XXXI PHYSICS IN COLLISION, Vancouver, BC Canada, August 28 - September 1, 2011

High p_T Jet Physics

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arXiv:1111.2484v1 [hep-ex] 10 Nov 2011

This report gives a selection of recent jet results from the LHC and Tevatron, including inclusive jet production, dijets, and jets produced in association with massive vector bosons.

I. INTRODUCTION

Jet production is the dominant high transverse-momentum (p_T) process at the Tevatron and LHC, and jet measurements are a key step in searches for physics beyond the Standard Model. For a jet with energy E and momentum $p = (p_x, p_y, p_z)$, its transverse momentum is given by $p_T = \sqrt{p_x^2 + p_y^2}$, and its rapidity is given by $y = \frac{1}{2} \ln \frac{E+pz}{E-pz}$. Jets are defined by jet-finder algorithms [1], clustered in a two-dimensional space of y and detector azimuthal angle ϕ, with a distance parameter defined as $R = \sqrt{\Delta y^2 + \Delta\phi^2}$. Here we focus on results with the anti-kt jet algorithm as used by ATLAS with ($R = 0.4, 0.6$) and by CMS with ($R = 0.5, 0.7$).

Due to the non-compensating nature of typical calorimeters, such that the ratio of electromagnetic to hadronic response differs from unity, jets must be calibrated to determine the Jet Energy Scale (JES). This is usually achieved using a combination of Monte Carlo and in-situ techniques. The resulting JES uncertainties are typically of order 1.5% in the central rapidity detector regions for CDF/DO, while for ATLAS/CMS they range from about 2.5% for central jets with ($50 < p_T < 800$) GeV, increasing up to 12% for forward jets.

In this report, the results from ATLAS and CMS comprise up to 48 pb^{-1} of integrated luminosity delivered by the LHC in 2010.

II. INCLUSIVE JETS

Inclusive jet production at the LHC centre-of-mass energies of $\sqrt{s} = 7$ TeV has been measured by ATLAS [2] and CMS [3], as show in Figure 1. The figure illustrates the inclusive jet double-differential cross section as a function of jet p_T in different regions of $|y|$ for jets identified using the anti-kt algorithm. Here the examples with $R = 0.4$ (ATLAS) and $R = 0.5$ (CMS) are shown. The data are compared to next-to-leading order perturbative QCD (NLO pQCD) calculations to which non-perturbative corrections have been applied. The error bars indicate the statistical errors on the measurements, and the dark shaded band indicates the quadratic sum of the experimental systematic uncertainties, dominated by the JES uncertainty. The measurements cover jet p_T from 20 GeV to 1.5 TeV, rapidities within $|y| < 4.4$, and span six orders of magnitude in cross sections.

Figure 2 gives the comparison of ATLAS inclusive jet data with predictions from different parton distribution function (PDF) sets (CTEQ 6.6, MSTW 2008, NNPDF 2.1, HERAPDF 1.5). The data points and the error bands are normalized to the theoretical predictions obtained by using the CTEQ 6.6 PDF set. Within the experimental uncertainties of 10-20%, the data are found to be in agreement with theoretical predictions from NLO pQCD.

III. DIJETS

Events with two high p_T jets (dijets) can be generated in proton-proton collisions by parton-parton scattering. They can be characterized by the invariant mass of the two jets, $M_{JJ}^2 = x_1 \cdot x_2 \cdot s$, where x_1, x_2 are the proton momentum fractions of the scattered partons. The dijet cross section as a function of M_{JJ} can be precisely calculated in pQCD, and can be sensitive to new physics such as contact interactions or strongly-decaying resonances.

Figure 3 shows the double-differential dijet production cross sections measured by CMS [4] as a function of M_{JJ}, in bins of $|y|_{max} = max(|y_1|, |y_2|)$ of the two

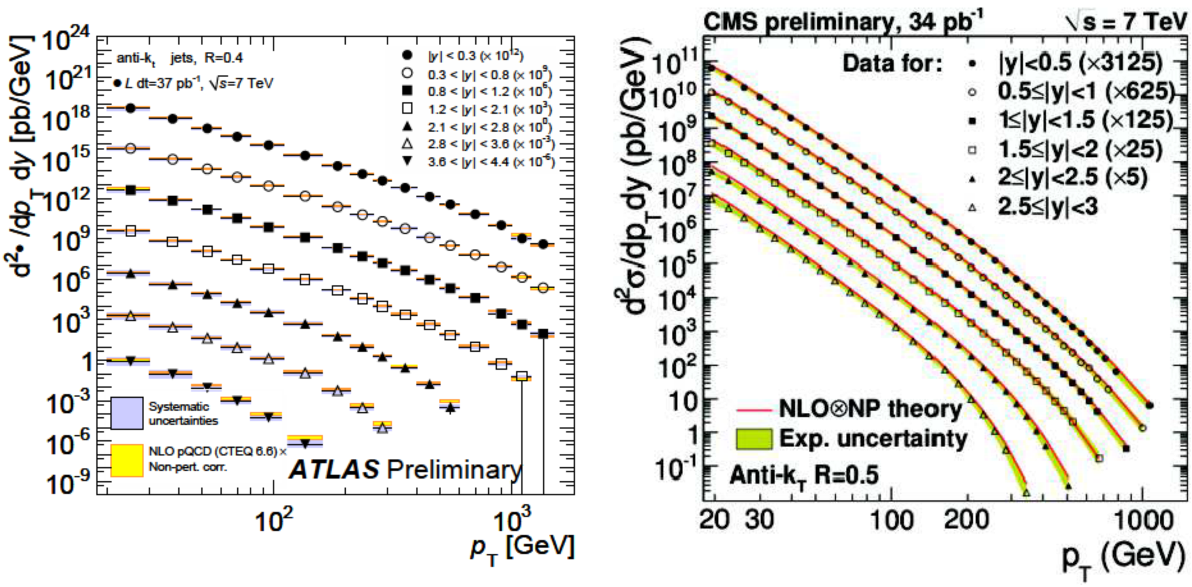

FIG. 1: Inclusive jet double-differential cross section as a function of jet p_T in different regions of $|y|$ for jets identified using the anti-kt algorithm with $R = 0.4$ (ATLAS) and $R = 0.5$ (CMS) measured at $\sqrt{s} = 7$ TeV. The data are compared to NLO pQCD calculations to which non-perturbative corrections have been applied. The error bars indicate the statistical errors on the measurements, and the dark shaded band indicates the quadratic sum of the experimental systematic uncertainties.

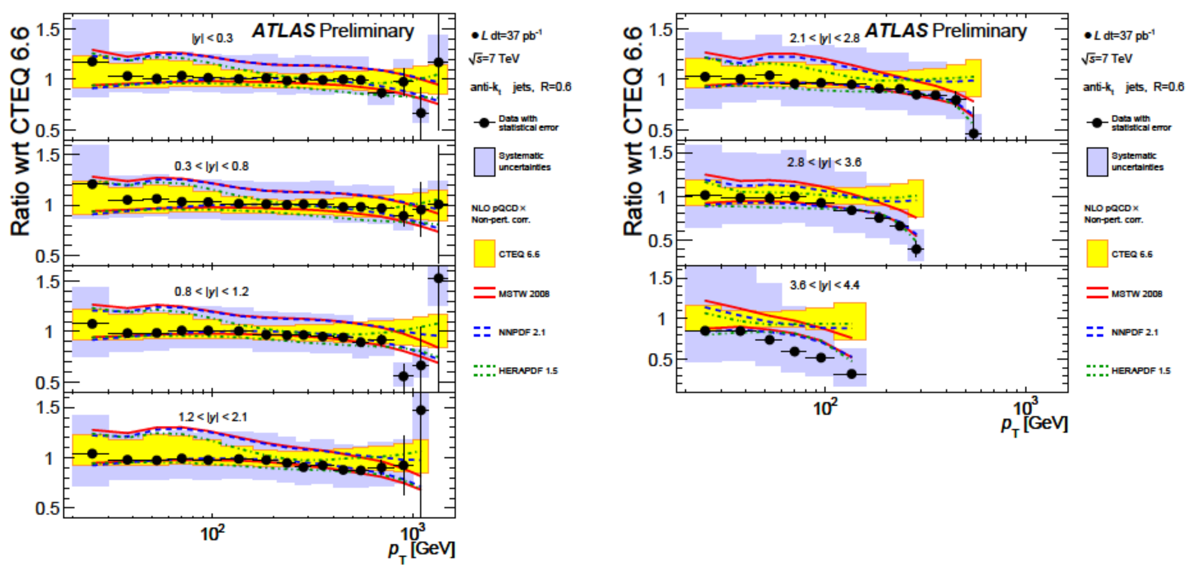

FIG. 2: Inclusive jet double-differential cross section as a function of jet p_T in different regions of $|y|$ for jets identified using the anti-kt algorithm with R=0.6, measured at $\sqrt{s} = 7$ TeV with ATLAS. The theoretical error bands obtained using different PDF sets (CTEQ 6.6, MSTW 2008, NNPDF 2.1, HERAPDF 1.5) are shown. The data points and the error bands are normalized to the theoretical predictions obtained by using the CTEQ 6.6 PDF set.

leading jets in the event. Low values of $|y|_{max}$ tend to probe large-angle (s-channel) scattering, while large values probe small-angle (t-channel) scattering. In this measurement, the dijet masses range from $M_{JJ} =$ 0.2 to 3.5 TeV, with corresponding parton momentum fractions ranging from $8 \cdot 10^{-4} \leq x_1 \cdot x_2 \leq 0.25$. The NLO theoretical predictions, at renormalisation and factorisation scales (μ_R and μ_F) equal to the average transverse momentum of the two jets (p_T^{ave}), together with non-perturbative corrections to take into account hadronisation effects and multiparton interactions, are superimposed on the plots as curves. The

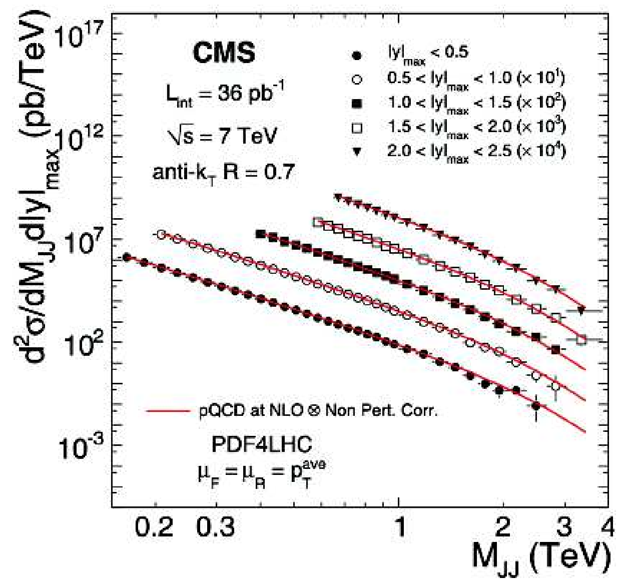

FIG. 3: Double-di erential dijet production cross sections (points) measured by CMS as a function of the dijet invariant mass M_{JJ} in bins of the variable y_{max}, compared to the theoretical productions (curves). The horizontal error bars represent the bin widths, while the vertical error bars represent the statistical uncertainties of the data.

experimental systematic uncertainties are dominated by the JES uncertainty, ranging from 3% to 5%, giving an uncertainty on the cross section of 15% (60%) at $M_{JJ} = 0\ 2$ (3) TeV. The data and theoretical predictions are found to be in good agreement within uncertainties.

An event display of a high-mass dijet event recorded by ATLAS [5] in 2011 is given in Figure 4. The invariant mass of the dijet system is 4.0 TeV, the two leading jets have ($p_T\ y$) of (1.8 TeV, 0.3) and (1.8 TeV, -0.5), and the event has a missing transverse energy, E_T^{miss}, of 100 GeV.

IV. JETS IN ASSOCIATION WITH VECTOR BOSONS

The production of massive vector bosons V in association with jets is a further test of pQCD. Recently NLO predictions have become available [6] for $V + n$ jets, where $n = 3\ 4$ for $V = Z\ W$ respectively.

A. Jets + W Bosons

Figure 5 gives the measurements by CMS [7] of jets in association with W bosons. The left gure shows the raw W event rate in the electron channel as a function of exclusive jet multiplicity, for jets with $E_T > 30$ GeV. The right gure shows the leading jet transverse energy E_T spectrum for the muon channel. Data are plotted as points, and predictions from Monte Carlo simulations for W signal (MadGraph) and other backgrounds are shown. In order to reduce backgrounds, a cut has been applied on the transverse mass $M_T = \sqrt{2p_T E_T^{miss}(1 \quad cos \quad)} > 50$ GeV, where is the angle in the xy plane between the lepton p_T and the E_T^{miss} vector direction. A good agreement is observed between data and theoretical predictions for jet E_T up to 250 GeV and nal states with up to six jets.

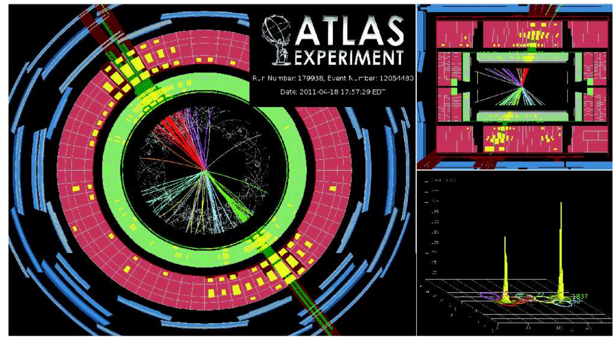

FIG. 4: A high-mass dijet event recorded by ATLAS in 2011. The invariant mass of the dijet system is 4.0 TeV, the two leading jets have ($p_T\ y$) of (1.8 TeV, 0.3) and (1.8 TeV, -0.5), and the event E_T^{miss}= 100 GeV.

Figure 6 (left) shows the measurement by ATLAS [8] of jets in association with a W boson expressed as a ratio of cross sections $(W+\quad N_{jet})\quad(W+\quad N_{jet}\quad 1)$ for inclusive jet multiplicities $N_{jet} = 1\quad 5$. The gure gives the W+jet cross section ratio as a function of corrected jet multiplicity for the muon channel. Figure 6 (right) gives the W+jet cross section as a function of the p_T of the rst jet in the event for the muon channel. The p_T of the rst jet is shown separately for events with 1 jet to 4 jets. Data are plotted as points, and predictions from ALPGEN, SHERPA, PYTHIA, MCFM, and BLACKHAT-SHERPA are superimposed as symbols. Theoretical uncertainties are shown only for MCFM and BLACKHAT-SHERPA. As PYTHIA is a LO calculation, it does not provide a good description of the data for jet multiplicities greater than one. However, the NLO predictions from MCFM and BLACKHAT-SHERPA, and multi-parton matrix element generators ALPGEN and SHERPA, are found to be in good agreement with the data.

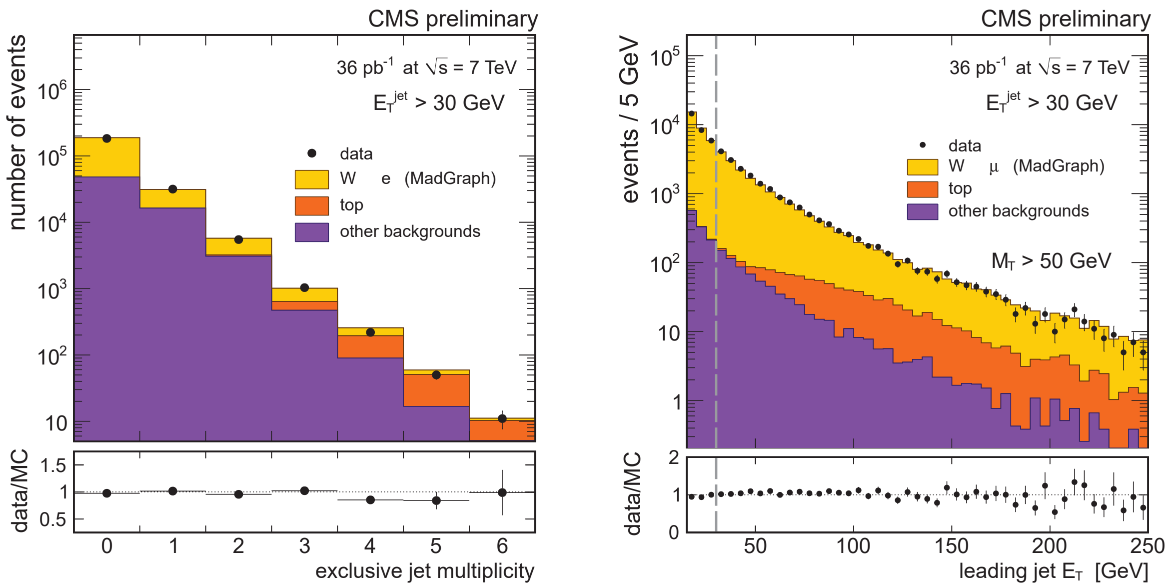

FIG. 5: The production of jets in association with W bosons as measured by CMS. The left gure gives the raw W event rate as a function of exclusive jet multiplicity in the electron channel. The right gure shows the uncorrected leading jet E_T spectrum for the $W+1$ jet sample for the muon channel. Data are plotted as points, and predictions from Monte Carlo simulations for W signal (MadGraph) and other backgrounds are shown as solid histograms. The line at p_T= 30 GeV corresponds to the threshold imposed for counting jets.

B. Ratio of Cross Sections for Jets + W Z Bosons

Figure 7 shows the ratio of cross sections measured by ATLAS [9] for events with one jet and a W boson in the nal state compared to those with one jet and a Z boson in the nal state, as a function of the jet p_T threshold. This ratio is useful as a number of theoretical and experimental uncertainties cancel. As the jet p_T threshold increases, the ratio is expected to decrease, as the e ective scale of the interaction becomes large compared to the di erence in boson masses; this dependence is observed in the data. The electron and muon channel results were found to be compatible, and are combined in a common ducial region of $_{lepton} < 2\,5$, $p_T^{lepton} > 20$ GeV. The results are compared to predictions from MCFM (corrected to particle level), and found to be in agreement.

C. $W+b$ Jets

W + b-jet production is a large background to searches for the Higgs boson in WH production with the decay H $b\bar{b}$. Previous measurements in proton-antiproton collisions by CDF [10] indicate a larger measured cross section than the NLO QCD prediction. The measurement by ATLAS [11] of the cross section for the production of a W boson with one or two jets is shown in Figure 8. The left gure gives the invariant mass of the W + b-jet system in the electron channel. The right gure shows the measured ducial cross section in the 1, 2, and 1+2 jet exclusive bins. Anti-kt jets with $R = 0\,4$ are reconstructed, with p_T >25 GeV and $y < 2\,1$ (see Table 1 of [11] for the full de nition of the ducial region). The measurements are compared with NLO predictions, with systematic uncertainties from the renormalisation scale, factorisation scale, PDF set, and non-perturbative corrections combined in quadrature. The results are consistent with NLO predictions at the 1.5 level.

D. $Z+b$ Jets

The production of one or more b-jets in association with a Z boson is another signi cant background to searches for new physics at the LHC. Figure 9 shows the main diagrams that contribute to $Z+b$ production at the LHC. The rst 2 diagrams have an initial state b-quark, while the last 2 have a $b\bar{b}$ pair produced explicitly in the nal state. A summary of measurements [12] from the LHC and Tevatron of the average number of b jets produced in association with a Z boson is given in Table I, compared to theoretical predictions from MCFM. In the case of ATLAS, the ratio is given with respect to the total Z production cross section, while for CMS, CDF, and D0 it is given with respect to the Z+jet production cross section. The MCFM NLO prediction is in agreement with the

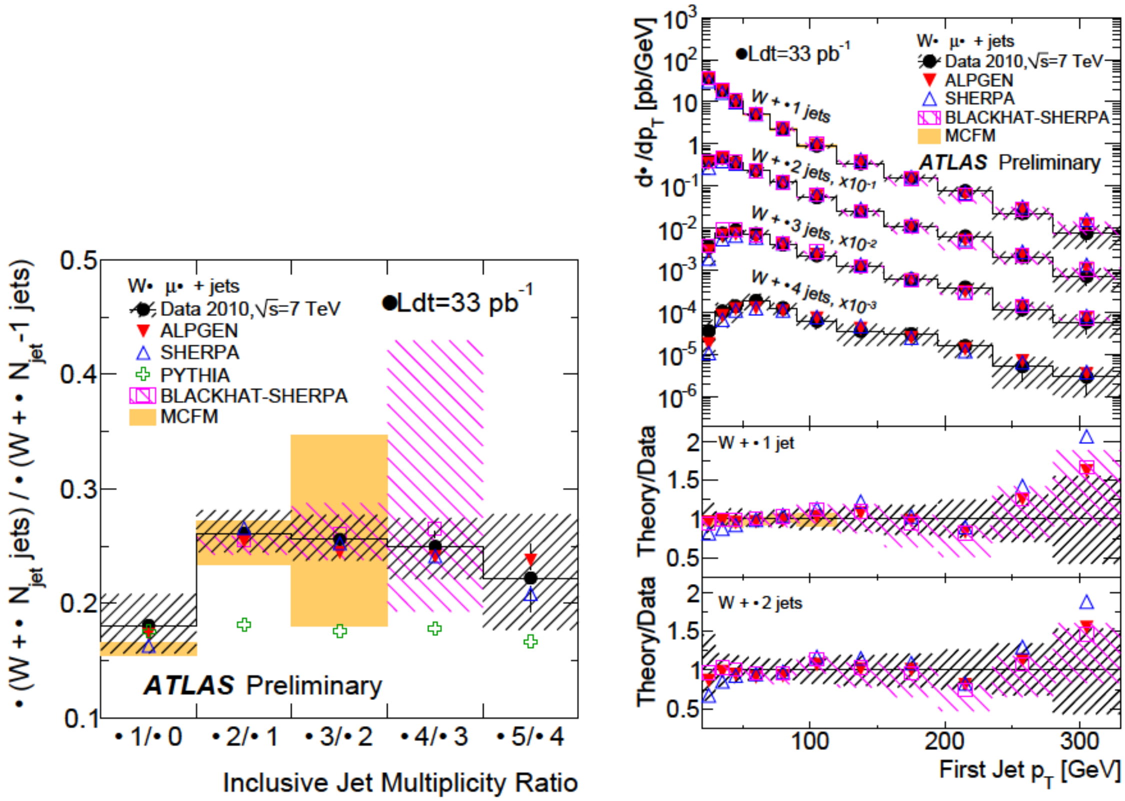

FIG. 6: The production of jets in association with W bosons as measured by ATLAS. The left figure gives the W+jet cross section ratio as a function of corrected jet multiplicity for the muon channel. Data are plotted as points, and predictions from ALPGEN, SHERPA, PYTHIA, MCFM, and BLACKHAT-SHERPA are superimposed as symbols. Theoretical uncertainties are shown only for MCFM and BLACKHAT-SHERPA. The right figure gives the W+jet cross section from ATLAS as a function of the p_T of the first jet in the event for the muon channel. The p_T of the first jet is shown separately for events with ≥ 1 jet to ≥ 4 jets.

data.

Finally, an example event display of a $Z \to e^+e^- + b-$jet candidate recorded by CMS is shown in Figure 10. The jets have p_T of 121, 62, 42, and 36 GeV, and the leptons have p_T of 119 and 32 GeV. The dilepton invariant mass is 90.3 GeV, the mass of the $b\bar{b}$ system is 192 GeV, and the mass of the $Zb\bar{b}$ system is 400 GeV.

V. CONCLUSION

Experiments at the LHC and Tevatron have performed an exhaustive set of measurements of jet production, of which a small sample are documented here, including inclusive jet, dijets, jets in association with W and Z bosons, and b-jets. These measurements provide extensive probes of perturbative QCD, which to date has passed these tests with flying colours.

Acknowledgments

The author would like to thank the people from ATLAS, CMS, CDF, and D0 who have made these measurements possible, and the organizers of the Physics in Collision Symposium.

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[1] Cacciarai, Salam, Soyez, JHEP 0804:063 (2008); Dokshitzer, Leder, Morretti, Webber JHEP 08:01 (1997); Wobisch, Wengler, hep-ph/9907280; Catani et al, Phys. Lett. N269 (1991); Nucl. Phys. B406 (1993); Ellis, Soper, Phys. Rev. D. 48 (1993).

[2] ATLAS Collaboration, Measurement of inclusive jet and dijet cross sections in proton-proton collision data at 7 TeV centre-of-mass energy using the ATLAS detector, ATLAS-CONF-2011-047 (2011).

[3] CMS Collaboration, Measurement of the Inclusive Jet

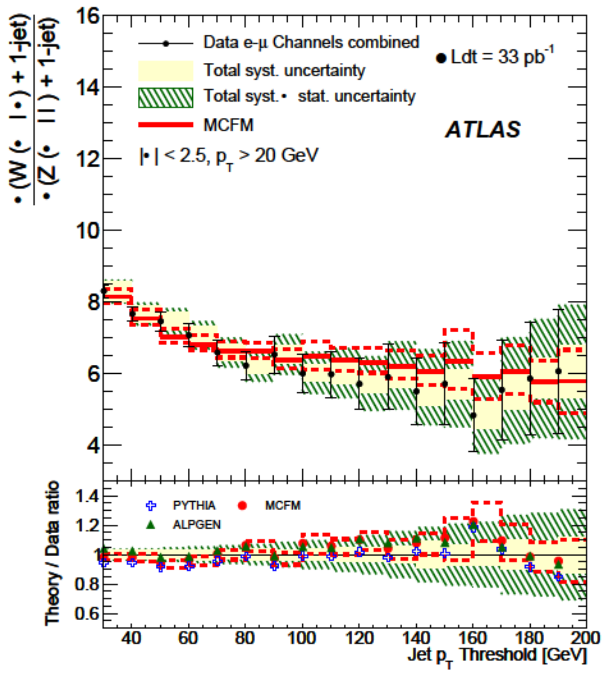

FIG. 7: The ratio of cross sections measured by ATLAS for events with one jet and a W boson in the final state, compared to those with one jet and a Z boson in the final state, as a function of the jet p_T threshold. Data are shown with black error bars indicating the statistical uncertainties. The yellow band shows all systematic uncertainties added in quadrature and the green bank shows statistical and systematic uncertainties added in quadrature. The theory uncertainty (dashed line) includes contributions from PDF and renormalisation and factorisation scales.

Cross Section in pp Collisions at sqrt(s) = 7 TeV, Phys. Rev. Lett 107 (2011) 132001.

[4] CMS Collaboration, Measurement of the differential dijet production cross section in proton-proton collisions at sqrt(s)= 7 TeV, Phys. Lett. B 700 (2011) 187-206.

[5] ATLAS Collaboration, https://twiki.cern.ch/twiki/bin/view/ AtlasPublic/EventDisplayPublicResults.

[6] C.F. Berger *etal*, Phys. Rev. Lett. 106, 092001 (2011).

[7] CMS Collaboration, Rates of Jets Produced in association with W and Z Bosons, CMS PAS EWK-10-012 (2011).

[8] ATLAS Collaboration, Measurement of the production cross section for W-bosons in association with jets in *pp* collisions using 33 pb^{-1} of data at sqrt(s) = 7 TeV with the ATLAS detector, ATLAS-CONF-2011-060.

[9] ATLAS Collaboration, A measurement of the ratio of the W and Z cross sections with exactly one associated jet in *pp* collisions at sqrt(s)= 7 TeV with ATLAS, arXiv:1108:4908.

[10] CDF Collaboration, First measurement of the b-jet cross section in events with a W boson in $p\bar{p}$ collisions at sqrt(s)=1.96 TeV, Phys. Rev. Lett. 104 (2010) 131801.

[11] ATLAS Collaboration, Measurement of the cross-section for the production of a W boson in association with b-jets in *pp* collisions at sqrt(s)=7 TeV with the ATLAS detector, arXiv:1109.1470.

[12] ATLAS Collaboration, Measurement of the cross-section for b-jets in association with a Z boson at sqrt(s)=7 TeV with the ATLAS detector, arXiv:1109.1403; CMS Collaboration, Jet Production Rates in Association with W and Z bosons in *pp* Collisions at sqrt(s)=7 TeV, arXiv:1110.3226; CDF Collaboration, Measurement of the b jet Production Cross Section for events with a Z boson with 7.8 fb^{-1} of data, CDF note 10594 (July 18, 2011); D0 Collaboration, A Measurement of the ratio of inclusive cross sections $(p\bar{p} \to Z + b\,\mathrm{jet})/(p\bar{p} \to Z + \mathrm{jet})$ at $\sqrt{s} = 1.96$ TeV, Phys. Rev. D 83:031105 (2011).

[13] CMS Collaboration, https://twiki.cern.ch/twiki/bin/view/ CMSPublic/PhysicsResults.

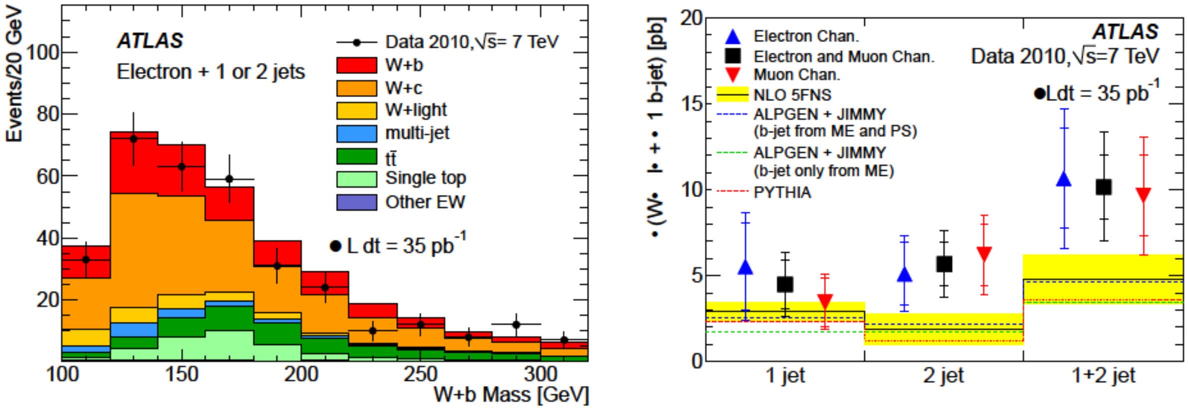

FIG. 8: Production of W bosons in association with a b-jet measured by ATLAS. The left figure gives the invariant mass of the $W + b$-jet system in the electron channel. The right plot gives the measured fiducial cross section in the 1, 2, and 1+2 exclusive bins. The measurements are compared with NLO predictions; the yellow band represents the total uncertainty on the prediction. LO predictions from ALPGEN+HERWIG+JIMMY and PYTHIA are given as well.

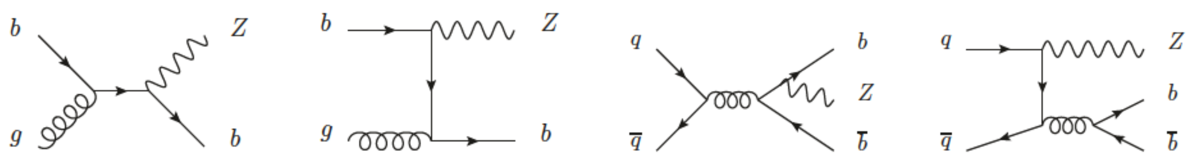

FIG. 9: Main diagrams for associated production at the LHC of a Z boson and one or more b-jets.

TABLE I: Measured ratios of Z plus b-jets versus overall Z production, compared to theoretical predictions (MCFM).

Collaboration	Ratio	Data	MCFM
ATLAS	$\sigma(Z+b)/\sigma(Z)$	$(7.6 \pm 0.18 \pm 0.15) \times 10^{-3}$	$(8.81 \pm 1.1) \times 10^{-3}$
CMS	$\sigma(Z+b)/\sigma(Z+j)$	$5.4 \pm 0.16\%$	$4.3 \pm 0.16\%$
CDF	$\sigma(Z+b)/\sigma(Z+j)$	$2.24 \pm 0.16 \pm 0.27\%$	2.2%
D0	$\sigma(Z+b)/\sigma(Z+j)$	$1.93 \pm 0.22 \pm 0.15\%$	$1.92 \pm 0.22\%$

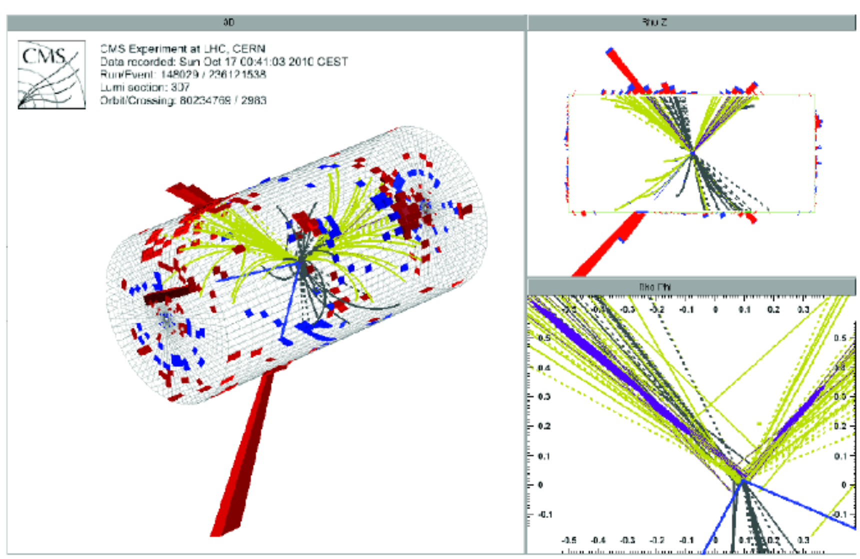

FIG. 10: An event display of a $Z \to e^+e^- + b$−jet candidate recorded by CMS. The bottom right view shows the 2 b-tagged jets as dark enlongated ovals.