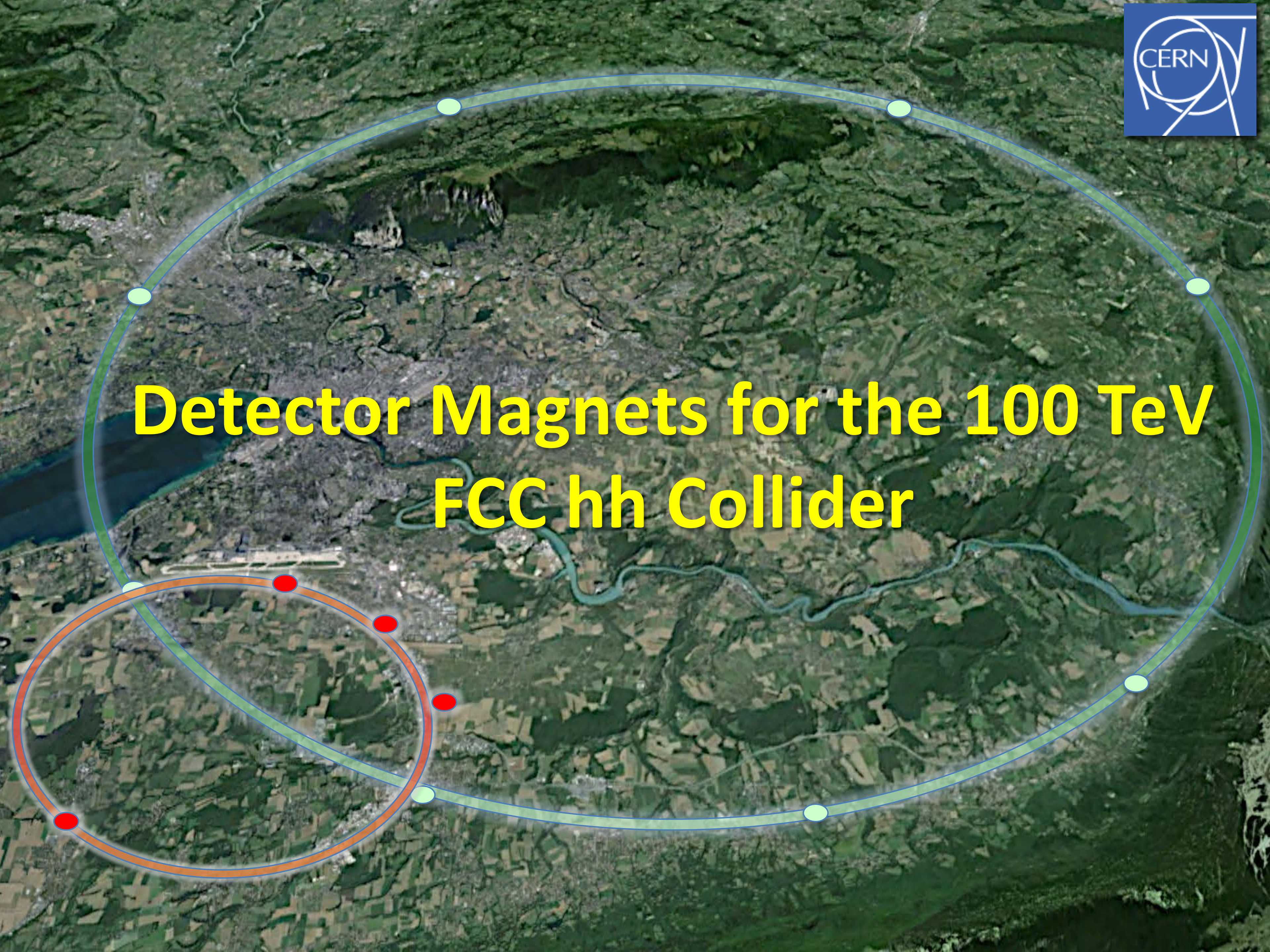
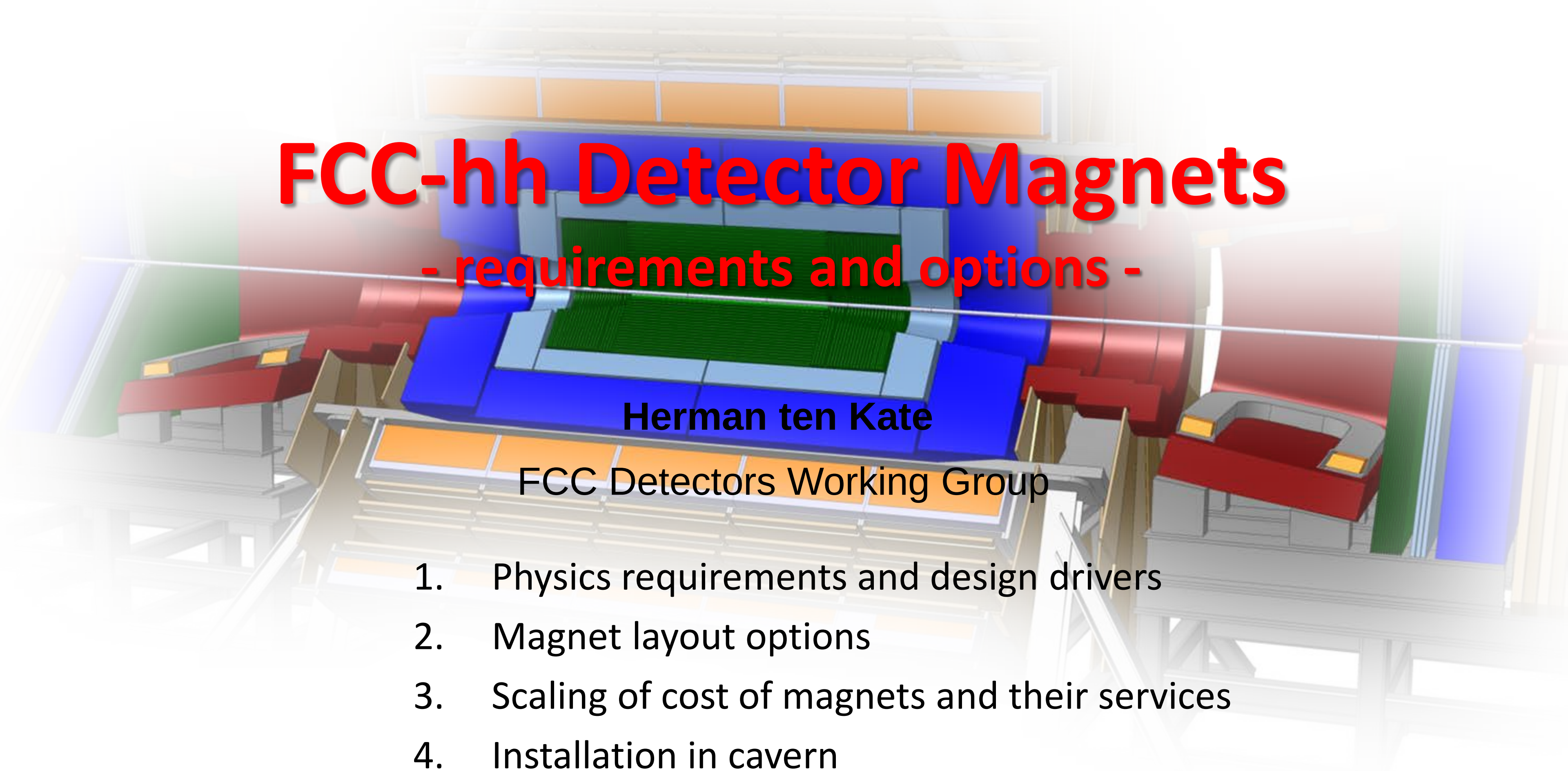
Detector Magnets for the 100 TeV FCC hh Collider





FCC-hh Detector Magnets

- requirements and options -

Herman ten Kate

FCC Detectors Working Group

1. Physics requirements and design drivers
2. Magnet layout options
3. Scaling of cost of magnets and their services
4. Installation in cavern
5. Working Group and R&D issue
6. Conclusion

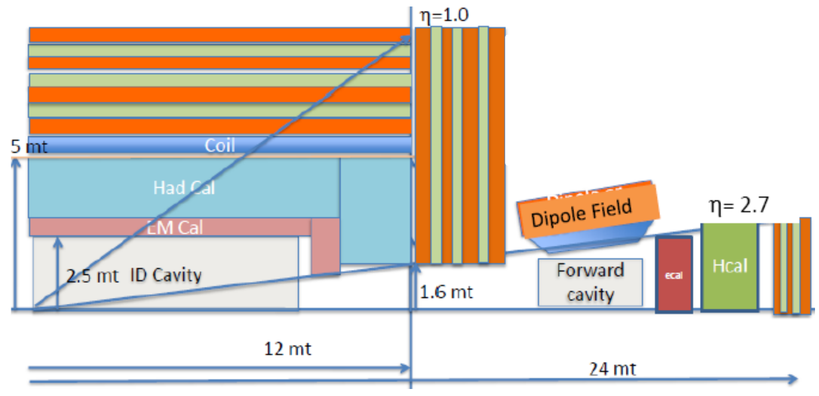
1. Introduction – initial requirements

Early requirements defined in January 2014:

- From 14 to 100 TeV collision energy: study consequences for scaling up to maintain or even improve the resolution starting with what we have in the present detectors (leading to much larger magnets with world record levels of stored energy).
- Cover the low angle forward direction (add an “LHCb”-like unit).
- Design for two different detectors and variants as long as affordable.
- Allowing contributions and incorporating bright ideas from people from all communities.
- Avoid tunnel vision in an early stage….., translated to magnets this means, consider both single solenoid and hybrid solenoid-toroid systems, leading to two reference designs, and their variants.

1. Design drivers for the magnets - sizing

Arguments determining the minimum radii of the detectors:



1. **Bending power in inner detector tracker and muon system**:

7 times higher collision energy, 14 > 100 TeV, but same tracking resolution

Sagitta of charged particles in magnetic field B ∝ B.L^2

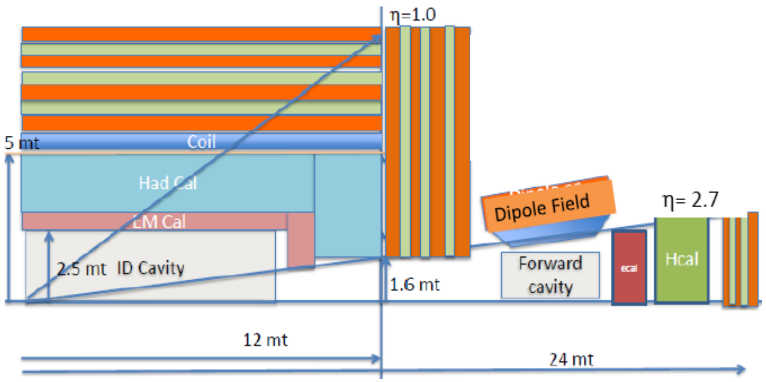
and momentum resolution ∝ σ/BL^2

thus ***σ*/BL² to be increased by a factor 7 !**

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$

- Try combination of higher point resolution, granularity, higher field and increase of radius. In single solenoid: scale up magnetic field from 3.5 up to 5 or 6 T and increase bore size.
- In the hybrid Solenoid-Toroid system,
  - Scale up Solenoid around ID from 2 T to 3-4 T in 3 m bore
  - Scale up toroid to about 2 T and increase tracking length.

1. Design drivers for the magnets - sizing



2. ECAL, and HCAL depth to stop all particles except muons

Increase radial thickness from 10 to 12λ

- Based on steel absorbers(with tungsten eventually less, but expensive) and
- **Assuming a 0.6 m deep ECAL and 2.2 m deep HCAL we see a total radial build of E+HCAL of 3.4 m including supports and clearances.**
- **With an inner tracker diameter of 3, 4 or 5 m (depending on field and tracker point resolution anticipated), the bore of the solenoid or toroid, when calorimeters are inside, is in the range of 10.0 to 12.0 m!**
- And the length scales accordingly.

Arguments determining the length of the system:

3. Coverage in forward direction, in central magnet up to eta=1.6 (23°)

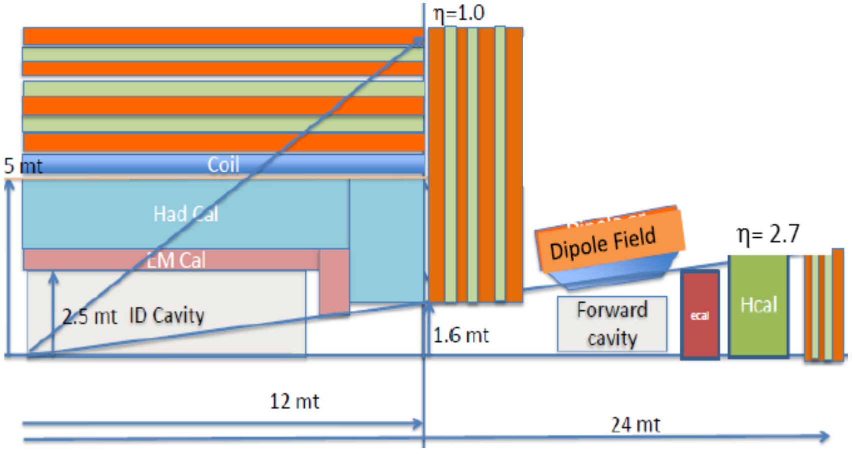
Length of solenoid is 3.84xR , L=R/tan (23°): **10 m bore, means 19 m long**

12 m bore, means 23 m long

1. Design drivers for the magnets - sizing

4. Extra forward tracker and ECAL to cover low angles

- Move unit out, from 5 to some 15 m, but the system gets longer!

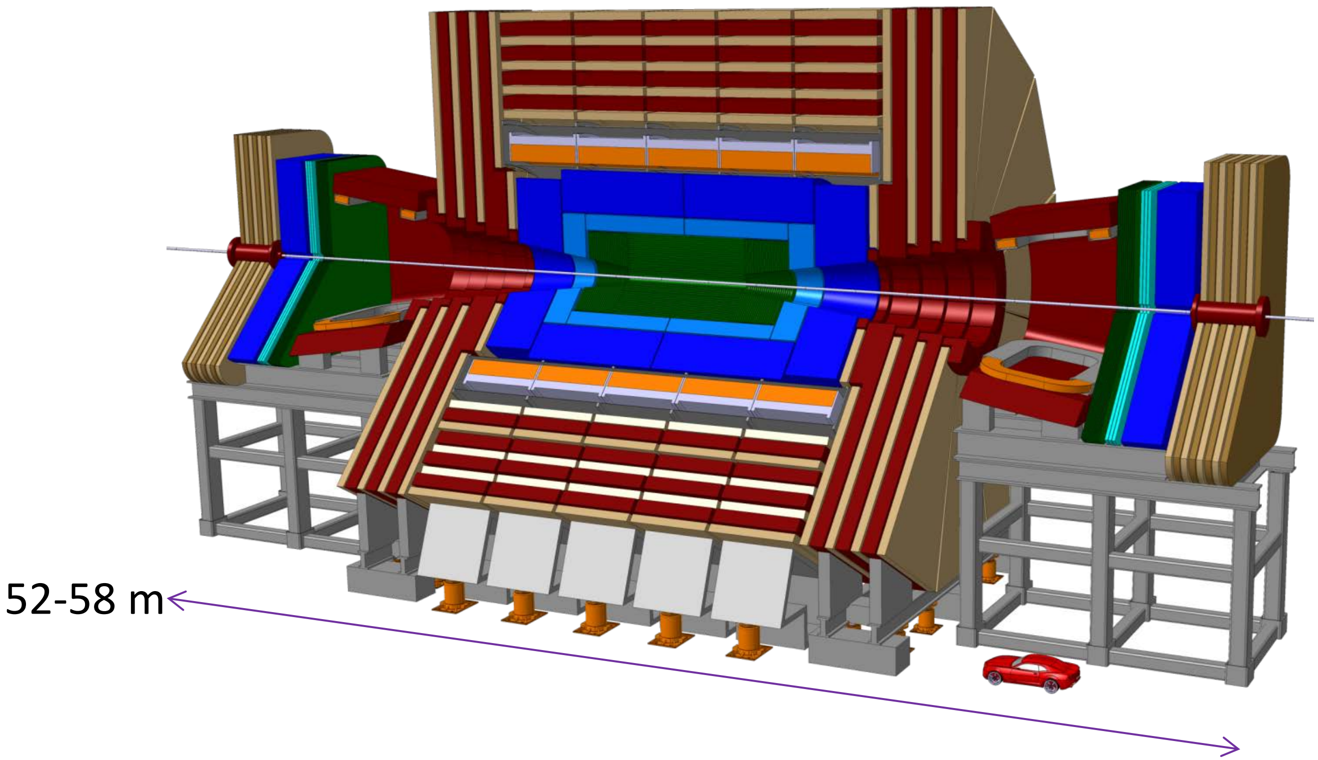


5. Low angle coverage, η>2.7 (7.7°) with 10 Tm in forward direction

- Solenoid is useless here.
- High field toroid difficult, since all current has to pass the small inner bore close to the beam pipe. Options:
- Add a dipole (like in LHCb) for on-beam bending featuring some 10 Tm
- Or invent another solution, may be a low field toroid.

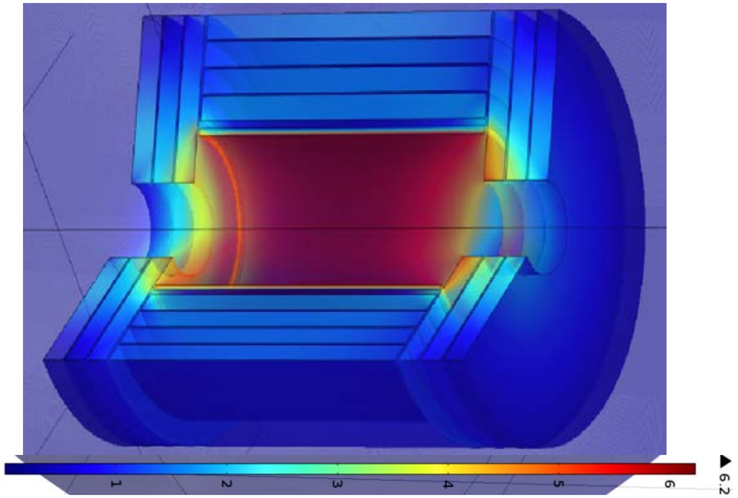
❖ **Note: presented here are maximum system sizes; for cost or technical reasons they may be scaled down a bit later on in the process….**

2. Option 1: Solenoid-Yoke + Dipoles (CMS+)



- **Solenoid:** 10-12 m diameter, 19-23 m long, respectively, and 5-6 T + iron yoke for flux shielding and muon tracking.
- **Dipoles:** 10 Tm with return yoke placed at z≈18 m.
  Practically no coupling between dipoles and solenoid.
  They can be designed independently at first.

2. Option 1: Solenoid – Yoke size reduction



Example: 6 T, 12 m bore, 23 m long,
28 m outer diameter.

- **Stored energy 54 GJ, 6.3 T peak magnetic field.**
- Yoke ? Thickness depends on how
  yoke is used.
- **For 100% shielding we need 6.3 m thick iron**
  to get the 10 mT stray field line at 22 m

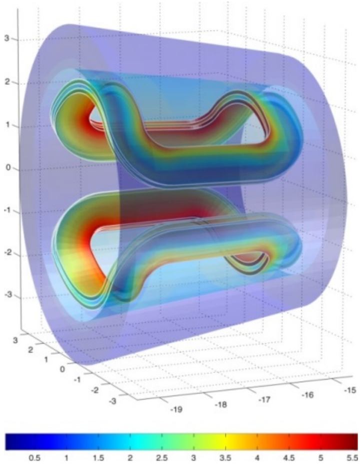
  ≈15 m^3, **mass ≈ 120 kt** (500-600 M€).

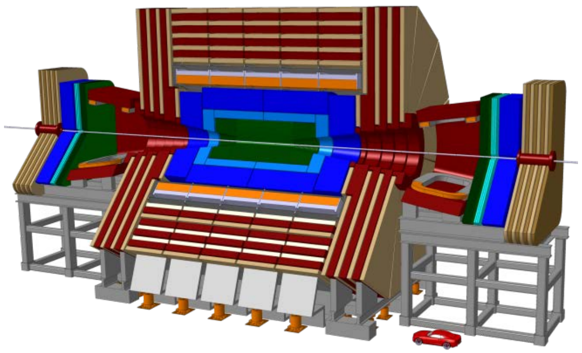
  Huge mass, serious consequences for cavern floor, installation, opening - closing system, not an elegant design.

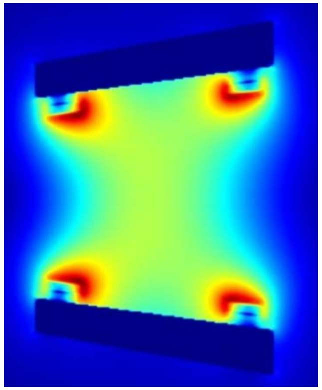
- **For muon tagging only, yoke thickness can be limited to some 3 m**, some **60 kt** needed (still 250-300 M€).

- When not fully shielding the fringe field has to be accepted, and/or locally be reduced by active compensation (as proposed for CLIC-SiD in end caps).

2. Option 1: Solenoid-Yoke + Dipoles



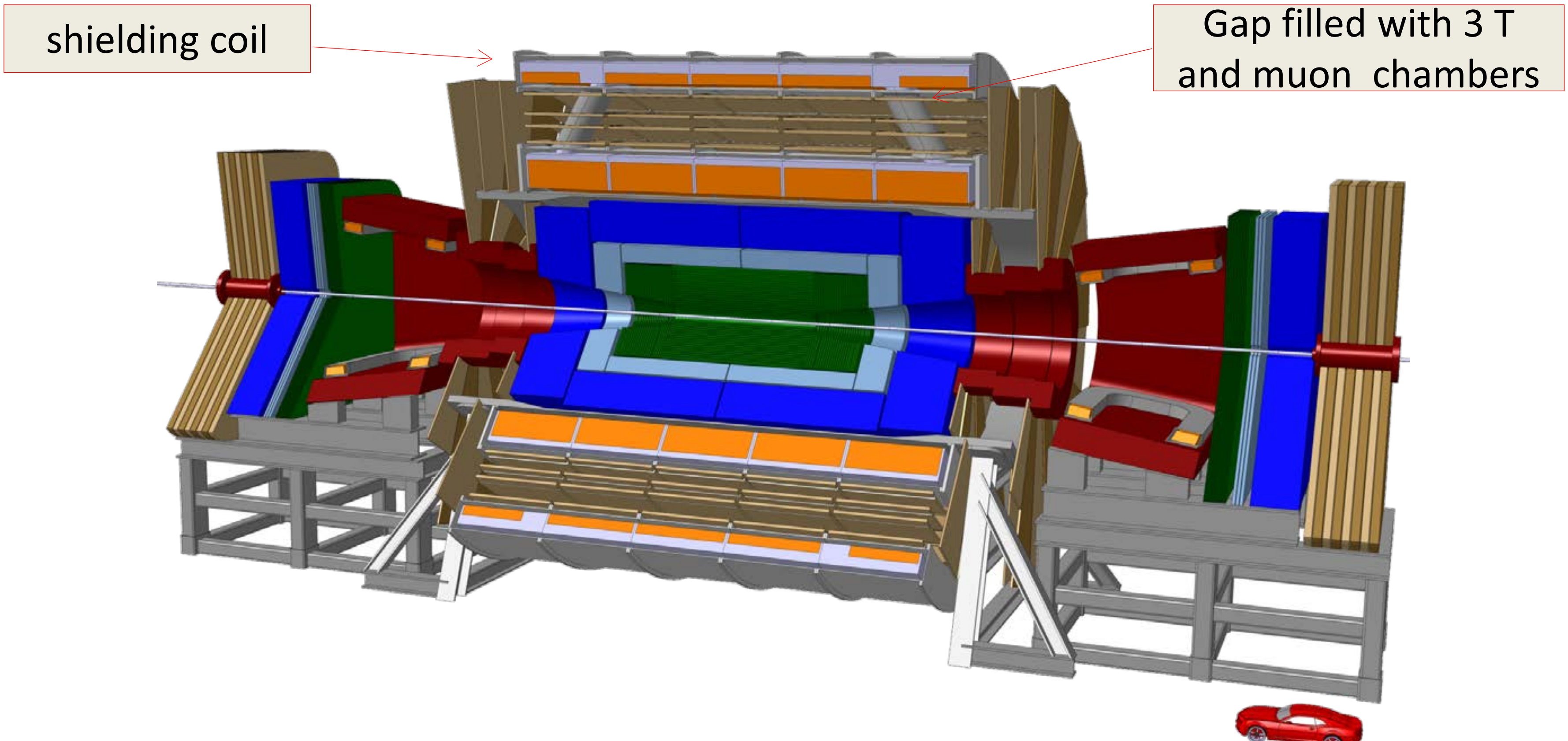




Example of 2 dipole designs, saddle coils (left) or flat racetracks (right).

- 2 dipoles, each generating ≈10 Tm.
- 2 designs briefly investigated, inclined saddle coils (left) or inclined racetrack.
- 2.2 T in the bore, some 5.6 T in the windings (to be minimized).
- 0.2 GJ per coil.
- Iron yoke to guide the field and for shielding the coils.
- Also a compact toroid may be a good option to be checked.

2. Option 2: Twin Solenoid + Dipoles

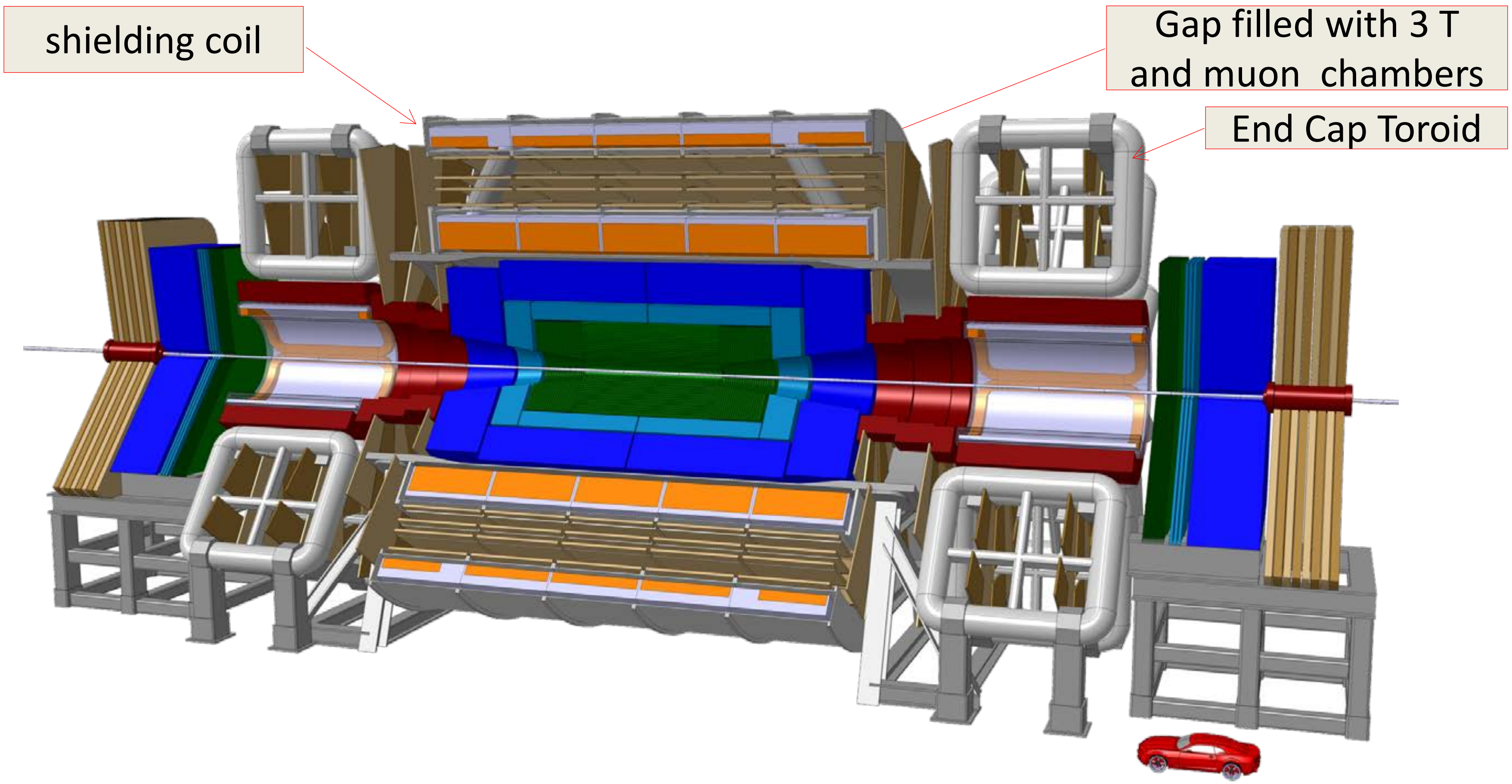


Twin Solenoid: 6 T, 12 m dia, 23 m long main solenoid + shielding coil

Important advantages:

- **Nice muon tracking space:** gap with ≈2-3 T for muon tracking in 4-5 layers.
- **Light:** shielding coil + structure ≈ 8 kt, much lighter than the iron yoke!

2. Option 2a: Twin Solenoid + Dipoles + Toroid



Twin Solenoid: 6 T, 12 m dia, 23 m long main solenoid + shielding coil

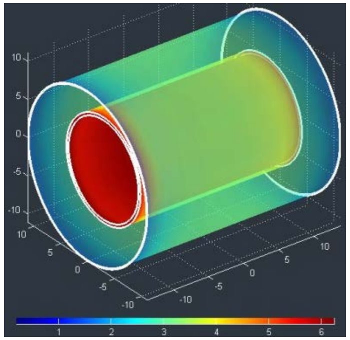
A variant, extra feature if needed:

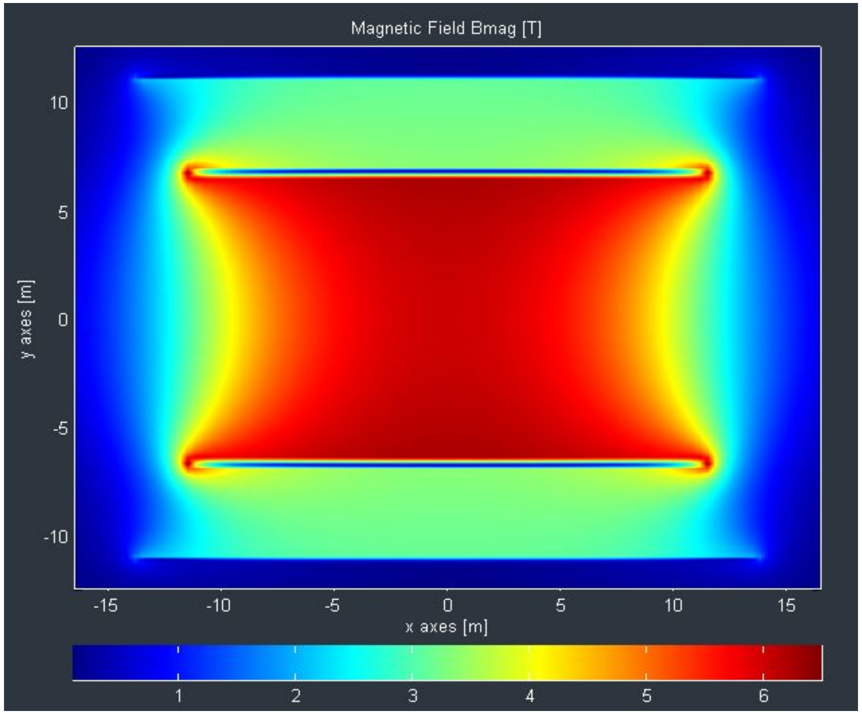
- Two end cap Toroids for optimal muon tracking in forward direction

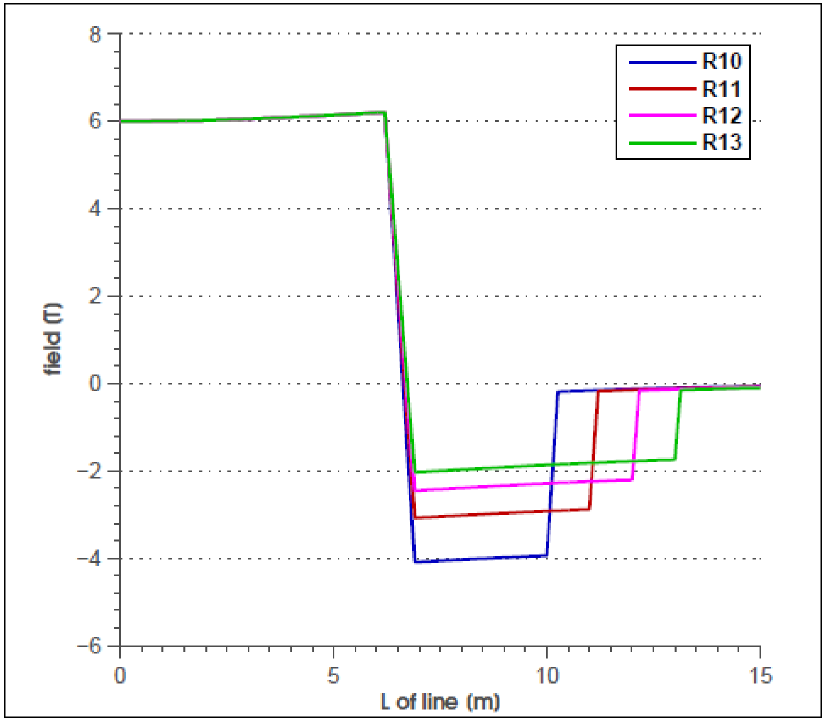
2. Twin Solenoid - field in main coil and gap

Example: 6 T in 12 m bore, 23 m long:

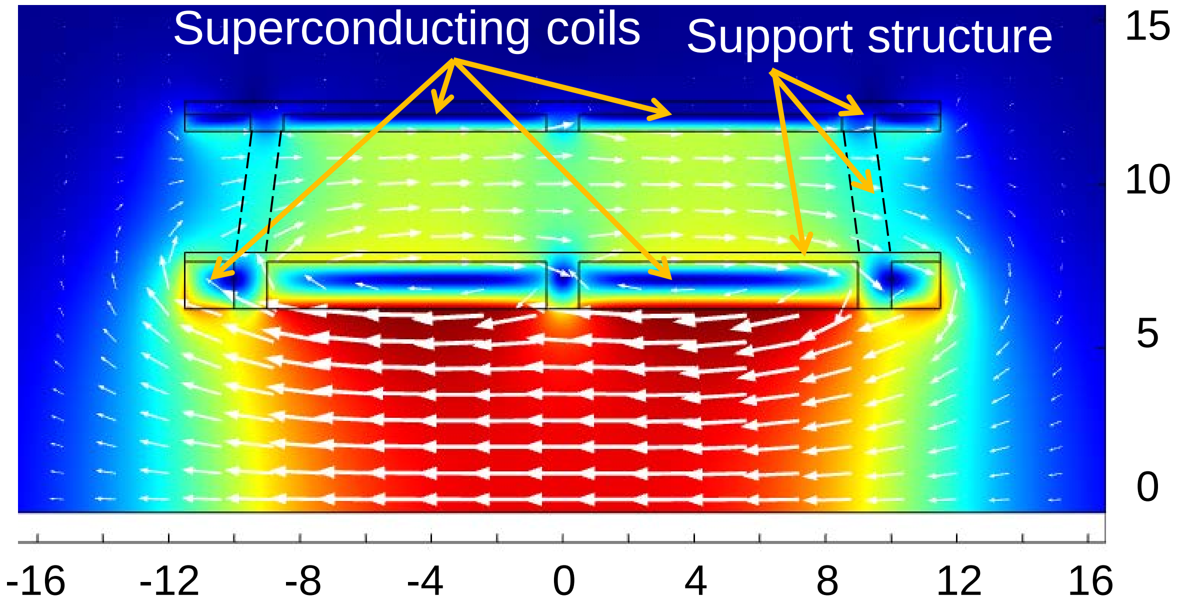
- 2 to 4 T in gap depending on gap size, to be tuned.
- ≈2 T in a 6 m gap or ≈4 T in a 3 m gap.
- Many ways to adjust to specific requests.

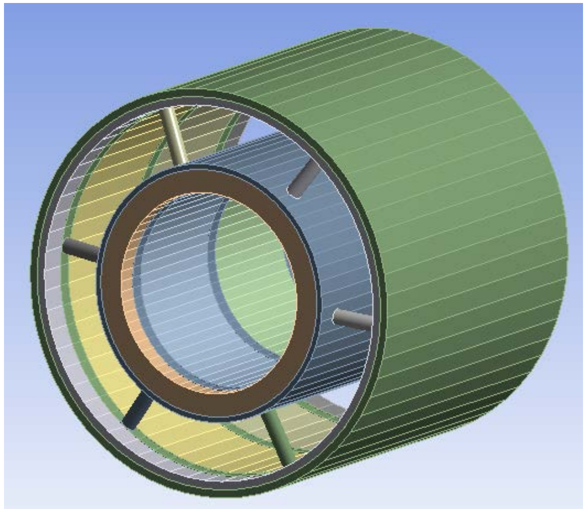






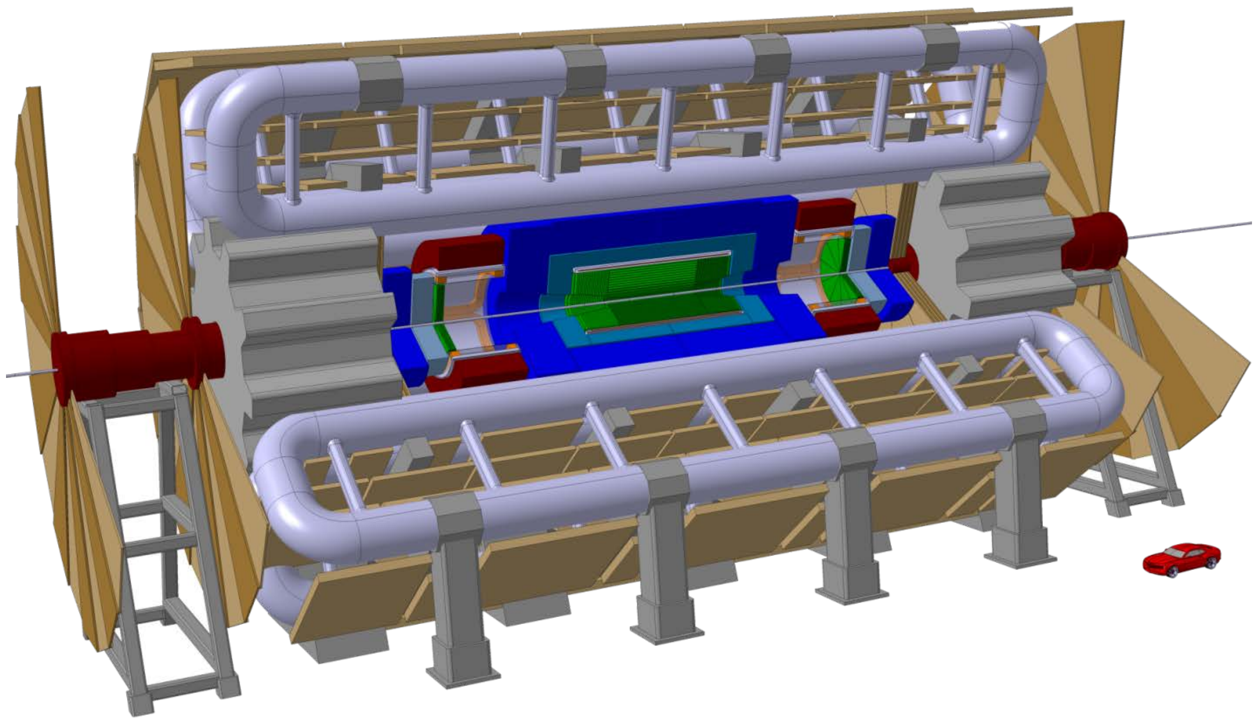
2. Twin Solenoid - Cold Mass Concept

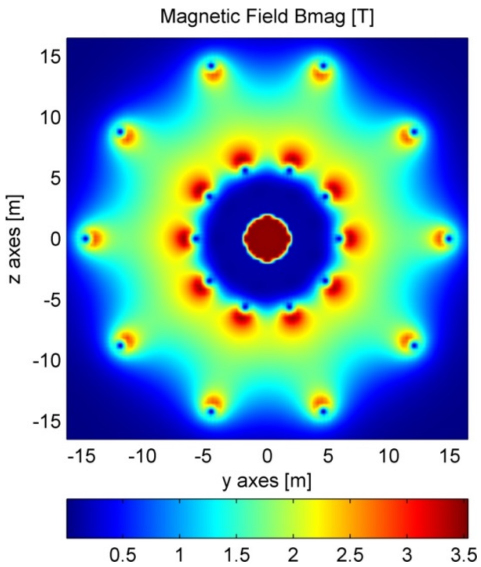




- Stored energy 54 GJ, conductor stored energy density: 12.6 kJ/kg.
- 6.0 T in center, 6.3 T peak field in turns, Conductor 4 kt, cold mass: ≈ 6 kt.
- 1.4 m thick inner coil and 0.4 m thick outer shielding coil.
- Large forces resulting from minor misalignments between the coils.
- Support cylinders and spokes are essential parts of the cold mass.
- 2.6 T in 3.5 m gap between solenoids for muon trackers.
- 5 mT line at 28 meters radius.

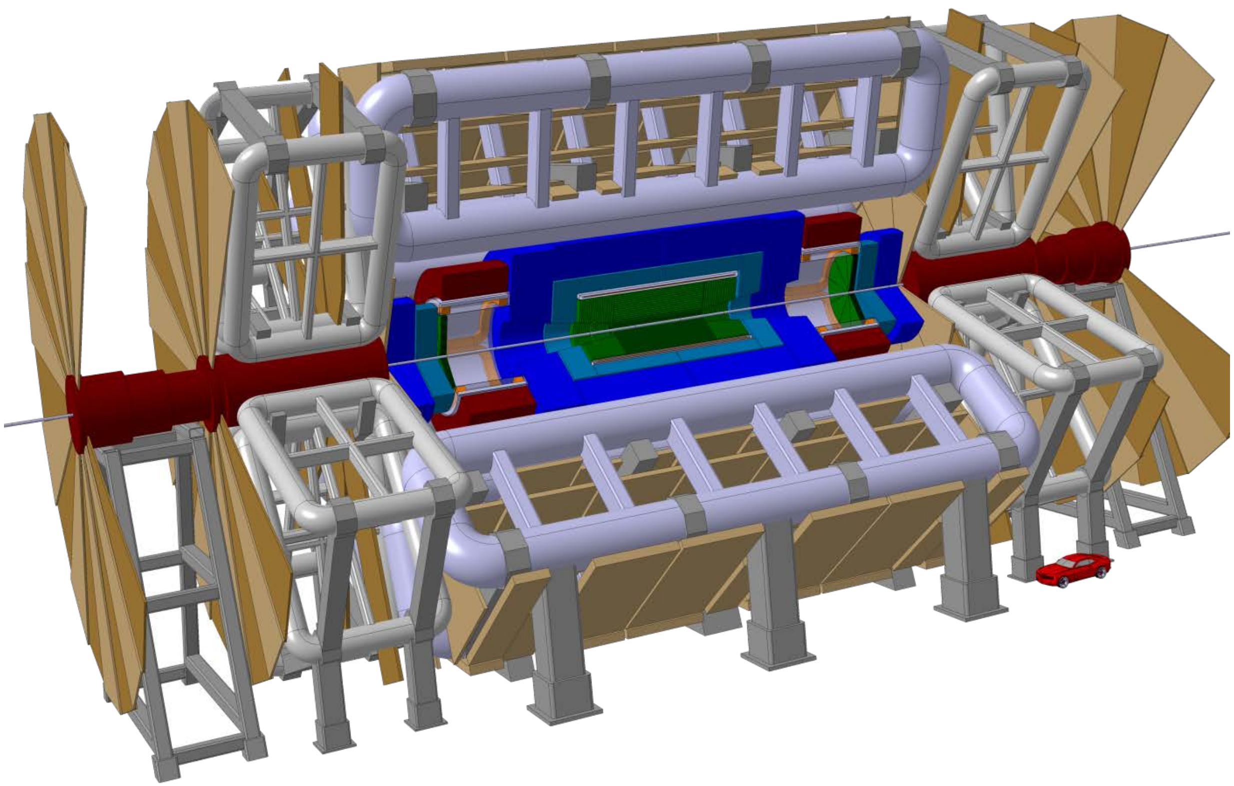
2. Option 3: Toroids + Solenoid + Dipoles (ATLAS+)





- **3.5 T Central Solenoid** for the inner detector trackers (0.6 GJ)
- One **Air core Barrel Toroid** with 16 Tm in toroid window (48 GJ)
- **Two End Cap Toroids** to cover medium angle forward direction (2x1.6 GJ)
- **Two internal Dipoles** to cover low-angle forward direction with 10 Tm.
- **Size: 30 m diameter x 52 m length (36,000 m^3)**.

2. Option 3: Toroids + Solenoid + Dipoles (ATLAS+)



Stored energy	40 GJ (34 GJ BT + 2x 3 GJ ECT)
Conductor mass	3.3 kt (10x 280 t BT modules + 20x 25 t ECT modules)
Length BT [m]	36
Inner radius BT [m]	7
Outer radius BT [m]	15
Length ECT [m]	8
Inner radius ECT [m]	2.5
Outer radius ECT [m]	15

Variant with shorter Barrel Toroid and full diameter End Cap Toroids, both in open structure. Advantages:

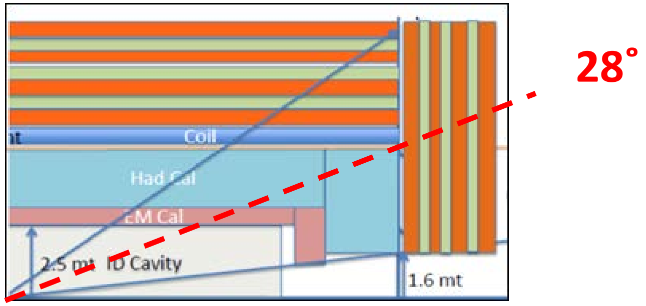
- Shorter coils, easier to handle
- Open end cap toroids allowing muon chambers inside
- Improved coverage in overlap sections

3. Cost scaling - impact of size and field

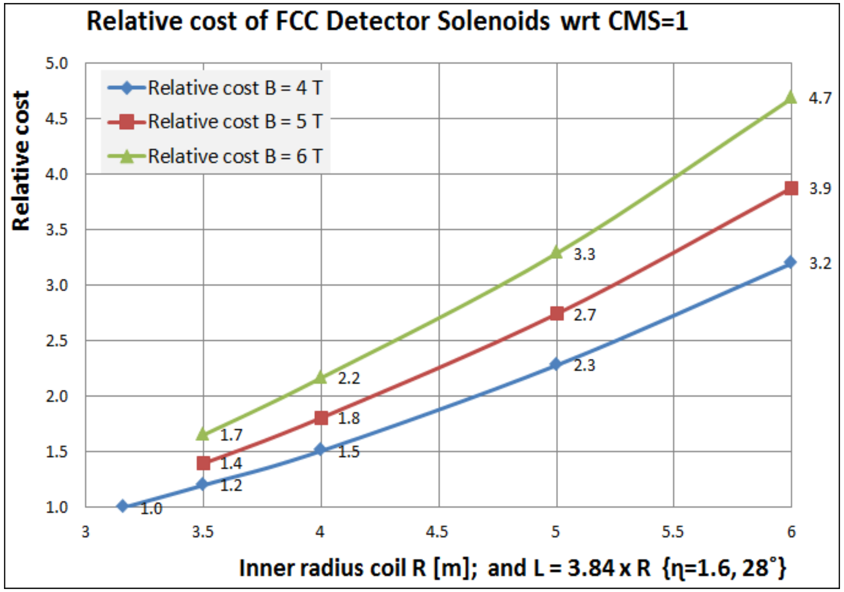
Effect of B and R ∝ L on Solenoid Cost:

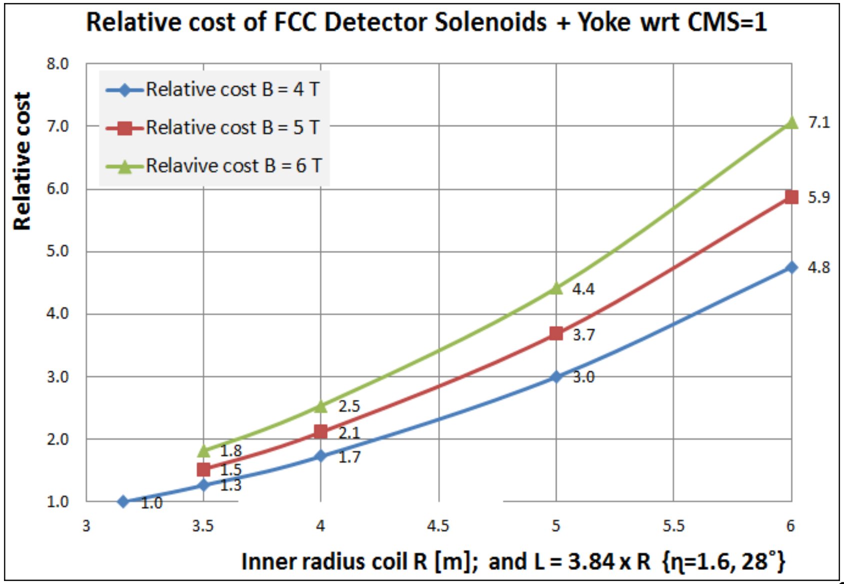
- Following scaling (A.Herve) calibrated with LEP & LHC detector magnets.
- Cost of 4, 5 and 6 T solenoids (no yoke) with radii of 3.5 to 6 m, length follows for fixed 28° opening angle.
- Same when including a minimum yoke (based on 4 M€/kt all-in).

✓ **Example: 6 T is ~60% more expensive in a 12 m bore than in a 10 m bore……!**



Disclaimer: these cost data are preliminary for such large systems, and a rough guide only !





3. Cost Magnet services – example cryogenics

Cost of a standalone helium plant

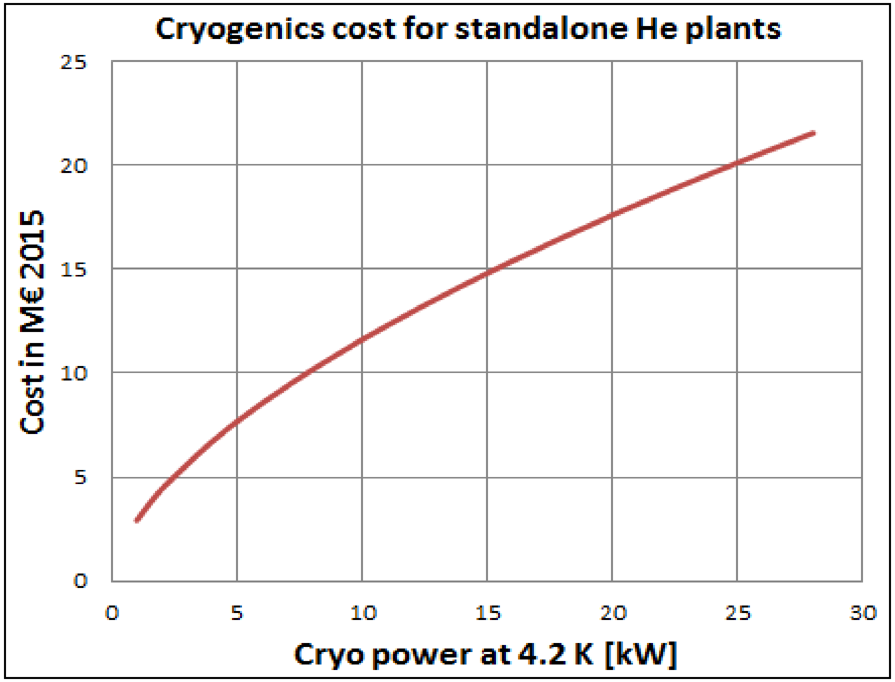
He plant cost ≈ 1.2 x 2.6 x $P(kW@4K)^{0.6}$ [in 2015 M€]

(1.2 amplification factor for auxiliaries, transfer lines; 2.6 is a constant, accounting for inflation)

Cryogenics power scales with surface of cryostat, in single solenoid 1, in twin solenoid 2 and in toroids many coils.

Example for CMS+ scaling:

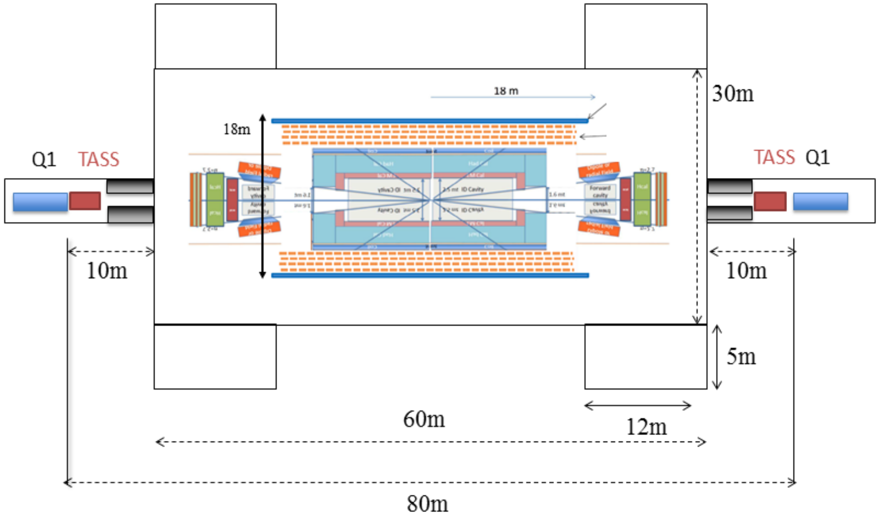
- CMS today has 1.5 kW.
- CMS+ in R=6m/L=23m version requires 4x, so 6 kW (8.5 M€).
- Twin Solenoid in R=6m/L-23m requires 12x, so 18 kW (16.5 M€).
- Why? 2 cryostats and more surface on the shielding coil!
- ATLAS+ needs some 20 kW (18 M€).



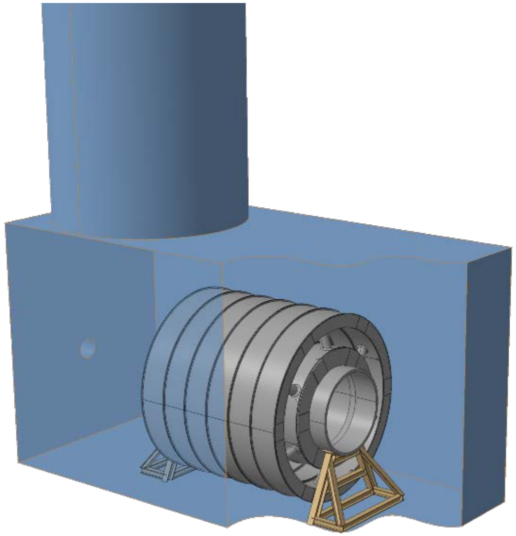
Cryo cost are in the 10-20 M€ range and small when compared to cost of magnets and iron, no worries.

4. Cavern size, shafts, opening and closing

- For all three options we have to find manufacturing, pre-assembly and installation scenarios and to define or respect limitations on cavern size, adjacent spaces for assembly and shafts diameters.

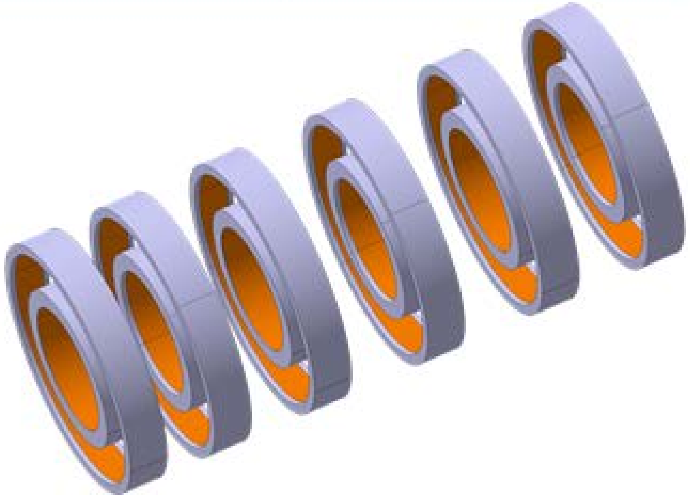


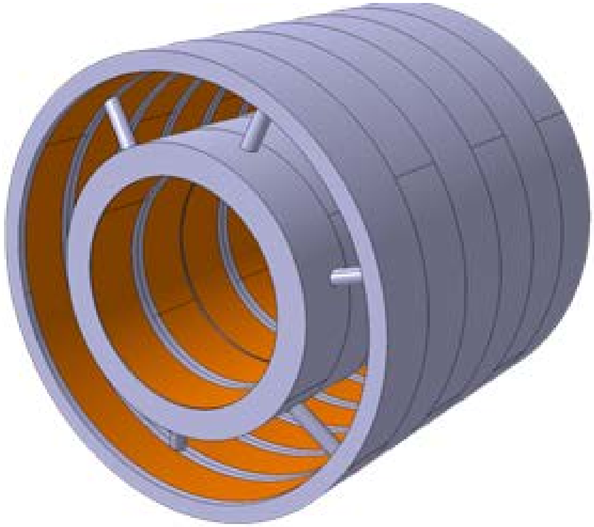
- Based on the net volume needed for magnet installation, also the additional space needed for opening, closing and repair have to be defined.



4. Twin Solenoid - modular design and structure

	Inner coil	Outer coil
Inner radius [m]	6.2	11.5
Thickness [m]	1.73	1.02
Length [m]	23.0	23.0
Mass [t]	4 800	4500
# of Modules	6	



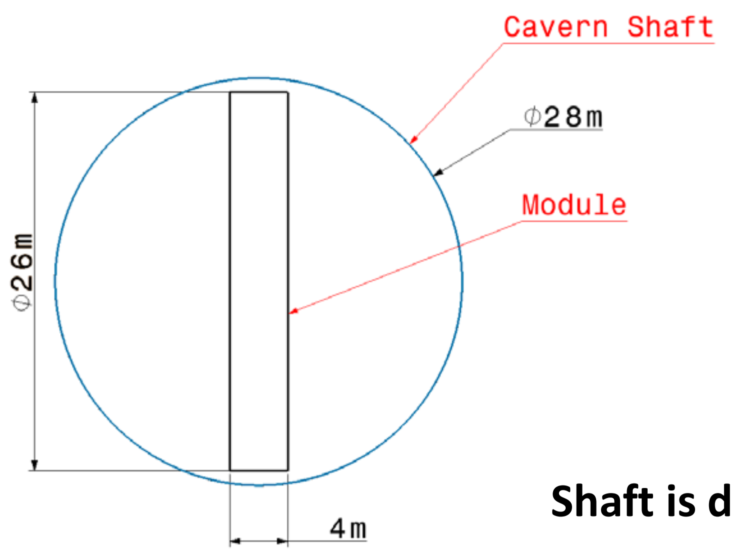


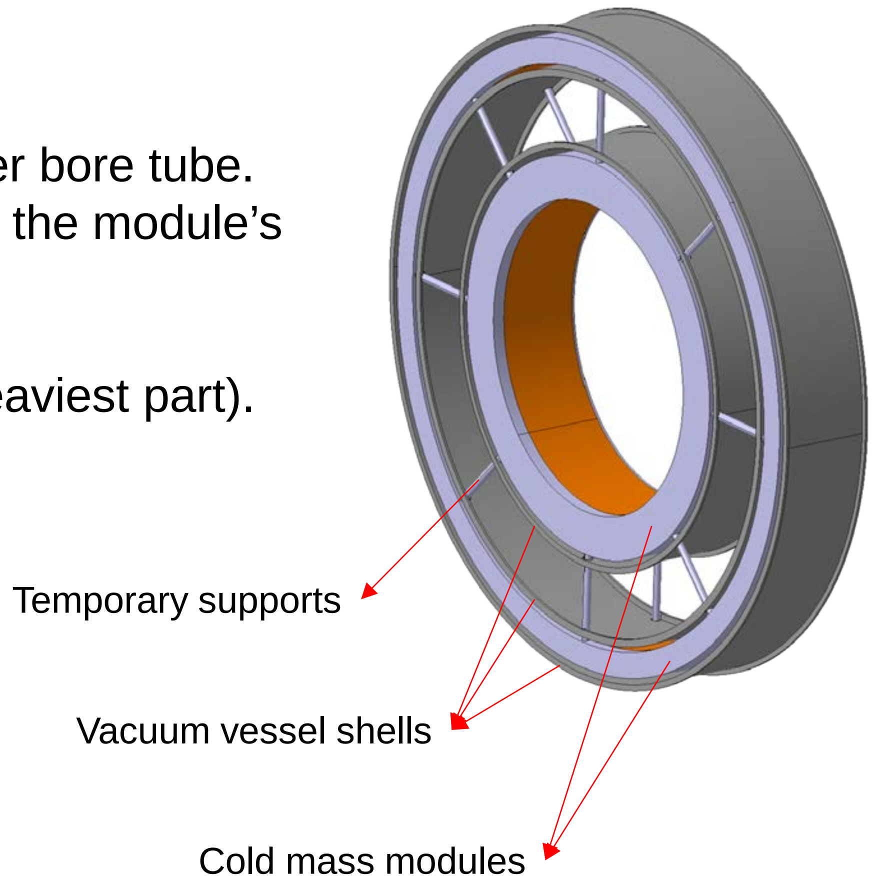
The twin solenoid solution was studied for a few months, to find a stable structure connecting both coils, as well a production and assembly scenario.

4. Twin Solenoid - modularity and shaft size

Cavern shaft of about 28 m needed

- Assembly based on modularity.
- Each coil module is composed of:
  - Inner coil
  - Outer coil
  - All cryostat shells, except inner bore tube.
- Cavern shaft diameter is driven by the module’s outer diameter and length.
- Clearance for safety is 0.8 m.
- Mass of each module is 2000 t (heaviest part).



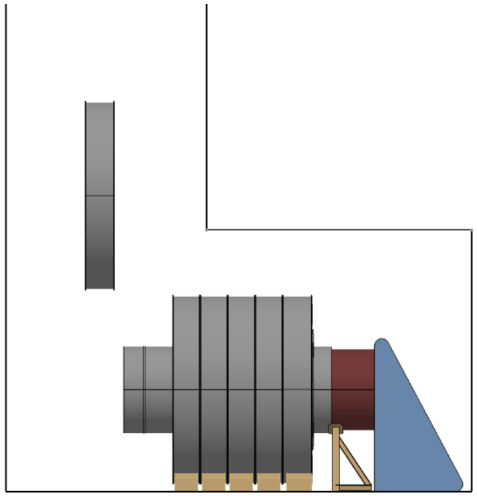


Shaft is deep and wide! also looking into other options.

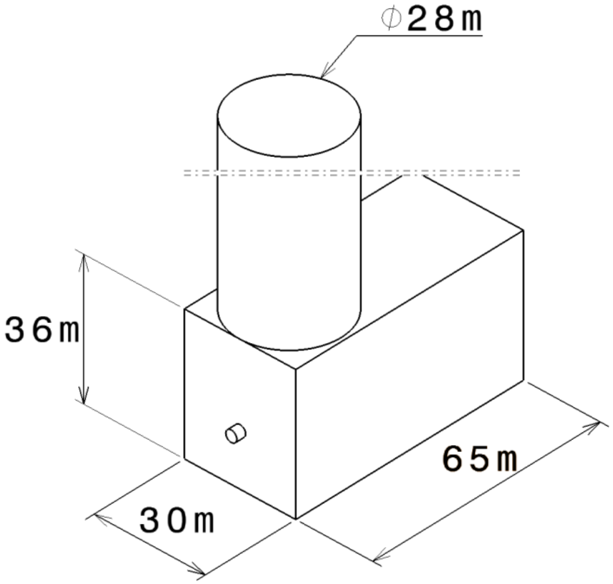
4. Twin Solenoid - assembly space in cavern

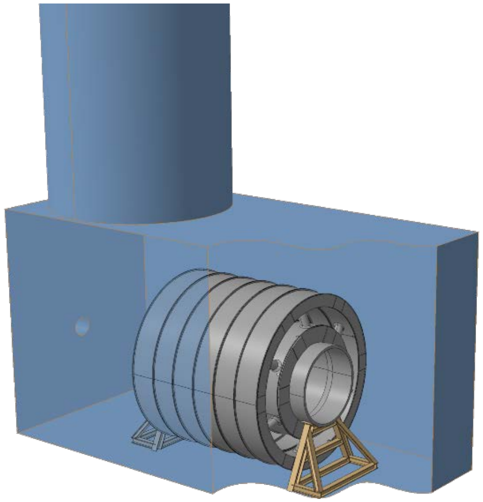
Minimum space needed for magnet assembly (1st look)

(cavern = this space + extra for surrounding systems)



- Height = diameter of magnet + overhead for crane.
- 65 m long hall necessary for magnet assembly.
- 2 m of lateral space.
- Note: ATLAS cavern is 35 x 53 x 40 m^3.



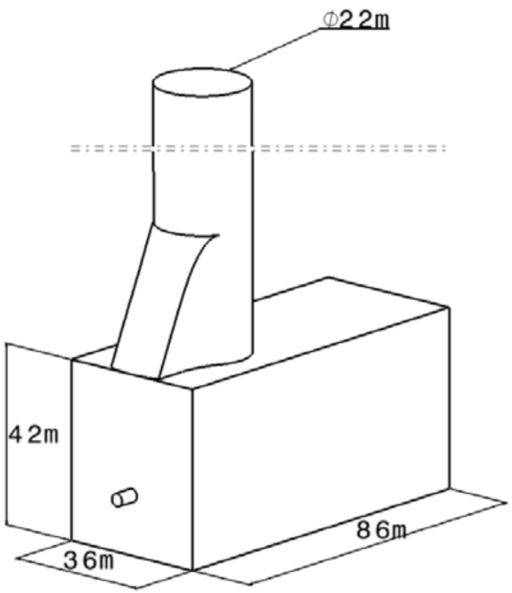


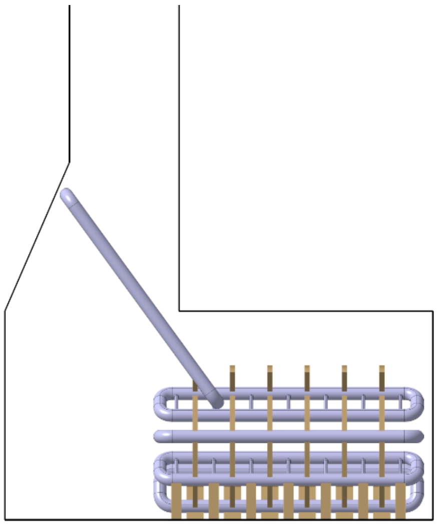
4. Toroid - assembly space in cavern

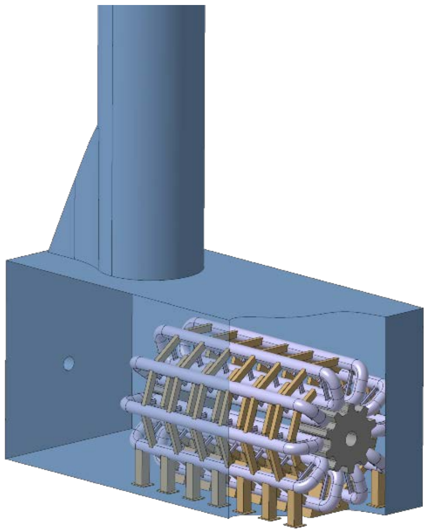
Minimum space needed for magnet assembly (1st look)

- Rotation of last coil requires extra space.
- Shaft may be chamfered.
- Volume for assembly is 1.85 times the Twin Solenoid.

	Twin Solenoid	Toroid
Length [m]	65	86
Width [m]	30	36
Height [m]	36	42
Shaft diameter [m]	28	22*







5. FCC-hh Detector Magnets Working group

The dreamed 6 T – 50 GJ class magnets are far beyond what has been demonstrated to work. A rigorous design and engineering effort has to start.

Charge: deliver the Magnets Chapter in the FCC-HH detector CDR (2018)

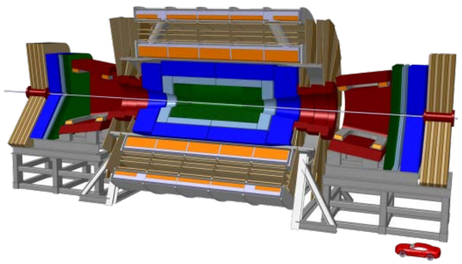
- Establish a work program and schedule
- Do the necessary design studies and engineering

New working group established, a team within CERN/PH with participation of other institutes.

Present composition:

- CERN: H. ten Kate, A. Dudarev, M. Mentink, Helder Silva, B. Cure, A. Gaddi, H. Gerwig, S. Klyukhin, and students
- CEA-Saclay: C. Berriaud
- ?..... other institutes welcome

Regular meetings with 2-3 weeks frequency.

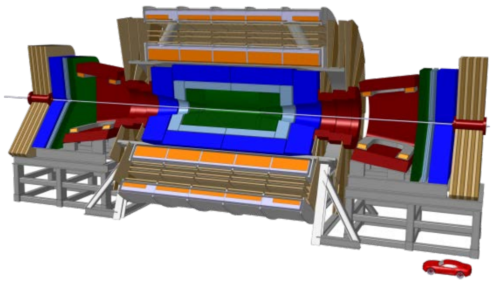


5. R&D issues

Three families of designs to be studied:

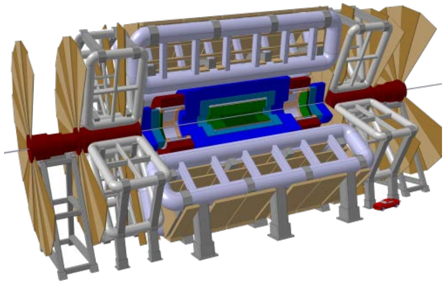
I - **Solenoids: range 5-6 T in 10-12 m bore, 19-23 m long**

- Solenoid – no yoke, unshielded
- Solenoid + minimum yoke, partly shielded
- Solenoid + fully shielding yoke
- Twin Solenoid



II - **Toroids+central solenoid+dipoles**: 1.5-2 T toroid + 3.5-4 T solenoid

- Barrel Toroid and End Cap Toroid shape variants
- Dipole positioning and shape

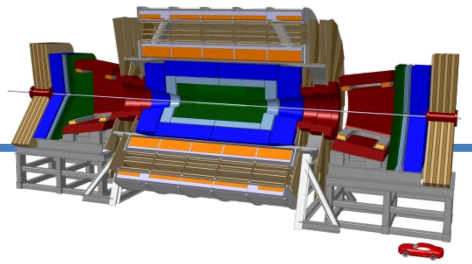


III – **Forward Dipole or Toroids for 10 Tm**

- Type of dipole, inclination opening, racetracks or cylindrical
- Small toroid

- **Plenty of room for good ideas for making clever designs.**

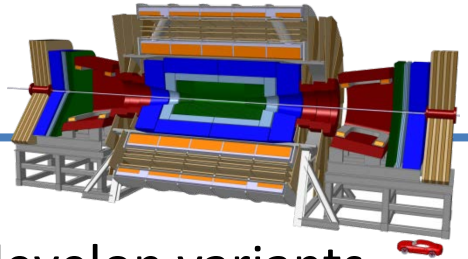
5. R&D issues



For each magnet variant complete the critical design:

- **Superconductor**: for 6 T class detector magnets, Al-Ni based or CICC, scale up conductors to 75-100 kA @ 6T, demonstrate temperature margin and stability, deliver a demonstration conductor.
- **Cold mass**: handling of stress, strain and temperature.
- **Cryogenics**: method of cooling, direct cooling of conductor, cooling power requirement.
- **Cryostat:** including cold mass supports.
- **Quench protection**: current, voltage, discharge times, temperature
- **Magnet in modules**: sizing and weight, assembly and installation scenarios, requirements for cavern, shafts, cranes.
- Magnetic shielding and Radiation shielding requirements
- Develop a **realistic schedule**, for R&D, production, installation
- **Cost estimate**, compare variants including assembly and installation.
- …and more

6. Conclusion



- ✓ 2 different detectors design are pursued, continue to develop variants.
- ✓ Solenoid + fully shielding yoke is very heavy and bulky, hardly feasible.
- ✓ Solenoid + minimum iron, looks more acceptable, what is minimum?
- ✓ Toroids give best BL^2 for most angles, more complex, certainly doable, but do we still need a high quality stand-alone muon spectrometer?
- ✓ The arguments for one of these and there sizing shall be extensively discussed regarding physics requirements, for guiding further work.
- ✓ Solenoid and toroids sizes can be reduced somewhat by altering the detector technologies, higher resolution inner tracker, change of absorber material; clear statements are needed on their feasibility.
- ✓ We have seen solenoids and toroids of unprecedented size and stored energy of 40-60 GJ, but so far no show stoppers identified.

The good news: there are no principle technical problems impeding the constructing of these magnets.