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Future physics potential of the CMS Phase II detector

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To extend the LHC physics program, it is foreseen to operate the LHC in the future with an unprecedented high luminosity. To maintain the experiment's physics potential in such harsh environment, the detector will need to be upgraded. At the same time the detector acceptance will be extended and new features such as a L1 track trigger will be implemented. Simulation studies evaluated the performance of the new, proposed detector components in comparison to the present detector with the expected aging after $1000\,\mathrm{fb}^{-1}$. The impact of the expected Phase II performance on representative physics channels is studied. The sensitivity to find new physics beyond the SM is significantly improved and will allow to extend the SUSY reach, search for dark matter and exotic long-lived signatures. Precision Higgs and standard model measurements will gain substantially due to the improved performance.

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1. Introduction

The CMS detector at the CERN LHC was designed to reconstruct all physics objects [1], including light quarks and gluons manifested as jets, heavy quarks, charged leptons and photons, with high efficiency, good resolution and low fake rate. It is foreseen to operate the LHC in the future at unprecedented high luminosity regime, i.e. the HL-LHC or Phase II, to extend its physics program. Luminosity will be leveled at $\approx 5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, resulting in an average of about 140 superimposed events (pileup, PU) per bunch crossing. The CMS detector will need to be upgraded accordingly, to maintain its physics potential in such environment, featuring an extended acceptance and novel features, such as a Level 1 (L1) track trigger.

The purpose of the Phase II CMS upgrade is to preserve the object quality that will be achieved during the current decade, but at the significantly higher luminosity and PU of the HL-LHC [2]. In fact, if typical object performance falls by even about 10%, the sensitivity to a particular complex final state can easily be degraded by more than 50%, effectively negating 5 years of HL-LHC running. The goal of the design of the Phase II upgrade is to equal or exceed, at pileup of 140, the performance of the Phase I detector at pileup of 50. Simulation studies evaluated the performance of the new proposed CMS detector in comparison to Phase I at nominal condition and aged after the collection of 1000 fb^{-1} of integrated luminosity.

2. The CMS detector performance in Phase II scenario

The main features of the CMS Phase II design include: A) a new silicon tracker, featuring a 4 times larger granularity than current one, improved resolution, a reduced material budget, the capability of providing L1 trigger information, and high pseudorapidity coverage with extended forward pixels up to $|\eta| \leqslant 3.0$; B) a High Granularity Calorimeter (HGCal) in the endcap, with silicon sensors providing 3D shower profiles; C) an improved muon system in the endcap, enhanced with GEM and RPC up to $|\eta| \leqslant 3.0$; D) a new approach to L1 trigger with higher latency and acceptance rate.

New reconstruction algorithms have been developed on the basis of the Run I experience, and have been adapted for the Phase II scenario. A complete and accurate description of each hard-scattering event will be provided by the reconstruction of all the physics objects in a unique manner, i.e. an exclusive list of particle candidates to be used as physics objects or that can seed more complex algorithms, such as jet, tau or missing transverse energy (MET) reconstruction [3].

The expected performance of object reconstruction is summarized in Figures 1 to 6. A new primary vertex (PV) reconstruction [5] is needed as one third of PVs per event, typically, cannot be reconstructed because of the small amount of low-p_T tracks per interaction, vertex merging, and a 5 cm luminous region RMS length.

Jets are the experimental signatures of the production of quarks and gluons in high-energy processes [3]. A new approach to pileup mitigation (called PUPPI) is being designed to remove PU-induced offsets and effects of detector and reconstruction imperfections [4]. MET is defined as the imbalance in the transverse momentum of all visible particles in the final state [6], and is often under-measured because of calorimeter threshold, track reconstruction inefficiency, non-linear

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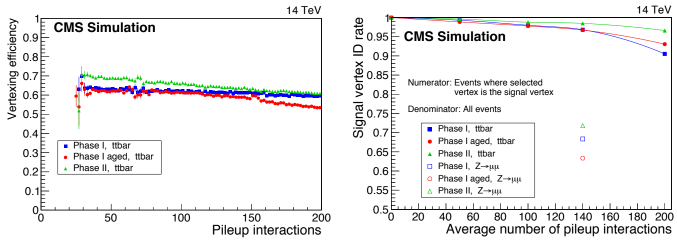

Figure 1: For the three detector conditions: (left) The efficiency for reconstructing and matching all generated vertices (signal and pileup) vs pileup; (right) the ratio of the number of events in which the vertex identified as the primary vertex by the new algorithm is matched to the generated signal vertex to the total number of events, plotted vs. pileup.

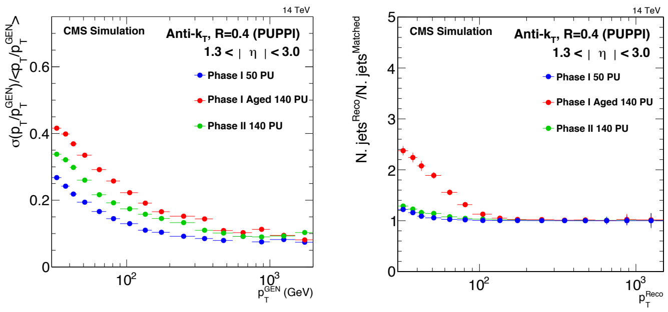

Figure 2: For the three detector conditions: (left) jet response resolution of corrected PUPPI jets as a function of jet p_T for jets (left) in the $1.3 < |\eta| < 3.0$ region; (right) ratio of the number of reconstructed PUPPI jets to the number of reconstructed jets matched to particle level jets for different p_T bins.

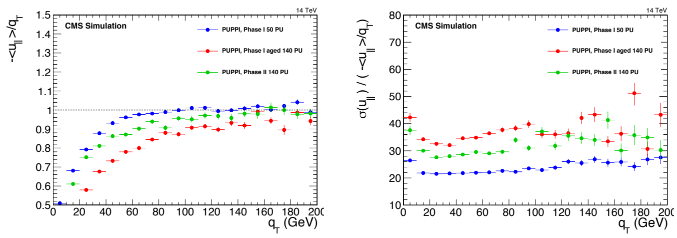

Figure 3: For the three detector conditions: (left) response curves of the hadronic recoil component parallel to Z boson as a function of Z boson q_T and (right) resolution curves for the parallel component of hadronic recoil to Z boson, measured in $Z \to \mu\mu$ events.

detector response. Performance evaluation of MET reconstruction is based on the measurement of hadron recoil in $Z \to \mu\mu$ events.

b-tagging is the identification of b-hadron decays distinctive signatures, such as displaced tracks, secondary vertices, soft leptons in jets [7]. Correct association to primary vertex is more difficult at high PU, and will be improved since Run I with inclusive vertex finder, and extended with forward pixels up to $|\eta| < 3.0$.

Electron and photon reconstruction will benefit from the upgraded ECAL readout in the barrel, the new HGCAL in the endcap which will be crucial to mitigate PU effects, the reduced

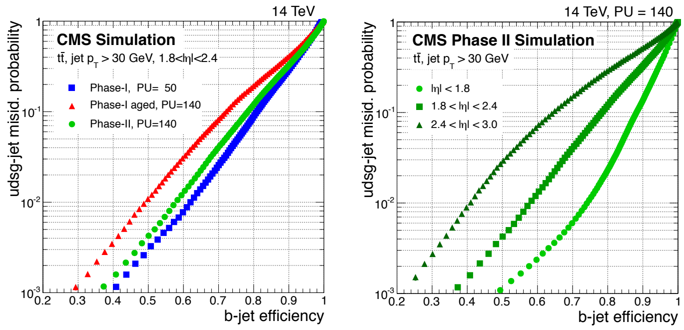

Figure 4: For the three detector conditions: characterisation of the b-tagging performance, expressed as mis-identification probability for $udsg$-jet as a function of b-jet tagging efficiency for jets with $p_T > 30\,\text{GeV}$ in top pair production events (left) for $1.8 < |\eta| < 2.4$ and (right) for different η ranges in the Phase II configuration.

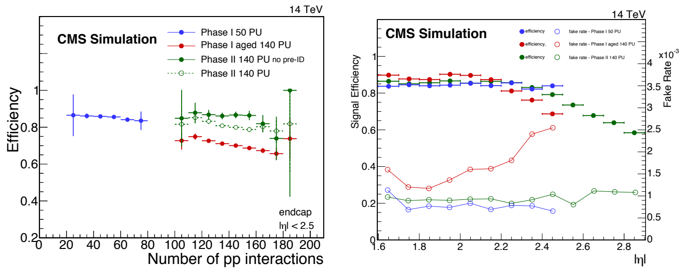

Figure 5: For the three detector conditions: (left) electron reconstruction efficiency in the HGCAL endcaps as a function of the number of pileup interactions per crossing in DY events; (right) photon selection efficiency and fake rate in the endcaps in bins of $|\eta|$.

bremsstrahlung and conversions in the tracker reducing fake rate and improve energy measurement [8, 9]. Muon reconstruction in the forward region will be preserved with extending coverage and redundancies at $|\eta| > 1.6$, where fluxes are higher [10]. Also, calorimeter upgrades will preserve the reconstruction of hadronic decays of tau leptons starting from light hadrons inside jets [11].

3. Highlights of the physics program with CMS in the Phase II scenario

The Standard Model (SM) is known to be an incomplete theory that cannot describe many observations and that requires some critical parameters, such as the Higgs boson mass, to be unnaturally fine tuned. The physics program at the HL-LHC will continue the quest about, among all, the nature of Dark Matter, the origin of matter-antimatter asymmetry and the origin of particle mass hierarchy, trying to clarify which of the proposed extensions of the SM should be rejected and which can be a realistic option for the future.

After the Run I observation, the Higgs boson mass is measured with a precision of 0.2%, while other properties are typically measured with a precision of 20%. Measurements of its self-coupling, coupling to fermions and bosons, partial and total widths, rare decays and a detailed CP analysis are paramount in the HL-LHC program (Figure 7).

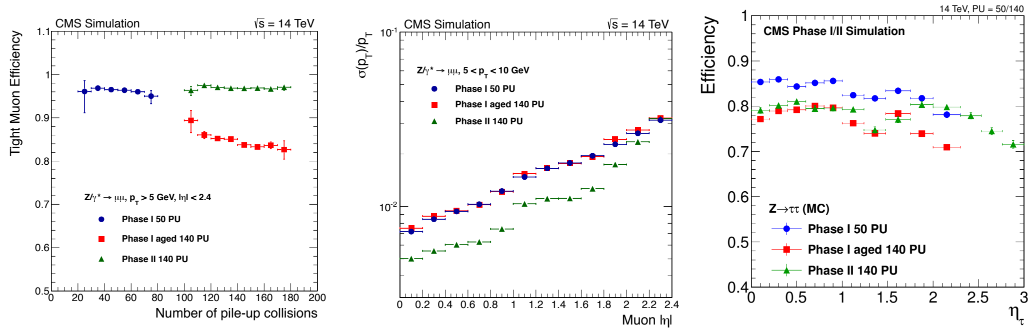

Figure 6: For the three detector conditions: (left) muon identification efficiency in DY events for the "tight" working point as a function of the number of simulated pileup interactions; (middle) muon p_T resolution estimated in a simulated Drell-Yan sample for low p_T muons as a function of the muon $|\eta|$; (right) efficiency of the selection of true taus with visible $p_T > 20$ GeV matched to a reconstructed tau candidate with $p_T > 20$ GeV using the tight working point of BDT-based electron rejection as a function of reconstructed tau $|\eta|$.

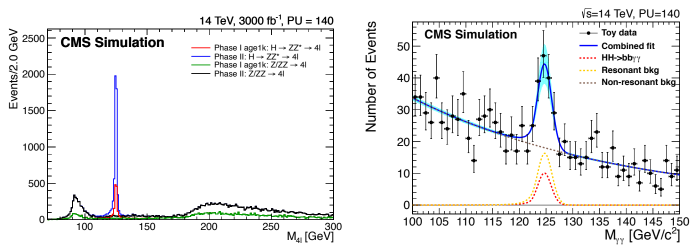

Figure 7: (left) Four lepton mass distributions obtained with 3000 fb^{-1} for the signal $H \to ZZ \to 4\ell$, and for the irreducible $ZZ \to 4\ell$ background, in the Phase II and in the aged Phase I configurations at pileup of 140. The complete final state reconstruction leads to a high purity signal peak over a smooth background distribution. The four lepton events allow for a detailed CP analysis of the Higgs particle by measuring angular distributions. Excellent electron and muon reconstruction at low transverse momentum and a large rapidity coverage are crucial as all 4 leptons are needed for an accurate reconstruction. Any single object inefficiency is potentiated. (right) Diphoton mass distributions obtained with 3000 fb^{-1} for the signal $HH \to bb\gamma\gamma$ in the Phase II configuration at pileup of 140. Higgs boson pair production at the HL-LHC will provide insight on Higgs boson trilinear coupling directly probing the Higgs field potential. Higgs pair production cross section is about 1000 times smaller than for single Higgs. An observation will be possible combining the $bb\gamma\gamma$, $bb\tau\tau$, $bbWW$ final states and results from both Atlas and CMS experiments.

The search for evidence of super-symmetries (SUSY) has been a major goal of the LHC program, exploring a wide range of scenarios. Extensive studies will be needed in case of evidence of new particles and to understand how SUSY is broken, requiring all the capabilities of the CMS detector during the whole HL-LHC run. Alternative models of new physics shall be explored in the absence of SUSY signals. Enhanced detector acceptance in the forward region, improved granularity and resolution will help to disentangle new models in case of a signal. Typical searches include, among others: new massive neutral resonances, Dark Matter in mono-jet or W + MET events, heavy stable charged particles and displaced signatures (Figure 8). Some searches demand special trigger and detection capabilities, like being sensitive to highly ionising particles, displaced vertices or very low-momentum tracks.

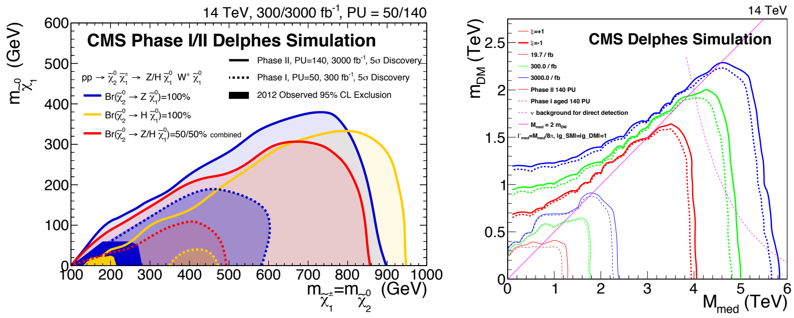

Figure 8: (left) Chargino/neutralino Search for chargino-neutralino production in the WZ + MET and WH + MET final states. The excluded regions are shown in the simplified model parameter space for various assumptions. The excluded region is bounded by the decreasing production cross section on the right, but by the decreasing MET as one approaches the diagonal. (right) Dark Matter Reach of the monolepton channel as a function of the DM mass and mediator mass for the two extreme cases of $\xi = \pm 1$.

Measurements of heavy-flavor physics at Run I proved CMS to be competitive despite being a non-dedicated experiment. The HL-LHC will offer new possibilities to study rare decays, exploiting larger muon acceptance, higher granularity and L1 track trigger to build L1 low mass dimuon candidates (Figure 9).

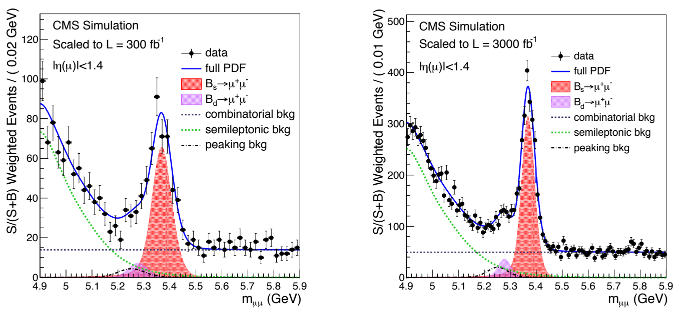

Figure 9: $B^0_{s,d} \to \mu\mu$ Projections of the mass fits to 300 fb^{-1} (left) and 3000 fb^{-1} (right) of integrated luminosity, respectively assuming the expected performances of Phase I and Phase II CMS detector. Both plots are limited to the barrel region. The improved invariant mass resolution allows to disentangle the two peaks. Sensitivity for the observation of the $B^0_d \to \mu\mu$ decay is expected to be about 6.8σ at the HL-LHC with the CMS Phase II detector.

Another key point of the HL-LHC physics program is Vector Boson Scattering (VBS). It is expected to be very sensitive to any new physics in EW sector, and it is currently unobserved. A VBS signal will be accessible when two quarks from the beams emit vector bosons interacting with each other, and deflected quarks originate peculiar tag jets: HL-LHC can be used as a vector boson collider, providing access to purely electroweak processes in a high energy regime. VBS observation is challenging because of large irreducible background. New central tracker is beneficial in reducing the jet-lepton misidentification rate and its extension to $|\eta| \leqslant 4.0$, with HGCal, reduces contamination from pileup. Preliminary studies show that the upgraded CMS detector will recover the performance of the Phase I and in some cases grant an improvement in the necessary performance for the verification of the EWSB in a model-independent way.

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