Electroweak Physics Results from CMS

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Summary. — We present results of the most recent CMS electroweak measurements performed at the LHC with the data collected in pp collisions at 7 TeV. Production of W and Z bosons is discussed at length, including differential cross sections and asymmetries with respect to several kinematic variables, the weak mixing angle measurement, and production of W and Z in association with light and heavy (b, c) quarks.

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1. – Introduction

In this report, we present the most prominent recent results on electroweak physics from the CMS experiment at the LHC. The LHC has concluded its 7 TeV proton-proton running and delivered to the CMS experiment 5.7 fb^{-1}. The measurements discussed in this paper are based on up to 2.1 fb^{-1}, and the remaining data are presently being analyzed. These data have been collected with the CMS detector over the years 2010 and 2011.

Throughout the year 2011, the instantaneous luminosity of the LHC has been increasing, and with the luminosity the number of multiple interactions per bunch crossing, so called pile-up, has increased as well. By the end of 2011, a typical pile-up level per bunch crossing at CMS was 15 interactions, which posed a challenge to all measurements reported here as it made more difficult to distinguish isolated leptons critical for any measurement involving W and Z bosons, as well as to correctly calculate energy of jets.

2. – Reconstruction of W and Z bosons

All measurements discussed in this paper involve W and Z bosons. They are reconstructed in the leptonic channels, typically electron or muon, as these channels offer the cleanest samples. The transverse energy and momentum of both electrons and muons is required to be above 20-25 GeV. Only isolated leptons are selected with a limited amount of energy seen in the detector in the cone $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$ of 0.3 or 0.4 around the

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lepton direction. For W decays, missing transverse momentum is required in the event, and for Z reconstruction, dilepton mass has to be consistent with the Z mass.

In nearly all measurements reported, the background prediction is derived from data. The reconstruction efficiencies and resolutions are estimated from data as well. Corrections for pile-up related effects are applied on event by event basis by subtracting the average pile-up activity in lepton isolation and jet energy.

3. – Inclusive W and Z production cross sections

The measurements of the inclusive W and Z cross sections in the electron and muon channels are most straightforward and are based on 36 fb^{-1} of 2010 data. These results have already been published in [1], and are systematics limited, thus they won't be updated with a larger dataset. The distributions shown in Figure 1 demonstrate the quality of the W signal in the event missing transverse energy distribution and of the Z signal in the dimuon mass distribution. All the measured inclusive cross sections are in agreement with theory, the complete list of numerical values is found in [1]. The full 7 TeV dataset of CMS contains roughly 100 times large sample of W and Z bosons. At present, W and Z reconstruction at CMS is very well understood, and clean W/Z samples are used widely for a variety of calibrations for more complex measurements.

Somewhat more challenging are measurements of the inclusive W and Z cross section in the tau channels. The measurements are also based on the 2010 CMS dataset. While these cross sections have relatively large errors, the measurements in tau channels allow one to calibrate and understand tau reconstruction which is critical for Higgs and new physics searches. The measurement of the $Z \to \tau\tau$ production [2] combines several possible tau decays. The considered cases are tau decays to electrons, muons, and hadronic tau decays to one or three charged particles with neutrals allowed. In Figure 2, a clean Z peak is seen in one of the decay modes. The production cross section in graphical form is found in Figure 3. The measurement of the W production with W decaying through its tau channel is performed as well [3]. The hadronic decays of tau lepton are employed, as for the Z case, with one or three charged hadrons with some neutral hadrons used in reconstruction. The W peak in the transverse mass distribution is found in Figure 2, and the numerical values for the cross section, including separate results for W$^+$ and W$^-$, are quoted in the table in Figure 3.

4. – Differential cross sections and asymmetries for W and Z

With a larger dataset collected in 2011, CMS has made several detailed measurements of W and Z production. The differential cross sections of Z production with respect to Z invariant mass and rapidity have been performed in the electron and muon Z decay channels [4, 5], and are useful for constraining proton PDFs. The measured behaviour of the invariant mass spectrum above the Z peak is especially important as this is where signs of new physics could be found. The measured $d\sigma/dM$ and $d\sigma/dy$, the latter is for the candidates in the mass range 60-120 GeV, are presented in Figure 4. The results are in a good agreement with theory predictions. At present, the measurement of the double differential cross section $d^2\sigma/dMdy$ is in progress in CMS.

The dependence of Z production cross section on the transverse momentum of the Z has been measured with 36 pb^{-1} of 2010 data [5] for the mass range 60-120 GeV. A more precise measurement with a much larger dataset is in progress. In Figure 5, the measured momentum dependence of the cross section is shown separately for the different momentum ranges. For lower momenta, non-perturbative QCD is in effect and the data are best described by Pythia with several free parameters. It is found that the Z2 and ProQ20 Pythia tunes work rather well. The distribution for the high-p_T region (above 25 GeV) is well predicted by perturbative calculations.

At LHC in proton-proton collisions, in order to produce a W^+, most commonly a valence u quark is combined with a sea $\bar{d}$ quark, and for W^- it is a valence d quark combined and a sea $\bar{u}$ quark. Due to a larger number of u valence quarks in comparison to d valence quarks, there is an overall excess of W^+ vs W^-. The overall ratio of W^+/W^- measured by CMS in the past is in a good agreement with SM predictions. Taking it one step further, one can measure this asymmetry as a function of W rapidity, the quantity very sensitive to proton PDFs. In the CMS measurement of this asymmetry [6], the muon decay channel of W is employed. Experimentally, the accessible quantity is the muon charge asymmetry as a function of the muon pseudo-rapidity:

$$A = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy} \rightarrow \frac{dN(\ell^+)/d\eta - dN(\ell^-)/d\eta}{dN(\ell^+)/d\eta + dN(\ell^-)/d\eta}$$

The observed asymmetry is plotted in Figure 6. In this measurement, the selected candidates are required to have the transverse momentum of at least 25 GeV. A good agreement with HERAPDF is observed. However, the measured distributions is more flat than the predictions produced using MSTW, CT10, and NNPDF.

5. – Measurement of the weak mixing angle

The weak mixing angle is one of the fundamental parameters of the standard model and is presently known to better than 0.1%. The previous measurements performed at Tevatron experiments achieved the accuracy of about 1%. In this paper, a CMS measurement of the weak mixing angle that is of similar accuracy is reported [7]. At LHC, measuring the weak mixing angle is more difficult than at the Tevatron. This measurement is made by analyzing the process $q\bar{q} \rightarrow \ell^+\ell^-$. At the Tevatron, in proton-antiproton collisions the forward-backward asymmetry of the ℓ^+ and ℓ^- production can be exploited. At LHC in pp collisions, this is not possible as the valence quark can come either of the colliding protons, while the sea anti-quark will come from the other, and no asymmetry is seen in ℓ^+ and ℓ^- production. Instead, in the CMS measurement of the weak mixing angle, a simultaneous fit of the three observables of the $q\bar{q} \rightarrow \mu^+\mu^-$ process is performed: of dimuon rapidity, their invariant mass, and the decay angle (see Figure 7). The shapes of the distributions of these observables have sensitivity to the value of the effective weak mixing angle, which is found to be

$$sin^2\theta_{eff} = 0.2287 \pm 0.0020(stat) \pm 0.0025(syst).$$

6. – W and Z production with accompanying jets

Measurements of W and Z production along with one or more jets provides a stringent test of perturbative QCD. Moreover, vector bosons accompanied by several jets produced via standard model processes is a background to searches for new physics, Higgs searches, and top quark measurements. Several characteristics of W and Z production at 7 TeV were measured by CMS. This report contains results based on 2010 dataset of 36 pb^{-1}. In this measurement, W and Z are identified through their decays into both electron and muon channels. Jets are reconstructed with the anti-k_T algorithm with the cone size 0.5 in ΔR, and their energy is corrected for pile-up. The measured dependencies include the production rates of W and Z plus n jets to inclusive of the corresponding vector boson production, as well as the ratio of the above mentioned ratios between W and Z. Several of these results are shown in Figure 8, while the complete set is found in [8]. The observed ratios are found to be in a good agreement with prediction from simulations based on the Madgraph generator.

7. – W and Z plus heavy quark production

The production of W accompanied by a c quark which hadronizes into a jet is sensitive to the strange content of proton PDF. This process at LHC proceeds primarily as hard scattering of an s or $\bar{s}$ and a gluon. More than 10% of W+jets events with jet $p_T > 20$ GeV contain a charm quark. Recently, CMS measured the ratio $R_c^{\pm} \equiv \sigma(W^+c)/\sigma(W^-c)$. This ratio is expected to be close to 1.0 as the s and $\bar{s}$ quarks have approximately the same PDF. The result [9] is consistent with the expectations:

$$R_c^{\pm} = 0.92 \pm 0.19(stat) \pm 0.04(syst).$$

Additionally, the fraction of the charm in W+jets events is of interest, and is reflected in the observable $R_c \equiv \sigma(W^{\pm} + c)/\sigma(W^{\pm} + jets)$. CMS measures this fraction to be [9]

$$R_c = 0.143 \pm 0.015(stat) \pm 0.024(syst),$$

which agrees with NLO predictions.

In measuring both R_c and $R_c^{\pm}$, W candidates are reconstructed in the muon channel. Jet reconstruction is the same as described in Section **6**. Jets containing the charm quark are found by requiring a displaced secondary vertex. Figure 9 depicts the discriminant based on the 3D decay length significance which is used to measure the number of W events with charm in the sample. The signal W+charm is quite clean.

The production of Z along with a b quark is sensitive to the b component of proton PDFs. Moreover, it is both a benchmark and a background to Higgs searches with decays involving b quarks. CMS measures the production cross section of the Z boson accompanied by one or two b quarks [10]. The Z bosons are reconstructed in both electron and muon channels, and jets are found as in Section **6**. The b jets are selected by requiring the presence of a secondary vertex in the jet. The cross section is measured in acceptance, where both leptons have $p_T > 20$ GeV and $|\eta| < 2.5$, dilepton mass is in the interval 76-106 GeV, and the b jets are required to have $p_T > 25$ GeV, $|\eta| < 2.1$, and be separated from the leptons by ΔR of at least 0.5. The quality of the selected sample is illustrated on the figure of the invariant mass of the particles in the secondary vertex found in b jet candidates (see Figure 9). The total production cross section of Zbb is found to be

$$\sigma(Zbb) = 0.37 \pm 0.02(stat) \pm 0.07(syst) \pm 0.02(theory) \ \ pb.$$

This value agrees well with the expectation, obtained using Madgraph, of 0.33 ± 0.01 pb. A breakdown by channel and results for different b quark multiplicities are found in Table I.

Multiplicity bin	ee	$\mu\mu$
$\sigma_{hadron}(Z+1b, Z \to \ell\ell)(pb)$	3.25±0.08±0.29±0.06	3.47±0.06±0.27±0.11
$\sigma_{hadron}(Z+2b, Z \to \ell\ell)(pb)$	0.39±0.04±0.07±0.02	0.36±0.03±0.07±0.03
$\sigma_{hadron}(Z+b, Z \to \ell\ell)(pb)$	3.64±0.09±0.35±0.08	3.83±0.07±0.31±0.14

TABLE I. – *Production cross section of the $Z + b(b)$ measured at CMS.*

8. – Conclusions

In this report, we present a number of detailed measurements of W and Z production and V+jets production including heavy quarks based on partial 7 TeV proton-proton data collected by the CMS experiment at LHC. All presented results are consistent with theory predictions. Most of these measurements are expected to be updated by CMS once the full analysis of the 2010-2011 7 TeV dataset is completed.

* * *

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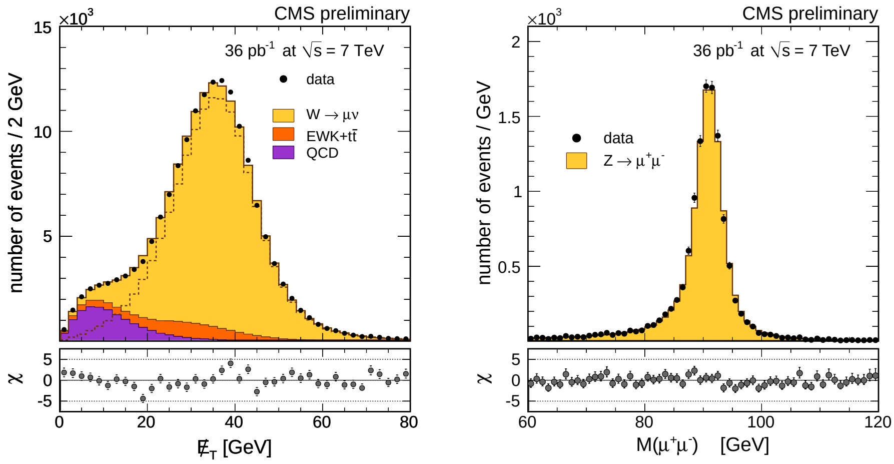


Fig. 1. – The W and Z samples in the muon channel observed in the 2010 CMS data.

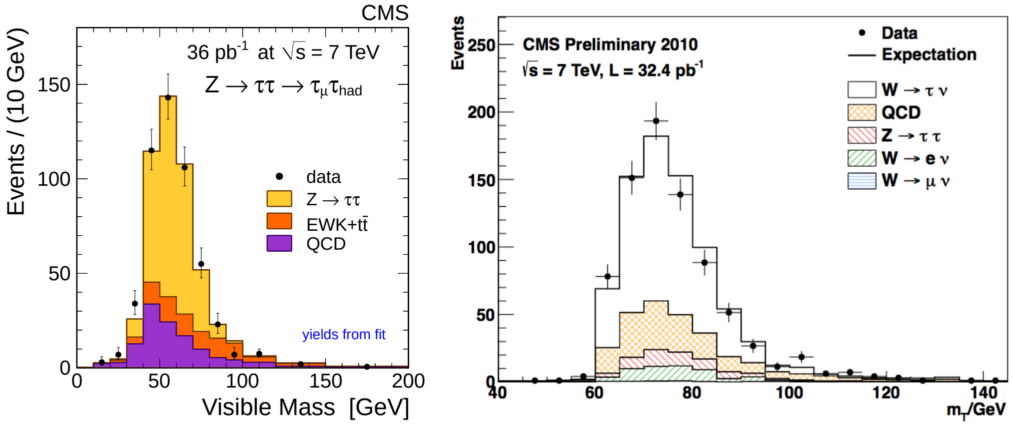
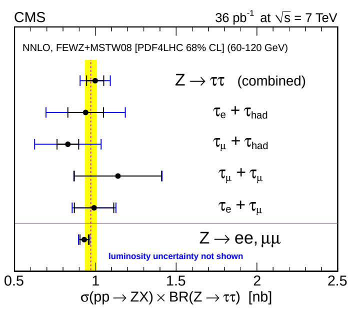


Fig. 2. – The visible mass distribution of the $Z \to \tau\tau$ candidates (left); the transverse mass distribution of the $W \to \tau\nu_\tau$ candidates (right).



Channel	$\sigma(pp \to WX) \times \mathcal{B}$ (nb)	NNLO (nb)
$W \to \tau\nu$	$8.96 \pm 0.51(\text{stat.})^{+2.32}_{-2.26}(\text{syst.}) \pm 0.36(\text{lumi.})$	10.44 ± 0.52
$W^+ \to \tau^+\nu$	$5.26 \pm 0.39(\text{stat.})^{+1.36}_{-1.29}(\text{syst.}) \pm 0.21(\text{lumi.})$	6.15 ± 0.29
$W^- \to \tau^-\nu$	$3.40 \pm 0.33(\text{stat.})^{+0.92}_{-0.93}(\text{syst.}) \pm 0.14(\text{lumi.})$	4.29 ± 0.23

Fig. 3. – The production cross section results for the Z and W decaying to tau lepton(s).

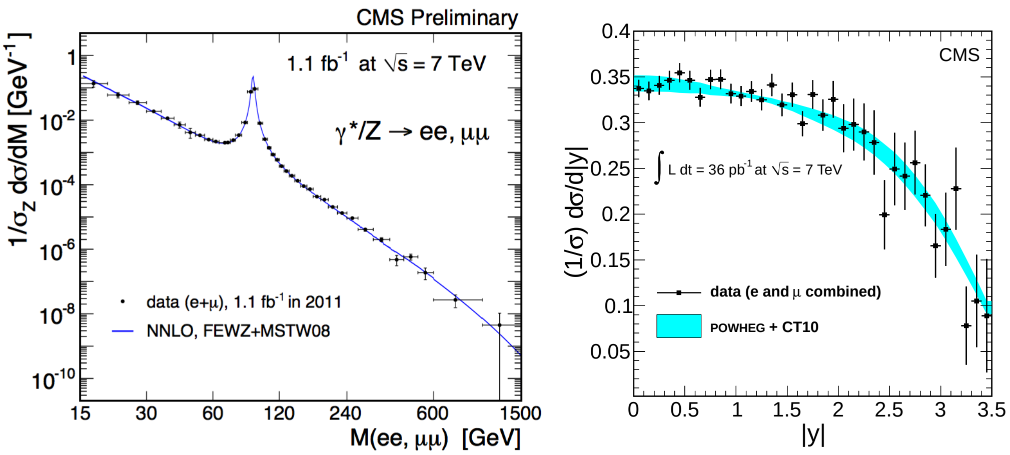


Fig. 4. – Differential cross sections of the Z boson production with respect to the mass (left) and rapidity (right) of the Z.

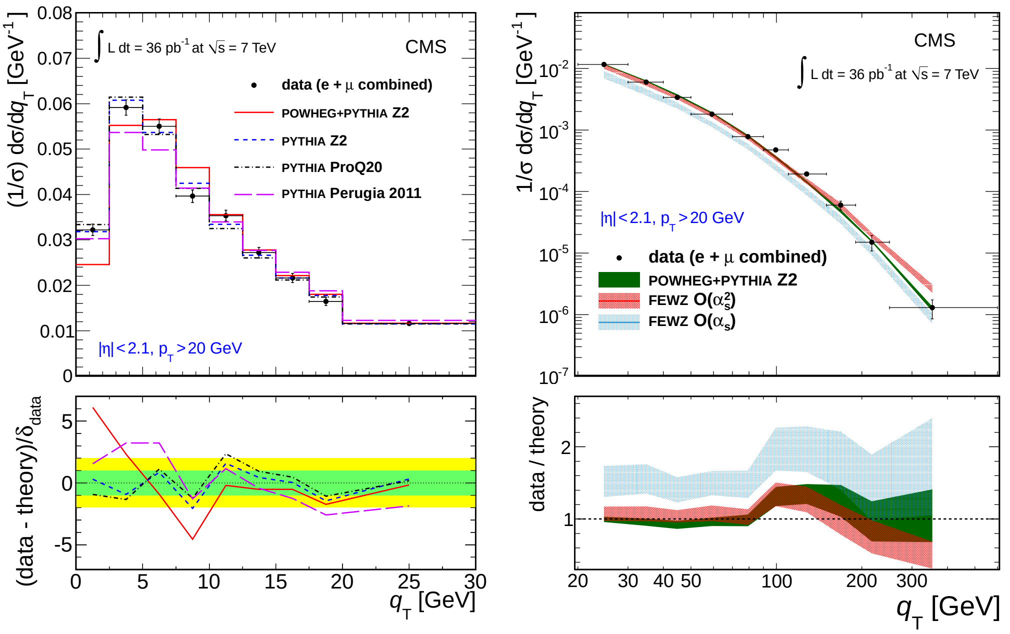


Fig. 5. – Differential cross section of the Z boson production with respect to the p_T of the Z for the lower (left) and higher (right) p_T regions.

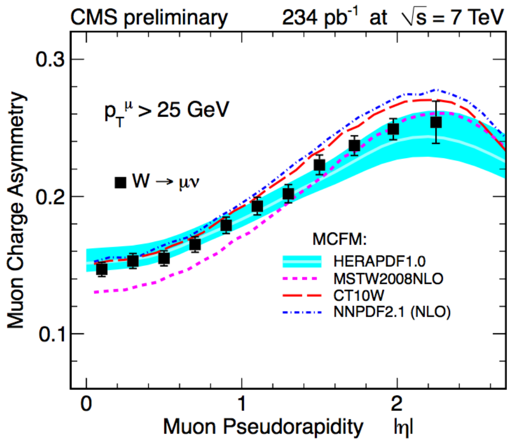


Fig. 6. – Muon charge asymmetry as a function of pseudorapidity for $W \to \mu\nu_\mu$ candidates.

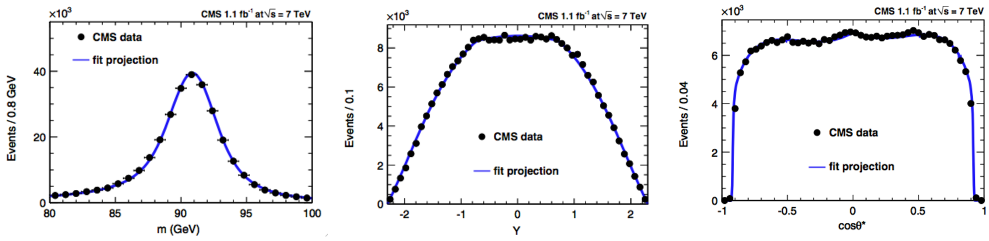


Fig. 7. – The distributions of the three observables (invariant mass, rapidity, and the decay angle) of dilepton pairs entering the multivariate analysis that yields the weak mixing angle measurement.

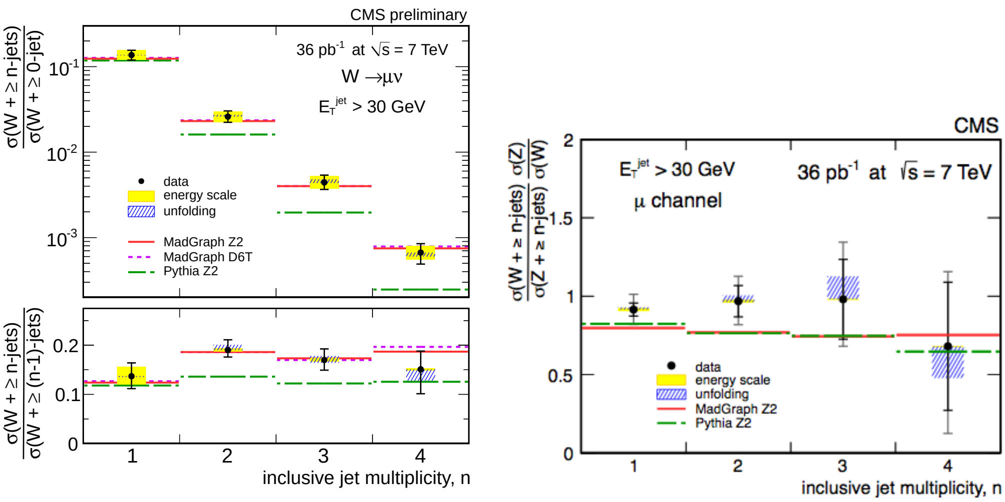


Fig. 8. – Multiplicities of jets produced in association with W and Z and normalized to the inclusive W and Z production.

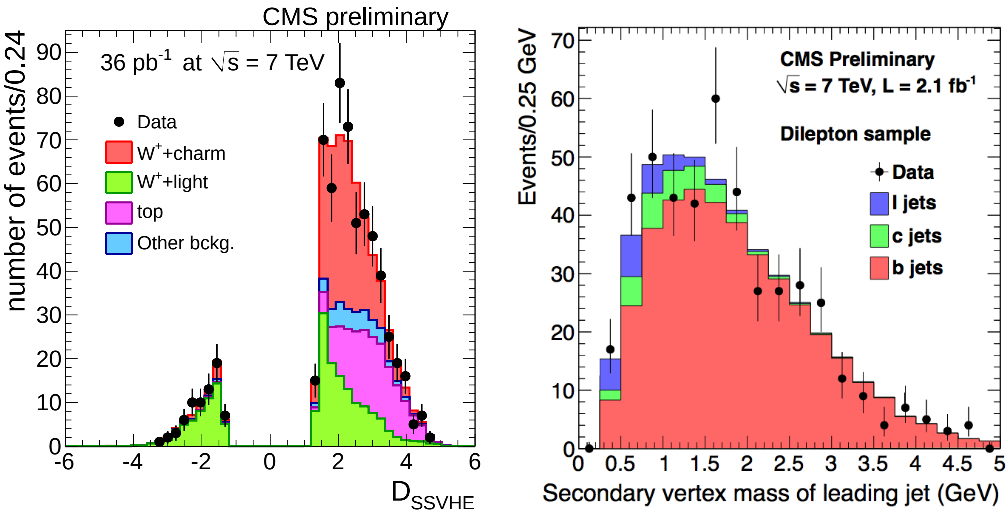


Fig. 9. – The distribution of the discriminant based on the significance of the secondary vertex displacement for W+charm candidates (left); the distribution of the leading jet secondary vertex mass for $Z + b(b)$ candidates (right).