11 Particle physics with the CMS experiment at CERN

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in collaboration with the:

CMS - Collaboration

In 2015, after the upgrade of the CERN Large Hadron Collider (LHC), the highest center of mass energy reached in proton-proton collisions went up from 8 to 13 TeV, resulting in a significant increase in sensitivity to elusive physics beyond the standard model (SM).

Here we present an overview of our CMS activities. We are involved in detector operation, maintenance and upgrade, trigger development and monitoring as well as physics data analysis. In particular, we are a major contributor to the CMS pixel detector. We maintain and operate the present detector which took its first data at 13 TeV in the middle of 2015. We help build the upgraded barrel pixel detector (Phase 1), to be installed towards the end of 2016. We also started work on the design and simulations of the Phase 2 upgrade, envisioned to be ready in 2023.

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. Important open questions are: is this boson just one of several Higgs bosons, what are its couplings, and what mechanism localizes the Higgs boson at this particular mass scale? Many models predict new particle states at a few TeV that generate loop corrections with the necessary cancellations to stabilize the Higgs boson mass. The new energy regime would allow us to directly produce them and study their properties.

Members of our group play important coordination roles. In the period covered by this report F. Canelli and A. de Cosa act as subgroup conveners within the Beyond 2 Generations (B2G) physics group, B. Kilminster leads the Future Higgs group, a subgroup of the Higgs group, A. Hinzmann is the convener of the JetMET algorithms and reconstruction group, Y. Yang leads the Monte Carlo production for the Physics Performance and Dataset group (PPD), C. Lange and A. de Cosa act as conveners of the CMS pixel DAQ group and pixel monitoring group, respectively, T. Hreus coordinates the Tracker Detector Performance group and L. Caminada and C. Lange are members of the Swiss CMS Tier3 steering committee. Currently, F. Canelli holds the position of group leader.

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

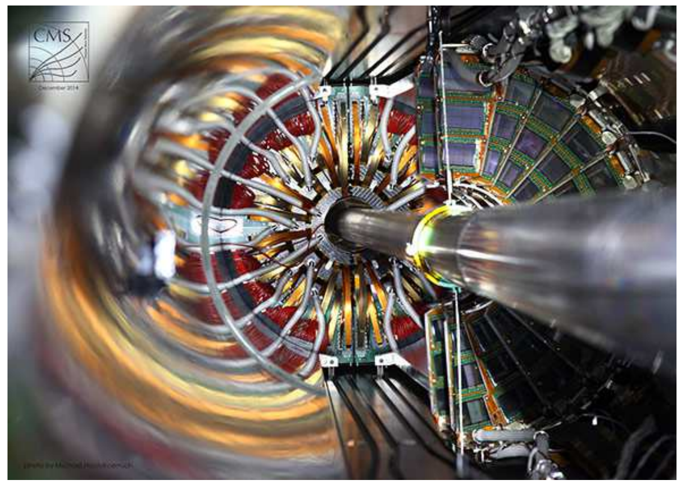

FIG. 11.1 – The CMS BPIX detector and a quadrant of the FPIX detector enclosing the beampipe. The picture has been taken during the re-installation in 2014.

11.1 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. The pixel detector, shown in Fig. 11.1 consists 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.

11.2 Detector maintenance and operation

The CMS pixel detector performed very reliably during the first period of LHC data taking. At the end of Run 1 the detector was installed on the surface for testing, maintenance and reparation work. We actively participated in this effort as well as the re-installation towards the end of 2014, which was completed within a week, allowing to quickly proceed with the closure of CMS. We were responsible for the BPIX calibration and commissioning. In order to limit the impact of radiation damage and minimize the leakage current during Run 2, we prepared the detector for operation at -10°C. This task was accomplished efficiently thanks to the expertise we acquired during the LHC shutdown when several calibration tools and routines have been developed.

Our efforts resulted in the successful and stable operation of the pixel detector during the data-taking at 13 TeV in 2015 when CMS recorded 3.8 fb^{-1} of proton-proton collision data with the pixel detector running at very high data-taking efficiency with more than 98% of its 66 million channels working.

Our group contributes to the monitoring of the detector operation parameters and performance which is crucial to allow for preventive actions and ensure high-quality physics data. In particular, we keep track of the evolution of the radiation damage of 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. In case of signs of detector performance degradation we use the opportunity during LHC technical stops to re-calibrate the pixel detector and recover from these effects. The resolution of the BPIX detector during Run 2, about $10\,\mu$m in the transverse plane and $30\,\mu$m in the longitudinal direction, represents a slight improvement with respect to Run 1 and is a key ingredient for the excellent tracking performance at CMS.

Also we are responsible for maintaining and improving the pixel online software and contribute to the pixel detector operations by regularly taking shifts in the CMS control room, or acting as on-call experts.

Trigger rate studies are a continuous and fundamental activity for CMS as the trigger menu is constantly evolving due to changes in beam parameters, detector conditions and reconstruction software. We developed code for online monitoring of individual and global trigger rates using both measured and simulated samples, allowing to asses the impact of these changes to the trigger menu.

Last but not least, our group contributes to the preparation and production of simulation samples that are needed by all physics groups in CMS. Even when there is no need to produce new samples, most existing samples have to be reprocessed with more realistic simulation conditions after better understanding the data.

11.3 Higgs Properties

We have entered a new phase in Higgs-boson physics, in which the properties of this new particle are being determined by measuring its couplings to SM particles with ever increasing precision. A deviation from the SM couplings would hint at new physics. Furthermore, many models contain a light Higgs boson with properties similar to those of the SM Higgs boson.

Our analyses not only probe the Higgs couplings to heavy quarks, but we also look for final states with Higgs bosons (see also Sec. 11.4.1) and search for additional Higgs bosons predicted for instance in supersymmetric models (SUSY).

11.3.1 Higgs boson couplings to top-quarks

Since the top quark is the heaviest particle of the SM, the only way to directly probe its Yukawa coupling is by studying the associated production of a Higgs boson and a pair of top quarks ($t\bar{t}H$). This channel also provides a complementary probe of the Higgs boson coupling to b quarks in case the Higgs boson decays into b-quarks. The LHC has no evidence yet for this production process. The current best limits are two to four times larger than the SM predictions [3]. During the past years we introduced a new matrix element method (MEM) to this search in CMS (see last year's report) which gave a 20% improvement over the previous analysis. The result has been published in 2015 [4].

Our $t\bar{t}H(\rightarrow b\bar{b})$ result using the Run 2 data [5] is shown in Fig. 11.2. We have analyzed the single lepton and di-lepton decay channels with an integrated luminosity of 2.7 fb^{-1}. To increase the sensitivity different event categories were distinguished using a multivariate approach combining the MEM with methods from machine learning. A combined template fit to the data in all categories results in an observed (expected) upper limit of 2.6 (3.6) times the SM cross section at 95% CL.

During 2015 we have extended our search to include the all-hadronic channel which represents about 46% of the total $t\bar{t}H(\rightarrow b\bar{b})$ cross section. A fully reconstructed final state contains four b-tagged and four light-flavor jets, which poses significant challenges due to the large QCD multi-jet background and the combinatoric self-background. We developed and implemented dedicated trigger paths which are now included in the Run 2 trigger menus. The offline analysis is ongoing.

11.3.2 MSSM Higgs boson search

To find out whether the recently discovered Higgs boson belongs to a larger family of Higgs bosons, as predicted for instance in the minimal SUSY model (MSSM), our group has searched the 8 TeV data for a heavier Higgs boson, produced in association with a b quark and decaying into a pair of b-quarks. To suppress the dominant background, which comes

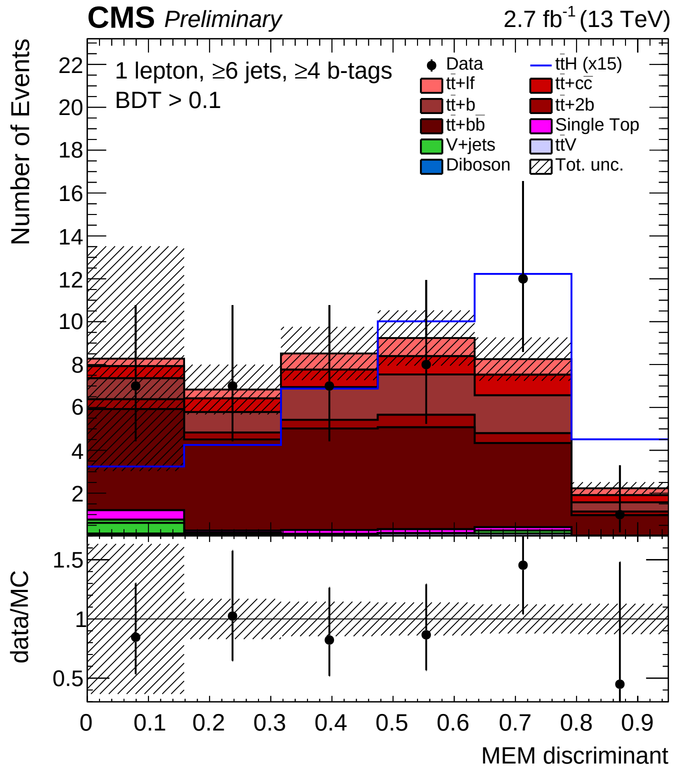

FIG. 11.2 – Matrix element method (MEM) discriminant for one category of events. The discriminant is calculated by the ratio of $t\bar{t}H$ and $t\bar{t}+b$ probabilities densities.

from multi-jet production, we developed new techniques for separating jets according to their flavor composition (b, c, and light quarks, as well as bb and cc jets from gluon-splitting). We also developed the signal modeling and contributed to the complex likelihood-fitting procedure needed to separate out the multiple flavors of jets in order to isolate the signal. The analysis was published in 2015 [6], and extends the $\tan\beta$ and MSSM Higgs boson mass reach (see Fig. 11.3).

[3] ATLAS collaboration, ATLAS-CONF-2014-011; CMS collaboration, arXiv:1303.0763v2.

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

[5] CMS collaboration, CMS-PAS-16-004.

[6] CMS collaboration, JHEP **011** (2015) 071.

11.4 Searches for new phenomena

Our group exploits different search channels at the LHC to directly look for new phenomena and signs of new physics. This includes searches for massive resonances in different final states with bosons and jets as well as direct searches for dark matter particles. The increased center-of-mass energy of 13 TeV greatly improves the sensitivity of these searches and a signal might show up already early during Run 2.

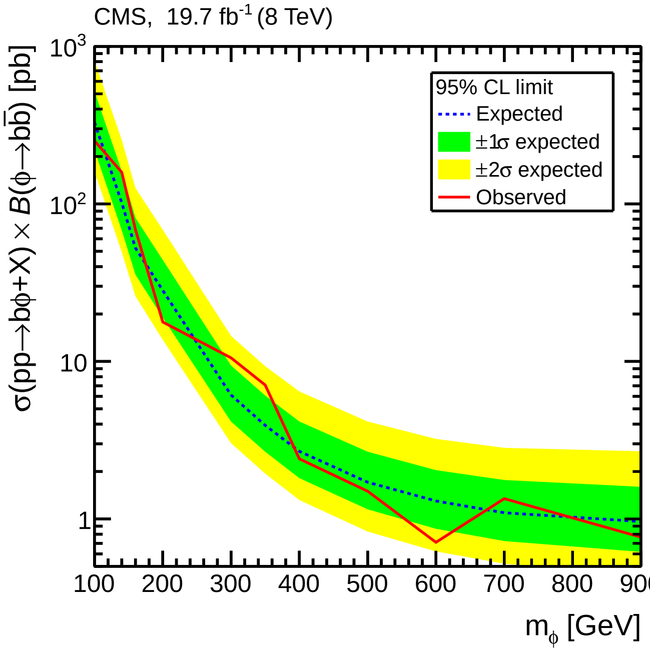

FIG. 11.3 – Expected and observed upper limits at 95% C.L. on $\sigma(pp \to b\phi + X)$ as a function of m_ϕ, where ϕ denotes a generic neutral Higgs-like state.

11.4.1 Search for heavy resonances in di-boson events

Over the past years our group has become the leading group at CMS in searches for heavy diboson resonances, motivated generically by many extensions to the SM, including extra dimensions, composite Higgs, heavy vector-triplets, and additional $U(1)$ gauge groups [7]. These models predict many new particles such as additional W' and Z' gauge bosons, which can have large branching ratios for decays into W, Z and H bosons, while decays into fermions are suppressed.

These final states require special identification techniques, as well as novel data-based approaches to model them. The di-boson pair from the decay of the heavy resonance in turn decays into highly boosted quarks and leptons that are merged into "fat" jets with substructure. In order to distinguish the substructure of these jets we have tested a variety of $W/Z/H$-tagging algorithms. The best scheme is based on the Lorentz invariant jet mass with the so-called pruning algorithm [8] and the jet shape variable N-subjettiness [9], which is an indicator for the number of hard quarks in the jet. Our approach, which efficiently separates the particles from quarks originating in boson decays from those originating in QCD radiation, has been employed in the most recent CMS searches.

Our efforts have focused on a wide variety of di-boson final states, mainly $X \to WW \to q\bar{q}q\bar{q}$, $X \to WW \to \ell\nu q\bar{q}$, $X \to WH \to \ell\nu b\bar{b}$, $X \to ZH \to q\bar{q}\tau^+\tau^-$, $X \to ZH \to q\bar{q}b\bar{b}$, and $X \to HH \to b\bar{b}\tau^+\tau^-$.

The interest in heavy di-boson resonances led to their consideration by CMS as high-priority analysis for the 13 TeV

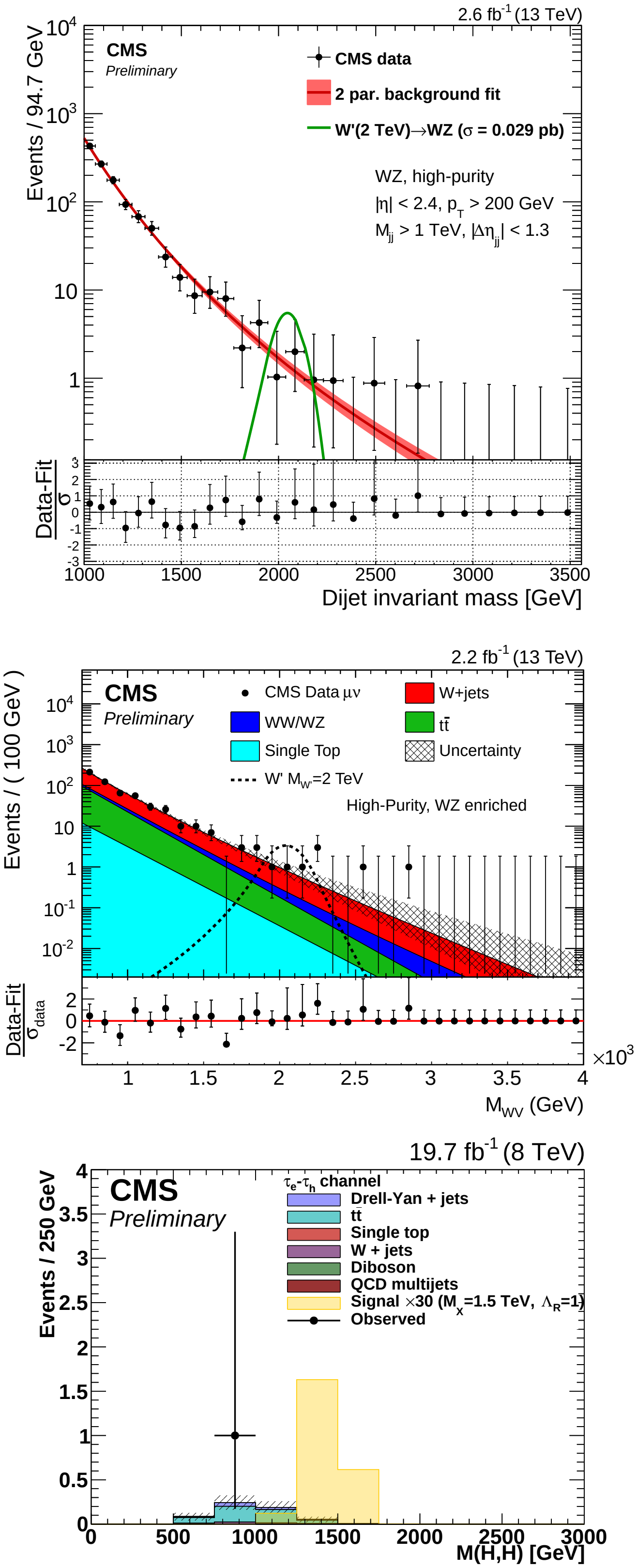

FIG. 11.4 – Measured invariant mass spectra in the search for massive resonances decaying into pairs of boosted W/Z bosons in the all-hadronic (top) and semi-leptonic final states (center) or decaying into HH with $HH \to b\bar{b}\tau^+\tau^-$ (bottom).

2015 dataset. Although the 2015 dataset is only 2.6 fb^{-1} compared to 19.7 fb^{-1} in 2012, the energy increase from 8 to 13 TeV leads to a similar sensitivity to 2 TeV resonances.

Our preliminary results of the search for massive resonances decaying into pairs of boosted W and Z bosons using the all-hadronic and semi-leptonic decay channels [10] are presented in Fig. 11.4. The analysis reveals no significant excess in the mass spectrum, but allows us to set limits on the production of new heavy particles.

We also searched for heavy particles decaying to boosted Higgs bosons using the Run 1 dataset [11]. The search for a high-mass resonance decaying to a W boson and a Higgs boson, with $H \to b\bar{b}$, and a leptonic W-boson decay as well as the search in the final state with a hadronically decaying Z boson and a Higgs boson in the $\tau^+\tau^-$ final state has been presented in last year's report. The novel feature of the latter analysis is the reconstruction and selection of a pair of boosted τ leptons. While we did not discover a signal, we improved our knowledge on boosted τ reconstruction and separation from backgrounds that will be useful in our future 13 TeV analyses.

We next extended this search in the same dataset to consider a heavy resonance decaying as $X \to HH \to \tau\tau b\bar{b}$. Our analysis is the first search at colliders that probes the final state with boosted Higgs bosons that decay into tau-leptons and bottom-quarks pairs, challenging both for object reconstruction and background estimation. We observe one event in the HH mass spectrum as illustrated in Fig. 11.4, and are very curious to perform the analysis with the 13 TeV data.

11.4.2 Di-jet angular distributions

Di-jet events provide an ideal testing ground for perturbative QCD and for new phenomena such as quark compositeness or additional, compactified spatial dimensions. Such new physics models exhibit angular distributions that are more isotropic than those predicted by QCD. With the increased center-of-mass energy, the 2015 data are sensitive to a significantly higher scale for contact interactions and extra dimensions. Our group is a major contributor to the very first 13 TeV search that was made public already one month after the end of 2015 data taking [12]. The measured angular distribution is compared to theoretical predictions in Fig. 11.5. No signs of new physics are observed and the existing limits on scales of contact interaction and extra dimension scales improved by 20%.

11.4.3 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. Our group has made a significant impact in the search

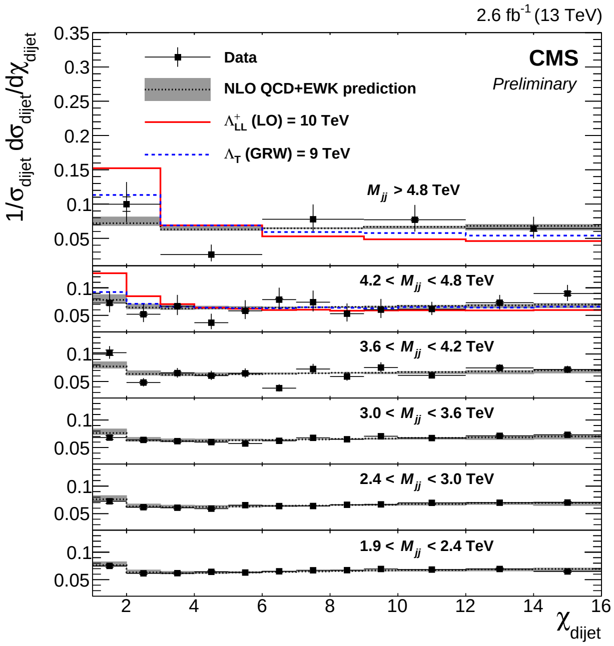

FIG. 11.5 – Normalized χ_{dijet} distributions in measured data compared to theoretical predictions, where $\chi_{\text{dijet}} = \exp(|y_1 - y_2|)$ with y_1 and y_2 the rapidities of the two highest p_{T} jets. The predictions quark compositeness (Λ_{LL}^{+}) and extra dimensions (Λ_T) are overlaid.

for DM in association with top quarks at CMS. This analysis is based on a model that assumes minimal flavor violation, for which couplings between fermionic DM and ordinary matter have the same structure as in the SM. In these models the discovery potential for scalar interactions is highly improved when investigating processes where DM couples to more massive third generation quarks, in particular top quarks [13].

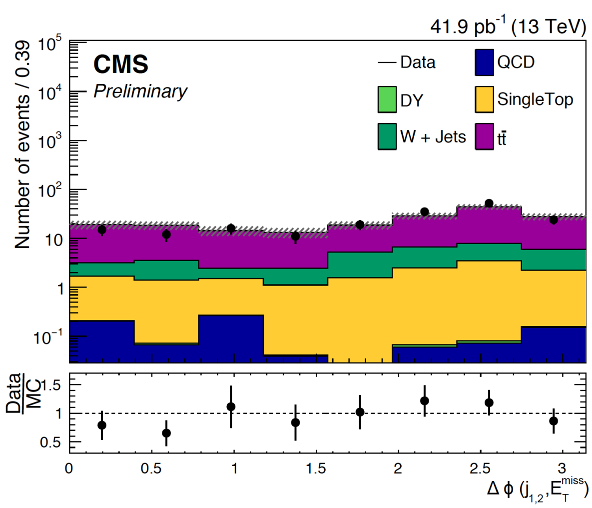

FIG. 11.6 – Distribution of minimum $\Delta\phi$ between the first two leading jets and the missing transverse energy in the events selected for the search for $t\bar{t}$+DM in the semi-leptonic channel at 13 TeV [16].

The DM particles escape detection and leave a signature of large missing energy recoiling against the top quarks. The result of the search performed at 8 TeV using the di-lepton and single-lepton top-pair decay channels [15] has been shown in last year's report.

The search for $t\bar{t}$+DM in the 13 TeV data is currently ongoing (see Fig. 11.6). Compared to our Run 1 results important improvements were achieved, such as an aceptance 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 [14], and a shape-based fit for the signal extraction. The results are expected to be published soon.

[7] 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.

[8] S.D. Ellis *et al.*, Phys.Rev. D **81** (2010) 094023.

[9] J. Thaler and K. Van Tilburg, JHEP **1103** (2011) 015.

[10] CMS collaboration, CMS-PAS-EXO-15-002.

[11] CMS collaboration, arXiv:1601.06431; Phys. Lett. B 748 (2015) 255.

[12] CMS collaboration, CMS-PAS-EXO-15-009.

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

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

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

[16] CMS collaboration, CMS-DP-2015-033.

11.5 Future upgrades

With a luminosity of 3.8 fb^{-1} recorded in 2015 the data-taking at 13 TeV has only started. During Run 2 we expect to collect about 100 fb^{-1} at a maximum instantaneous luminosity of 2×10^{34} cm^{-2}s^{-1}. In order to maintain the excellent tracking performance of the pixel detector in these conditions, we will install a new upgraded pixel system during the long LHC technical stop in 2016/17.

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 will be 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 powering, cooling, and readout electronics.

We are in charge of three major areas in the Phase 1 BPIX upgrade: the supply tube mechanical structure, the cooling system, and the assembly, installation, testing and commissioning of the readout electronics, powering, and control of the pixel modules. All three moved from the prototyping to the production phase.

Together with the UZH workshop we have finished building half of the production supply tube mechanical structure. This multi-layer carbonized foam structure houses the electronics, cooling, power distribution, module control boards, and DC-DC converters (see Fig. 11.7). Work to finish the remaining half of the supply tube, and integrate the various components is ongoing. Furthermore, we have designed and are constructing a new light-weight cooling system, which differs from the current design in that the tubes are much narrower, operate at six times higher pressure, and use two-phase liquid-gas CO_2 cooling instead of single-phase C_6F_{14} liquid coolant. The system has a complicated looping structure in order to cool the individual detector components including pixel modules, DC-DC converters and opto-hybrids. We have tested our prototype in a cooling plant at CERN to demonstrate the expected two-phase cooling curves. To protect against corrosion, we moved to special-quality steel alloy for all parts, and are now implementing computerized, machine-automated laser welding. The system has undergone mechanical and temperature stress tests and was found to withstand 200 atmospheres of pressure and water tests without leaking or corrosion.

During the design and prototyping phase of the CMS BPIX Phase 1 upgrade detector, we were responsible for the testing of the complete system. In particular, we verified the proper interplay of the upgrade detector modules and supply tube electronics with the pixel DAQ and power system. For this purpose, we set up a slice of the full readout chain in our lab at UZH which consists of a group of pixel detector modules connected through optical links to the front-end boards for readout and control and powered using a set of DC-DC converters. We produced hardware tools and developed software algorithms to allow for a fast and efficient testing procedure. Thereby we became experienced in the operation of the new system and are able to evaluate its performance in detail, which is crucial for a reliable and fast testing of the production CMS Phase 1 pixel system. We have also set up a parallel DAQ system, using μTCA which makes it compatible with the future CERN standard.

[17] CMS collaboration, CERN-LHCC-2012-016 (2012).

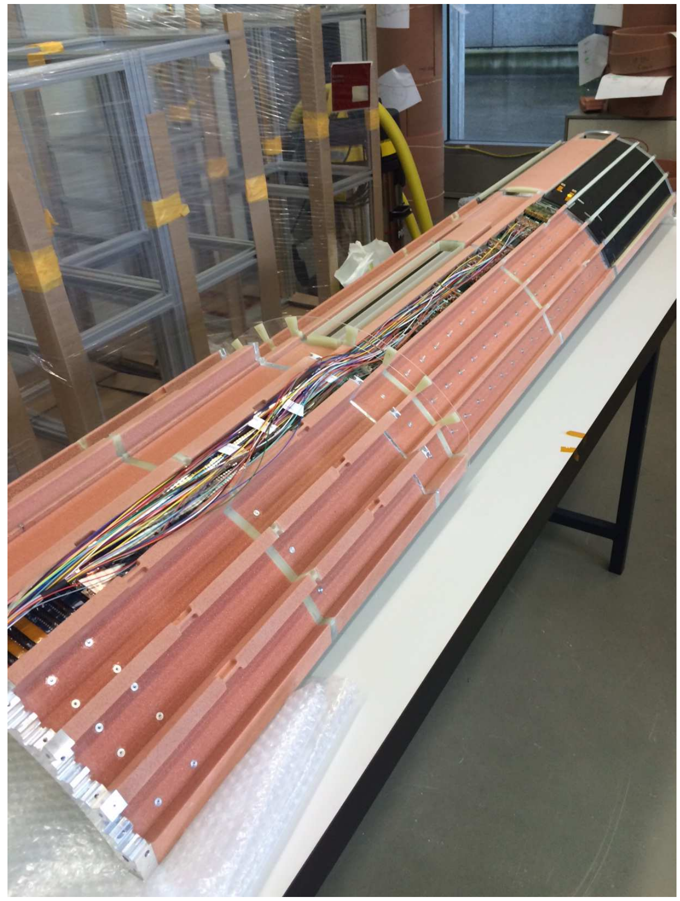

FIG. 11.7 – CMS Phase 1 pixel supply tube mechanics with readout electronics in one slot.