W+jets, Z+jets, multijets and new physics searches

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W+jets, Z+jets and QCD multijet production processes at hadron colliders are backgrounds to many searches for physics beyond the Standard Model which involve leptons and missing energy in the final state. We review the current theoretical and experimental status of these processes at the LHC. Furthermore, we discuss several methods that allow for reliable predictions for these processes in the context of new-physics searches.

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1. W/Z+jets and QCD multijet production at hadron colliders

At hadron colliders we rely on the appearance of leptons, photons or missing transverse energy as phenomenological probes of spontaneously broken electroweak sectors with the addition of a viable dark matter candidate [1]. Searches for new (renormalizable) interactions at the LHC face two immediate implications from the phenomenological success of the electroweak Standard Model (SM): New physics spectra (not including the Higgs) are either heavy compared to the weak scale $\mathcal{O}(100\text{ GeV})$ and/or they are weakly coupled. To constrain, rule out, or even verify any realistic scenario of physics beyond the SM we therefore have to overcome the phenomenology-dominating SM backgrounds such as W+jets, Z+jets or QCD multijet production. Consequently, lots of effort has been devoted to the detailed investigation of these processes by both the experimental and the theoretical communities.

Over the past couple of years there has been remarkable progress in various aspects of W/Z+jets and QCD multijet production phenomenology, ranging from improved perturbative precision all the way to first measurements with early LHC data. The latter results allowed both ATLAS and CMS to establish the electroweak SM hypothesis at a new energy frontier by performing Monte Carlo comparisons and Monte Carlo validation [2].

Furthermore, W+jets, Z+jets and multijets, acting as "Standard Model candle processes", have been used by the experimental collaborations for various calibration purposes. Of particular importance to, e.g., searches for supersymmetry [3] are measurements of the jet energy scale uncertainty [4], the calibration of the missing energy reconstruction [5] and the determination of the fake-$\not{E}_T$ distribution by detector effects [6]. The performance of one of the most versatile tools to suppress Standard Model backgrounds in Higgs searches, namely the central jet veto [7], has only recently been studied at the LHC in QCD multijet final states [9].

A quantitative knowledge of the impact of QCD corrections on both the signal and background phenomenology is crucial to connect current and future LHC results with theoretical predictions. At hadron colliders such as the LHC, higher order corrections from QCD tend to be large as a consequence of a sizable amount of initial state radiation. While early contributions to the field

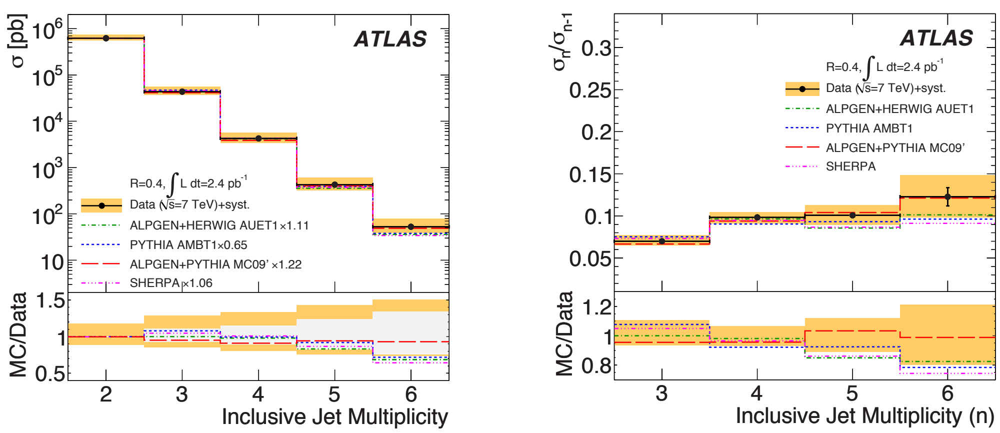

Figure 1: Inclusive QCD multijet production measured by ATLAS (figures taken from Ref. [8]). The impact of the jet multiplicity-correlated pile-up can shift the higher n_{jets} bins above the MC-expected values.

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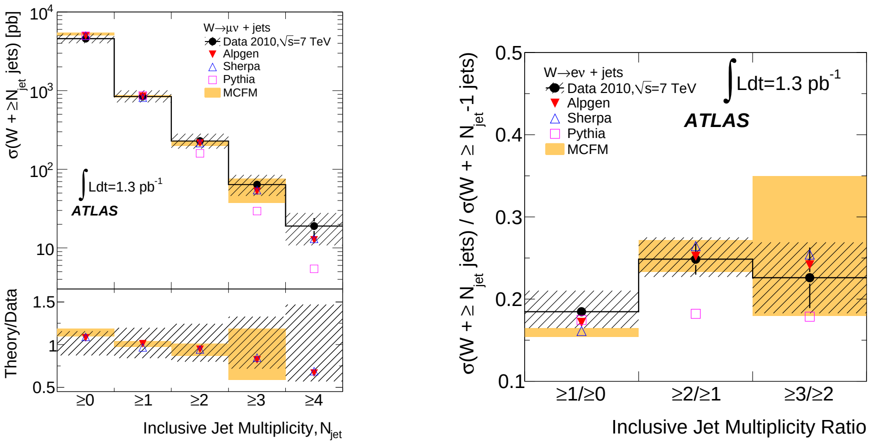

Figure 2: Inclusive W+jets production measured by ATLAS (figures taken from Ref. [2]).

of precise predictions to W/Z+jets and QCD multijet production using Feynman graph-based approaches date back almost twenty years [10], recent developments in next-to-leading order (NLO) computations involving generalized unitarity methods allowed the computation of the inclusive production of W/Z in association with up to four jets [11]. Matching these fixed order predictions with parton showers in various approaches is currently a very active field of research [12]. Due to large contributions from initial state radiation, matching also provides a good approximation if limited to the tree level [13] approximation with the overall normalization obtained from data and/or higher order Monte Carlos.

Progress in multiloop computations has lead to even higher (next-to-next-to-leading order) precision for selected $2 \to 2$ scattering amplitudes, see, e.g., Ref. [14].

2. W/Z+jets and QCD multijet production and new physics searches

The multijet, multilepton, and missing energy signatures of W/Z+jets and QCD multijets processes are typical signatures that arise in beyond the SM scenarios with strong interactions and a dark matter candidate. Disregarding spin correlations etc., the bulk of such models can be mapped onto the minimal supersymmetric Standard Model on a phenomenological level. This very popular and well-motivated extension of the SM was also one of the first new physics models[1] to be constrained by the LHC experiments using the jets plus missing energy channel [3] (for a recent update see Ref. [16]).

While these first results are based on very inclusive cuts and counting experiments with very small statistics, following the ATLAS and CMS [17] documentations we expect more specific analyses to appear soon. The reason is that in their current form the analyses can and should be optimized for specific new physics mass spectra.

2.1 Model-independent searches in the jets plus missing energy channel

Quite generically, theories of strong interactions which pose a solution to the WIMP miracle can be pictured as in Fig. 3: Producing pairs of massive new colored states results in a sizable

[1] We note that dominant QCD corrections to SUSY production processes have become available in a fully automated fashion with the MADGOLEM package only recently [15].

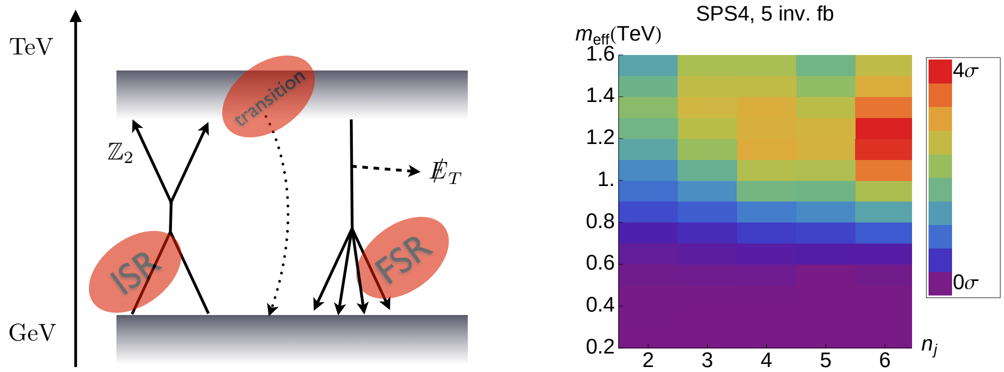

Figure 3: Left panel: sketch of a typical strongly interacting massive new physics spectrum including a dark matter candidate (protected by a $\mathbb{Z}_2$) symmetry. Right panel: Example of the Likelihood map based on $(n_{\rm jets}, m_{\rm eff})$ of SPS4 [19] for a luminosity of $\mathscr{L} = 5\ {\rm fb}^{-1}$ and $\sqrt{s} = 7$ TeV. For details see text.

amount of initial and final state radiation (ISR/FSR) and a number of hard decay jets. Depending on the details of the spectrum there might also be resolvable transition radiation (for a model-independent phenomenological classification approach see Ref. [18]).

Given that the number of jets distribution of hard jets from QCD and W/Z+jets shows a so-called staircase behavior (Figs. 1, 2), i.e. the ratios of inclusive multiplicities within theoretical and experimental uncertainties is constant

$$\text{const} = R = \frac{\sigma_{n+1}}{\sigma_n} \equiv R_{(n+1)/n} \tag{2.1}$$

for the first couple of bins[2] before phase space suppression causes departure, we can turn the specific radiation pattern motivated by Fig. 3 into an inclusive search strategy [19] in the jets plus missing energy channel. For W+jets production [11] it has been shown that the QCD corrections stabilize the staircase scaling Eq. (2.1). Most notably, the scaling property of Eq. (2.1) implies the identical behavior for the *exclusive* number of jets via the geometrical series. This not only opens up the possibility to straightforwardly benefit from the merits of QCD corrections in an exclusive final state notion, but also allows to consistently reduce the uncertainties of any other jet inclusive observable in a data-driven approach. Thereby measuring low multiplicity bins can be used to constrain the higher ones.

Furthermore, we can utilize the departure from the exclusive staircase scaling to gain information on a measured resonance's color charge and mass [19, 20]. As an example we show in Fig. (3) the result of such an analysis of the SPS4 benchmark point for an integrated luminosity of 5 fb^{-1} at the LHC with 7 TeV center-of-mass energy. SPS4 has an "inverted" mass hierarchy $m_{\tilde{q}} \sim 750$ GeV $> m_{\tilde{g}} \sim 730$ GeV and long decay chains for gluinos through bottom squarks appear in the high $n_{\rm jets}$ bins only. The sensitivity that is computed from the departure of the exclusive number of jets in a log-likelihood ratio approach is augmented by a mass scale of the process, which contains orthogonal information on the new physics mass scale. The precise definition of the additionally introduced mass scale to the binned log-likelihood depends on the phenomenological question we would like to address. To close in on the mass scale of the SUSY particles we choose the effective mass $m_{\rm eff} = \not{E}_T + \sum_{\rm all\ jets} p_{T,j}$, where the number of jets is again to be understood as an exclusive quantity.

[2] Note that the 3/2 $n_{\rm jet}$ bin ratio (the 2/1 ratio in case of W/Z+jets) is notorious because of the definition of the underlying hard process [19], e.g. jet cuts are trivially fulfilled for a two (one) jet final state.

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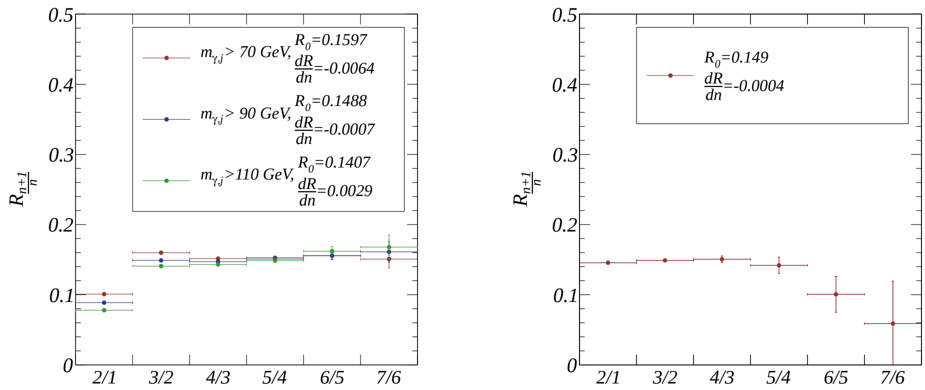

Figure 4: Staircase scaling in γ+jets (left panel) in comparison to Z+jets production (right panel), taken from Ref. [21]. The center of mass energy is $\sqrt{s} = 7$ TeV.

The described procedure automatically reveals phase space regions that are inconsistent with the background-only hypothesis. Since the analysis is as inclusive as possible, sculpting of either the signal or the background distribution is avoided to large extent and the inclusive corrections from QCD can be trusted.

2.2 Predicting Z+jets backgrounds to new physics searches

Another important role is played by Z+jets in searches for supersymmetry, because, with the Z decaying to two neutrinos, it gives rise to an irreducible background. A strategy which is typically pursued by the experiments is to extract this background from a measurement of photon+jets by establishing a phenomenological translation of γ+jets production into Z+jets [3]. The knowledge of QCD corrections and theoretical uncertainties is indispensable to judge on the validity and quality of such an extrapolation. This issue has been elaborated on recently in Refs. [22, 23].

Another question, which is reasonable to ask in the light of the previous section, is how we can relate a potentially observed staircase scaling pattern in photon+jets production to Z+jets. This question has been addressed in Ref. [21]. Due do the massless photon and its special role in jet fragmentation, observing staircase scaling in γ+jets production is non-trivial due to collinear enhanced phase space regions. Once these are separated off by invoking a cut on, e.g., the invariant jet-photon mass $m_{j\gamma} \gtrsim m_Z$, photon+jets production exhibits the staircase pattern in the exclusive number of jets, which perfectly relates to Z+jets. In Fig. 4 we show the exclusive jet multiplicities along with the central values of a fit

$$R^{(staircase)}_{(n+1)/n} = R_0 + \frac{dR}{dn} n. \tag{2.2}$$

The size of the error bars corresponds to the limited Monte Carlo statistics of 10^8 CKKW-matched events, generated with SHERPA [24]. This opens up an until now unconsidered observable to further constrain ($Z \to$ invisible)+jets by measuring γ+jets at the LHC.

2.3 Veto probabilities in Higgs searches

A recent application for jet scaling is central jet veto (CJV) survival probabilities in searches for the Higgs boson [25]. In weak boson fusion (WBF), requiring hard ($m_{j_1 j_2} > 600\,\text{GeV}$), widely

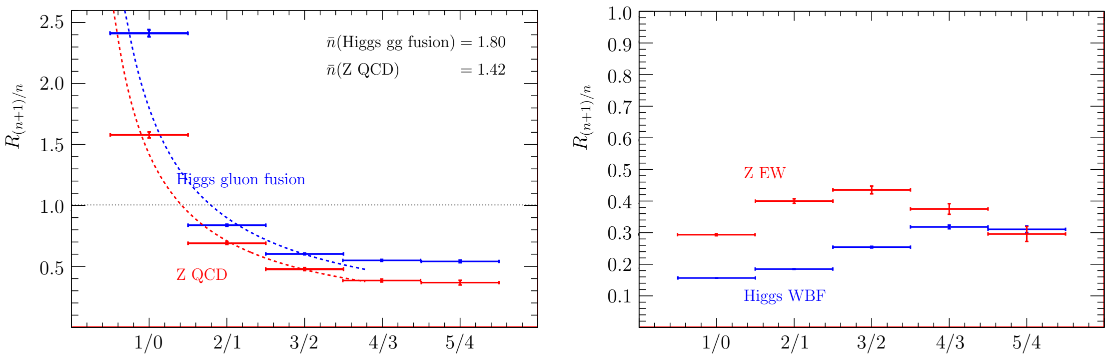

Figure 5: Exclusive gap jet ratios after WBF cuts: (left) Higgs gluon fusion (blue) and Z+jets (Z QCD) at $\mathscr{O}(\alpha_s^2 \alpha_{EW})$ (red) and (right) WBF (blue) and Z-jets at $\mathscr{O}(\alpha_{EW}^3)$ (red). For the left-hand plots the parameter $\bar{n}$ is extracted from the ratio-fit. Both figures are taken from Ref. [25].

separated ($\Delta\eta_{j_1 j_2} > 4.4$) and opposite hemisphere ($\eta_{j_1} \cdot \eta_{j_2} < 0$) tagging jets greatly improves signal efficiency [26]. Reduced additional central QCD radiation compared with the dominant Z+jets background provides a further distinguishing feature. A CJV is therefore imposed on events displaying gap jets with $p_\perp > 20$ GeV [27]. The crucial question is how WBF cuts affect staircase scaling and thus the extrapolation of the CJV to higher jet multiplicities. For this purpose a second distinct pattern can be introduced, *Poisson* scaling, typically associated with soft-collinear exponentiation. Here the exclusive n-jet cross-section σ_n and ratio $R^{(Poisson)}_{(n+1)/n}$ are defined in terms of the inclusive rate $\hat{\sigma}_0$ and the expected number of jets $\bar{n}$ as

$$\sigma_n = \hat{\sigma}_0 \, \frac{e^{-\bar{n}} \bar{n}^n}{n!} \qquad R^{(Poisson)}_{(n+1)/n} = \frac{\bar{n}}{n+1} \,. \tag{2.3}$$

Before imposing WBF cuts, both signal and background processes display staircase scaling as expected. After cuts, Poisson scaling is realized in non-color-singlet exchange (see Fig. 5), notably Z+jets at $\mathscr{O}(\alpha_s^2 \alpha_{EW})$ and Higgs production via gluon fusion. In contrast, Poisson scaling is never produced for color-singlet mediated processes such as Higgs production in WBF and Z+jets at $\mathscr{O}(\alpha_{EW}^3)$.

References

[1] for a review of beyond the SM phenomenology see, e.g., D. E. Morrissey, T. Plehn, T. M. P. Tait, [arXiv:0912.3259 [hep-ph]].

[2] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **698** (2011) 325; S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **107** (2011) 021802.

[3] CMS Collaboration, arXiv:1101.1628 [hep-ex].

[4] see, e.g., The Atlas collaboration ATL-PHYS-PUB-2009-000; The CMS collaboration CMS-PAS-JME-09-005.

[5] The Atlas collaboration, ATLAS-CONF-2010-057; The CMS collaboration, CMS-JME-10-009.

[6] The Atlas collaboration, ATLAS-CONF-2010-065, ATLAS-CONF-2010-084; The CMS collaboration, CMS-PAS-JME-10-004, CMS-PAS-QCD-10-011.

[7] V. D. Barger, R. J. N. Phillips, D. Zeppenfeld, Phys. Lett. **B346**, 106-114 (1995).

[8] Atlas Collaboration, [arXiv:1107.2092 [hep-ex]].

[9] G. Aad *et al.*, arXiv:1107.1641 [hep-ex].

[10] W. T. Giele, E. W. N. Glover, D. A. Kosower, Nucl. Phys. **B403** (1993) 633-670; J. M. Campbell, R. K. Ellis, Phys. Rev. **D65** (2002) 113007; S. D. Ellis, Z. Kunszt, D. E. Soper, Phys. Rev. Lett. **69** (1992) 1496; S. Frixione, Z. Kunszt, A. Signer, Nucl. Phys. **B467** (1996) 399; Z. Nagy, Phys. Rev. Lett. **88** (2002) 122003; Z. Nagy, Phys. Rev. **D68** (2003) 094002.

[11] C. F. Berger *et al.*, Phys. Rev. Lett. **102** (2009) 222001, Phys. Rev. D **80**, 074036 (2009), Phys. Rev. D **82**, 074002 (2010), Phys. Rev. Lett. **106**, 092001 (2011); H. Ita, Z. Bern, L. J. Dixon, F. F. Cordero, D. A. Kosower and D. Maitre, arXiv:1108.2229 [hep-ph]. R. K. Ellis, W. T. Giele, Z. Kunszt, K. Melnikov and G. Zanderighi, JHEP **0901**, 012 (2009); R. K. Ellis, K. Melnikov and G. Zanderighi, Phys. Rev. D **80**, 094002 (2009).

[12] S. Frixione, F. Stoeckli, P. Torrielli and B. R. Webber, JHEP **1101**, 053 (2011); S. Alioli, P. Nason, C. Oleari and E. Re, JHEP **1006**, 043 (2010); S. Hoche, F. Krauss, M. Schonherr and F. Siegert, JHEP **1108**, 123 (2011).

[13] S. Catani, F. Krauss, R. Kuhn *et al.*, JHEP **0111** (2001) 063; F. Krauss, JHEP **0208** (2002) 015; M. L. Mangano, M. Moretti and R. Pittau, Nucl. Phys. B **632** (2002) 343.

[14] C. Anastasiou, E. W. N. Glover, C. Oleari, M. E. Tejeda-Yeomans, Nucl. Phys. **B605** (2001) 486-516; C. Anastasiou, L. J. Dixon, K. Melnikov, F. Petriello, Phys. Rev. **D69** (2004) 094008; Z. Bern, A. De Freitas, L. J. Dixon, JHEP **0306** (2003) 028.

[15] T. Binoth, D. Goncalves Netto, D. Lopez-Val, K. Mawatari, T. Plehn and I. Wigmore, arXiv:1108.1250 [hep-ph].

[16] G. L. Bayatian *et al.* [CMS Collaboration], arXiv:1109.2352 [hep-ex].

[17] G. Aad *et al.*, JINST **3** (2008) S08003; G. L. Bayatian *et al.*, J. Phys. G **34** (2007) 995.

[18] D. Alves *et al.*, arXiv:1105.2838 [hep-ph].

[19] C. Englert, T. Plehn, P. Schichtel, S. Schumann, Phys. Rev. **D83**, 095009 (2011).

[20] T. Plehn and T. M. P. Tait, J. Phys. G **36** (2009) 075001;

[21] C. Englert, T. Plehn, P. Schichtel and S. Schumann, arXiv:1108.5473 [hep-ph].

[22] Z. Bern *et al.*, arXiv:1106.1423 [hep-ph].

[23] S. Ask, M. A. Parker, T. Sandoval, M. E. Shea and W. J. Stirling, arXiv:1107.2803 [hep-ph].

[24] T. Gleisberg, S. Hoeche, F. Krauss, M. Schonherr, S. Schumann, F. Siegert and J. Winter, JHEP **0902** (2009) 007; S. Schumann, F. Krauss, JHEP **0803** (2008) 038; S. Hoeche, F. Krauss, S. Schumann, F. Siegert, JHEP **0905** (2009) 053.

[25] E. Gerwick, T. Plehn and S. Schumann, arXiv:1108.3335 [hep-ph].

[26] D. L. Rainwater, D. Zeppenfeld and K. Hagiwara, Phys. Rev. D **59**, 014037 (1999); T. Plehn, D. L. Rainwater and D. Zeppenfeld, Phys. Rev. D **61**, 093005 (2000).

[27] U. Baur, E. W. N. Glover, Phys. Lett. **B252**, 683-689 (1990). V. D. Barger, K. Cheung, T. Han, D. Zeppenfeld, Phys. Rev. **D44**, 2701 (1991); V. D. Barger, R. J. N. Phillips, D. Zeppenfeld, Phys. Lett. **B346**, 106-114 (1995); D. L. Rainwater, R. Szalapski, D. Zeppenfeld, Phys. Rev. **D54**, 6680-6689 (1996); B. E. Cox, J. R. Forshaw and A. D. Pilkington, Phys. Lett. B **696** (2011) 87; S. Ask, J. H. Collins, J. R. Forshaw, K. Joshi and A. D. Pilkington, arXiv:1108.2396 [hep-ph].

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