# FCC-hh Accelerator and Detectors

## CERN Academic Training, Oct. 12th, 2017

**W. Riegler**

**Material from 2017 FCC week Berlin**
https://indico.cern.ch/event/556692/

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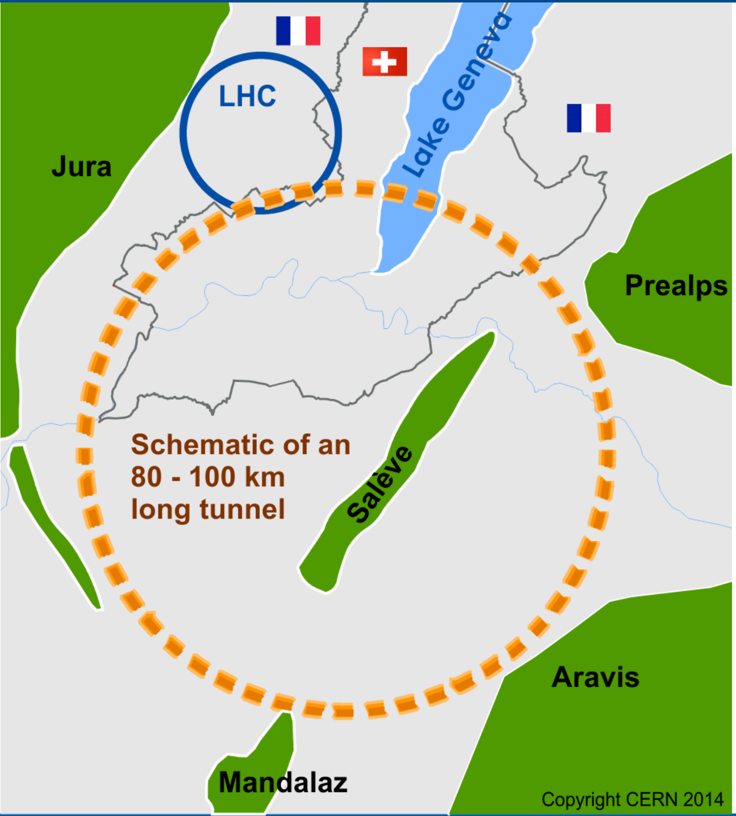
# Scope of FCC Study




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

- ***pp*-collider (*FCC-hh*)**
- → main emphasis, defining infrastructure requirements
- **~16 T ⇒ 100 TeV *pp* in 100 km**
- **~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

- **HE-LHC** with *FCC-hh* technology (LHC Ring 8→16T, 14→28TeV)
- **CDR for end 2018**

# Conceptual Design Report

**1 – PHYSICS**

Physics opportunities across all scenarios

**2 Hadron Collider Summary**

**3 – Hadron Collider Comprehensive**

- 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**

# FCC-pp collider parameters

| parameter | FCC-hh | | HE-LHC | HL-LHC | LHC |
|---|---|---|---|---|---|
| collision energy cms [TeV] | 100 | | 27 | 14 | 14 |
| dipole field [T] | 16 | | 16 | 8.33 | 8.33 |
| circumference [km] | 97.75 | | 26.7 | 26.7 | 26.7 |
| beam current [A] | 0.5 | | 1.12 | 1.12 | 0.58 |
| bunch intensity [$10^{11}$] | 1 | 1 (0.2) | 2.2 (0.44) | 2.2 | 1.15 |
| bunch spacing [ns] | 25 | 25 (5) | 25 (5) | 25 | 25 |
| synchr. rad. power / ring [kW] | 2400 | | 101 | 7.3 | 3.6 |
| SR power / length [W/m/ap.] | 28.4 | | 4.6 | 0.33 | 0.17 |
| long. emit. damping time [h] | 0.54 | | 1.8 | 12.9 | 12.9 |
| beta* [m] | 1.1 | 0.3 | 0.25 | 0.20 | 0.55 |
| normalized emittance [μm] | 2.2 (0.4) | | 2.5 (0.5) | 2.5 | 3.75 |
| peak luminosity [$10^{34}$ $cm^{-2}s^{-1}$] | 5 | 30 | 25 | 5 | 1 |
| events/bunch crossing | 170 | 1k (200) | ~800 (160) | 135 | 27 |
| stored energy/beam [GJ] | 8.4 | | 1.3 | 0.7 | 0.36 |

# Baseline Parameters for the Hadron Machine

**The present working hypothesis is:**

- peak luminosity baseline: $5x10^{34}$
- peak luminosity ultimate: ≤ $30x10^{34}$

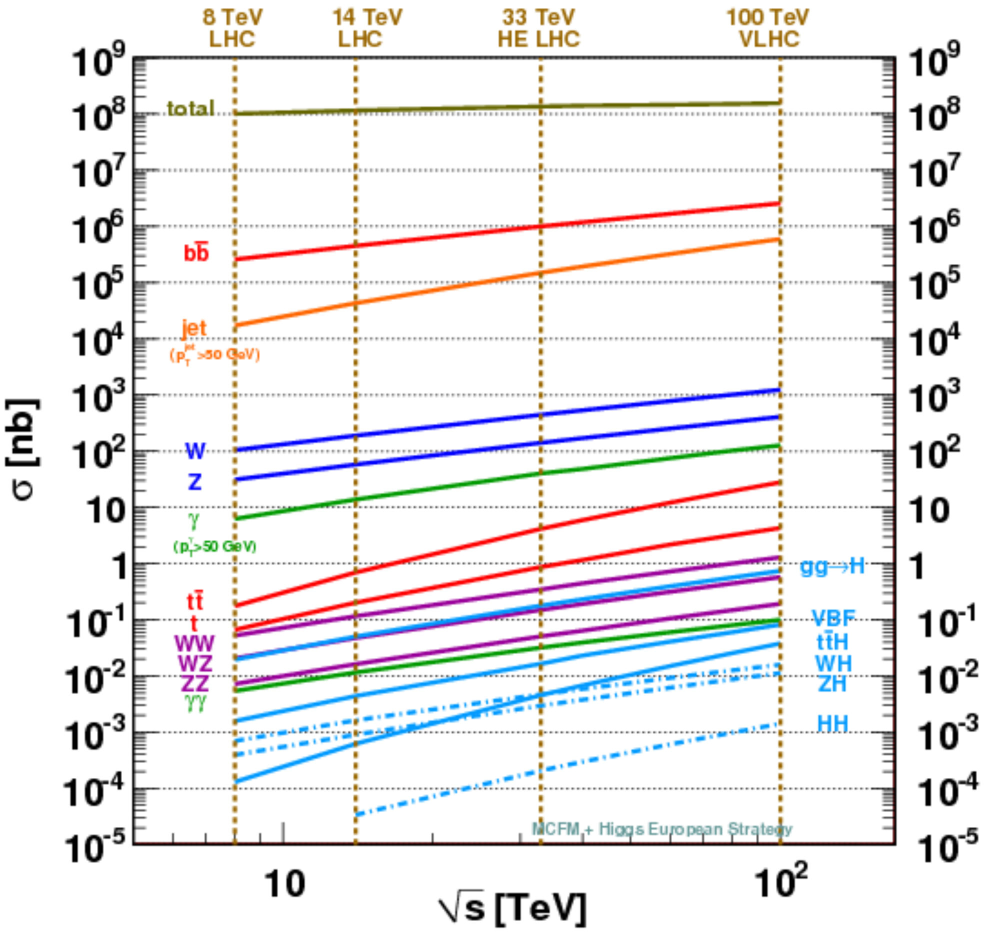
- integrated luminosity baseline ~250 fb-1 (average per year)
- integrated luminosity ultimate ~1000 fb-1 (average per year)

**An operation scenario with:**

- 10 years baseline, leading to 2.5 ab-1
- 15 years ultimate, leading to 15 ab-1

**would result in a total of O(20) ab-1 over 25 years of operation.**

# Crossections for key processes




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

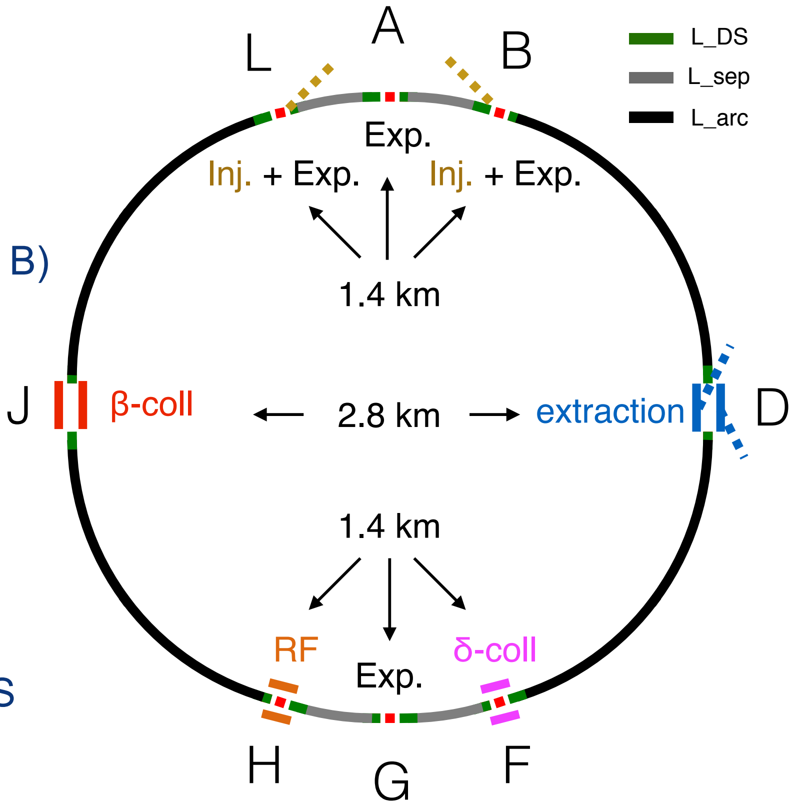
The crossection for interesting processes shows however significant increase !

→ **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.

# FCC-hh new layout

- Two high-luminosity experiments (A & G)
- Two other experiments combined with injection (L & B)
- Two collimation insertions
  - Betatron cleaning (J)
  - Momentum cleaning (F)
- Extraction insertion (D)
- Clean insertion with RF (H)
- Compatible with LHC or SPS as injector




**New features**:

- **Overall length 97.75 km**
- **Economy length 2.25 km**
- Injections upstream side of experiments
- **Avoids mixing of extraction region and high-radiation collimation areas**

Taking this layout as fixed
(for CDR preparation)

# Implementation - new footprint baseline

Alignment | Shafts | Query

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

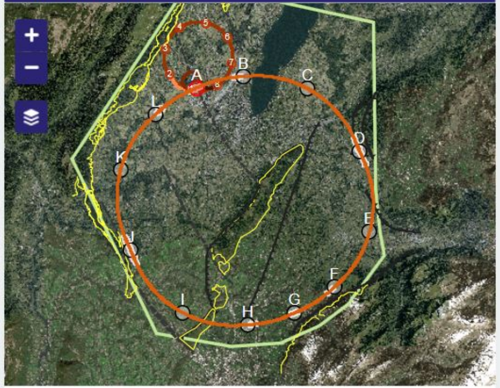
LOAD SAVE CALCULATE

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 |

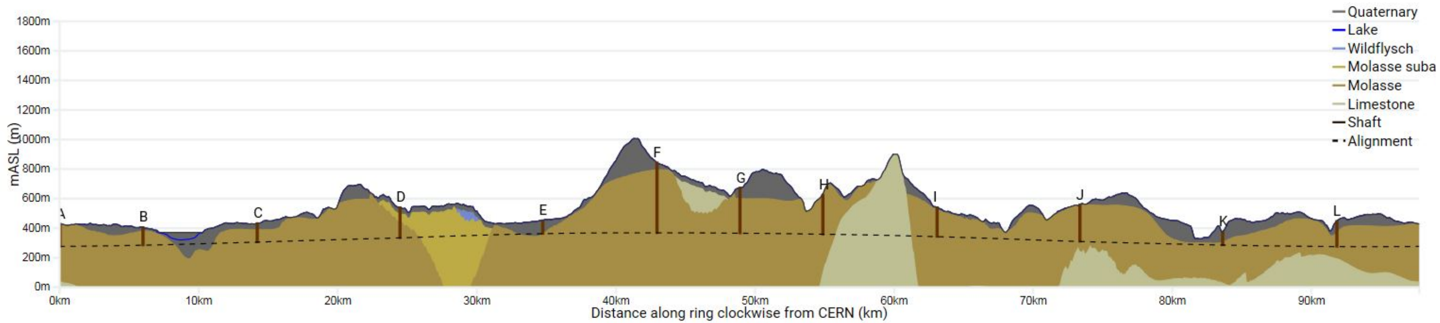
Alignment Location




Geology Intersected by Shafts | Shaft Depths

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

Alignment Profile




Geology Intersected by Tunnel | Geology Intersected by Section

84.6% 5.2% 5.5%

Optimisation in view of accessibility surface points, tunneling rock type, shaft depth, etc.

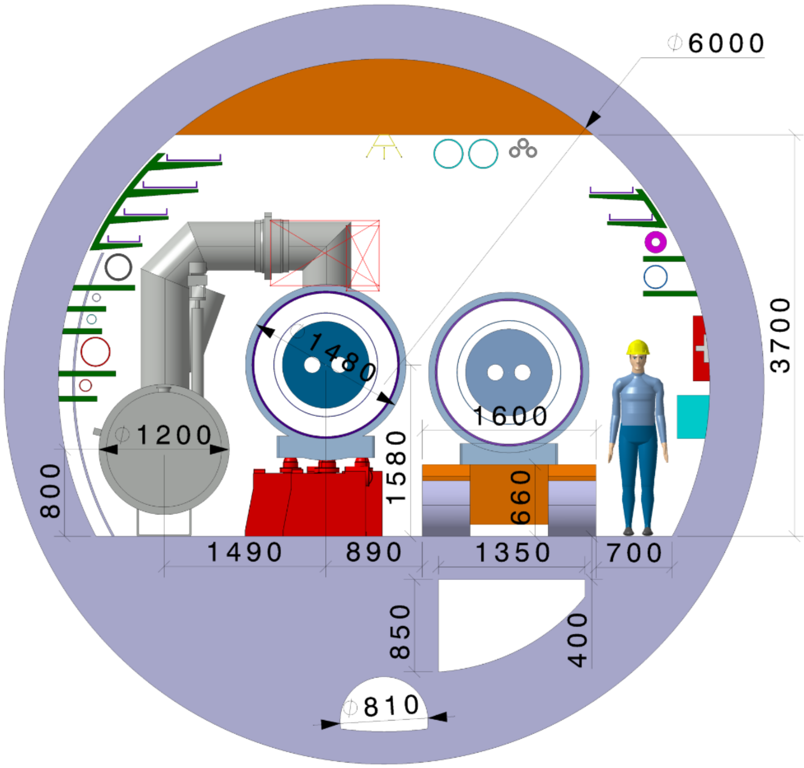
**Tunneling**

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

**Shallow implementation**

- ~ 30 m below lakebed
- Reduction of shaft length and technical installations
- One very deep shaft **F** (RF or collimation), alternatives being studied, e.g. inclined access

# FCC-hh integration




## Basic layout following LHC concept

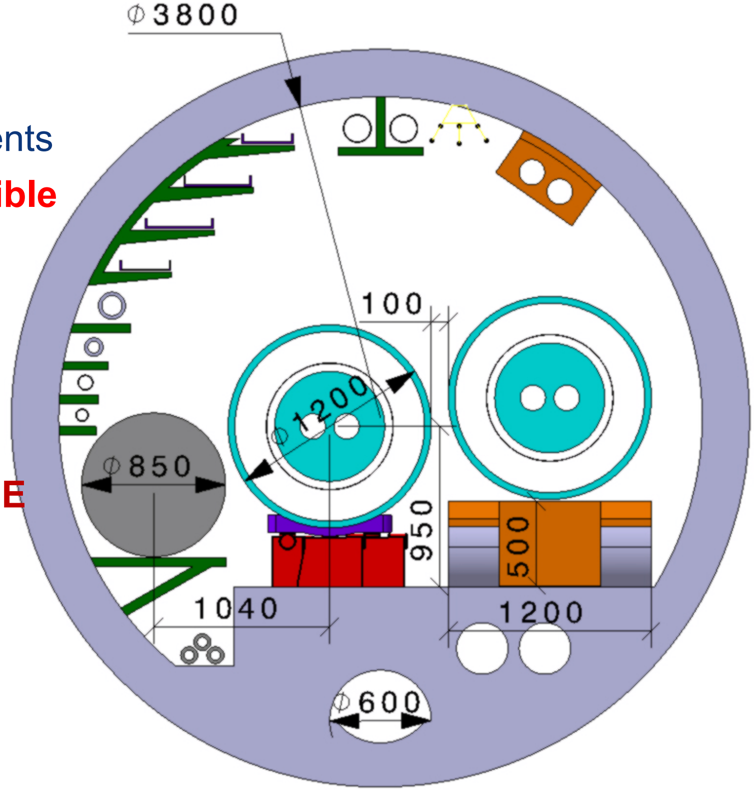
- **6 m inner tunnel diameter**
- Main space allocation:
  - 1200 mm cryo distribution line (QRL)
  - 1480 mm installed cryomagnet
  - 1600 cryomagnet magnet transport
  - >700 mm free passage.

# HE-LHC integration aspects

**Working hypothesis for HE LHC design:**

**No major CE modifications on machine tunnel and caverns**

- Similar geometry and layout as LHC machine and experiments
- **Maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm**
- **Classical 16 T cryostat design based on LHC approach gives ~1500 mm diameter!**




**Strategy: develop a single 16 T magnet, compatible with both HE LHC and FCC-hh requirements:**

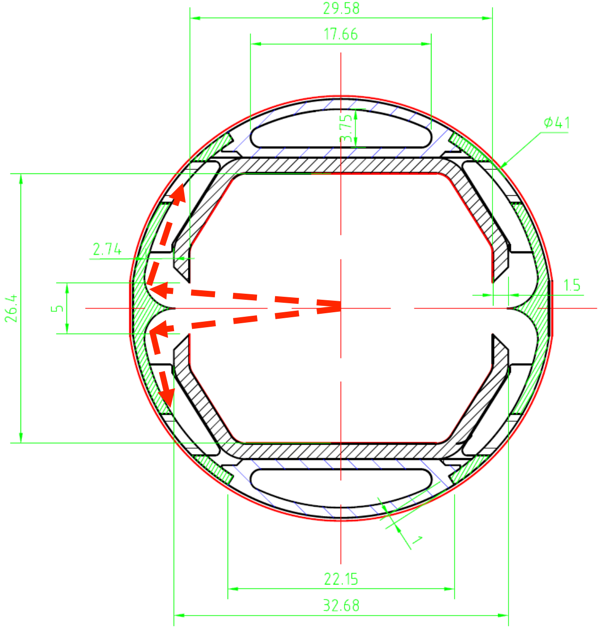
- **Allow stray-field and/or cryostat as return-yoke**
- **Optimization of inter-beam distance (compactness)**

**→ Smaller diam. also relevant for FCC-hh cost optimization**

# Cryogenic beam vacuum system

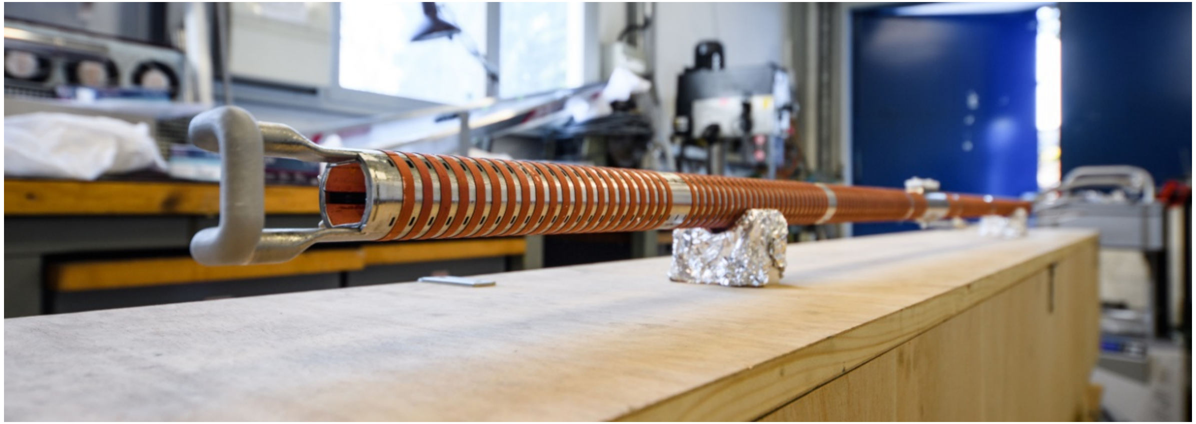
**One of the most critical elements for FCC-hh**

- Absorption of synchrotron radiation at ~50 K for cryogenic efficiency (5 MW total power)
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.




**FCC Beamscreen prototype for test at ANKA:**

External copper rings for heat transfer to cooling tubes



# Beam and Luminosity Evolution

During the beams are in collision the instantaneous value of the luminosity will change:

$$\mathcal{L}(t) = A\frac{N_b^2(t)}{\sqrt{\epsilon_x(t)\epsilon_y(t)}}$$

The beam evolution with time is obtained by solving a system of four differential equations (dominant effects only shown here, more included in simulations):

$$\frac{\mathrm{d}N_b}{\mathrm{d}t} = -\sigma_{c,\mathrm{tot}}A\frac{N_b^2}{\sqrt{\epsilon_x\epsilon_y}}$$ Intensity

$$\frac{\mathrm{d}\epsilon_x}{\mathrm{d}t} = \epsilon_x(\alpha_{\mathrm{IBS},x} - \alpha_{\mathrm{rad},x})$$ Hor. Emittance

$$\frac{\mathrm{d}\epsilon_y}{\mathrm{d}t} = \epsilon_y(\alpha_{\mathrm{IBS},y} - \alpha_{\mathrm{rad},y})$$ Ver. Emittance

$$\frac{\mathrm{d}\sigma_s}{\mathrm{d}t} = \frac{1}{2}\sigma_s(\alpha_{\mathrm{IBS},s} - \alpha_{\mathrm{rad},s})$$ Bunch Length

with

$$A = f_{\mathrm{rev}}k_b/(4\pi\beta^*)$$

- $f_{\mathrm{rev}}$ : revolution freq.
- $k_b$ : no. bunches/beam
- $\beta^*$ : β-function at IP
- $N_b$ : no. particles/bunch
- $\epsilon$ : geom. emittances
- $\sigma_s$ : bunch length
- $\sigma_{c,\mathrm{tot}}$ : total cross-section
- $\alpha_{\mathrm{IBS}}$ : IBS growth rate
- $\alpha_{\mathrm{rad}}$ : rad. damping rate

J. Jowett, M. Schaumann, FCC week Washington 2015

# Effects on the Emittance – a new regime

## Intra-Beam Scattering (IBS)

*Multiple small-angle Coulomb scattering within a charged particle beam.*

Emittance Growth

Growth rate dynamically changing with **beam properties**:

$$\alpha_{IBS} \propto \frac{r_0^2}{\gamma^4} \boxed{\frac{N_b}{\epsilon_x \epsilon_y \sigma_s \sigma_p}}$$

IBS is weak for initial beam parameters, but increases with decreasing emittance .

## (Synchrotron) Radiation Damping

*A charged particle radiates energy, when it is accelerated, i.e. bend on its circular orbit.*

Emittance Shrinkage

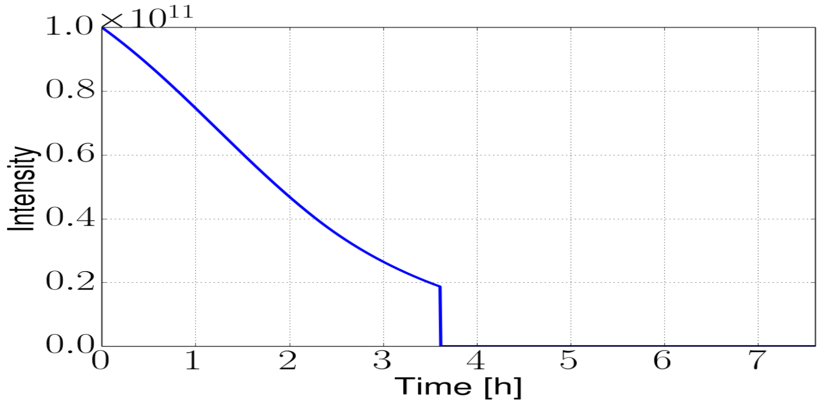
Damping rate is **constant** for a given energy:

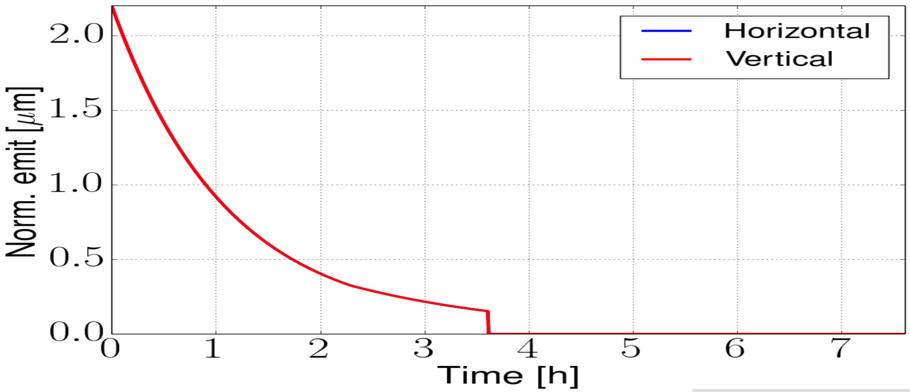
$$\alpha_{rad} \propto \frac{E^3 C_\alpha}{\rho_0 C_{ring}}$$

$$\frac{\alpha_{\mathrm{rad,FCC}}}{\alpha_{\mathrm{rad,LHC}}} \approx \frac{E^3_{\mathrm{FCC}}/C^2_{\mathrm{FCC}}}{E^3_{\mathrm{LHC}}/C^2_{\mathrm{LHC}}} \approx \frac{7^3}{4^2} \approx 22$$

**Fast emittance decrease at the beginning of the fill,**
**until IBS becomes strong enough to counteract the radiation damping.**

# pp Luminosity evolution during a fill




Developed model including most relevant effects

- Improvement with more detail planned

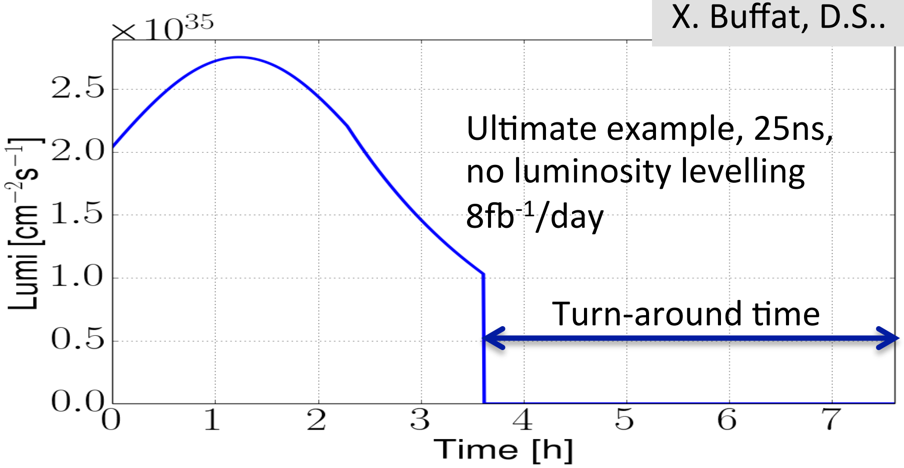
⇒ Reach 8fb$^{-1}$/day with ultimate for 25ns spacing

⇒ 5ab$^{-1}$ per 5 year run

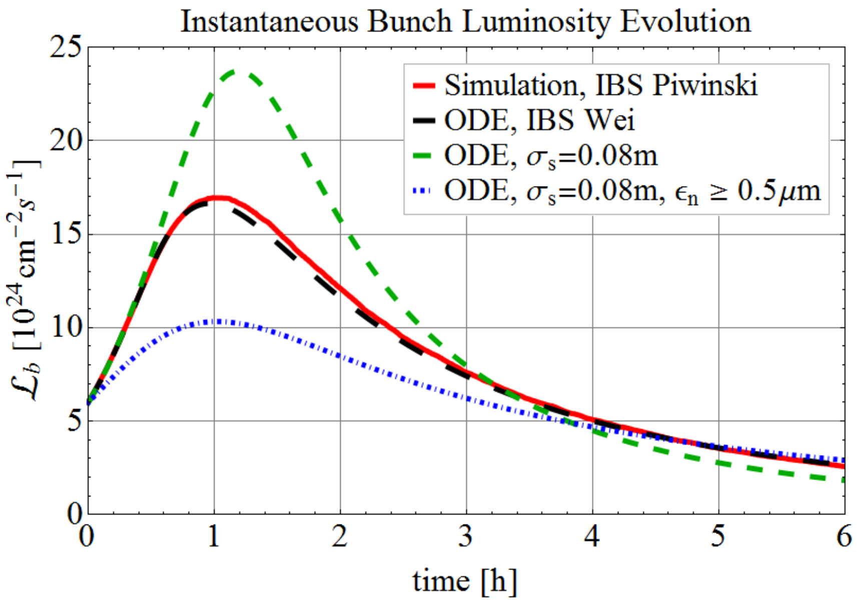
⇒ Beam is burned quickly

⇒ A reason to have enough charge stored

X. Buffat, D.S..



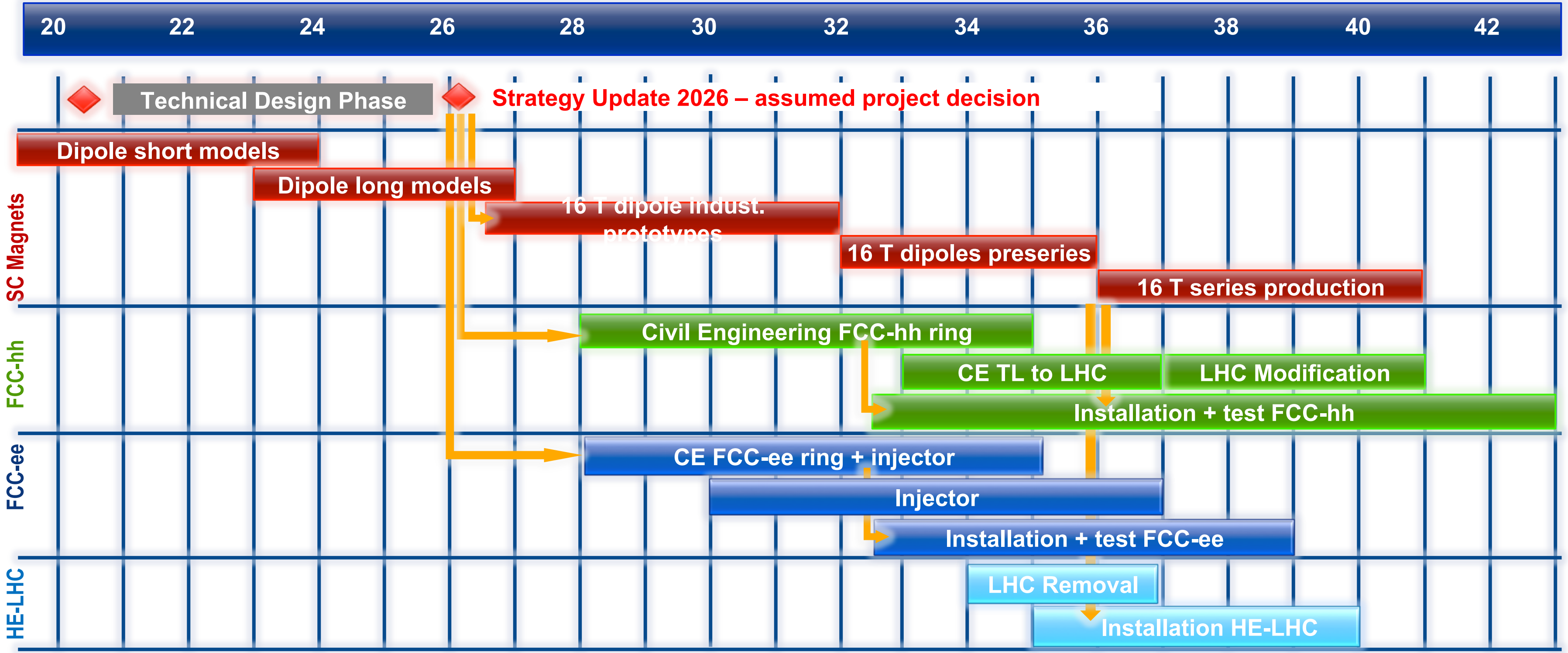
# Pb-Pb Luminosity evolution during a fill




FCC-hh is also a very powerful Heavy Ion collider !

J.M. Jowett, M. Schaumann, FCC Week 2015, Washington DC, 24 March 2015

# Draft Schedule Considerations



# 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 $\eta$ acceptance and extreme granularity.

# Physics at a 100 TeV Hadron Collider

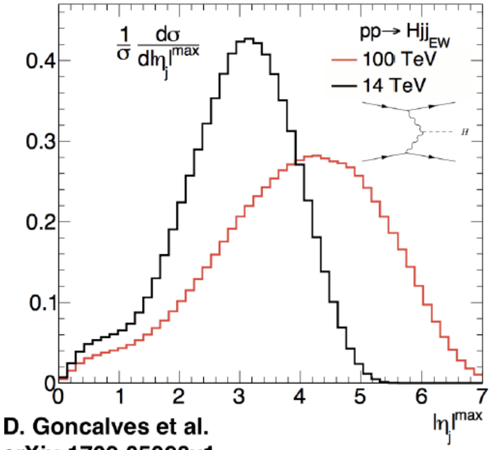
- ## Ultimate discovery machine
  - **directly** probe new physics up to **unprecendented** scale [1606.00947]
  - discover/exclude:
    - heavy resonances "strong" m(q*) ≈ 50 TeV,
      "weak" m(Z') ≈ 30TeV,
    - SUSY m(gluino) ≈ 10 TeV,
      m(stop). ≈ 5 TeV
- ## Precision machine
  - probe Higgs **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 at a 100 TeV Hadron Collider

## Higgs Physics

- Higgs self-coupling (bbγγ, bbττ, bb+leptons)
- Top-Yukawa:
  - ttH, H → γ γ (threshold), H → b b (boosted)
- Rare Higgs decays ( H → cc, H → μμ , H → Z γ)
- "Big Five": Higgs decays (H → 4l, WW ,γ γ, ττ, bb)
- VBF (VBS)
- BSM Higgs ($H^{+/-}$ → tb)

- γ, leptons, $p_T$, η acc
- b/tau tagging performance
- fwd jet tagging
- id performance and fake rates rejection




D. Goncalves et al.
arXiv:1702.05098v1

## Top physics

### Top physics couplings:

- tt γ /Z
- ttH/ttZ ratio? [1507.08169]
- tWb (single top s-channel)

- final state pT, η acceptance (especially for VBF) and resolution
- tagging efficiencies and mistag rates (c, b , top , higgs)
- id efficiencies and fake rates

# Physics at a 100 TeV Hadron Collider

## Benchmarks analyses (BSM)

### "Strong" SUSY:

- gluinos, squarks: jets + MET, s.s dileptons + jets + MET:
  - $M_g$ = 12 TeV, $M_{LSP}$ = 100 GeV
  - $M_g$ = 8 TeV, $M_{LSP}$ = 7.8 TeV (compressed region)
- stops: 0/1 leptons + jets + MET:
  - $M_{Stop}$ = 9 TeV, $M_{LSP}$ = 100 GeV
  - $M_{Stop}$ = 5 TeV, $M_{LSP}$ = 4.8 TeV (compressed region)

- lepton pT thresholds in compressed scenarios
- MET resolution
- tracking/ calo granularity in boosted regions
- lepton id requirements in boosted leptonic top decays

### "Weak SUSY/ DM":

- EW-ino: 3/4 leptons + MET
- Higgsino (disappearing tracks) Ryu Sawada
- Dark Matter Phil Harris

- lepton id, lepton threshold in compressed regions?
- MET tails
- disappearing tracks

### "Heavy Resonances":

- Z' → tt, jj, ee/μμ:
  - $M_Z$ = 5, 30 TeV

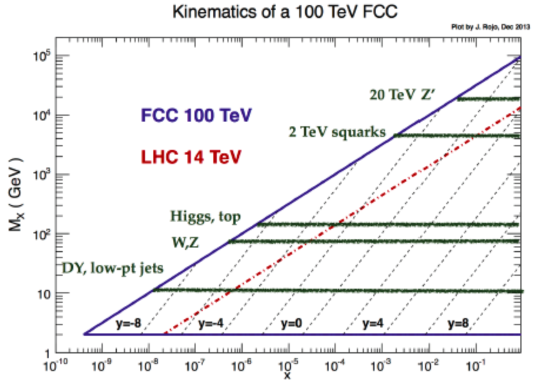
- boosted tops
- high pT electron/muon resolution

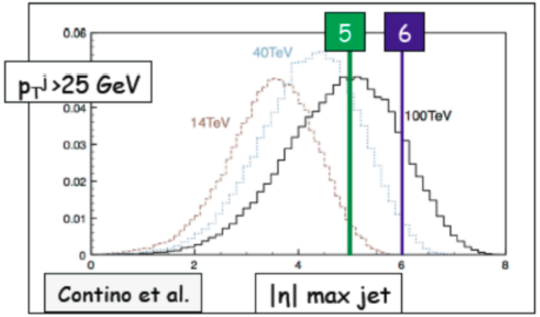
# Detector Specifications

## Towards defining the FCChh detector
### Physics constraints

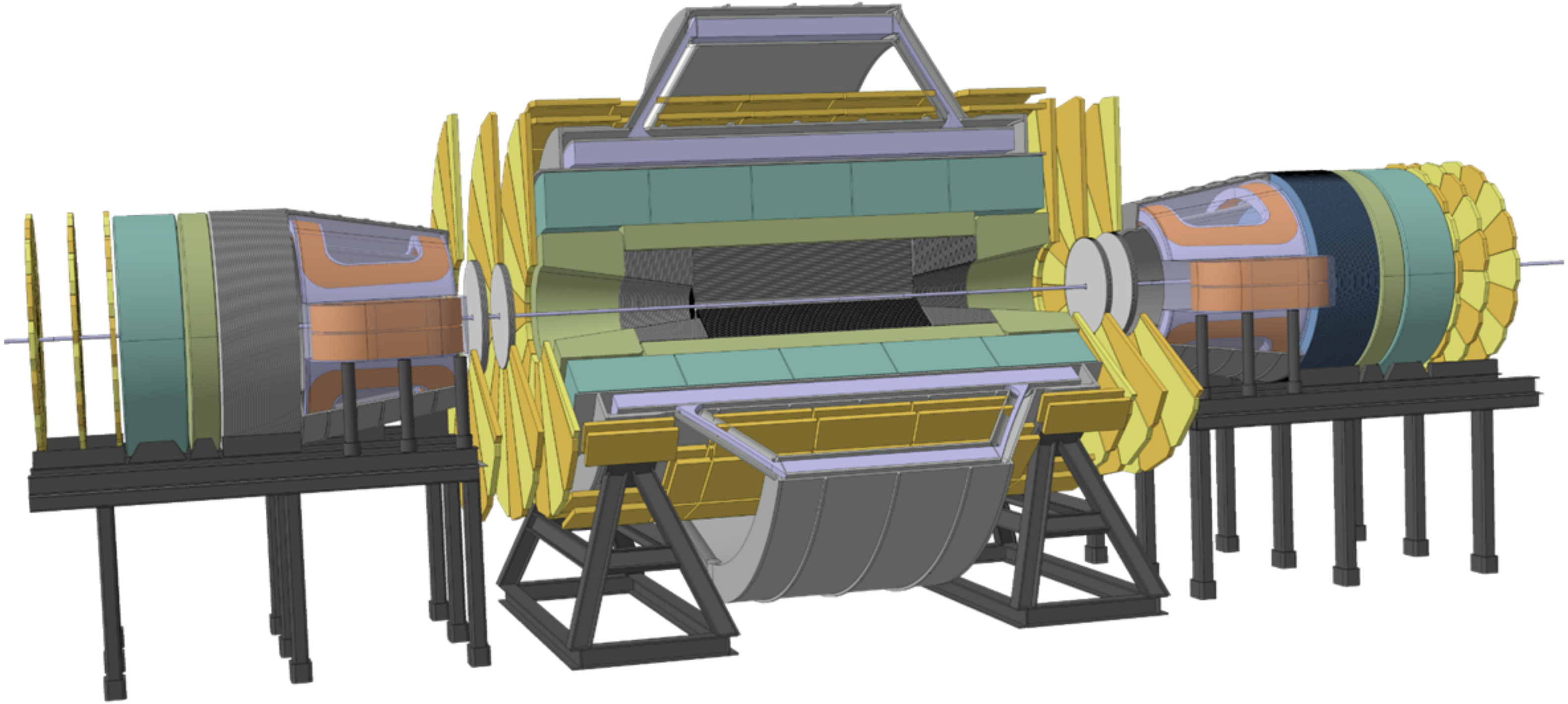
- Physics will be more forward
  - less for "high pT" physics
  - more for "low pT" physics (W/Z/Higgs, top)
  - in order to maintain sensitivity in need **large rapidity** (with tracking) and **low pT** coverage

→ precision muon up to |η| < 4
→ calorimetry up to |η| < 6
→ Can we deal with 1k pile-up will at large rapidities?

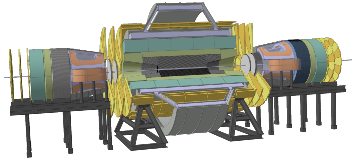


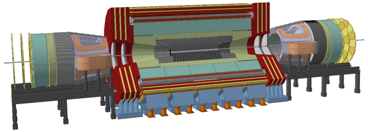
# FCC week 2016: Twin Solenoid 6T, 12m bore, Dipoles 10Tm



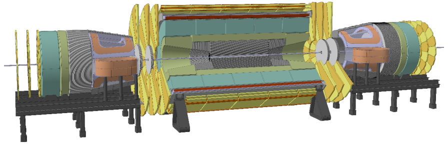
# Magnet systems under consideration



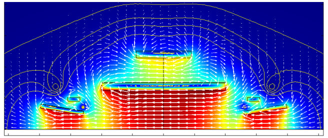
**Twin solenoid with dipoles (min. shaft diameter 27.5m)**



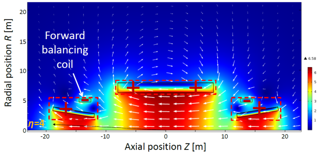
**Partially shielded solenoid with dipoles**



**Unshielded solenoid with dipoles**



**Twin solenoid with balanced conical  solenoid**




**Unshielded solenoid with balanced conical  solenoid**

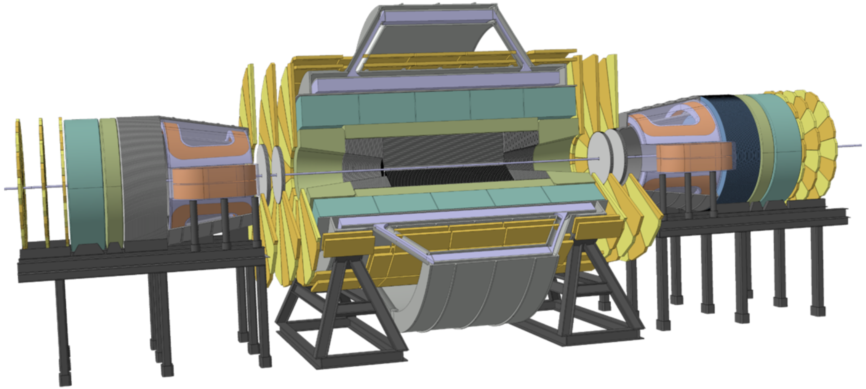
# New Reference Design

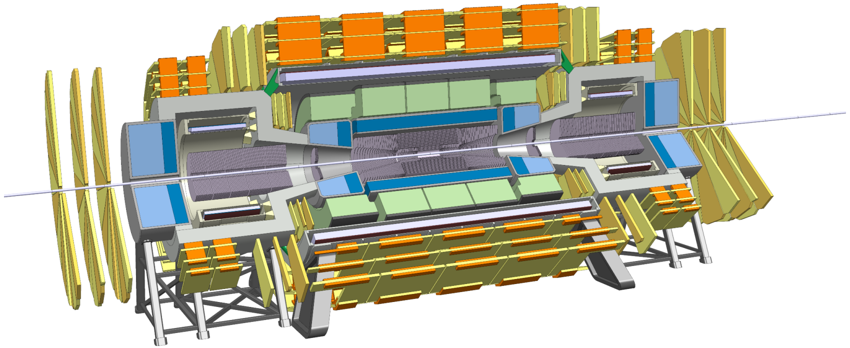
6T, 12m bore solenoid, 10Tm dipoles, shielding coil

→ 65 GJ Stored Energy
→ 28m Diameter
→ >30m shaft
→ Multi Billion project

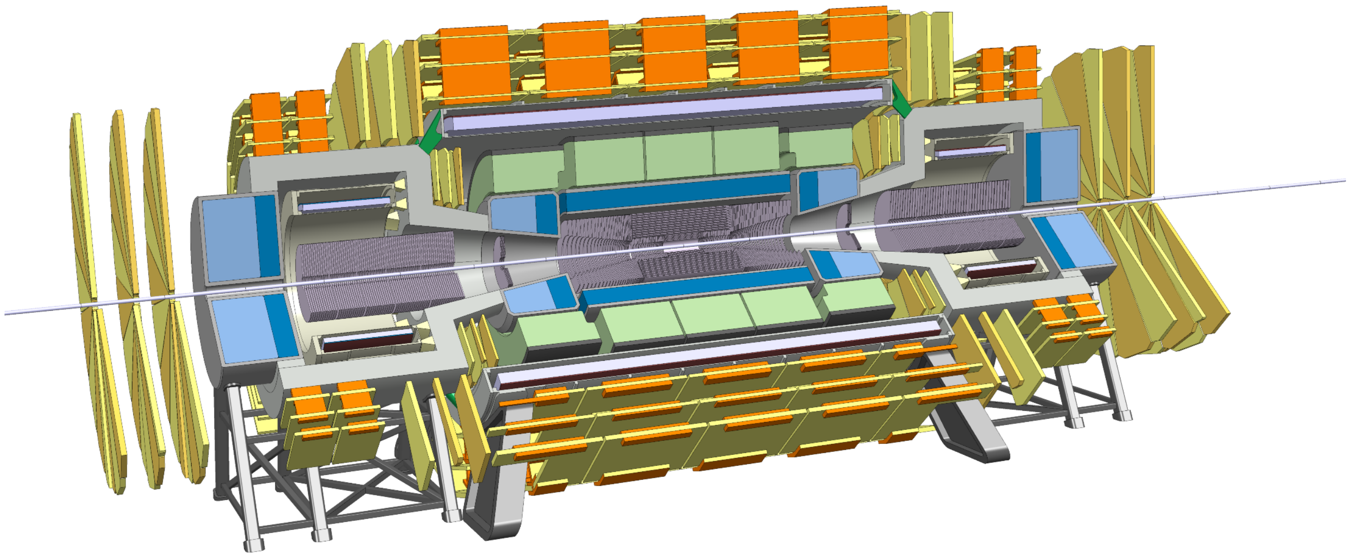
4T, 10m bore solenoid, 4T forward solenoids , no shielding coil

→ 14 GJ Stored Energy
→ Rotational symmetry for tracking and trigger !
→ 20m Diameter (≈ ATLAS)
→ 15m shaft
→ ≈ 1 Billion project





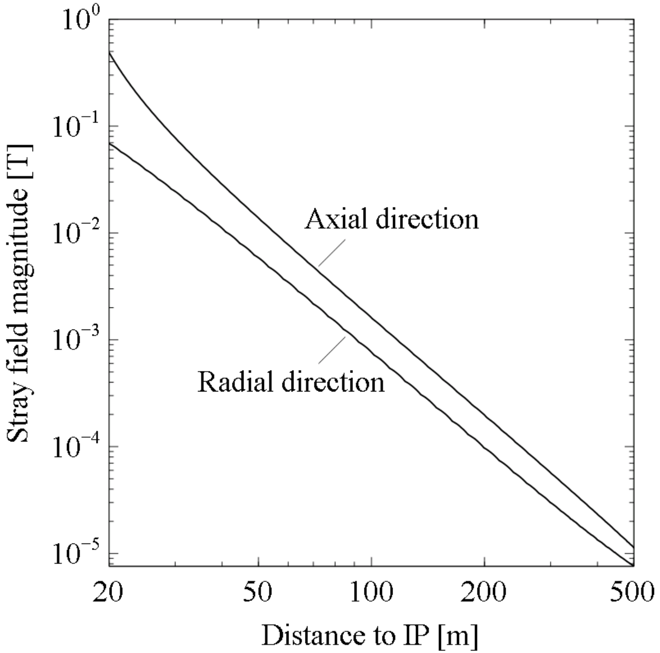
# Reference detector for the CDR



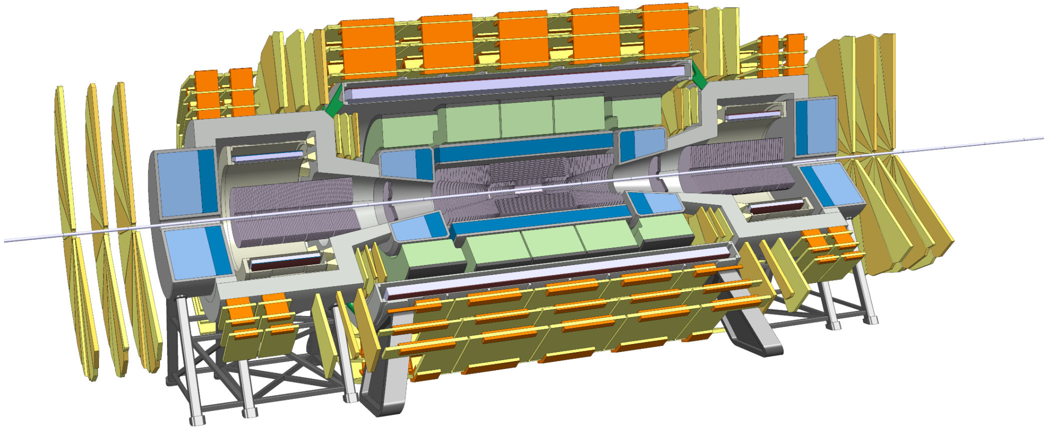
- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

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.

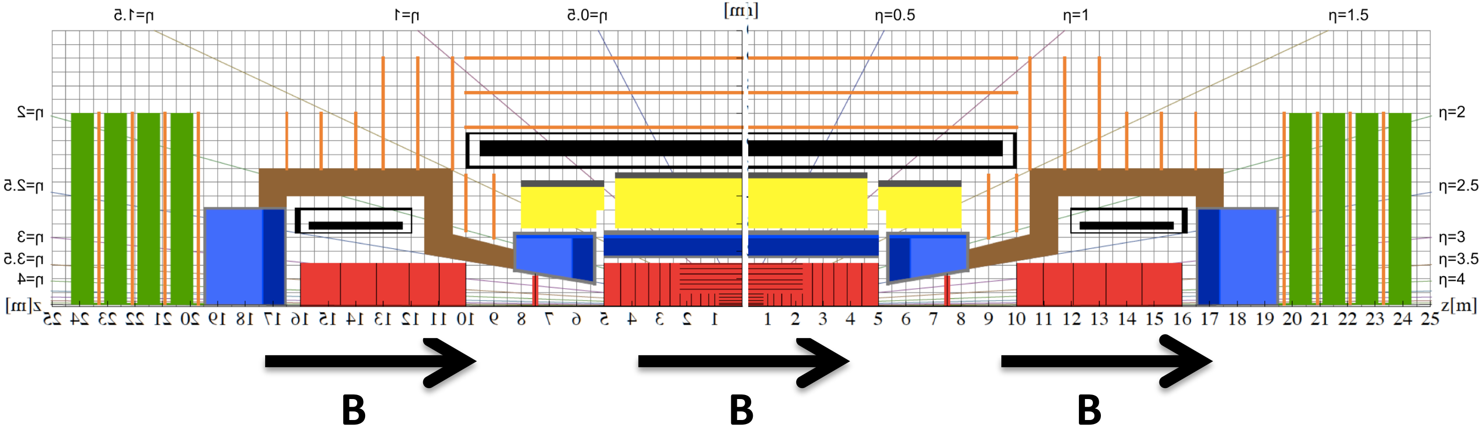
# Stray Field

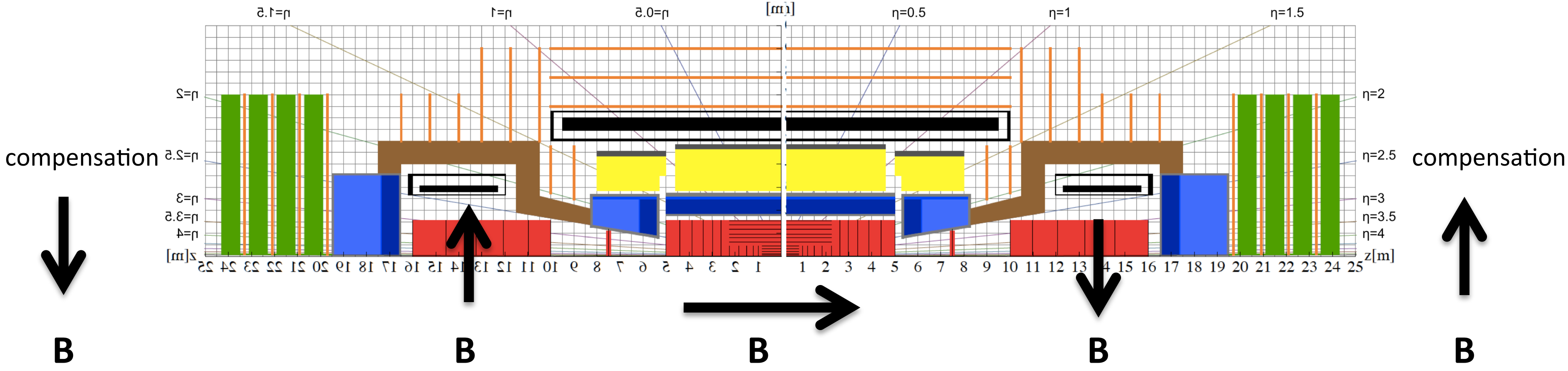


$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
Stray field magnitude [T]
20
50
100
200
500
Distance to IP [m]
Axial direction
Radial direction

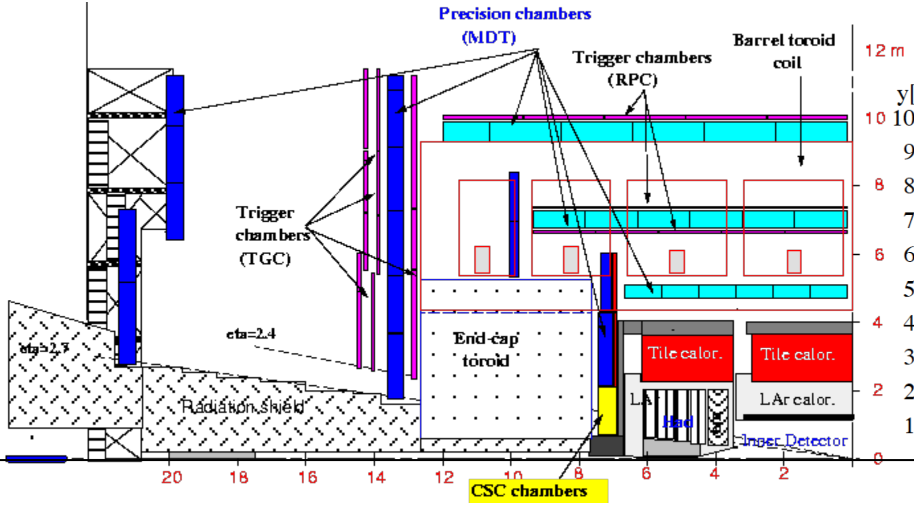



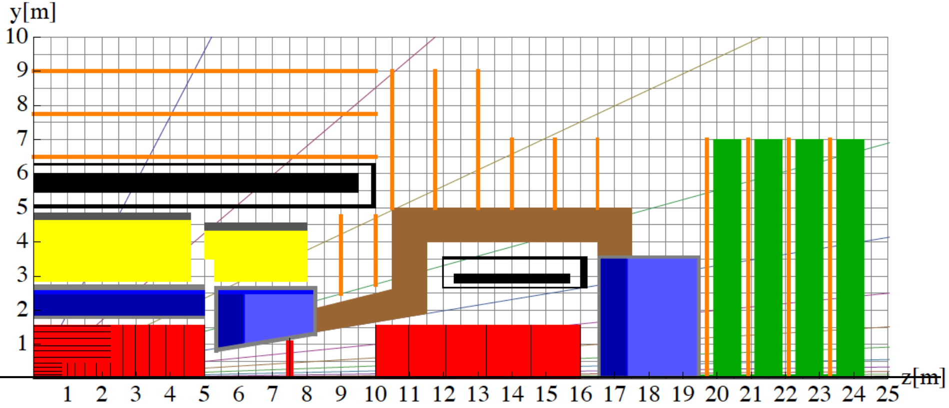
# CDR will discuss performance with forward dipoles

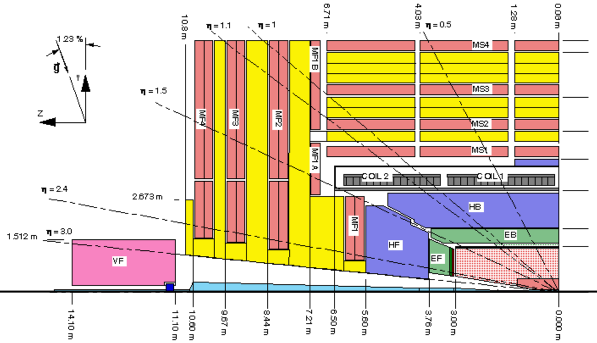


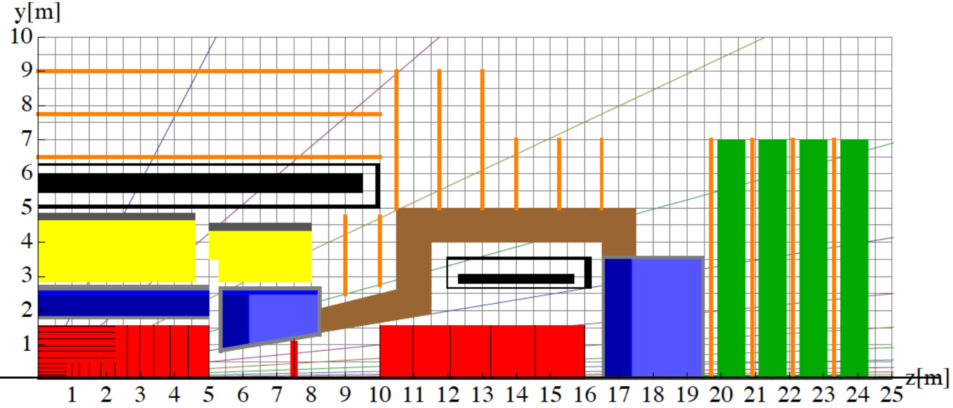



# Comparison to ATLAS & CMS

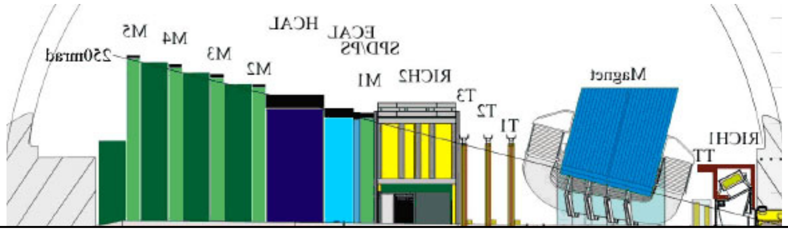


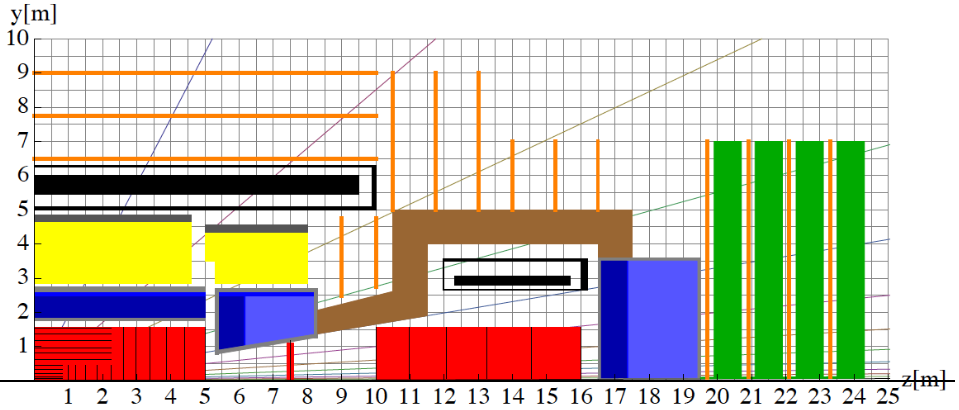



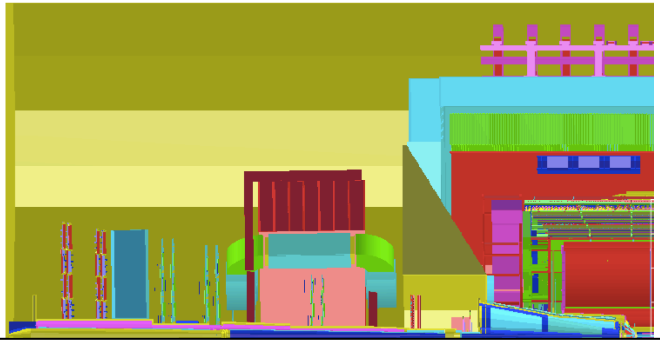



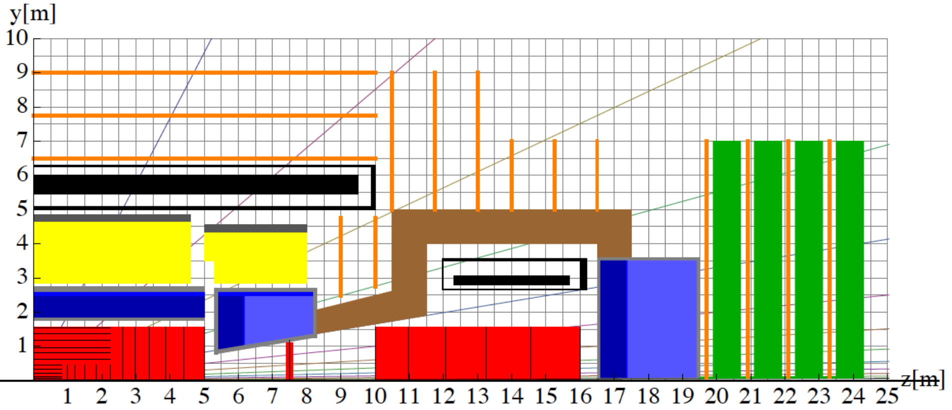



# Comparison to LHCb & ALICE

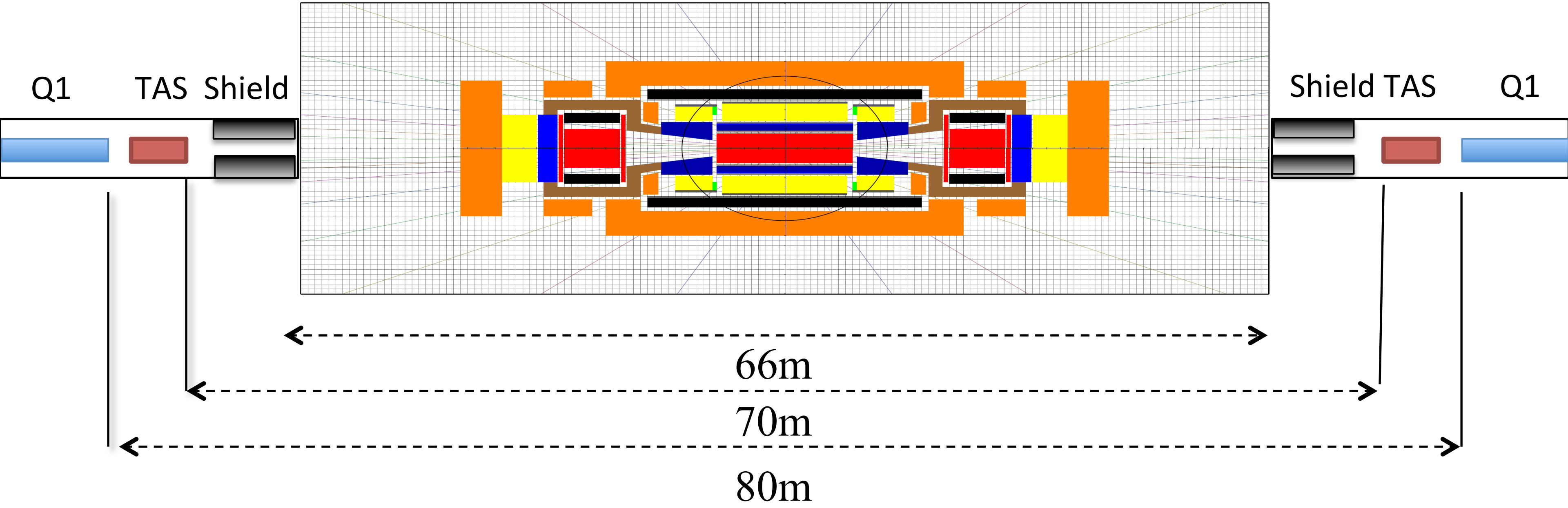






# Cavern Length



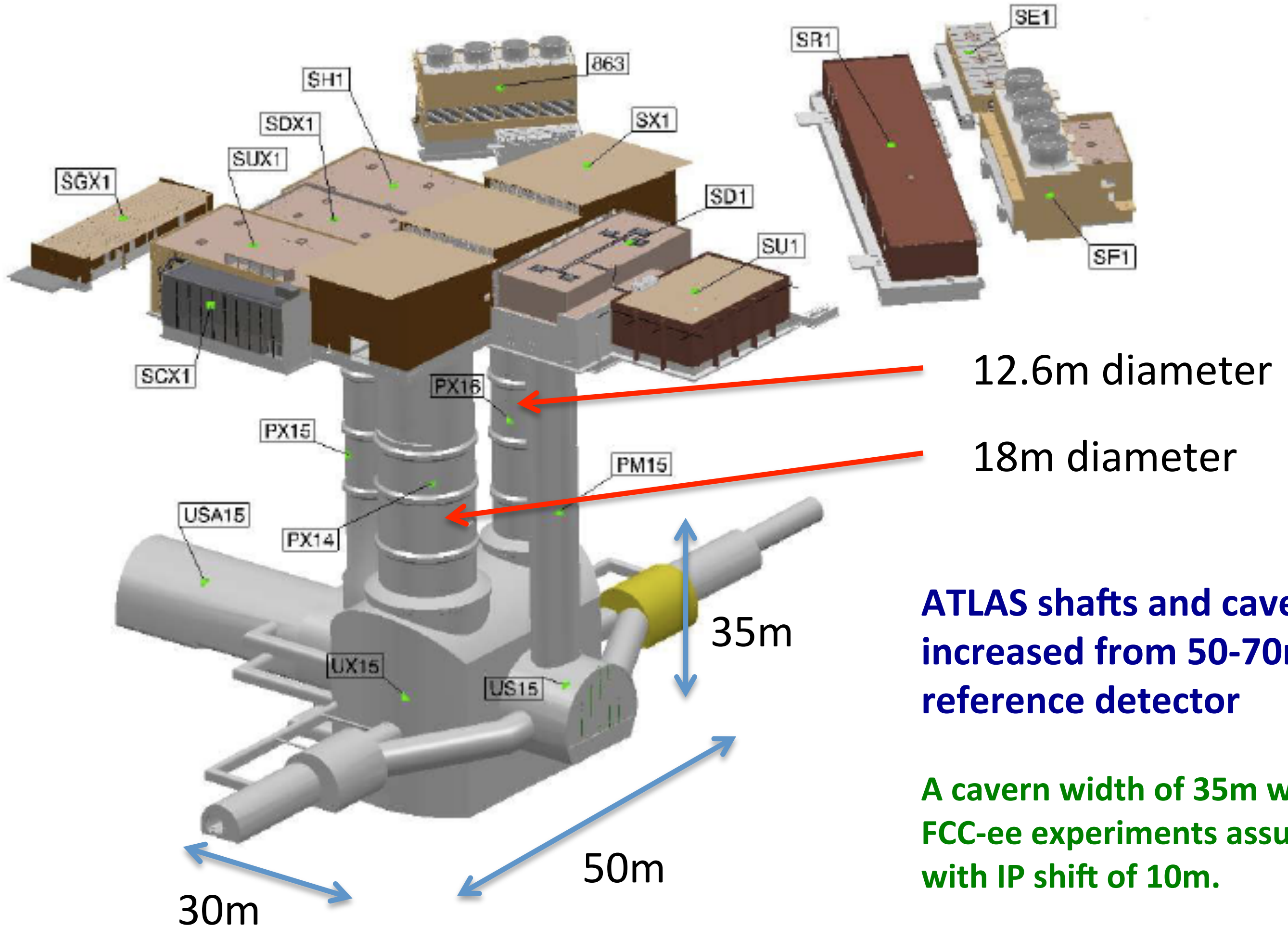

**L*=40m** → **Distance between Q1&Q1 = 80m**

**TAS = 3.5m** → **Distance between TAS & TAS = 70m**

**TAS Shielding in Tunnel = 2m** → **Cavern Length = 66m**

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

# ATLAS Cavern

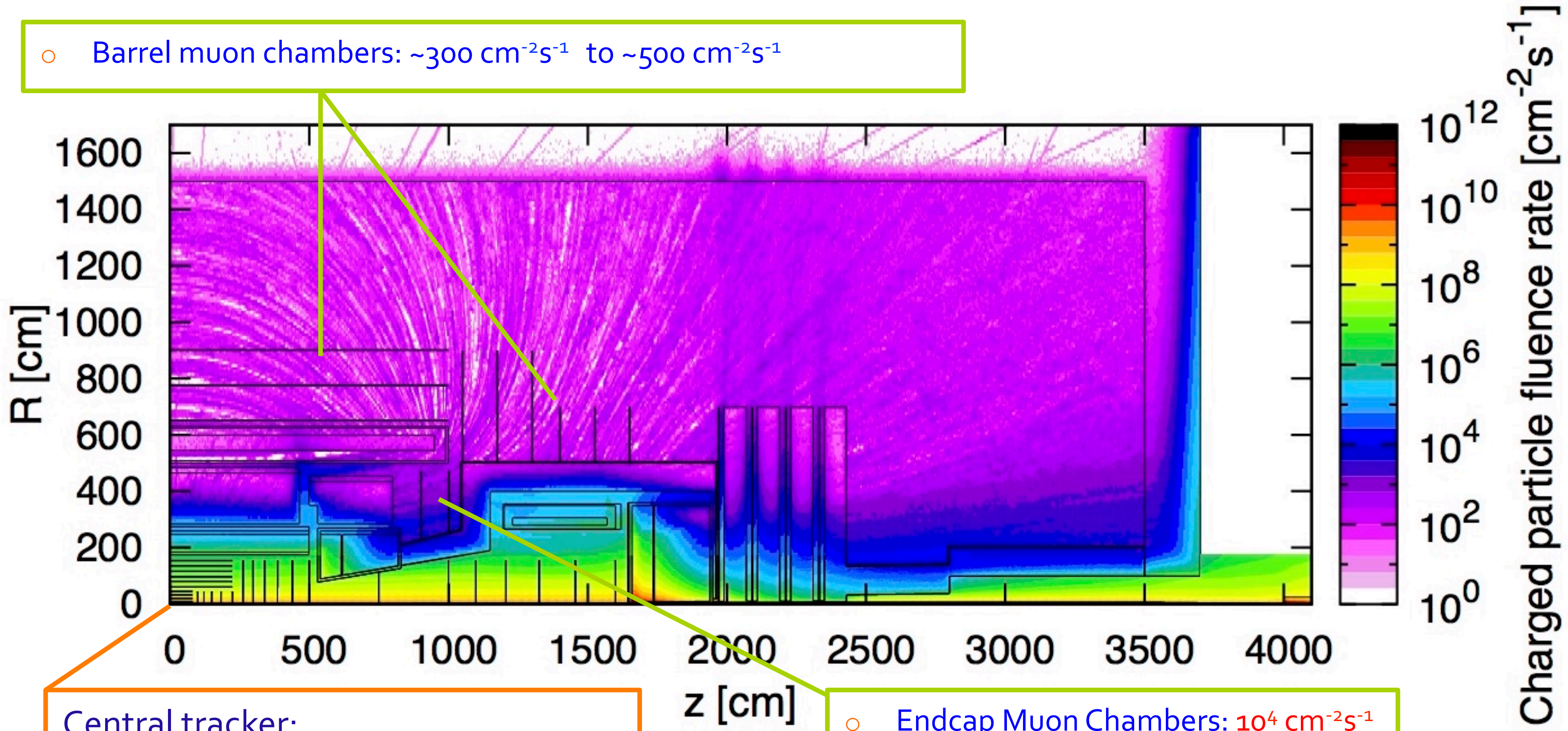



**ATLAS shafts and cavern, with cavern length increased from 50-70m will accommodate the reference detector**

**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

ATLAS muon system HL-LHC rates (kHz/cm²):

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

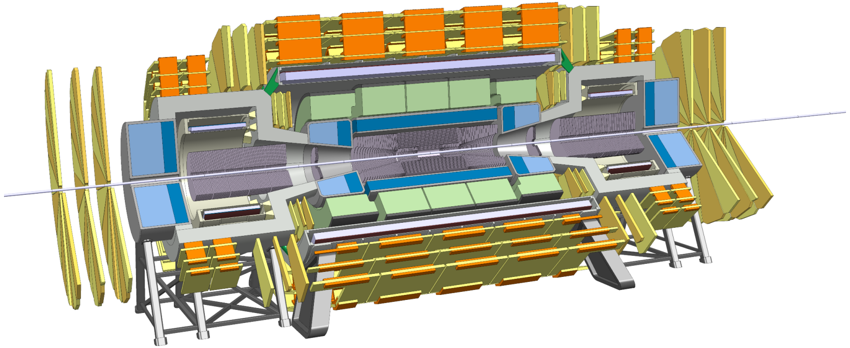
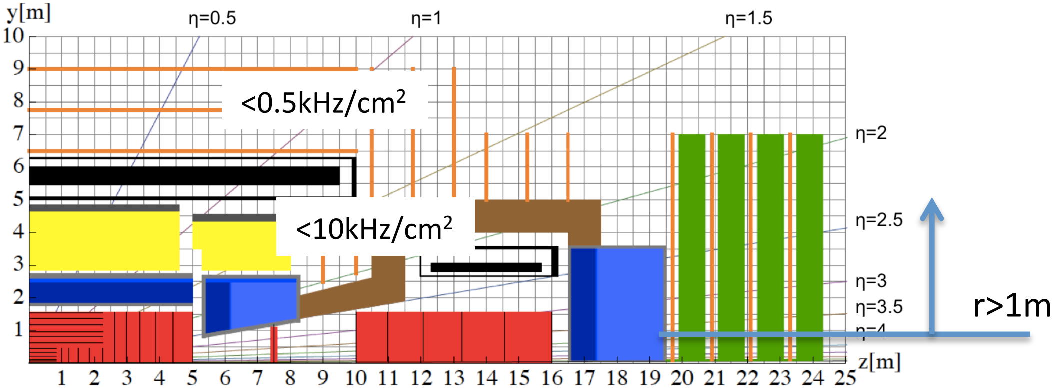


Table 4.5: Expected rates on the muon detector when operating at an instantaneous luminosity of $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ at a collision energy of 14 TeV. The values are averages, in kHz/cm$^2$, over the chamber with the minimum illumination, the whole region and the chamber with maximum illumination.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

LHCb

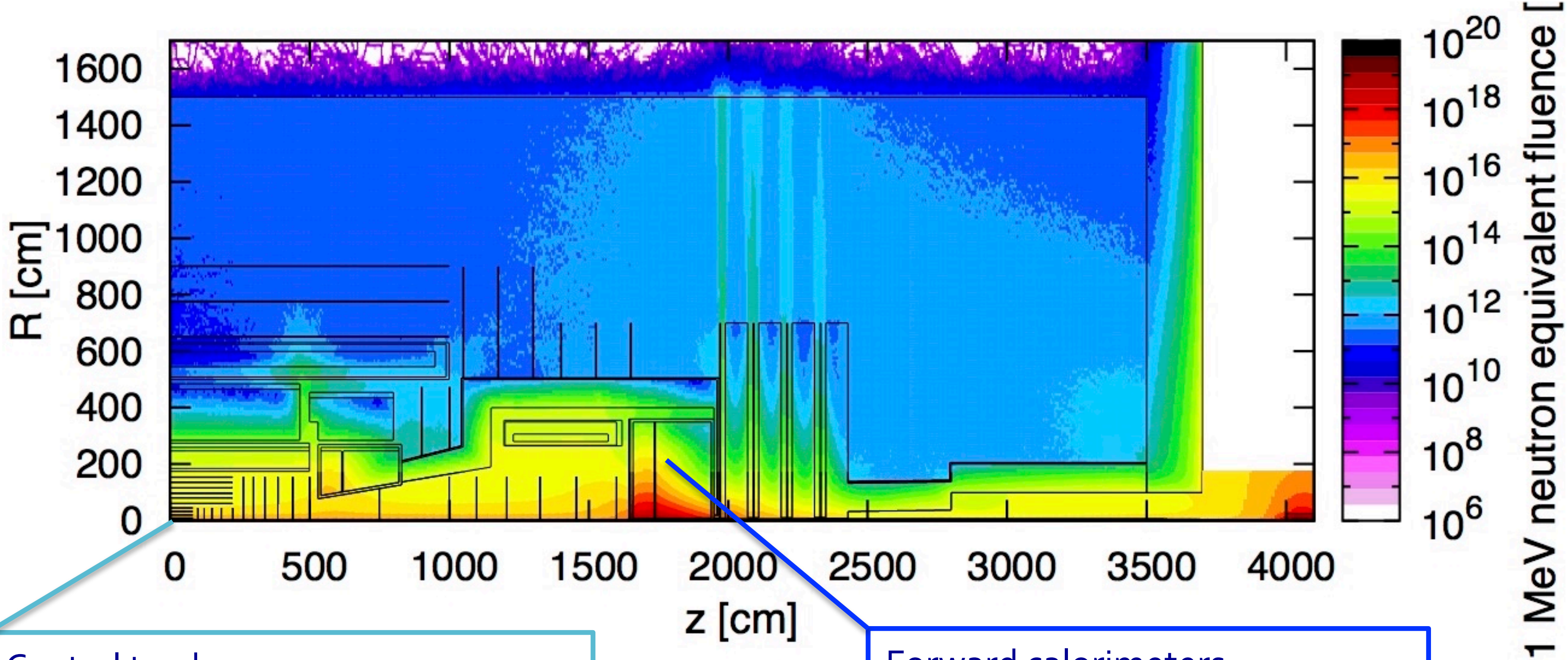
| Region | Minimum | Average | Maximum |
|---|---|---|---|
| M2R1 | 162 ± 28 | 327 ± 60 | 590 ± 110 |
| M2R2 | 15.0 ± 2.6 | 52 ± 8 | 97 ± 15 |
| M2R3 | 0.90 ± 0.17 | 5.4 ± 0.9 | 13.4 ± 2.0 |
| M2R4 | 0.12 ± 0.02 | 0.63 ± 0.10 | 2.6 ± 0.4 |
| M3R1 | 39 ± 6 | 123 ± 18 | 216 ± 32 |
| M3R2 | 3.3 ± 0.5 | 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 |




r>1m rate<500kHz/cm²

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

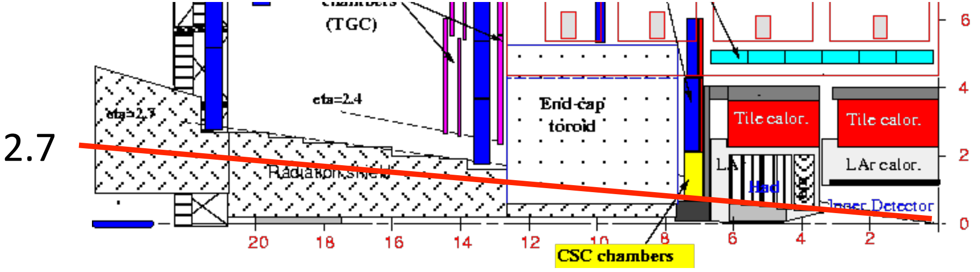
# 1 MeV neutron equivalent fluence for 30ab$^{-1}$

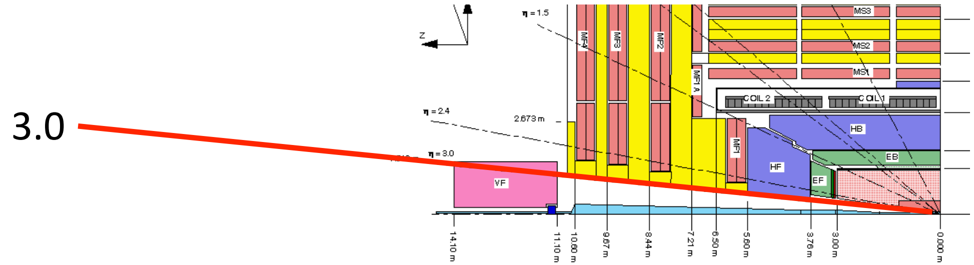


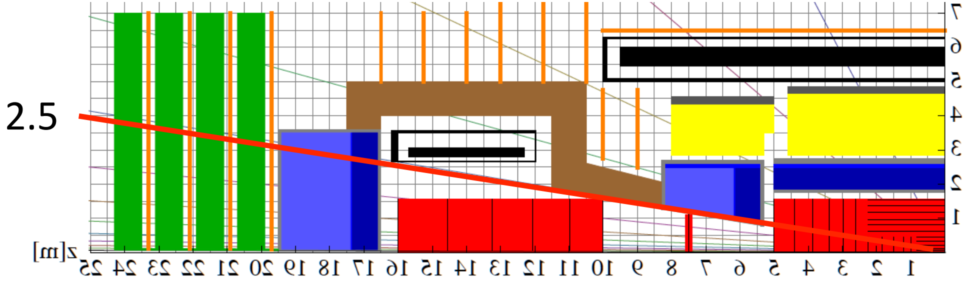

Central tracker:
- first IB layer (2.5 cm ): ~5-6 $10^{17}$ cm$^{-2}$
- external part: ~5 $10^{15}$ cm$^{-2}$

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



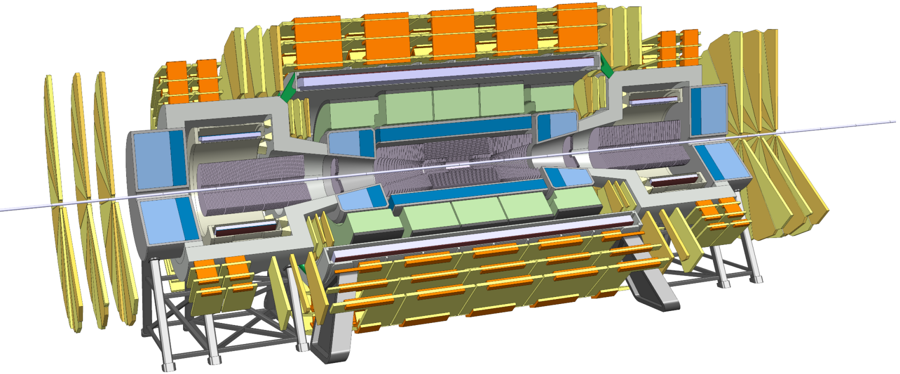

**The forward calorimeters are a very large source of radiation (diffuse neutron source).**

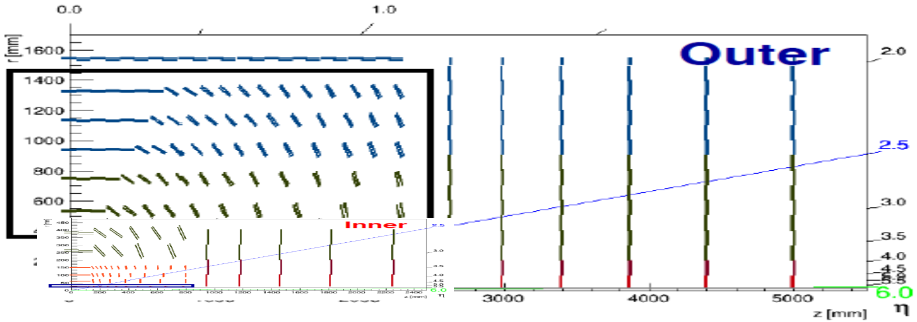
**In ATLAS the forward calorimeter is inside the endcap calorimeter, in CMS the forward calorimeter is inside enclosed by the return Yoke.**

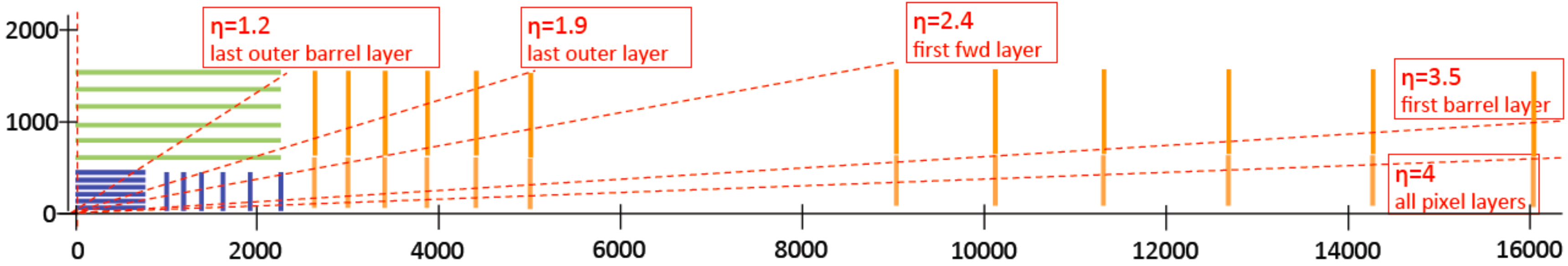
**For the FCC, the forward calorimeter is moved far out in order to reduced radiation load and increase granularity.**

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

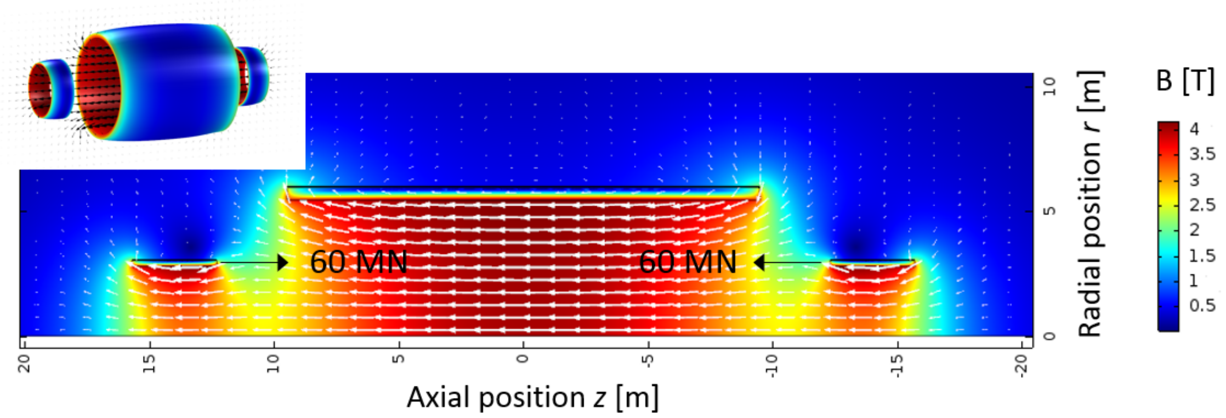
# Tracker Radius 1.6m, Length 32m

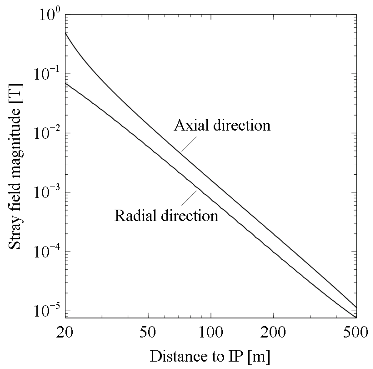


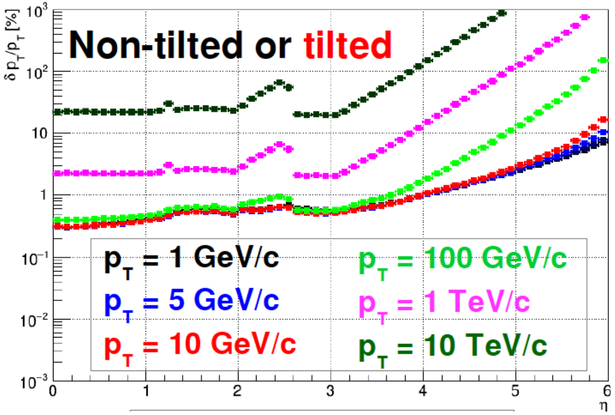


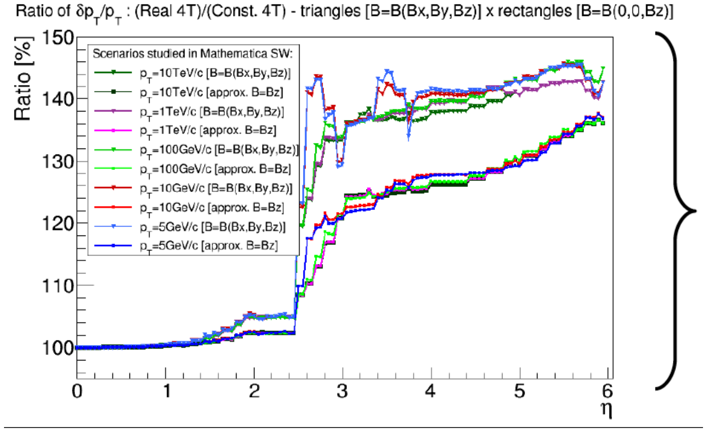



# Magnetic Field, Tracking



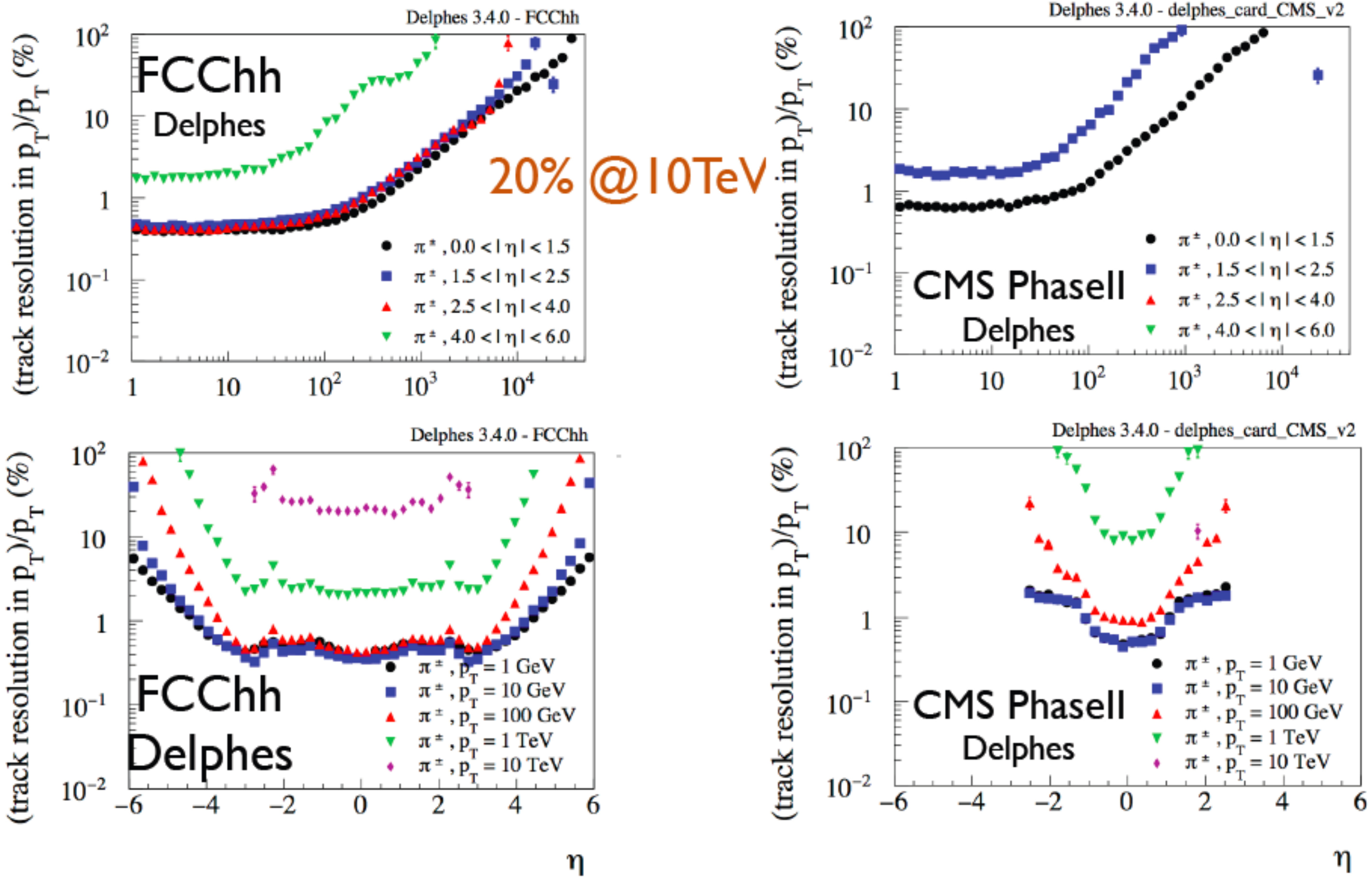



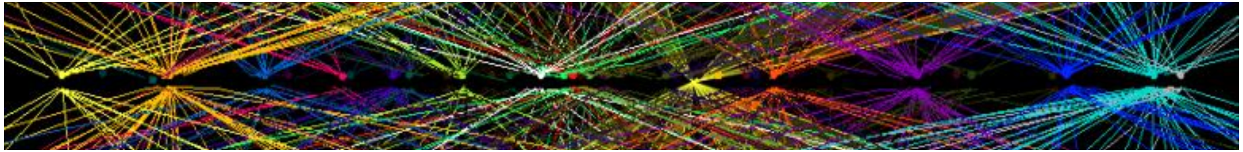

Forward solenoid adds about 1 unit of η to full lever arm acceptance.

B-field non uniformities deteriorate the tracking by 35-45% with respect to a constant field of 4T, which has negligible impact on performance.

# Parametrized Tracking Performance

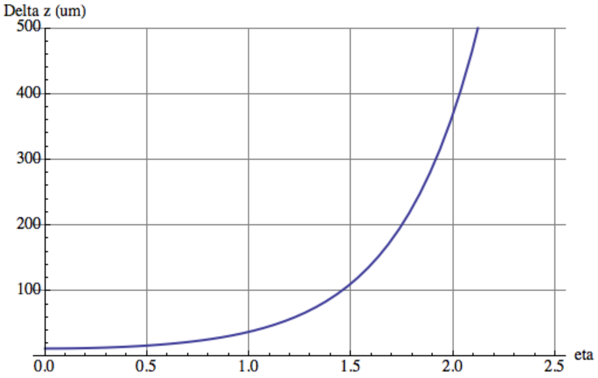


# Pileup of 1000 (25ns Bunchcrossing)



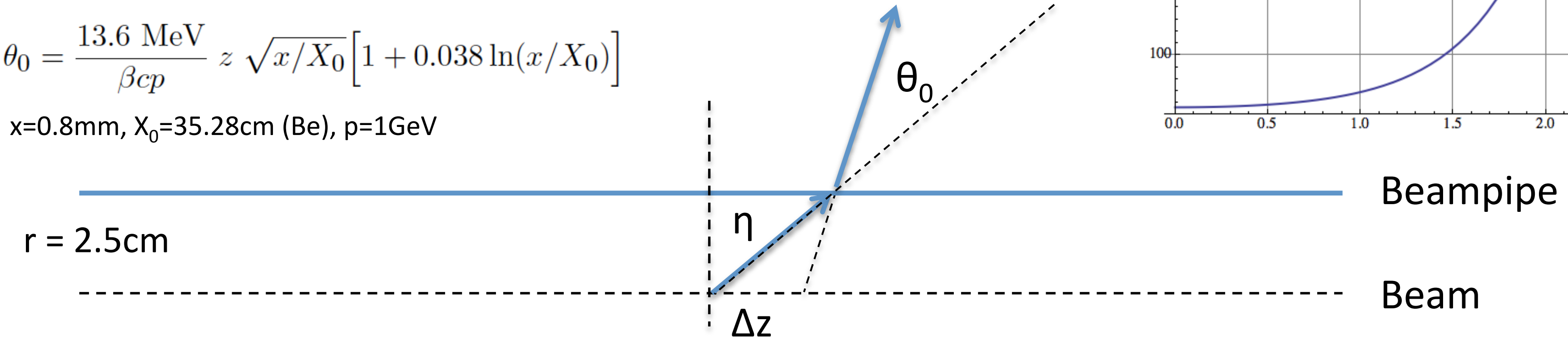
HL-LHC average distance between vertices at z=0 is
**≈ 1mm in space and 3ps in time.**

For 6 times higher luminosity at FCC-hh (an HE-LHC) this would become
**≈ 170µm in space and 0.5ps in time.**




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

x=0.8mm, $X_0$=35.28cm (Be), p=1GeV



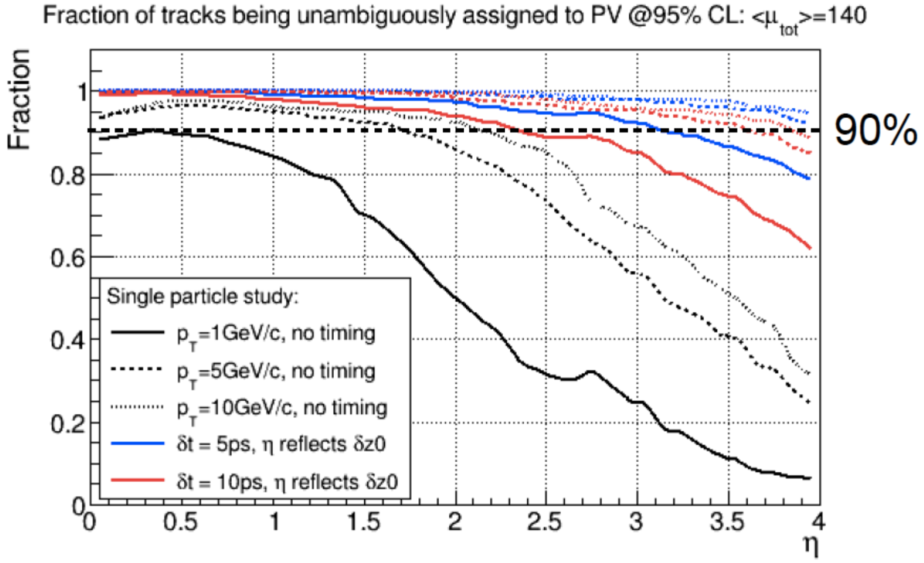

Even having a perfect tracking detector, the error due to multiple scattering in the beampipe for η > 1.7 is already larger than the average vertex distance !

Timing, very clever new ideas needed …

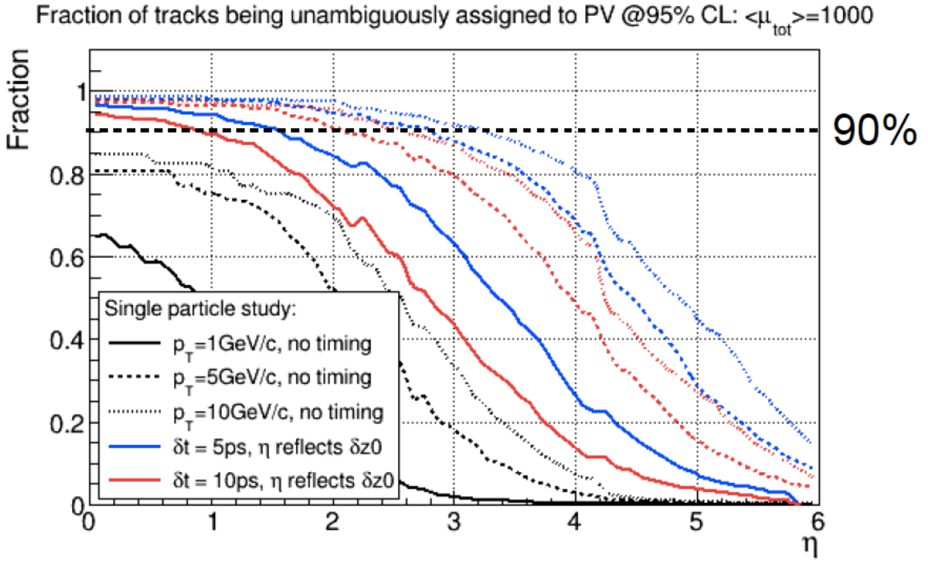
# Vertexing at Pileup of 1000, Timing

→ Compare FCC-hh scenario to HL-LHC conditions (PU~140), using e.g. CMS Ph2 upgrade layout

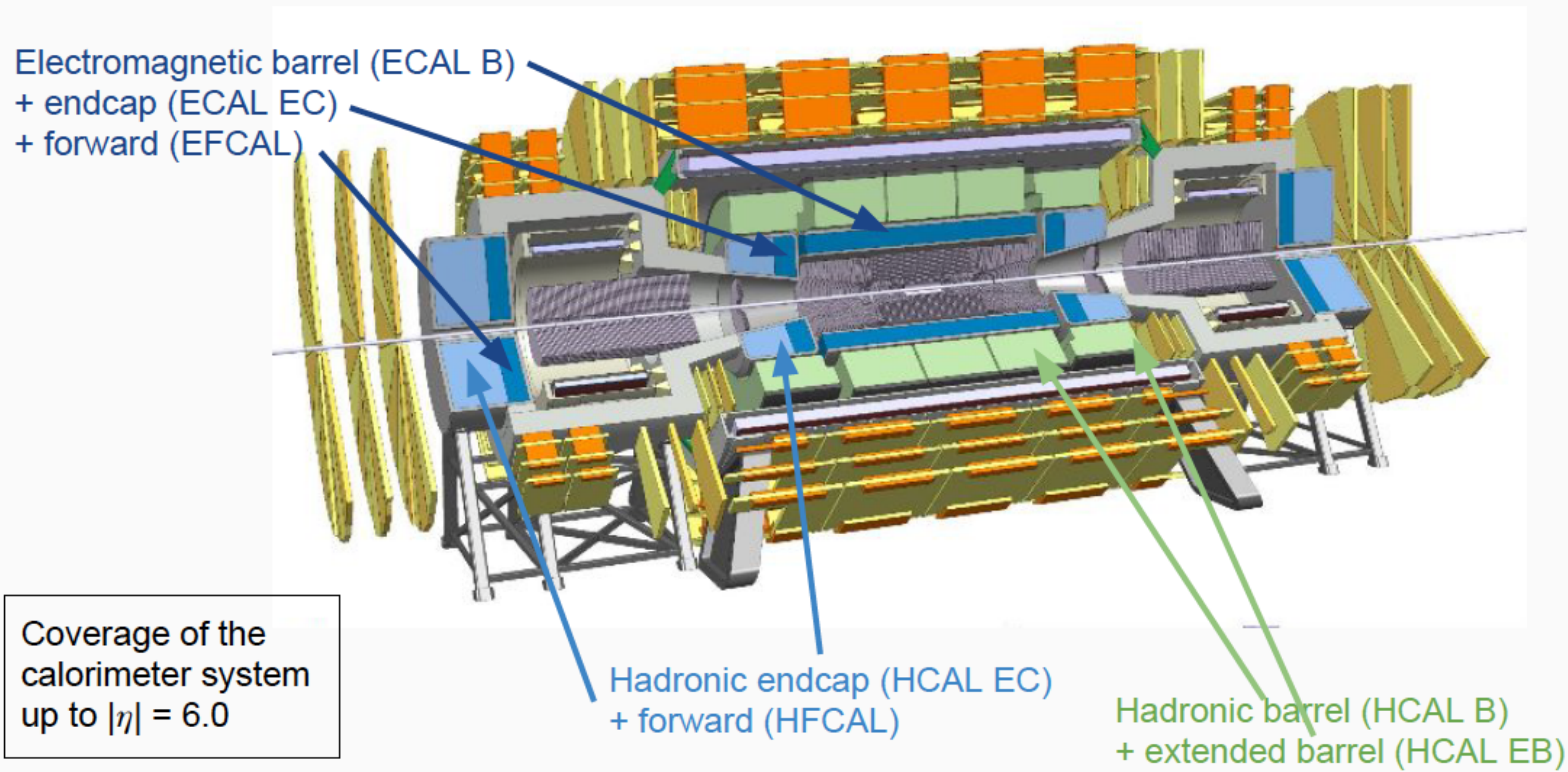
**HL-LHC scenario @ PU=140**
**CMS Ph2 Upgr. tracker**




**FCC-hh scenario @ PU=1000**
**Tilted layout**

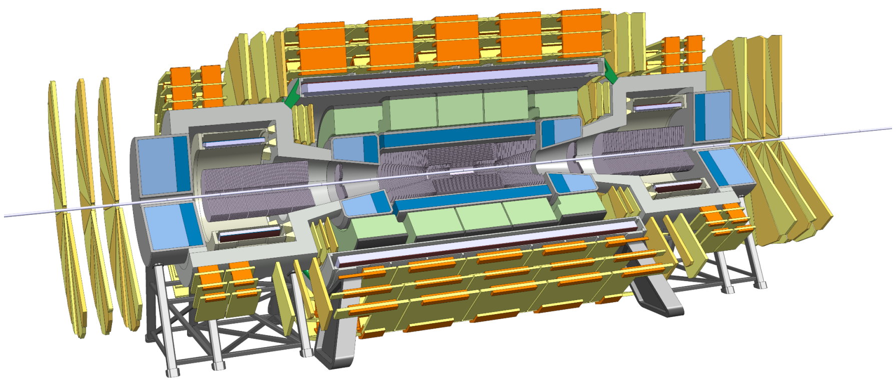


# Calorimetry




Coverage of the calorimeter system up to $|\eta| = 6.0$

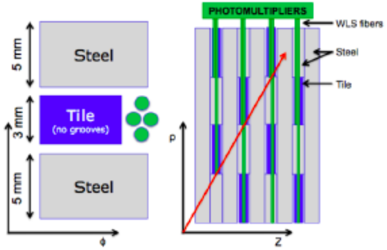
# Calorimetry

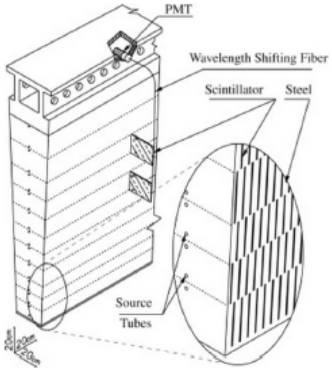


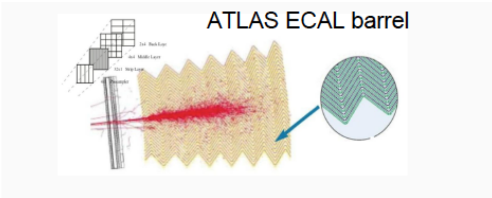
Barrel HCAL in Fe/Sci similar to ATLAS Tilecal

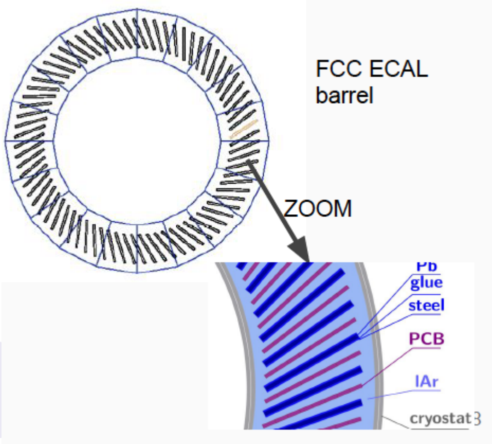
Barrel ECAL, Endcap ECAL/HCAL, Forward ECAL/ HCAL are in LAr technology, which is intrinsically radiation hard.

Silicon ECAL and ideas for digital ECAL with MAPS are being discussed.




$\sim 11\,\lambda$ FCC-hh HCAL, pion resolution:
$\sigma E/E = 43\,\%/\sqrt{E} \oplus 2.7\%$

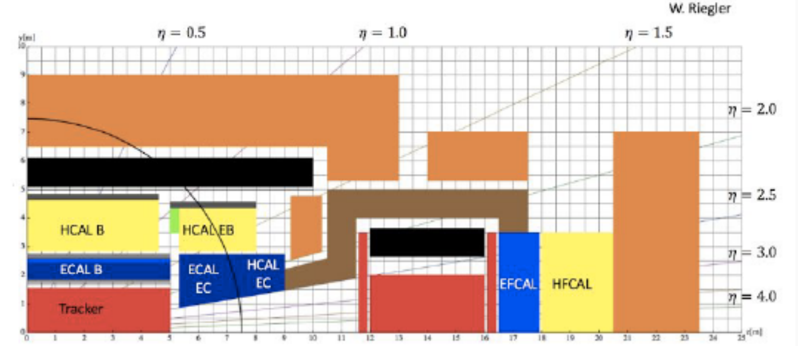
Goal energy resolution of 10% / sqrt($E$) ⊕ 1%

# Calorimeter Granularity

High-granularity calorimeter using LAr / Pb (Cu) + scintillators / Steel technologies

2-4 x better granularity than ATLAS calorimeters

- Granularity to be optimized based on further studies (e.g. pile-up rejection)

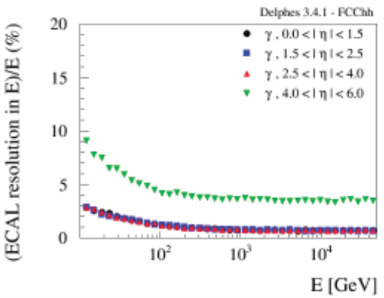


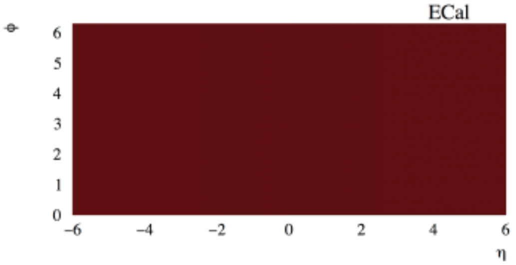

| NAME | Technology | η coverage | # long.layers | Δη x Δφ | # channels (x10[6]) |
|---|---|---|---|---|---|
| **ECAL B** | LAr / Pb | < 1.7 | 8 | 0.01 x 0.012 | 1.3 |
| **ECAL EB** | LAr / Pb | 1.5 – 2.5 | 6 | 0.01 x 0.012 | 0.6 |
| **HEC** | LAr / Cu | 1.7 – 2.5 | 6 | 0.025 x 0.025 | 0.1 |
| **EFCal** | LAr / Pb | 2.3 – 6.0 | 6 | 0.025 x 0.025 | 0.5 |
| **HFCal** | LAr / Cu | 2.3 – 6.0 | 6 | 0.05 x 0.05 | 0.1 |
| **HCAL B** | Scint. Tiles / Stain. Steel | < 1.3 | 10 | 0.025 x 0.025 | 0.2 |
| **HCAL EB** | Scint. Tiles / Stain. Steel | 1.0 – 1.8 | 8 | 0.025 x 0.025 | 0.07 |
| **Total** | LAr / Pb | | | | **2.3** |
| | LAr / Cu | | | | **0.2** |
| | Scint. Tiles / Stain. Steel | | | | **0.3** |

# Parameterised Performance
## ECAL

### FCChh Delphes

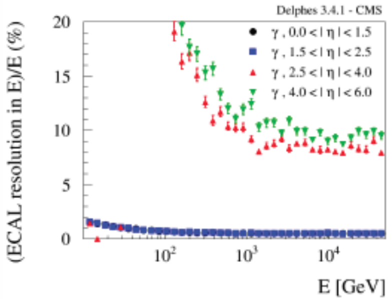
| | σ(η,φ) | σ(E)/E |
|---|---|---|
| 0 < \|η\| < 2.5 | 0.0125 | 10% / √E ⊕ 0.7% |
| 2.5 < \|η\| < 4.0 | 0.025 | 10% / √E ⊕ 0.7% |
| 4.0 < \|η\| < 6.0 | 0.025 | 30% / √E ⊕ 3.5% |

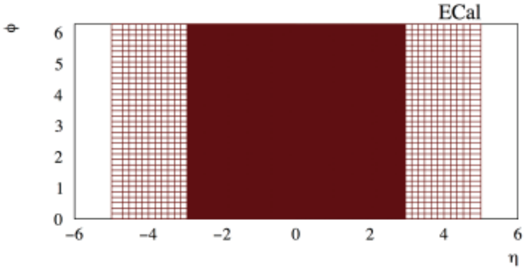



### CMS Delphes

| | σ(η,φ) | σ(E)/E |
|---|---|---|
| 0 < \|η\| < 3.0 | 0.02 | 5% / √E ⊕ 0.5% |
| 3.0 < \|η\| < 5.0 | 0.175 - 0.35 | 200% / √E ⊕ 10 % |

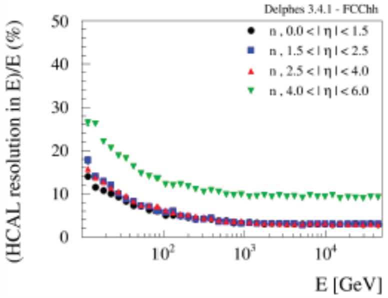


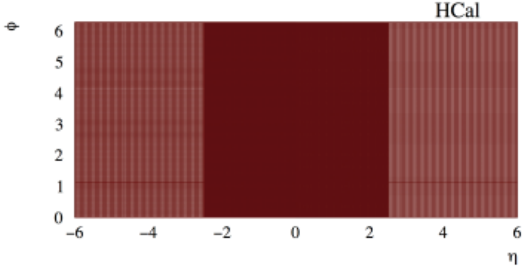



# Parameterised Performance
## HCAL

### FCChh Delphes

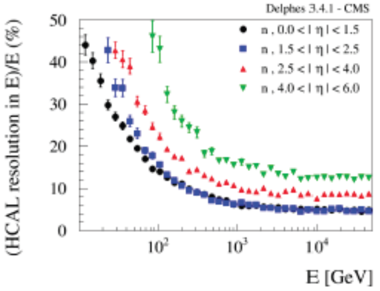
| | σ(η,φ) | σ(E)/E |
|---|---|---|
| 0 < \|η\| < 2.5 | 0.025 | 50% / √E ⊕ 3% |
| 2.5 < \|η\| < 4.0 | 0.05 | 50% / √E ⊕ 3% |
| 4.0 < \|η\| < 6.0 | 0.05 | 100% / √E ⊕ 10% |

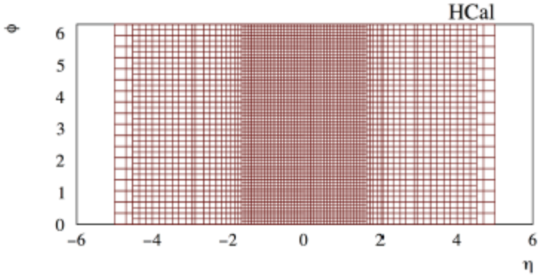



### CMS Delphes

| | σ(η,φ) | σ(E)/E |
|---|---|---|
| 0 < \|η\| < 1.7 | 0.08 | 110 % / √E ⊕ 5% |
| 1.7 < \|η\| < 3.0 | 0.175 | 110 % / √E ⊕ 5% |
| 3.0 < \|η\| < 5.0 | 0.175 - 0.35 | 250% / √E ⊕ 13 % |



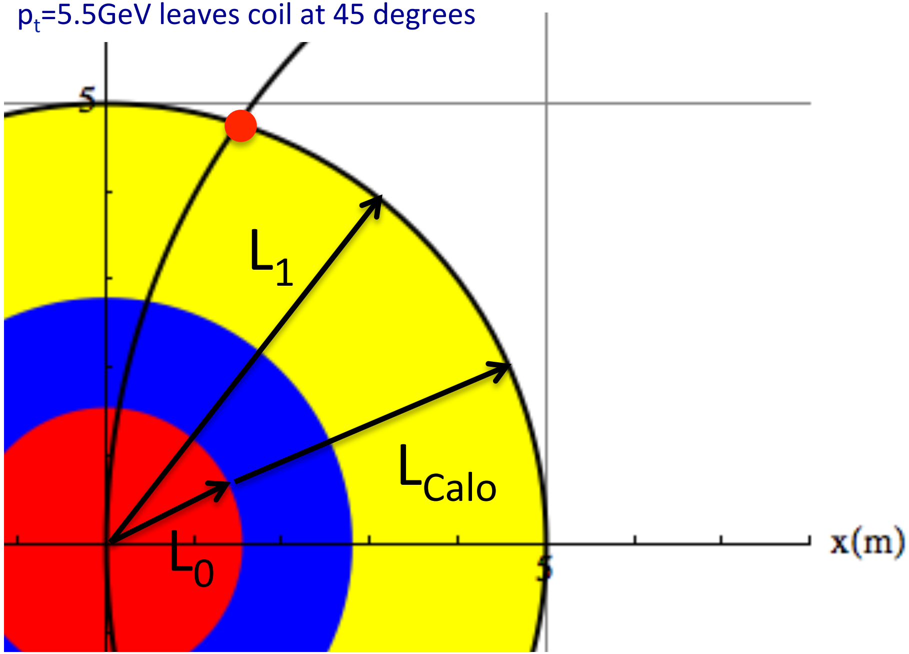



# Muon system performance estimate

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 $\sigma_0$.

The measurement point at $L_1$ has a position error $\sigma_1$ that is given by the multiple scattering inside the calorimeters ($\sigma_y$ in the following).

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

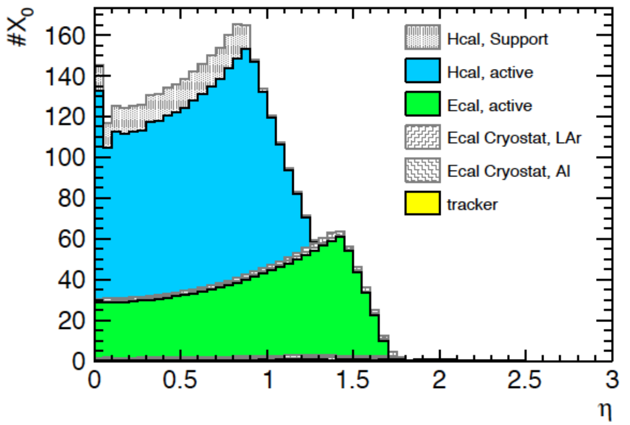
# Muon system performance estimate

**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 $\sigma_0$**

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




**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

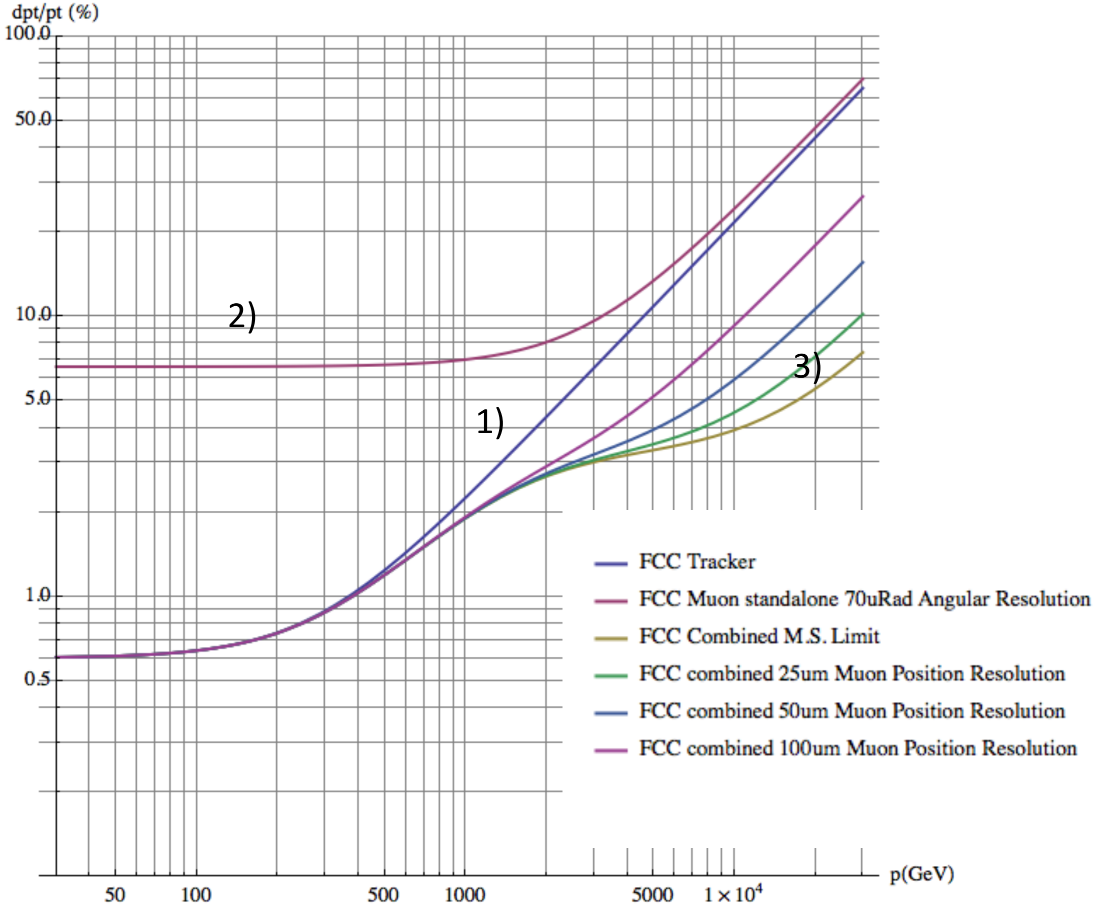
3) Tracker combined with the position of the muon where it exists the coil

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



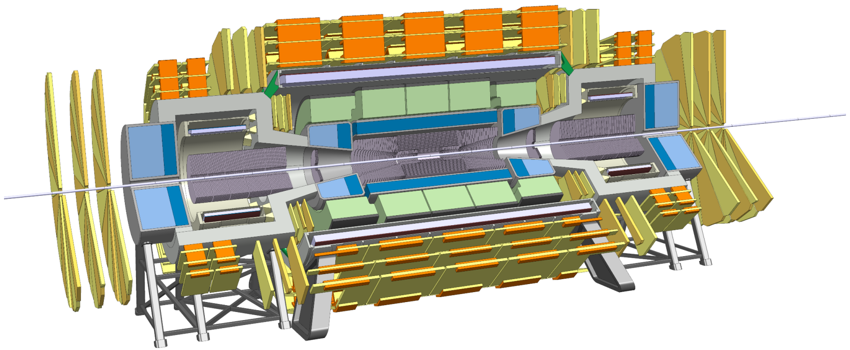
# Trigger/DAQ

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.

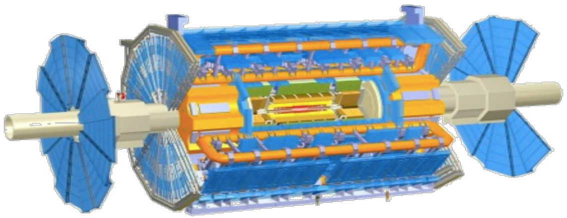


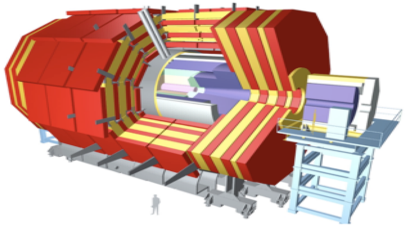
Question:

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)





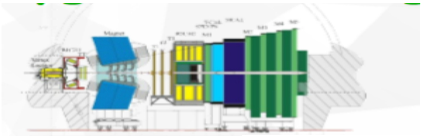
**Hardware trigger to reduce events rate by factor 40**

40 MHz

| ATLAS | | CMS |
|---|---|---|
| Level 1 | 0.5-1 MHz | Level 1 |
| 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 !**



40 MHz

DAQ

40 MHz

LLT: μ,e/γ, hadrons

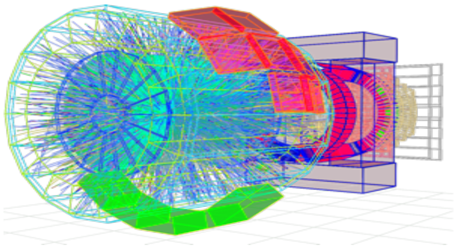
5-40 MHz

HLT: event recon.

20 kHz (0.1 MB/event)

Storage

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.

# 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 $30 \times 10^{34}\ cm^{-2}s^{-1}$ 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.