Performance of the silicon tracker of the CMS experiment during 2016 LHC data taking

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Outline

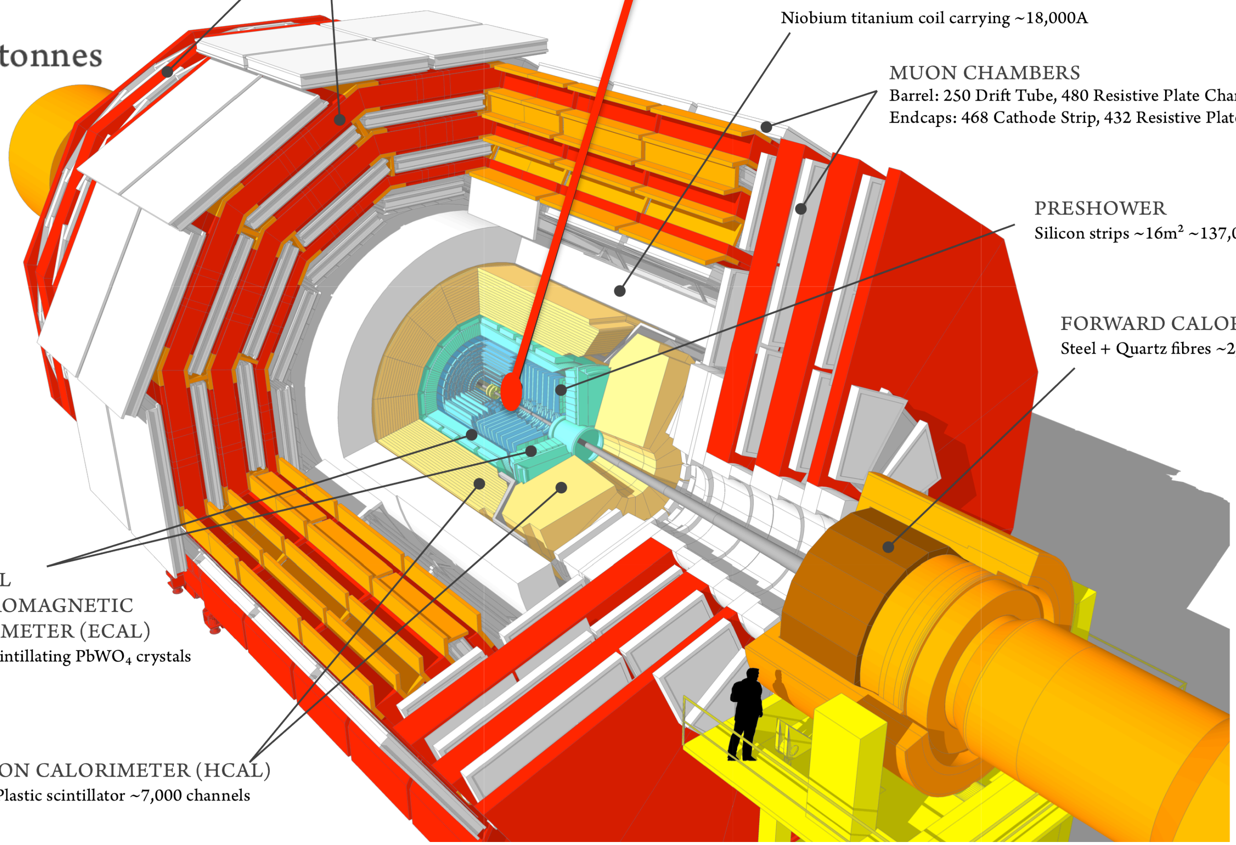
- The CMS detector and the tracker
- LHC data taking in 2016
- Pixel detector status and performance
- Strip detector status and performance
- Track reconstruction performance
- The pixel phase 1 upgrade and pixel pilot blades
- Summary and conclusions

The CMS detector in 2016

The **C**ompact **M**uon **S**olenoid

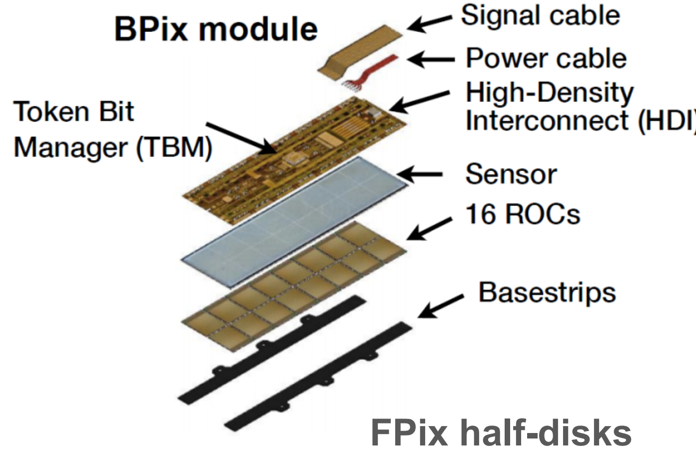
Total weight	: 14,000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T

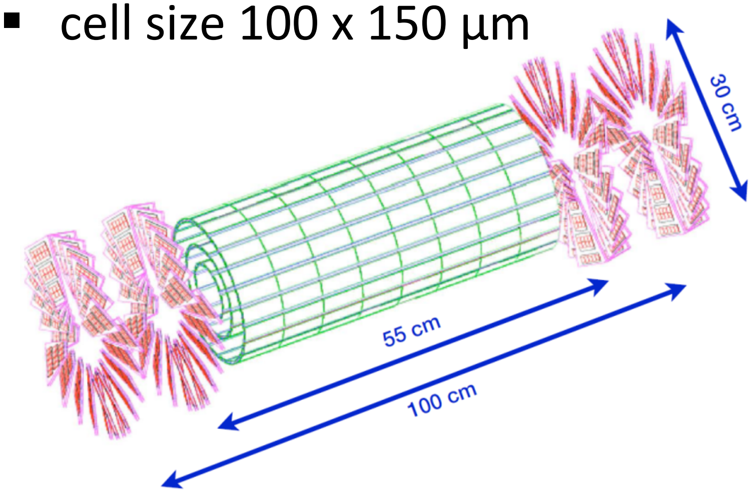
The silicon tracker, made of:
- pixels (inner part)
- microstrips (outer part)

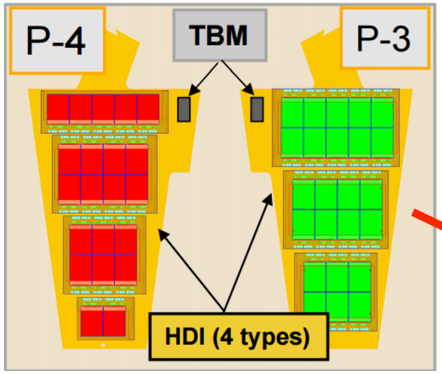


The silicon pixel detector in 2016 (has been upgraded in 2017)

- 3 Barrel layers (BPix) (4.4, 7.3, 10.2 cm from Interaction Point (IP))
- 2 Endcap disks on each end (FPix)
- 768 modules in BPix, 192 panels in FPix
- n+ implant on n bulk, 285 µm thickness
- 1 Read Out Chip (ROC) serves 52 x 80 pixels
- 48 + 18 M pixels
- cell size 100 x 150 µm

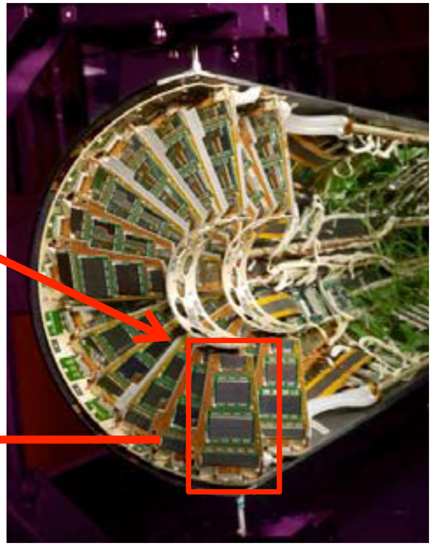






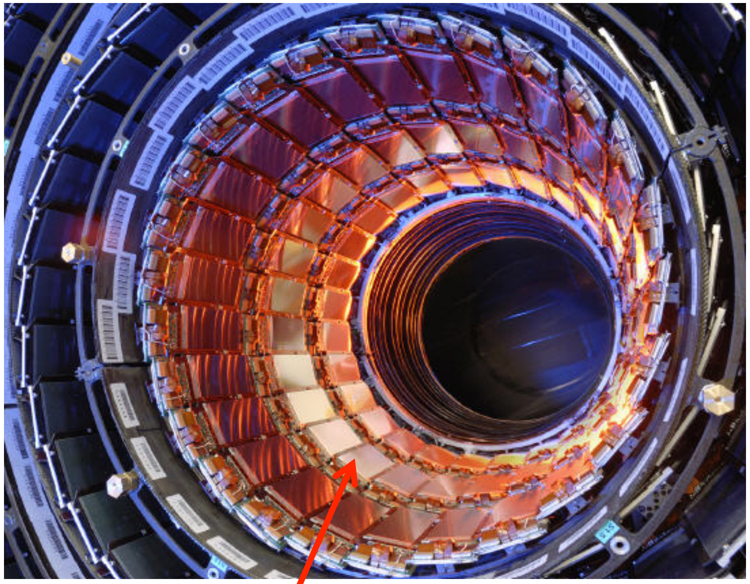
FPix "Blade" made of two counterposed **panels** with different ROC number and shape

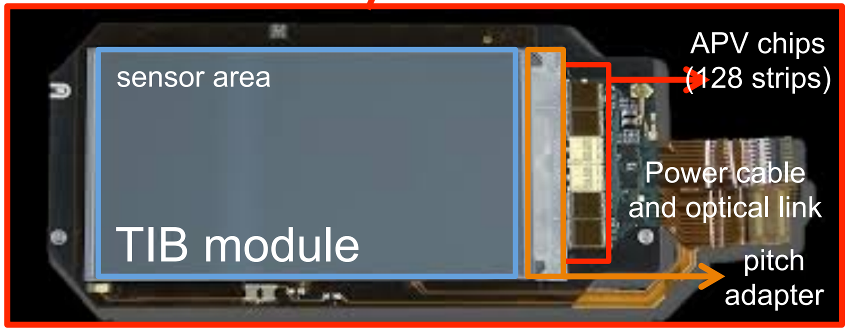
FPix half-disks

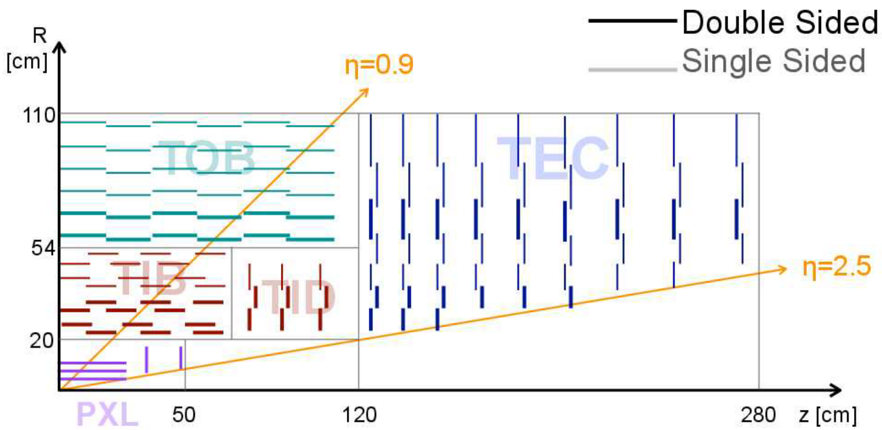


The silicon strip detector

- Total active area 200 m²
  - 10 layers in the barrel (4 inner layers (TIB) + 6 outer layers (TOB)),
  - 3 inner disks (TID) + 9 endcap disks (TEC)
  - pseudo-rapidity coverage up to 2.5
  - 9.6 M read-out channels
- Silicon strip modules:
  - p+- on-n sensors, 320/500 μm thickness
  - 512/728 strips per module (4-6 APV chips)
  - Double sided modules
    - ✓ 100 mrad angle, 3D position measurement
  - strip pitch 83-205 μm
  - strip length ~8cm-20cm



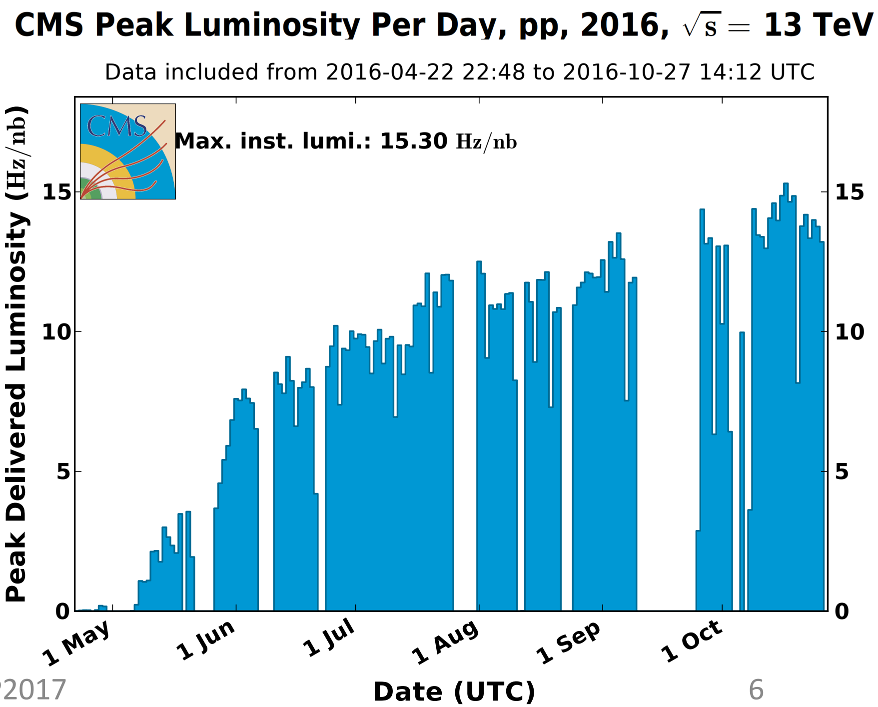




2016 data taking conditions

- LHC beam conditions:
  - proton-proton collisions at 13TeV centre-of-mass energy
  - 25ns bunch spacing
  - maximum number of colliding bunches: 2208
  - ~25 average (and up to ~49) pile-up interactions per bunch crossing

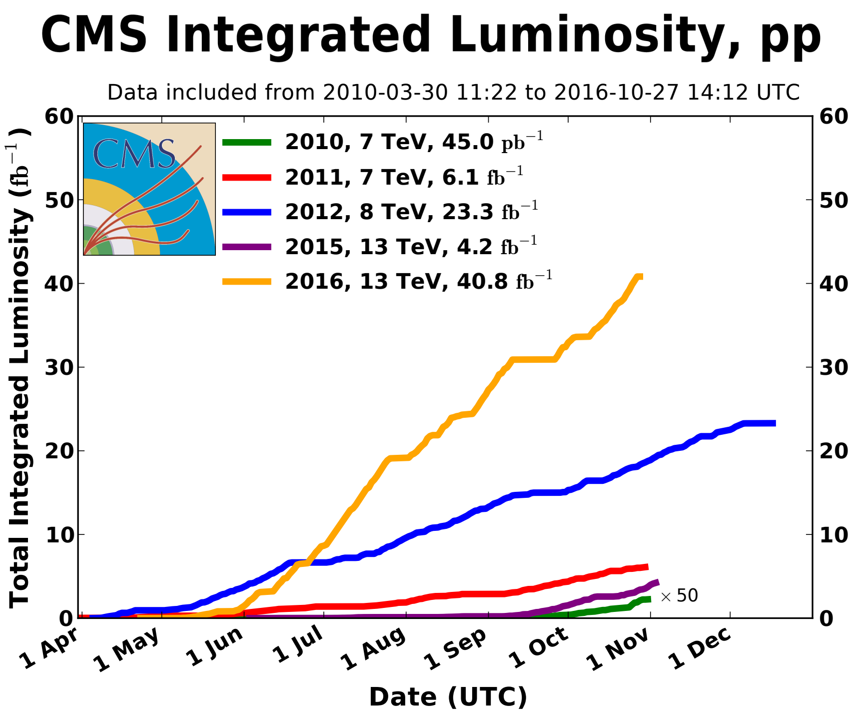
- Peak luminosity: 1.53 10^{34} cm^{-2} s^{-1}
  - ~50% more than original design value
  - twice higher than Run I



CMS data taking performances in 2016

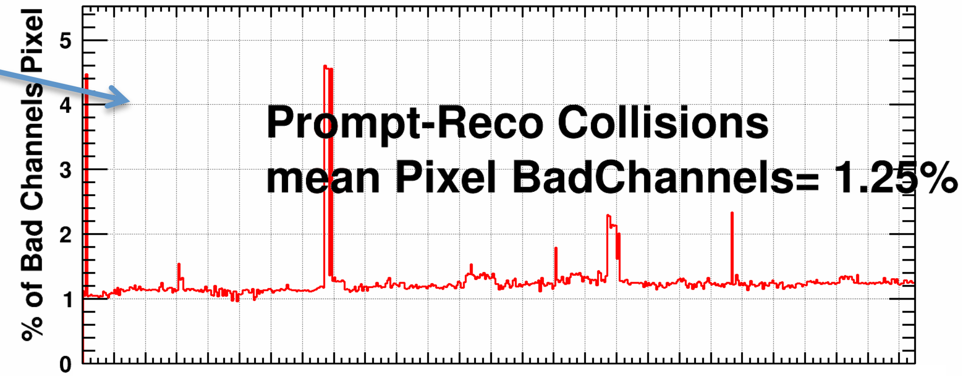
- Total luminosity delivered: 40.82 fb^{-1}
  - recorded by CMS: 37.76 fb^{-1} (~92.5% efficiency)
  - data losses due to the Tracker: ~2%
    - mostly due to (quickly fixed) operations issues

CMS and its tracker performed really well !



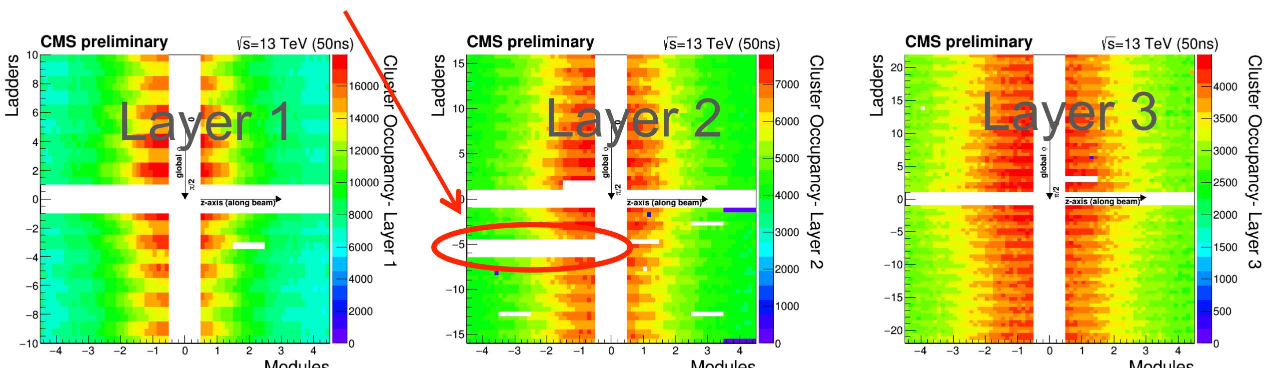
Status of the pixel detector in 2016

- Bad channels are monitored on a daily basis for the entire pixel detector
- Bad channels on average stable over 2016
- Peaks and fluctuations in the trend are due to given operation and data acquisition issue. Those are quickly recovered.
- Mean number of bad components:
  - BPix 1.63%
  - FPix 0.22%

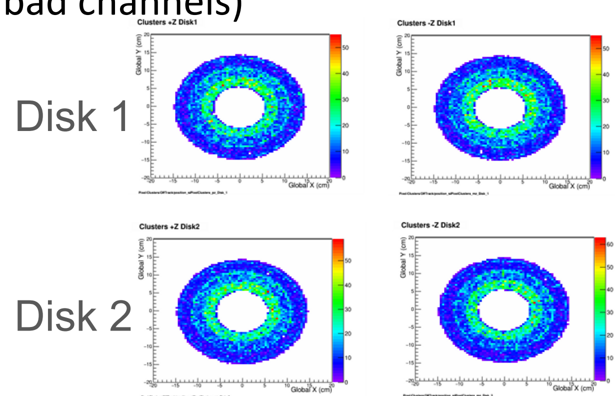


all runs of 2016

- Cluster occupancy only shows very few holes within the pixel detector
  - Unrecoverable inefficiencies in BPix layer 2 (main contribution to bad channels)



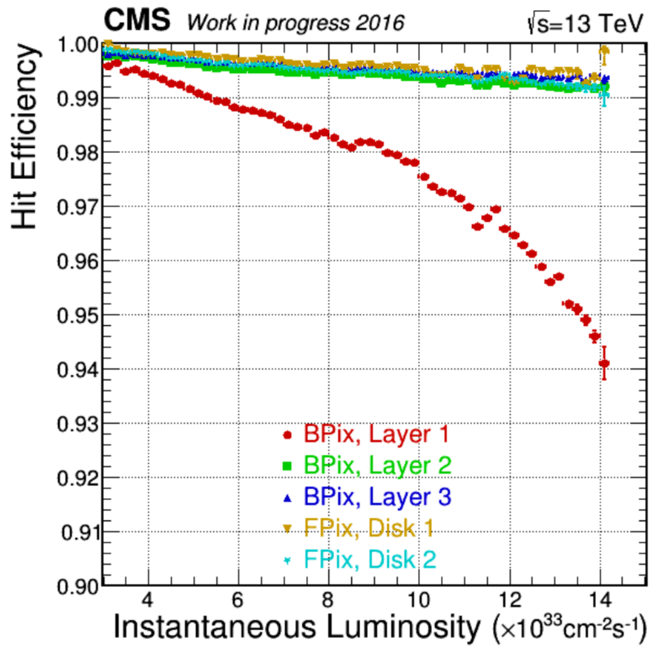
BPix cluster occupancy



FPix cluster occupancy

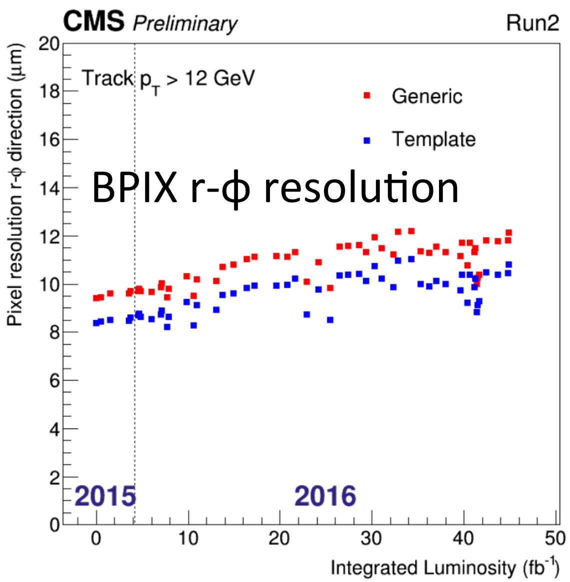
Pixel detector performance (I)

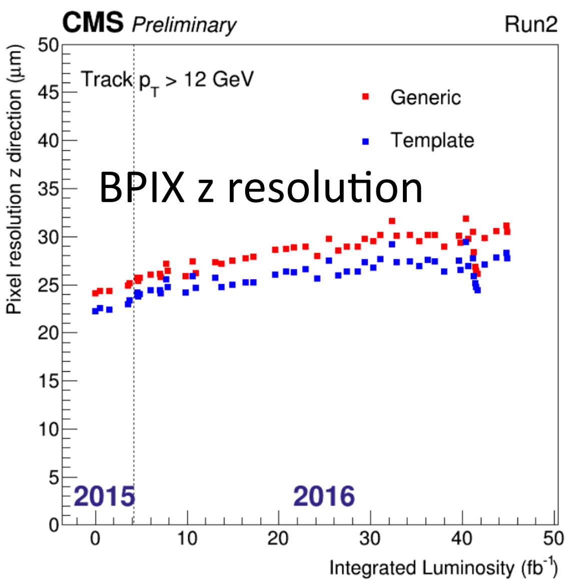
- Pixel hit efficiency stays above 99% for all layers and disks except for the first layer of the BPix
- Dynamic inefficiency increasing with instantaneous luminosity (already seen in run I and expected with the current pixel detector design)
- 2017 new Pixel detector will correct this issue, leading to high performance on all layers

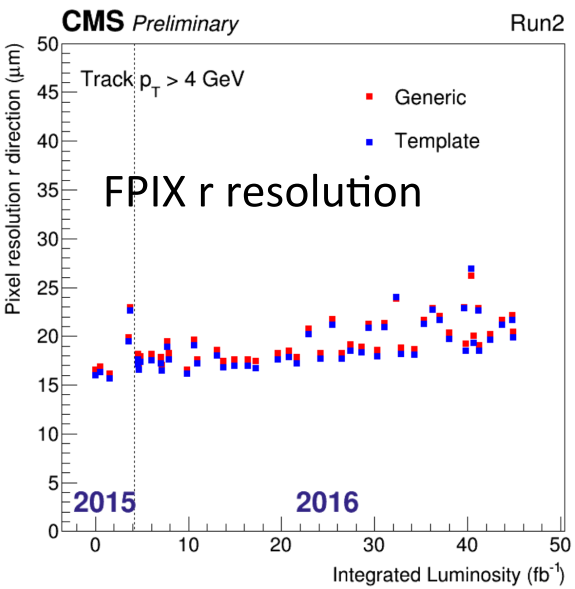


Pixel detector performance (II)

- Excellent hit resolution:
  - BPix: ~10µm in the transverse plane (r-ϕ); ~25µm along the beam axis (z)
  - FPix: ~20µm in the radial direction (r)
- Positions are reconstructed with two algorithms:
  - Generic: fast online algorithm (based on track position and angle)
  - Template: detailed algorithm used afterwards in offline reconstruction
  - The generic algorithm is performing well and is close to the template algorithm performance

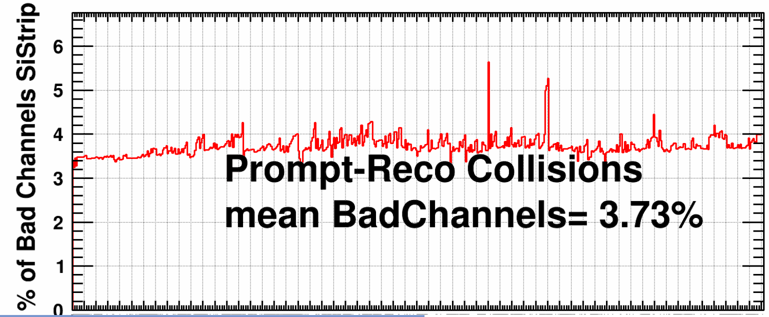




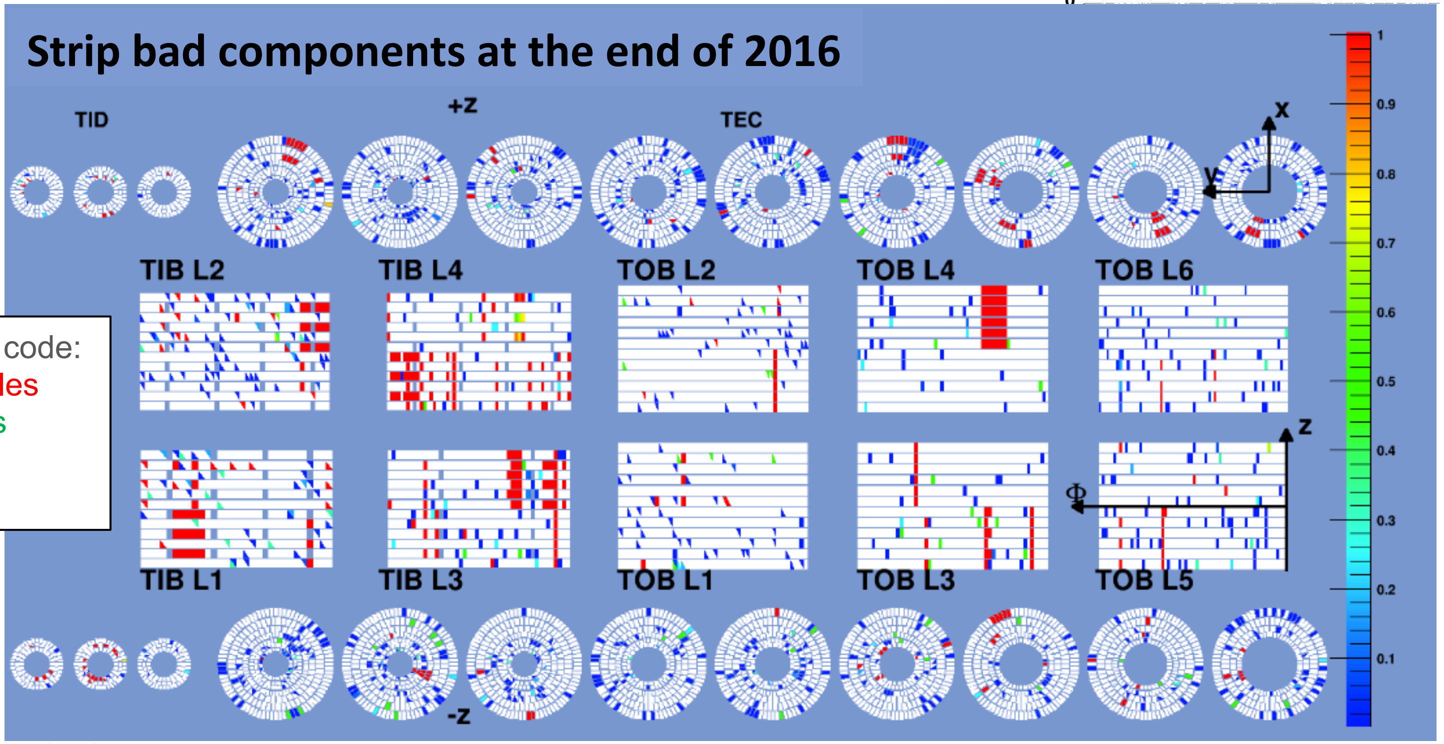


Status of the strip detector in 2016

- **Bad components in the strip detector are monitored on a run basis:**
  - Mean number of bad components in 2016: 3.73% (similar to run I)
  - Monitored from faulty full modules (red) to single strips (blue)
  - Bad components automatically masked on a run basis



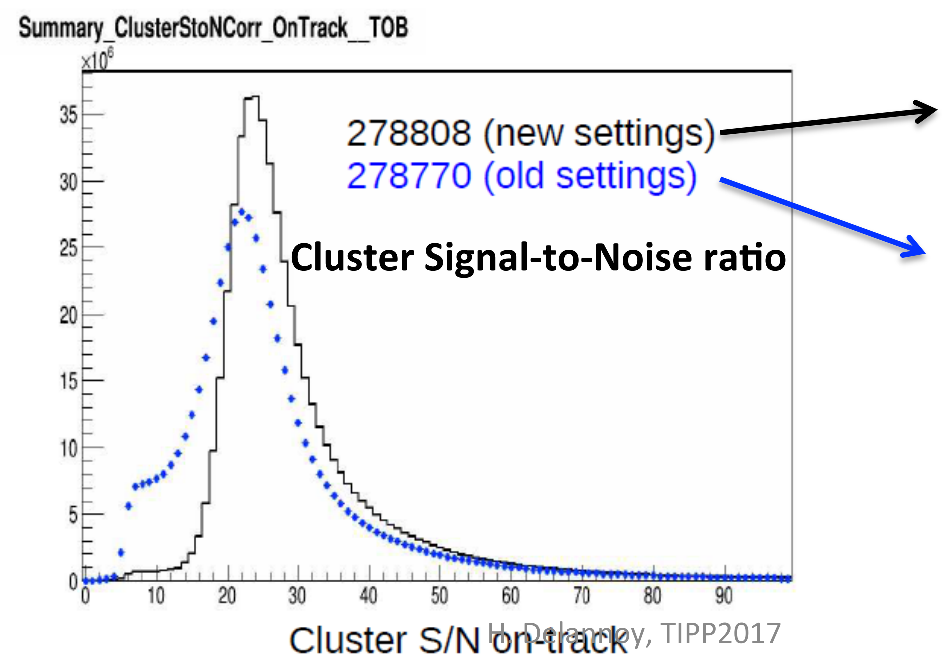
all runs of 2016



Color code:
Modules
Fibers
APV
Strips

Strip tracker dynamic inefficiency

- A decrease of signal over noise ratio associated to loss of tracking hits has been observed in late 2015 and part of 2016
  - Effect increasing with Inst. Lumi. and occupancy
  - Problem was initially believed to be due to heavily ionizing particles (HIPs)
  - Finally traced to saturation effects in the pre-amplifier of the APV chip
- Fixed in mid August changing the APV chip settings to increase the drain speed of the pre-amplifier, thus allowing for faster recovery
  - About 20 fb^{-1} of data affected
- Effect mitigated thanks to data re-reconstruction with a less demanding track reconstruction

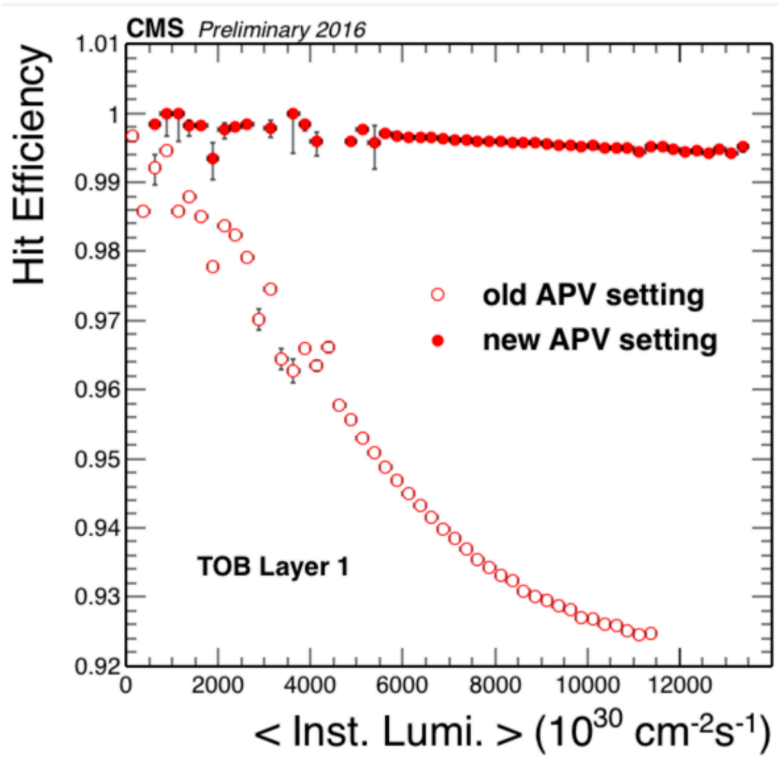


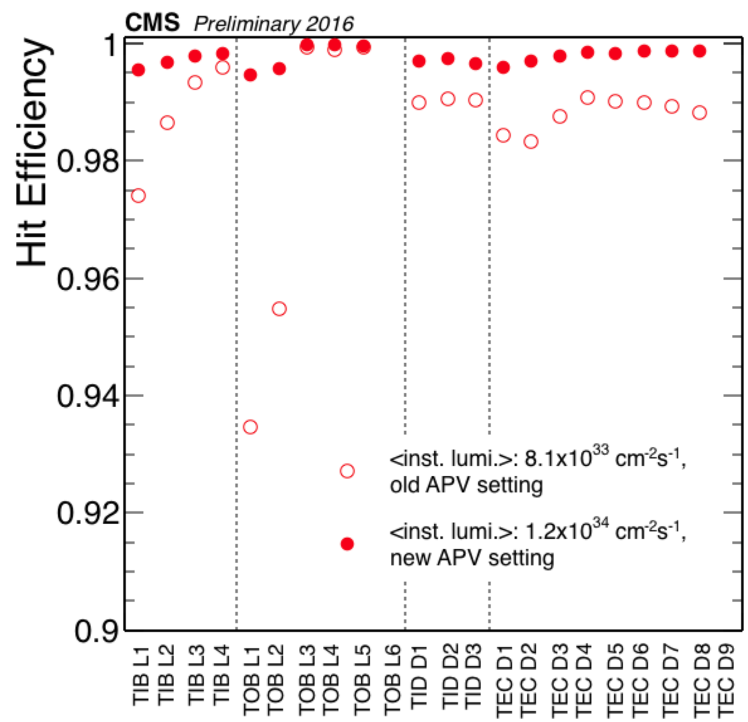
after correcting the saturation issue of the pre-amplifier

20 fb^{-1} affected

Strip detector performance

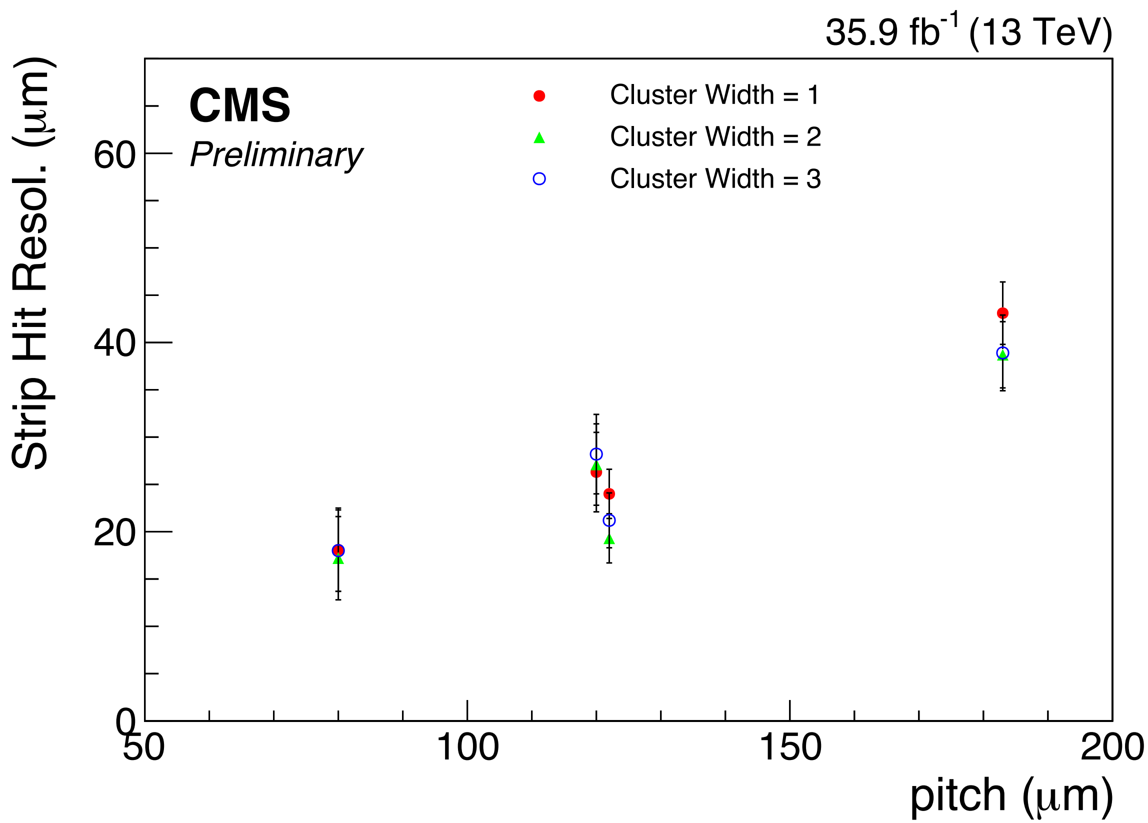
- The saturation effect was increasing with instantaneous luminosity
- After changing the electronics settings, the hit efficiency is back to more than 99% (as it was during run I) for the full strip detector





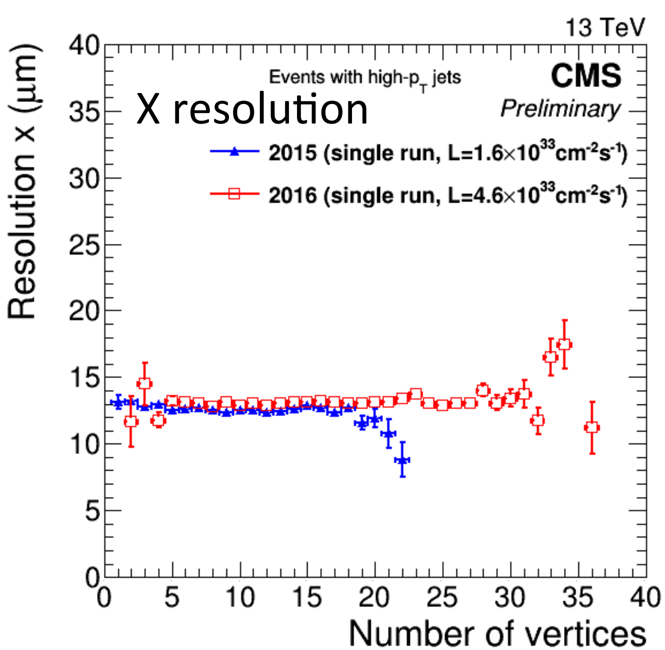
Strip detector performance

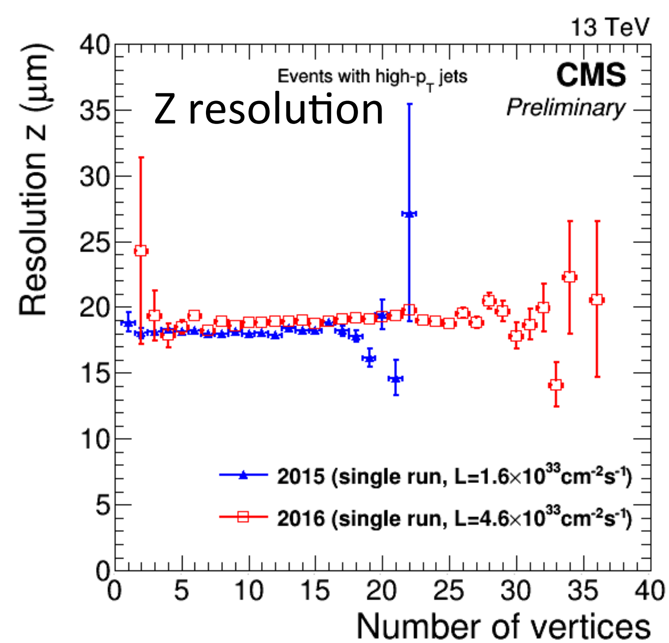
- Good hit resolution in strip tracker between 18 and 45 µm, depending on:
  - strip pitch
  - cluster width



Track reconstruction performance

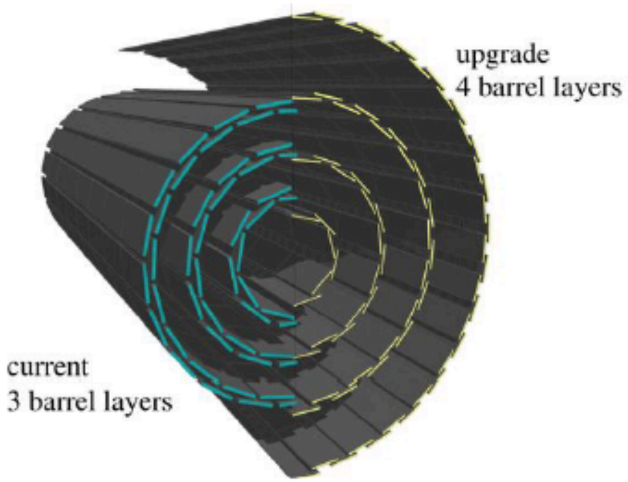
- Primary vertex resolution:
  - ~ 13 µm in the transverse plane, and 19 µm along the beam axis
  - slight degradation (~10%) from 2015 to 2016 due to Pixel dynamic inefficiencies leading to larger fraction of tracks with hit missing from the innermost pixel barrel layer.

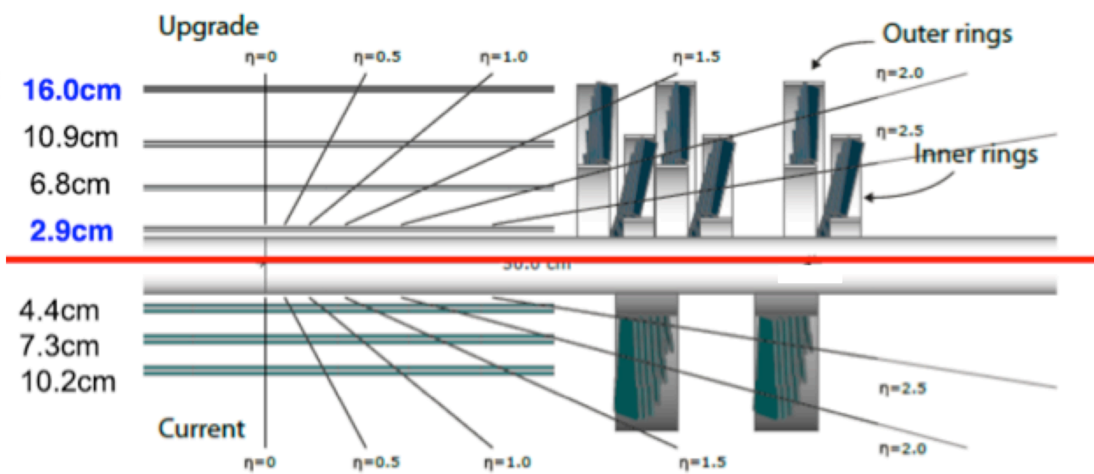




The pixel phase 1 upgrade

- The CMS Pixel detector has been replaced in 2017 (Phase I)
  - upgraded Pixel detector with 4 barrel layers and 3 disks on each side (from 66M to 124M pixels)
  - new digital ROC will cure dynamic efficiency losses
  - new CO_2 cooling
  - see talks from S. Hasegawa (FNAL) and B. Vormwald (University of Hamburg) about, respectively, the construction and the commissioning of the pixel phase 1 detector

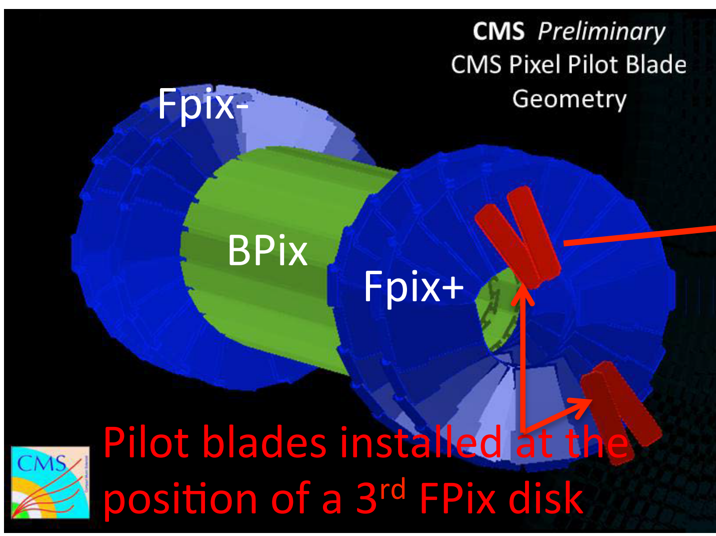


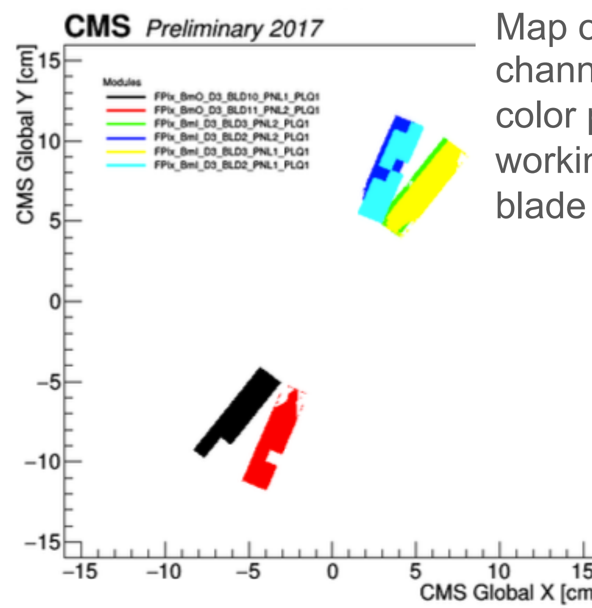


- For commissioning the 2017 pixel detector, a fraction of the new detector had been already inserted within CMS to test the new sensors and electronics.

The pilot blades for the pixel phase 1 upgrade

- Pilot blades equipped with Phase I modules installed in 2014 within CMS
  - ➢ integrated in the central DAQ and DCS systems, included in data taking as any other CMS subdetector
  - ➢ fundamental input in view of the commissioning of the full detector (early 2017)
  - ➢ successful commissioning of this firsrt part of the new pixel detector and many lessons learned
  - ➢ see poster about pilot blades data reconstruction by T. Vami (Wigner Research Centre for Physics)





Map of active channels (one color per working pilot blade module)

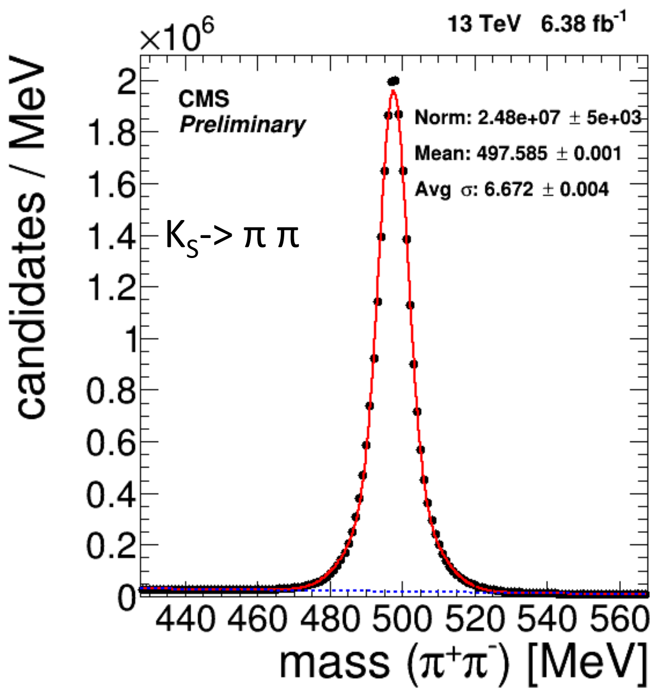
Summary and conclusions

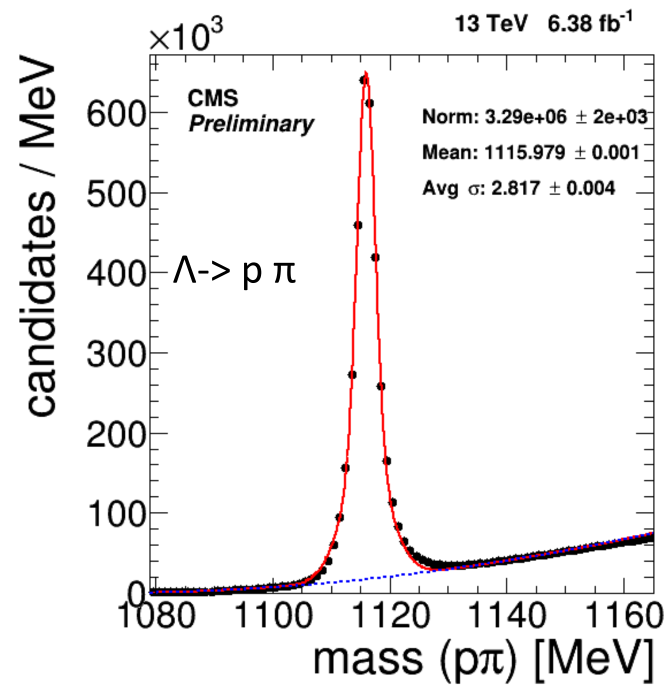
- CMS tracker took efficiently very good data for physics in 2016, even at instantaneous luminosity going beyond original design
- Features encountered in 2016 due to beam conditions:
  - First layer of the Barrel Pixel detector affected by dynamic inefficiencies
    - Promising and much better performance expected with the new pixel detector starting to operate this year
  - Strip Detector affected by inefficiencies with increasing instantaneous luminosity and occupancy
    - After having changed the drain speed of the pre-amplifier, thus allowing for faster recovery, the efficiency was fully recovered.
- Track reconstruction performance stable with respect to Run I
  - effect on ~20fb^{-1} data mitigated by loosening track reconstruction
- Phase 1 pilot detector provided valuable information towards the commissioning of the upgrade detector

BACKUP

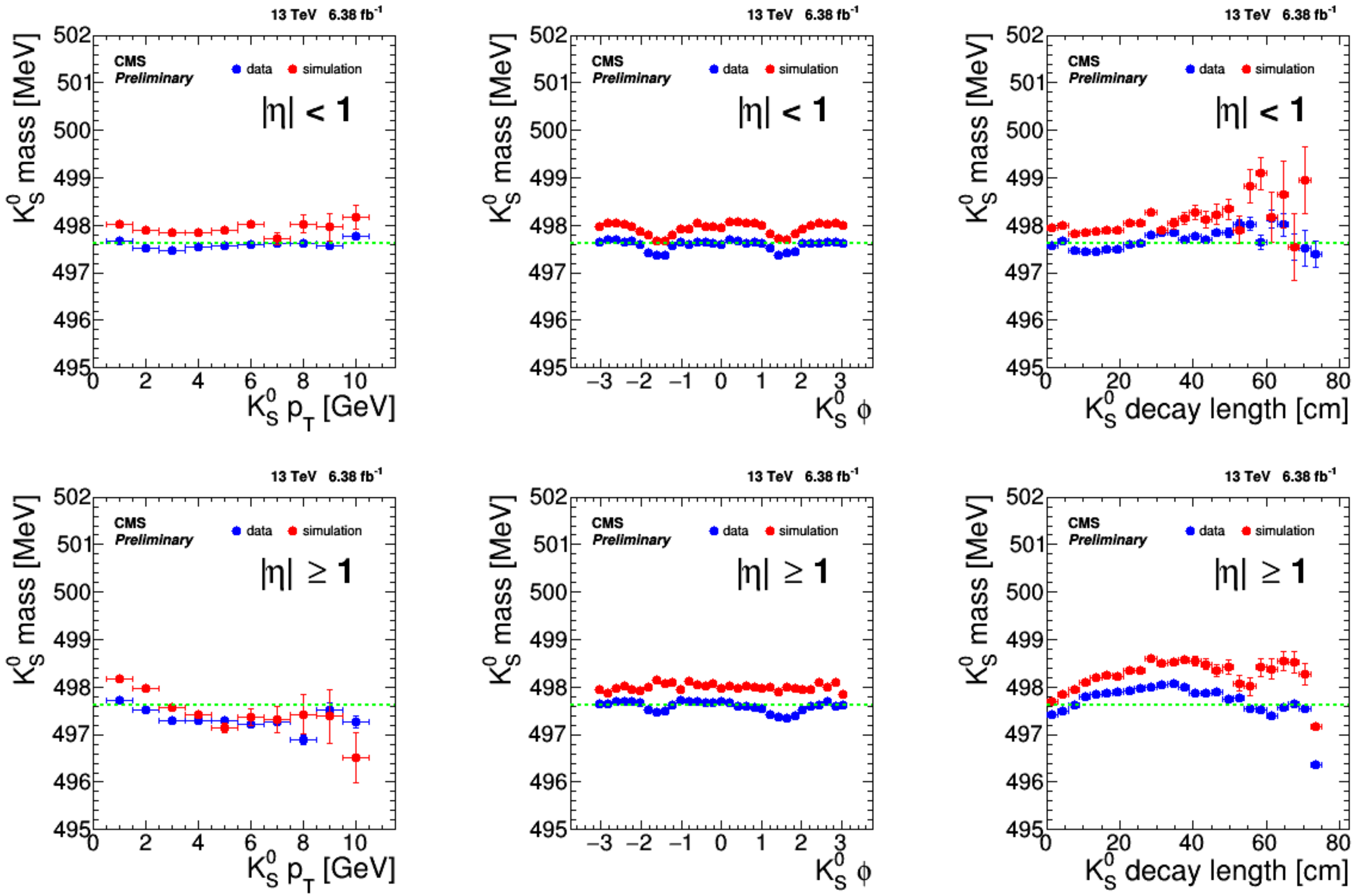
Track reconstruction performance (II)

- Reconstruction of invariant mass distributions of particles using only tracker information:
  - $K_S \to \pi\,\pi$, $\Lambda \to p\,\pi$
  - central values and widths of resonances are in very good agreement with expected values





Track reconstruction performance (III)



How was measured the pixel…

- **hit efficiency:**
  - **Hit Efficiency is the probability to find any clusters within a 500 micron area around an expected hit.**
  - Expected hits are provided by good quality tracks
    - Associated to primary vertex with small impact parameter
    - with p_T> 1.0 GeV
    - Missing hit allowed only on layer under investigation (valid hits are expected on two “other” layers/disks)
  - Module selection:
    - Bad read-outs removed
    - ROCs under SEU (temporarily dysfunctioning ROCs) removed
    - ROC and module edges, as well as, overlap areas of adjacent modules within a layer rejected
    - Only modules with good illumination by tracks are selected
- **hit resolution:**
  - Tracks with p_T> 12 GeV having hits in all three layers of the pixel barrel detector are selected.
    - They are re-fitted without the hit in the 2nd layer. Then, **the residual difference between the hit position and the interpolated track is plotted**. A student-t function is fit to the distribution.
    - **Assuming the resolution is the same in all three layers** the width of the function fit divided by $\sqrt{3/2}$ gives the intrinsic pixel resolution. This takes into account that the hit positions in layers 1 and 3 are smeared as well.

How was measured the strip…

- **hit efficiency:**
  - Computed from a selection of events with less than 100 tracks
    - Use "combinatorialTracks" with at least 8 hits
    - Trajectories that fall within sensor acceptance. Excludes bonding region for modules with 2 sensors.
    - Known bad modules are excluded from the measurement
  - **The module is considered as efficient if the distance between the trajectory crossing point and the cluster is less than 15 strips**. They also have to fall in strips read by the same APV. For double layers, both are taken into account. The average efficiency is computed. The absence of an explicit requirement of hits on tracks on layers close to the one analysed yield a bigger uncertainty when trajectories are propagated to the last detector planes (TOB-L6 and TEC-D9). Thus the hit efficiency is underestimated in these regions
- **hit resolution:**
  - **Computed by using hit in overlapping modules of the same layer ("pair method").**
  - Tracks are selected with the cuts:
    - p_T> 3 GeV
    - number of hits >= 6
    - chi2 prob >= 10-3
  - Selection of pairs:
    - at most 4 strips cluster width
    - Clusters are of the same width in both the modules
    - Clusters are not at the edge of the modules
    - Predicted path (distance of propagation from one surface to the next) < 7 cm
    - Error on predicted dX < 0.0025 (loose)

How was measured the tracks…

- **primary vertex resolution:**
  - The performance of the vertexing has been studied by a data driven method referred to as the split-vertex technique, where tracks forming a vertex are split into **two sets and vertices are fit independently to each. From a difference in their reconstructed position a vertex position resolution is derived.**