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Peer-reviewed journal publications (ordered by submission date)

Measurement of the inclusive $\mathrm{t\bar{t}}$ production cross section in pp collisions at $\sqrt{s} = 5.02$ TeV
High-Energy Particle Physics *arXiv:2112.09114*

- Brief abstract: We report the updated top quark pair production cross section as measured in proton-proton collisions at a center-of-mass energy of 5.02 TeV. The data were collected in 2017 and correspond to an integrated luminosity of 304 pb^{-1}, increasing by more than a factor 10 compared to the data set recorded in 2015. The measurement is performed using events with one electron and one muon of opposite sign, and at least two jets. To further reduce the statistical uncertainty, a combination with the result obtained in JHEP 03 (2018) 115 is performed, obtaining a total uncertainty of 7.9%, and in agreement with the standard model.
- Contribution (description): Monte Carlo simulated event samples are used to define the analysis strategy, to estimate the background contribution, and to evaluate efficiencies and uncertainties. All simulated processes are generated at next-to-leading order with the events then interfaced to PYTHIA8 and the dedicated CMS ("CP5") tune for parton showering, hadronization, and the underlying event. For the study of the signal acceptance dependency on top quark mass, generator-level samples have been used with values of top quark mass varied from the nominal one. In all cases, state-of-the-art parton distribution functions (NNPDF3.1) at next-to-next-to-leading order are used. The standard model prediction for top quark pair production is calculated at next-to-next-to-leading order (NNLO) in perturbative quantum chromodynamics (QCD) including soft-gluon resummation at next-to-next-to-leading-log (NNLL). The theory uncertainty reflects variations in the factorization and renormalization scales, and possible choices of PDFs and the value of the strong coupling constant. Theoretical predictions using different PDF sets have comparable values and uncertainties, once consistent values of the top quark mass and the strong coupling constant are associated with the respective PDF set. We found the combined measurement to provide improved uncertainties in the gluon PDF at high x region.
- Contribution (keywords): *Data analysis, Methodology, Visualization, Writing review and editing*

Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS
Eur. Phys. J. C 81 (2021) 800
High-Energy Nuclear and Particle Physics, Physics Instrumentation and Detectors *arXiv:2104.01927*

- Brief abstract: We report the first-ever measurement of the luminosity recorded by the CMS detector installed at LHC interaction point 5, using proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016. A good understanding of the luminosity is critical to minimize the systematic uncertainty in physics measurements since the uncertainty in the luminosity measurement is often the dominant source of systematic uncertainty. When applying the "van der Meer" calibration to the entire run periods, we achieved a relative precision of 1.6% and 1.2% in the integrated luminosities, respectively. These are among the most precise luminosity measurements at bunched-beam hadron colliders.
- Contribution (description): We developed advanced techniques to estimate and correct for the bias associated with the residual differences (at the scale of μm) between the measured beam positions and the ones provided by the operational settings of the LHC magnets, the factorizability of the proton bunch spatial density functions in the coordinates transverse to the beam direction, and the

modeling of the effect of electromagnetic interactions among protons in the colliding bunches. In addition, detailed luminometer rate corrections and the inclusion of novel luminometry techniques (such as the data from the Radiation Monitoring System for the Environment and Safety) lead to ultraprecise estimates of the calibration time stability and independence to pileup. In the coming years, a similarly precise calibration of the real-time luminosity delivered by LHC will become increasingly important for standard operations. Under those conditions, the impact of some effects is expected to be larger, but in principle they can be mitigated using techniques described in our measurement.

- Contribution (keywords): *Conceptualization, Data analysis, Methodology, Project administration, Software development, Visualization, Writing—original draft, Writing—review and editing*

Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC JINST 16 (2021) P05014

Physics Instrumentation and Detectors *arXiv:2012.06888*

- Brief abstract: We present the performance of the reconstruction and identification algorithms for electrons and photons during Run 2 with the CMS experiment. Results obtained from lead-lead collision data collected at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV are, for the first time, separately given, which require specific modifications because of the significantly higher final-state particle multiplicity ("underlying event") compared with proton-proton collisions. More specifically, clustering and tracking algorithms are integrated in a modified "particle-flow" framework. For electrons and photons reconstructed in lead-lead collisions, we found the uncertainty in the energy scale, i.e., the residual discrepancy between the corrected and the nominal Z boson mass, to be better than 1 (3)% in the barrel (endcap) region.
- Contribution (description): The additional energy deposited by particles from the underlying-event activity in the electromagnetic calorimeter can be clustered together with the energy deposited from genuine electrons, hence affecting the energy scale of reconstructed electrons in a centrality-dependent (i.e., the degree of nuclei overlap) manner. Reconstruction, identification, and energy correction algorithms have been revised for electrons, and optimized to perform in the extreme conditions of high underlying-event activity in central lead-lead collisions. We show the comparison in the Z boson invariant mass between data and Monte Carlo simulated events at next-to-leading order, where excellent agreement is seen after electron energy (scale and resolution) and reconstruction efficiency corrections applied.
- Contribution (keywords): *Data analysis, Methodology, Visualization, Writing—review and editing*

Evidence for top quark production in nucleus-nucleus collisions **Phys. Rev. Lett. 125 (2020) 222001**

High-Energy Nuclear Physics *arXiv:2006.11110*

- Brief abstract: The top quark, the heaviest elementary particle known, is accessible in nucleus-nucleus collisions at LHC, and constitutes a novel probe of the quark-gluon plasma (QGP). Here, we report the first-ever evidence for the production of top quarks in nucleus-nucleus collisions, using lead-lead collision data at a nucleon-nucleon center-of-mass energy of 5.02 TeV recorded by the CMS experiment. Two methods are used to measure the cross section for top quark pair production via the decay into charged leptons (electrons or muons) and bottom quarks. One method relies on the leptonic information alone, and the second one exploits, in addition, the presence of bottom quarks. The measured cross sections are compatible with expectations from scaled proton-proton data and perturbative QCD predictions incorporating state-of-the-art parametrizations of gluon and quark density functions inside bound nuclei.
- Contribution (description): With this measurement we performed the first step in using the top quark as a novel and powerful probe of the QGP. We take advantage of dilepton final states characterized by higher purity, and (i) make use of the final-state dilepton kinematic properties alone, and (ii) impose extra requirements on the number of jets "tagged" as originating from b quarks.More specifically, we motivate the first method by the fact that leptons propagate un-

scathed through the QGP, thereby providing favorable conditions for the detection of the top pair production. We apply the second method, which enhances the signal over background in standard proton-proton analyses, with realistic estimates of the impact of b quark energy loss, also known as "jet quenching", in the QGP. The correction for the underlying event predominantly formed in nucleus-nucleus collisions is done on a particle-by-particle basis for the lepton isolation and jets. To estimate the the nonprompt-lepton background in the most sensitive final state, a novel event mixing technique is developed. Finally, boosted decision trees are trained on the simulated signal versus the Drell–-Yan quark-antiquark annihilation background. This classifier is based exclusively on leptonic quantities to minimize effects from the imprecise knowledge of the jet properties in the heavy ion environment.

- Contribution (keywords): *Conceptualization, Data analysis, Methodology, Project administration, Software development, Visualization, Writing—original draft, Writing—review and editing*

Pileup mitigation at CMS in 13 TeV data **JINST 15 (2020) P09018**
Physics Instrumentation and Detectors *arXiv:2003.00503*

- Brief abstract: At high instantaneous luminosity, many collisions occur simultaneously within one proton-proton bunch crossing. Identification of the interesting collision from additional "pileup" collisions is needed for effective physics performance. In CMS Collaboration, several techniques capable of mitigating the impact of these pileup collisions have been developed during Run 1, e.g., the isospin-based neutral particle ("$\delta\beta$") correction, and, most recently, pileup per particle identification (PUPPI). In this paper, we surveyed, among others, the performance of these techniques for muon isolation for up to pileup of 50. The analysis makes use of data corresponding to 35.9 fb^{-1} collected with the CMS experiment in 2016 at 13 TeV.
- Contribution (description): It is possible to distinguish prompt (charged) leptons from those originating, e.g., from semileptonic decays of hadrons, by forming the lepton isolation that provides a powerful handle: this can be parametrized based on the isolation efficiency and the misidentification rate. While $\delta\beta$ correction rejects charged particles associated with pileup vertices, PUPPI applies a more stringent selection to charged particles and rescales the four-momentum of neutral particles according to their probability to originate from the leading primary vertex. Although both techniques reduce the dependence on pileup interactions (stable efficiency and pileup-resilient misidentification rate), a stronger reduction is achieved with PUPPI, especially for events with more than approximately 30 simultaneous interactions. In terms of misidentification rate, all different PUPPI isolation quantities (depending on whether charged leptons are included in the PUPPI weight calculation or not) are observed to be more stable across pileup when compared with the $\delta\beta$-corrected isolation. In terms of efficiency, the "PUPPI-no-lepton" shows a more stable behavior compared with the $\delta\beta$-corrected isolation, whereas "PUPPI-with-lepton" shows a stronger dependence on pileup. The stability of the "PUPPI-combined" isolation efficiency is between the two PUPPI isolation configurations and similar to the $\delta\beta$-corrected isolation. The performance improvements from PUPPI-combined isolation expected from simulation studies are also confirmed by measurements in data by selecting $\text{Z} \to \mu\mu$ events. Pileup suppression techniques will be crucial for future running of the LHC, where even more challenging conditions per bunch crossing are expected.
- Contribution (keywords): *Data analysis, Visualization*

Measurement of differential cross sections and charge ratios for t-channel single top quark production in proton–proton collisions at $\sqrt{s} = 13$ TeV
Eur. Phys. J. C 80 (2020) 370
High-Energy Particle Physics *arXiv:1907.08330*

- Brief abstract: Using a data set corresponding to an integrated luminosity of 35.9 fb^{-1}, we selected events containing one muon or electron and two or three reconstructed jets. The cross section is then measured at parton and particle levels a function of a series of kinematic variables relevant to

the top quark production, e.g., polarization angle (defined by the momenta of the charged lepton and the spectator quark, and calculated in the top quark rest frame), and decay, e.g., the top quark the W boson transverse momentum from the top quark decay. These results demonstrate a good understanding of the underlying electroweak production mechanism of single top quarks, and in particular, the electroweak vector−axial-vector coupling predicting highly polarized top quarks.

- Contribution (description): For the first time, the charge ratio is measured differentially as a function of the top quark, charged lepton, and W boson kinematic observables. It is found that the standard definition of the charge ratio in the literature can yield large variances when the precision in certain intervals of the differential cross section for the top antiquark is low. Therefore, the charge ratio is normalized to the sum of the top quark and top antiquark cross sections, accounting for correlations between the top quark and antiquark spectra. The resulting charge ratios are compared to next-to-leading order predictions using the NNPDF3.0, MMHT14, and CT10 parton distribution functions (PDF). The theoretical uncertainty is estimated from variations of the corresponding PDF eigenvectors and the strong coupling constant. Within the uncertainties, the measured charge ratios are in good agreement with the predictions from all three PDF sets.
- Contribution (keywords): *Methodology, Writing—review and editing*

Observation of nuclear modifications in $\mathrm{W}^{\pm}$ boson production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV
Phys. Lett. B 800 (2020) 135048

High-Energy Nuclear Physics *arXiv:1905.01486*

- Brief abstract: The measurement of the production of W bosons (separately in positively and negatively charged muons) is performed using the largest proton-nucleus data sample at LHC, corresponding to approximately 174 nb^{-1} (equivalent to 36 pb^{-1} of nucleon-nucleon collision data). Differential cross sections, muon charge and "forward-to-backward" (i.e., W boson yields for the proton-going over the nucleus-going beam directions) asymmetries, are reported as a function of the muon pseudorapidity in the nucleon-nucleon center-of-mass frame.
- Contribution (description): The main signature of the $\mathrm{W}^{\pm} \to \mu^{\pm}\nu_{\mu}$ process is the presence of an isolated high-p_{T} muon. The simulated sample of W bosons, further "embedded into" a dedicated simulation tuned to reproduce the global-event properties of the proton-nucleus data, is used to derive the efficiency of the muon trigger, isolation, reconstruction, and selection criteria. The single-muon efficiencies are also directly estimated from data in a $\mathrm{Z} \to \mu\mu$ sample using the "tag-and-probe" (TnP) technique. The data and MC simulated reconstruction efficiencies are observed to be consistent with each other. To correct for any residual differences between data and MC simulation, the efficiency estimated from the MC sample is multiplied by the TnP correction factors on an event-by-event basis. The measurements are then compared to the predictions from theoretical calculations based on parton distribution functions (PDFs) at next-to-leading-order. The results favor PDF calculations that include nuclear modifications and provide constraints on the nuclear PDF global fits.
- Contribution (keywords): *Data analysis, Methodology, Writing—review and editing*

Search for associated production of a Higgs boson and a single top quark in proton-proton collisions at $\sqrt{s} = 13$ TeV
Phys. Rev. D 99 (2019) 092005

High-Energy Particle Physics *arXiv:1811.09696*

- Brief abstract: The first search for the production of a Higgs boson in association with a single top quark ("tHq" and "tHW") is presented in Run 2, based on data corresponding to an integrated luminosity of 35.9 fb^{-1}. Dedicated analyses of multilepton final states and final states with single leptons and a pair of bottom quarks are combined with a reinterpretation of a measurement of Higgs bosons decaying to two photons for the final result. More specifically, we derived constraints on the magnitude and, uniquely, relative sign of Higgs boson couplings to top quarks and vector bosons. Currently, the data favor a positive value of the top quark Yukawa coupling (parametrized

in terms of "coupling modifiers"), and exclude negative values outside the range of $[0.9, 0.5]$ times the standard model top quark Yukawa coupling of ≈1. The sensitivity is driven by the two-photon channel at negative values of the coupling modifiers.

- Contribution (description): Performed the selection of the tHq and tHW signal processes as part of an inclusive diphoton final state measurement, in which we categorize all events with two prompt high-p_T photons into different event categories, each enriched with a particular production mechanism of the Higgs boson. The statistical analysis proceeds by fitting the diphoton invariant mass with the signal (modeled with a sum of Gaussian functions from simulation) and background (determined from the data without reliance on simulated events) contributions.
- Contribution (keywords): *Data analysis, Methodology, Software development, Visualization, Writing—review and editing*

Measurement of the inclusive $\mathrm{t\bar{t}}$ cross section in pp collisions at $\sqrt{s} = 5.02$ TeV using final states with at least one charged leptons

JHEP 03 (2018) 115

High-Energy Particle Physics *arXiv:1711.03143*

- Brief abstract: The top quark pair production cross section is measured for the first time in pp collisions at a center-of-mass energy of 5.02 TeV. The data correspond to an integrated luminosity of 27.4 pb^{-1}. The measurement is performed by analyzing events with at least one charged lepton—the semileptonic final state with a large branching ratio and moderate amount of background, and dilepton final state characterized by higher purity. The measured cross section, with a total relative uncertainty of 12%, is in agreement with the expectation from the standard model. The impact of the presented measurement on the determination of the gluon distribution function is investigated.
- Contribution (description): Conceptualization, realization, and documentation of the analysis ("analysis contact"), including the simulation of all physics processes, physics object reconstruction, measurement of the trigger and event selection efficiencies, and the determination of the background sources. For the extraction of top quark pair production cross section, a fit to kinematic variables in the semileptonic final state (based on two light-flavor jets produced in the decay of one of the W bosons) is performed in different categories of lepton flavor and jet multiplicity. The results are then combined in the final measurement with the dilepton final state, which are used as input to a quantum chromodynamics analysis at next-to-next-to-leading order to investigate the impact on the determination of the gluon distribution in the less-explored kinematic range of high Bjorken-x.
- Contribution (keywords): *Conceptualization, Data analysis, Methodology, Project administration, Software development, Visualization, Writing—original draft, Writing—review and editing*

Observation of top quark production in proton-nucleus collisions **Phys. Rev. Lett. 119 (2017) 242001**

High-Energy Nuclear Physics *arXiv:1709.07411*

- Brief abstract: We report the first observation of top quark production in proton-nucleus collisions using proton-lead data collected at a nucleon-nucleon center-of-mass energy of 8.16 TeV, corresponding to approximately 174 nb^{-1}. The measurement is performed using events with exactly one isolated electron or muon and at least four jets. The measured cross section is consistent with predictions from perturbative quantum chromodynamics as well as scaled proton-proton measurements. This first measurement paved the way for further detailed investigations of top quark production in nuclear interactions, providing in particular a new tool for studies of the strongly interacting matter created in nucleus-nucleus collisions
- Contribution (description): Conceptualization, realization, and documentation of the analysis ("analysis contact"), including the simulation of all physics processes, physics object reconstruction, measurement of the trigger and event selection efficiencies, and the determination of the background sources. The number of jets passing a threshold on the b-jet identification discriminant is used to classify the selected events into no, exactly one, or at least two tagged-jet categories, and all three event categories are exploited in a maximum-likelihood fit to extract the signal cross section, and

simultaneously constrain the background contamination and determine the efficiency of the b jet identification. The parametrization of the signal in the fit model is derived from the MC simulation, while that of the backgrounds is obtained from control regions in the data. The compatibility of the data with the background-only hypothesis has been evaluated using a profile-likelihood ratio as a test statistic. Even with the most conservative assumptions, the background-only hypothesis is excluded with a significance above five standard deviations.

- Contribution (keywords): *Conceptualization, Data analysis, Methodology, Project administration, Software development, Visualization, Writing—original draft, Writing—review and editing*

Measurement of the single top quark and antiquark production cross sections in the t channel and their ratio in proton-proton collisions at $\sqrt{s} = 13$ TeV

Phys. Lett. B 800 (2019) 135042

High-Energy Particle Physics *arXiv:1812.10514*

- Brief abstract: With a data set corresponding to an integrated luminosity of 35.9 fb^{-1}, in this analysis we use about 18 times more data compared to our early Run 2 analysis (Phys. Lett. B 772 (2017) 752), while it exploits, in addition, the electron final state. More specifically, we select events with one muon or electron, and different categories of jet and b jet multiplicity and multivariate discriminators are applied to separate the signal from the background. The cross sections for the t-channel production of single top quarks and antiquarks and their ratio are measured in agreement with the predictions from the standard model.
- Contribution (description): Because of the theoretically challenging simulation of QCD multijet processes, this background contribution is suppressed as much as possible by having optimized the lepton isolation, whereas the remaining contamination is modeled from from sideband regions in data enriched in QCD multijet events. The statistical uncertainty plays only a minor role for the achieved precision of the current measurement, which is limited by the systematic uncertainty in the modeling of the signal process. Although deeper understanding of these effects and improved procedures to estimate the uncertainty are crucial to further decrease the systematic uncertainty, the cancellation of systematic effects when measuring the ratio of cross sections leads to a significantly improved precision with respect to the results of previous measurements at LHC. The measured ratio of the cross sections is compared to predictions using different state-of-the-art parton distribution functions (PDFs) to describe the inner structure of the proton. Good agreement with most PDF sets is found within the uncertainty of the measurement.
- Contribution (keywords): *Methodology, Writing—review and editing*

New physics searches with heavy-ion collisions at the CERN Large Hadron Collider

J. Phys. G: Nucl. Part. Phys. 47 (2020)

High-Energy Nuclear Physics *arXiv:1812.07688*

- Brief abstract: This document summarizes proposed searches for beyond the standard model (BSM) physics accessible in the heavy-ion mode at LHC, both through hadronic and ultraperipheral $\gamma\gamma$ interactions, and that have a competitive or, even, unique discovery potential compared to standard proton-proton (pp) collision studies. We argue that such interesting possibilities constitute a well-justified scientific motivation, complementing standard quark-gluon-plasma physics studies and prolonging the heavy-ion program past its currently scheduled end in 2029 (Run 4). In particular, by running with light- and intermediate-mass ion species, an operation mode that has been partly considered so far with xexon-xenon (oxygen-oxygen) collisions in Run 2 (Run 3), we can accumulate nucleon-nucleon integrated luminosities in the accessible fb^{-1} range per month.
- Contribution (description): Ultraperipheral ion collisions offer, in particular, a unique way to exploit the LHC as an intense $\gamma\gamma$ collider, profiting from the $\sim Z^4$ enhancement factor in their cross sections, providing a clean and well understood environment within which to search for BSM states with QED couplings at masses below about 100 GeV, i.e., that are otherwise not accessible in the pp mode. In the case of BSM signals produced through hard scatterings, the absence of pileup,

the improved primary and displaced vertexing, and the lower trigger thresholds in heavy-ion mode compared to high-pileup pp collisions, provide superior conditions for searches for BSM long-lived particles (LLP) at low masses: An illustrative case has been made based on right-handed neutrinos with masses below 5 GeV, where the higher luminosities attainable with lighter ions lead to a larger number of observable LLP events per unit of running time than in pp collisions. The huge electromagnetic fields present in UPC lead to exponential enhancements of the cross sections for magnetic monopoles, and allow for first-principle calculations that are otherwise exponentially suppressed in similar pp analyses.

- Contribution (keywords): *Methodology, Writing—review and editing*

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams
CERN Yellow Rep. Monogr. 7 (2019) 1159

High-Energy Nuclear Physics *arXiv:1812.06772*

- Brief abstract: The future opportunities for high-density QCD studies with ion and proton beams at LHC are presented. Among the major scientific goals identified are the investigation of the microscopic parton dynamics underlying QGP properties and the exploration of parton densities in nuclei in a broad kinematic range. To address these scientific goals, high-luminosity lead-lead and proton-lead programs are considered priorities for Runs 3 and 4. High-luminosity runs with light- and intermediate-mass ion species nuclei are considered an appealing case for extending the heavy-ion program at the LHC its currently scheduled end in 2029 (Run 4).
- Contribution (description): As high-momentum transfer (Q^2) processes have a short space-time scale, they are not affected by the long-wavelength particle excitations of the QGP. This implies that the primary production rates of hard processes in nucleus–nucleus (and proton-nucleus) collisions are determined perturbatively, allowing for improved global nPDF fits, in particular, with high-precision W and Z boson, dijet, and for the first time top quark measurements. While the first Run 2 results, e.g., on W boson production, already feature experimental uncertainties smaller than the nPDF ones, the larger luminosity by approximately a factor 5–10 expected in Runs 3–4 will allow for another large jump in direct constraints on nPDFs from data. In that context, we performed novel studies, i.e., the projection measurement of differential cross sections for top quark pair production, for an improved constraining power on nPDFs.
- Contribution (keywords): *Data analysis, Methodology, Visualization, Writing review and editing*

Cross section measurement of t-channel single top quark production in pp collisions at $\sqrt{s} = 13$ TeV
Phys. Lett. B 772 (2017) 752

High-Energy Particle Physics *arXiv:1610.00678*

- Brief abstract: The cross section for the production of single top quarks in the t channel is measured for the first time in proton-proton collisions at 13 TeV. The analyzed data correspond to an integrated luminosity of 2.2 fb^{-1}. For the event selection, we required one muon and two jets one of which identified as originating from a bottom quark. Several kinematic variables are then combined into a multivariate discriminator to distinguish signal from background events, and a fit to the distribution of the discriminating variable yields the total cross section and the ratio of top quark and top antiquark production. From the total cross section the absolute value of the CKM matrix element, V_{tb}, is also calculated. All results are in agreement with the standard model predictions.
- Contribution (description): Because of the theoretically challenging simulation of QCD multijet processes, this background contribution is suppressed as much as possible by having optimized the lepton isolation, whereas the remaining contamination is modeled from from sideband regions in data enriched in QCD multijet events. The measured ratio of the cross sections is compared to predictions using different state-of-the-art parton distribution functions to describe the inner structure of the proton. Good agreement with most PDF sets is found within the uncertainty of the measurement, dominated by the statistical uncertainty but whose impact was subsequently

minimized in Phys. Lett. B 800 (2019) 135042.
- Contribution (keywords): *Data analysis, Methodology, Visualization, Writing review and editing*

Physics-analysis summaries

This section details physics-analysis summaries (**not yet converted to or superseded**) by peer-reviewed journal publications.

First look at top-quark selections with 13 TeV data
High-Energy Particle Physics *CMS-DP-2015-019*

- Brief abstract: In this detector performance note we present for the first time some illustrative event displays and distributions of observables designed to study top quark in pairs or singly. The data set consists of the first proton-proton collision data recorded by the CMS detector at a center-of-mass energy of 13 TeV with a magnetic field of 3.8 T, during the LHC development run with a bunch spacing of 50 ns that initially took place in July 2015. Preliminary expectations from Monte Carlo next-to-leading order simulation are compared to data.
- Contribution (description): We identified a candidate event that passes a selection designed for the t-channel single top electroweak production with a single muon at the final state.
- Contribution (keywords): *Data analysis, Visualization*

I contributed to **all Run 2 (2015-–2018) luminosity-related physics-analysis summaries** with the majority of (CMS-PAS-LUM-17-001, CMS-PAS-LUM-17-004, CMS-PAS-LUM-18-002,CMS-PAS-LUM-19-001) or entirely from (CMS-PAS-LUM-16-001, CMS-PAS-LUM-17-002, CMS-DP-2021-002) the elements of "Conceptualization, Data analysis, Methodology, Project administration, Software development, Visualization, Writing—original draft, Writing—review and editing".

Conference proceedings

Flow harmonics in heavy ion physics at CMS and ATLAS
55th Rencontres de Moriond, La Thuile, Italy, 27 March–3 April 2021 *arXiv:2105.07287*

- Abstract: How can we gain a detailed insight into the hydrodynamic response of the system created in heavy ion collisions to the fluctuating initial geometry and viscous effects? Do we create a strongly interacting medium in proton-nucleus and proton-proton collisions, or rather a system of partons undergoing few scatterings? To what extent can we discriminate between initial momentum correlations and flow generated as a response to the initial geometry via interactions in the final state? Do measurements of identified particle flow confirm the observations from inclusive charged hadrons? An experimental overview of anisotropic flow measurements, ranging from large down to the smallest collision systems, is given in these proceedings.

Evidence for top quark production in nucleus-nucleus collisions **PoS HardProbes2020 (2020) 191**
10th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions (HardProbes2020), Austin, Texas, June 1–6 2020
arXiv:2009.02421

- Abstract: Using 1.7 ± 0.1 nb[1] of lead-lead ($A = 208$) collision data recorded by the CMS experiment at a nucleon-nucleon center-of-mass energy of 5.02 TeV, we report evidence of top quark pair ($\mathrm{t\bar{t}}$) production. The $\mathrm{t\bar{t}}$ cross section ($\sigma_{\mathrm{t\bar{t}}}$) is extracted from likelihood fits to a multivariate discriminator using lepton kinematic variables in dilepton final states and two methods. One method relies on the leptonic information alone, and the second one exploits, in addition, the presence of bottom quarks. The measured $\sigma_{\mathrm{t\bar{t}}}$ is $2.54^{+0.84}_{0.74}$ and $2.03^{+0.71}_{0.64}$ μb in the two cases, respectively, consistent with predictions from perturbative quantum chromodynamics. We demonstrate, for the

first time, that top quark decay products (leptonically decaying W bosons and bottom quarks) can be identified, irrespective of any possible final-state interactions with the quark-gluon plasma.

Review of results using heavy ion collisions at CMS **doi: 10.17161/1808.30727**

Workshop of QCD and Forward Physics at the EIC, the LHC, and Cosmic Ray Physics in Guanajuato, Mexico, November 18–21 2019

arXiv:2006.05556

- Abstract: Ultrarelativistic heavy ion collisions at the laboratory provide a unique chance to study quantum chromodynamics (QCD) under extreme temperature ($approx$150 MeV) and density ($approx$1 GeV/fm^3) conditions. Over the past decade, experimental results from LHC have shown further evidence for the formation of the quark-gluon plasma (QGP), a phase that is thought to permeate the early Universe and is formed in the high-density neutron-star cores. Various QCD predictions that model the behavior of the low-x gluon nuclear density, a poorly explored region, are also tested. Since the photon flux per ion scales as the square of the emitting electric charge Z^2, cross sections of so far elusive photon-induced processes are extremely enhanced as compared to nucleon-nucleon collisions. Here, we review recent progress on CMS measurements of particle production with large transverse momentum or mass, photon-initiated processes, jet-induced medium response, and heavy quark production. These high-precision data, along with novel approaches, offer stringent constraints on initial state, QGP formation and transport parameters, and even parametrizations beyond the standard model.

Evidence for top quark production in nucleus-nucleus collisions **Nucl. Phys. A 1005 (2021) 121731**

XXVIIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (Quark Matter 2019)

arXiv:1912.12104

- Abstract: Droplets of quark-gluon plasma (QGP), an exotic state of strongly interacting quantum chromodynamics (QCD) matter, are routinely produced in heavy nuclei high-energy collisions. Although the experimental signatures marked a paradigm shift away from expectations of a weakly coupled QGP, a challenge remains as to how the locally deconfined state with a lifetime of a few fm can be resolved. The only colored particle that decays mostly within the QGP is the top quark. Here we demonstrate, for the first time, that top quark decay products are identified, irrespective of whether interacting with the medium (bottom quarks) or not (leptonically decaying W bosons). Using 1.7 ± 0.1 nb[1] of lead-lead ($A = 208$) collision data recorded by the CMS experiment at a nucleon-nucleon center-of-mass energy of 5.02 TeV, we report evidence of top quark pair ($\mathrm{t\bar{t}}$) production. Dilepton final states are selected, and the cross section ($\sigma_{\mathrm{t\bar{t}}}$) is measured from a likelihood fit to a multivariate discriminator using lepton kinematic variables. The tt^- measurement is additionally performed considering the jets originating from the hadronization of bottom quarks, which improve the sensitivity to the $\mathrm{t\bar{t}}$ signal process. After background subtraction and analysis corrections, the measured $\sigma_{\mathrm{t\bar{t}}}$ is 2.02 ± 0.69 (tot) and 2.56 ± 0.82 (tot) μb in the two cases, respectively, consistent with predictions from perturbative QCD.

Results on TOP physics from CMS

International Workshop on Future Linear Colliders, LCWS2017, 23–27 October 2017, Strasbourg, France

arXiv:1801.08398

- Abstract: After the discovery of the top quark more than 20 years ago, top quark production cross sections have been meticulously studied. The rich variety of results from the LHC experiments are complemented with increasingly accurate theoretical predictions of heavy quark production and decay. Measurements of the top quark production provide a benchmark test of perturbative quantum chromodynamics and the standard model (SM), constraining at the same time the background in Higgs boson searches as well as extensions beyond the SM. Recent top quark measurements from CMS are reviewed, illustrating past and current experimental methods along with their attained precision. A perspective of top quark physics at the High-Luminosity LHC and at future colliders is briefly given.

Observation of top quark production in proton-nucleus collisions

10th International Workshop on Top Quark Physics, Braga, Portugal, September 17–22, 2017 *arXiv:1712.06102*

- Abstract: The multi-TeV energies available at LHC have opened up the possibility to measure, for the first time, various large-mass elementary particles in nuclear collisions. The current study presents the first observation of top quark—the heaviest elementary particle in the standard model—using proton-lead collisions. The measurement is based on a data set whose integrated luminosity amounts to 174 nb^{1}, as recorded by CMS at a center-of-mass energy per nucleon pair of 8.16 TeV. The pair production process is measured using events with exactly one isolated lepton, electron or muon, and at least four jets, leading to a cross section of 45 ± 8 nb. This is well compatible with theoretical predictions from perturbative quantum chromodynamics at next-to-next-to-leading order with soft gluon resummation at next-to-next-to-leading logarithmic accuracy. The statistical significance of the signal against the background-only hypothesis is above five standard deviations.

Study of the top quark production in complementary phase space regions and impact on PDFs in CMS

Rencontres de Blois 2017, Blois, France, May 28–June 2, 2017 *arXiv:1712.06103*

- Abstract: The first measurement of the top quark pair production cross section ($\sigma_{\mathrm{t\bar{t}}}$) in proton-proton collisions at $\sqrt{s} = 5.02$ TeV is reviewed. The data have been collected by the CMS experiment at the LHC and analyzed considering events with at least one charged lepton. The extraction of $\sigma_{\mathrm{t\bar{t}}}$ can be used to constrain the gluon distribution function (PDF) at large longitudinal parton momentum fraction and to establish experimentally the relation between the top-quark mass as implemented in Monte-Carlo generators and the Lagrangian mass parameter. The impact of the measurement on the determination of the gluon PDF is illustrated through a quantum chromodynamic analysis at next-to-next-to-leading order and the result is furthermore put in context with other top quark measurements in different phase space regions. The measurement has paved the way for the first observation of top quark production in nuclear collisions and the subsequent study of modifications induced on the bound gluon PDF.

Associated production of top quarks with the Higgs boson at $\sqrt{s} = 13$ TeV **PoS DIS2017 (2018) 290**

XXV International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS 2017), Birmingham, UK, 3–7 April 2017 *arXiv:1712.06104*

- Abstract: The top quark, being the heaviest elementary fermion known in the Standard model, has the largest coupling to the Higgs boson. The associated production of top quarks with the Higgs boson, either in pairs ($\mathrm{t\bar{t}H}$) or singly (tH), provides direct experimental access to the top-Higgs coupling y_{t}. The $\mathrm{t\bar{t}H}$ (tH) production mode, while proceeding at a rate of about 100 (1000) times smaller than gluon fusion, bears a highly distinctive experimental signature, which includes leptons and/or jets from the decay of the two (single) top quarks. The latest results of $\mathrm{t\bar{t}H}$ searches at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of up to 35.9 fb^{1} as collected from CMS are shown and tantalizing evidence is found for measuring this crucial process with sufficient precision. However, higher precision data set is needed in order to confirm or disprove the previous observed excess. Initial searches for tH production mode at a center-of-mass energy of 13 TeV achieve comparable sensitivity to that of the Run 1 analysis.

Constraining QCD multijet background in the t-channel single-top quark production at $\sqrt{s} = 13$ TeV **PoS TOP2015 (2016) 059**

8th International Workshop on Top Quark Physics (TOP2015), Ischia, Italy, 14-18 September, 2015 *arXiv:1712.06106*

- Abstract: Precision measurement of the cross section for single top production is an important test of the Standard Model (SM). The purity of the collected data in single top events is limited by the understanding of the shape and yield of background contributions. Besides electroweak

and $t\bar{t}$ processes, QCD multijet events constitute a non-negligible background for the considered signal $bq' \to tq$ (t-channel) process. The data-driven technique for constraining QCD contribution, employed in the measurement of the t-channel single top-quark cross section using the very first LHC proton-proton collisions at $\sqrt{s} = 13$ TeV with the CMS detector, is described. The data set corresponds to an integrated luminosity of $\mathcal{L} = 42$ pb^{-1}.

Theses

First measurements of the $t\bar{t}$ cross section in LHC pp and pPb collisions at 5.02 and 8.16 TeV and determination of the absolute luminosity in the CMS experiment

High-Energy Nuclear and Particle Physics, Physics Instrumentation and Detectors *PhD thesis*

- Abstract: Soon after the discovery of the bottom quark, the quest for the top quark had begun. The search carried out for nearly 20 years because the mass of the top quark turned out to be unexpectedly large, around 40 times the mass of the bottom quark. The discovery of the top quark in nuclear collisions had to further wait another 20 years for the 2016 proton-nucleus run at the CERN LHC. The first top quark measurement in nuclear collisions is demonstrated with the observation of the top quark pair process, using 174±6 nb[1] of proton-nucleus collisions at 8.16 TeV with the CMS experiment. The measurement is performed by analyzing events with exactly one isolated electron or muon and at least four jets. The inclusive cross section that is simultaneously measured in the two final states is 45±8 nb, consistent with perturbative QCD calculations as well as the expectations from scaled proton-proton data. Measurements of top quark pair production at various energies probe different values of x, the fractional momentum of the proton carried by the partons. Using a data sample of 27.4±0.6 pb[1] collected by the CMS experiment during the proton-proton run at 5.02 TeV in 2015, the first measurement of the inclusive top quark pair cross section is also presented for events with one or two leptons (electrons or muons), and at least two jets. A moderate decrease of the uncertainty in the gluon distribution is observed in the less-explored kinematic range of x0.1. To determine the luminosity and the associated uncertainty the van der Meer scan technique is used, a purely experimental method.

Academic advisor: *Andrea Giammanco*

Higher-Order Azimuthal Anisotropy of $\Lambda + \overline{\Lambda}$ hyperons in PbPb collisions at $\sqrt{s} = 2.76$ TeV measured with the ALICE Detector at LHC

High-Energy Nuclear Physics *MSc thesis*

- Abstract: The second- to fourth-order Fourier coefficients ($\upsilon_n, n = 2 - 4$) are measured for $\Lambda + \overline{\Lambda}$ hyperons as a function of transverse momentum (p_{T}) in the (0–60)% most central lead-lead collisions at 2.76 TeV with the ALICE experiment. The υ_n coefficients are observed to increase with p_{T} up to about 3.5 GeV, then to saturate and decrease, a pattern persistent all over centralities. A linear-p_{T} dependence and mass ordering at low p_{T} (< 2.5 GeV) are clearly observed across the harmonics. The coefficients exhibit a centrality-dependent crossing point at p_{T} <8 GeV. The enhanced flow of baryons over mesons at this p_{T} region is investigated in the realm of the coalescence mechanism. The $\upsilon_n(p_{\mathrm{T}}) \approx n\upsilon_2(p_{\mathrm{T}}/n)$ scaling found to barely hold at LHC energies. A nonparticular particle-species dependency is seen at p_{T} >10 GeV for υ_2, consistent with a path-length driven emission of particles.

Academic advisor: *Panos Christakoglou*

Testing the Boosted Decision Trees (BDT) performance for Λ's and $\overline{\Lambda}$ identification in PbPb collisions within the Heavy Ion Jet INteraction Generator (HIJING) model

High-Energy Nuclear Physics *CERN Summer Student Program 2014*

- Abstract: Advanced analysis methods are imperative, given the enormous challenge risen to scien-

tific and industrial problems. The vast data sets in High-Energy Physics research are characterized by multiple variables and are usually accompanied by rare signal processes. Automated algorithms have been developed, whose primary task is that of learning from data so as to correctly respond to future inputs. The present analysis takes advantage of object-oriented implementations in C++/ROOT for the multivariate technique dubbed as Boosted Decision Trees (BDT). Simple in interpretation, yet powerful discrimination tool, a decision tree partitions the input space into a series of rectangle regions; many individual predictor-trees of modest quality are combined in turn to produce a highly effective majority classifier. In the actual report, unmasking of background that mimics the behavior of signal candidates is performed for the weak decay of Λ ($\overline{\Lambda}$) hyperons to $p\pi^-(\bar{p}\pi^+)$. The splitting of the feature space is simply achieved based on variables which delineate the decay topology. Superior performance is registered for the BDT technique, when compared to the regular hard cut technique.

Academic advisor: *Stan Bentvelsen*

Elliptic Flow of K_s^0 's, Λ's and $\overline{\Lambda}$'s in Pb-Pb 20–40% Central collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV measured with the ALICE Detector at LHC

High-Energy Nuclear Physics *Bachelor thesis*

- Abstract: We report the measurement of elliptic flow $v_2(p_{\rm T})$ in extended transverse momentum range for the identified cases of K_s^0 (< 8.5 GeV), Λ and $\overline{\Lambda}$ (< 7.5 GeV) in Pb-Pb 20–40% central collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV measured with the ALICE detector at LHC. While K_s^0's reach a maximum of $v_2 = 0.167 \pm 0.0007$ (stat) at $p_{\rm T}\approx$3 Gev, the baryon (anti-baryon) $v_2(p_{\rm T})$ continues to rise until it reaches a maximum of $v_2(p_{\rm T}) = 0.213 \pm 0.0013$ (stat) $(0.214 \pm 0.0014(stat))$ at $p_{\rm T}\approx$4 GeV. For larger $p_{\rm T}$, the $v_2(p_{\rm T})$ values exhibit a gradual decrease for all three cases. Quark scaling properties are also examined, indicating that at intermediate and high $p_{\rm T}$ scaling does not hold for strange particles $v_2(p_{\rm T})$.

Academic advisor: *Peter Christiansen*