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Status and performance of the CMS muon system in Run2

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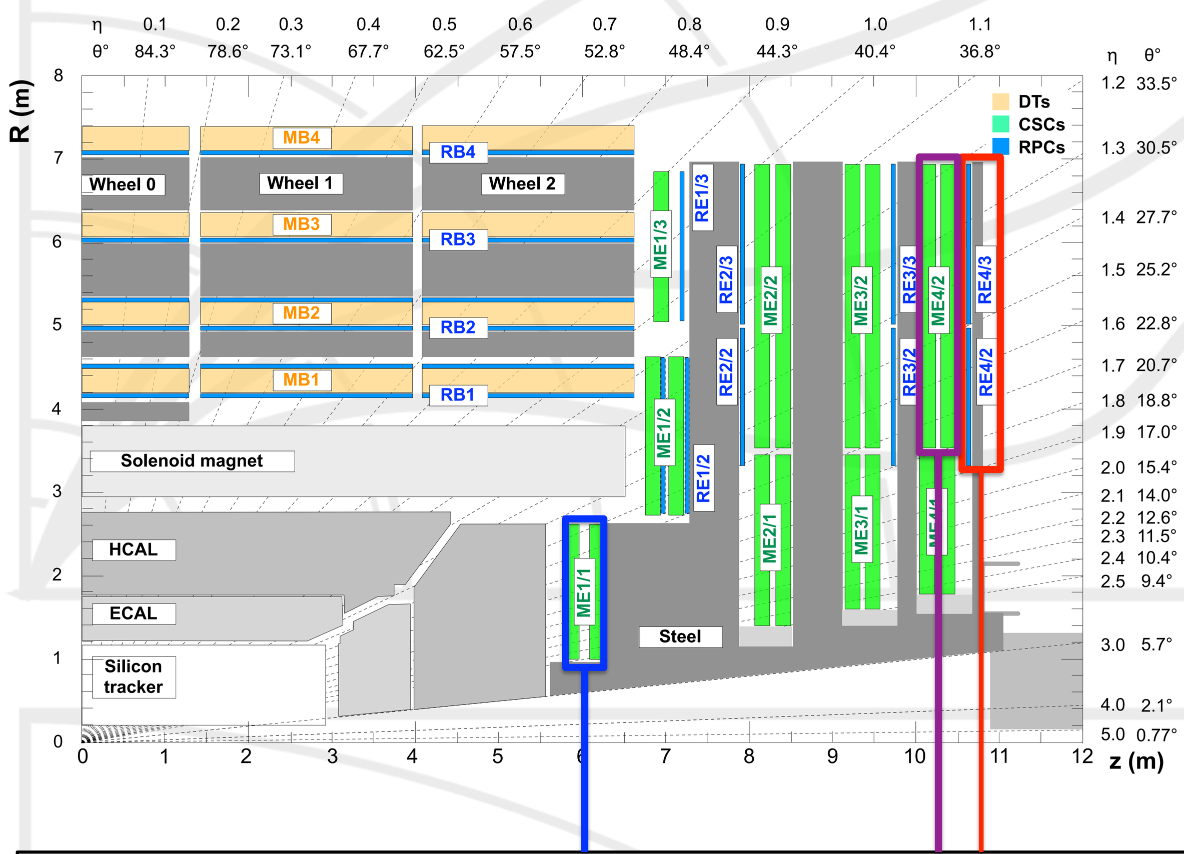
The CMS Muon System [1]

The muon system consists of gaseous detectors with three different technologies :
Drift Tubes (DT) in the barrel (|η| < 1.2)
Cathode Strip Chambers (CSC) in the endcaps (0.9<|η|< 2.4)
Resistive Plate Chambers (RPC) |η| < 1.6 for L1 trigger and |η| < 1.8 for reconstruction).

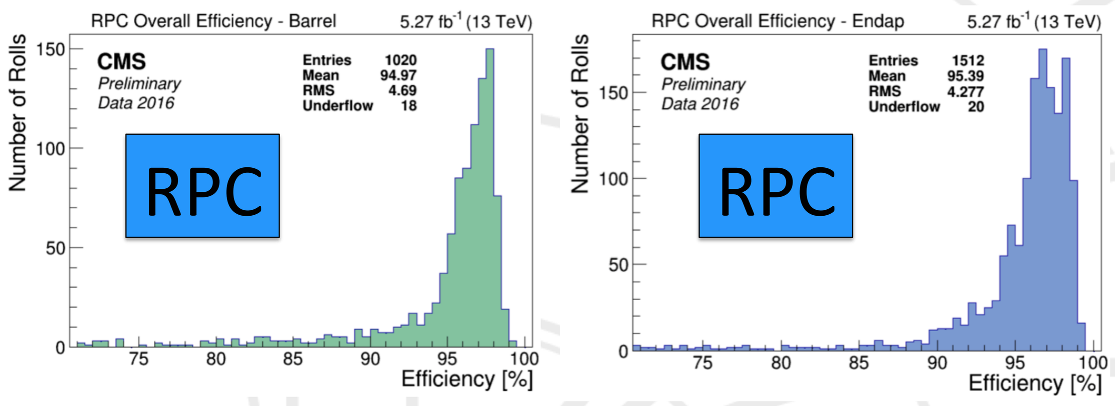


Detector changes/improvements in run 2
CSC: ME4/2 rings: 72 new chambers within 1.2<|η|<1.8
CSC: ME1/1A chamber electronics upgrade
Run1: only 16 channels to read 48 strips per chamber (ganged by 3)
Run2: full 48 channel readout
RPC: Added RE4 rings: (144 new chambers)
Effects
- The system redundancy is increased with 4 stations, higher efficiency for triggers requiring 3 stations in L1
- Possibility to tighten the trigger quality requirements, allows to reduce rate and keep reasonably low thresholds at high inst. lumi

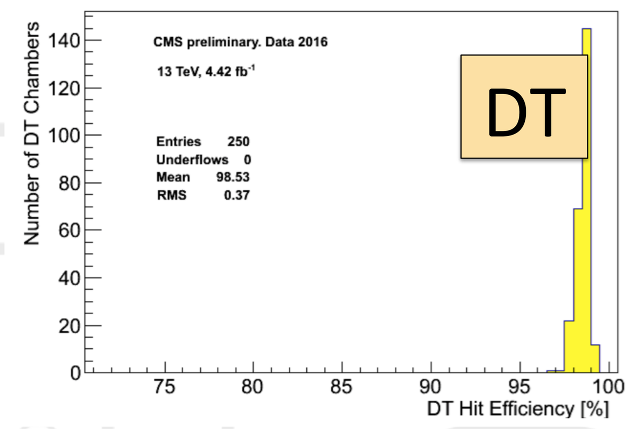
DT: relocation of readout and trigger electronics out of the experimental cavern
Effects
- Freedom to intervene during running time
- Allows improved trigger primitives algorithms to be developed

CMS Muon Detectors Performance [3]

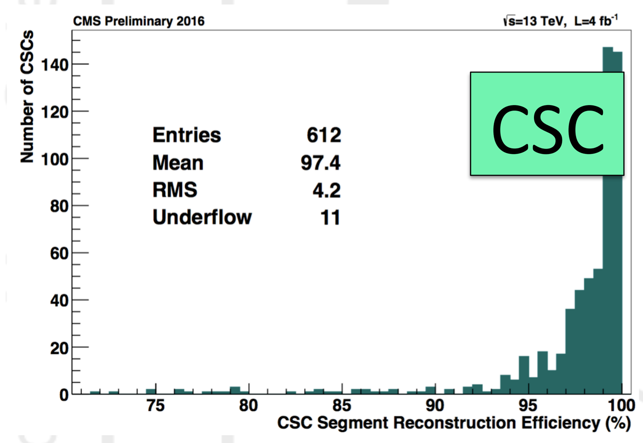
Muon systems are efficiently taking high-quality data



Efficiency (%) of each RPC in the CMS Barrel (left) and Endcap (right) Muon detector to provide reconstructed hits.



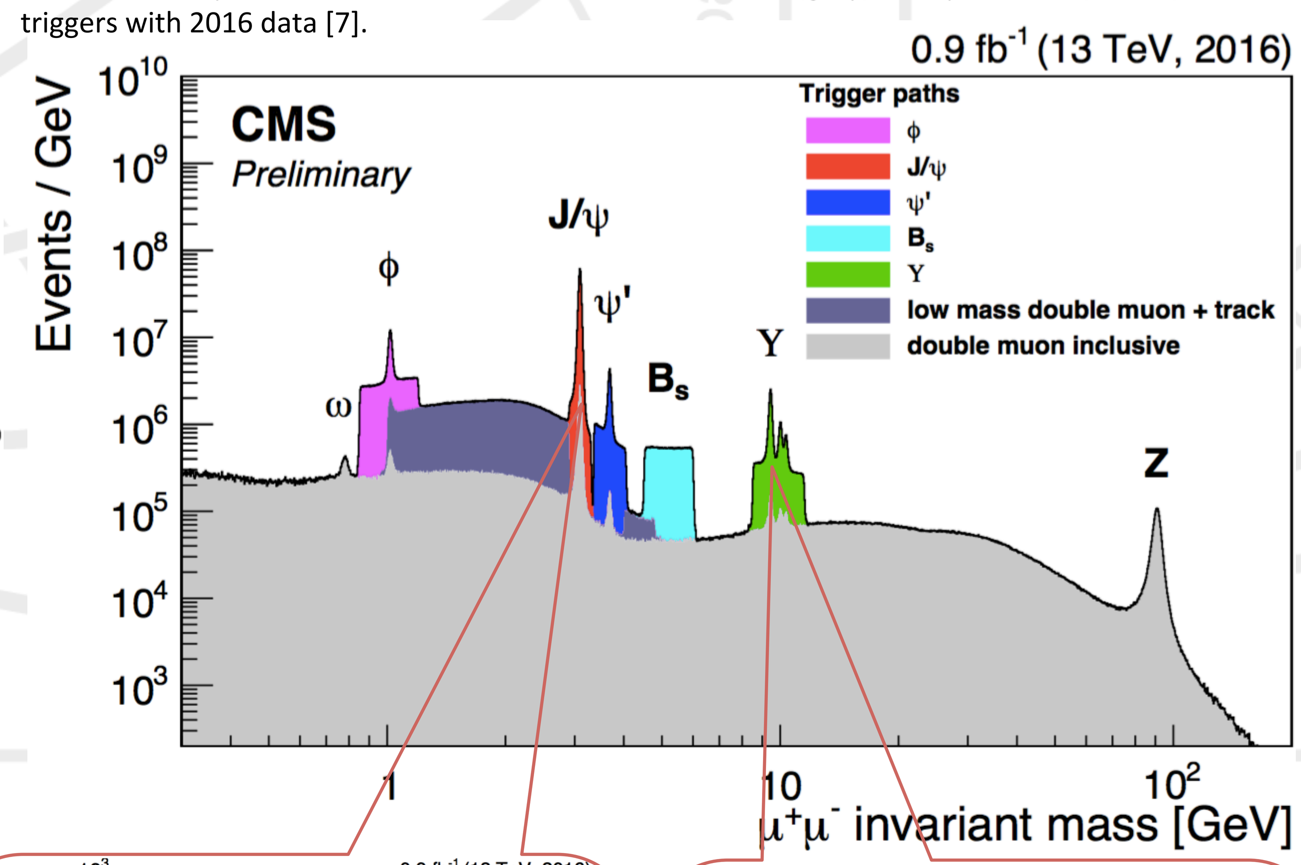
Efficiency (%) of each DT chamber in the CMS Barrel Muon detector to provide reconstructed hits.

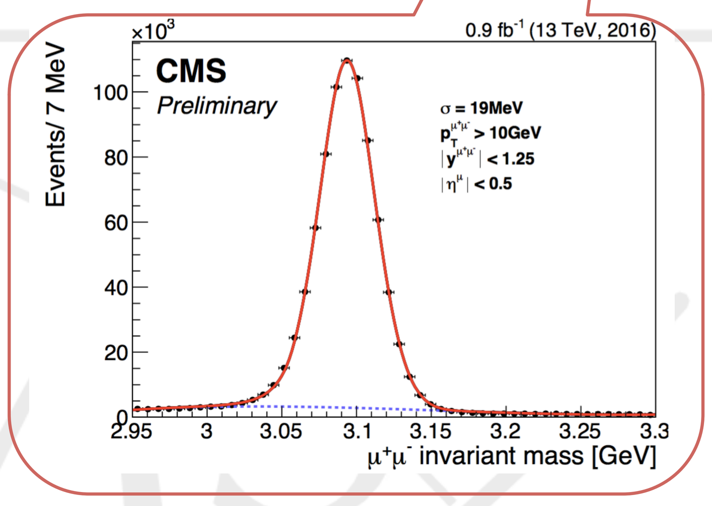


Efficiency (%) of each CSC in the CMS Endcap Muon detector to provide reconstructed muon track segments.

Dimuon invariant mass spectrum

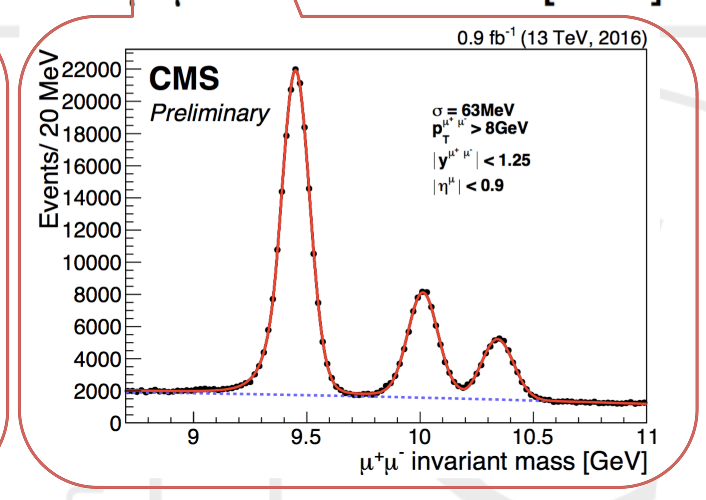
Dimuon mass spectrum from events collected with inclusive (gray) and specialized (colour) muon triggers with 2016 data [7].





Dimuon invariant mass in vicinity of J/ψ [2]
Trigger Conditions: Opposite-sign muon pair with invariant mass in range 2.95 - 3.3 GeV
Fit Method:
- Mass PDF: double Crystal Ball *(common mean, n and α parameters)*
- Background PDF: second order Chebychev polynomial

Trigger: dimuon p_T > 10 GeV,|$y^{\mu\mu}$| < 1.25
Offline muon: |η^{μ}| < 0.5

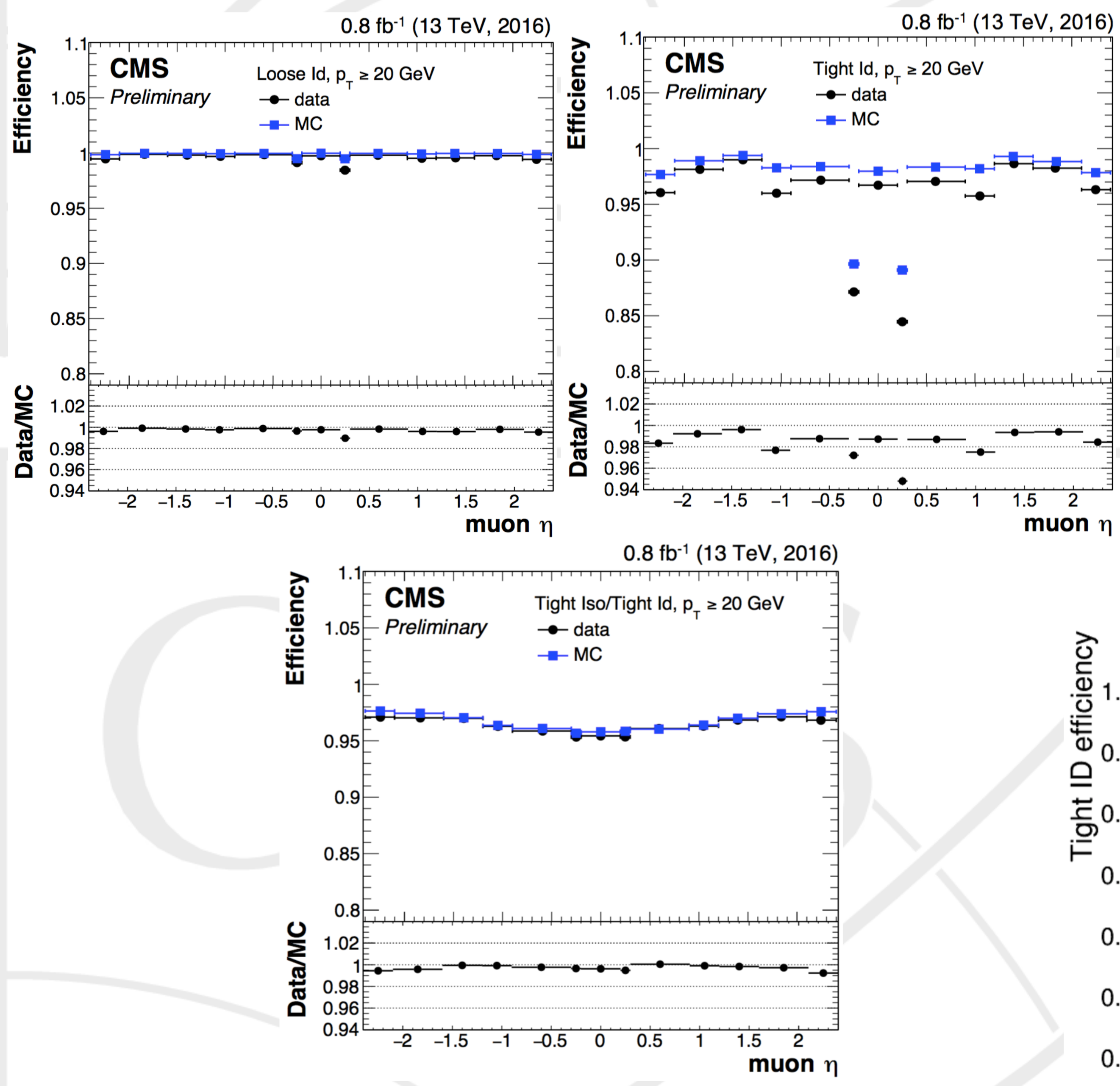


Dimuon invariant mass in vicinity of Υ(nS) [2]
Trigger Conditions: Opposite-sign muon pair with invariant mass in range 8.5 - 11 GeV
Fit Method:
- Mass PDF: Υ(1S): double Crystal Ball *(common mean, n and α parameters)* Υ(2S): Crystal Ball Υ(3S): Crystal Ball
- Background PDF: first order Chebychev polynomial

Trigger: dimuon p_T > 8 GeV, |$y^{\mu\mu}$| < 1.25
Offline muon: |η^{μ}| < 0.9

Efficiency estimation [2]

Efficiencies are computed by means of the tag-and-probe method exploiting Z→μ+μ- resonances. The method requires a muon pair consisting of a **tagged** muon that triggers the event, with a tight requirement, and a **probe** muon with loose selection used for the efficiency measurement.



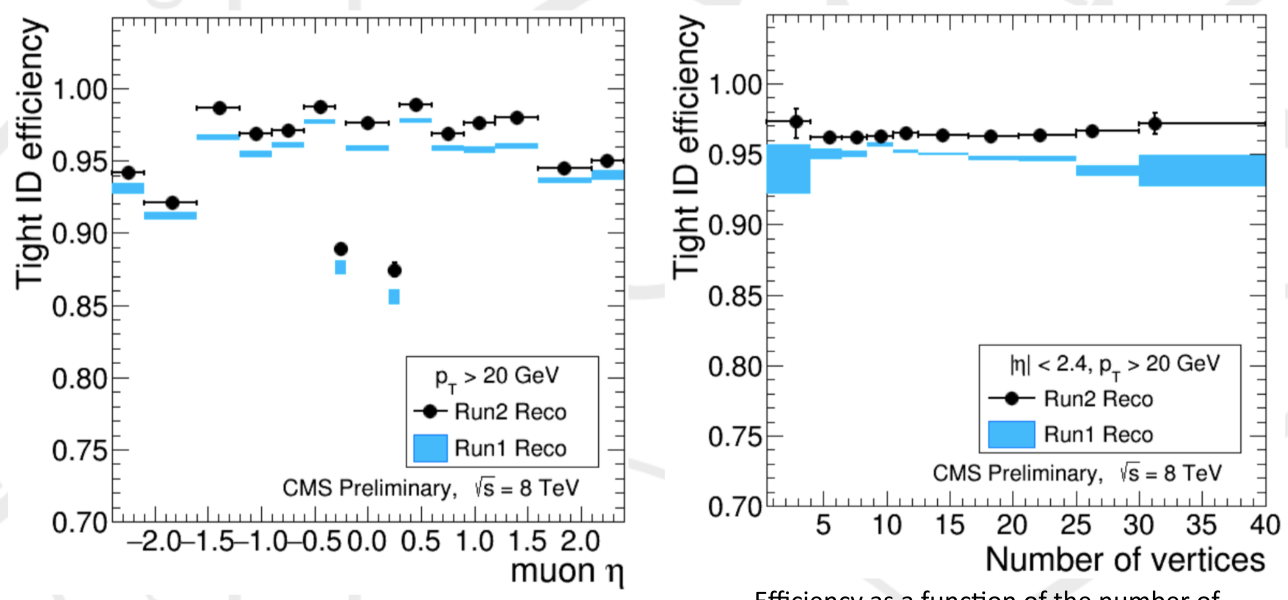
Muon Loose and Tight ID efficiency: Computed with the tag- and-probe method.
Data: Collision data at 13 TeV and 25ns bunch spacing, prompt Reconstruction (using startup calibration and alignment), dataset of events collected using single muon triggers, integrated luminosity: 0.8 fb^{-1}.
Monte-Carlo: Drell-Yan + Jets LO sample, re-weighting is applied to match the pileup distribution in data.

Muon reconstruction and Identification improvements

- **The particle-flow (PF) [4]** event reconstruction aims at reconstructing and identifying all stable particles in the event, *i.e.*, electrons, muons, photons, charged hadrons and neutral hadrons, with a thorough combination of all CMS sub-detectors towards an optimal determination of their direction, energy and type.

Muon Identification (ID) [5]:
- **Loose ID:** PF muon, global or tracker muon.
- **Tight ID:** PF muon, global muon, requirement on global track χ / n d.o.f. (<10), inner track extrapolation matching muon segments reconstructed in at least two station layers, at least one muon valid hit, at least one pixel valid hit, and 5 tracker layers involved in the inner track reconstruction, cuts on the impact parameter.

A loss of muon reconstruction efficiency in the tracker, that increased with pileup, was observed in 2012 data. In order to recover it, 2 additional muon- specific tracking iterations have been implemented for Run-2: 1. an Outside-in iteration, seeded from the muon system, designed to recover the missing muon-track in the tracker and 2. an Inside-Out iteration designed to re-reconstruct muon-tagged tracks with looser requirements to improve the hit-collection efficiency. In addition to recovering the small inefficiency the new algorithm has also improved the muon track quality, in particular the number of hits per track. This is reflected in the identification efficiency of standard selections as the Tight Muon selection.



Efficiency as a function of muon pseudorapidity for muon p_T > 20 GeV

Efficiency as a function of the number of reconstructed vertices for muon p_T > 20 GeV and |η| < 2.4

Tag-and-Probe efficiency for **Tight Muon ID** on Z→μμ events from a subsample of data recorded in the last part of the 2012 Run, reconstructed with both the Run-1 and Run-2 reconstruction algorithms. The Run-2 reconstruction improves the average efficiency by 1-2%, in particular in events with high multiplicity of proton- proton interactions per bunch crossing (pileup) [6].

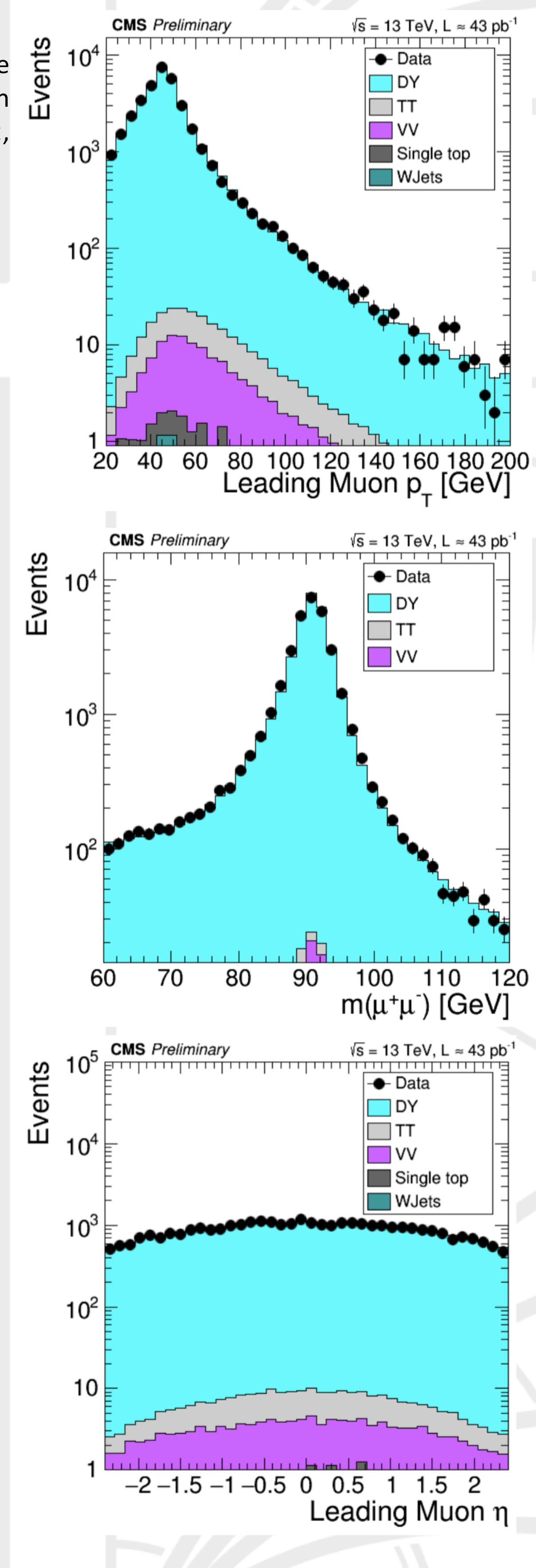
Muon collision data-Monte Carlo comparison [6]

Data
Collision data from the startup of the 2015 run at 13 TeV and 50 ns bunch spacing, double Muon dataset, integrated luminosity ~43 pb^{-1}.

Monte Carlo
Samples of Drell–Yan, W + jets, top-antitop, single-top, dibosons generated with MadGraph_aMC@NLO, detector alignment and calibration conditions as expected after about 1 fb^{-1} of integrated luminosity. Overall normalization of simulated distributions scaled to the data yield. No event re-weighting is applied to match the pileup distribution in data.

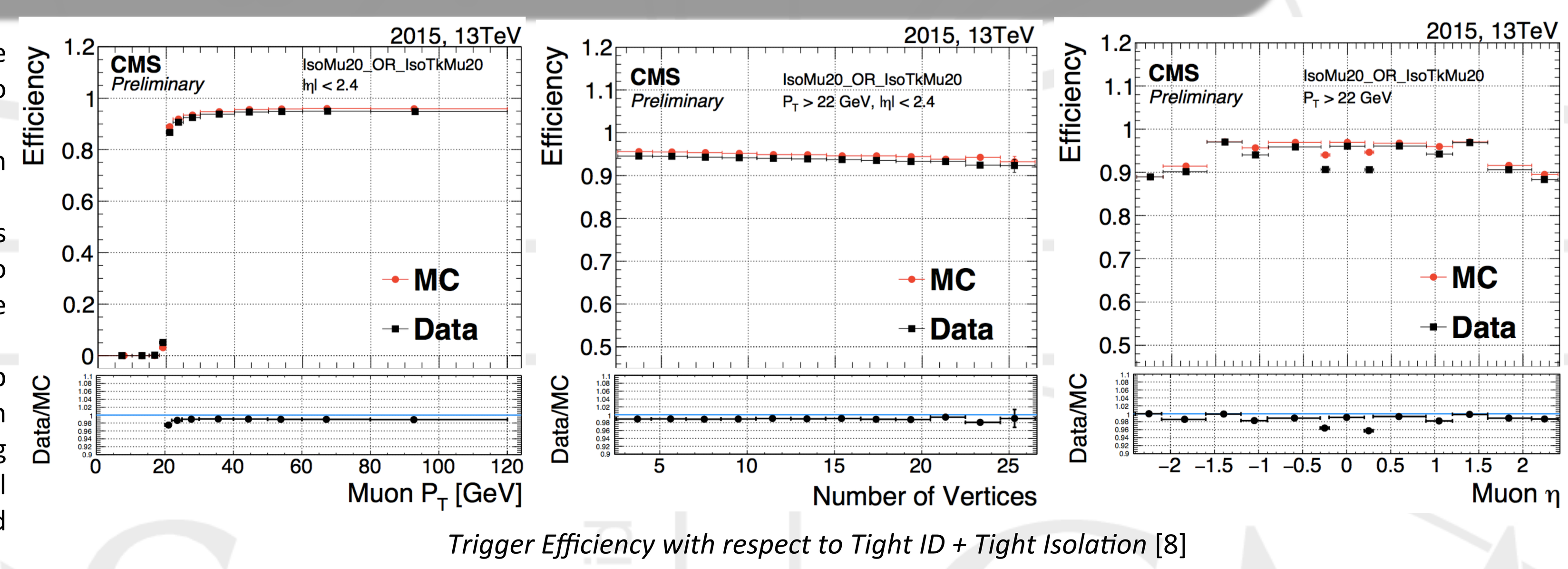
Trigger
Double-muon trigger with p_T thresholds of 17 and 8 GeV on higher- and lower-p_T muon, loose tracker-based isolation on each muon.

Offline selection
At least two opposite-sign muons passing the Loose ID , p_T >20 and 10 GeV, |η|<2.4, di-muon invariant mass between 60 and 120 GeV. If more than one muon pair satisfies the requirements above, the pair with invariant mass closest to the nominal Z boson mass is selected.



Muon trigger improvements in HLT

The muon triggers where updated with respect to the 2012 configuration. The CMS trigger is staged in two levels:
Level-1: hardware-based, uses information of the muon system exclusively.
High Level Trigger (HLT): software based, combines information from muon system and inner tracker to identify and reconstruct muons. Information from the calorimeters is also used to compute muon isolation.
Single muon HLT triggers: Tracking algorithms and pileup mitigation techniques were improved. Isolation computation updated from single isolation cut (combining tracker and calorimeter information) to sequential isolation cuts tuned independently for tracker and calorimeter components.
Double muon HLT triggers: A loose track based relative isolation cut was also added to both legs of the high pT double muon triggers to reduce rates and keep thresholds identical to the ones used at the end of Run I.



Trigger Efficiency with respect to Tight ID + Tight Isolation [8]

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[6] CMS Collaboration, *"Muon Reconstruction and Identification Improvements for Run-2 and First Results with 2015 Run Data"*, CMS DP-2015/015.
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