Updates on Performance of Physics Objects with the Upgraded CMS detector for High Luminosity LHC.

The CMS Collaboration

Abstract

This document contains a collection of performance plots obtained with the simulation of the upgrade Phase2 CMS detector for HL-LHC at the centre of mass energy of 14 TeV. Two pileup scenarios with and average $\bar{\mu} = 140$ and 200 collisions per event have been considered. We present updated results compared to the Technical Proposal (CMS-TDR-15-02) and Scope Document (CERN-LHCC-2015-019) for: track, muon, jet reconstruction and btagging performance. In addition, a set of plots containing studies of performance as a function of the linear pile up density along the beam axis are presented for tracking, vertexing, b-tagging, tau identification, muon isolation and missing $E_T$ resolution.
Updates on performance of physics objects with the upgraded CMS detector for HL-LHC, prepared for ECFA 2016

The CMS Collaboration
Updates on tracking performance

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Iterative tracking efficiency

Iteration by iteration tracking efficiency for a ttbar sample with average pileup of 140 reconstructed with Phase-II detector. The label of each iteration identifies the seeding algorithm used in it.

Denominator: simulated tracks produced with pseudorapidity(\(\eta\)) less than 3.5 and less than 3.5 cm from the centre of the beam spot in radial direction.

Numerator: denominator & associated to a reconstructed track;
Association: reconstructed track has >75% of hits from the simulated track.
Tracking efficiency as a function of $\eta$ (left) and transverse momentum (right) for $t\bar{t}$ events simulated for the Phase-II detector with superimposed pileup collisions of 140 (full dots) and 200 (open dots). Plots are produced for the subset of tracks passing the high-purity quality requirements. The results are for charged particles produced less than 3.5 cm from the centre of the beam spot in radial direction. The efficiency as a function of $\eta$ is for generated particles with $p_T > 0.9$ GeV.
Fraction of reconstructed tracks that are not matched to simulated charged particles as a function of $\eta$ (left) and transverse momentum (right) for $t\bar{t}$ events simulated for the Phase-II detector with superimposed pileup collisions of 140 (full dots) and 200 (open dots). Plots are produced for the subset of tracks passing the high-purity quality requirements.
Single muon efficiency

Tracking efficiency as a function of $\eta$ for single muon events with 10 GeV transverse momentum simulated for the Phase-II detector with superimposed pileup collisions of 140 (full dots) and 200 (open dots). Plots are produced for the subset of tracks passing the high-purity quality requirements. The results are for charged particles produced less than 3.5 cm from the centre of the beam spot in radial direction.
Comparison of resolution, as a function of pseudorapidity, in three track parameters for the current (black) and upgraded (red) detectors for single, isolated muons with transverse momentum of 10 GeV. From left to right: \( \phi \), \( \cot \theta \) and transverse momentum. For each bin in \( \eta \), the solid (open) symbols correspond to the half-width for 68% (90%) intervals centered on the mode of the distribution in residuals, as described in the text.
Updates on muon performance

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ME0 Bending Angle

- Bending angle of the tracks reconstructed in ME0 for muons with $p_T = 5$ GeV (red) and 30 GeV (black) in a PU200 environment. The track bending angle is computed as the difference in global phi of the first and the last crossed layer. The peak(s) in the distributions are due to the signal muons (from primary interaction), while the distribution superimposed to the signal is due to the pile-up particles (muons, pions, kaons) or to the particles coming from the neutron-induced background.
Muon ID selections

- **Tight**
  - Particle identified as a muon by the PF event reconstruction
  - Global muon track, including hits in the inner tracking system and in the muon detectors
  - At least one muon chamber hit used in the global track fit
  - Global track fit chi2/ndof < 10
  - Muon Inner track extrapolation matched to segments in at least two muon stations (by the Tracker Muon algorithm)
  - Hits on more than 5 layers of the inner tracking system
  - At least one pixel hit

- Cuts on the impact parameters in the transverse and longitudinal planes w.r.t. the primary vertex of the event: |d_{xy}| < 0.2 cm, |d_z| < 0.5 cm

- Largest summed squared p_T is no more able to identify the correct primary vertex (PV) at high PU
- The impact parameter calculation is done w.r.t. the PV closest in global z to the simulated vertex
Definitions

• **SIGNAL:**
  - Reconstructed/Identified muons associated to muons produced by the generator in the \(Z/\gamma^* \rightarrow \mu \mu\) event generation

• **FAKES/BACKGROUND:**
  - Mismatch TRK-MUO:
    • OOT muons associated to (uncorrelated) in-time TRK track
    • In-time muons from PU matched to an uncorrelated TRK track
  - Punch-through's
  - Muons from decays in flight of the main interaction
  - All the real muons coming from PU interactions
  - Duplicated muons
  - Reco/identified muons having only invalid hits in the muon system
Definitions

• **Efficiency:** # of simulated muons from signal process associated to a reconstructed or identified muons / # of simulated muons from signal process

• **Transverse momentum resolution:**
  
  \[ \frac{q}{p_T} = \frac{q^{\text{rec}}/p_T^{\text{rec}} - q^{\text{sim}}/p_T^{\text{sim}}}{(q^{\text{sim}}/p_T^{\text{sim}})} \]

  – Resolution is the core width = sigma parameter of the gaussian fit of the distribution
  – Range for the fit: [-0.3, +0.3]

• **Average Background Multiplicity:** number of reconstructed/identified muons not associated to any simulated signal muon over the total number events
Tight muon identification efficiency in $Z(*)/\gamma^* \rightarrow \mu\mu$ events as a function of the simulated muon pseudorapidity for the PhaseII detector and three pile-up scenarios: $<\text{PU}> = 0$ (blue), $<\text{PU}> = 140$ (black) and $<\text{PU}> = 200$ (red). A cut of 5 GeV/c is applied on the muon pT in order to suppress the soft muon contribution.
Tight ID efficiency vs. PU interactions

- Tight muon identification efficiency in $Z(*)/\gamma^* \rightarrow \mu\mu$ events as a function of the number of pile-up collisions for the PhaseII detector and three pile-up scenarios: $<\text{PU}> = 0$ (blue), $<\text{PU}> = 140$ (black) and $<\text{PU}> = 200$ (red). A cut of 5 GeV/c is applied on the muon $p_T$ in order to suppress the soft muon contribution.
Average background-muon multiplicity for the Tight Muon identification as a function of muon $p_T$. The plot shows the average number of background muons per event that are expected to pass the Tight ID selections for the PhaseII detector and three pile-up scenarios: $<\text{PU}> = 0$ (blue), $<\text{PU}> = 140$ (black) and $<\text{PU}> = 200$ (red). Level of background-muons is lower than $\sim 3 \times 10^{-3}/\text{event} / \text{GeV}$ if the Tight ID is applied.
Muon $p_T$ resolution vs. $|\eta|$ 

- Transverse momentum resolution in $Z(*)/\gamma^* \rightarrow \mu\mu$ events with a $p_T$ greater than 40 GeV as a function of the muon pseudorapidity, for the PhaseII detector and three pile-up scenarios: $<PU> = 0$ (blue), $<PU> = 140$ (black) and $<PU> = 200$ (red).
Displaced L1Mu trigger plots for approval targeting ECFA2016
The forward region is important for signatures with muon pairs of modest pT that require a dimuon trigger. The plot above is an example for dark SUSY events with 4 displaced muons in the signature, generated by Madgraph. The acceptance increases with 40% if the second leg is between 1.6 < |eta| < 2.4.

Note: this is distribution at generator level.
The installation of GE2/1 during Long Shutdown 3 will improve the local trigger efficiency and the direction measurement in station 2 at trigger level. The direction measurement is critical to reject soft mismeasured muons in the trigger. The plots compare the muon directions in station 1 and station 2 without GE2/1 installed (left) and with GE2/1 installed (right). The muon direction measurement in station 2 from GE2/1-ME2/1 is comparable to measurement in station 1 from GE1/1-ME1/1.
Current L1Mu assigns muon pT with assumption that muon originates from beam-spot, and therefore can not trigger on displaced muons above certain impact parameter. A displaced muon trigger algorithm is proposed that utilizes only the positions of the trigger stubs in 3 CSC stations and assigns muon L1 pT without a beam-spot constraint. The plot shows the turn-on efficiency of this proposed displaced muon trigger algorithm at 10 GeV trigger threshold in different eta regions. In low eta region (blue dots) this algorithm gives a sharp turn-on and decent efficiency in plateau. The magnetic field weakens closer to the beam-pipe (higher pseudo-rapidity). Therefore low pT muons bend less at higher eta. This results in less sharp turn-on curves in the high eta region (purple squares and green triangles).
Once GE1/1 and GE2/1 are installed the large lever arms between GE1/1-ME1/1 chamber pairs and between GE2/1-ME2/1 chamber pairs will allow for a good measurement of the muon directions in stations 1 and 2, respectively. A proposed displaced muon trigger algorithm based on the comparison of the muon directions in the two stations has good efficiency at trigger $p_T > 10$ GeV (above 90%) for muons independent of the impact parameter up to 50 cm. This algorithm provides a new handle to discriminate against low $p_T$ muons at L1 for displaced muon trigger.
The measurement of the directions in at least 2 muon barrel stations provides a handle to discriminate high pT muons from low pT muons independent of the impact parameter up to 50 cm. A proposed displaced muon trigger algorithm based on the comparison of muon directions in DT1 and DT4 has good efficiency at trigger pT > 10 GeV (above 90%).
The tracker-trigger has an excellent trigger performance for prompt muons. Displaced muons with impact parameter beyond dxy of 1 cm will not have matching track-trigger tracks (L1Tk). This can be used to veto the prompt muon trigger candidates associated to track-trigger tracks. The loose veto rejects prompt muons by matching a L1Tk within a radius R<0.12 with an L1Tk pT > 4 GeV. The medium and tight veto apply L1Tk pT cuts of 3 and 2 GeV respectively on L1Tk in R<0.12. The left plot compares the prompt muon trigger rate at 140 pileup (red) with the loose (orange), medium(green) and tight (blue) veto working points in the range 0<|eta|<2.4, and the right plot shows the corresponding rate ratio with respect to rate of prompt single muon. The loose veto reduces the trigger rate by a factor 2-3 while maintaining a trigger efficiency of 95% at 20 GeV trigger pT. Medium and tight veto have larger reduction factors, between 3-4 and 5-7 respectively, but are less efficient at trigger pT > 20 GeV, namely 94% and 84% respectively.
Updates on performance of tagging b-jets

The CMS Collaboration
Characterization of the b-tagging performance, expressed as mis-identification probability for udsg-jet (left) and c-jet (right) as a function of b-jet tagging efficiency for jets with $p_T > 30$ GeV and $|\eta| < 2.4$. Simulated ttbar events are used in Phase-I conditions with $<\text{PU}> = 50$ (black) or $<\text{PU}> = 140$ with aging (gray), and for Phase-II condition with $<\text{PU}> = 140$ (red) or 200 (green). Events are selected only if the correct primary interaction vertex is reconstructed.

The b-tagging performance for the Phase-I aged detector scenario at high pileup is significantly degraded compared to Phase-I without aging at medium pileup. However the performance in Phase-II largely compensates that performance loss, despite the higher number of pileup collisions.
Characterization of the b-tagging performance, expressed as mis-identification probability of udsg-jet as a function of b-jet tagging efficiency for jets with $p_T > 30$ GeV and pseudorapidity $|\eta| < 1.8$ (left) and $1.8 < |\eta| < 2.4$ (right). Simulated ttbar events are used in Phase-I conditions with $<\text{PU}>= 50$ (black) or $<\text{PU}>= 140$ with aging (gray), and for Phase-II condition with $<\text{PU}>= 140$ (red) or 200 (green). Events are selected only if the correct primary interaction vertex is reconstructed.

The b-tagging performance for the Phase-I aged detector scenario at high pileup is significantly degraded compared to Phase-I without aging at medium pileup. However the performance in Phase-II largely compensates that performance loss, despite the higher number of pileup collisions.
Jets and Jet Energy Correction Performance Studies for HL-LHC

The CMS Collaboration
Jets and Jet Energy Corrections at CMS

Applied on data → From in-situ MPF/Z-jet, flat in $p_T$

- Reconstructed Jets
  - pileup ($A, \rho, p_T, \eta$)
  - pileup ($A, \rho, p_T, \eta$)
  - MC ($p_T, \eta$)

- Applied on MC
  - L1
  - L2L3
  - L2L3Res

- Calibrated Jets
  - dijets ($\eta$)
  - $\gamma$+Jet/Z+Jet

- Upgraded Detector Geometries:
  - The technical proposal (TP) plots use the upgraded, but flat outer tracker, muon system and calorimetry with an extended phase-I pixel detector.
  - Compared to the TP geometry, the following study, limited to jets within $|\eta| < 1.3$, includes the update to the “tilted geometry” of the outer tracker modules, and un-aged calorimeter in the central region.
  - The plots for approval use 9000 events from the CMSSW_8.1.0_pre8 RelVal samples:
    - PU0: /RelValTTbar_14TeV/CMSSW_8.1.0_pre8-PU25ns_81X_mcRun2_asymptotic_v1_2023tilted-v1/GEN-SIM-RECO
    - PU140: /RelValTTbar_14TeV/CMSSW_8.1.0_pre8-PU25ns_81X_mcRun2_asymptotic_v1_2023tiltedPU140-v1/GEN-SIM-RECO
    - PU200: /RelValTTbar_14TeV/CMSSW_8.1.0_pre8-PU25ns_81X_mcRun2_asymptotic_v1_2023tiltedPU200-v1/GEN-SIM-RECO
Response of uncorrected PF jets as a function of $p_T^{GEN}$ for $\mu = 140$ (left) and $\mu = 200$ (right) using the new phase-II simulations. The response for the $\mu = 140$ simulation is about the same as in the TP and the response for the $\mu = 200$ sample scales similarly.
Response of corrected PF jets as a function of $p_T^{\text{GEN}}$ for $\mu = 140$ (left) and $\mu = 200$ (right) using the new phase-II simulations. Using jet energy correction (JEC) derived especially for these sample and pileup (PU) regimes we can correct the jets to a response which is approximately 1 and remove the response dependence on $\mu$. There is some remaining non-closure for the $\mu = 0$ curves. It may be that the L2L3 corrections derived from $\mu \geq 140$ samples are not applicable to a $\mu = 0$ sample.
Response

Response of **uncorrected** PF+Puppi jets as a function of $p_T^{\text{GEN}}$ for $\mu = 140$ (left) and $\mu = 200$ (right) using the new phase-II simulations. Basic, uncorrected PUPPI jets perform almost as well as fully corrected PF jets. The PUPPI algorithm removes most of the pileup energy and $\mu$ dependence before additional corrections are applied. The response is slightly less than 1, which is expected because the jet energy hasn’t been corrected for any $p_T$ or $\eta$ dependencies. PUPPI works equally well for $\mu = 200$ as it does for $\mu = 140$. Unlike in the TP, PUPPI was not specifically tuned for the new simulations and its performance will improve after tuning.
Response of corrected PF+Puppi jets as a function of $p_T^{GEN}$ for $\mu = 140$ (left) and $\mu = 200$ (right) using the new phase-II simulations. After applying the JEC the PUPPI jet’s response is very close to 1. The response will improve with more events in the simulation with which to derive JEC, additional upgraded pieces of the detector simulation, and a tuned version of PUPPI. There is some remaining non-closure for the $\mu = 0$ curves. It may be that the L2L3 corrections derived from $\mu \geq 140$ samples are not applicable to a $\mu = 0$ sample.
Corrected jet response resolution as a function of $p_T^{GEN}$ for $|\eta| < 1.3$ (left) and $1.3 < |\eta| < 2.5$ (right) using the current $\mu = 140$ phase-II simulations. The AK4PFPuppi curve (yellow) can be compared to the green markers on the corresponding TP plots (figure 9.5). This shows that the current simulation has similar, if not better jet resolution than seen in the TP. It is yet to be seen if this is due to the lack of phase-II calorimetry in the new simulation. Unsurprisingly, PF+Puppi performs better than the other jet collections. Even if the JEC are able to correct the response of all jet collections equally well, there will still be an improvement to the resolution by using PUPPI.
Corrected jet response resolution as a function of $p_T^{GEN}$ for $|\eta| < 1.3$ (left) and $1.3 < |\eta| < 2.5$ (right) using the current $\mu = 200$ phase-II simulations. This is an extension of figure 3, which shows only a small loss in resolution at low $p_T^{GEN}$ when moving to a higher PU profile. PF+Puppi jets continue to have the best resolution.
Resolution In Various Pileup Regimes

Corrected jet response resolution in the barrel ($|\eta| < 1.3$) as a function of $p_T^{\text{GEN}}$ for $\mu = 140$ (left) and $\mu = 200$ (right) using the new phase-II simulations. The pileup removal JEC are doing a reasonable job of removing the $\mu$ dependence for the resolution, at least for $p_T^{\text{Ref}} > 50$ GeV. Below that it is hard to say anything when only using 9000 events.
References


CMS Pile-Up Density Studies
Introduction to Tracking Studies vs density

- Showing the following quantities vs. pileup density
  - Tracking efficiency
  - Tracking fake rate
  - Number of reconstructed vertices vs simulated vertices
  - Primary vertex (PV) reconstruction + tagging efficiency
  - Track-PV association efficiency, fake rate, and pileup rate

- Studies made with the following beamspot configurations
  - Box-shaped beamspot with ±5 cm, ±11 cm, ±15 cm, and ±20 cm
    - Quantity of interest is limited to |z| < 5 cm, using average pileup density of the sample
  - Gaussian beamspot with σ=4.4 cm and σ=3.3 cm
    - Quantity binned in z, using average pileup density in that z bin
  - All cases with pileup 140 and 200
Tracking efficiency as a function of pileup density for the box-shaped and gaussian beamspots for simulated tracks with $p_T > 0.9$ GeV and $d_0 < 3.5$ cm. In addition, for box-shaped beamspots the origin of the simulated tracks is restricted to $|z| < 5$ cm. The efficiency is independent of both the pileup density and the overall pileup scenario.
Tracking fake rate as a function of pileup density for the box-shaped and gaussian beamspots for tracks with $p_T > 0.9$ GeV. In addition, for box-shaped beamspots the track $d_z$ wrt. origin and the simulated primary vertex $z$ are restricted to $|z| < 5$ cm. The fake rate is largely independent of the pileup density for a given overall pileup scenario, but does depend on the scenario itself.
Reconstructed vs. simulated vertices

The ratio of the number of reconstructed vertices and the number of simulated vertices, extracted as a slope of a linear fit to a 2D scatter plot, for box-shaped beamspots. With higher pileup density, less vertices per interaction are reconstructed. The ratio also depends on the overall pileup scenario. The vertices are reconstructed as in Run1 without any tuning for high pileup.
The efficiency to reconstruct and tag the primary vertex (PV) as a function of pileup density for the box-shaped and gaussian beamspots. The vertex with the highest $\sum p_T^2$ is tagged as the PV. For box-shaped beamspots the simulated PV is restricted to $|z| < 5$ cm. The efficiency is largely independent of the pileup density for a given overall pileup scenario, but does depend on the scenario itself.
The efficiency of tracks associated to the reconstructed PV with $|dz(PV)| < 1$ mm as a function of pileup density for the box-shaped and gaussian beamspots for events where the PV is correctly reconstructed and tagged. In addition, for box-shaped beamspots the simulated PV position is restricted to $|z| < 5$ cm. The efficiency is independent of both the pileup density and the overall pileup scenario.
The rate of fake tracks associated to the reconstructed PV with $|dz(PV)| < 1$ mm as a function of pileup density for the box-shaped and gaussian beamspots for events where the PV is correctly reconstructed and tagged. In addition, for box-shaped beamspots the simulated PV position is is restricted to $|z| < 5$ cm. With higher pileup density the fake rate is also higher. The fake rate also depends on the overall pileup scenario.
The rate of pileup tracks associated to the reconstructed PV with $|dz(PV)| < 1$ mm as a function of pileup density for the box-shaped and gaussian beamspots for events where the PV is correctly reconstructed and tagged. In addition, for box-shaped beamspots the simulated PV position is is restricted to $|z| < 5$ cm. With higher pileup density the pileup rate is also higher, but is independent of the overall pileup scenario.
B-tag efficiency study

Efficiency of b-jet tagging as a function of the density of pileup (PU) events along the beam axis (z). The b-jet tagging efficiency is computed for a fixed mis-identification probability of udsg light jets of 0.01. Statistical errors are shown, including those on the choice of the operating point. Results are based on ttbar Monte Carlo simulation for Phase-II conditions with \( <PU> = 140 \) (red) or 200 (green). Two event samples are generated with a gaussian beam spot along \( z \) of width \( \sigma(z) = 3.3 \text{ cm} \) or \( 4.4 \text{ cm} \). For each sample, the b-jet efficiency is computed by selecting events in three ranges according to the generated \( z \) value of the hard interaction: \( |z| < 2 \text{ cm} \), \( 2 < |z| < 4 \text{ cm} \), \( 4 < |z| < 6 \text{ cm} \), determining distinct PU density regions.

The displayed lines are fits to the \( \sigma(z) = 4.4 \text{ cm} \) samples which have a large number of events. The hatched area describes the systematics due to the comparison between gaussian and flat generated beam spots. The computation of the b-jet tagging efficiency includes those events with a wrongly identified primary interaction vertex. The b-jet tagging efficiency is found smaller at 200 PU than at 140 PU. For each PU condition, a trend is observed to have a smaller b-jet tagging efficiency as the PU density increases.
Efficiency of identifying isolated hadronic tau lepton decays as a function of the local density of pileup (PU) events along the beam axis. Only statistical uncertainties are shown. The efficiency is computed using $Z/\gamma^* \rightarrow \tau\tau$ events while keeping the jet-to-tau misidentification probability constant at 2\% in top quark pair events. Only objects with $p_T > 22$ GeV and $|\eta| < 2.1$ are considered, and there are requirements both on the reconstructed particle configuration (to be compatible with hadronic tau lepton decays) and the isolation in terms of the transverse momentum sum of charged particles in the vicinity. The methodology is the same as used for tau identification during LHC Run 2 [1].

Results are based on simulation samples for the Phase-II upgrade of the CMS detector, with an average pile-up of 140 or 200 events. They have either a Gaussian distribution of the beam spot along the beam axis with a standard deviation of 33 mm or a flat profile within a nominal distance to the detector origin of ±50 mm. The flat profile corresponds to a density of 1.4 events/mm (PU=140) and 2 events/mm (PU=200).

A clear trend of decreasing efficiency can be observed with respect to the pile-up density.

Selection efficiency of the “loose” muon track isolation working point is plotted vs. linear pileup density for 200 pileup and 140 pileup beamspots with 33mm width. The isolation variable is calculated by summing the transverse momentum of tracks in a cone of $\Delta R < 0.3$ about the muon, using only the tracks with a vertex fitting weight of 0.5 or greater. The working point is defined by requiring the isolation sum divided by the muon’s transverse momentum be greater than 0.10. The efficiency is calculated with respect to generator-matched reconstructed muons, requiring only that the muon transverse momentum be larger than 20 GeV.

The study is carried out with a fixed working point, and is therefore pessimistic compared to the efficiency at fixed background rejection. A 2-4% global reduction in efficiency is seen between 200 and 140 pileup scenarios, and there is a strong negative trend in the efficiency as a function of vertex density.
Distribution of the perpendicular hadronic recoil as computed with PUPPI in Z→μμ events as a function of the local particle density defined by the position of the primary vertex with respect to the full simulated beam profile.

Resolution is shown as a function of the average number of pileup events per mm for flat beam profiles with 200PU (red) and 140 PU (yellow) samples and for a gaussian beam profile sample(blue). The hadronic recoil is response corrected for all cases. A line is fit to the gaussian beam profile sample(blue) to guide the eye.