



# CMS: Latest Results and Prospects

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## Outline

- Introduction
- Standard Model Results
  - Standard Model Physics
  - B Physics
  - Heavy-Ion Physics
  - Higgs Physics
  - Top Quark Physics
- Beyond the Standard Model Results
  - Beyond 2 Generations
  - Exotica
  - Super Symmetry
- Future Prospects
- Summary and Conclusions

## Large Hadron Collider (LHC)

- Largest and highest-energy particle collider
  - At CERN, beneath the France-Switzerland border near Geneva
- Proton and heavy-ion collision programs
  - Record-setting center-of-mass energies and luminosities



## LHC Schedule

2019	2020	2021	2022	2023	2024	2025	2026	2027
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2028	2029	2030	2031	2032	2033	2034	2035	2036
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Last updated: June 2021

Longer term LHC schedule

## Compact Muon Solenoid (CMS)



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**SketchUpCMS** 

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## **CMS** Collaboration



## CMS Run 2 Overview

- Excellent LHC performance
  - Peak Luminosity ~2 ×  $10^{34}$  Hz/cm<sup>2</sup> (2x design value)
  - $\circ$  ~160 fb<sup>-1</sup> of proton-proton collisions at 13 TeV
- Excellent CMS performance
  - Data-taking efficiency > 92%
  - CMS papers submitted > 1070
  - $\circ$  ~137 fb<sup>-1</sup> of pp data "good for physics"
  - Upgraded detector in preparation for Run 3
  - Long-term upgrades underway for High-Luminosity LHC







#### CMS Integrated Luminosity, pp, $\sqrt{s} = 13$ TeV

## **CMS Public Results**



#### TWICE THE HIGGS, TWICE THE FUNI

The Higgs boson, once the sought after hely grail of particle physics, has now been with us for almost a decade. By now physicists are able to use the Higgs boson itself as a tool for the next discovery beyond the standard model. Interestingly,...

#### READ MORE



#### TRID OF J/W PARTICLES IN ONE GO.

High-energy particle accelerators are unique tools to study the structure of matter at the shortest. distances. The most powerful accelerator today is the CERN Large Hadron Collider (LHC) that has so far collided beams of protons up to center-ofmate

READ MORE



#### WWW,TRIBOSON, CMS20.001 2821

Apart from the "World Wide Web." three Ws may also have a different interpretation in the LHC era. The standard model of particle physics is a mathematical construct that connects three of the four fundamental forces of nature and classifies 

#### READ MORE



#### DOES THE BEHAVIOUR OF THE HIGGS BOSON MATCH THE EXPECTATIONS?

The standard model of particle physics is our current best theory to describe the most basic building blocks of the universe, the elementary particles, and the interactions among them. At the heart of the standard model is a hypothesis describing.

#### BEAD MORE

#### **CMS Public Briefings**



#### LHC AS THE VECTOR BOSON COLLIDER

After the Higgs boson discovery in the year 2012. the standard model of particle physics offers a complete and consistent description of elementary particle interactions that, despite the many attempts, has not been faisified by experimental.

#### READ MORE



#### A NEW WINDOW INTO THE SHADOW WORLD: EXOTIC PARTICLE DECAYS IN THE MUON DETECTORS.

As physicists seek the elusive particles that may reveal a new understanding of the universe's inner workings, one intriguing possibility is the conceivable existence of new particles that live in a shadow universe, called the "dark sector." The... READ MORE



Physics



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CMS Public Results Salact, Docume Departed MAL



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HIG 28-091	Analysis of the CP structure of the Tokone coupling between the Higgs boson and $r$ leptons is protoc protoc collision as $\sqrt{1} = 11$ TeV	Sampled to 2007	16 Dentier 3021
130218-001	beautile flux long illust particular decaying in lagrange with large impact parameter in product proton collisions at $\sqrt{s}=3$ TeV	Tolevelous to CPUC	16 Desider 2021
300123-001	However, of double party materiag in indusive production of four jets with low transmission momentum in process parton collinians at $\sqrt{s} = 10$ bet	Scheding to PEP	13 Sector 2021
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549-25-810	Sharp of quark and gloon (at substructure in 2 rise and dijot awards from pp collisions	Salvatura (10.240)	8 September 2021
108.05.201	Observations at $M_{\rm p}^{\rm c}$ mesons and measurement of the $M_{\rm p}^{\rm c}/H^{\star}$ plott ratio in POPb collisions at $\sqrt{v_{\rm pp}}=3.00$ TeV	Landord to PLB	8 Exploration 2021
TOP-JU HOR	Observation of W production in the single ispton channel is pproxiliation of $\sqrt{v}=13$ TeV	Accepted by JHER	3 Exploring 2021
108.25.308	Measurement of the top opacit means using events with a single reconstructed top quark in $qp$ collisions at $\sqrt{s}=13$ TeV	Samualta 269	34 Keigent 2021
106.86.907	Monocentral of dimension of production cross anothers in the full knowledge using topics-gene average from protocordinates at $\sqrt{r}=12.769$	Accustual to FRG	4 da gest 2011
10523-001	Probleg effective field theory operates in the established postation of tag quarks with a 2 lancer in custification final material $\sqrt{5}=10700$	To developed by 2012P	29.64 BD
CHILDRAN ON C	Source for non-particles in course with enceptic jets and large mixing measures non-error in protocarcters collisions at $\sqrt{s} = 12$ MV	Accepted to JHER	77 hde 2021
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303-25-812	Combined searches for the production of responsymmetric top quark particles in proton collision and $\sqrt{\gamma}=15$ TeV	Accepted to \$2550	22 Adv (M23
00528-010	Smooth for long-liver Lyandoles alwaying in the CMS endage muon detectors in gratem gratem collisions at $\sqrt{2}$ = .13 MV	Accessed by PPL	70 Mg 2021
1001 23 219	Measurement of the inclusive and differential $11\gamma$ cross sectors in the single lighter channel and EFT interpretation at $\sqrt{1} = 12{\rm feV}$	Salesbacks.PEP	3.869.3821
02010.001	Measurement of prompt open-chains production errors wettern in protoc-period coefficient $\mathbf{r}_i\sqrt{s}=0.5W$	Sub-Madria (PEP	3 say 2021
SWC45-K18	Measurements of the electrowesk different production come sections is precise proton collisions at $\sqrt{s} = 5.02$ TeV using leptonic ducage	Accepted to MR,	2.549.2821

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#### **CMS Physics Publications**

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5549-20-014	Measurement of the indusive and differential WZ prediction oper surfaces, potential angles, and triple gauge roughlings to percellation of $\sqrt{\pi}$ = 1.1 NeV	Kaselahat ta Lingé bergy Phys.
1017-18-003	Search for long doed puricies decaying to leptons with large impact ascension in posters proton solviers at $\sqrt{s}=11$ MV	Interviewed to Tax. Phys. J.C.
100-20 OII	$\operatorname{Mady}(\mathcal{A})$ quark and given jet substructive in $\mathcal{I}$ ( ) it and sight even if for application	and equipping in with several sales.
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Ski#-20-012	Measurement of the discretional difference and active trace and are by preserved interval $\sqrt{s}=500$ TeV and popular decays	Adopted for publication in Phys. Rev. Let
HER-10-007	Engineerization of jets metaloing a primp of J/prosecon in PDPBs and pp collisions at $\sqrt{2}_{46}^{(1)} = 3.02$ GeV	Saladad to Piye Lett 8
1000-20-016	Measurement of the electroweak production of $2\gamma$ and two jets in process particle collisions at $\sqrt{s} = 15$ fee and covariant on averaginal quarks gauge matching	84pa, 844 12364 (1821) 0.073003
849-35 cm	Managements of a boson pilo jeta and setable needles to double peter-scattering in pp colleges at 12 by	Accepted for publication in 1. High lively Phys.
SMP-10-012	$Measurements of the pp \rightarrow W^{2}$ system $pp \rightarrow Z^{2/2}$ meas sections at $\sqrt{3}=13$ MeV and limits an averaging standing property of the proper	Accepted for publication in 2.75ph Trang Phys.
110-02-000	search beingster flower addeling depays of the Higgs larger in the privati of flow states in prister privati substation of $\sqrt{e}$ — 15 KeV	High New IV NA USERUMANA

#### **CMS Publication Search Page**

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## Standard Model Results



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## **Standard Model Results**



# **Standard Model Physics**

# Z invisible width

- First measurement of Z invisible width at a hadron collider
- Most precise direct measurement of the Z invisible width  $\Gamma_{inv}$ 
  - Competitive with the combined direct measurement from LEP
- Simultaneous fit to data regions containing  $Z \rightarrow invisible$  and  $Z \rightarrow ee/\mu\mu$
- $\Gamma_{inv}$ = 523 ± 3 (stat) ± 16 (syst) MeV





# **B** Physics

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# Observation of triple J/ $\psi$ production [BPH-21-004]

- First observation of triple  $J/\psi$  production
  - Significance in excess of five standard deviations
- Contributions from single-, double-, and triple-parton scattering
  - Final states with three muon pairs
- $\sigma(\mathrm{pp} o \mathrm{J}\psi\,\mathrm{J}\psi\,\mathrm{J}\psi\,\mathrm{X}) =$  272 $^{+141}_{-104}$  (stat)  $\pm$  17 (syst) fb
  - Measured final state is found to be dominated by DPS and TPS contributions







# Heavy-Ion Physics

# First observation of $B_c^+$ meson in Pb Pb collisions

- Decay channel:  $B_c^+ \rightarrow (J/\psi \rightarrow \mu\mu)\mu\nu$
- Only meson containing two different flavored heavy quarks
  - Provides unique bridge between charmonia, bottomonia, and open heavy mesons
- Insight into interplay between suppression and enhancement mechanisms



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# Higgs Physics H

## Higgs Highlights

- Run 1
  - Higgs discovery!
  - Consistent with spin 0
  - Mass measurement at 0.2% level
  - Couplings consistent with SM predictions
- Run 2
  - Observation of all main production mechanisms (ggF, ttH, VBF, VH)
  - Observation of decays to bosons and third-generation fermions
  - Excellent mass measurement [125.38 ± 0.14 GeV]
- All measurements consistent with Standard Model predictions thus far



## Evidence for Higgs boson decay to a pair of muons [HIG-19-006] [JHEP 01 (2021) 148]

- First evidence of Higgs coupling with 2nd generation fermions
  - Observed (expected) significance  $3.0\sigma$  ( $2.5\sigma$ )
- Rare decay (branching fraction ~2x10<sup>-4</sup>)
- Large irreducible bkg from  $Z \rightarrow \mu\mu$
- ggH, VBF, VH, ttH categories
- $\mu = 1.19^{+0.41}_{-0.39}$  (stat)  $^{+0.17}_{-0.16}$  (syst)





## Inclusive and differential $H \rightarrow \tau \tau$ cross sections

[HIG-20-015] [Submitted to Phys. Rev. Lett.]

- First differential measurements of  $H \rightarrow \tau \tau$  cross section
- Integrates over production modes (ggF, VBF, VH, ttH)
- Measured as functions of  $p_T(H)$ ,  $N_{Jets}$ ,  $p_T(leading jet)$
- Significant improvement over measurements in other final states
  - Events with a large jet multiplicity or with a Lorentz-boosted Higgs boson





## Search for H(bb)H(bb)

[HIG-20-005]

Di-Higgs production exploring several couplings: HHH, HVV, HHVV 

 $\mu_{qqF}=1$ 

K<sub>2V</sub>

- Dedicated HLT triggers with 3 b-jet 0
- Targets both ggF and VBF production 0
- New multivariate analysis strategy
  - New background estimation from multiple control regions
- B-tagging improvements
  - Phase-1 pixel detector upgrade 0
  - Latest tagger from BTV (DeepFlavour) Ο







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# **Top Physics**

## Probing effective field theory (EFT) with ttZ

[TOP-21-001] [Submitted to J. High Energy Phys.]

- Search for new EFT top guark interactions
  - Associated production of 1 or 2 top guarks with a Z boson in multilepton final states 0
  - Events with 3 or 4 light leptons, divided into signal and control (WZ/ZZ) regions 0
  - Dimension-6 EFT operators and relative Wilson coefficients considered 0
  - Machine learning optimizes sensitivity to each EFT parameter Ο

NN-C12-tZq output







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## Measurement of $tt_{\gamma}$ cross section

[TOP-18-010] [Submitted to J. High Energy Phys.]

- $\begin{array}{c} \overline{b} \\ \overline{b} \\ \overline{c} \\ \overline{$
- Associated ttX production provides direct probe into top quark couplings
  - Can be modified in BSM models
- Measurement of top quark pair and associated photon cross section
  - One highly energetic  $e/\mu$ , one isolated photon, and  $\geq 3$  jets ( $\geq 1$  b-tagged)
  - $\circ$   $\sigma_{tt_{\gamma}}^{fid.}$  = 800 ± 7 (stat) ± 46 (syst) fb
    - Good agreement with Standard Model prediction
  - Differential cross sections in  $p_T(\gamma)$ ,  $|\eta(\gamma)|$ ,  $\Delta R(l,\gamma)$  are measured and interpreted with SMEFT
    - Most stringent direct limits on anomalous EM dipole moment interactions



# Beyond the Standard Model Results

# **Beyond 2 Generations**

## **B2G Results**

W→WZ→qqqq, HVT model B W→WZ→woā, HVT model B W→WZ→Łxq2, HVT model B W→WZ→llaå, HVT model B W→WH→oãbĎ, HVT model B W→WH→tybb, HVT model B W-→WH→q₫TT, HVT model B W combination (2016), HVT model B Z'→WW→qqqq, HVT model B Z→ZH→gább, HVT model B Z'→ZH-+2200 HVT model B Z'→ZH→U/bb, HVT model B Z→ZH→qátt, HVT model B 7' combination (2016), HVT model B V→VH→gābū, HVT model B V-VH-(vv, Iv, II)bb, HVT model B V→VH→gdīt, HVT model B V' cambination (2016), HVT model B  $G \rightarrow WW \rightarrow t \nu q \bar{q}$ , Bulk G.  $k(\overline{M}_{22} = 0.5)$  $G \rightarrow ZZ \rightarrow U \nu \nu$ , Bulk G,  $k/\overline{M}_m = 0.5$ G combination (2016), Bulk G,  $k/\overline{M}_{\rm B} = 0.5$ R→HH→aörr, Radion A=1TeV R→HH→bbbb, Radion A=3TeV R→HH→Ivogbb, Radion, A=37eV

 $\begin{array}{l} Z \to \mbox{fb} \ B(Z \to \mbox{fb} = 100\%, \ \Gamma/M_{\rm c} = 1\% \\ Z \to \mbox{if}, \ B(Z \to \mbox{fb} = 100\%, \ \Gamma/M_{\rm c} = 10\% \\ Z \to \mbox{fb}, \ B(Z \to \mbox{fb} = 100\%, \ \Gamma/M_{\rm c} = 30\% \\ Q_{\rm cc} \to \mbox{fb}, \ K \ All \ Les \ Nein \ G_{\rm cc} \\ = 4\pi (T \to (227, 147) \to 10.4\%, \ R \ Les \ B(T \to \mbox{fc} = 100\%, \ LO(Z \to \mbox{fb} = 10.4\%, \ LO(Z \to \mbox{fb} = 10.4$ 

YY→bWbW→(µadad, B(Y→bW)=100% TT→bWbW→(vadad, B(T→bW)=100%) TT-+tZtZ-+(l\*, l\*l\*, l\*l\*l\*) + jets. B(T-+tZ)=100% TT→tHtH→baabbbadbb, B(T→tH)=100%  $TT \rightarrow (l \pm . l \pm l \pm . l \pm l \pm ! \mp) + jets$ . TT singlet  $TT \rightarrow (l^+, l^-l^+, l^-l^+l^+) + jets, TT doublet$  $BB \rightarrow tWtW \rightarrow (l \pm , l \pm l \pm , l \pm l \pm l \pm ) \pm ] ats, B(B \rightarrow tW) \rightarrow 100\%$ BB-+bZbZ +bqdbqd, B(B++tZ)=100% BB→bHbH, B(B→bH)=100%  $BB \rightarrow (l^{\pm}, l^{\pm}l^{\pm}, l^{\pm}l^{\pm}l^{\pm}) + jets, BB singlet$ BB→(I±,I±I±,I±I±I∓) + jets, BB doublet  $X_{3/3}X_{3/3} \rightarrow tWtW \rightarrow (t^{+}, t^{+}t^{+}) + jets, B(X_{3/3} \rightarrow tW) = 100\%, RH$  $X_{uv}X_{uv} \rightarrow tWtW \rightarrow (l^{-1}, l^{-1}l^{-1}) + jets, B(X_{uv} \rightarrow tW) = 100\%, LH$ Tart+tZ+bgql+l-, narrow 1 bT,\_-btZ-bbog(+1-, namew T B→bH→bbb, narrow B B→tW→lv + jots, narrow B

#### **Overview of CMS B2G results**



## Search for resonances into WWW [B2G-21-002]

- Search for decays via a scalar radion (R)
  - $\circ \quad X \to WR \to WWW \text{ (hadronic decays)}$
  - Two or three massive, Lorentz-boosted jets
- Results combined with complementary search in the *l*+jets final state





WKK

 $\bar{q}'(v)$ 

WKK

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## Exotica

## Exotica Results



## Search for long-lived particles decaying in CMS Muon Endcap

[EXO-20-015] [Accepted for publication in Phys. Rev. Lett.]

- Higgs decaying to two neutral long lived scalars
  - Each decaying to a pair of b-quarks, d-quarks or tau leptons
  - Most stringent limits to date on BR(Higgs $\rightarrow$ SS $\rightarrow$ uu/dd/ $\tau\tau$ )
- Novel reconstruction technique: CMS endcap muon detectors as calorimeter
  - Hits in the CSC are clustered using the DBScan algorithm
  - Method validated using Z events where one muon undergoes bremsstrahlung in the Endcap Muon Detector and the photon produces an EM shower





### Search for $H \rightarrow \text{long-lived particles in associated Z boson production}$ [EXO-20-003] [Submitted to J. High Energy Phys.]

- Search for long-lived particles (LLP) pairs decaying into jets, with associated Z production  $\ell^+$ 
  - At least two displaced jets (3 tracking-based displacement variables)
  - Both light (d) and heavy (b) jets are considered
- Benchmark model: Higgs decay to a pair of scalar LLPs
  - Probing decay lengths from 1 mm to 1 m



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# SUSY

## **SUSY Results**







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## Top Squark in Compressed Spectra

[SUS-20-002] [Accepted for publication in Eur. Phys. J. C]

- Compressed spectra where SUSY mass differences are small (~GeV)
- Signatures with  $\geq 2$  jets and large  $E^{T}_{miss}$ 
  - Categorized into events with 0, 1, 2 leptons
- Deep neural network algorithm used to separate signal from background
- Includes dark matter interpretation
  - Via a spin-0 mediator in association top pair





# **Future Prospects**

## CMS LS2 activities

- New beam pipe installed (Phase-2 design)
- Phase-1 pixel <u>re-installed</u> (new layer 1 and DCDC)
- Rebuilt BRIL luminosity sub-detectors installed
- HCAL Phase-1 readout upgrade completed
- New GEM subsystem (GE1/1 chambers installed)





## Run 3 preparation

- LHC test/pilot beams program just completed
  - Full detector, including Run 3 upgrades, exercised during stable beams
- DAQ/Trigger/HLT upgrades
  - Heterogeneous architecture (CPU/GPU) in High Level Trigger
    - New possibilities for trigger algorithms leveraging GPUs
    - Testbed for HL-LHC Computing and triggering
  - Increase in data scouting and data parking
  - Dedicated and improved long-lived particle triggers

Mode	GPDs	LHCb	ALICE
р-р	160/fb	25-30 fb (-50/fb by LS4)	200/pb
Pb-Pb	6/nb (13/nb by LS4)	1/nb (2/nb by LS4)	6/nb (13/nb by LS4)
р-Рь	0.5/pb (~1.2/pb by LS4)	0.1/pb (~0.6/pb by LS4)	0.25/pb (~0.6/pb by LS4)
0-0	0.5/nb	0.5/nb	0.5/nb
р-О	LHCf 1.5/nb	0.1/pb	

Run 3 Luminosity Targets



## High Luminosity LHC (HL-LHC)

LHC / HL-LHC Plan





High Luminosity LHC Project

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## CMS Phase-2 Upgrades

#### CMS TDRs



CMS

#### L1-Trigger

DAQ/HLT

\* HLT output: 7.5 kHz

\* 40 MHz data scouting

- \* Tracks in L1-Trigger at 40 MHz
- \* PFlow selection 750 kHz L1 output

#### Beam Radiation Instr. and Luminosity

\* Bunch-by-bunch luminosity measurement: 1% offline 2% online



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MS Barrel Calorime

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#### Barrel Calorimeters

\* ECAL crystal granularity readout at 40 MHz with precise timing for  $e/\gamma$  at 30 GeV \* ECAL and HCAL new Back-End boards



HALL DESIGN DED

# CMS

#### Muon Detectors

\* DT & CSC: new FE/BE readout \* RPC back-end electronics \* New GEM/RPC 1.6 < n < 2.4 \* Extended coverage to n = 3

#### **MIP Timing Detector**

Precision timing with: \* Barrel layer: Crystals + SiPMs \* Endcap layer: Low Gain **Avalanche Diodes** 





CMS

#### **Endcap Calorimeter**

\* 3D showers and precise timing Si, Scint+SiPM in Pb/W-SS

#### Tracker

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to  $\eta \approx 3.8$

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## Higgs Prospects at HL-LHC [FTR-18-011] [FTR-18-019]

- HL-LHC facilitates precision Higgs coupling measurements
  - Couplings (except rarest) constrained to <10% level
  - Direct access to Higgs potential shape and  $\kappa_{\lambda}$  sensitive to BSM physics
- Observing di-Higgs production is a flagship measurement
  - Expect to achieve 3σ observation significance from combination of channels
  - Expected ~10% improvement in b-tagging efficiency from new tracker



# Mono-Z search for dark matter at HL-LHC

- Expected sensitivity and exclusion in searches for new invisible particles
  - Push sensitivity to large DM mass and push down in couplings
  - Extends sensitivity of mediator masses by ~ factor of 2 relative to current LHC results



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## **Summary and Conclusions**

- LHC and CMS performing very well and preparing for Run 3 & beyond
- Wealth of results from Run 2 dataset
  - Higgs consistent with Standard Model predictions
  - No signs of new physics yet
- Run 3 upgrades installed and tested
  - Ready for data-taking in 2022
- The High-Luminosity LHC era will provide an unprecedented dataset
  - All CMS Technical Design Reports prepared
  - Further characterize the SM and expand the search for new particles and interactions



### Probing charm dynamics in 5.02 TeV PbPb [HIN-20-001]



- Measure multiparticle (4) azimuthal correlations of prompt D<sup>0</sup> mesons
  - Elliptic flow of D<sup>0</sup> mesons extracted using a four-particle cumulant method, as a function of D<sup>0</sup> transverse momentum and centrality
  - The prompt D<sup>0</sup> meson v2 ratios using four- and previous two-particle cumulant methods are below unity and comparable to those of charged particles



### Measurement of b quark fragmentation using charmed mesons TOP-18-012

- First measurement of b quark fragmentation function in ttbar events at LHC
- Charm mesons produced inside b jets from tt pairs
  - Used to determine the shape parameter of the Lund-Bowler fragmentation function Ο
  - Significantly improves experimental constraints on shape of the function



## VBF HH→4b boosted [B2G-21-001]

- BSM VBF HH cross section can dramatically increase for large m<sub>нн</sub>
- First test of the VVHH coupling in boosted topology
  - Multivariate GNN classifier (ParticleNet) applied to identify H→b-jet decays
- Limits set for for a range of signal hypotheses of different  $\kappa_{2V}$  and  $\kappa_{V}$  couplings



