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Jet physics at CMS

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Summary. — Measurements of the high momentum jet production in proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$ and $8\,\text{TeV}$ with the CMS experiment at the LHC are summarized. The CMS experimental program in this domain is, on the one hand, oriented toward the observables which may help to constrain the QCD parameters: strong coupling constant and evolution and proton PDF. On the other hand, a large effort is dedicated to the understanding of the conditions under which the soft gluon radiation plays an important role in the LHC physics. Different MC parton showering models are studied and measurements are provided to improve them.

PACS 13.87.-a – Jets in large-Q^2 scattering.
PACS 12.38.-t – Chromodynamics, quantum.

1. – Introduction

During the last data taking campaign from 2010 to 2012 the CMS detector collected a large data sample in the proton-proton collisions provided by the LHC at the centre of mass of $\sqrt{s} = 7\,\text{TeV}$ and $\sqrt{s} = 8\,\text{TeV}$. Those data was used to explore the quantum chromodynamics (QCD) properties at different momentum scales and kinematic regimes. In this report we would concentrate on the production of the jets with the a large transverse momentum ($p_T > 30$–$50\,\text{GeV}$). The physics program of the previous generation of colliders (ee like LEP, ep like HERA or $p\bar{p}$ like Tevatron) have shown that in this regime the next-to-leading-order (NLO) QCD calculations, supplemented with non-perturbative corrections and the factorisation theorem, are usually able to describe the production cross sections. The effect of the soft gluon emissions was usually observed to be sub-leading with respect to the NLO (or NNLO) corrections, provided that the observables under consideration was infrared and collinear safe.

After a brief presentation of the experimental aspects of the jet reconstruction in CMS we would consider the two major aspects of the QCD program at CMS. First we would present the inclusive jet observables and study the conditions under which the classical fixed order approach performs well. Then we would concentrate on the multi-jet production with multiples scales and large rapidity gaps between the hard jets where the soft gluon effects are expected to be important.

2. – Jet reconstruction

The description of the CMS detector can be found elsewhere [1]. From the point of view of the jet reconstruction the main features of the CMS apparatus are: a fully silicon based tracker immersed into an uniform magnetic field of 4 T along the z-direction. It allows to measure a charged particle momentum with a high precision from $O(0.5\,\mathrm{GeV})$ up to $O(0.5\,\mathrm{TeV})$ in the region in pseudorapidity $\eta < 2.5$. The PbW0 electromagnetic calorimeter shows an excellent performance in measuring the energy of electromagnetic particles for the energy range going from $O(1\,\mathrm{GeV})$ and up to $O(1\,\mathrm{TeV})$. It is complemented with the brass/scintillator hadronic calorimeter up to $\eta < 3$. The region $3.3 < |\eta| < 5.0$ is covered by an iron/quartz-fiber hadron forward calorimeter. Finally one shall notice that in general the response of the calorimetry to the hadrons exhibits significant non-linearities.

The Particle Flow technique [2] (PF) optimise the performances of this setup. The charged hadrons, electrons and muons are reconstructed by combining the tracks (tracker and muon chambers) with the calibrated calorimetric clusters. The photons are built from the remaining electromagnetic clusters. Finally remaining hadronic clusters are considered as neutral hadrons. In summary 90% of the energy of a jet, which is carried by the charged hadrons and photons, is reconstructed by linear and precise components of the CMS detector, while only 10% carried by the neutral hadrons fully rely on the ECAL/HCAL combination.

The different particles candidates identified by the PF algorithm are fed into the jet reconstruction algorithm as implemented in the FASTJET package [3]. The anti-k_T clustering algorithm [4] is used by the CMS Collaboration with two possible values of the radius parameter $R = 0.5$ and $R = 0.7$, denoted henceforth $AK5$ and $AK7$. To suppress non-physical jets, *i.e.* jets resulting from noise in the ECAL and/or HCAL calorimeters, identification criteria based on the PF candidates content was applied.

The difference between the measured momentum of the jet and the true momentum at the particle level was estimated by the simulation. It appears to be of the order of 5–10% slowly vanishing with the jet momentum [5]. The transverse momentum of the reconstructed jet is corrected in average for the detection effects and as for the extra energy clustered into jets from additional proton-proton interactions within the same or neighbouring bunch crossings (in-time and out-of-time pileup) [5]. The uncertainty (called JES), associated to the calibration procedure is typically of the order of 1–3% depending on the data-taking period and jet kinematics [5]. This is usually the dominating source of the uncertainty on the jet measurements.

In addition to the average transverse momentum correction all the measured cross sections provided by the CMS experiment are unfolded for the detector resolution effects. They can be therefore directly compared to the prediction at the particles level.

The CMS detector records events using a two-level trigger system consisting of a hardware-based level-1 (L1) trigger and a software-based high-level trigger (HLT). All the QCD analyses uses online reconstructed jets to select their events. The most widely used class of jet trigger is the *single jet trigger* requesting at least one jet with online p_T above a threshold ranging from 30 GeV up to 370 GeV. The triggers was progressively prescaled together with the rise of the instantaneous luminosity provided by the LHC.

3. – Inclusive production of high p_T jets

The measurement of the inclusive jet and di-jet productions is a bread and butter measurement to validate the QCD predictions in a hadronic collider. At CMS it was

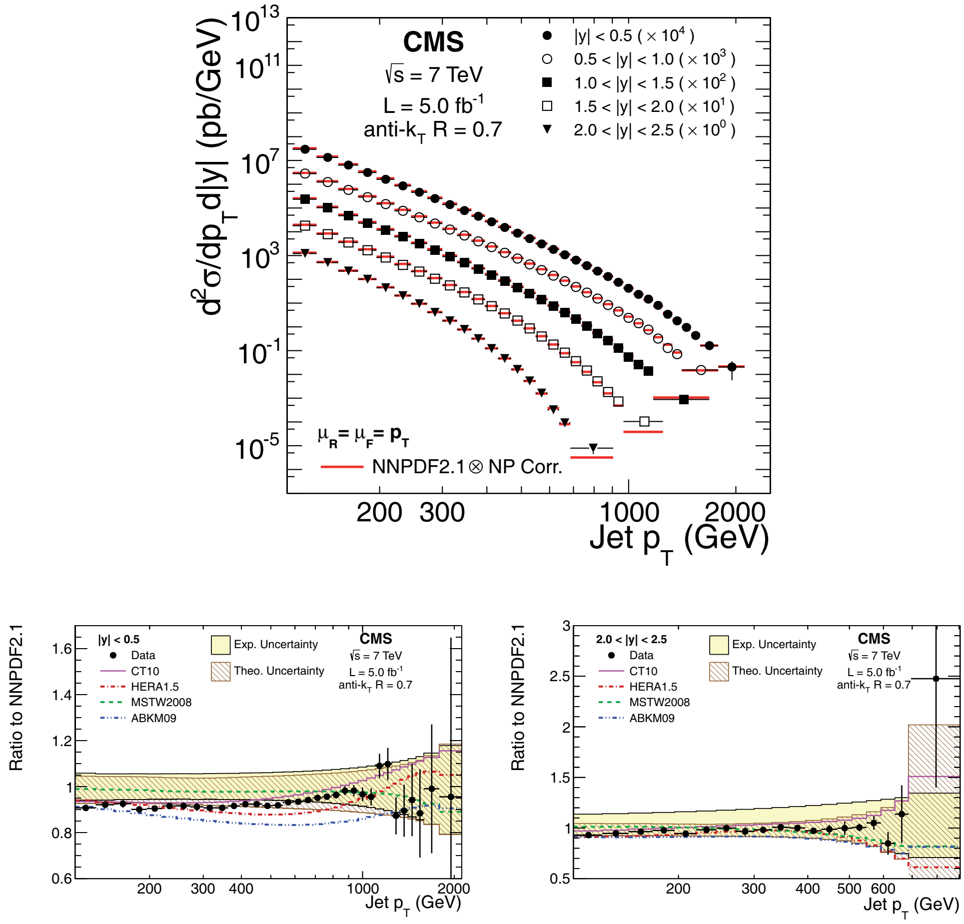

Fig. 1. – Inclusive jets cross sections measured at $\sqrt{s} = 7\,\mathrm{TeV}$ with $R = 0.7$.

performed at $\sqrt{s} = 7\,\mathrm{TeV}$ with two different jet radius parameters AK5 [6,7], and AK7 [8] and at 8 TeV for the inclusive jets cross section with AK7 [9]. This new measurement of the inclusive jets cross section extends up to $p_T = 2\,\mathrm{TeV}$ the reach in transverse momentum. The $\sqrt{s} = 7\,\mathrm{TeV}$ is shown on fig. 1 compared to the NLO+NP predictions with the NNPDF2.1 proton structure function (PDF) [10].

In general the measurements with $R = 0.7$ are fairly well described by the fixed order predictions in all the rapidity regions. The differences are covered on the one hand by the experimental uncertainties dominated by the JES and on the other hand by the theory uncertainties. Those ones are driven by the scale dependence of the NLO predictions, and by the uncertainty on the PDF parametrization. This consideration also applies to the results at 7 TeV: inclusive and dijet cross sections.

Given the good description agreement with the fixed order predictions in that energy regime, the CMS Collaboration exploited the ratio of the 3-jet to 2-jet cross sections at 7 TeV to extract the strong coupling constant

$$\alpha_S(M_Z) = 0.1148 \pm 0.0014(\mathrm{exp.}) \pm 0.0018(\mathrm{PDF}) + 0.0050 - 0.0000(\mathrm{scale}) \tag{1}$$

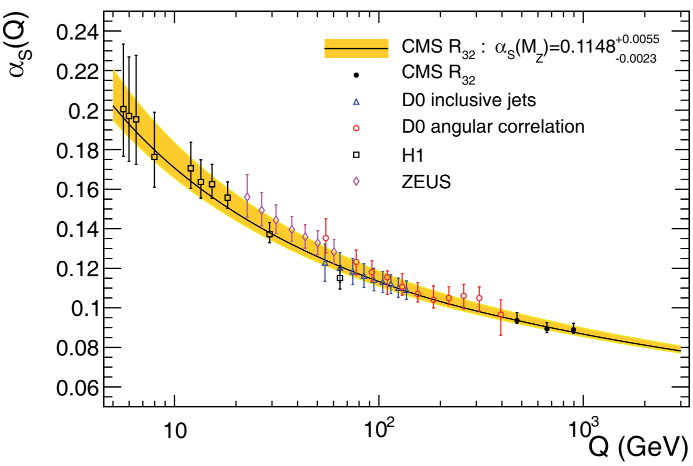

Fig. 2. – The strong coupling running as extracted by different collider experiments including CMS.

and test its running properties at the unprecedented energy scales up to 1 TeV [11] as shown on fig. 2. The experimental precision is very competitive with other experiments. The general picture provided by the colliders experiments is that the predictions of the $SU(3)_c$ renormalization group equation are verified over 3 orders of magnitude in the energy scale.

When the radius parameter is reduced to $R = 0.5$ it is interesting to observe on fig. 3 a tendency of the fixed order predictions to overestimate by one standard deviation the measurements. The effect is growing when going from the central jets production to the forward jets production.

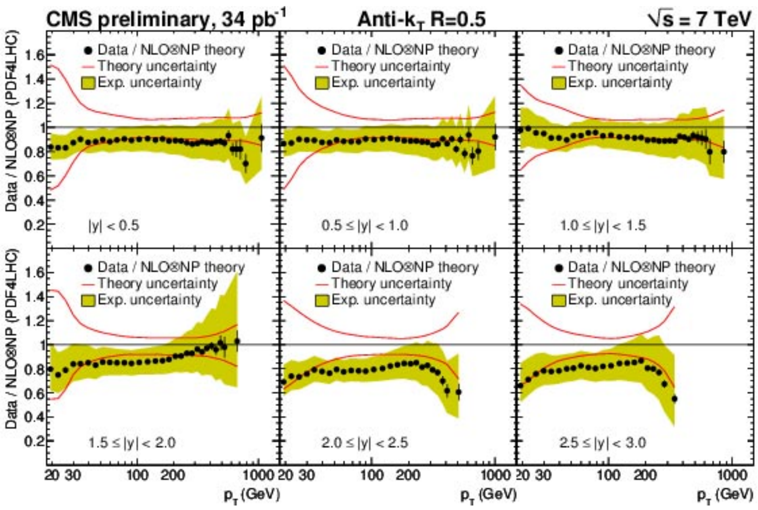

Fig. 3. – Inclusive jets cross sections measured at $\sqrt{s} = 7\,\text{TeV}$ with $R = 0.5$.

Some indication about the nature of this tendency appears when the effects of the parton showers are considered on top of the NLO calculations as implemented for example in the POWHEG events generator [12]. The parton shower corrections K^{PS} are defined as the ratio of the inclusive jet cross section with the parton shower switched on and off [13, 14]. Typically $K^{PS} = 0.8$–0.95 for the AK5 jets and $K^{PS} = 1.0$–1.05 for AK7. The structure of the correction factors appears from an interplay between the final state radiation (FSR) which reduces the NLO cross section at a given p_T and the initial state radiation (ISR). The effect of ISR consist mainly in shifting the longitudinal momentum of the incoming parton accessible for the scattering. This effect is more important in the forward region due to the asymmetry in the parton-parton collision.

The effect of the parton longitudinal momentum shift in the PDFs is also observed in the inclusive b-jet production measured by the CMS Collaboration [15]. It appears that the use of the PS correction factors is necessary on top of the fixed orders calculations to describe the measurements. It is shown in that a use of the transverse momentum dependant PDFs like uPDFs avoid the necessity to use the PS correction [13].

A direct test of the impact of the ISR and FSR components of the PS models was performed in the specific kinematic regions where the contribution of each of them is expected to be enhanced. The impact of the ISR was studied through the azimuthal angular decorrelation in the central di-jet events [16]. The variable of interest $\Delta\phi_{\text{jet1,jet2}} = \pi/2$ for the LO di-jet production. It could reduces typically down to $2\pi/3$ when a third jet is considered. A larger decorrelation corresponds essentially to the presence of a multi-jet emission in the event. The fixed order NLO calculations describes poorly the region of $\Delta\phi_{\text{jet1,jet2}} < 2\pi/3$ as shown on fig. 4. At the same time the LO+PS models such as PYTHIA6 [17] or MADGRAPH [18] performs fairly well. A simple exercise was performed in varying the amount of ISR in PYTHIA by changing the value of the k_{ISR} parameter. The results provided on fig. 4 exhibit clearly the importance of this phenomenon.

The impact of the FSR was studied by looking on the evolution of the collinear emission in the jet cone using the jet shapes variables [19]. The different LO+PS generators was compared to the data measurements of the amount of transverse momentum of the AK7 jet laying outside of the cone with radius $r = 0.3$: $1 - \psi(r = 0.3)$. This variable quantifies the transverse size of the jet. The low momentum jets ($p_T \approx 20\,\text{GeV}$) appears to be quite wide with $1 - \psi(r = 0.3) \approx 45\%$ while when the momentum increases the jet becomes more and more narrow. For example at $p_T \approx 1\,\text{TeV}$ only 5% of the jet energy lie outside of the central cone defined by $r = 0.3$. It appears that the PS model and the soft radiation and underlying event tune plays an important role in the description of the in-cone radiation. Nevertheless all the MC models describe within 20% this small amount of radiation produced outside of the central cone. Therefore they are expected to provide a good description of the FSR effect in the variables such as total jet p_T.

4. – Jet production in the highly asymmetric collisions

The soft radiation effects are expected to show up when the collision is highly asymmetric ($x_1 \to 1$ and $x_2 \to 0$). In that case the angular phase-space available for the ISR is very large. A simple measurement of the very forward inclusive jets cross section in the region between $3.2 < \eta < 4.7$ [20] was performed with first $\sqrt{s} = 7\,\text{TeV}$. It shows a good agreement within the experimental uncertainties between the data and the fixed order NLO calculations or LO+PS MC simulations. Some of them consider alternatives to the DGLAP evolution such as CASCADE MC [21] generator which includes parton radiation from QCD evolution in $1/x$ inspired by the CCFM evolution.

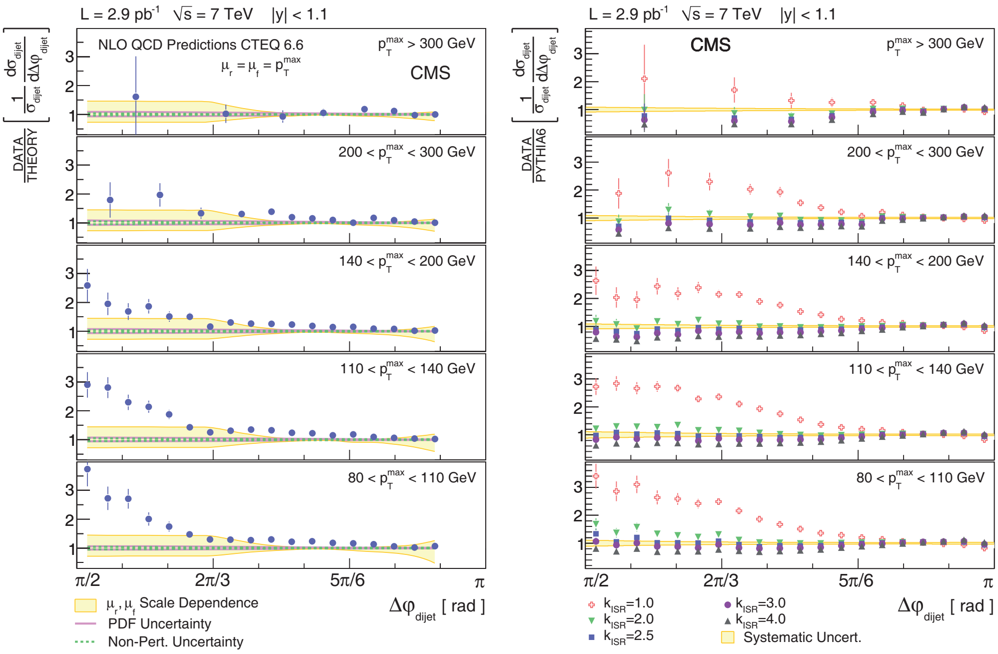

Fig. 4. – Angular decorrelation effects in data compared to the fixed order calculations at NLO (left) and compared to the PYTHIA MC generator with different values of k_{ISR} parameter (right).

An alternative way to open the phase-space to the soft radiation is provided by the so called Mueller-Navelet (MN) di-jet events [22]. The MN jets are defined as the pair of the most forward and backward jets in the event with the rapidity gap $\Delta^{\mathrm{MN}} y = |y_{\mathrm{jet1}} - y_{\mathrm{jet2}}|$. The understanding of the inter-jet radiation in the rapidity gap is fundamental to be able to separate a vector-boson fusion mechanism in the Higgs production (VBF) from the QCD background.

The study of the additional jet production as function of $\Delta^{\mathrm{MN}} y$ was performed by the CMS Collaboration using the $35\,\mathrm{pb}^{-1}$ collected at $\sqrt{s} = 7\,\mathrm{TeV}$ in 2010 [23] and $5\,\mathrm{pb}^{-1}$ collected in 2011 [24]. Those data sample was characterised by the lower PU conditions with respect to the data collected in 2011. This point is important for the physics implying the forward jets lying outside of the tracker reach ($|\eta| > 2.5$).

On fig. 5 (left) the ratio of the number of the inclusive MN dijet events events with $p_T > 35\,\mathrm{GeV}$ to the exclusive one is shown. The study as function of $\Delta^{\mathrm{MN}} y$ shows a slow increase of the inter-jet activity together with the opening of the phase-space. The MC inspired by the DGLAP evolution, as implemented in PYTHIA, limits the rise of the ratio due to the strong k_T ordering of the emission. In contrast the CCFM inspired evolution consider a random walk in k_T and predicts more activity in the inter-jet region. Unexpectingly the results clearly tend to prefer the DGLAP like evolution. This result is confirmed by fig. 5 (right) where the azimuthal decorrelation between the MN jets is shown for $3 < \Delta^{\mathrm{MN}} y < 6$. The CCFM inspired evolution predicts a much larger decorrelation than the DGLAP like models.

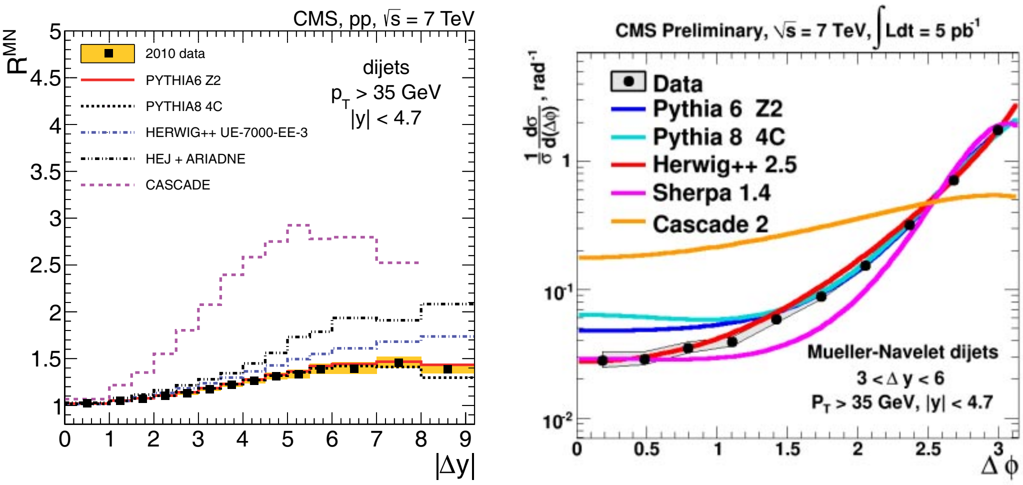

Fig. 5. – The inter-jet activity in the Mueller-Navlet events.

5. – Conclusion

The measurements of the hard jets production by the CMS Collaboration was presented. The inclusive multi-jet production appears to be reasonably well described by the fixed order calculations under the condition that a sufficiently larger radius parameter is used. In general the larger is the jet radius the less the observable appears to be sensitive to the details of the soft radiation. The maximal size is mainly limited by the experimental ability to mitigate the PU effects. Under those conditions the jet observables provides a very powerful tool to measure directly the QCD parameters such as the strong coupling running or the proton PDFs.

A detailed study of the different components of the parton showering models and their ability to describe the data in the sensitive phase-space regions (azimuthal decorrelation, jet shapes, angular coherence etc. . .) was performed by the CMS Collaboration: ISR, FSR, colour coherence. In general the main features are rather well captured by the LO+PS MC generators even if more tuning might be necessary in some cases. In contrary to describe the same observables the fixed order calculations needs soft gluon resummation.

The soft gluon production was considered in the events with a large rapidity gap between the hard jets. It appears that the k_T ordered PS models inspired by the DGLAP evolution predict coherent results with respect to the measurements. In contrary the $1/x$ emission-ordered models inspired by the CCFM evolution predict too much inter-jet activity. Those results are encouraging the use of the DGLAP inspired models to predict the background contamination of the electroweak induced interactions like VBF which are tagged by requesting a rapidity gap between two most outward jets.

REFERENCES

[1] CMS Collaboration, *JINST*, **3** (2008) S08004.
[2] CMS Collaboration, CMS-PAS-PFT-10-001.
[3] Cacciari M. and Salam G. P., *Phys. Lett. B*, **641** (2006) 57 hep-ph/0512210.
[4] Cacciari M., Salam G. P. and Soyez G., *JHEP*, **04** (2008) 063 arXiv:0802.1189 [hep-ph].
[5] Chatrchyan S. *et al.* (CMS Collaboration), *JINST*, **6** (2011) P11002 arXiv:1107.4277 [physics.ins-det].
[6] Chatrchyan S. *et al.* (CMS Collaboration), *Phys. Rev. Lett.*, **107** (2011) 132001 arXiv:1106.0208 [hep-ex].
[7] Chatrchyan S. *et al.* (CMS Collaboration), *Phys. Lett. B*, **700** (2011) 187 arXiv:1104.1693 [hep-ex].
[8] Chatrchyan S. *et al.* (CMS Collaboration), arXiv:1212.6660 [hep-ex].
[9] (CMS Collaboration), CMS-PAS-SMP-12-012.
[10] Ball R. D., Del Debbio L., Forte S., Guffanti A., Latorre J. I., Rojo J. and Ubiali M., *Nucl. Phys. B*, **838** (2010) 136 arXiv:1002.4407 [hep-ph].
[11] Chatrchyan S. *et al.* (CMS Collaboration), arXiv:1304.7498 [hep-ex].
[12] Hoche S., Krauss F., Schonherr M. and Siegert F., *JHEP*, **04** (2011) 024 arXiv:1008.5399 [hep-ph].
[13] Dooling S., Gunnellini P., Hautmann F. and Jung H., arXiv:1212.6164 [hep-ph].
[14] Hautmann F., arXiv:1304.8133 [hep-ph].
[15] Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **04** (2012) 084 arXiv:1202.4617 [hep-ex].
[16] Khachatryan V. *et al.* (CMS Collaboration), *Phys. Rev. Lett.*, **106** (2011) 201804 arXiv:1102.2020 [hep-ex].
[17] Sjostrand T., Mrenna S. and Skands P. Z., *Comput. Phys. Commun.*, **178** (2008) 852 arXiv:0710.3820 [hep-ph]; Sjostrand T., Mrenna S. and Skands P. Z., *JHEP*, **05** (2006) 026 hep-ph/0603175.
[18] Alwall J., Herquet M., Maltoni F., Mattelaer O. and Stelzer T., *JHEP*, **06** (2011) 128 arXiv:1106.0522 [hep-ph].
[19] Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **06** (2012) 160 arXiv:1204.3170 [hep-ex].
[20] Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **06** (2012) 036 arXiv:1202.0704 [hep-ex].
[21] Jung H., Baranov S., Deak M., Grebenyuk A., Hautmann F., Hentschinski M., Knutsson A., Kramer M. *et al.*, *Eur. Phys. J. C*, **70** (2010) 1237 arXiv:1008.0152 [hep-ph].
[22] Mueller A. H. and Navelet H., *Nucl. Phys. B*, **282** (1987) 727.
[23] Chatrchyan S. *et al.* (CMS Collaboration), *Eur. Phys. J. C*, **72** (2012) 2216 arXiv:1204.0696 [hep-ex].
[24] CMS Collaboration, FSQ-12-002.