

Production of prompt photons associated with jets at LHC in k_T -factorization

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Abstract. We use the k_T -factorization approach to calculate total and differential cross sections of associated production of prompt photons and hadronic jets at the LHC energies. Our consideration relies on the PEGASUS Monte-Carlo generator with implemented $\mathcal{O}(\alpha_s^2)$ off-shell gluon-gluon subprocess $g^*g^* \rightarrow \gamma q\bar{q}$ and several subleading quark-initiated contributions from $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$ subprocesses, taken into account in the collinear limit. Using Monte-Carlo generators CASCADE and PYTHIA, we investigate parton showering effects and compare our predictions with the data, taken by CMS and ATLAS collaborations at the LHC. We demonstrate reasonable description of the data and the importance of parton shower effects in the k_T -factorization.

Investigation of prompt¹ photon and associated jet production is an important topic of modern experimental and theoretical research. The reason for such an interest is the fact, that one can directly probe the hard subprocess dynamics, since the produced photons are highly insensitive to final hadronization effects. Also it can provide a test for different parton distributions in proton. Particularly, the associated prompt photon and jet production allows one to study correlation observables and to investigate with them production mechanisms and parton evolution details. Finally, such processes contribute to the background for Standard Model processes, like Higgs production (in diphoton decay mode), and some new physics processes [1, 2].

A useful tool to study high energy physics processes is so-called k_T -factorization approach [3, 4], based on the Balitsky-Fadin-Kuraev-Lipatov (BFKL) [5] or Ciafaloni-Catani-Fiorani-Marchesini (CCFM) [6] gluon evolution equations, which resum large logarithmic terms proportional to $\ln s \sim \ln 1/x$, important at high energies². The k_T -factorization takes into account the parton dynamics more naturally by keeping the transverse momenta k_T of the incoming partons. The cross section in the k_T -factorization is then a convolution of off-shell matrix elements and transverse momentum dependent (TMD), or unintegrated parton distribution functions. One of the main advantages of the k_T -factorization approach is effective taking into account in form of TMD densities a large piece of higher order corrections (namely, part of NLO + NNLO + ... terms corresponding to real gluon emissions in initial

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¹The photons are called prompt, if they originate from the hard partonic subprocess, rather than from secondary decays.

²The CCFM equation also takes into account additional terms proportional to $\ln 1/(1-x)$.

state) even within the leading-order (LO). k_T -factorization has become a widely exploited tool and it is of interest and importance to test it in as many cases as possible³.

The k_T -factorization approach has been successfully applied already to the inclusive prompt photon hadroproduction processes [8–10], as well as to the associated prompt photon and heavy quark jet production [11–13]. The associated prompt photon and non-tagged jet production was studied in [14, 15]. In [14] the photon-jet correlations were investigated at RHIC and Tevatron energies. However, contributions from parton showers in initial states (which are important for jet determination) were not considered in those calculations. A naive model [16] to take into account such effects was applied in [15]. In this model initial state radiation (ISR) jets are believed to carry the transverse momentum, opposite to the momentum of the corresponding initial parton from the hard subprocess. The rapidity of such a jet is taken to be uniformly distributed in some quite broad region. That leads to some difficulties in simultaneous description of transverse momentum, rapidity and azimuthal angle difference distributions.

In the present paper we make an attempt to improve the results of [15] with taking into account parton shower effects. Using newly developed Monte-Carlo generator PEGASUS [17] with the CASCADE [18] program, we calculate total and differential cross-sections and compare our results with data, taken by CMS and ATLAS collaborators at the LHC [19–21].

Let us briefly describe the calculation steps. The leading contribution to the γ + jet production in our consideration comes from the off-shell gluon fusion subprocess:

$$g^*(k_1) + g^*(k_2) \rightarrow \gamma(p) + q(p_1) + \bar{q}(p_2). \quad (1)$$

The corresponding gauge-invariant off-shell amplitude was calculated earlier [11, 22] and it is included into the CASCADE program [18] and newly developed parton-level Monte-Carlo event generator PEGASUS[17]. The calculation procedure for the off-shell matrix element involves a special gluon polarization sum rule:

$$\sum \epsilon^\mu \epsilon^{*\nu} = \frac{k_T^\mu k_T^\nu}{\mathbf{k}_T^2}, \quad (2)$$

where ϵ is the gluon polarization vector, and k_T — its non-zero transverse momentum. In all other respects the calculation is the same as in the case of on-shell gluons.

We also take into account a number of quark-initiated processes, namely:

$$q_v(k_1) + g(k_2) \rightarrow \gamma(p) + q(p_1), \quad (3)$$

$$q(k_1) + \bar{q}(k_2) \rightarrow \gamma(p) + g(p_1), \quad (4)$$

$$q(k_1) + q'(k_2) \rightarrow \gamma(p) + q(p_1) + q'(p_2), \quad (5)$$

$$q(k_1) + \bar{q}(k_2) \rightarrow \gamma(p) + q'(p_1) + \bar{q}'(p_2). \quad (6)$$

In (3) the initial quark is valence, since the contribution from the sea is already included in the k_T -factorization by subprocess (1). As it was shown in [23], despite the fact, that quark densities are typically much lower than the gluon density at the LHC conditions, these processes may become important at very large transverse momenta (or, respectively, at large parton longitudinal momentum fraction x , which is needed to produce large p_T events) where the quarks are less suppressed or can even dominate over the gluon density. Here we find it reasonable to rely upon collinear factorization scheme, which provides better theoretical grounds in the large- x region. So, we consider a combination of two techniques with each of them being

³More details about the k_T -factorization formalism can be found, for example, in review [7].

Table 1. Basic parameters, used for simulations.

	CMS [19]	ATLAS [20]	ATLAS [21]
E_T^γ , GeV	> 40	> 45	> 25
p_T^{jet} , GeV	> 30	> 40	> 20
$ \eta^\gamma $	< 2.5	< 2.37 (excl. $1.37 < \eta^\gamma < 1.52$)	< 1.37
$ \eta^{\text{jet}} $	< 2.5	< 2.37	< 4.4
E_T^{max} , GeV	5	3	3
$\Delta R^{\gamma\text{-jet}}$	0.5	1.0	1.0
R_{jet}	0.5	0.6	0.4

used at the kinematic conditions where it is best suitable (gluon induced subprocess (1) at small x and quark-induced subprocesses (3) — (6) at large x values).

Then, to calculate the contribution of subprocess (1) to the studied cross sections, we use the k_T -factorization formula:

$$\sigma = \int dx_1 dx_2 d\mathbf{k}_{1T}^2 d\mathbf{k}_{2T}^2 d\hat{\sigma}_{gg}^*(x_1, x_2, \mathbf{k}_{1T}^2, \mathbf{k}_{2T}^2, \mu^2) f_g(x_1, \mathbf{k}_{1T}^2, \mu^2) f_g(x_2, \mathbf{k}_{2T}^2, \mu^2), \quad (7)$$

where x_1 and x_2 are the longitudinal momentum fractions of the initial gluons, \mathbf{k}_{1T}^2 and \mathbf{k}_{2T}^2 are their transverse momenta, and $f_g(x, \mathbf{k}_T^2, \mu^2)$ is the TMD gluon distribution in a proton. A comprehensive collection of the latter can be found in the TMDlib package [24]. In the present work we use JH'2013 gluon densities [25]. The input parameters of the initial gluon distribution were fitted from the best description of the precision DIS data on the inclusive $F_2(x, Q^2)$ and $F_2^c(x, Q^2)$ data. To calculate the quark-induced contributions (3) — (6) we used standard collinear QCD factorization formula and adopt MSTW2008 (LO) parton distributions [26]. Numerical calculations at the parton level in the k_T -factorization approach and collinear QCD factorization were performed using the Monte-Carlo event generator PEGASUS [17].

The jets can be formed from both final partons produced in the hard subprocesses (1)—(6) and the partons originating from the ISR. In order to reconstruct the ISR, we implement the CASCADE Monte-Carlo generator [18] for the off-shell gluonic subprocess (1). Technically, we produce a Les Houches Event (LHE) file [27] in our parton level calculations and then process the file with CASCADE. Concerning the collinear subprocesses (3)—(6), we prefer to apply the latest version of PYTHIA package [28] to them. The jets are reconstructed with the anti- k_T algorithm, implemented in the FastJet tool [29]. From these hadronic jets we choose the one, carrying the largest transverse momentum and satisfying the experimental cuts, and then we compute the cross-section of γ +jet production.

In the numerical calculations we applied the same photon isolation cuts as used in the experimental procedure. The photon is required to be isolated based on the amount of hadronic transverse energy $E_T^{\text{had}} \leq E_T^{\text{max}}$ deposited in a cone of size $\Delta R = \sqrt{(\eta^{\text{had}} - \eta^\gamma)^2 + (\phi^{\text{had}} - \phi^\gamma)^2}$ around the photon. To get rid of collinear divergences we strictly follow the approach, proposed in in [9].

Before showing the results, let us briefly describe essential parameters of our calculations. We use one-loop strong running constant in collinear case and two-loop one in the k_T -factorization. We keep $n_f = 4$ massless quark flavours and take $\Lambda_{QCD} = 200$ MeV. The fine structure constant is fixed as $\alpha = 1/137$. The anti- k_T algorithm radius R_{jet} , the separation $\Delta R^{\gamma\text{-jet}}$ and cuts were taken the same, as in experimental analyses, and they are collected in Table 1. We concentrate on the data, taken at $\sqrt{S} = 7$ TeV, since they were measured at relatively low p_T , so they probe the region of low x , in which we are specially interested.

Now let us present the results of our simulations [30]. They are shown on Figs. 1—4. The results, including the effects of both initial and final state radiation, are shown with uncertainties, connected with the scale variations, and depicted as green bands. To estimate the theoretical uncertainties in the quark-involving subprocesses (3)—(6), calculated using the collinear QCD approach, we varied the scales $\mu_R = \mu_F$ by a factor of 2 around their default value, that was taken to be equal to the prompt photon transverse energy, E_T^γ . In the k_T -factorization, the scale uncertainties were estimated by using the auxiliary gluon densities JH'2013 set + and JH'2013 set - instead of default density JH'2013. These two sets refer to the varied hard scales in the strong coupling constant α_S in the off-shell amplitude: JH'2013 set + stands for $2\mu_R$, while JH'2013 set - refers to $\mu_R/2$. The factorization scale in k_T -factorization calculation was taken as $\mu_F^2 = \hat{s} + \mathbf{Q}_T^2$, that is dictated by the CCFM evolution algorithm. We also show the results, obtained only with initial state parton showers (dashed lines). The histograms, obtained with the 'naive approach' to produce jets, where no parton showers are taken into account [16] are also presented. We also show separately the contribution of subprocess (1), calculated with the k_T -factorization. Note, that cross sections as functions of $\cos\theta = \tanh \frac{y^\gamma - y^{\text{jet}}}{2}$ and the invariant mass $m^{\gamma\text{jet}}$ were measured by ATLAS at additional limitations on phase space: $\cos\theta < 0.83$, $m^{\gamma\text{jet}} > 161$ GeV and $|y^\gamma + y^{\text{jet}}| < 2.37$ (Fig. 4).

The results show in general good agreement with the data of the ATLAS and CMS collaborations for both JH2013 set 1 and 2. Some disagreement can be found, however, for intermediate transverse momenta in some regions in rapidity. The $\cos\theta$ and $m^{\gamma\text{jet}}$ distributions clearly favor JH2013 set 1 results. The reason for that could be the additional limitation of the phase space in those measurement, that moves the region to larger x , where the two sets behave differently. One can easily see, that the subprocess (1) dominates at small transverse momenta and does not contribute at larger values. Another observation is that the final state radiation effects are quite negligible in the most of the distributions, excluding only the region of very small $\Delta\phi$. Concerning the results, obtained within the 'naive' approach [16], the achieved overall description of the considered experimental data is systematically worse, both in normalization and shape. Although the simple approach is able to describe more or less adequately the measured E_T^γ distributions in some kinematical region (as it is shown in Fig. 2), it fails for more exclusive observables, such as $\Delta\phi^{\gamma\text{-jet}}$ variable (see Fig. 3). Thus, it indicates again the importance of taking into account contributions from initial state parton showers for the proper determination of the leading jet in the k_T -factorization approach.

In conclusion, we have considered the associated production of prompt photon and hadronic jets. The investigation is performed in so-called 'combined' scheme, taking k_T -factorization approach, being effective at small x , supplemented with a number of collinear approach contributions, allowing to describe the data also at larger x . We take into account parton shower effects, using CASCADE for k_T -factorization subprocess and PYTHIA for collinear subprocesses. The obtained results give generally good description of the data, taken by ATLAS and CMS collaborations at $\sqrt{S} = 7$ TeV, and show the importance of parton showers effects. This extends the k_T -factorization framework to a new class of processes.

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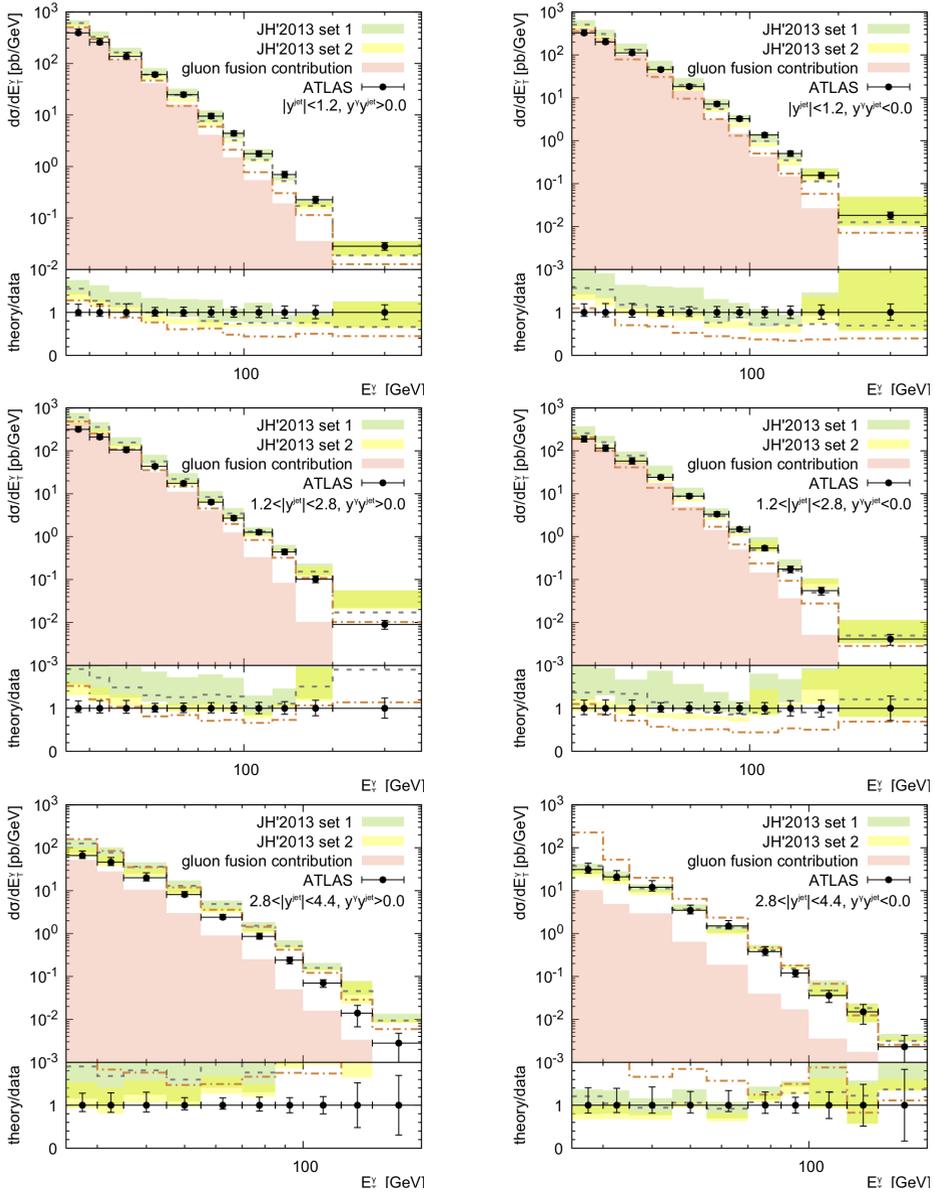


Figure 1. The differential cross sections of associated $\gamma + \text{jet}$ production at $\sqrt{s} = 7$ TeV as function of the prompt photon transverse energy E_T^γ in different regions of rapidities. The green and yellow shaded band represent the results obtained with JH'2013 set 1 and set 2 gluon densities (with scale uncertainties). Dashed histograms corresponds to the predictions without final-state parton showers, dash-dotted histograms correspond to the results, obtained with simple approach[16]. Separately shown contribution from the off-shell gluon-gluon fusion subprocess (1). Everywhere the JH'2013 set 1 gluon density was used. The experimental data are from ATLAS[21].

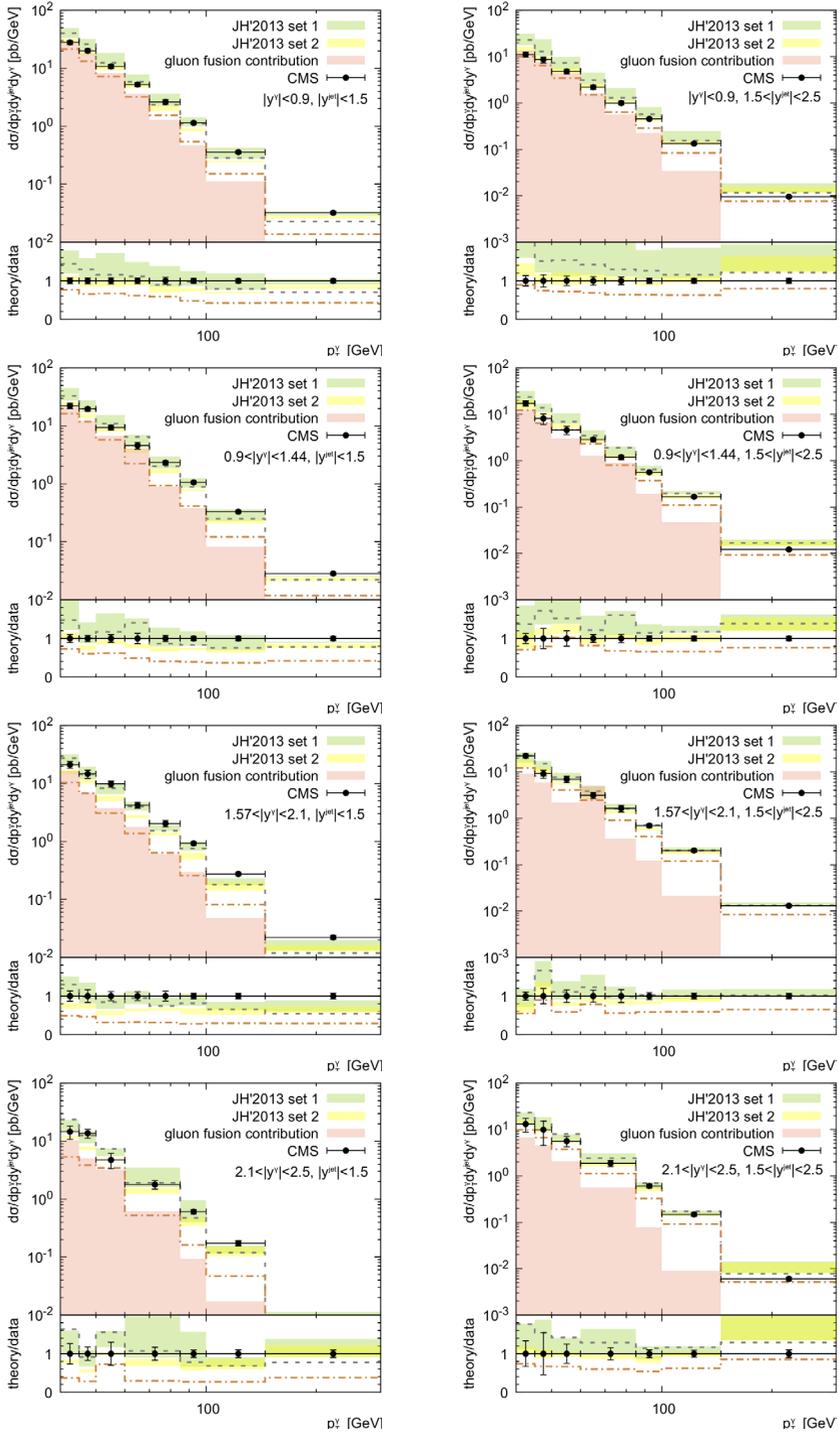


Figure 2. The triple-differential cross sections of associated γ + jet production at $\sqrt{s} = 7$ TeV as function of the photon transverse energy in different regions of rapidities. Notation of histograms is the same as in Fig. 1. The experimental data are from CMS[19].

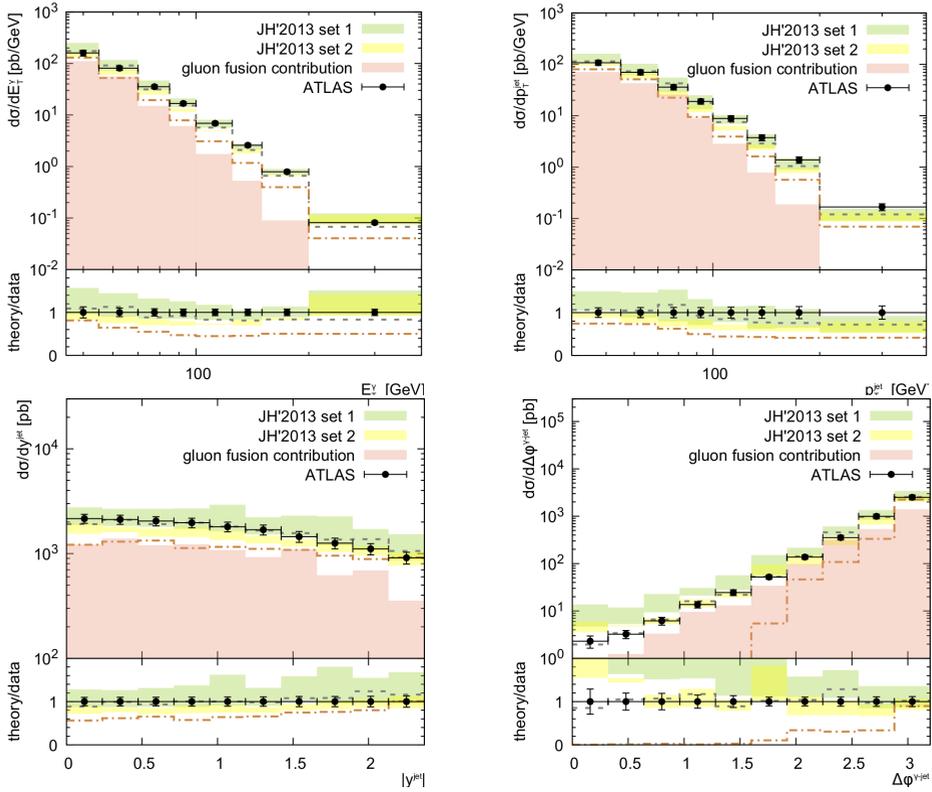


Figure 3. The differential cross sections of associated prompt photon and jet production at $\sqrt{s} = 7$ TeV as functions of photon transverse energy E_T^γ , jet transverse momentum p_T^{jet} , jet rapidity y^{jet} and azimuthal angle difference between the prompt photon and the leading jet $\Delta\phi$. Notation of histograms is the same as in Fig. 1. The experimental data are from ATLAS[20].

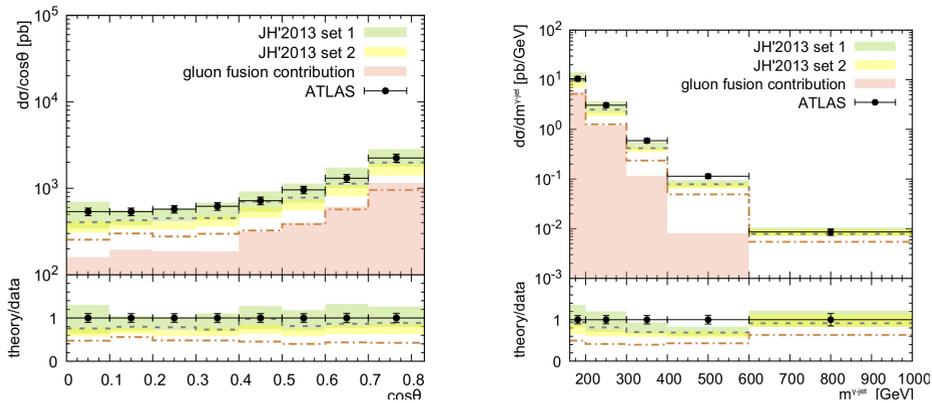


Figure 4. The differential cross sections of associated prompt photon and jet production at $\sqrt{s} = 7$ TeV as function of scattering angle $\cos\theta$ and the invariant mass of the prompt photon and the leading jet. Additional cuts $\cos\theta < 0.83$, $m^{\gamma\text{-jet}} > 161$ GeV and $|y^\gamma + y^{\text{jet}}| < 2.37$ are applied. Notation of histograms is the same as in Fig. 1. The experimental data are from ATLAS[20].