CMS experimental results

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Abstract. The main goal of QCD studies is to improve our detailed description of the Standard Model physics. Studies of QCD are key to understand production of all BSM signals and backgrounds at the LHC. QCD measurements are important for data interpretation, background studies and precision studies. This study is focussed on the recent interesting results from the CMS Experiment at CERN.

1 Introduction

LHC provides experimental access to large phase space, accurate results from various final state, studies with PDFs, etc. These help to perform many important and interesting QCD studies experimentally. In this article, the recent results from CMS Experiment [1] have been presented. The results are mainly related to Higgs Physics, Exotica, Top Quark, Standard Model Physics and B-Physics.

2 Recent results related to Higgs Boson

2.1 Higgs Boson mass and width

Higgs Boson mass (m_H) is one of the most important free parameters of SM. Other Higgs Boson properties depend on mass. With $H \rightarrow ZZ^* \rightarrow 4l$ decay, the value reads, $m_H = 125.08 \pm 0.12(\pm 0.10\ (stat) \pm 0.07\ (syst))\ GeV$ using $Run\ 1 + 2$ results [2]. Higgs Boson width is measured in $H \rightarrow ZZ$ channel, instead of direct measurement. Full Run 2 data has been used. The on-shell and off-shell productions have been compared in different decay channels. The measured value is, $\Gamma_H = 2.9^{+1.9}_{-1.4}$ MeV. Observed (expected) upper and lower 95% CL is, $0.6 < \Gamma_H < 7.0\ (0.1 < \Gamma_H H < 10.5)$ MeV. The measured Higgs widths are compatible with the SM prediction [3].

With the channel $H \rightarrow \gamma\gamma$ the value of mass becomes, $m_H = 125.38 \pm 0.14\ [\pm 0.11(stat) \pm 0.08(syst)]$ GeV The 1σ and 2σ CL intervals are determined considering the asymptotic approximation is valid.

2.2 Search for rare decays of the Higgs boson into a photon and meson

This process is sensitive to light quark Yukawa coupling, may become significant in BSM scenarios. Higgs boson decays into a photon and a $\rho^0(770),\ \phi\ or\ K^{*0}(892)$ meson are

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searched by using proton-proton collision data collected by the CMS experiment at the LHC at $\sqrt{s} = 13\ TeV$. Events are selected in which the mesons decay into pairs of charged pions, pairs of charged kaons, and charged kaon-pion pairs respectively. $B\,(H \to \phi\gamma) \sim 10^{-6}$, $B\,(H \to \rho^0\gamma) \sim 10^{-5}$ and $B\,(H \to K^{*0}\gamma) \sim 10^{-19}$, the decays are powerful probes of possible anomalous flavour-changing Higgs boson couplings. This analysis uses single photon and meson/VBF jet trigger for partial Run-2 data (ggF and VBF modes) and lepton triggers for full Run-2 (VH production). Analysis is done by the reconstruction of photon and di-track invariant mass, mass windows applied to di-track system to mitigate meson misidentification. Signal selection has been improved using multivariate classifier.

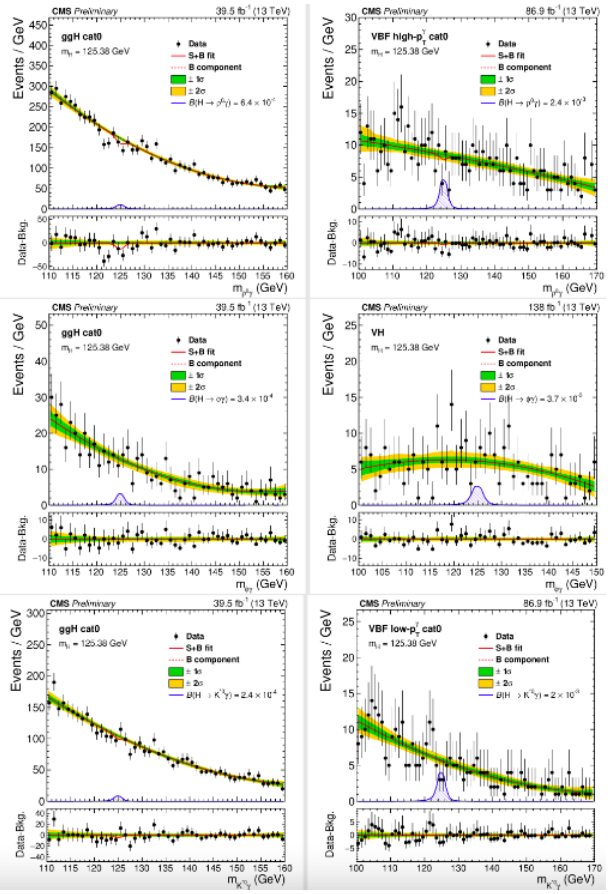

Figure 1. Post-fit m_{M_γ} distributions in data and the background model for ggH cat0 (upper left) and VBF high-$p_T^\gamma/cat0$ (upper right) of the $H \to \rho^0\gamma$ search, ggH cat0 (middle left) and the VH category (middle right) of the $H \to \phi\gamma$ search, ggH cat0 (lower left) and the VBF low-$p_T^\gamma/cat0$ (lower right) of the $H \to K^*(892)^0\gamma$ search. The signal simulation is shown normalized at a branching fraction corresponding to the expected upper limit [4]. Signal and background fit components, as well as 1- and 2-σ fit uncertainty bands are also shown.

Upper limits at the 95% confidence level on the Higgs boson branching fractions constitute the most stringent experimental limits to date [4], as shown in the Fig. 1.

The interesting results of a model-independent search for the pair production of new bosons decaying into muons in proton-proton collisions at $\sqrt{s} = 13 TeV$ has been discussed in Ref [5].

3 Recent results related to Exotica

3.1 Search for low-mass long-lived particles decaying to displaced jets in proton-proton collisions at $\sqrt{s} = 13.6$ TeV

A search for low-mass long-lived particles (LLPs) decaying into jets has been performed using proton-proton collision data corresponding to an integrated luminosity of 34.7 fb^{-1}, collected at a center-of-mass energy of 13.6 TeV in 2022 [6]. Novel techniques in trigger, reconstruction, and machine learning were developed for and employed in this search, leading to significant improvements over existing results. The observed yields are consistent with the background predictions. The best limits to date are set for LLPs with masses between 15 and 55 GeV and with proper decay lengths smaller than $\sim 1\ m$. The search provides the first exclusions of hadonically decaying tau leptons with decay lengths smaller than $\sim 1\ m$. The branching fraction limits outperform previous results by a factor of up to 10 (8) as shown in Fig. 2.

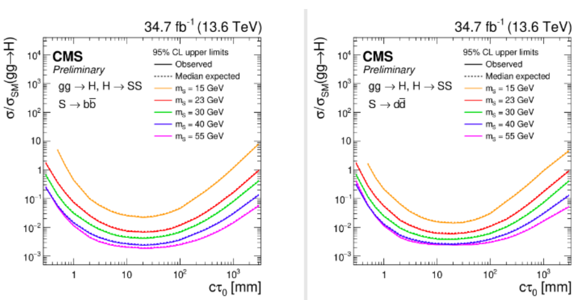

Figure 2. The 95% CL upper limits on the branching fraction B ($H \rightarrow SS$) for $S \rightarrow b\bar{b}$ (upper left) and $S \rightarrow d\bar{d}$ (upper right) for different LLP masses m_s and proper decay lengths $c\tau_0$ [6].

3.2 Search for new physics with emerging jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

A search for emerging jet signatures arising from a strongly interacting dark sector produced in hadron collisions has been presented, using data corresponding to a total integrated luminosity of 138 fb^{-1} at $\sqrt{s} = 13\ TeV$ [7]. The signal model contains a family of dark quarks that couples to the SM quarks via a scalar mediator X_{dark}. Dark pions (π_{dark}) with a significant lifetime are produced by the hadronization of the dark quarks and then decay to SM particles at vertices displaced from the original interaction point. As the scalar mediator is assumed to be produced in pairs, with each decaying to a SM quark and a dark quark, the signature of this process is two SM jets plus two jets of particles with the constituents emerging from displaced vertices. Both unflavored and flavor-aligned couplings between the SM quarks and the dark quarks are examined in the search. The selection criteria were optimized for each class of couplings and as a function of the mediator particle mass, the dark pion mass, and the dark pion lifetime, using both a traditional cut-based selection and a graph neural

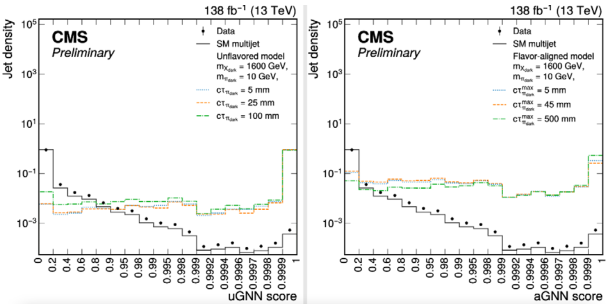

Figure 3. Distributions of the GNN output score for jets obtained from SM multijet simulation events (dark gray line), signal jets from the unflavored model (colored lines, left), and signal jets from the flavor-aligned models (colored lines, right). Results of the uGNN (aGNN) are shown on the left (right). The performance of the GNN varies only slightly over a wide range of the $c\tau$ of the dark mesons. The distributions are normalized to unit area [7].

network. The observed 95% confidence level exclusion limits agree with the expected limits. For the unflavored model, dark mediator masses up to $m_{X_{dark}} < 1950$ GeV are excluded for $c_{\tau_{\pi_{dark}}} \sim 100$ mm and $m_{\pi_{dark}} \sim 10$ GeV, while the flavor-aligned model result excludes $m_{X_{dark}} < 1850$ GeV at $c_{\tau_{\pi_{dark}}} \sim 500$ mm for $m_{\pi_{dark}} \sim 10$ GeV. This result as presented in Fig. 3, greatly surpasses the previous search for emerging jets in the unflavored scenario, increasing the experimental limit of the dark mediator particle by ~ 500 GeV to set the most stringent limits to date, and provides the first direct exclusion of the flavor-aligned scenario.

4 Recent results related to top quarks

4.1 Observation of quantum entanglement in top quark pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV

It is fascinating to see how the largest accelerator on Earth can also provide tools to explore fundamental quantum mechanics effects. A measurement of the extent of entanglement in top quark-antiquark ($t\bar{t}$) events produced in proton-proton collisions at a center-of-mass energy of 13 TeV is performed with the data recorded by the CMS experiment in 2016, and corresponding to an integrated luminosity of 36.3 fb^{-1} [8]. This measurement exploits the spin correlation variable D, which at the $t\bar{t}$ production threshold, and in absence of BSM contributions, provides access to the full spin correlation information. We directly measure entanglement at the parton level. Also, our analysis is the first to consider non-relativistic bound-state effects in the production threshold by including the ground state of toponium, η^t. The D variable represents an entanglement proxy, where less than -$\frac{1}{3}$ signals the presence of entanglement (Fig. 4). This proxy is measured using events containing two oppositely charged electrons or muons produced in pp collisions at a center-of-mass energy of 13 TeV. A combined signal model of ($t\bar{t} + \eta^t$) has been utilized in the measurement. A binned likelihood fit has been used to extract the entanglement proxy, directly from the distribution of cos ϕ, where ϕ is the angle between the two charged decay leptons in their respective parent top quark rest frames. This result has an observed (expected) significance of 5.1 (4.7) σ, corresponding to the observation of top quark entanglement. The measured value of D is in good agreement with the MC modelling in this phase space when including the expected η^t bound state contribution.

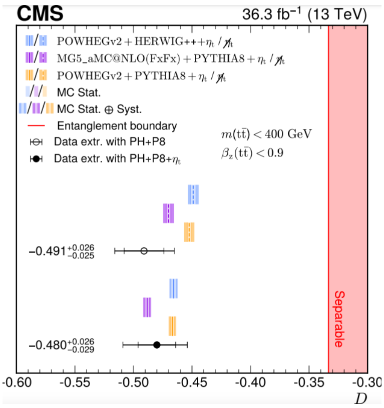

Figure 4. Measurement of the entanglement proxy D in data (black filled or open point) compared with MC predictions including (solid line) or not including (dashed line) contributions from the η^t−state. The legend denotes MC predictions without the toponium state with a slash. The boundary for entanglement is indicated by the shaded region at $D = -\frac{1}{3}$ [8].

4.2 Measurement of inclusive and differential cross sections for single top quark production in association with a W boson in proton-proton collisions at $\sqrt{s} = 13$ TeV

The first measurement of the inclusive and normalised differential cross sections for the production of single top quarks in association with a W boson in proton-proton collisions at a centre-of-mass energy of 13.6 TeV are presented. This is the first single top measurement at Run 3 from CMS. This is a challenging measurement as it is a rare process. The data used

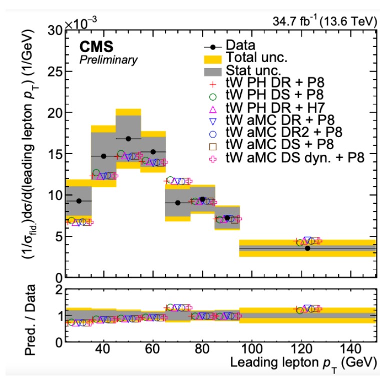

Figure 5. Normalised fiducial differential tW production cross section as function of the p_T of the leading lepton. Predictions from $POWHEG(PH) + PYTHIA8(P8)DR$ and DS, $POWHEG + HERWIG7(H7)DR$, $MadGraph-5\_aMC@NLO(aMC) + PYTHIA8DR, DR2, DS$, and DS with a dynamic factor are also shown. The grey band represents the statistical uncertainty and the orange band the total uncertainty. In the lower panel, the ratio of the prediction to the data is shown [9].

were recorded with the CMS detector at the LHC during 2022, and correspond to an integrated luminosity of 34.7 fb^{-1} [9]. The analyzed events contain one muon and one electron in the final state. For the inclusive measurement, multivariate discriminants are used exploiting the kinematic properties of the events to separate the signal from the dominant top quark antiquark production background. A cross section of $84.1 \pm 2.1(stat)^{+9.8}_{-10.2}(syst) \pm 3.3(lumi)$ pb is obtained, as shown in the Fig. 5, consistent with the predictions of the standard model. A fiducial region is defined according to the detector acceptance for performing the differential measurements. The resulting differential distributions are unfolded to particle level and show good agreement with the predictions at next-to-leading order in perturbative QCD.

5 Recent results related to the standard model physics

5.1 Measurement of the Drell-Yan forward-backward asymmetry and of the effective leptonic weak mixing angle using proton-proton collisions at 13 TeV

The electroweak mixing angle, $sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$, relates the masses of the W and Z bosons and is a key parameter in the standard model (SM) of particle physics. The forward-backward asymmetry in Drell–Yan production and the effective leptonic electroweak mixing angle are measured using a sample of proton-proton collisions at $\sqrt{s}$ = 13 TeV collected by the CMS experiment and corresponding to an integrated luminosity of 137 fb^{-1} [10]. The measurement uses both dimuon and dielectron events, and is performed as a function of the dilepton mass and rapidity. Using the CT18Z set of parton distribution functions (PDF), we obtain,

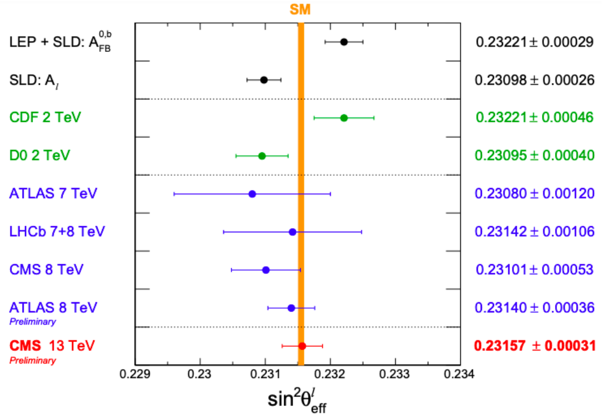

Figure 6. Comparison of the $sin^2\theta^l_{eff}$ values measured in this analysis with previous measurements and the SM prediction [10].

$sin^2\theta^l_{eff} = 0.23157 \pm 0.00010\ (stat) \pm 0.00015\ (syst) \pm 0.00009\ (theo) \pm 0.00027\ (PDF)$, the total uncertainty being 0.00031. The measured value agrees with the standard model prediction. The total uncertainty varies between 0.00024 and 0.00035, depending on the PDF set. With significantly smaller uncertainty than that of previous CMS results, increase in the size of the data samples, improved analysis techniques and the inclusion of central-forward dielectrons, this is the most precise measurement of the effective weak mixing angle at a hadron collider, with a precision comparable to the results obtained at LEP and SLD, as presented in the Fig. 6.

5.2 Strong coupling constant (α_s) in CMS at 13 TeV

Strong coupling constant (α_s) is the only free parameter except quark masses. In CMS, values have been measured in a wide spectrum of analyses at 13 TeV. For NNLO prediction, fit uncertainty has become dominant. Uncertainties are cancelled out for ratios of cross sections. Simultaneous measurements (dijet + $t\bar{t}$) can improve the results. NNLO predictions missing for some measurements like jet substructure. Running of α_s is consistent with the Renormalization Group Equations over 3 orders of magnitude (Refer to Fig. 7).

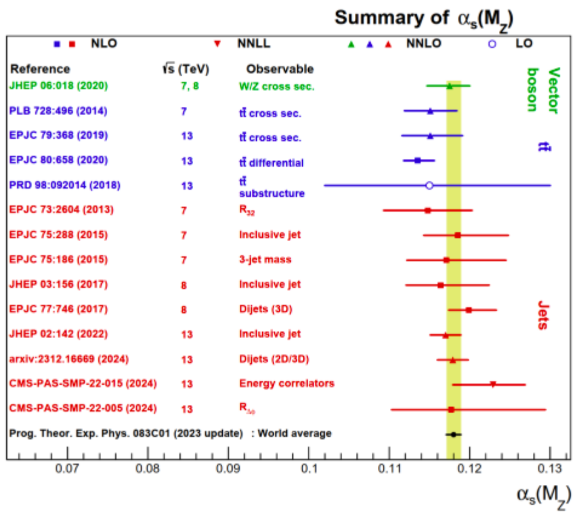

Figure 7. Summary of the strong coupling constant (α_s) measurements for 13 TeV.

6 Recent results related to the B-physics

6.1 Measurement of time-dependent CP violation in $B_s^0 \to J/\psi\phi\ (1020)$ decays with the CMS detector

A study of CP violation in $B_s^0 \to J/\psi\phi(1020)$ decays is presented, based on the data collected by the CMS experiment at the LHC. The measurement is based on a data sample of roughly 491 000 reconstructed signal events corresponding to an integrated luminosity of 96.5 fb^{-1}, collected in proton-proton collisions at 13 TeV in 2017-2018 [11]. A time- and flavor-dependent angular analysis of the $\mu^+\mu^-K^+K^-$ final state is performed to extract the values of the CP-violating phase ϕ_s, the decay width difference ($\Delta\Gamma_s$), and absolute mass difference (Δm_s) between the light and heavy B_s^0 mass eigenstates, their average decay width Γ_s, and the direct CP violation parameter $|\lambda|$. The analysis utilizes a pioneering inclusive flavor tagging framework based on state-of-the-art machine learning techniques.

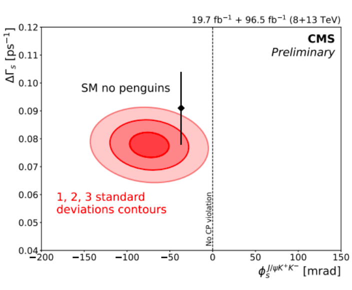

Figure 8. The two-dimensional one, two, and three standard deviations contours in the $\phi_s - \Delta\Gamma_s$ plane for the combined results. The contours take into account both statistical and systematic uncertainties. The SM prediction is represented by the black rectangle, with the central value indicated with the black diamond [11].

CMS has used a graph neural network (cutting-edge AI algorithm for accurate flavour tagging) to separate mesons from anti-mesons. In combination with similar CMS results from Run 1, CMS reports a ϕ_s value deviating from zero with a significance of 3.2 standard deviations. This result provides the first evidence for CP violation in these B_s^0 decays (as presented in the Fig. 8), a milestone in our CP violation program.

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