The CMS muon system: status and upgrades for LHC Run-2 and muon performance with 13 TeV data

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Outline

☐ Summary of updates since the end of Run-1 until ~today
  ▸ Detector, reconstruction, trigger

☐ Expected impact on performance
  ▸ From simulation, re-reconstruction of Run-1 data samples

☐ Overall CMS muon performance with 13 TeV data
  ▸ 2015 or 2016 datasets
  ▸ Detector / local reconstruction
  ▸ Offline physics identified objects
  ▸ Trigger

☐ Conclusion
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  ▸ Trigger

☐ Conclusion

Disclaimer: a huge topic, outcome of the work of many people! Can’t present everything. Just showing “significant” highlights, more results linked along the rest of the talk. Thanks to all the ones who contributed!
The CMS detector

- **Electromagnetic calorimeter**
- **Muon system**
- **Superconducting magnet** (3.8 T) and return yoke
- **Inner tracker** (silicon pixels, strips)
- **Hadronic calorimeter**

Size and weight:
- length: 21.6 m
- diameter: 14.6 m
- weight: ~12500 t

LHC collider at CERN
The CMS detector

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CMS muon system main goals:

1. Efficient $\mu$ identification
2. Improve $\mu$ momentum resolution at high $p_T$ (above ~ 200 GeV)
3. "Robust" stand-alone $\mu$ trigger (capable of bunch-crossing assignment)

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CMS trigger:
1. Design machine bunch-crossing (BX) rate 40 MHz
2. Reduce collected data rate (down to $O(10^{2-3})$ Hz)
   a. Level-1 (L1) trigger: HW system (~40 MHz → <100 kHz)
   b. High Level Trigger (HLT): CPU farm (~100 kHz → $O(10^{2-3})$ Hz)

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Hadronic calorimeter
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Inner tracker (silicon pixels, strips)
Muon system overview (DTs)

Coverage $|\eta| < 1.2$

DT chamber:
- 4 + 4 detection layers in $r\phi$
- 4 detection layers in $r-z$ (for 3 innermost stations)
- segment resolution: $\sim 100 \, \mu m$ in $r\phi$ ($\sim 2$ ns time resol.)
- provides segments to L1 trigger (incl. BX Id)

Drift cell design:
- size: 4.2 x 1.3 mm
- gas mixture: 85% Ar - 15% CO$_2$
- $\sim$ const drift velocity: $\sim 54 \, \mu m/\text{ns}$ ($t_{MAX} \sim 400 \, \text{ns}$)
- hit resolution: $\sim 250 \, \mu m$

Geometry (250 chambers in total):
- 4 concentric rings of stations
- 12 sector slices
- 5 wheels in the whole barrel

What’s new in Run-2?
- Relocation of RO boards outside the experimental cavern (easier access to critical components)
- New trigger boards (TwinMux) allow combination of DT/RPC information for L1 segments
- New “on chamber” trigger boards in $r-z$ view
- Improved local reconstruction algorithm
  - More details later in these slides

More in DOI: 10.1088/1748-0221/8/11/P11002
**Muon system overview (CSCs)**

Coverage 0.9 < |η| < 2.4

Geometry (540 chambers):
- 2 end-caps
- 4 disks / end-cap
- 2-3 rings / disk
- 18-36 chambers / ring

MWPC with cathode strip readout:
- gas mixture: 40% Ar - 50% CO₂ - 10% CF₄
- strips width pitch: 8.4 -16 mm (meas. position in r-φ)
- wires measure radial coordinate
  (+ perform BX identification at trigger level)
- 6 detection layers per chamber
- segment resolution: ~75 - 150 μm (~3 ns time resol.)

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**What’s new in Run-2?**

- Complete installation of ME4/2 rings
- 72 new chambers installed!
- Unganged readout of ME1/1A chambers
  - Run-1: 16 RO channels for 48 strips
  - Run-2: 48 RO channels for 48 strips
  - Improves resolution of offline and L1 segments
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- Installation of RE4 rings
  - 144 new chambers installed!
  - Increases overall efficiency
  - More robust against failures in the long term
  - Allows tighter quality cuts at L1 (can reduce rate as well)

Muon system overview (RPCs)

Coverage $|\eta| < 1.8$ (1.6) readout (trigger)

Chamber/performance details:
- double gap RPCs operating in avalanche mode (tolerate rates up to $\sim 1$kHz/cm$^2$)
- gas mixture: 96.2% $C_2H_2F_4$ - 3.5% $C_4H_{10}$ - 0.3% $SF_6$
- hit spatial resolution: $\sim 1$ cm in r-$\varphi$
- Fast detector, excellent hit timing resolution: $\sim 2$ ns (add redundancy/robustness to trigger system)

Geometry:
- segmentation similar to DT/CSC
- 480 chambers in barrel
- 576 chambers in end-caps

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DT Performance @ 13 TeV
(highlights)

More details in G. Masetti’s talk on Monday

DT local reconstruction updates
- Run-1: based on a combinatorial pattern recognition, assuming in-time muons using 2D linear segment fit
- Run-2: using mean-timer property, including segment time as parameter for a 3D linear segment fit
- Improves timing resolution: ~2 ns for prompt muons
- Efficient identification of out-of-time muons (can reject them at ID level, or use them, e.g. to study exotic signatures!)

DT resolution measurement
- Hit residual computed w.r.t. locally reconstructed segments, hits may be part of the segment itself
- Induces bias: analytically-computed corrections are then applied to widths of residuals
- Results: ~210 μm in example in line with “design” and Run-1 measured performance
- Complete map of DT hit resolutions available in G. Masetti’s slides

More results in CMS DP-2016/046 and https://twiki.cern.ch/twiki/bin/view/CMSPublic/MuonDPGResults
CSC Performance @ 13 TeV
(highlights)

- CSC segment reconstruction efficiency computed using “Tag and Probe” method (on $Z \rightarrow \mu \mu$ events)
  - More details about the method in backup
  - Very high overall efficiency: $\langle \varepsilon \rangle \approx 97\%$
  - Inefficiencies mostly due to chambers with non functioning board(s) (occasional, or that need intervention)

- CSC resolution (on $Z \rightarrow \mu \mu$ events)
  - Hit residual computed w.r.t. segments rebuilt w.o. hit under study
  - Segment resolution computed combing resolution from single hits
  - Resolution in line with “design performance”, improvement from un-ganging well visible
  - 2015→2016 variations likely dominated by impact of atmospheric pressure changes on gas mixture response

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RPC Performance @ 13 TeV (highlights)

- RPC hit efficiency w.r.t. “DT/CSC only muon tracks”
  - Build a “muon spectrometer only” track ignoring RPC hits
  - Propagate the track to an RPC chamber and look for geometrical matching of RPC hits
  - In general, efficiency > 95%
    - Inefficiencies originating from:
      - known hardware problems
      - chambers with gas leak issues (barrel)
      - chambers with low voltage issues (end-caps)

- RPC hit BX assignment
  - In case of multiple hit matching: calibration done on the basis of the BX assignment of the earliest hit
  - Overall “out-of-time-firing” well under control
    (from <0.1% to a few 0.1%)

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Muon object reconstruction overview
1. Local hit - segment reconstruction ($RPC - DT/CSC$)
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2. Reconstruction of muon spectrometer stand-alone track(s) \((p_T \text{ estimated})\)
Muon object reconstruction overview

1. Local hit - segment reconstruction *(RPC - DT/CSC)*
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6. Plus more, e.g.: 
   a. “Ad hoc” high-
   b. Computation of isolation quantities around muons 
      (*both based on detector quantities and “particle flow” ones*)
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Particle Flow (PF) reconstruction:
- “global event” reconstruction paradigm
- outputs a list of particles identified across different detectors
- identify the “primary vertex” (PV) from PU
- uses particles from PV to build jets, compute missing-\(E_T\), lepton isolation …
Main changes to muon reconstruction occurred during the first LHC long technical stop:

1. Better integration of muon $p_T$ assignment into PF
   - Many possible track fits available as products of muon reconstruction
   - Muon “best $p_T$” assignment logic revised, fully integrated with PF (e.g. give consistency with missing-$E_T$ …)

2. New “muon specific” tracking introduced
   - Aimed at restoring pile-up dependent efficiency losses, *more in next slide*

3. Plus also:
   - Improved efficiency for close-by stand-alone muons
   - Deployment of “ad-hoc” reconstruction for displaced muons (e.g. for EXO signatures - CMS DP-2015/015)
   - Use of alignment position errors of muon chambers in standalone and global muon fitting
Muon seeded tracking iterations

- A pile-up dependent loss of tracking reconstruction efficiency was identified in 2012
  - Two "muon specific" tracking iterations were added to keep high efficiency for muons
  - *Inside-out*: re-reconstruct tracker muon tagged tracks with looser requirement, to increase hit efficiency
  - *Outside-in*: use "high quality" standalone tracks to seed a tracking and recover missing muon inner tracks

- Tracking and muon-ID efficiency with "Tag and Probe" (on $Z \rightarrow \mu\mu$ events)
  - 2012 data re-reconstructed including new iterations
  - Muon tracking efficiency restored to ~ 100% after deployment of additional iterations
  - Significant impact also on quality cuts used for Tight muon-ID criteria: ~ +2% $\varepsilon$

**Inner track reconstruction**

**Muon identification**

Muon physics object performance @ 13 TeV (highlights)

Muon reconstruction+ID / isolation efficiencies ("Tag and Probe") with 2015 data
- Numerator: inner tracks are for RECO+ID, Tight-ID for isolation
- More details on IDs in backup, in summary:
  - Loose-ID: a PF muon with an inner track
  - Tight-ID: further (inner/global) track quality cuts + inner track matches ≥ 2 muon stations
  - PF Isolation, relative to muon p_{T}, applies strategy to mitigate pile-up dependence (details in backup)

Very good performance of muon physics objects
- **Reconstruction** of a PF prompt muon \( <\varepsilon> \sim 100\% \), Tight-ID \( <\varepsilon> \sim 97\% \)
  (drops at \(|\eta| \sim 0.3\) due to cracks between muon barrel wheels)
- Very good description of ID and isolation in MC
The trigger challenge

- CMS muon triggers worked very successfully throughout Run-1
- Keeping the same acceptance for physics in Run-2 is challenging
  - For “general purpose” triggers: must keep thresholds low enough to collect inclusive W/Z events
- But:
  - Luminosity $\sim 0.7 \cdot 10^{34} \rightarrow \sim 1.4 \cdot 10^{34} + 8 \rightarrow 13 \text{ TeV} \sigma$ increase $= \sim 4$ times more physics rate!
  - Some room to adjust bandwidth at HLT but must cope with the 100 kHz L1 limit!
  - Expected pile-up increase (in-time $\sim 25 \rightarrow \sim 40$, out-of-time $50 \rightarrow 25$ ns operation)
    - Impacts isolation performance and tracking CPU timing

More results in: [https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults](https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults)
Muon HLT “updates”

More in:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/HighLevelTriggerRunIResults
Muon HLT “updates”

- Overall muon HLT reconstruction approach similar to offline one
  1. Tracks built using muon system only (L1 - L2 \(\Rightarrow\) stand-alone, has cut on \(p_T\))
     - More on L1 in L. Cadamuro’s talk later today

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2. Global HLT tracks (L3) built by “cascade” algorithm
   - Run 3 different tracking logics, from fastest to slowest (saves CPU time)
   - Issue in 2012 run: L3 reconstruction inefficient at high pile-up
   - Solved by:
     - refining hit assignment in pattern recognition (geometrical \(\rightarrow\) \(\chi^2\) based)
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  4. Isolation strategy for single muon trigger revised
     - The main handle to control rate for triggers @ $\sim$25 GeV $p_T$ cuts!
     - Profit of faster tracking (can still run isolation algorithms!)
     - Move from single combined cut to sequential cuts (ECAL/HCAL/TRK): better rate rejection for same efficiency

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     - Profit of faster tracking (can still run isolation algorithms!)
     - Move from single combined cut to sequential cuts (ECAL/HCAL/TRK): better rate rejection for same efficiency
  3. Apply “loose” isolation cuts on double muon triggers: ~50% rate reduction for ~same efficiency

More in: https://twiki.cern.ch/twiki/bin/view/CMSPublic/HighLevelTriggerRunIResults
Trigger scenarios in Run-2

Thresholds for “general purpose” single and double lepton triggers, still cut low in the $p_T$ spectra of inclusive W/Z production.

Also maintaining good acceptance for lower invariant mass dimuon resonances (using dedicated triggers)!

<table>
<thead>
<tr>
<th>L1 single-$\mu$ $p_T$ cut</th>
<th>HLT single-isolated-$\mu$ $p_T$ cut</th>
<th>HLT single-$\mu$ $p_T$ cuts</th>
<th>L1 double-$\mu$ $p_T$ cuts</th>
<th>HLT double-$\mu$ $p_T$ cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valid for all the 2015 run (peak inst. lumi. $\sim 0.5 \cdot 10^{34}$)</td>
<td>16 GeV</td>
<td>20 GeV</td>
<td>50 GeV (</td>
<td>$\eta$</td>
</tr>
<tr>
<td>Highest cuts used in 2016 (peak inst. lumi. $\sim 1.4 \cdot 10^{34}$) (until ~today)</td>
<td>22 GeV</td>
<td>24 GeV</td>
<td>50 GeV (</td>
<td>$\eta$</td>
</tr>
</tbody>
</table>

From https://arxiv.org/abs/1609.02366 (submitted to JINST): HLT single-isolated-$\mu$ (double-$\mu$) $p_T$ cuts in 2012 were, 24 (17/8) GeV.
Single muon trigger efficiency in 2015

- Single (isolated) muon trigger efficiency with "Tag and Probe" (Z→μμ events)
  - Denominator: Tight-ID muons passing Tight PF isolation cuts
  - Efficiency for the OR of Mu (L1+L2+L3) and TkMu triggers

- Overall high efficiency for single muon triggers: ⟨ε⟩ ~95%
  - Rather flat vs. # of primary vertices, main modulations as function of η already present at L1

- Very good data/MC agreement
  - Within ~2% averaging on the whole period (but in |η| ~0.3 cracks)
  - Mind: trigger evolves!
  - One single MC scenario vs different trigger configurations in data
Summary

- A large list of updates/improvements (spanning from detector to high level object reconstruction) was performed to the CMS muon system in preparation for Run-2

- System redundancy was increased, improving overall efficiency, and adding robustness for long term operation

- Improved detector response and updated (or new) algorithms brought:
  - More stability of overall performance in high pile-up conditions
  - Better HLT performance in many fronts

- Analyses using muons in Run-2 could, until now, profit of very good performance of final muon objects
  - Moreover “features” such as displaced muon reconstruction and better use of offline timing information were added

- The acceptance of general purpose muon triggers was kept, until now, similar to the one of Run-1 despite the significant increase in overall rates!
Thank you for your attention!
Questions ?
Backup
DT Single hit resolution summary

CMS Preliminary (Data 2016)

13 TeV. 4.42 fb⁻¹
The tag-and-probe method

☐ Select a good muon (*apply quality cuts*) with proper matching with HLT information from a sample of events trigger by single muon HLT trigger (*tag*)

☐ Select an appropriate object (i.e. a track for muon id. efficiency computation or a good offline muon for HLT studies ...) that has a compatible vertex with the tag (*probe*)

☐ Select a criteria to define “efficient” (passing) probes (i.e. a given set of quality cuts for offline muon id efficiency or matching with HLT info for trigger efficiency)

☐ **Exploit dimuon resonances**: compute invariant mass of tag and probe for failing and passing probes separately, perform a fit around the mass range of expected di-muon resonances (J/Ψ or Z)
Muon ID definitions

- **Tight Muon ID:**
  - Global Muon
  - Particle Flow Muon
  - `globalTrack.normalizedChi2 < 10`
  - `globalTrack.numberOfMuonValidHits > 0`
  - `numberOfMatchedStations > 1`
  - `|dxy| < 0.2 cm, |dz| < 0.5 cm`
  - `numberOfValidPixelHits > 0`
  - `trackerLayersWithMeasurement > 5`

- **Isolation:**
  - Relative Combined Particle Flow Isolation
  - Pile-Up correction strategy: $\Delta \beta$ correction
  - Isolation cone $\Delta R = 0.4$
  - Isolation cut $< 0.15$

\[
PF_{\text{reliso}}\Delta \beta = \frac{\sum_{\text{cone}} p_T(\text{ch. had from PV}) + \max(0, \sum_{\text{cone}} E_T(\text{photon}) + \sum_{\text{cone}} E_T(\text{neutral had}) - 0.5 \sum_{\text{cone}} p_T(\text{ch. had from PU}))}{p_T(\mu)}
\]

- **Loose Muon ID:**
  - Particle Flow Muon
  - Global OR Tracker Muon
A whole new L1 trigger in 2016

- Documented at length in CMS-TDR-12, operating in the 2016 run
- An upgrade of the whole L1 trigger HW (beyond primitives) and SW
- Implies a new strategy for muon tracking at L1
  - **Before**: barrel - end-cap segmentation of track finders (exchanging information in overlap)
  - **Now**: three separate TFs for barrel, overlaps, and end-caps
  - **Before**: separate track finding for DT, RPC and CSC (combined by Global Muon Trigger)
  - **Now**: merge information from different detectors at track building (Global Muon Trigger mostly takes care of boundaries in coverage)
    - Needs different flow of detector level trigger outputs
    - Room for combining information already at the trigger segment/hit level (e.g. TwinMux)
- More modern HW makes possible to refine L1 algorithms
  - Better rate rejection for the same (slightly lower) efficiency
  - Working rather well, presently “lively” evolving
- More details in G. Masetti’s and L. Cadamuro’s talks, anyhow:
  - Reasonably high efficiency for single muon triggers
  - Changes along the trigger chain working properly (bottom plot shows DT trigger segment efficiency as read out at input of the old L1 track finders and in the TwinMux)

More in: CMS-TDR-12 and CMS-DP-2016/050