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Overview of the CMS detector performance at LHC Run 2

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On behalf of the CMS Collaboration

Outline

- **The CMS detector**
- **Run II overview**
  - LHC and CMS
- **What's new in Run 2**
  - Detector upgrades
- **Pixel Tracker**
  - Main features
  - Upgrade
  - Performance
- **Silicon Strips**
  - Main features
  - Performance
- **Electromagnetic Calorimeter**
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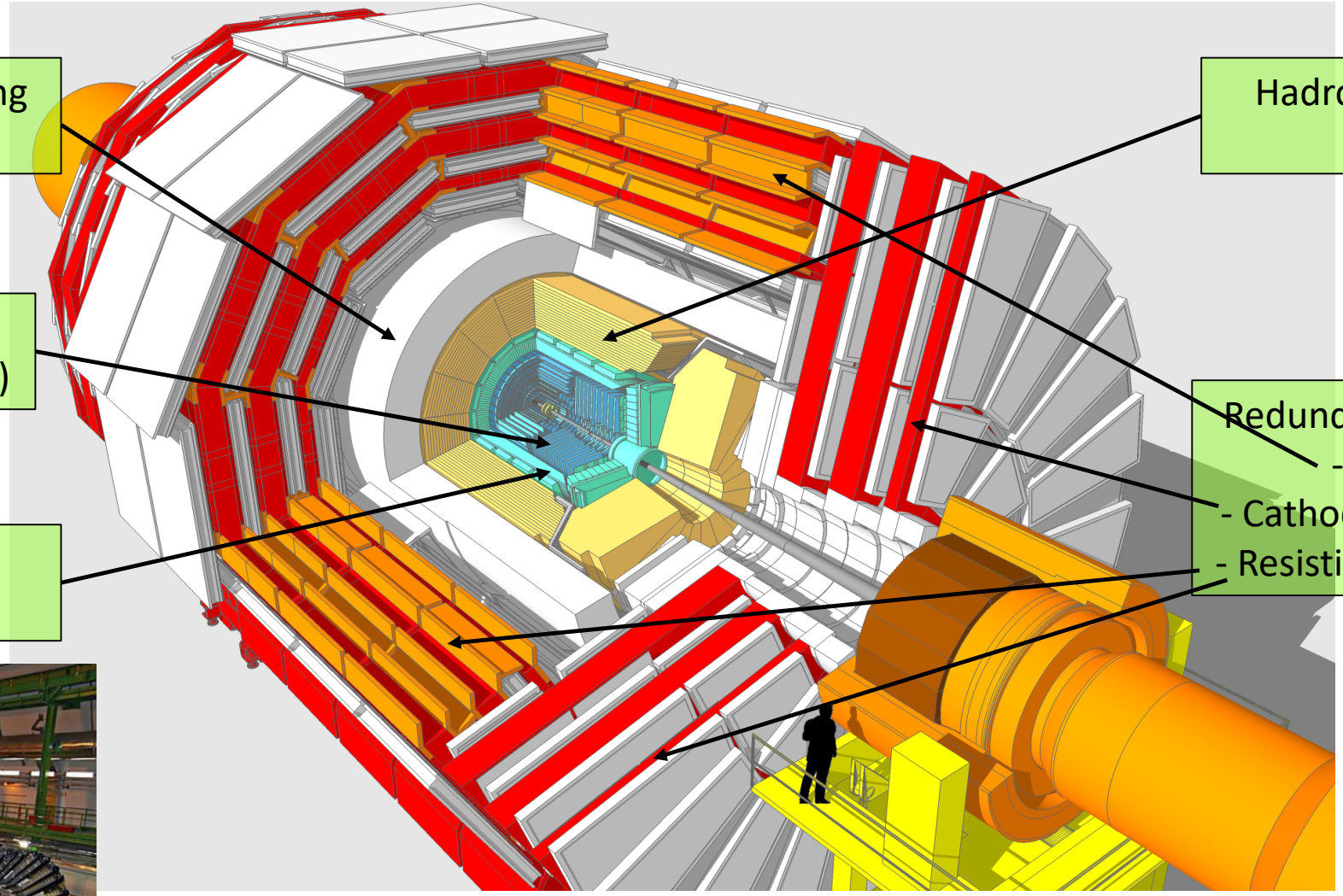
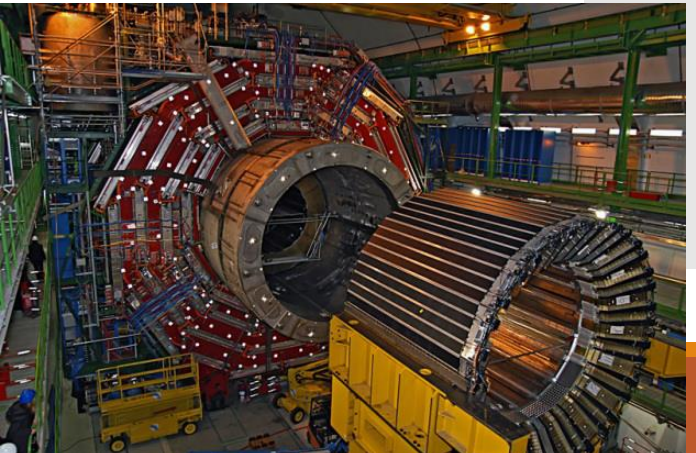
  - Calibration
  - Alignment and energy resolution
- **Hadronic Calorimeter**
  - Main features
  - Upgrades
  - Performance
- **Muon system**
  - Main features
  - Upgrades
  - Overall performance
- **Drift Tubes, Cathode Strip Chambers, Resistive Plate Chambers**
  - Main features
  - Performance

The CMS Detector

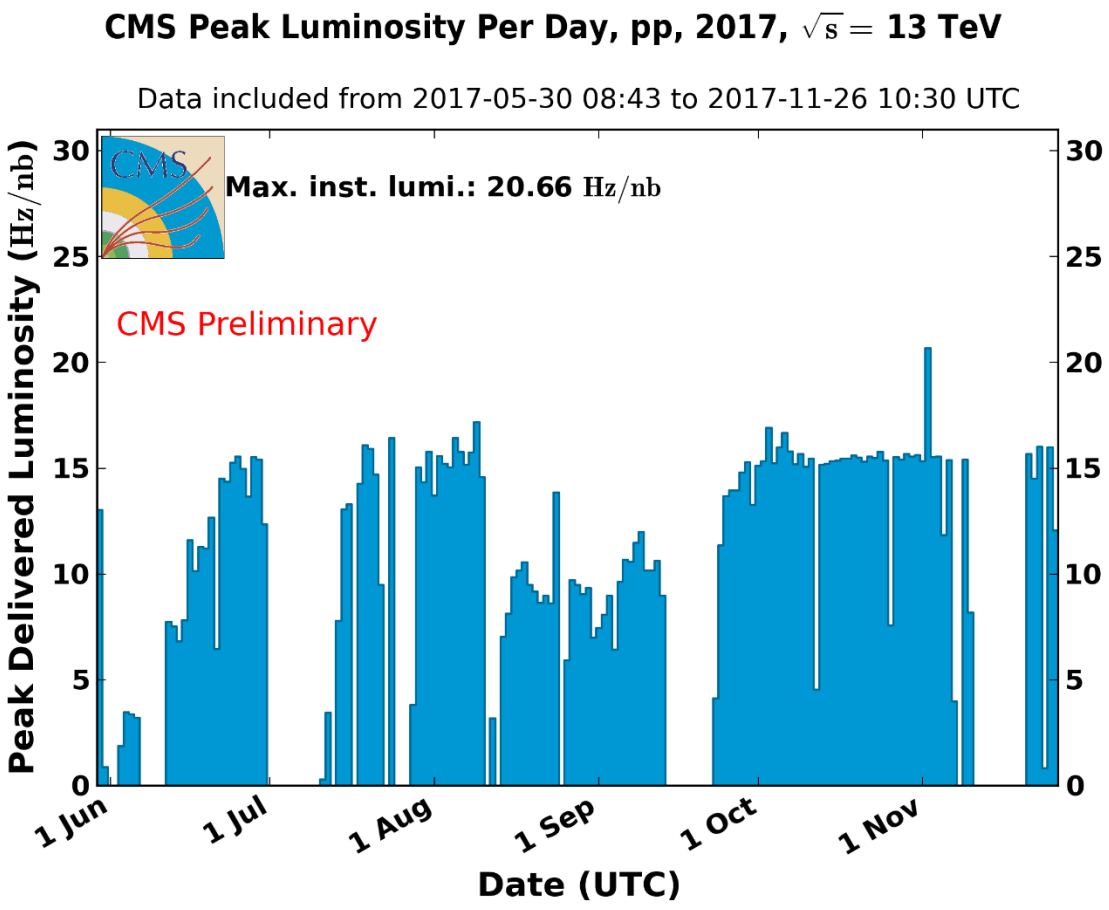




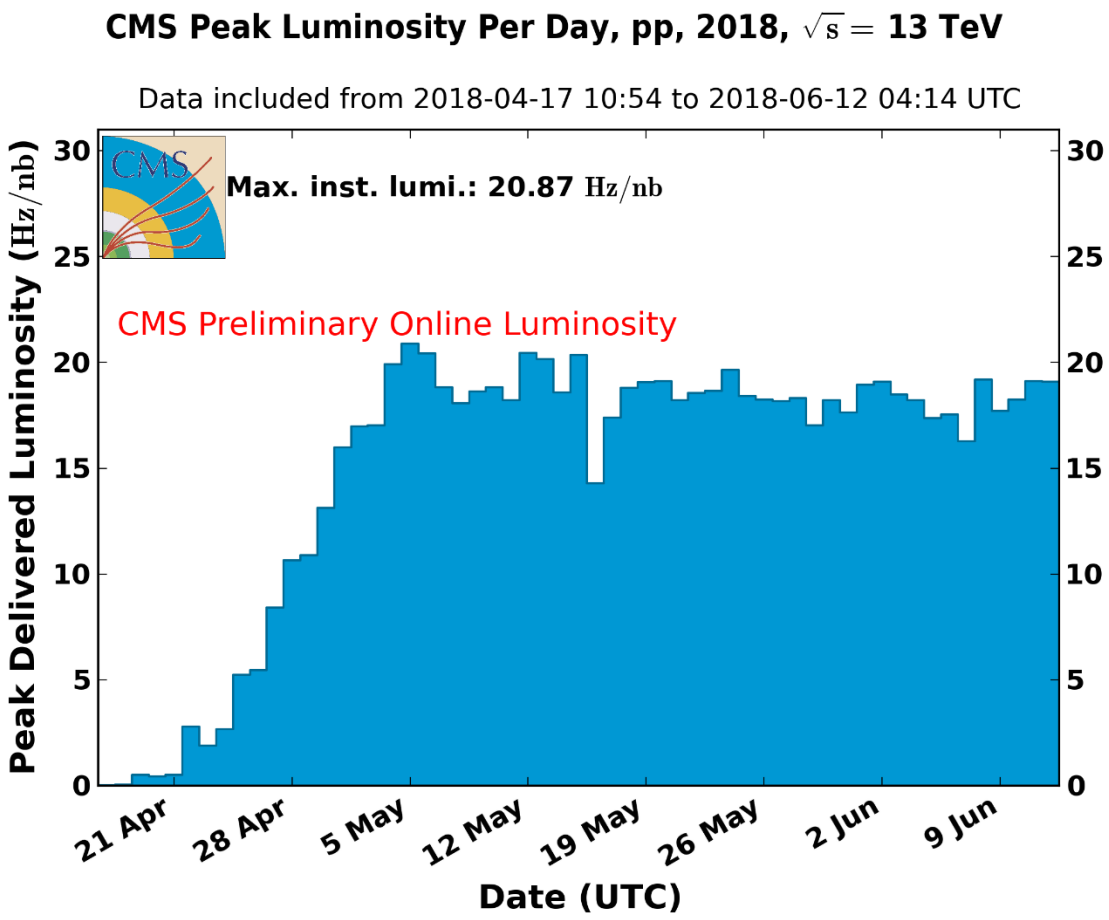
Run II: LHC luminosity

- Peak luminosity ~2 10^{34}
- Corresponding to Pile-Up > 55

2017



2018



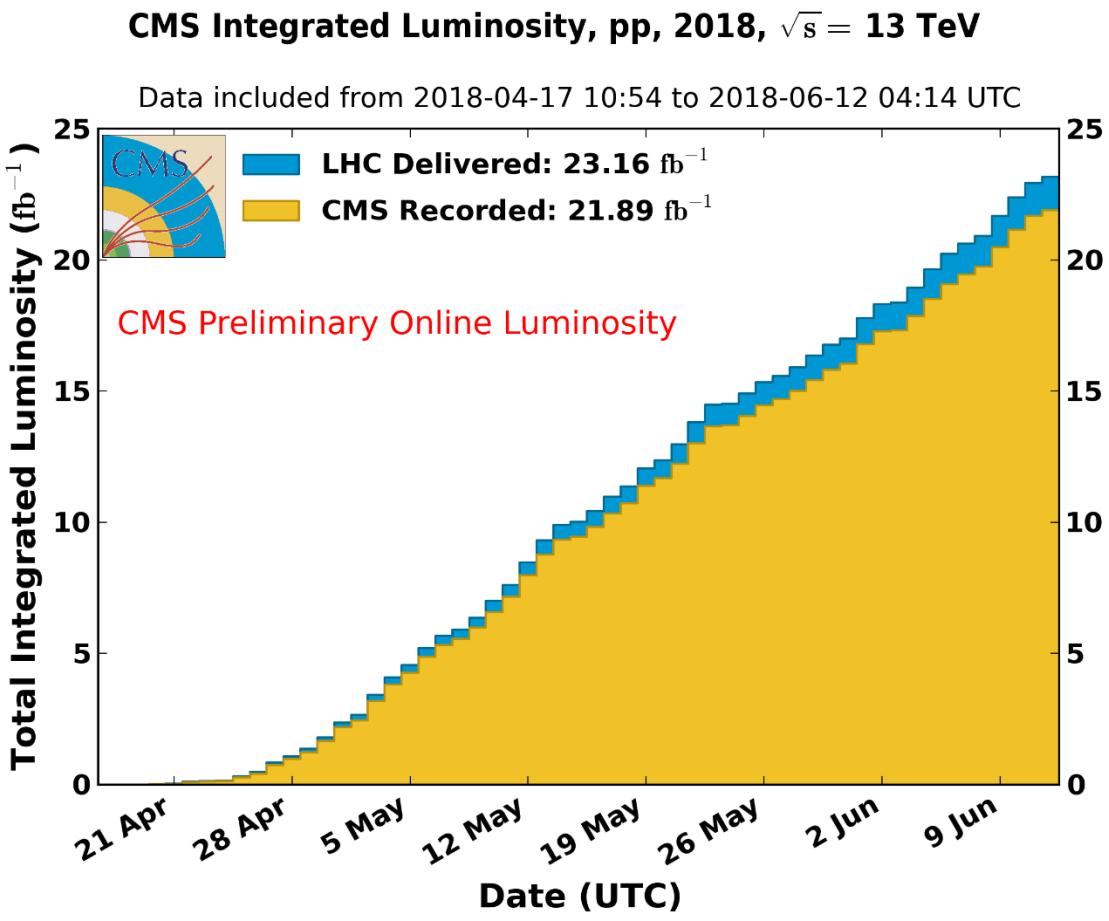
2016: Max inst. Lumi. 15.30 Hz/nb

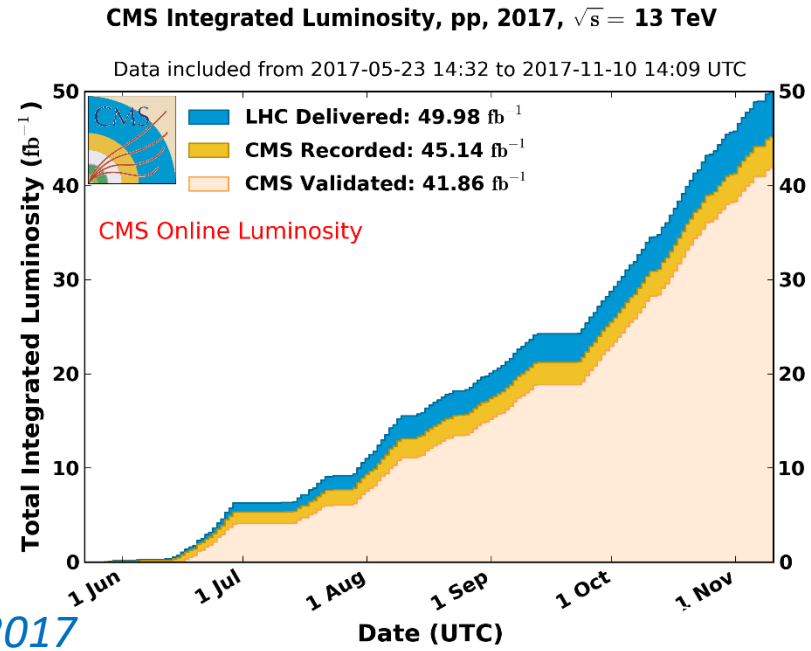
Run II: CMS data & operation in 2018

CMS is running very well

- very fast commissioning of CMS after the intervention during the technical stop
- very good recording efficiency (>94%)
- Deadtime negligible also at the highest luminosity (about 2x than design)
- Fraction of active channels high and stable

2018

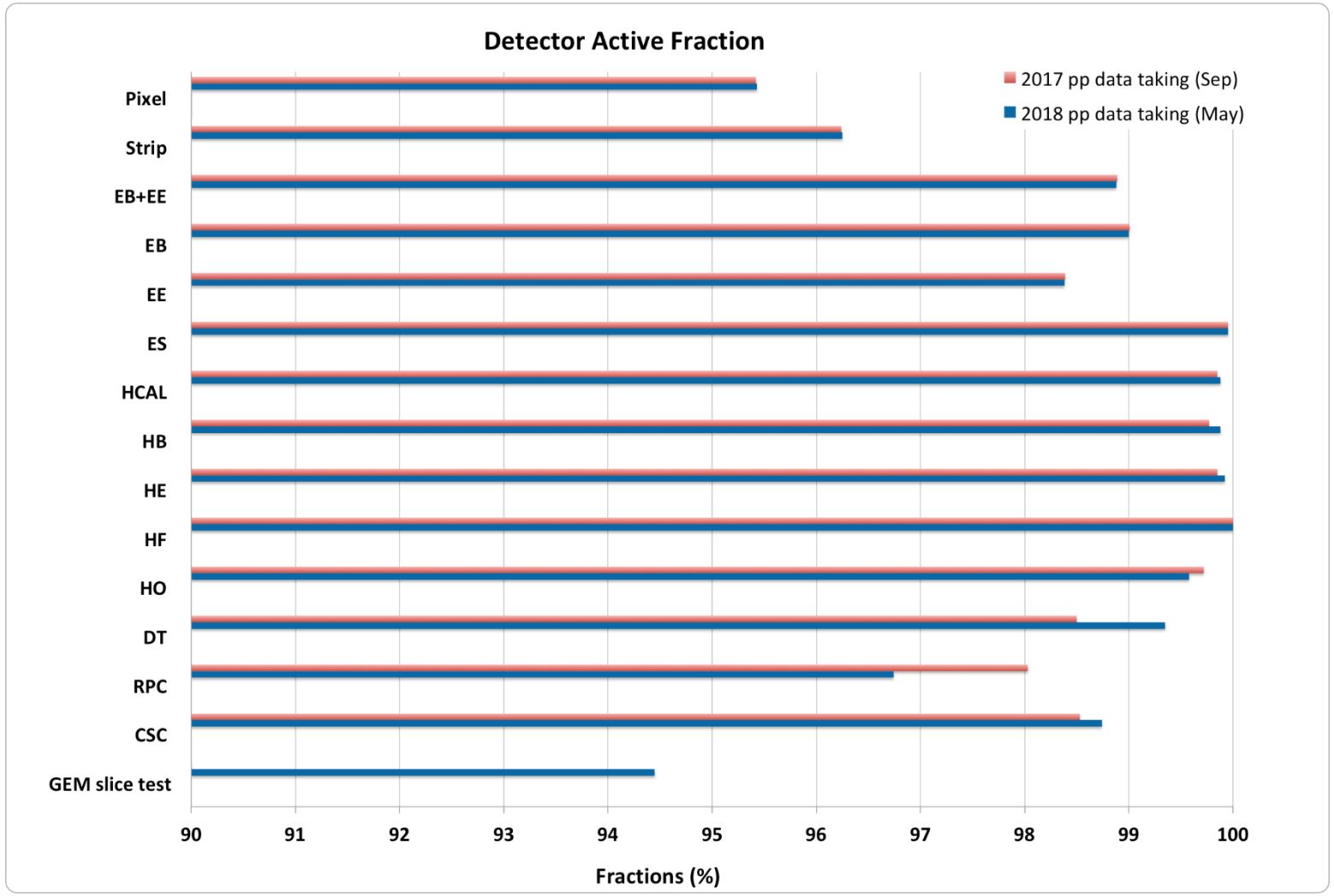




2017

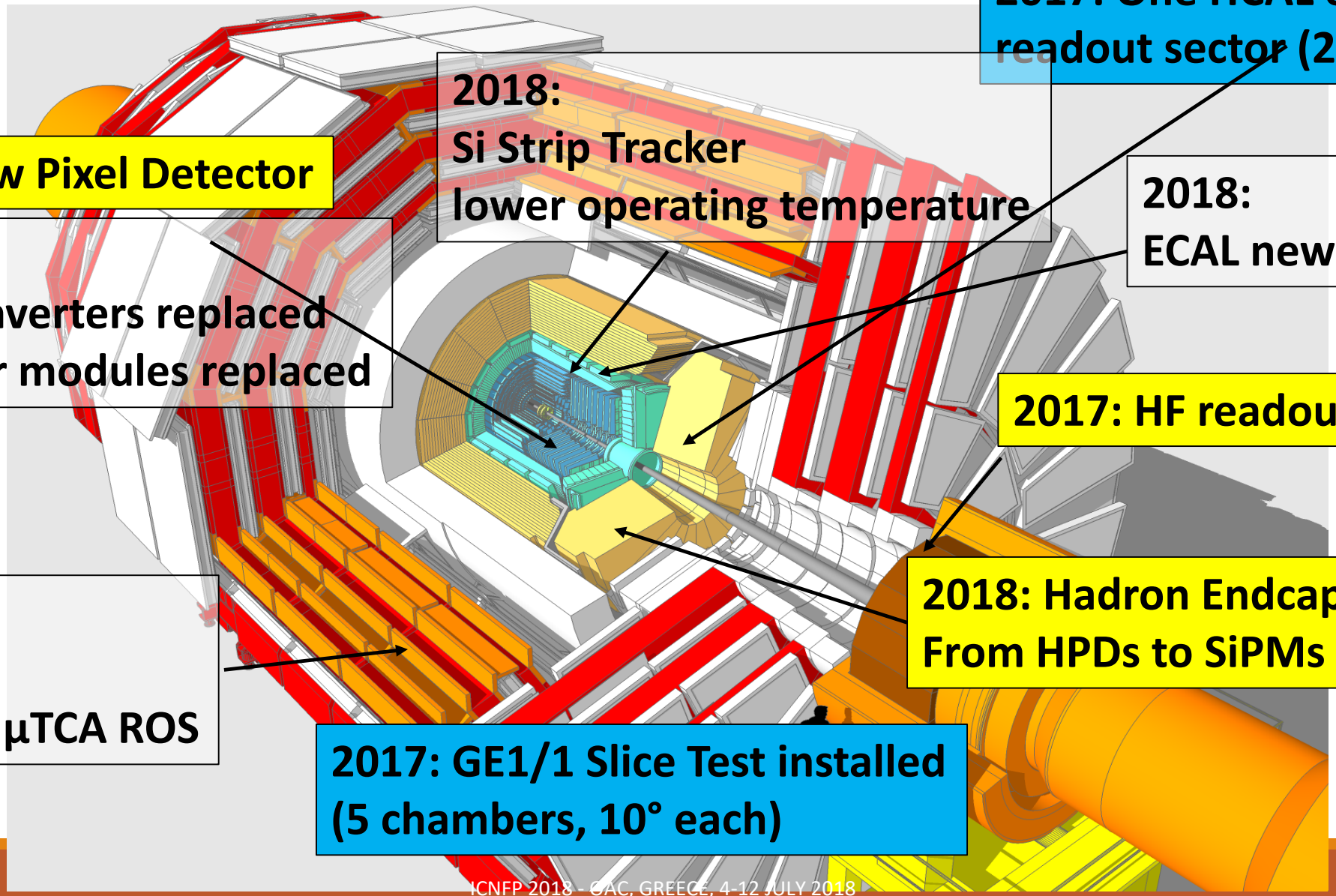
2016:
CMS Recorded
37.76 fb^{-1}

Run II: CMS Active Fraction in 2018



Current fraction of active channels in 2018 datataking is high and stable
(picture: May 2018 compared to Sept 2017)

CMS detector: 2017 & 2018 changes



2017: One HCAL endcap readout sector (20°) upgraded

2018:
Si Strip Tracker
lower operating temperature

2017: New Pixel Detector

2018:
ECAL new DAQ links

2018:
DCDC converters replaced
six sensor modules replaced

2017: HF readout upgraded

2018: Hadron Endcap Calorimeter
From HPDs to SiPMs in endcaps

2018:
Drift Tubes
from VME to µTCA ROS

2017: GE1/1 Slice Test installed
(5 chambers, 10° each)

Upgraded Tracker: Silicon Pixel

MOTIVATION

Dynamic inefficiencies in Pixel observed during Run I

- Dead time at high instantaneous luminosity caused by limited size of readout bandwidth
- Scale: about 5% inefficiency at PU 40 in Barrel Layer 1

Installed 28th Feb – 9th March 2017
Ready 24th March 2017

UPGRADED PIXEL

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

✓ **Increased tracking efficiency**

✓ **Reduction of fake rate**

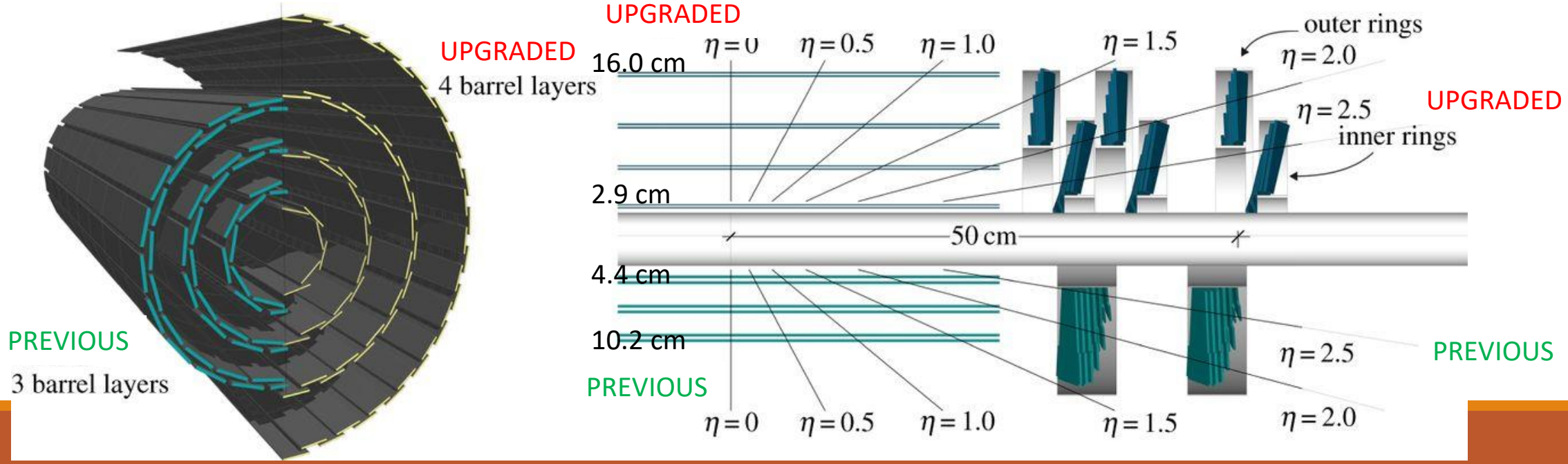
✓ **Improved impact parameter resolution**

Upgraded Tracker: Silicon Pixel

Installed 28th Feb – 9th March 2017
Ready 24th March 2017

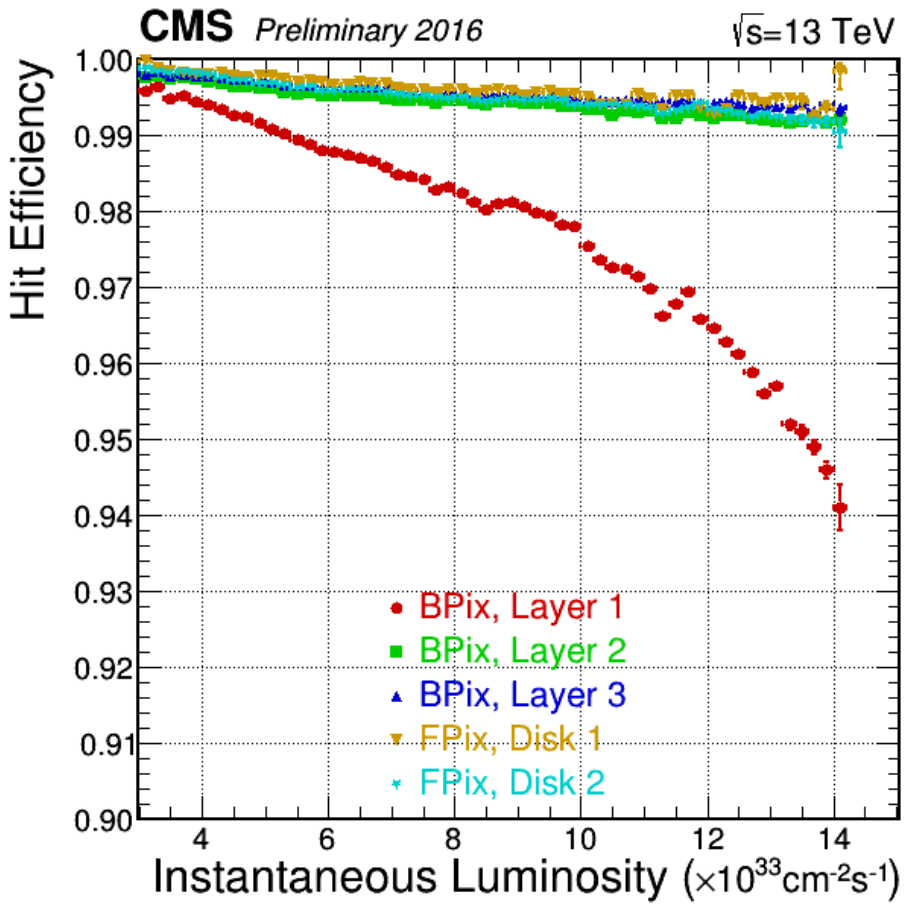
- **Full replacement of Pixel**
  - One additional barrel layer
  - One additional forward disk
  - Innermost layer closer to Interaction Point
  - Outermost layer further from Interaction Point

- **New readout chips (ROCs) with reduced data loss at higher collision rates of Phase I**
  - 40 MHz analog (old) → 160 Mbit/s (digital)
- **Higher bandwidth readout electronics (factor 8)**
  - 40 Mbit/s (old) → 320 Mbit/s (new)
- **DC-DC power converter to allow reuse of existing fibers and cables**

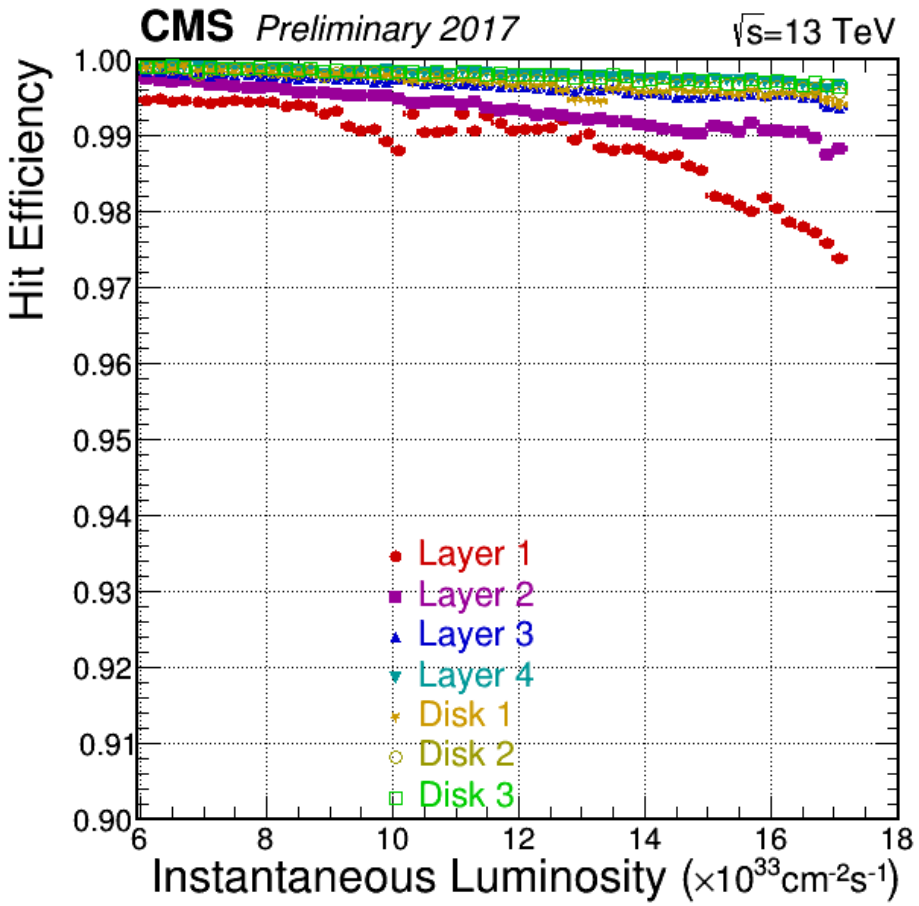


Upgraded Tracker: Silicon Pixel

***Run I** dynamic efficiency (2016)*



***Run II** dynamic efficiency (2017)*



$\gtrsim$ **98%**

Upgraded Tracker: Silicon Pixel

Late 2017 - Early 2018

In late 2017 about 5% of the DC/DC power units failed

- marginal impact on 2017 data quality

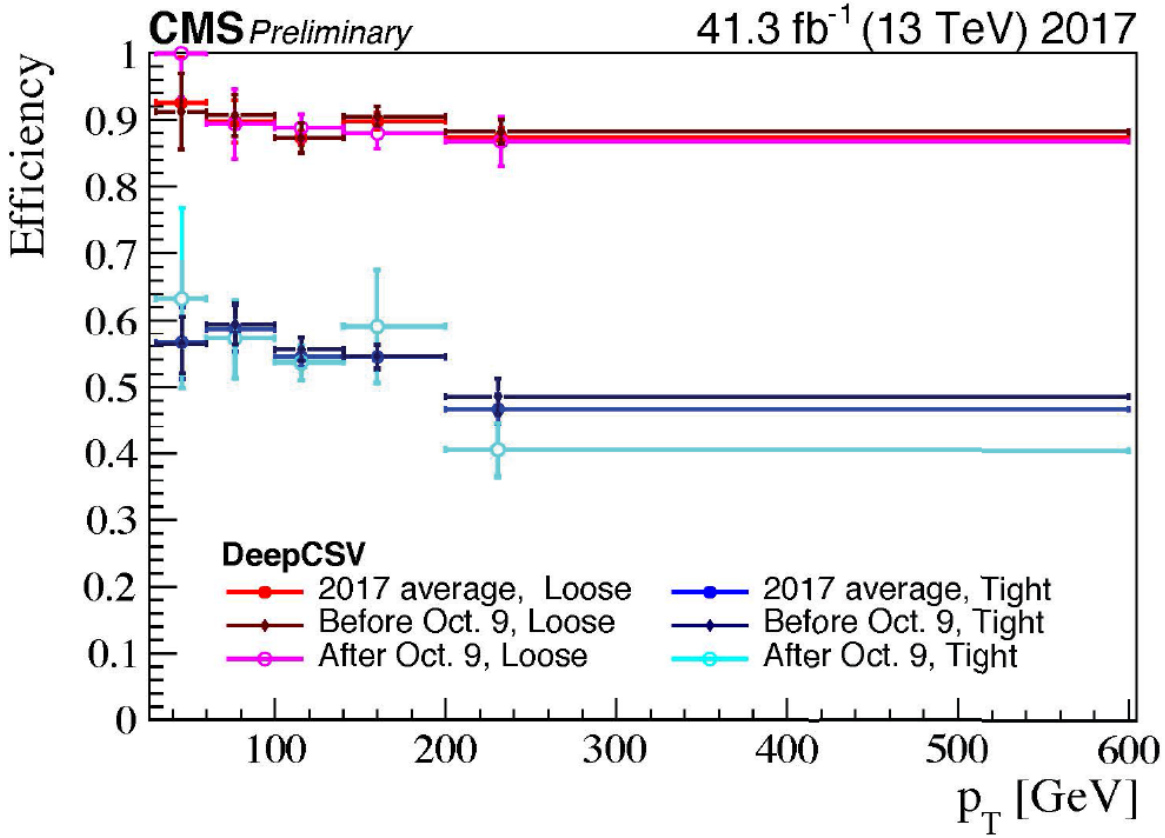
During 2017-2018 technical stop all the 1200 DC/DC modules have been replaced

- the pixel detector has been removed, opened and reinserted
- Also 6 sensor modules replaced in the barrel layer (damaged as side effect)

Presently: fraction of active channels is about 96%

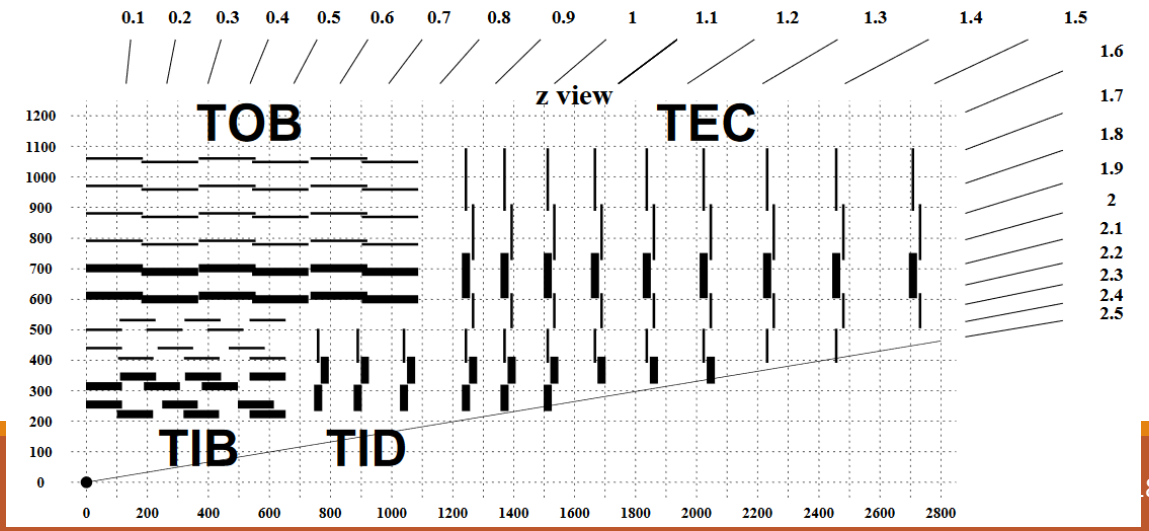
- **As high as beginning 2017**
- **No DC/DC converter failure so far in 2018**

b-tagging efficiency in 2017



Tracker: Silicon Strips

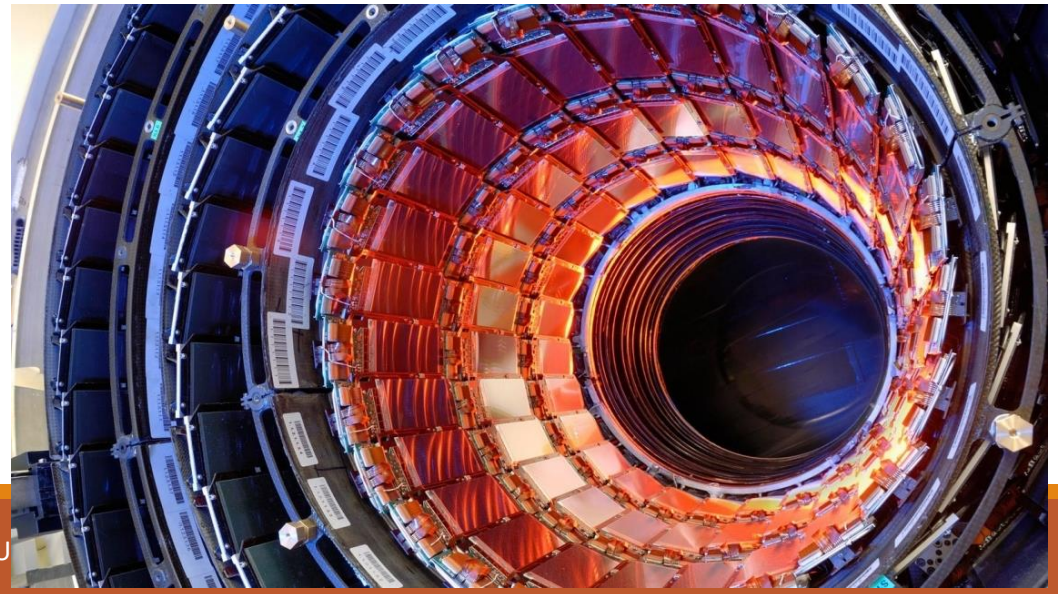
- 200 m^2 of p-in-n type silicon strip sensors (p-type strip implants in n-type bulk)
- Strip pitches: 80 µm to 205 µm
- Strip lengths: 10 cm to 20 cm
- Thickness: 350 or 500 µm
- Provide 2D resolution, using stereo layers associating back to back 2 microstrip detectors (relatve angle of 100 mrad)
- Analog readout



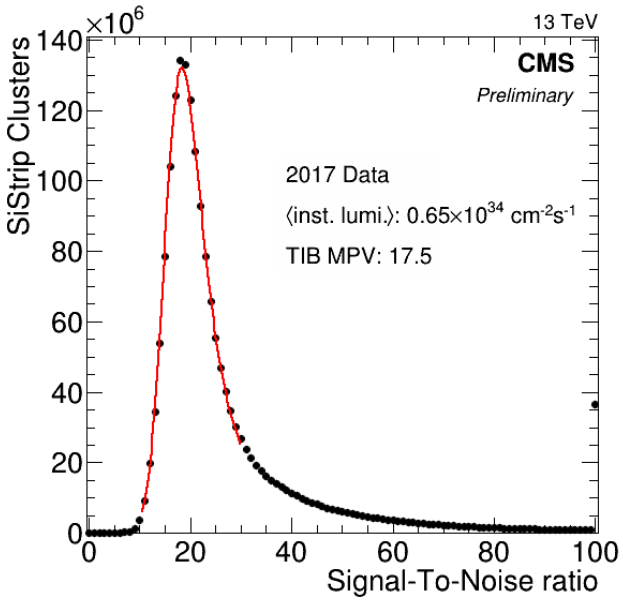
UPGRADES:

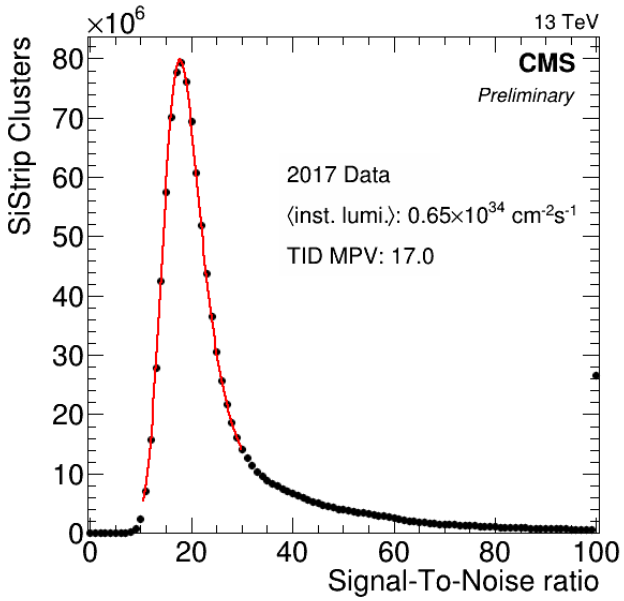
Cold provided for Run 2 to mitigate long term damages (2017)

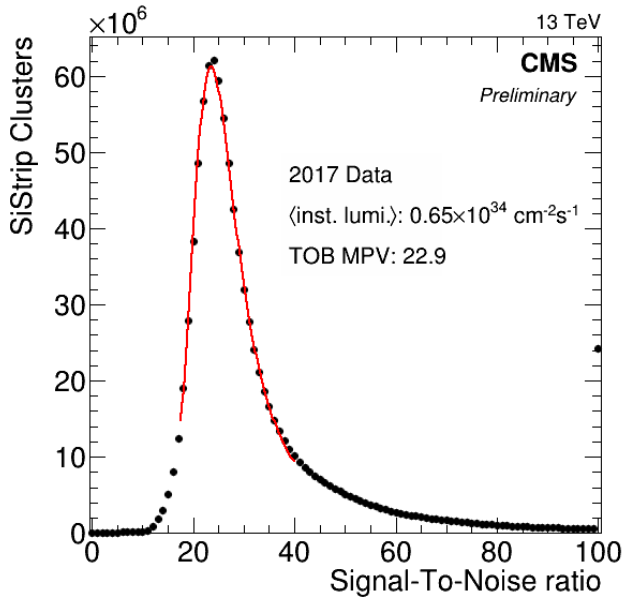
- All condensation issues addressed
- During Run I (2010-2013) it operated at +4 °C using fluorocarbon cooling system
- In Run II currently running at **–20 °C**

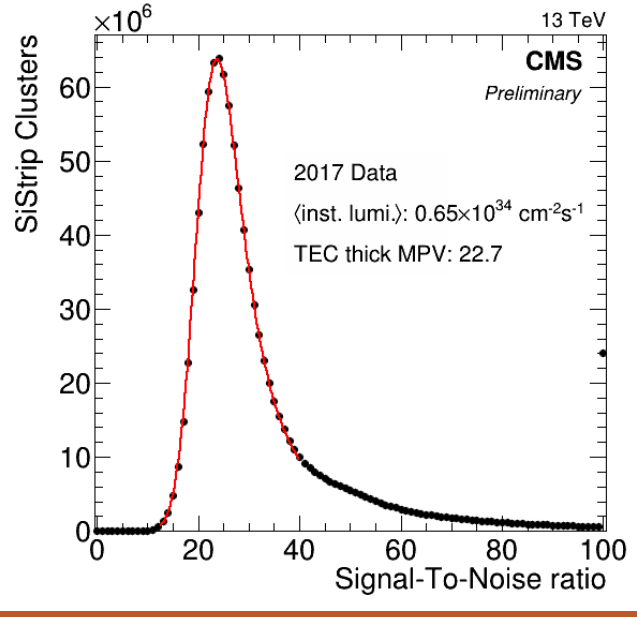


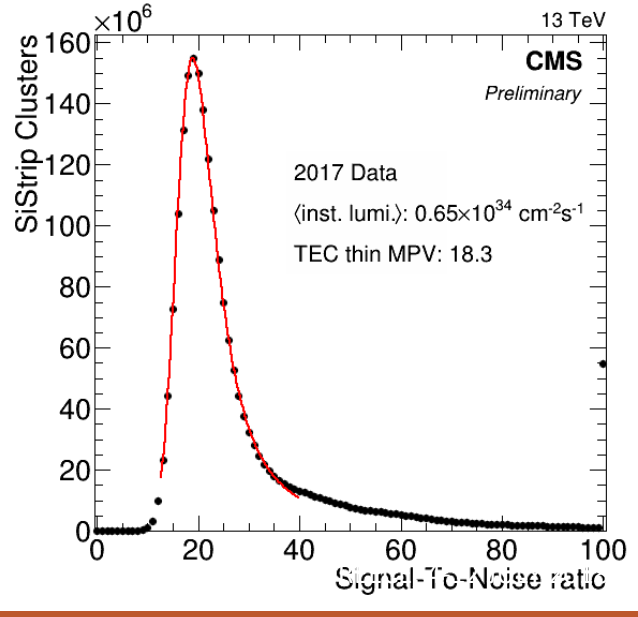
Tracker: Silicon Strips







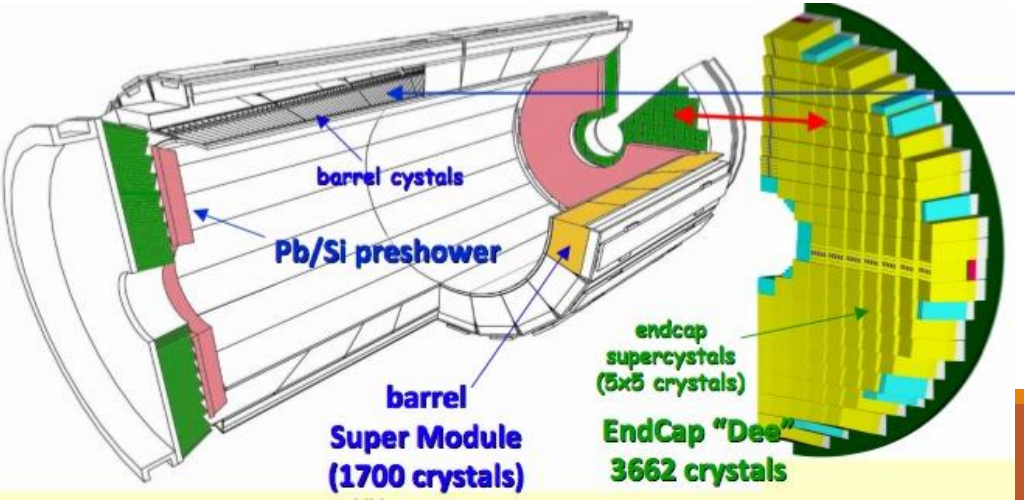




- ✓ Very good status from the beginning of 2017 data taking
  - Good signal/noise ratio

Electromagnetic Calorimeter

- Lead tungstate ($PbWO_4$) crystals
  - Density: 8.3 g/cm^3
  - Molière radius: 2.2 cm
  - Radiation length: X_0=0.89 cm
- Homogeneous calorimeter
- High granularity and Compact calorimeter
- Fast scintillation response
  - ~80% of the light emitted in 25 ns
- Excellent time resolution



BARREL

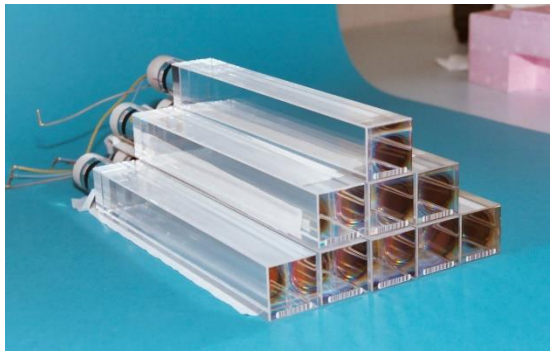
- $|\eta|<1.48$
- ~61K crystals in 36 SuperModules (SM)
- 2x2x23 cm^3 covering 26 X_0
- Photodetector: Avalanche Photo Diodes (APD)

ENDCAP

- $1.48<|\eta|<3.0$
- ~15k crystals in 4 Dees
- 3x3x22 cm^3 covering 24 X_0
- Photodetector: Vacuum Photo Triodes (VPT)

PRESHOWER

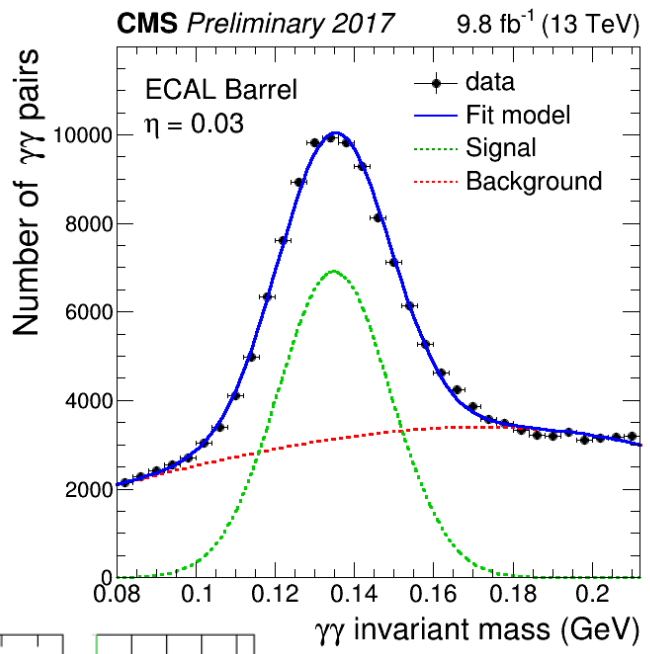
- $1.65<|\eta|<2.6$
- ~137k silicon strips in 2 planes per endcap
- $3X_0$ of lead radiator

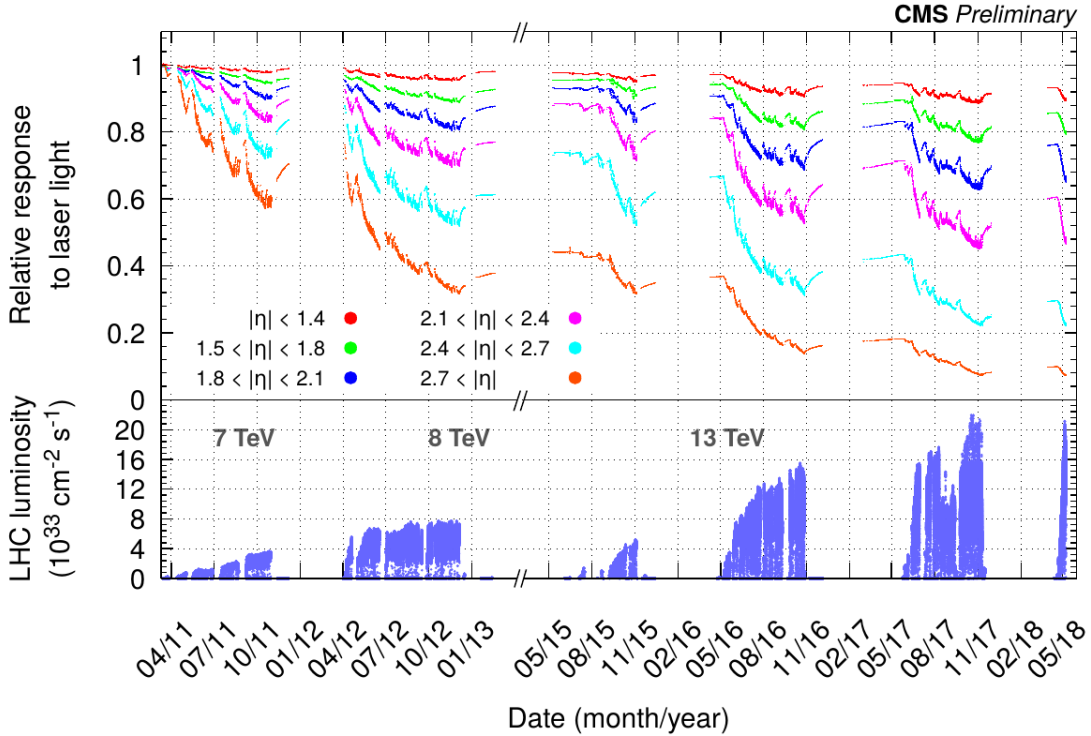


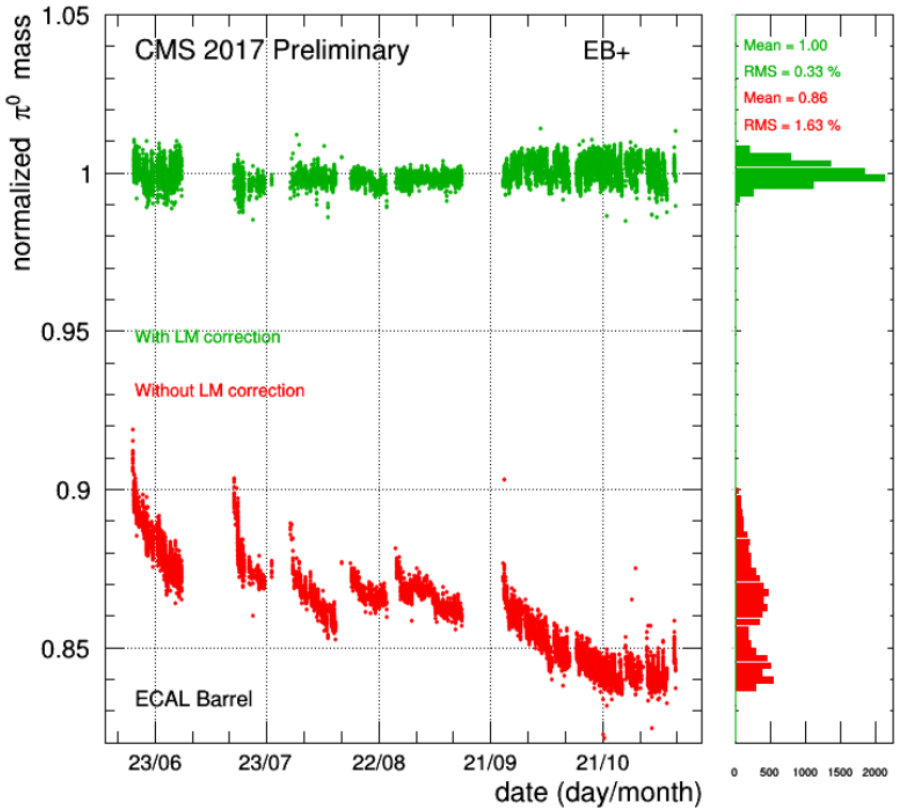
Electromagnetic Calorimeter

- Channel response changes with radiation
  - short term (in-fill) variations
    → inst. luminosity dependent
  - long term drifts
    → integrated luminosity dependent
  - Monitored with laser light every 40 min
    → Corrections in trigger and offline

- $\pi_0 \rightarrow \gamma\gamma$ decays as prompt feedback
  - monitor the effectiveness of the laser monitoring (LM) calibration
  - inter-calibrate the energy of ECAL crystals







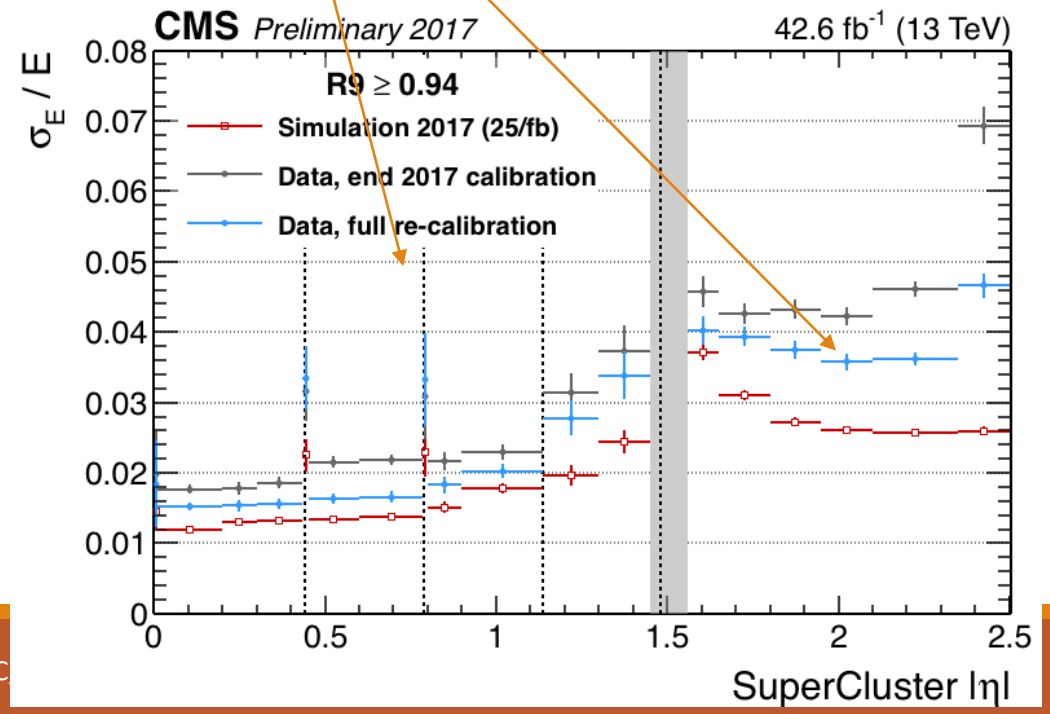
Electromagnetic Calorimeter

ALIGNMENT

- Relative ECAL-tracker precision meets the ECAL alignment goals or electron ID and di-photon resonance reconstruction
  - 3×10^{-3} (ϕ units) in the barrel
  - 6×10^{-3} (ϕ units) in the endcaps
  - 1×10^{-3} (η units) in the barrel
  - 3×10^{-3} (η units) in the endcaps
  - goal: 20×10^{-3} in ϕ, 4×10^{-3} in η units
- Preshower aligned within the resolution of the silicon strips (±0.055 cm)

ENERGY RESOLUTION

- affected by amount of material in front of the ECAL
- degraded close to the eta cracks between ECAL modules
- significantly improved by **dedicated calibration using the full 2017 dataset** (blue) w.r.t. the EOY 2017 calibration (grey)
  - EOY 2017 calibration corrects only time dependent effects



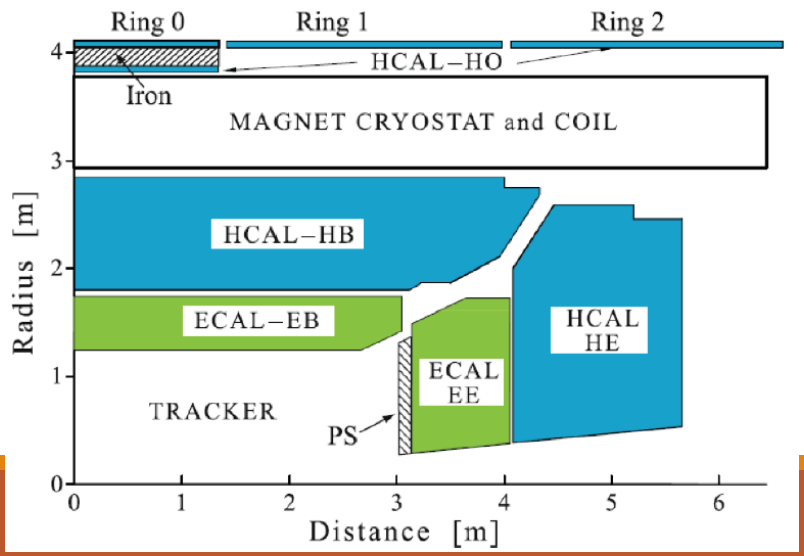
Hadronic Calorimeter

BARREL $0 < |\eta| < 1.3$

- Sampling calorimeter brass absorber/plastic scintillator tiles
- Hybdrid photo-detector (HPD) readout

Outer (HO)

- Outside the solenoid
- Tail catcher
- Scintillator layers
- SiPMs readout (since LS1)



UPGRADED

HADRON FORWARD (HF)

$2.9 < |\eta| < 5 \quad |z| = 11\ m$

- Cherenkov light from scintillating quartz fibers, steel absorber
- Upgraded readout: **new PMTs with dual readout (2017) and upgraded electronics**

✓to better discriminate real hit from muon hitting the PMT window

ENDCAP (HE)

- **HPDs completed replaced with SiPM (2018)**

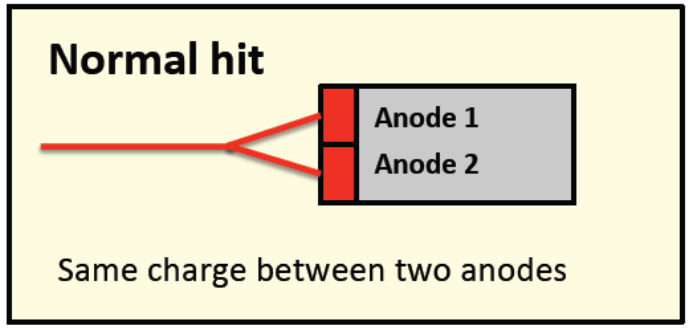
✓Finer longitudinal segmentation is possible

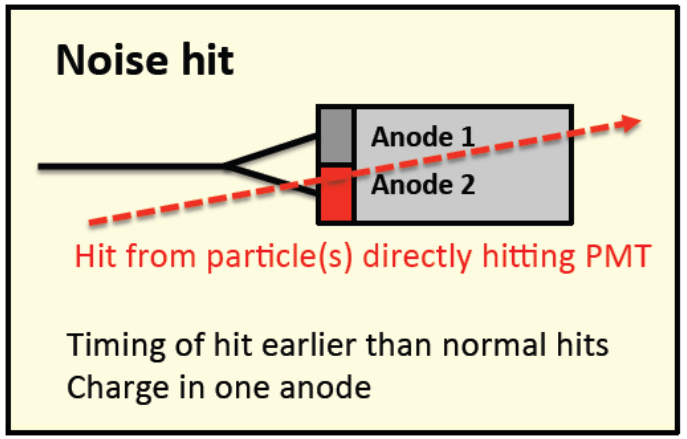
✓Photo-detection efficiency increased by 2.5x

✓Source of coherent noise eliminated

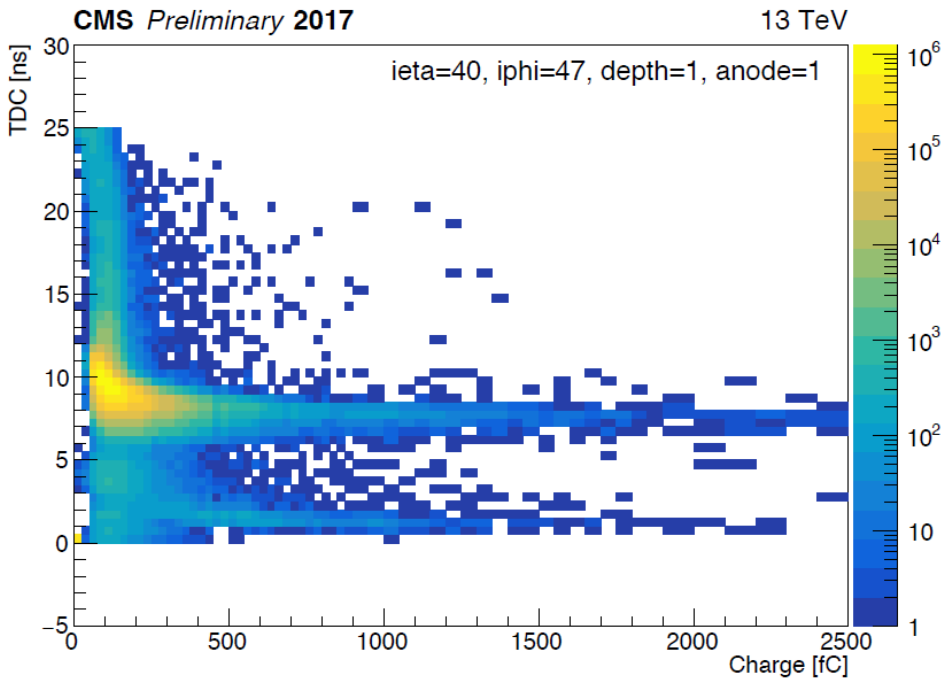
✓Much improved uniformity of response

Upgraded Hadron Forward

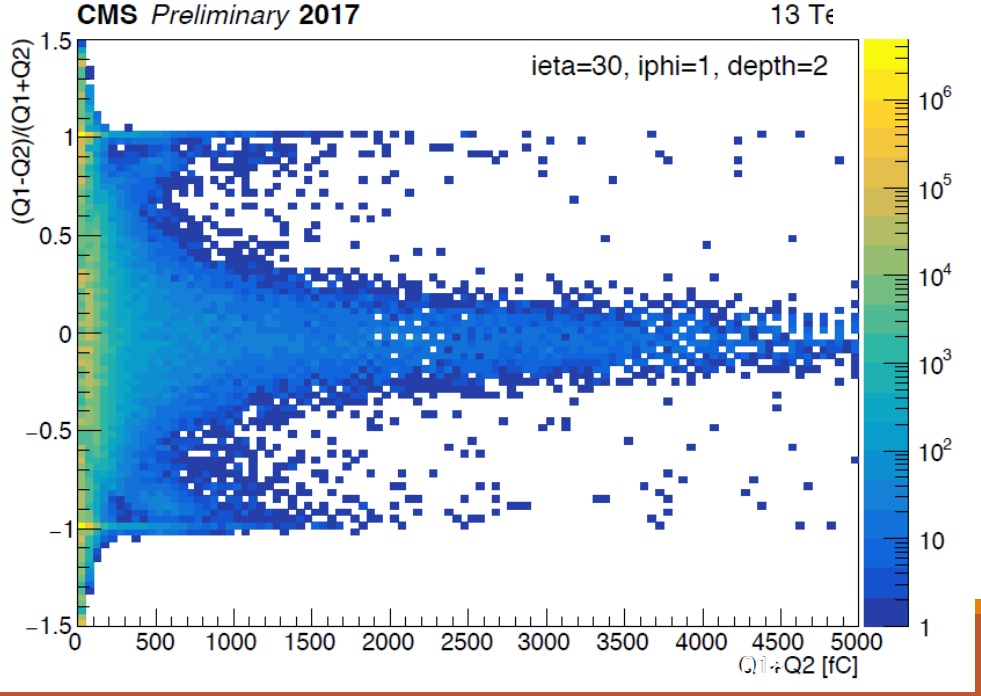




- Faster hits (< 5ns) come from particles hitting directly the MPT
- Normal hits are around 8 ns



TDC vs charge of anode 1



- Contributions around ±1 are not consistent with hits in fibers

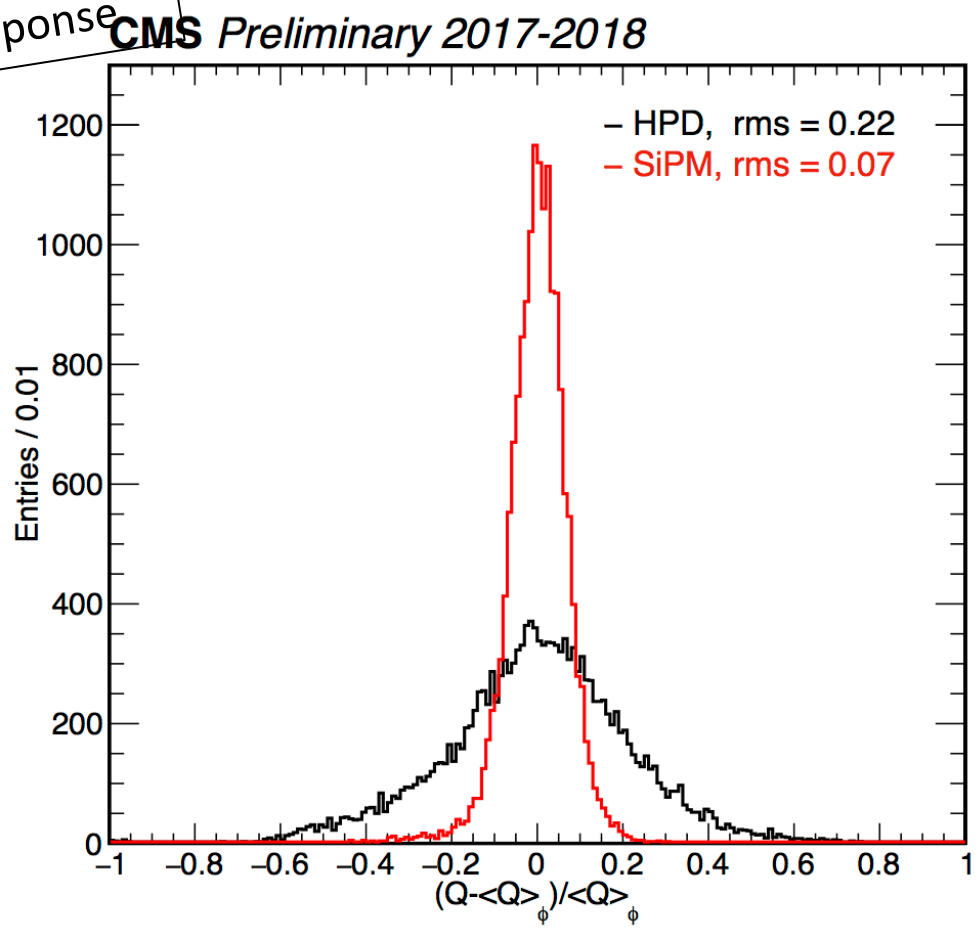
Charge asymmetry vs total charge in 1 channel

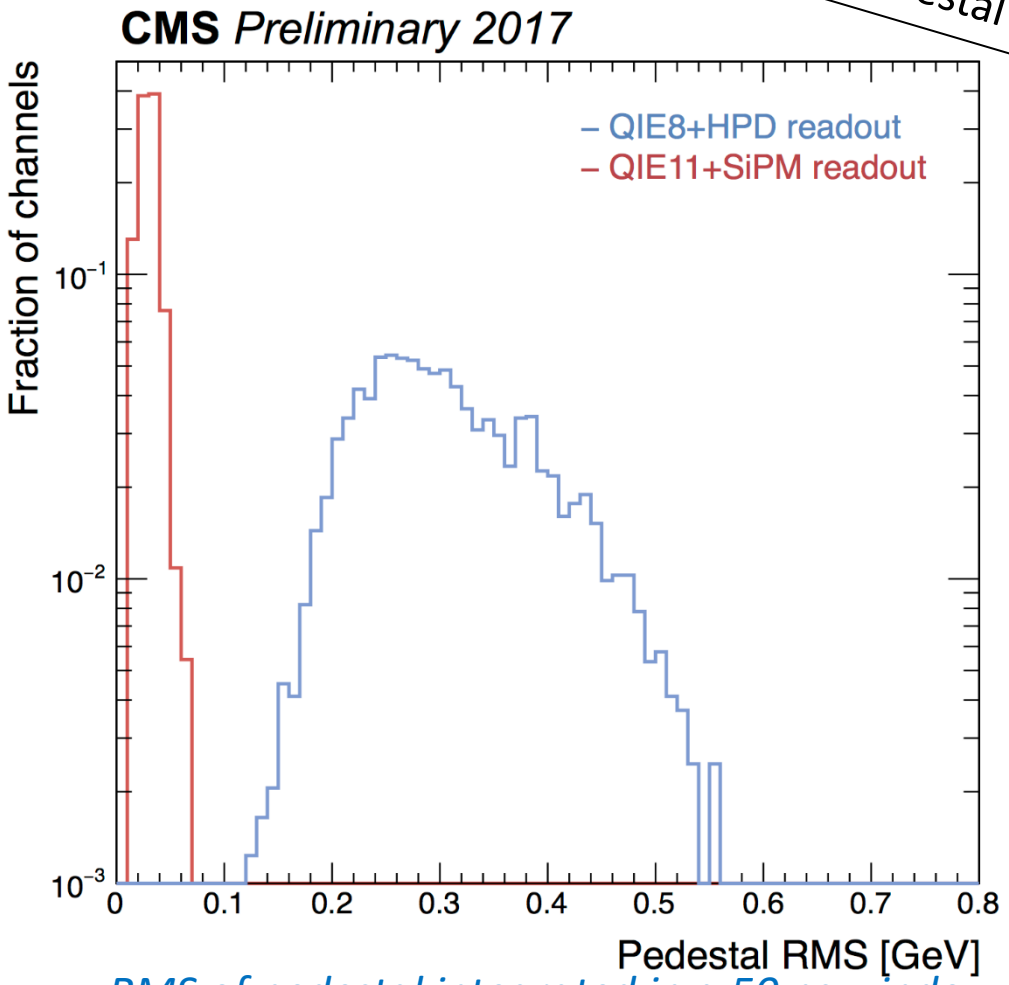
Upgraded Hadron Endcap

Much improved uniformity of the raw response

Comparison HPD vs SiPM

Much smaller pedestal RMS





Signal from ^{60}Co (wire-source inserted into tubes embedded in HE megatiles) measured at same eta and depth with different readout.

RMS of pedestal integrated in a 50 ns window.

Muon System

CONFIGURATION

- Drift Tubes (DTs) in the barrel ($|\eta|<1.2$) and Cathode Strip Chambers (CSCs) in the endcaps ($1.0<|\eta|<2.4$)
  - precision position measurements and trigger
- Resistive Plate Chambers (RPCs) in barrel and endcaps up to $|\eta|<1.8$
  - coarse position measurements and redundant trigger

CSC station ME4/2 and RPC station RE4/2 RE4/3 added in 2015

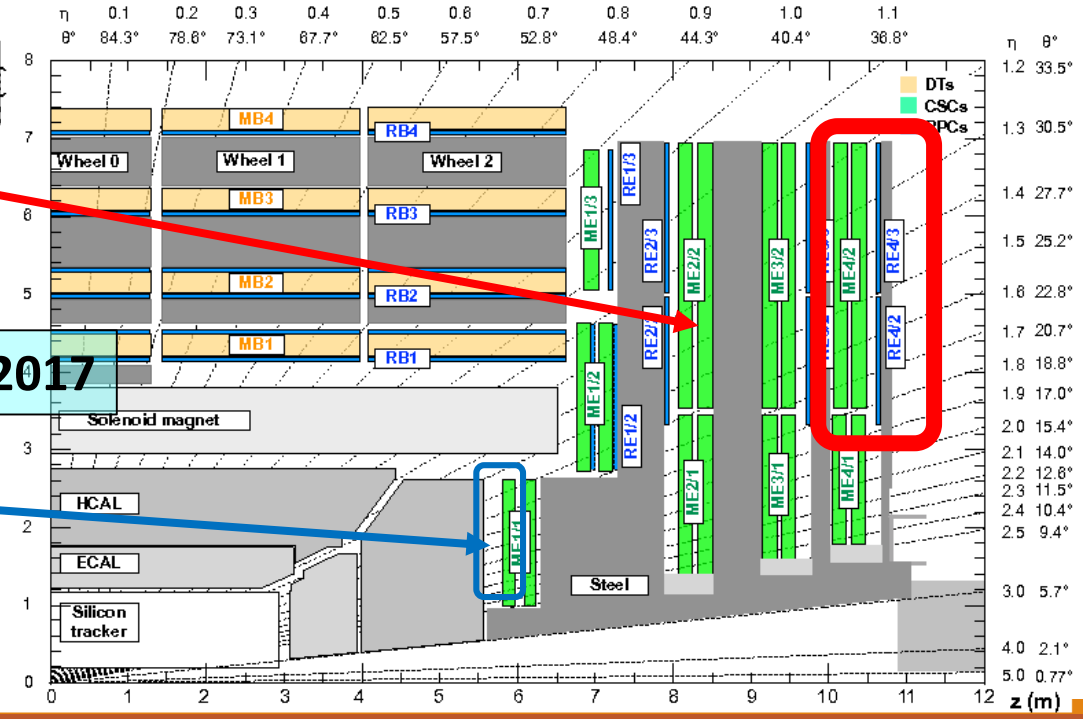
- $1.2<|\eta|<1.8$
- Increased system redundancy →L1 trigger track met more often →trigger quality cuts with reasonable rate at higher luminosity

Gas Electron Multiplier (GEM) station GE1/1 Slice Test added in 2017

- $1.6<|\eta|<2.2$ in the negative endcap only
- Five chambers covering 50° in total
- As a test before the full installation (foreseen LS2)
- Will work with CSC to reduce L1 soft muons trigger rates for HL-LHC

GOALS

- Efficient μ identification
- Improve high-p_T μ momentum resolution
- Robust stand-alone μ-trigger for BX assignment



DT "new" Local Reconstruction

RUN I

- segments were formed by a combinatorial pattern recognition
- assuming an in-time muon through a chamber
- fitting the individual hits with a straight line

RUN II: MEAN-TIMER ALGORITHM

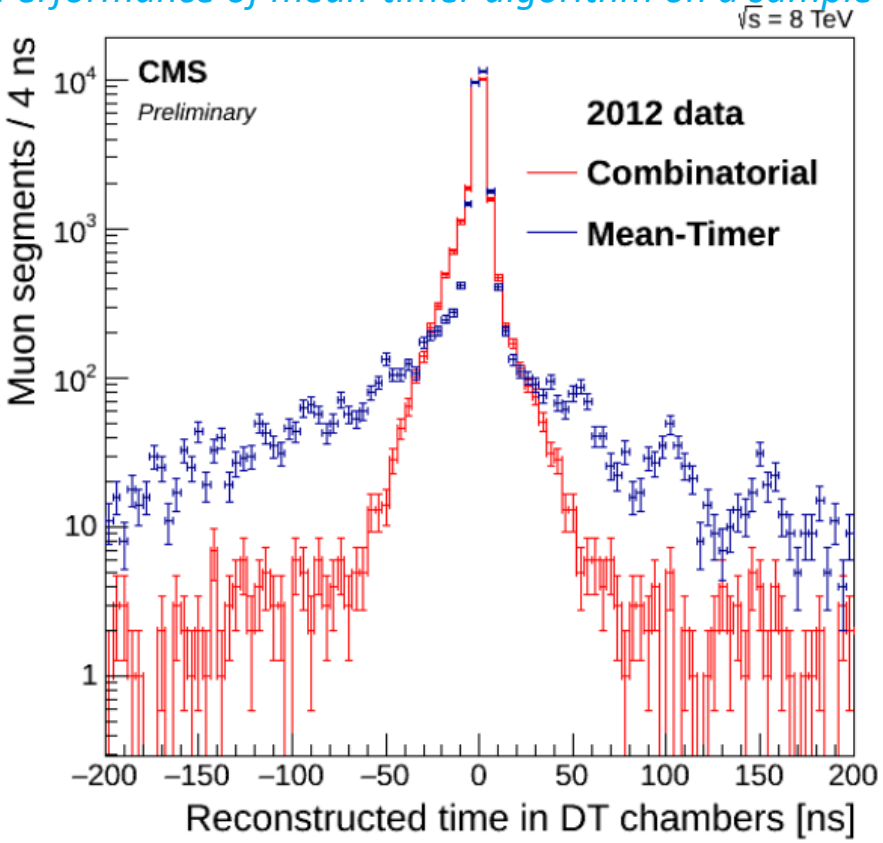
- The time of particle crossing is a free parameter in the segment fit
- Based on the DT geometry (half-cell staggered layers) and almost constant drift velocity

✓ Improved the **δ -ray rejection**
✓ Improved **position resolution**
✓ Excellent measurement of the segment time with **~2 ns resolution for in-time muons**
✓ It can be used to **identify out-of-time muons**, with time delays up to ~ 10 bunch crossings, and improve their rejection

✓ Improved **standalone muon performance** is relevant for searches of **exotic particles**
- ➢ Like massive particles decaying far from the interaction point
- ➢ Possibly delayed w.r.t. the time of the interaction

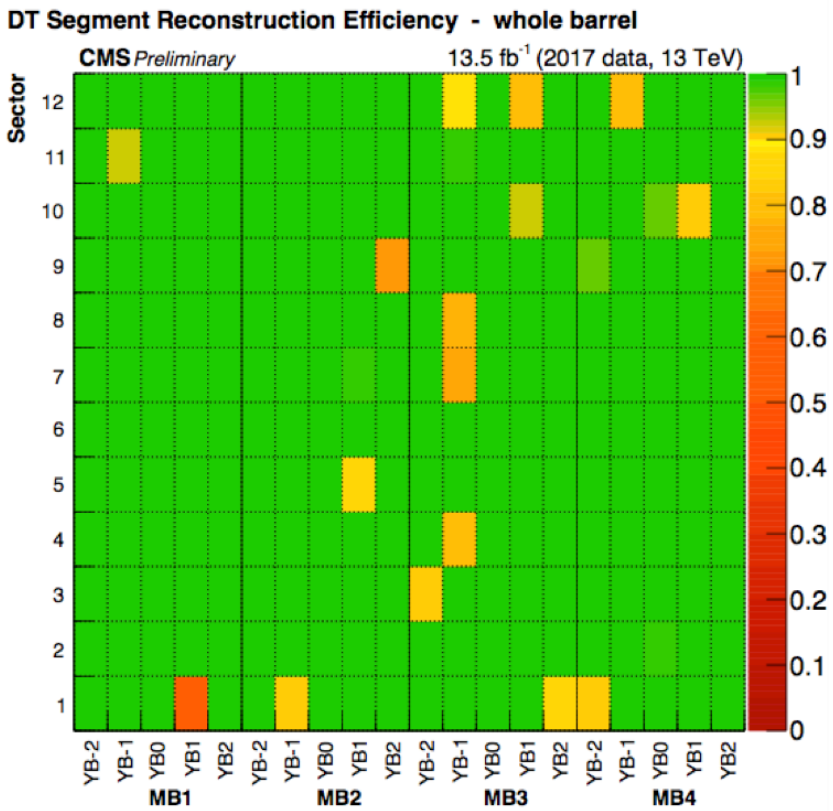
DT "new" Local Reconstruction

Performance of mean-timer algorithm on a sample of Run1 data



DT Segm. Reco. efficiency > 99%

Few exceptions due to known hardware problems.



- sharpening of the central peak due to in-time muons
- increased efficiency for out-of-time muons
- 50 ns spacing between BXs clearly visible on the right

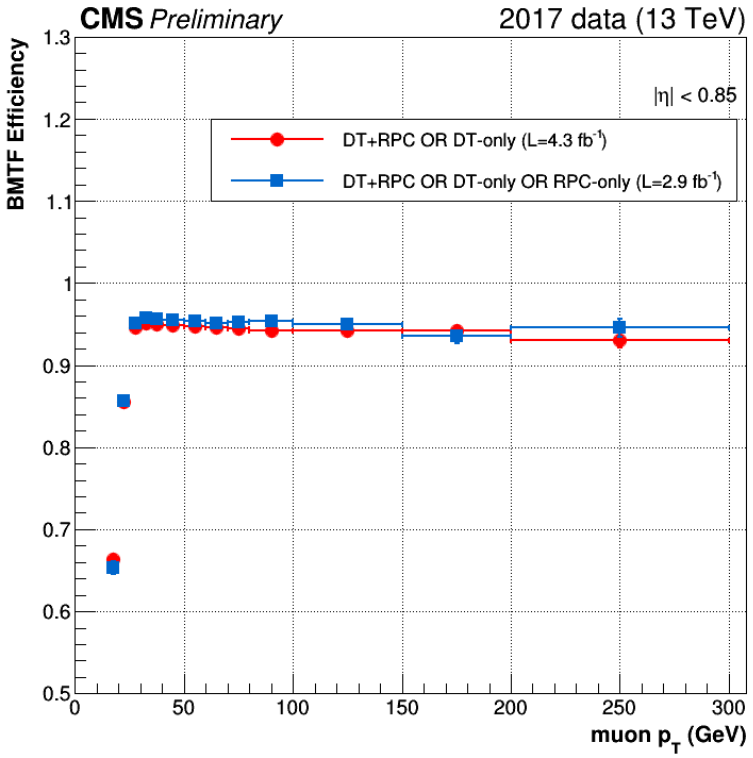
Resistive Plate Chambers (RPC)

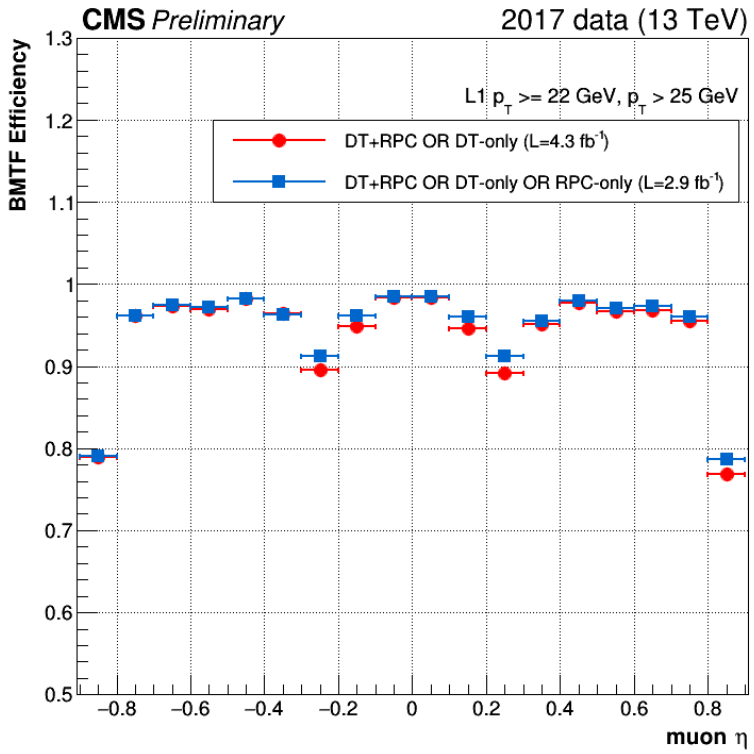
NEW: Since November 2017 **RPC-only segments** in L1 Barrel Muon Track Finder (**BMTF**) in MB1 and MB2
(2 RPC layers present per station)

- Before: DT+RPC segments, DT-only segments

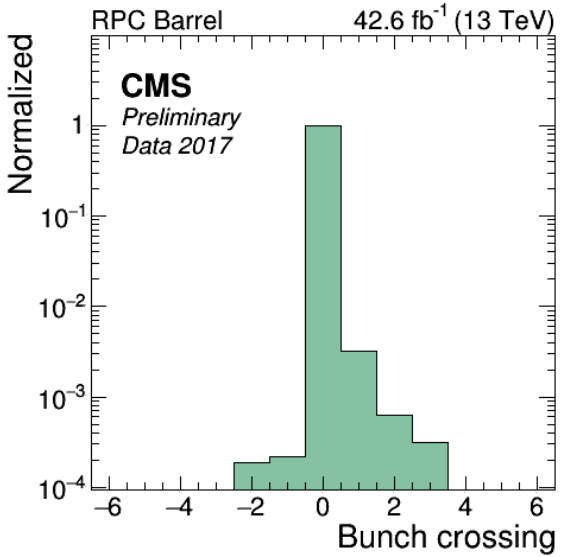
RPC-only segments:

- improve overall BMTF efficiency by ≈ 0.7%
- reduce the trigger rate by 3% for barrel muons with pT > 25 GeV (due to improved BMTF pT assignment)
- Improve efficiency in the space between wheel up to 2% (|η| ≈ 0.25, |η| ≈ 0.85)



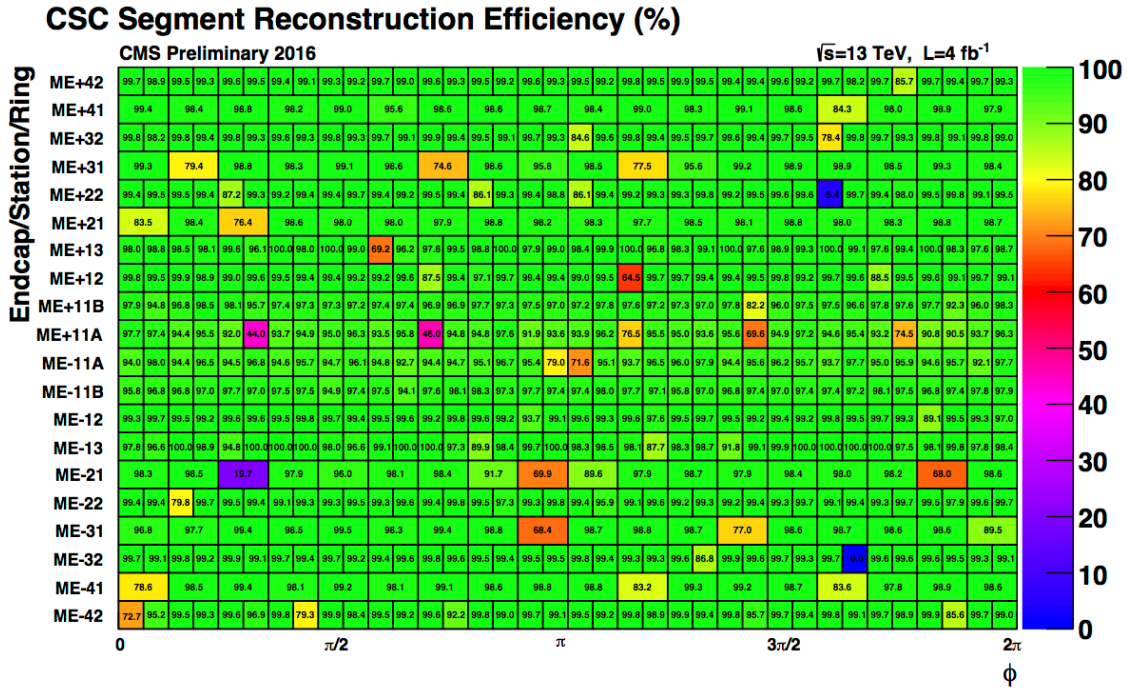


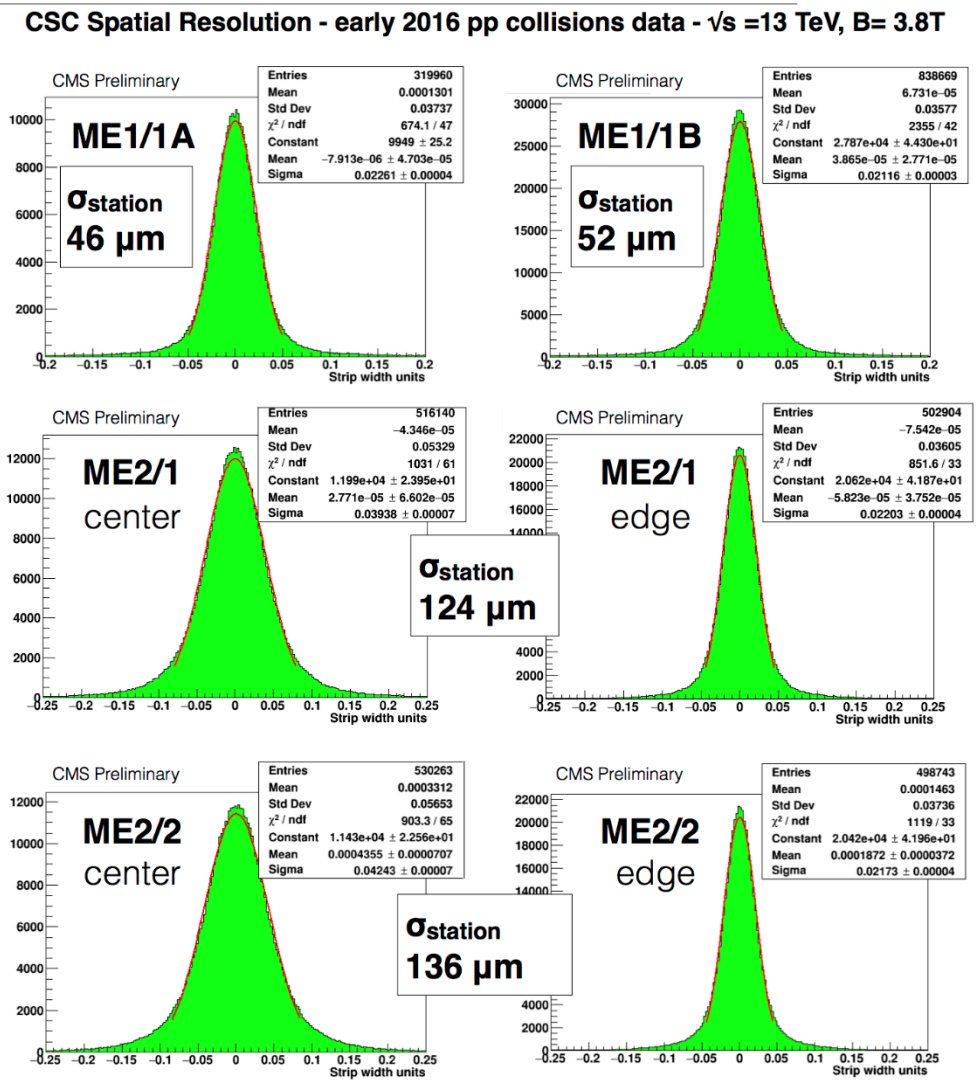
- No dependence on luminosity observed
- Stable RPC performance of efficiency, bunch crossing distribution, cluster size



Cathode Strip Chambers (CSC)

- Very high CSC efficiency <ε>~97%
- Very high CSC Trigger Primitive efficiency
- Stable time and spatial resolution within the design specifications of the system (changes related to atmospheric pressure)

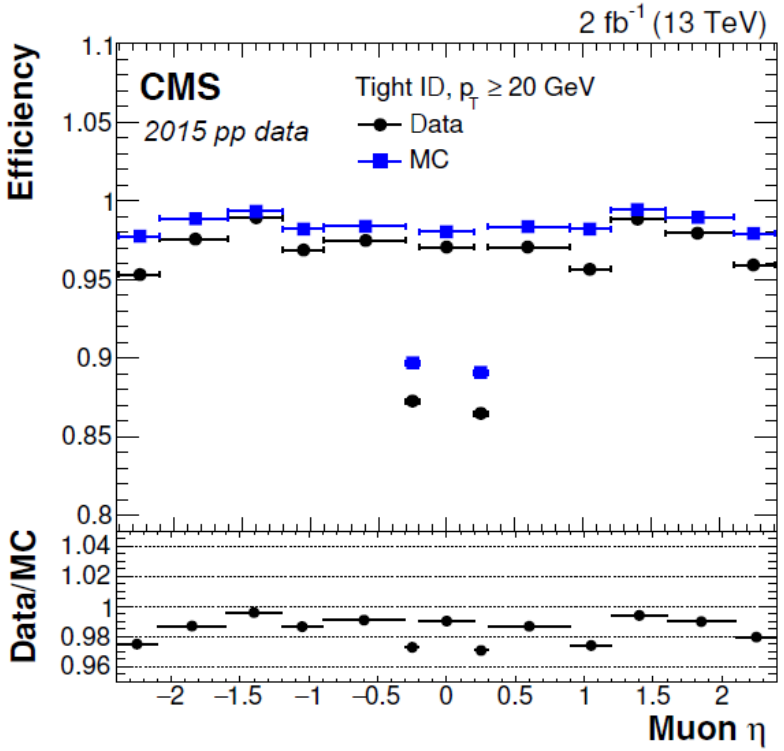




Better resolution obtained for hits is near the edge of a strip, than near the center

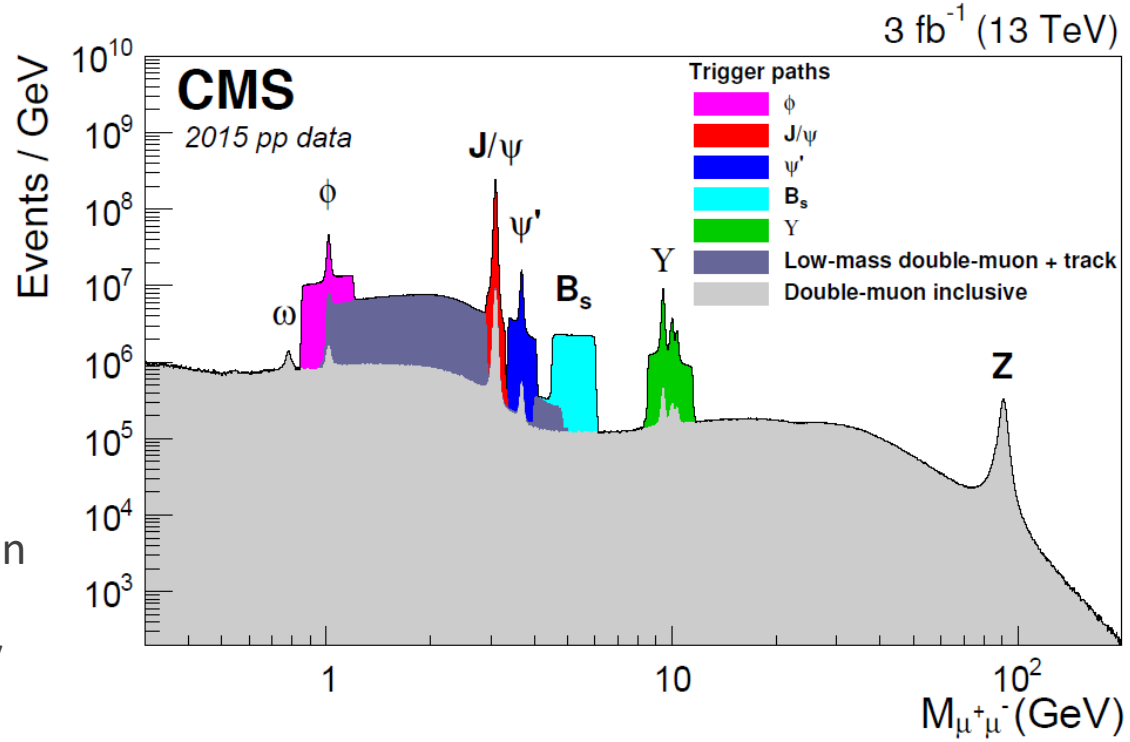
Overall Muon System

- Run II (2015 and later): many modifications to the muon system made before Run 2 to prepare for higher collision energy and luminosity
  - to detectors, HLT algorithms and offline reconstruction



Muon reconstruction and identification efficiency for tight muons with p_T>20 GeV

- Unambiguous identification of particles decaying into muons over a broad energy range



Invariant mass of $\mu^+\mu^-$ pairs selected by inclusive trigger on isolated double-muons

Compared to results collected in 2010
($\sqrt{s}$ = 7 TeV, inst. lumi. ~40 times lower)
muon performance in Run 2 is better than / or at least as good as in 2010

- Detector performance within the design specifications
- Muon reconstruction results well reproduced by Monte Carlo simulation

Summary

- Before and during Run 2 CMS has started some upgrades of its detectors and trigger system in order to get prepared for high luminosity
- Upgrades have started showing performance improvements
  - pixel dynamic efficiency, HF and HE upgrades, DT new local reconstruction, …
- So far, during Run 2 LHC has delivered collisions with peak luminosity $\sim 2\ 10^{34}\ cm^{-2}s^{-1}$ (Pile-Up > 55)
- CMS is running well with very good recording efficiency, high and stable fraction of active channels
- Let's take good data!