10 Particle physics with the CMS experiment at CERN

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in collaboration with:

CMS - Collaboration

The CMS experiment acquired a record year of data in 2016, collecting over 40 fb^{-1} of 13 TeV center of mass proton-proton collisions, more than all previous years combined. During an extended year-end shutdown between 2016 and 2017 data taking, a new 4-layer pixel detector was installed in the center of CMS, set to provide the experiment with improved triggering, tracking, and vertexing capabilities.

Here we present an overview of our CMS activities. Our major activity in 2016 was completing and commissioning the new 4-layer Phase 1 pixel detector system. We have also maintained and operated the present pixel detector which has taken data from 2010 to 2016, and are beginning with simulation studies and the design of a future Phase 2 pixel upgrade, envisioned to be ready in 2023. Besides our work on the original and upgraded pixel detectors, we are also involved in trigger development and monitoring as well as physics data analysis on a number of different topics.

Our physics analysis program addresses fundamental questions in particle physics. After the discovery of a Higgs particle at the LHC [1], studying its properties is among the primary goals. We are testing the fermionic couplings of the Higgs boson, with several analyses geared towards its couplings to tau leptons, top quarks, and bottom quarks. We are testing several theoretical models which could extend the Standard Model (SM), with new particle states at a few TeV. These generate loop corrections with the necessary cancellations to stabilize the Higgs boson mass. Models such as supersymmetry, extra dimensions, and vector-like quarks justify the mysteriously low Higgs boson mass, and predict a wide range of new particles, which we are sifting through CMS data to observe.

Members of our group play important coordination roles. In the period covered by this report, S. Donato acted as co-convener of the Software Tools, Online Releases and Menus subgroup under Trigger Coordination. A. de Cosa was subgroup convener within the Beyond 2 Generations (B2G) physics group, A. Hinzmann acted as convener of the JetMET algorithms and reconstruction group, and C. Seitz as subgroup convener within the inclusive Supersymmetry (SUSY) physics group. Y. Takahashi was main editor of the Higgs Tau observation group. S. Donato and L. Caminada are members of the Swiss Tier 3 computing steering committee. F. Canelli is on the CMS Management Board, and B. Kilminster is on the Management Board for the phase 1 upgrade and the Tracker group.

[1] ATLAS collaboration, Phys. Lett. B **716** (2012) 29; CMS collaboration, Phys. Lett. B **716** (2012) 30.

10.1 The CMS experiment

CMS [2] is one of the multipurpose detectors at the LHC. It consists of different layers of detectors optimized for position and energy measurements of particles produced in collisions. An all-silicon tracker, an electromagnetic calorimeter, and a hadronic sampling calorimeter are all contained within a large-bore 3.8 T superconducting solenoid. Beyond the solenoid there are four layers of muon detectors. The CMS tracker is composed of the inner pixel detector and the outer silicon strip detector. Up until the end of 2016, the pixel detector has consisted of three barrel layers (BPIX) at 4.4, 7.3, and 10.2 cm, and two forward/backward disks (FPIX) at longitudinal positions of $\pm$34.5 cm and $\pm$46.5 cm and extending in radius from about 6 to 15 cm. The high segmentation of the pixel detector allows for high-precision tracking in the region closest to the interaction point. The pixel detector information is crucial for primary vertex and pile-up vertex reconstruction, and identification of long-lived τ-leptons and B-hadrons. The performance of the current pixel detector has been excellent. It is noteworthy that the BPIX was built by the Swiss Consortium, PSI, ETH and the University of Zurich.

[2] CMS collaboration, JINST **3** (2008) S08004.

10.2 Detector maintenance and operation

The CMS pixel detector is a central component in the reconstruction of high-quality data used in Physics analysis. It performed very reliably during the whole period of data taking at the LHC at a very high efficiency and with more than 98% of its 66 million channels working. Our group made significant contributions to the operation of the pixel detector as well as the re-calibration during technical stops of the accelerator. Our group is responsible for the monitoring of detector performance and operational parameters, which is crucial in order to respond with preventive actions that ensure high-quality physics data. In particular, we keep track of the evolution of the radiation damage to the silicon sensors with increasing luminosity, measure threshold and noise distributions, as well as pixel hit resolutions, and determine the impact of pixel dynamic inefficiencies.

The pixel detector hit efficiency as a function of instantaneous luminosity is shown in Fig. 10.1. The efficiency is well above 99% for the outer two layers of the BPIX detector and forward disks, while limitations in the readout speed at higher luminosities degrade the efficiency for the innermost layer. In order to maintain the excellent performance of the pixel detector at the higher luminosities foreseen in the coming years, the pixel detector has been exchanged with an upgraded system as described in section 10.3.

To be well-prepared for a short commissioning period and to gain experience with the upgraded system, a pilot pixel system was installed into CMS and has been operating since 2014. The pilot system suffered from read-out problems that prevented it from data-taking within the CMS data acquisition system. Our group scrutinized and determined the nature of these erroneous events, leading to new firmware, which reduces the error rate by 3 to 4 orders of magnitude, eventually allowing the pilot system to successfully join the CMS data-taking.

Our group is also involved in another key part of the CMS detector, the trigger system. We took care of development and maintenance of the High Level Trigger (HLT) code, along with preparation and testing of trigger menus in the different 2016 data taking scenarios, including the special proton-lead collision data taking. We contributed in the monitoring of HLT trigger rates by producing dedicated MC samples. We also worked in the online b-tagging development with both 2016 and 2017 pixel geometry [3].

[3] CMS collaboration, CMS-DP-2017/011.

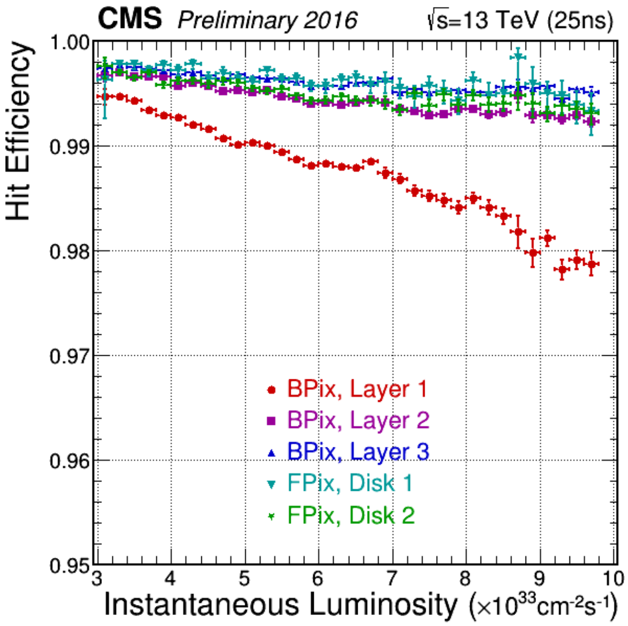

Fig. 10.1 – The pixel detector hit efficiency as a function of instantaneous luminosity for the three barrel layers and the two forward disks as measured during data-taking in 2016.

10.3 Upgrades

Our group, together with ETH Zürich and PSI, led the development and construction of a new and improved pixel system, the so-called Phase 1 pixel upgrade. The CMS Phase 1 pixel upgrade combines a new pixel readout chip, which minimizes detection inefficiencies, with several other design improvements. The current 3-layer BPIX, 2-disk FPIX detector was replaced with a 4-layer BPIX, 3-disk FPIX detector. The upgraded BPIX detector consists of four 57 cm long layers of silicon pixel modules serviced by 2.2 m of supply tubes which transport cooling tubes, electrical power, and optical signals to and from the pixel detector. The addition of an extra layer, closer to the beam pipe, demands a complete redesign of the power, cooling, and electronics.

Together with the UZH workshop we built the supply tube mechanical structure and designed and fabricated the new lightweight, thin-walled CO_2 cooling system. The supply tube multi-layer carbonized foam structure houses the electronics, cooling, power distribution, module control boards, and DC-DC converters. The cooling system is constructed in a complicated looping structure in order to cool the individual detector components including pixel modules, DC-DC converters and opto hybrids. In order to protect against possible corrosion, we use a special-quality steel alloy for all parts, and implement computerized, machine-automated laser welding. The production of the supply tube mechanics and the cooling system has been completed and passed highest quality assurance standards.

The assembly of the readout electronics, the power lines and the cooling loops on the supply tube structure took place at the end of 2016 at UZH. The dense arrangement of the many individual components in the constrained radial envelope make the assembly procedure very challenging. During and after the assembly all the components need to be tested and validated before merging the supply tubes and the pixel detector modules. More than 2000 single optical fibers and 1000 low-voltage and high-voltage power-lines had to be connected and tested as shown in Fig 10.2.

The fully tested supply tubes were then merged with the BPIX detector at PSI in January 2017 before transporting the completed detector system to CERN. Our group made significant contributions during an intense period of detector

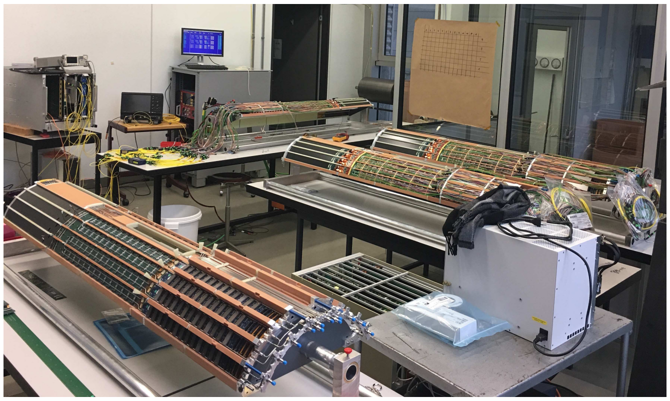

FIG. 10.2 – Shown are the four CMS pixel supply tubes half-shells in various stages of completion, with control and readout electronics, power, fibers, and cooling.

checkout and testing in view of the installation in CMS only one month later. This allowed us to transport the detector in a fully functional state to CERN and to successfully install it into CMS within the tight schedule. Our efforts now focus on commissioning and calibration to prepare the detector for stable and efficient operation during the next run.

The upgraded pixel detector is designed to provide optimal performance for the whole Phase 1 operation, until the third long shutdown of the accelerator (2023-2025) when a new pixel detector for the High Luminosity (HL) LHC will be installed (Phase 2). To meet the challenges arising from the increased luminosity of the machine, we are already now performing R&D for the next generation of pixel systems. In particular efforts are ramping up to evaluate the performance of different designs concerning the number and positioning of the pixel layers, the optimal pixel size as well as the overall mechanical design and technical implementation.

10.4 Analysis algorithms

Our group regularly contributes to measuring and improving the CMS performance in terms of physics objects (such as particles and jets) and algorithms. The group helped producing the jet energy scale and resolution measurement [4], as well as validating a likelihood-based tagger capable of discriminating jets initiated by quarks from those initiated by gluons [5]. We introduced machine learning techniques to improve the performance of the quark-gluon tagger, increasing the probability of correct assignment of quark initiated jets with up to 10% compared to the previous likelihood-based tagger at the same mis-tag rate.

We have extended efforts in the identification of τ objects, especially in the development of a *boosted tau* algorithm [6] capable of identifying two τ-leptons produced in close proximity to one another, as would be the case in the decay of a heavy particle. This can be used to identify boosted Higgs and Z bosons decaying to τ-leptons. Together with our major contribution to the development of algorithms used to identify boosted W and Z bosons decaying into quarks, we have a comprehensive search program for new physics in the boosted boson topology. In parallel, we are working on tackling one of the main challenges of LHC Run-2, namely the mitigation of effects related to multiple interactions in the same bunch crossing ("pileup"). One approach is to use local shape information, event pileup properties and tracking information together to mitigate the effect of pileup on jet observables. This technique was validated in data for the first time and was found to maintain W-tagging performance up to at least 40 simultaneous interactions [5].

[4] CMS collaboration, JINST **12** P02014.

[5] CMS collaboration, CMS-PAS-JME-16-003.

[6] CMS collaboration, CMS-DP-2016-038.

10.5 Higgs Properties

10.5.1 Higgs boson couplings to top quarks

The search for the Higgs boson produced in association with a top-quark pair (ttH) is the only way to directly probe the order-one Higgs-top coupling and, among ttH channels, the search for the Higgs boson decaying into b quarks probes only third-generation Higgs-fermion couplings, with the largest Higgs branching ratio of $H \to bb$ ($\sim 58\%$).

An excess of 4.4 standard deviations over SM backgrounds was observed in the search for ttH after Run-1, combining ATLAS and CMS results, while an excess of 2.0 standard deviation was expected [7]. This corresponds to a Higgs boson cross section of $\mu = 2.3^{+0.7}_{-0.6}$ times the SM prediction and might be a hint of New Physics.

We have searched for $t\bar{t}H(\to b\bar{b})$ with $12.9\,\mathrm{fb}^{-1}$ of Run-2 data both in the single and double lepton final states [9]. The analysis exploited the Matrix Element Method (MEM) we developed in the last years [8] combined with a machine learning discriminant. The MEM distribution of an analysis category is shown in Fig. 10.3. A background under fluctuation has been reported ($\mu = -0.19^{+0.80}_{-0.81}$) while an excess of 1.5 standard deviations was expected. This analysis will be updated with the whole 2016 dataset ($\sim 38\ \mathrm{fb}^{-1}$).

We are looking to include the fully hadronic final state which has a branching ratio as large as 46% in the $t\bar{t}H(\to b\bar{b})$ analysis. Challenges are the multijet QCD background and its estimate from data, along with the application of the MEM in an environment with significant combinatorial background given the large number of jets in the final states. Meanwhile, we are developing a trigger with online b-tagging for the 2017 data taking, exploiting the new pixel detector.

[7] CMS and ATLAS collaborations, JHEP **08** (2016) 045.

[8] CMS collaboration, EPJ C **75** (2015) 251.

[9] CMS collaboration, CMS-PAS-HIG-16-038.

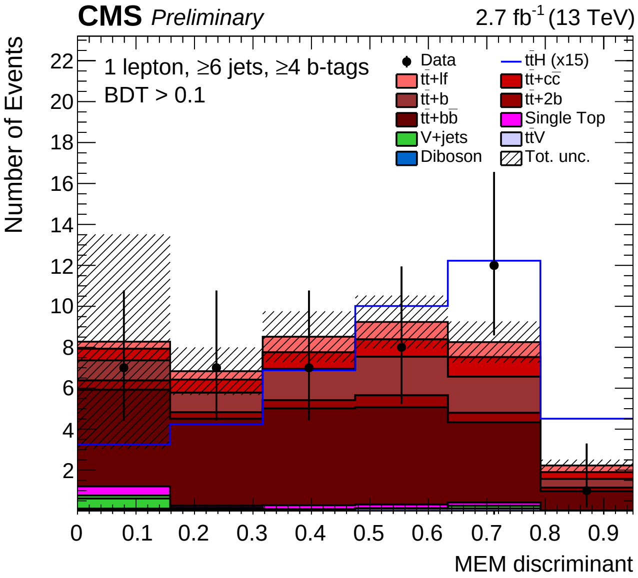

FIG. 10.3 – The MEM discriminant for one category of ttH candidate events before the final fit.

10.5.2 Higgs coupling to τ leptons

Discovering the fermionic final states of the Higgs boson and measuring its coupling strength are imperative to verify or detect possible deviations from the Standard Model. The $\tau\tau$ final state of the Higgs boson is the most promising channel due to its large SM-expected event rate in conjunction with its manageable backgrounds. In LHC Run-1, there was an excess of events corresponding to 3.2 standard deviations over the predicted backgrounds. Our group pushed forward this measurement using 2016 data, mainly contributing to the most sensitive $\tau_\mu\tau_\mathrm{h}$ and $\tau_e\tau_\mathrm{h}$ final states, with τ_μ and τ_e a leptonic (electron or muon) decay of the tau-lepton, and τ_h a hadronic decay. The results are extracted via two-dimensional maximum likelihood fits in the planes defined by the full or visible $\tau\tau$ mass, and the event kinematics. We observed an excess of events with 4.9 standard deviations for a mass of 125 GeV. The observed signal rate is in good agreement with the SM expectation. Figure 10.4 shows the observed signal. This is a good starting point to further investigate Higgs boson properties, especially the Charge-Parity ($\mathcal{CP}$) nature of the Higgs boson in fermionic Higgs boson decays.

Related to this, we are extending our analysis to search for low mass $\tau\tau$ resonances, predicted by many new physics models. In some scenarios, taus from the new resonance would possess non-trivial polarizations. Our experience of measuring τ polarization in $Z \to \tau\tau$ will be exploited in the next year.

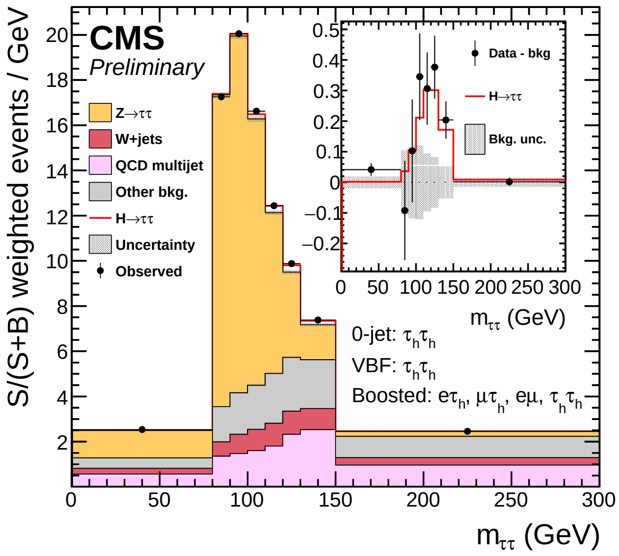

FIG. 10.4 – New CMS observation of H $\to \tau\tau$, produced by combining several final states.

10.6 Searches for new phenomena

10.6.1 Search for vector-like quarks

Many extensions of the SM, such as composite Higgs, extra dimensions, and little Higgs, predict the existence of a new class of heavy quarks, named vector-like quarks (VLQ) [10–14]. The existence of such particles would represent a solution to the hierarchy problem. Single electroweak production of VLQs has not yet been well-explored, despite the production being dominant above masses of 700 GeV. Our group has made a significant impact in the search for singly produced VLQs, carrying out two different searches, looking for massive B and T VLQs. Our focus is on two specific final states: $T \to tZ \to bq\bar{q}\,\nu\nu$ and $B \to bH \to b\,b\bar{b}$.

The new heavy resonances decay into highly boosted quarks and bosons, whose decay products are merged into a unique “fat" jet, for which we use special techniques for identification. The two searches are performed with the entire dataset collected at 13 TeV in 2016 and are currently ongoing. The results are expected to be published soon.

[10] S. Fajfer, A. Greljo, J. F. Kamenik and I. Mustac, JHEP **1307** (2013) 155.

[11] P. W. Graham, A. Ismail, S. Rajendran and P. Saraswat, Phys. Rev. D **81** (2010) 055016.

[12] M. Schmaltz and D. Tucker-Smith, Ann. Rev. Nucl. Part. Sci. **55**, 229 (2005).

[13] N. Arkani-Hamed, A. G. Cohen and H. Georgi, Phys. Lett. B **513** (2001) 232.

[14] L. Wang and X. F. Han, Phys. Rev. D **86** (2012) 095007.

10.6.2 Search for heavy resonances in di-boson events

The UZH group plays a leading role in searches for heavy resonances, with masses larger than 1 TeV, decaying into a pair of standard model bosons (W, Z, or the Higgs boson). These heavy resonances are predicted by a large number of theoretical models that extend the SM and provide an explanation for the hierarchy problem. The most credited theories include extra dimensions, composite Higgs, heavy vector-triplets, and additional $U(1)$ gauge groups [15]. These models predict the presence of massive spin-0 Radions, spin-2 Gravitons, or spin-1 heavy W' or Z' bosons which may decay with a significant branching fraction into SM bosons.

As a consequence of the heavy mass of the new particles, and the large Lorentz boost of the decay products, the pair of particles originating from the decay of the SM bosons usually have a small angular separation and special identification and reconstruction techniques must be employed. In 2016, the new generation PUPPI [16] and Soft Drop [17] algorithms have been commissioned by the Zurich group, ensuring an optimal reconstruction of the boson mass and the jet substructure even in the harsher data-taking conditions encountered in 2016. A novel reconstruction algorithm for identifying boosted $H \to \tau\tau$ decay was developed and commissioned within our group (Fig. 10.5) [18]. This technique is currently being used in the $X \to HH \to b\bar{b}\tau\tau$ and $X \to VH \to q\bar{q}\tau\tau$ analysis ($V = W, Z$), produced also by the Zurich group.

These advanced techniques are applied to searches for diboson resonances. In the first months of 2016, we completed the searches for the processes $X \to VV \to q\bar{q}q\bar{q}$, $X \to WV \to \ell\nu q\bar{q}$ [19], and $X \to VH \to (\nu\nu, \ell\nu, \ell\ell)b\bar{b}$ [20] based on the 2015 data set, accounting for 2.3 fb^{-1}. The latter represented a novelty for CMS, and both of them have been accepted for publication by refereed journals. The sensitivity of the individual searches is boosted by combining all $\sqrt{s} = 8$ and 13 TeV searches with boosted W, Z, and Higgs bosons in 12 final states, setting the most stringent limits on new models at the time [21]. As their combination is found to yield a large gain in sensitivity (Fig. 10.6), this work represents a powerful tool for future resonance searches with the large expected diboson event data sample at the LHC.

In 2016, the LHC has provided an integrated luminosity of 36 fb^{-1}, and searches for heavy particles are among the most benefited by the larger dataset. The UZH group completed two high-profile searches in hadronic final states, $X \to VV \to q\bar{q}q\bar{q}$ [22, 23] and $X \to VH \to q\bar{q}b\bar{b}$ (Fig. 10.7) [24]. These two searches exploit synergy by using common identification techniques for boosted W and Z bosons. The VH analysis, performed for the first time in Run II, represents one of the first applications of an algorithm designed to recognize the presence of two b quarks in the same hadronic jet. Although no significant excess over the estimated background has been observed, these searches put the most stringent limits on the parameters of the models

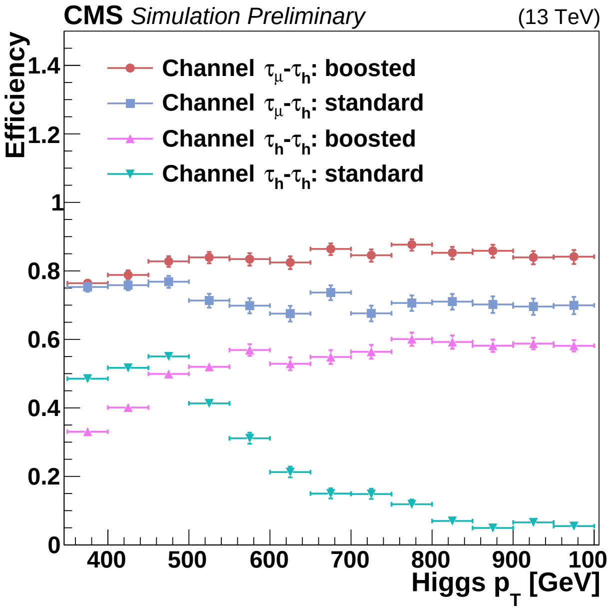

FIG. 10.5 – Reconstruction efficiency for $H \to \tau\tau$ decays with large Higgs boson Lorentz boost, as a function of the Higgs boson transverse momentum, for the CMS standard τ and the dedicated "boosted" reconstruction [18].

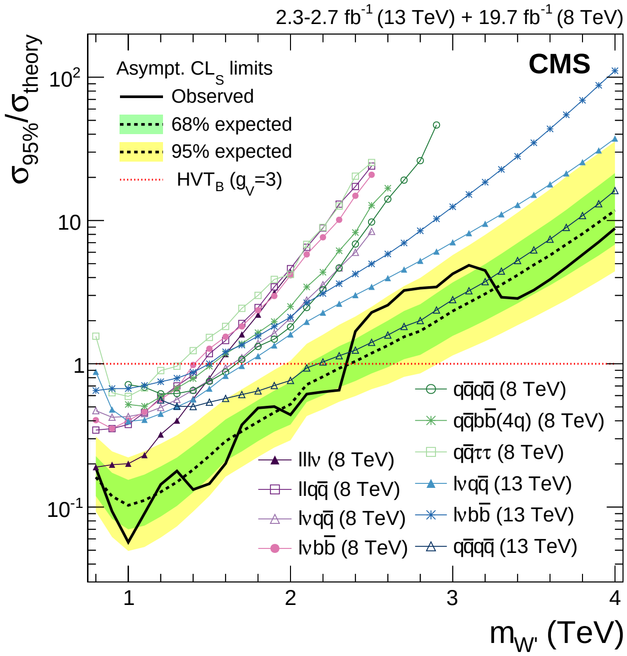

FIG. 10.6 – Expected and observed upper limits at 95% C.L. on σ/σ_{theory}, where σ_{theory} is the cross section predicted by a heavy vector triplet model, as a function of the mass of a heavy W' resonance $m_{W'}$. Different markers indicate the expected limits of the various analyses used in the combination [21].

to date (Fig. 10.6). These new results are expected to be published soon, and the combination of the searches performed with the 2016 data promises to further increase the exclusion limit on the mass of the resonances.

[15] K. Agashe *et al.*, Phys. Rev. D **76** (2007) 036006;
L. Randall, R. Sundrum,
Phys. Rev. Lett. **83** (1999) 3370;
D. Marzocca *et al.*, JHEP **08** (2012) 013;
R. Rattazzi *et al.*, JHEP, 2011(10), 2011;
D. Pappadopulo *et al.*, arXiv:1402.4431.

[16] D. Bertolini *et al.*, JHEP **2014** (2014) 59.

[17] A. J. Larkoski *et al.*, JHEP **05** (2014) 146.

[18] CMS Collaboration, CERN-CMS-DP-2016-038.

[19] CMS collaboration, CMS-PAS-B2G-16-004, submitted to JHEP.

[20] CMS collaboration, CMS-PAS-B2G-16-003, submitted to PLB.

[21] CMS collaboration, CMS-PAS-B2G-16-007.

[22] CMS collaboration, CMS-PAS-B2G-16-021.

[23] CMS collaboration, CMS-PAS-B2G-17-001.

[24] CMS collaboration, CMS-PAS-B2G-17-002.

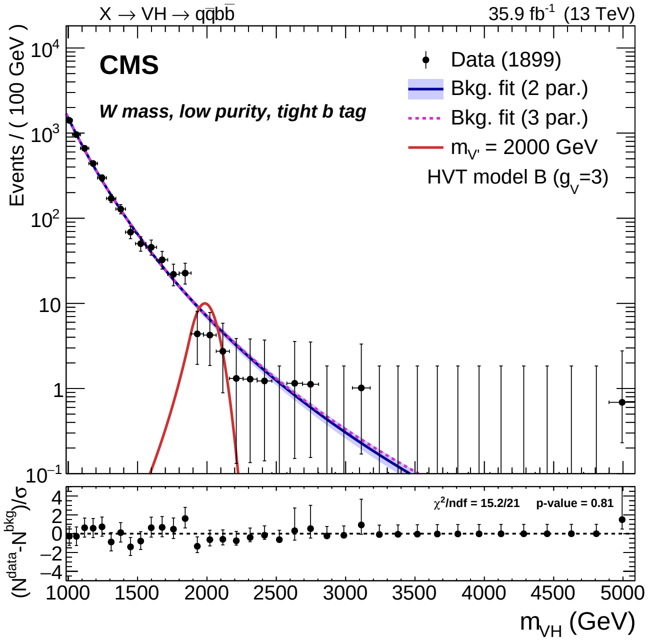

FIG. 10.7 – Spectrum of the reconstructed $V \rightarrow q\bar{q}$ and $H \rightarrow b\bar{b}$ invariant mass in the category of the $X \rightarrow VH \rightarrow q\bar{q}b\bar{b}$ analysis where the highest-mass event has been observed [24].

10.6.3 Supersymmetry

One of the favored extensions of the SM is supersymmetry (SUSY), predicting a variety of new particles at the TeV scale, that differ in spin from their SM counterparts. SUSY provides an elegant solution to some of the shortcomings of the SM, including the hierarchy problem and the nature of dark matter.

One SUSY model describes pair production of gluinos ($\tilde{g}$), the superpartner of the SM gluons, where each gluino decays into two top quarks and the lightest supersymmetric particle (LSP), $\tilde{\chi}^0_1$. These events would provide a striking signature with many jets, leptons, and missing energy in the final state. Our group has been part of one of the efforts to search for this type of decay in the exclusive single lepton final state, which has the advantage of a large branching ratio and a fairly clean SM background mainly originating from top quark pair production with additional jets. Figure 10.8 shows the interpretation of the results in terms of the gluino simplified model, where gluinos up to a mass of 1800 GeV are excluded. This result is based on the full dataset of $35.9\,\mathrm{fb}^{-1}$ collected during 2016 and was made public in March 2017 [25], with a journal publication currently in preparation.

[25] CMS collaboration, CMS-PAS-16-042.

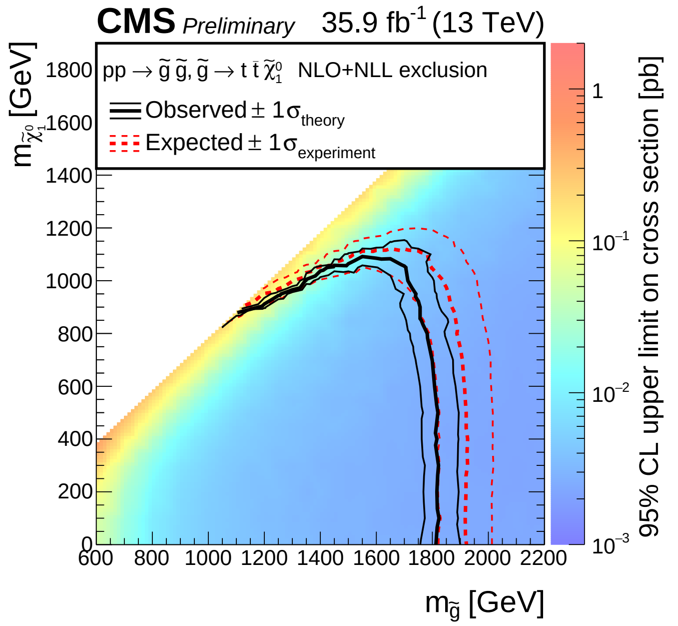

FIG. 10.8 – Cross section limits at a 95% CL for the $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}^0_1$ simplified model, as a function of the gluino and LSP masses. The solid black (dashed red) lines correspond to the observed (expected) mass limits, with the thicker lines representing the central values and the thinner lines representing the $\pm 1\sigma$ uncertainty bands related to the theoretical (experimental) uncertainties.

10.6.4 Search for dark matter particles with top quarks

In several new physics models a weakly interacting massive particle arises naturally as a dark matter (DM) candidate. So far, however, there is no established knowledge about its properties and interactions with ordinary matter. DM may couple to matter in proportion to mass, leading to DM being produced with top quarks at the LHC [26].

The DM particle would escape detection, therefore the signature of this type of event is large missing energy recoiling against the top quarks. Our group has made a significant impact on this search with 8 TeV [28] and the 13 TeV data collected in 2015 [29]. Compared to our Run 1 results important improvements were achieved, such as an acceptance increase by including the hadronic final state, the use of simplified models with an explicit definition of the mediator for the interpretation of the results [27], and a shape-based fit for the signal extraction. Fig. 10.9 shows new exclusion limits expected to be published soon. In addition to top quark pairs, DM can also be produced in association with a single top quark [30]. This new process is expected to increase the sensitivity of the $t\bar{t}$+DM channel up to a factor of two. The search for this new type of processes is currently ongoing in our group.

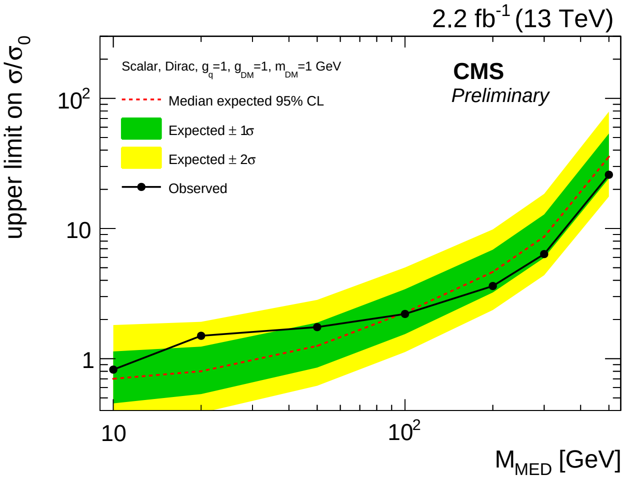

FIG. 10.9 – Expected and observed 95% CL upper limit on the ratio of the DM production cross section to the model expectation as a function of the scalar mediator mass (m_{MED}) with the single-lepton and hadronic channels combined. A DM mass of 1 GeV is assumed [29].

[26] J. M. Beltran *et al.*, HEP pp. 1 17, 2010;
T. Lin *et al.*, Phys. Rev. D, 88, (2013) 063510.

[27] D. Abercrombie *et al.*, arXiv:1507.00966.

[28] CMS collaboration, JHEP **06** (2015) 121.

[29] CMS collaboration, CMS-EXO-16-005.

[30] D. Pinna *et al.*, arXiv:1701.05195.