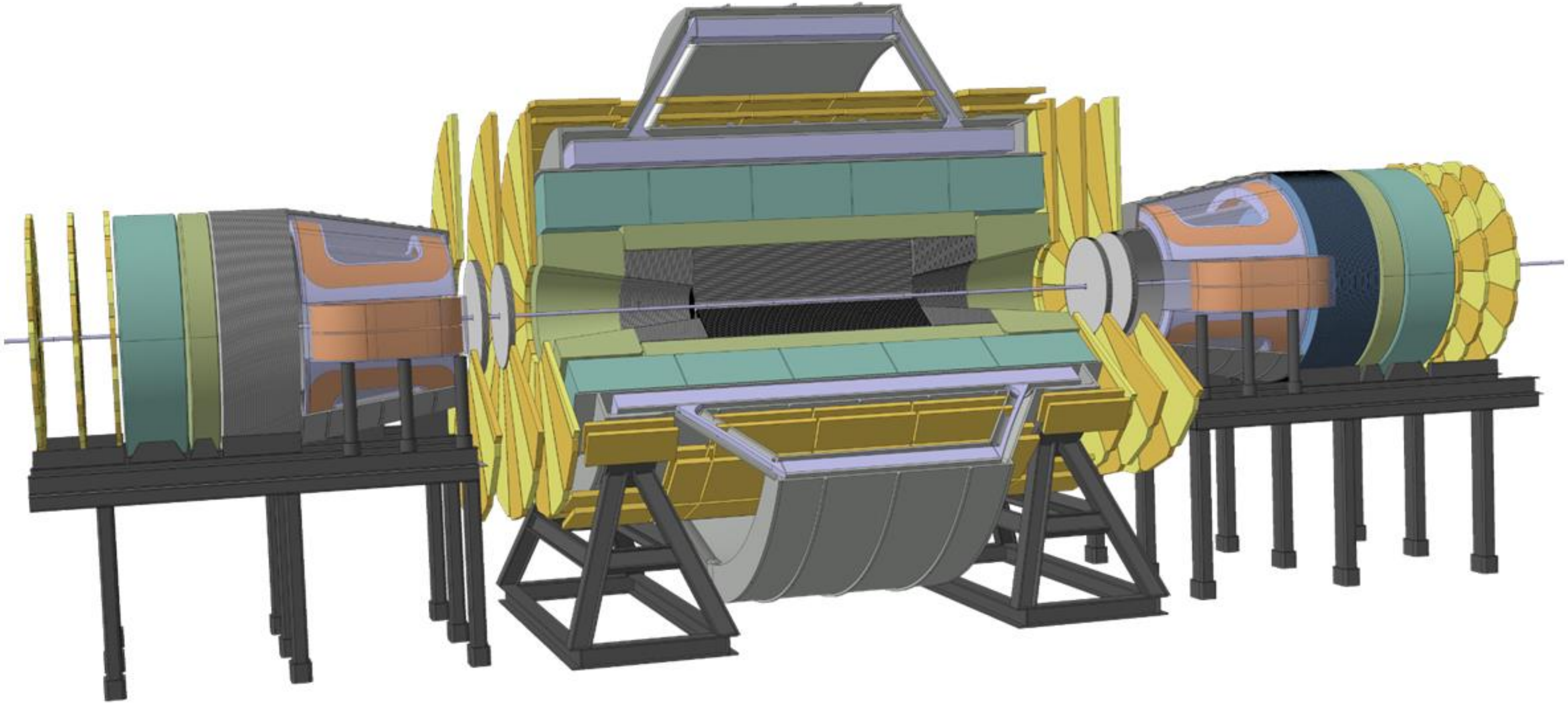
Calorimeter:

- 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

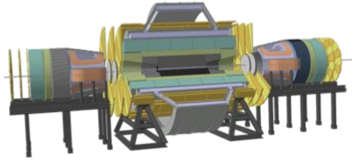
Long-lived particles live longer:

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

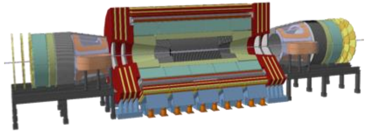
FCC week 2016: Twin Solenoid 6T, 12m bore, Dipoles 10Tm



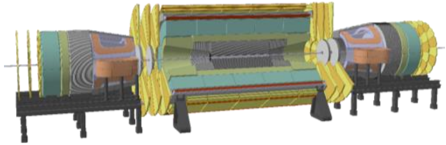
Magnet systems under consideration



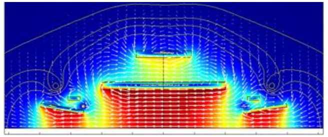
Twin solenoid with dipoles (min. shaft diameter 27.5m)



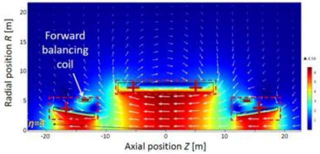
Partially shielded solenoid with dipoles



Unshielded solenoid with dipoles

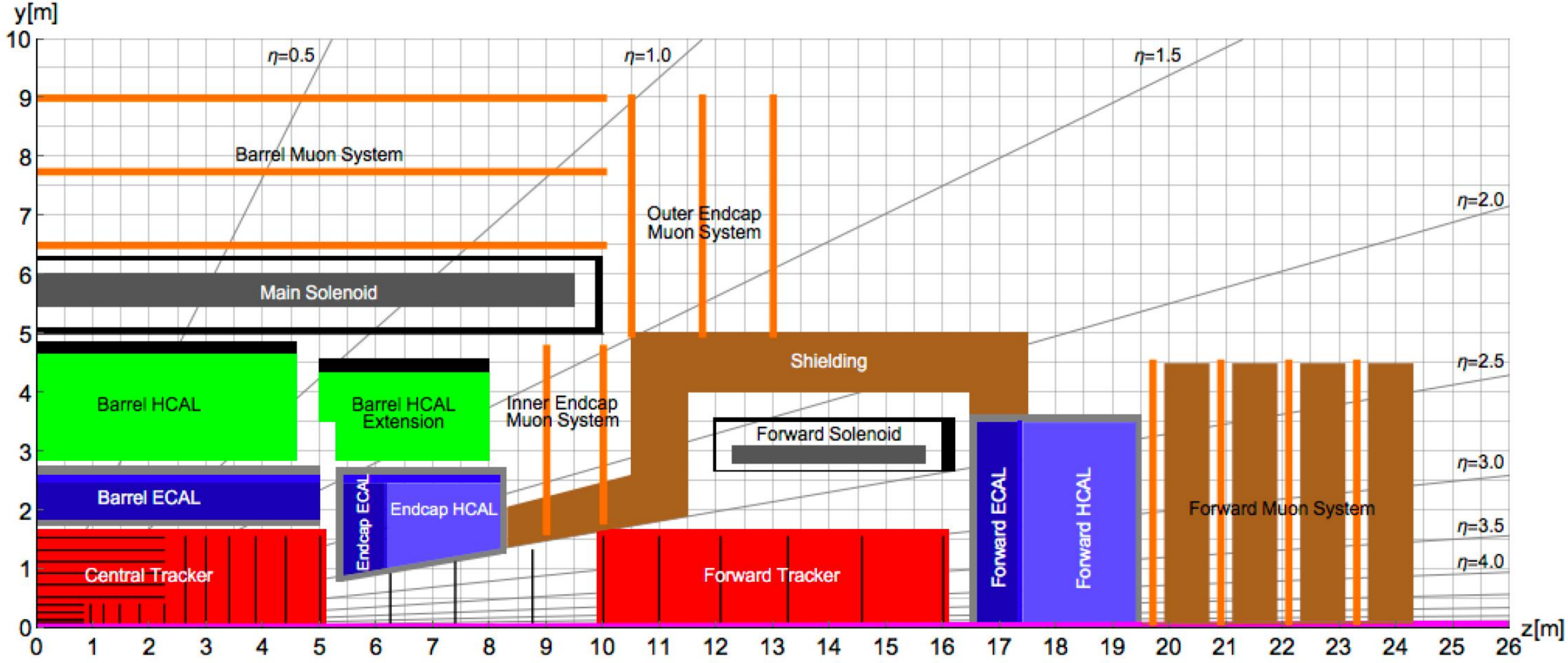


Twin solenoid with balanced conical solenoid

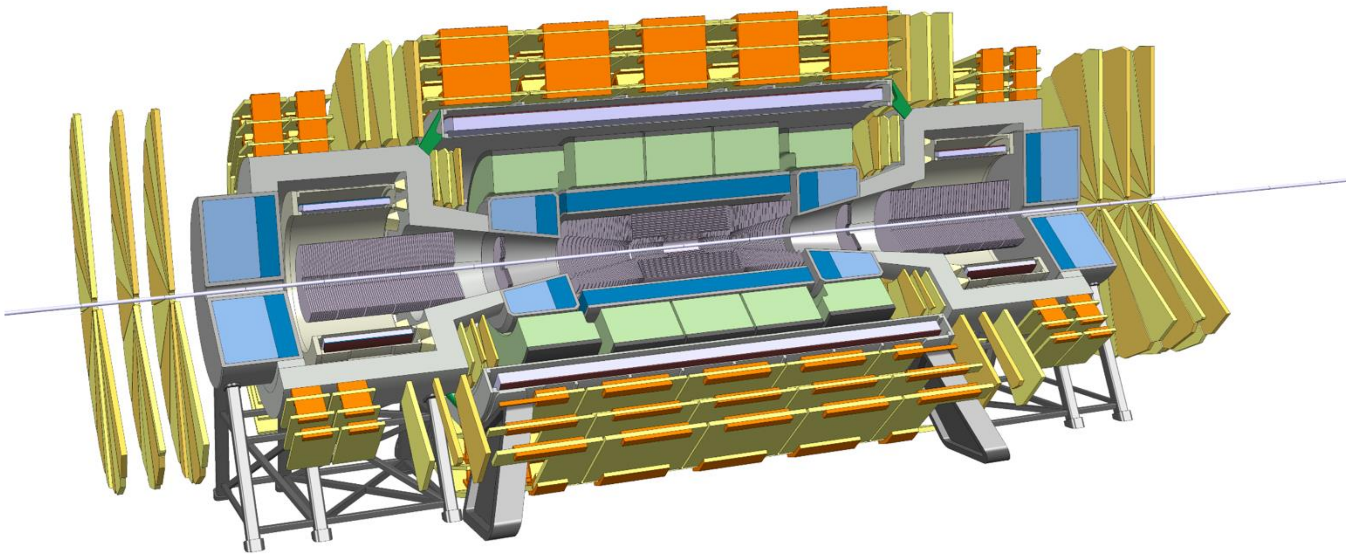


Unshielded solenoid with balanced conical solenoid

FCC-hh reference detector layout



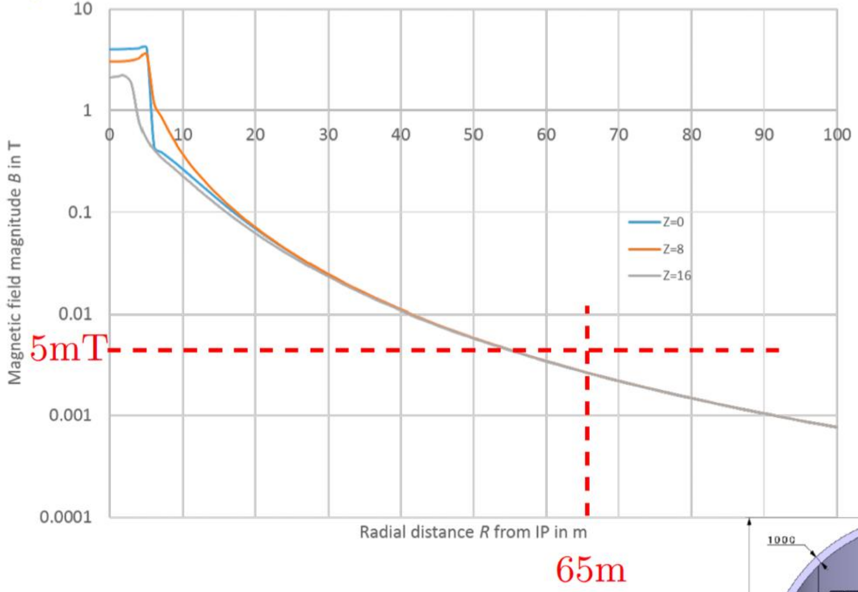
Reference detector for the CDR

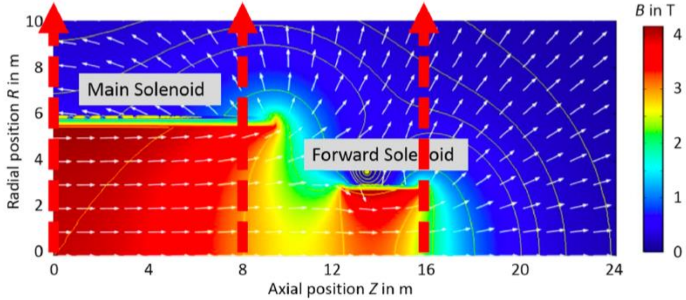


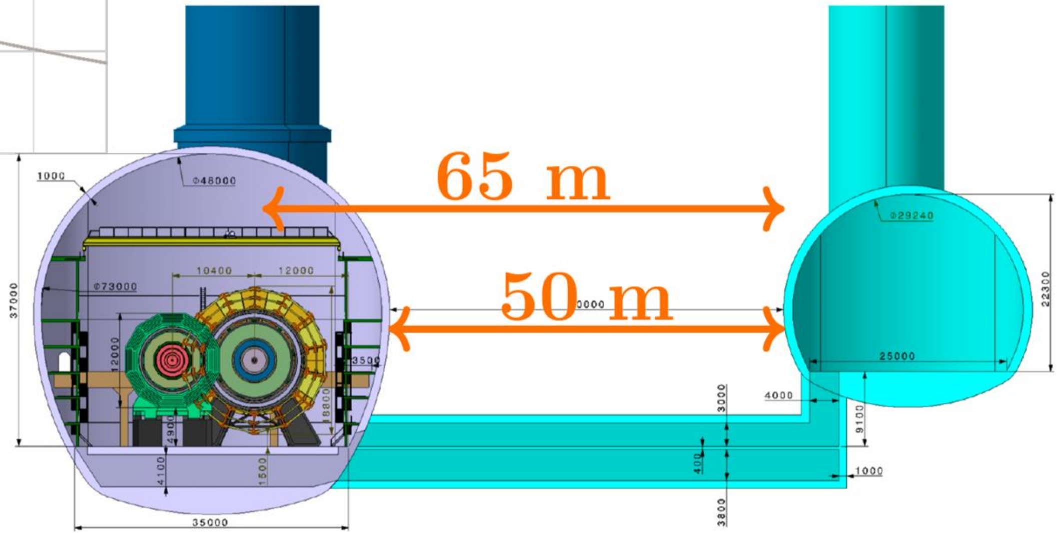
- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

This is a reference detector that 'can do the job' and that is used to define the challenges.
The question about the specific strategy for detectors at the two IPs is a different one.

Stray field and service cavern

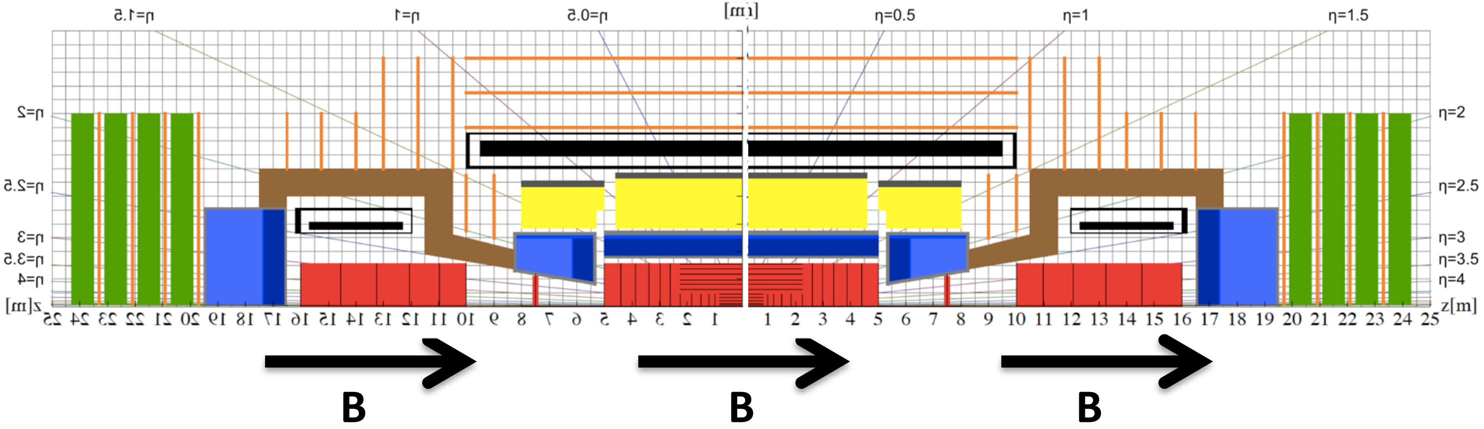


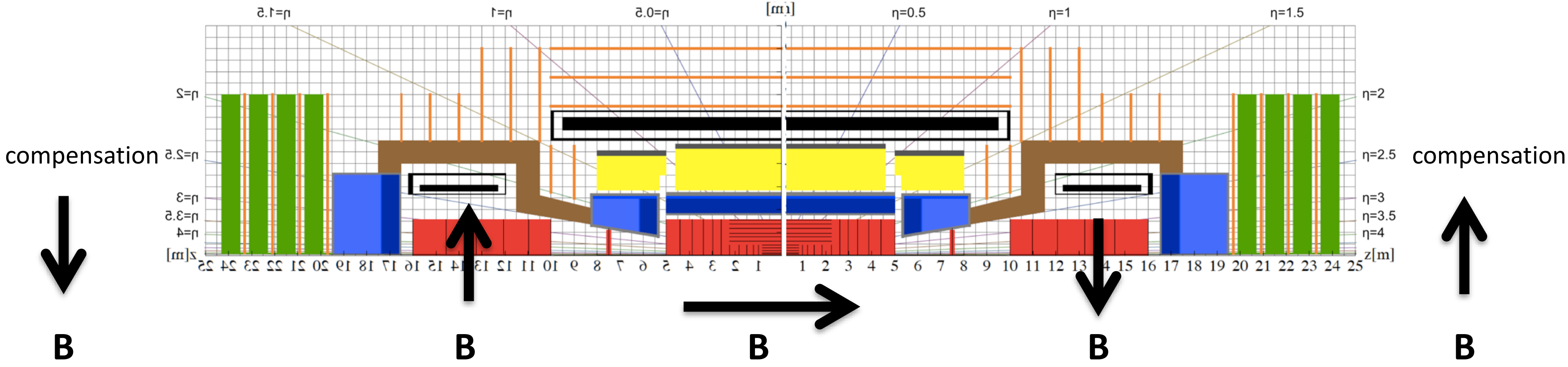




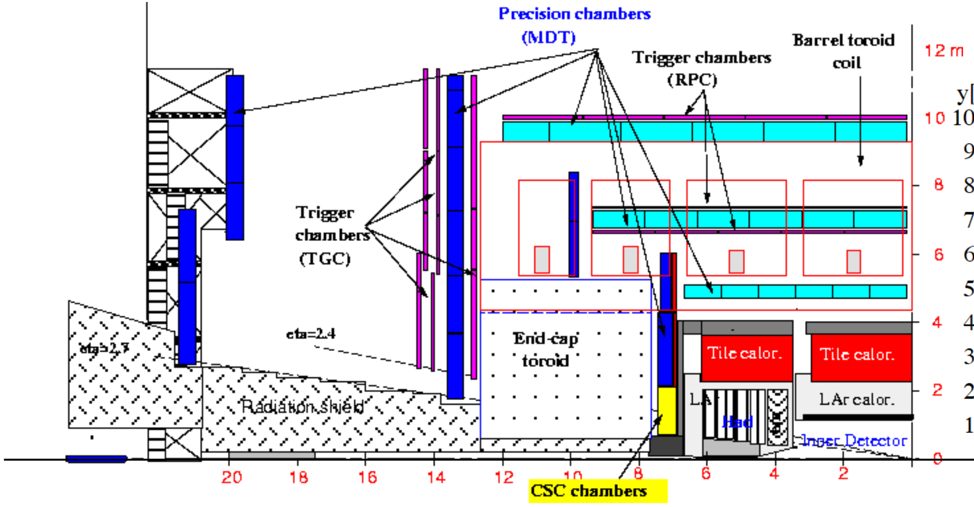
See talk by Erwin Bielert **Thu 8:30**

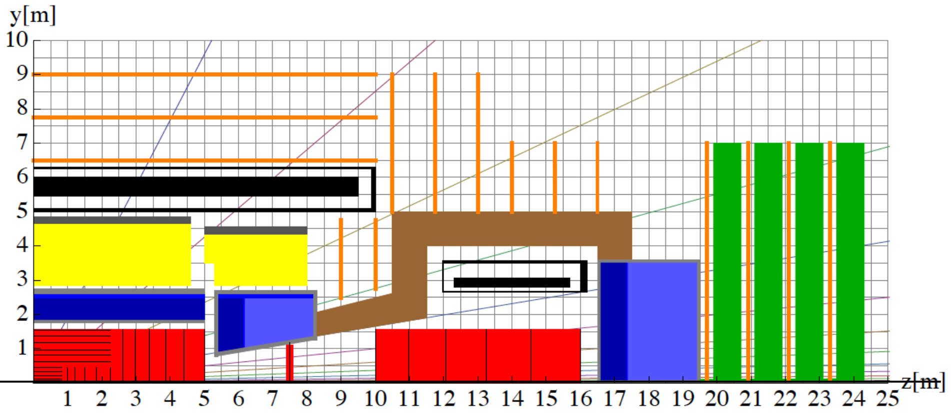
CDR will discuss performance with forward dipoles

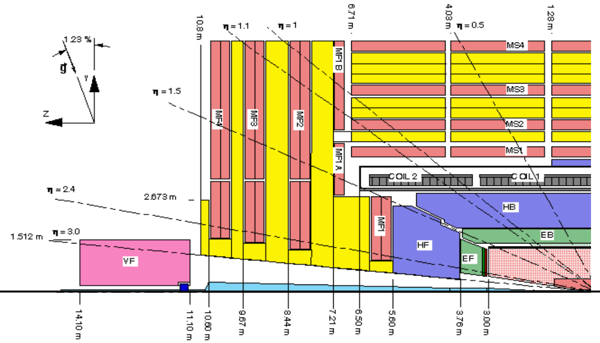


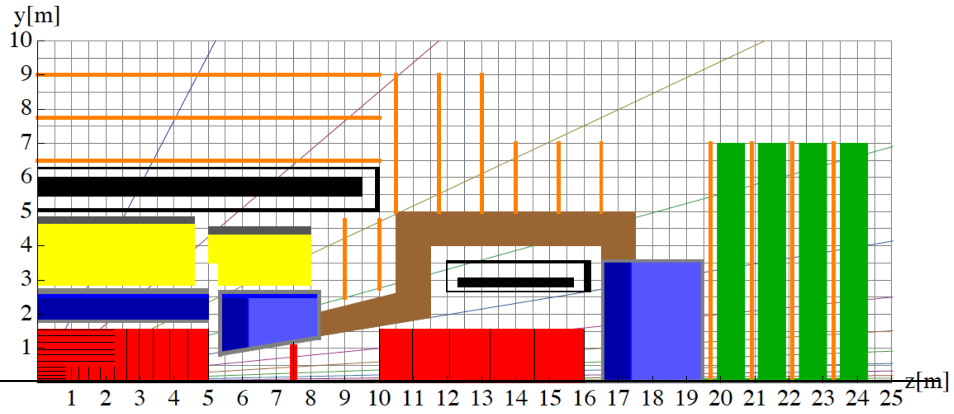


Comparison to ATLAS & CMS

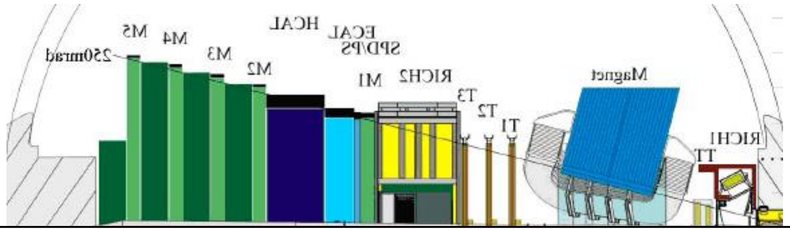


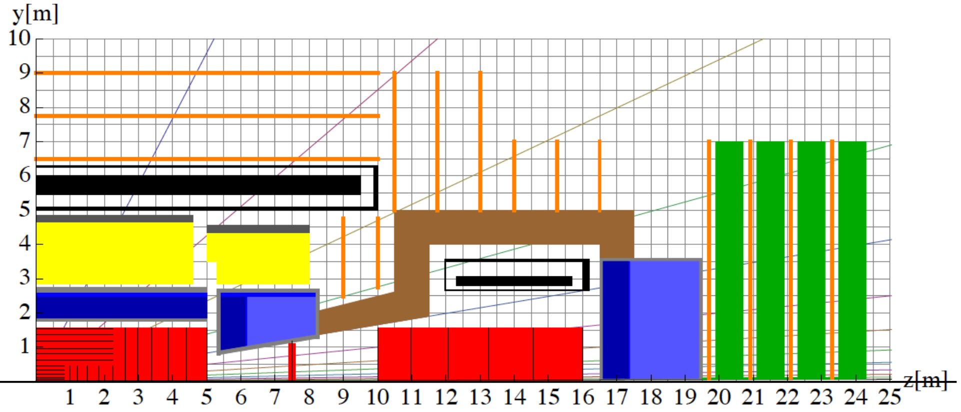


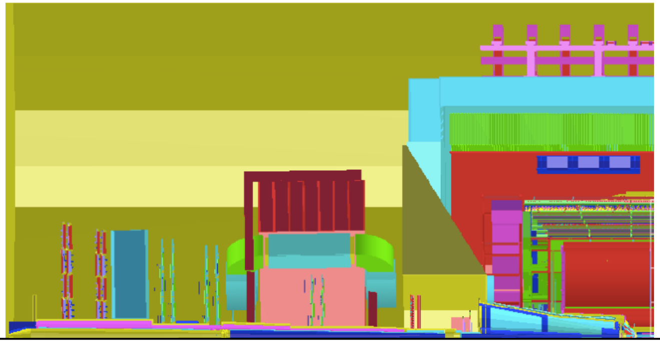


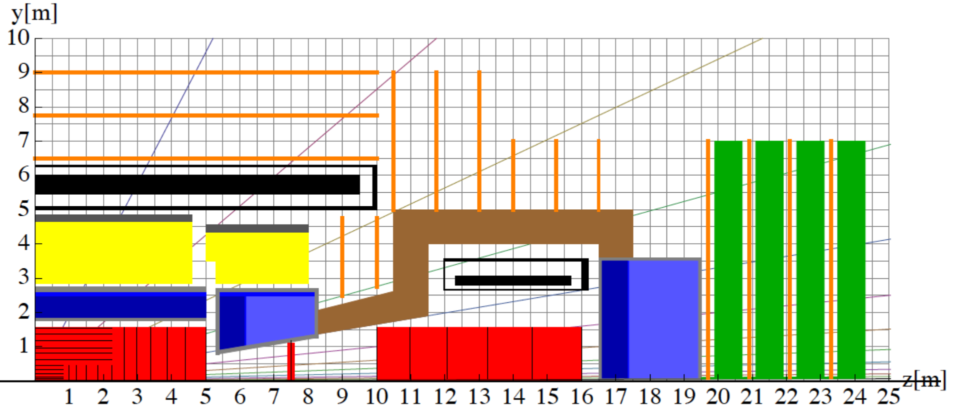


Comparison to LHCb & ALICE

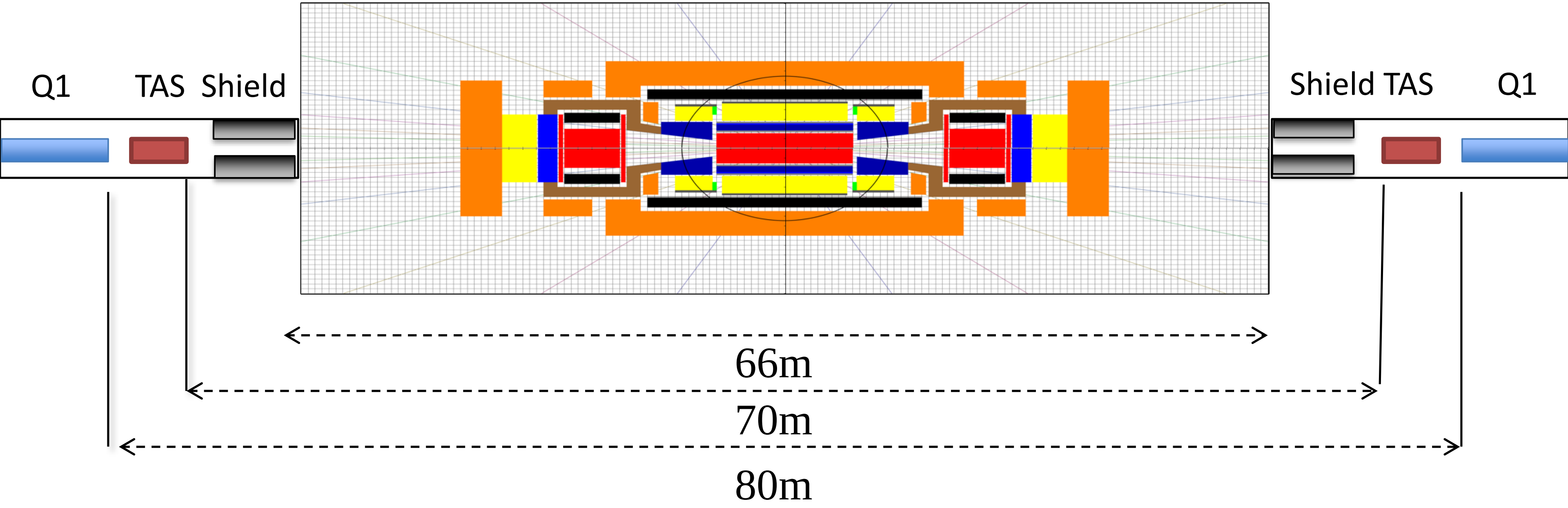








Cavern Length



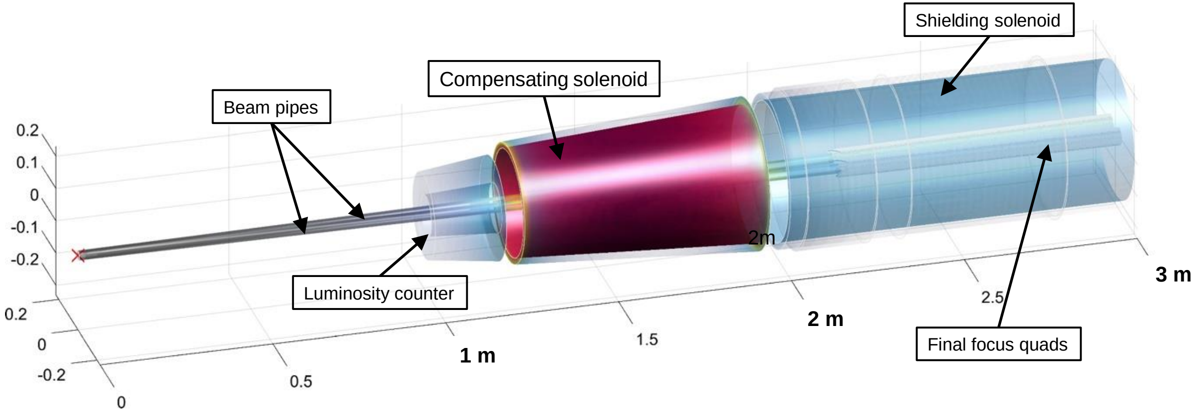
L*=40m
TAS = 3.5m
TAS Shielding in Tunnel = 2m

→ Distance between Q1&Q1 = 80m
→ Distance between TAS & TAS = 70m
→ Cavern Length = 66m

Cavern length of 66m is compatible with the opening scenario of the present detector.

Constraints for e+e- detectors

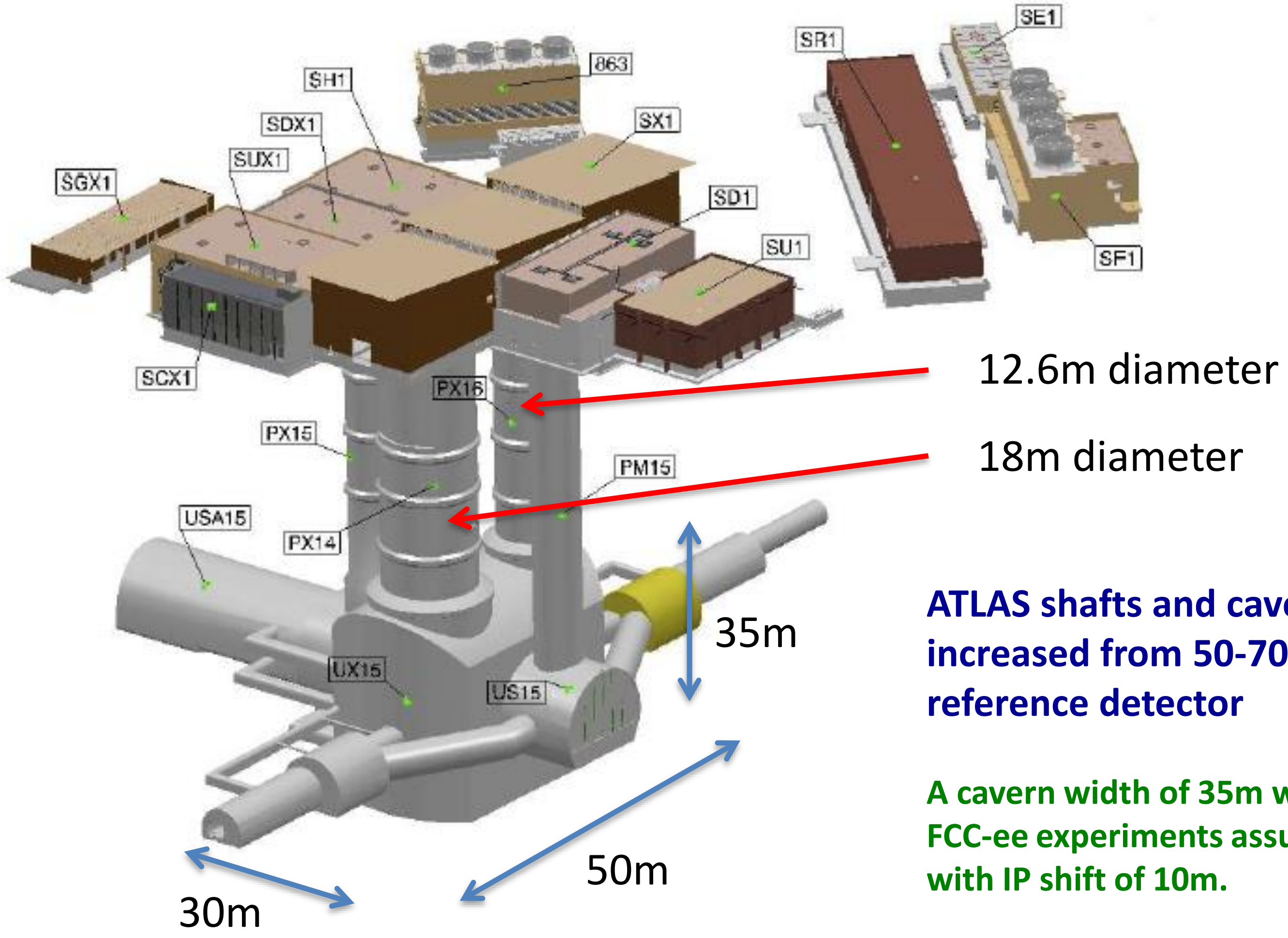
Not much room left for the luminosity counter (with low-angle Bhabha $e^+e^- \rightarrow e^+e^-$)
Front face at 1.2 m from the IP (typically twice closer to IP than at LEP)



L* ~ 2m in contrast to 40m for FCC-hh !
Final focussing magnets, machine elements and luminosity calorimeter are sticking into the detector !!

Machine-detector interface for FCC-ee detectors is quite complex !

ATLAS Cavern

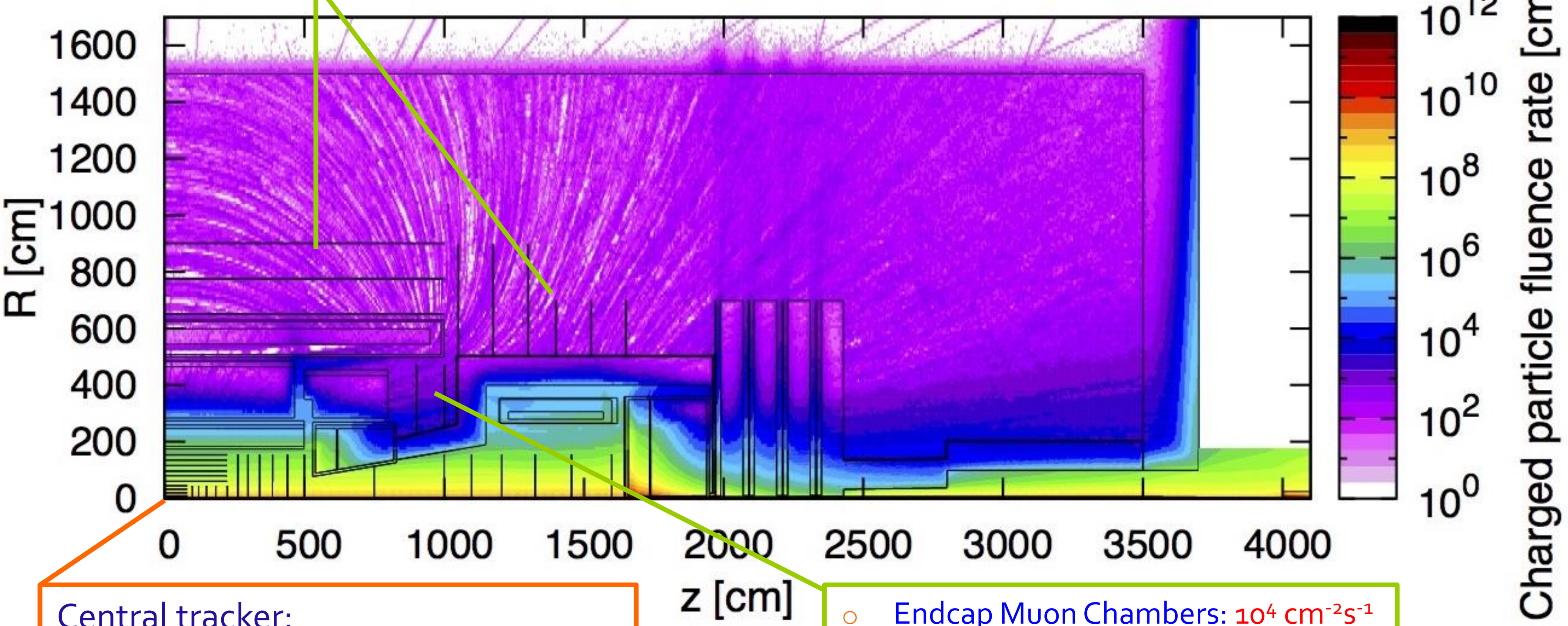


ATLAS shafts and cavern, with cavern length increased from 50-70m will accommodate the reference detector

A cavern width of 35m would also accommodate the FCC-ee experiments assuming the present footprint with IP shift of 10m.

Charged Particle Fluence @ $L=30x10^{34}cm^{-2}s^{-1}$

- Barrel muon chambers: ~300 $cm^{-2}s^{-1}$ to ~500 $cm^{-2}s^{-1}$

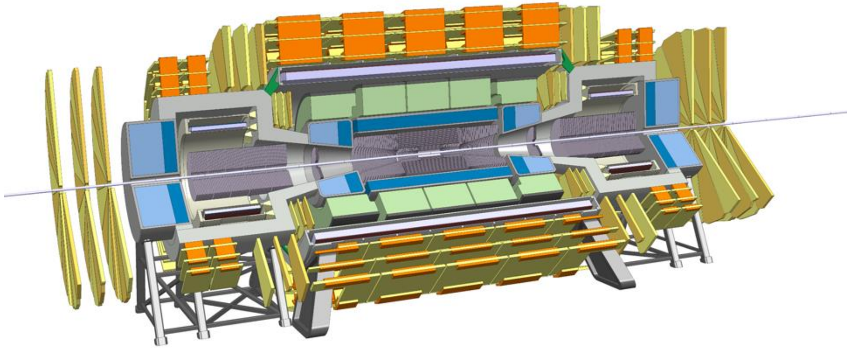


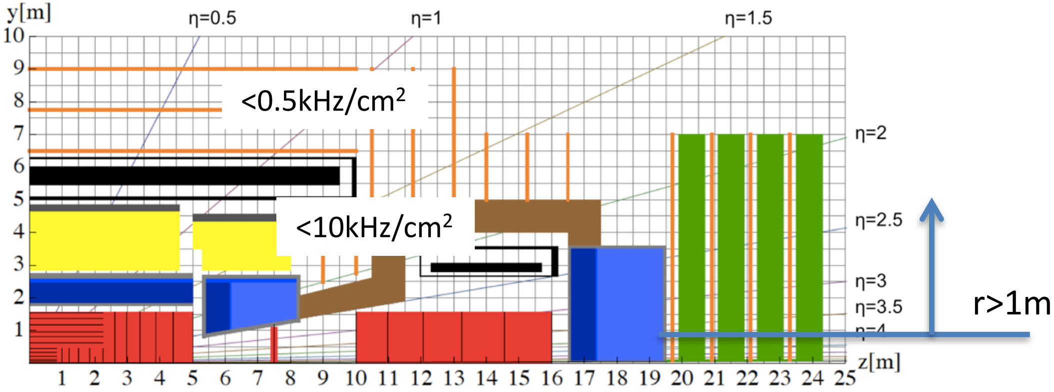
Central tracker:

- first IB layer (2.5 cm): ~1.2 10^{10} $cm^{-2}s^{-1}$
- external part: 3 10^6 $cm^{-2}s^{-1}$

- Endcap Muon Chambers: 10^4 $cm^{-2}s^{-1}$

Muon Systems





r>1m rate<500kHz/cm^2

ATLAS muon system HL-LHC rates (kHz/cm^2):

MDTs barrel:	0.28
MDTs endcap:	0.42
RPCs:	0.35
TGCs:	2
Micromegas und sTGCs:	9-10

Table 4.5: Expected rates on the muon detector when operating at an instantaneous luminosity of 2×10^{33} cm^{-2}s^{-1} at a collision energy of 14 TeV. The values are averages, in kHz/cm^2, over the chamber with the minimum illumination, the whole region and the chamber with maximum illumination. The values are extrapolated from measured rates at 8 TeV.

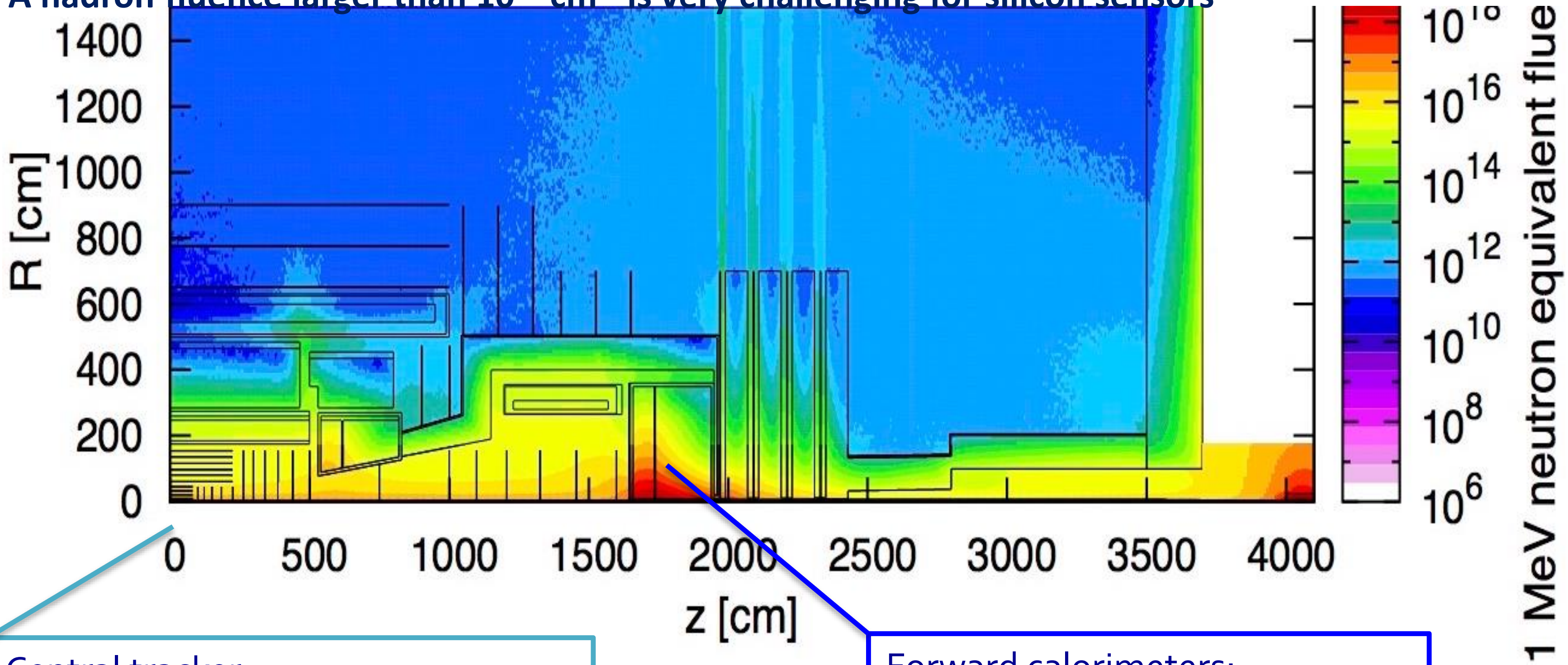
LHCb

Region	Minimum	Average	Maximum
M2R1	162 ± 28	327 ± 60	590 ± 110
M2R2	15.0 ± 2.6	52 ± 8	97 ± 15
M2R3	0.90 ± 0.17	5.4 ± 0.9	13.4 ± 2.0
M2R4	0.12 ± 0.02	0.63 ± 0.10	2.6 ± 0.4
M3R1	39 ± 6	123 ± 18	216 ± 32
M3R2	3.3 ± 0.5	11.9 ± 1.7	29 ± 4
M3R3	0.17 ± 0.02	1.12 ± 0.16	2.9 ± 0.4
M3R4	0.017 ± 0.002	0.12 ± 0.02	0.63 ± 0.09
M4R1	17.5 ± 2.5	52 ± 8	86 ± 13
M4R2	1.58 ± 0.23	5.5 ± 0.8	12.6 ± 1.8
M4R3	0.096 ± 0.014	0.54 ± 0.08	1.37 ± 0.20
M4R4	0.007 ± 0.001	0.056 ± 0.008	0.31 ± 0.04
M5R1	19.7 ± 2.9	54 ± 8	91 ± 13
M5R2	1.58 ± 0.23	4.8 ± 0.7	10.8 ± 1.6
M5R3	0.29 ± 0.04	0.79 ± 0.11	1.69 ± 0.25
M5R4	0.23 ± 0.03	2.1 ± 0.3	9.0 ± 1.3

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

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

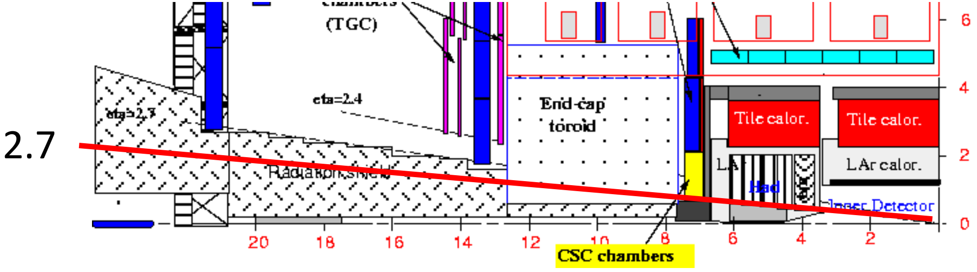
A hadron fluence larger than 10^{16} cm^{-2} is very challenging for silicon sensors

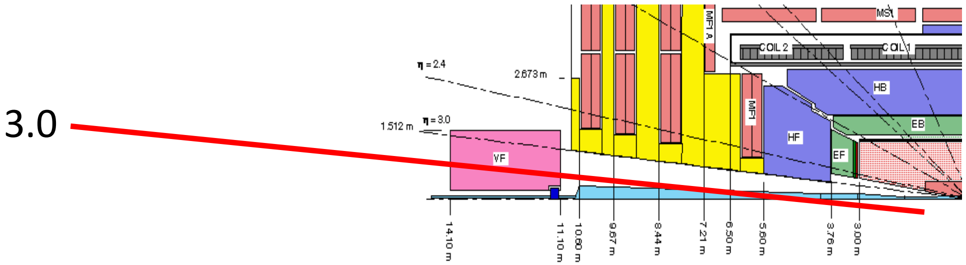


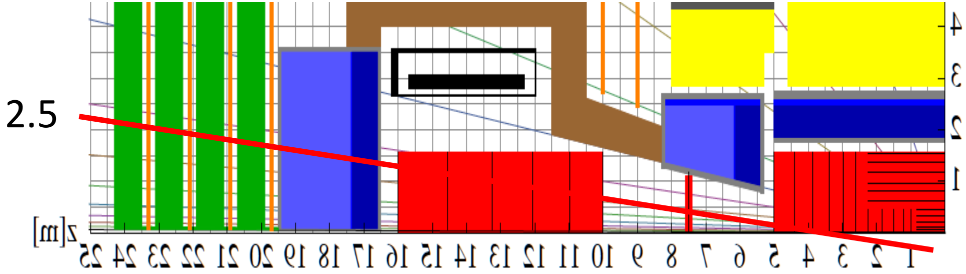
Central tracker:
- first IB layer (2.5 cm): ~5-6 10^{17} cm^{-2}
- external part: ~5 10^{15} cm^{-2}

Forward calorimeters:
- maximum at ~5 10^{18} cm^{-2} for both the EM and the HAD-calo
- 10^{16} cm^{-2} at R=2 m

Comparison to ATLAS & CMS







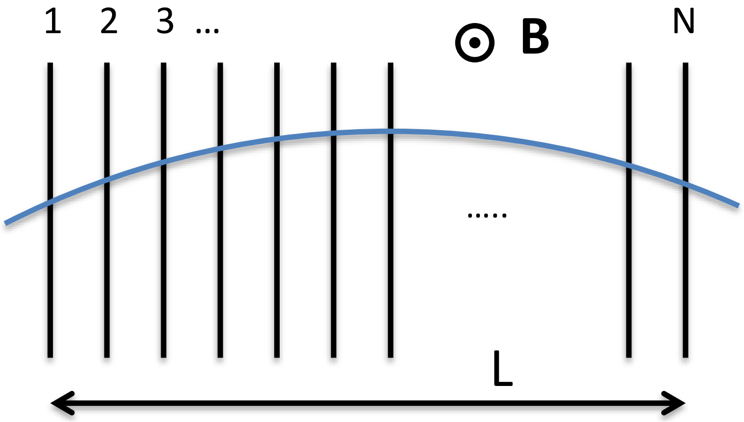
The forward calorimeters are a very large source of radiation (diffuse neutron source).

In ATLAS the forward calorimeter is inside the endcap calorimeter, in CMS the forward calorimeter is inside enclosed by the return Yoke.

For the FCC, the forward calorimeter is moved far out in order to reduced radiation load and increase granularity.

→ A shielding arrangement is needed to stop the neutrons to escaping into the cavern hall and the muon system.

Tracker Point Resolution and Multiple Scattering



σ ... point resolution/plane

X_{tot}/X_0 ... total material budget

N equidistant layers

Position Resolution

$$\frac{\Delta p_t}{p_t} = \frac{\sigma[m]\, p[\mathrm{GeV/c}]}{0.3\, B[T]\, L^2[m^2]} \sqrt{\frac{720\,(N-1)^3}{(N-2)\,N\,(N+1)\,(N+2)}}$$

$$\approx \frac{\sigma[m]\, p[\mathrm{GeV/c}]}{0.3\, B[T]\, L^2[m^2]} \sqrt{\frac{720}{N+4}}$$

Multiple Scattering, Equal weighting

$$\frac{\Delta p_t}{p_t} = \frac{0.0136}{0.3\beta\, B[T]\, L[m]} \sqrt{\frac{X_{tot}}{X_0}} \sqrt{\frac{10}{7}\,\frac{12+(N-1)N^2(N+1)}{(N-2)N(N+1)(N+2)}}$$

$$\approx \frac{0.0136}{0.3\beta\, B[T]\, L[m]} \sqrt{\frac{X_{tot}}{X_0}} \sqrt{\frac{10}{7}}$$

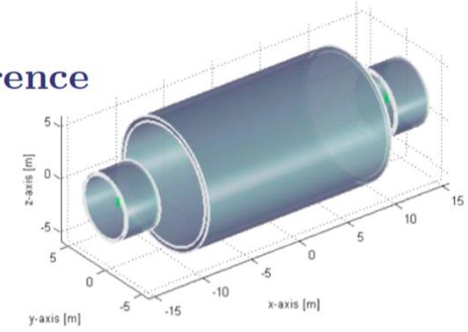
≈1.2

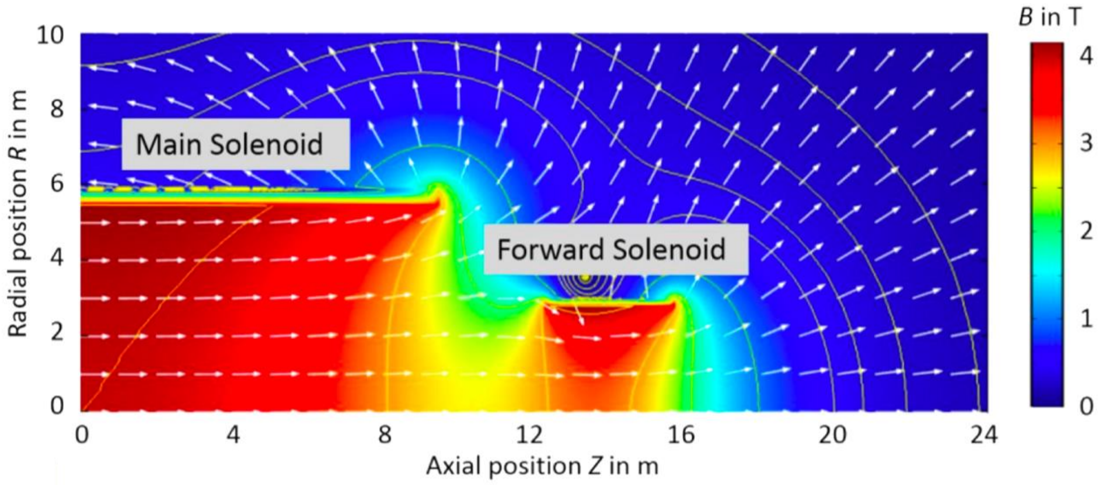
$$\approx \frac{0.0542}{\beta\, B[T]\, L[m]} \sqrt{\frac{X_{tot}}{X_0}}$$

Taking into account the correlation (Kalman filter etc.) this number can be reduced to 1.0

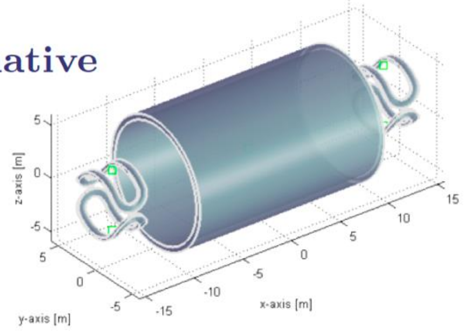
Magnet

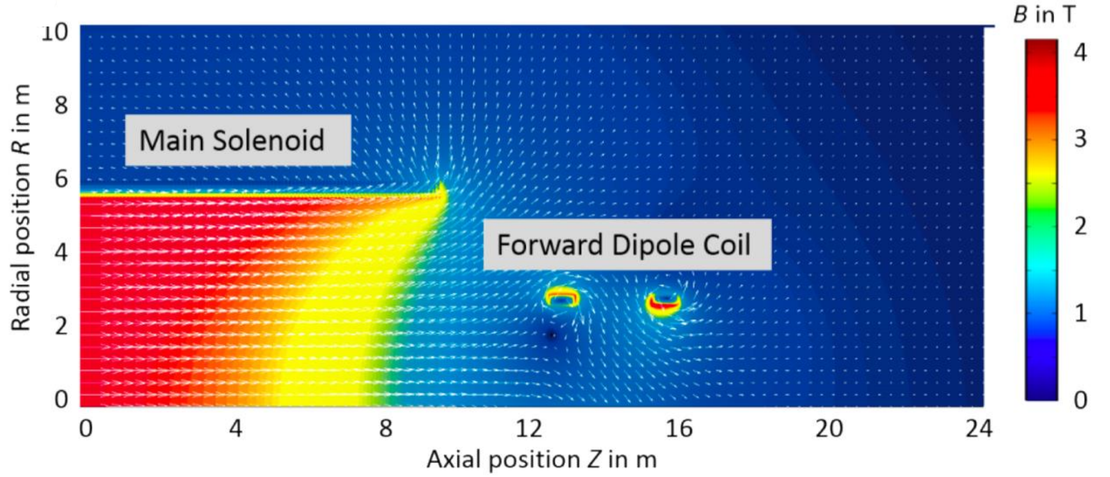
reference



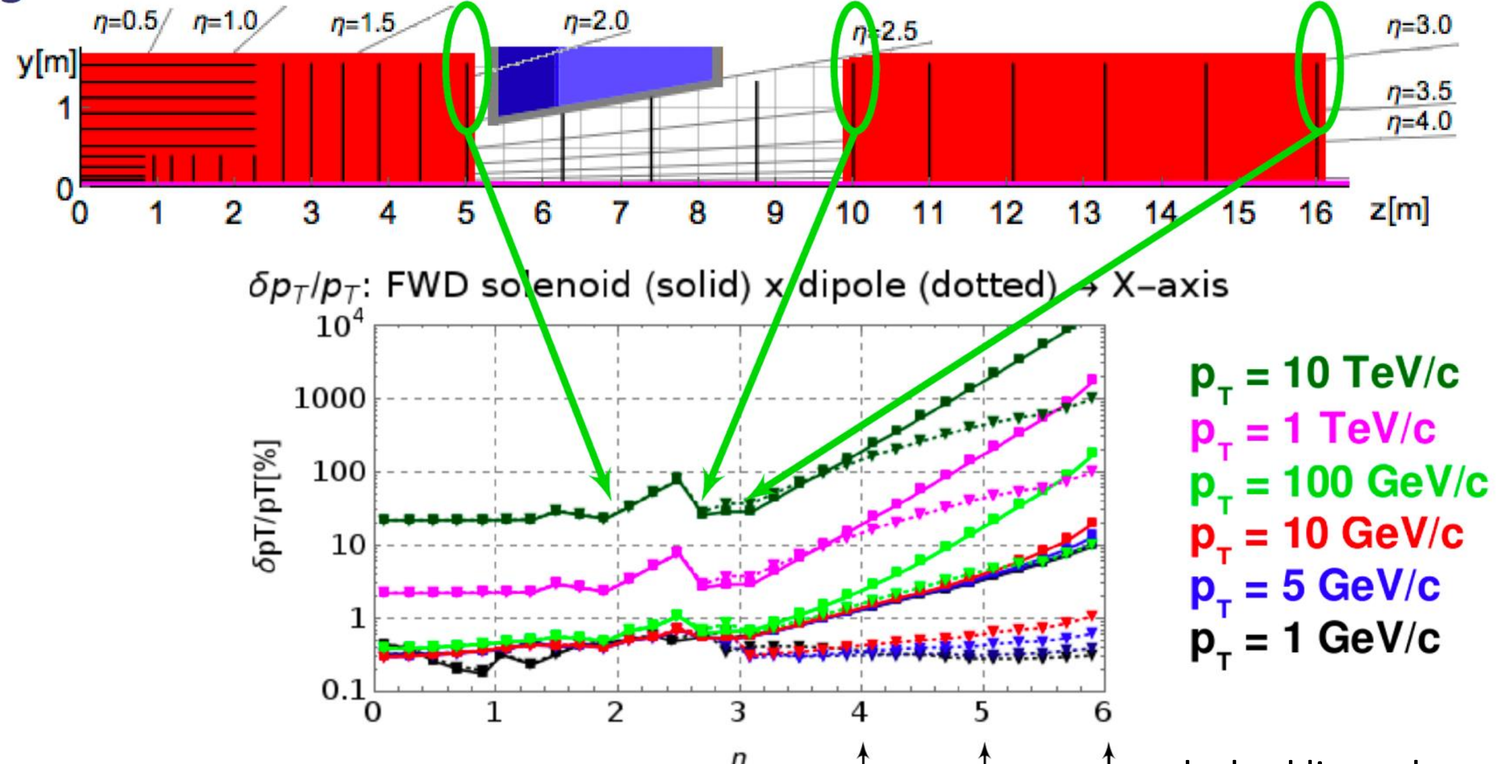


alternative





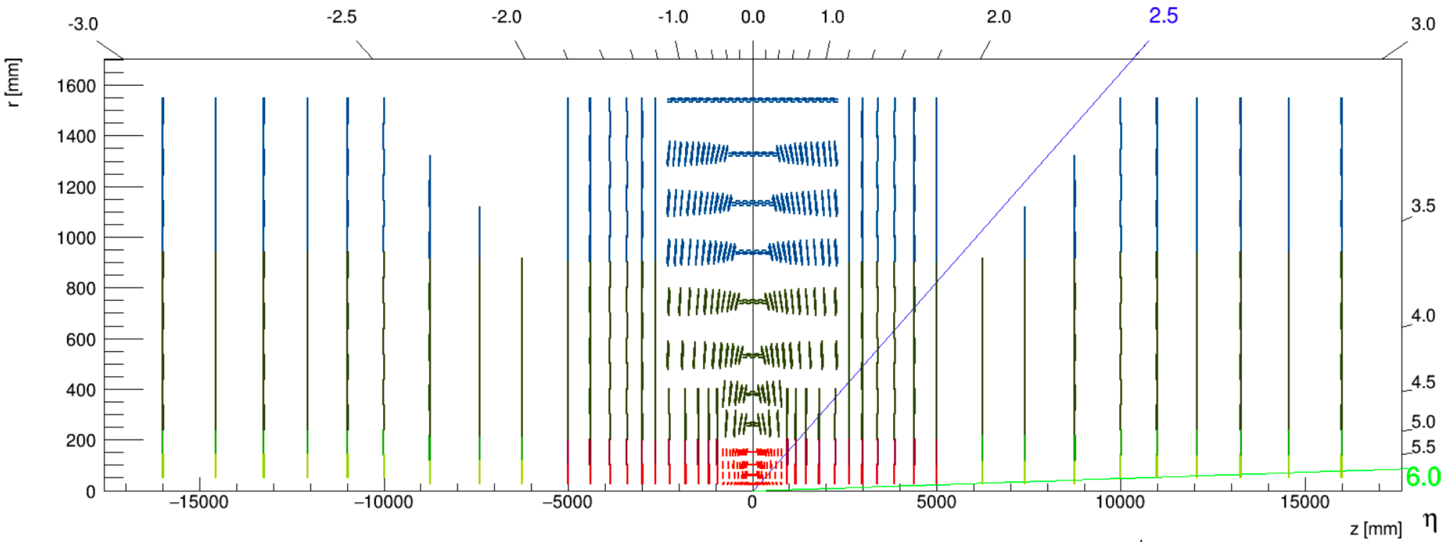
Magnet: momentum resolution

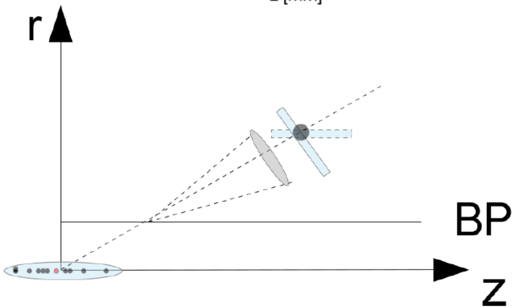


dashed lines show the dipole option

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

Tracker

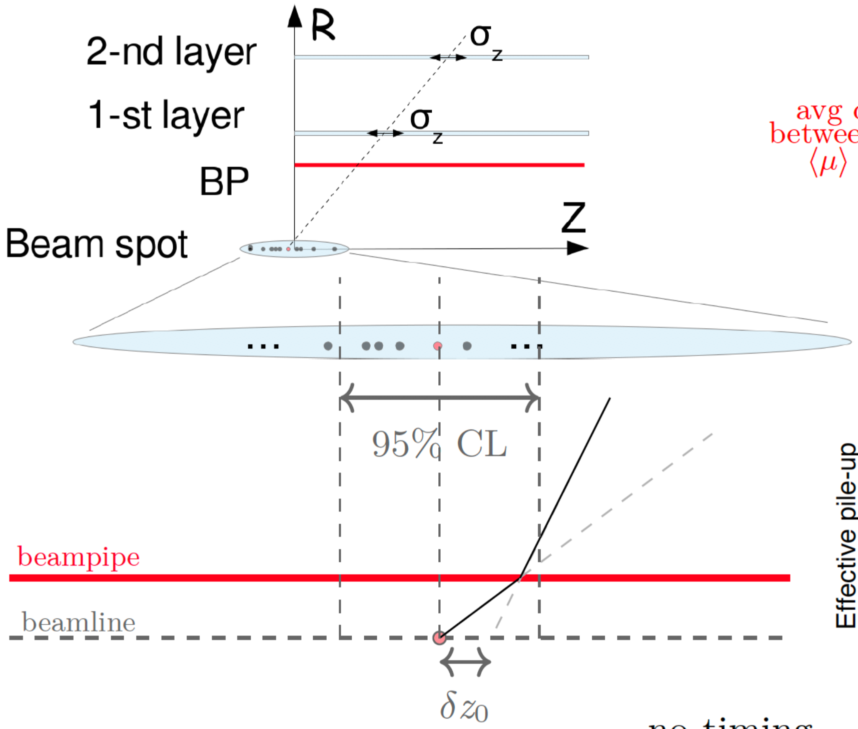


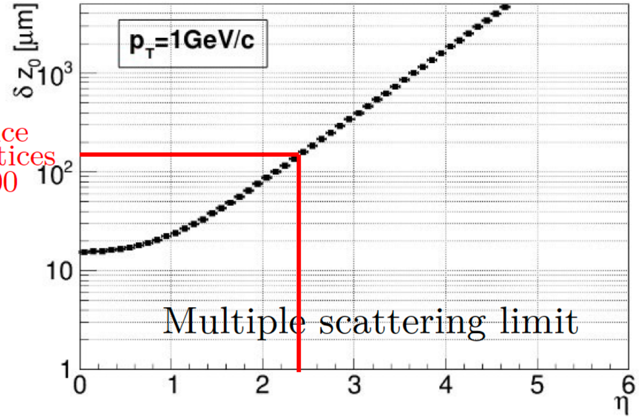


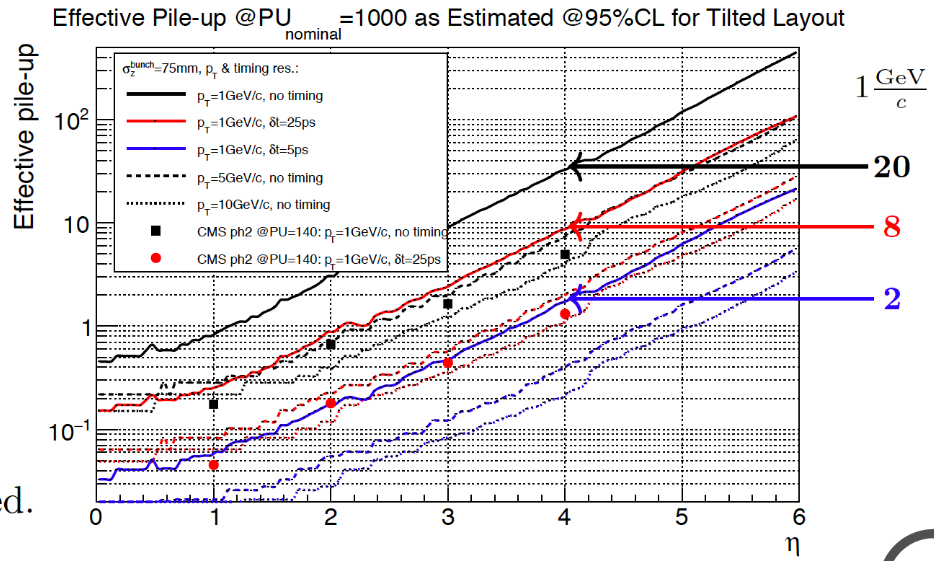
- Minimization of the effect of multiple scattering (material budget).
- Optimised by the pattern recognition and vertexing.

→ Inclined tracker modules.

Tracker



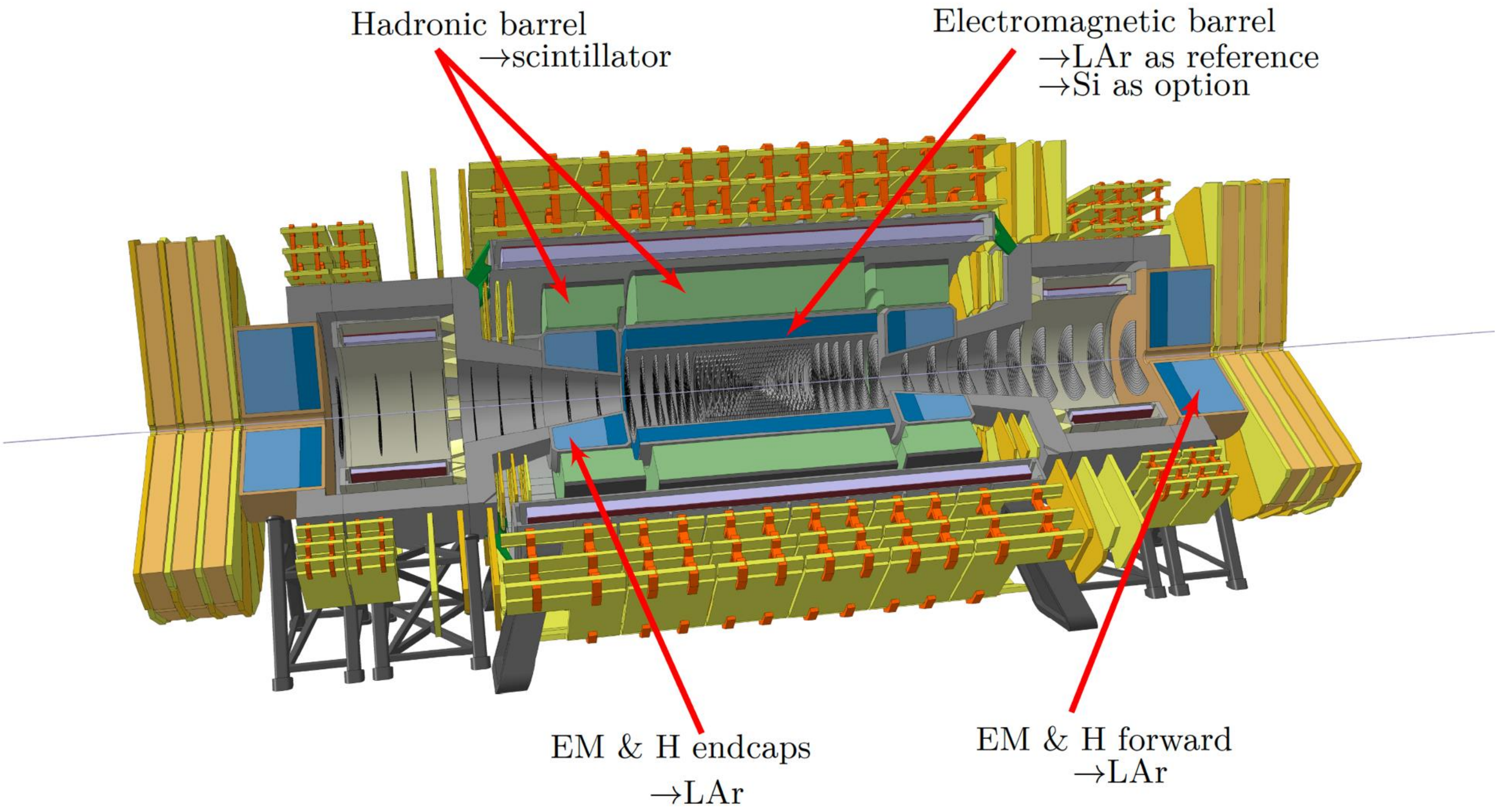




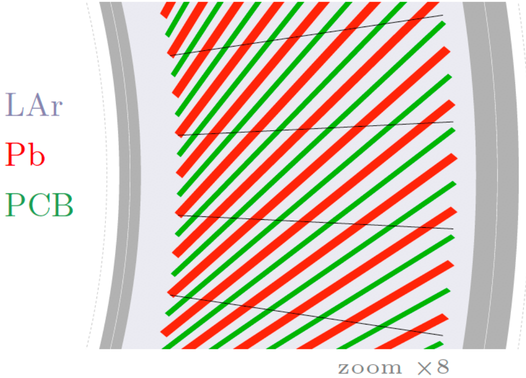
no timing
δt=25 ps
δt=5 ps

To mitigate the pile-up effect tracking with precise timing information required.

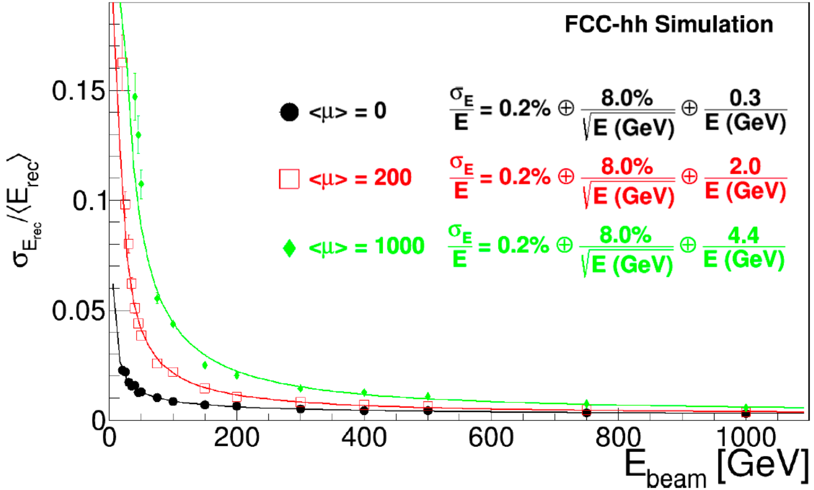
Calorimetry

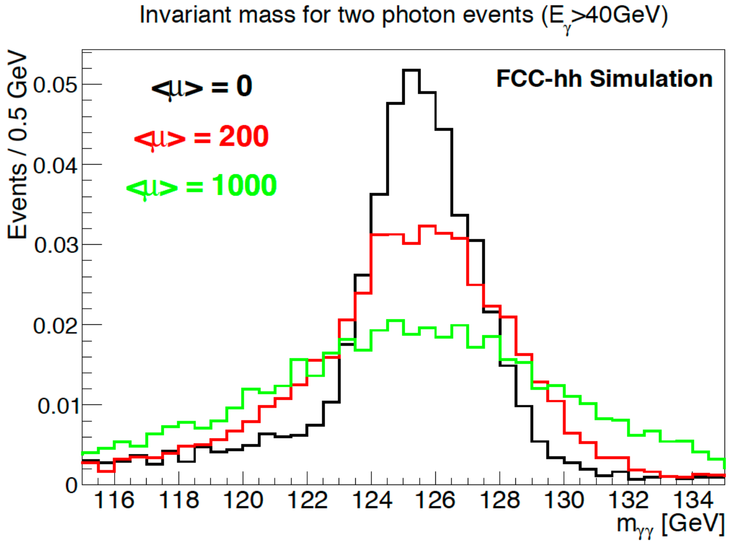


LAr electromagnetic calorimeter

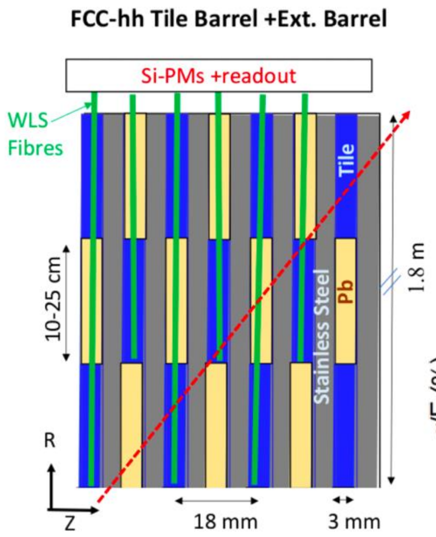


- Much more granular than ATLAS calorimeter (×10).
- High longitudinal and lateral segmentation possible with straight, multilayer electrodes.
- Huge impact of pile-up in calorimeter standalone measurements - need to subtract pile-up using pile-up track identification.



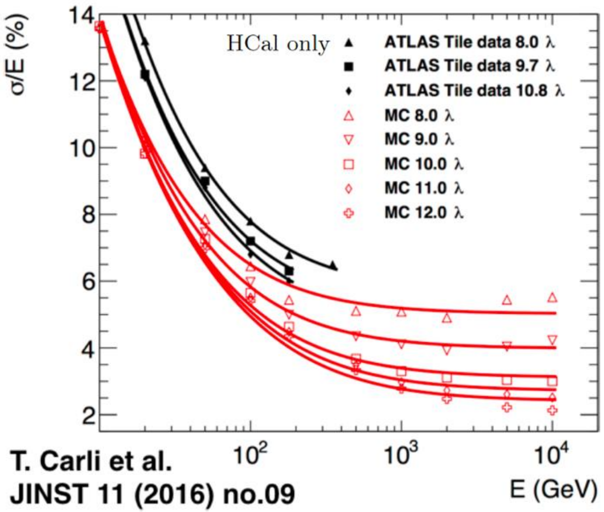


Hadronic barrel calorimeter



- 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 $\eta = 0$.

calorimeter depth



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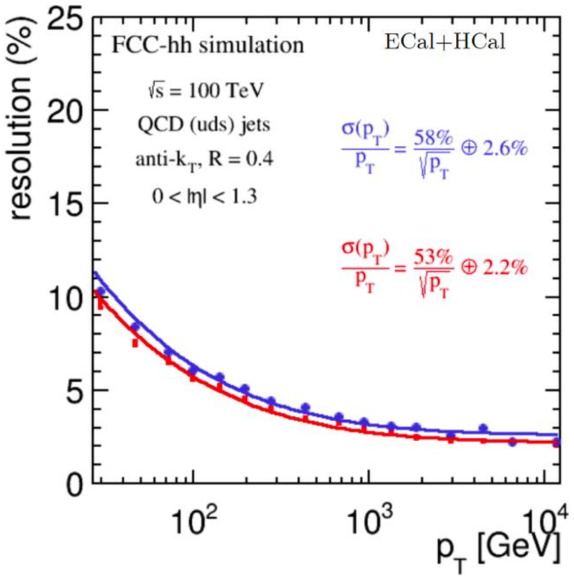
jet resolution

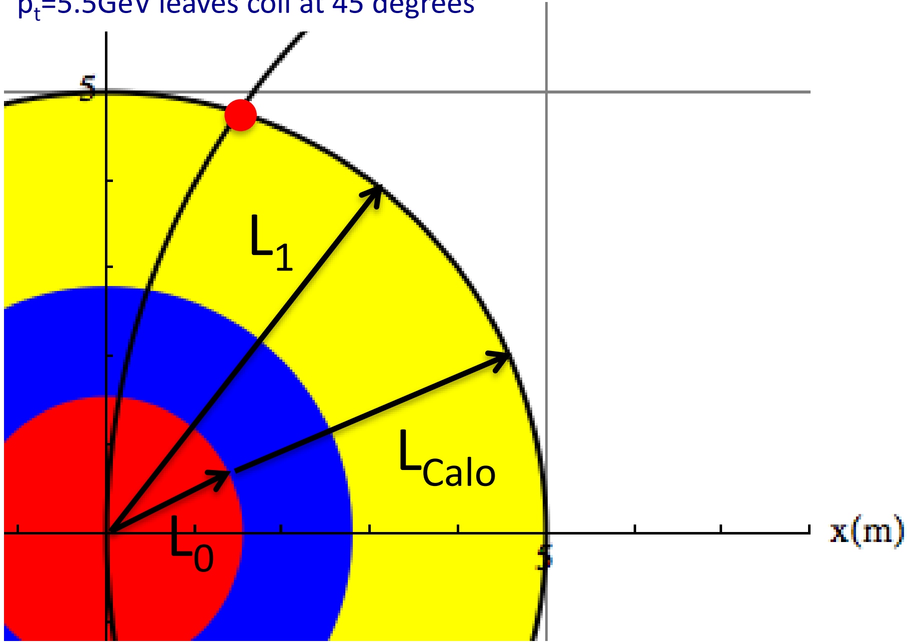


Muon system performance estimate

Three ways to measure the muon momentum

1) Tracker only with identification in the muon system
2) Muon system only by measuring the muon angle where it exits the coil
3) Tracker combined with the position of the muon where it exists the coil

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



We assume a constant magnetic field inside the coil radius L_1.

The measurement points in the tracker of radius L_0 are equidistant and have all the same resolution σ_0.

The measurement point at L_1 has a position error σ_1 that is given by the multiple scattering inside the calorimeters
(σ_y in the following).

The formula for the momentum resolution is given in the next slide.

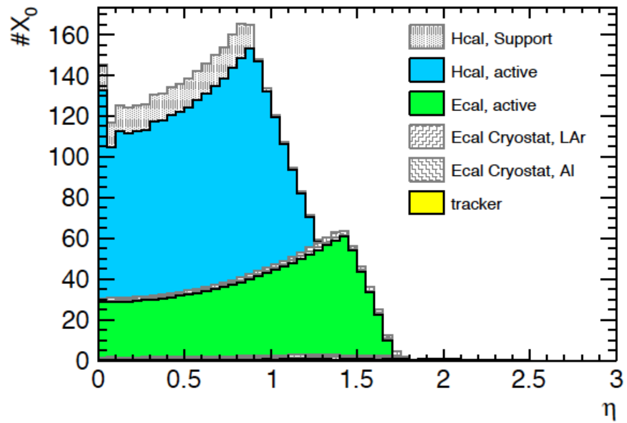
Muon system performance estimate

2) Muon System standalone by measuring the angle of the muon when exiting the coil

$$\frac{\Delta p}{p} = \frac{2p}{0.3 L_1 B}\sqrt{\theta_0^2 + \sigma_{theta}^2} \qquad \theta_0 = \frac{0.0136}{\beta p[GeV/c]}\sqrt{\frac{L_{Calo}}{X0_{Calo}}}\left(1 + 0.038\log\frac{L_{Calo}}{X0_{Calo}}\right)$$

1) Inner Tracker of radius L_0 with N+1 equidistant layers of resolution σ_0

$$\frac{\Delta p}{p} = \frac{p}{0.3B}\frac{\sigma}{L_0^2}\sqrt{\frac{720N^3}{(N-1)(N+1)(N+2)(N+3)}} \approx \frac{p}{0.3B}\frac{\sigma}{L_0^2}\sqrt{\frac{720}{N+5}} \qquad N \gg 1$$



3) Combined

$$\frac{\Delta p}{p} = \frac{p}{0.3B}\frac{\sigma_0}{L_0^2}\sqrt{\frac{720N^3(c_1\sigma_0^2 + c_2\sigma_1^2)}{(N+1)(N+2)(c_3\sigma_0^2 + c_4\sigma_1^2)}}$$

$$\begin{aligned}
c_1 &= 2[2N(L_0^2 - 3L_0L_1 + 3L_1^2) + L_0^2] \\
c_2 &= L_0^2(N+1)(N+2) \\
c_3 &= 3\left[L_0^2(3N^3 - N - 2) - 12L_0L_1(2N^3 - N^2 - N) + 12L_1^2(7N^3 - N^2 - N)\right] + 60N^3\frac{L_1^4}{L_0^2} - 120N^3\frac{L_1^3}{L_0} \\
c_4 &= L_0^2(N-1)(N+1)(N+2)(N+3)
\end{aligned}$$

$$\sigma_y = \frac{1}{\sqrt{3}} L_{Calo}\,\theta_0$$

Muon Systems

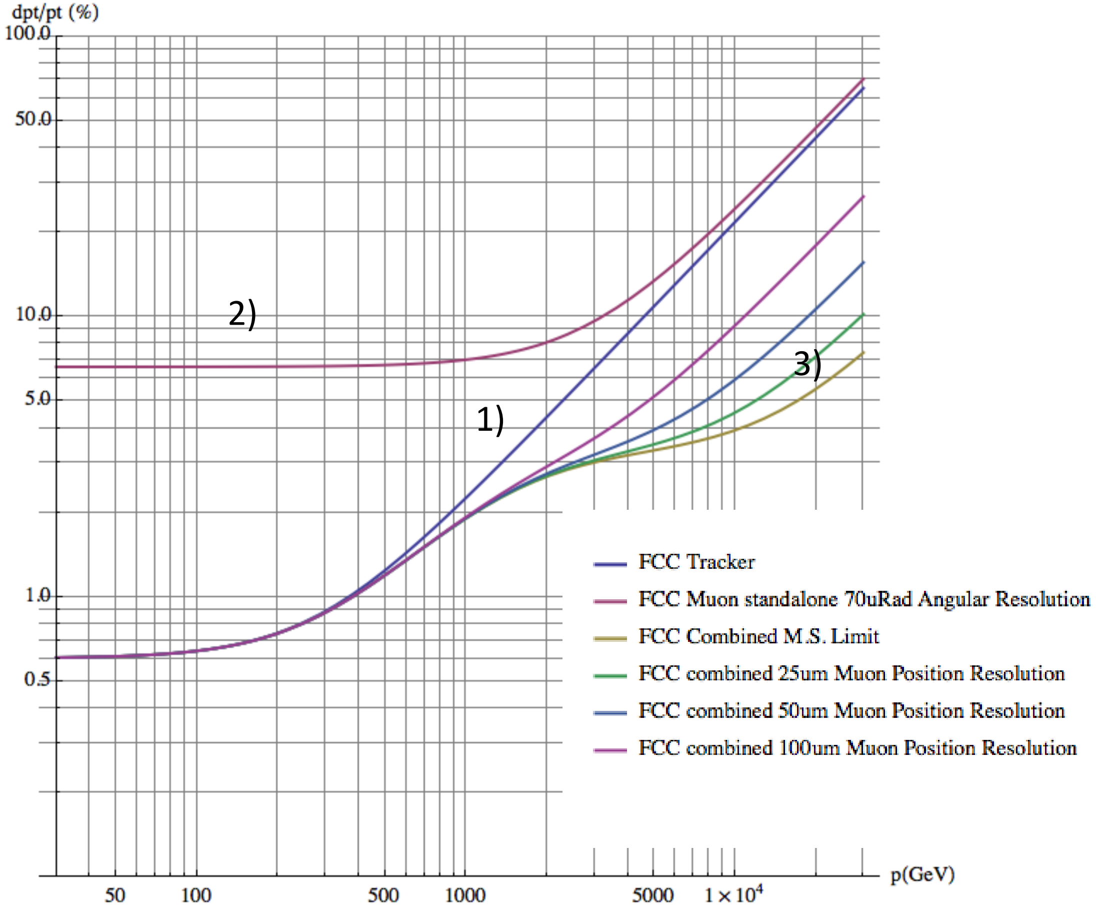
1) Tracker only with identification in the muon system
2) Muon system only by measuring the muon angle where it exits the coil
3) Tracker combined with the position of the muon where it exists the coil

With 50µm position 70µRad angular resolution resolution we find (η=0)

<10% standalone momentum resolution up to 3TeV/c

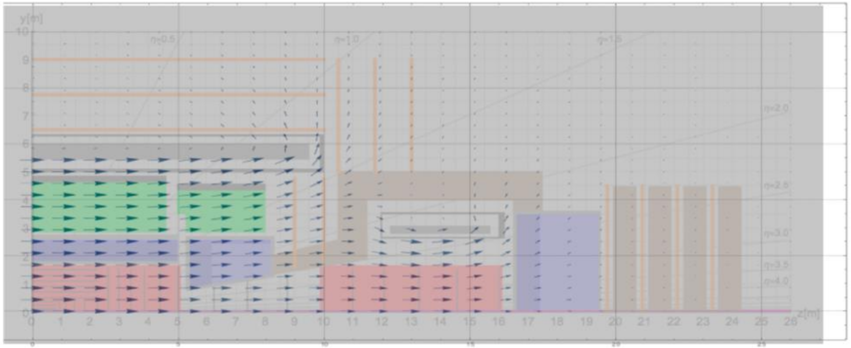
<10% combined momentum resolution up to 20TeV

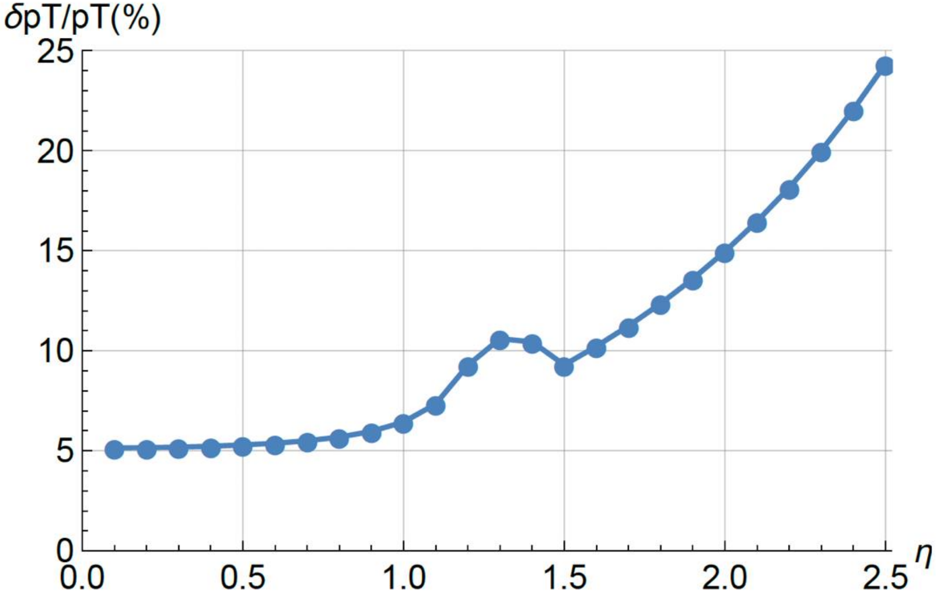
All within reach of ‘standard’ muon system technology



Muon standalone performance

- 200 X_0 of material in front of muon system
- perfect muon chamber resolution





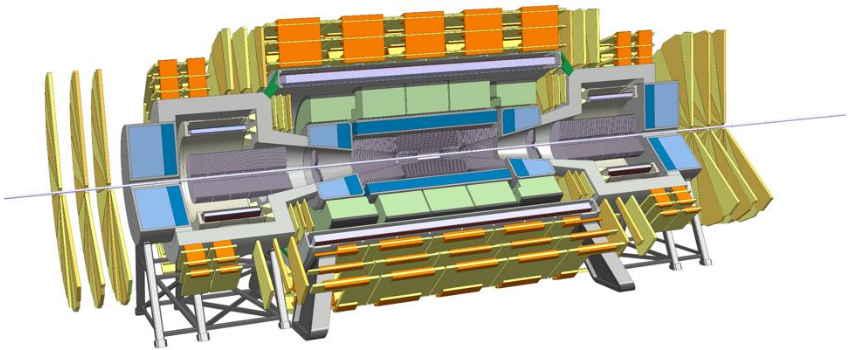
Trigger/DAQ

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.

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 800TByte/s.

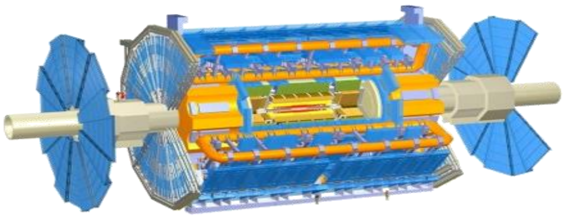


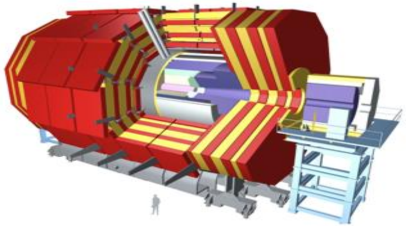
Question:

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.

ATLAS & CMS @ HL-LHC (2025-2026)





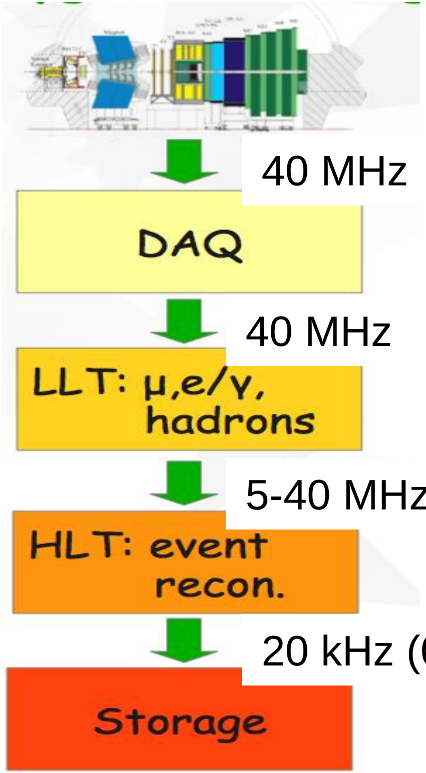
40 MHz

Hardware trigger to reduce events rate by factor 40

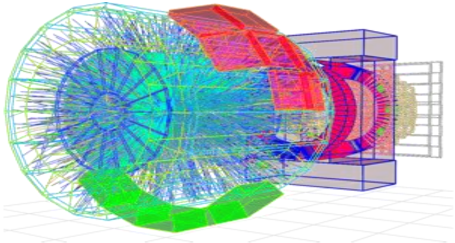
ATLAS		CMS
↓	40 MHz	↓
Level 1		Level 1
↓	0.5-1 MHz	↓
HLT		HLT
↓ 5-10 kHz (2MB/event)		↓ 10 kHz (4MB/event)
Storage		Storage
10-20 GB/s	← PEAK OUTPUT →	40 GB/s

ALICE & LHCb in LS2 (2019-2020)

No Hardware trigger, all data into HLT !



2 GB/s



50 kHz

Reconstruction + Compression

50 kHz (1.5 MB/event)

Storage

75 GB/s

← PEAK OUTPUT →

Moore‘s Law

http://www.livescience.com/23074-future-computers.html

“If the doubling of computing power every two years continues to hold, then by 2030 whatever technology we're using will be sufficiently small that we can fit all the computing power that's in a human brain into a physical volume the size of a brain”,

explained Peter Denning, distinguished professor of computer science at the Naval Postgraduate School and an expert on innovation in computing.

"Futurists believe that's what you need for artificial intelligence. At that point, the computer starts thinking for itself.“

→ Computers will anyway by themselves figure out what to do with the data by 2035.

Strategic R&D

The ATLAS/CMS Phase2 TDRs are being prepared. R&D for Phase2 is coming to an end.

The FCC CDR will be finished by end of 2018.

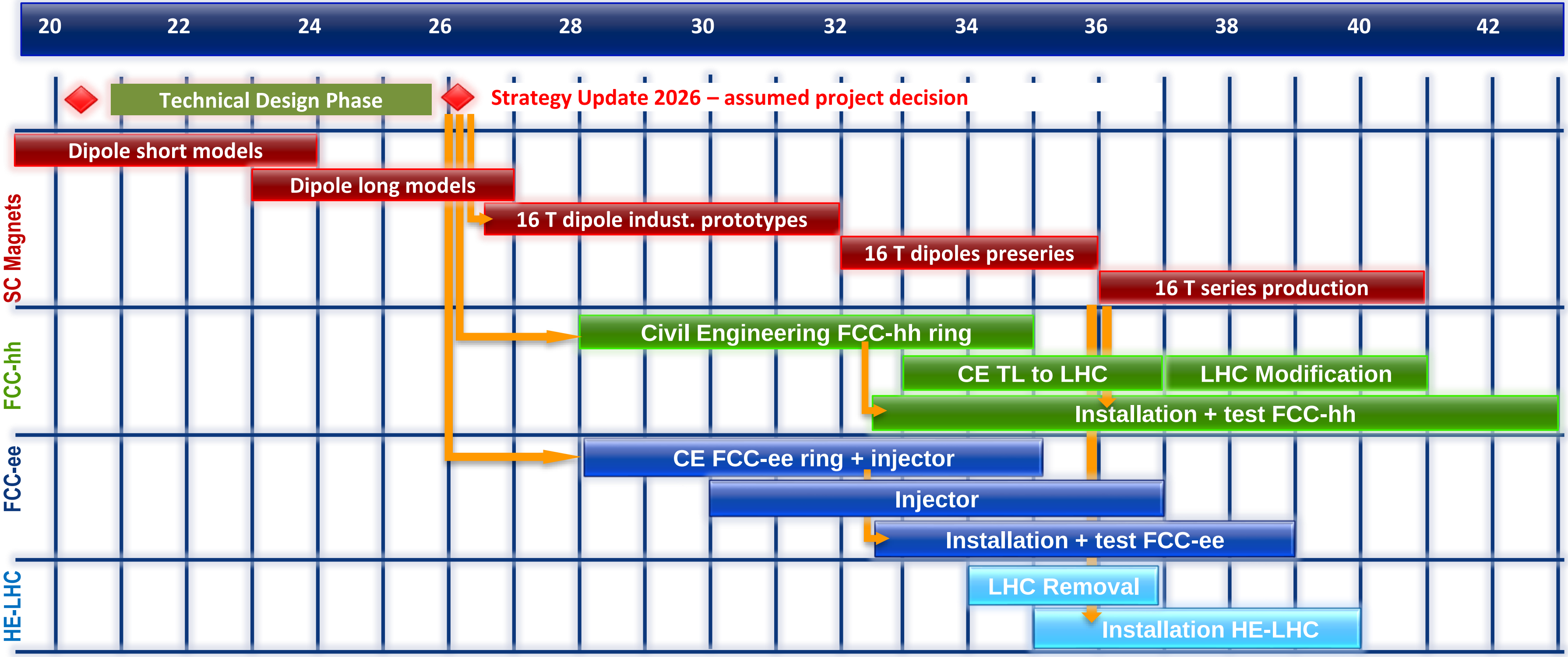
Strategic detector R&D plans must be discussed now, and put in place by 2019, that push and develop technology towards the next step.

FCC-hh and HE-LHC have very similar detector technology requirements in terms of resolution and radiation hardness.

FCC-hh, FCC-ee, FCC-eh have similar sensor technology requirements in terms of resolution and material budget.

Key technologies are radiation hard silicon sensors, radiation hard Monolithic Active Pixel Sensors (MAPS), Large scale integrated CMOS sensors, high speed low power optical links, radiation hard calorimetry, high precision timing detectors, large scale muon systems, and related electronics etc.

Draft Schedule Considerations



Summary

A 100TeV hadron collider with 100km circumference and 16T dipoles is being studied as the next machine to push the energy frontier.

A peak luminosity of 30×10^{34} $cm^{-2}s^{-1}$ at 25ns bunchcrossing results in a pileup of ≈ 1000.

An integrated luminosity of 20-30 ab^{-1} results in a fluence of ≈ 10^{16}-10^{18} 1MeVneq/cm^2 in the tracker volume and the forward calorimeters.

A general purpose reference detector is being studied to set the scale of the challenges for performing experiments at this machine.

We think that detectors can be built that can extract all the physics potential from such a machine, but a high profile R&D programme for detectors and electronics technologies has to be conducted.