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Associated production of heavy flavored final state and vector boson and search for $\mathrm{H} \to \mathrm{bb}$ at CMS experiment

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The mechanism of production of heavy-flavor mesons, containing b or c quarks, in association with vector bosons $\mathrm{W}^{\pm}$ and Z^{0} is only partially understood in the Standard Model. The study of events with one or two well-identified and isolated leptons accompanied by b-jets or b-mesons is therefore crucial to refine the theoretical calculations in perturbative QCD, as well as validate associated prediction from simulation. The understanding of these processes is furthermore required by Higgs physics studies and searches beyond the Standard Model. Using the LHC proton-proton collision data collected by the CMS detector in 2010 and 2011 at a centre of mass energy of 7 TeV, the production cross-section of Z^{0} plus one or several b-jets, as well as of $\mathrm{W}^{\pm}$ plus two b-jets, are computed. Finally, the measurement of the associated production rate of a c-quark and a $\mathrm{W}^{\pm}$ boson with respect to boson charge and to $\mathrm{W}^{\pm}$ in association with light jets are also presented, allowing to probe and to constrain the strange quark content of the proton. Recent results on $\mathrm{H}\to\mathrm{b\bar{b}}$ associated production are also discussed.

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1. Why the associated production?

The measurement of the vector boson production in association with jets is of fundamental importance for testing the Standard Model prediction and providing better knowledge of major backgrounds in the related physics searches. For example the measurement of the production rate of vector boson V in association with n−jets sheds light on the current status of perturbative QCD calculation. Experimentally, the leptonic decays of the vector boson is preferred, given the clean signature of its decay products in the detector and being an easy handle for triggering the event. Concerning jets, those originating from heavy b-quarks are of large interest because of the physics process behind and moreover events containing them can be easily identified, given the secondary vertex decay footprint of the relative hadrons.

At the same time, the measurement of the production of a vector boson e.g. in association with jets originating from b-quarks is of fundamental importance both as a benchmark channel to the production of the Higgs boson in association with b quarks, as well as a Standard Model background to Higgs and beyond standard model physics involving final states with leptons and b-jets. Similarly, the measurement of the production rate of a $W^{\pm}$ and c-quark allows to probe and to constrain the strange quark content of the proton.

2. Associated $W^{\pm}$ boson and c-quark production

The measurement of the associated production of a $W^{\pm}$ boson and a charm-quark jet ($W^{\pm}$ + c) in pp collisions has been performed by CMS experiment at a center-of-mass energy of 7 TeV, exploiting data corresponding to a total integrated luminosity of $5\,\mathrm{fb}^{-1}$ [2]. $W^{\pm}$ boson candidates are identified by their decay into a charged lepton (muon or electron) and a neutrino. The $W^{\pm}$ + c measurements are performed for charm-quark jets in the kinematic region $p_T^{jet} > 25\,\mathrm{GeV}$, $|\eta_{jet}| < 2.5$, for two different thresholds of transverse momentum of the lepton: $p_T > 25\,\mathrm{GeV}$ for the $W^{\pm}$ boson muon decay channel only, and $p_T > 35\,\mathrm{GeV}$ for both the muon and the electron $W^{\pm}$ boson decay channels, and in the pseudorapidity range $|\eta| < 2.1$. The remarkable performance of the CMS tracking detector and the algorithms devised for reconstruction of vertices allow for an efficient selection of candidates with a displaced secondary vertex having three or two tracks corresponding to the decay products of charm mesons. Hadronic and inclusive semileptonic decays of charm hadrons are used to measure the total production cross sections.

The analysis exploits the intrinsic charge correlation in $W^{\pm}$ + c production between the charge of the $W^{\pm}$ boson and the charge of the c quark, which are always of opposite sign. The $W^{\pm}$ boson decay into a well-identified charged lepton and the final-state mesons allow to determine unequivocally the signs of both the $W^{\pm}$ boson and the charm-quark jet candidates. Independent opposite-sign and same-sign samples of events are hence defined. The background contribution from processes that are charge symmetric are subtracted in an essentially model-independent way through a same-sign sample subtraction from the opposite-sign sample in the relevant variables used in the analysis.

Results are reported in Fig. 1. Cross sections and ratios are also measured differentially with respect to the absolute value of the pseudorapidity of the lepton from the $W^{\pm}$ boson decay. These are the first measurements from LHC directly sensitive to the strange quark and antiquark content of the

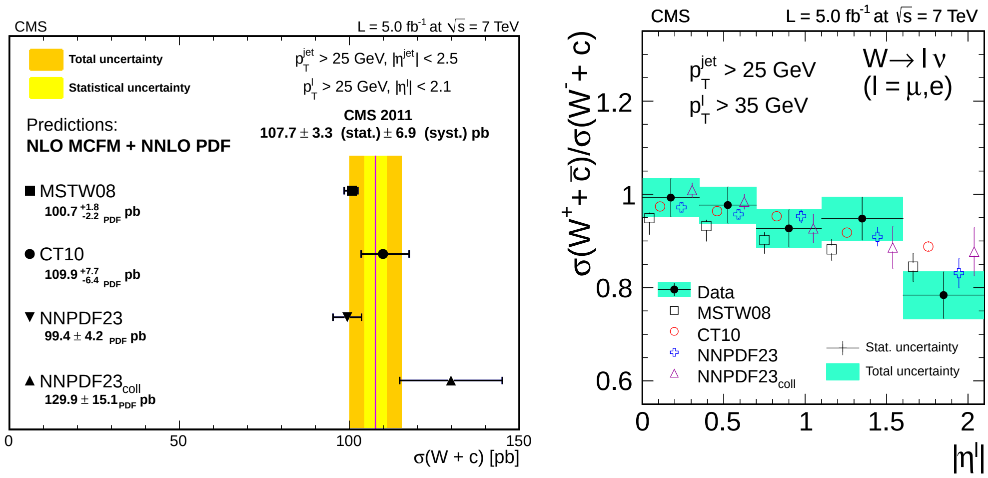

Figure 1: Left. Comparison of the theoretical predictions for W$^{\pm}$ + c computed with `MCFM` and several sets of PDFs with the average of the experimental measurements. The plot shows the predictions for a p_T threshold of the lepton from the W$^{\pm}$ boson decay of $p_T^l > 35$GeV. The uncertainty associated with scale variations is $\pm5\%$. Right. Comparison of the theoretical predictions for $\sigma(\mathrm{W}^+ + \bar{\mathrm{c}})/\sigma(\mathrm{W}^- + \mathrm{c})$ computed with `MCFM` and several sets of PDFs with the average of the experimental measurements.

proton. Results are compared with theoretical expectations and are consistent with the predictions based on global fits of parton distribution functions.

3. Associated production of W$^{\pm}$ boson and b-quark jets

According to SM, the primary contribution for b$\bar{\mathrm{b}}$ production in association with a W$^{\pm}$ boson is due to the splitting of a gluon into a b$\bar{\mathrm{b}}$ pair. Two different models for b-quark production are available, depending on whether there are four or five quark flavors in the proton parton distribution functions (PDFs). Therefore, a precise experimental measurement of the W$^{\pm}$ + b$\bar{\mathrm{b}}$ production cross section provides important input to the refinement of theoretical calculations in perturbative quantum chromodynamics (QCD), as well as the validation of MC techniques. A key feature of the CMS measurement [3] is the b$\bar{\mathrm{b}}$ phase space that is covered. Previous measurements have concentrated on W$^{\pm}$ boson production with at least one observed b-quark jet, for which the predictions differ from the experimental results. This difference is larger in the production of events with a collinear b$\bar{\mathrm{b}}$ pair reconstructed as one jet, topology which is afflicted by significant theoretical uncertainties. Focusing on the observation of W$^{\pm}$ boson production with two well-separated b-quark jets, this analysis provides a complementary approach by probing a kinematic regime that is better understood theoretically.
The W$^{\pm}$ +b$\bar{\mathrm{b}}$ events are selected in the W$^{\pm}$ $\rightarrow \mu\nu$ decay mode with a muon of $p_T > 25$GeV and $|\eta| < 2.1$, and exactly two b-tagged jets with $p_T > 25$GeV and $|\eta| < 2.1$, where jets are reconstructed using the anti-kT jet algorithm with $\Delta\mathrm{R} = 0.5$. The measured cross section is found to be $0.53 \pm 0.05(\mathrm{stat}) \pm 0.0(\mathrm{sys}) \pm 0.06(\mathrm{theo}) \pm 0.01(\mathrm{lumi})$ pb.
The cross section is then computed from the reconstructed objects unfolded to the level of final-

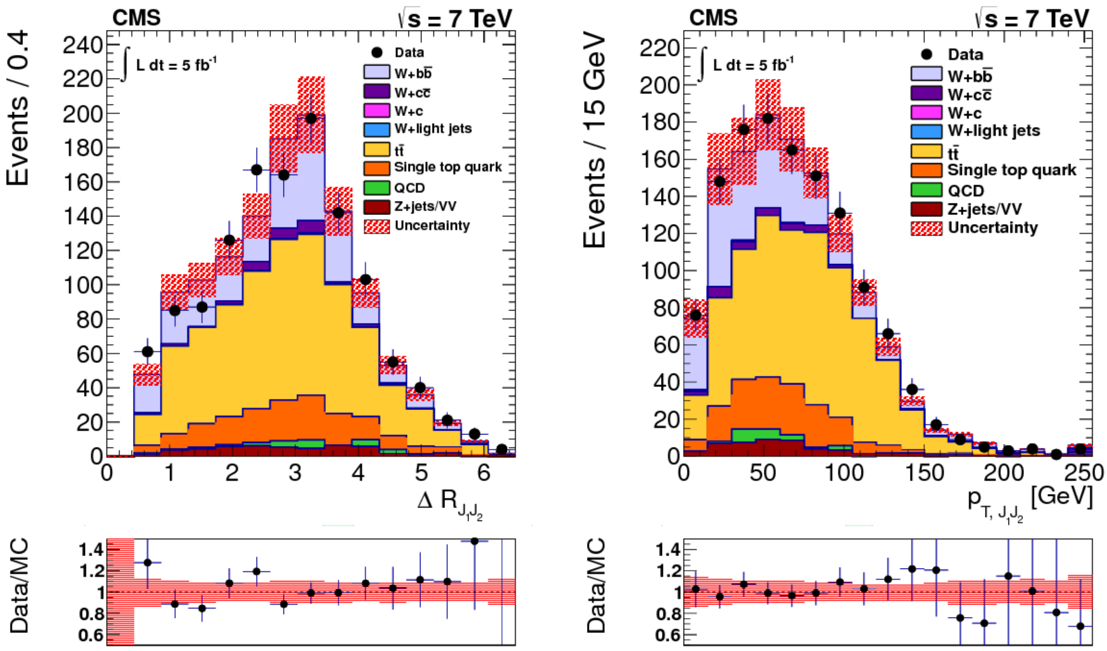

Figure 2: Left. The distribution of the angular distance ΔR between the two selected b jets. Right. Distribution of the transverse momentum of the di-jet system. In both plots, the uncertainty band corresponds to the total uncertainty in the fitted yields.

state particles, corresponding to events with a muon and two particle jets matching the kinematic definitions, and further requiring the particle jets to be matched to B hadrons. A correction factor to scale from the hadron level to the level of final partons (just before hadronization) is computed with MADGRAPH, and found to be $C(b \rightarrow B) = 0.92 \pm 0.01$. It can be used to compare the measured values to the NLO cross section calculated with MCFM. The NLO cross section computed with MCFM is found to be 0.52 ± 0.03 pb, in agreement with the measured one. The contribution from Double Parton Scattering (DPS) has found to be around 15% of the NLO cross section prediction. Kinematic of the $W^{\pm}$ +b$\bar{\text{b}}$ system is compared to the SM predictions, and the simulation is found to well describe the observed distributions from data, as visible in Fig. 2.

4. Associated production of Z^0 boson and b-quark jets

Calculations of the theoretical cross section for this process, driven by perturbative QCD, are currently derived in two schemes: fixed-flavour [5] and variable flavour [6].
The main experimental backgrounds arise from the production of Z^0 with jets of other flavors misidentified as b jets and from $t\bar{t}$ + jets events: is therefore essential to reduce them as much

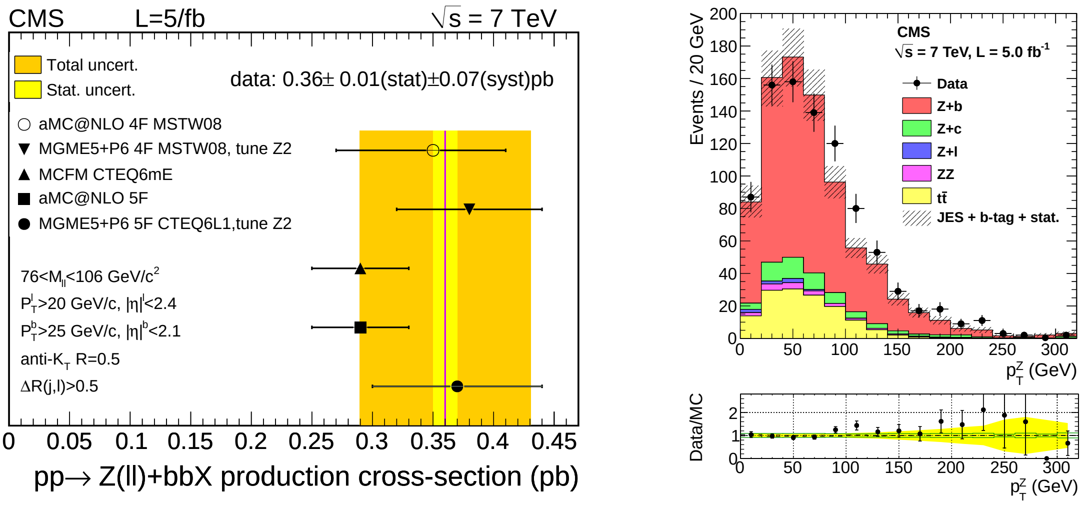

Figure 3: Left: Measured production cross section for process involving $Z^0 \rightarrow ll$ with at least two b-jets compared to various theoretical predictions. Right: p_T of the lepton pairs after the di-lepton+b-jet selection. The yellow bands in the lower plots represent the statistical uncertainty on the MC yield.

as possible and finally quantifying the remaining contribution in a precise and reliable way. The production of b jets in association with a Z^0 boson has been studied [7] using 5 fb^{-1} of proton-proton collision data recorded by the CMS detector at a centre-of-mass energy of 7 TeV and it is measured separately for a Z^0 boson produced with exactly one jet and with at least two b jets. Jets and leptons are reconstructed according to standard criteria described in [9]. Opposite charges for the leptons ℓ, where $\ell = e$ or μ, are required when forming pairs, and the lepton invariant mass $M_{\ell\ell}$ is required to lie between 60 and 120 GeV. Jets originating from b quarks are tagged by taking advantage of the long b-hadron lifetime in the phase space $p_T > 25$ GeV and $|\eta| < 2.1$. The Simple Secondary Vertex (SSV) algorithm [8], requiring secondary vertices built from at least three tracks in order to improve the purity of the selection, is exploited. Separation between leptons and jets is also applied ($\Delta R(\ell, j) > 0.5$).

The extraction of the purity is based on a (data-driven) one dimensional template fit of the mass of the secondary vertex of the leading and sub-leading p_T b-jet, resulting in a fraction of around 55 (75)% for one b-jet (more than two b-jets) category. The $t\bar{t}$ contribution is extracted from extrapolation of upper sideband of $M_{\ell\ell}$ under the signal region [60-120] GeV, and it is found to be of the order of 5 (14)% for one b-jet (more than two b-jets) category.
The MADGRAPH simulation interfaced with PYTHIA is used to derive the correction from the reconstructed level to the hadron level and to evaluate efficiencies. The measured cross sections are reported in Fig. 3 (left) and compared to various theoretical predictions: data favour the predictions in the five-flavor scheme, where b quarks are assumed massless. The shapes of the kinematic variables are found to be in fair agreement with the predictions made by the MADGRAPH event generator, and normalised to the integrated luminosity in data using the cross-section value which includes the NNLO corrections to the inclusive Z^0 production. The residual discrepancy, for example noticeable in the dilepton p_T spectrum of Fig. 3 (right), may be a consequence of the higher order

terms absent in the MADGRAPH tree-level simulation in the variable-flavour scheme with massless b quarks and it has been noticed also in subsequent measurements [10].

5. Search for Higgs boson decaying into b-quark jets produced in association with a vector boson

As an example of direct relevance of a SM process measurement as background for search of new physics, the case of associated production of vector boson together with Higgs boson decaying into b-quark jets is reported. Given the boosted kinematic regime of the Higgs decay products, the control of kinematic variable shown in Sec. 4, like p_T of the lepton pairs or ΔR between the two b-jets is of crucial importance.
To get rid of the high QCD background rate when studying direct $H \to b\bar{b}$ decay mode, the signature provided by associated production of Z^0 and $W^{\pm}$ bosons is used. The CMS search [11] is done with a total luminosity of at 5 fb^{-1} at 7 TeV and 18.9 fb^{-1} at 8 TeV. The analysis is done in a total of six topologies with a Z^0 decaying to an electron pair, muon pair, a pair of neutrinos or a $W^{\pm}$ decaying to an electron, muon or tau. The strategy heavily utilizes Boosted Decision Tree (BDT) techniques to discriminate the Higgs boson signal from the backgrounds. The BDT includes event kinematics, b-jet tagging discriminators, and various system angles. The events are then categorized based on the transverse momentum of the vector boson. The analysis has a broad excess that is consistent with a Higgs boson of $m_H = 125\,\text{GeV}$. The excess has a significance of 2.1 standard deviations at $m_H = 125\,\text{GeV}$ with a best fit $\mu = \sigma/\sigma_{SM} = 1.0 \pm 0.5$.

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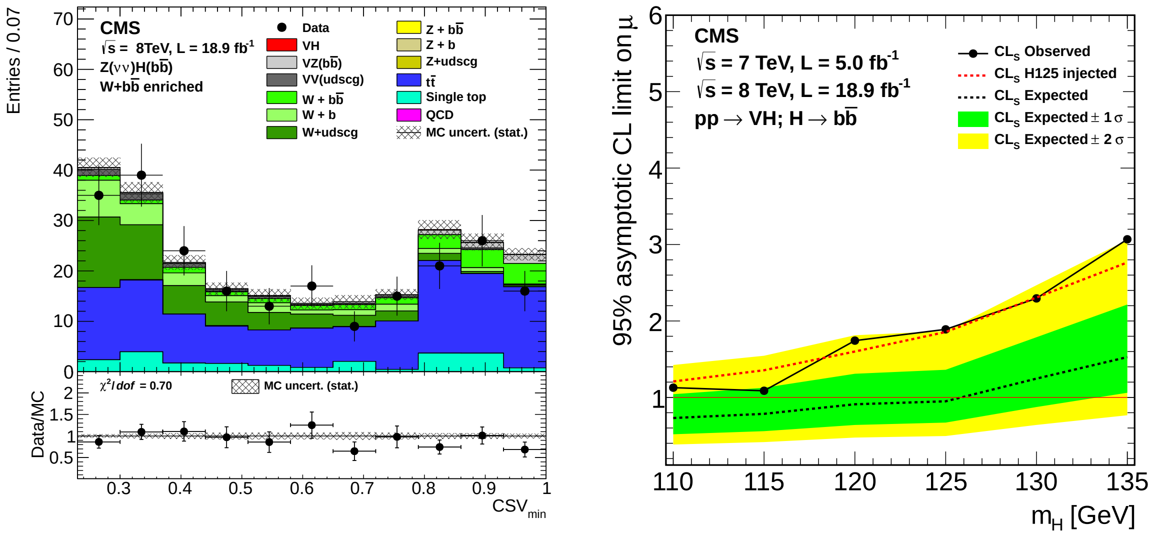

Figure 4: Left: B-tag discriminator distribution in the simulated samples and in data in the W + heavy flavour jets high-boost control region for the Z($\nu\nu$)H channel after applying the data/MC scale factors (SF). All derived SF have been found to be compatible with one, except SF(V+b) = 2, due to a possible mis-modelling in the generator of gluon splitting process (already seen in Z^0 + b measurement). Right: The expected and observed 95% CL upper limits on the product of the VH production cross section times the $H \to b\bar{b}$ branching fraction, with respect to the expectations for the standard model Higgs boson. The limits are obtained combining the results of the searches using the 2011 (7 TeV) and 2012 (8 TeV) data. The red dashed line represents the expected limit obtained from the sum of expected backgrounds and the SM Higgs boson signal with a mass of 125 GeV.