LHC detectors : their performances and Upgrades

International Workshop on LHC Physics and related topics
10-12 October - Tirana - Albania

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

LHC detectors : their performances and Upgrades

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

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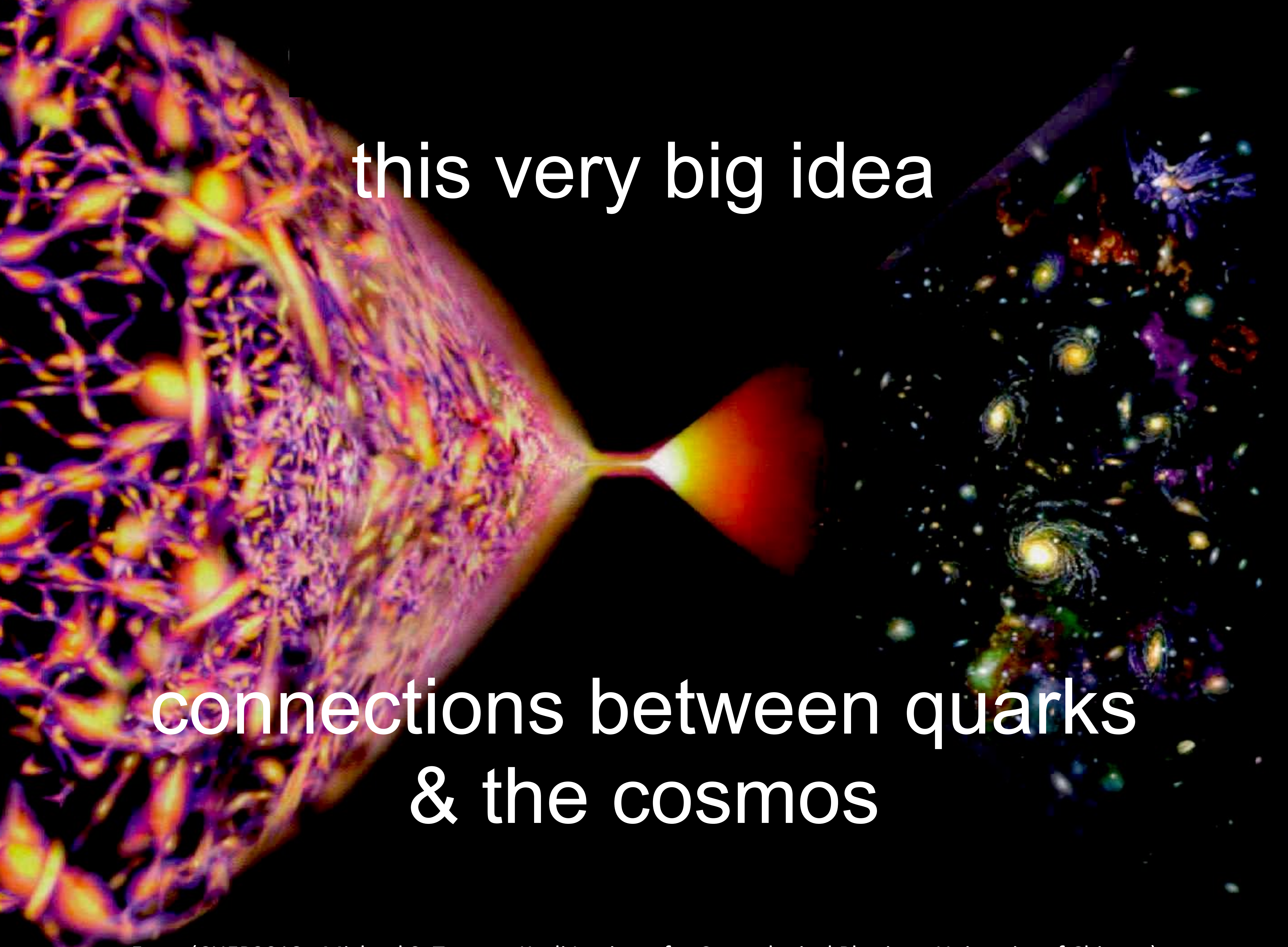
The Universe is very big (billions and billions of everything) and often beyond the reach of our minds and instruments

Big ideas and powerful instruments have enabled revolutionary progress

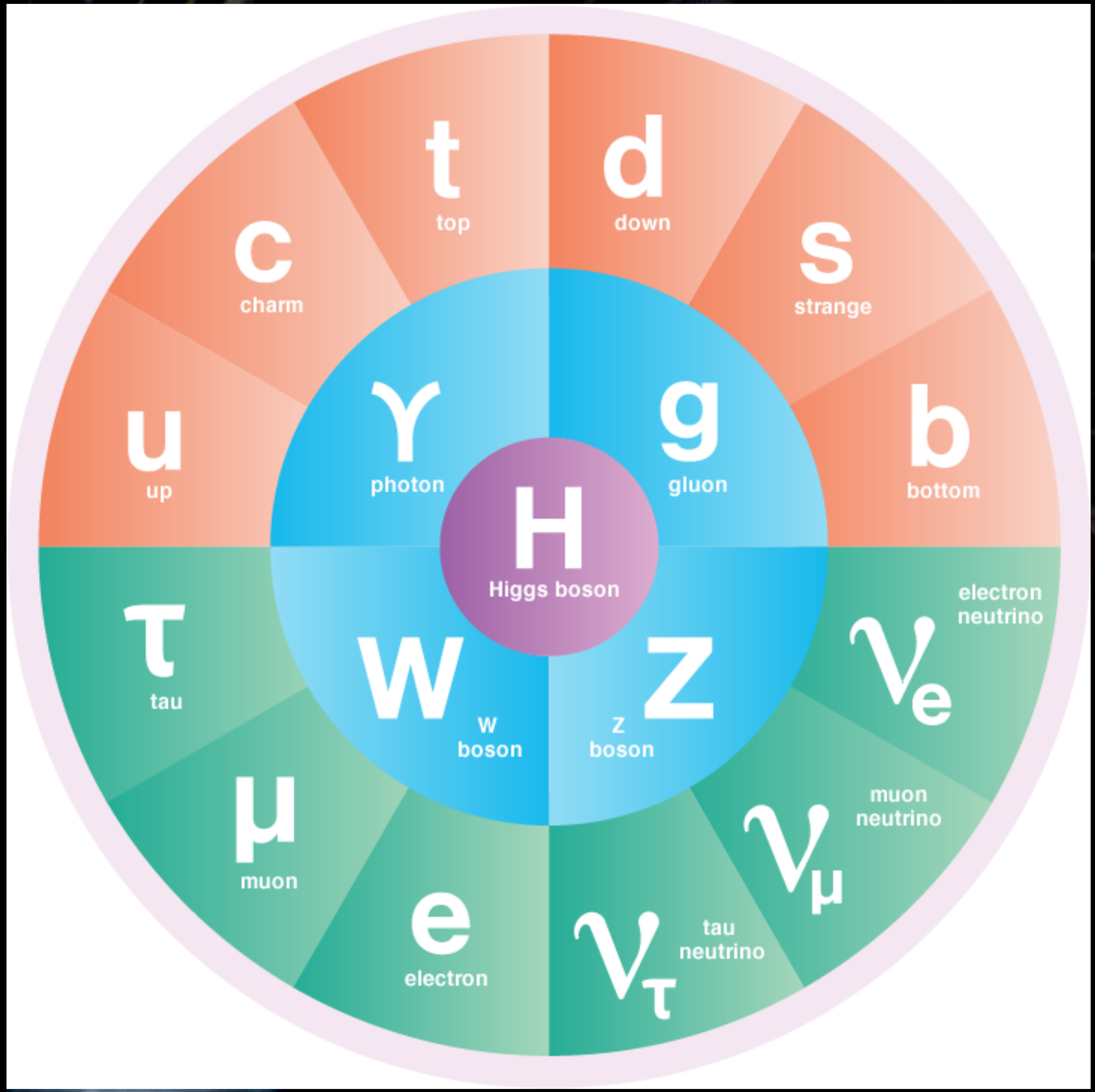


this very big idea

connections between quarks & the cosmos

From (CHEP2018 - Michael S. Turner - Kavli Institute for Cosmological Physics = University of Chicago)

Inducing the quark soup revolution



From (CHEP2018 - Michael S. Turner - Kavli Institute for Cosmological Physics = University of Chicago)

How we come there

- *a jiffy* after the beginning:* tremendous burst of expansion (inflation) that smoothed spacetime, created hot quark soup, and turned subatomic quantum fluctuations into seeds for galaxies
- *until 0.00001 sec:* quark soup era during which ordinary matter and dark matter arose
- *0.00001 to 300 sec:* neutrons and protons, then nuclei of the lightest elements were created
- *100,000 years to 5 billion years:* gravity of dark matter builds cosmic structure from quantum seeds
- *5 billion years on:* Dark energy takes over and speeds up the expansion

*a jiffy = 10^{-40ish} sec

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Early burst of enormous expansion

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Elementary particles as Dark Matter

WIMPs

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Dark Energy

Repulsive vacuum energy!

CDM

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Basic questions about the very small and the very big

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Physics @ LHC

Our game

Find new particles/new symmetries/new forces?

Prove and confirm models

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More questions

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⇨ The Unexpected !!

Studies of CP Violation and Quark Gluon Plasma

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Studies of CP Violation and Quark Gluon Plasma


LHC ring:
27 km circumference


CMS
LHCb
ALICE
LHC ring:
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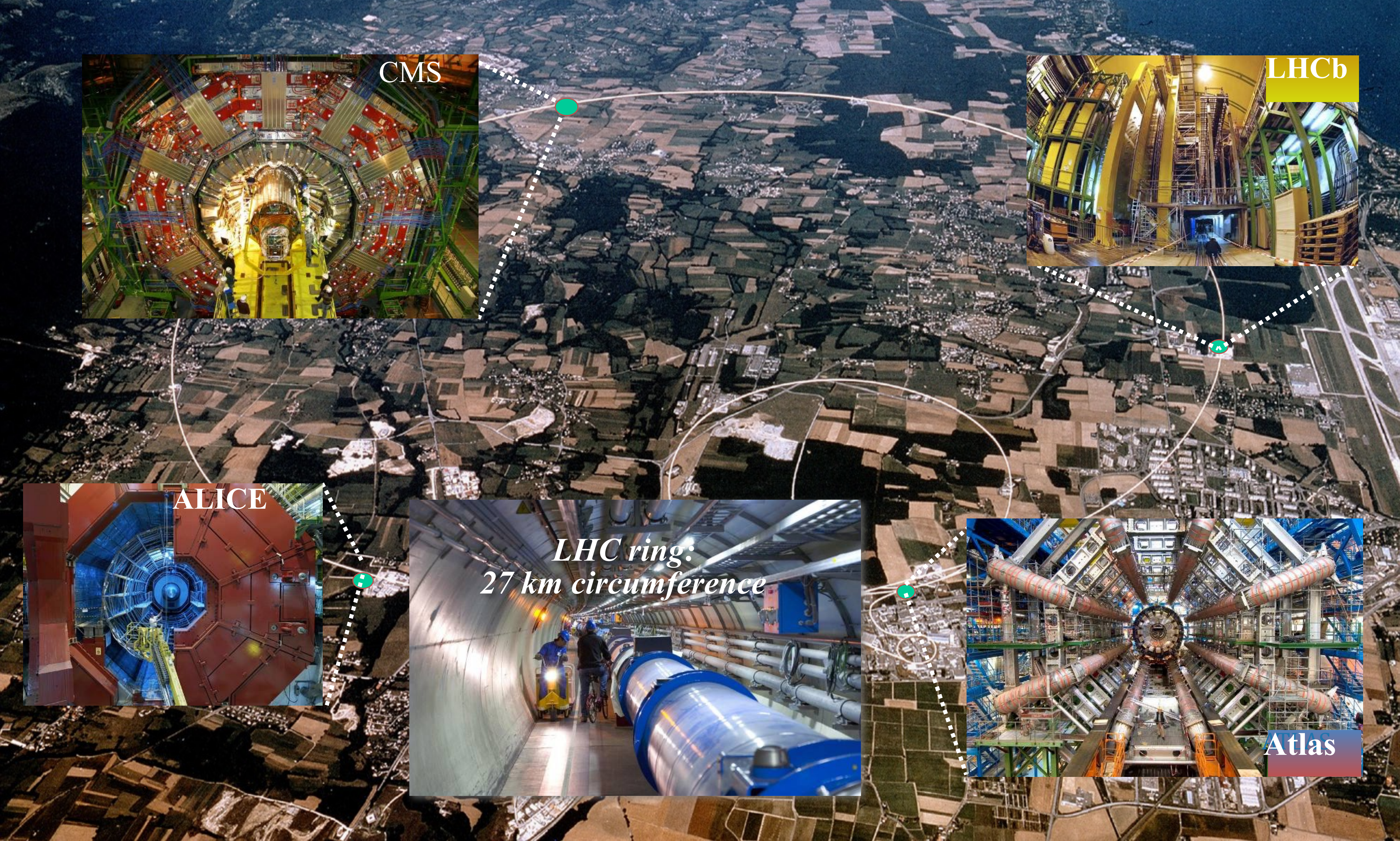
Atlas

LHC

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



Physics capabilities and Objectives

- 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.

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  - 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

Detector Requirements : The challenges

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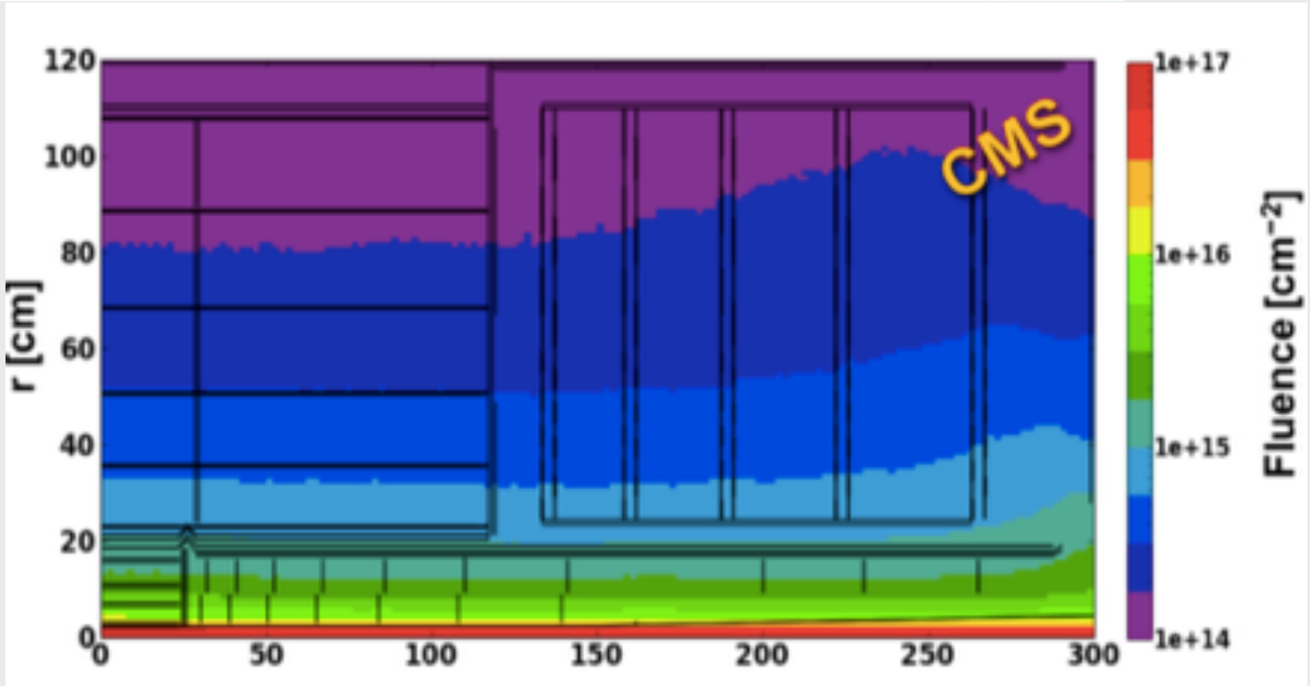
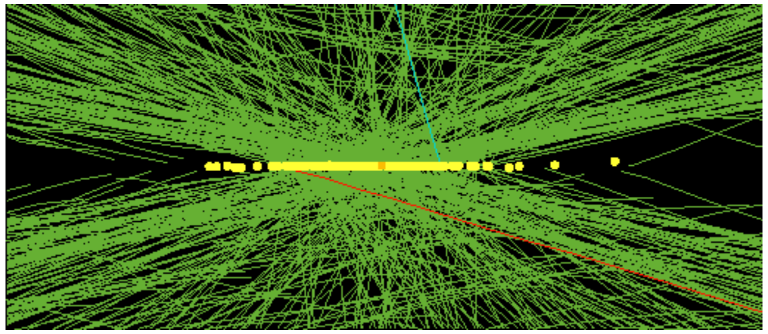


Expected Fluences in CMS at 3 ab^{-1}



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

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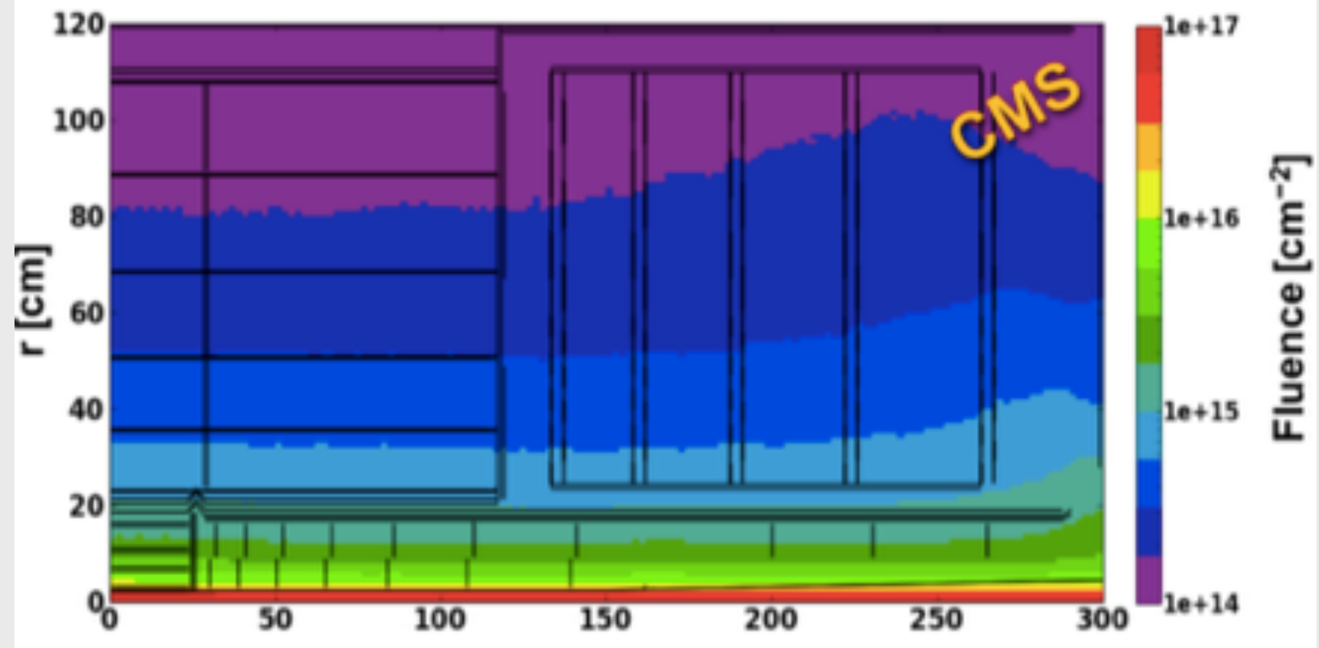

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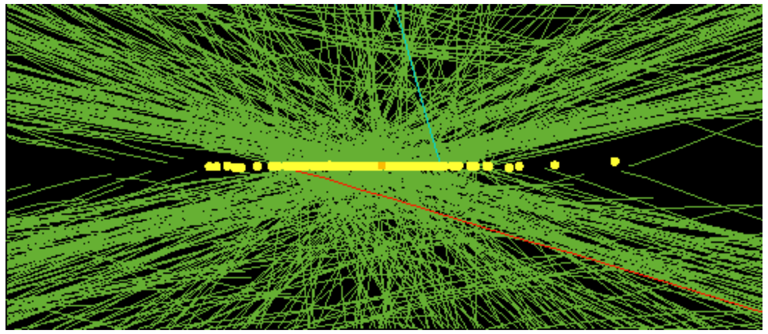

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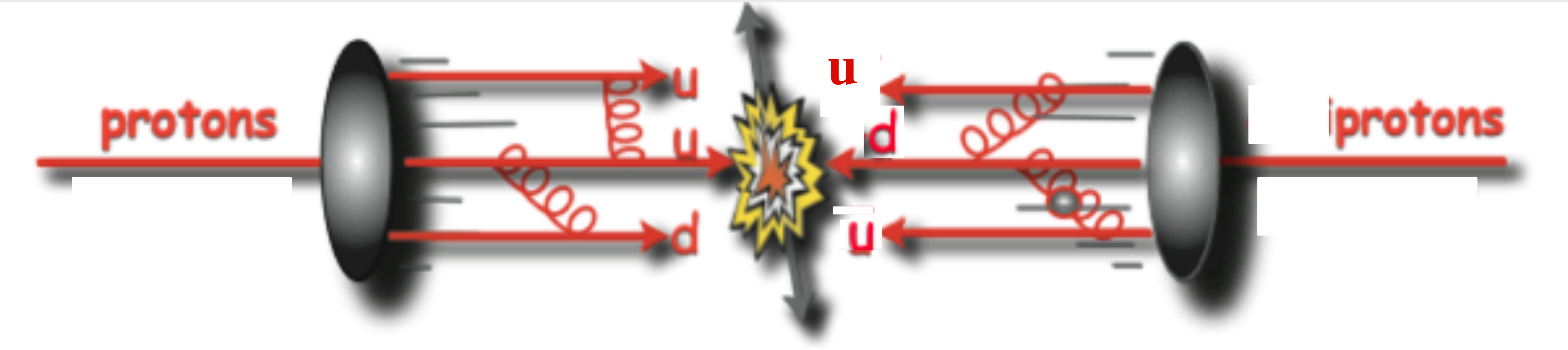
- ***Challenge in photo-detection***
- ***Challenge in silicon***
- ***Challenge in data collection / trigger***
- ***High Radiation Levels***
  - ***Require radiation hard (tolerant) detectors and electronics***

Hadron Colliders



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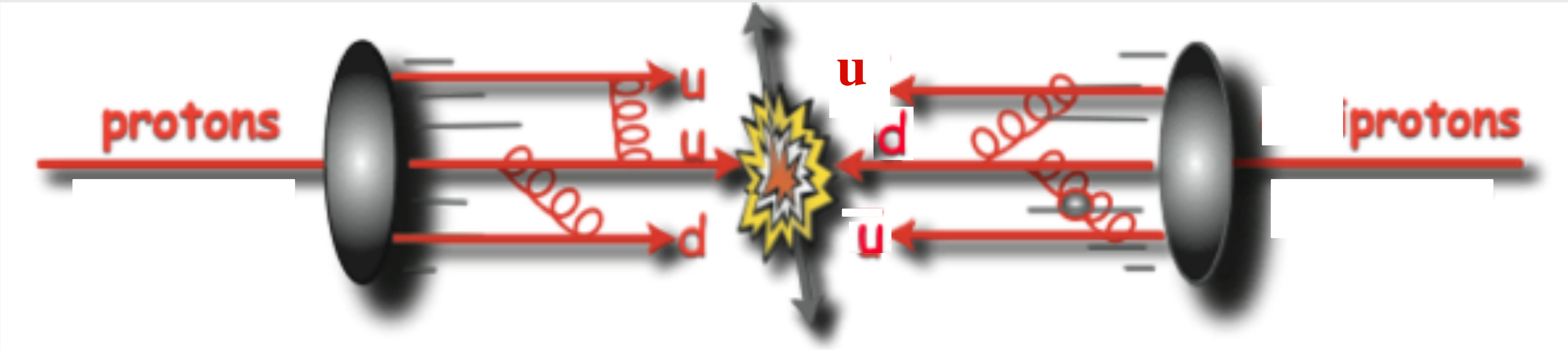

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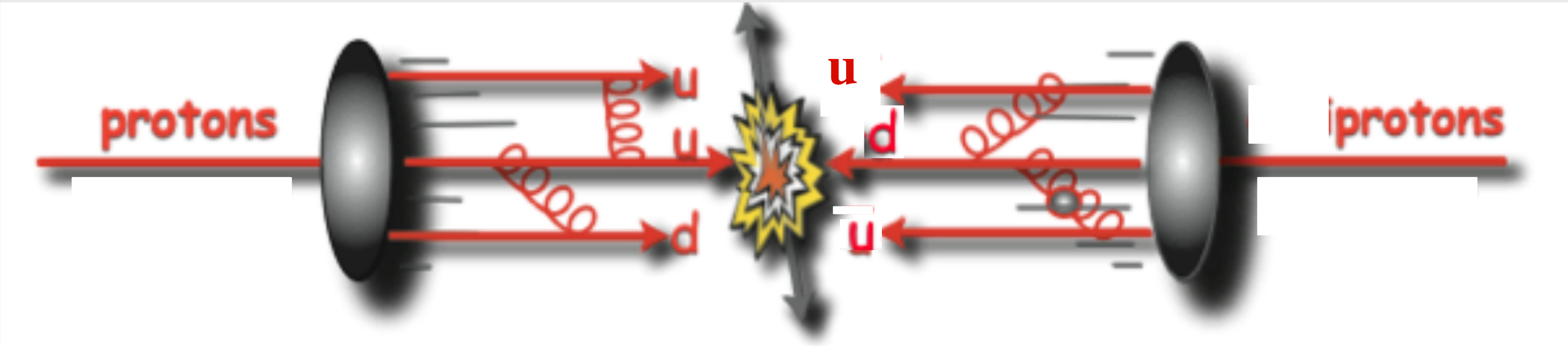

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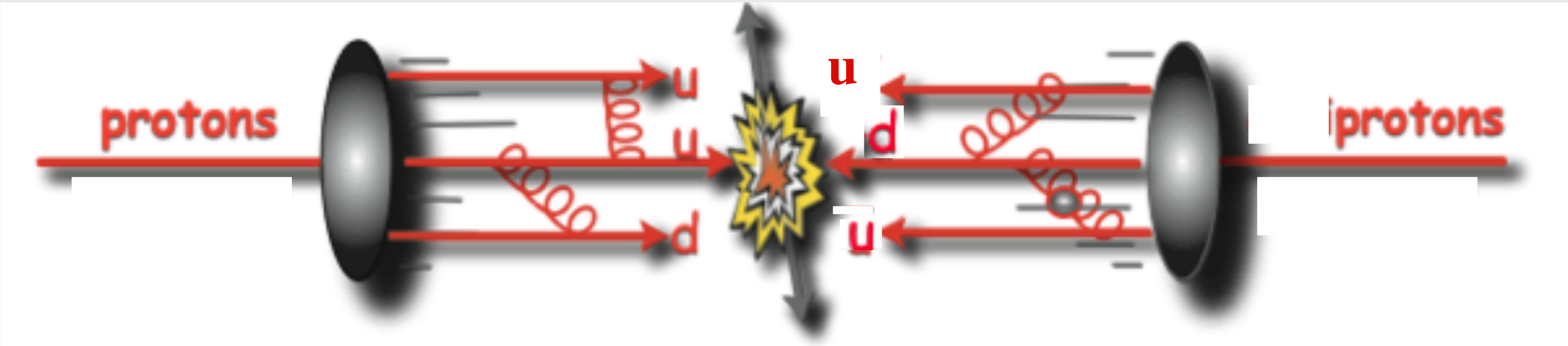

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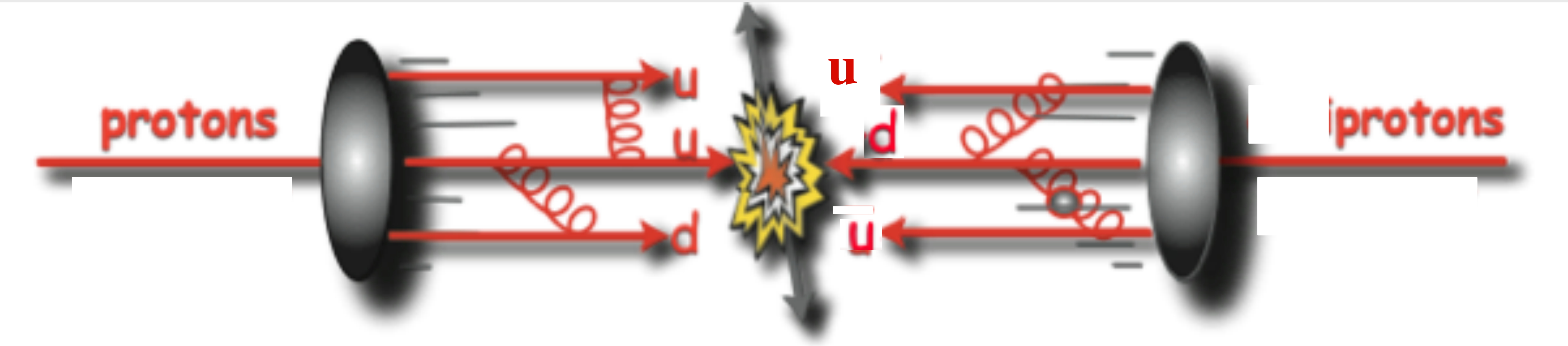

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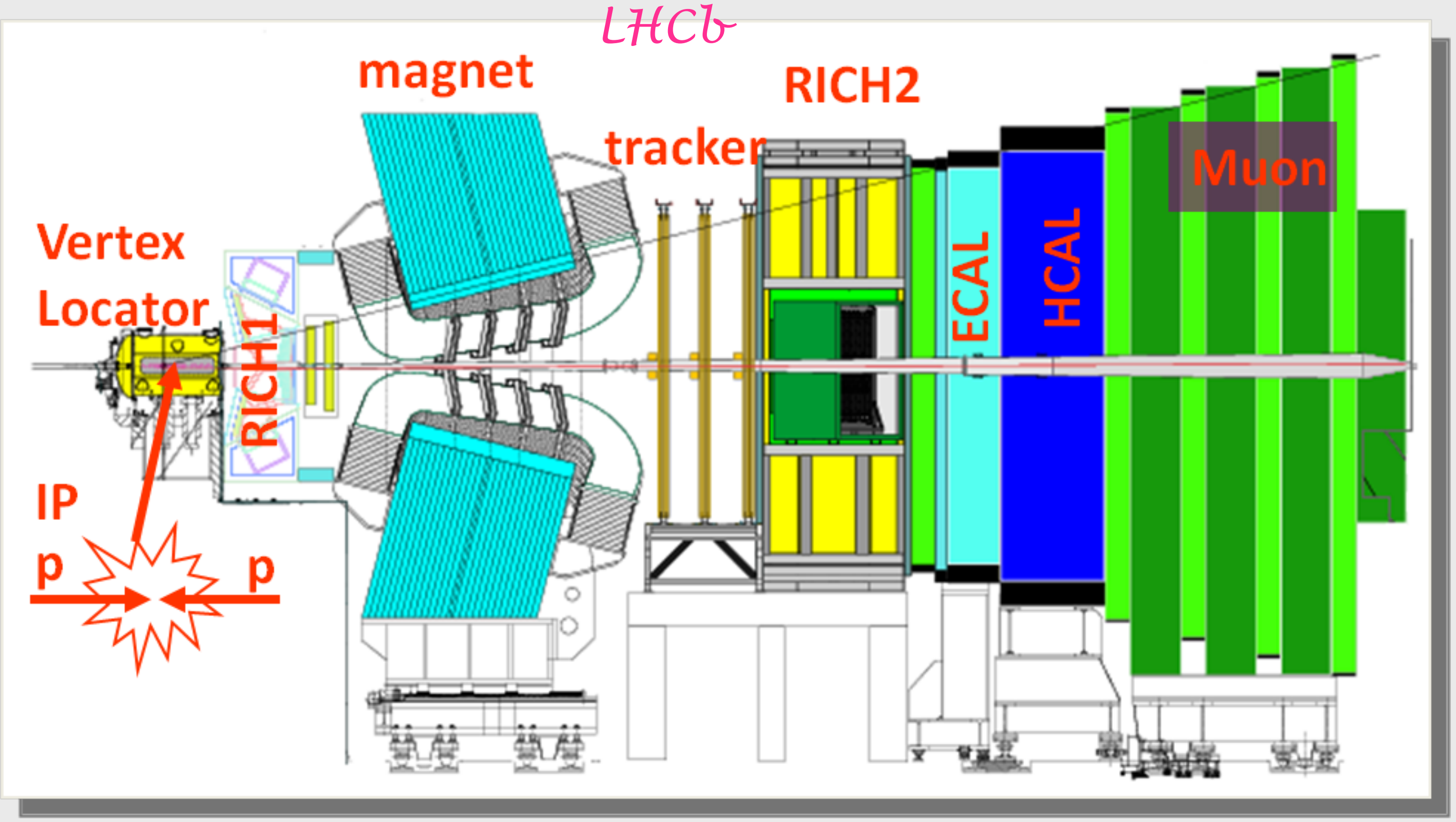
↔ Can't be achieved with a single detector ↔ Integrate detectors to a detector system

The LHC detectors : a modular concept



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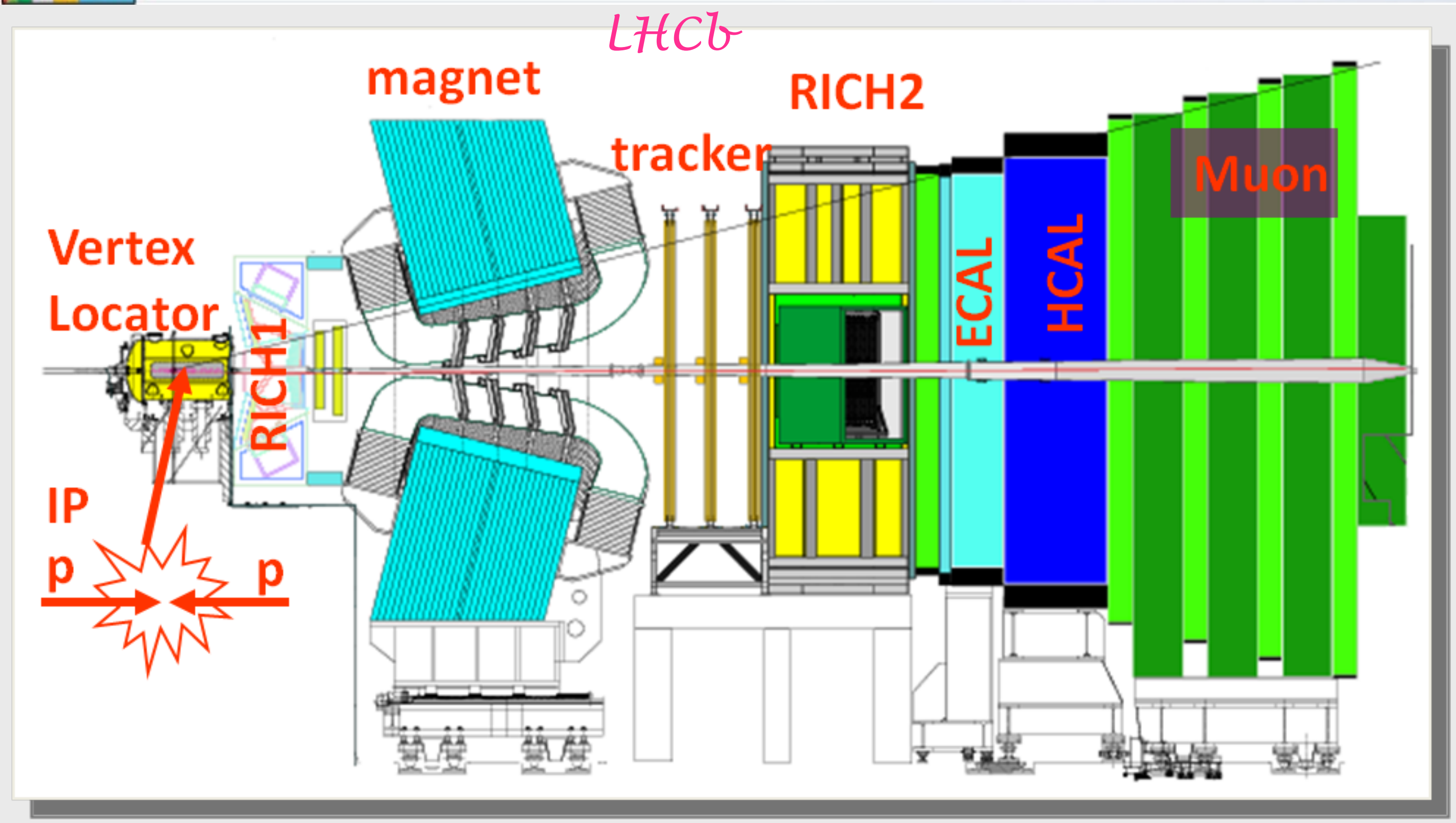
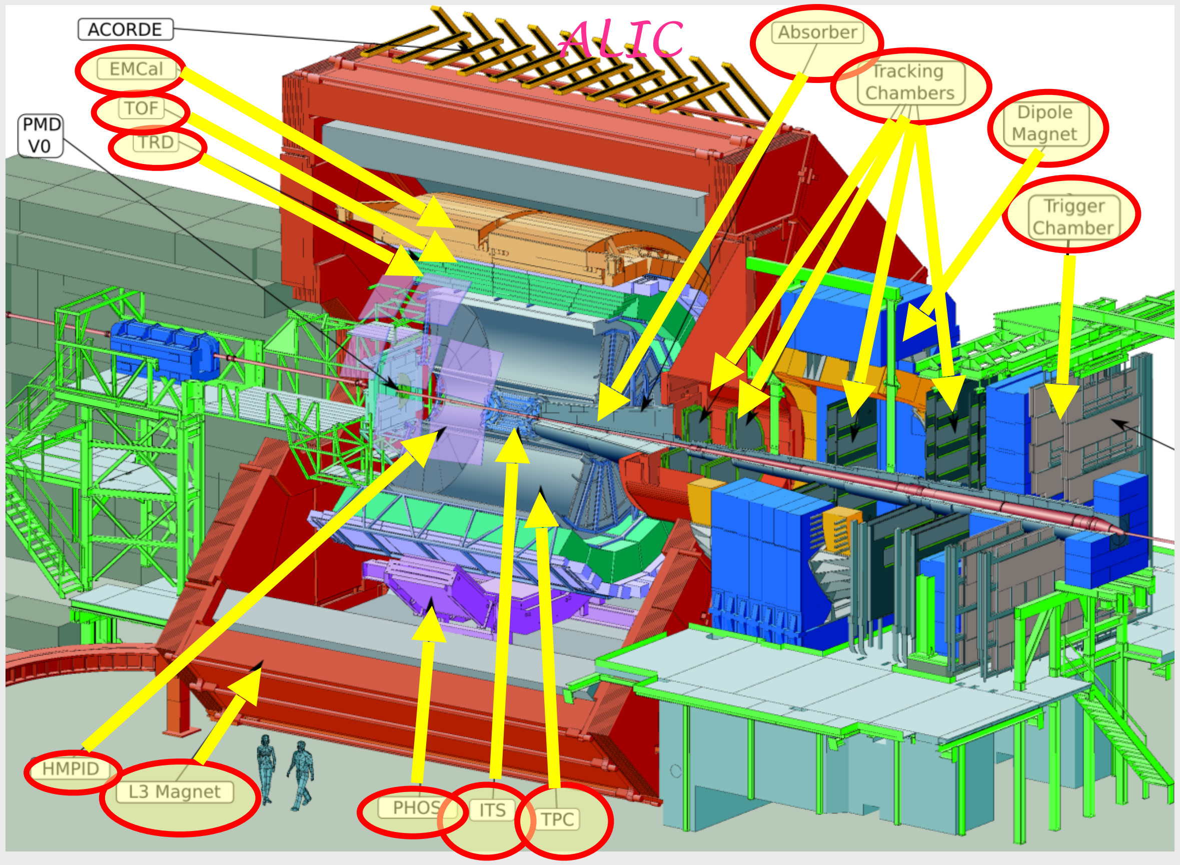
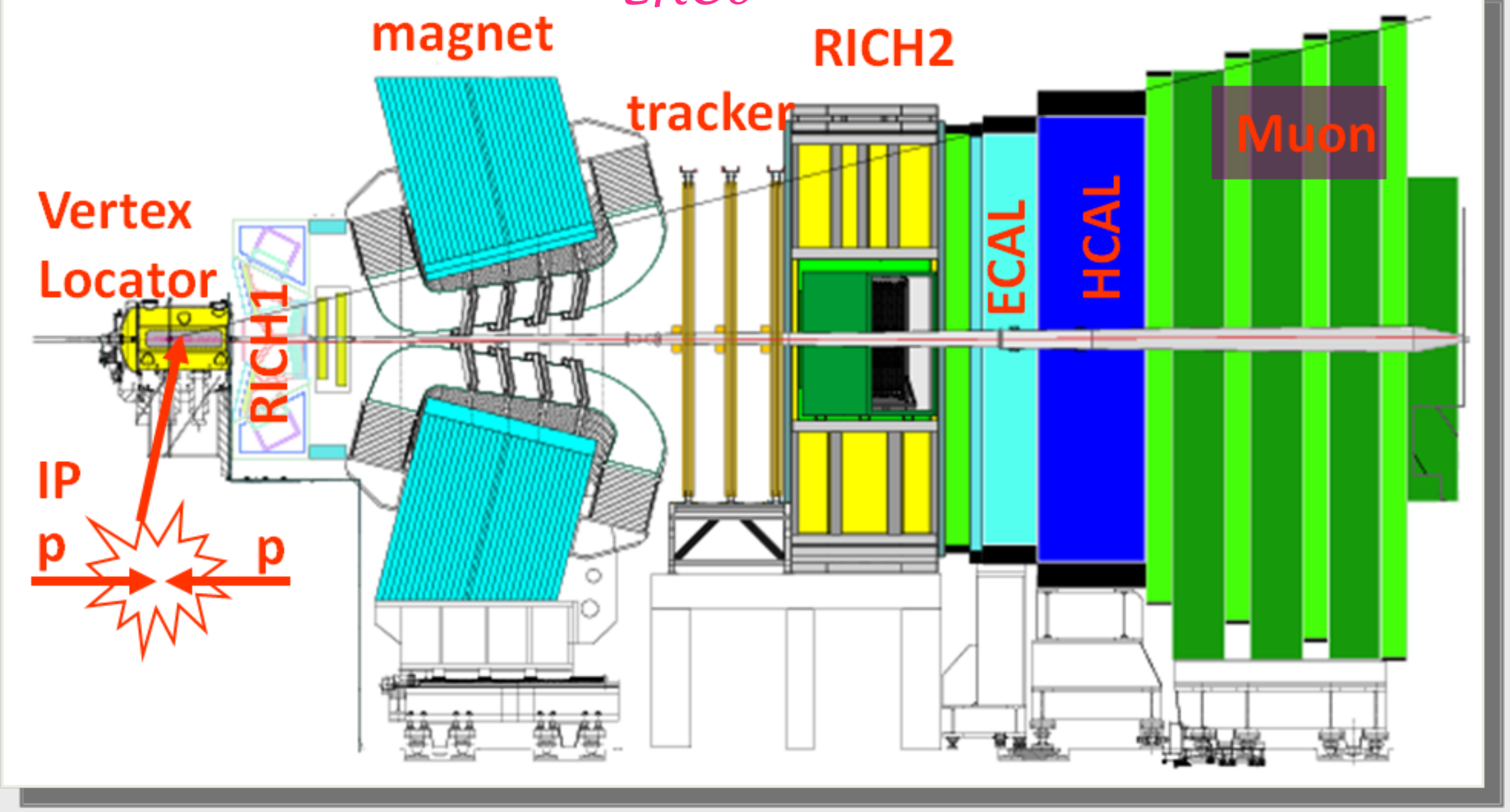


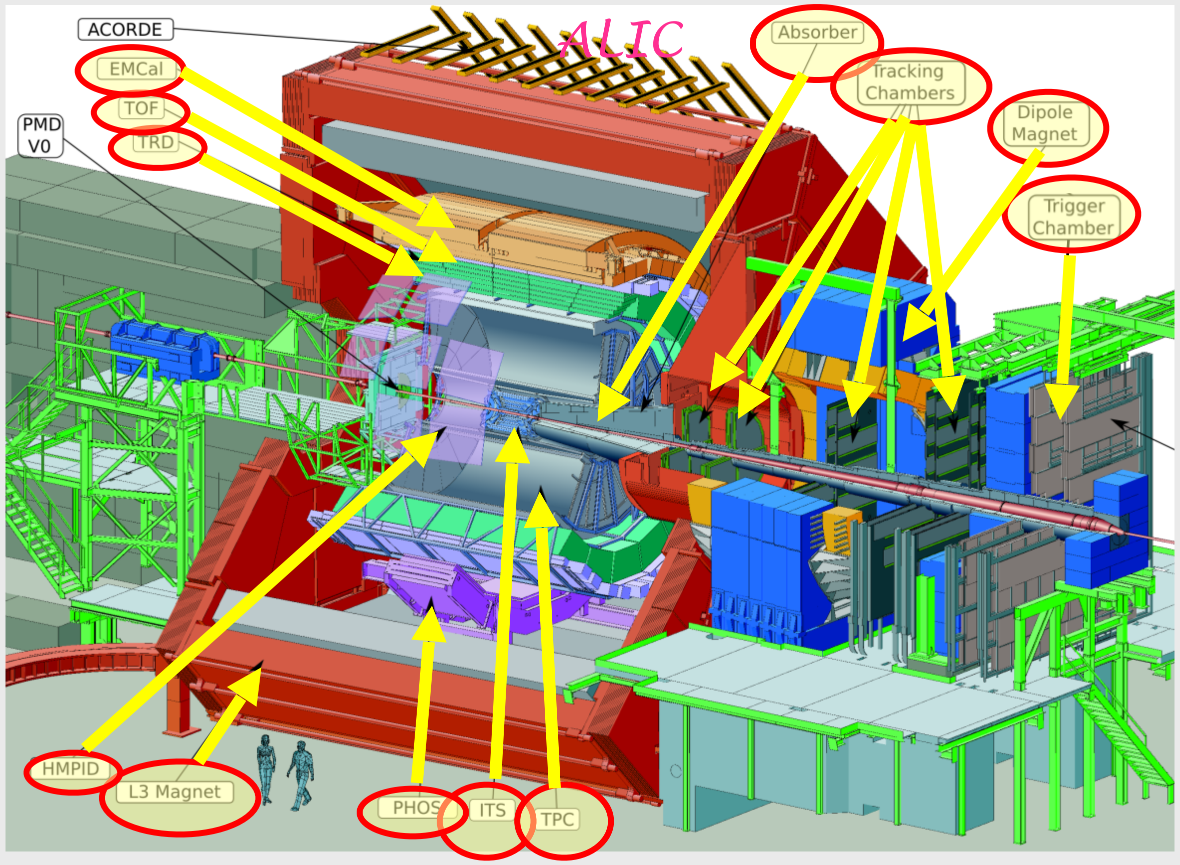


The LHC detectors : a modular concept

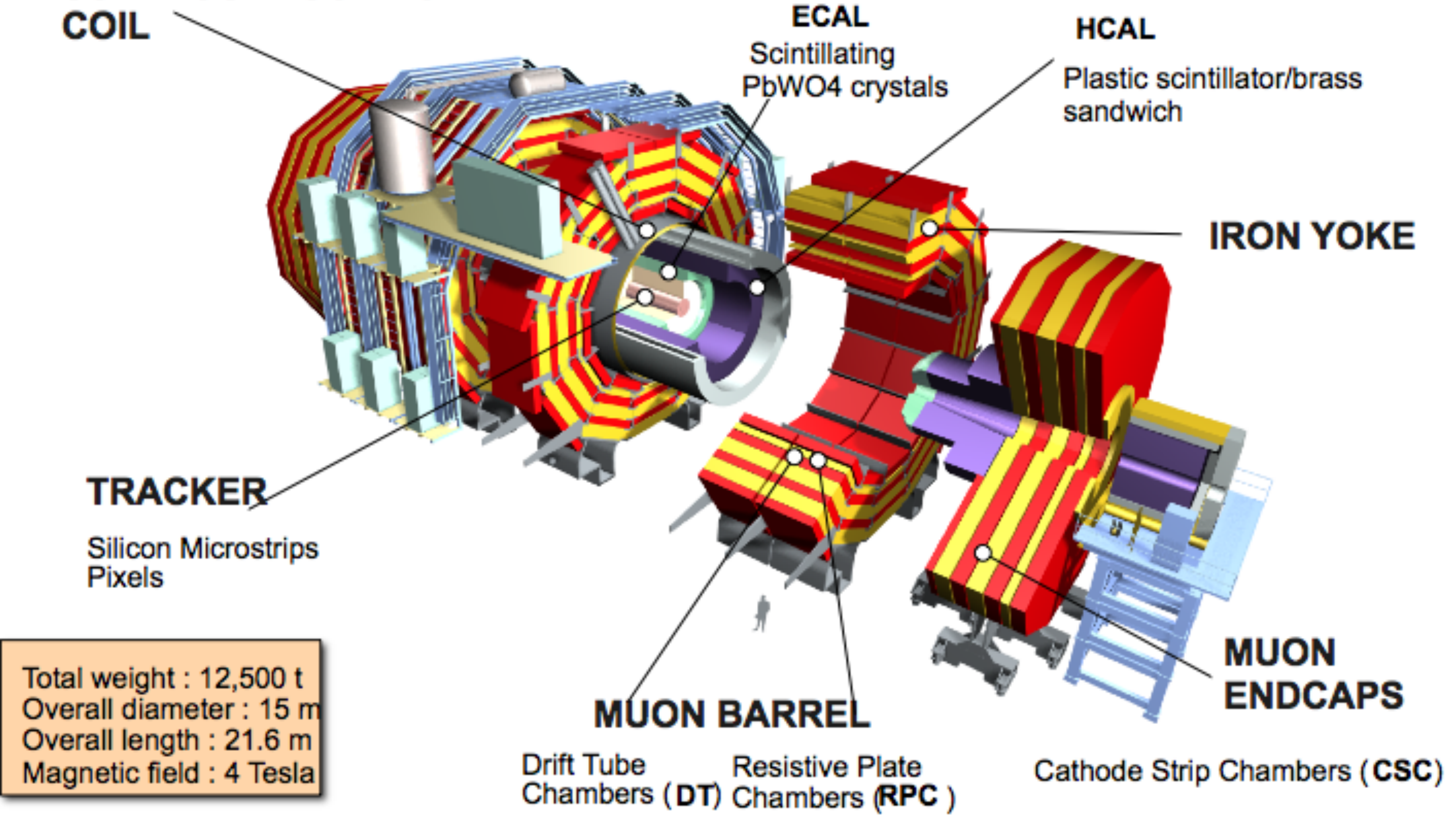
LHCb



ALIC



CMS



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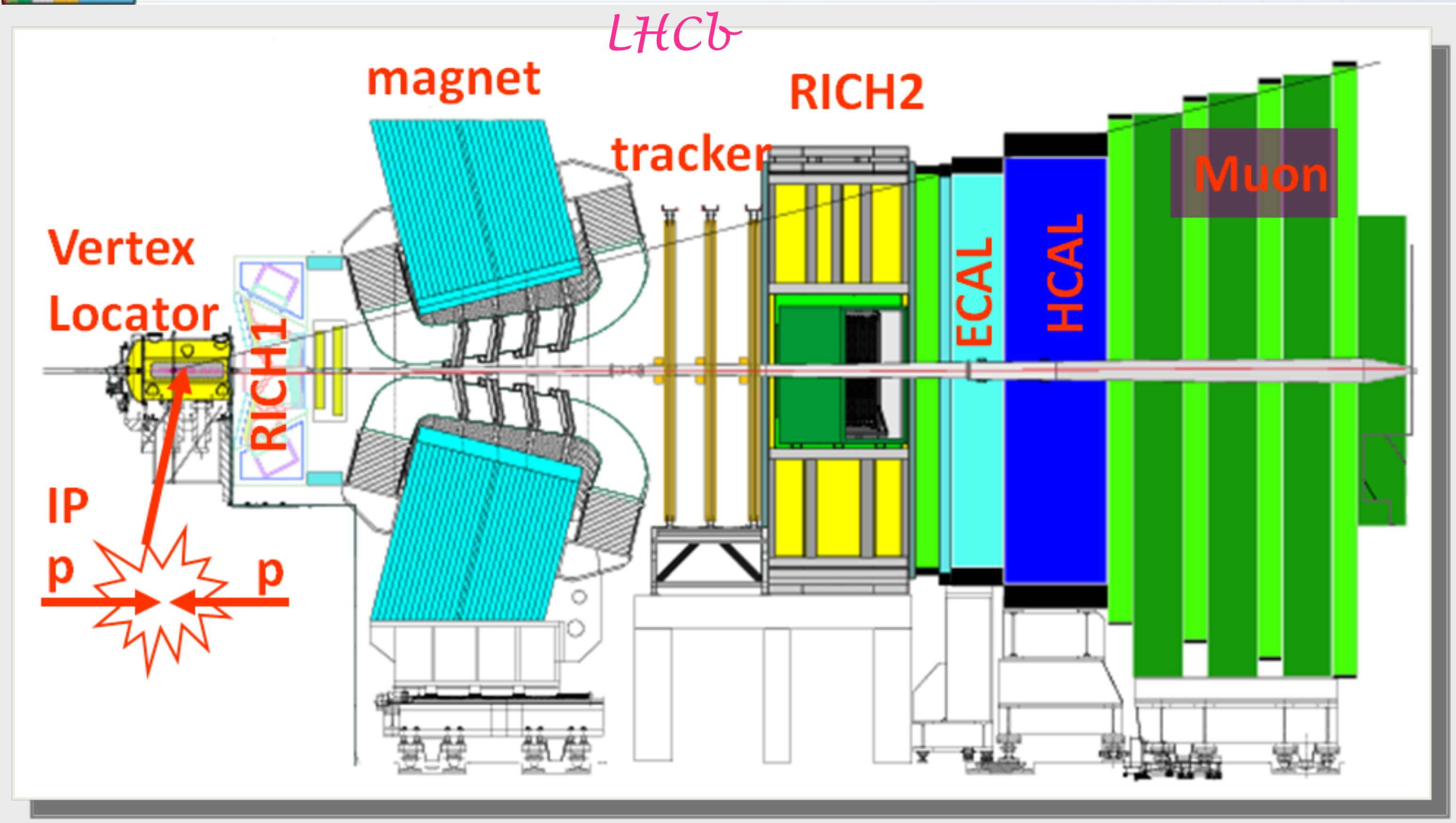
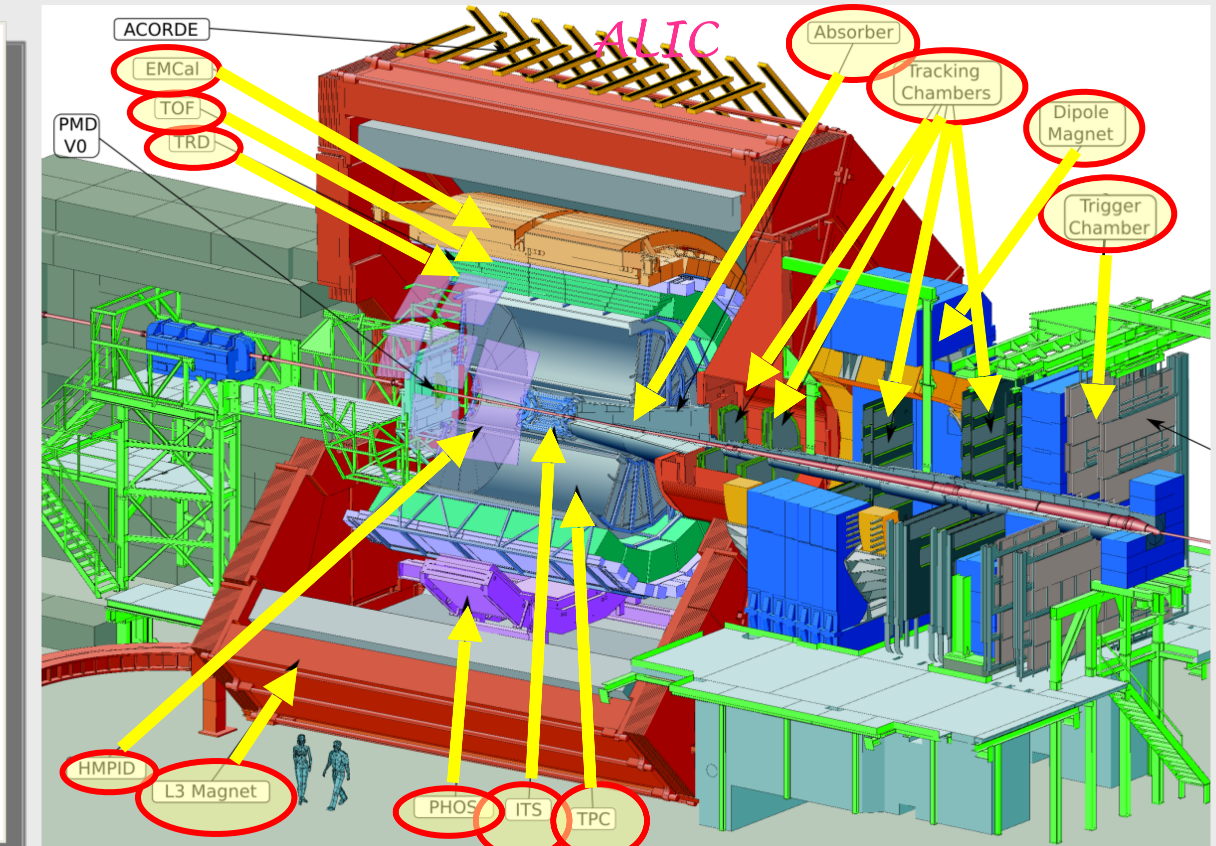
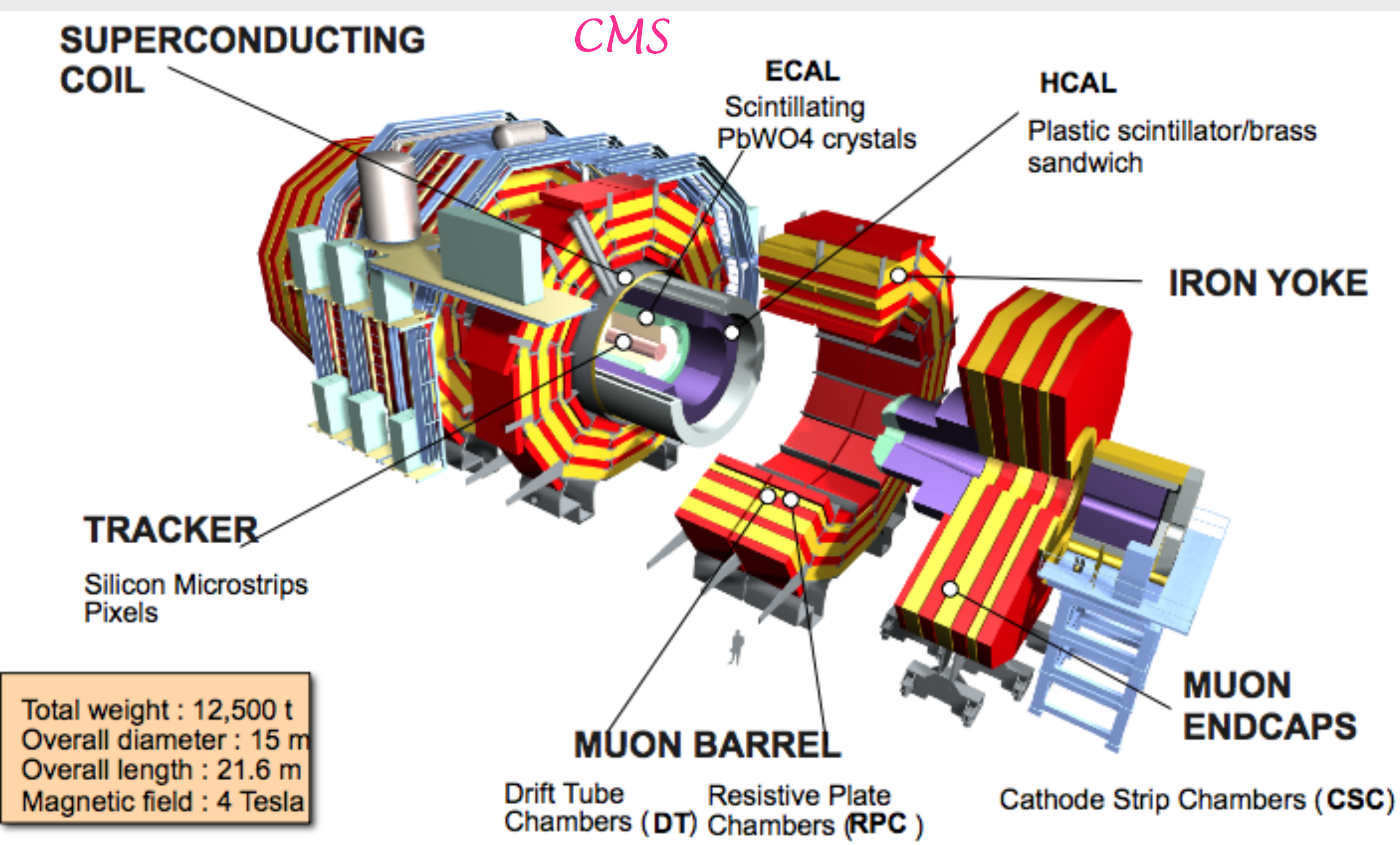
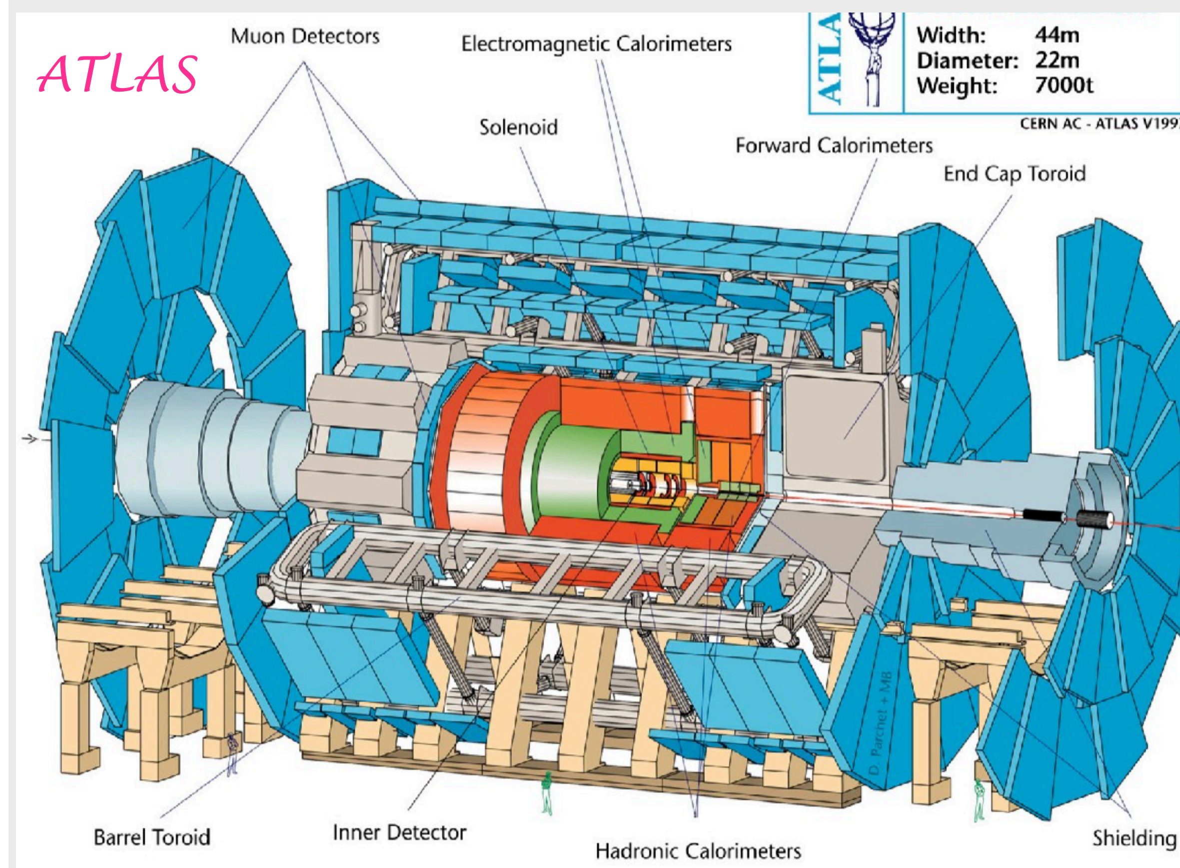


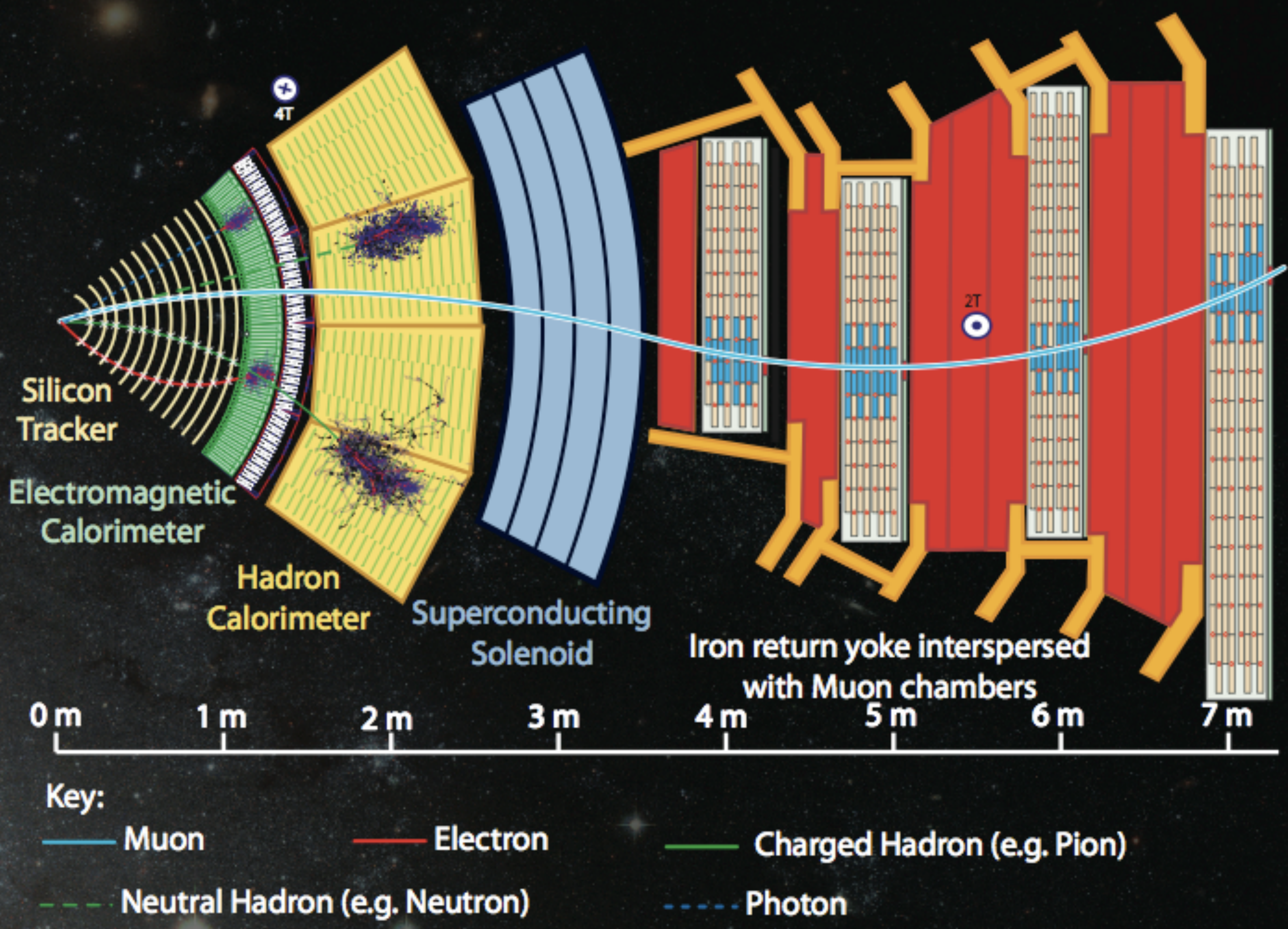




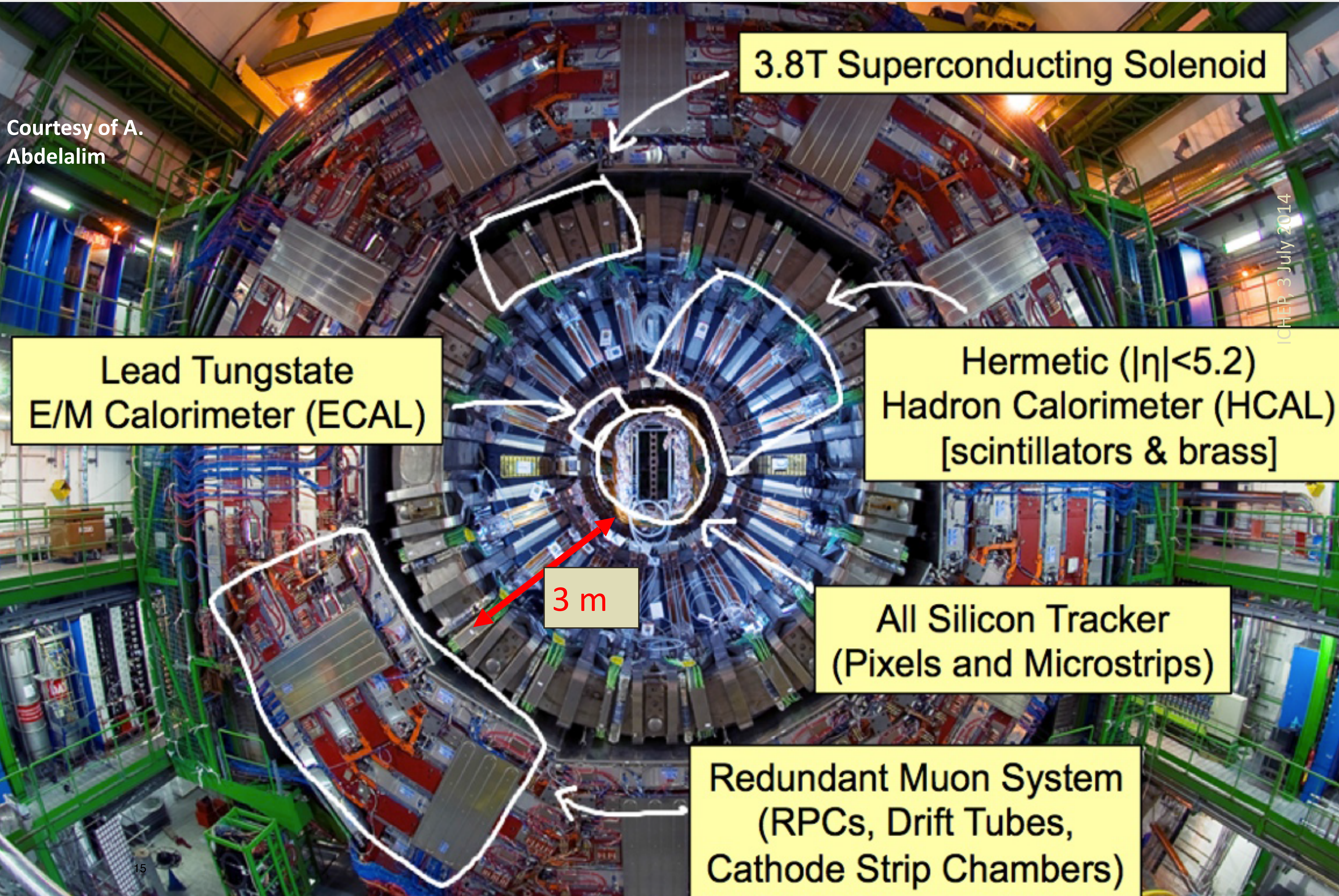


Pattern Recognition

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.

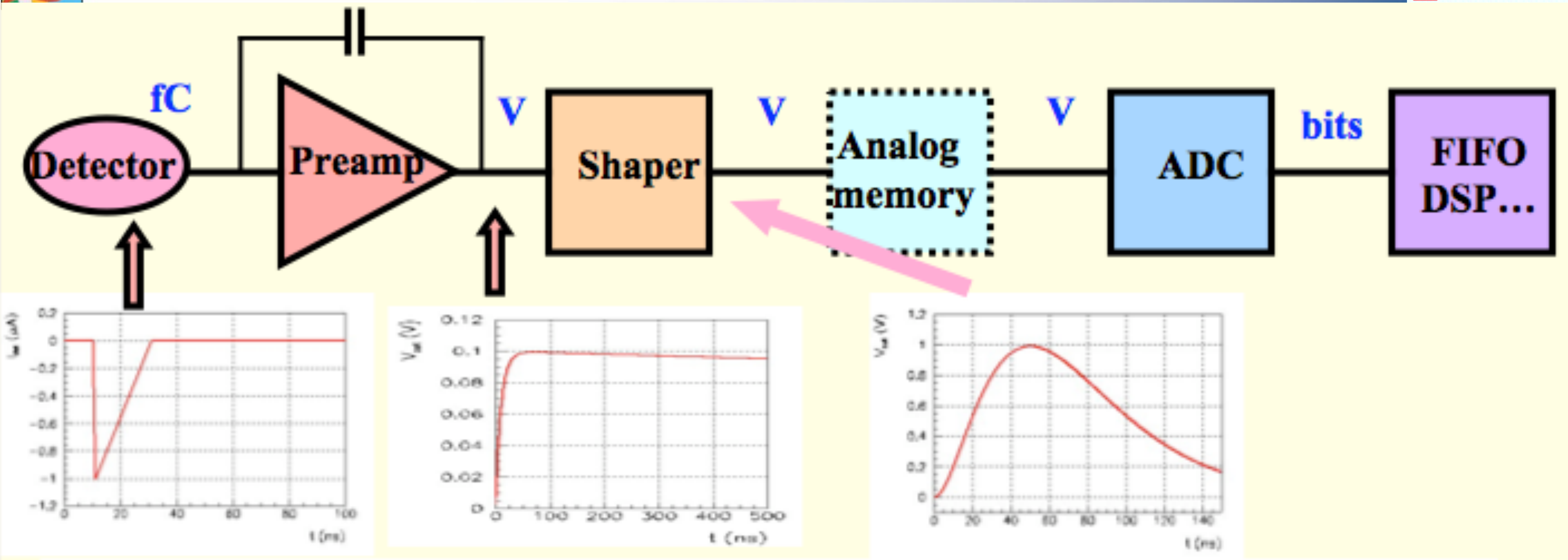


The real CMS detector



Courtesy of A. Abdelalim

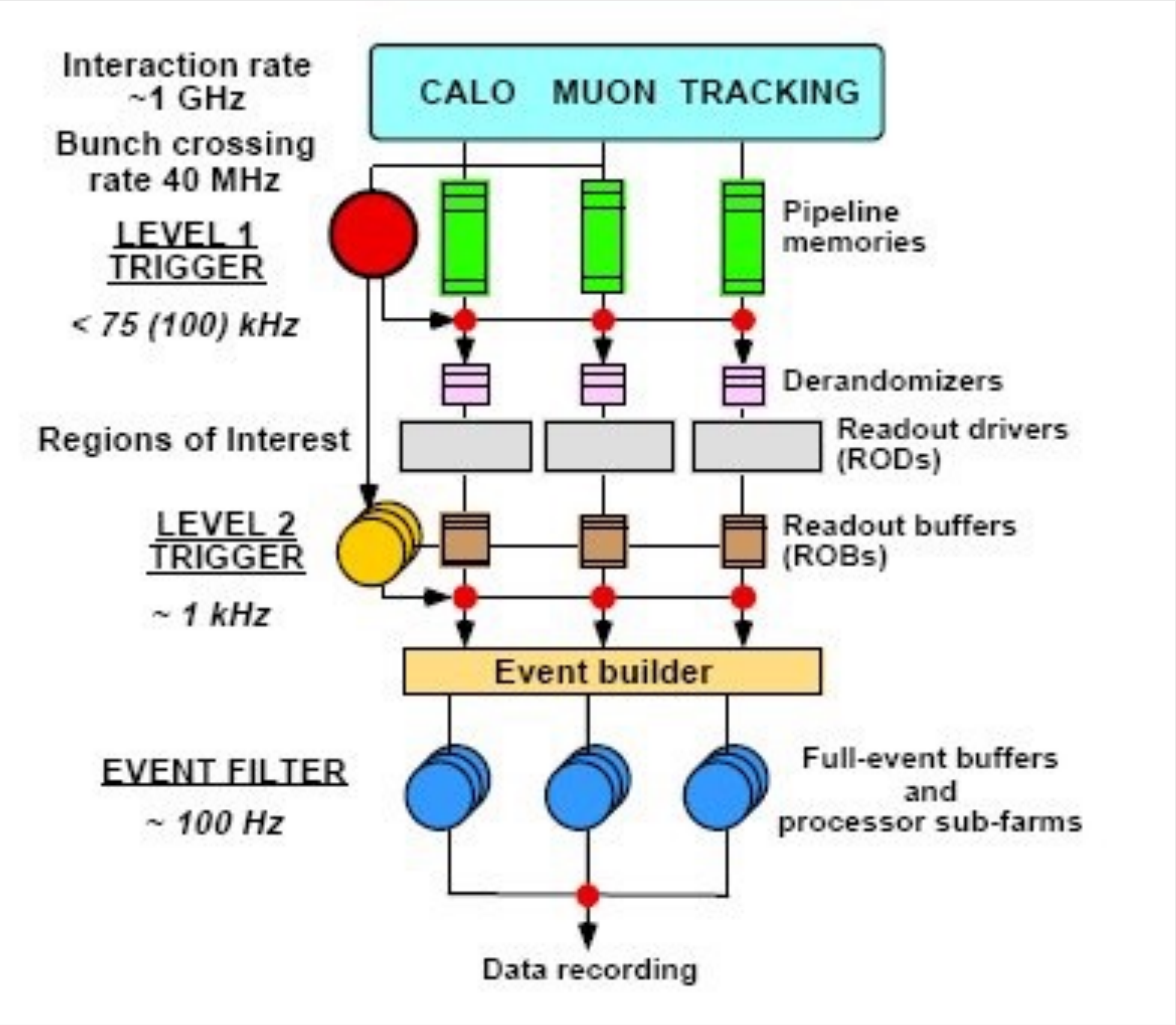
Overview of readout electronics



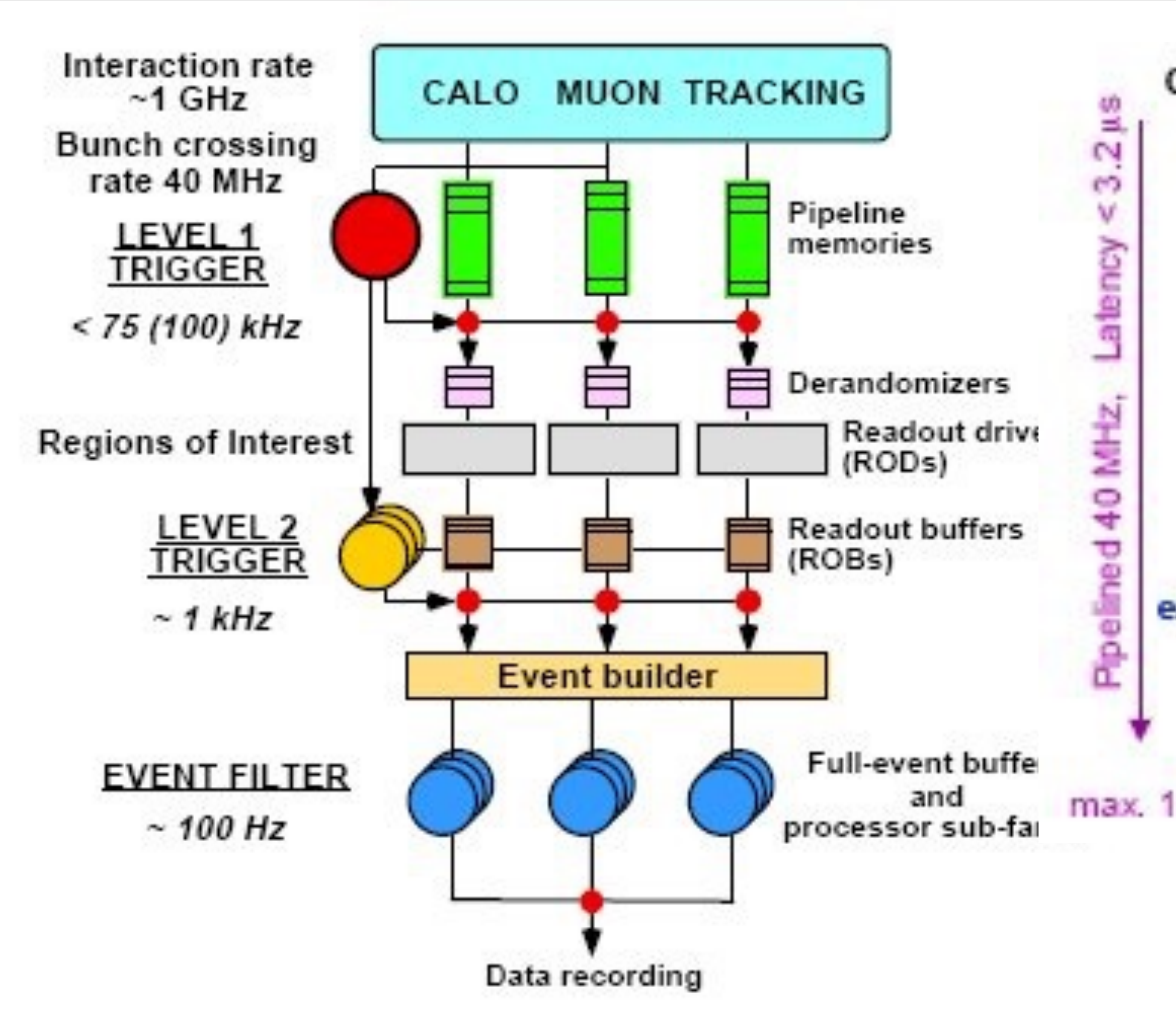
Most front-ends follow a similar architecture :

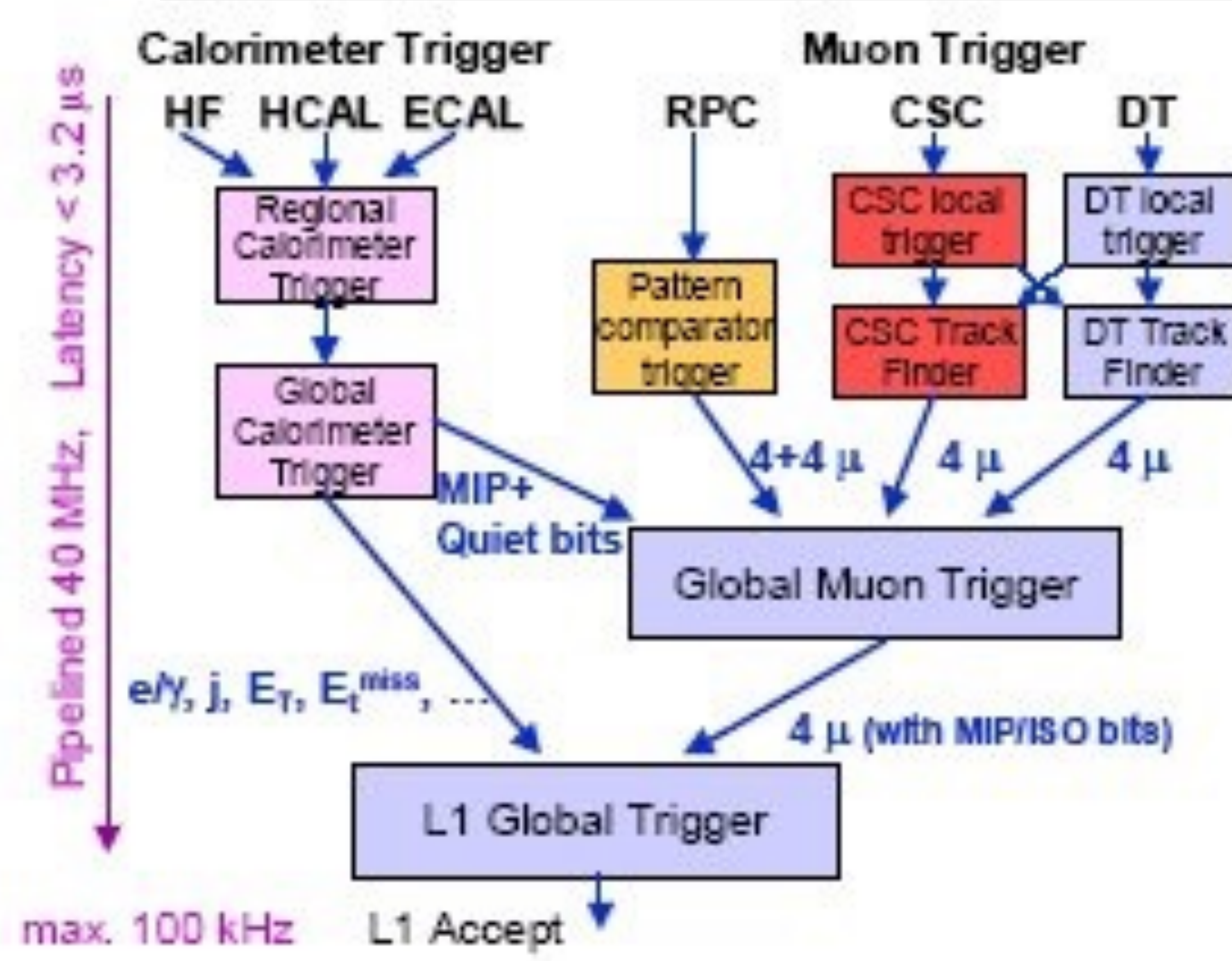
- Very small signals (fC) -> need amplification and optimisation of S/N (filter)
- Measurement of amplitude and/or time (ADCs, discris, TDCs)
- Several thousands to millions of channels needs time to decide to keep or not the event : memory

Pipelined-multilevel-triggers

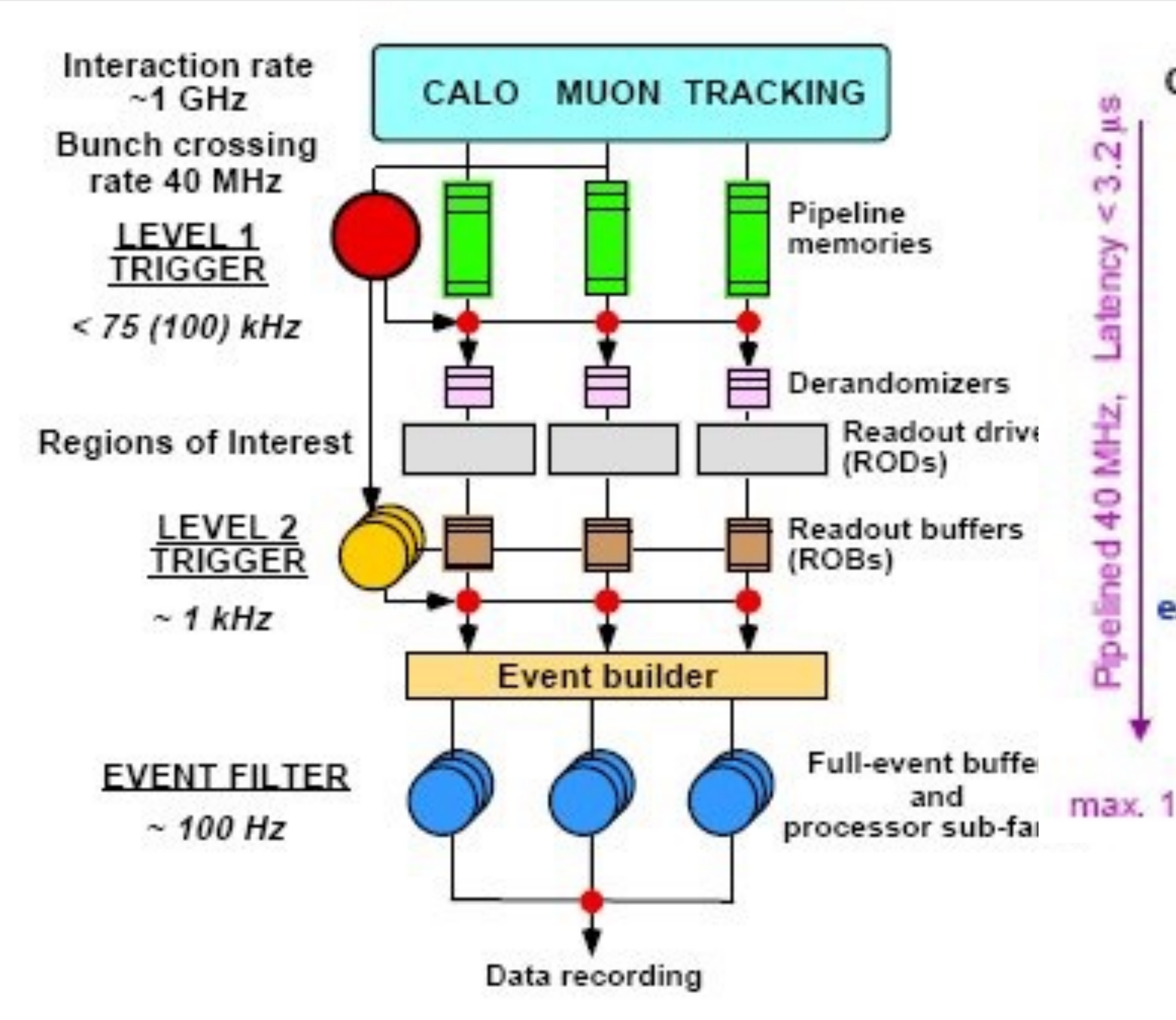


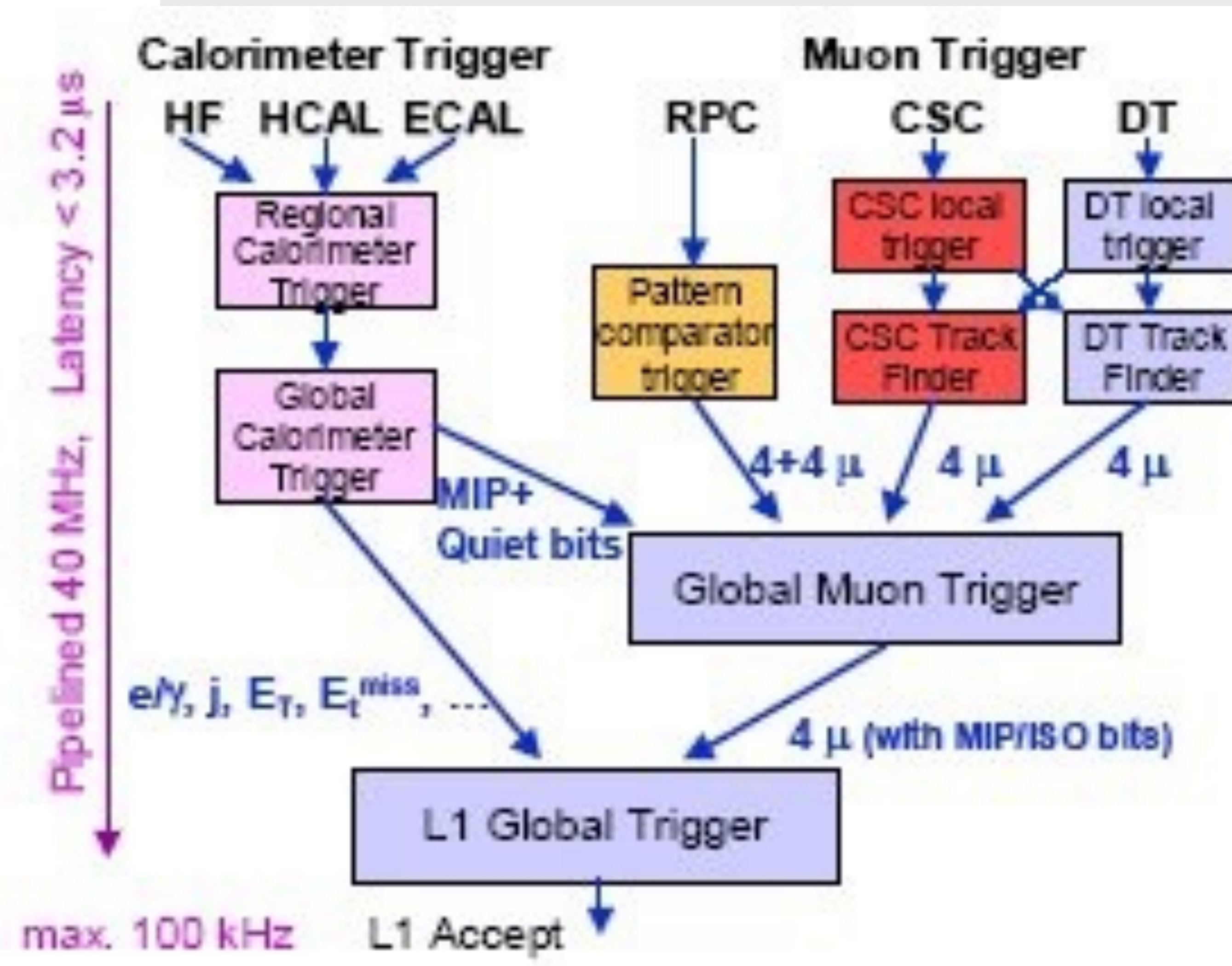
Pipelined-multilevel-triggers





Pipelined-multilevel-triggers



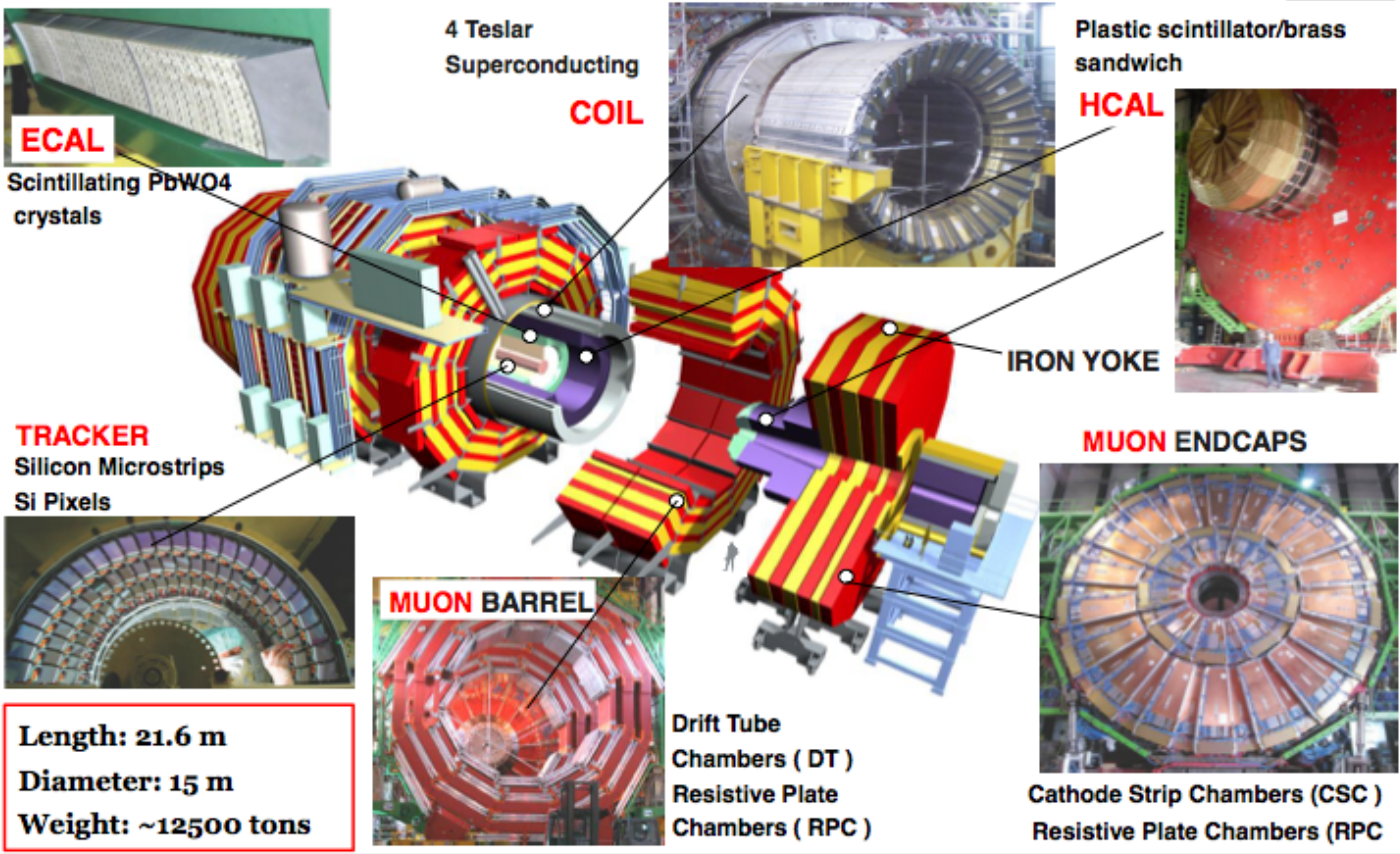


40 MHz LVL1 100 kHz (LVL2+LVL3) 100Hz

synchronous
3 μs

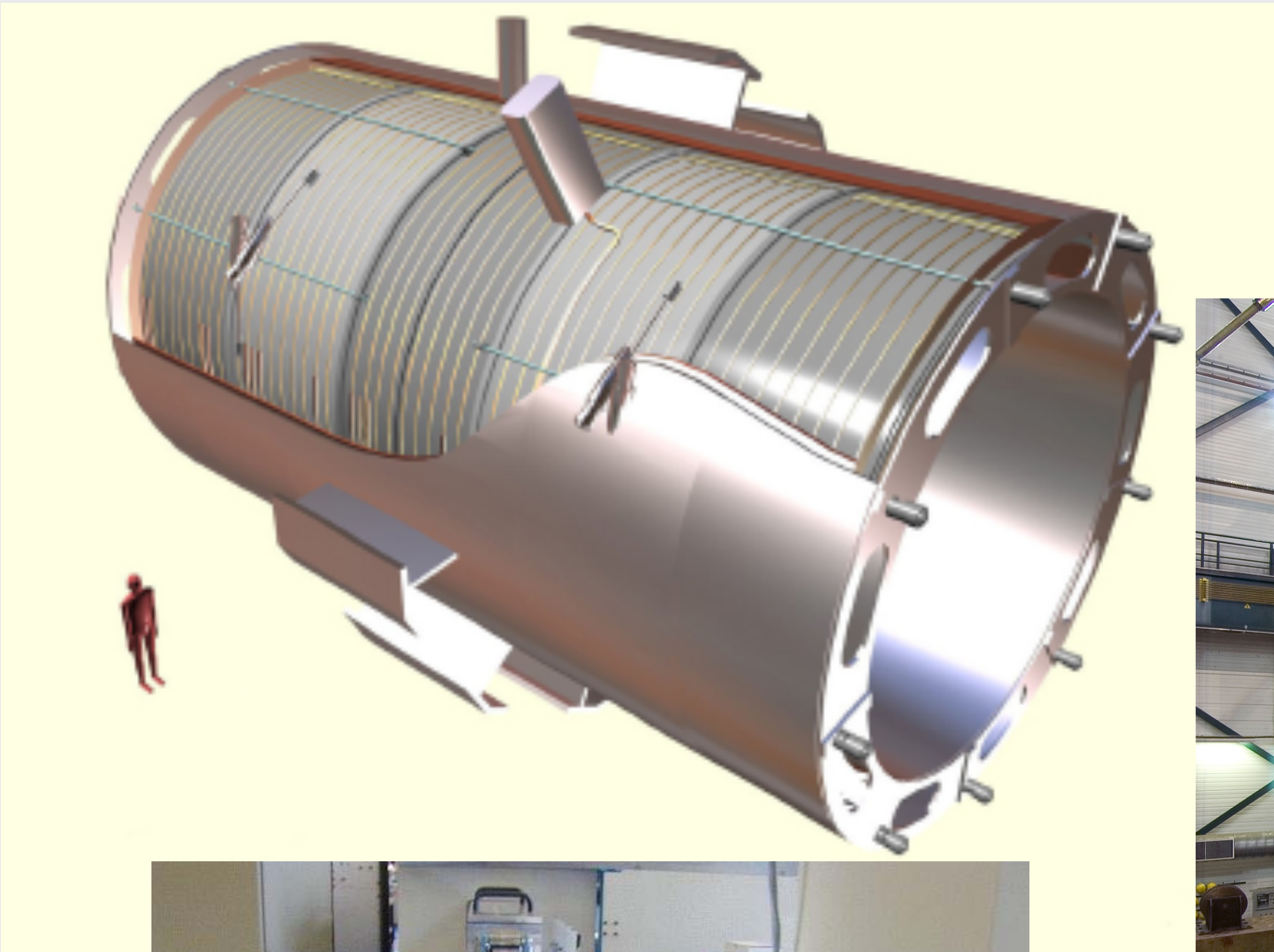
asynchronous

CMS detector

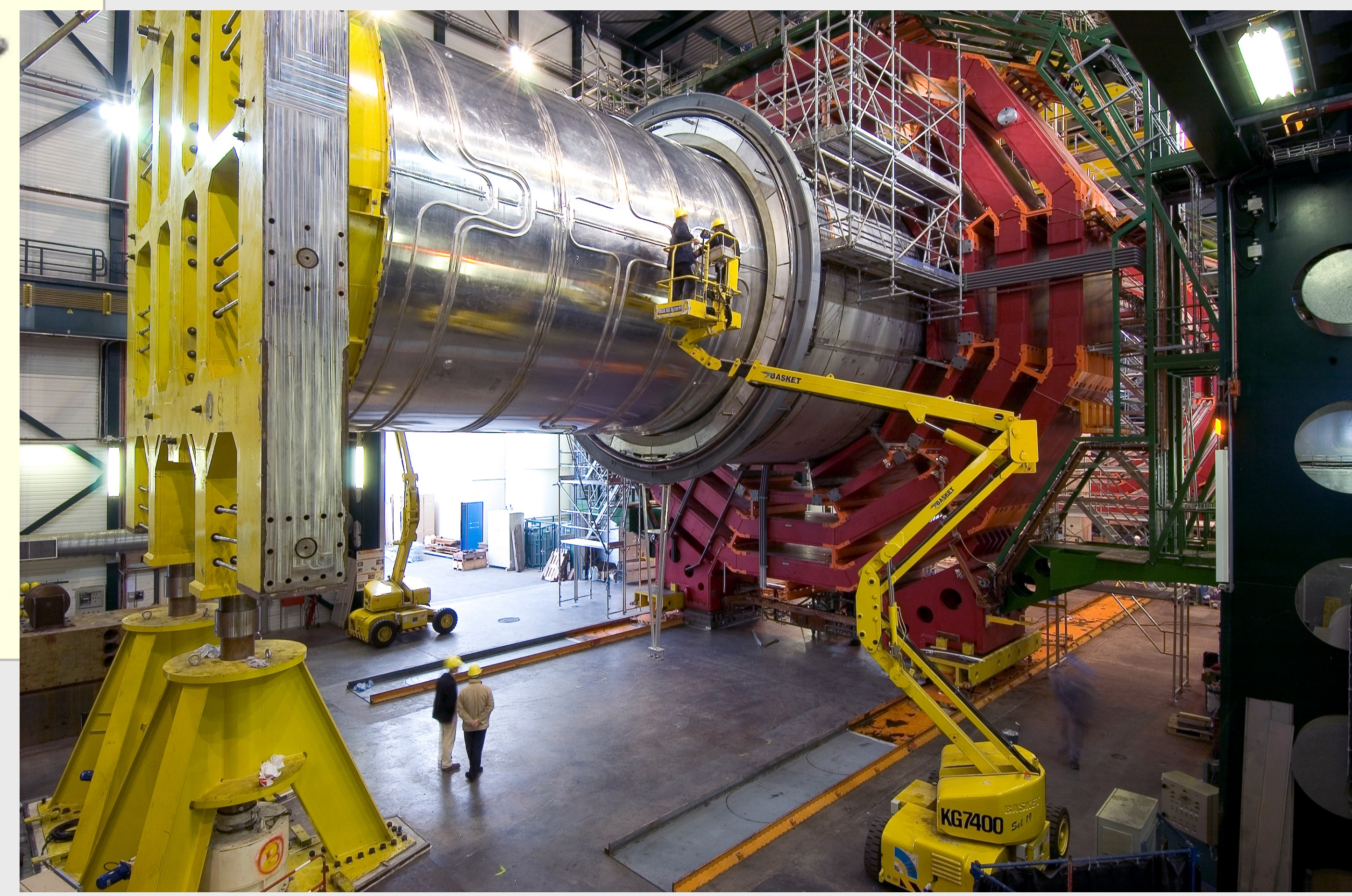


Length: 21.6 m
Diameter: 15 m
Weight: ~12500 tons

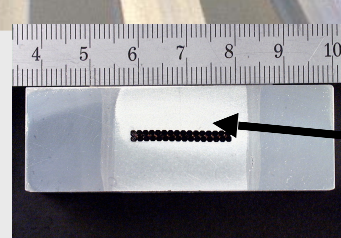
CMS solenoid - largest in the world -



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



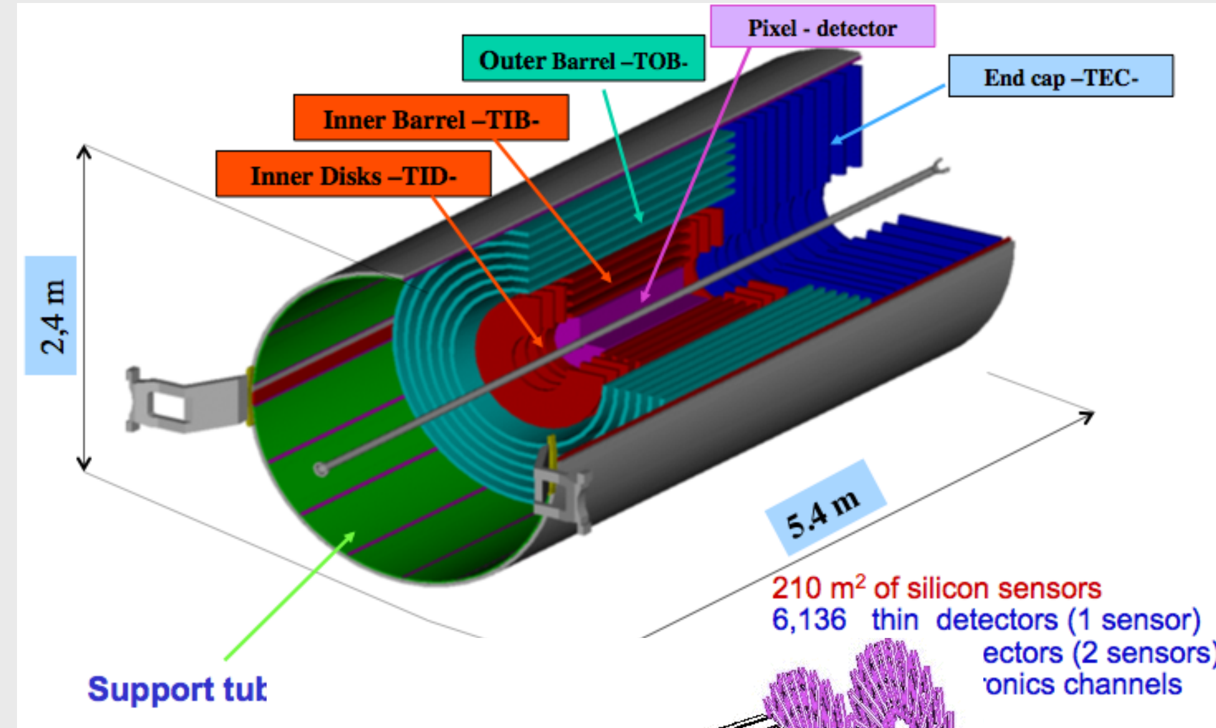
Insertion of coil in vacuum tank in September 05

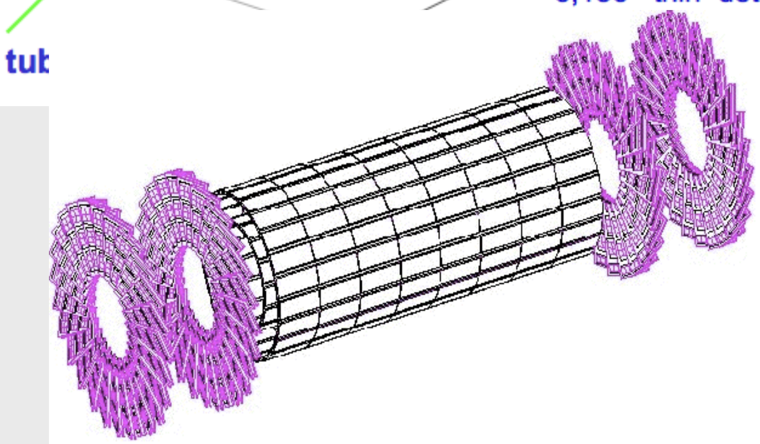


s.c cable: all 21 lengths (53 km) finished in 2003

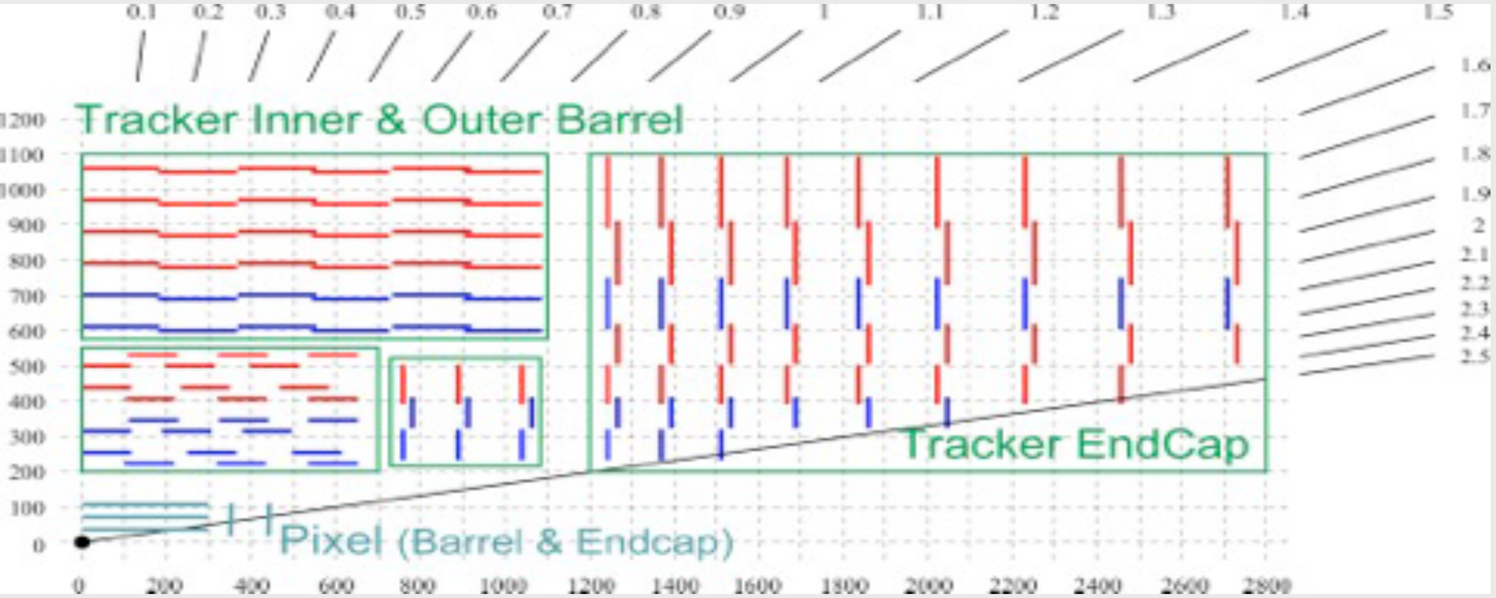
Insert with superconductor

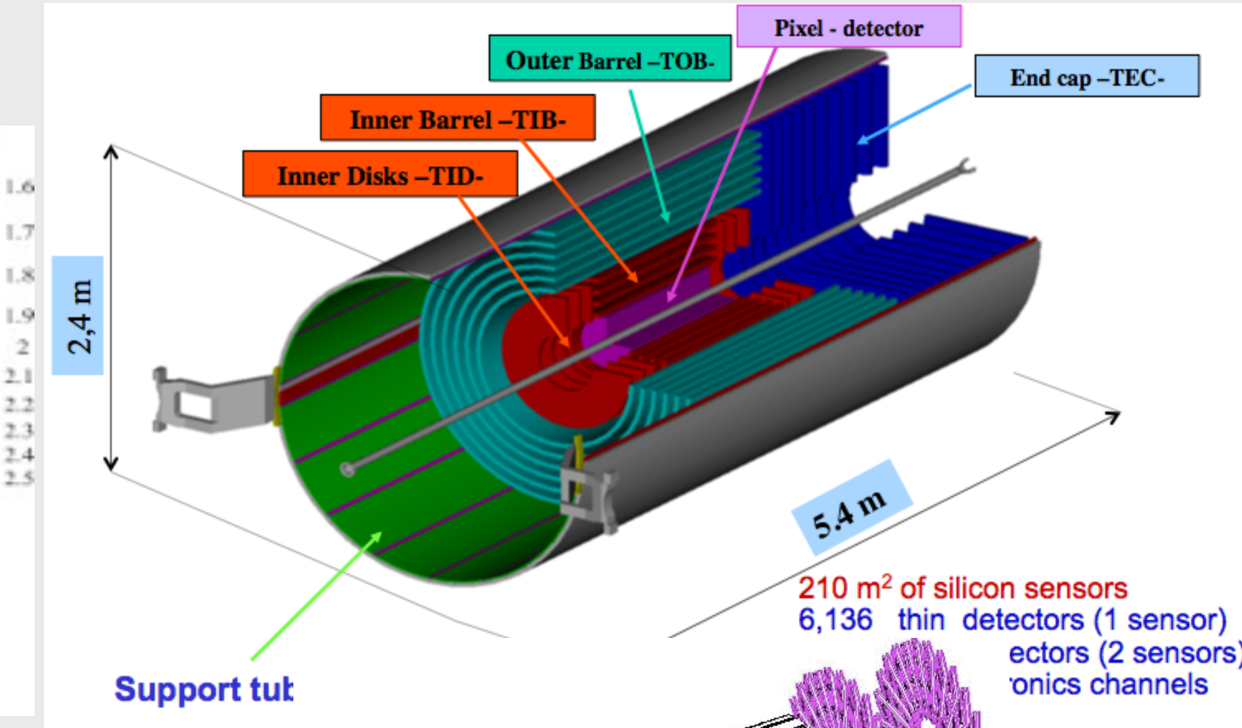
The Silicon CMS tracker

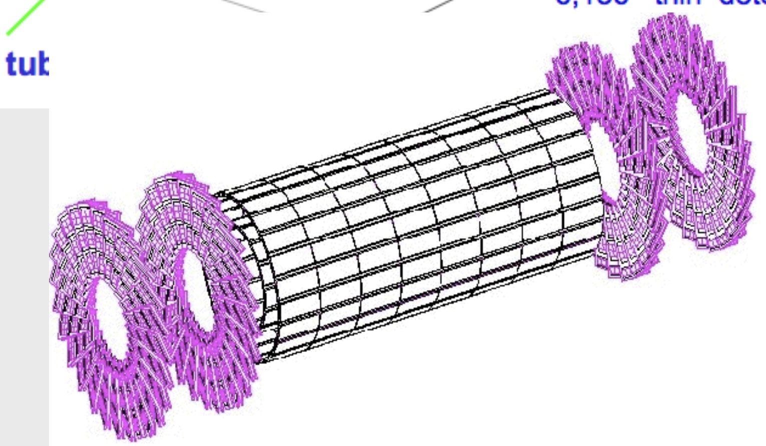




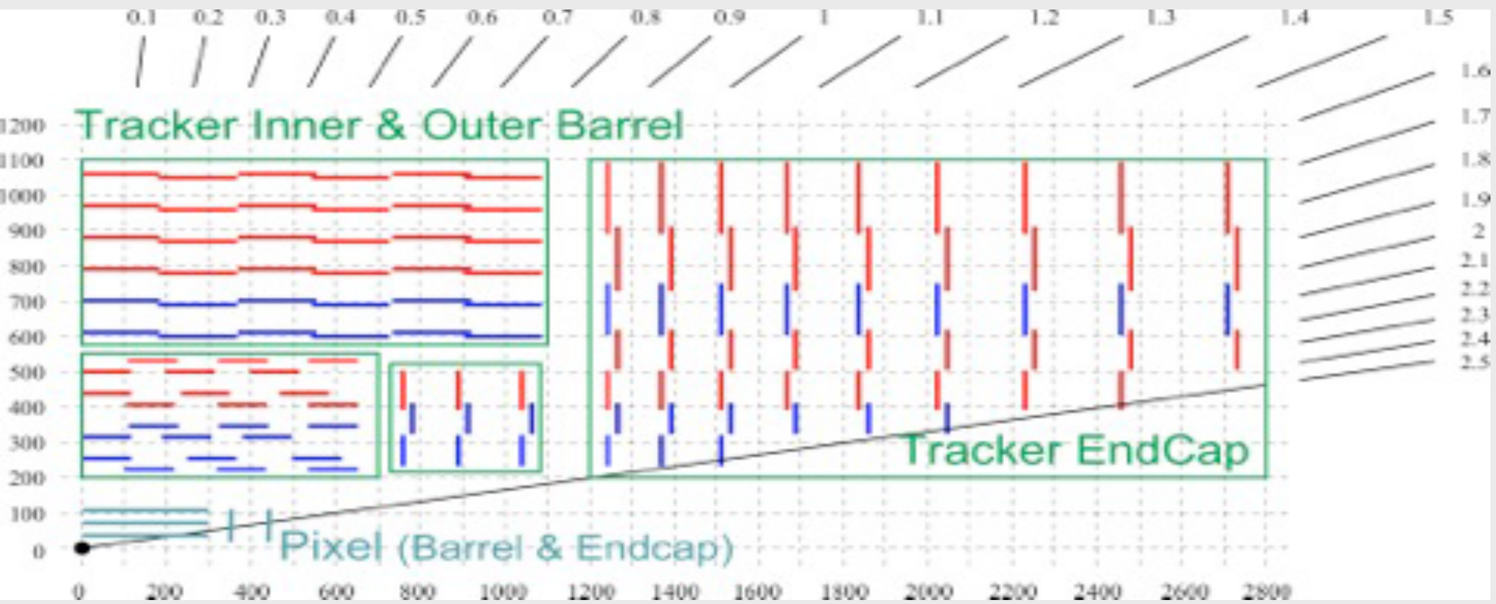
The Silicon CMS tracker

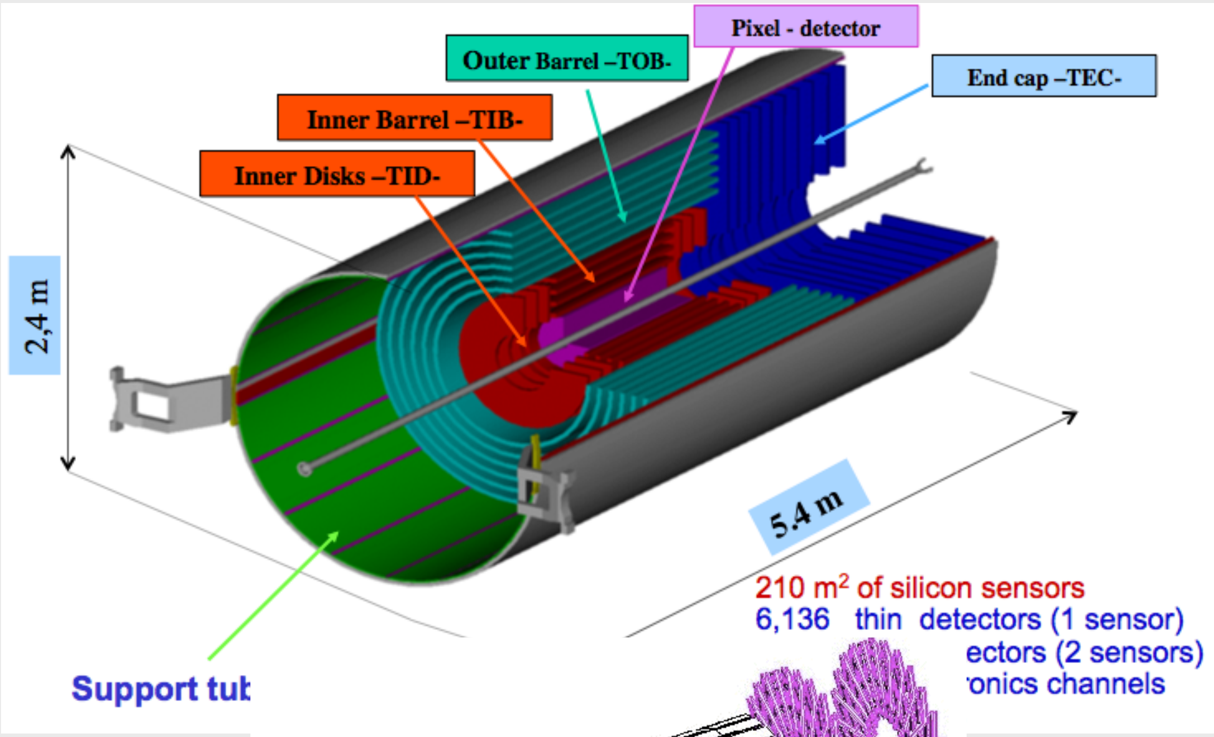


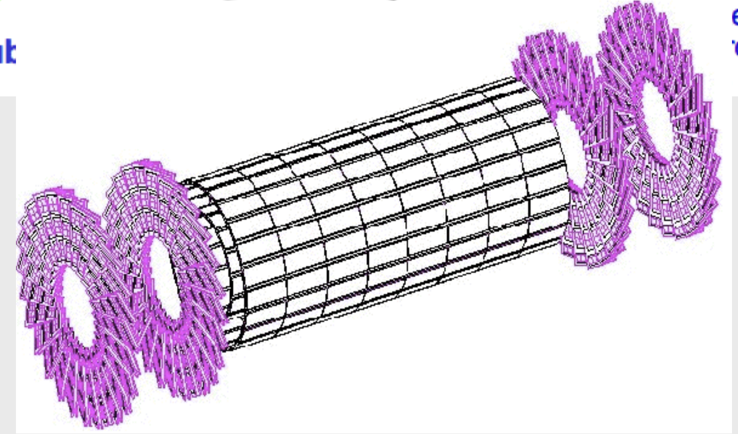


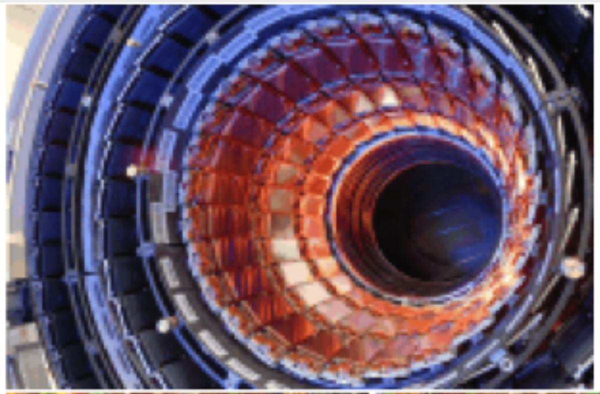


The Silicon CMS tracker





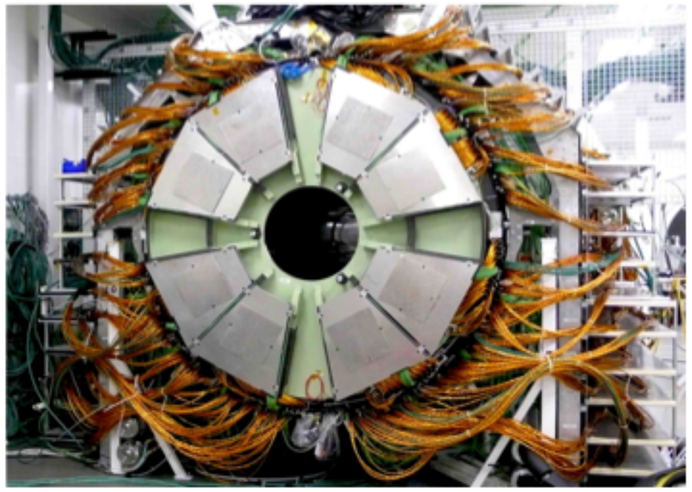


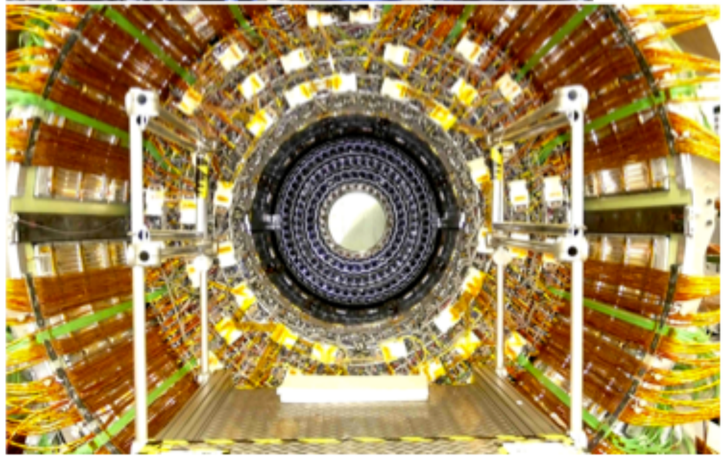


TIB+ completed

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

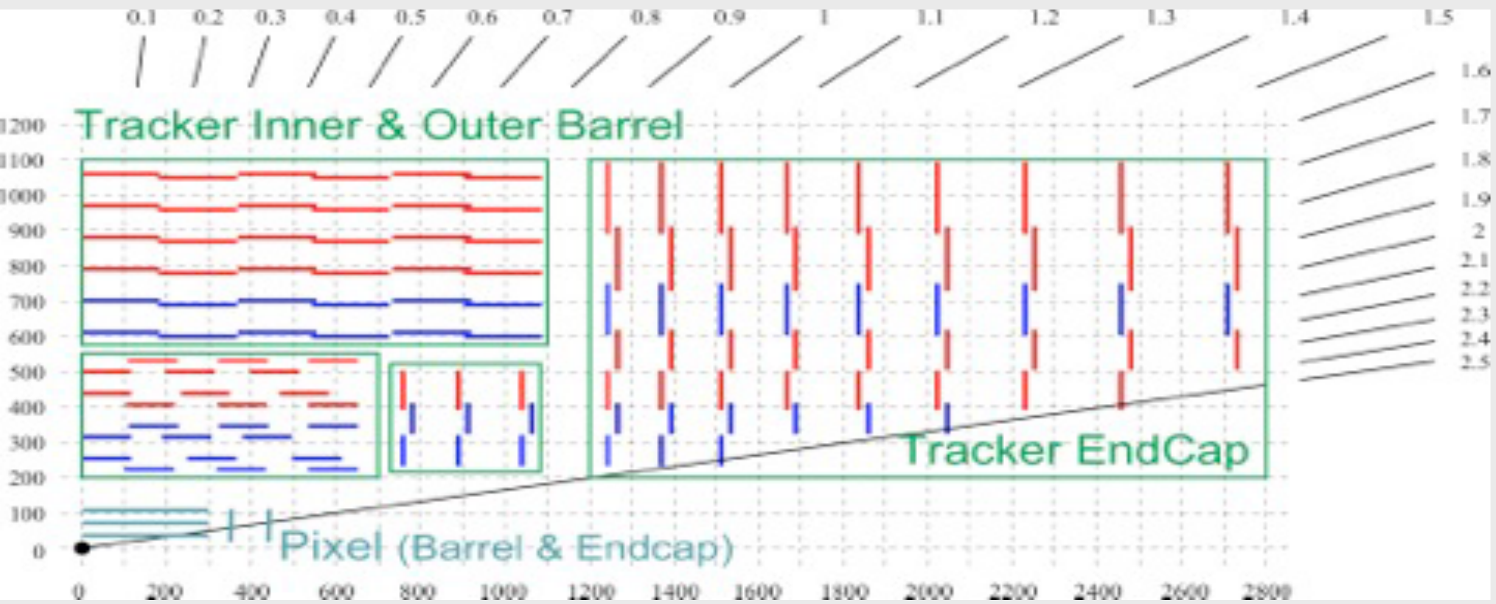
TEC inserted into TST

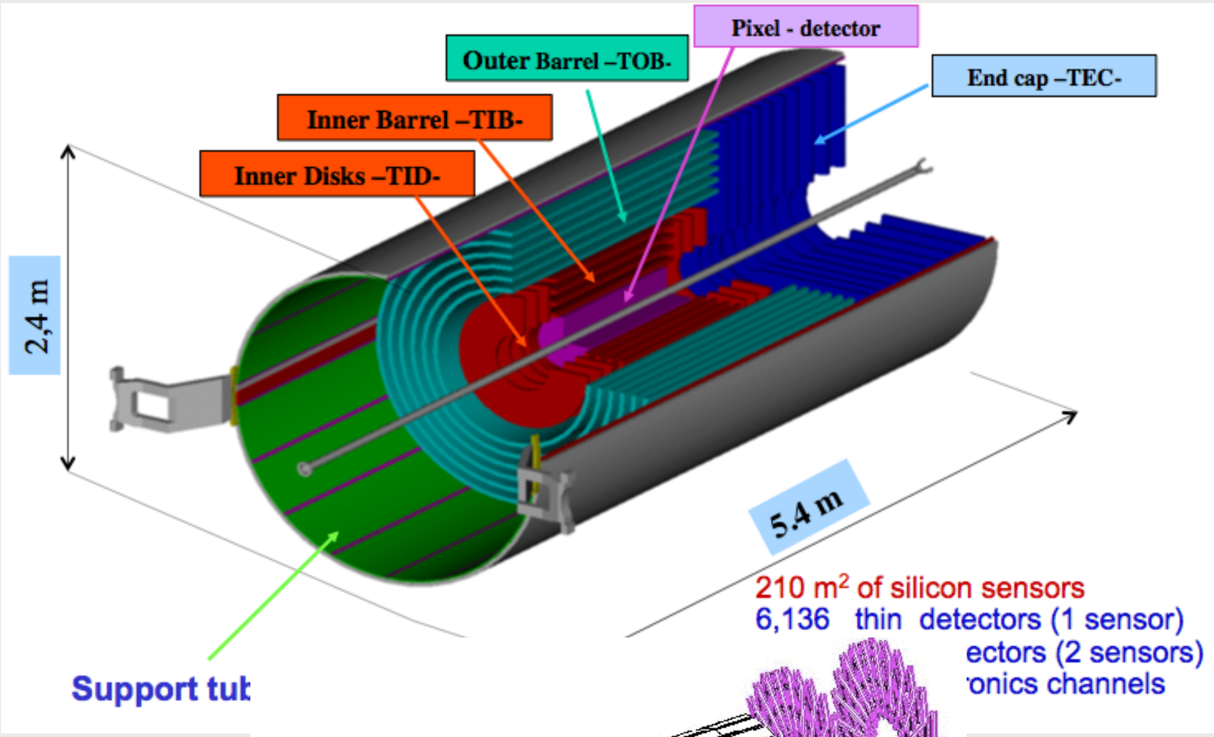


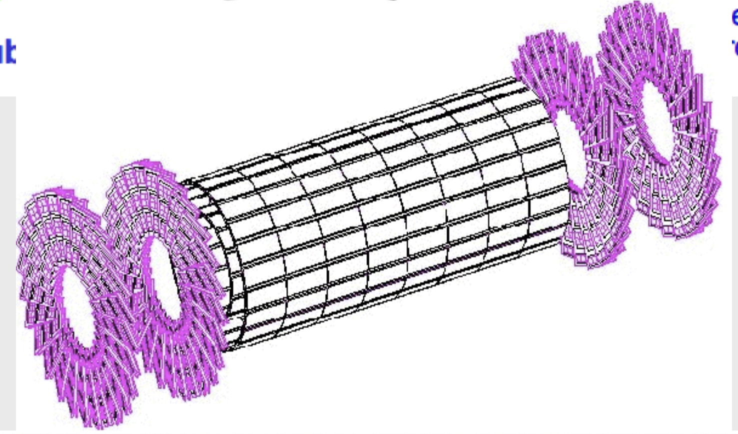


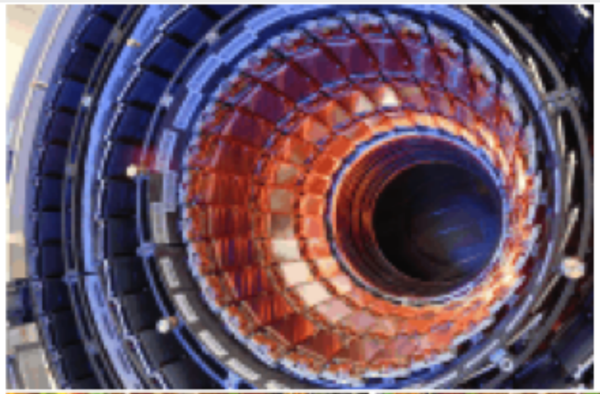
TIB+ inserted into TOB

The Silicon CMS tracker









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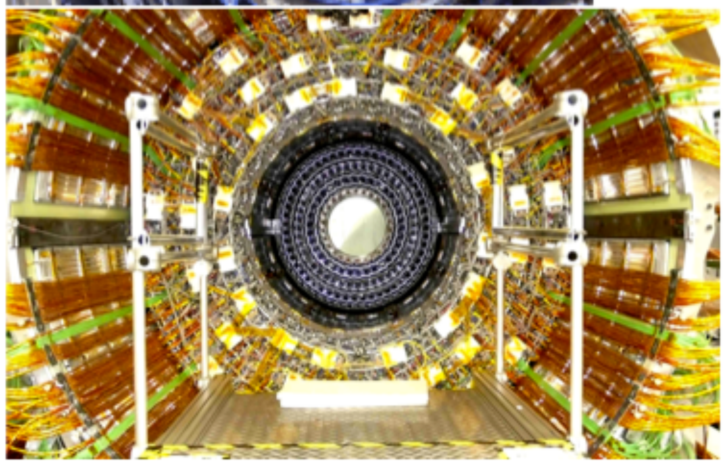
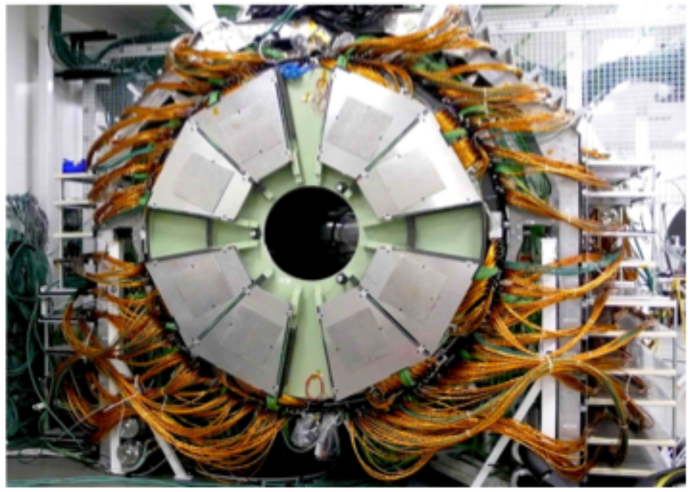
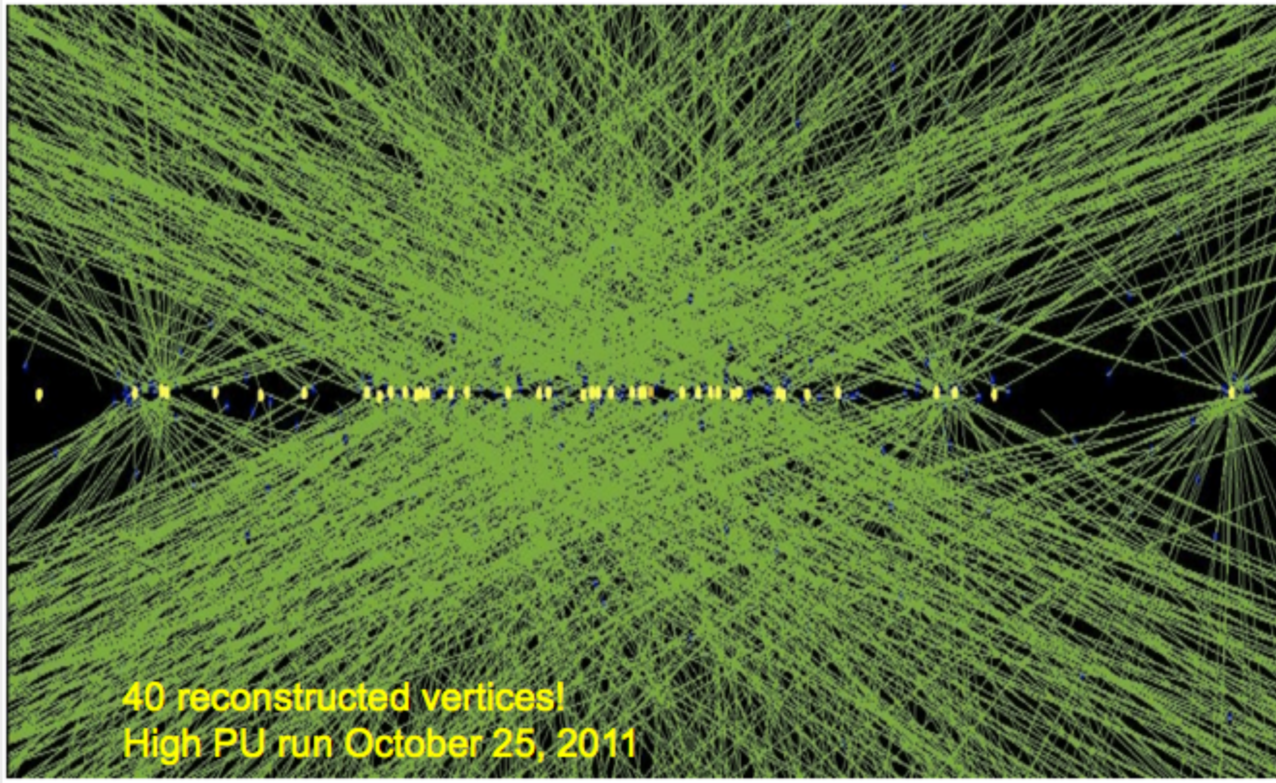


TEC inserted into TST



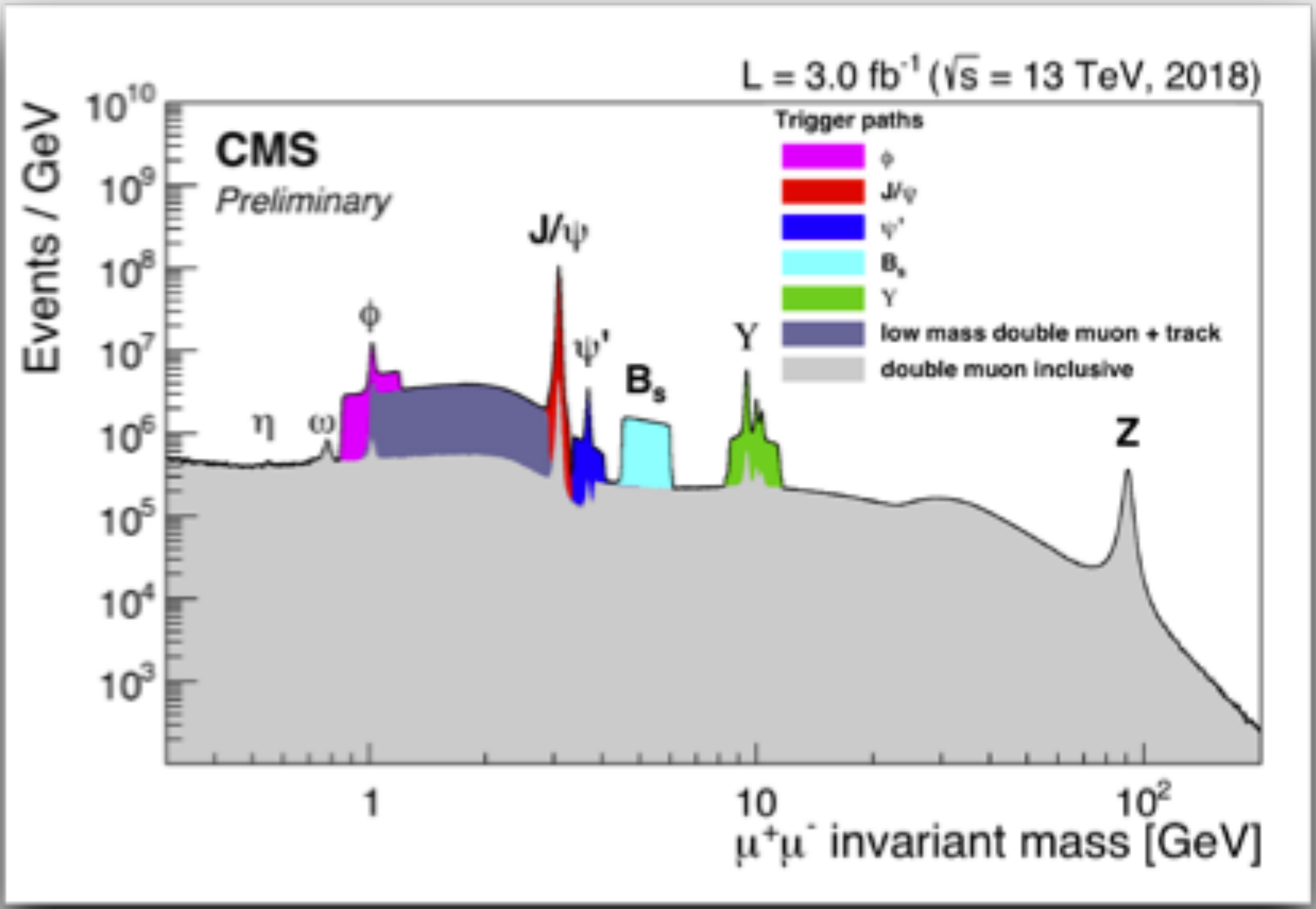
TIB+ inserted into TOB

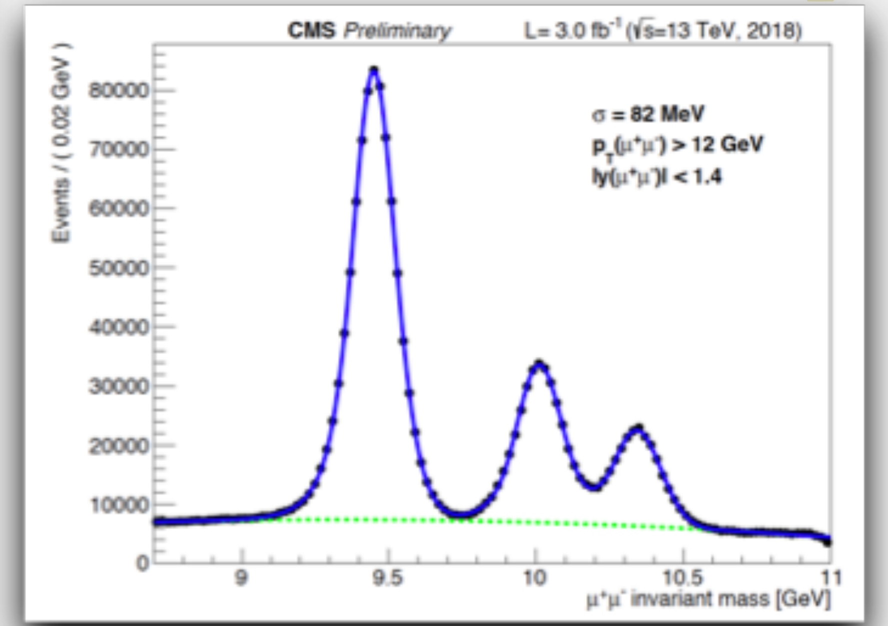


Tracking and Vertex Performance

- *Excellent final tracking performance for physics*

And excellent muon trigger!

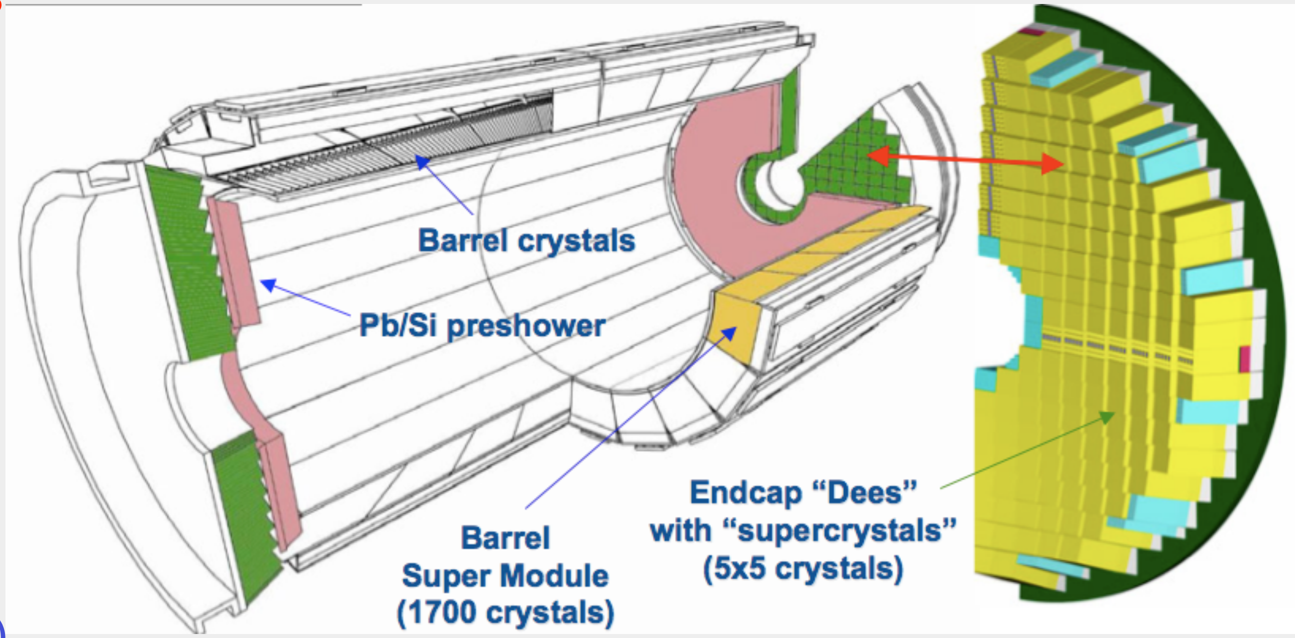


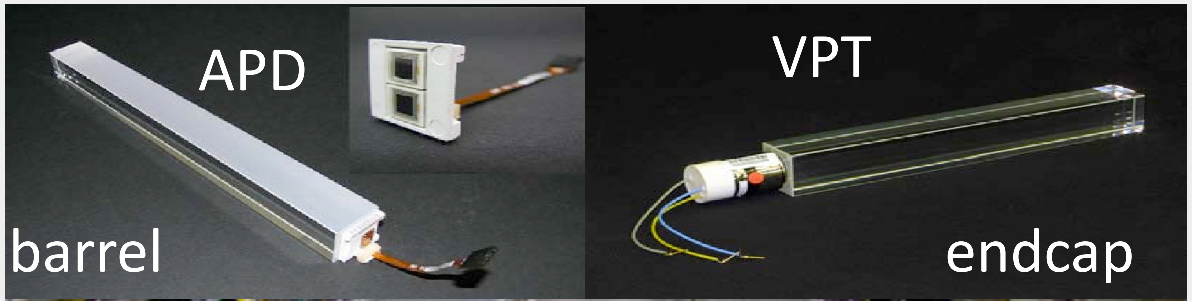


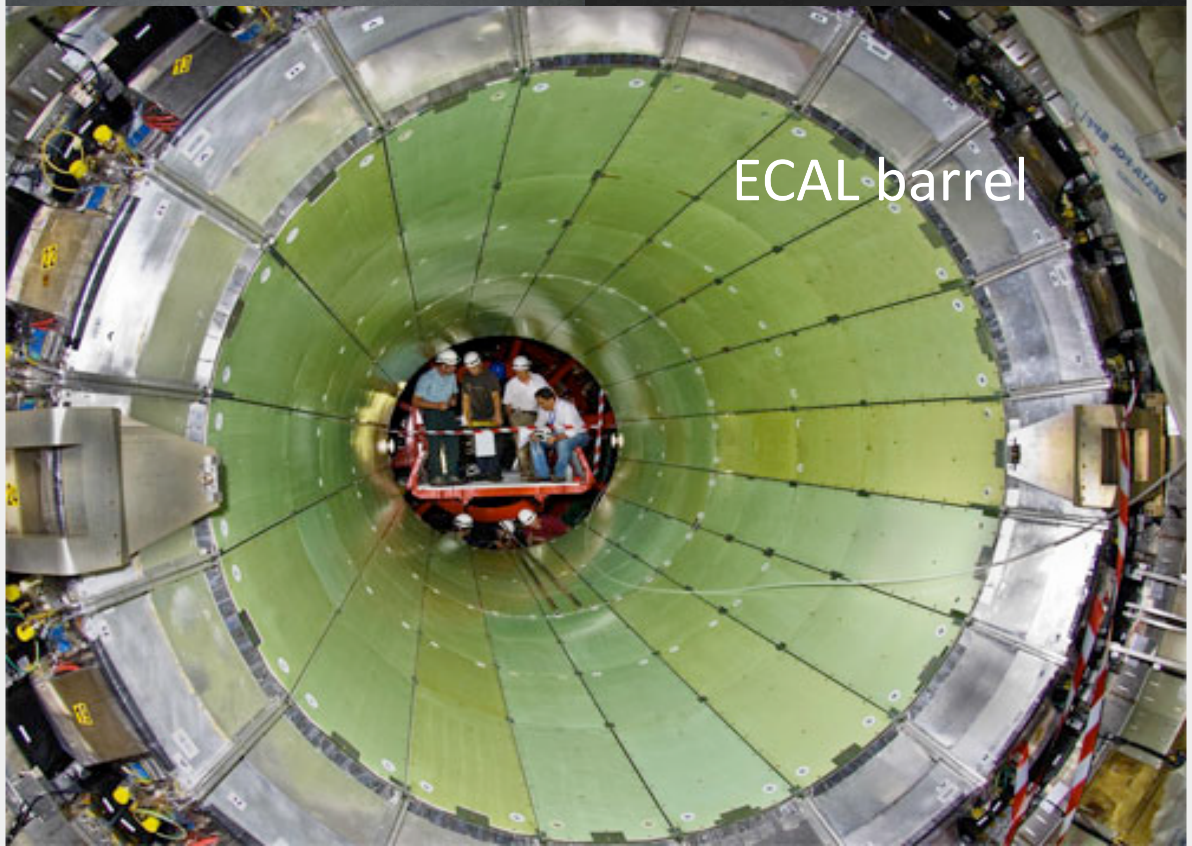
Electromagnetic calorimeter

- 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…)

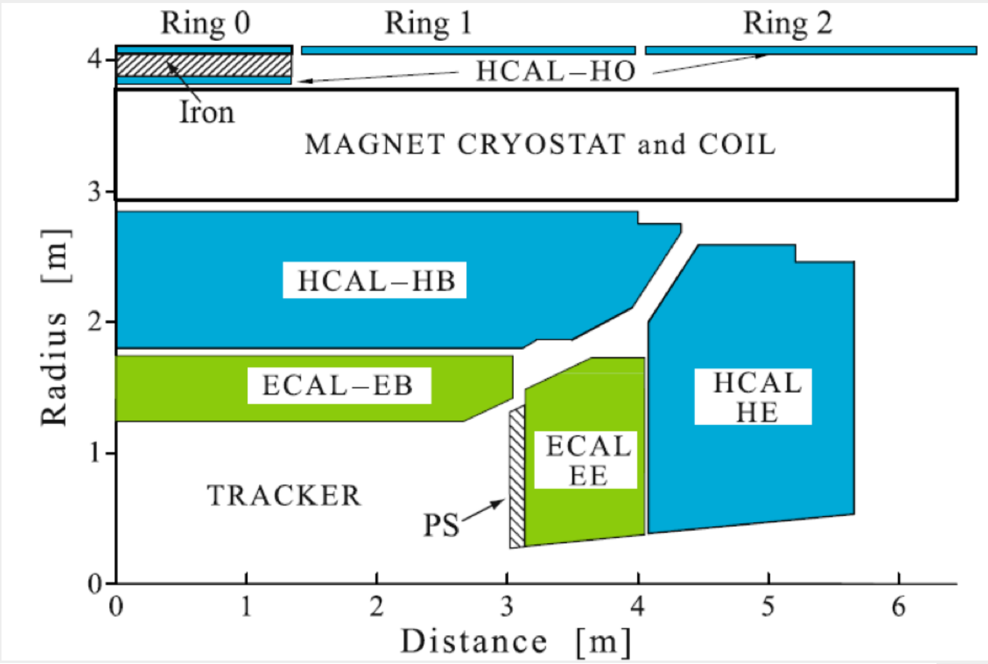
$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E\,(GeV)}} \oplus \frac{0.128}{E\,(GeV)} \oplus 0.3\%$$

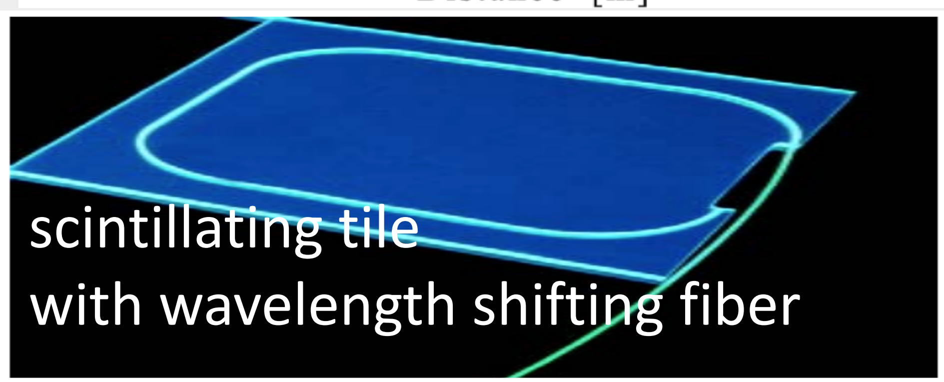


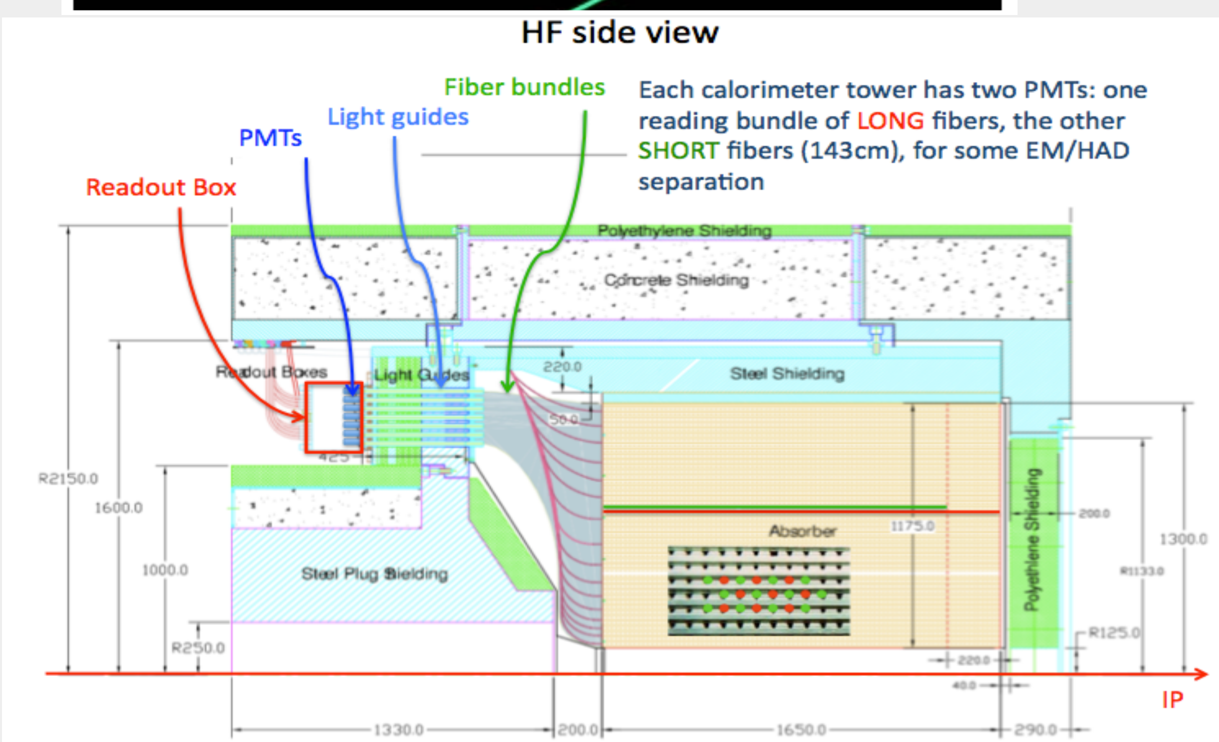




Hadron calorimeter

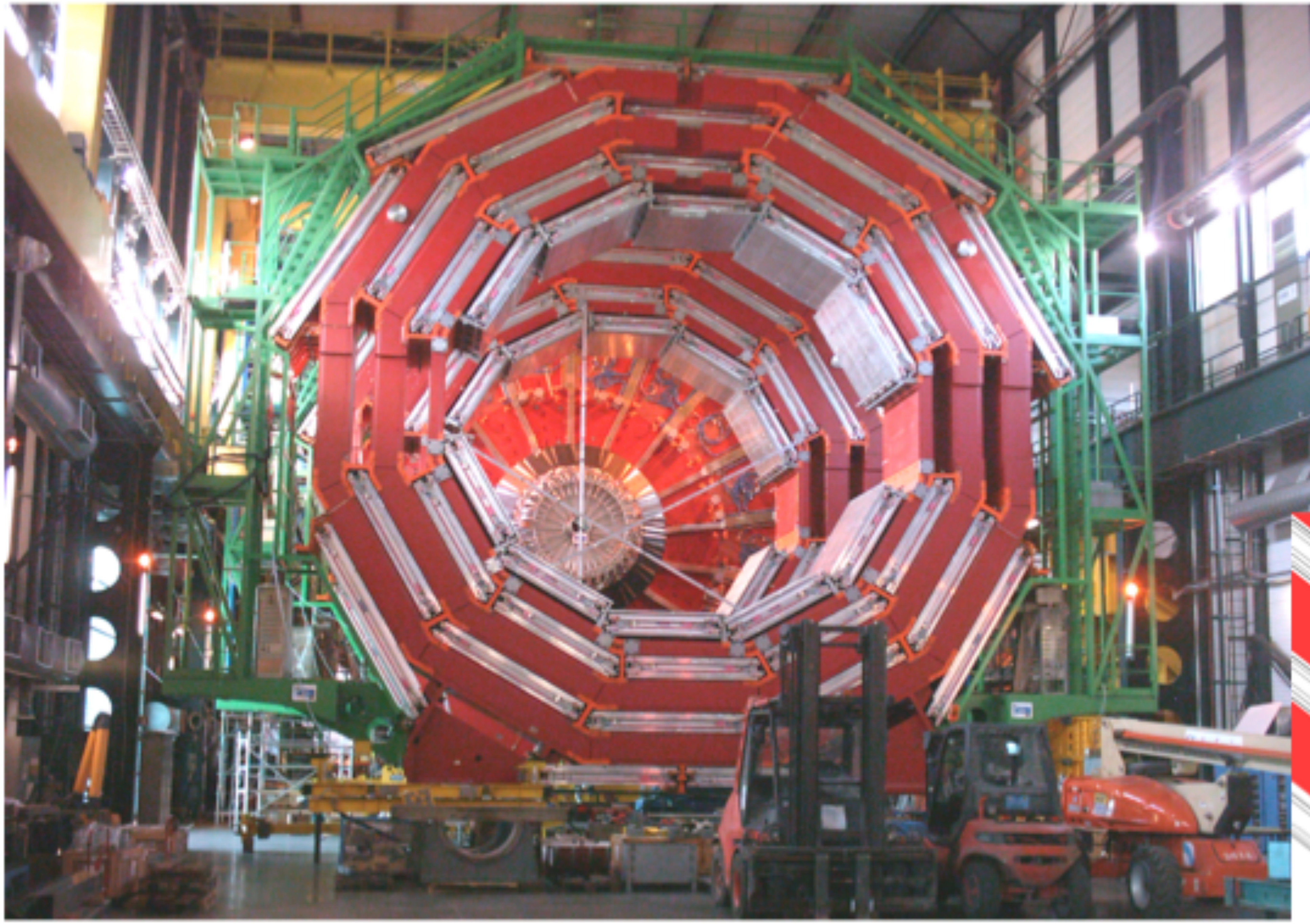






- HCAL Barrel (HB) 0<|η|<1.3 and Endcap (HE) 1.3<|η|<3
  - Sampling calorimeter, alternating layers of brass absorber and plastic scintillator tiles.
  - Hybrid photo-detector (HPD) readout
- Outer (HO): Outside solenoid
  - Tail catcher with scintillator layers
  - HPD readout
- Forward (HF) at |z|=11 m: 2.9<|η|<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

Barrel Muon System



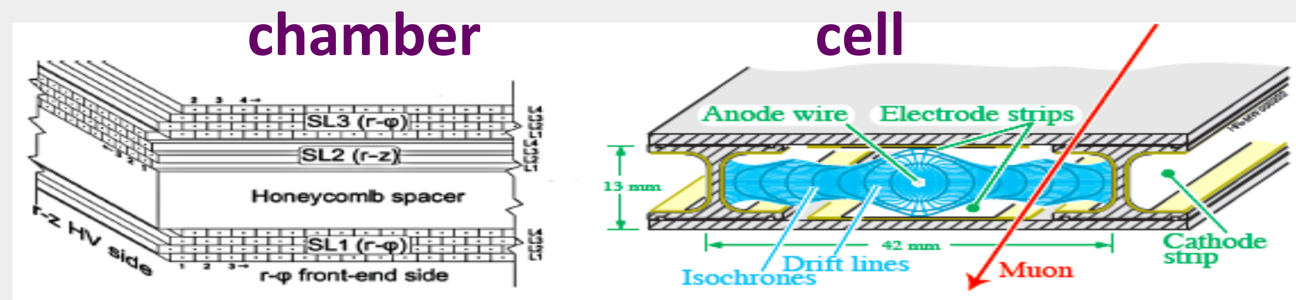
12 layers per chamber

Muon System

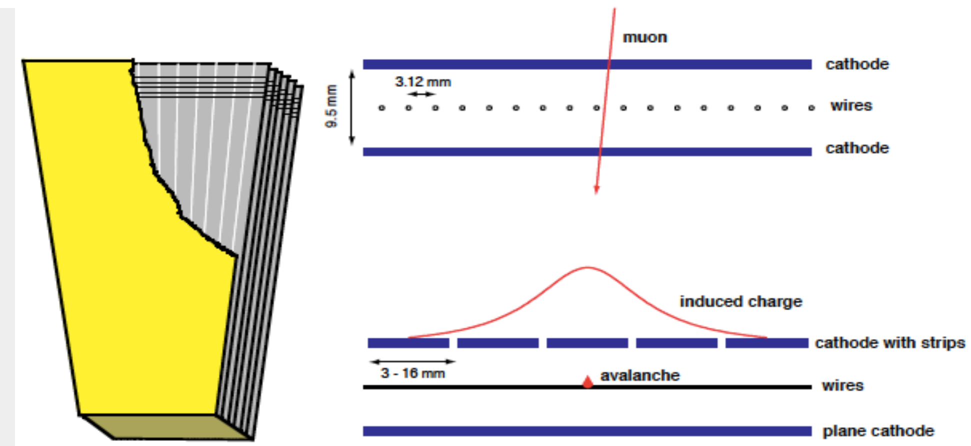
- Drift Tubes (DT) |η|< 1.2
  - 4 stations/wheel
  - cell 42x13 mm²
  - gas mixture 85% Ar, 15% CO_2
  - drift velocity ~ 55 μm/ns, maximum drift time ~ 400 ns
  - Time resolution <3 ns, spatial ~100 μm

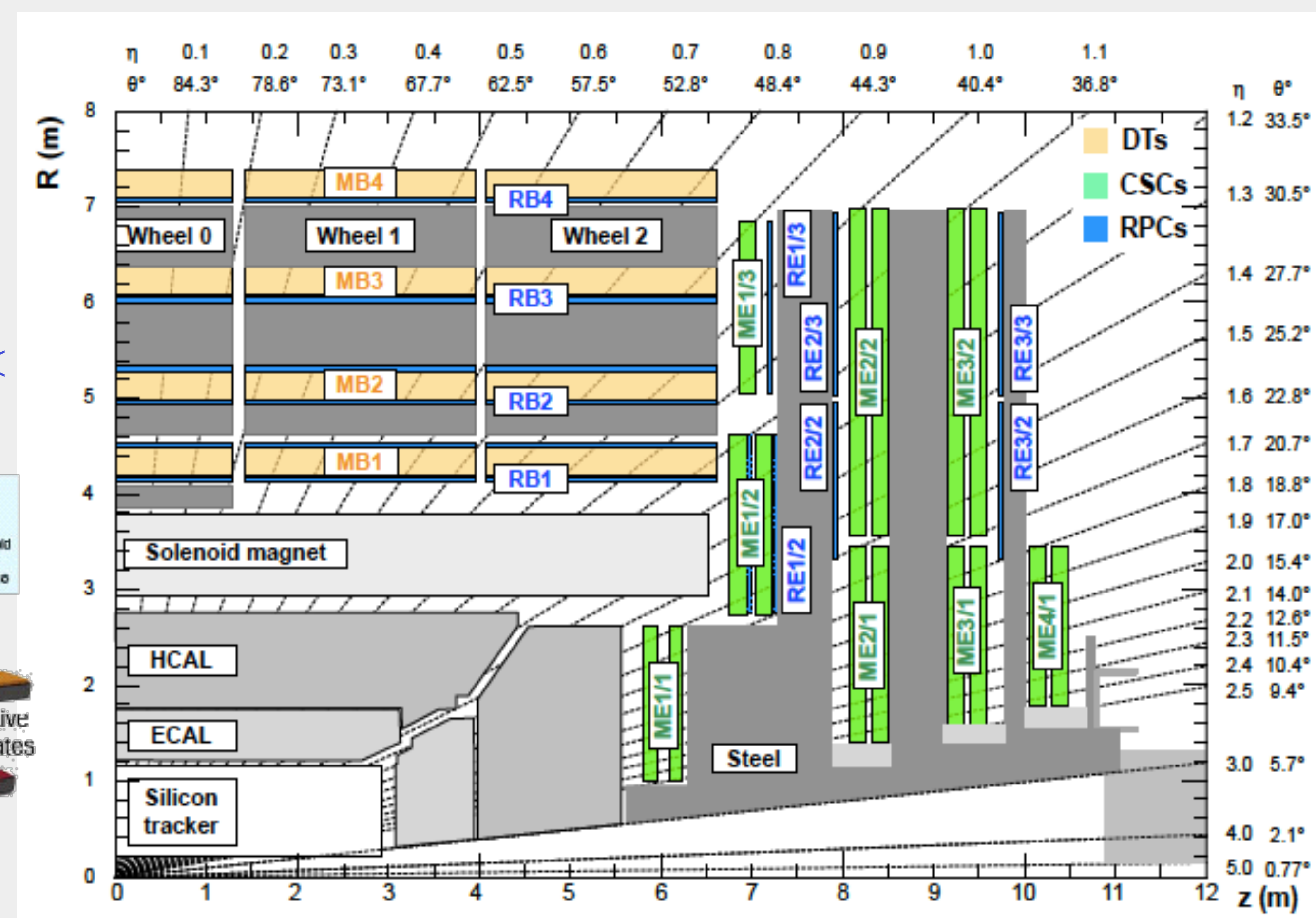
- Cathode Strip Chambers (CSC) 0.9<|η|< 1.2 (MWPC)
  - 1 CSC has 6 layers, strips measure r-ϕ, wires radial
  - gas 50% CO_2, 40% Ar, 10% CF_4
  - 4 stations subdivided in rings
  - Time resolution ~3ns, spatial 50-150 μm

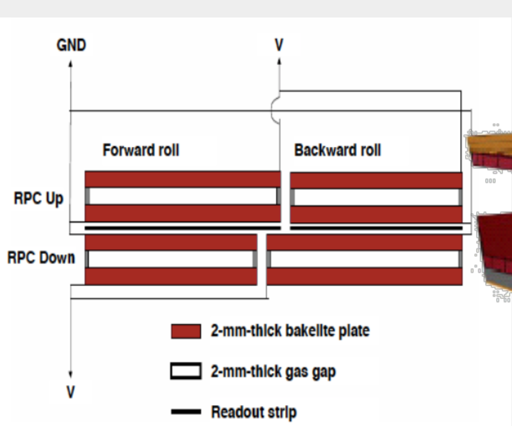
- Resistive Plate Chambers (RPC) |η|< 1.6
  - Double-gap chambers in avalanche mode
  - gas 95.2% Freon, 4.5% isobutane
  - Triggering redundancy, time resolution < 3 ns (spatial ~ 1cm)

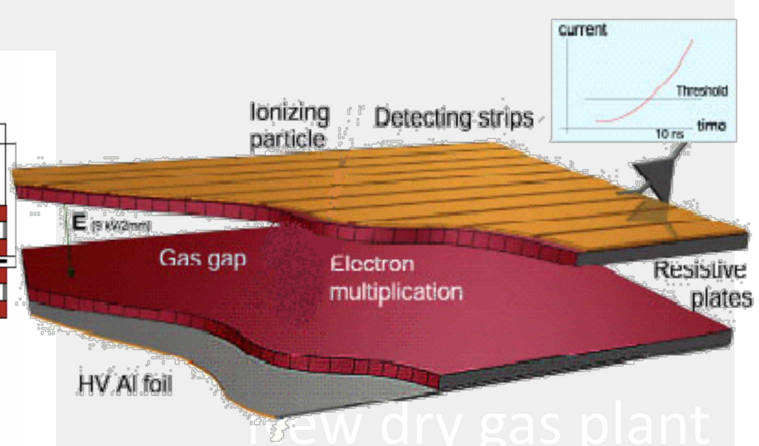


$$x_{hit} = t_{drift} \cdot v_{drift} \equiv (t_{TDC} - t_{ped}) \cdot v_{drift}$$









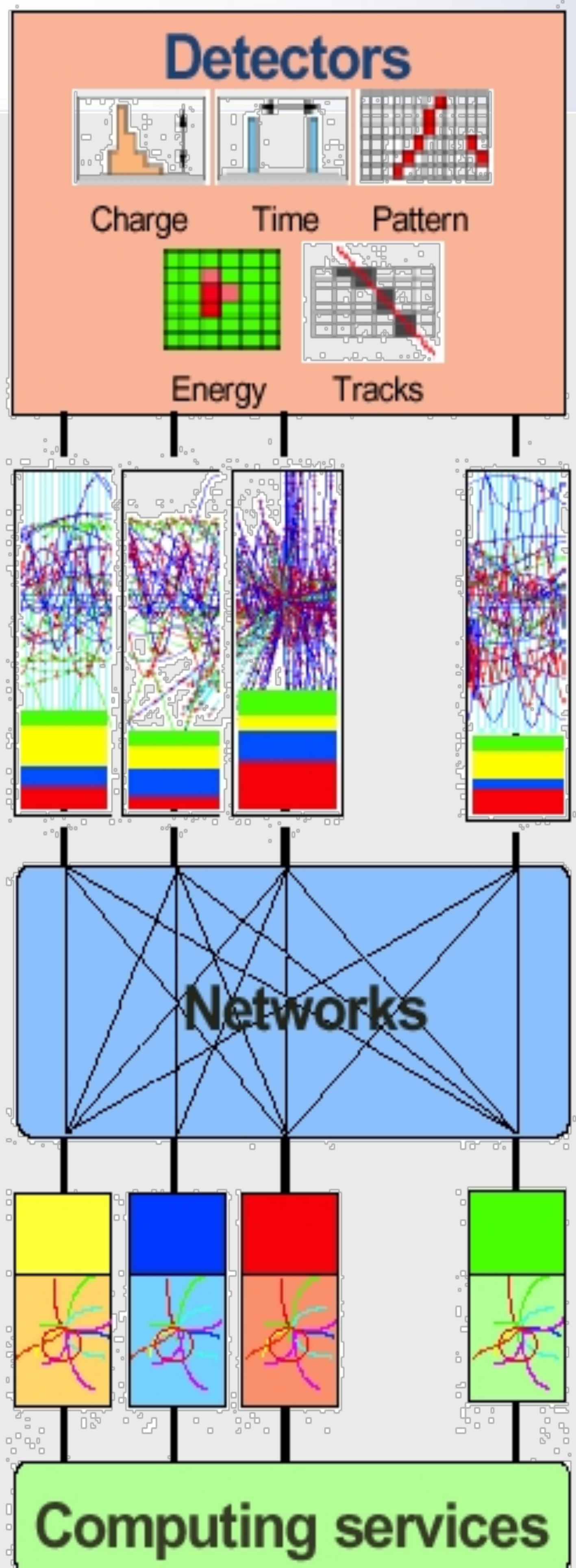
40 MHz
COLLISION RATE

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

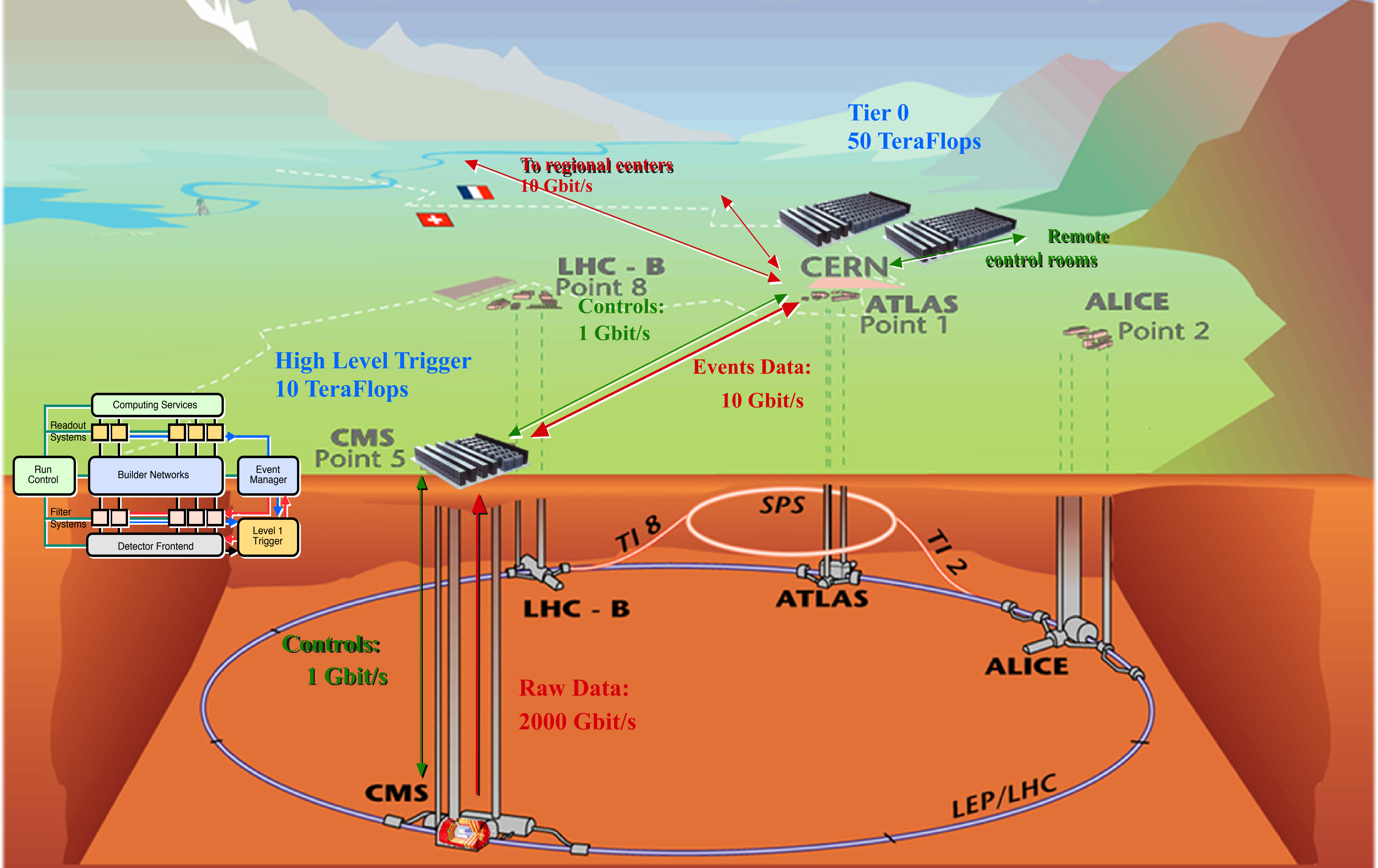
EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and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

5 TeraIPS

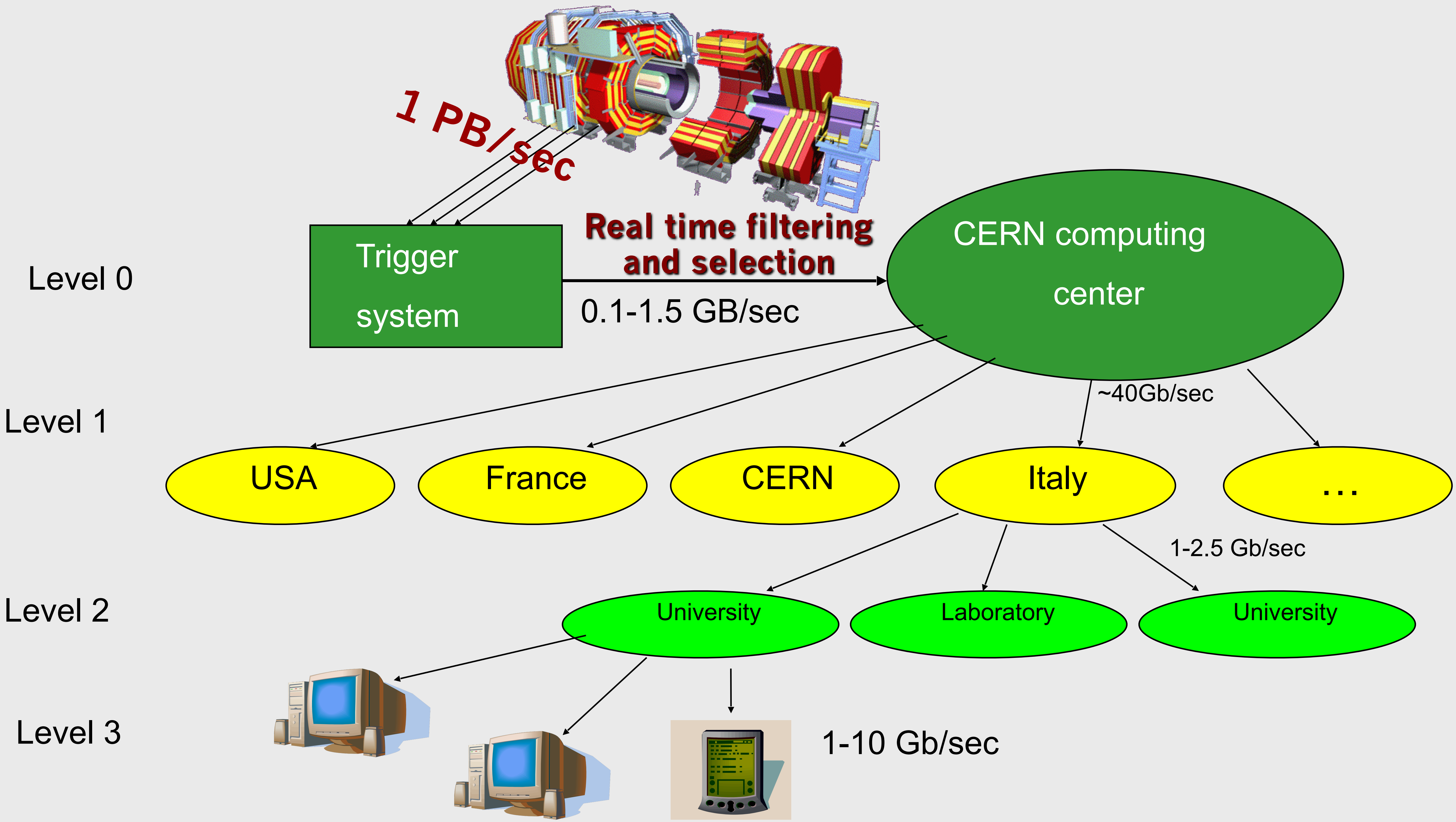
EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

Petabyte ARCHIVE

CMS data flow and on(off) line computing



Large Computing Grid (LCG)



1 PB par an

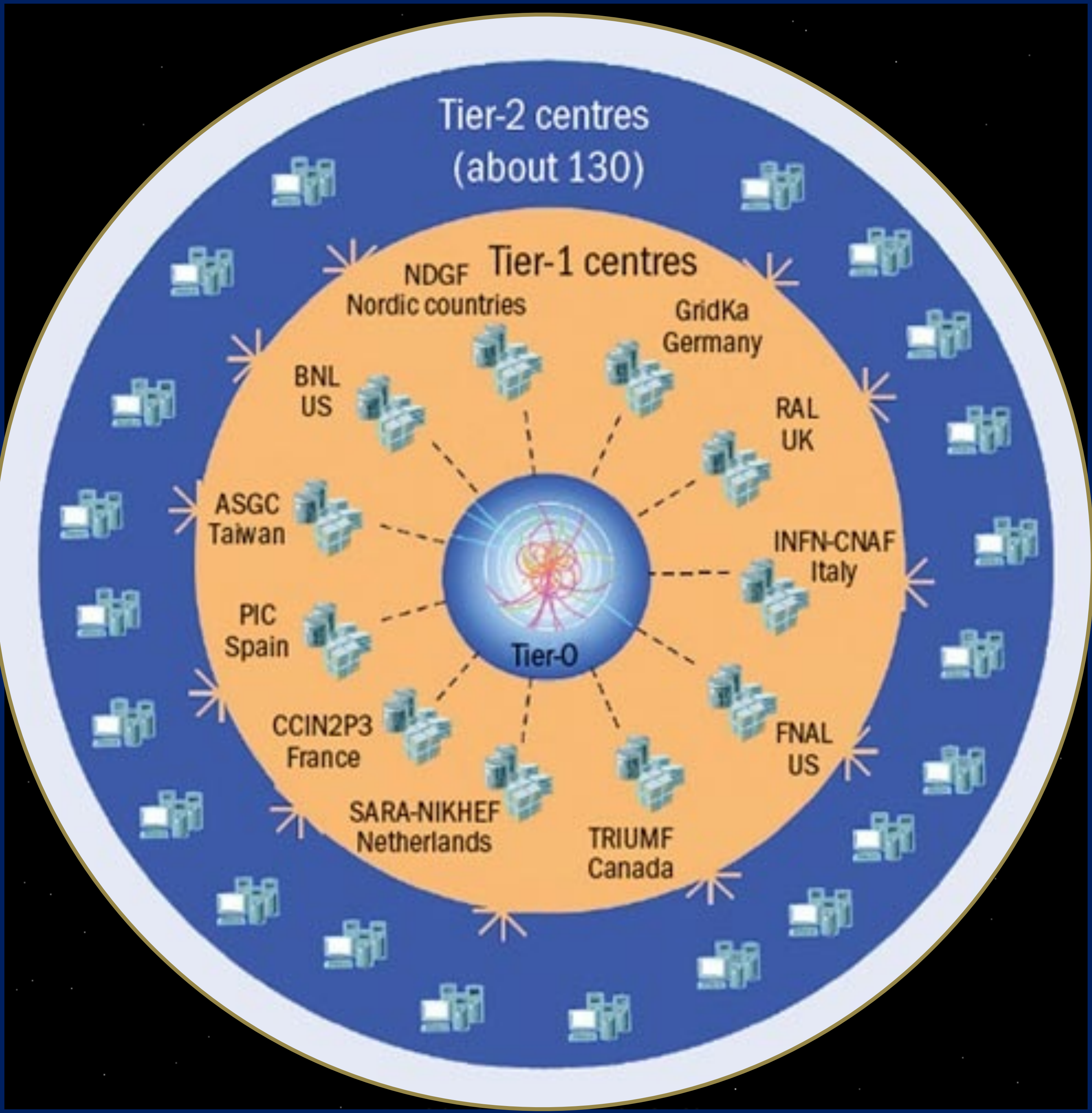
The Worldwide LHC Computing Grid

The Worldwide LHC Computing Grid

WLCG:
An International collaboration to distribute and analyse LHC data

Integrates computer centres worldwide that provide computing and storage resource into a single infrastructure accessible by all LHC physicists

The Worldwide LHC Computing Grid



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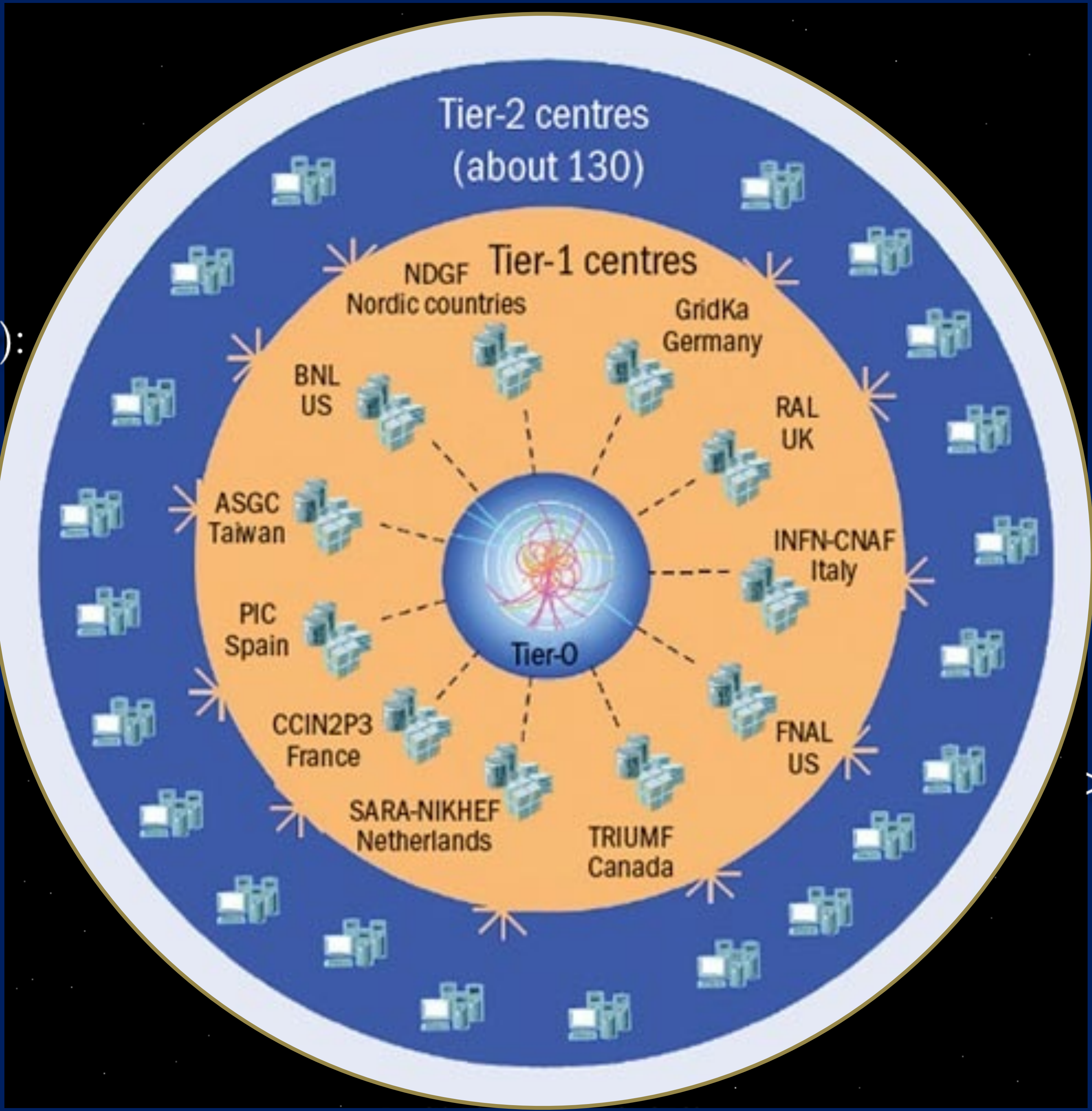
The Worldwide LHC Computing Grid

Tier-0
(CERN and Hungary): data recording, reconstruction and distribution

Tier-1: permanent storage, re-processing, analysis

Tier-2: Simulation, end-user analysis



nearly 160 sites, 35 countries

~250'000 cores

173 PB of storage

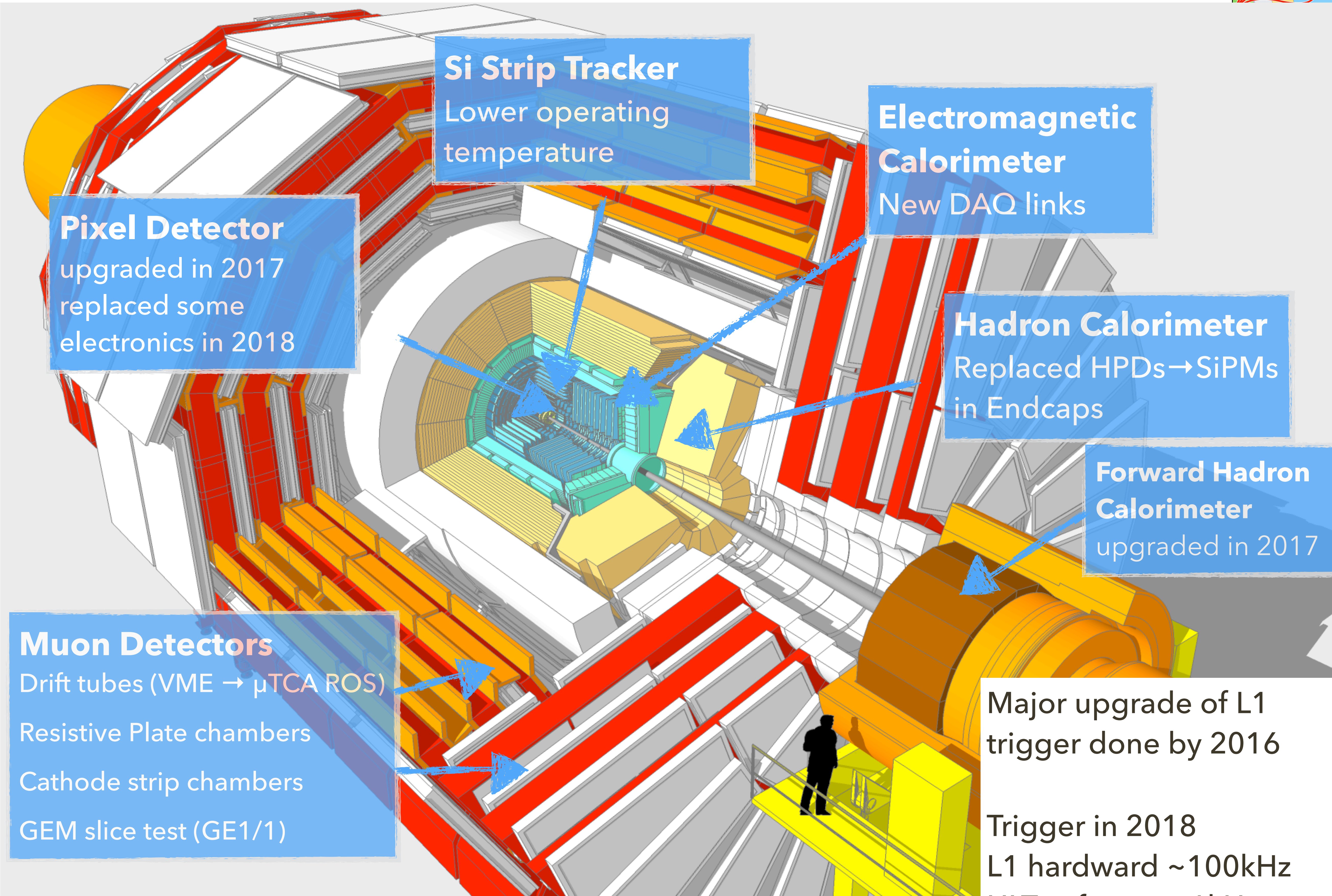
> 2 million jobs/day

10 Gb links

WLCG:
An International collaboration to distribute and analyse LHC data

Integrates computer centres worldwide that provide computing and storage resource into a single infrastructure accessible by all LHC physicists

What's new in CMS Detector in 2018?



Major upgrade of L1 trigger done by 2016

Trigger in 2018
L1 hardward ~100kHz
HLT software ~1kHz

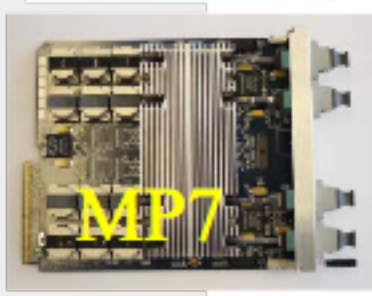
Level - 1 Trigger upgrade

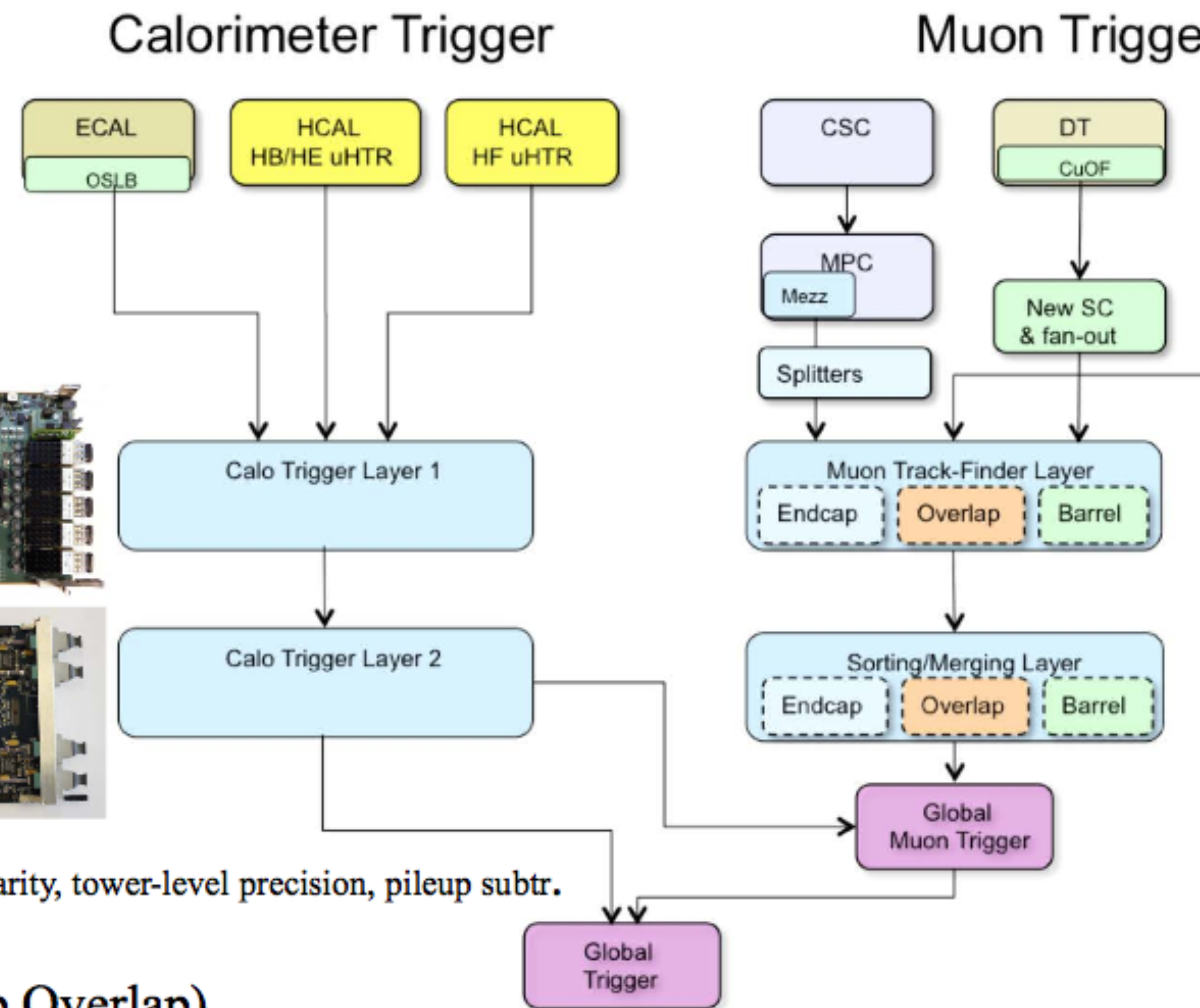
CERN-LHCC-2013-011
(CMS-TDR-012)

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

Larger FPGAs, finer granularity input, high speed optical links

- 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

L1 Trigger upgrade

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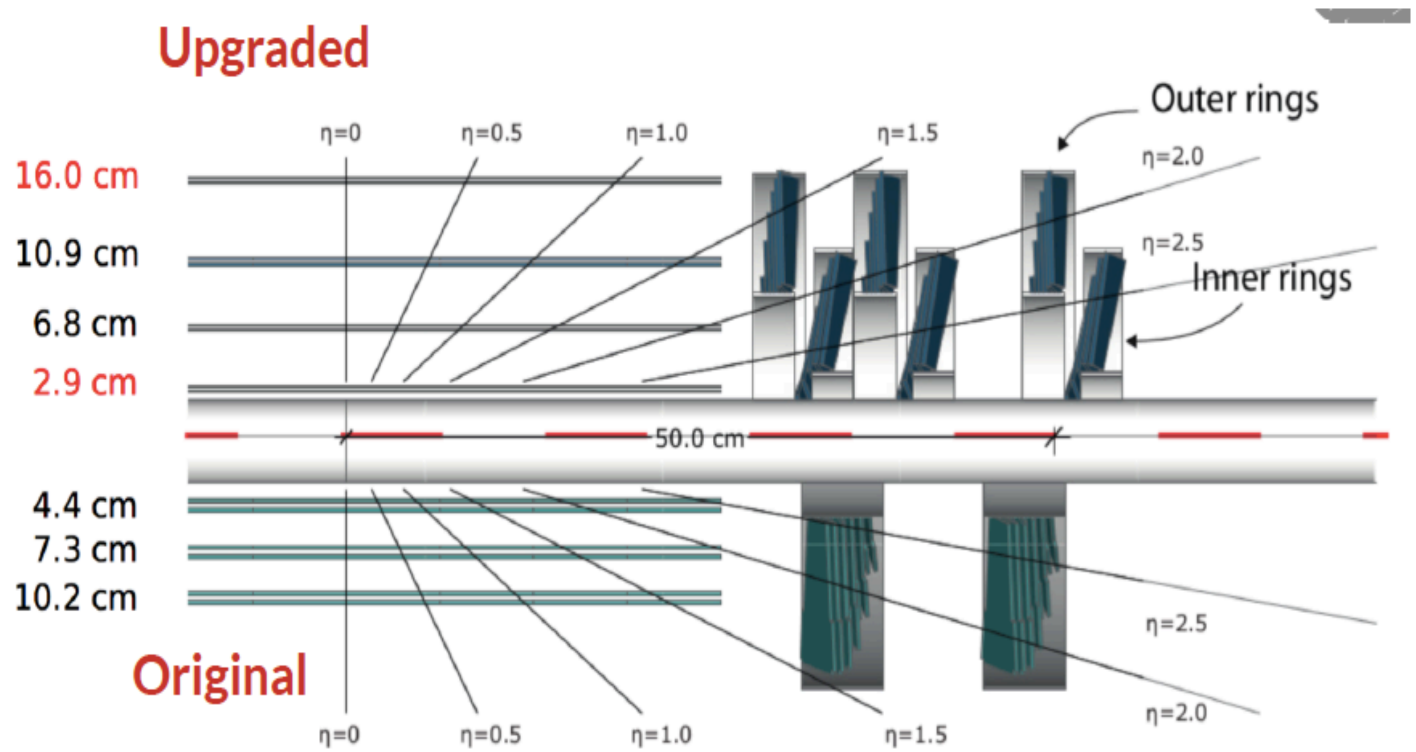
Larger FPGAs, finer granularity input, high speed optical links

Trigger efficiency @ $2 10^{34}$ $cm^{-2}s^{-1}$

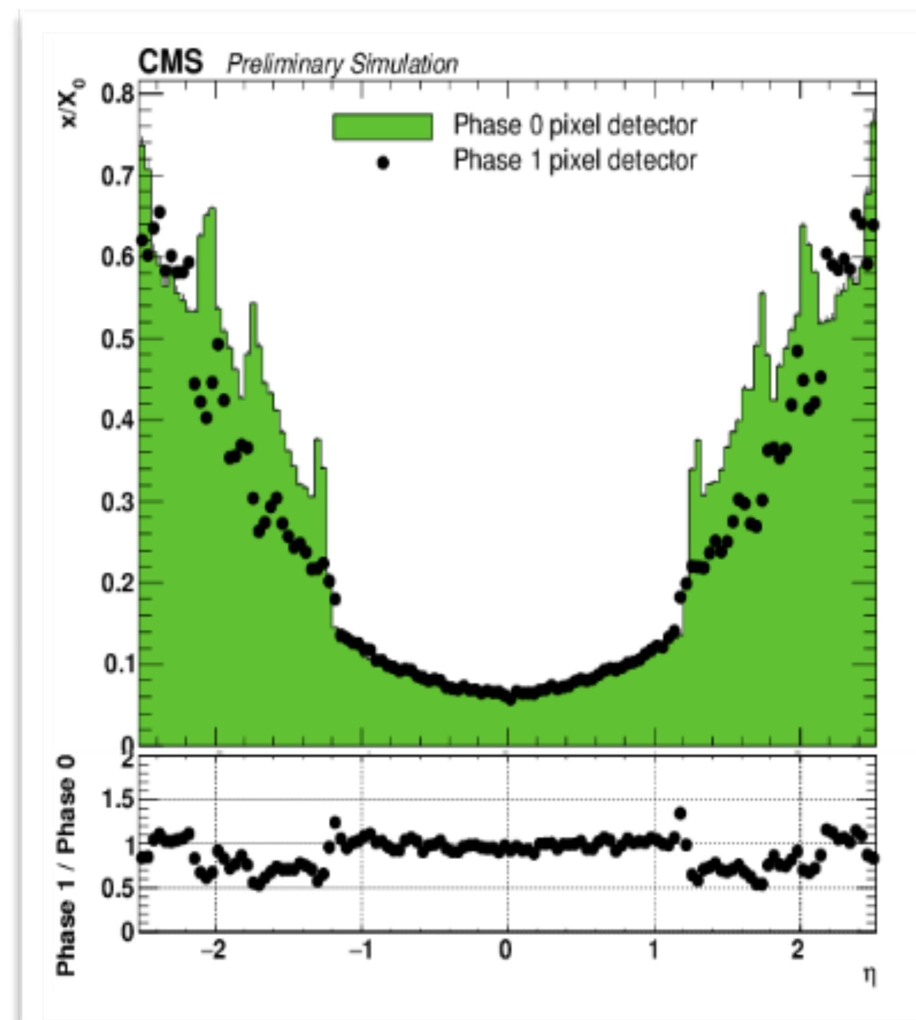
Channel	Current	Upgrade
W(eν),H(bb)	37.5%	71.5%
W(μν),H(bb)	69.6%	97.9%
VBF H(ττ(μτ))	19.4%	48.4%
VBF H(ττ(ετ))	14.0%	39.0%
VBF H(ττ(ττ))	14.9%	50.1%
H(WW(eeνν))	74.2%	95.3%
H(WW(μμνν))	89.3%	99.9%
H(WW(eμνν))	86.9%	99.3%
H(WW(μeνν))	90.7%	99.7%

Tracker: New Silicon Pixel Detector



Motivation for upgrade:

In Phase 0 pixel dynamic inefficiencies / dead time caused by limited size of readout bandwidth, affecting detector performance for high instantaneous luminosity



Upgraded pixel main characteristics:

- One additional barrel layer and forward disk
- Inner most layer moved closer to the IP
- Outer most layer moved further from the IP

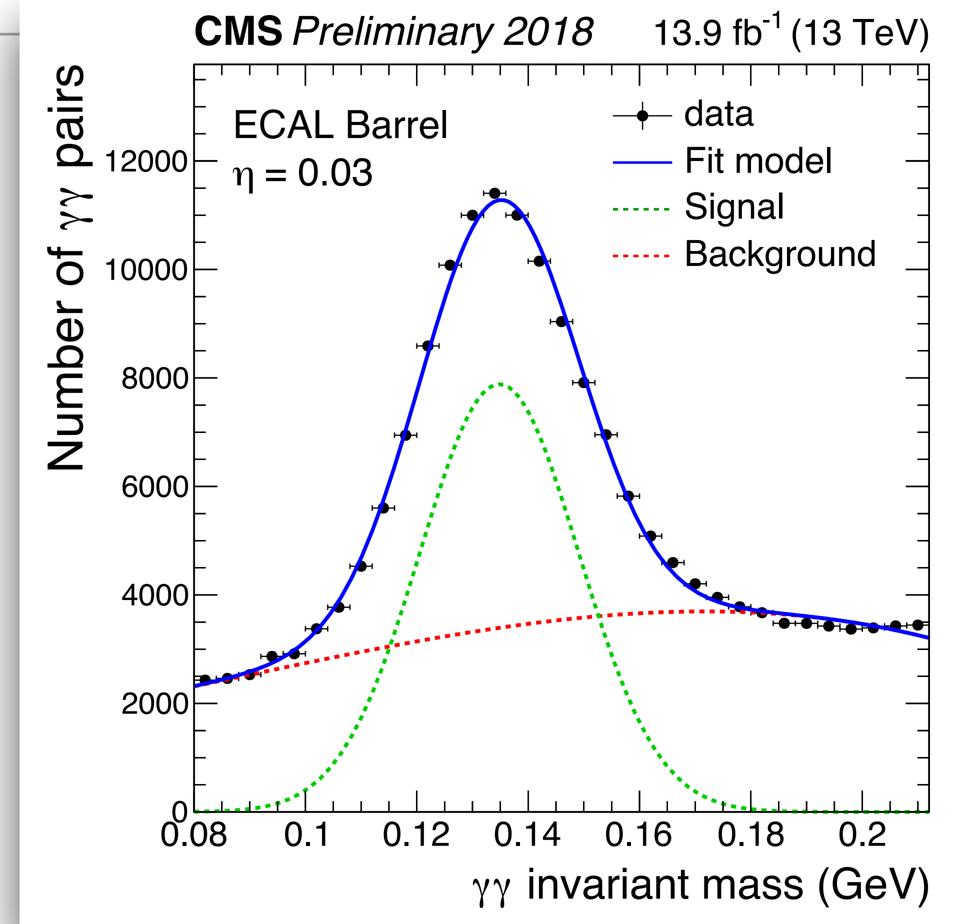
- Higher rate capability
- Increased number of channels
- Reduced material budget

Increased tracking efficiency (especially at high |η|) , reduction of fake rate, improvement in impact parameter resolution

ECAL Performance in 2018

Commissioning 2018:

- New optical links to CMS DAQ for faster data transmission from ECAL FEDs
- automatic recovery of front end errors for trigger and data links

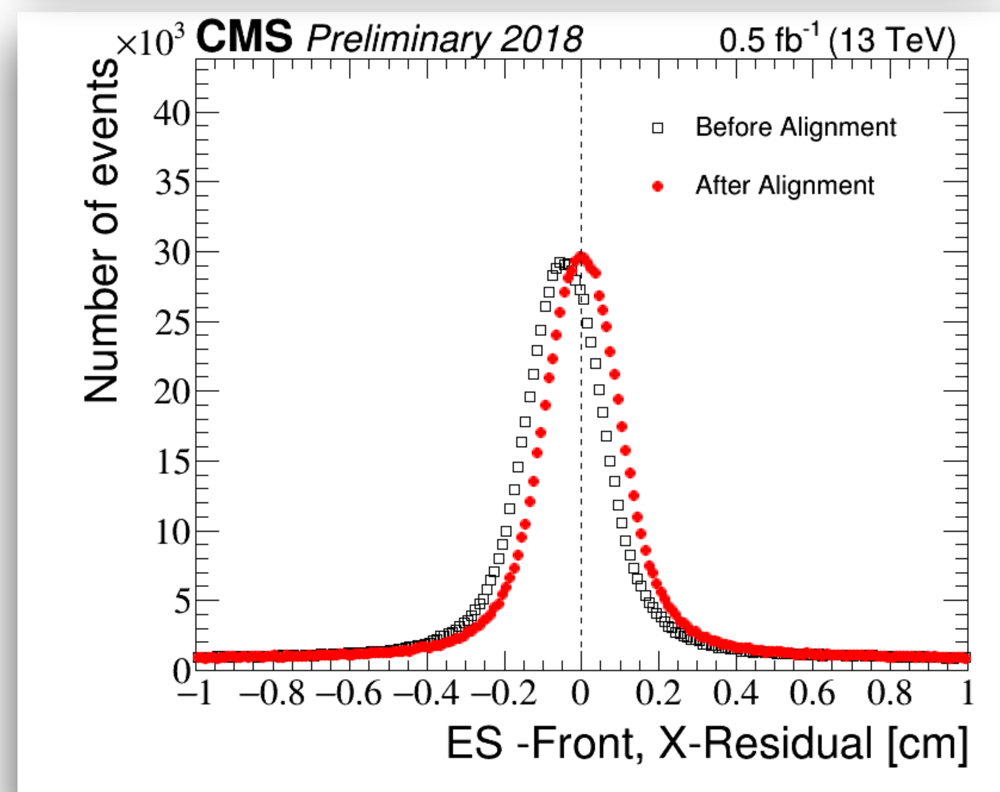


Stability of the relative energy scale measured from the invariant mass distribution of $\pi^0 \rightarrow \gamma\gamma$ decays in Barrel

- continuously monitored via automatic prompt calibration tools

Alignment

- ECAL and Pre-shower (ES) aligned using 2018 data, after opening/closing CMS
- Information is used to tighten the identification cuts for electrons at HLT

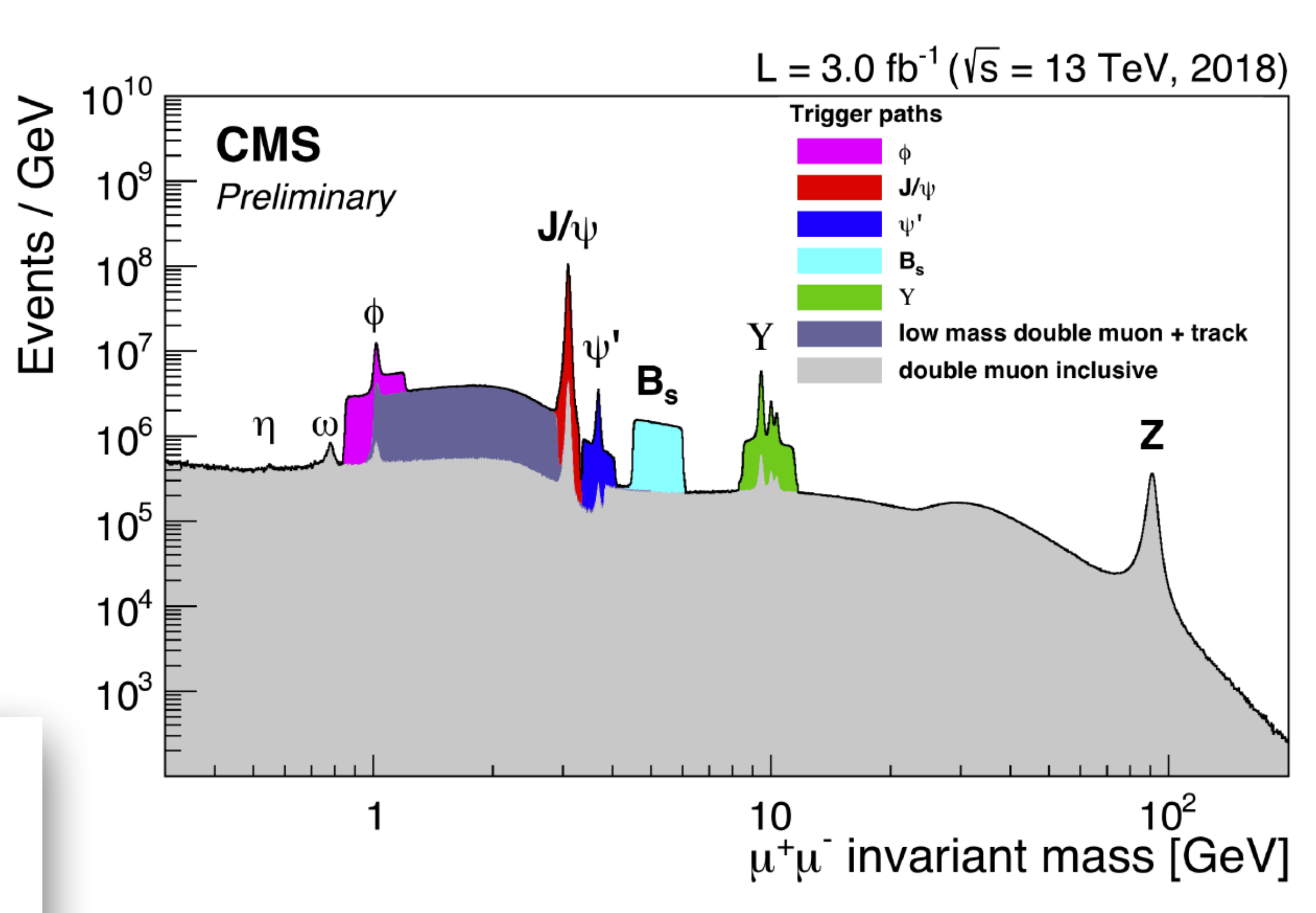


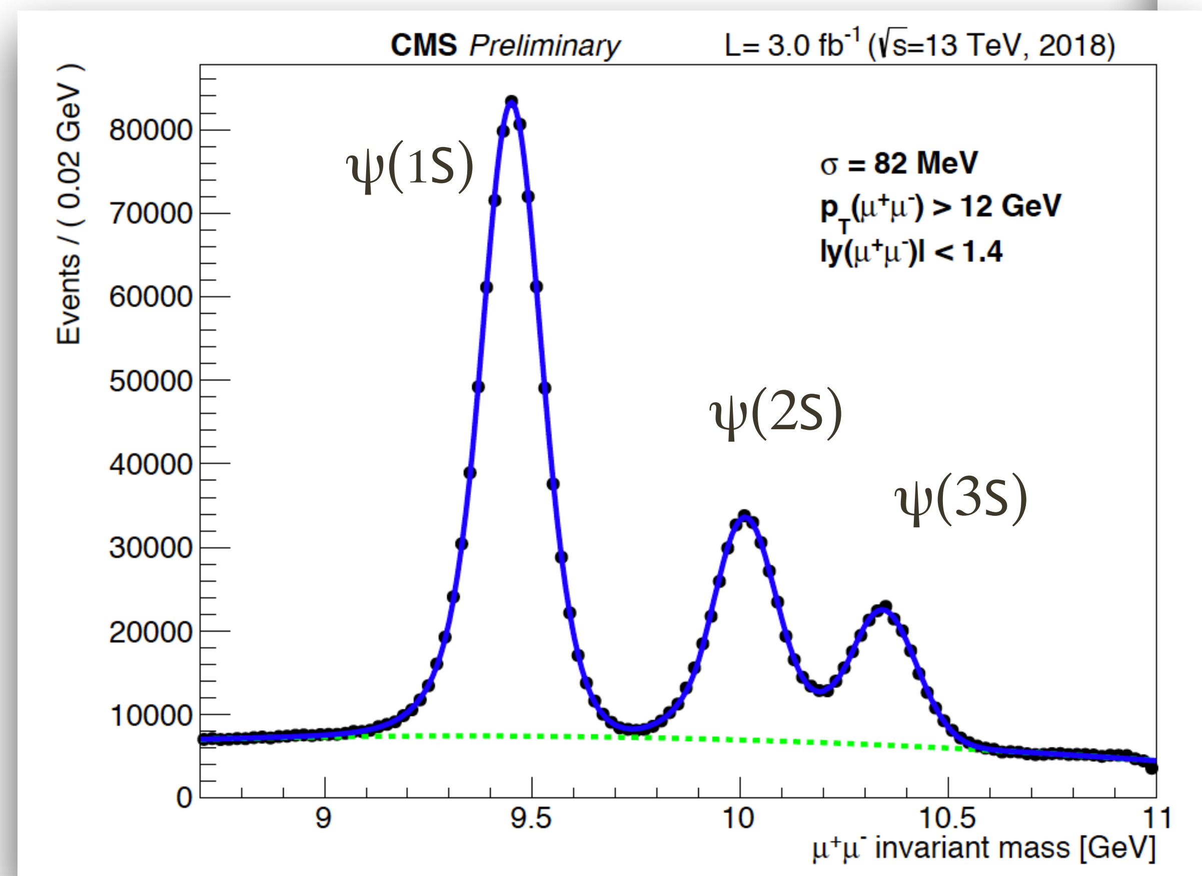
Δx of the ES energy deposits wrt the tracks before and after alignment.

Tracking and b-tag performance in 2018

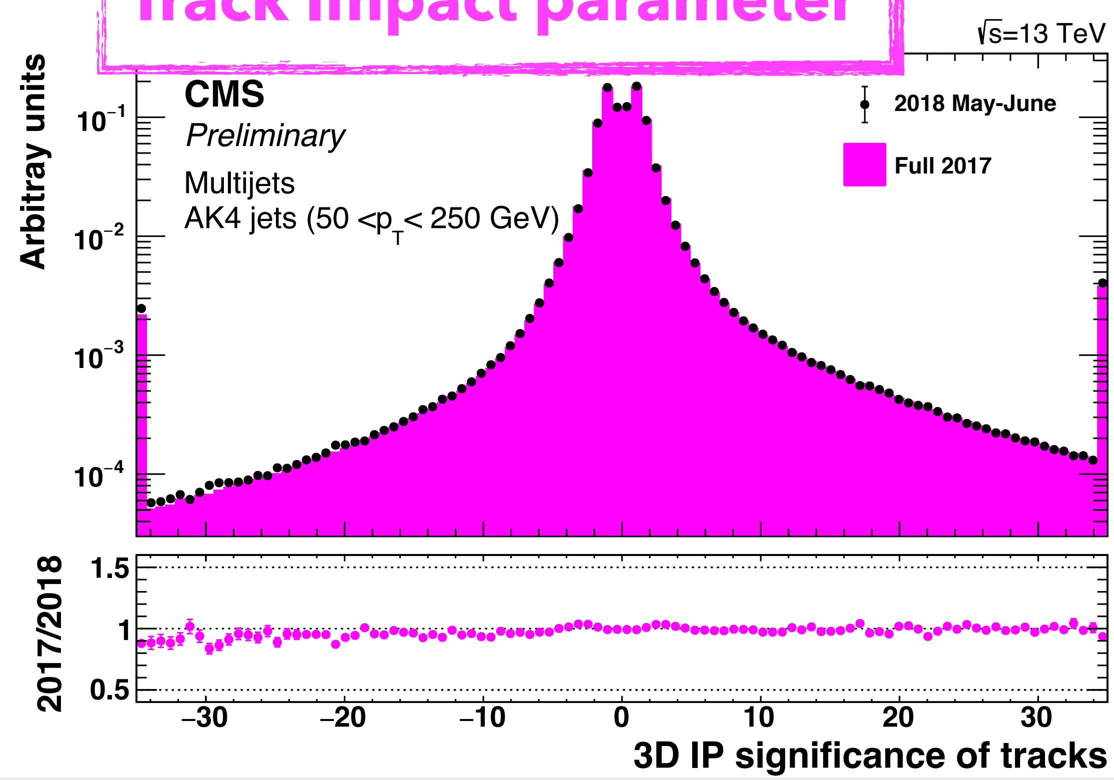
Mass distribution from various di-muon triggers

- Very good tracking performance for physics
- ...and very good muon trigger performance tool



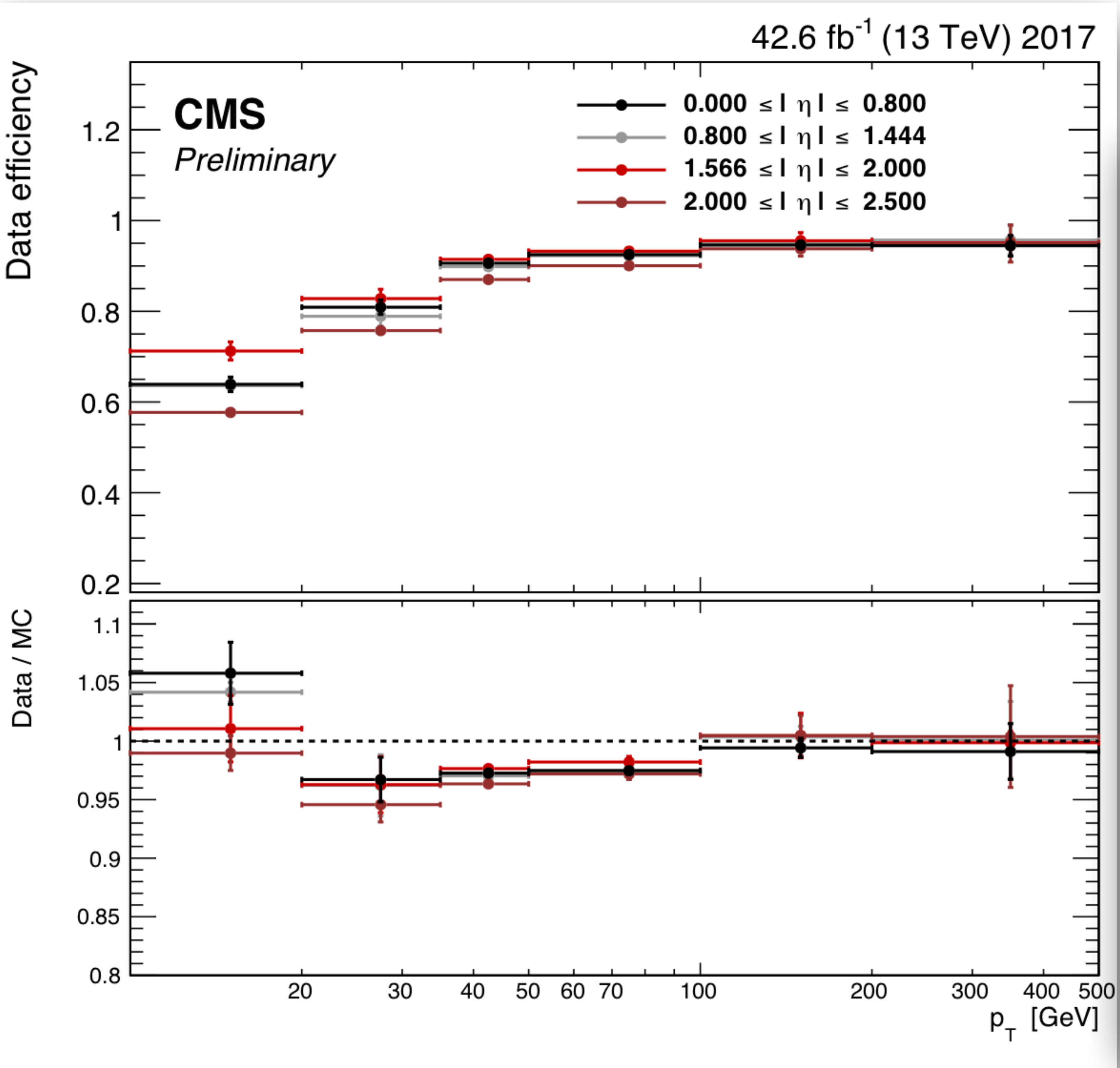


Track Impact parameter

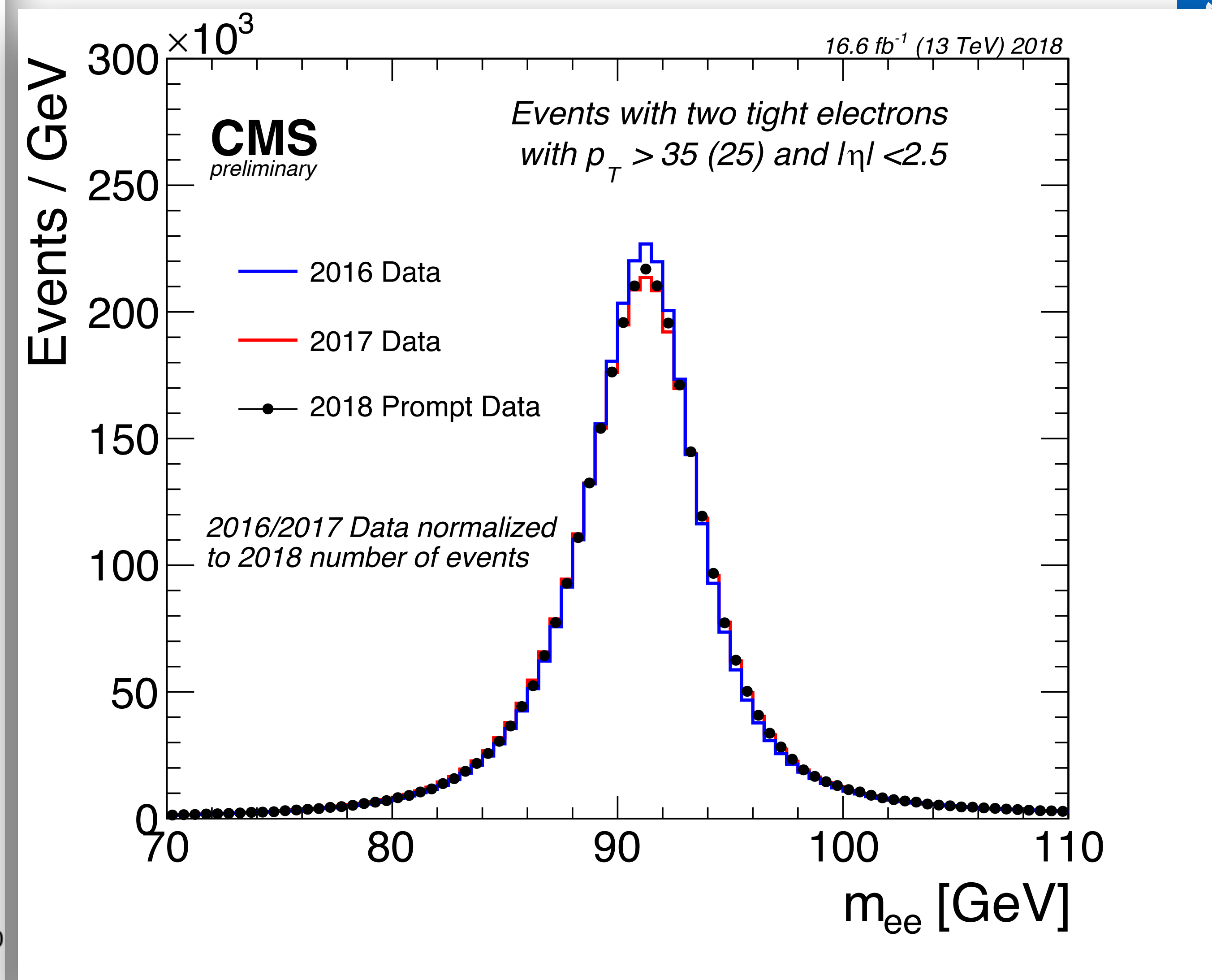


Electron performance

Loose electron ID



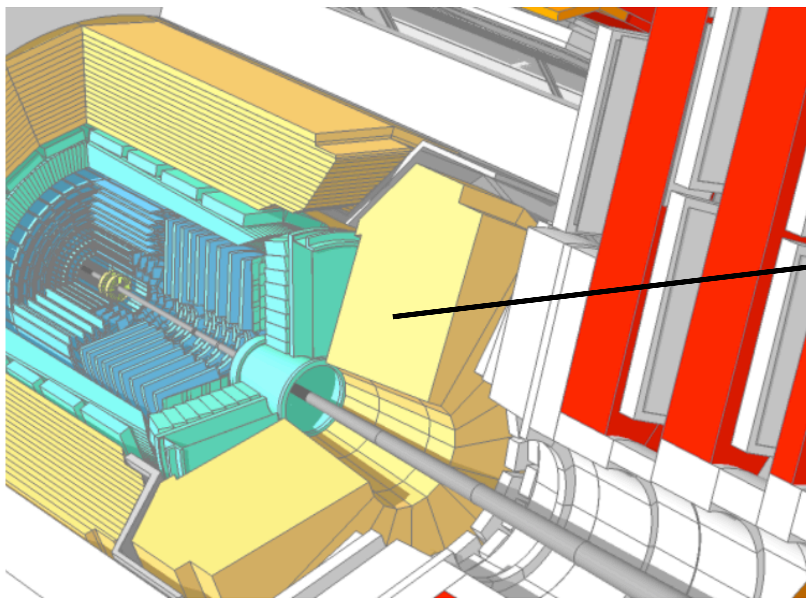
Zee invariant mass - comparing 2018 w/ 2016/17

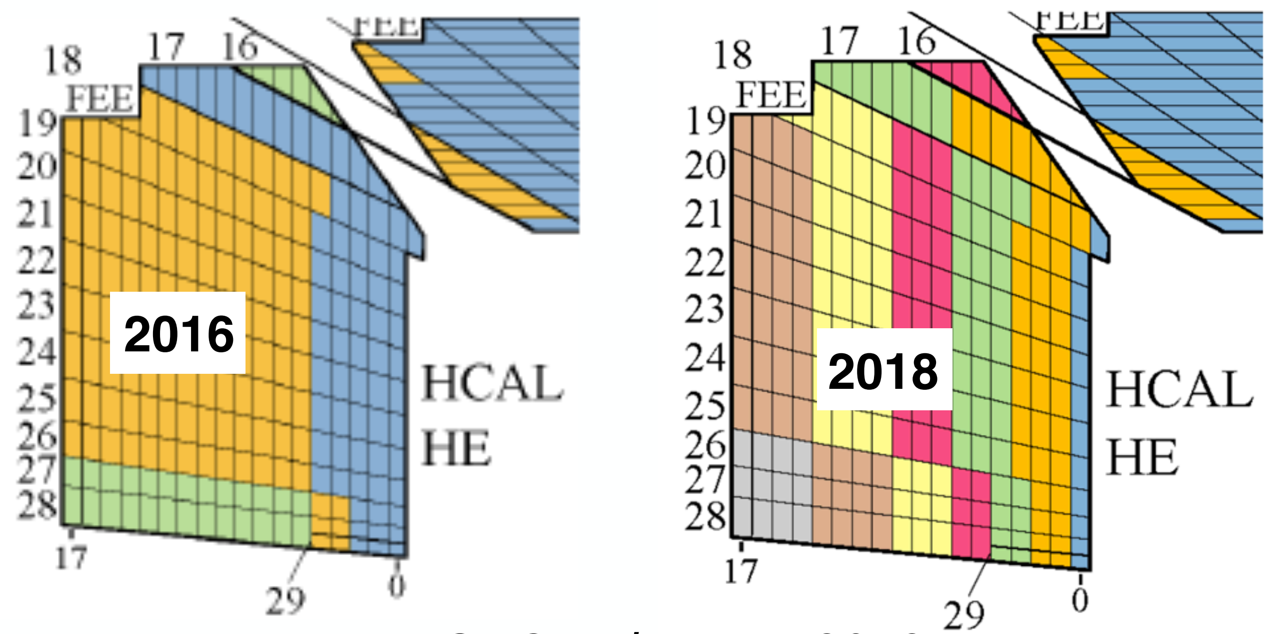


Good electron identification efficiencies in 2017 data, and well modelled in simulation

HCAL Upgrade in 2018

Phase-I upgrade of front end electronics of HE - replaced all HPDs with SiPMs



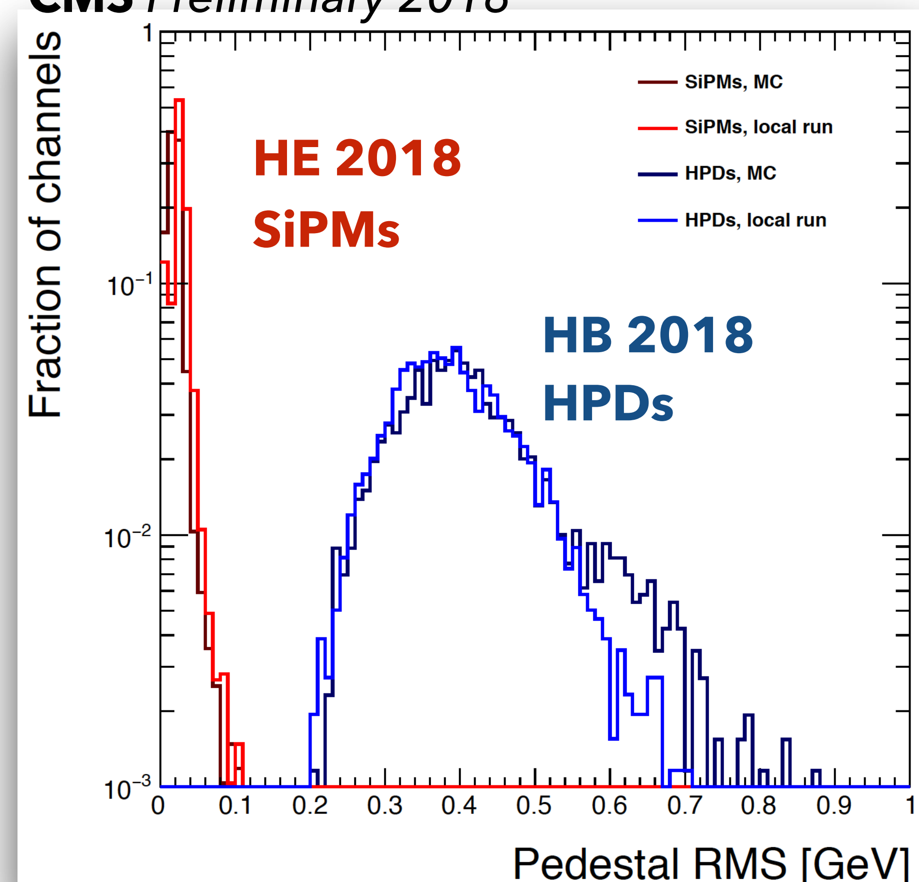


The upgraded HE is running stably

Several benefits with the upgrade:

- Eliminated progressive HPD damage
- Increased photo detection efficiency by x2.5
    - **Extend longevity of HE till the end of Run 3**
- Increased longitudinal segmentation
- Add per-channel timing information
- better S/N (e.g. for MIP)

CMS *Preliminary 2018*

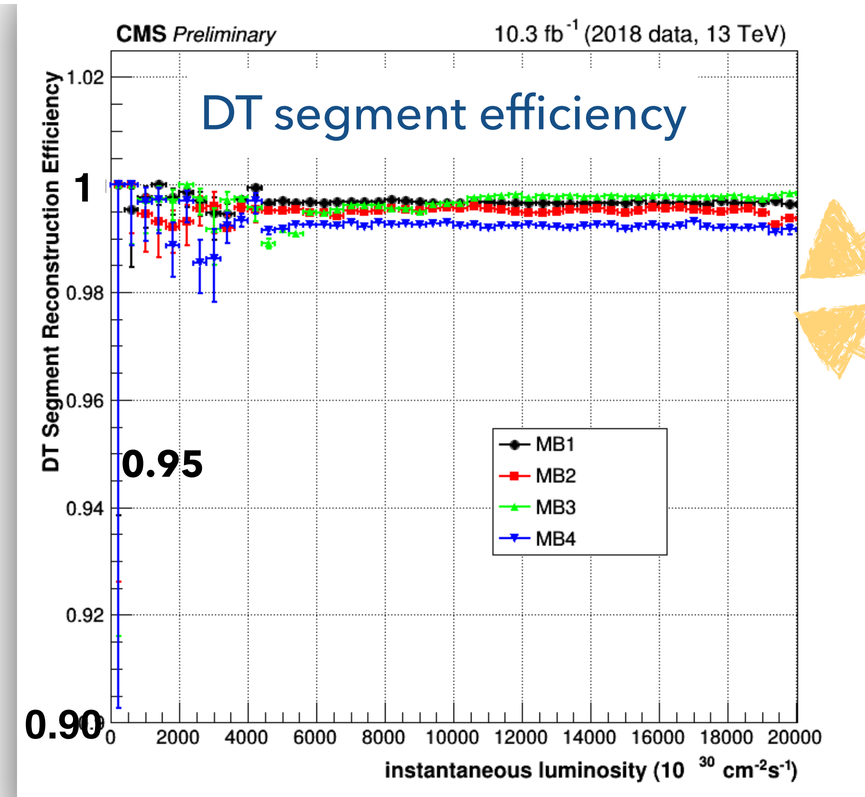


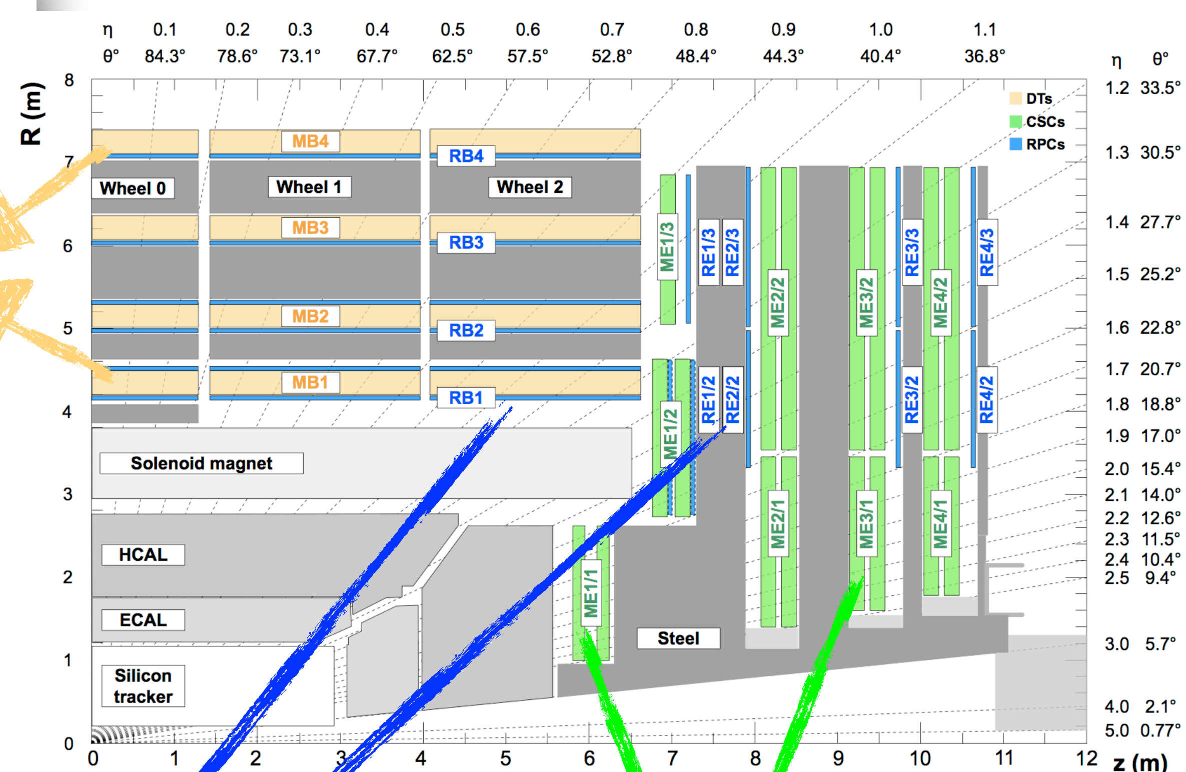
Muon Detectors Performance in 2018

Muon operations proceeding smoothly with good fraction of active electronics channels

DT readout system upgraded from VME→μTCA

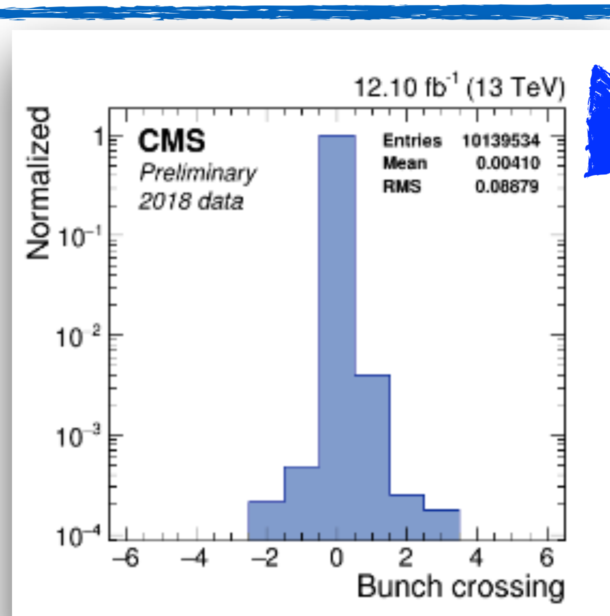
Excellent performance !!



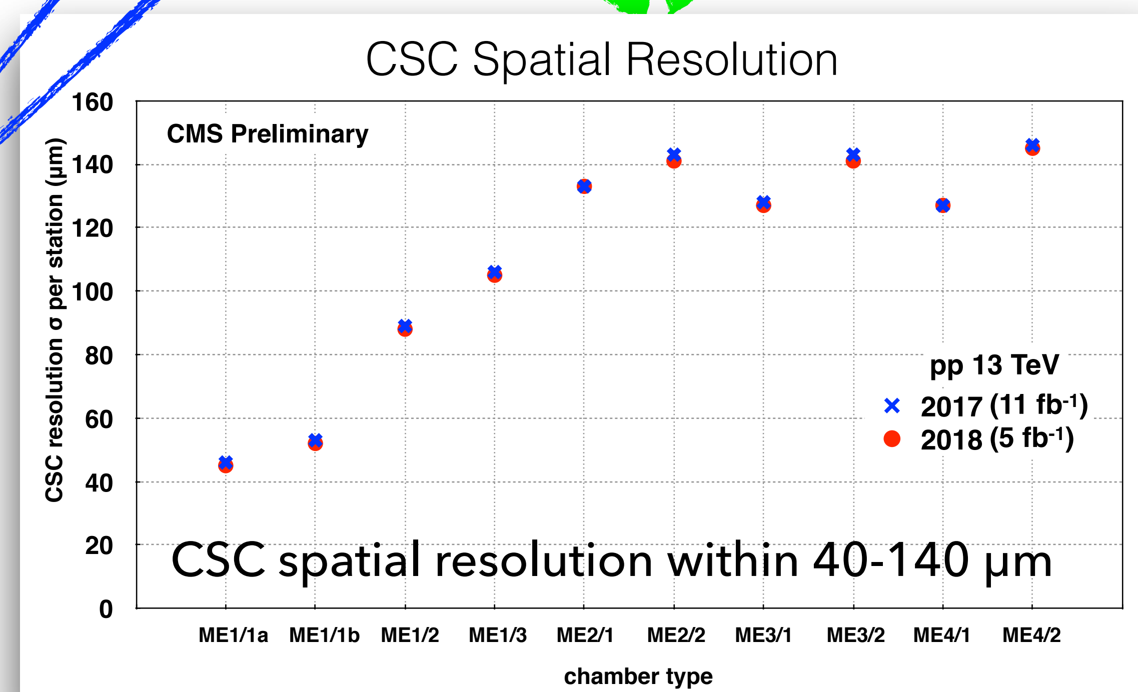


Detectors performance (local hit & segment efficiencies, resolutions) are in agreement with 2017

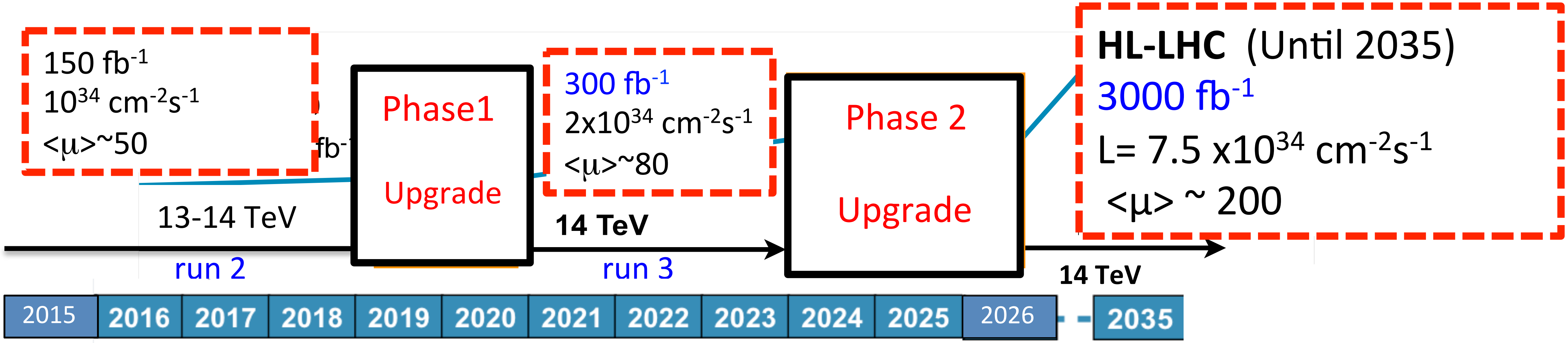
Good bunch crossing assignment in the trigger based on RPC hits

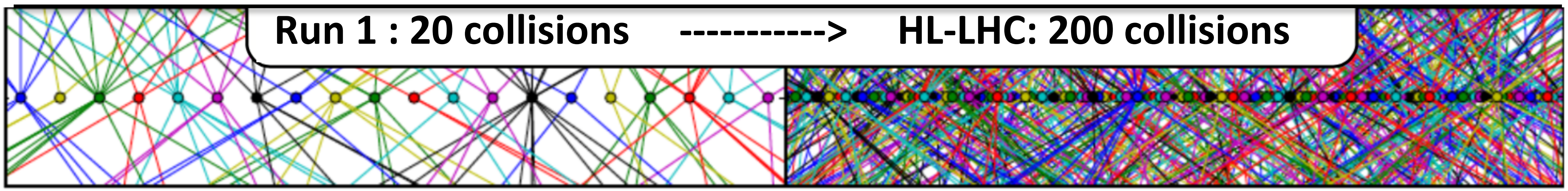


CSC Spatial Resolution



LHC ATLAS and CMS upgrades





Detector challenges:

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

- Run1: $\langle\mu\rangle=20$;$\langle n_{PU\ jets\ pT>30GeV}\rangle \sim 0.04$

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

x10 x185

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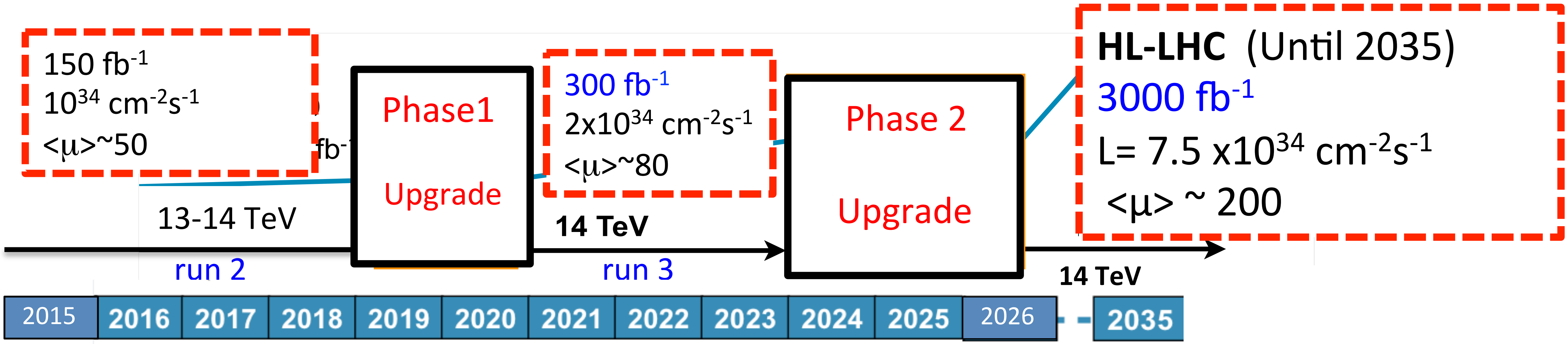

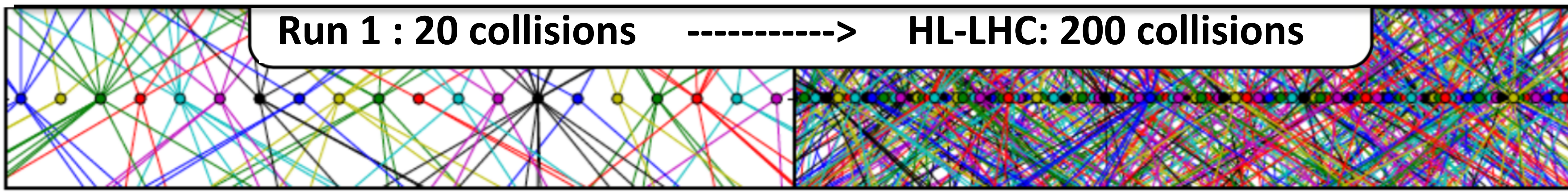

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Upgrades needed to:

· keep performance (tracking, b-tag, jet/Etmiss,...)

. Trigger rates acceptable with low P_T thresholds

key issues: radiation tolerance and detector occupancy