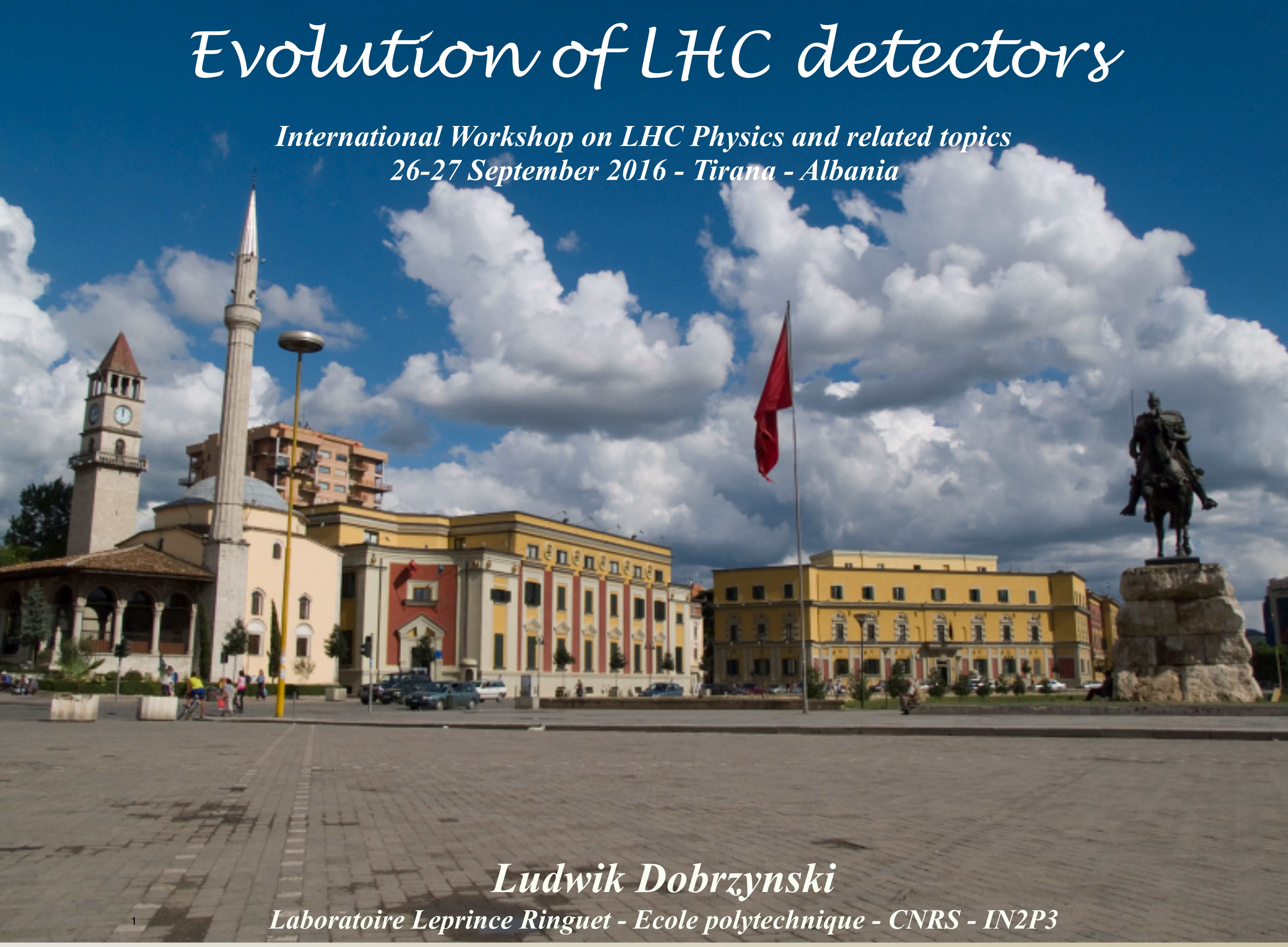

Evolution of LHC detectors

International Workshop on LHC Physics and related topics
26-27 September 2016 - Tirana - Albania

Ludwik Dobrzynski
Laboratoire Leprince Ringuet - Ecole polytechnique - CNRS - IN2P3

Evolution of LHC detectors

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- Introduction
- Physics objectives
- Hadron collider detectors
- Detector upgrades for future searches
- Conclusion

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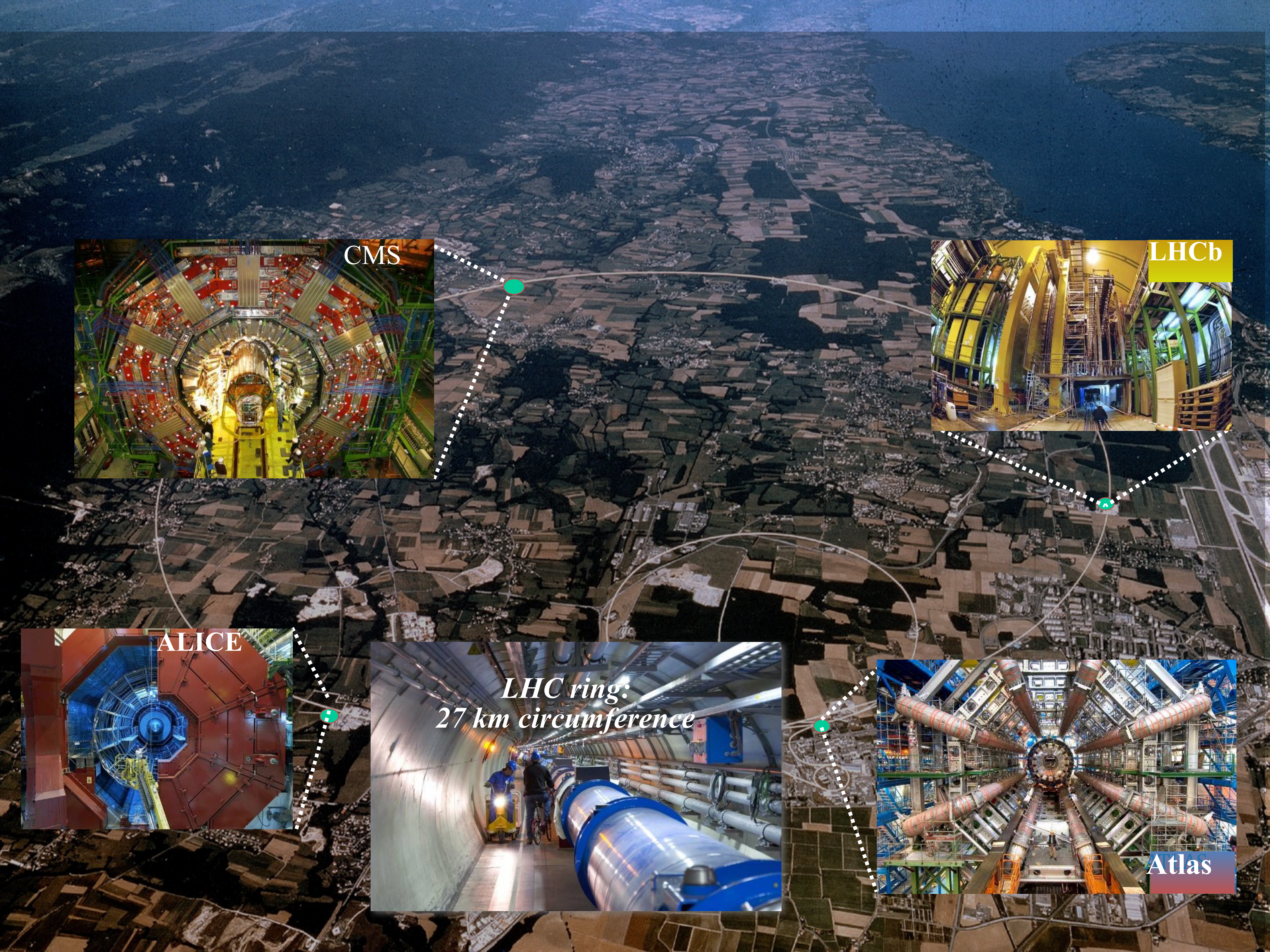
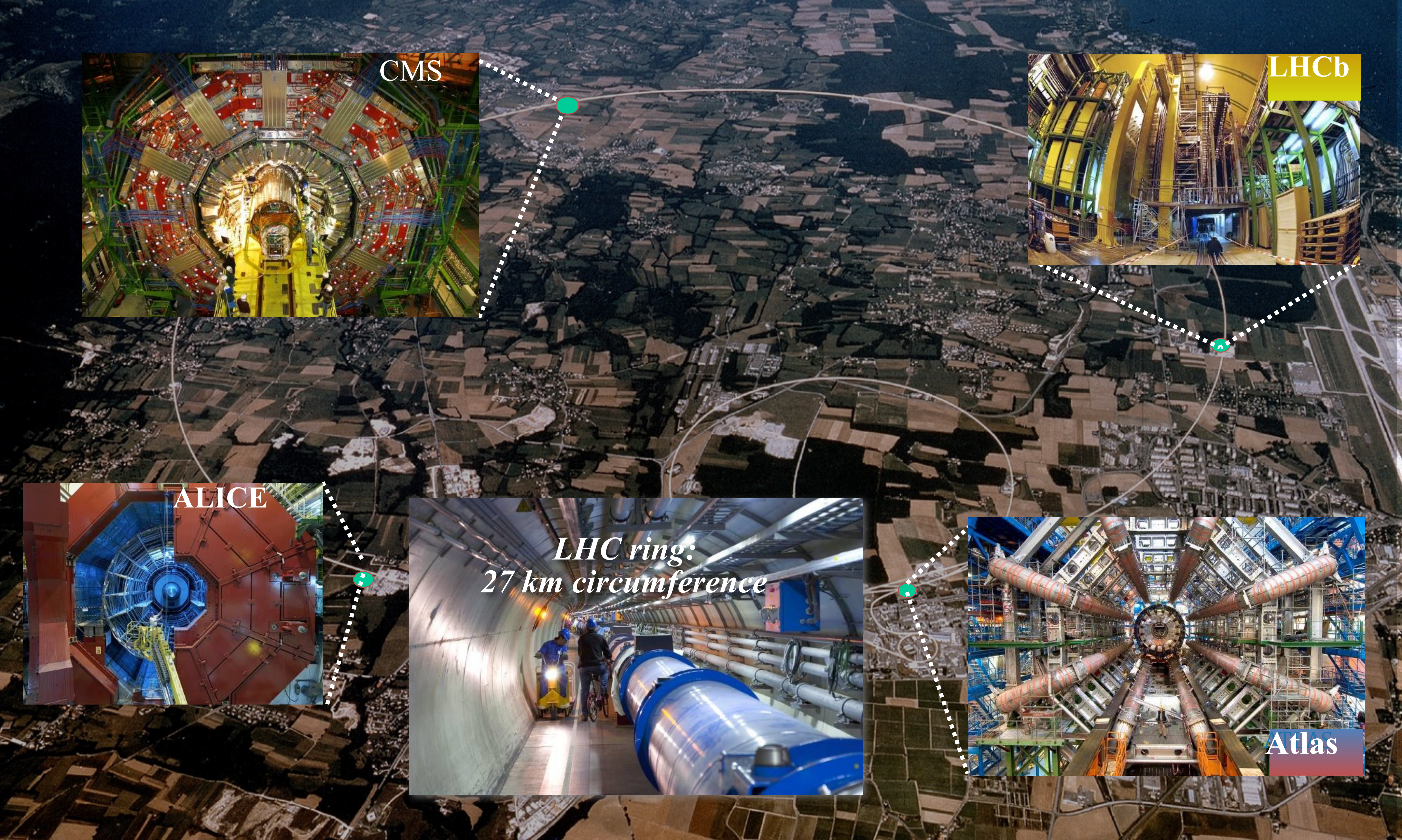
LHC ring:
27 km circumference


CMS
LHCb
ALICE
LHC ring:
27 km circumference
Atlas

LHC

Explore of a new energy frontier in Proton-proton collisions at E_{CM} = 13 TeV and Pb-Pb collision at 5 TeV



LHC

Explore of a new energy frontier in Proton-proton collisions at E_{CM} = 13 TeV and Pb-Pb collision at 5 TeV

Physics Objectives of the Experiments

Physics Objectives of the Experiments

- ***The four major LHC experiments together cover very different areas of physics.***
  - ALICE is designed for Pb-Pb collisions having very high multiplicities. This necessitates the use of slower detectors, putting an upper limit on usable luminosities. In Pb-Pb mode the LHC can deliver 8kHz of interactions, while in pp the maximum interaction rate the experiment can handle is about 100 kHz.
  - ***ATLAS and CMS*** are looking for rare processes in pp interactions, for which they need the highest possible luminosity.
  - ***LHCb has been optimized for beauty decays*** requiring a very high ***"level 1"*** trigger rate (around 1 MHz). By using the trigger to select interesting decay modes, this rate is reduced to a final level trigger rate of around 200 Hz
- ***In pp mode, the physics potential comes both from the greatly increased energy and the greatly increased luminosity, offering the possibility to access processes that up till now have been too rare to be studied.***
- ***In PbPb mode, annual data collection rates are comparable to RHIC but there is a 25-fold increase in centre-of-mass energy. A challenge is that PbPb running time is only ~1 month, so data acquisition rates need to be an order of magnitude higher than at RHIC.***

Physics @ LHC goals

Find new particles/new symmetries/new forces?

⇨ **Origin of Mass -** Higgs boson(s)

⇨ **Supersymmetric particles -** a new zoology of particles, dark matter particle? …

⇨ **Extra space-time dimensions:** gravitons, Z' etc. ?

⇨ **The Unexpected !!**

Studies of CP Violation and Quark Gluon Plasma

Detector Requirements

- For collider experiments the detectors should be :
  - Radiation hard
  - Provide Excellent particle measurements / resolutions (e/photons/μ/tau/ME_T,b/tau-tagging etc.)

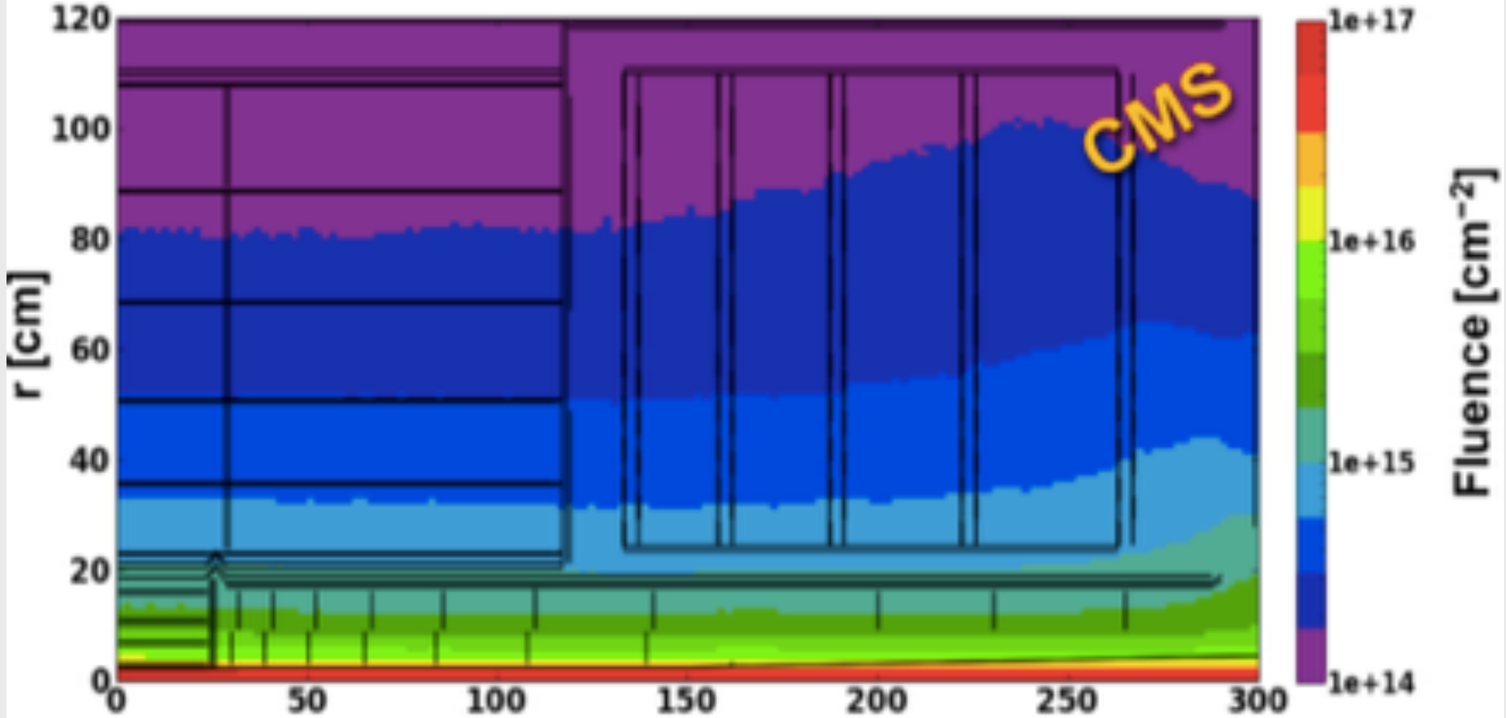
- Even in the presence of up to 200 pileup
  - Detectors need good resolution especially at high energy (i.e. small constant terms, minimize contributions from multiple scattering)
  - High rate radiation hard readout with deep buffering to support large dynamic range/occupancy and complex triggers

- Excellent timing resolution
  - Needs and requirements slightly different across experiments, but roughly in the O(10-100ps) range
  - Important at LHC for mitigating pileup, Heavy Flavor / neutrino experiments for particle id, rejecting cosmics
  - Trigger/Data Acquisition systems also have challenging demands
    - Excellent timing synchronization over long baselines
    - Fast hardware trigger / fast trigger event reconstruction in events with large occupancy for the collider program

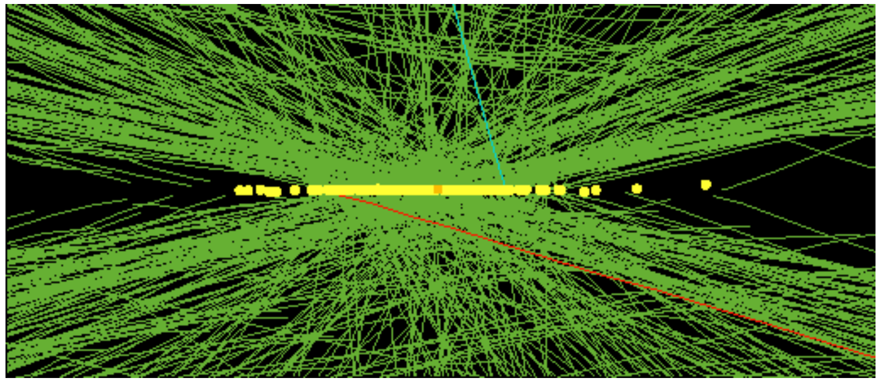
- Detectors and their electronics must be constructible, affordable, and maintainable!

Collider Detectors : The challenges

- ***Requirements:***
  - *Tracker sensors that can withstand an extremely high radiation environment*
  - *Good track resolution in a busy environment: up to150- 200 events per 25 nsec crossing*
  - *Innovative triggering at level 1 to keep up with the flood of data*
  - *New calorimeter designs with high degree of pixelation and potentially fast timing.*
  - *Challenge in photo-detection*
  - *Challenge in silicon*
  - *Challenge in data collection / trigger*

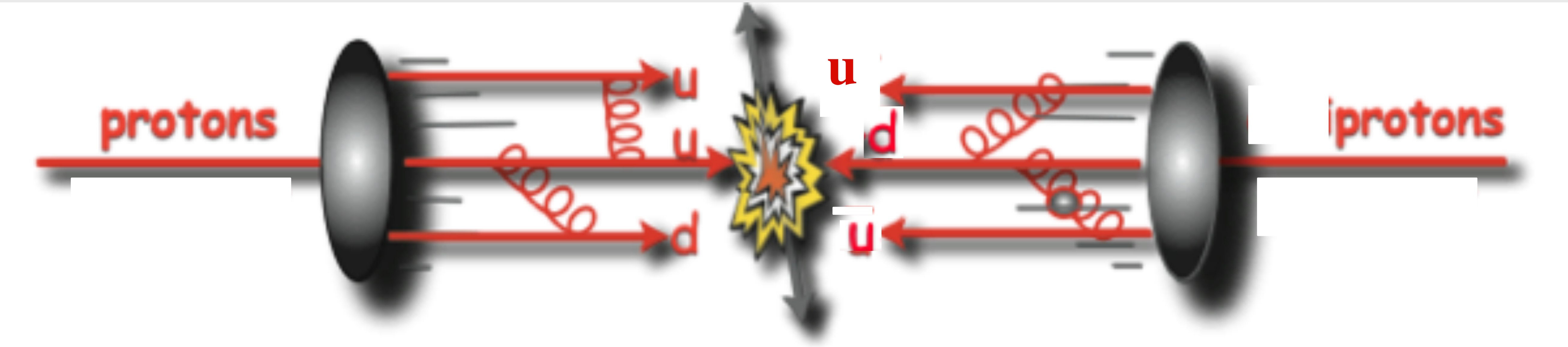


Expected Fluences in CMS at 3 ab^{-1} z[cm]



What an event with 140 vertices looks like in the CMS tracker

Hadron Colliders



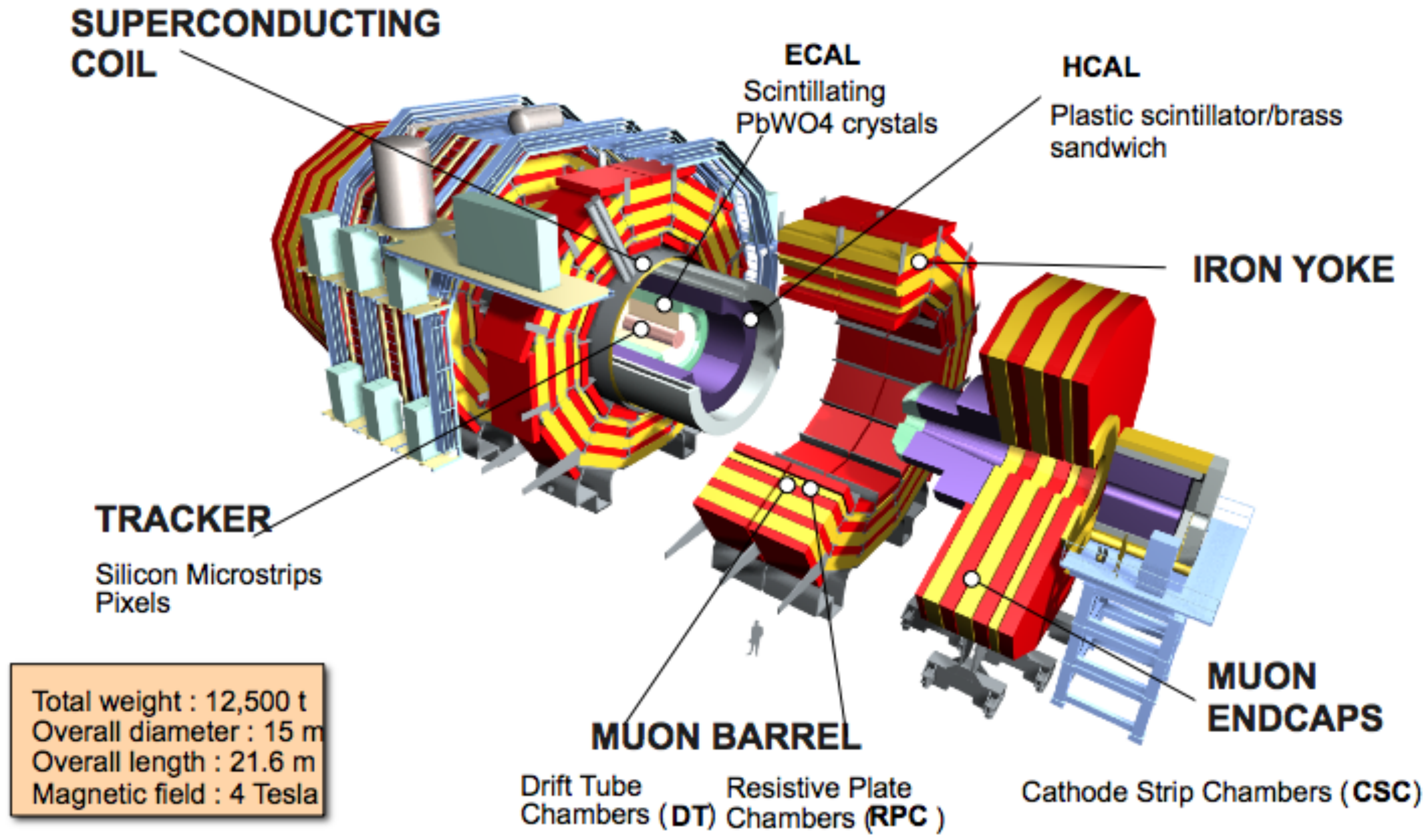
- ***Protons are composite*** Partons (valence+sea quarks, gluons) carry longitudinal momentum fraction of the proton (x)
- ***Longitudinal parton momenta are unknown***
- Parton distribution functions (PDFs): estimate the momentum fraction carried by a parton inside the proton

What do we want to measure

- ***Number of particles***
- ***Event topologie***
- ***momentum / Energie***
- ***Particle identity***
- ***Transverse Missing energy/momentun***

↔ Can't be achieved with a single detector ↔ Integrate detectors to a detector system

The CMS detector : a modular concept

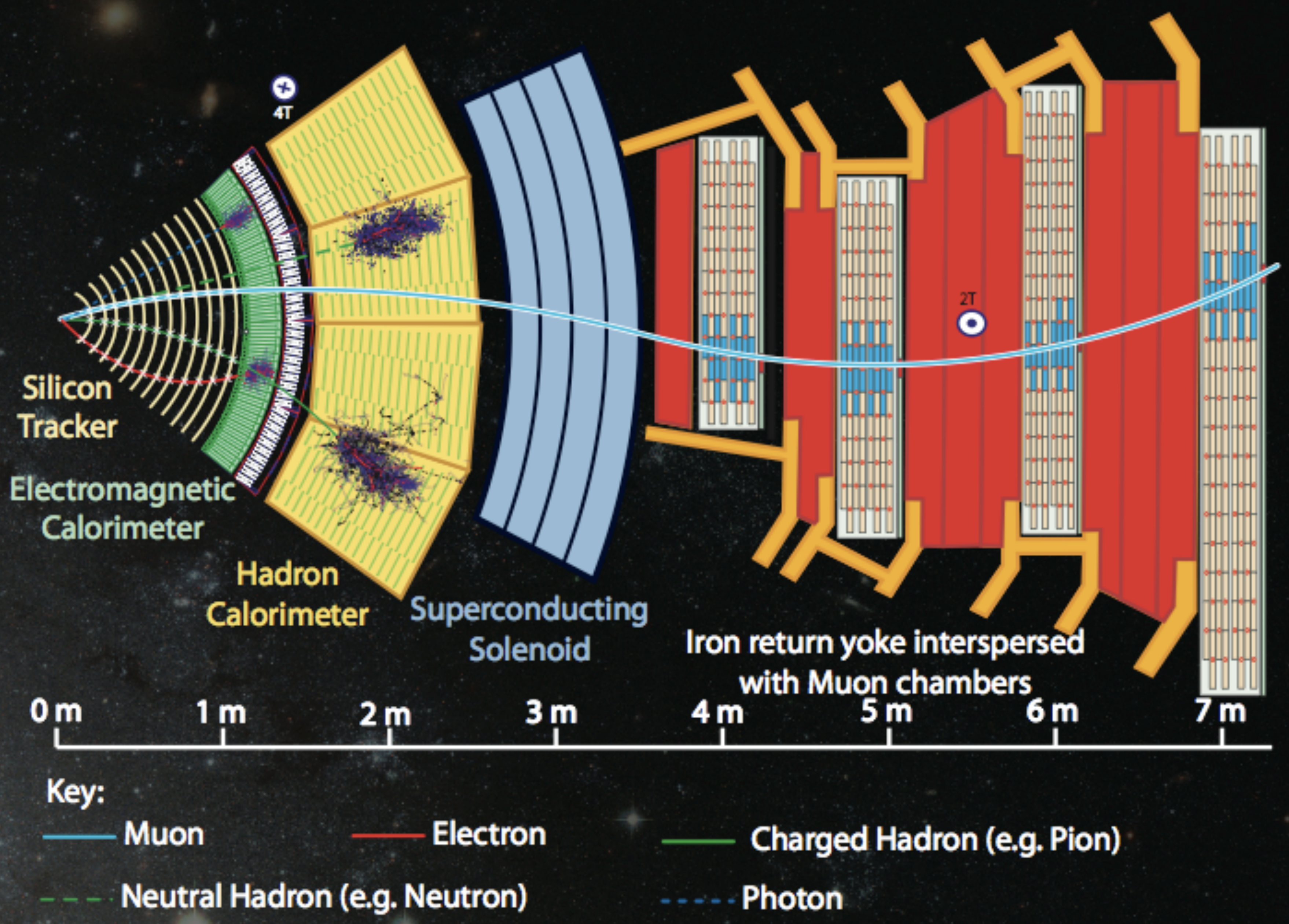


Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

The CMS detector : Physics object access

Pattern Recognition

New particles discovered in CMS will be typically unstable and rapidly transform into a cascade of lighter, more stable and better understood particles. Particles travelling through CMS leave behind characteristic patterns, or 'signatures', in the different layers, allowing them to be identified. The presence (or not) of any new particles can then be inferred.



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✦ High Interaction Rate

pp interaction rate **1 billion interactions/s**

Data can be recorded for only ~400 out of 40 million crossings/sec

Level-1 trigger decision takes ~2-3 μs

- **electronics need to store data locally (pipelining)**

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large number of superposed events in each crossing
several 1000 tracks stream into the detector every 25 ns
need highly granular detectors with good time resolution for low occupancy

- **large number of channels (~ 100 M ch)**

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✦ High Radiation Levels

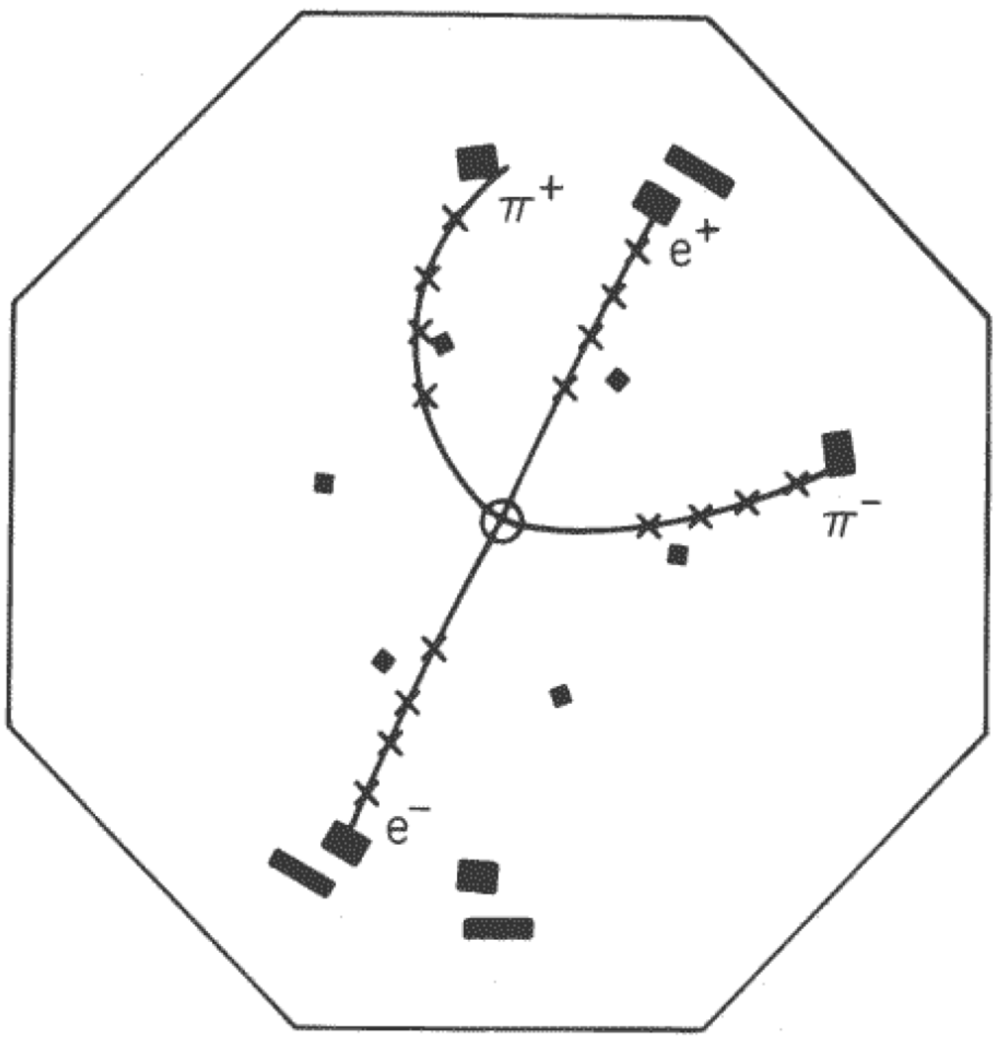
- **radiation hard (tolerant) detectors and electronics**

Increasing challenges

MARK-I detector (SLAC)

e+e- @ 3 GeV

Ψ´ (excited state of J/Ψ)



Increasing challenges

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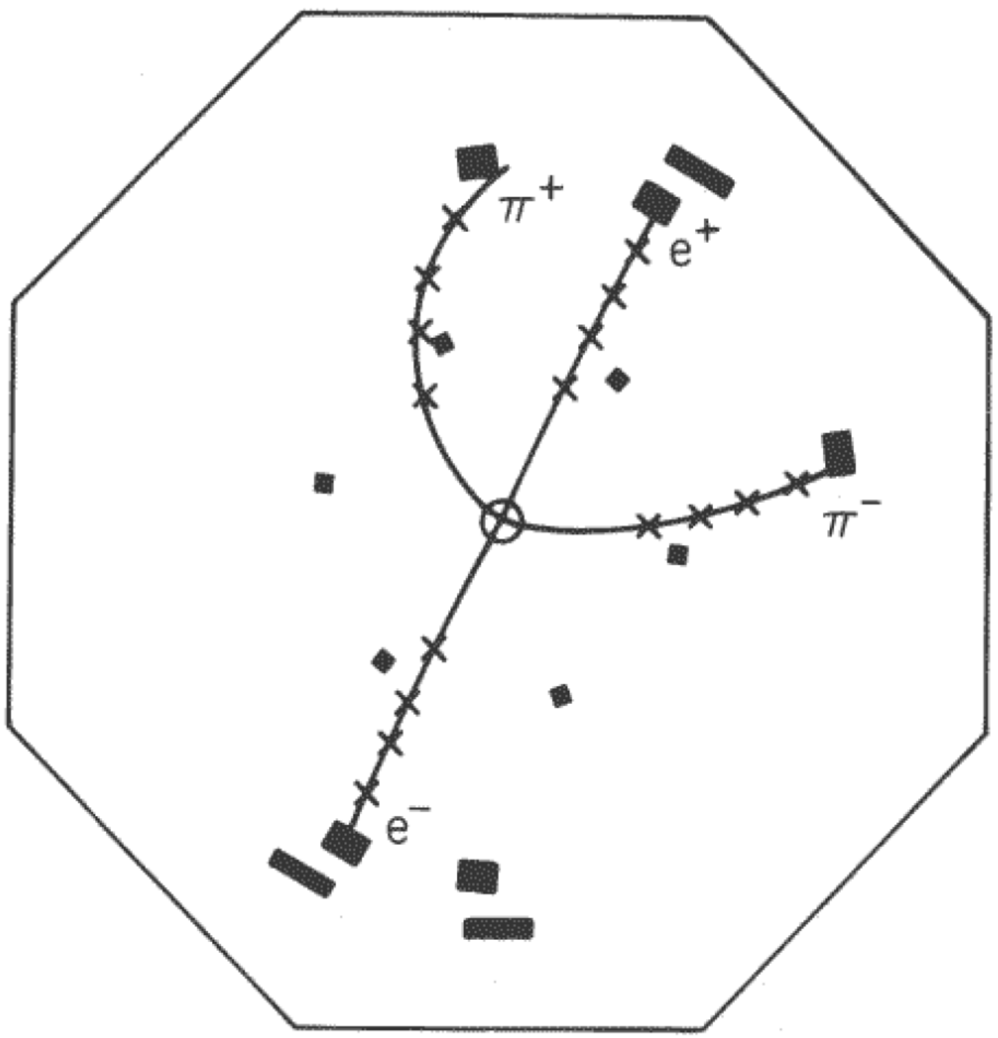
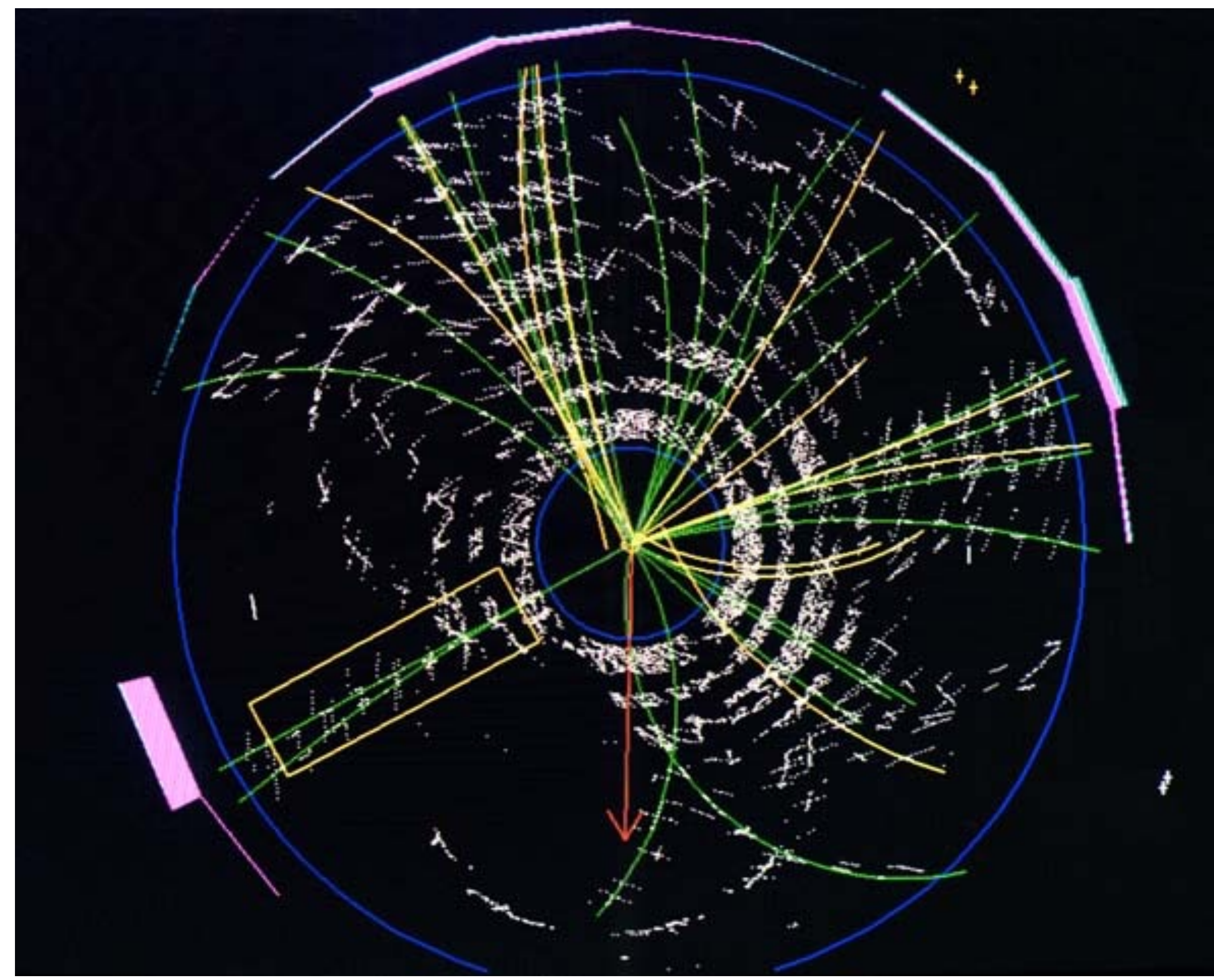


Top quark discovery at CDF and D0
pbarp @ 1,8 TeV



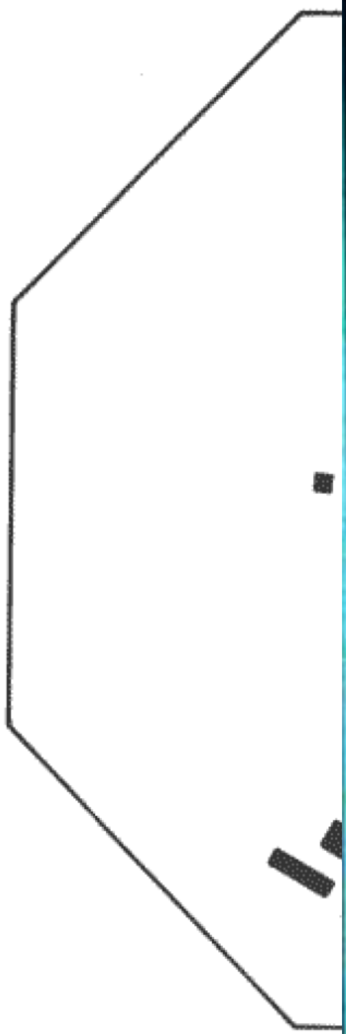
Increasing challenges

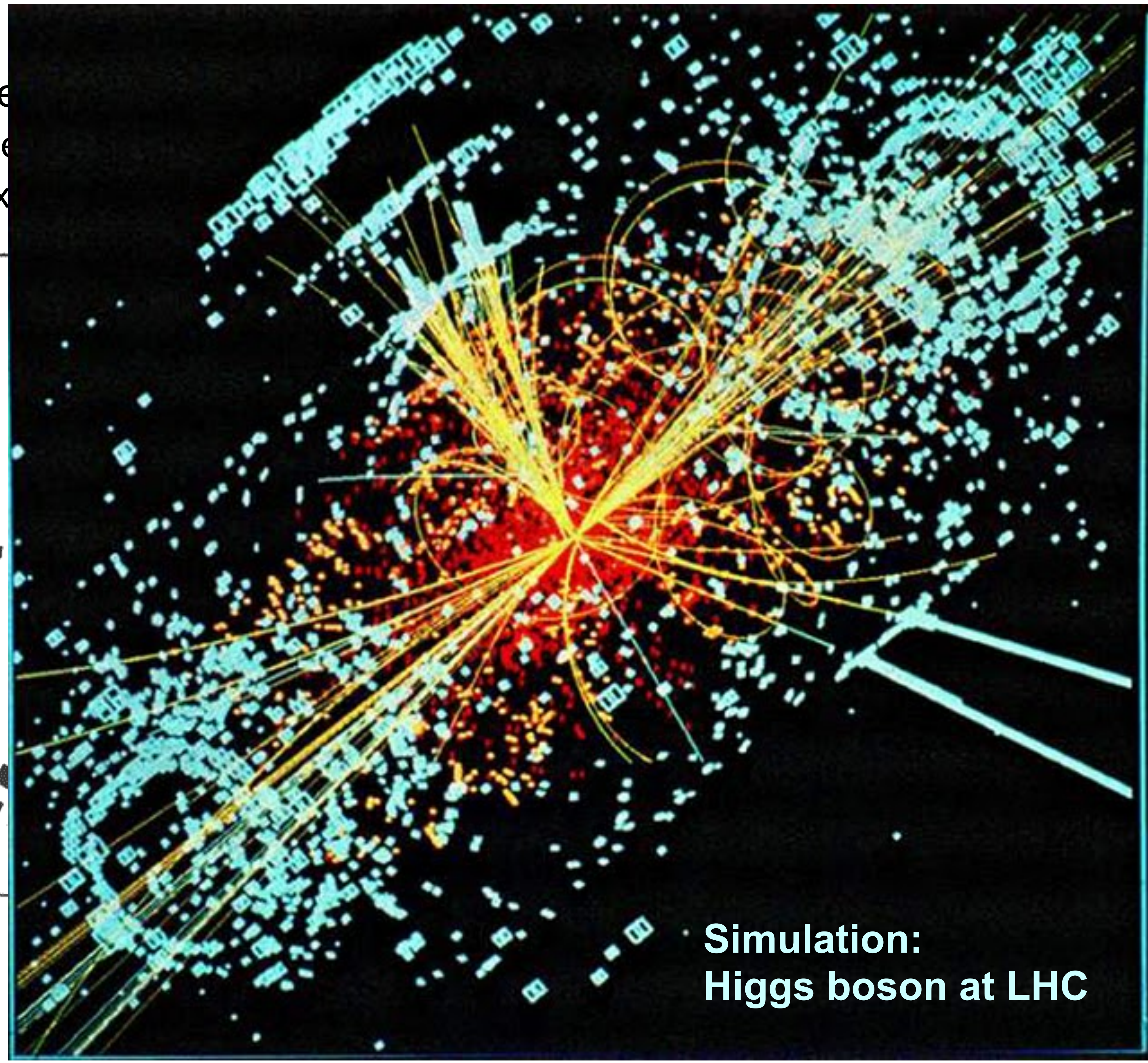
MARK-I de

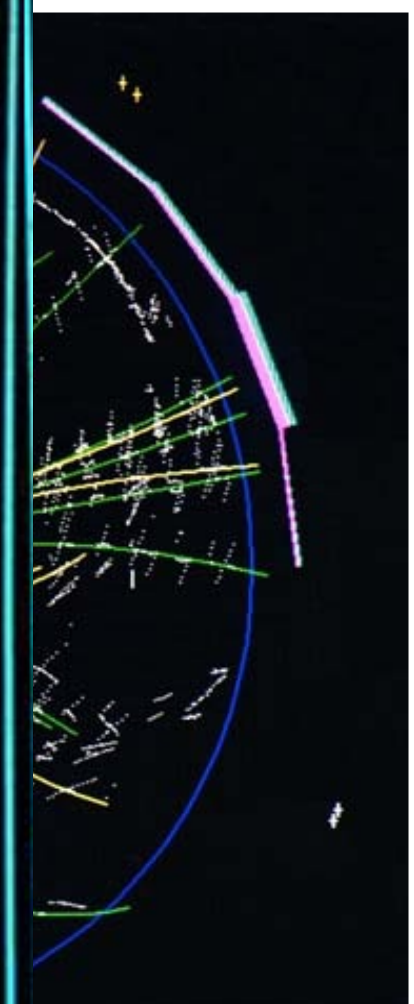
e+e

Ψ´ (ex

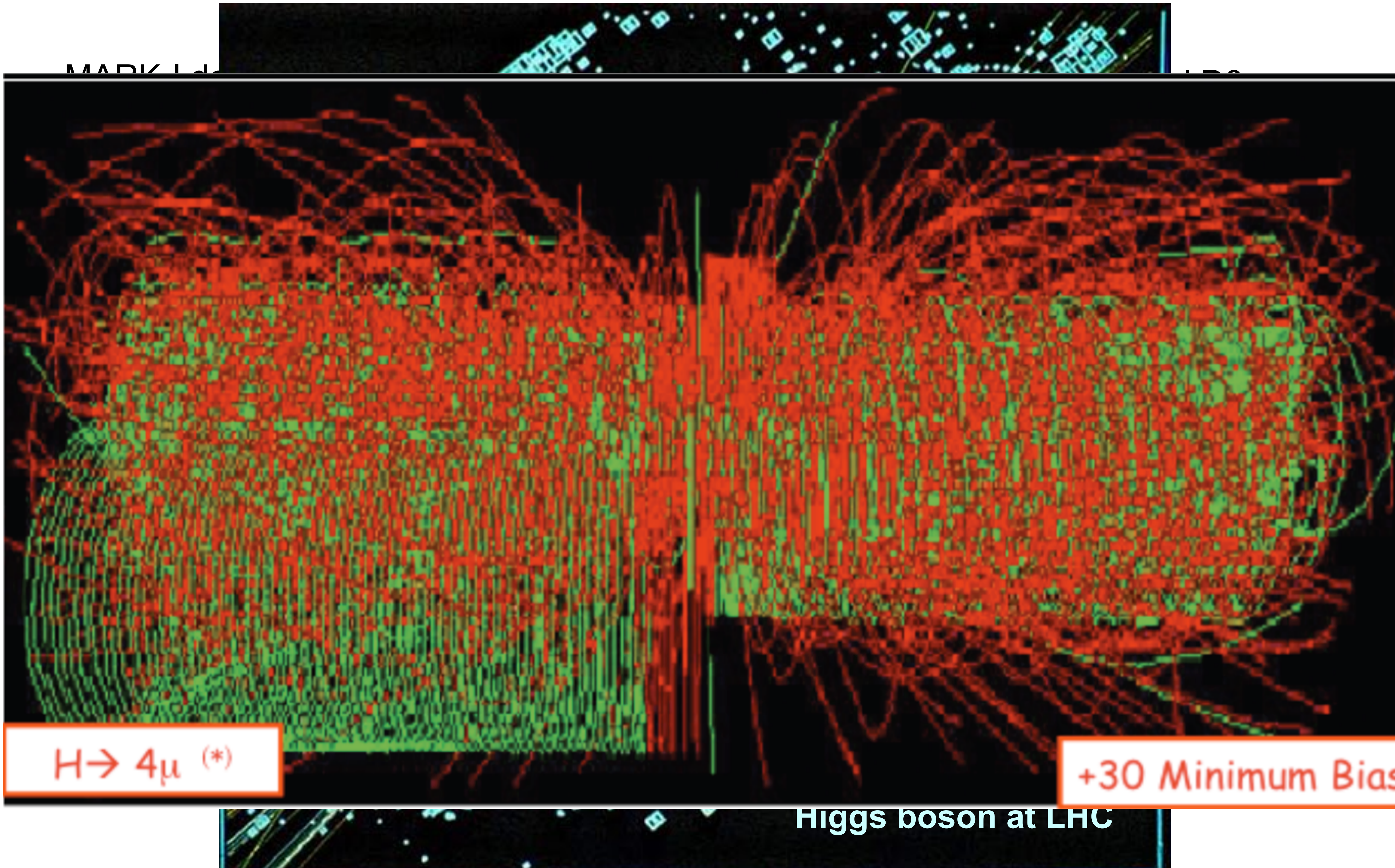
d D0



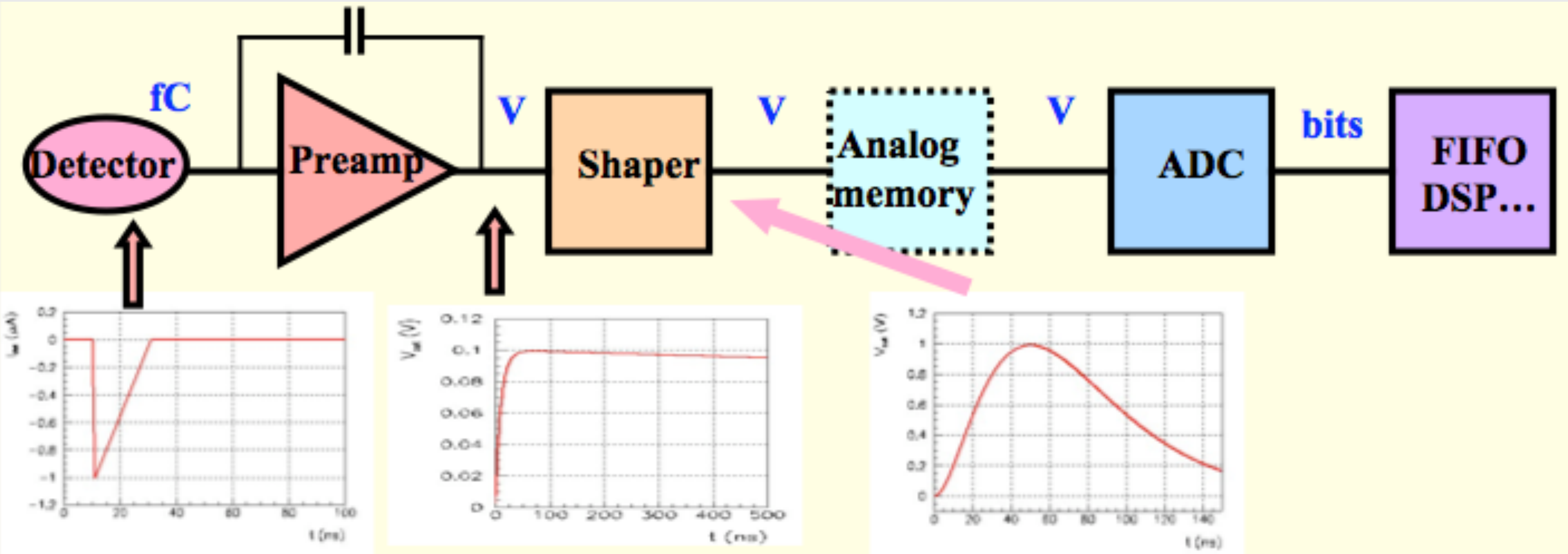




Increasing challenges



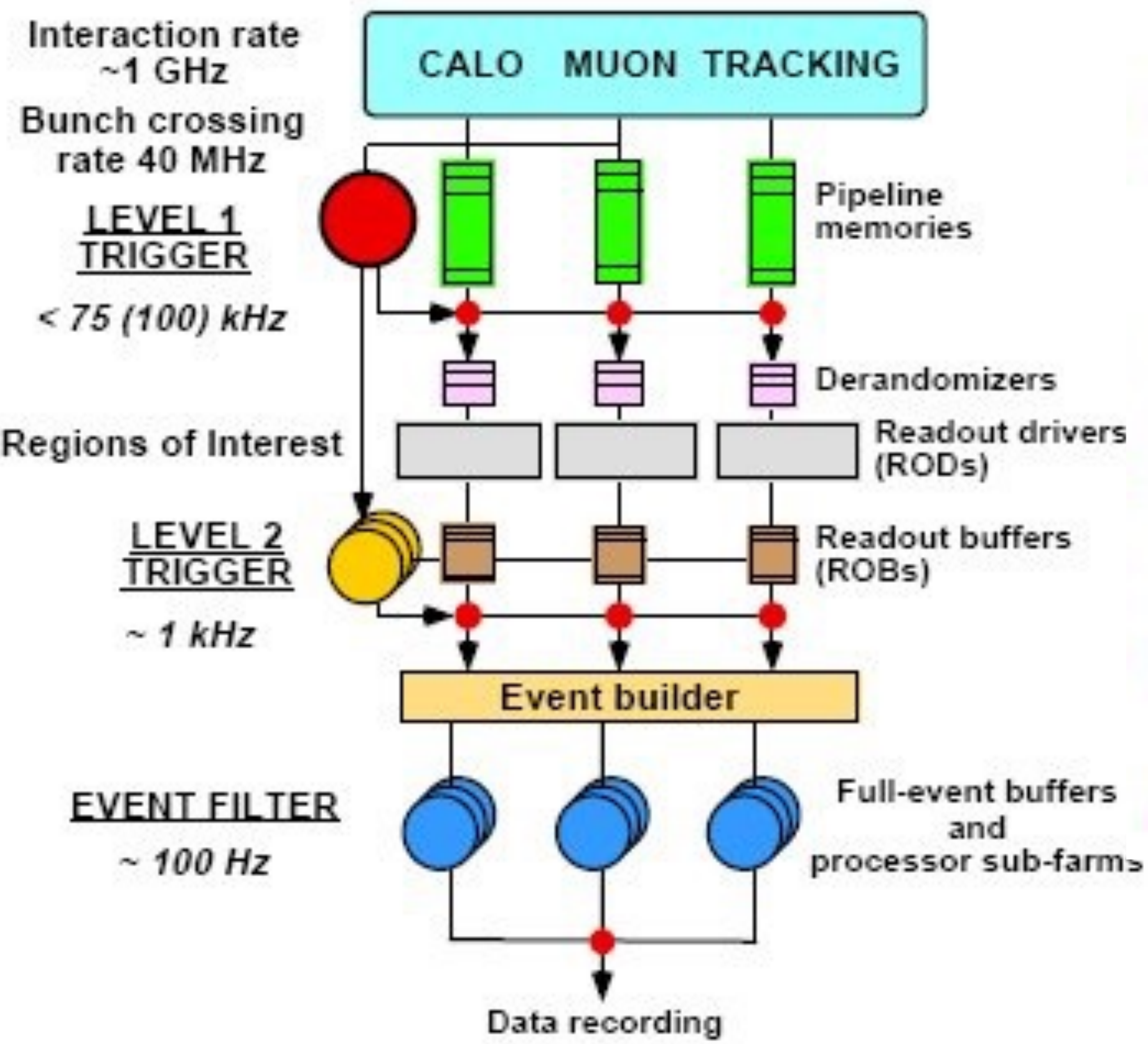
Overview of readout electronics

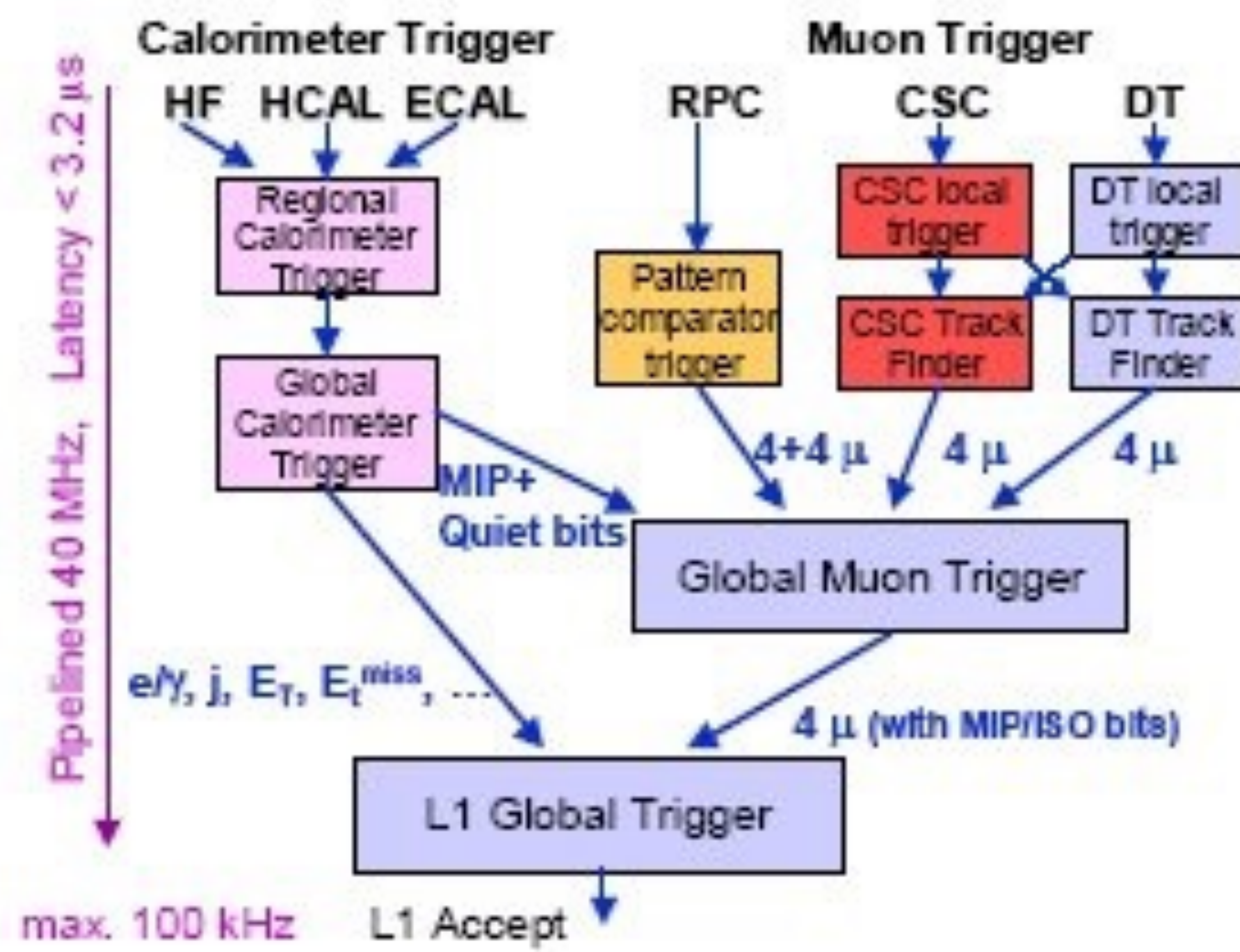


Most front-ends follow a similar architecture :

- Very small signals (fC) -> need amplification and optimisation of S/N (filter)
- Measurement of amplitude and/or time (ADCs, discris, TDCs)
- Several thousands to millions of channels
- Needs time to decide to keep or not the event : memory

Pipelined-multilevel-triggers



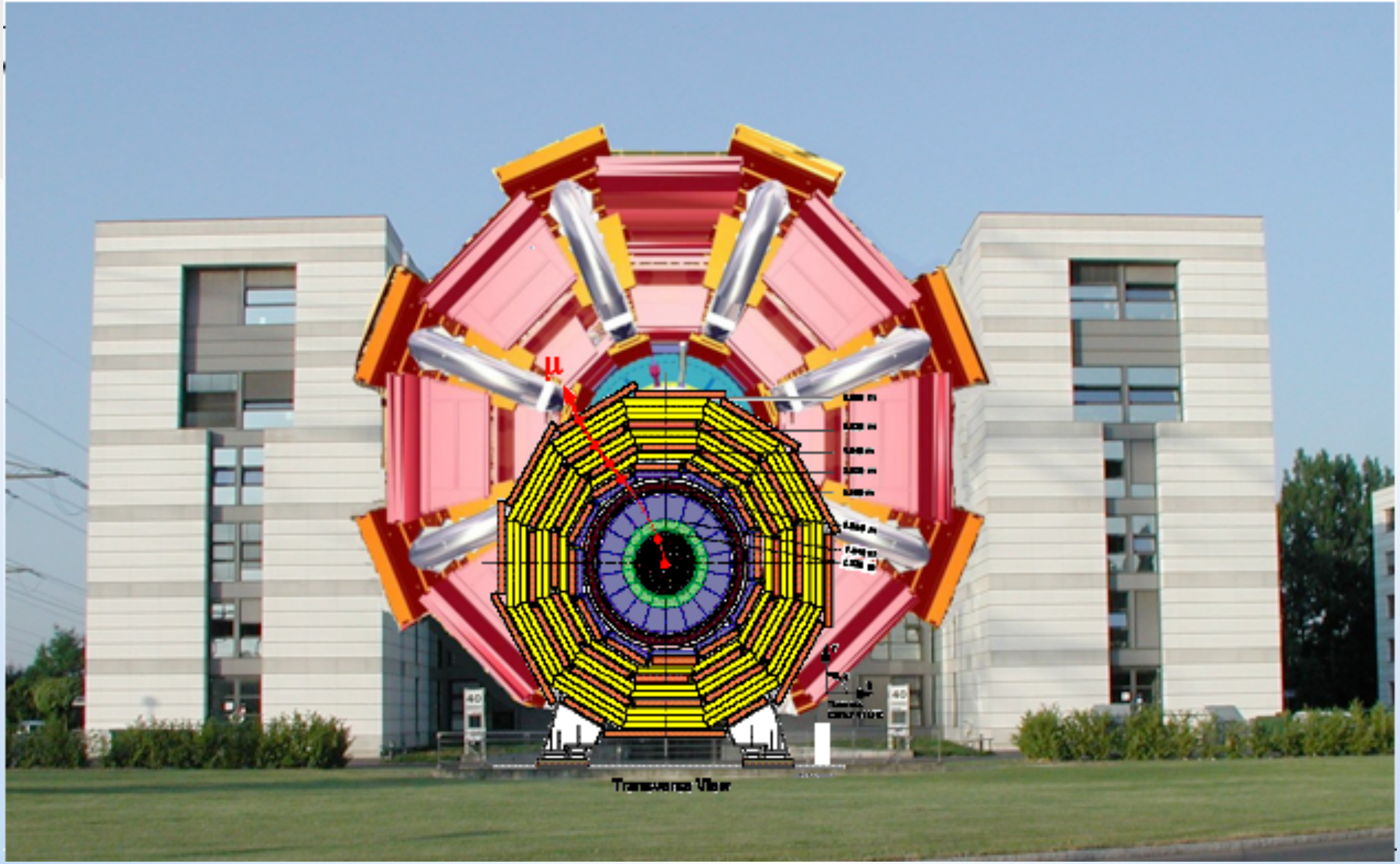


40 MHz	LVL1	100 kHz	(LVL2+LVL3)	100Hz

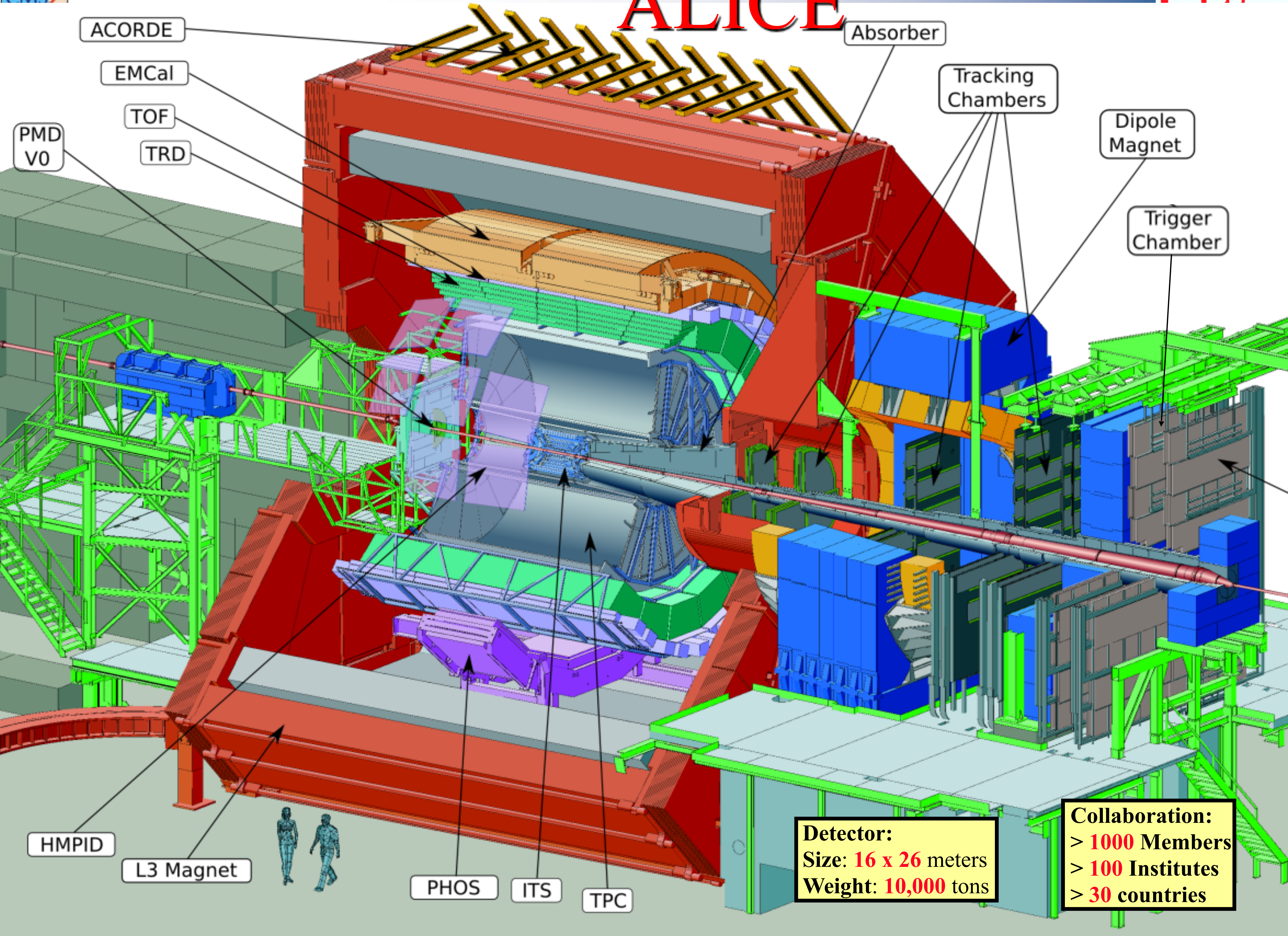
synchronous → asynchronous →

3 µs

ATLAS et CMS



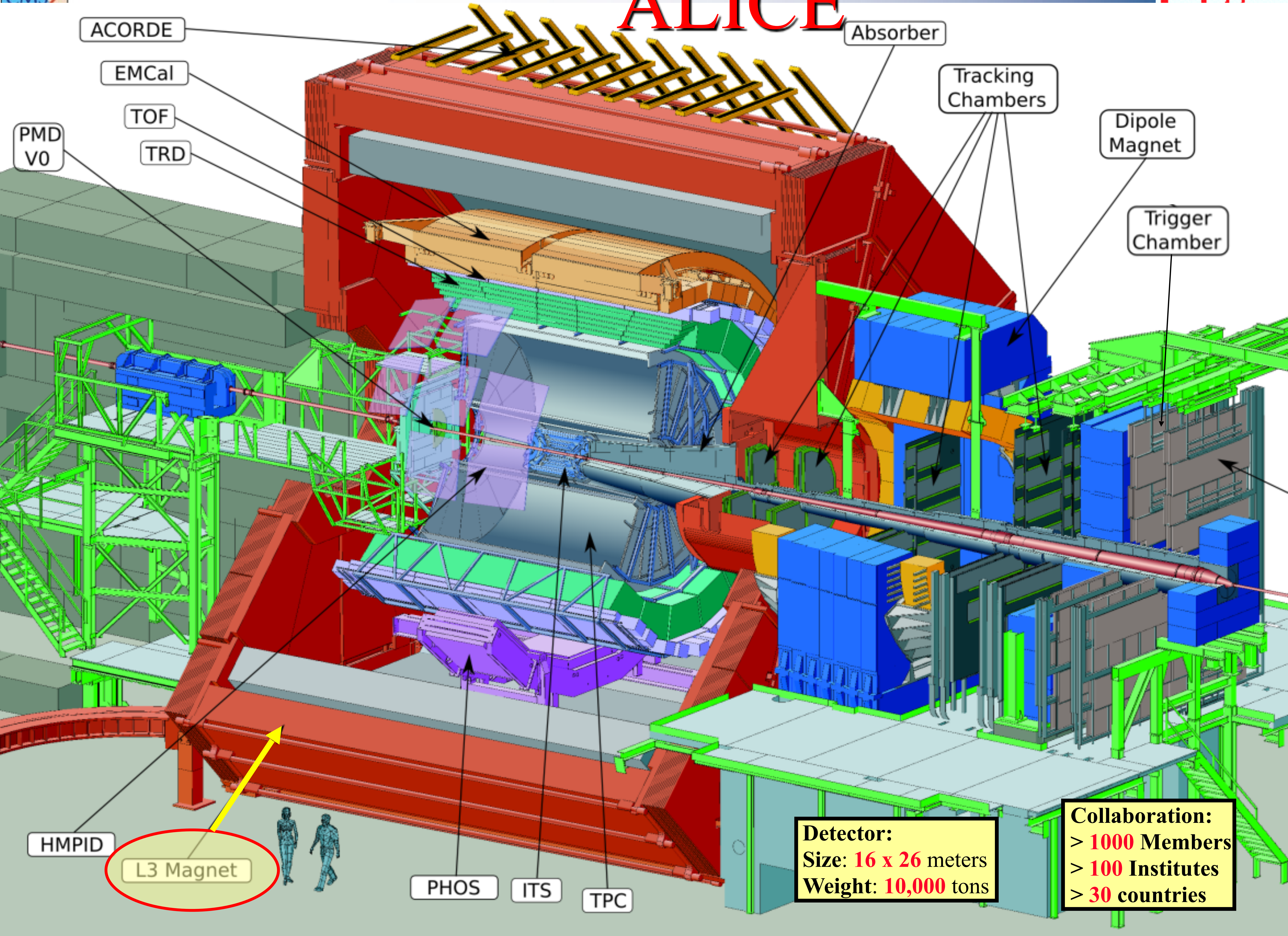
ALICE



Detector:
Size: 16 x 26 meters
Weight: 10,000 tons

Collaboration:
> 1000 Members
> 100 Institutes
> 30 countries

ALICE



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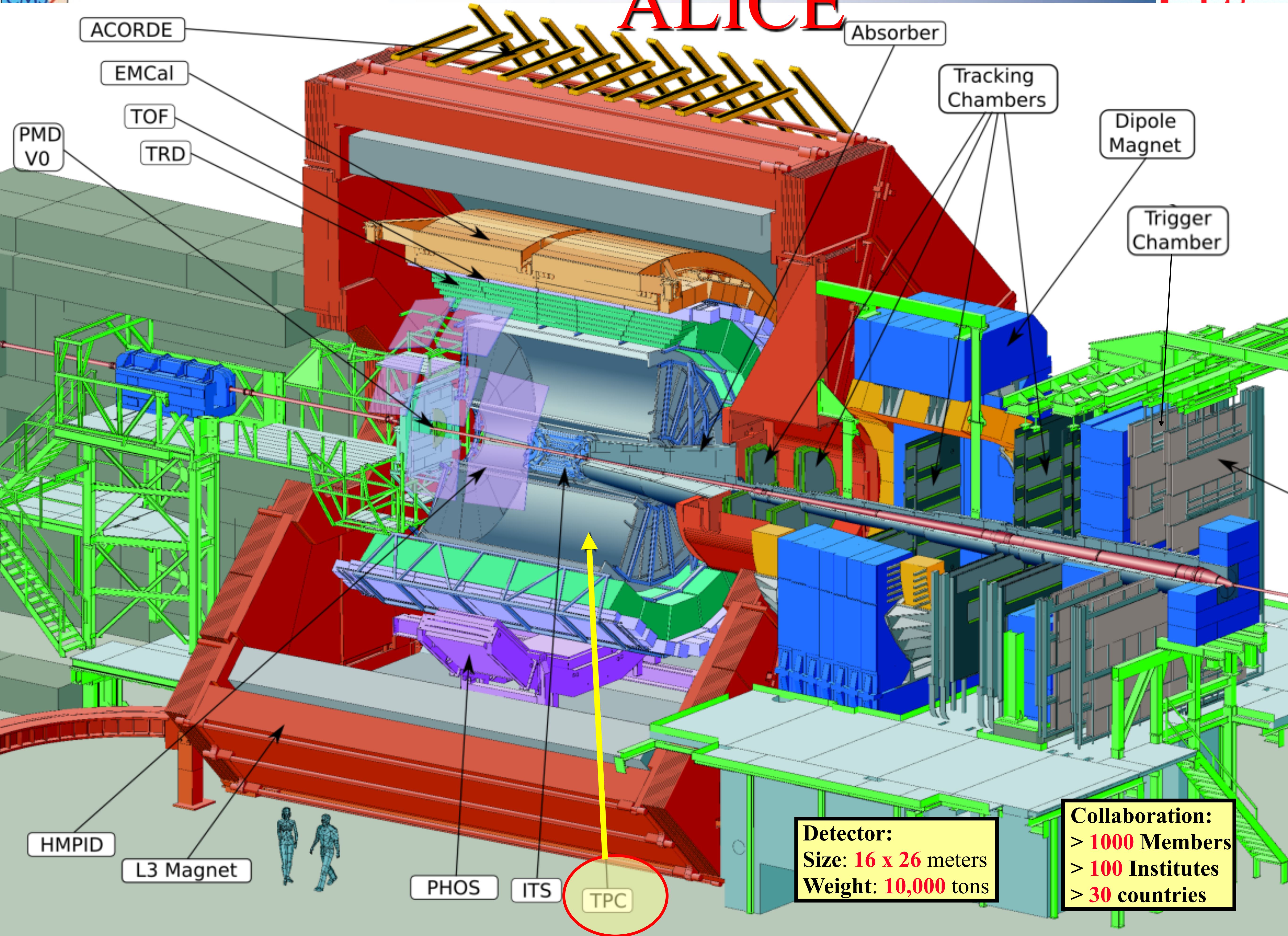

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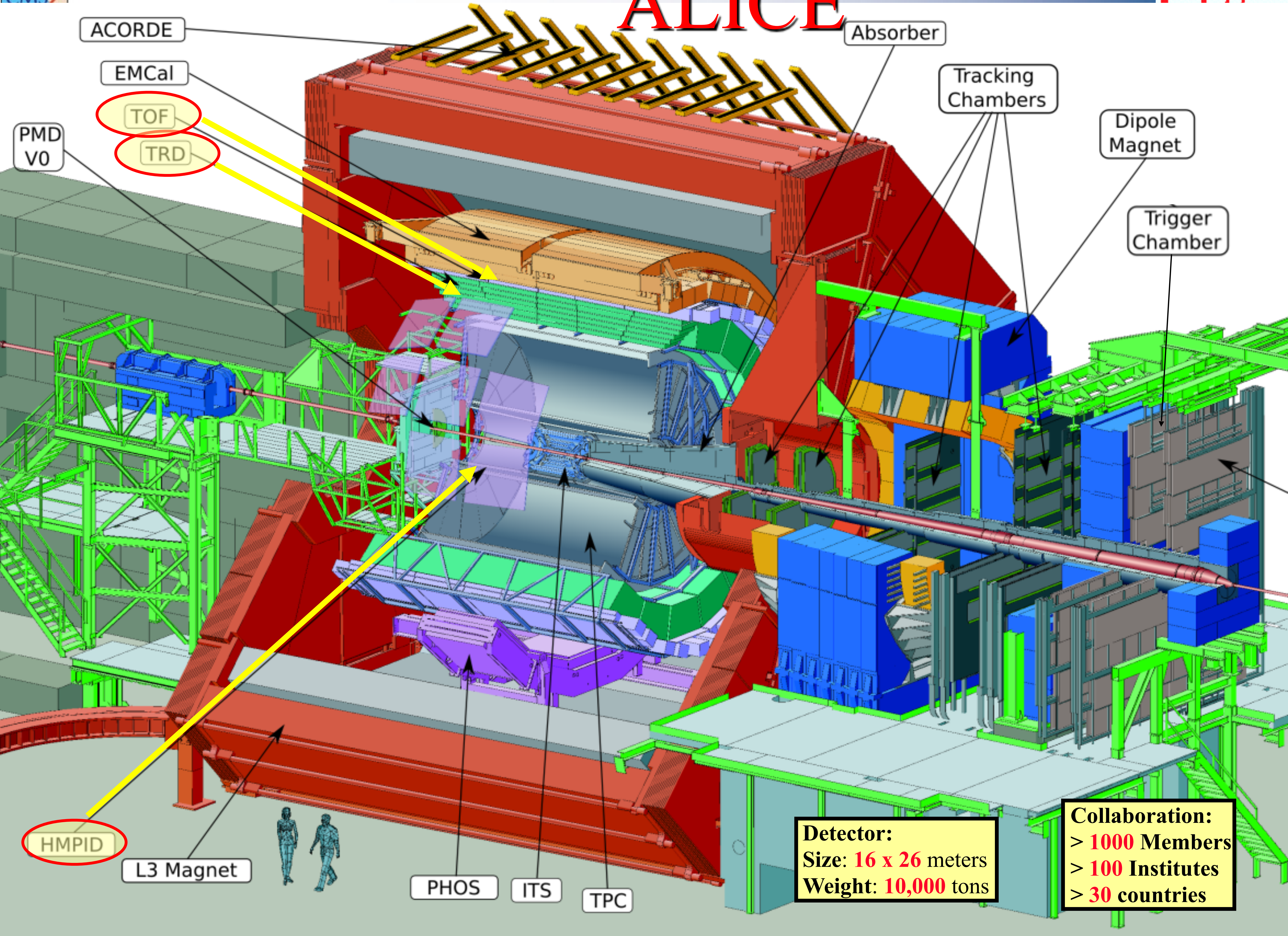

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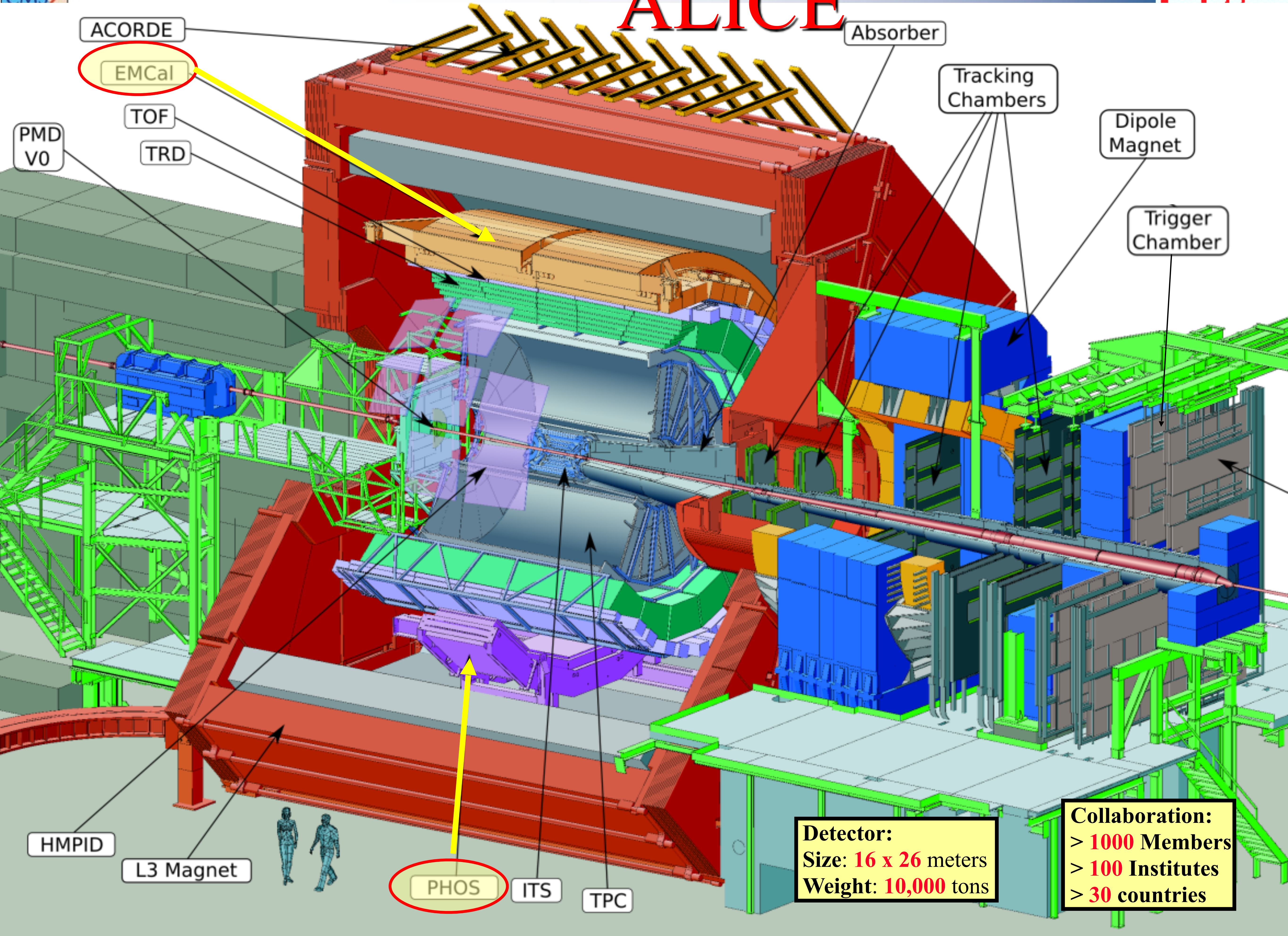

ACORDE
EMCal
TOF
TRD
PMD
V0
Absorber
Tracking Chambers
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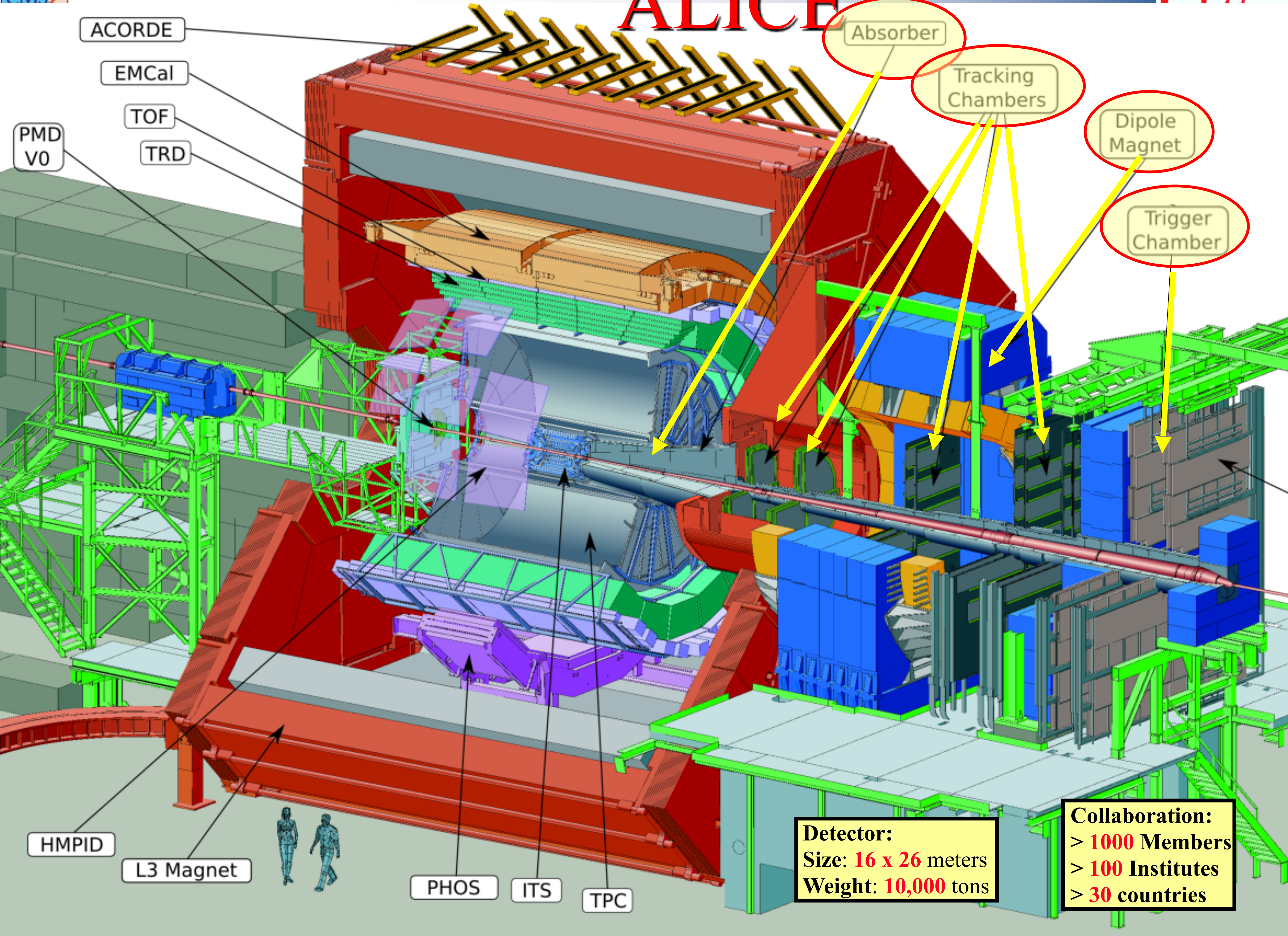

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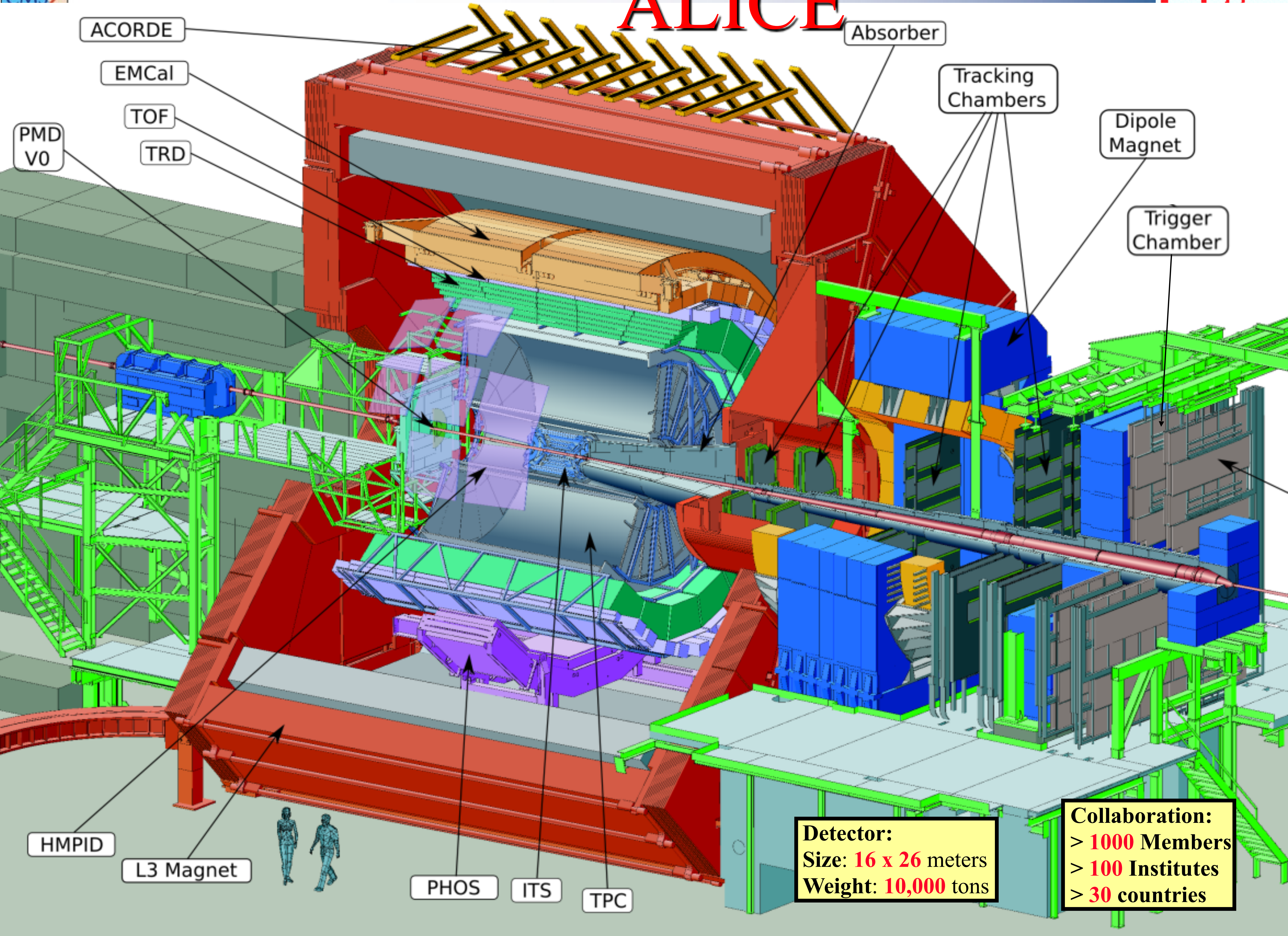
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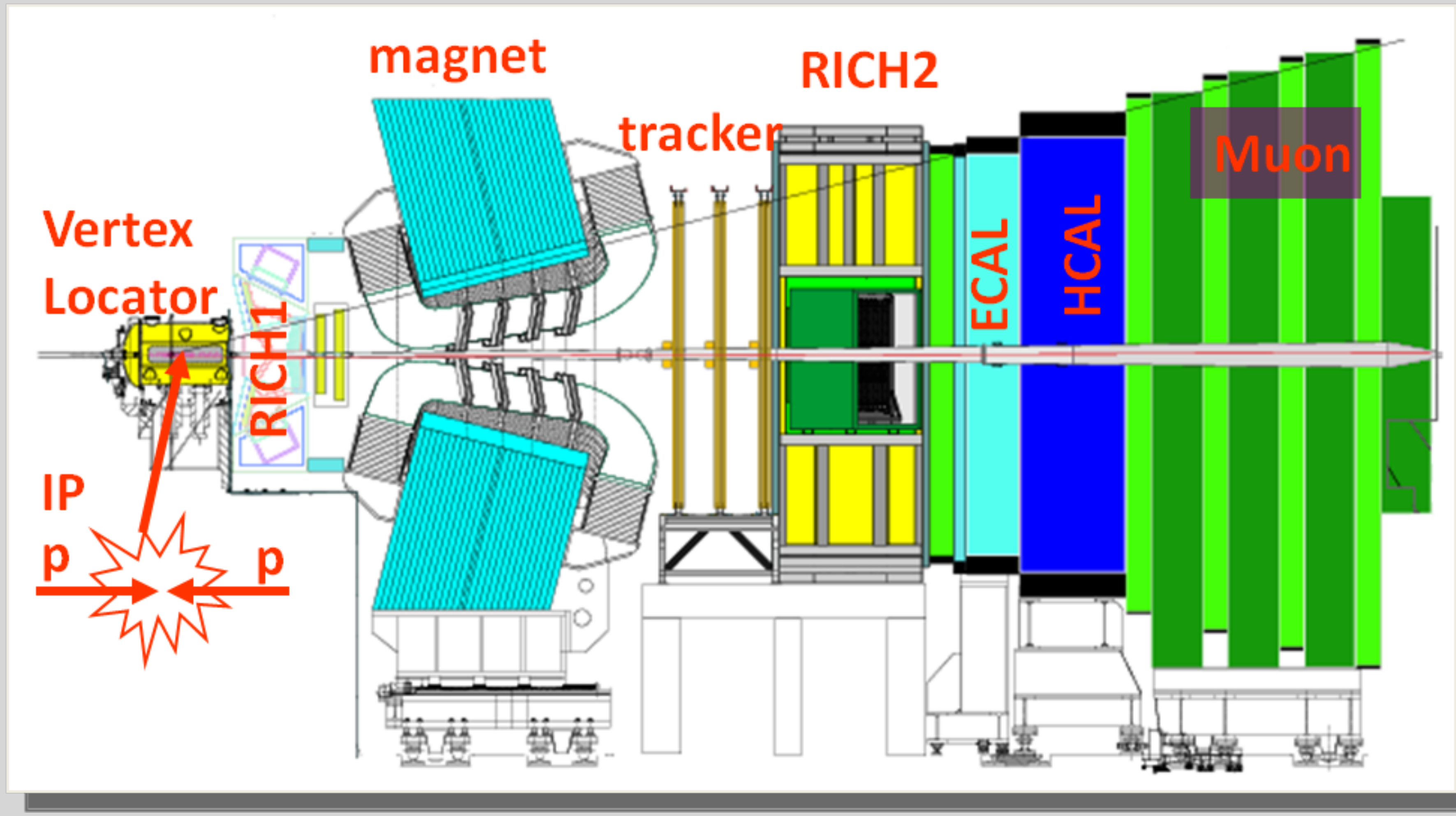
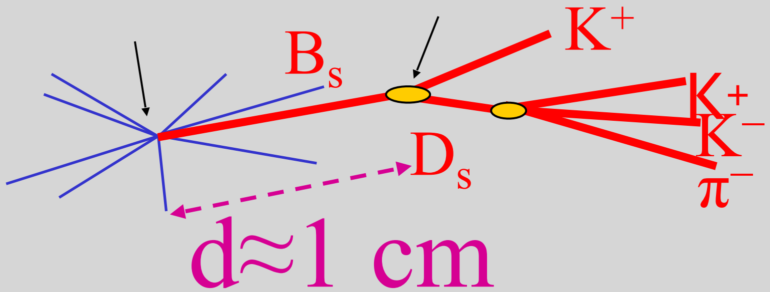
The LHCb Detector

Forward Spectrometer
- Angular acceptance : $15<\theta<300$ mrad
- Nominal luminosity: $L = 2 \times 10^{32} cm^{-2}s^{-1}$



Example

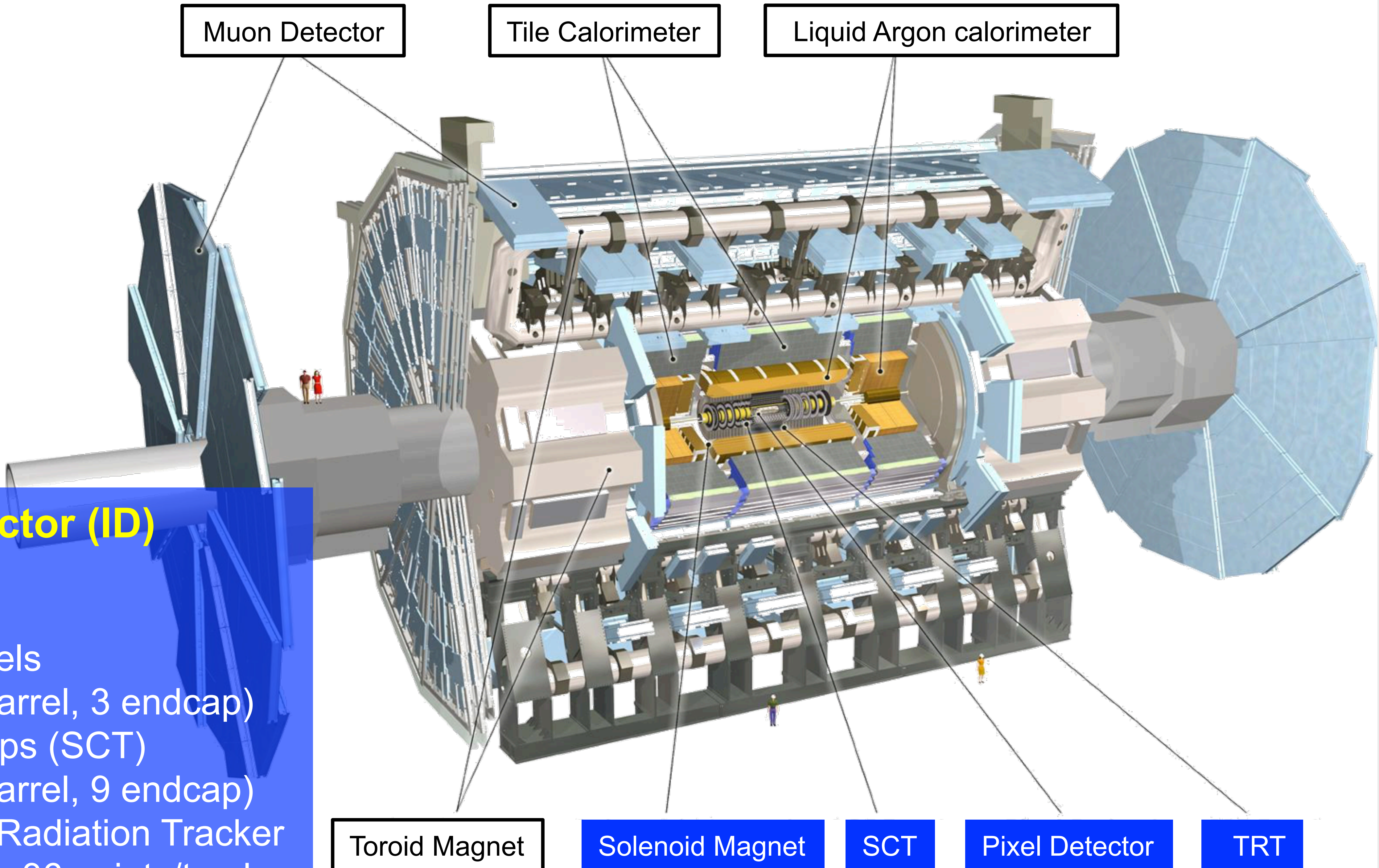
Primary vertex



Key parameters

- Vertexing: proper time resolution 30-50 fs
- Charged tracks $\Delta p/p = 0.35$ % - 0.55%
- Excellent mass resolution $\Delta m = 7 – 20$ MeV
- Muon ID: $\varepsilon(\mu\rightarrow\mu) = 94$ %, mis-ID $\varepsilon(\pi\rightarrow\mu) = 1$-3 %
- RICH π-K separation: $\varepsilon(K\rightarrow K) = 95$ %, mis-ID $\varepsilon(\pi\rightarrow K) \sim 7$ %

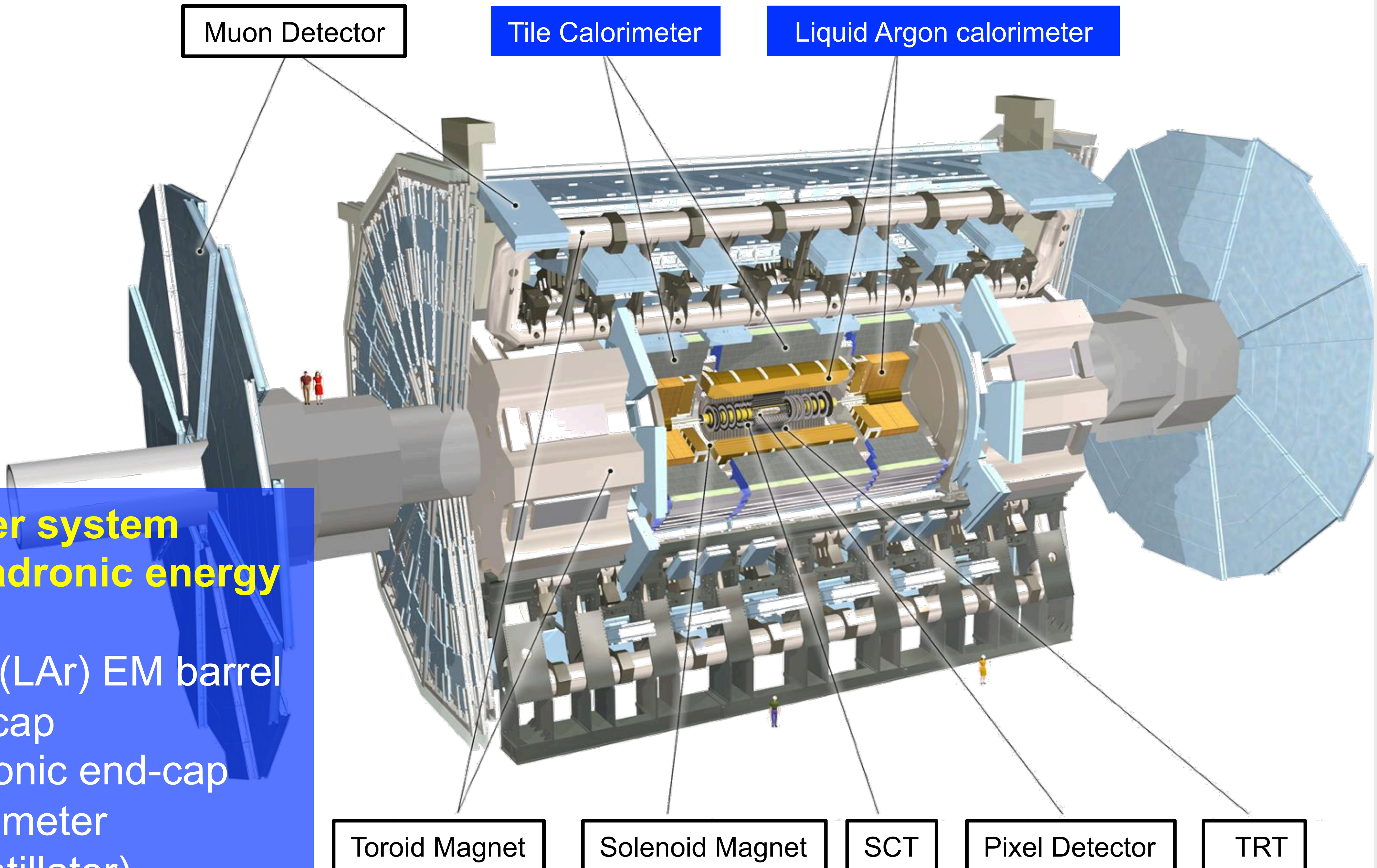
The ATLAS detector



Inner Detector (ID)
Tracking

- Silicon Pixels (4 layers barrel, 3 endcap)
- Silicon Strips (SCT) (4 layers barrel, 9 endcap)
- Transition Radiation Tracker (TRT) up to 36 points/track
- 2T Solenoid Magnet

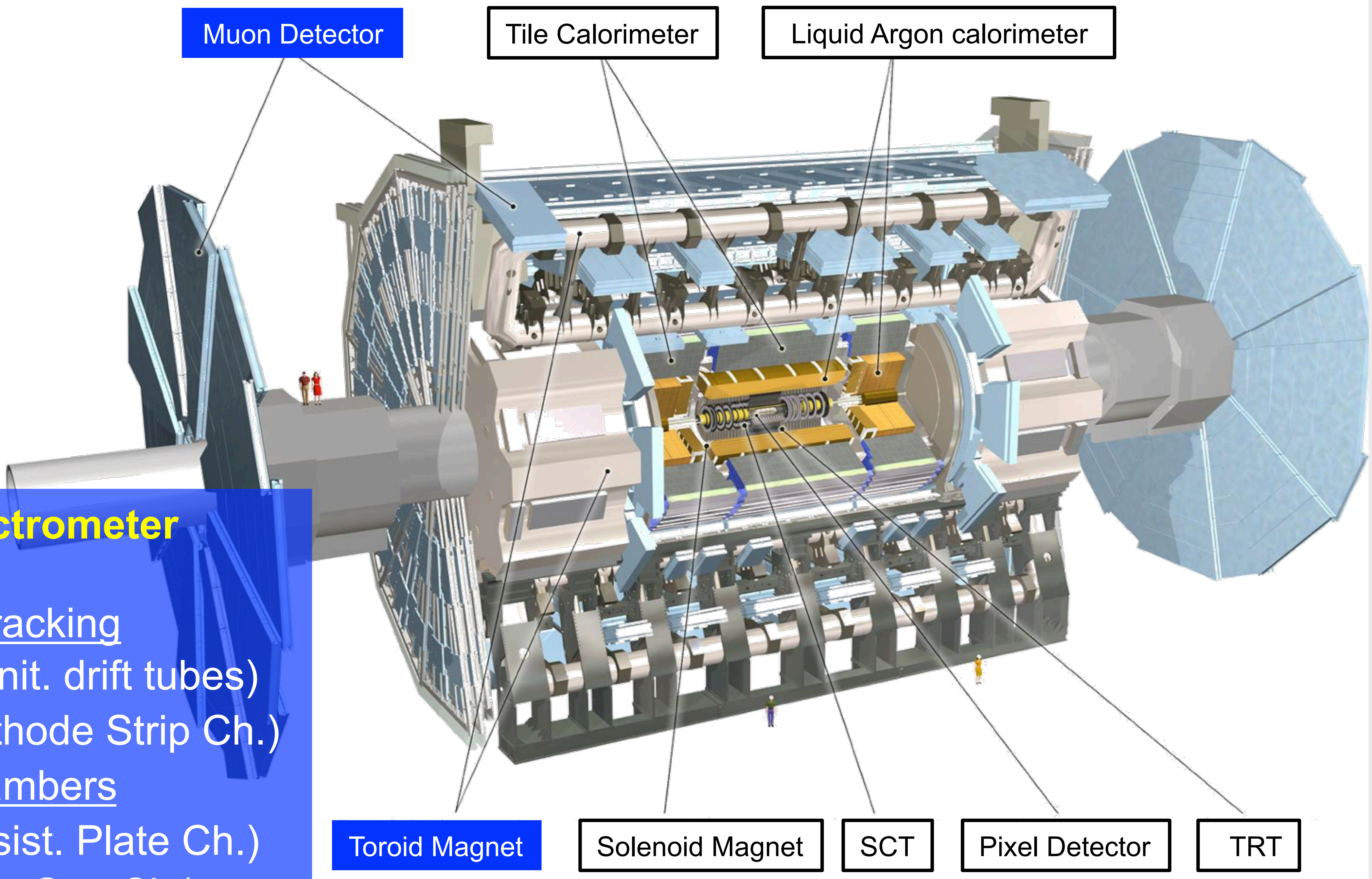
The ATLAS detector



Calorimeter system
EM and Hadronic energy

- Liquid Ar (LAr) EM barrel and end-cap
- LAr Hadronic end-cap
- Tile calorimeter (Fe – scintillator) hadronic barrel

The ATLAS detector



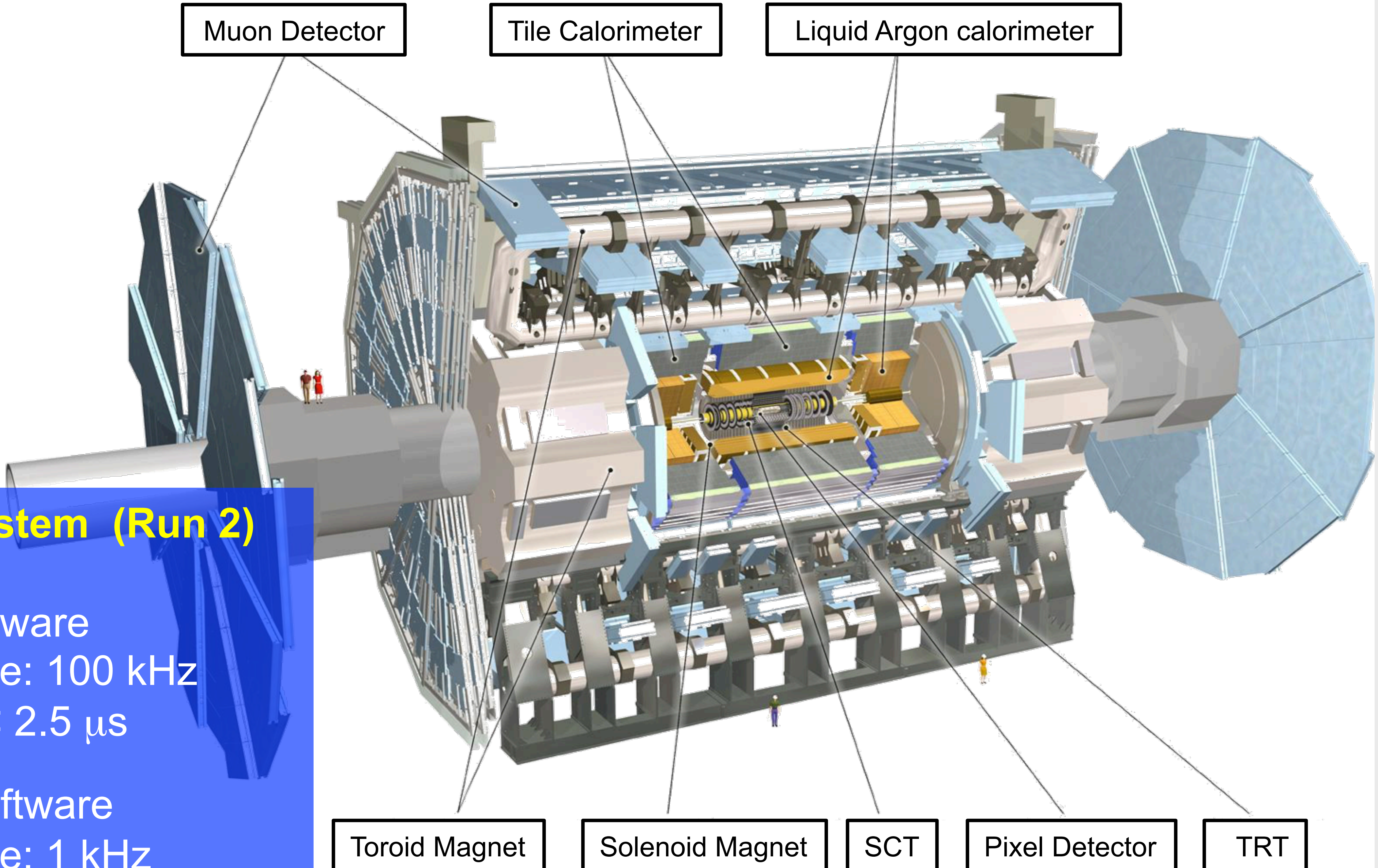
Muon spectrometer
μ tracking

Precision tracking
- MDT (Monit. drift tubes)
- CSC (Cathode Strip Ch.)

Trigger chambers
- RPC (Resist. Plate Ch.)
- TGC (Thin Gap Ch.)

- Toroid Magnet

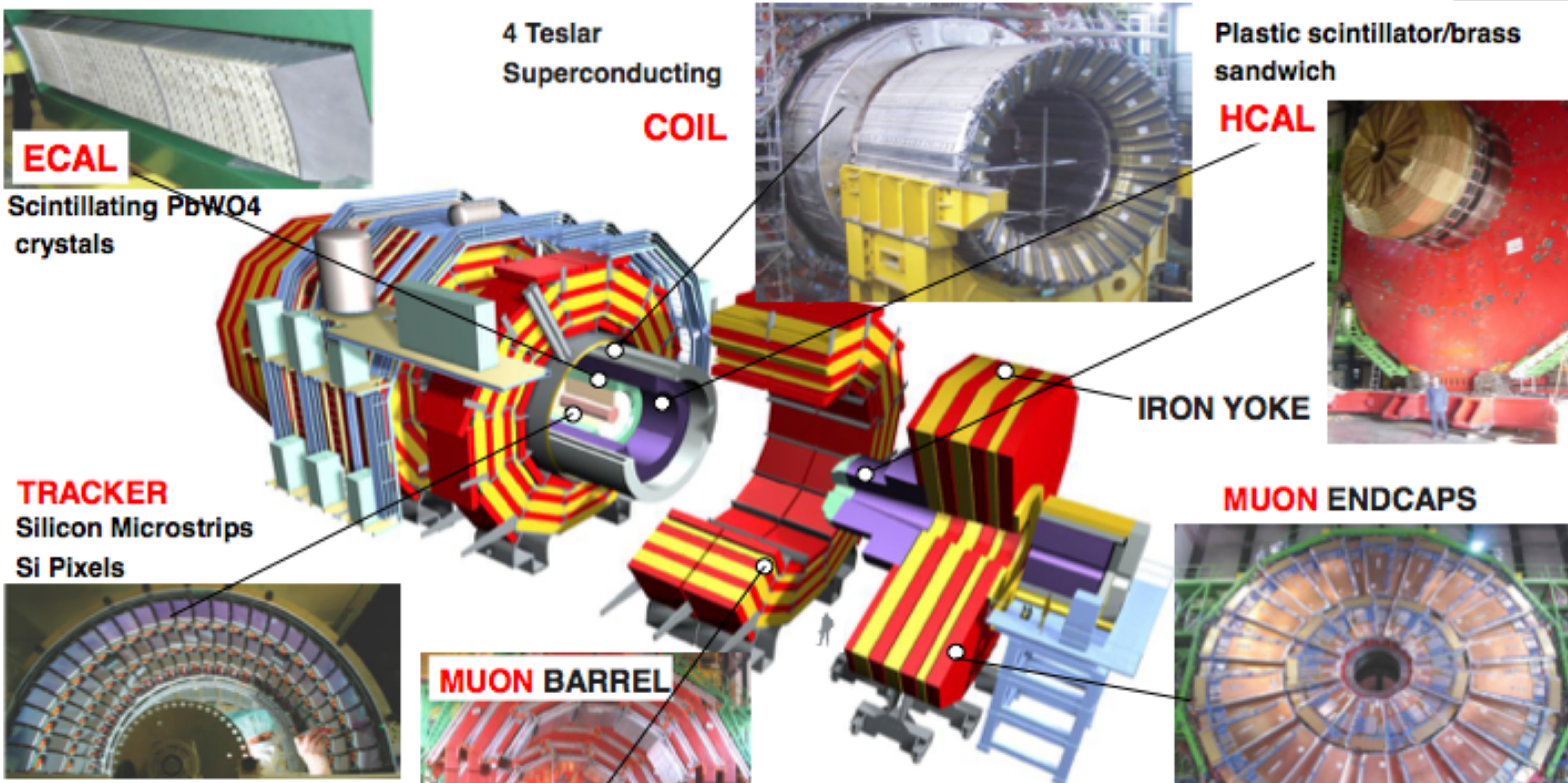
The ATLAS detector



Trigger system (Run 2)

- L1 – hardware
  output rate: 100 kHz
  latency: < 2.5 μs
- HLT – software
  output rate: 1 kHz
  proc. time: ~ 550 ms

CMS detector

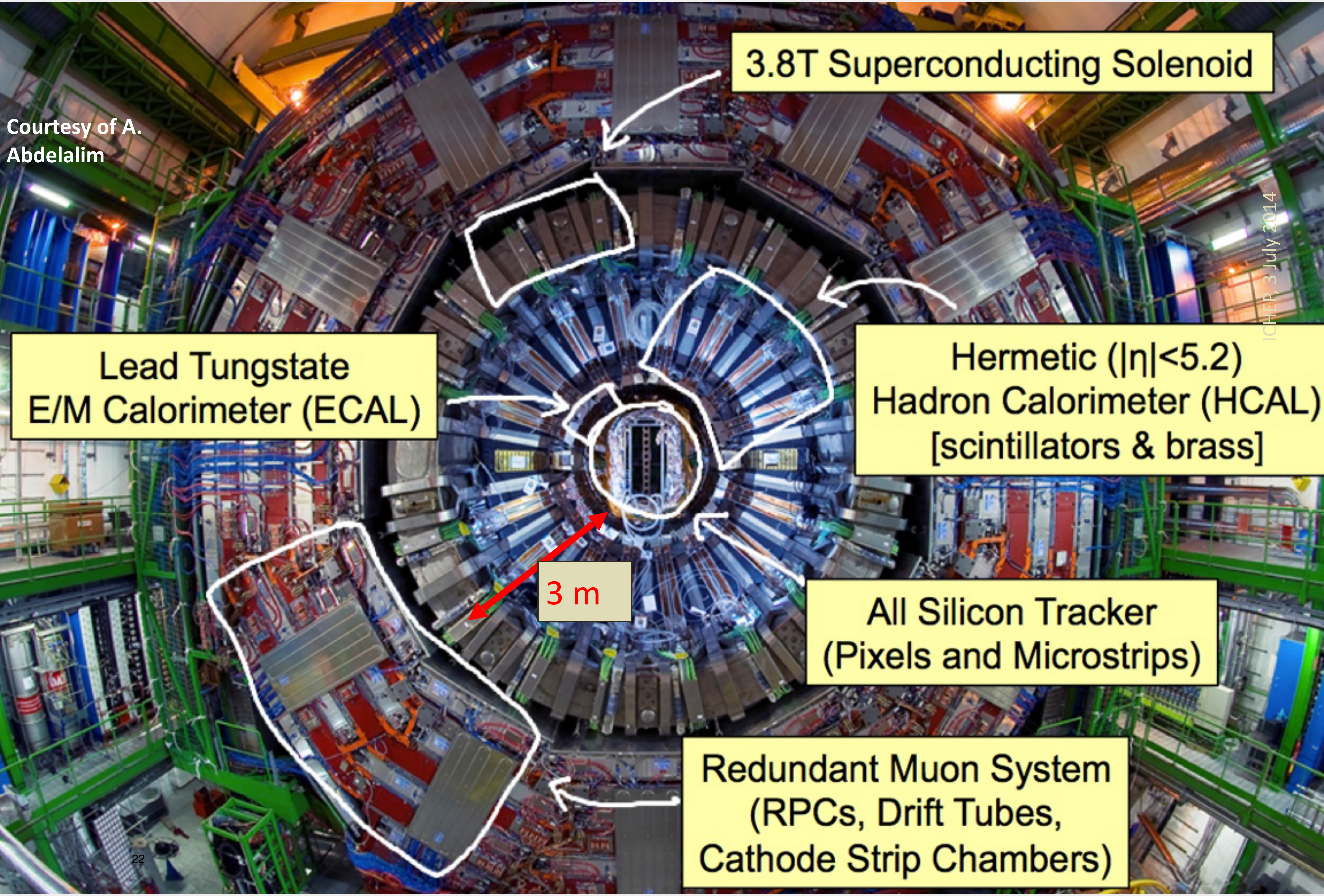


Length: 21.6 m

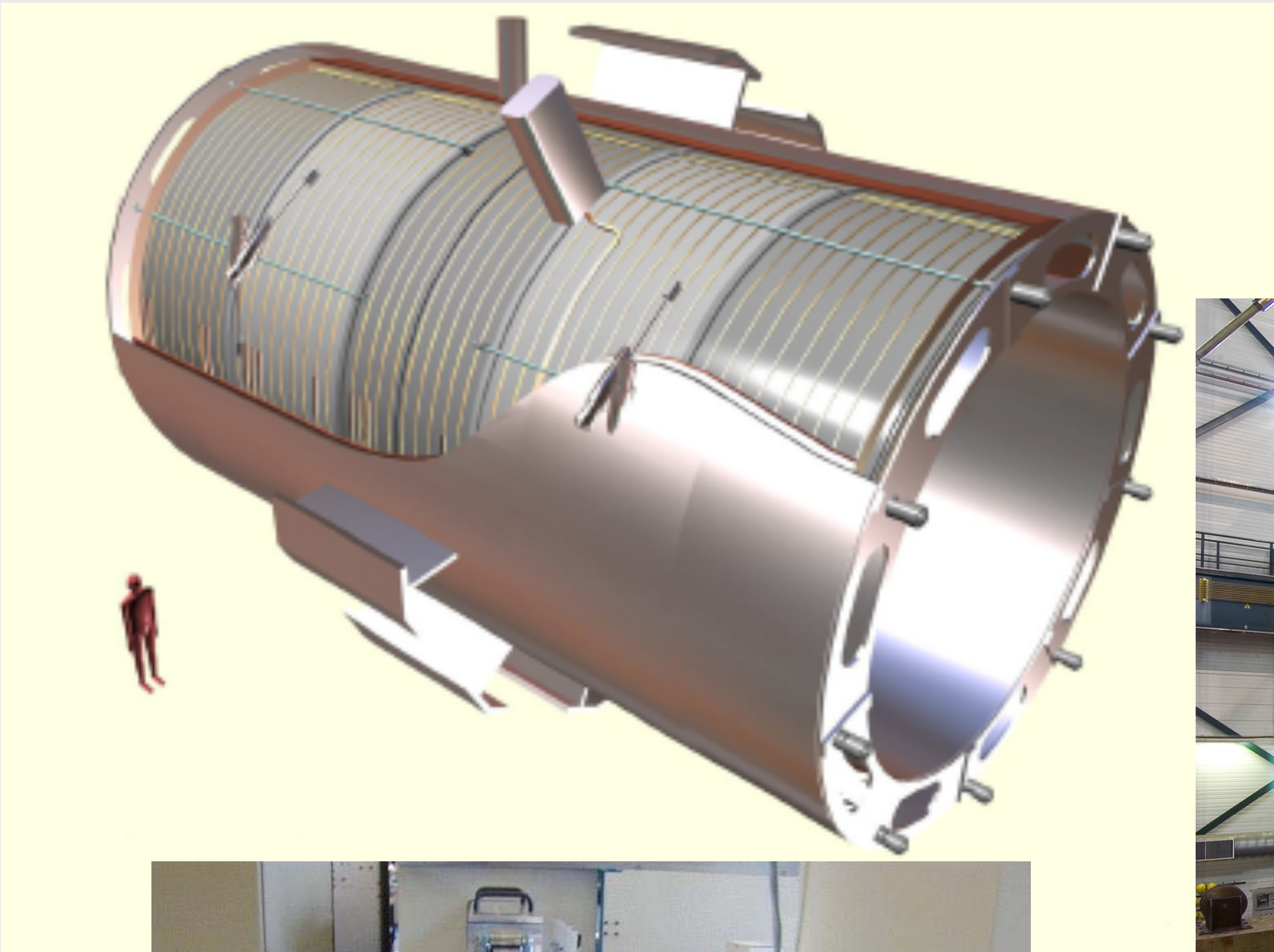
Diameter: 15 m

Weight: ~12500 tons

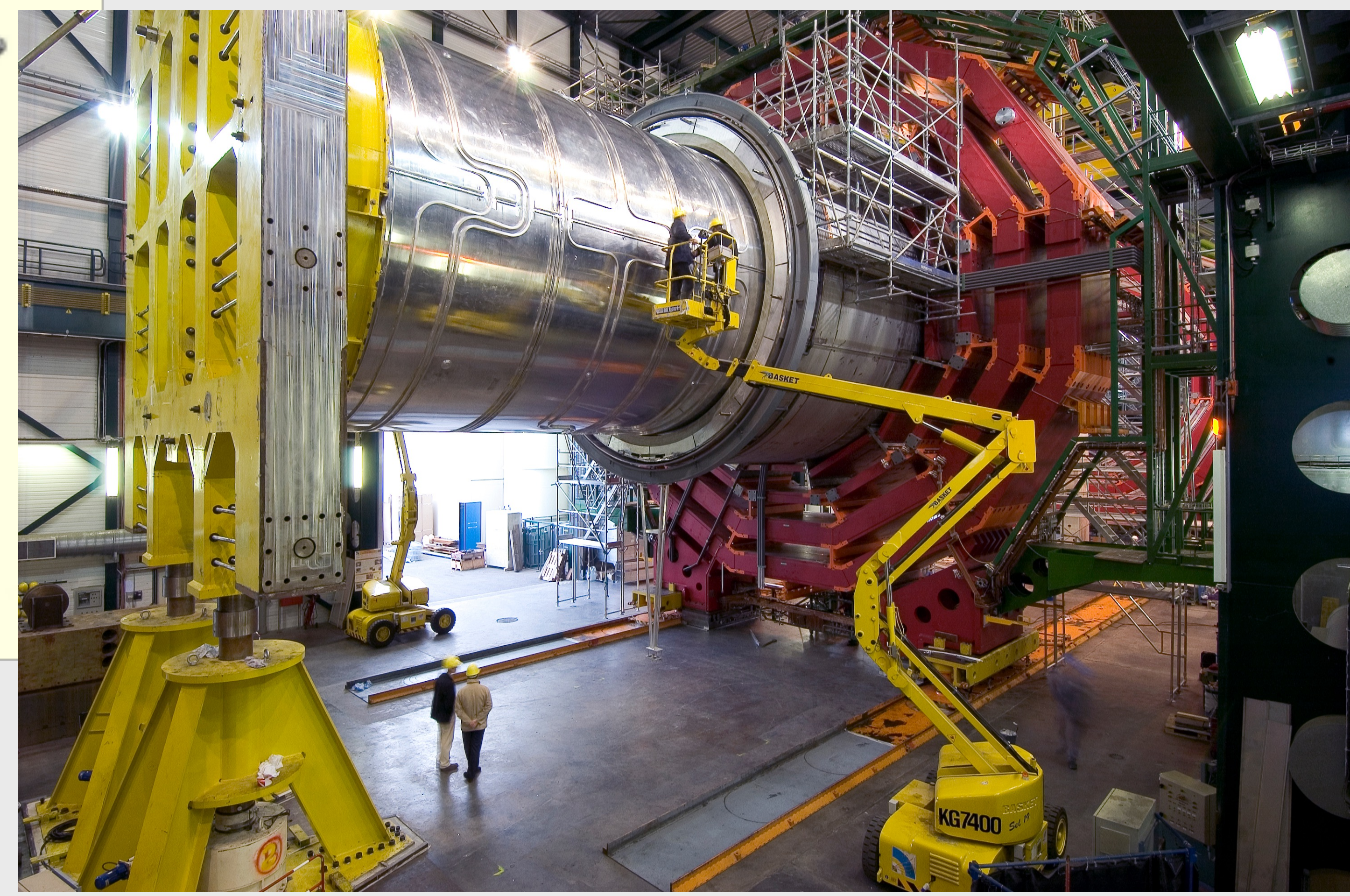
The real CMS detector



CMS solenoid - largest in the world -

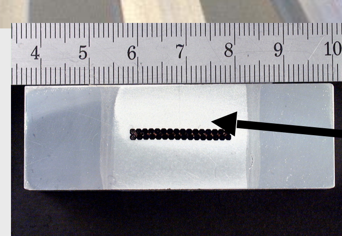


all 5 coil modules finished in 2004
assembly in CMS hall, Jan. 2005



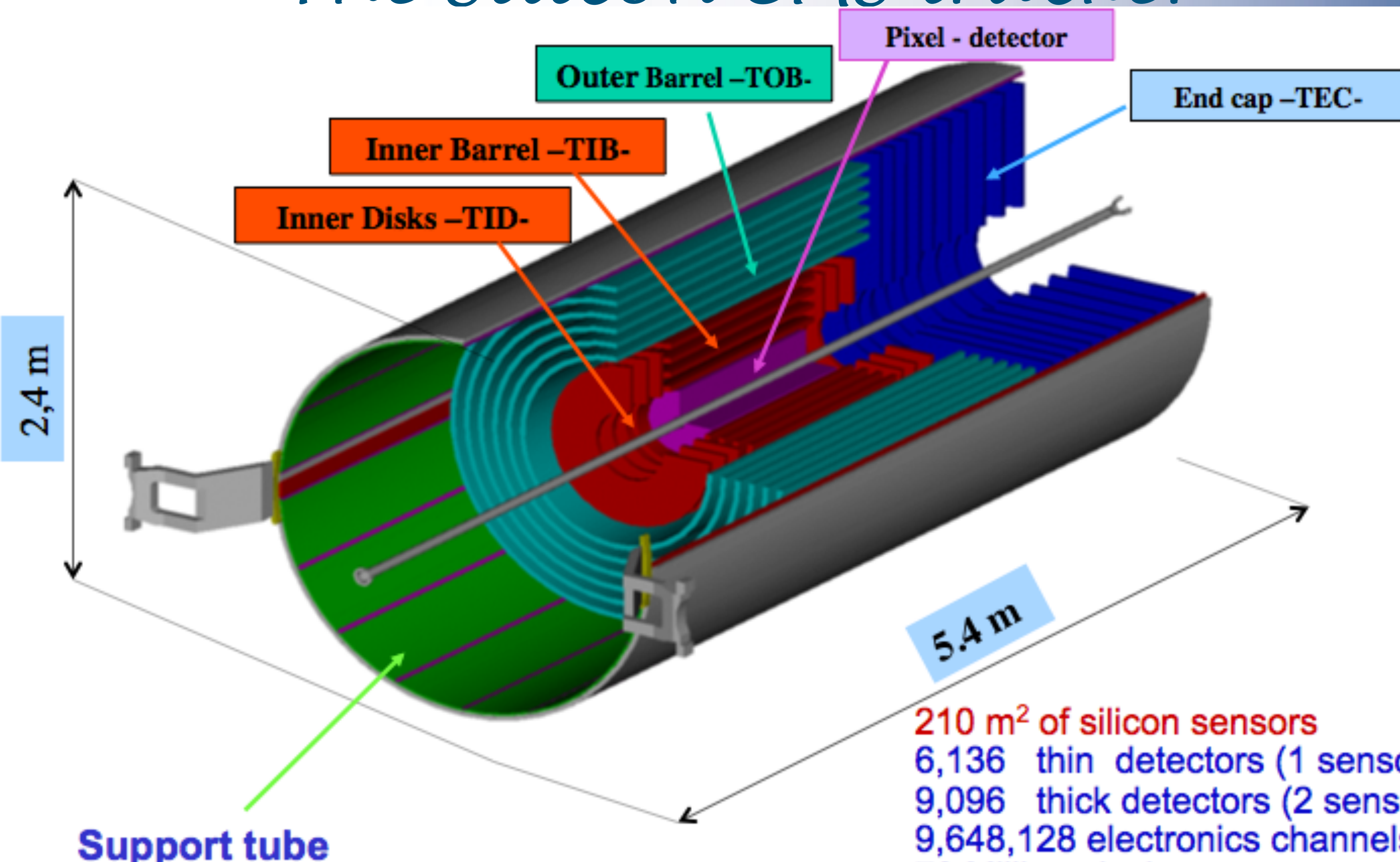
Insertion of coil in vacuum tank in September 05

s.c cable: all 21 lengths (53 km) finished in 2003

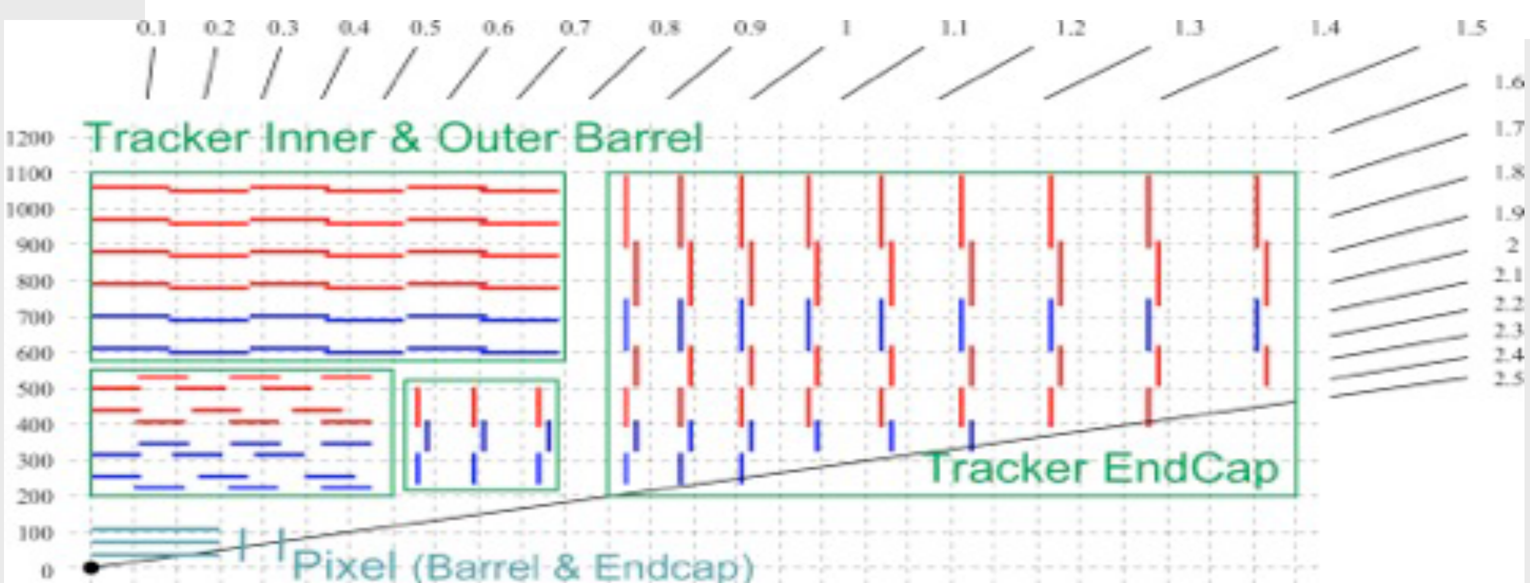


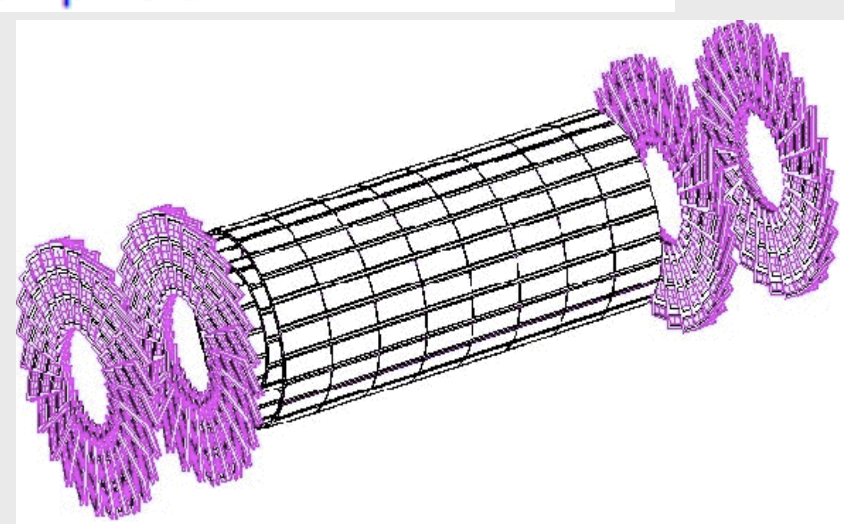
Insert with superconductor

The Silicon CMS tracker

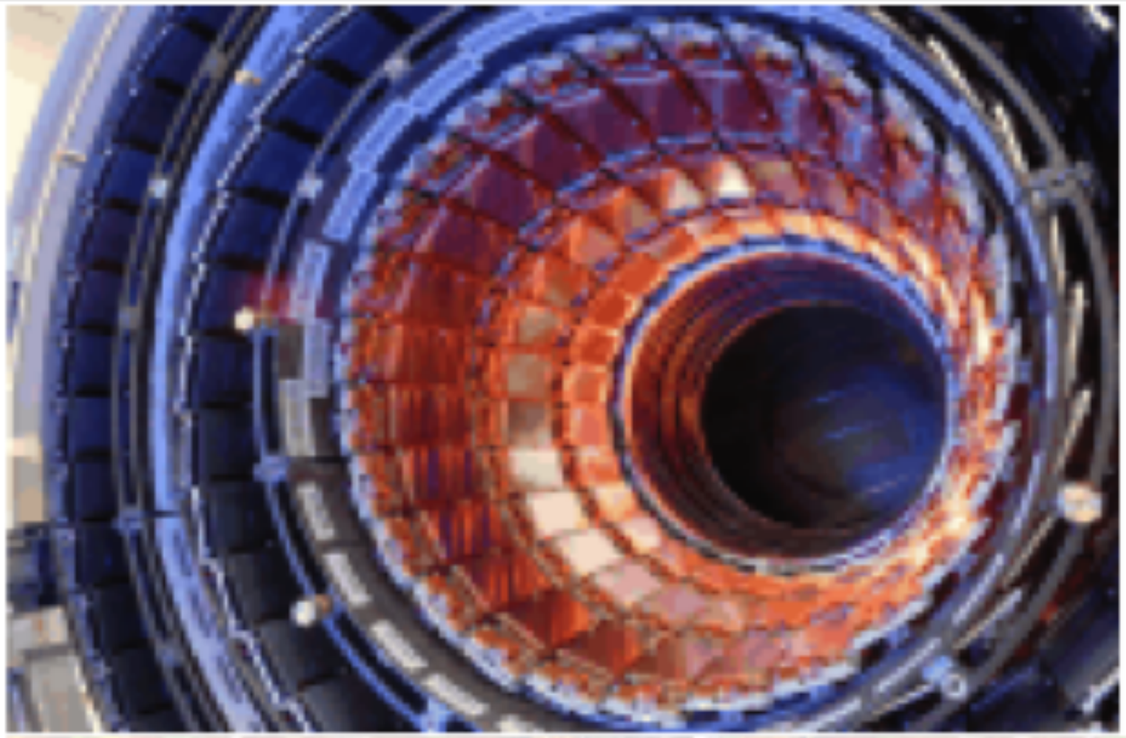


210 m^2 of silicon sensors
6,136 thin detectors (1 sensor)
9,096 thick detectors (2 sensors)
9,648,128 electronics channels
70 Million pixels





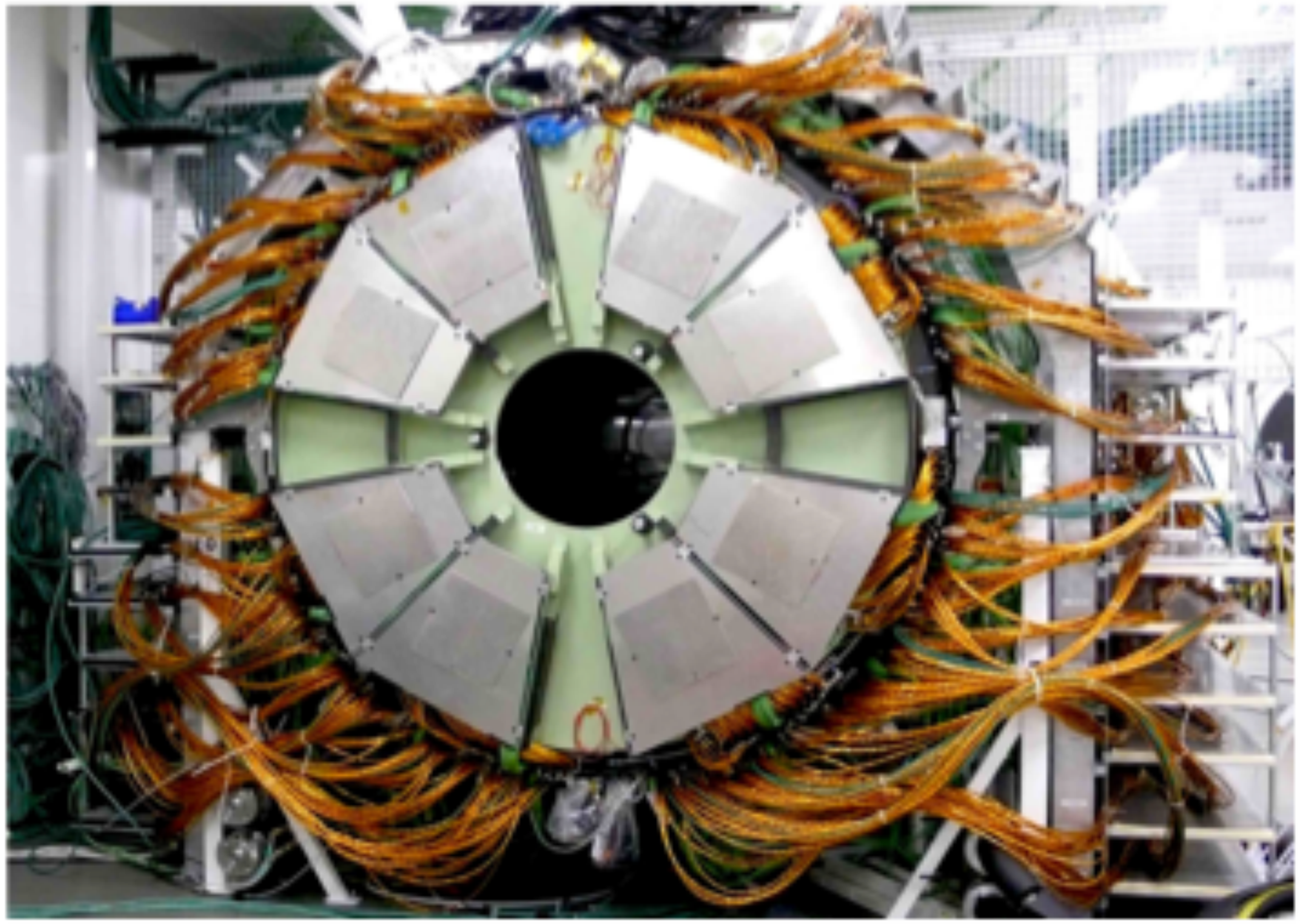
CMS tracker : components

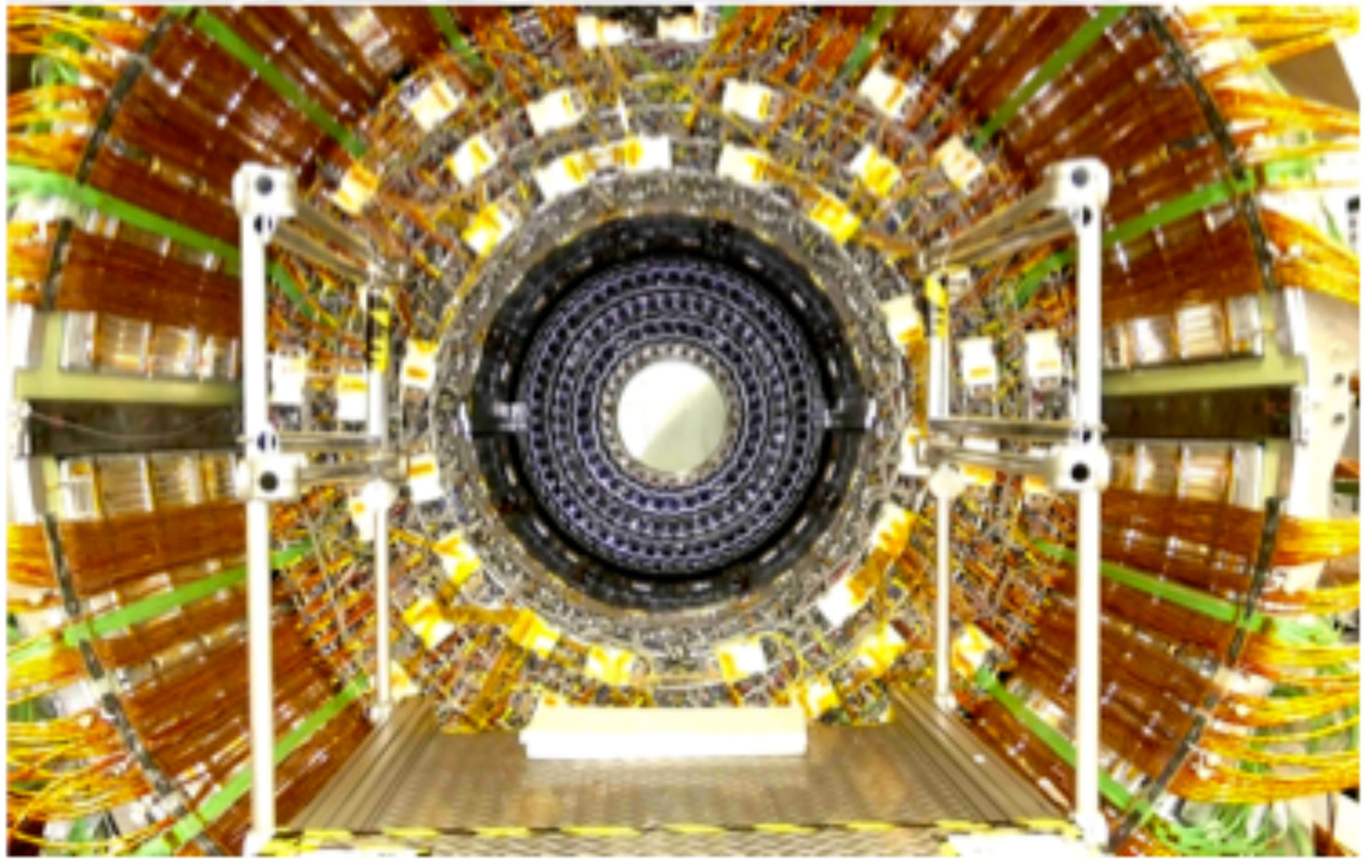


TIB+ completed

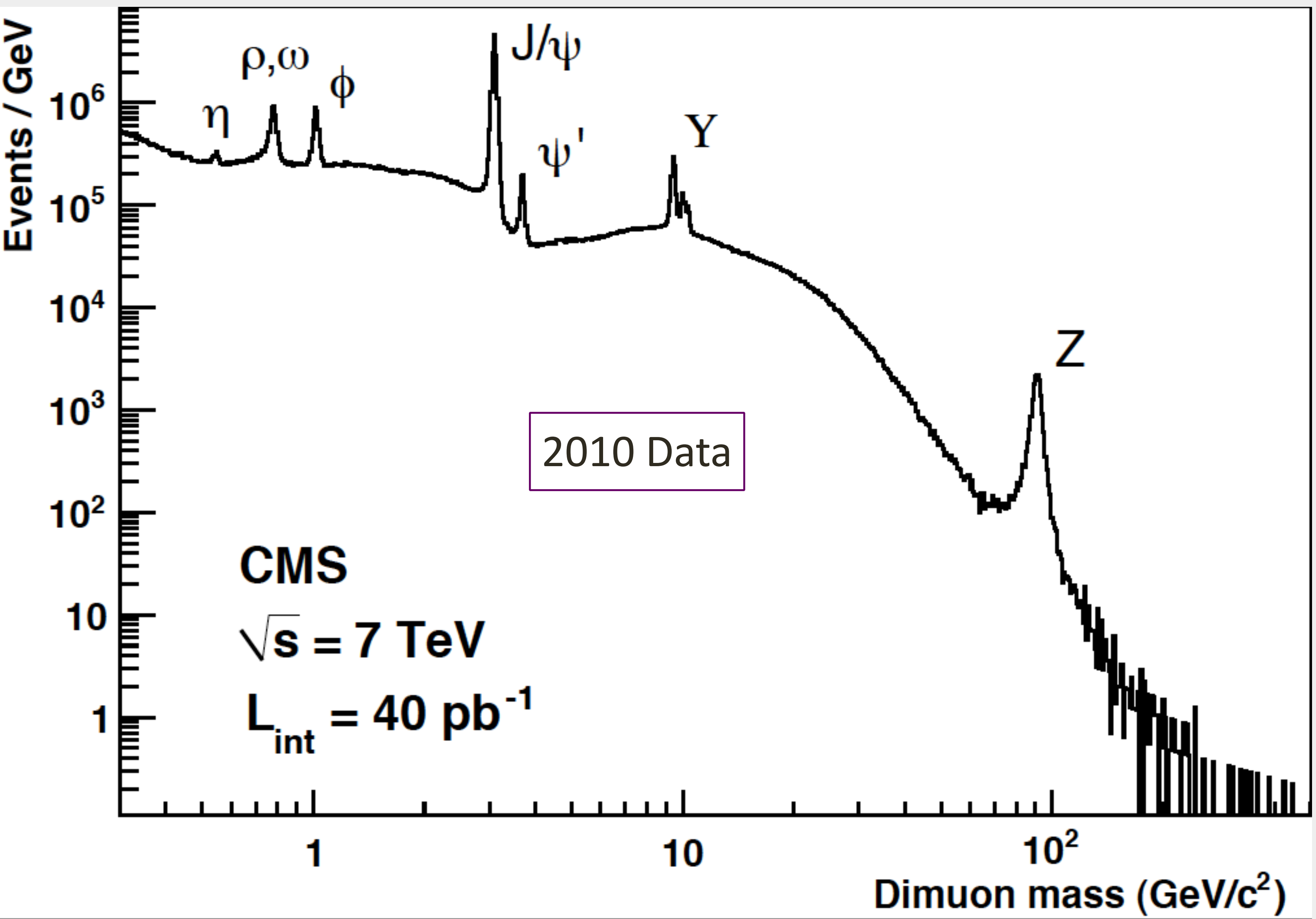
Tracker of CMS:
10 million Si-microstrips
and 70 million Si-pixels

TEC inserted into TST



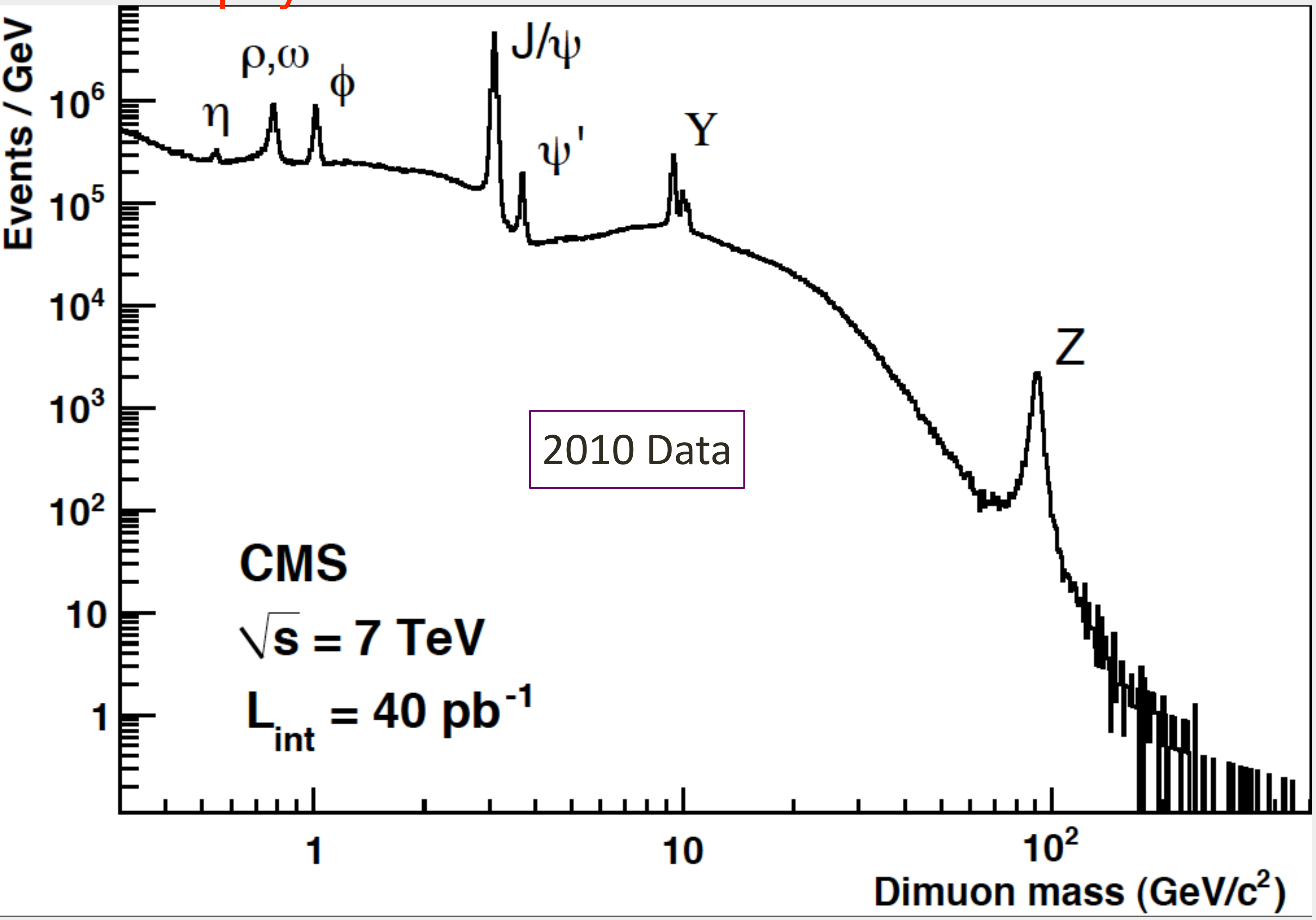


TIB+ inserted into TOB



And excellent muon trigger too!

- Excellent final tracking performance for physics



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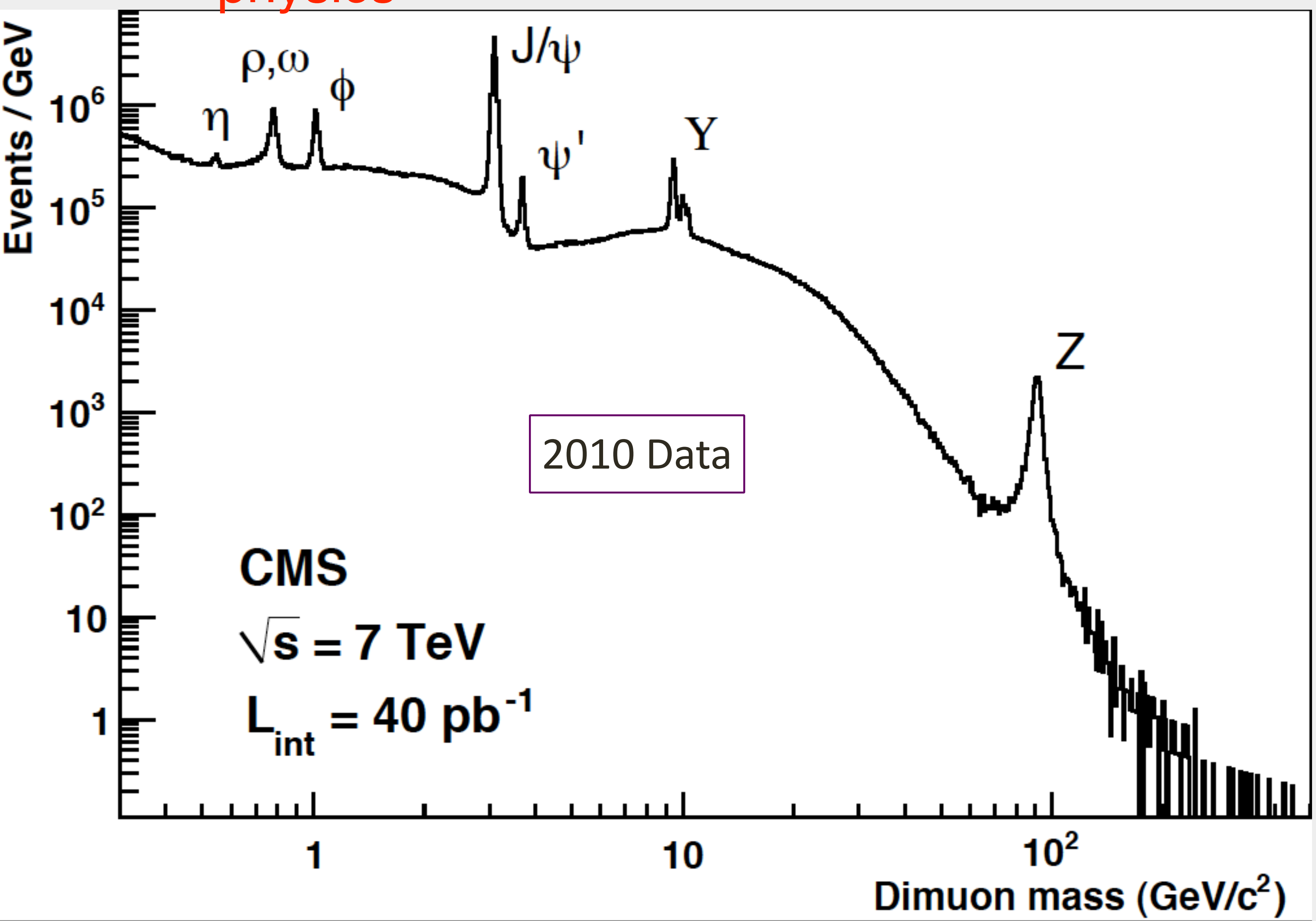
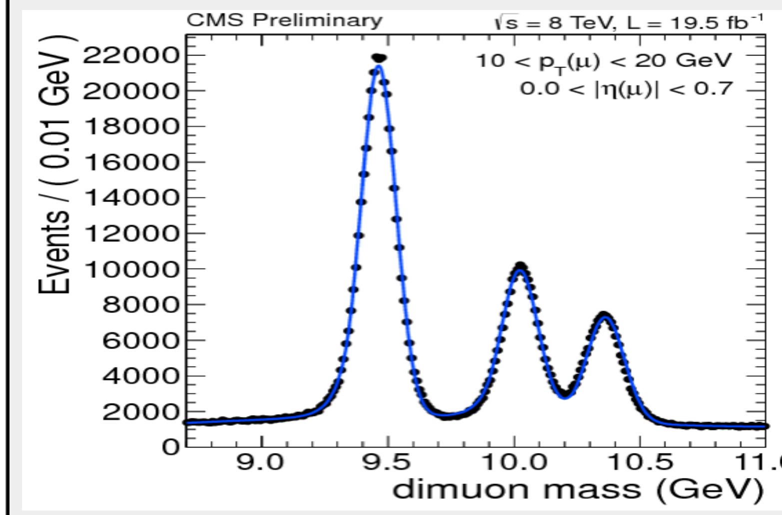
Tracking and Vertex Performance

- Excellent final tracking performance for physics

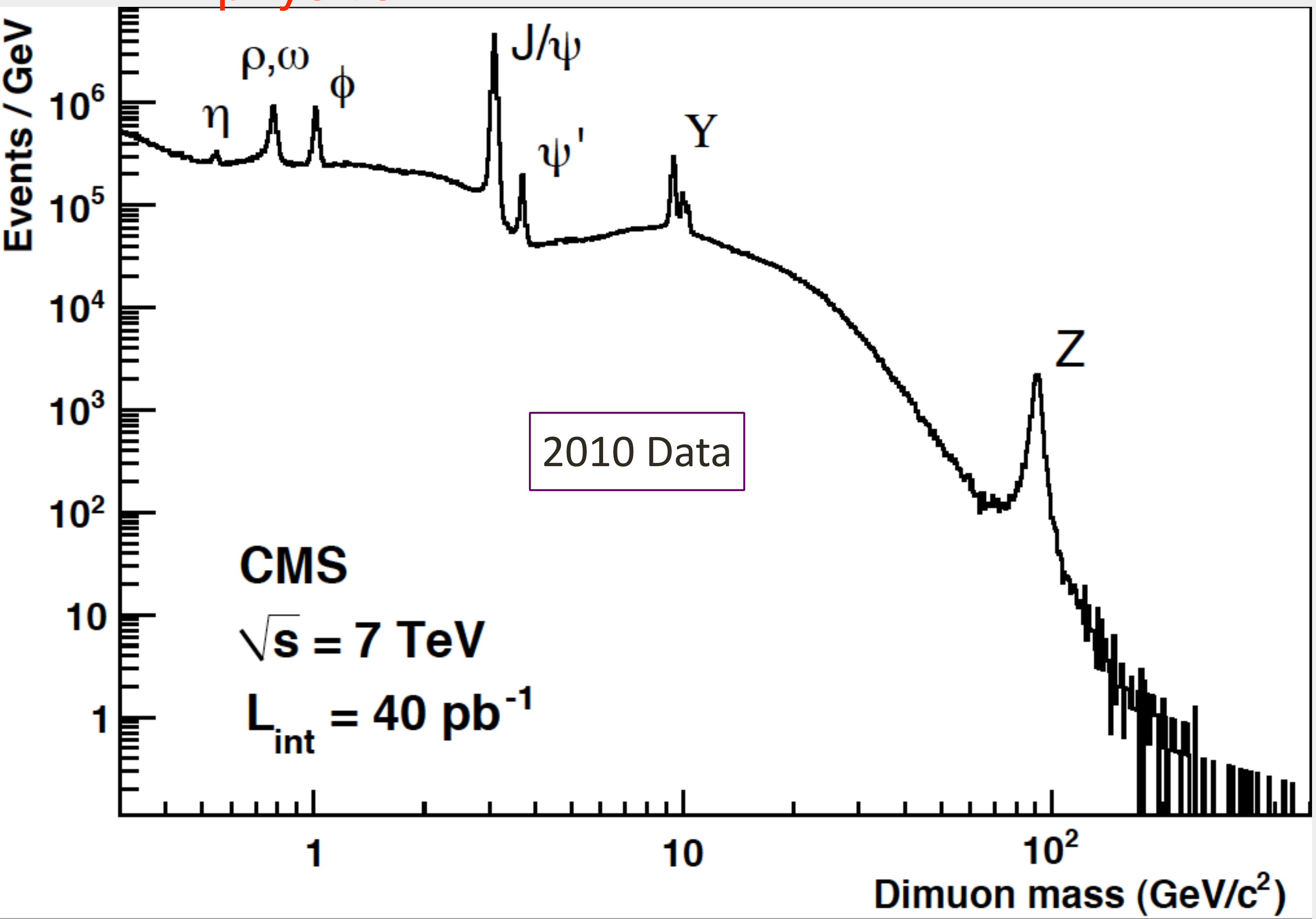


2012 Data

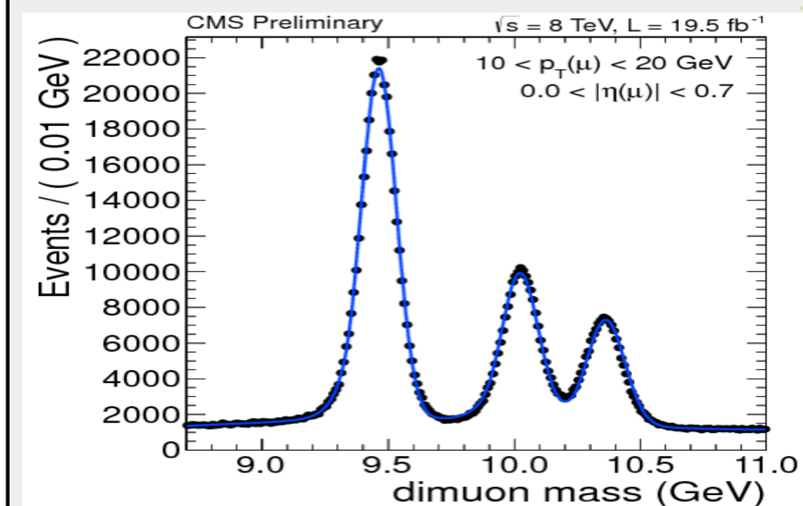


And excellent muon trigger too!

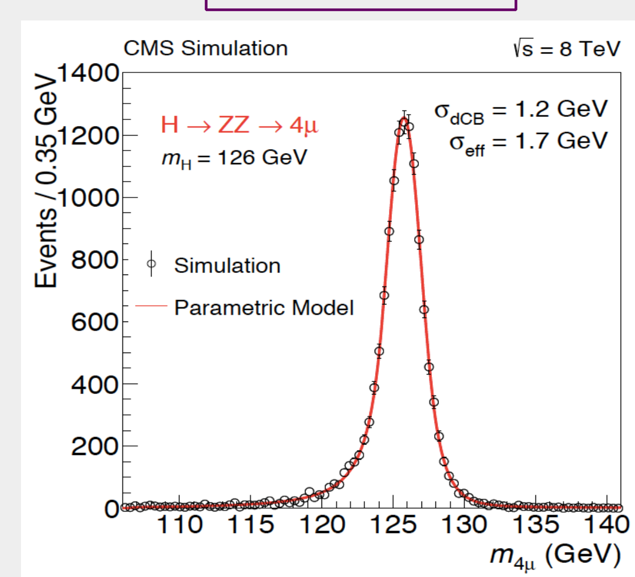
- Excellent final tracking performance for physics



2012 Data

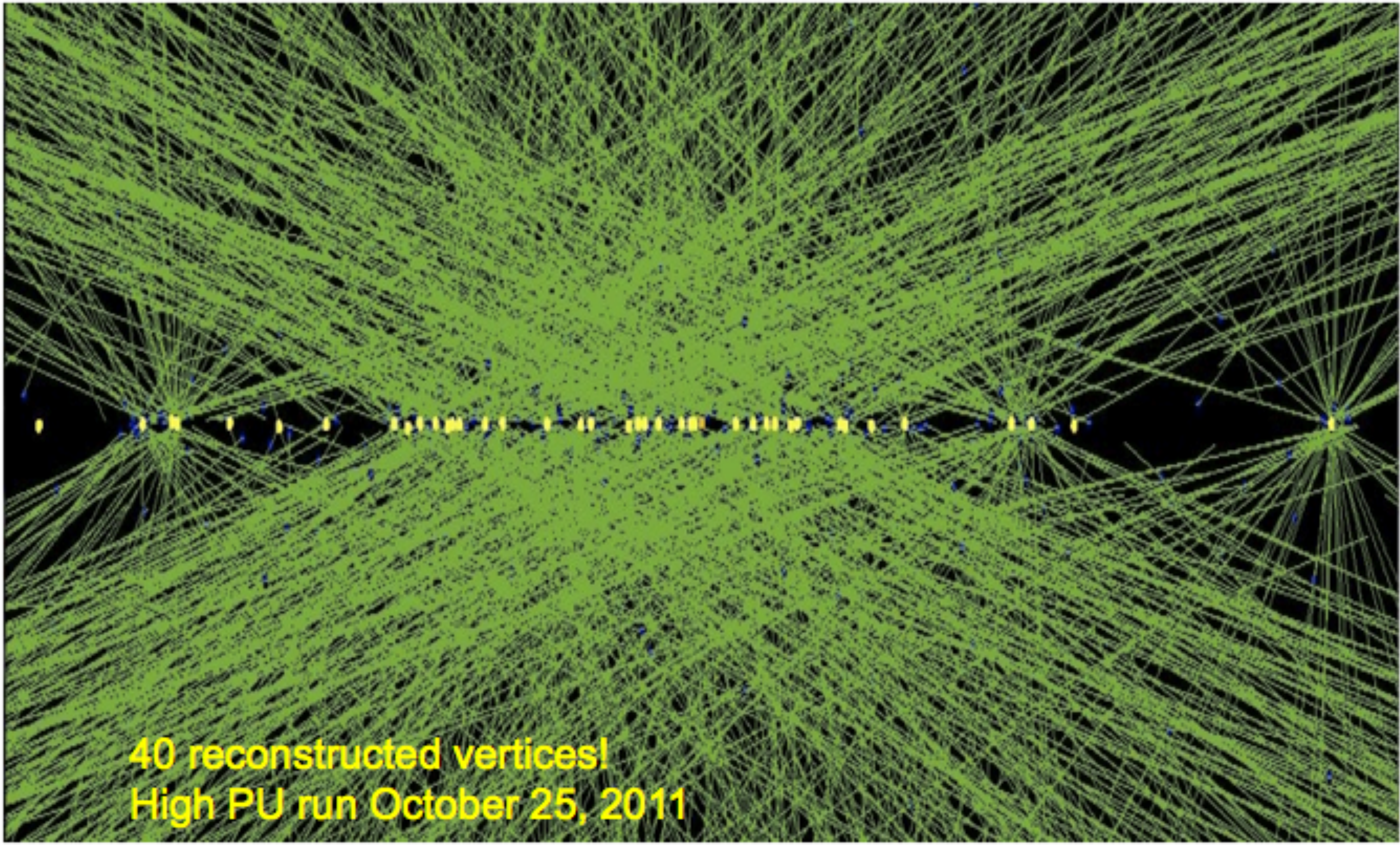


Simulation



And excellent muon trigger too!

Pile-up for 30 superimposed events



Electromagnetic calorimeter

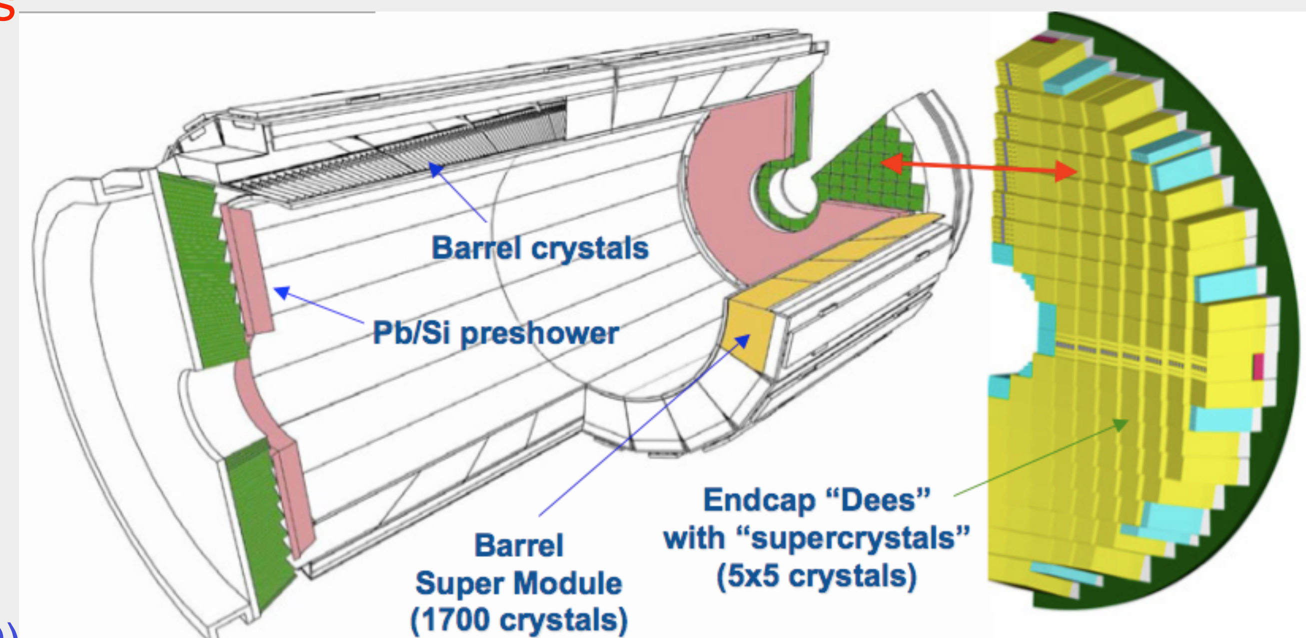
- Homogeneous Lead tungstate $PbWO_4$ crystals
- Fast scintillation response, excellent time resolution
  - about 80% of the light emitted in 25 ns
- Compact & high granularity
  - Molière radius 2.2 cm
  - Radiation length X_0 0.89 cm

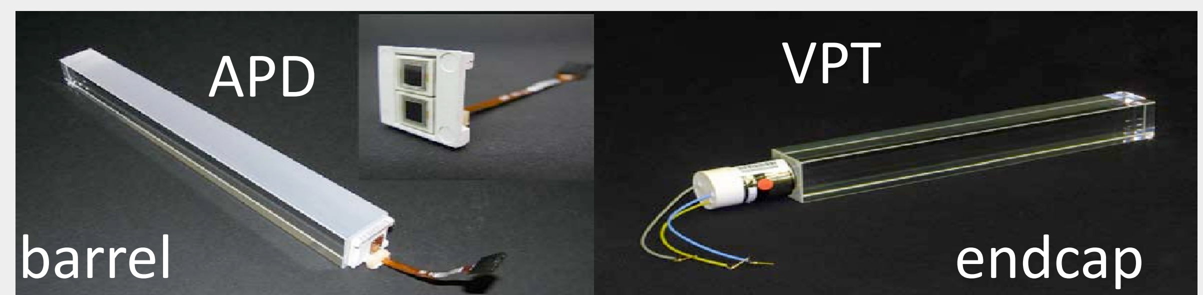
- Barrel $|\eta|<1.48$:
  - ~61K crystals in 36 SuperModules (SM)
  - $2x2x23\ cm^3$ covering 26 X_0
  - Photodetector: Avalanche Photo Diodes (APD)
- Endcap $1.48 <|\eta|<3.0$
  - ~15k crystals in 4 Dees
  - $3x3x22\ cm^3$ covering 24 X_0
  - Photodetector: Vacuum Photo Triodes (VPT)
- Preshower $1.65 <|\eta|<2.6$
  - ~137k silicon strips in 2 planes per endcap
  - $3X_0$ of lead radiator

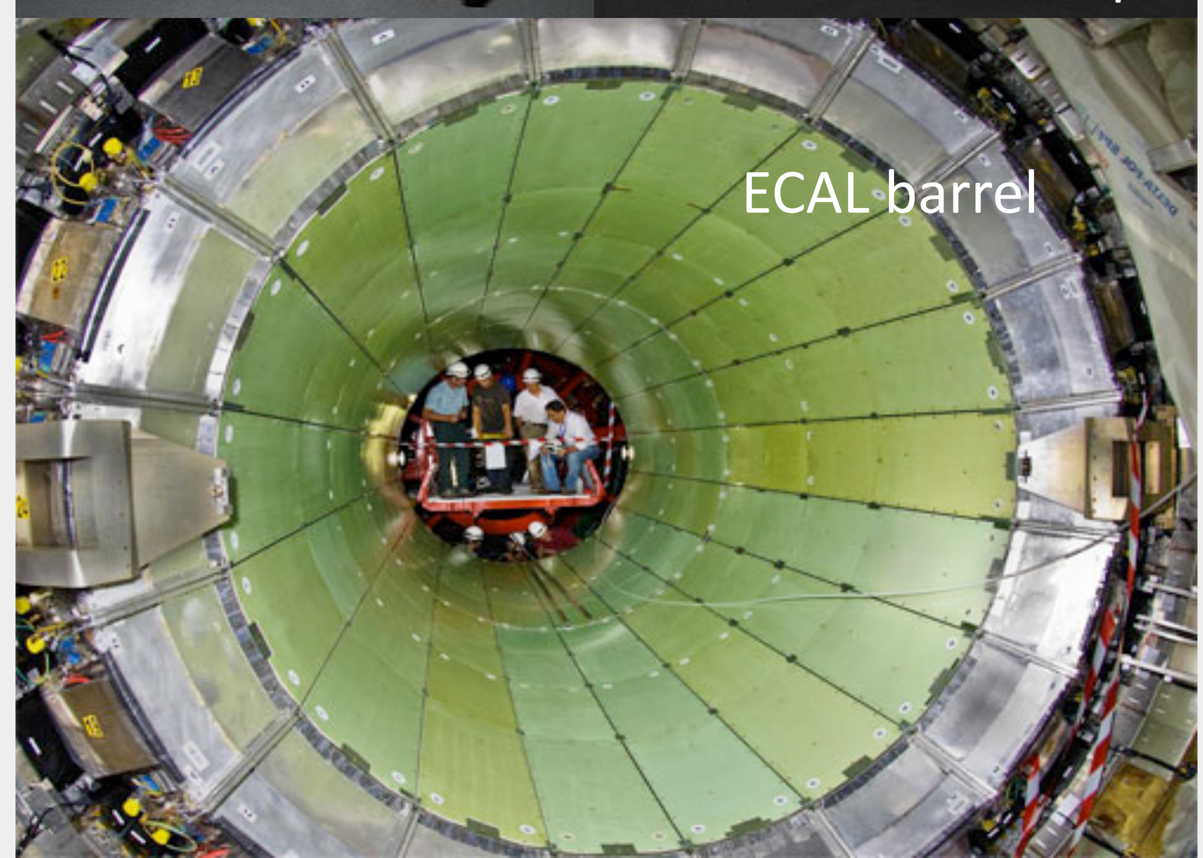
- No longitudinal segmentation

- Energy resolution for electrons impinging on the center of a 3x3 barrel crystal matrix from Test Beam (no upstream material, no magnetic field, etc…)

$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E\ (GeV)}} \oplus \frac{0.128}{E\ (GeV)} \oplus 0.3\%$$



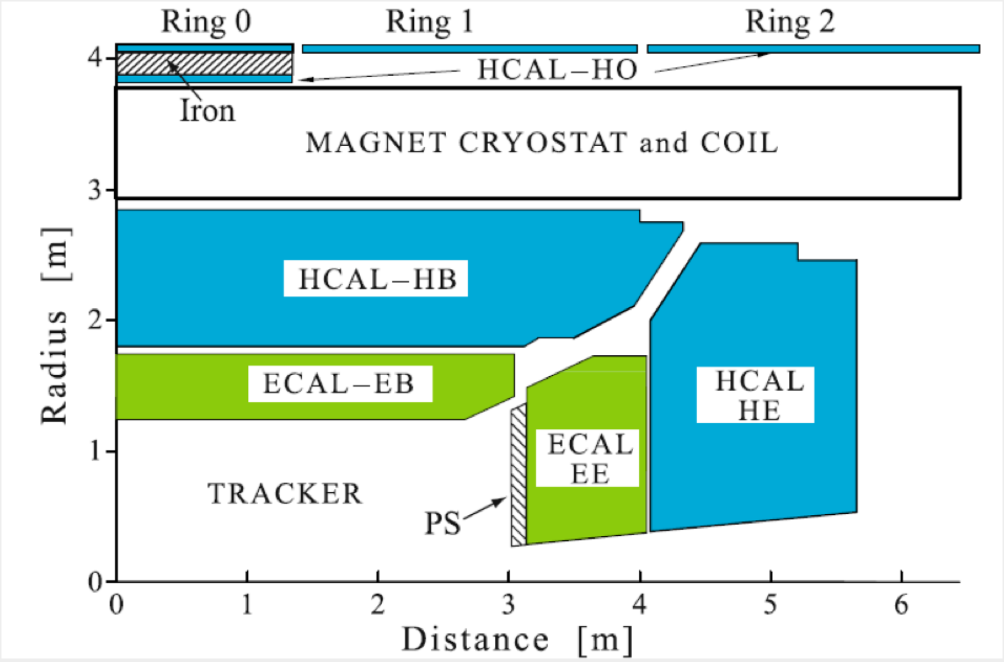


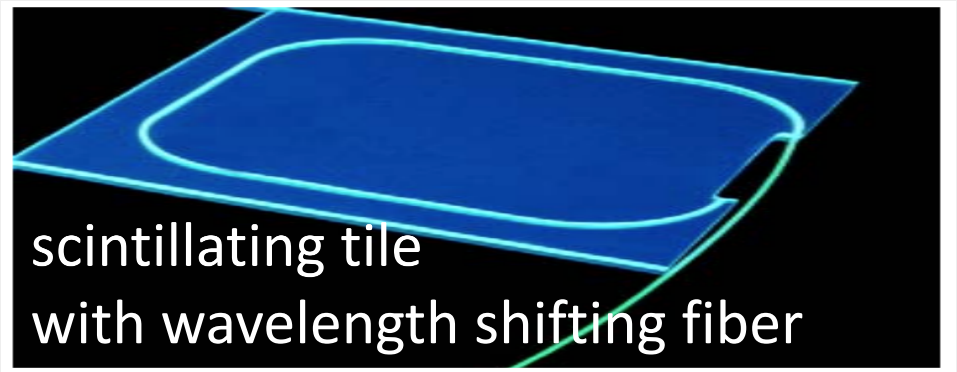


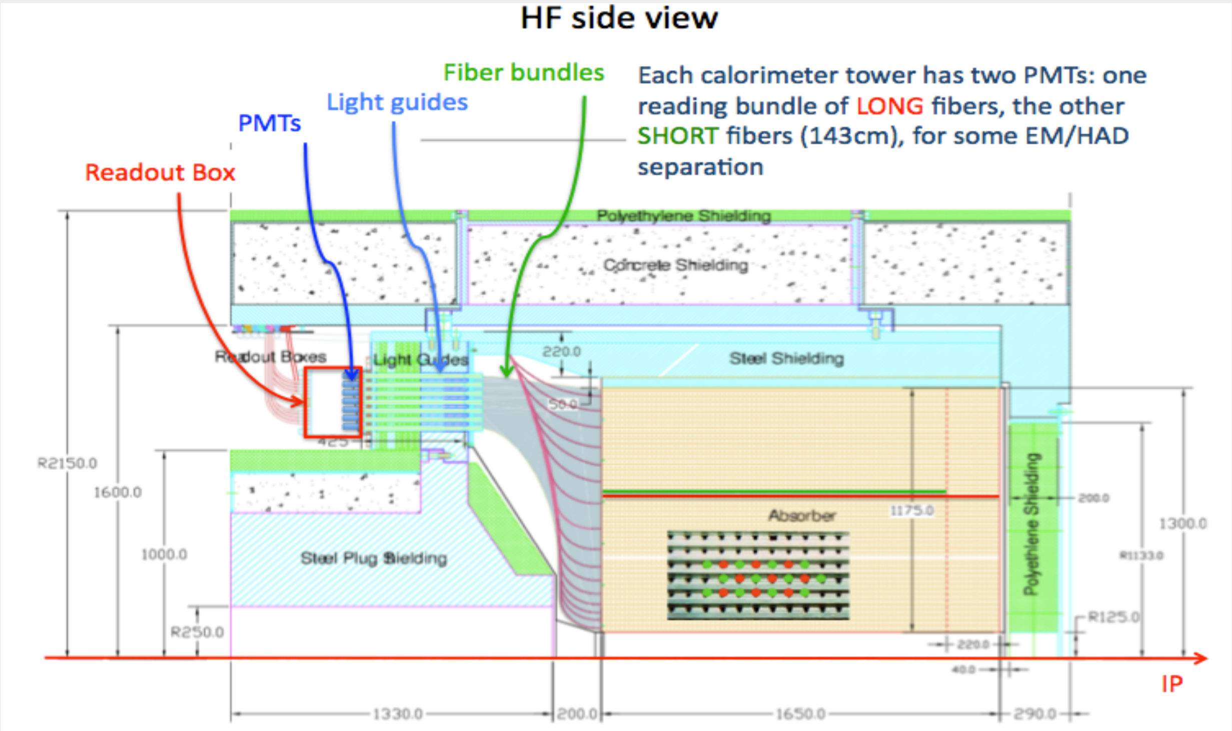
Hadron Calorimeter : brass-scintillator sampling calorimeter

Hadron calorimeter

- HCAL Barrel (HB) 0<lηl<1.3 and Endcap (HE) 1.3<lηl<3
  - Sampling calorimeter, alternating layers of brass absorber and plastic scintillator tiles.
  - Hybrid photo-detector (HPD) readout
- Outer (HO): Outside solenoid
  - Tail catcher with scintillator layers
  - HPD readout
- Forward (HF) at lzl=11 m: 2.9<lηl<5
  - Cherenkov light from scintillating quartz fibers in steel absorber
  - read out with conventional PMTs
- Stability of photo-detector gains monitored using LED system
- Pedestals, and signal synchronization (timing) monitored using Laser data







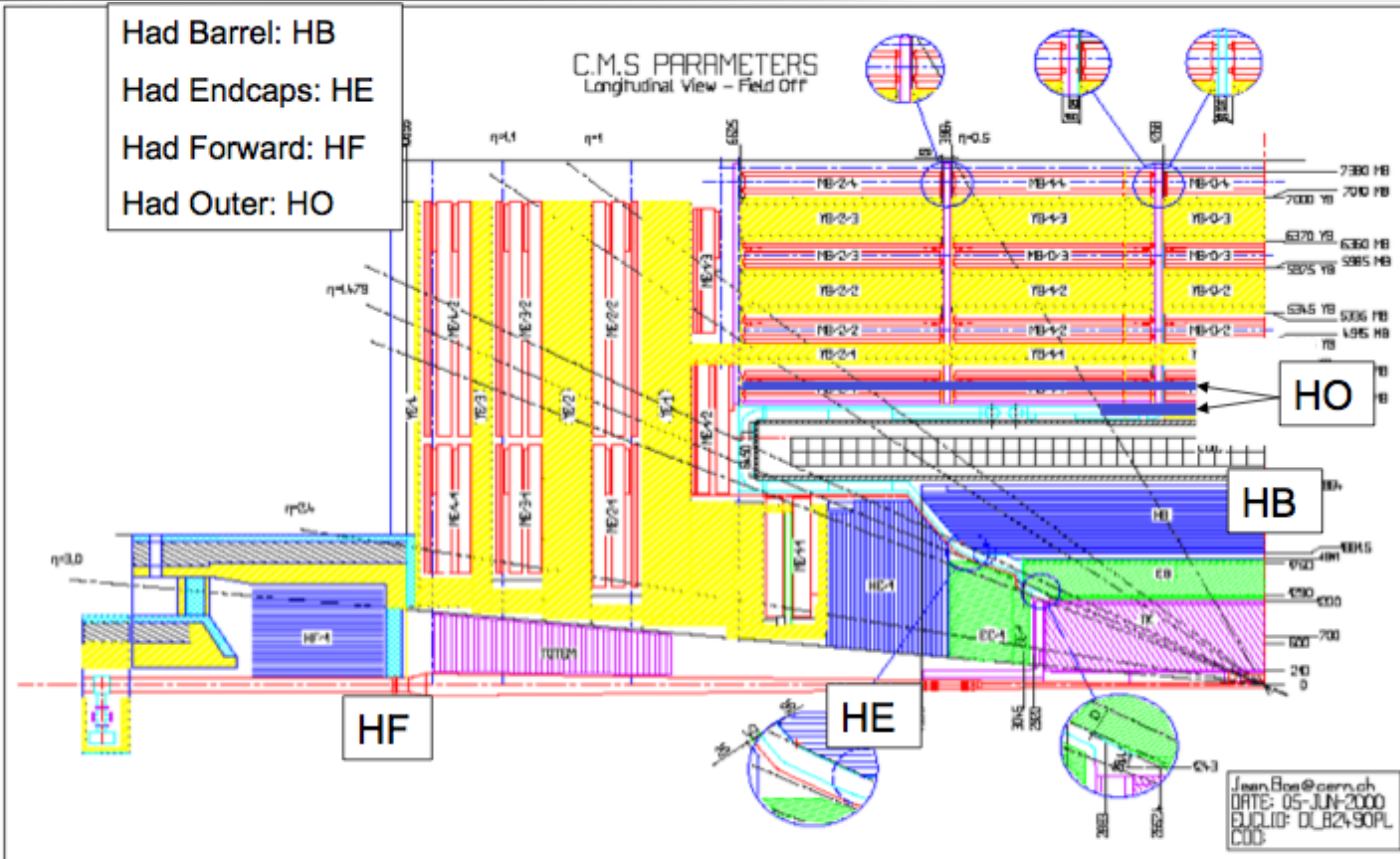
Hadron calorimeters in CMS

Had Barrel: HB

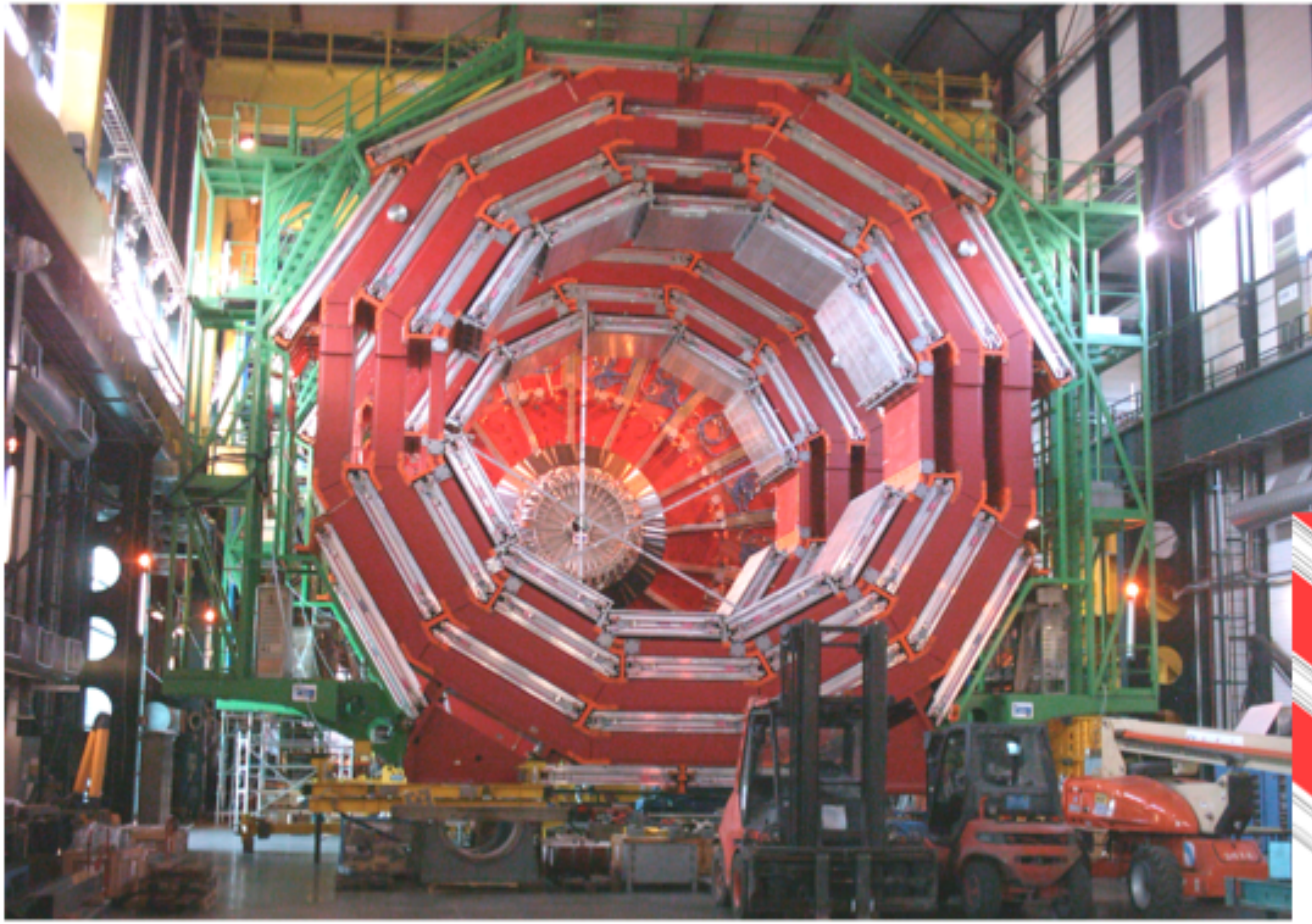
Had Endcaps: HE

Had Forward: HF

Had Outer: HO



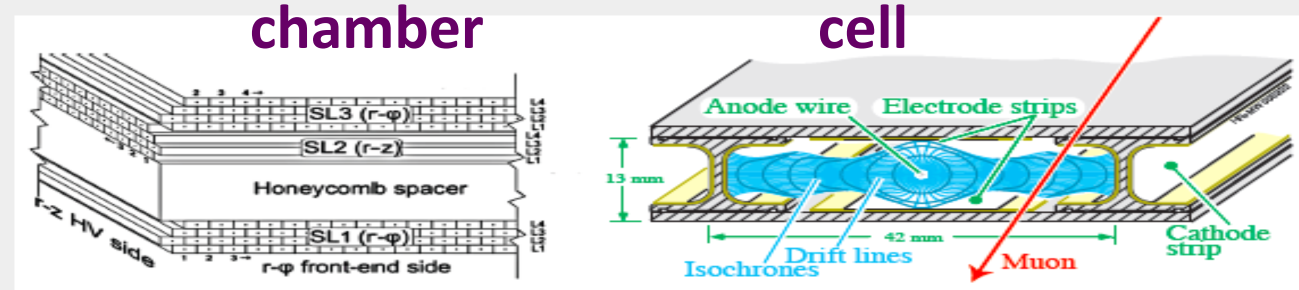
Barrel Muon System



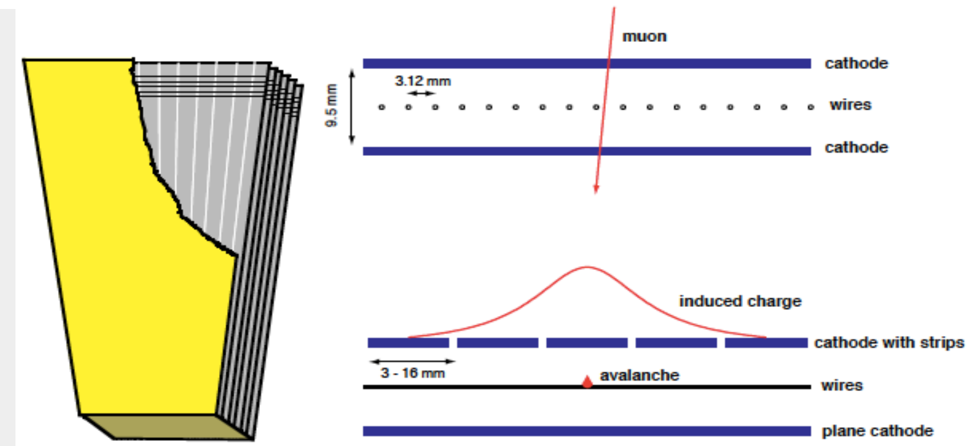
12 layers per chamber

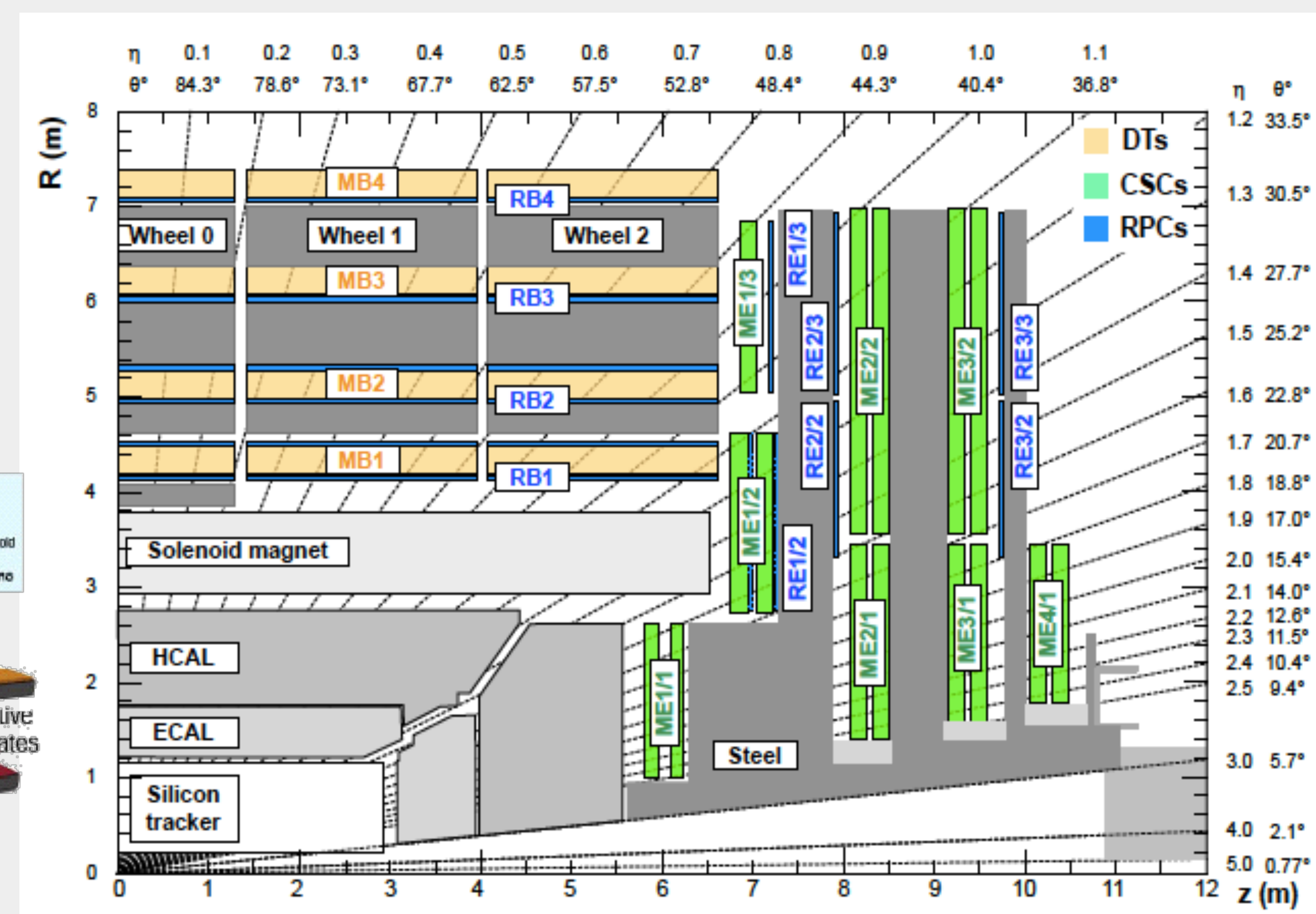
Muon System

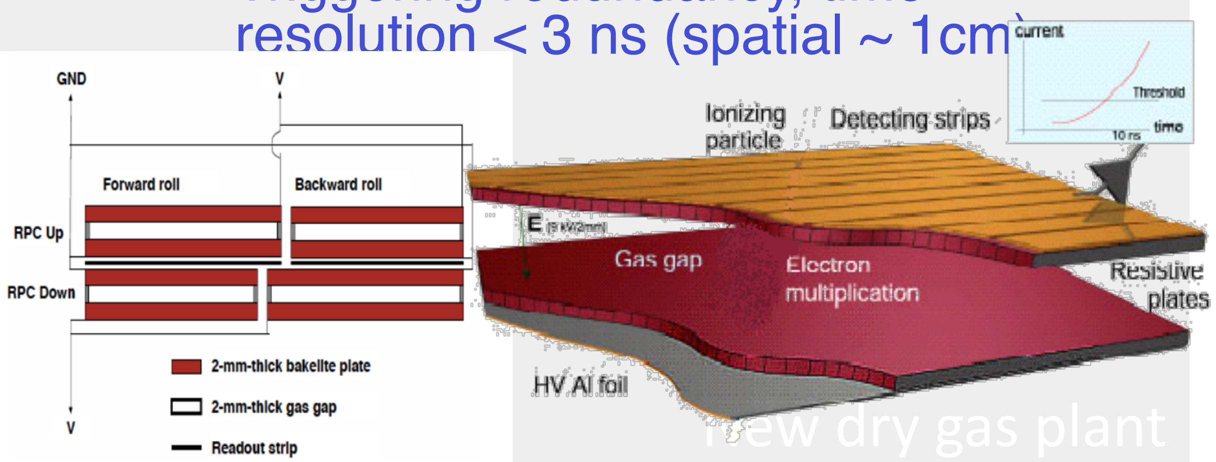
- Drift Tubes (DT) |η|< 1.2
  - 4 stations/wheel
  - cell 42x13 mm^2
  - gas mixture 85% Ar, 15% CO_2
  - drift velocity ~ 55 μm/ns, maximum drift time ~ 400 ns
  - Time resolution <3 ns, spatial ~100 μm
- Cathode Strip Chambers (CSC) 0.9<|η|< 1.2 (MWPC)
  - 1 CSC has 6 layers, strips measure r-ϕ, wires radial
  - gas 50% CO_2, 40% Ar, 10% CF_4
  - 4 stations subdivided in rings
  - Time resolution ~3ns, spatial 50-150 μm
- Resistive Plate Chambers (RPC) |η|< 1.6
  - Double-gap chambers in avalanche mode
  - gas 95.2% Freon, 4.5% isobutane
  - Triggering redundancy, time resolution < 3 ns (spatial ~ 1cm)



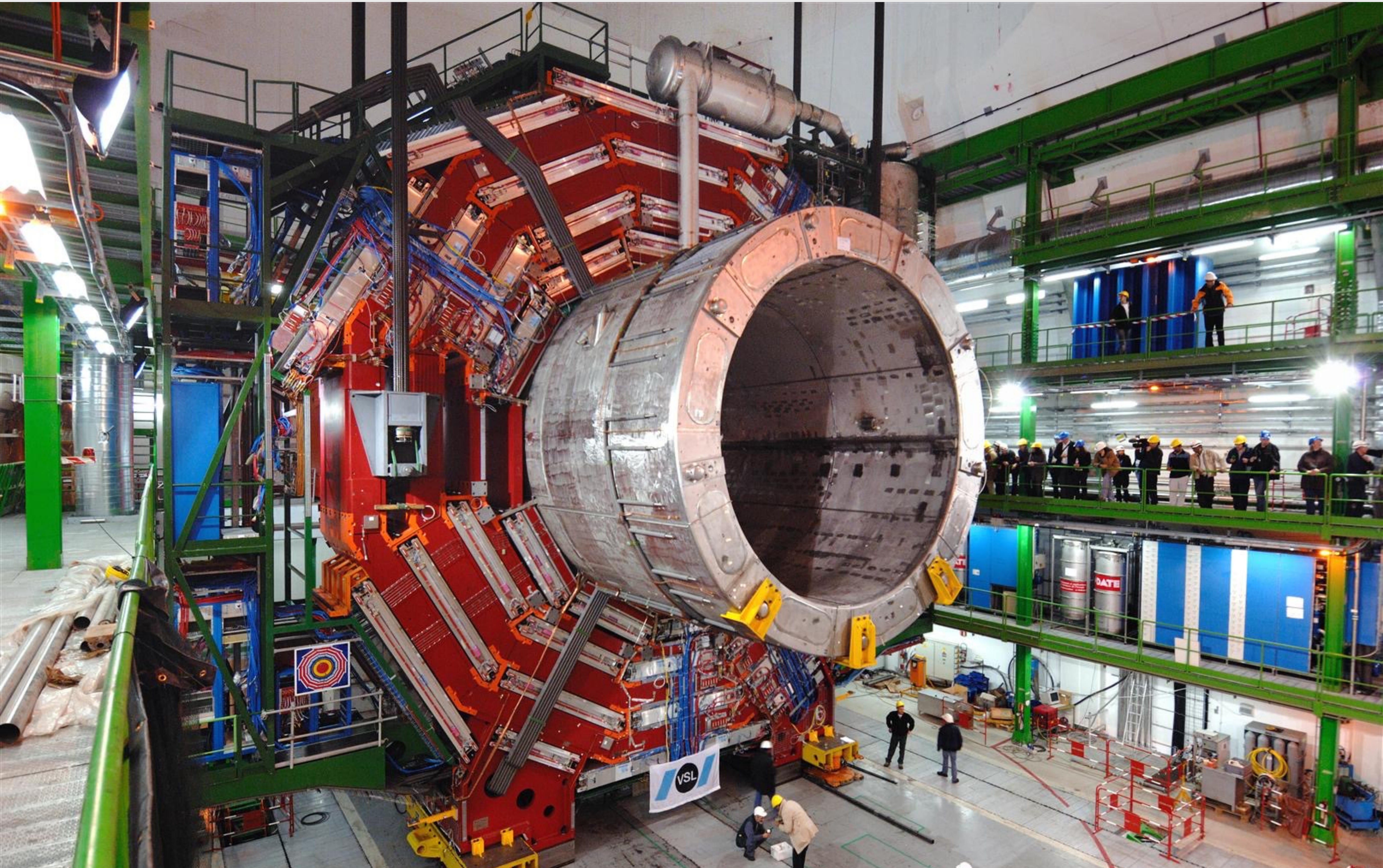
$$x_{hit} = t_{drift} \cdot v_{drift} \equiv (t_{TDC} - t_{ped}) \cdot v_{drift}$$



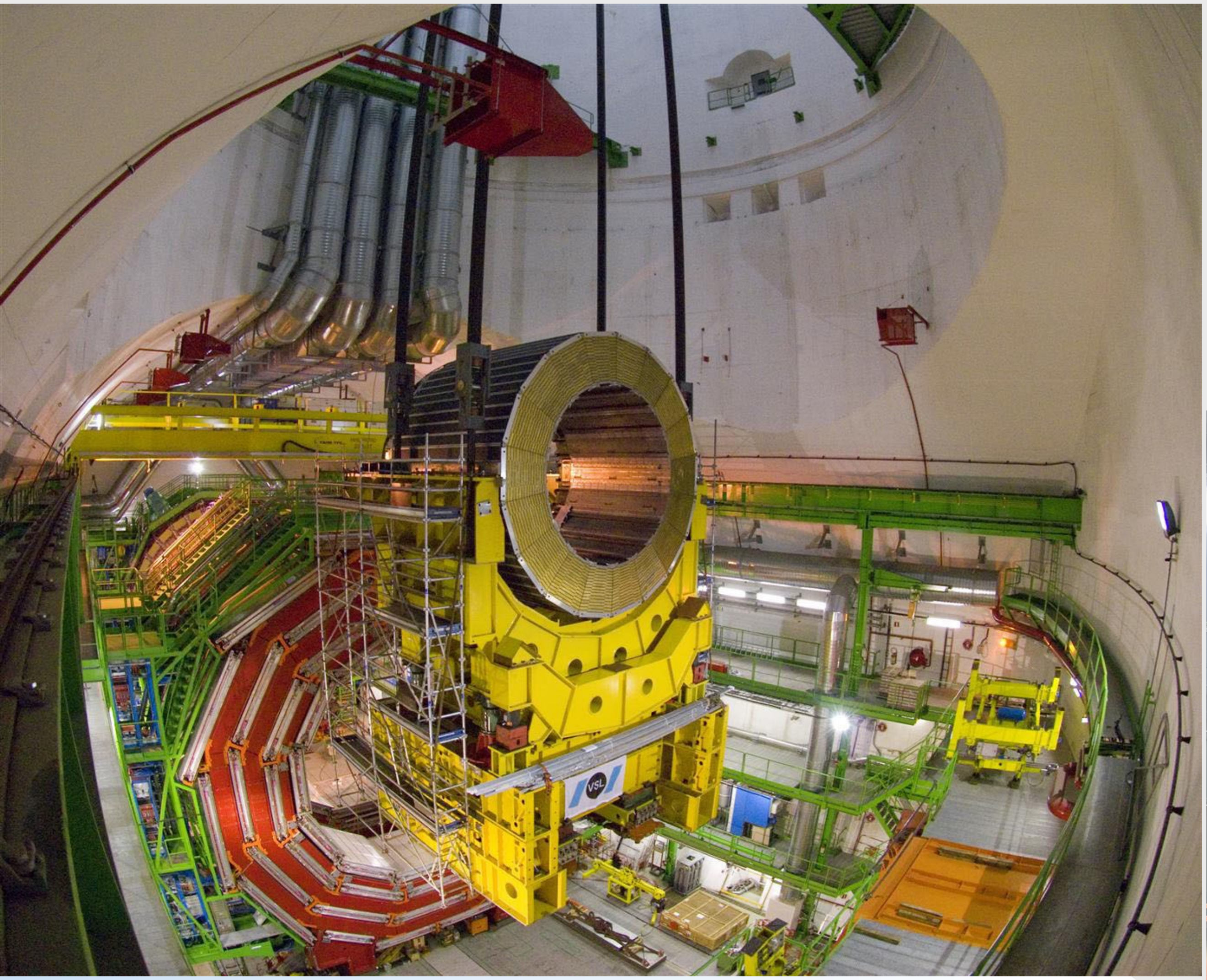


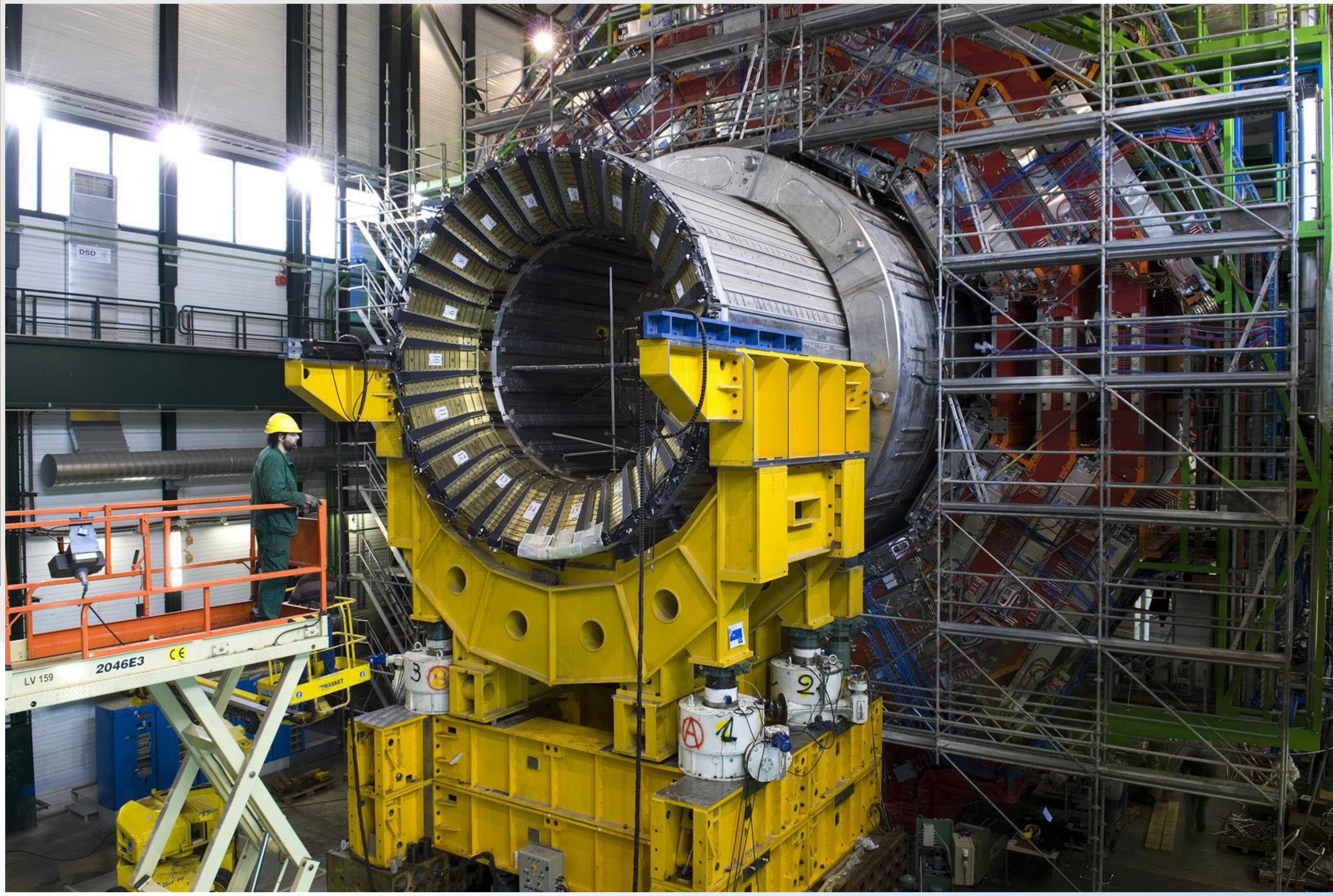


YB0 in the CMS experimental cavern in Feb 2007

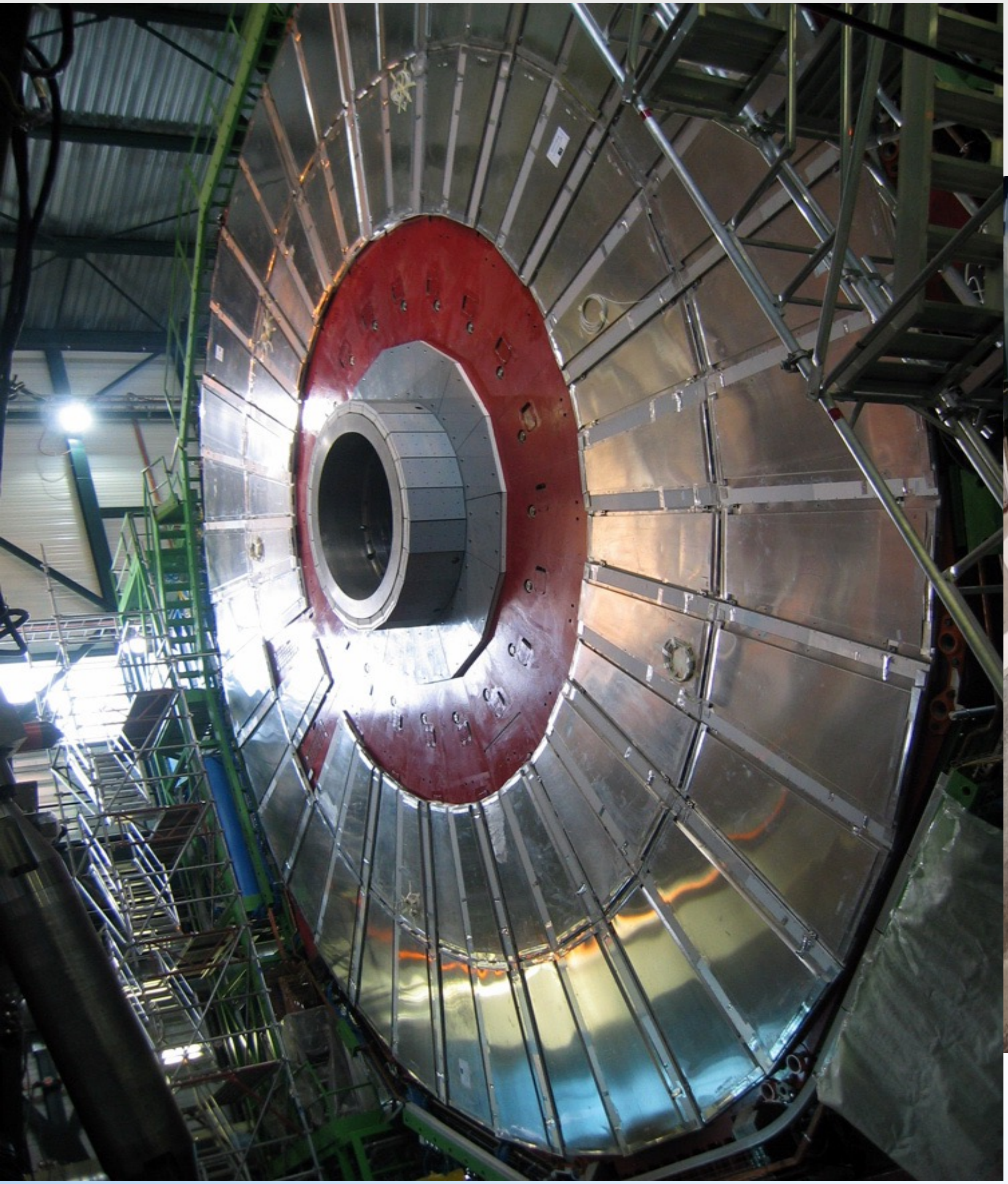


Hadron Calorimeter

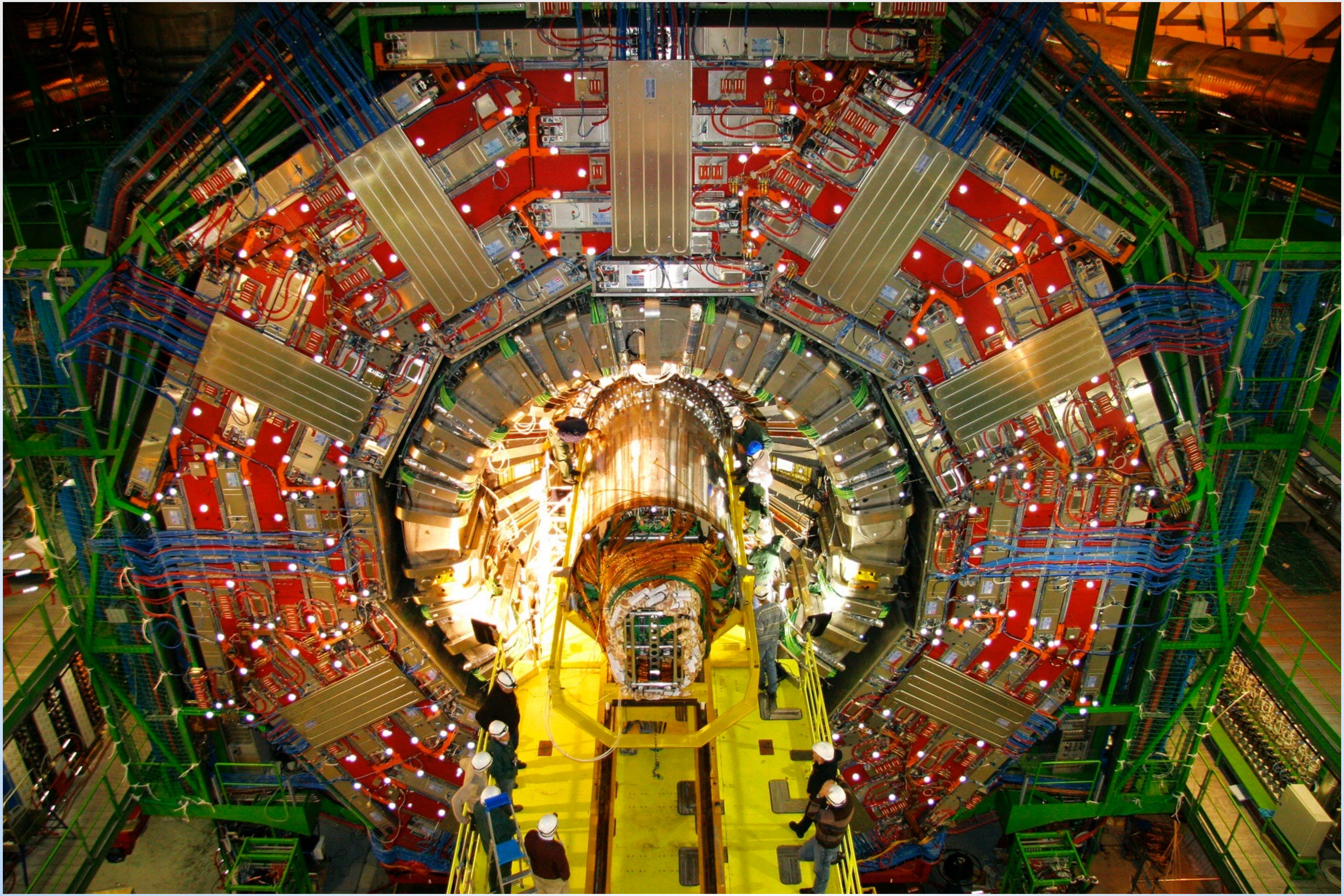




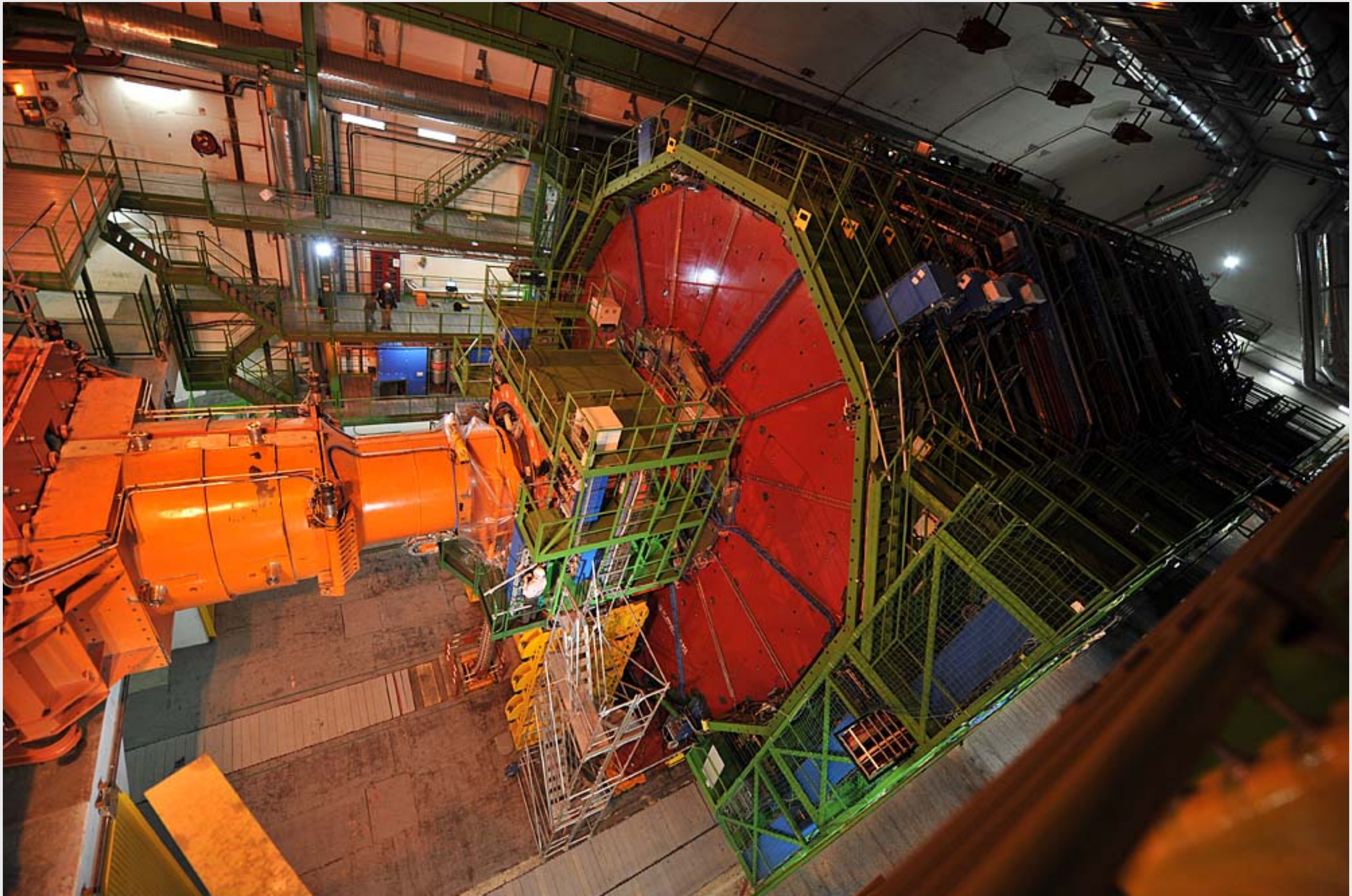
Muons chamber



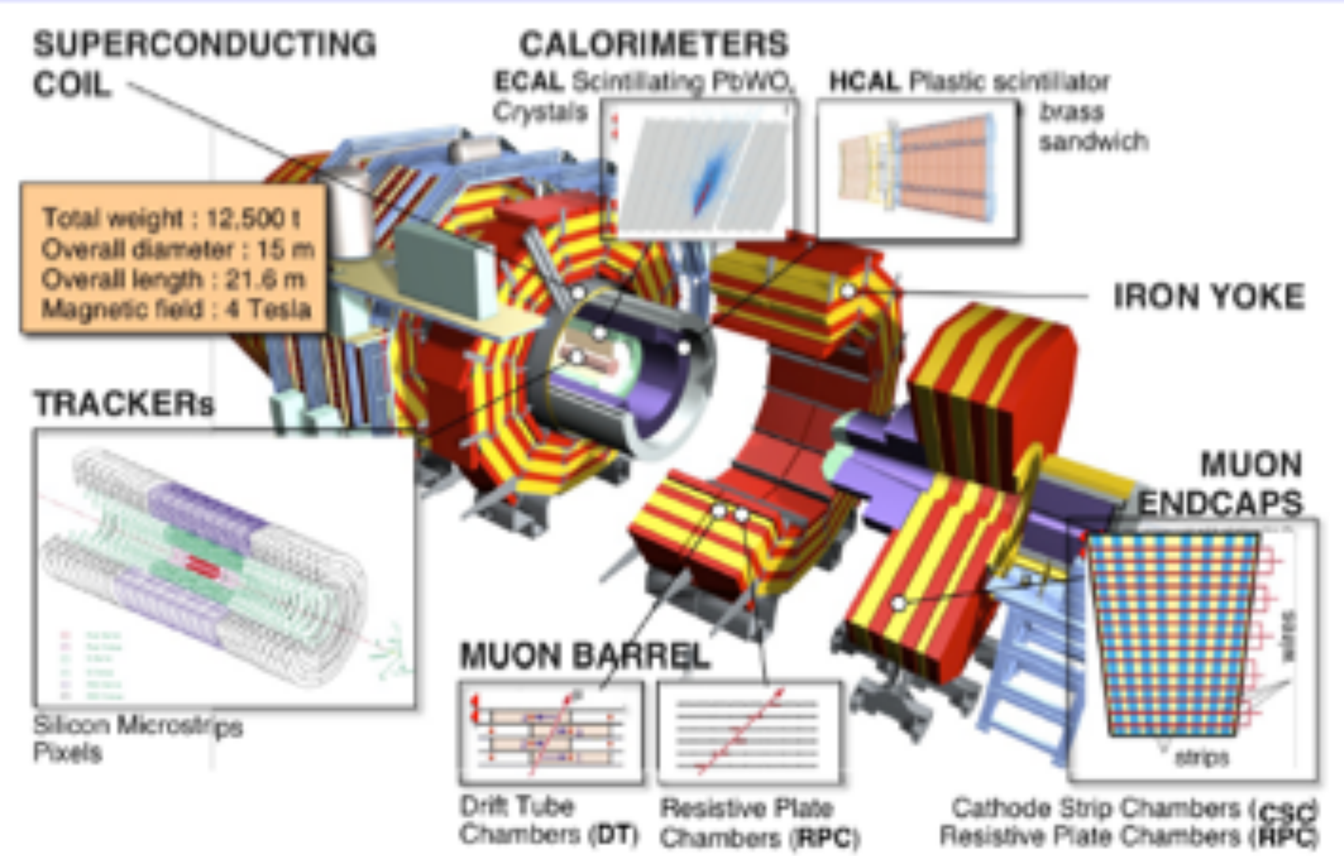
Tracker Insertion



Final closure of CMS - September 2008 - ready for initial collisions



CMS performence



|η|<2.5 : Tracker

$\sigma/p_T \approx 10^{-4} p_T \oplus 0.005$

|η|<4.9 : EM Calorimeter

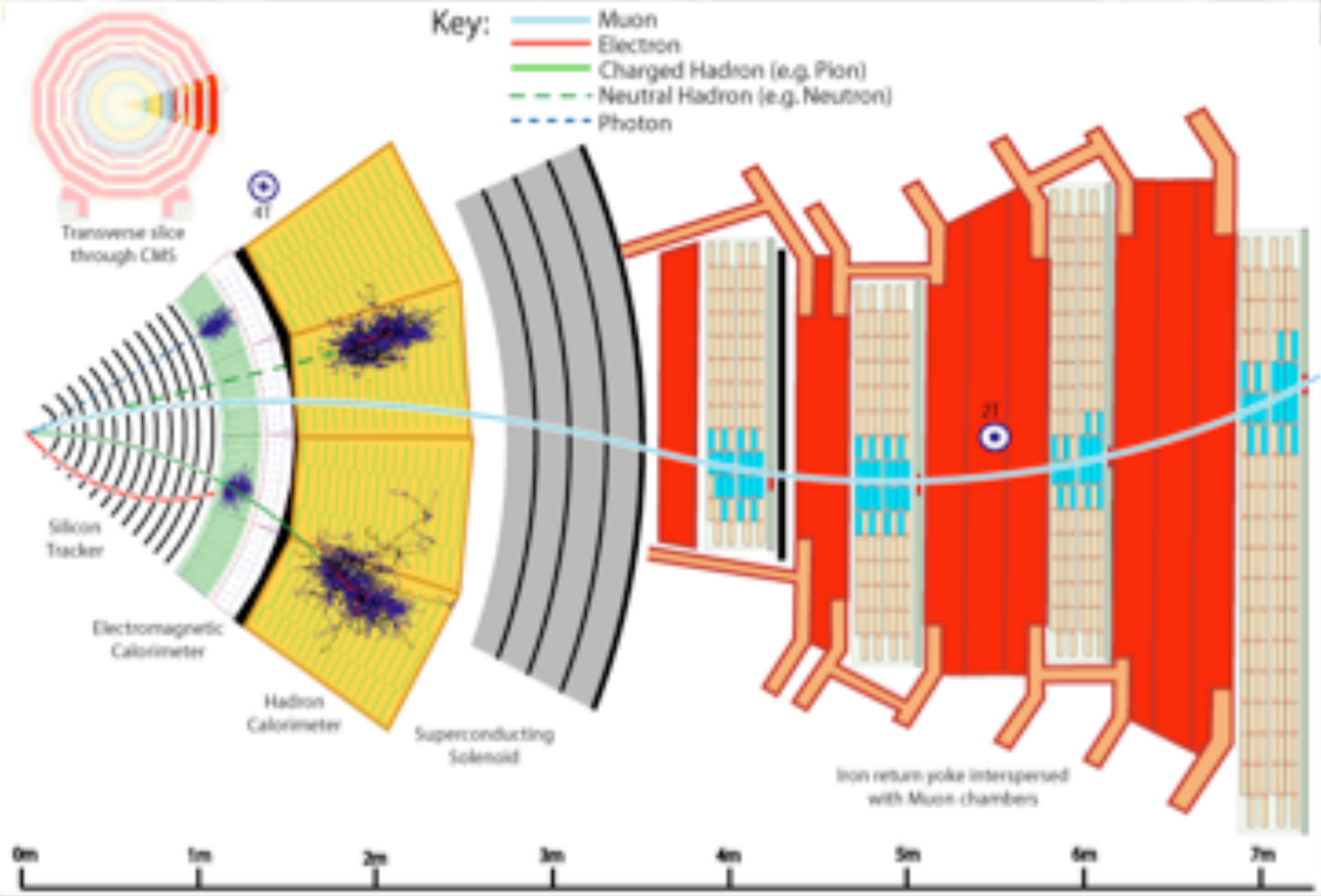
$\sigma/E \approx 0.03/\sqrt{E} + 0.003$

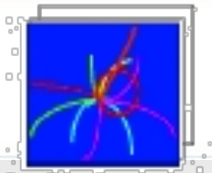
|η|<4.9 : HAD Calorimeter

$\sigma/E \approx 1.0/\sqrt{E} + 0.05$

|η|<2.4 : Muon spectrometer

$\sigma/p_T \approx 0.10$ *(1TeV muons)*





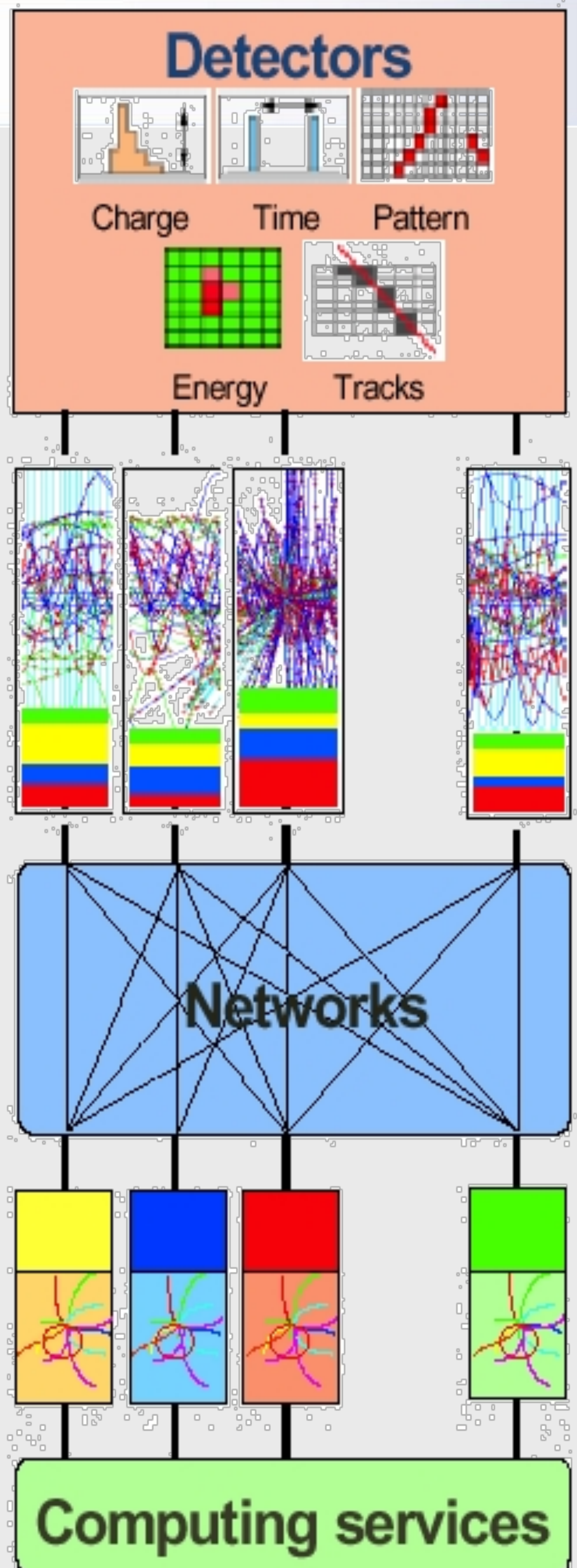
40 MHz
COLLISION RATE

100 kHz
LEVEL-1 TRIGGER

1 Terabit/s
(50000 DATA CHANNELS)

500 Gigabit/s

Gigabit/s SERVICE LAN



16 Million channels
3 Gigacell buffers

1 Megabyte EVENT DATA

200 Gigabyte BUFFERS
500 Readout memories

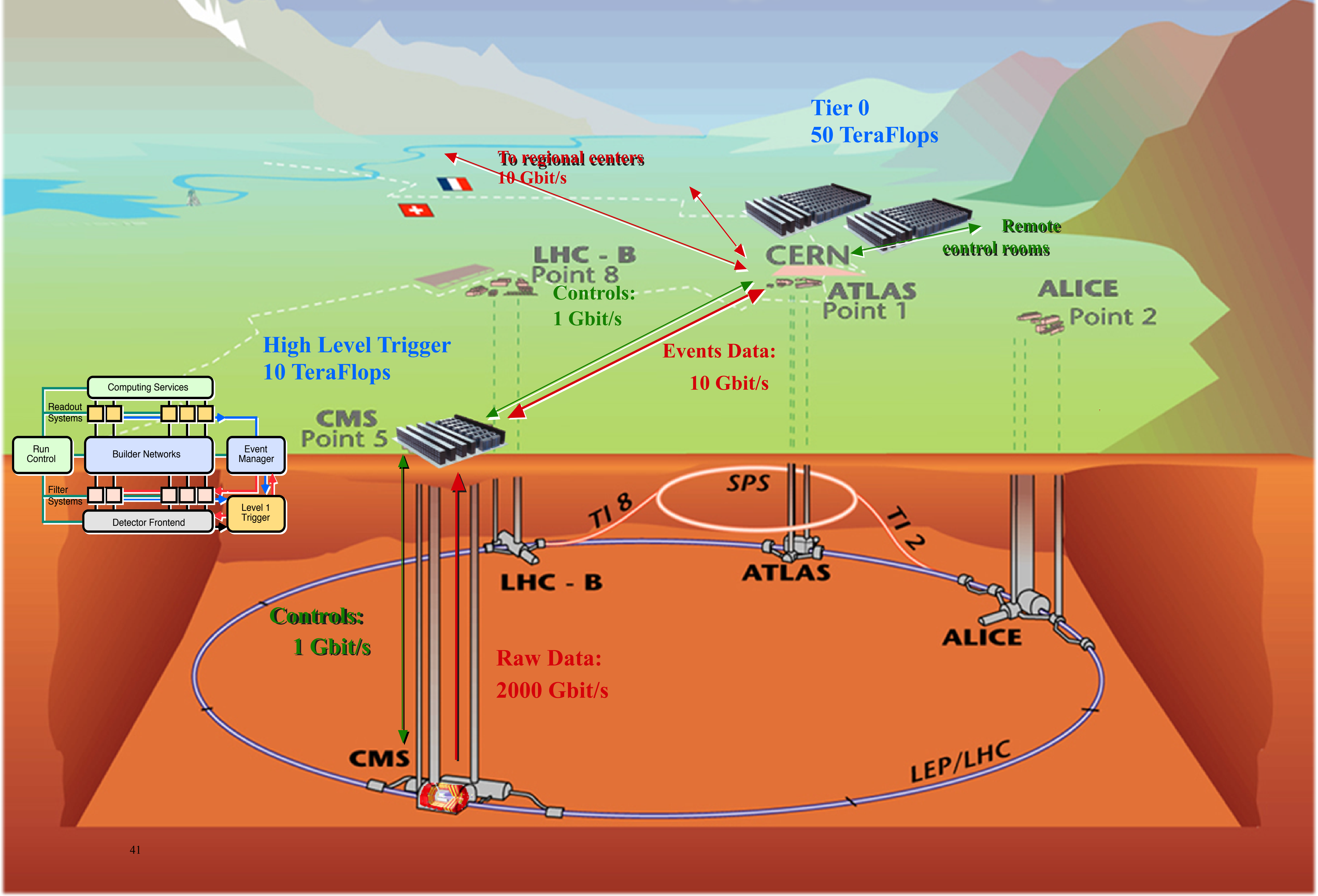
EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear) to RDPMs

5 TeraIPS

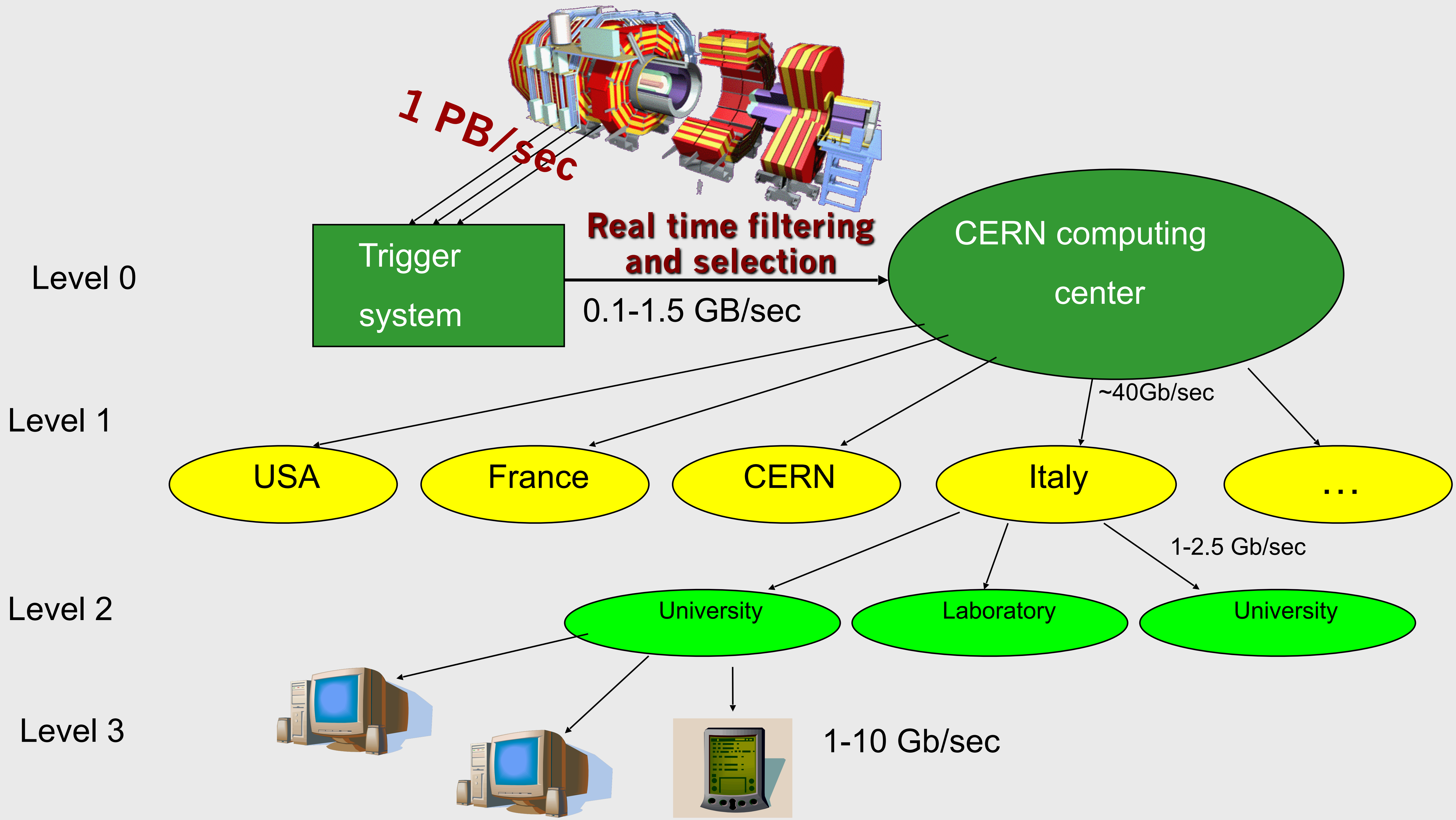
EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

Petabyte ARCHIVE

CMS data flow and on(off) line computing



Large Computing Grid (LCG)



1 PB par an

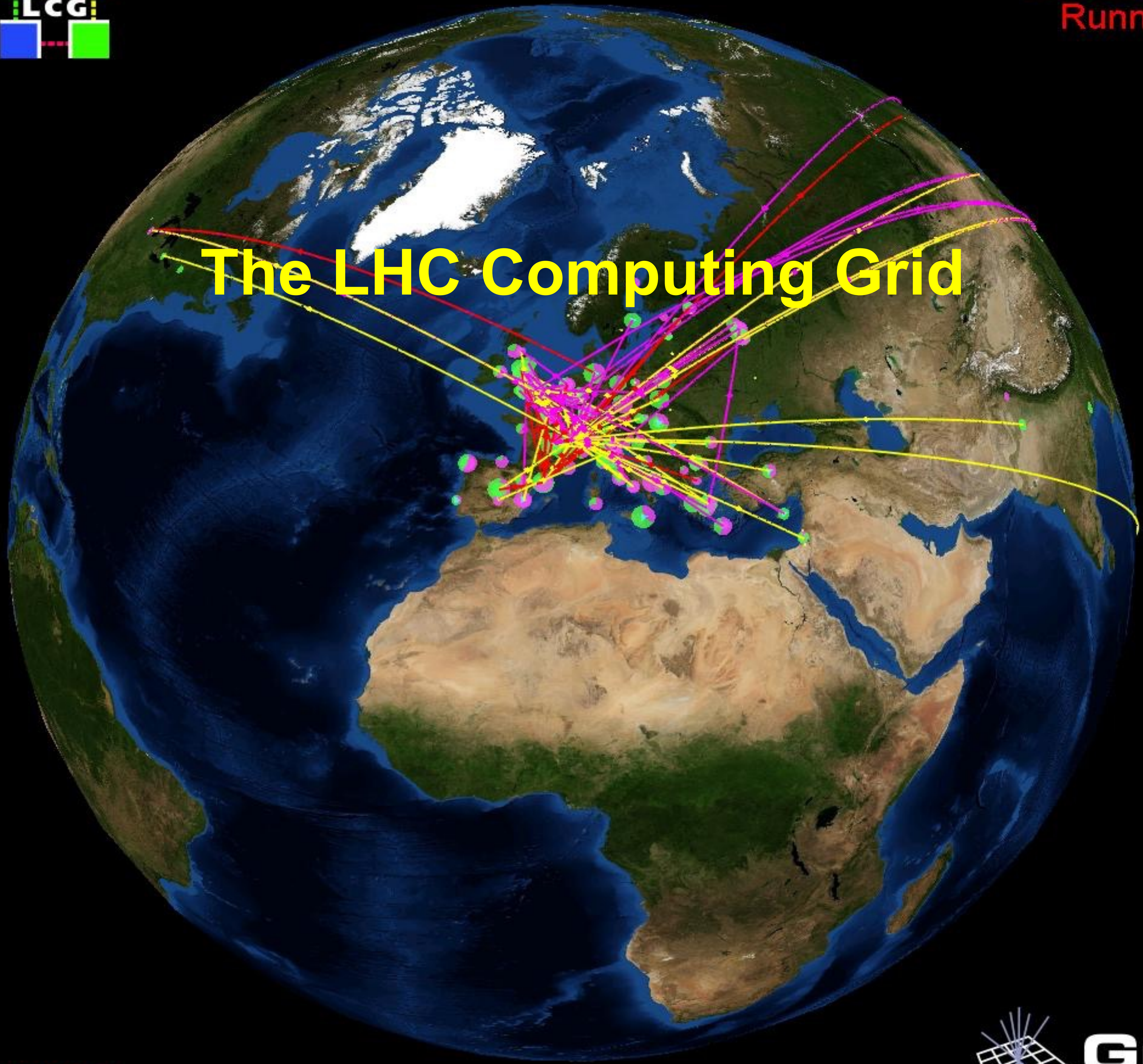
wLCG Grid: Tier-0 and the 10 ATLAS Tier-1s

The experiments will produce **~15 Millions de Gigabytes** of data/Year

(~20 millions of CDs!)

The analysis of LHC data require **~100,000 Today fasted PC.**

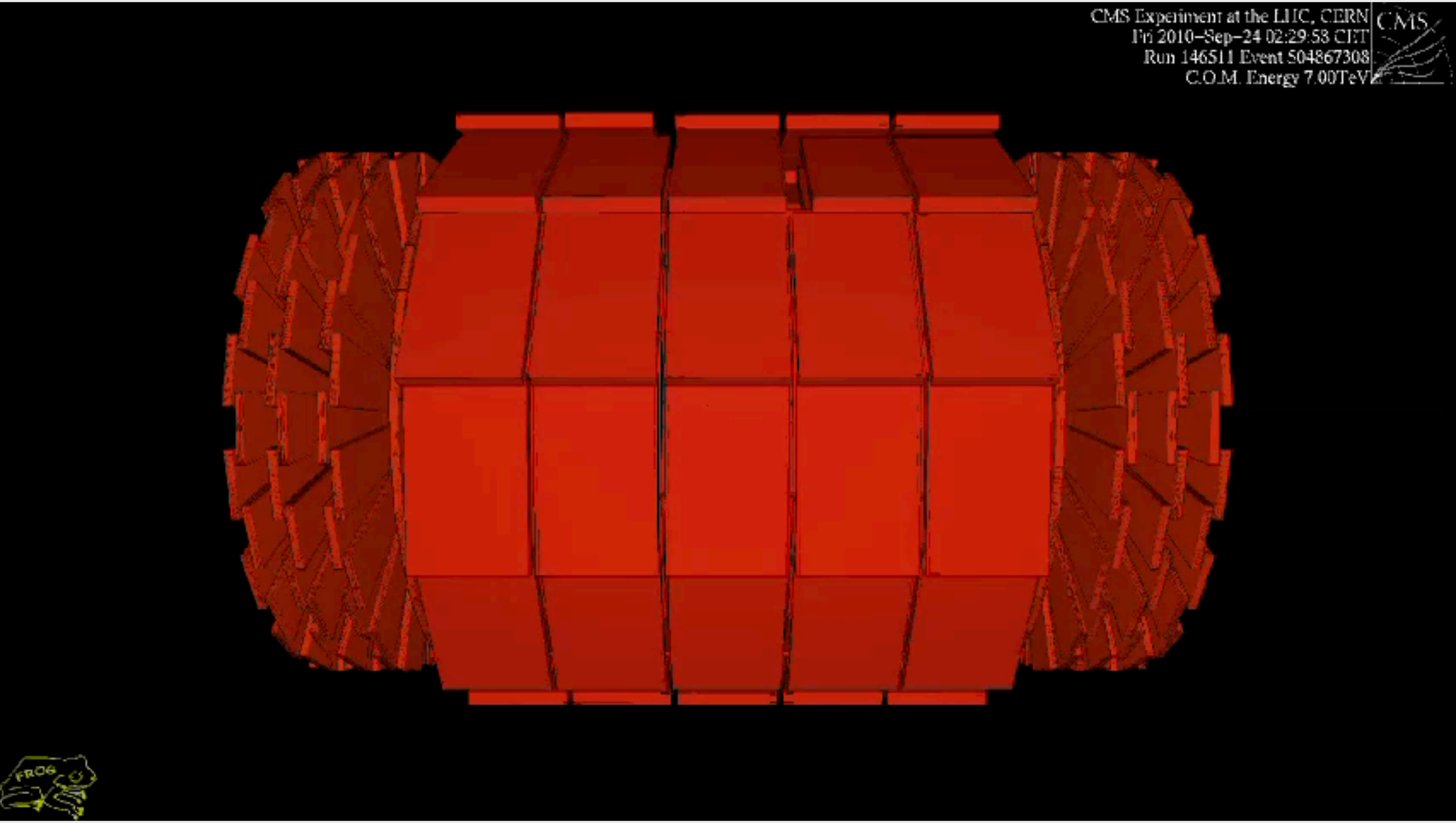
The LHC Computing Grid



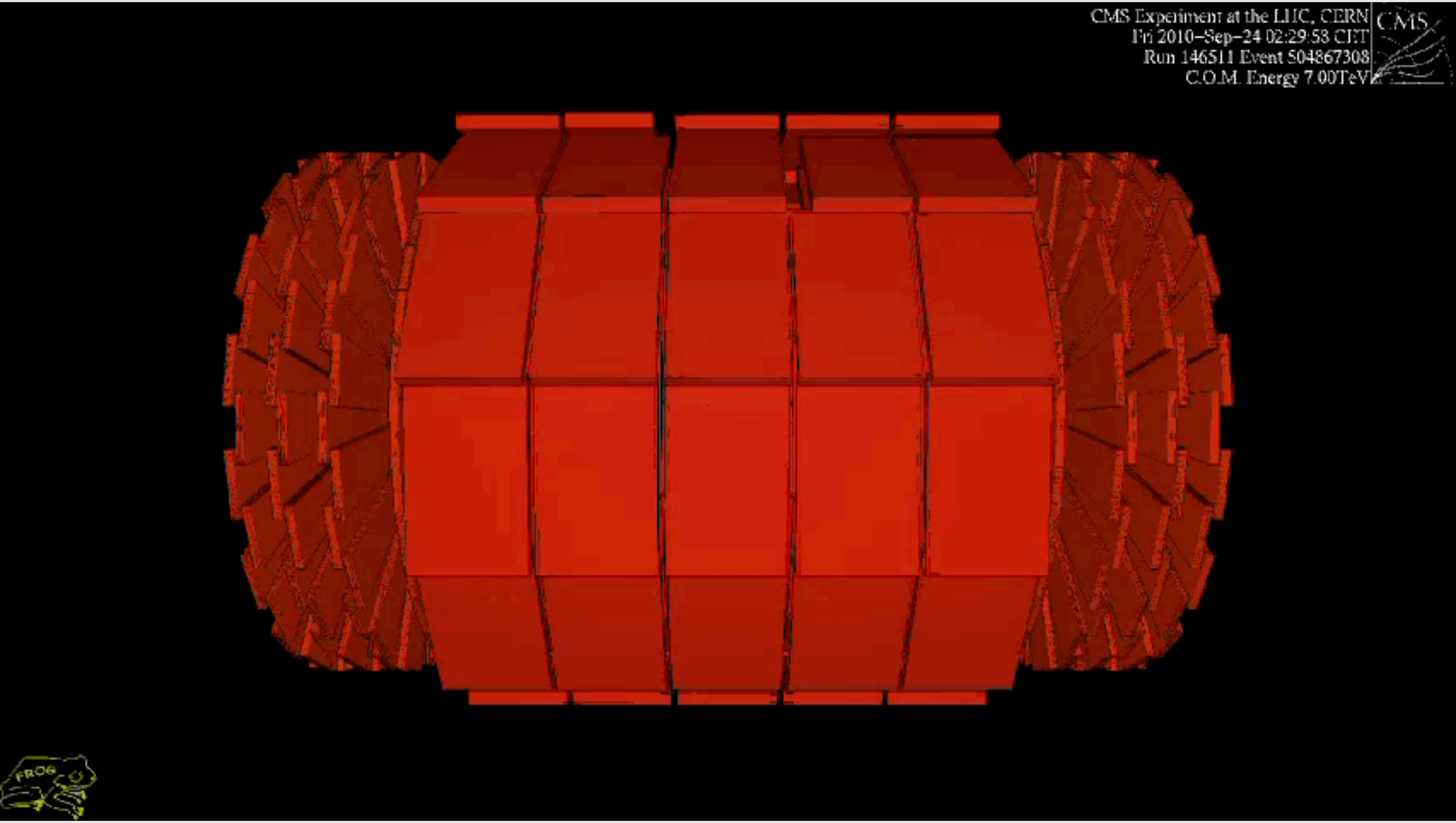
egee Enabling Grids for E-sciencE LCG

GridPP UK Computing for Particle Physics

First Searches for New Physics



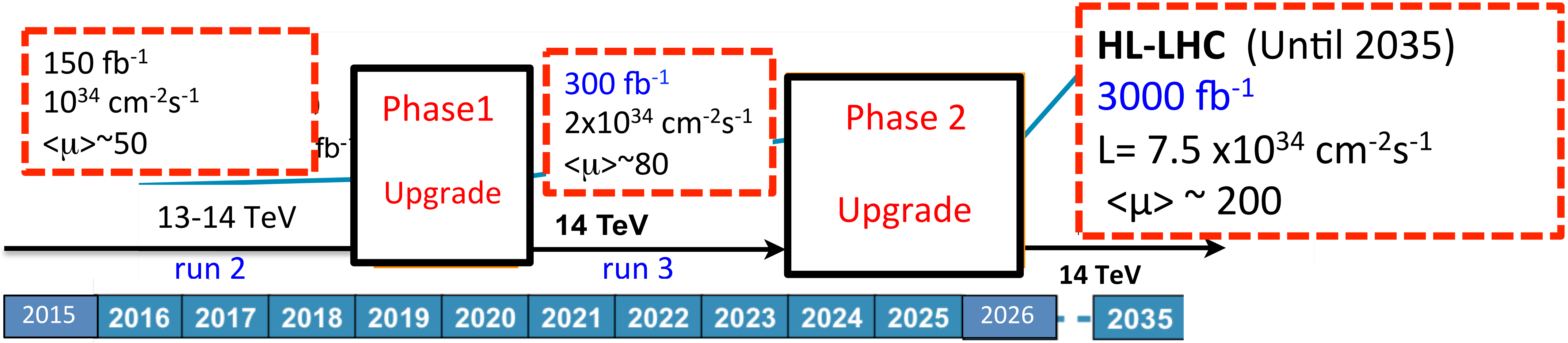
First Searches for New Physics

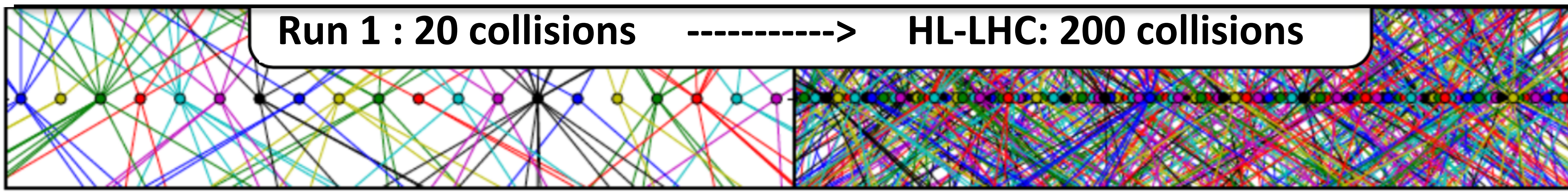


First Searches for New Physics

First CMS ZZ→4μ Event

LHC ATLAS and CMS upgrades road map





Detector challenges:

- x 10 more radiation (~ 10^{16}neq/cm^2 ; 10 MGy)
- x 10 more pile-up

- Run1: $<\mu>=20$;$<n_{PU\ jets\ pT>30GeV}>$ ~ 0.04

- HL-LHC: $<\mu>=200$;$<n_{PU\ jets\ pT>30GeV}>$ ~ 7.4

x10 x185

Upgrades needed to:

- keep performance (tracking, b-tag, jet/Etmiss,...)
- Trigger rates acceptable with low P_T thresholds

key issues: radiation tolerance and detector occupancy

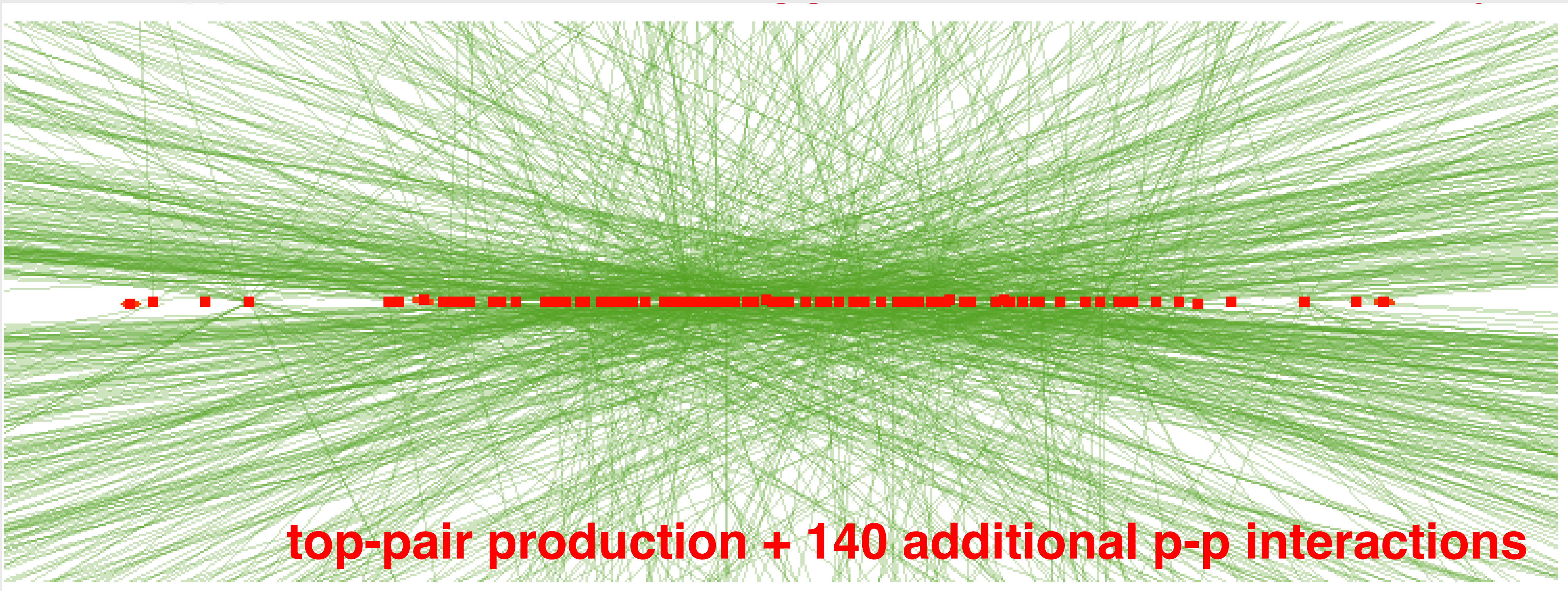
Physics motivaton at HL@LHC

- Electroweak symmetry Breaking
  - **Higgs precision measurements** (coupling and spin MCP quantum numbers)
  - **Higgs rare and invisible decays (H@>μμ , H@>Zγ,...)**
  - **Top Yukawa coupling (tH)**
  - **Higgs self coupling**

- Beyond the Standard Model
  - **Higgs sector** (search for deviations from SM)
  - **Dark mater**
  - **SUSY**
  - **Exotics**

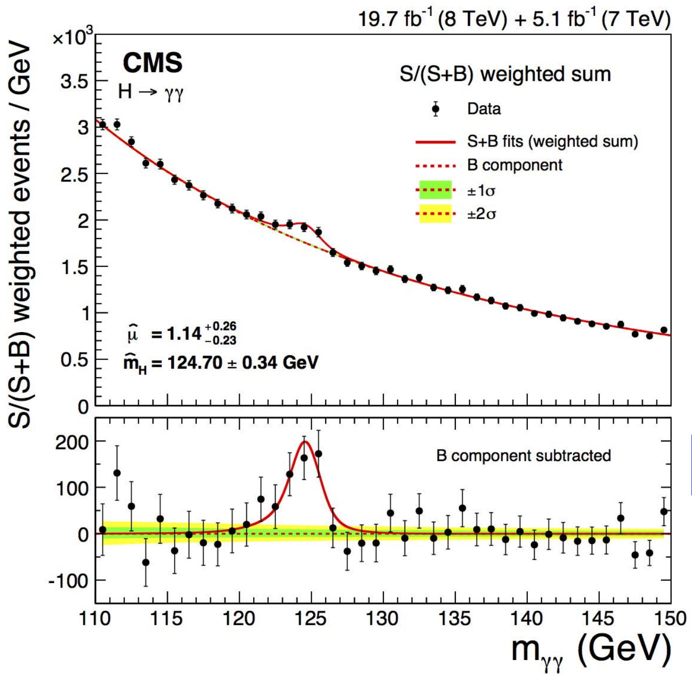
Phase II Upgrade motivations

- ***Radiation-induced ageing***
  - Replacement of tracker and part of calorimeters
- ***High pile-up in Run-4***
  - Upgrade of front-end and back-end electronics, trigger and DAQ
- ***Physics***
  - Access opportunities at 3/ab: Higgs; SUSY; SMP rare decays

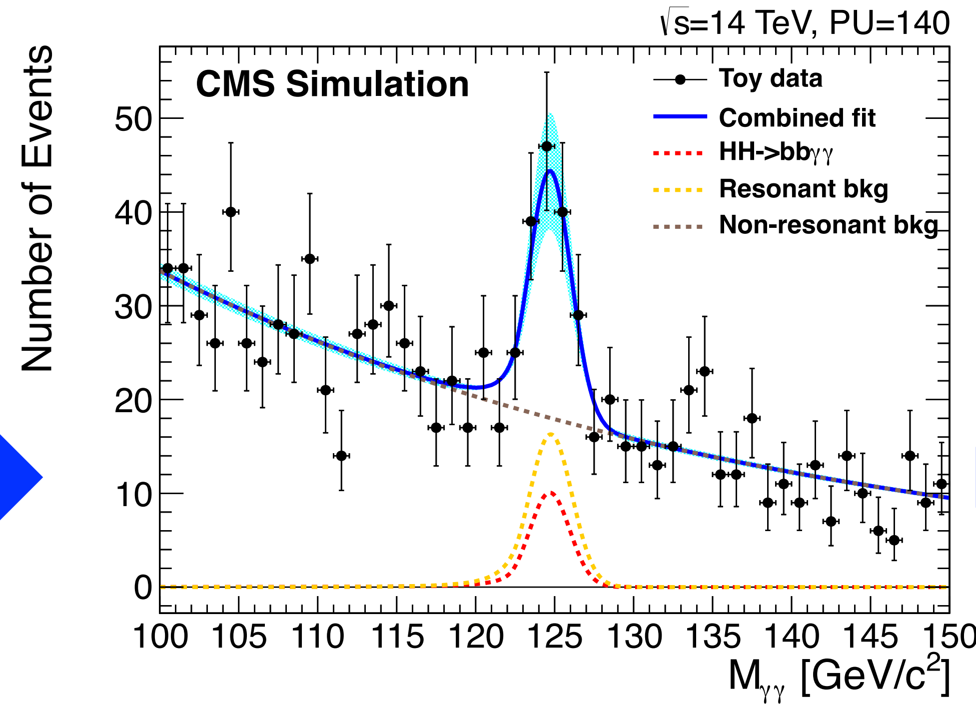


HL-LHC Physics Motivation

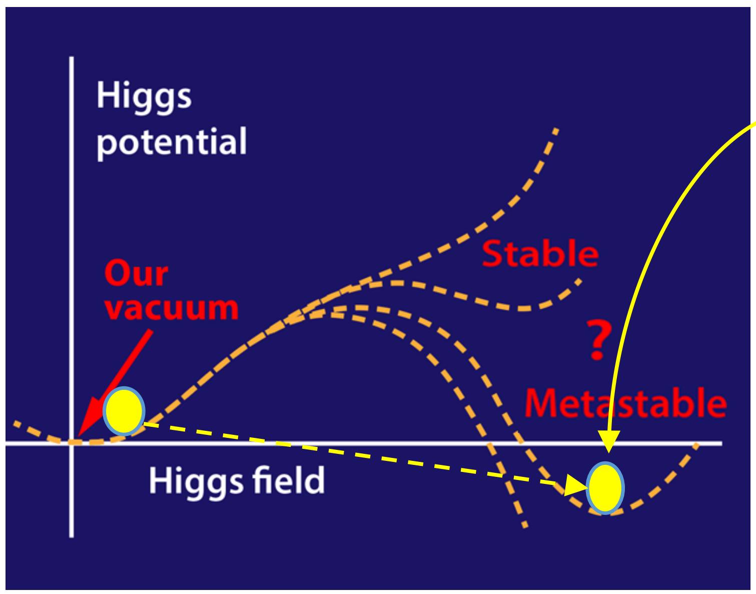
H→γγ discovery @ LHC



H(bb)H(γγ) discovery @ HL-LHC

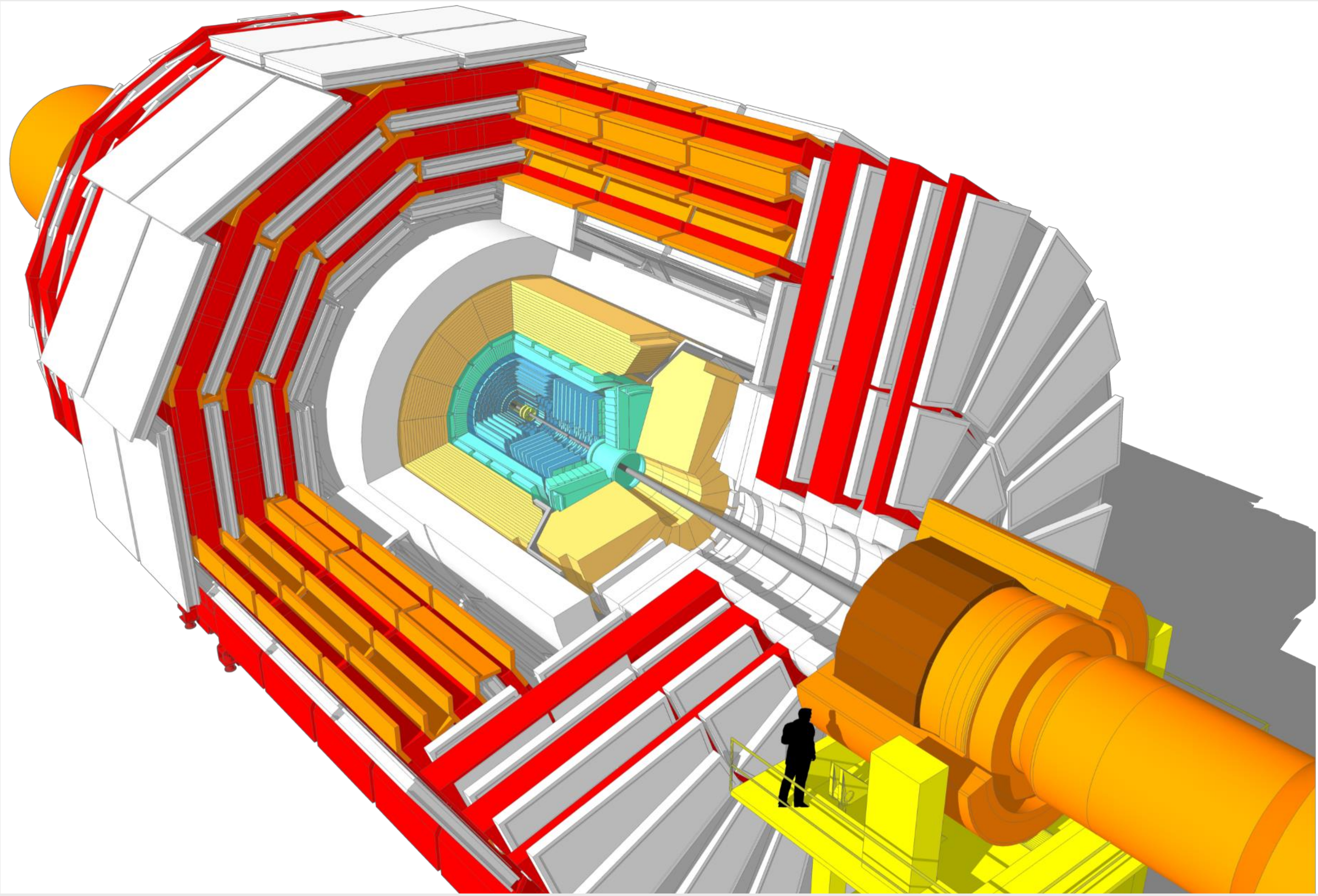


Vacuum stability of Universe



- **Electrons and photons are critical for precision Higgs Boson studies, as well as many BSM searches, at HL-LHC**
- **Discovery of SM di-Higgs (HH) production is one of the main goals of the HL-LHC**
- HH production will help us measure the Higgs Boson self coupling, which determines the shape of the Higgs potential and helps us understand the vacuum stability of the universe

CMS Upgrade : Phase II Overview



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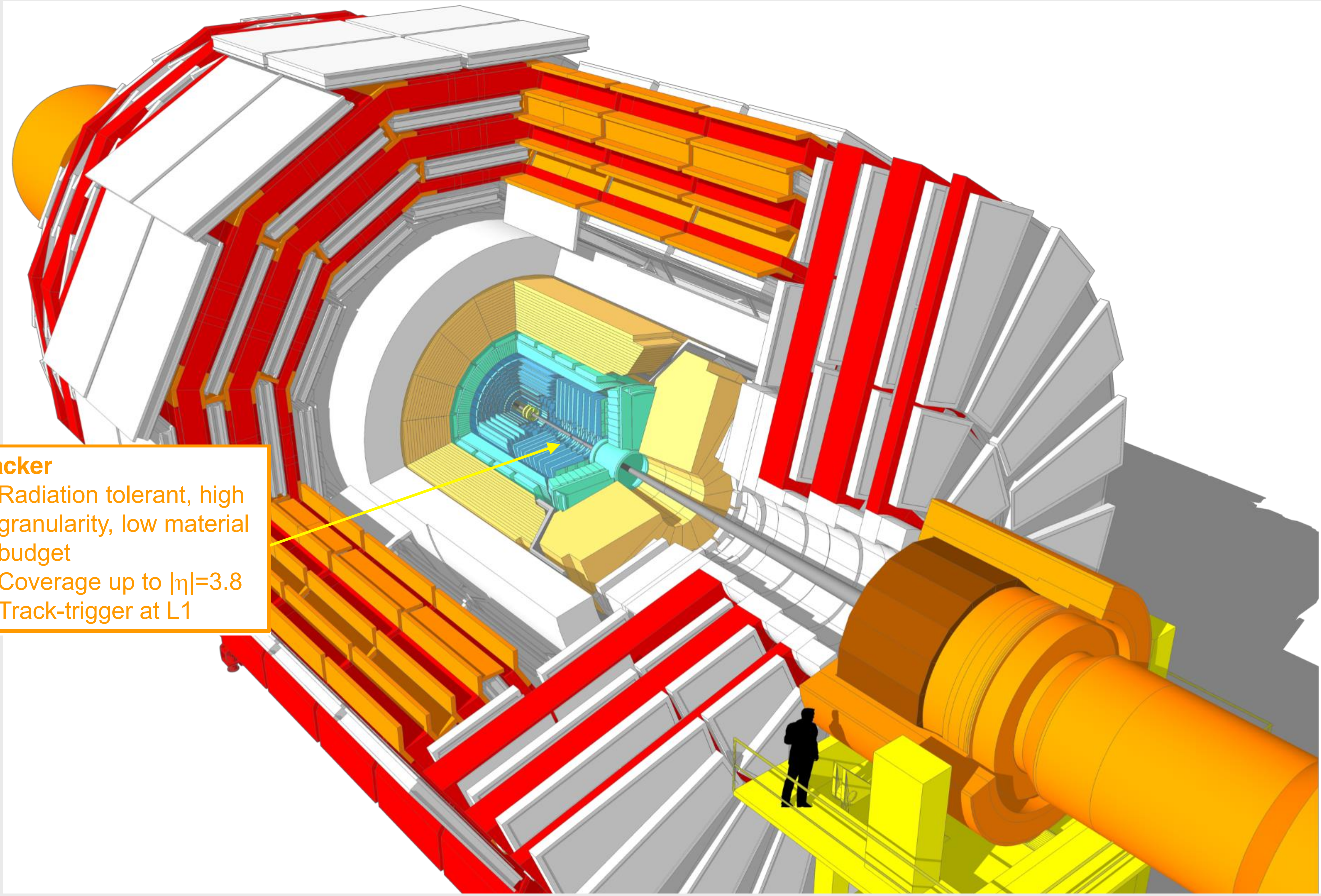
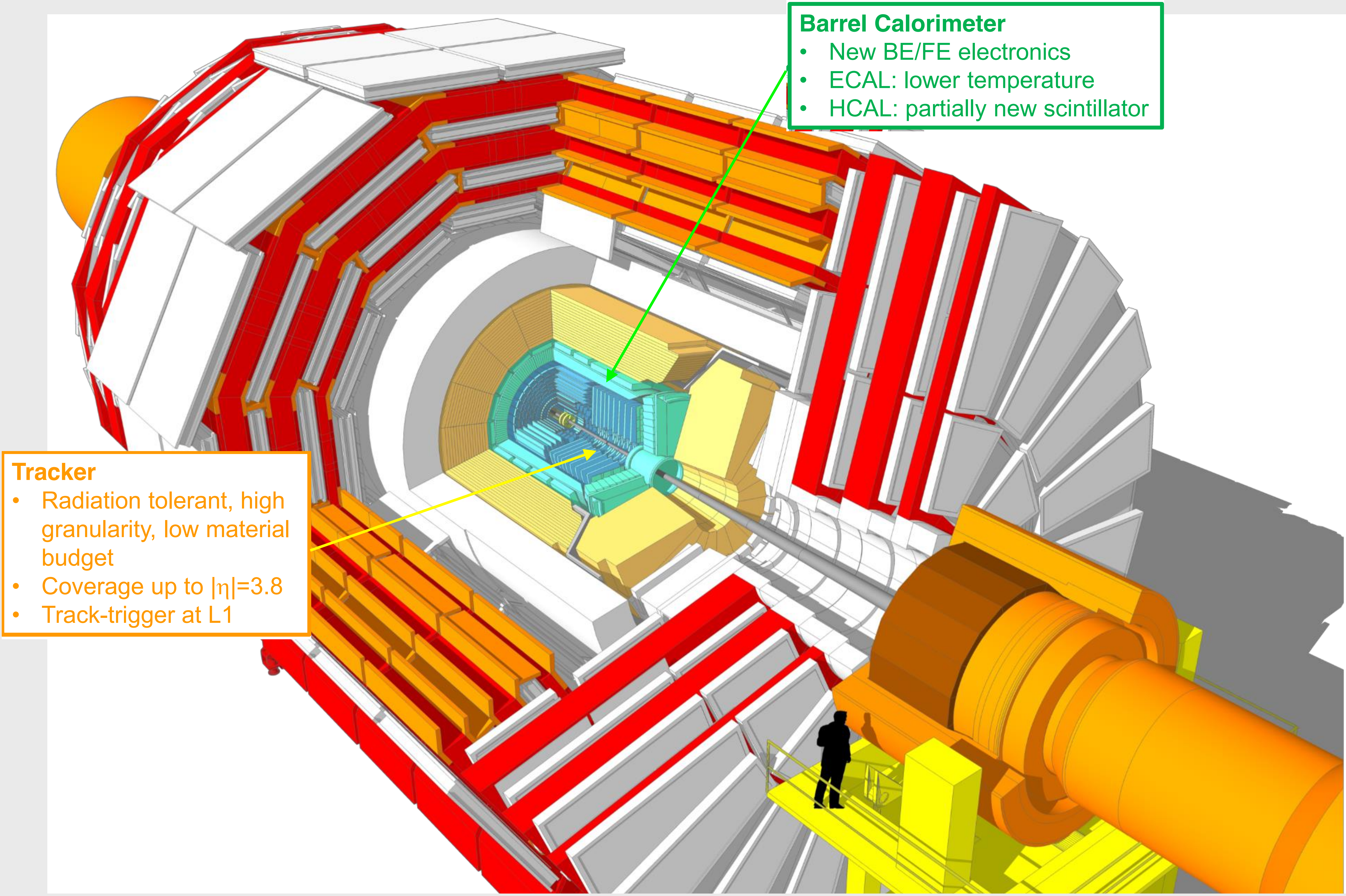


Tracker
- Radiation tolerant, high granularity, low material budget
- Coverage up to $|\eta|=3.8$
- Track-trigger at L1

CMS Upgrade : Phase II Overview



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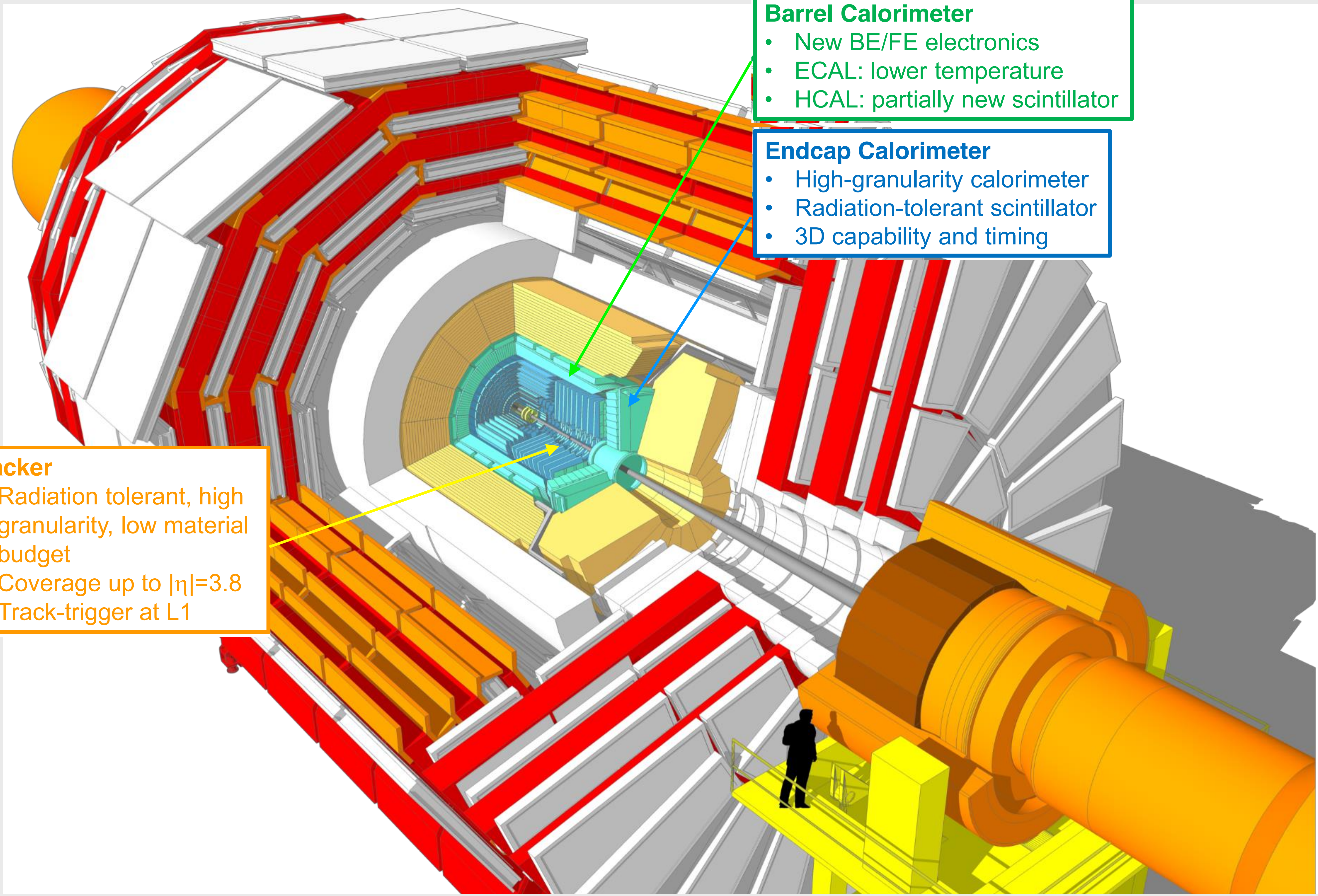

Barrel Calorimeter
- New BE/FE electronics
- ECAL: lower temperature
- HCAL: partially new scintillator

Endcap Calorimeter
- High-granularity calorimeter
- Radiation-tolerant scintillator
- 3D capability and timing

Tracker
- Radiation tolerant, high granularity, low material budget
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CMS Upgrade : Phase II Overview

Muon System
- New DT/CSC BE/FE electronics
- GEM/RPC coverage in $1.5<|\eta|<2.4$
- Muon-tagging in $2.4<|\eta|<3.0$

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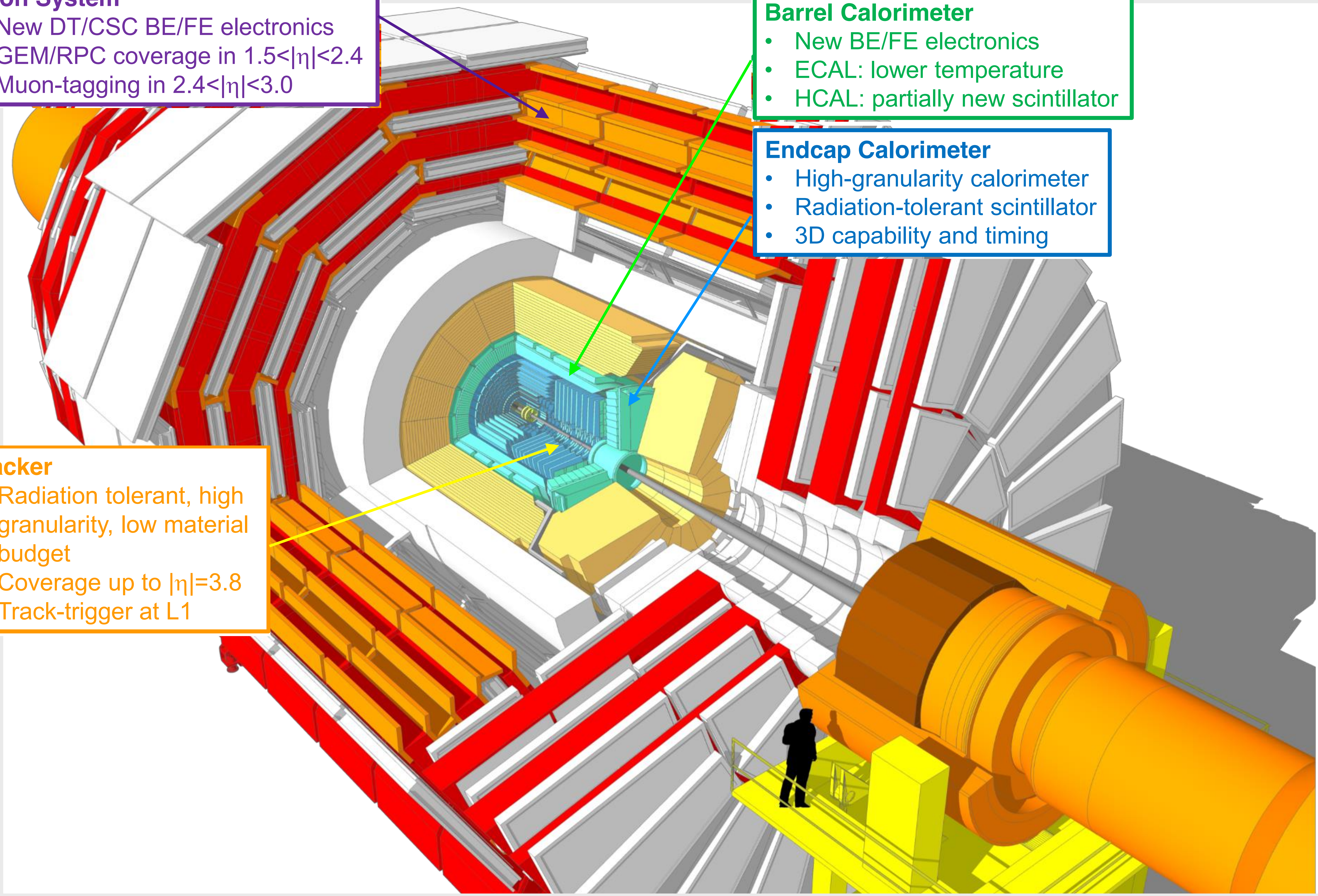

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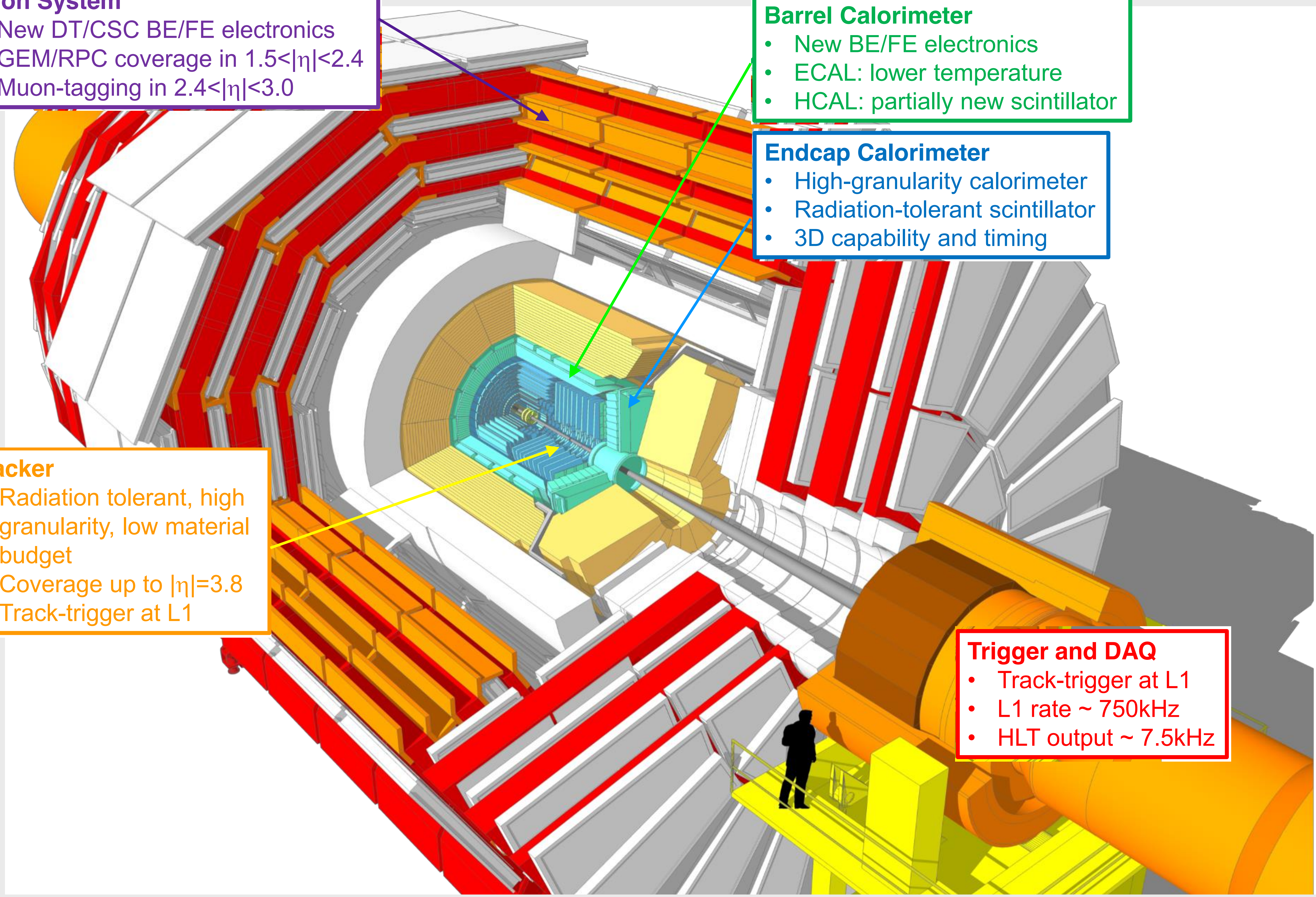


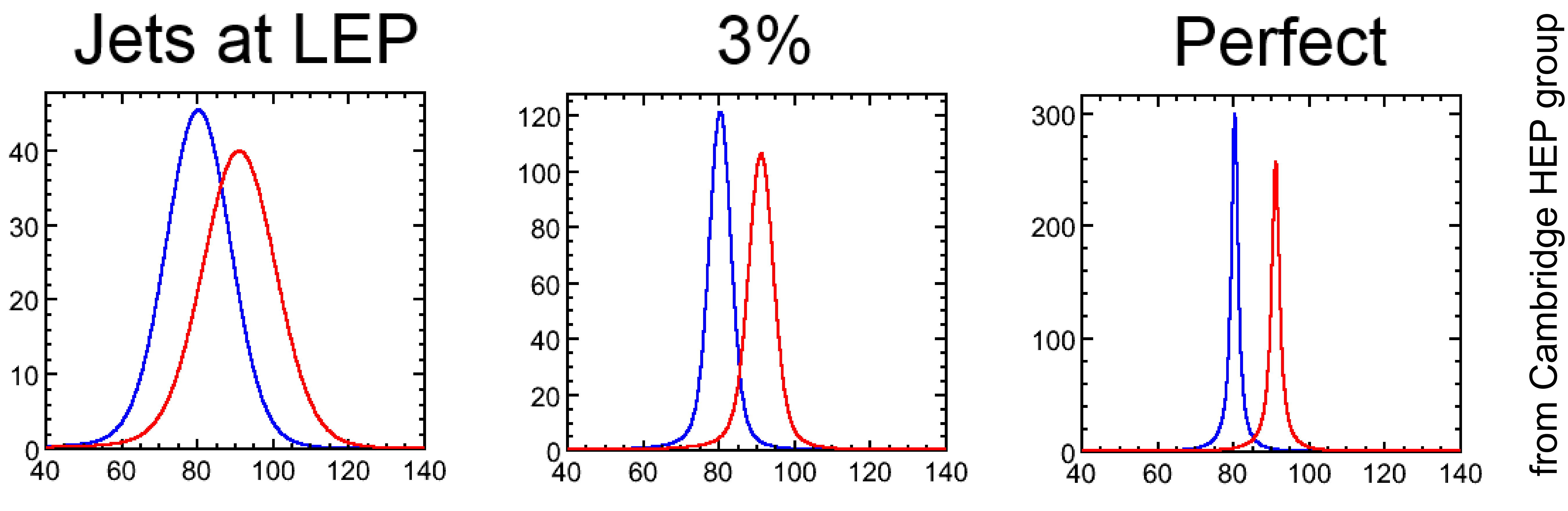
Tracker
- Radiation tolerant, high granularity, low material budget
- Coverage up to |η|=3.8
- Track-trigger at L1

Trigger and DAQ
- Track-trigger at L1
- L1 rate ~ 750kHz
- HLT output ~ 7.5kHz

What are the Challenges?

- ***Identification of unique energy deposits in high pileup***
  - If particles from pileup are merged together with those from primary vertex, determining the precise particle content of the event becomes difficult
- ***The computing time it takes to associate 300,000 calorimeter hits per event***
  - Need to make sure algorithms efficient from perspective of physics **and** computing
- ***Maintaining good physics object performance in the presence of pileup***
  - Not only dedicated reconstructions like electron/photon
  - Jets / MET performance very important for the physics mission of the HL-LHC

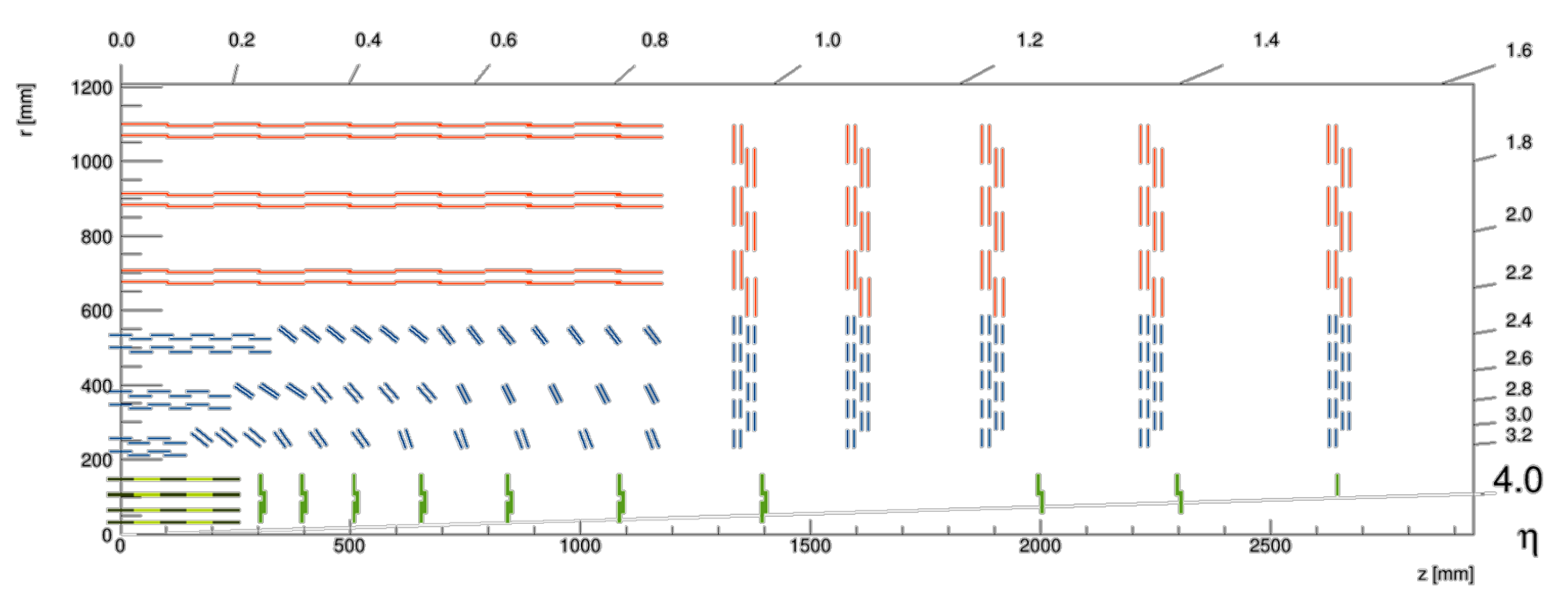
Distinguish the decays *W → jet jet* and *Z → jet jet* by their reconstructed mass



- required resolution: $\sigma(E_{jet})/E_{jet} \approx$ 3-4%
- interesting jet energy range: $E_{jet} \approx$ 40 to 500 GeV
- not possible with calorimeter information alone → use Particle Flow Algorithms

Tracker

- <u>Outer Tracker</u>
  - Double-layer modules for trigger purpose
  - 6 barrel layers; 5 forward disks
  - Higher granularity
  - 4 times current detector
- <u>Pixel Tracker</u>
  - 10 forward disks, coverage up to
  - |eta|~3.8
  - Inner layer at 3cm from beam line
- <u>Mechanics and Electronics</u>
  - Low material budget
  - Operations at -30C
  - Readout at 750kHz



Tracker

Requirements

- Radiation tolerance
- Increased granularity
- Improved 2-track separation

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  - *Double-layer modules for trigger purpose*
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  - *Higher granularity*
  - *4 times current detector*
- *Pixel Tracker*
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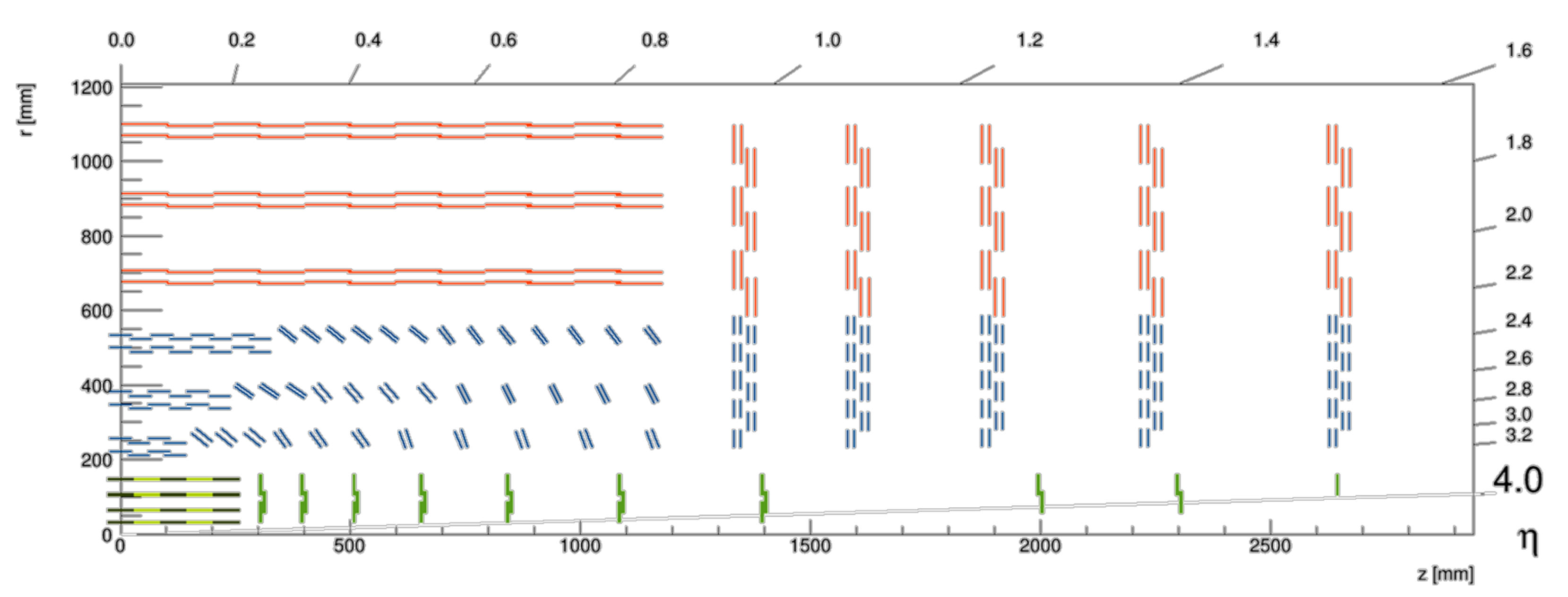

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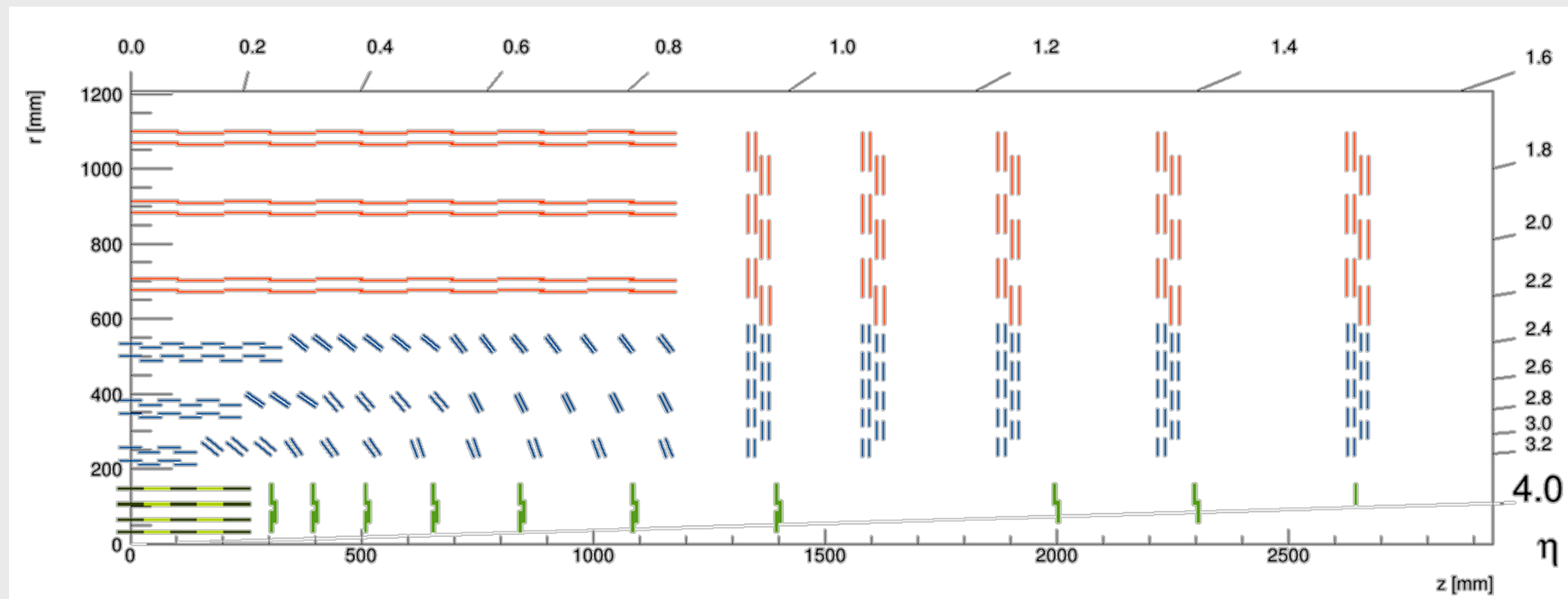
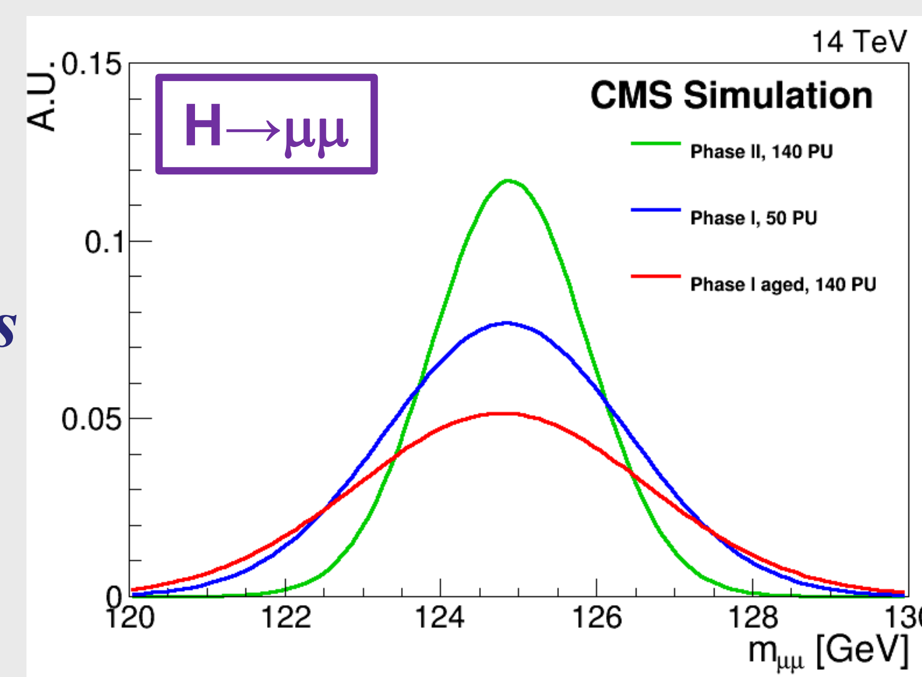
  - *Operations at -30C*
  - *Readout at 750kHz*



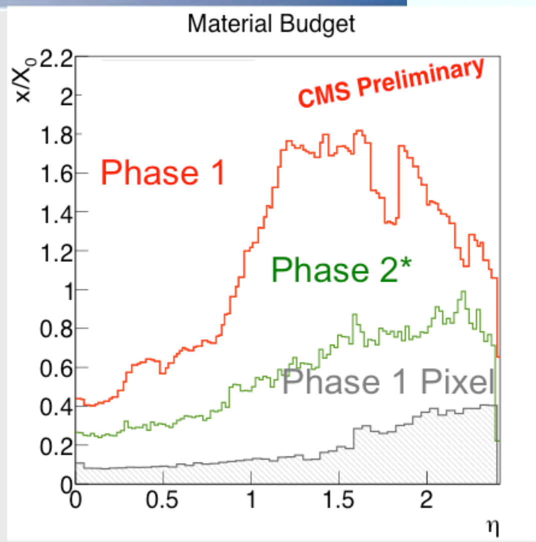
Higgs Physics



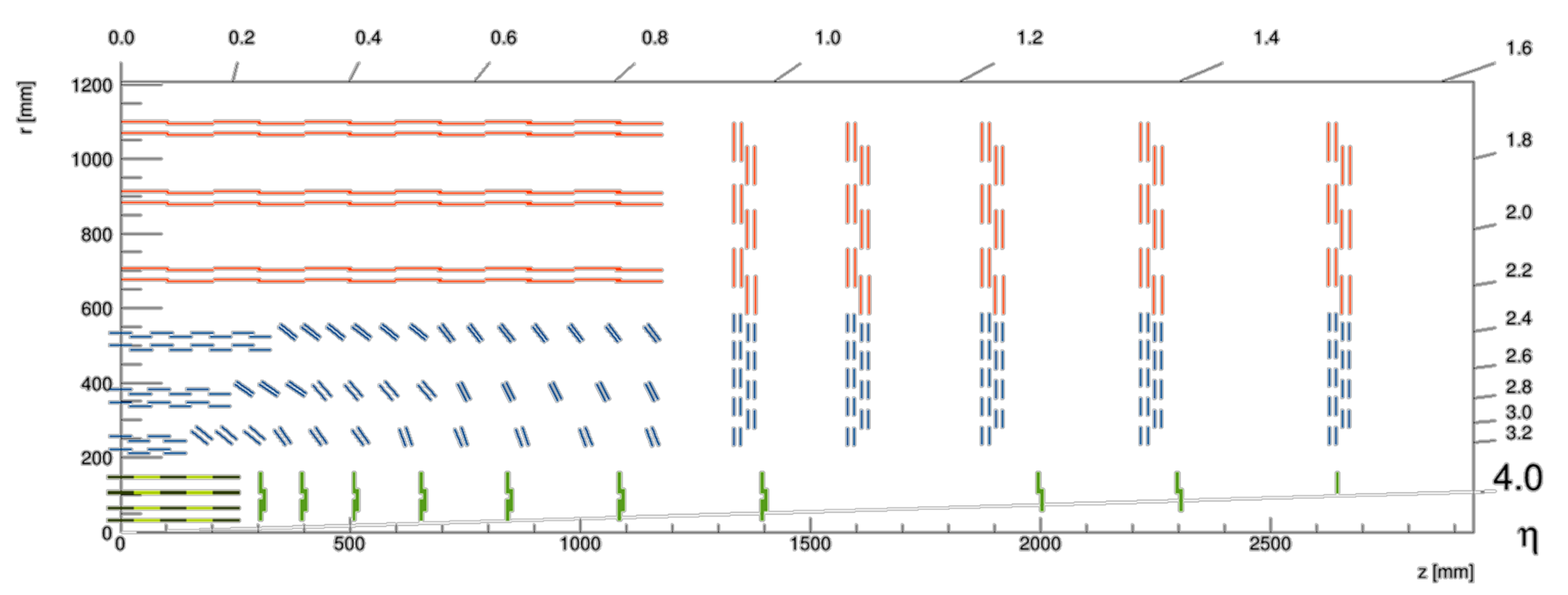
Tracker

Requirements

- Radiation tolerance
- Increased granularity
- Improved 2-track separation
- Reduced material
- Robust pattern recognition
- Support for L1 trigger upgrade
- Extended tracking acceptance



- *Outer Tracker*
  - *Double-layer modules for trigger purpose*
  - *6 barrel layers; 5 forward disks*
  - *Higher granularity*
  - *4 times current detector*
- *Pixel Tracker*
  - *10 forward disks, coverage up to*
  - *|eta|~3.8*
  - *Inner layer at 3cm from beam line*
- *Mechanics and Electronics*
  - *Low material budget*
  - *Operations at -30C*
  - *Readout at 750kHz*



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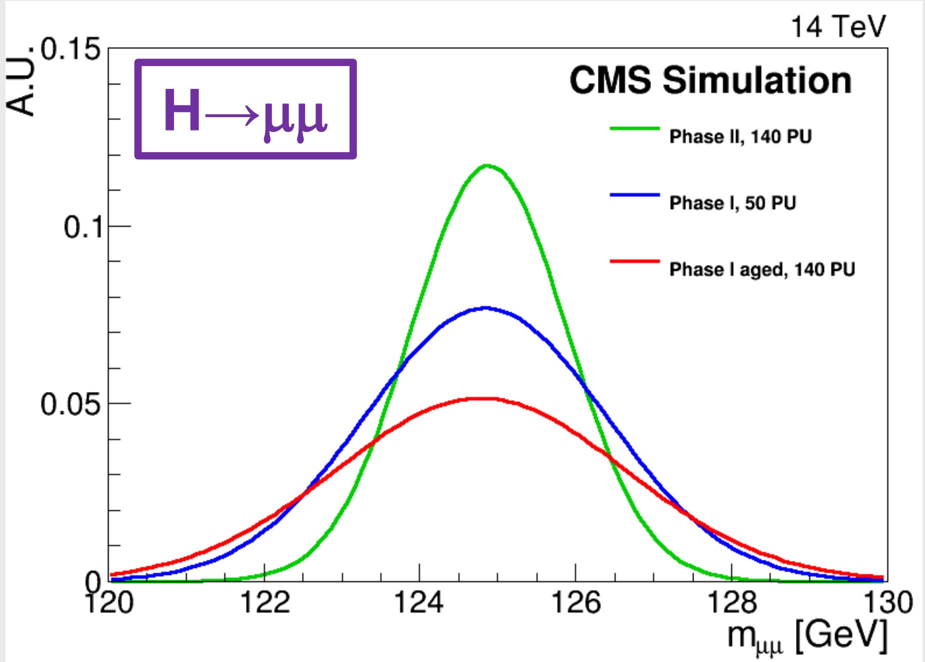
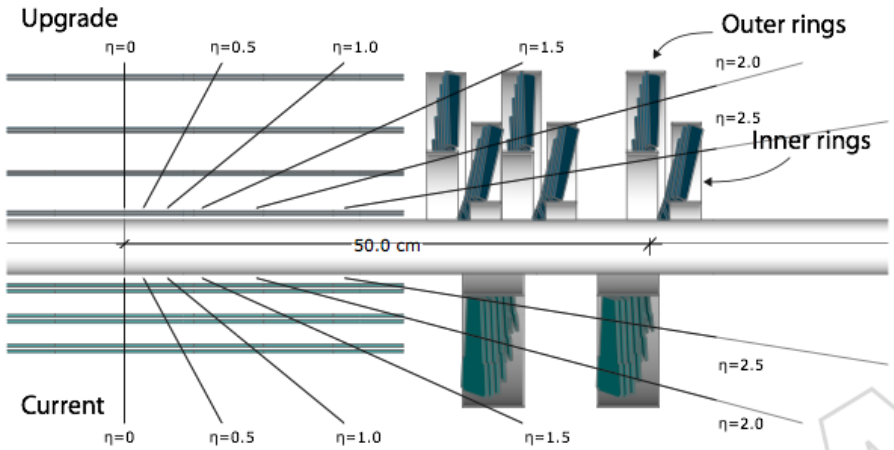
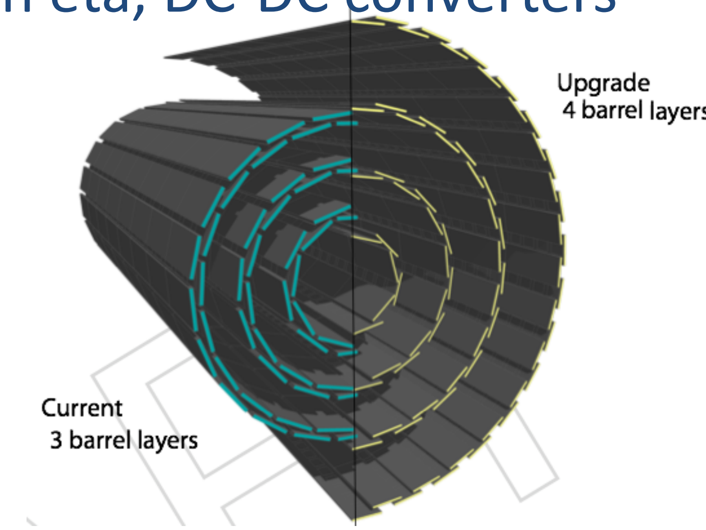


New pixel detector (EYETS)

Features of New Design

- Robust design: 4 barrel layers and 3 endcap disks at each end
- Smaller inner radius (new beampipe), large outer
- New readout chip with expanded buffers, embedded digitization and high speed data link
- Reduced mass with 2-phase CO_2 cooling, electronics moved to high eta, DC-DC converters





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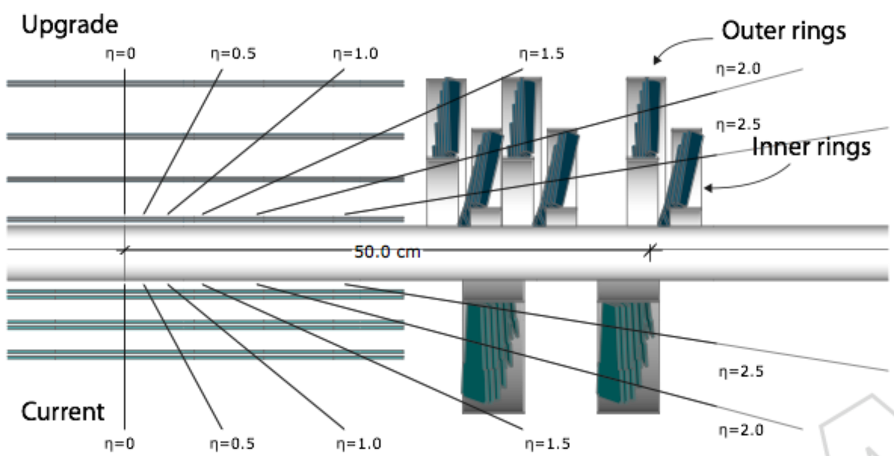
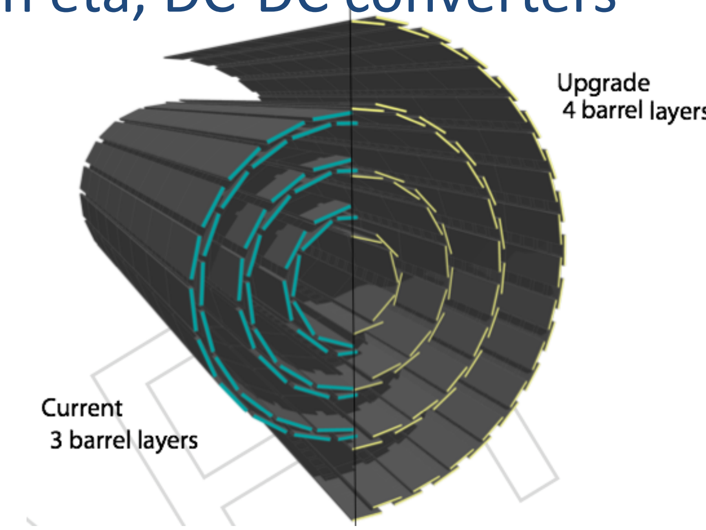


Will be installed (2016-2017)



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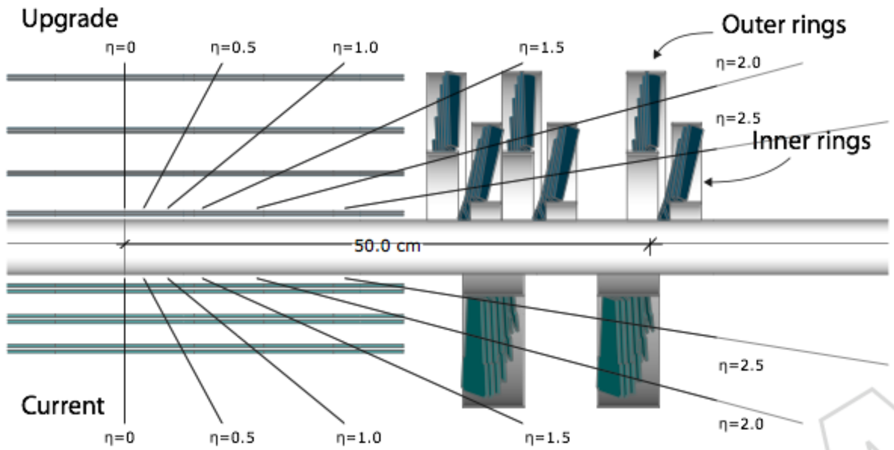

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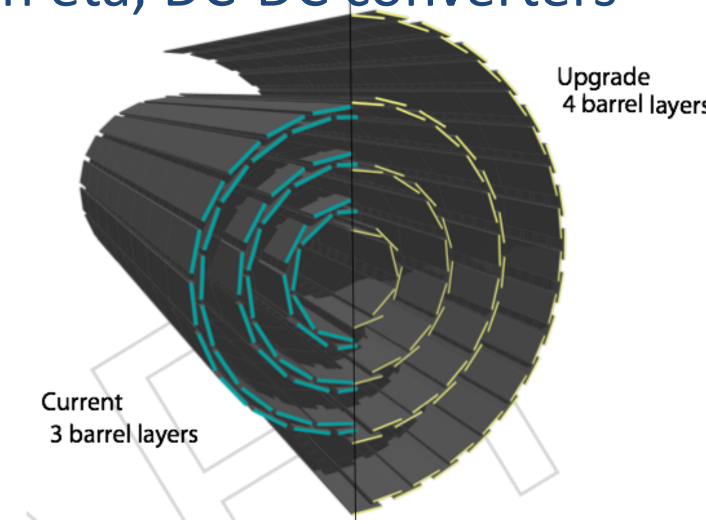

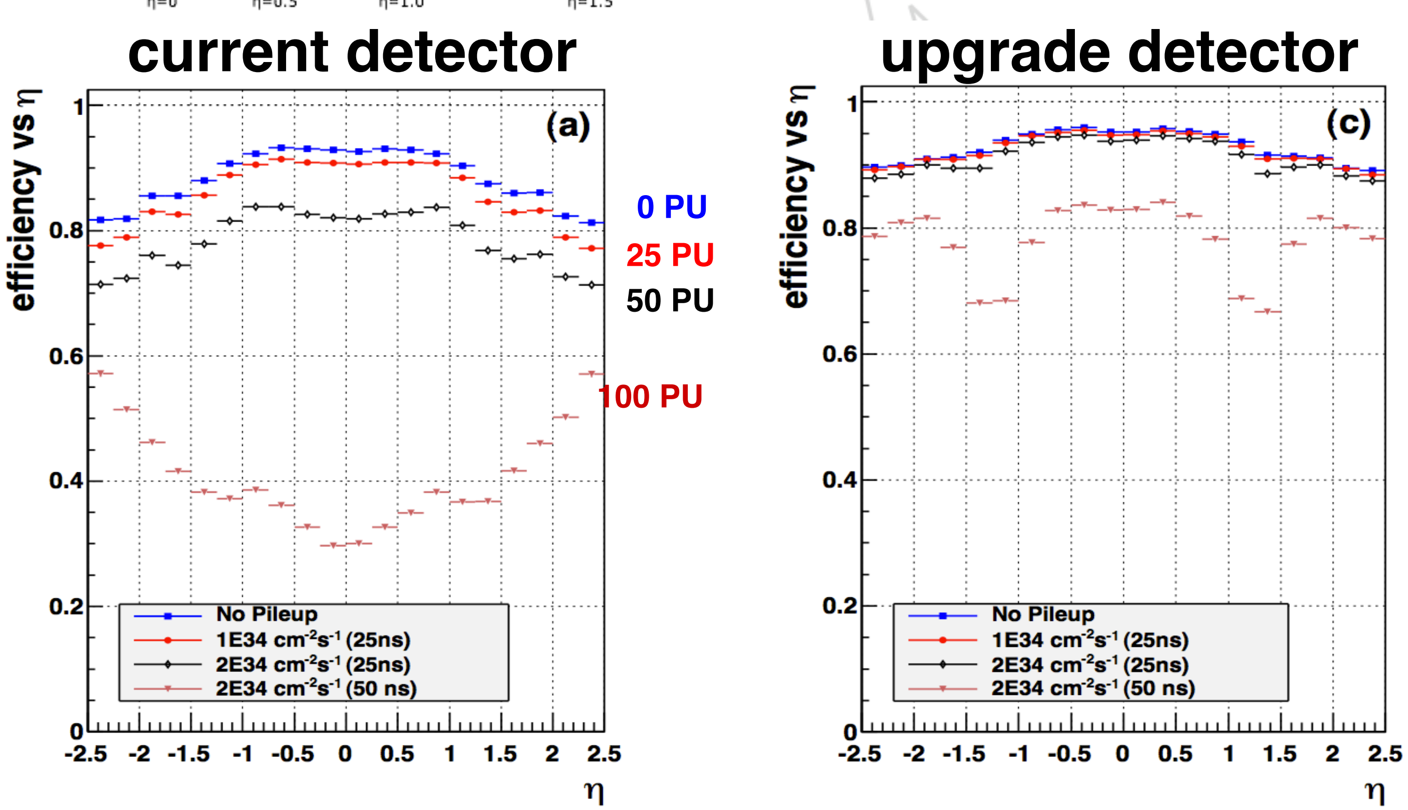

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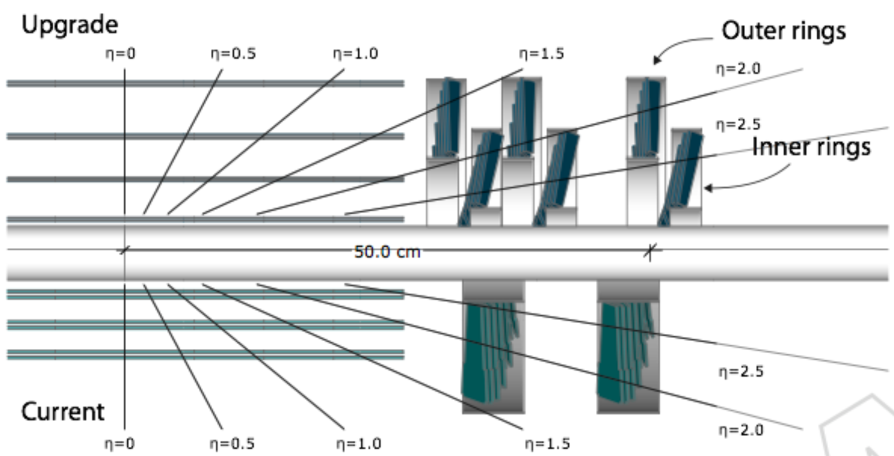

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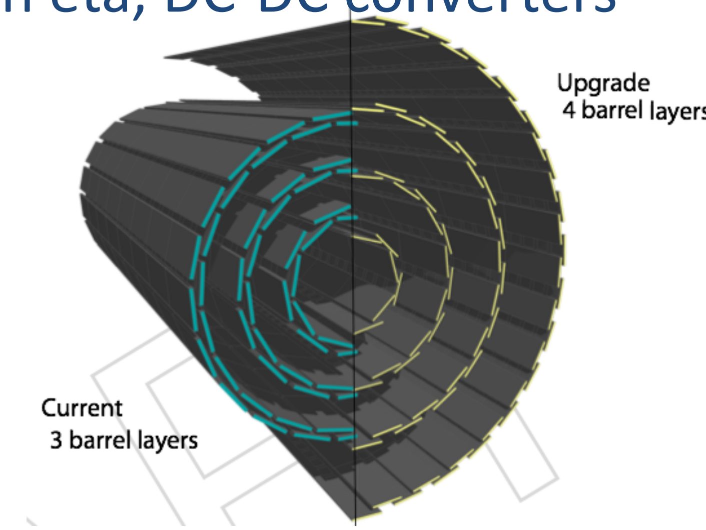
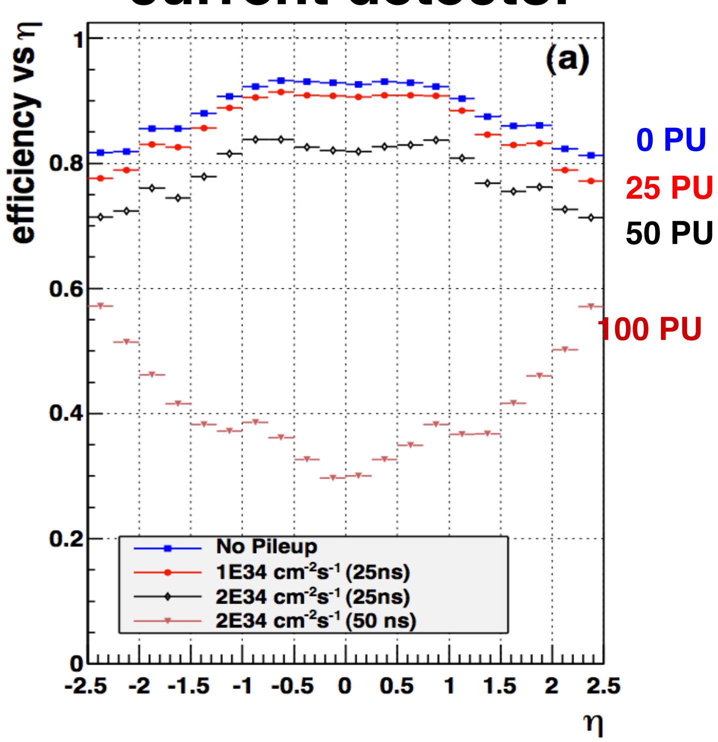
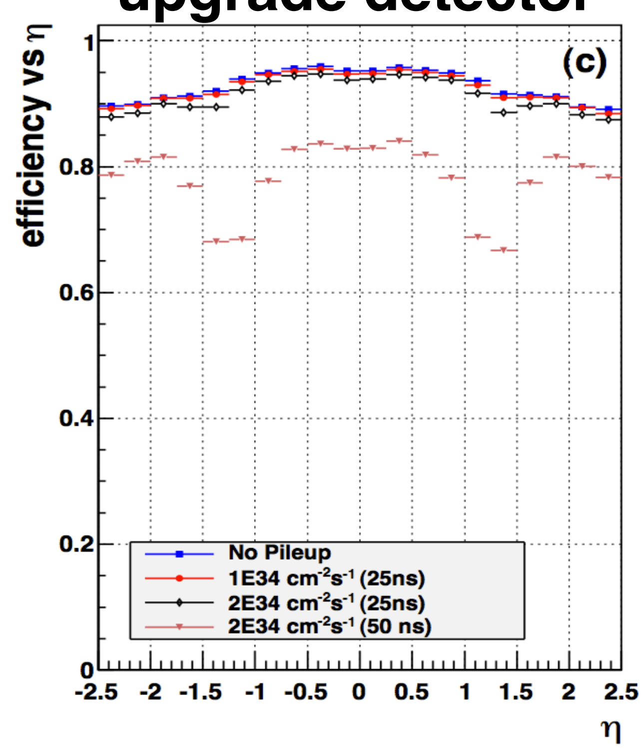


current detector



upgrade detector



Using same Higgs selections as 2012

Significant gain in signal reconstruction efficiency:

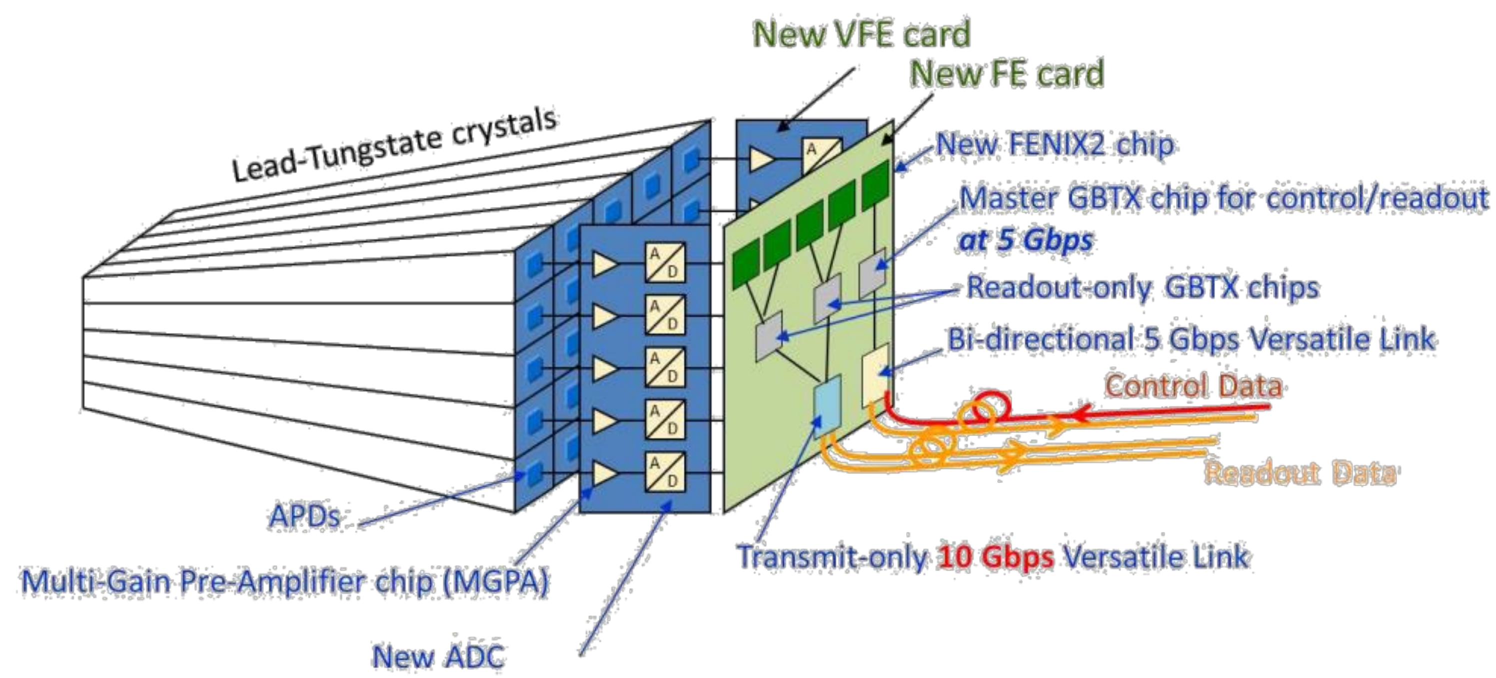
H→	4μ	+41%
H→	2μ2e	+48%
H→	4e	+51%

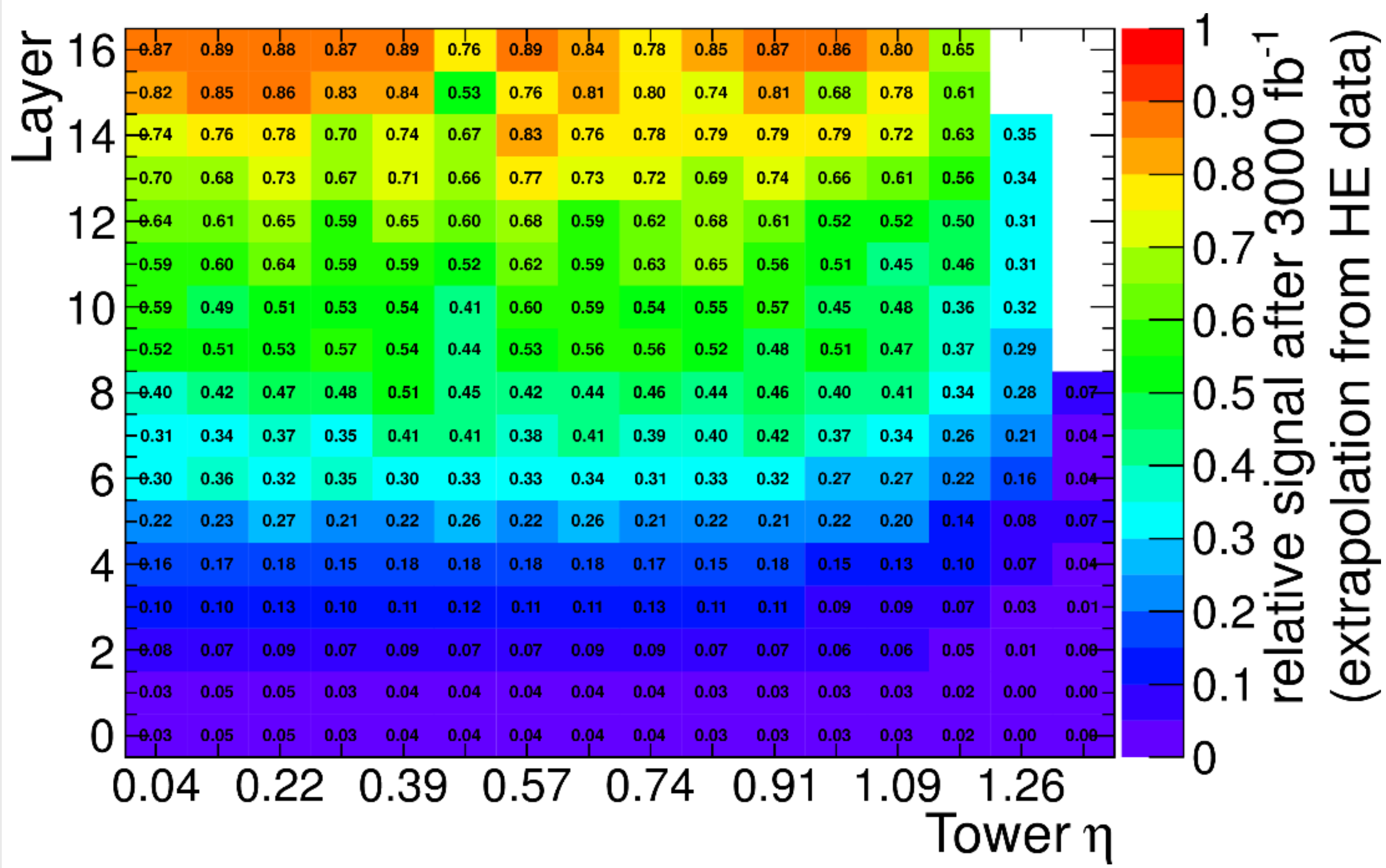
Primary vertex resolution improved by ~1.5 - 2

Barrel Calorimeters

- ***Electromagnetic Calorimeter***
  - Homogeneous, $PbWO_4$
  - New front-end and back-end electronics to satisfy HL-LHC trigger requirements
  - Cooling to 8C and optimization of VFE (very-front-end) electronics to reduce noise
    - Interesting side-effect: cooling $PbWO_4$ increases its light output

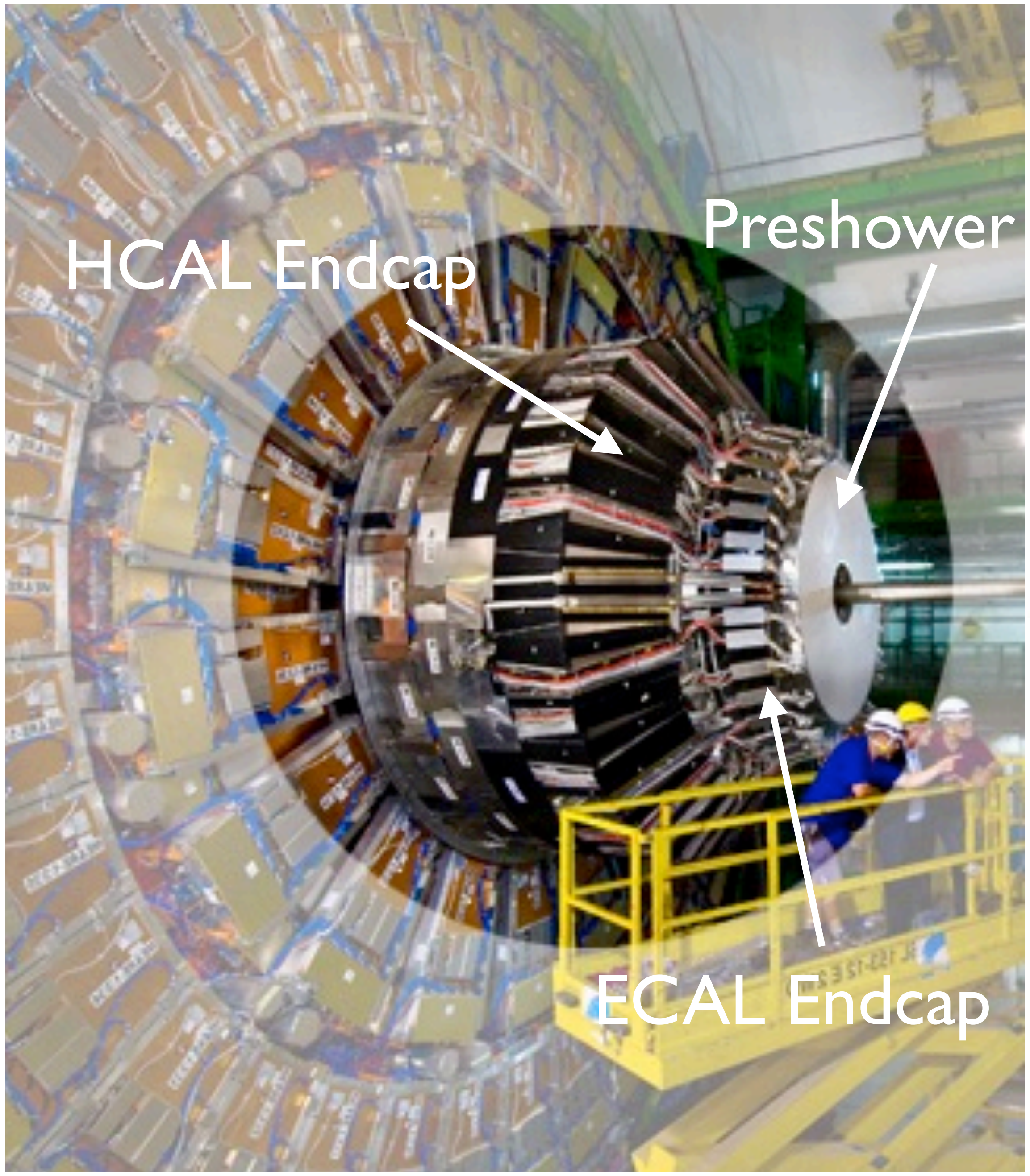
- ***Hadronic Calorimeter***
  - Plastic/brass sampling calorimeter
  - Replacement of inner layers with radiation-tolerant scintillator
  - New back-end electronics



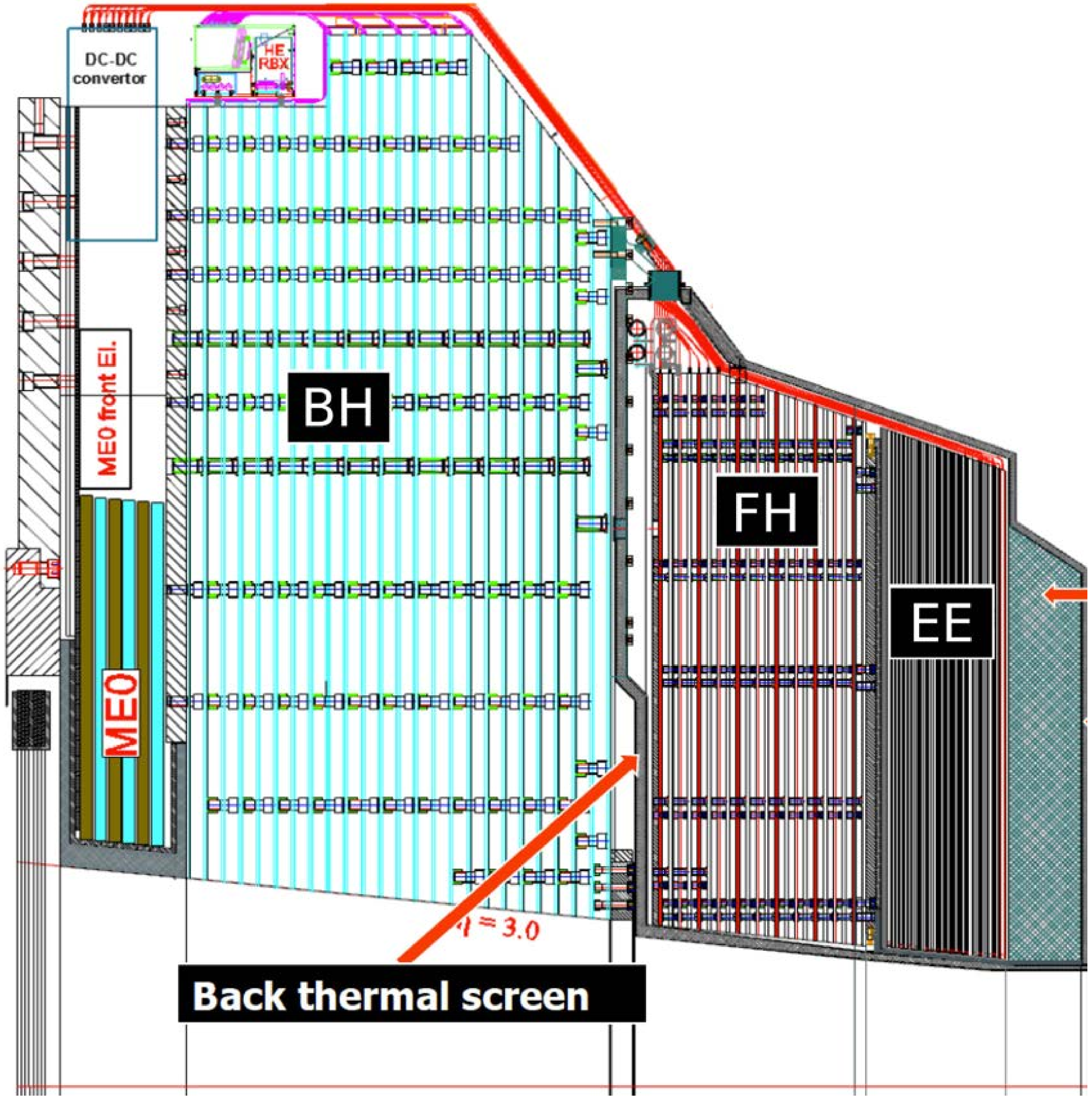


HL-LHC Endcap Calorimeter Upgrade

Current Endcap Calorimeter



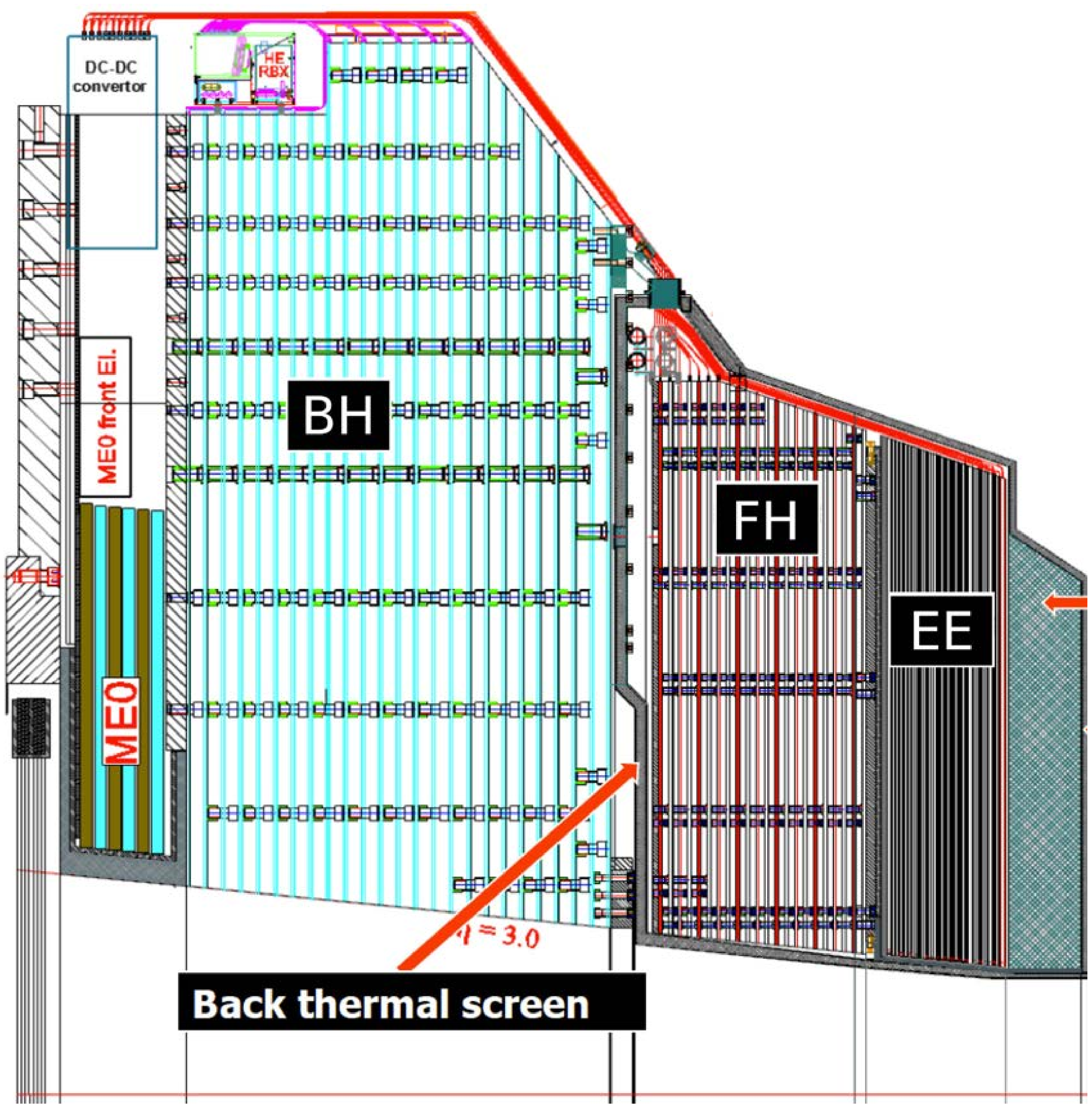
High Granularity Endcap Calorimeter



HL-LHC Endcap Calorimeter Upgrade

Current Endcap Calorimeter | High Granularity Endcap Calorimeter

- ***Challenging conditions push toward new paradigm***
  - ✦High-granularity silicon- readout, based on ILC/CALICE detector
  - ✦*Si/W EE, 26X_0, 1.5l; Si/brass FH, 3.5l*
  - ✦*Plastic scintillator/brass BH, 5l*
- **high R&D activity**
  - ✦*Radiation-tolerant on-detector electronics*
  - ✦*Cold plastic scintillator*



HL-LHC Endcap Calorimeter Upgrade

Current Endcap Calorimeter | High Granularity Endcap Calorimeter

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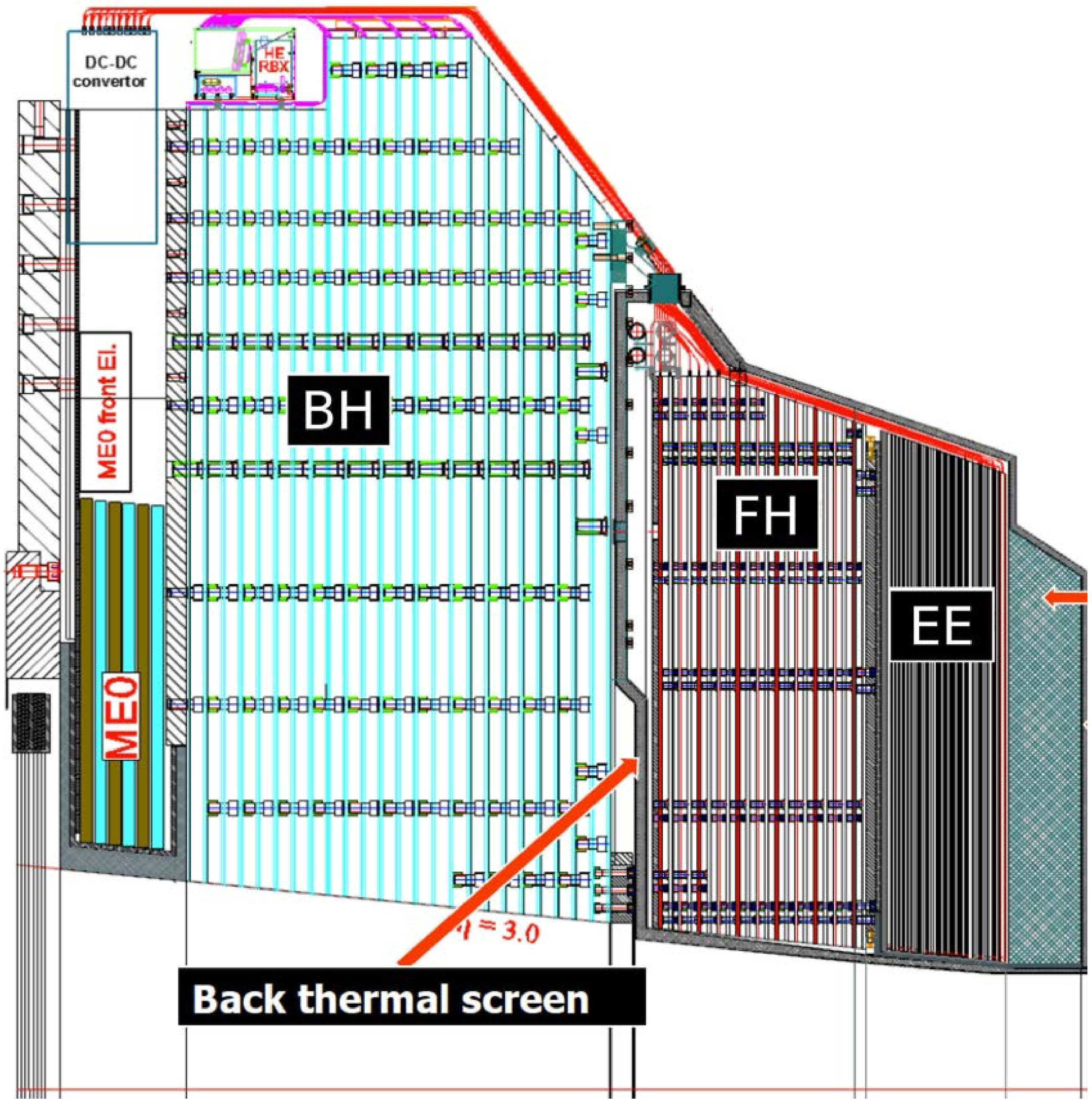
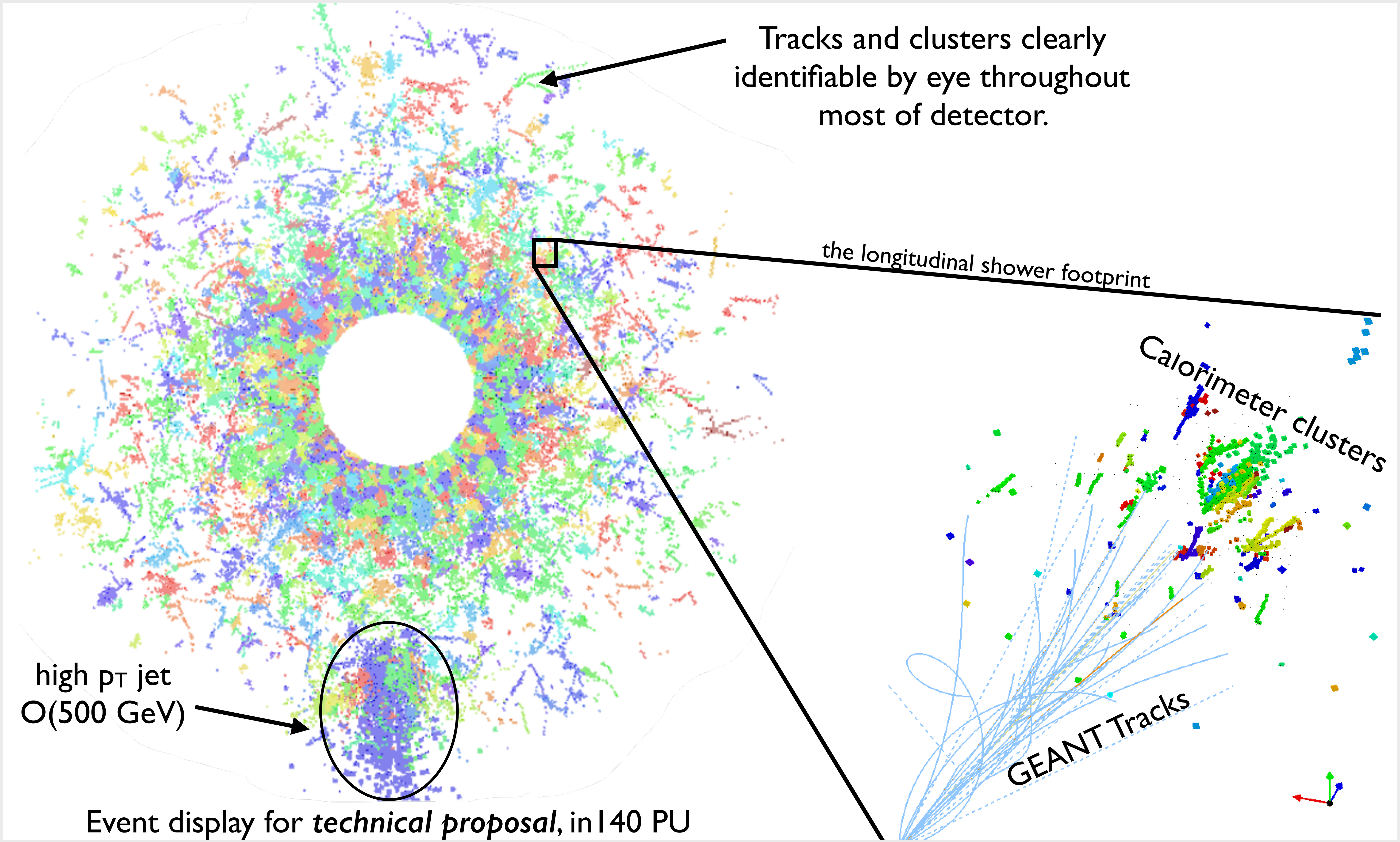


***Fine granularity calorimetry** (~26X_0 in 28 layers W/Cu ECAL, 10.5 λ_0 over 52 layers)*

enables precise particle flow techniques and ideas applied to calorimetry

- ✦ Now must follow particles through the calorimeter layers
- ✦ Fine sampling brings robustness against pileup

Imaging Showers with the HGCal



Event display for ***technical proposal***, in140 PU

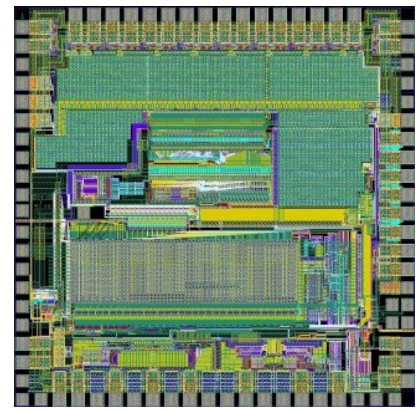
CMS HCAL Read-Out Upgrades

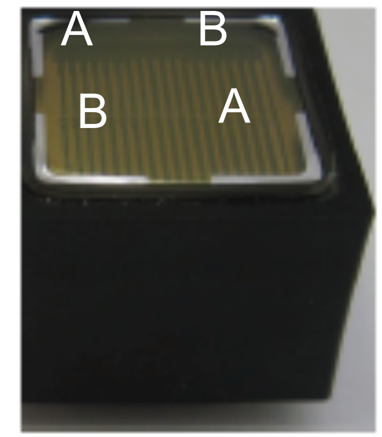
Installation during LS1(HO)/LS2(HB/HE)

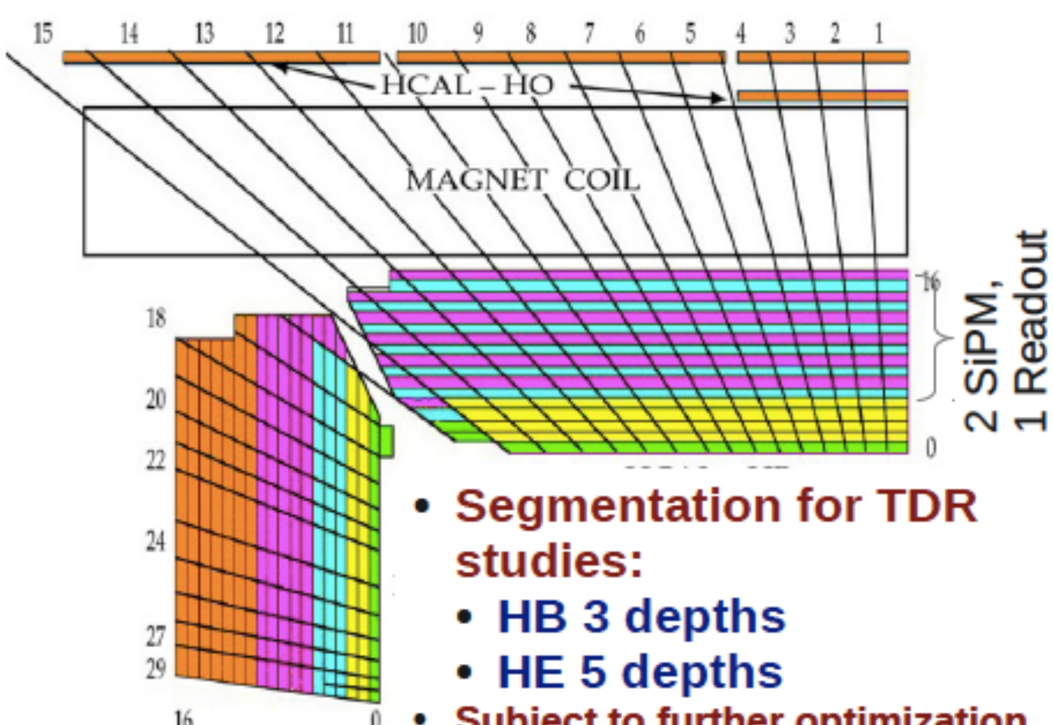
Installation during LS1

HB/HE/HO
From HPD to SiPM's

HF
From single to multi-anode PMT's

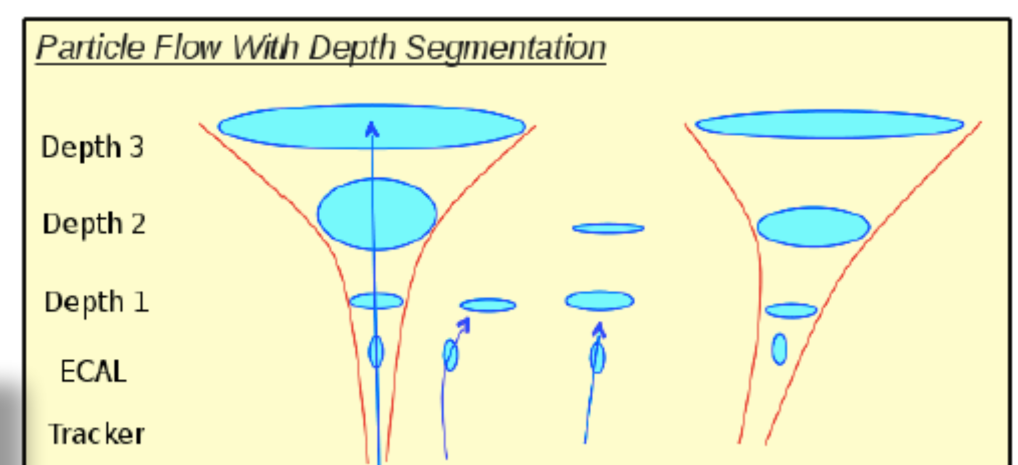






- Segmentation for TDR studies:
  - HB 3 depths
  - HE 5 depths
- Subject to further optimization

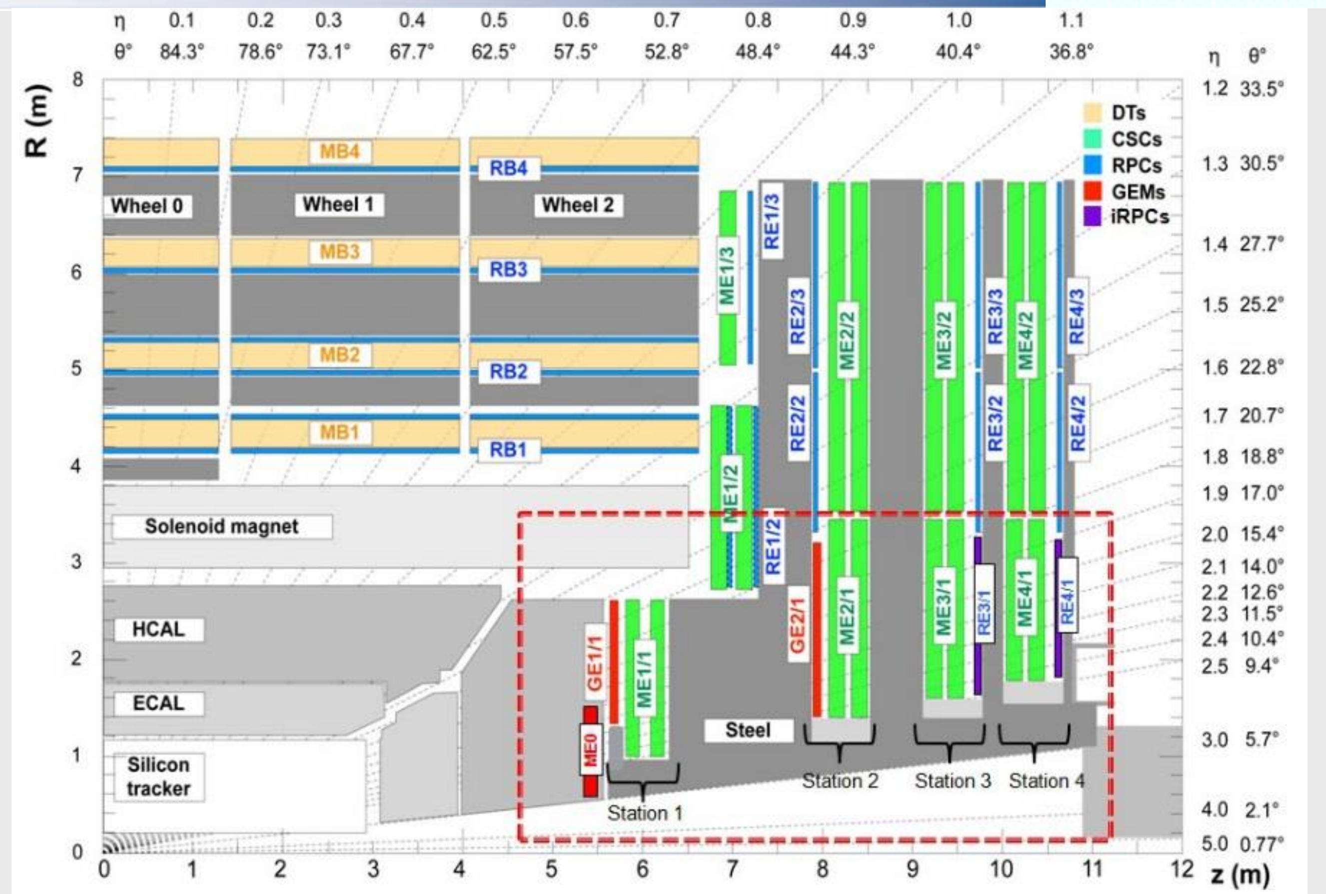
- Use SiPM's to increase HB/HE Depth Segmentation
- Improved PF Hadronic shower localization
- Provides effective tool for pile-up mitigation at high luminosity
- Mitigate radiation damage to scintillator & WLS fibers

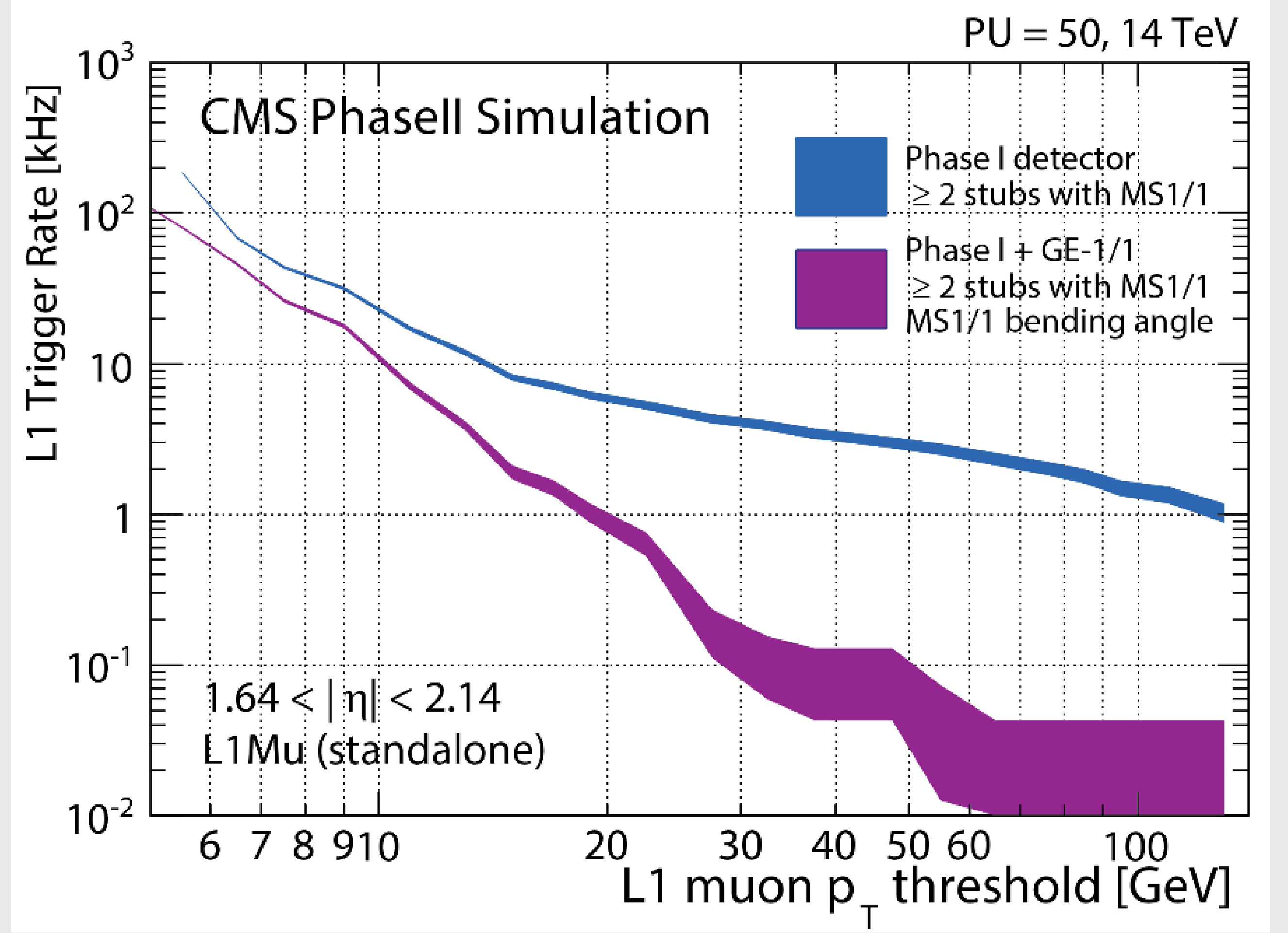


Depth segmentation: mitigate high pileup

Muon System

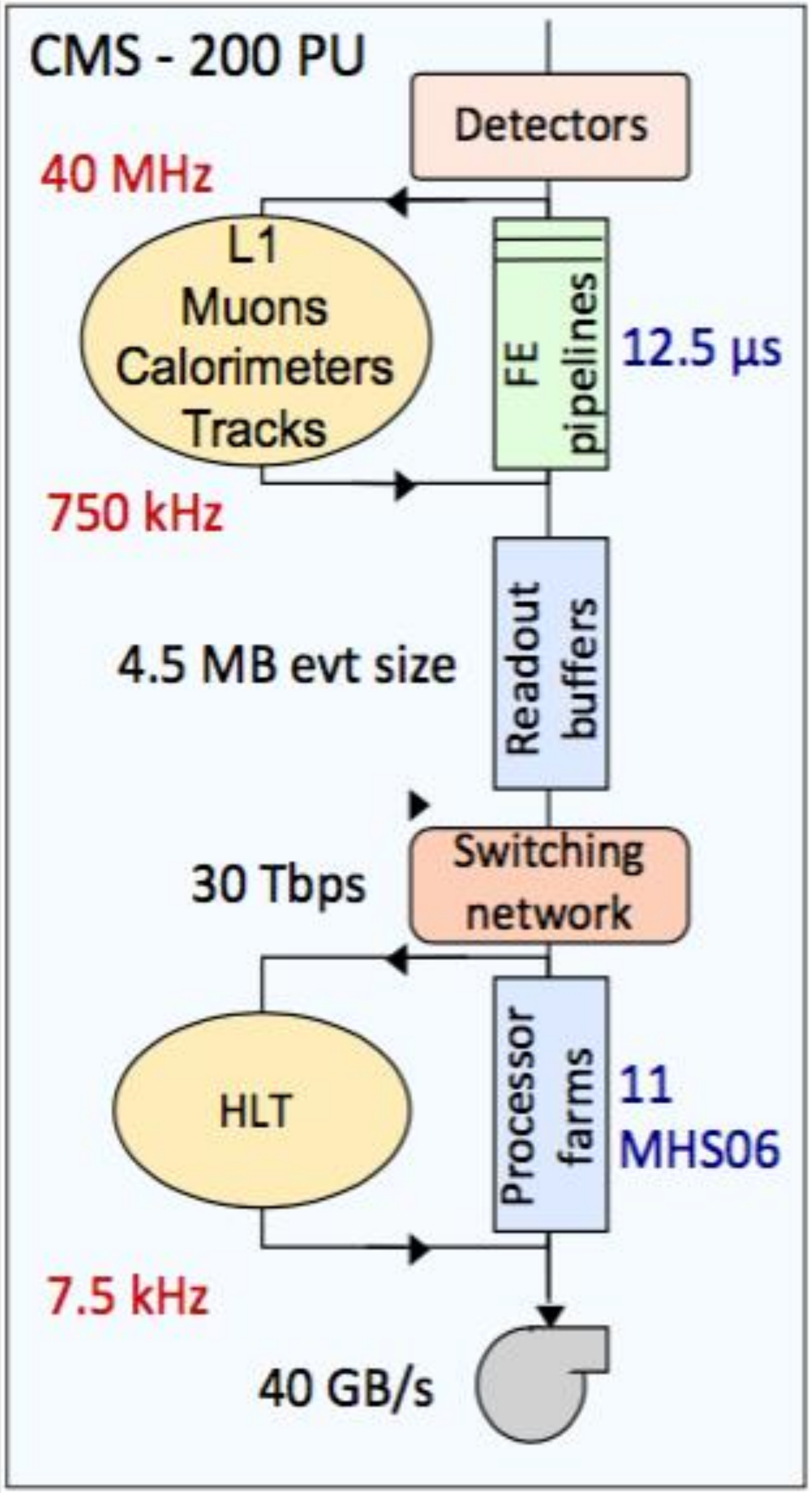
- ✦ *Extension of current muon system*
  - ✦ *Current chambers predicted to survive until end of HL-LHC*
  - ✦ *Complete coverage of RPC up to |η| ~2.4 with fine-pitch chambers*
- ✦ *New GEM chambers*
  - ✦ *Improve trigger and reconstruction*
  - ✦ *Extend muon tagging to |η|~3*
- ✦ *Installation schedule*
  - ✦ *First GEM detector scheduled for installation during LS2 (2019-2020)*
  - ✦ *Fine-pitch RPC, Muon-Tagger chambers and second GEM station will be installed during LS3 (2024-2025)*





Trigger and DAQ

- ***L1 Trigger***
  - Increase output to 750kHz, latency to 12.5μs, from 100kHz with 3.4μs latency
  - New track-trigger
- ***High-Level Trigger***
  - Processing power scales with pile-up and L1 rate: expect factor ~ 50 w.r.t. Run-1
  - Output rate increase by ~10 to 7.5kHz
- ***DAQ***
  - Increase bandwidth (800 links @ 100Gbps) to reach 30Tbps throughput



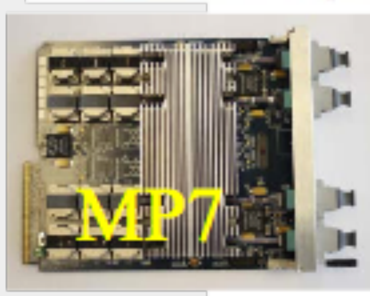
Level - 1 Trigger upgrade

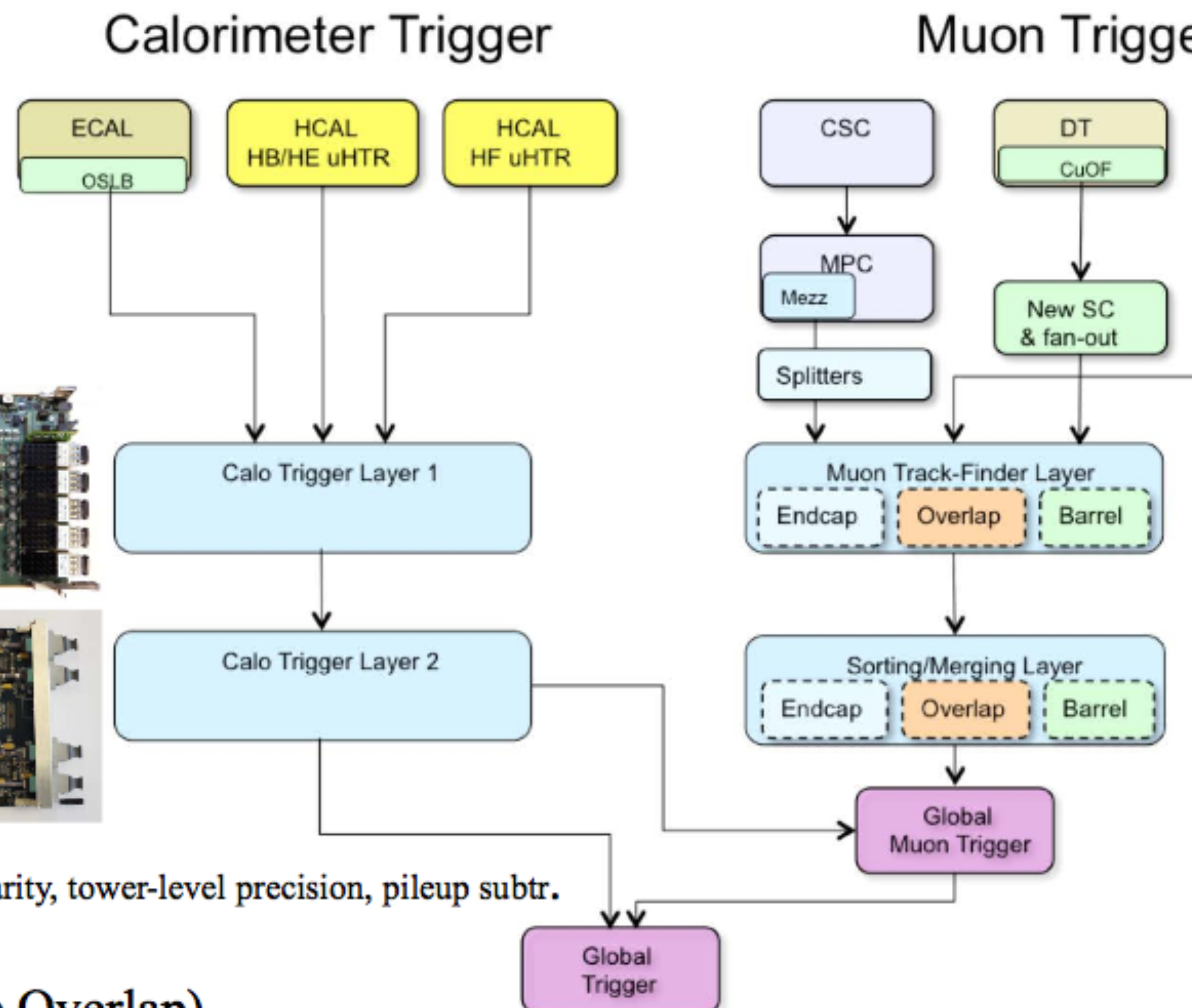
CERN-LHCC-2013-011
(CMS-TDR-012)

New hardware!

Limited number of boards.

Ambitious plan assume parallel running of a (part of) new system in 2015. Full replacement 2015/16 YEST





Global Trigger:
- more algorithms,
- flexibility

Calorimetry:
- improved algorithms, granularity, tower-level precision, pileup subtr.

Muons:
- 3 partitions (Barrel,Endcap,Overlap)
- explore the available information at early step of triggering.

Currently independent candidates from DTTF, CSCTF, PACT merged at GMT

More needed for phase2!

L1 Trigger upgrade

- **Level-1 trigger rate** limited to **1kHz**, 4μs latency by detector readout.
- Mitigate through improved:
  - **muon triggers**: improved μ p_T resolution w/ full information from 3 systems in track finding, more processing
  - **calorimeter triggers**: finer granularity, more processing means better e/γ/μ isolation & jet/τ resolution w/ PU subtraction
- Increased system flexibility and algorithm sophistication
- Build/commission in parallel with current system – staged installation, will benefit already at start of Run 2

Larger FPGAs, finer granularity input, high speed optical links

Trigger efficiency @ 2e34 $cm^{-2}s^{-1}$

Channel	Current	Upgrade
W(eν),H(bb)	37.5%	71.5%
W(μν),H(bb)	69.6%	97.9%
VBF H(ττ(μτ))	19.4%	48.4%
VBF H(ττ(ετ))	14.0%	39.0%
VBF H(ττ(ττ))	14.9%	50.1%
H(WW(eeνν))	74.2%	95.3%
H(WW(μμνν))	89.3%	99.9%
H(WW(eμνν))	86.9%	99.3%
H(WW(μeνν))	90.7%	99.7%

UPGRADE Concluding Remarks

- Upgrade projects are a continuous effort, overlapping with operations
  - Unique opportunity for training new physicists;
  - important to establish strong community to share knowledge of key personnel and ensure growth of next generation of physicists
- Phase-1 upgrade is used for RUN 2
  - Many parts are already installed and in commissioning phase
- Phase-2 upgrade is in its initial stage
  - Very exciting R&D programs on-going to define the future detectors
- The HL-LHC will open an astonishing set of physics opportunities
  - A successful upgrade program is crucial to exploit them

Conclusions

The LHC is an incredible technological and scientific endeavor - world wide unique and comparable to the Space programmes.

Twenty years spent on the design: R&D, prototyping, construction, assembly and commissioning all experiments have recorded high energy collision data.

The LHC has gradually rise the collision energy (now 13 TeV) and luminosity (now as high as 1.3 10^{34} $cm^{2}s^{-1}$)

The four major experiments ATLAS, CMS, ALICE and LHCb have taken high quality data operating extremely successfully, with very high efficiencies and generate hundreds of publications

The LHC will continue feed the world particle physics community for the next ~ 20 years

All systems are performing very well.
An upgrade programme prepare the detectors to accept and treat higher luminosities and extract new physics from large pile up background.

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Twenty yea ... **issioning**
all experim ...

The LHC h ... *as 1.3 10^{34}*
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All systems ...
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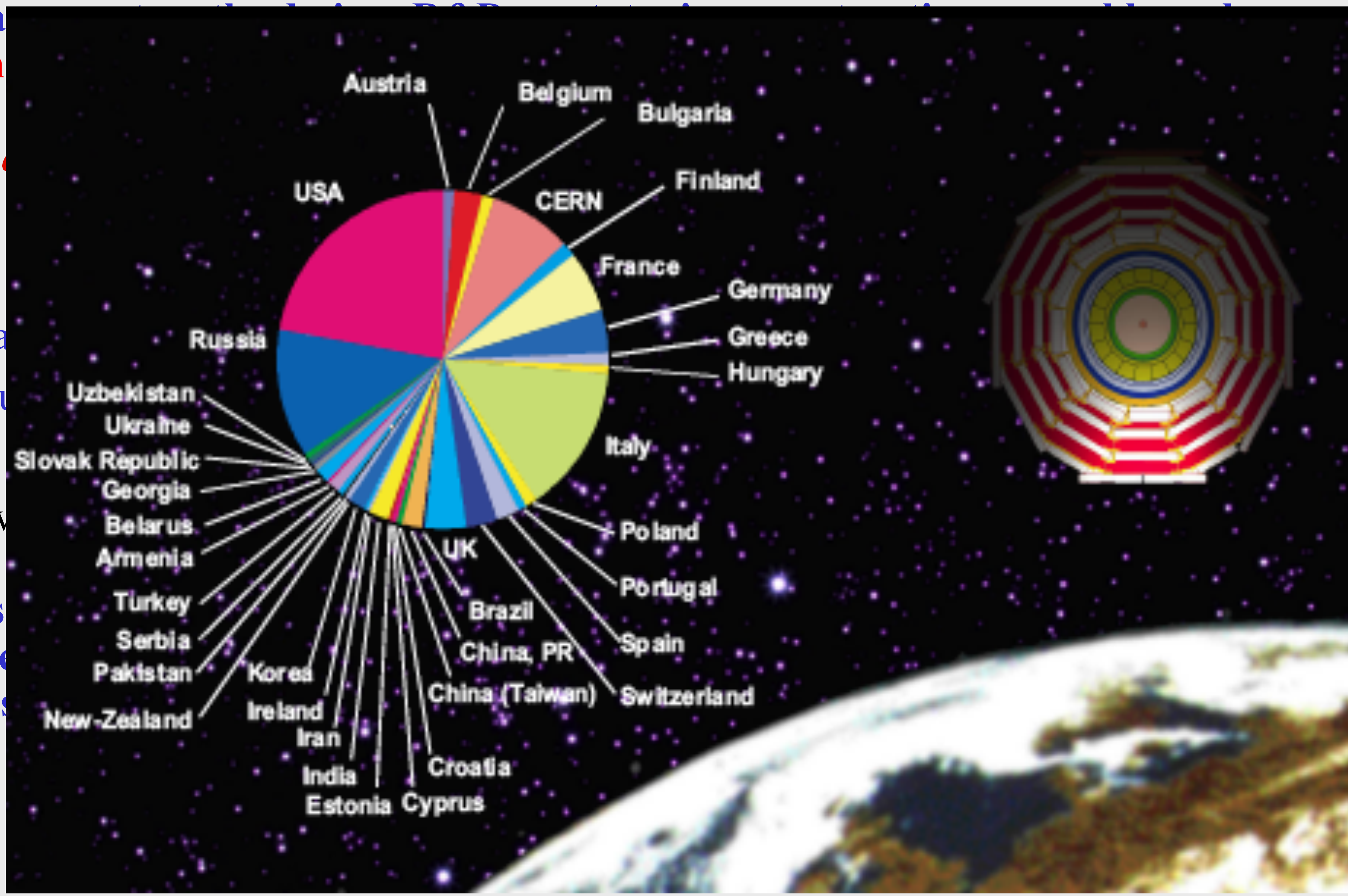
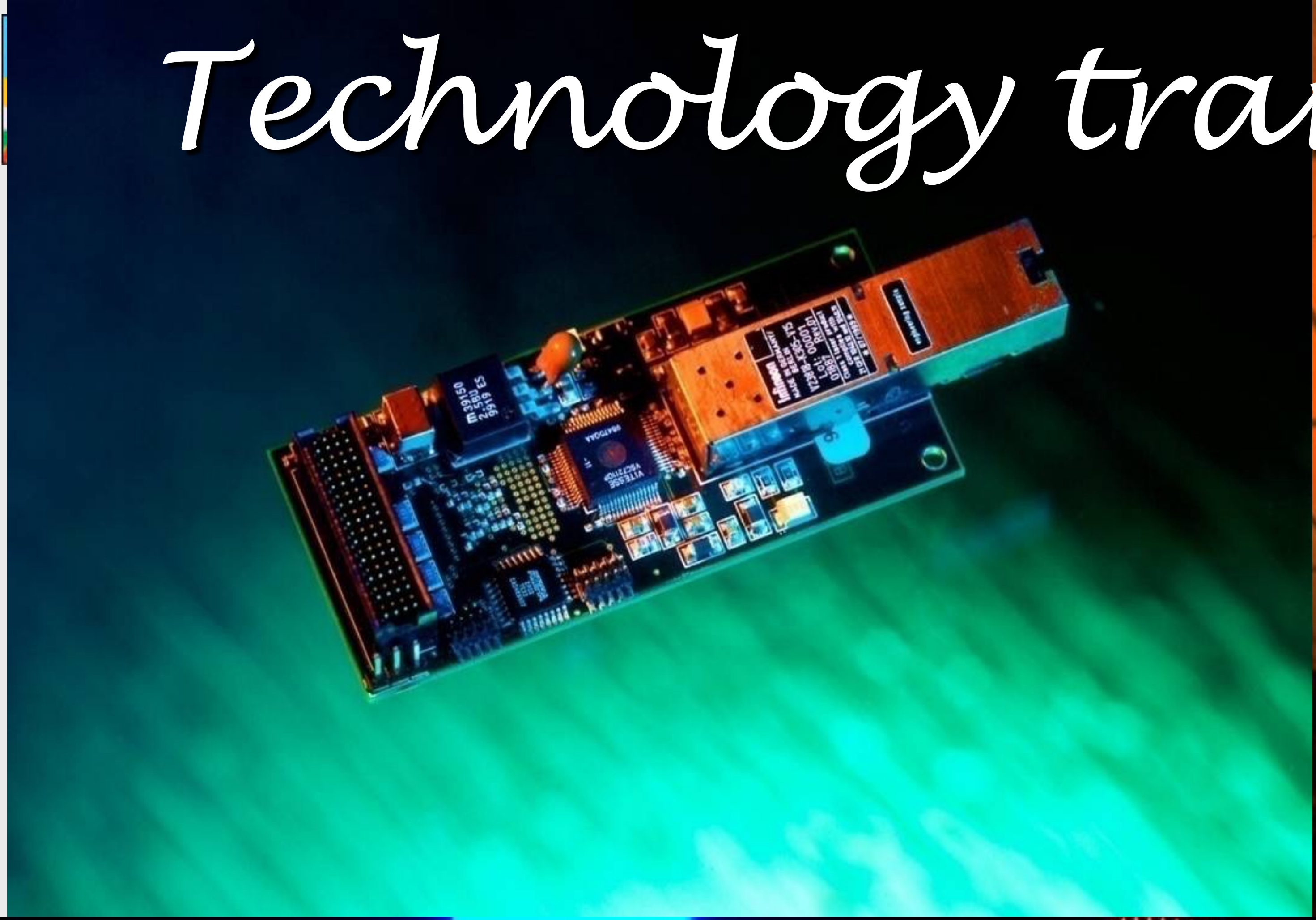
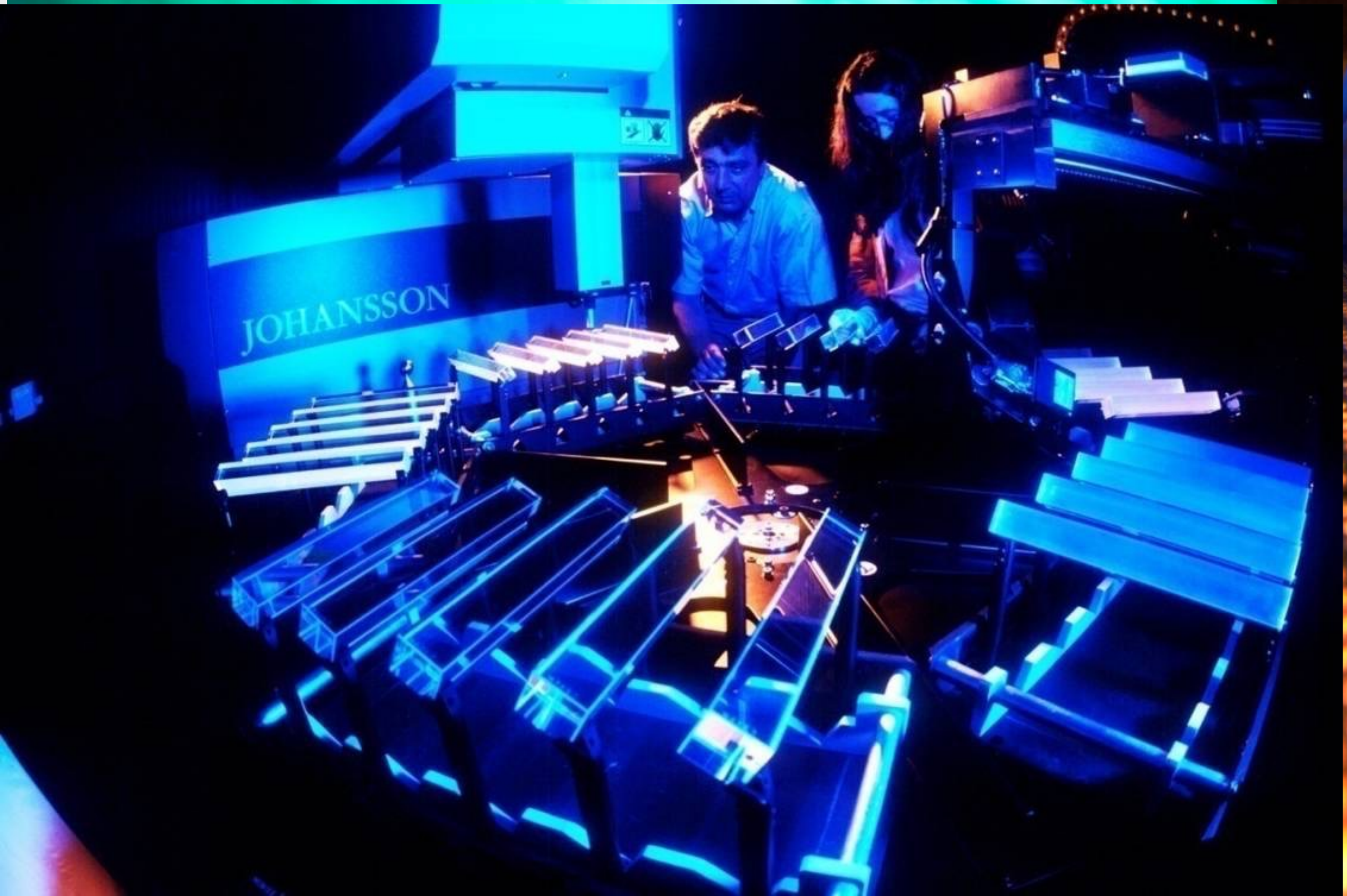
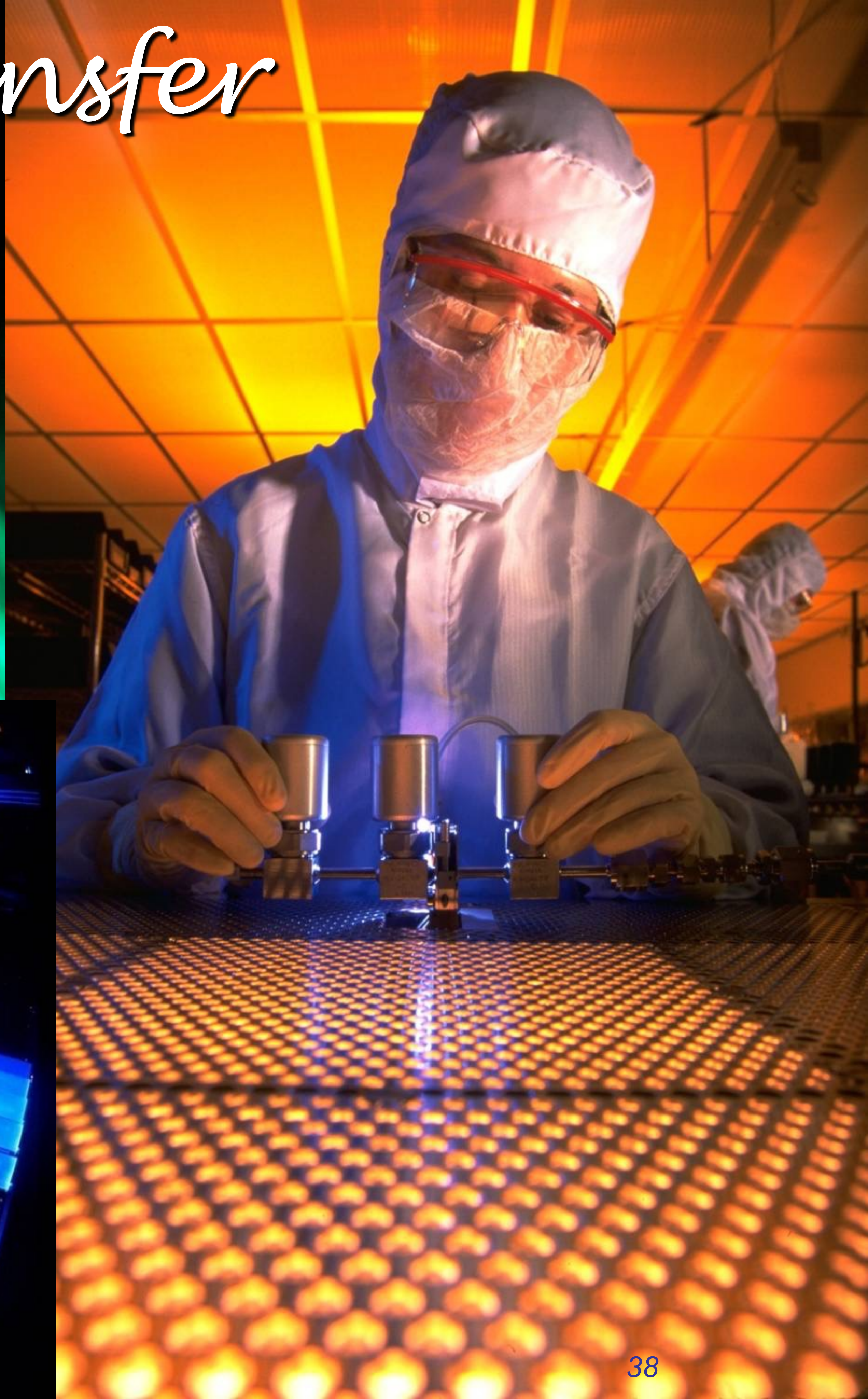


Technology transfer

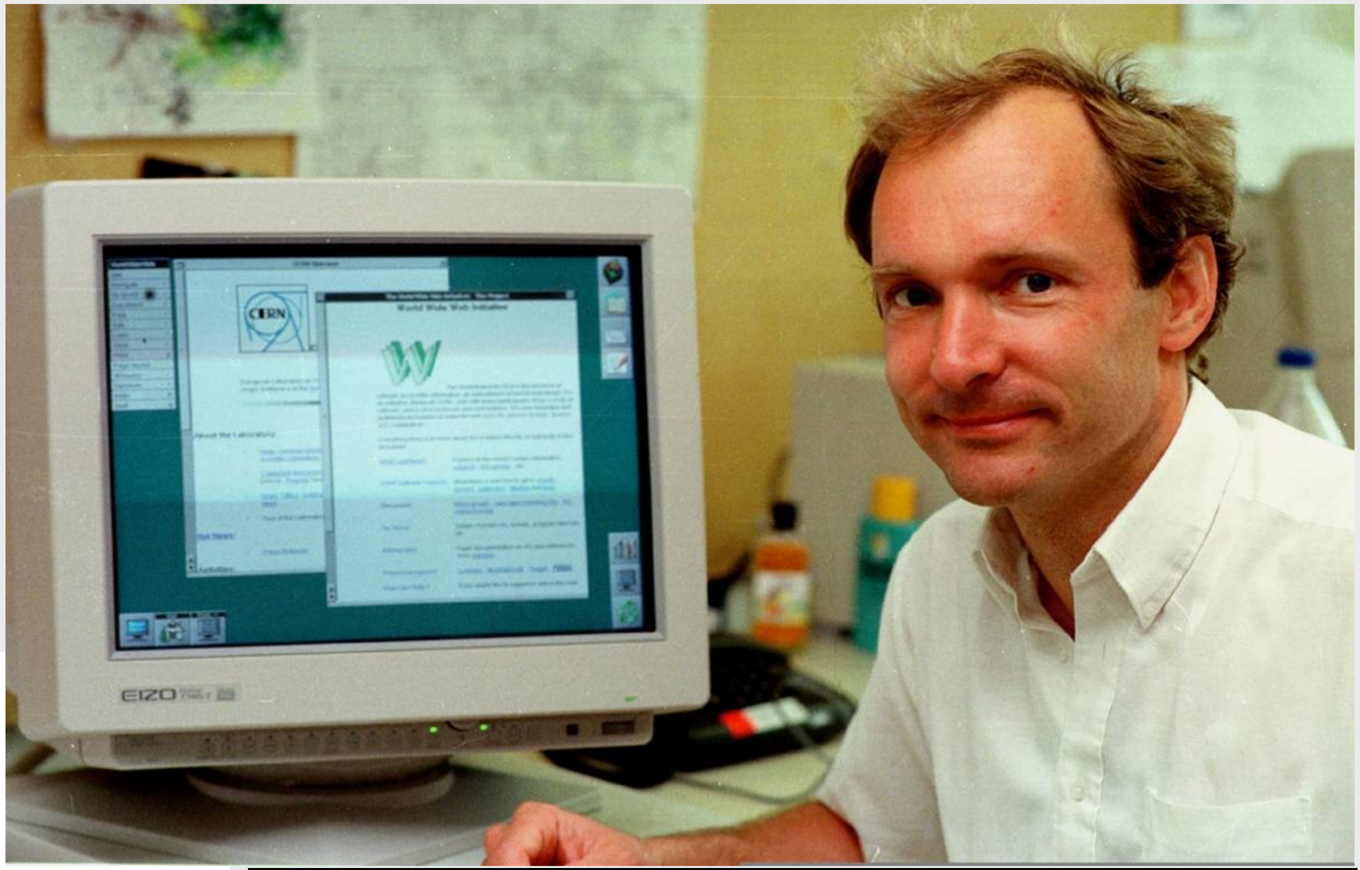


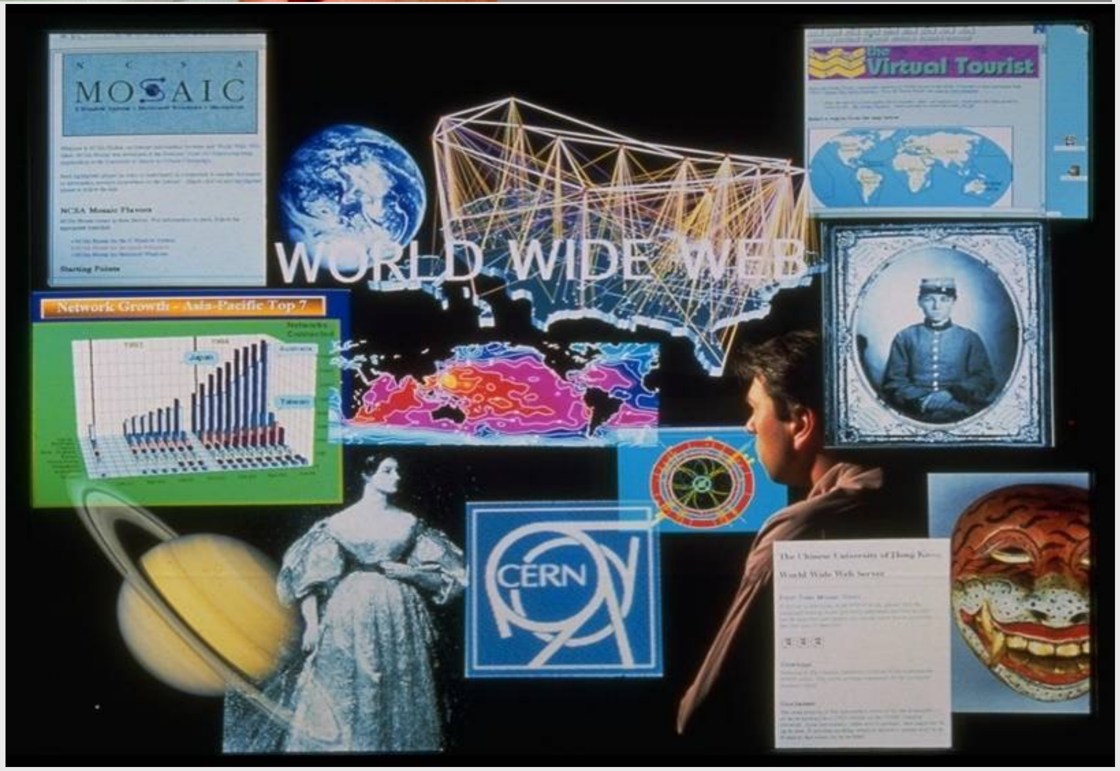




WWW

CERN invented the WEB!!!





BACKUP

To access more informations

- Phase-1 Pixel Detector Upgrade TDR
  http://cds.cern.ch/record/1481838/files/CMS-TDR-011.pdf
- Phase-1 Hadron Calorimeter Upgrade TDR
  http://cds.cern.ch/record/1481837/files/CMS-TDR-010.pdf
- Phase-1 Level-1 Trigger Upgrade TDR
  http://cds.cern.ch/record/1556311/files/CMS-TDR-012.pdf
- Phase-2 CMS Upgrade Technical Proposal
  http://cds.cern.ch/record/2020886/files/LHCC-P-008.pdf
- Phase-2 CMS Upgrade Scope Document
  http://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf