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W and Z production in association with light and heavy-flavour jets at the LHC and the Tevatron

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Abstract.
Measurements of W and Z production in association with jets provide a stringent test of perturbative QCD calculations. In addition, these measurements are of great relevance to searches for new particles and new interactions as these Standard-Model processes often represent a significant background. In these proceedings, recent results on the W and Z production for light and heavy-flavour jets at the Tevatron and the LHC are presented.

1 Introduction

The study of massive vector-boson production in association with one or more jets is an important test of quantum chromodynamics (QCD). These final states are also a significant background to studies of Standard-Model processes such as $t\bar{t}$, diboson, and single-top production, as well as studies of the Higgs boson and searches for physics beyond the Standard Model. Thus, measurements of the cross section and kinematic properties with comparisons to theoretical predictions, are of significant interest.

With the large data samples from both the Tevatron and the LHC, measurements of vector-boson production in association with jets can now be extended to include measurements in new phase spaces such as events with large transverse momentum of the Z boson, differential measurements in more observables such as jets with large forward rapidities and differential measurements of processes with small cross sections such as Z boson production with two b-quarks. These precision measurements across multiple areas of phase space are of particular importance today, especially for new physics searches and studies of the Higgs boson as vector-boson production is a major background to all of these processes.

For the measurements presented in these proceedings, W and Z boson events are selected for electron ($W \to e\nu$, $Z \to ee$) and muon ($W \to \mu\nu$, $Z \to \mu\mu$) decays. To select W boson events, one high $p_{\rm T}$ lepton and significant missing transverse energy and/or a large transverse mass are required. For Z boson events, two high $p_{\rm T}$ leptons are required and the dilepton mass must be close to the Z-mass peak. Jets are required to have large $p_{\rm T}$. For the ATLAS [1] and CMS [2] detectors, the jets are reconstructed using the anti-k_T algorithm and a typical jet minimum $p_{\rm T}$ requirement is 30 GeV.

For vector-boson production in association with light jets, the backgrounds include QCD mulitjet events, $W \to \tau\nu$ events where the τ decays to an electron or muon, single-top events, diboson events, and $t\bar{t}$ events. For W production, Z boson events are also a background. The dominant background at low jet multiplicities is the multijet background. This background arises when multijet events either contain a b-quark which then decays semi-leptonically or contain a light-flavour jet which is mis-identified as a lepton. For the high multiplicities, the dominant background is $t\bar{t}$ events.

For vector-boson production in association with heavy-flavour jets, the backgrounds are similar to those listed above. In addition for these measurements, backgrounds from W and Z bosons in association with light jets or c-quark jets which are mis-identified as b-jets are a major background.

The dominant uncertainty for all the measurements discussed here is the uncertainty on the energy scale of the jets. For ATLAS and CMS, the jet energy scale uncertainty is roughly 2% for central jets but increases to up to 5% for jets with large forward rapidities. For measurements of heavy-flavour jet production, additional uncertainties on the b-tagging algorithms must be considered and are often as large as the uncertainties on the jet energy scale.

2 W and Z production in association with light-flavour jets

2.1 Recent W+jets results

Using the large data sets from the Tevatron to explore new phase spaces in W+jets production, a recent measurement using the D0 detector [3] studies for the first time the probability of additional jet emission in inclusive W+2-jet events [4]. This variable is important for understanding

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jet vetoes in high jet multiplicity final states, which is particularly important for vector-boson fusion Higgs searches and vector-boson fusion electroweak production. These results, using a sample of $W \to e\nu$ events corresponding to 3.8 fb^{-1}of data, are corrected for all detector acceptances and efficiencies.

Figure 1 shows the probability for additional jet emission as a function of dijet rapidity separation in three configurations: the rapidity separation between the two hardest jets, the rapidity separation between the two hardest jets with an additional requirement that the additional jet be emitted into the rapidity gap defined by the rapidity interval between the two hardest jets and the rapidity separation of the most forward/backward jets. As seen in the figure, the probability of emitting an additional jet is large, up to 50% for jets with large rapidity separations. Several differences are observed compared to the theoretical predictions especially to the SHERPA predictions [5] which underestimate the emission probability and to a lesser extent the NLO BLACKHAT+SHERPA predictions [6]. The NLO HEJ predictions [7] show the best agreement across the full range and have small scale uncertainties even at the highest rapidity separations.

2.2 Recent Z+jets results

With the large data samples from the LHC, measuring the properties of boosted Z boson candidates is now possible. Measuring these Standard-Model cross sections in boosted phase spaces is important for understanding both the Standard Model but also for understanding the performance of the Monte Carlo predictions in these new phase spaces. Using 5.0 fb^{-1} of data at $\sqrt{s}$ = 7 TeV, the CMS collaboration measured the azimuthal correlations and the transverse thrust of events with a Z boson candidate as a function of the jet multiplicity [8]. These measurements, done both inclusively in the Z boson transverse momentum (p_T^Z), and in a boosted phase space ($p_T^Z > 150$ GeV) are corrected for detector effects and compared to the predictions from MADGRAPH [9], SHERPA, POWHEG [10] and PYTHIA [11] Monte Carlo generators. Figure 2 shows the distribution of the logarithm of the transverse thrust ($ln(\tau_\perp)$) for the boosted phase space of $p_T^Z > 150$ GeV for data and the simulations. The transverse thrust is a measure of the sphericity of the leptons and jets in the event. Large negative values of $ln(\tau_\perp)$ indicate events where the leptons from the Z boson and the jets are back-to-back in the transverse plane whereas $ln(\tau_\perp) = 0$ indicates events where the leptons and jets are distributed evenly throughout the transverse plane. In general, the simulations describe the data well in this boosted phase space although there are areas of tension especially for large negative values of $ln(\tau_\perp)$.

2.3 Vector-boson fusion results

The electroweak production of a W or Z boson plus two jets, with the requirement that the boson is centrally produced and that the two jets are well separated in rapidity, has a sizeable cross section at the LHC and can be

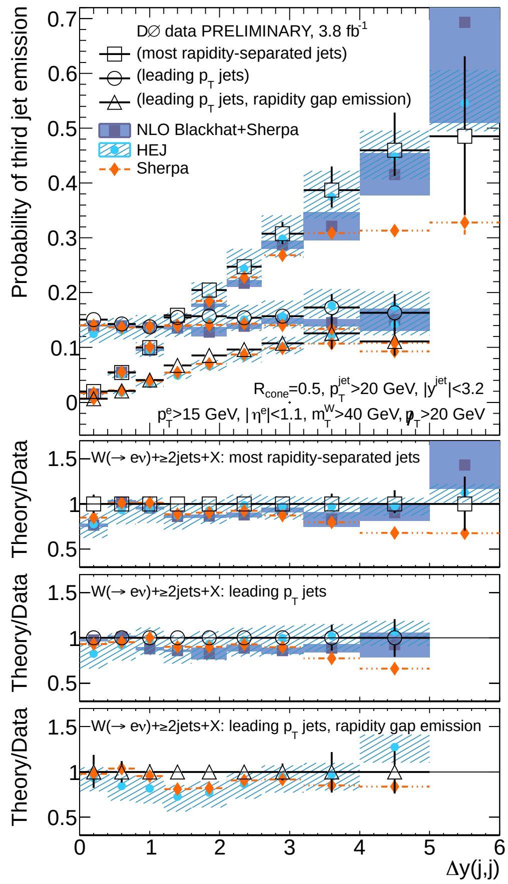

Figure 1. Measurement of the probability of emission of a third jet in inclusive W+2-jet events as a function of the dijet rapidity separation of the two most rapidity separated jets (open squares), of the two leading p_T jets (open circles), of the two leading p_T jets with a requirement that the third jet be emitted into the rapidity gap defined by the two leading jets (open triangles) [4]. Comparison is made to NLO BLACKHAT+SHERPA predictions, HEJ all-order resummation predictions and SHERPA matrix element parton shower matched Monte Carlo predictions.

measured for the first time. There are three classes of diagrams in the electroweak production of the W and Z bosons with two jets: bremsstrahlung, vector-boson fusion processes and multiperipheral diagrams. Large negative interferences exist between these three diagrams. As in the W+jets measurement from D0 discussed in section 2.1, these events typically have two forward jets with a large rapidity separation and consequently the emission of a third jet is very probable. Therefore, these processes are also a crucial measurement for understanding the selection of the forward jets and the veto of the third jet emissions which are routinely used in searches for vector-boson fusion Higgs production.

From the CMS collaboration, a first measurement of the cross section of the electroweak two lepton plus two jet production process ($\ell\ell jj$) [12] is made and compared to theoretical predictions. The following parton-level selections are used: $m_{\ell\ell} > 50$ GeV, $p_T^j > 25$ GeV, $|\eta_j| < 4.0$, $m_{jj} > 120$ GeV. The cross section of the electroweak Z

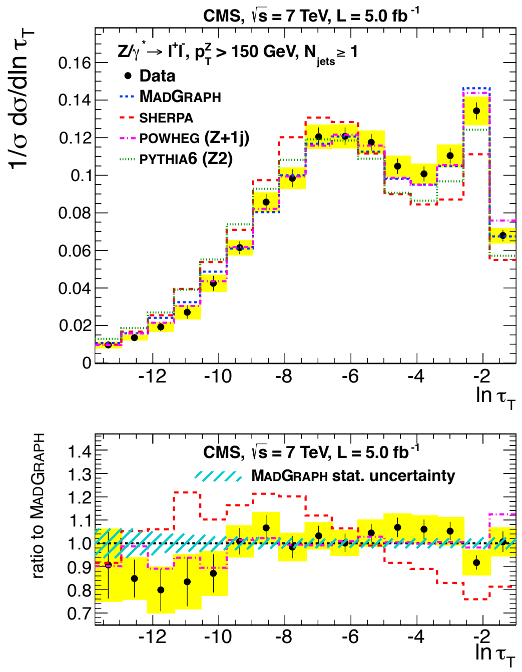

Figure 2. Distributions of the logarithm of the transverse thrust for the boosted phase space ($p_T^Z > 150$ GeV) from data [8] and simulations from SHERPA, POWHEG, PYTHIA and MADGRAPH. The error bars on the data points represent the statistical uncertainty on the data after the unfolding, the shaded (yellow) bands represent the sum of statistical and systematic errors. The lower plot shows the ratio between data, SHERPA and POWHEG with respect to MADGRAPH. The ratio between PYTHIA and MADGRAPH is not shown due to large deviations. The shaded yellow band represents the total error on the data on the ratio data-MADGRAPH, the dashed cyan band around 1 represents the relative statistical error on the MADGRAPH distribution.

boson production with the Z boson decaying into pairs of muons or electrons is measured using a data sample collected in 2011 and corresponding to an integrated luminosity of 5.1 fb^{-1} for the muon channel and 5.0 fb^{-1} for the electron channel.

For the event selection, the two highest p_{T} jets within $|\eta| < 4.7$ (labeled $j1$ and $j2$) are selected as tagging jets. The optimisation of the selections was done by maximising the signal significance defined as number of signal over the square-root of the number of background events. The selection requirements on the momentum and pseudorapidity of the tagging jets (p_T^{j1}, p_T^{j2}, η_{j1}, η_{j2}), the dijet invariant mass (m_{j1j2}), and the Z boson rapidity in the frame of the tagging jet rapidity defined as $y^\star = y_Z - 0.5(y_{j1} + y_{j2})$ are varied in order to achieve a maximal signal significance. The dominant background for this measurement is from Drell-Yan processes.

Figure 3 shows the dijet invariant mass distribution. The contributions from the Drell-Yan background and the electroweak $\ell\ell jj$ signal processes are determined in the signal extraction procedure whereas the contributions from the $t\bar{t}$ and diboson backgrounds are estimated from simulation. The signal extraction is done in two ways. The first approach is to fit the m_{j1j2} distribution to determine the relative number of signal and Drell-Yan background events. The second method uses a multivariate analysis, where a boosted decision tree (BDT) is trained to give a high output value for signal-like events based on angular information of the $\ell\ell jj$ system. A fit is preformed again using the BDT output. As the BDT method provides smaller errors on the fit parameters, this method is used as the default method. After combining both the muon and electron channels, the measured cross section is $\sigma_{\mathrm{meas}} = 154 \pm 24(\mathrm{stat}) \pm 46(\mathrm{exp}) \pm 27(\mathrm{theory}) \pm 3(\mathrm{lumi})$ fb. This is in agreement with the theoretical cross section of 166 fb, which is calculated with the next-to-leading-order QCD corrections.

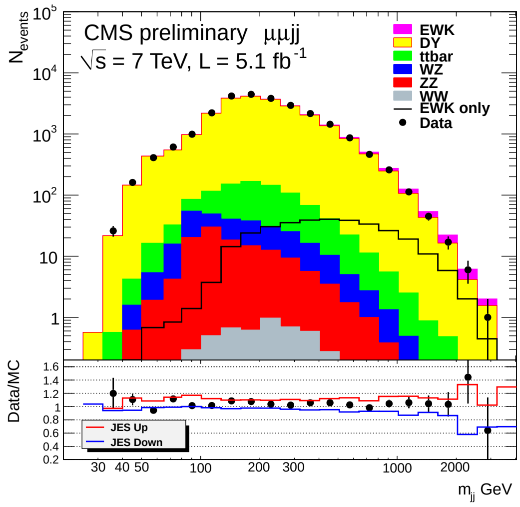

Figure 3. The m_{jj} distribution after selection [12]. The expected contributions from the dominant Drell-Yan background and the signal processes are evaluated from the fit and the contributions from the small $t\bar{t}$ and diboson backgrounds are estimated from simulation. The signal labeled EWK is shown in pink. The bottom panel shows the ratio of data over the expected contribution of the signal plus backgrounds along with the statistical uncertainties. The red and blue lines indicate the systematic uncertainty due to the jet energy scale (JES).

3 W and Z production in association with heavy-flavour jets

3.1 Recent W+c heavy-flavour results

A recent result using the CDF detector [13] presents the first observation of W boson production in association with a single charm quark using 4.3 fb^{-1}of data [14]. As the Tevatron is a proton-antiproton collider, W+c production is dominated at the lowest order through sg and $\bar{s}$g fusion. Therefore the measurement of W+c cross section is particularly sensitive to the gluon and s-quark parton density functions. In addition k-factors for leading-order Monte Carlo predictions of this process have large uncertainties which can start to be constrained through this measurement.

For this measurement, the analysis exploits the correlation between the charge of the W boson and the charge of

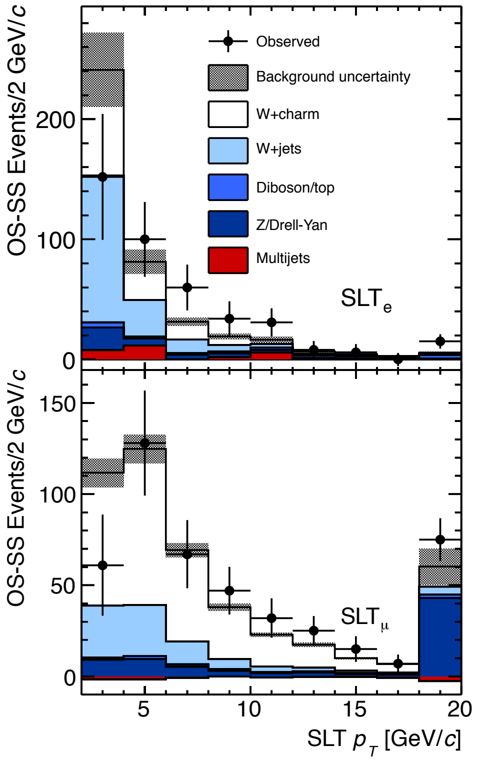

Figure 4. The soft electron and soft muon p_{T} distributions measured using the CDF detector [14]. The W+c contribution is derived using ALPGEN simulations normalised to the measured cross section.

the soft lepton from the semi-leptonic decay of the charm hadron. In $W^{+}\bar{c}$ and W^{-}c events, the charge of the soft lepton from the semi-leptonic decay of the c-quark and the charge of the W boson are always of opposite-sign, neglecting any effects due to slow-rate charm quark oscillations. By measuring the difference between events with the opposite-sign charge and same-sign charge, the major backgrounds such as W+$c\bar{c}$ and W+$b\bar{b}$ largely cancel. Figure 4 shows the distributions of the measured p_{T} spectrum for soft lepton tagged muons and electrons from the charm decay, compared to the predicted spectrum given by the W+c signal and estimated backgrounds. The ALPGEN [15] simulations predict a slightly larger number of events. The inclusive measured W+c cross section though is in agreement with the NLO calculations.

3.2 Recent W+b heavy-flavour results

Previous measurements of the production of W bosons in association with b-jets from the CDF and ATLAS collaborations have lead to conflicting conclusions. The CDF measurement of the W+b cross section significantly exceeds the NLO prediction [16] while the ATLAS result using 35pb^{-1}of data [17] is in agreement with the NLO expectation. Resolving these differences is of great importance to many Higgs studies and new physics searches with heavy-flavour jets as W+b production is often a dominant background. Independent and updated measurements are therefore needed to understand the W+b production at hadron colliders.

Using the D0 detector, a measurement of the W+b cross section is made using data corresponding to an integrated luminosity of 6.1 fb^{-1} [18]. The fraction of W+b events in the sample is determined by performing a binned maximum likelihood fit using a b-tagging discriminant distribution to the observed data. The templates for W+light-flavour, W+b, and W+c jets are taken from the efficiency-corrected simulations. The measured cross sections from this analysis are in agreement with NLO QCD calculations and predictions obtained using the SHERPA and MADGRAPH generators.

Using the ATLAS detector, an updated measurement of the W+b cross section is presented using 4.6 fb^{-1} [19]. The cross sections are presented as a function of jet multiplicity as well as the transverse momentum of the leading b-jet. Both $W \to \mu\nu$ and $W \to e\nu$ events are considered and all events are required to have exactly one b-tagged jet. The backgrounds from QCD multijet, $t\bar{t}$ and single-top events are estimated directly from data in order to reduce the theoretical uncertainties on their normalisation. The $t\bar{t}$ background, for example, is estimated in data by selecting events with at least four jets and exactly one b-tagged jet. A binned maximum likelihood fit to the distribution of a b-tagging discriminant is performed in this control region to extract the $t\bar{t}$ yield. The $t\bar{t}$ simulation is then used to extrapolate the measured yield into the W+b signal regions.

In the 1-jet final state, the measured cross section is found to be consistent within 1.5 sigma with LO and NLO predictions. In the 2-jet final state, the measured cross section is in good agreement with the theoretical calculations. Figure 5 shows the differential cross sections as a function of the p_{T} of the leading b-jet for 1- and 2-jet events. In the 1-jet final state, the measured p_{T} spectra is larger than the LO and NLO predictions, but compatible within the theoretical and experimental uncertainties.

3.3 Recent Z+heavy-flavour results

With the large data sets from the LHC, not only the cross sections of rarer processes such as Z+b and Z+bb production can be measured but also some differential distributions such as the cross section as a function of the p_{T} of the b-jet. Using the CMS detector, a measurement of the Z+b production cross section including differential distributions using 2.2 fb^{-1} is presented [22]. These results are compared to theoretical predictions in the variable-flavour scheme, which allows the b-quark to participate directly in the hard scattering by integrating the gluon-splitting process into the parton distribution functions. As seen in Figure 6 (left), the p_{T} distribution for the leading b-tagged jet is shown to be in fair agreement with the predictions from MADGRAPH, where the predictions have been normalised to the NNLO Z cross section. The residual discrepancy may be a consequence of the higher-order terms

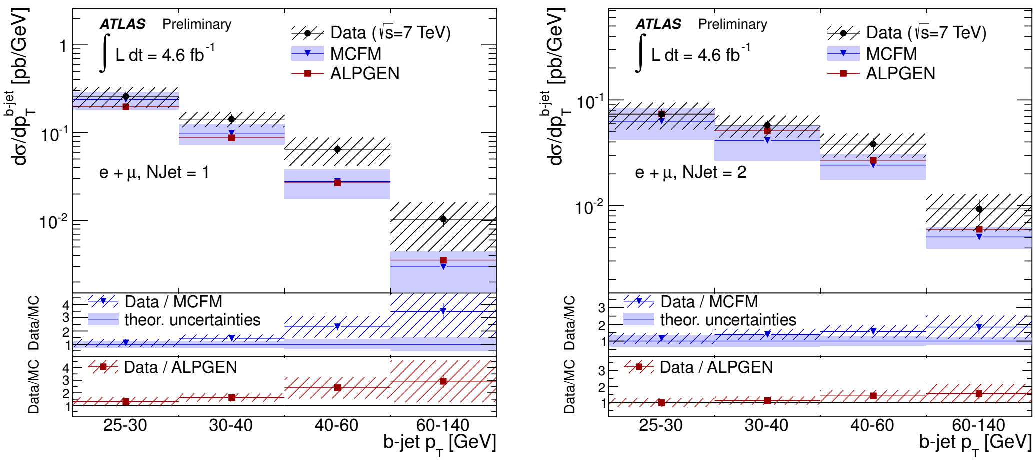

Figure 5. Measured differential W+b-jet cross sections with the statistical plus systematic uncertainty as a function of the b-jet p_T in the 1-jet (left) and 2-jet (right) samples, obtained by combining the muon and electron channel results [19]. The measurements are compared to the MCFM [20] and ALPGEN/HERWIG [21] predictions.

absent in the MADGRAPH tree-level simulation in the variable-flavour scheme with massless b-quarks.

A measurement of the Z+bb cross section has also been presented using 2.1 fb^{-1} of data with the CMS detector [23]. This measurement of the production of the Z boson in association with b-quarks is an important measurement at the LHC, both as a benchmark channel to the production of the Higgs boson in association with b-quarks and as a background to new physics searches in final states with leptons and b-jets. Shown in Figure 6 (right) is the p_T distribution of the b-jet pair. There is an overall disagreement between data and simulations, which shows an excess of events at higher values of p_T. This discrepancy needs to be further studied with more statistics and possibly with NLO predictions.

The angular correlation between B hadrons produced in association with a Z boson is also studied using the CMS detector and 4.6 fb^{-1}of data [24]. In this measurement, B hadrons are identified by displaced secondary vertices and therefore this analysis does not make use of jets. This allows for studying Z+bb production at small angular separations, where detailed understanding of the dynamics of the b-quarks or B hadrons remains difficult, in particular in the soft/collinear region where the gluon-splitting contribution remains not well known. The measured differential cross section as a function of the opening angle, ΔR between the two B candidates in the signal region is compared to predictions from MADGRAPH and aMC@NLO [25]. The measured distribution agrees reasonably well with the predictions although the data suggest a globally flatter slope. Larger data samples will allow for more precise study of the angular separation in different regions of the Z p_T spectrum.

4 Conclusions

These proceedings summarise recent results for measurements of vector-boson production in association with either light or heavy-flavour jets from the CDF, D0, ATLAS and CMS collaborations. For light-flavour production, these results include measurements of third jet emission in W+jets events, measurements of Z+jets in boosted phase spaces and a first measurement of electroweak $\ell\ell jj$ production. For heavy-flavour production, measurements of the W+c production, W+b production, Z+b production and Z+bb production were presented. All of these measurements provide important insight on perturbative QCD and are critical for better understanding of the background processes to Higgs studies and new physics searches.

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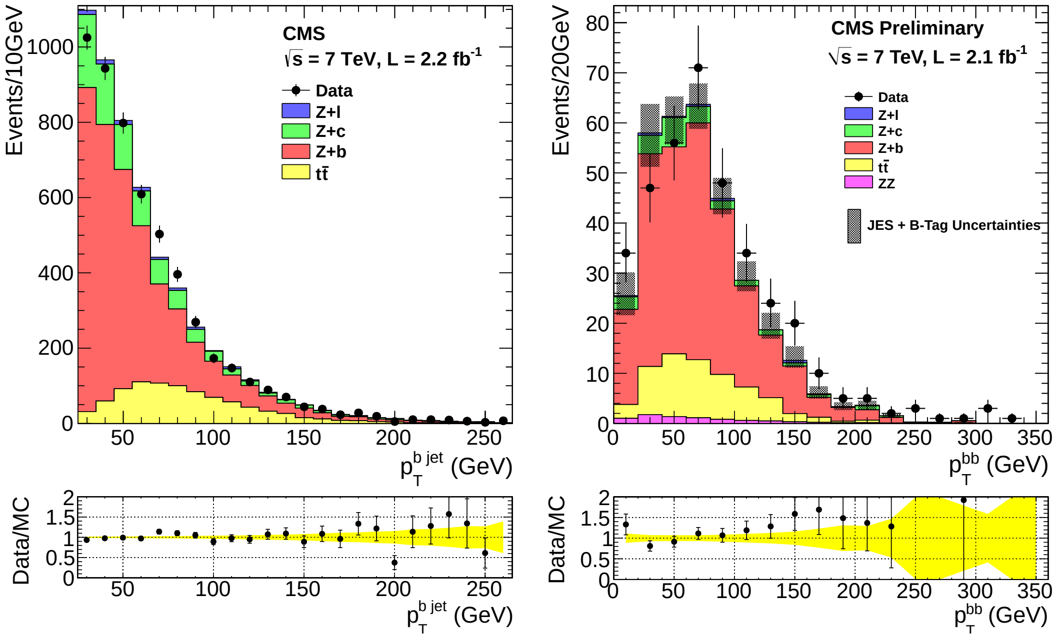

Figure 6. Left: p_T of the leading-p_T b-jet after the dilepton+b-jet selection in Z+b events [22]. Right: The p_T distribution of the bb pair for Z+bb events [23]. The grey band in the upper plot represents the systematic effect due to varying the jet energy scale uncertainty and adding in quadrature the uncertainty due to varying the systematic uncertainty on the b-tag efficiency. In both figures, the yellow band in the lower plots represents the statistical uncertainty on the yield from the simulations.

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