PERFORMANCE AND TRACK-BASED ALIGNMENT OF THE UPGRADED CMS PIXEL DETECTOR

Valeria Botta (DESY) on behalf of the CMS Collaboration

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THE CMS TRACKER

- Innermost part of the CMS detector
- Composed by silicon modules
  - Pixel
  - Strip
- Modules arranged in
  - Cylindrical layers in the central region “barrel”
  - Disks in the forward regions “endcaps”
- The *Pixel* detector has been replaced and upgraded

pixel layout before upgrade
THE UPGRADED PIXEL DETECTOR

- One more barrel layer, one more forward disk
- Innermost barrel layer closer to the interaction point
- Improved readout electronics
- Lower material budget (CO₂ cooling)

More in the previous talk by R. Bartek on construction and commissioning of the new pixel

Better tracking also at high instantaneous luminosities
**EXPECTED TRACKING PERFORMANCE**

New (2017) vs. old (2016) tracker, from simulation

- **Fake rate reduced by a factor ~3, and higher track efficiency**
- **Better track impact parameter resolution by ~ 30%**
**EXPECTED VERTEX AND B-TAG PERFORMANCE**

**New (2017) vs. old (2016)**

from simulation

**New (Phase1) vs. old (2016)**

from simulation

- Better identification of b-jets,
- +10% efficiency at the same fake rate.
REACHING THE EXPECTED PERFORMANCE

The expected design performance can be achieved only with excellent hardware and calibration

- **Position resolution** \( \sigma_{\text{pos}} = \sigma_{\text{hit}} \oplus \sigma_{\text{align}} \). For pixel hits

  - \( \sigma_{\text{hit}} \): intrinsic hit resolution, \( O(10 \mu m) \)
  - \( \sigma_{\text{align}} \): uncertainty on the modules positions, \( O(1 \mu m) \)

![Graph of CMS Preliminary 2016 data showing the number of hits vs. residual in the r-phi direction, with a fit to the expected resolution of \( (0.09 \pm 0.02) \mu m \) and \( (13.27 \pm 0.03) \mu m \) for the RMS.]

![Graph of CMS Preliminary 2016 data showing the number of modules vs. residual in the x'-x'_hit direction, with alignments for cosmic rays + collisions and various scenarios.]

\( \sqrt{s} = 13 \text{ TeV} \)
Tracks are reconstructed fitting a set of hits on the tracker modules.

Assuming wrong modules positions leads to bias in the reconstructed track: real ≠ fitted

Wrong positions leads to large residuals

Track-hit residuals are an measure of misalignment

Measure the real modules positions, with a large set of tracks that correlate the alignment parameters, minimising track-hit residuals:

Can achieve a precision ≲ \( O(10 \ \mu m) \) with large statistics and several track topologies

\[
\chi^2(p, q) = \sum_j \sum_i \left( \frac{m_{ij} - f_{ij}(p, q_j)}{\sigma_{ij}} \right)^2
\]
PIXEL ALIGNMENT WITH COSMIC RAYS

- Potentially large initial misalignment of the new pixel
- Several alignments performed, with increasing granularity

1. alignment of forward and barrel pixel high-level structures
2. alignment of the whole pixel at module level

- Cosmic ray data taking (before pp collisions)
  - CMS Magnet off (0T)
    1. alignment of forward pixel
    2. alignment of barrel pixel
    3. alignment at module-level
  - CMS Magnet on (3.8T)
    4. update of high-level structures alignment
      (no module level due to stat.)

end of cosmic ray data taking, start of p-p run
The largest (and first) position correction was a 3 mm shift of the FPIX z-minus endcap.

- Unbiased track-hit residuals, the hit under consideration is not used in the track fit.
- Reduced bias (syst. effects) and width (local precision) after each alignment iteration.
RESULTS ON 0T COSMIC RAY DATA - BPIX

For the barrel pixel, the largest position correction was a 2 mm horizontal shift along x.

- Unbiased track-hit residuals, the hit under consideration is not used in the track fit.
- Reduced bias (syst. effects) and width (local precision) after each alignment iteration.
Cosmic ray tracks are split in two halves, look at differences in their track parameters.

After each alignment iteration, reduced bias (syst. effects) and width (local precision).
Magnetic field change induces movements in the detector, need to update the alignment (at high-level due to limited stat.)

Track-hit residuals in barrel pixel, z direction

Track split, $\Delta \eta$ of the two track halves

Successfully measured the pixel modules position after installation, good starting point for the collision run.
- Tracks with hits in layers 1,2,3 (2,3,4) refitted excluding layer-2(3)hit.
- Fit to distribution of hit residuals between hit position and interpolated track.

- Layer 2 and 3 resolutions are compatible with each other
- Layer 2 resolution compatible with the one for the old detector
SUMMARY

- Shown expected improvements in tracking, vertexing and b-tagging thanks to the new CMS pixel detector
- Presented results of the first track-based alignment of the new pixel detector
  - performed with cosmic-ray data prior to LHC proton-proton run
  - successfully measured the pixel position after installation
  - very good starting point for the pp data taking
- Presented first performance results of the new pixel detector
  - first hit resolution measurements in line with expectations

THANK YOU FOR YOUR ATTENTION!
REFERENCES


2. CMS Collaboration "Alignment of the CMS tracker with LHC and cosmic ray data" 2014 JINST 9 P06009 doi:10.1088/1748-0221/9/06/P06009

3. CMS Collaboration "Alignment of the CMS silicon tracker during commissioning with cosmic rays" 2010 JINST 5 T03009 doi:10.1088/1748-0221/5/03/T03009
Tracks with hits in layers 1,2,3 (2,3,4) refitted excluding layer-2 (3) hit.

Fit to distribution of hit residuals between hit position and interpolated track

Resolution in z-direction known to have dependence on the track angle
Valeria Botta (DESY)

Performance and track-based alignment of the upgraded CMS pixel detector

EPS-HEP 06.07.2017
Cosmic ray tracks are split in two halves, look at differences in their track parameters.

After each alignment iteration, reduced bias (syst. effects) and width (local precision).
Cosmic ray tracks are split in two halves, look at differences in their track parameters

After each alignment iteration, reduced bias (syst. effects) and width (local precision)
Unbiased track-hit residuals (the hit under consideration is not used in the track fit)

After each alignment iteration, reduced bias and width
RESULTS ON 0T COSMIC RAY DATA - BPIX RESIDUALS

- Unbiased track-hit residuals, the hit under consideration is not used in the track fit
- After each alignment iteration, reduced bias and width

Unbiased track-hit residuals, the hit under consideration is not used in the track fit

After each alignment iteration, reduced bias and width

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After each alignment iteration, reduced bias and width
Unbiased track-hit residuals, the hit under consideration is not used in the track fit

After each alignment iteration, reduced bias and width
Unbiased track-hit residuals, the hit under consideration is not used in the track fit

After each alignment iteration, reduced bias and width

Before alignment
\( \mu: -27.7 \ \mu \text{m RMS: } 498.5 \ \mu \text{m} \)
Pixel ML alignment (0T data)
\( \mu: 2.4 \ \mu \text{m RMS: } 183.3 \ \mu \text{m} \)
Pixel HL alignment (3.8T data)
\( \mu: -1.0 \ \mu \text{m RMS: } 162.4 \ \mu \text{m} \)

Before alignment
\( \mu: 0.7 \ \mu \text{m RMS: } 465.2 \ \mu \text{m} \)
Pixel ML alignment (0T data)
\( \mu: 2.7 \ \mu \text{m RMS: } 215.5 \ \mu \text{m} \)
Pixel HL alignment (3.8T data)
\( \mu: 2.8 \ \mu \text{m RMS: } 187.3 \ \mu \text{m} \)
Positions of the pixel detector centres with respect to the tracker outer barrel.

For the new pixel tracker, the measure is obtained from the alignment derived using 3.8T cosmic-ray data collected in 2017.
2016 ALIGNMENT PERFORMANCE

- Unbiased track-vertex residuals

- Z mass from di-muon events
EXPECTED TRACKING PERFORMANCE

New (2017) vs. old (2016) tracker, from simulation

- Higher track efficiency
- Better vertex resolution (xy plane)
New (2017) vs. old (2016) tracker, from simulation

[Graphs showing tracking efficiency and track fake rate vs. average pileup]

- **Graph (a)**: Average tracking efficiency (%) vs. average pileup.
- **Graph (b)**: Average track fake rate (%) vs. average pileup.