Challenges for Particle Detectors at Future Circular Colliders

RD50 collaboration meeting

2 December 2015

W. Riegler, CERN

Material on accelerators from M. Benedikt

Abstract

Future Circular Collider (FCC) is an integral conceptual design study for post-LHC particle accelerator options in a global context. It is exploring the potential of hadron and lepton circular colliders, performing an in-depth analysis of infrastructure and operation concepts and considering the technology research and development programs that would be required to build a future circular collider. A conceptual design report will be delivered before the end of 2018 , in time for the next update of the European Strategy for Particle Physics. This talk will give an overview of the FCC studies and present specific aspects of experiments and detectors at the 100TeV hadron collider that is a key part of this study.

Strategic Motivation

- **European Strategy for Particle Physics 2013:**

  "…to propose an ambitious post-LHC accelerator project….., CERN should undertake design studies for accelerator projects in a global context,…with emphasis on proton-proton and electron-positron high-energy frontier machines.…."

- **ICFA statement 2014:**

  "…. ICFA supports studies of energy frontier circular colliders and encourages global coordination.…."

- **US P5 recommendation 2014:**

  "….A very high-energy proton-proton collider is the most powerful tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window…."

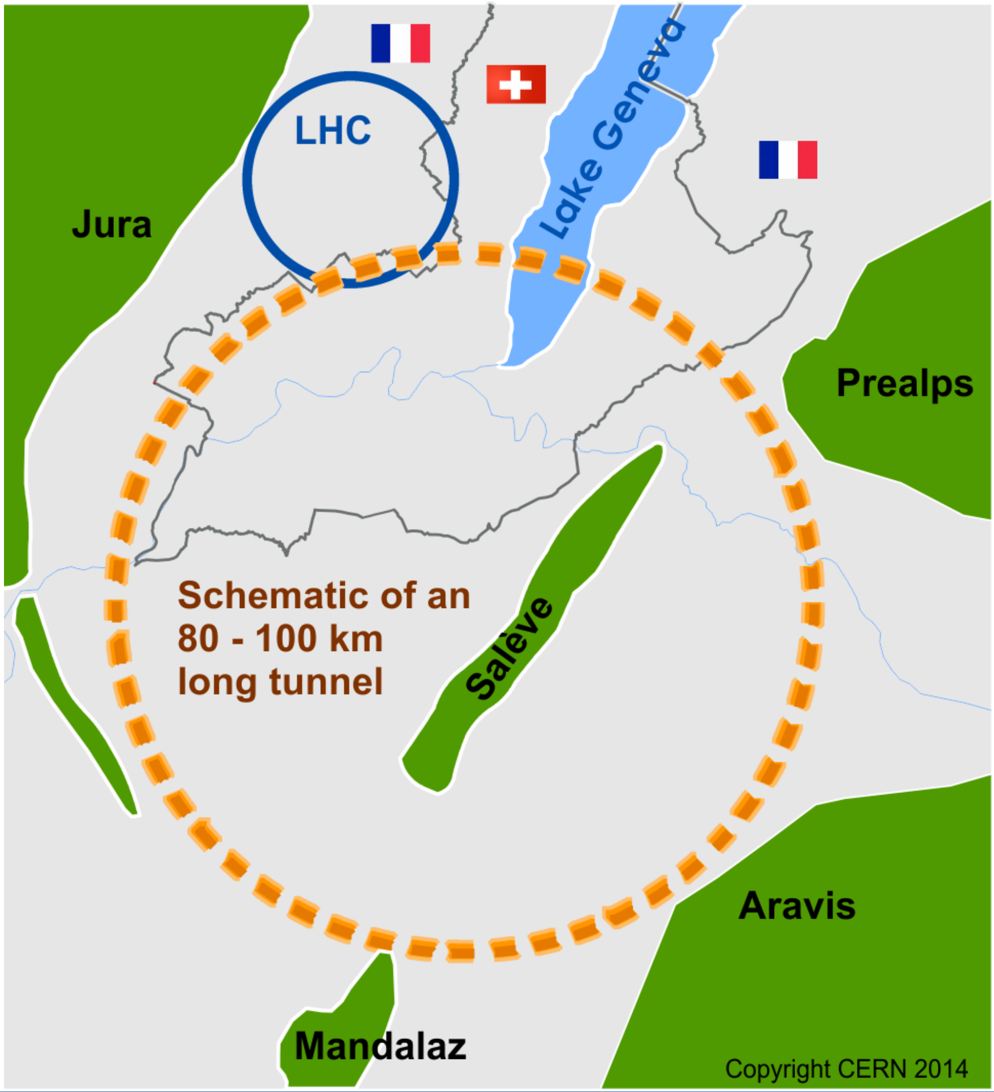
Future Circular Collider Study

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

- **80-100 km infrastructure** in Geneva area
- ***e^+e^-* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (FCC-he) option**
- **HE-LHC** with FCC-hh technology



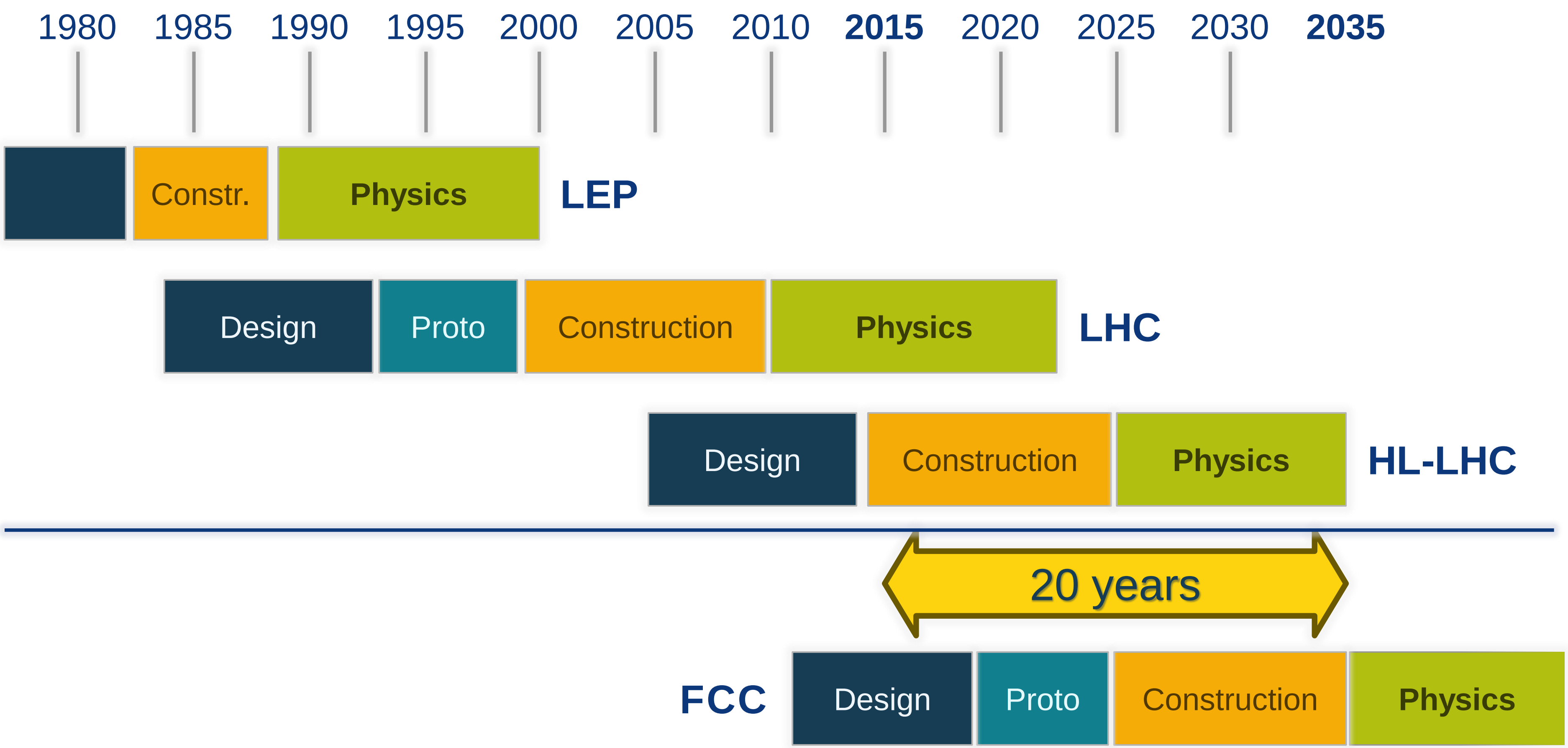
FCC motivation: pushing the energy frontier

The name of the game of a hadron collider is **energy reach**

$$E \alpha B_{dipole} \times R_{bending}$$

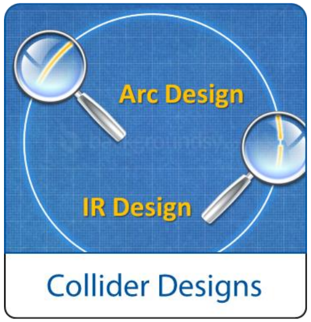
Cf. LHC: factor ~4 in radius, factor ~2 in field → **O(10) in E_{cms}**

CERN Circular Colliders and FCC



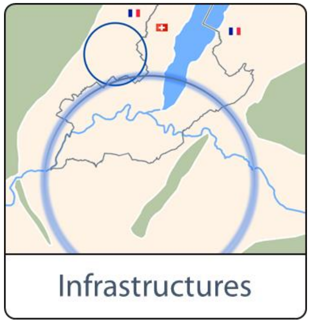
FCC Conceptual Design Report by end 2018 for the European strategy update

FCC Scope: Accelerator and Infrastructure



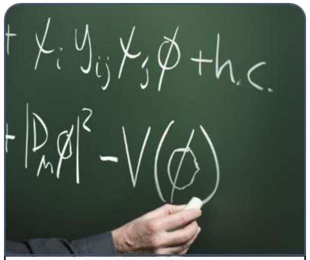
FCC-hh: **100 TeV pp collider as long-term goal**
→ defines infrastructure needs
FCC-ee: **e^+e^- collider**, potential intermediate step
FCC-he: **integration aspects** of pe collisions

Push key technologies
in dedicated R&D programmes e.g.
16 Tesla magnets for **100 TeV** pp in **100 km**
SRF technologies and RF power sources



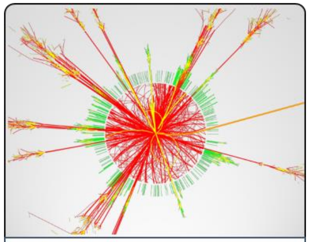
Tunnel infrastructure in Geneva area, linked to CERN accelerator complex
Site-specific, requested by European strategy

Scope: Physics & Experiments



Physics Cases

Elaborate and document
- Physics opportunities
- Discovery potentials



Experiments

Experiment concepts for hh, ee and he
Machine Detector Interface studies
Concepts for worldwide data services

Cost Estimates

Overall cost model
Cost scenarios for collider options
Including infrastructure and injectors
Implementation and governance models

LEP – highest energy e^+e^- collider so far

circumference 27 km
in operation from 1989 to 2000
maximum c.m. energy 209 GeV
maximum synchrotron radiation power 23 MW

FCC-ee physics areas

- highest possible luminosities at all working points
- *beam energy range from 35 GeV to ≈200 GeV*
- **physics programs / energies:**

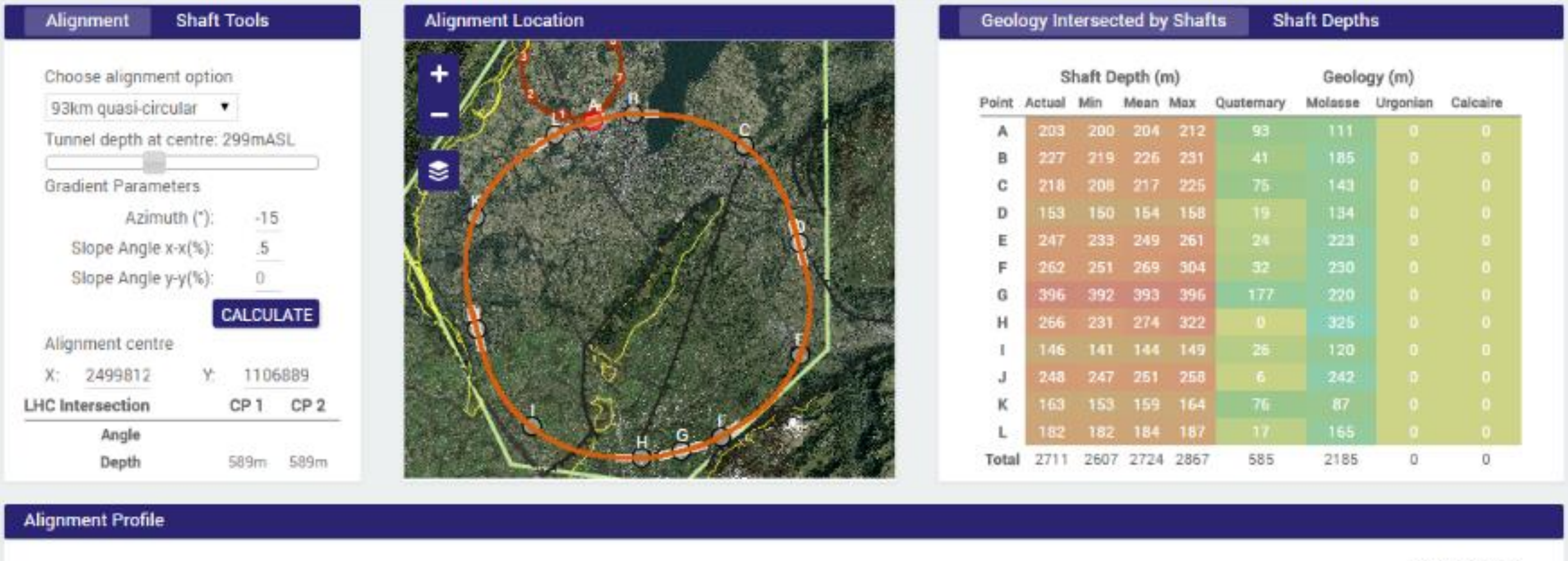
Z (45.5 GeV) Z pole, 'TeraZ' and high precision M_Z & Γ_Z

W (80 GeV) W pair production threshold, high precision M_W

H (120 GeV) ZH production (maximum rate of H's)

t (175 GeV): $t\bar{t}$ threshold, H studies

Site investigations



	Shaft Depth (m)				Geology (m)			
Point	Actual	Min	Mean	Max	Quaternary	Molasse	Urgonian	Calcaire
A	203	200	204	212	93	111	0	0
B	227	219	226	231	41	185	0	0
C	218	208	217	225	75	143	0	0
D	153	150	154	158	19	134	0	0
E	247	233	249	261	24	223	0	0
F	262	251	269	304	32	230	0	0
G	396	392	393	396	177	220	0	0
H	266	231	274	322	0	325	0	0
I	146	141	144	149	26	120	0	0
J	248	247	251	258	6	242	0	0
K	163	153	159	164	76	87	0	0
L	182	182	184	187	17	165	0	0
Total	2711	2607	2724	2867	585	2185	0	0

- 90 – 100 km fits geological situation well
- LHC suitable as potential injector

FCC-hh preliminary layout

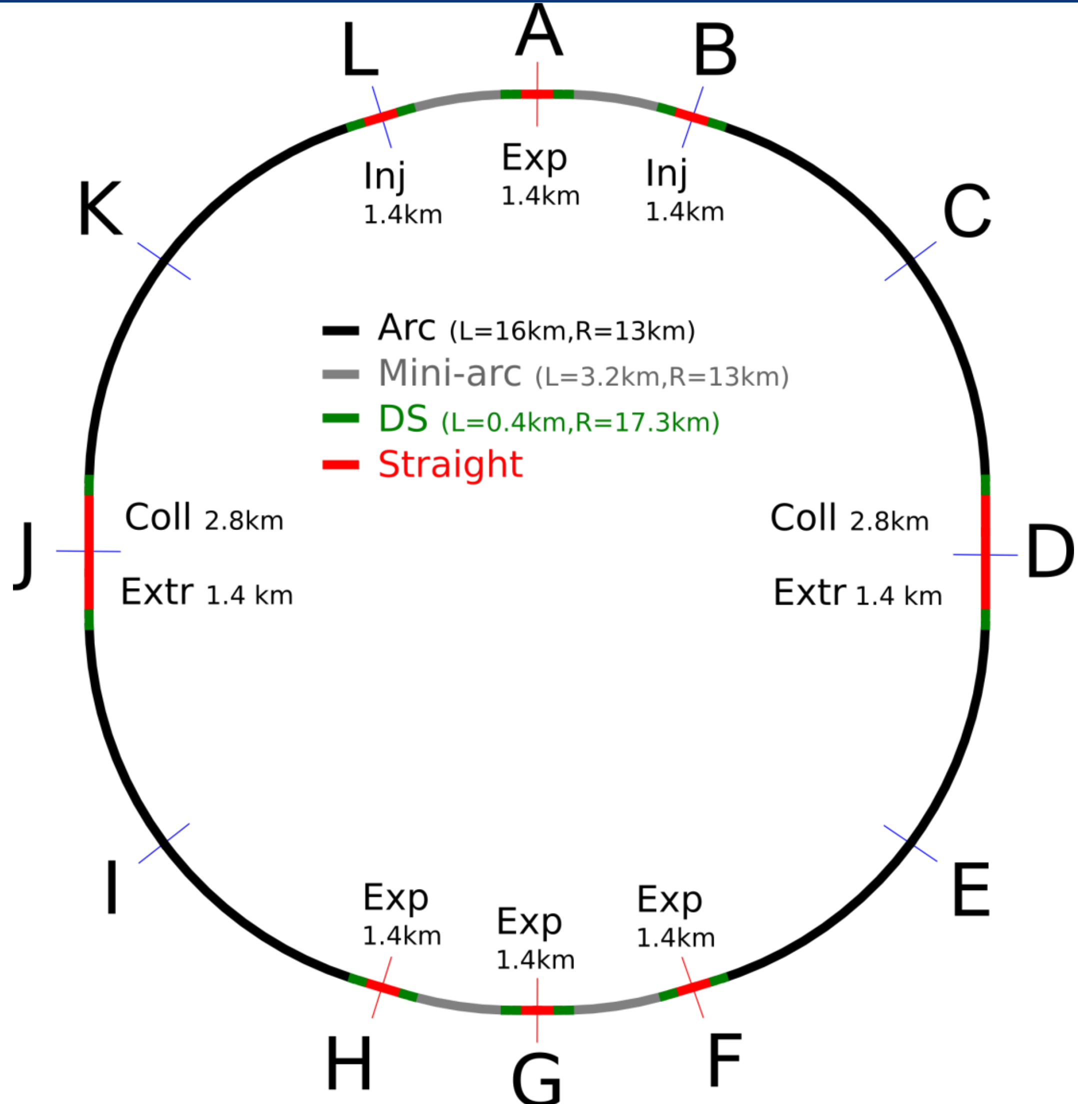
100 km layout for FCC-hh (different sizes under investigation)

⇒ **Two high-luminosity experiments (A and G)**

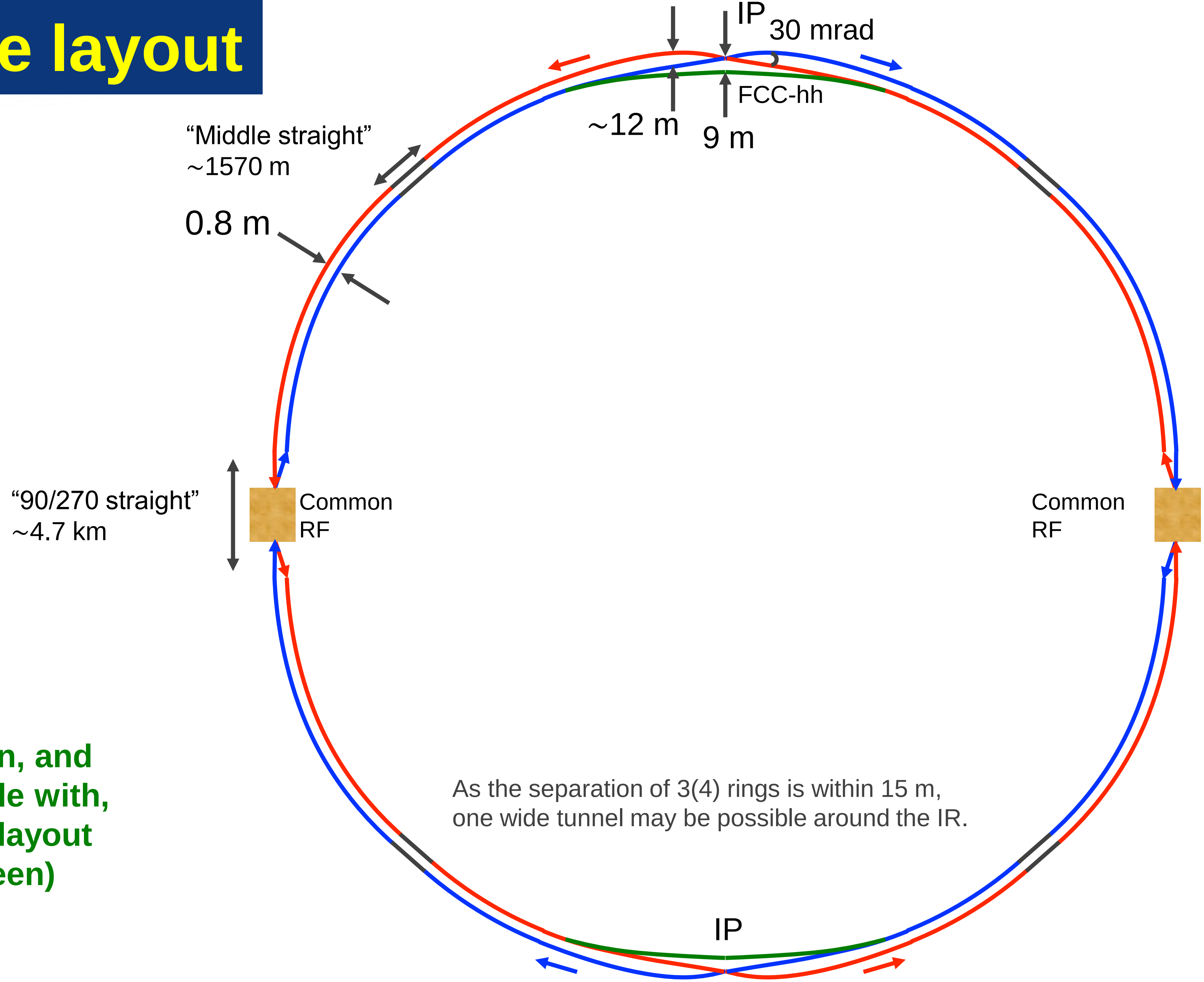
⇒ **Two other experiments (F and H) grouped with main experiment in G**

⇒ **Two collimation lines**

⇒ **Two injection and two extraction lines**



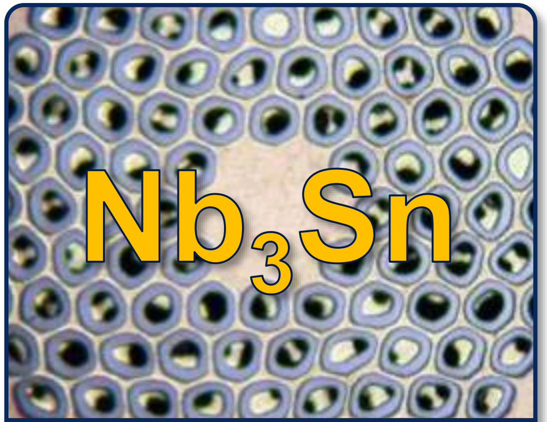
FCC-ee layout



As the separation of 3(4) rings is within 15 m, one wide tunnel may be possible around the IR.

Based on, and compatible with, FCC-hh layout (in green)

Key Technology R&D - HFM



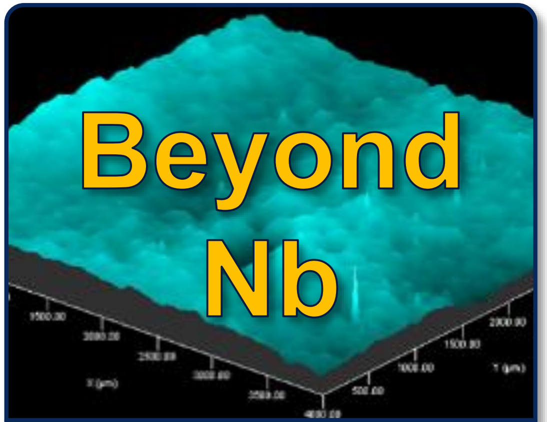
Conductor R&D

Magnet Design

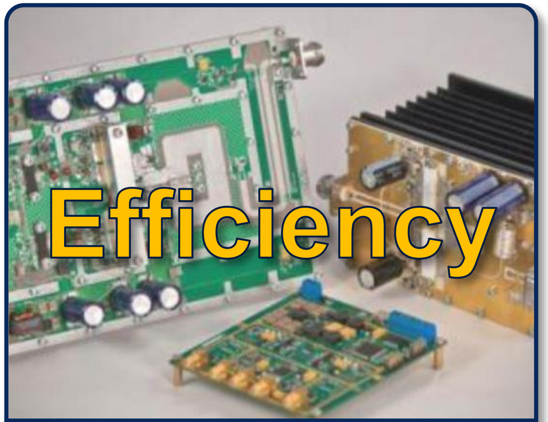
- Increase critical current density
- Obtain high quantities at required quality
- Material Processing
- Reduce cost

- Develop 16T short models
- Field quality and aperture
- Optimum coil geometry
- Manufacturing aspects
- Cost optimisation

Key Technology R&D - RF



Superconducting RF



Power Conversion

- Evaluate new fabrication techniques
- Study novel superconducting materials
- Improve thin film / coating techniques
- Optimise operation temperature to improve energy efficiency

- Push klystron efficiency beyond 75%
- Increase power range efficiency of solid-state amplifiers
- Assess power reach of IOTs

Synchrotron radiation/beam screen

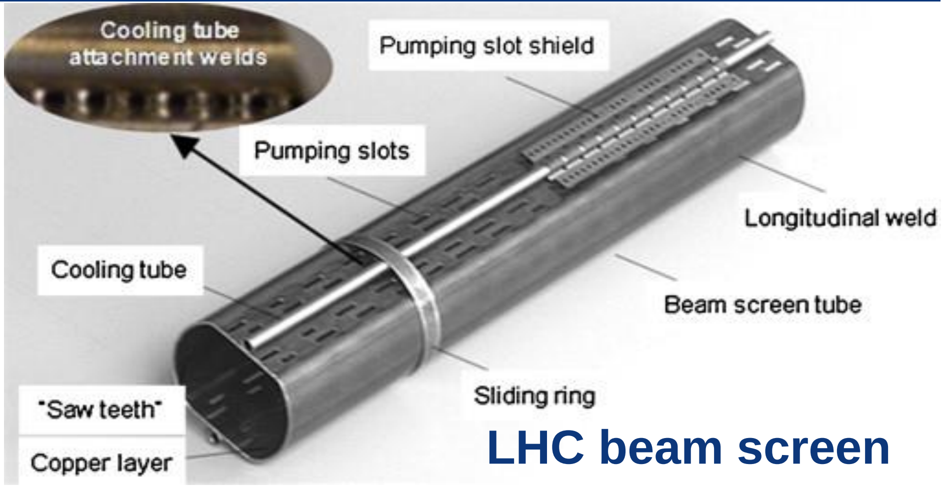
High synchrotron radiation load (SR) of protons @ 50 TeV:

~30 W/m/beam @16 T (LHC <0.2W/m)

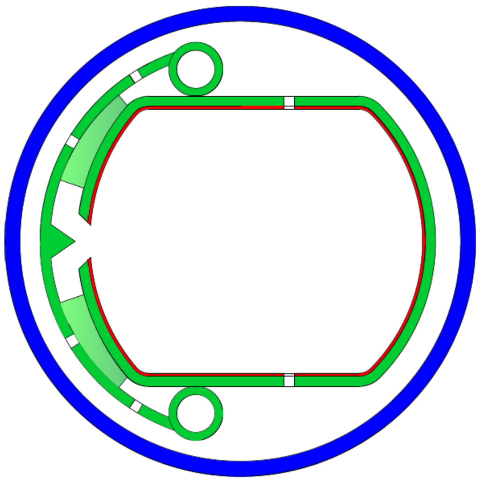
→ 5 MW total in arcs

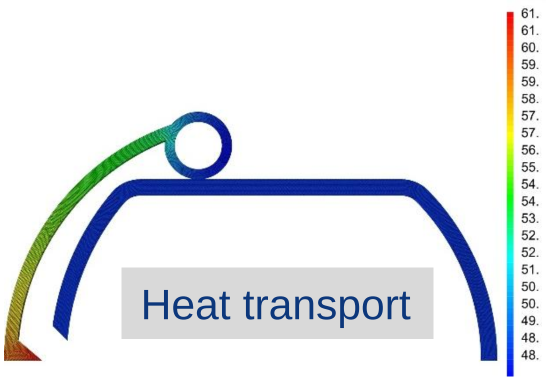
New type of chamber

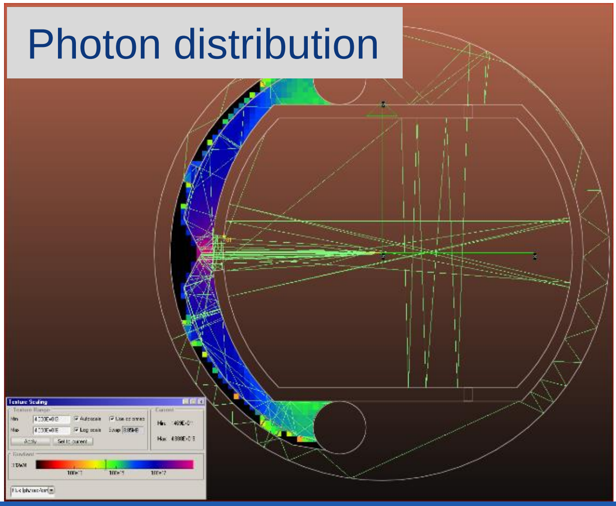
- absorption of synchrotron radiation
- avoids photo-electrons, helps vacuum



LHC beam screen

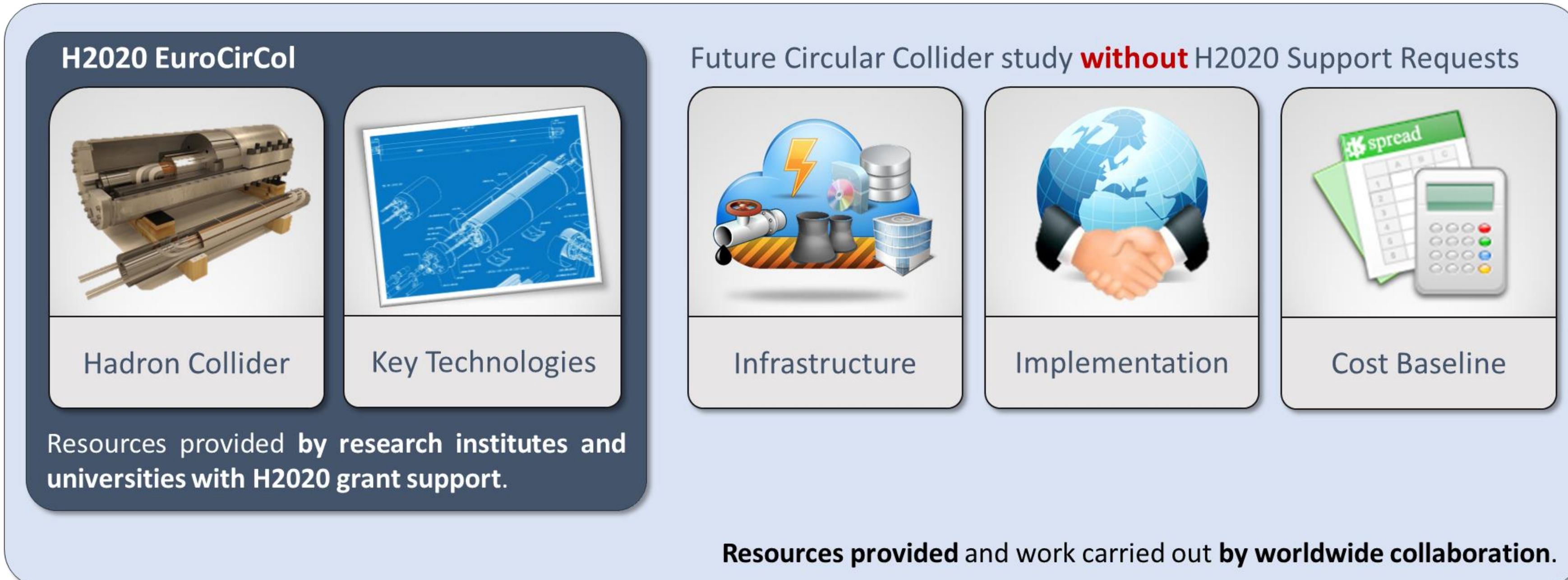






EuroCirCol EU Horizon 2020 Grant

EC contributes with funding to FCC-hh study



- Core aspects of hadron collider design: arc & IR optics design, 16 T magnet program, cryogenic beam vacuum system
- **Recognition of FCC Study by European Commission.**

FCC International Collaboration

- 61 institutes
- 23 countries + EC

Status: 14 September 2015

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:

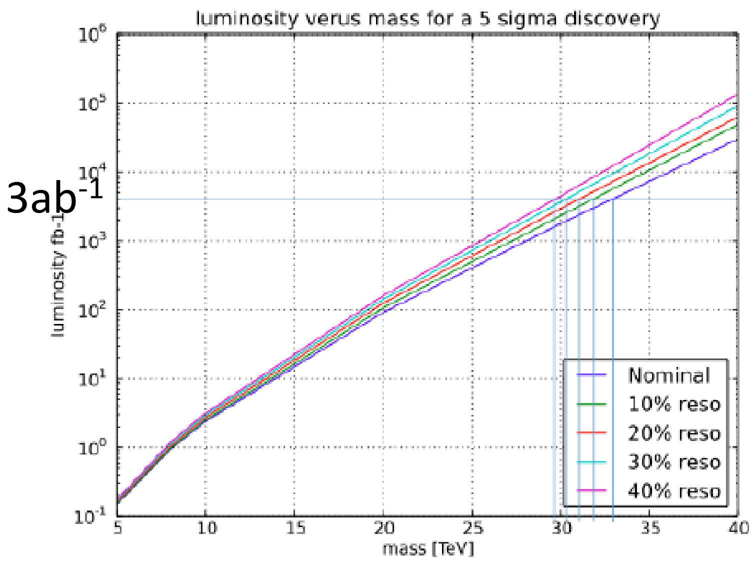
- **10 years baseline, leading to 2.5 ab-1**
- **15 years ultimate, leading to 15 ab-1**

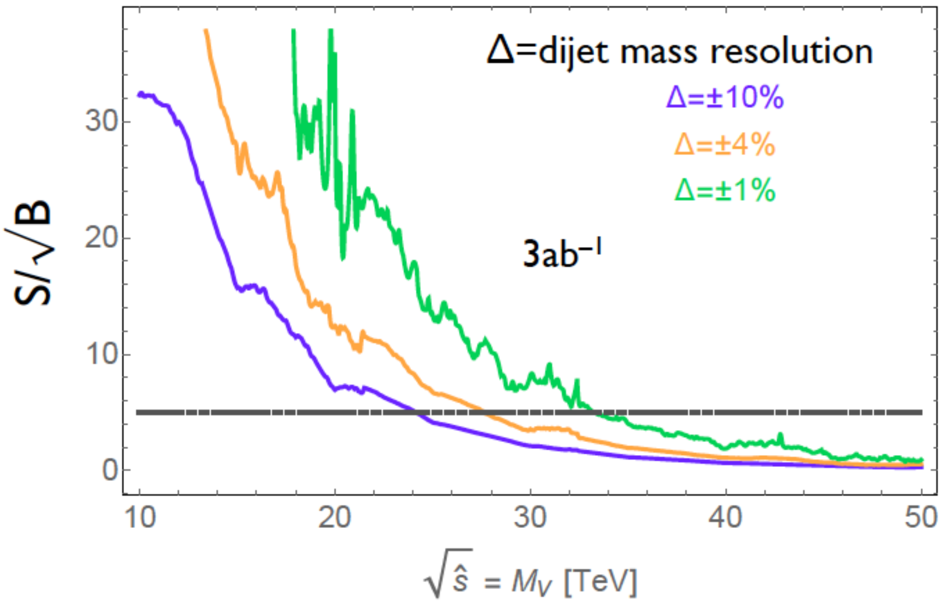
would result in a total of O(20) ab-1 over 25 years of operation.

FCC Hadron Detector Concepts

Physics at the Lσ Limit

C. Helsens, M. Mangano





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

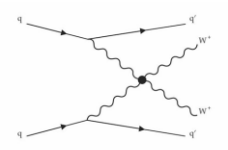
$$\frac{\Delta E}{E} \propto \frac{1}{\sqrt{E}} + k$$

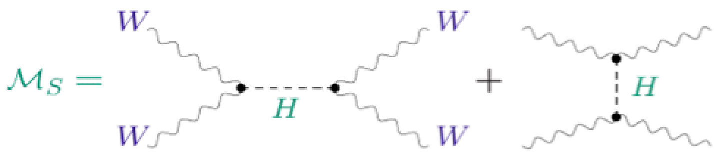
Muon momentum resolution O(15%) at 10TeV.

→ Constant term dominates, 1-2% goal
→ full shower containment is mandatory !
→ Do not compromise on 12 lambda !

WW scattering by VBF Mechanism

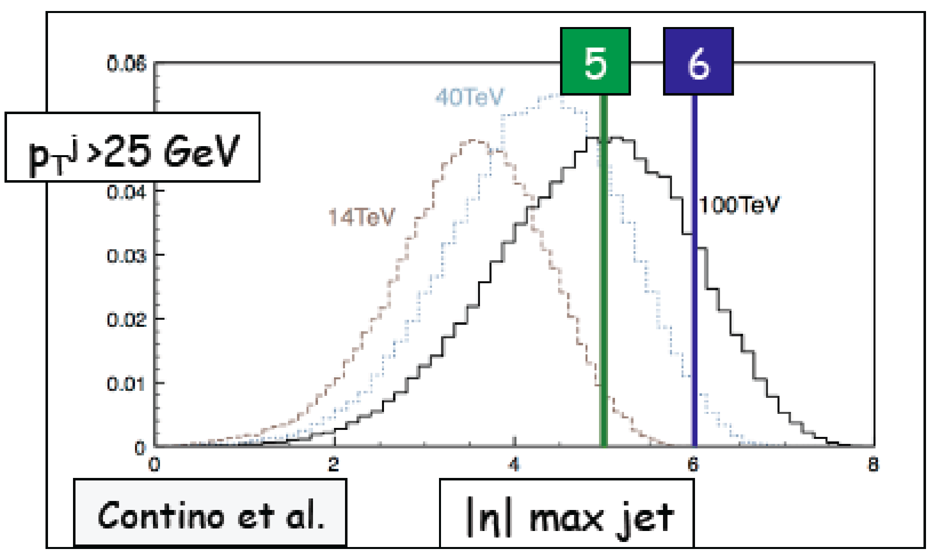
Is H playing it’s role ? Unitarity at 1TeV ? Are there high mass resonances WW, ZZ, HH, …



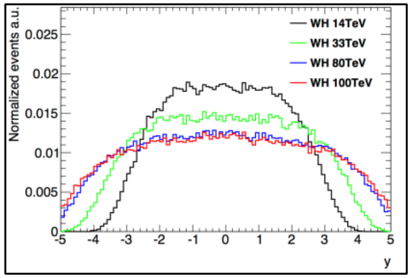


VBF jets between η~2 and η~6
need to be well measured and separated from pile-up

Muons (and electrons) around ~1 TeV p_T
need to be triggered, identified, precisely measured



Higgs Measurements



H→ 4l acceptance vs η coverage (l p_T cuts applied)

	14 TeV		100 TeV	
	2.5	4	2.5	4
ggF	0.74	0.99	**0.56**	0.88
WH	0.66	0.97	**0.45**	0.77
ZH	0.69	0.98	**0.48**	0.80
ttH	0.84	1	**0.56**	0.90
VBF	0.75	0.98	**0.55**	0.87

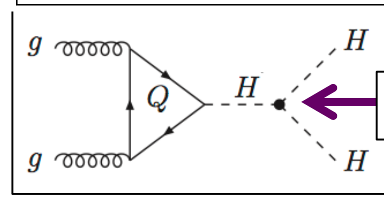
H. Gray, C. Helsens

		|η| < 2.5	|η| < 4	|η| < 5
YY	100 TeV	0.74	0.95	0.99
	14 TeV	0.90	1	1

→ 30-50% acceptance loss for H→ 4l at 100 TeV wrt 14 TeV if tracking and precision EM calorimetry limited to |η|<2.5 (as ATLAS and CMS)
→ can be recovered by extending to |η|~ 4

Examples:
ttH : x 60 (from LHC 14)
HH : x 42

"Heavy" final states require high √s, e.g.:
HH production (including measurements of self-couplings λ)
ttH (note: ttH→ ttμμ, ttZZ "rare" and particularly clean)



g_{HHH} ~ λv

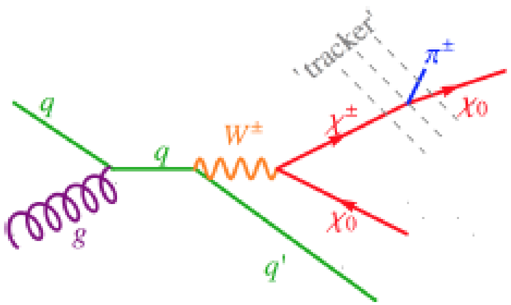
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	+2000	3000	3000
λ	[redacted]	83%	46%	21%	13%	21%	10%	20%	8%

More Exotic

Disappearing Tracks - Introduction

$M_{\chi^\pm} - M_{\chi_0} = 165$ MeV $> m_\pi \quad \Rightarrow \quad$ lifetime $\tau \simeq 6\,\mathrm{cm} \simeq 0.2\,\mathrm{ns}$

Almost all $\chi^\pm$s decay to χ_0 + soft pions before reaching detectors



Feng Strassler 1994

Feng Moroi Randall Strassler Su 1999

...

Low Wang 1404.0682

Filippo Sala

Physics at a 100 TeV Hadron Collider

Exploration + Higgs as a tool for discovery

Numerous physics opportunities with a large number of possible measurements.

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.

Approximate Overall Needs

Tracking: Momentum resolution H15% at p_t=10TeV

Precision tracking (momentum spectroscopy) and Ecal up to η=4

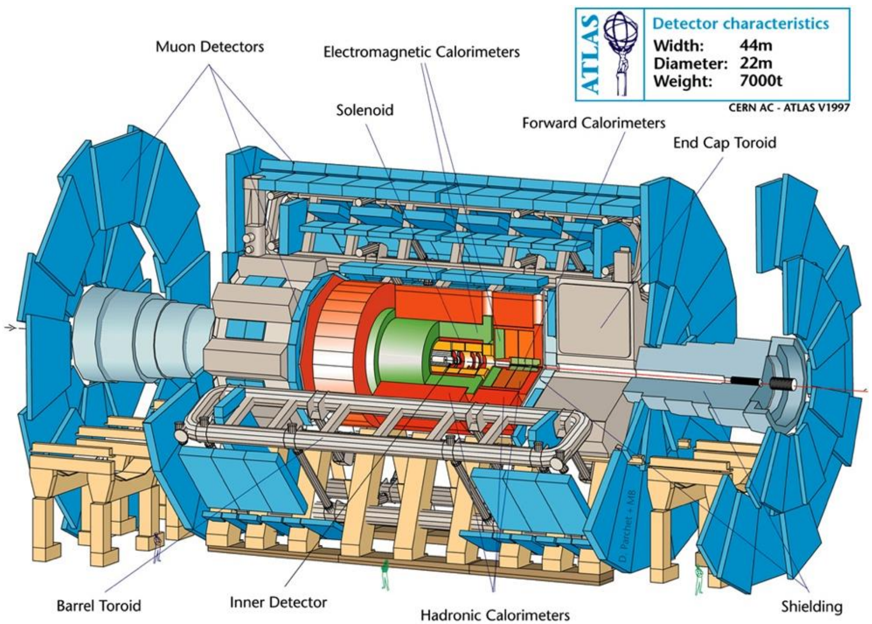
Tracking and calorimetry for jets up to η=6.

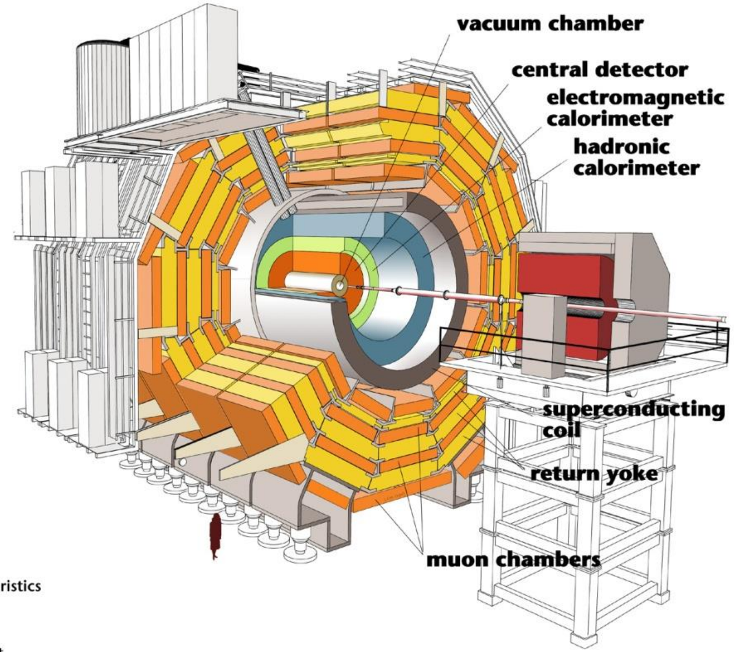
12 λ_{in} calorimetry, 1-2% constant term.

Calorimeter granularity of 0.05x0.05 or 0.025x0.025 to mitigate pileup and measure jet substructure and boosted objects.

B-tagging, timing for pileup rejection etc. …

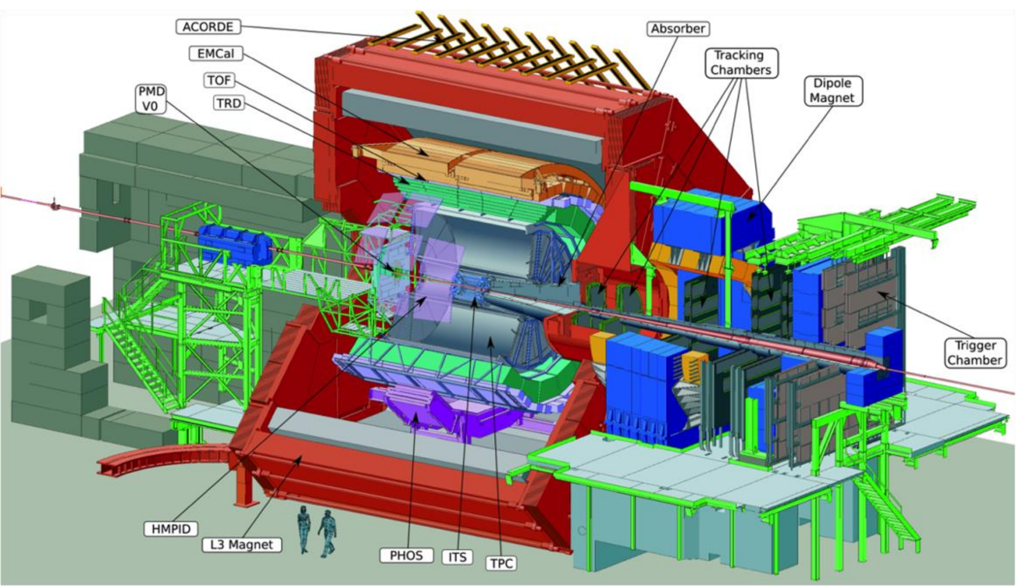
ATLAS, CMS, ALICE, LHCb

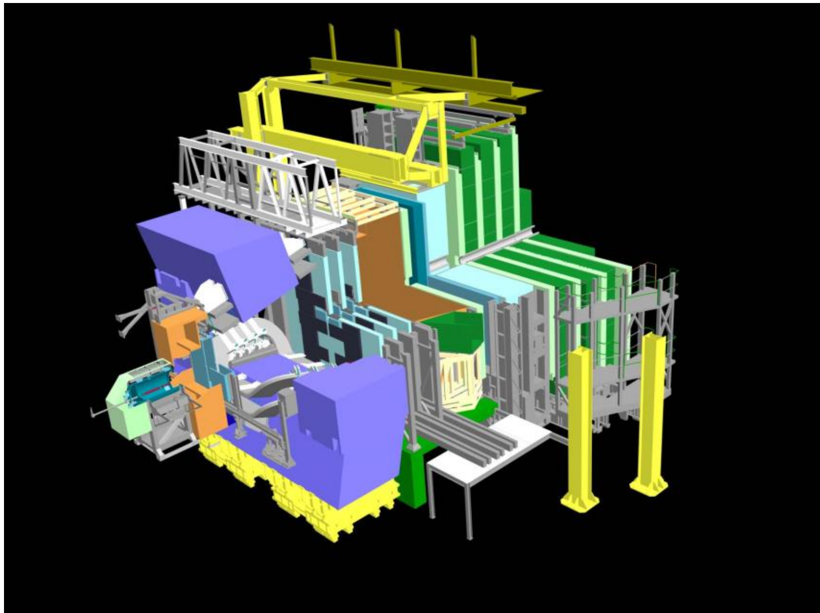


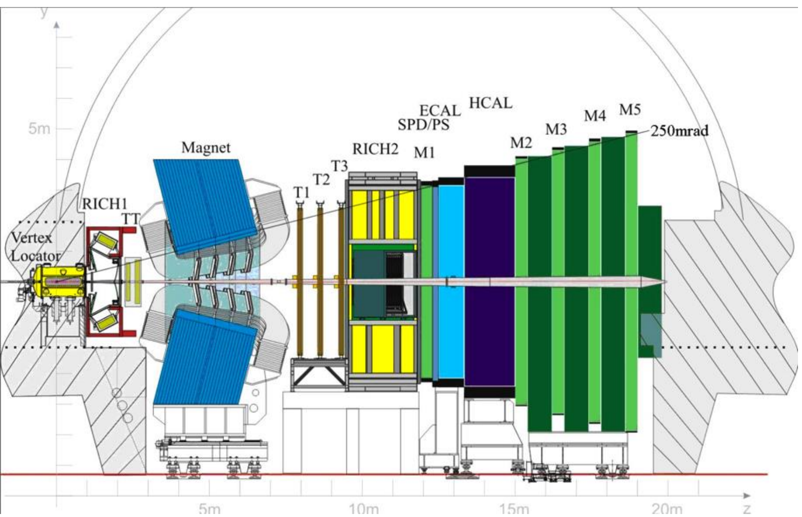


Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t



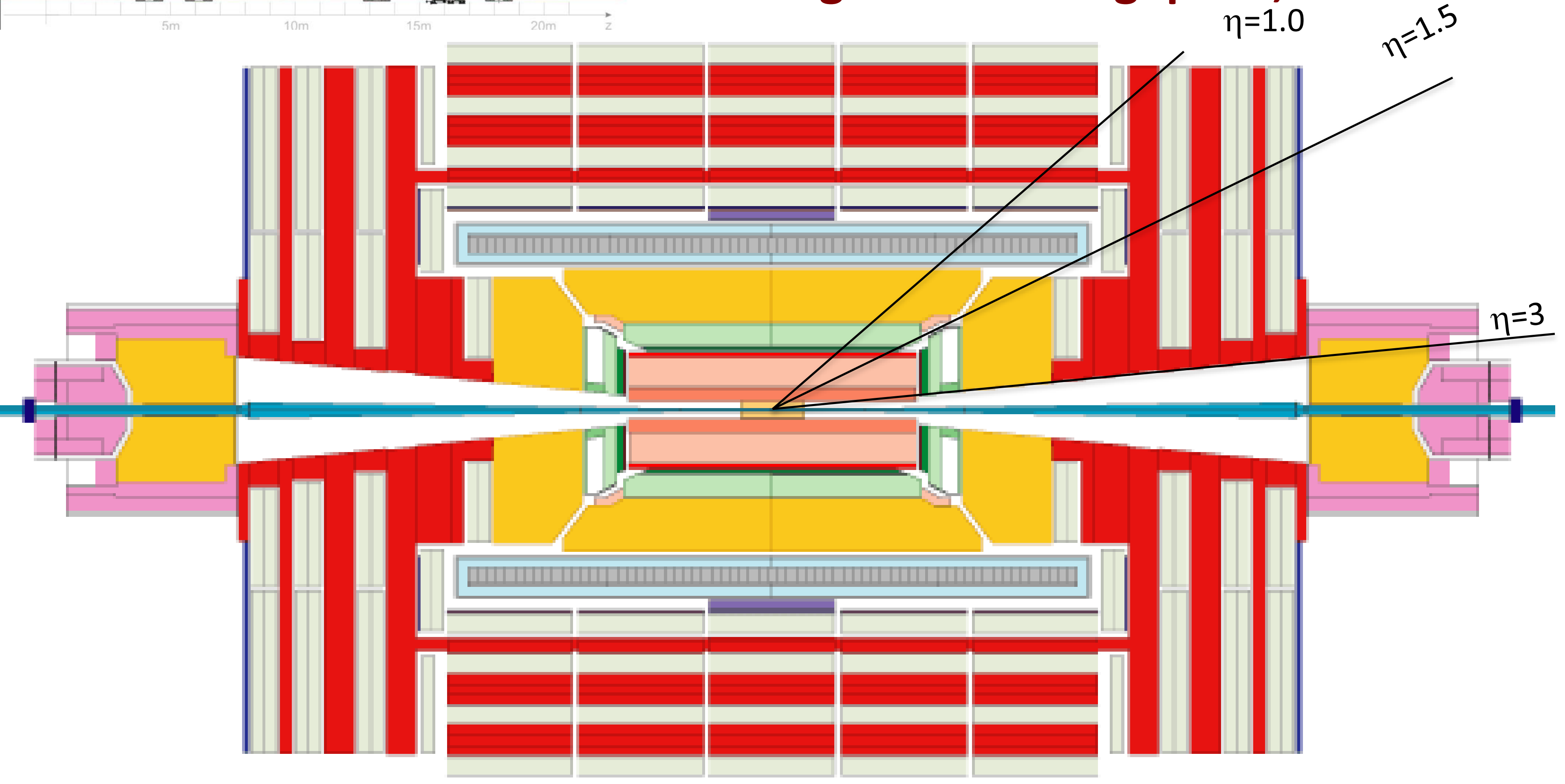




Tracking LHCb η = 2 - 5

... all with impressive performance ...

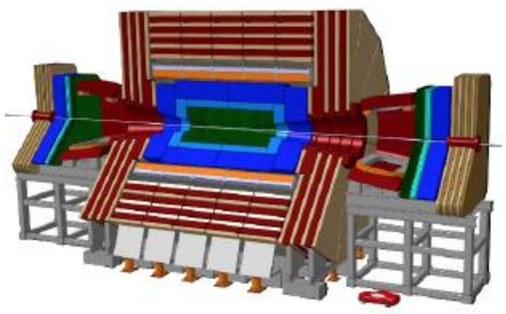
Tracking CMS tracking η -2.5,2.5



FCC Magnet System Concepts

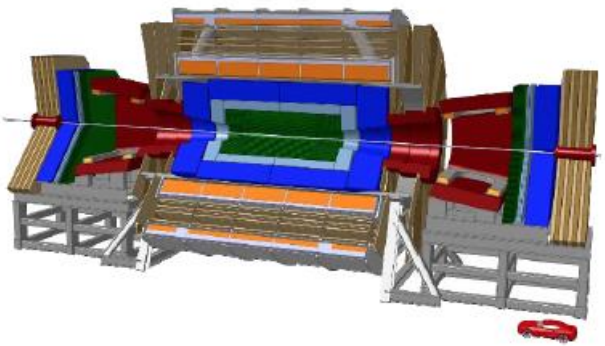
H. Ten Kate et al.

Inclusion of Dipoles in the Forward region for momentum measurement over a large eta range.



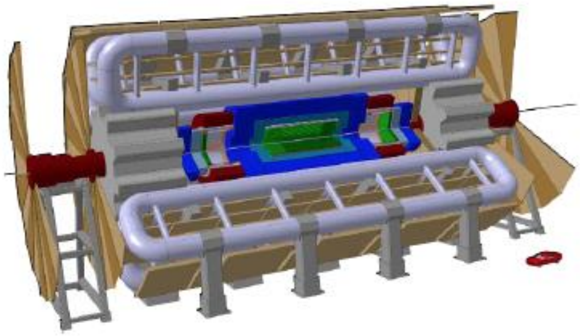
(1) Solenoid with light yoke + Forward Dipoles

Huge mass,
Iron very expensive



(2) Twin Solenoid, no yoke + Forward Dipoles

Shielding Solenoid, very large system



(3) Solenoid + three toroids + internal Forward Dipoles

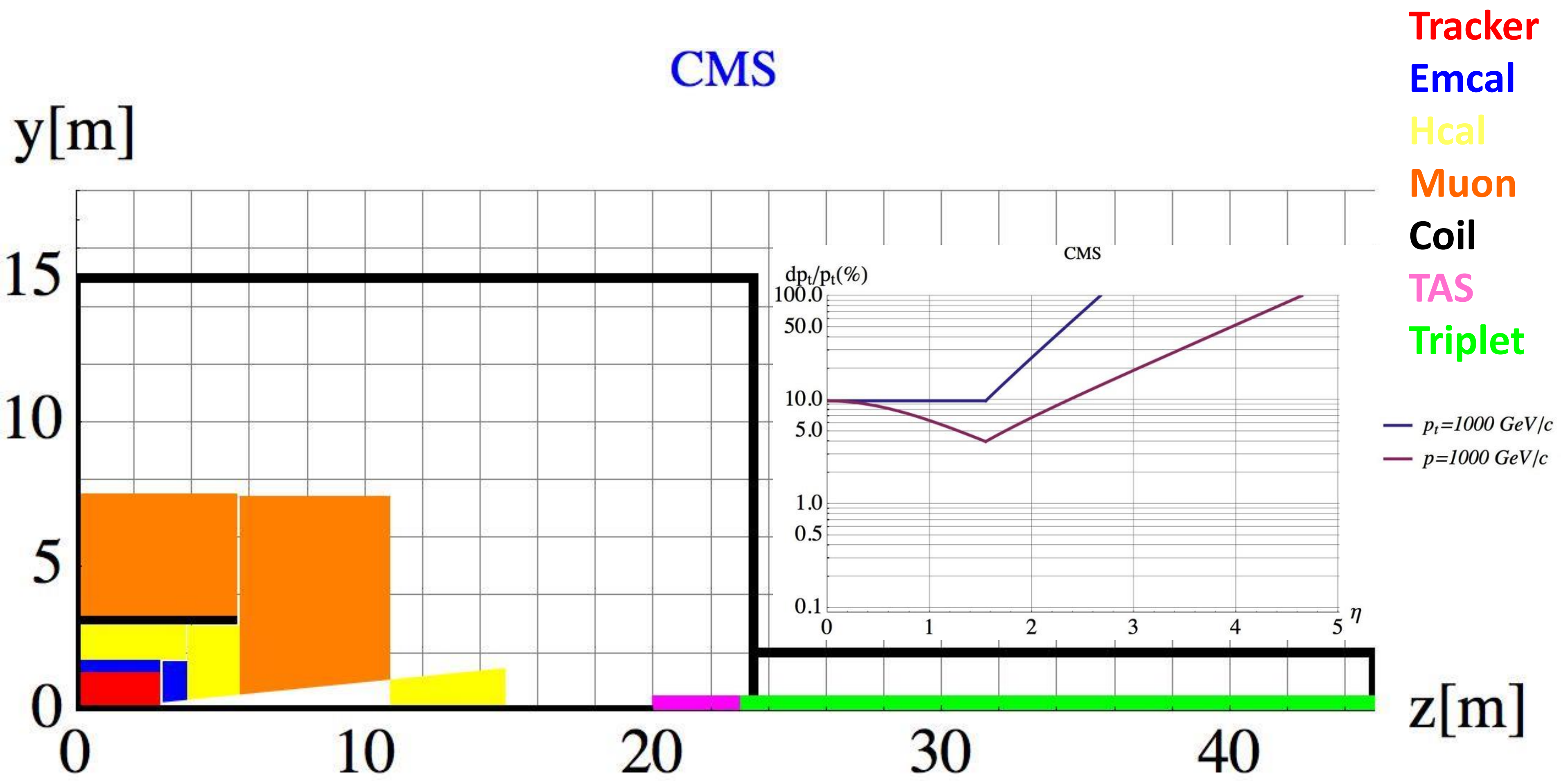
The ATLAS 'standalone' Muon Toroid was motivated by things like:

- **worries that trackers might not work at LHC rate**
- **Space for excellent HCAL, good jet calorimetry**
- **Independent magnet system**

At this moment we are using this magnet system as a baseline

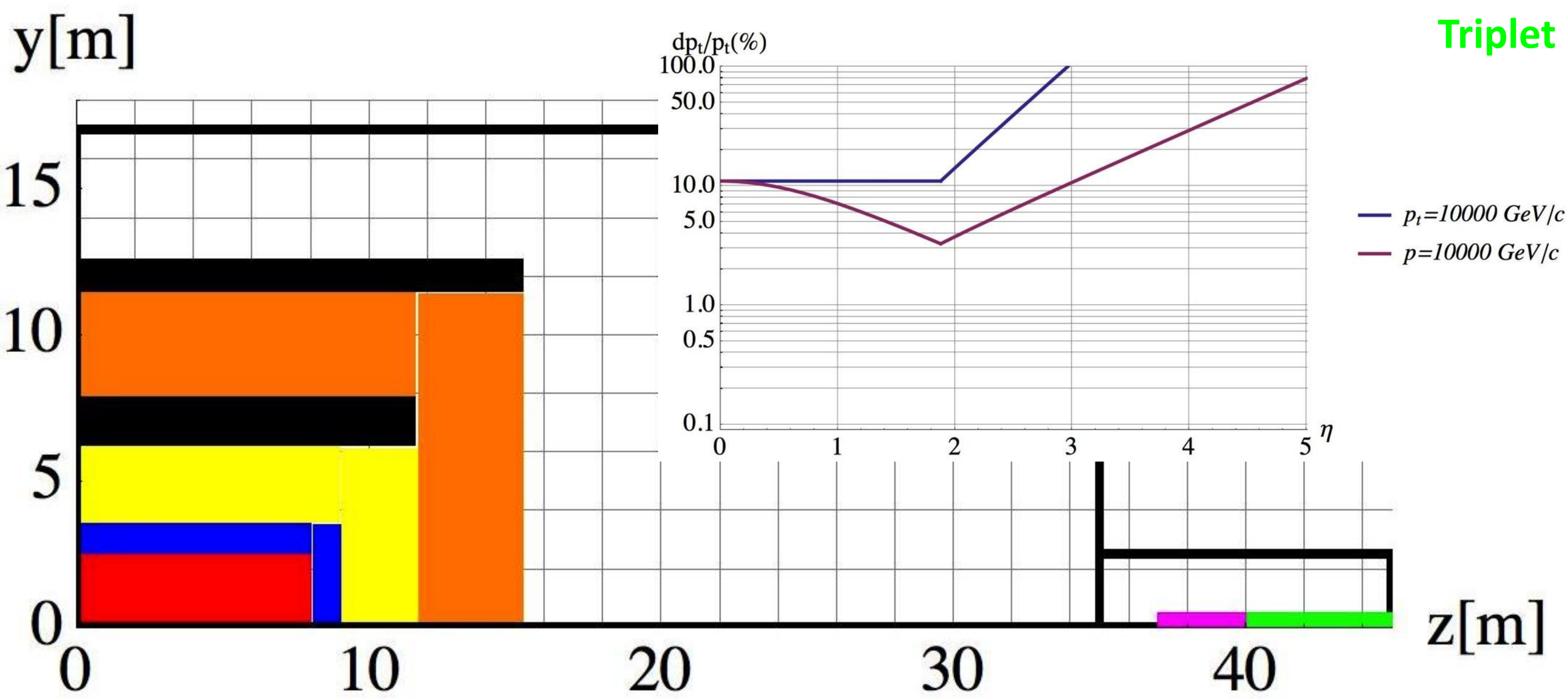
CMS

- LHC L*=23m, TAS shielding inside the cavern
- Tracker r=1.2m in B=3.8T
- Compact Crystal ECAL, 'short' HCAL of and 5.82 λ_{int}, cut at η = 3 to move FCAL away.
- Iron Yoke to return Flux, instrumented with muon chambers.
- CMS muons are relying on a properly working tracker.



Twin Solenoid 7xBL^2 scaling

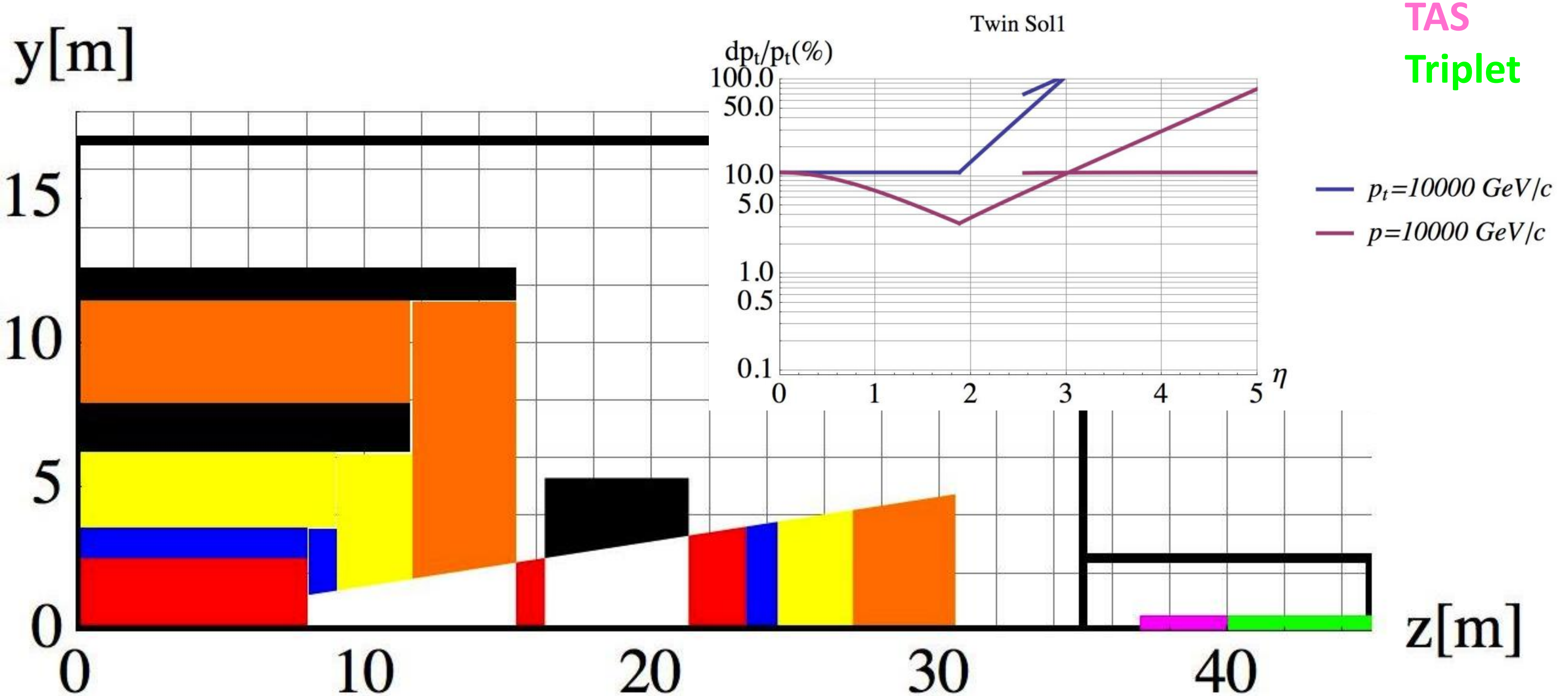
- FCC L*=40m, hide inside tunnel
- Solenoid and shielding solenoid with B=6T in Tracker and B=3T in Muon System
- Tracker r=2.5m, L=16m, tracker resolution same as CMS detector
- ECAL+HCAL = 2.4m = 12 λ_{int}
- Momentum resolution gets marginal at $\eta>3$.



Twin Solenoid 7xBL^2 scaling+Forward Dipole

- Opening at $\eta = 2.5$
- Adding a forward Dipole for momentum spectroscopy.
- Moving forward calorimeters to larger distance decreasing the particle densities and overlaps.
- Allows separate instrumentation and upgrade of forward detectors
- Integration and maintenance is a challenge

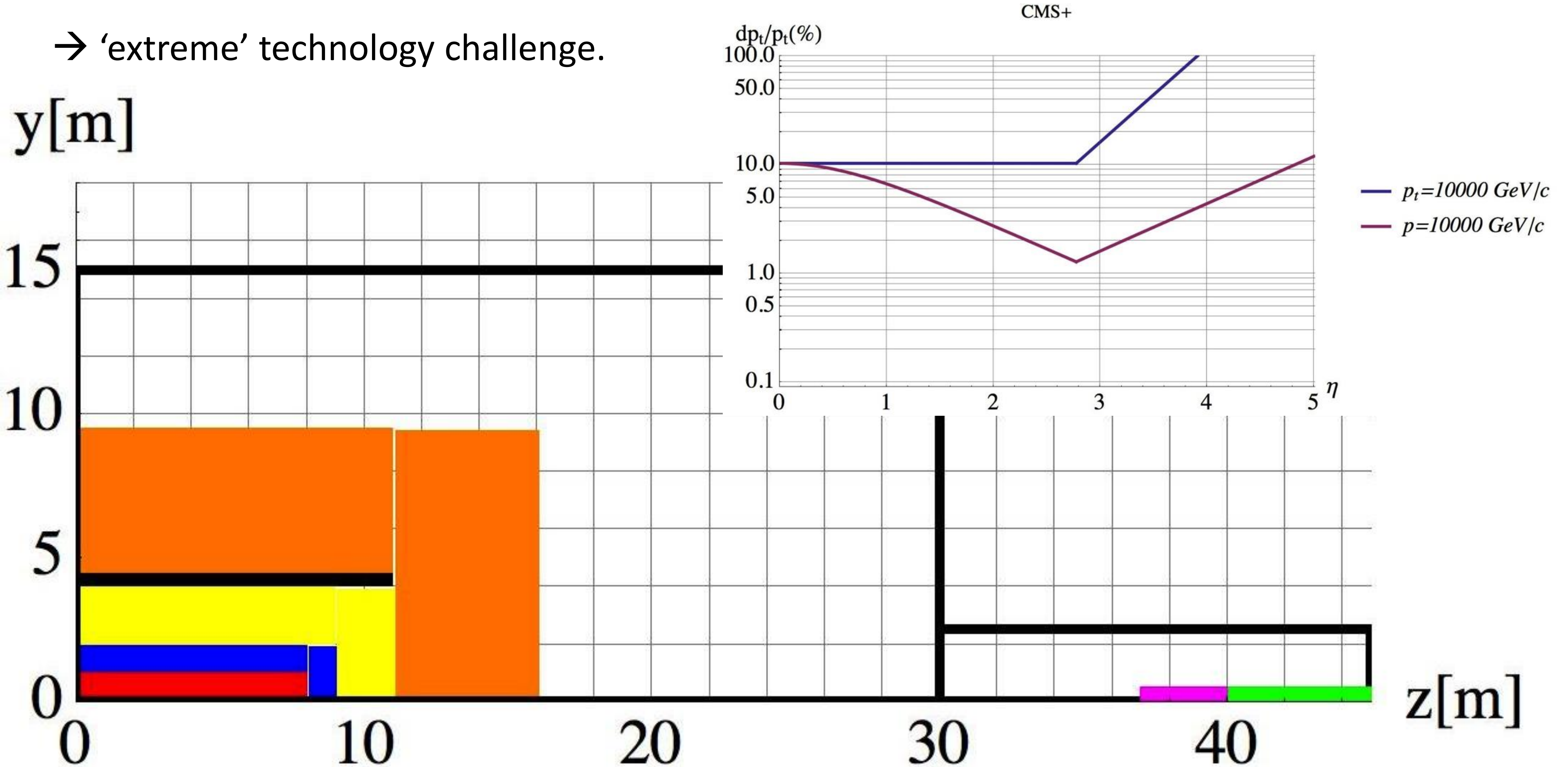
Tracker
Emcal
Hcal
Muon
Coil
TAS
Triplet



CMS scaled detector with very long extreme resolution tracker

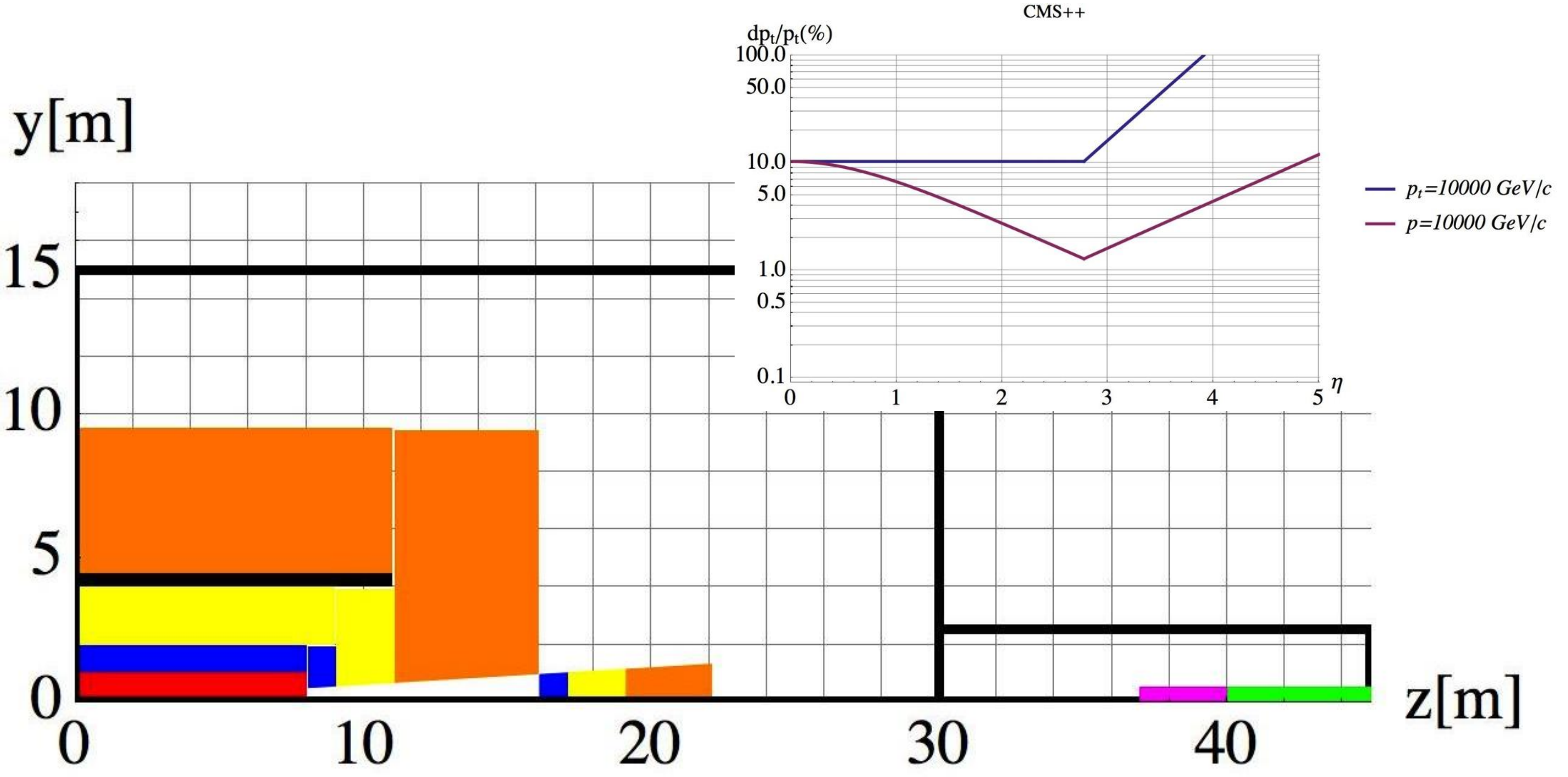
- Maximum coil producing 6T with affordable iron yoke (r=4m)
- Tracker radius 1m, resolution has to be improved factor 6 (15 layers, 3um resolution)
- 8m long tracker gives large η acceptance.
- 2.8m available for EMCAL+HCAL e.g. very compact W/Si particle flow calorimeters
- Very high granularity forward calorimeters needed
- Muon system a’la CMS

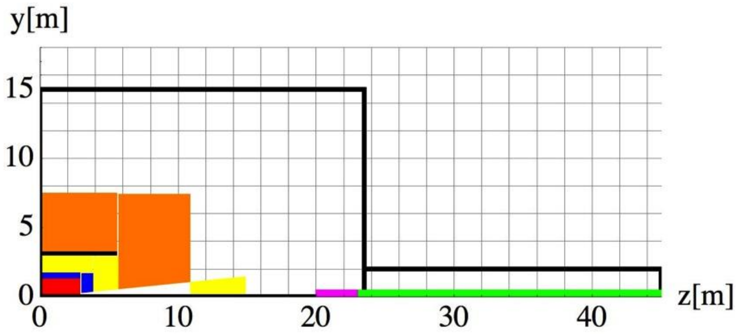
→ ‘extreme’ technology challenge.



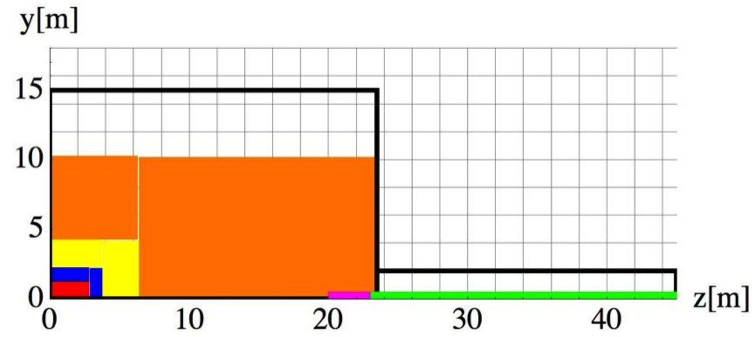
CMS scaled detector, very forward calorimetry move out

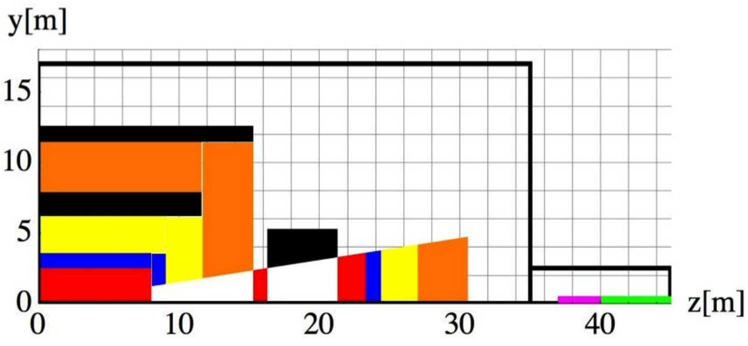
- Forward calorimetry moved to large distance from η = 3.5 for reduced occupancy and radiation load





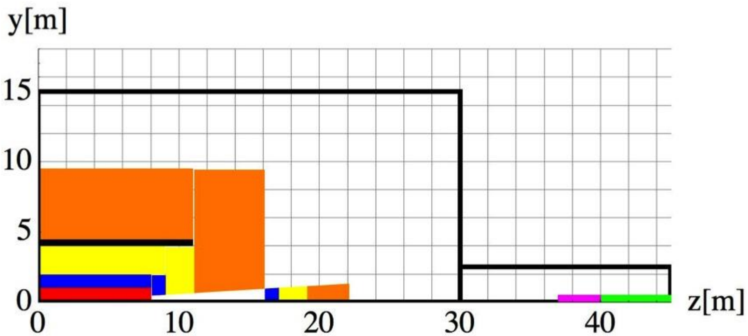
CMS & ATLAS





Twin Solenoid
+ Dipole

Popular at Present



CMS+

Key Point and Strategy

If the FCC hadron machine with 16T magnets, 5MW synchrotron radiation and a 100km tunnel can be realized, there is no doubt that a detector, that makes full use of the physics potential, can be built.

Much of detector technology is driven by silicon technology and computing power i.e. we can count on significant improvements.

Since the maximum energy and delivered luminosity are the key goals for the FCC-hh machine, the detector efforts should put minimal constraints at the machine efforts.

What do MB events at 100TeV look like

14TeV → 100TeV:

Inelastic crossection 14 →100TeV changes from 80 → 108mb.

Multiplicity 14 →100TeV changes from 5.4 → 8 charged particles per rapidity unit.

Average p_T of charged particles 14 → 100 TeV 0.6 →0.8 GeV/c, i.e. bending radius in 4T magnetic field is 50 → 67cm.

Transverse energy increase by about a factor of 2.

→ The Min. Bias events at FCC are quite similar to the Min. Bias events at LHC.

Very Rough Estimate for Silicon Detectors

Estimate for radiation load of first Pixel Layer at r=3.7cm:

HL-LHC 3ab^{-1}
1MeVneq Fluence = 1.5×10^{16} cm^{-2}
Dose = 5MGy

FCC 3ab^{-1}
1MeVneq Fluence = 3×10^{16} cm^{-2}
Dose = 10MGy

FCC 30ab^{-1}
1MeVneq Fluence = 3×10^{17} cm^{-2}
Dose = 100MGy

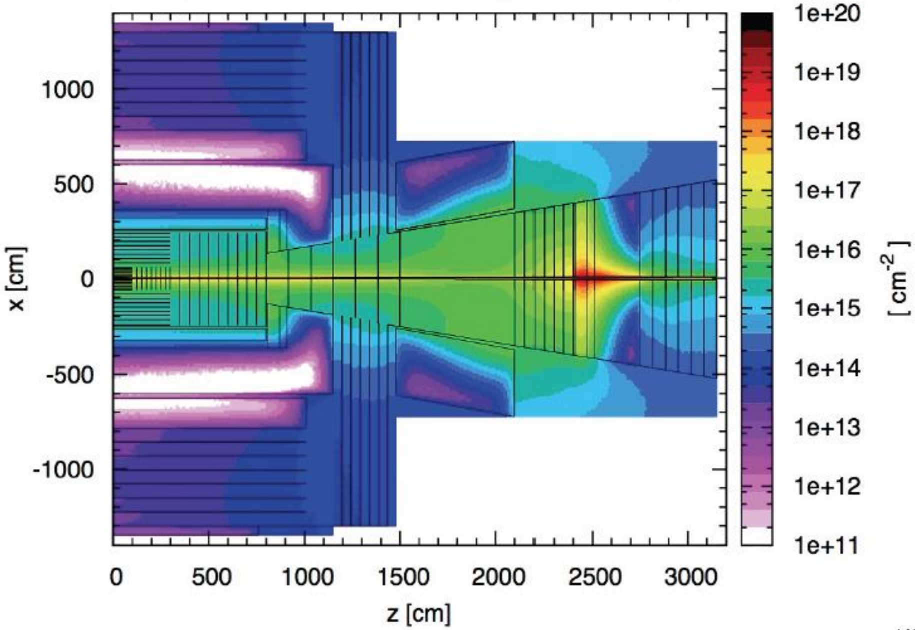
Estimate for radiation load of first Pixel Layer at r=2.5cm:

FCC 30ab^{-1}
1MeVneq Fluence = 7×10^{17} cm^{-2}
Dose = 220MGy

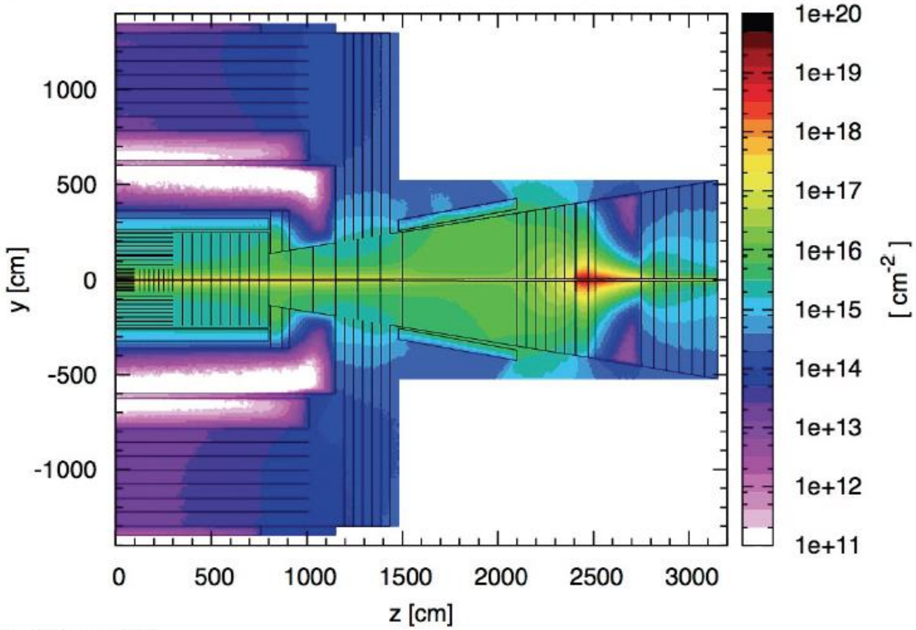
→ With safety factors we go into the 10^{18}/cm^2 and GGy range !

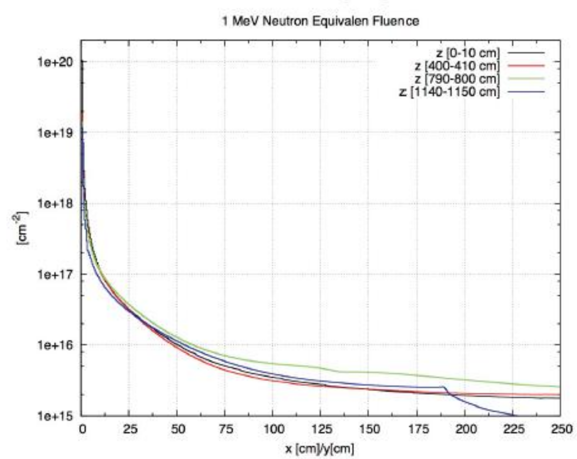
1 MeV Neutron Equivalent Fluence

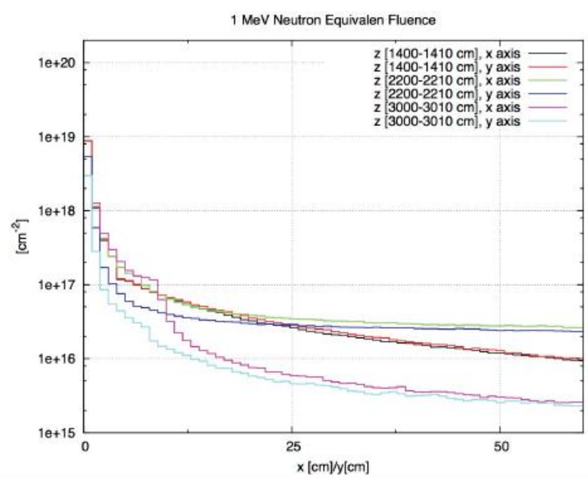
1 MeV Neutron Equivalent Fluence after an integrated luminosity of 30 ab^{-1}, y=0



1 MeV Neutron Equivalent Fluence after an integrated luminosity of 30 ab^{-1}, x=0

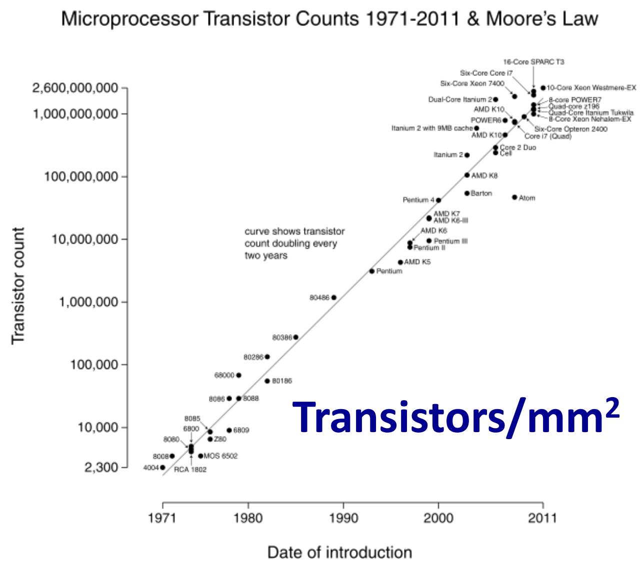


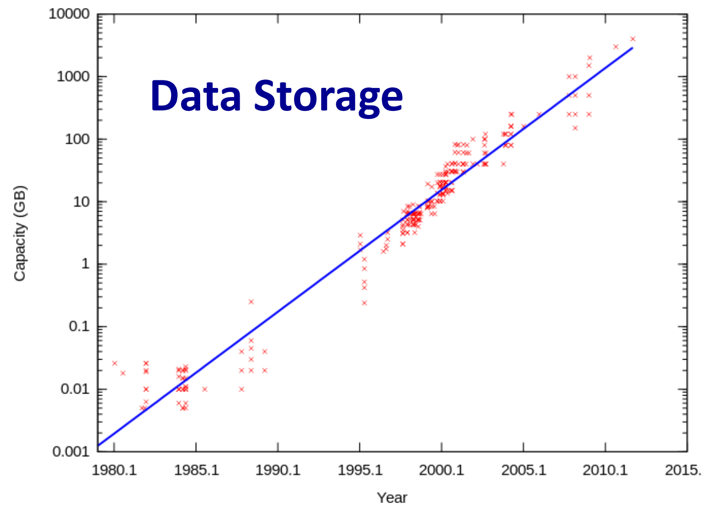


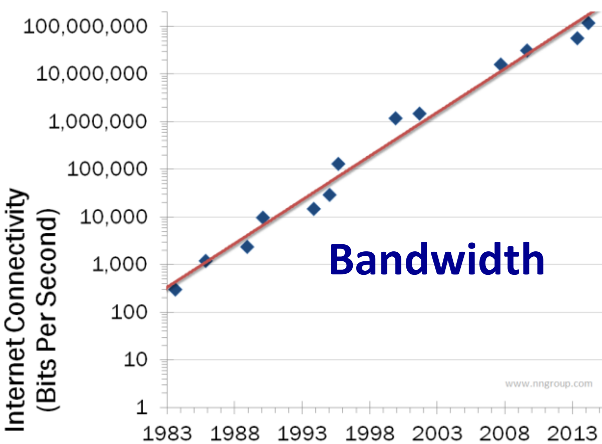


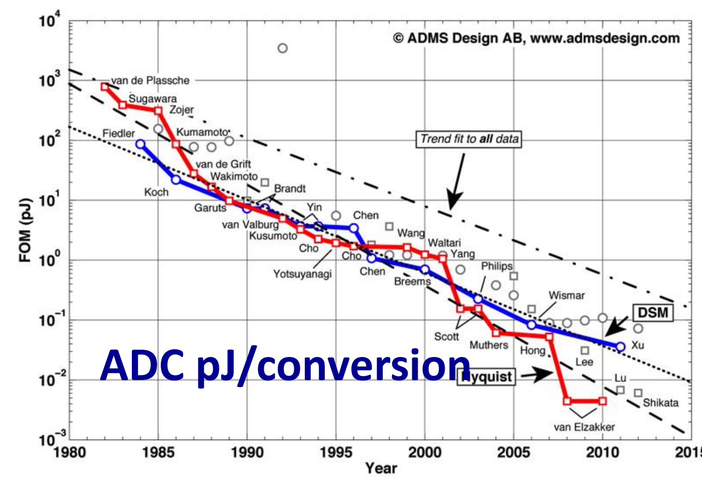
Different radial binning!

Prospects for ‚Microelectronics‘







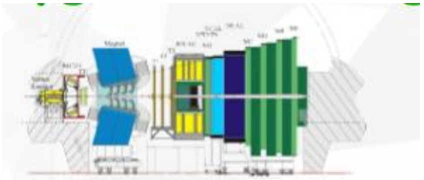


All these figures showed doubling times of < 2 years up to now ! Some scalings will stop, but different tricks might come in.

May dream about a factor 2^{10} = 1024 from 2014 – 2034 (of course extremely optimistic)

This would allow major detector improvements !

LHCb & ALICE in 2018



40 MHz

DAQ

40 MHz

LLT: μ,e/γ, hadrons

5-40 MHz

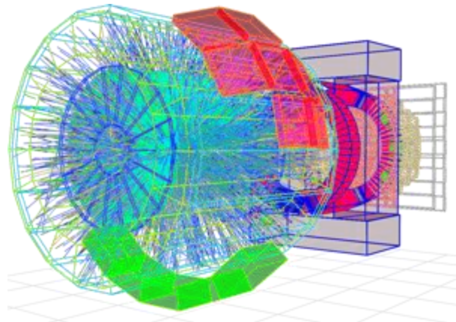
HLT: event recon.

20 kHz (0.1 MB/event)

Storage

2 GB/s

4 TByte/s into PC farm for HLT selection.



1 TByte/s into PC farm for data compression. All events to disc.

50 kHz

Reconstruction + Compression

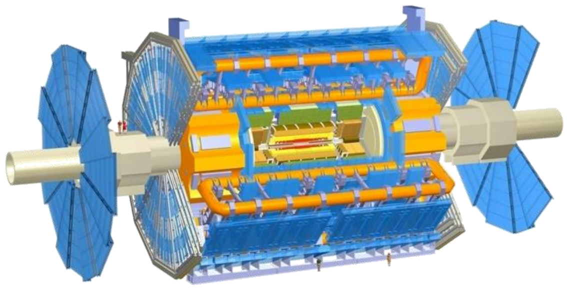
50 kHz (1.5 MB/event)

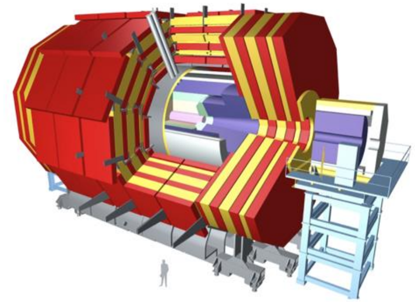
Storage

75 GB/s

← PEAK OUTPUT →

ATLAS & CMS in 2018





40 MHz

Level 1 | Level 1

0.5-1 MHz

HLT | HLT

5 TByte/s into PC farm for HLT selection.

Would be 200TByte/s without Level1

5-10 kHz (2MB/event) | 10 kHz (4MB/event)

Storage | Storage

10-20 GB/s ← PEAK OUTPUT → 40 GB/s

Hardware Trigger ?

CMS HL-LHC results in 200TByte/s into the online system for a triggerless readout.

For 2022 this is considered too difficult.

Assuming that the total track rate for 100TeV pp collisions (Phase I) is only a factor 2 larger, there is very little doubt that by 2035 and FCC-hh detector can be read out in a triggerless fashion.

In 2035 maybe no hardware trigger necessary ! All data to the online system, synchronous or asynchronous, where a sophisticated selection and compression can be done.

!! N.b. the techniques to get the data out of the detector with a small amount of material is a key question to be solved !!

Even if one would afford to read all data to HLT for PhaseII, the amount of copper lines to get all the signals out of the silicon detector would destroy the tracker performance.

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.

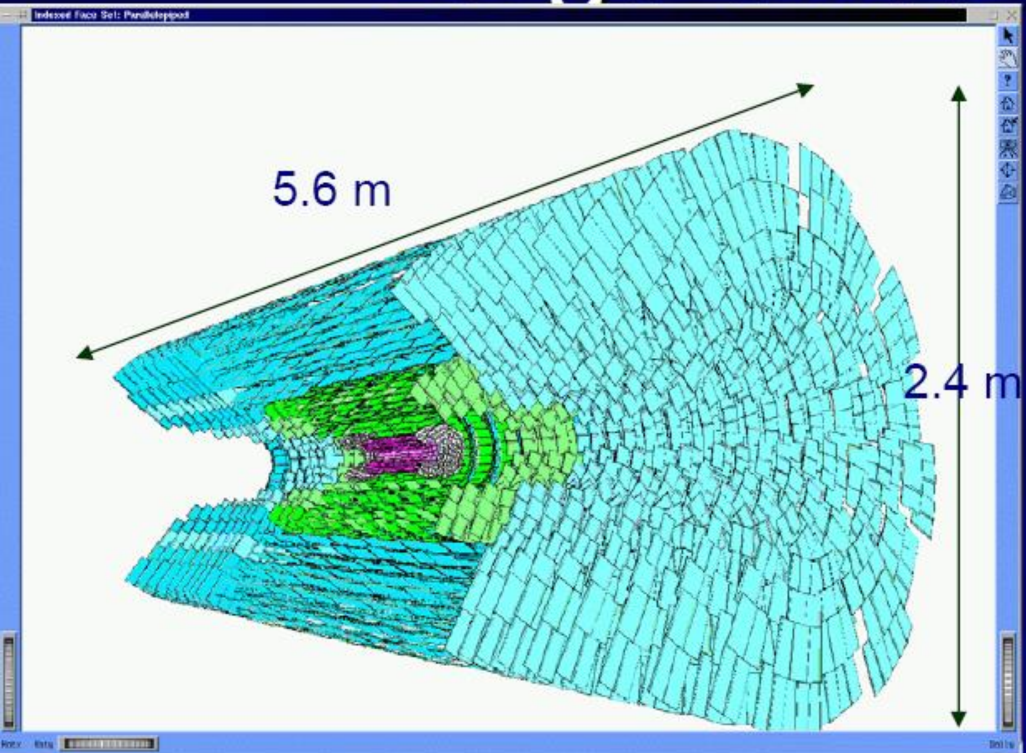
"Futurists believe that's what you need for artificial intelligence. At that point, the computer starts thinking for itself."

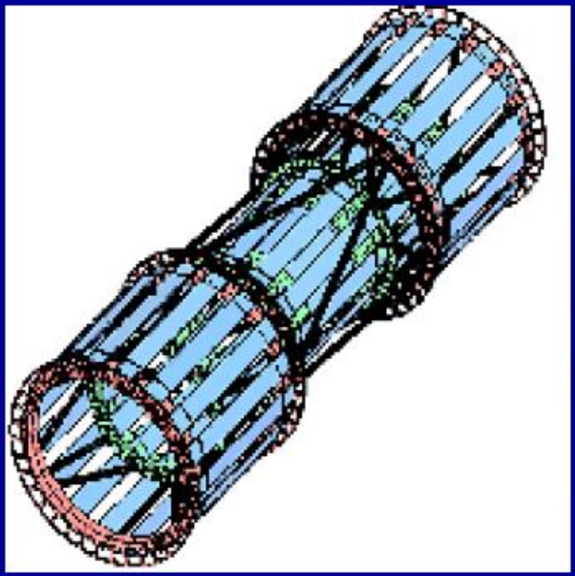
→ **Computers will anyway by themselves figure out what to do with the data by 2035.**

Magnet systems and shielding will be rather conventional and can be worked out to some detail now.

For detector technology and computing power we are allowed to dream a bit.

Large Silicon Systems





CMS tracker (~2007)

12000 modules

~ 445 m^2 silicon area

~ 24,328 silicon wafers

~ 60 M readout channels

CDF SVX IIa (2001-)

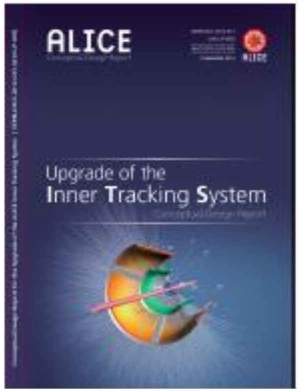
~ $11 m^2$ silicon area

~ 750 000 readout channels

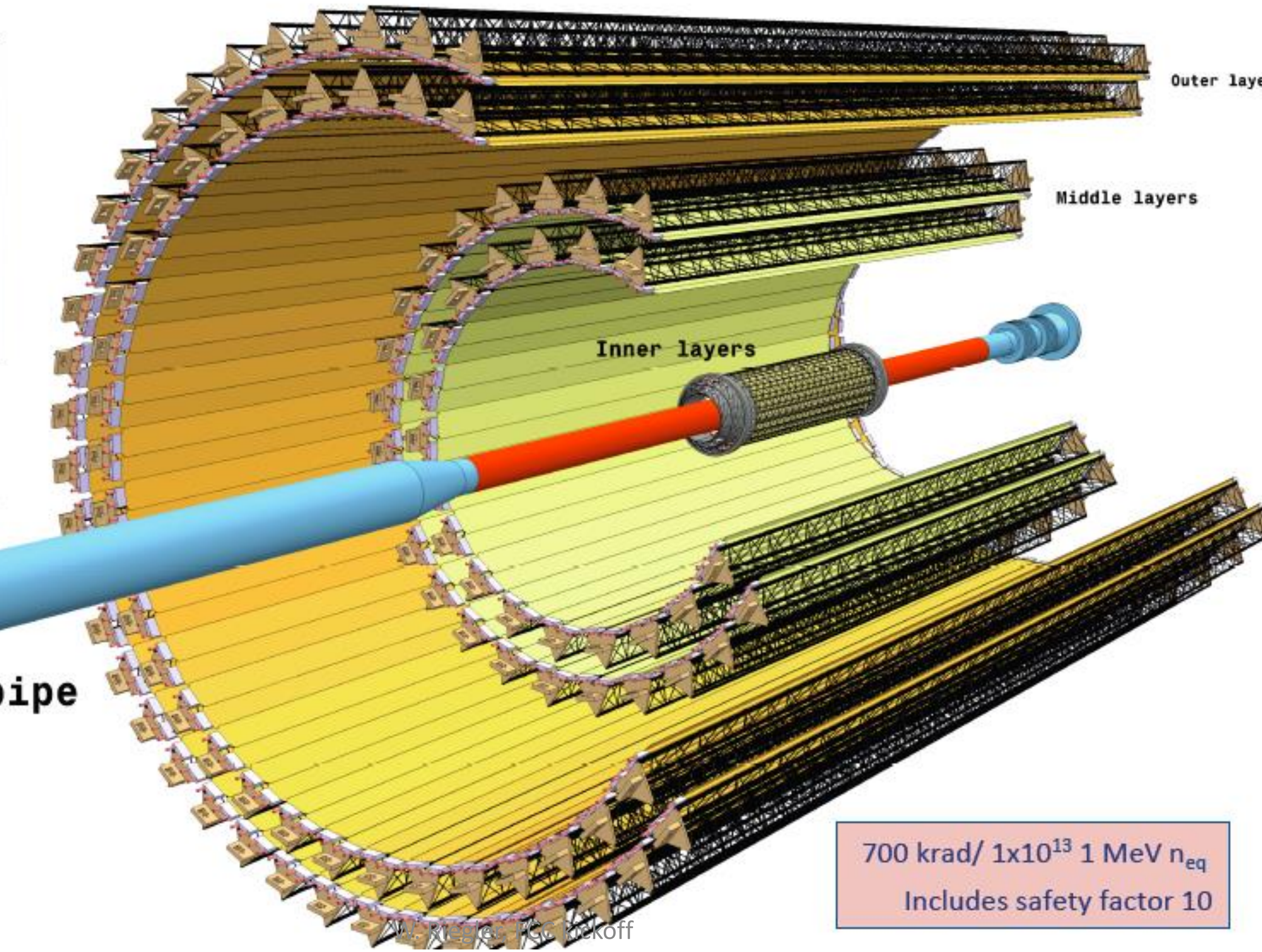
ALICE 2018 upgrade, 20x20um monolithic pixels

New ITS Layout

25 G-pixel camera
($10.3\ m^2$)



CERN-LHCC-2013-024



7 layers of MAPS

Radial coverage
22 – 406 mm

700 krad/ $1x10^{13}$ 1 MeV n_{eq}
Includes safety factor 10

PIXEL Chip - technology

→ **Technical design report for the upgrade of the ALICE inner tracking system** CERN-LHCC-2013-024

Monolithic PIXEL chip using
Tower/Jazz 0.18 µm technology

- feature size 180 nm
- gate oxide < 4nm
- metal layers 6

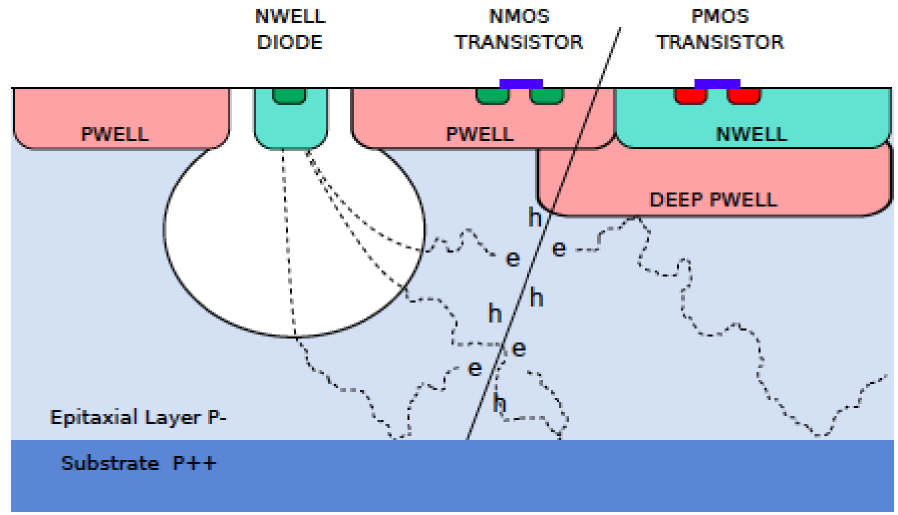
- high resistivity epi-layer
  - thickness 18-40 µm
  - resistivity 1-6 k Ω×cm

- "special" deep p-well layer to shield PMOS transistors (allows in-pixel truly CMOS circuitry)

- Possibility to build single-die circuit larger than reticle size

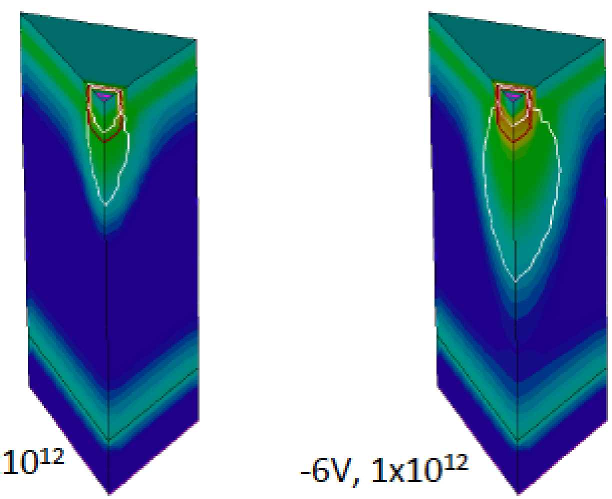
Standard processing, no bump bonding (>>50% of Pixel detector cost). Allows implementation of complex processing electronics inside the entire pixel area.

→ Revolution !



Schematic cross-section of CMOS pixel sensor
(*ALICE ITS Upgrade TDR*)

TCAD simulation of total diode reverse bias
(*ALICE ITS Upgrade TDR*)



$-1V, 1x10^{12}$ $-6V, 1x10^{12}$

diode 3µm x 3µm square n-well with 0.5µm spacing
to p-well white line: boundaries of depletion region

Pixel Revolution Hybrid → Monolythic

Table 2.2: Chip design options.

Architecture (discriminator, read-out)	Pitch ($r\phi \times z$) (µm^2)	Integration time (µs)	Power consumption (mW cm^{-2})
MISTRAL (end-of-column, rolling-shutter)	22 × 33.3	30	200
ASTRAL (in-pixel, rolling-shutter)	24 × 31 36 × 31	20	85 60
CHERWELL (in-strixel[a], rolling-shutter)	20 × 20	30	90
ALPIDE (in-pixel, in-matrix sparsification)	28 × 28	4	< 50

[a] A strixel is a 128-pixel column over which the electronics are distributed.

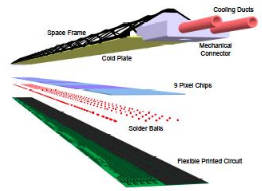
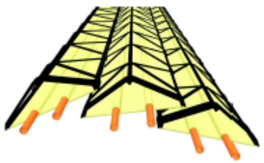
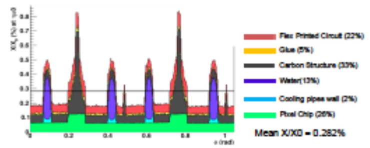
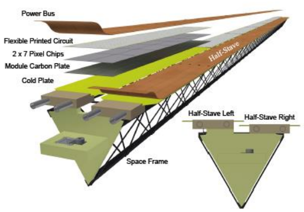
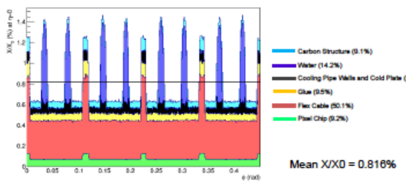


Figure 4.1: Schematic view of the Inner Barrel Stave.









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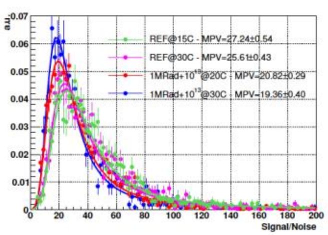

Figure 2.22: SNR of seed pixel measured with MIMOSA-32ter at the CERN-SPS, at two operating temperatures, before and after irradiation with the combined load of 1 Mrad and 10^{13} 1 MeV n_{eq}/cm^2.

Dramatic decrease in cost.

Very low power consumption, possibly <100mW/cm^2 i.e. simple water cooling

Ultra low material budget <0.5% for inner layers, <1% for outer layers.

Question of speed and radiation hardness:

At present,
integration time of 4µs (noise, electron diffusion)
radiation resistance up to few 10^{13} neq.

Development (next 20 years) towards larger (full) depletion will improve speed and radiation hardness significantly.

Also – in case one has a full pixel tracker one can use 1 or 2 layers with ‚fast' pixels to do the BCID (25ns or even 5ns) and then match the other hits.

With a full pixel tracker of 20x20um pixels one can pile up a fair amount of events before occupancy gets to large !!!

Conclusions

Studies of accelerators and detectors for the post-LHC energy frontier are ongoing.

A conceptual design report is planned for 2018.

Basic concepts for detectors at these future colliders are being worked on.

Silicon sensors will play a key role in these future detectors, for tracking and probably also for High Granularity Calorimetry.

Radiation hard MAPS will be a key technology.

How about some brand new tracker concepts ?!

Join in !