Resummation effects in the forward production of Z_{0}+jet at the LHC

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Resummation effects in forward production of Z_0+jet at LHC

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Abstract

We calculate several differential cross sections for Z_0 and high-p_T jet production in the forward rapidity region at the LHC using the hybrid High Energy Factorization. We test various unintegrated gluon distributions involving subleading BFKL effects (such as kinematic constraint, running strong coupling and DGLAP correction) and compare the results with experimental data obtained by the LHCb experiment. We find that the hard scale dependence of unintegrated gluon distributions, which effectively resums the Sudakov-type logarithms on the top of the resummation of the small x logarithms, is essential to describe the normalized azimuthal decorrelations between the Z_0-boson and the jet.

1 Motivation

The Large Hadron Collider opens an opportunity to explore kinematic regions where particles produced in high-energy collisions posses large transverse momenta and rapidities. The production of electroweak bosons and jets is a vital part of tests of Standard Model as well as searches of physics beyond the Standard Model. Furthermore it has been recognized in [1] that by studies of associated production of electroweak bosons and jets may provide a new insight into the transverse partonic structure of hadrons at small x, where x is the momentum fraction of the hadron taken by a parton participating in the hard collision. Furthermore, such a final state, being a combination of colorful and colorless particles, gives the opportunity for particularly interesting investigations complementary to results obtained in studies of pure jet final states [2–6] and Drell-Yan pairs [7]. In particular the final state rescatterings due to soft color exchanges should have less impact on the properties of produced final state as compared to pure jet final states.

This work is motivated by a recent LHCb measurement [8] at $\sqrt{s} = 7\,\mathrm{TeV}$ of the process

$$pp \to Z_0 \left(\to \mu^+\mu^-\right) + \mathrm{jet} \tag{1}$$

in the forward direction within the pseudorapidity range $2.0 < \eta < 4.5$. The final-state muon and anti-muon were required to have transverse momenta $p_{T\mu} > 20\,\mathrm{GeV}$ while the leading jet was considered with two different cuts: $p_{T\,j} > 10\,\mathrm{GeV}$ and $p_{T\,j} > 20\,\mathrm{GeV}$. The jets were reconstructed using the anti-k_T algorithm with radius $R = 0.5$ and they were required to be separated from muon tracks on the $\phi - \eta$ plane (azimuthal angle-pesudorapidity) by a distance $R = 0.4$. The muon-pair was required to have an invariant mass within the range $60\,\mathrm{GeV} < \mathrm{M}_{\mu\mu} < 120\,\mathrm{GeV}$. The rapidity constraint assures that in the partonic picture of the process, one of the initial state partons carries a rather small fraction x_A of the corresponding hadron momentum p_A, while the other must have a fraction $x_B \gg x_A$ (c.f. Fig. 1).

In order to describe the process perturbatively, one definitely needs to go beyond the pure collinear factorization and support the calculation by a resummations. In the modern advanced approaches this is achieved by parton showers and hadronization as implemented for example in Pythia [9]. In the present work we consider another approach, namely a resummation of logarithms of $\ln(1/x_A)$ and $\ln(\mu/k_T)$, where μ is a hard scale and k_T is a certain additional scale given by the imbalance of the final states on the transverse plane. This approach captures certain aspects of the process more accurately already at lowest order of the strong coupling constant in the hard process.

In the present paper, we will therefore attempt to study the process within so called High Energy Factorization, or more precisely, using so-called hybrid High Energy Factorization motivated by the works [10–13]. Within the asymmetric kinematic situation $x_B \gg x_A$ described above, the cross section for the process under consideration can be expressed by the following formula

$$d\sigma_{AB\to\mu^+\mu^-+\mathrm{jet}+X} = \int d^2k_{TA} \int \frac{dx_A}{x_A} \int dx_B \sum_b \times \mathcal{F}_{g^*/A}\left(x_A, k_{T\,A}, \mu\right)\, f_b\left(x_B, \mu\right)\, d\hat{\sigma}_{g^*q_b\to q_b\mu^+\mu^-}\left(x_A, x_B, k_{T\,A}, \mu\right), \quad (2)$$

where $\mathcal{F}_{g^*/A}$ is the unintegrated gluon distribution for hadron A, f_b is a collinear PDF and $d\hat{\sigma}_{g^*q_b\to q_b\mu^+\mu^-}$ is the hard cross section obtained from a gauge invariant tree-level off-shell amplitude for the process $g^*q_b \to q_b\mu^+\mu^-$, and where q_b refers to quarks as well as anti-quarks (Fig. 1).

Let us note, that the original High Energy Factorization prescription was designed to study inclusive small x processes and the corresponding unintegrated gluon distribution was assumed to undergo the Balitski-Fadin-Kuraev-Lipatov (BFKL) evolution equation (see e.g. [14]). For more exclusive processes it is however necessary to include the subleading BFKL effects, such as kinematic constraint ensuring energy conservation, large-x correction, running strong coupling constant, and – notably – the hard scale dependence. The last, denoted in Eq. (2) as μ, turns out to be essential to describe the data under consideration. In the present work we shall not discuss the validity of the model (2) on the theoretical level. Instead, we shall test it phenomenologically against the existing data. For a more detailed review of various approaches to the small x factorization and related issues see e.g. [15]. For a derivation of hybrid High Energy Factorization from the dilute limit of the Color Glass Condensate approach see [16].

2 Results

Using the formalism described in the preceding section we have computed the cross sections for $Z_0 + \mathrm{jet}$ production. We have used two programs to calculate off-shell $qg^* \to q\mu^+\mu^-$ amplitude (with Z_0 and γ exchange) and to cross-check the results. The first program is A Very Handy

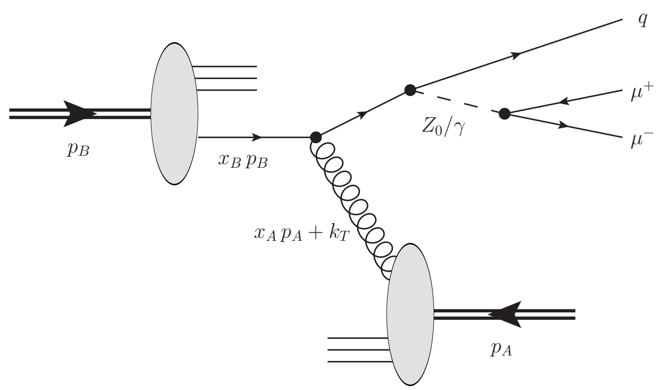

Figure 1: Diagrammatic representation of the hybrid high energy factorization for forward Z_0+jet production. The upper blob corresponds to a collinear PDF, whereas the lower one corresponds to the unintegrated gluon distribution. The gluon entering the hard scattering is off-shell with virtuality k_T^2.

LIBrary (AVHLIB) [17] in Fortran, in which the approach of [18] is implemented. It computes amplitudes entirely numerically and includes a full Monte Carlo program. The second is the electroweak extension of the program OGIME [19]. It calculates amplitudes analytically in a form that can be interfaced with a Monte Carlo program. More specifically, the analytic expressions were implemented in the C++ code LxJet [20]. Note, however, that since there are no final state gluons, the ordinary Feynman diagram depicted in Fig. 1 (with appropriate high energy projector for the off-shell gluon as described in [10]) is enough to obtain the gauge invariant amplitude for this process, and all the complications discussed in [18, 21–24] do not have any impact here.

For the numerical computation we use the kinematic cuts as described in the previous section, i.e. the ones used in [8]. We use standard values for the electroweak parameters: electroweak coupling $g_{\rm ew} = 0.308$, Z_0 boson mass $M_Z = 91.2\,\text{GeV}$ and width $\Gamma_Z = 2.495\,\text{GeV}$. We work with the 5 flavour scheme and use the CTEQ10NLO set [25] for the collinear PDFs. For the unintegrated gluon distributions we consider the following models (in brackets with bold font we give our abbreviations for the models):

- BFKL evolution with kinematic constraint, running strong coupling constant, DGLAP effects including the contribution from the quark sea [26] and supplemented with the nonlinear term [27]; the initial condition has been fitted to HERA data [28] (`KS`)
- hard scale dependent `KS`; the hard scale dependence is achieved by implementing the Sudakov form factor on the generated events in such a way that the total cross section remains unchanged [5] (`KS+Sudakov`)
- similar to above, but the Sudakov form factor is implemented to the `KS`density in such a way that the integrated gluon density remains unchanged [29] (`Kutak-nonlinear-PRD15`)
- the simplified Kimber-Martin-Ryskin model [30] applied to MRSTW08 PDFs; this model gives unintegrated gluon distribution that is hard scale dependent (`KMR`)
- BFKL evolution with kinematic constraint, running strong coupling constant and the DGLAP contribution coming only from gluons and fitted to the LHC jet data [15] (`LHC-fit`)

unintegrated gluon distribution model	$p_{T\,j} > 10\,\mathrm{GeV}$	$p_{T\,j} > 20\,\mathrm{GeV}$
`KS`	$4.1^{+1.0}_{-0.7}$ pb	$2.3^{+0.6}_{-0.4}$ pb
`Kutak-nonlinear-PRD15`	$4.1^{+1.0}_{-1.0}$ pb	$2.4^{+0.6}_{-0.5}$ pb
`KMR`	$5.8^{+1.5}_{-1.3}$ pb	$3.3^{+0.9}_{-0.6}$ pb
`LHC-fit`	$3.4^{+0.8}_{-0.6}$ pb	$2.0^{+0.5}_{-0.4}$ pb
LHCb data	16.0 ± 1.4 pb	6.3 ± 0.5 pb

Table 1: Total cross sections obtained from different models for the unintegrated gluon density. The model uncertainties are defined through variations of the hard scale. For the data the total uncertainty is estimated as an average square error from statistical, systematic and luminosity errors as given in [8]. We do not include models `KS+Sudakov` and `LHC-fit+Sudakov` as the Sudakov-type resummation applied there does not change the total cross section.

- hard scale dependent LHC fit (`LHC-fit+Sudakov`)

The hard scale was chosen to be the average of the three large scales appearing in the problem: the mass of the Z_0 boson, its p_T and the p_T of the jet. We present the results for numerical simulations in Figs. 2-10 and compare them with LHCb data. Figs. 2,3 present normalized azimuthal decorrelations for $p_{Tj} > 10\,\mathrm{GeV}$ and $p_{Tj} > 20\,\mathrm{GeV}$ respectively (the azimuthal decorrelation is defined as the differential cross section in the difference of azimuthal angles of the reconstructed Z_0 boson and the leading jet). We present also results for normalized differential cross sections in the transverse momentum p_{TZ} of Z_0 boson (Figs. 4,5), in rapidity y_Z of Z_0 (Figs. 6,7), in the transverse momentum p_{Tj} of the jet (Fig. 10), and – finally– in the rapidity separation between the Z_0-boson and the jet Δy (Figs. 8,9). The shaded boxes in Figs. 2-10 represent the theoretical uncertainty obtained by varying the hard scale by a factor of two. The differential cross sections are normalized to the total cross section, as in [8]. We list the total cross sections for different models in Table 1.

3 Discussion and conclusions

Let us first discuss the normalized differential cross sections. We can conclude that the azimuthal decorrelations are described reasonably well for both jet p_T cuts for most of the models. It was however essential for this observable to include the hard scale dependence in unintegrated gluon distributions. As this observable is the most sensitive one for the small x effects this underlines the importance of the resummation of the logarithms $\ln(\mu/k_T)$, where μ is the hard scale provided by the hard process and k_T is the transverse momentum of the gluon in unintegrated gluon distributions, on the top of the small x logarithms. The effect of this Sudakov-type resummation was also important for the transverse momentum spectrum of Z_0 boson. For the other observables it has had much less impact.

Since our calculations are not interfaced with any sort of final state parton shower we expected rather rough description of transverse momenta spectra. Our actual study shows however that the situation is relatively good for the spectrum of Z_0 boson (except very low transverse momentum), Figs. 4-5, and indeed fails for the jet spectrum, Fig. 10. This can be attributed to the fact that all unintegrated gluon distributions we have used contain contribution from pieces of splitting functions subleading at low x (see [15] for an analysis of the impact of this correction on jet p_T spectra). This correction seems to be enough for the colorless final state while the color rescattering for the final state jet is evidently missing. Also, the next-to-leading correction in the hard process is necessary to improve the description of the transverse momentum spectra. The LHC-jet-motivated unintegrated gluon densities, which were actually fitted to the LHC jet transverse momentum spectra behave similar to the other gluon densities. This gives one more clue that the improvement in the hard process in terms of higher order corrections or/and a resummation is necessary.

For $p_{Tj} > 20\,\mathrm{GeV}$ the `Kutak-nonlinear-PRD15` and the `KMR` models overestimate the normalized transverse momentum spectrum of the Z_0 boson. These models implement a hard scale dependence but the spectra they give are almost the same as from the `KS`model, which is hard-scale-independent (the difference is however in the uncertainty which is much bigger for the hard-scale-dependent models). This means that the Sudakov-type resummation in the former models has no effect for this observable with such large p_T cut. On the contrary, the Sudakov-type resummation with unitarity constraint (in the sense of preserving the total cross section) applied to the `KS` or `LHC-fit` improves the results.

Interestingly, the unintegrated gluon distribution which comes from the fit to the LHC jet data does not perform better that the distributions obtained from the inclusive DIS data. This suggests that the effects of factorization breaking due to the lack of universality is rather weak at the phenomenological level. As already mentioned above, this suggests also that one needs higher order corrections in the hard process. Indeed, as observed in [15] the p_T spectra cannot be described by improving the evolution of unintegrated gluon distribution itself. One should mention, that the evolution equations that were fitted to the LHC data did not include a contribution from the sea quarks on the dense hadron side, whereas this contribution is present in the other approaches. It is however unlikely that this can improve the situation.

Present calculations did not take into account the situation where the off-shell initial-state parton is a quark or an anti-quark. We expect this contribution to be small, as at small x gluons dominate significantly. On the other hand, the process $\bar{q}q \to Z_0\,(\to \mu^+\mu^-) + g$ gives an important contribution in the collinear approach. Since in reality the probed values of x are not extremely small, such process might be important in the High Energy Factorization. Practical applications require however a set of unintegrated quark distributions, consistent with the unintegrated gluon distributions. Inclusion of those is left for future studies.

As seen from the Table 1 our calculations strongly underestimate the total cross section as compared to the data. This should be probably attributed to the hard multi-parton interaction (MPI) effects which are not taken into account in the Hybrid High Energy Factorization. This statement is supported by the observation that the description of the azimuthal decorrelations is very good up to the normalization, which, when corrected, will only shift the data eventually forming a "pedestal". It is also known that MPIs indeed contribute only a pedestal to the azimuthal decorrelations (see e.g. [31, 32]), as the two partons coming from independent scatterings are completely decorrelated (to leading order) and thus the azimuthal decorrelation distribution is flat. The subject of MPIs in the High Energy Factorization is however rather complicated and needs a separate study. In principle, on the dense hadron side (i.e. for the one probed at small x), the soft MPIs can be partially taken into account by means of the nonlinear term in the evolution equation, as for example in the `KS` unintegrated gluon density or its extensions. Therefore, one has to be careful not to make a double counting when using some phenomenological models by an inclusion of double hard scattering mechanism. Actually the problem extends beyond the saturation regime as the High Energy Factorization contributes to higher twists as well as MPIs, at least for certain observables [33]. These subjects are however beyond the scope of the present work.

Acknowledgments

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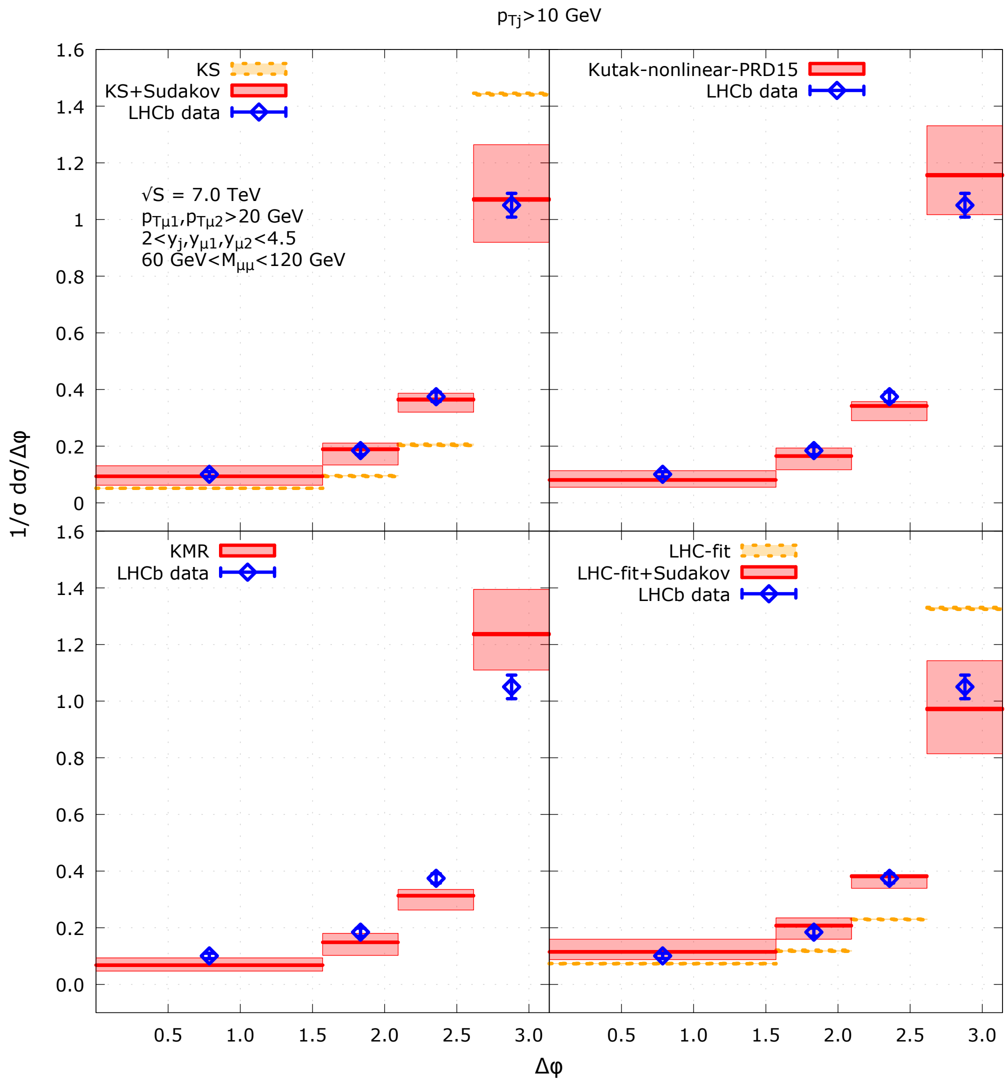

Figure 2: Azimuthal decorrelations for $p_{T\,j} > 10\,\mathrm{GeV}$ normalized to the total cross section.

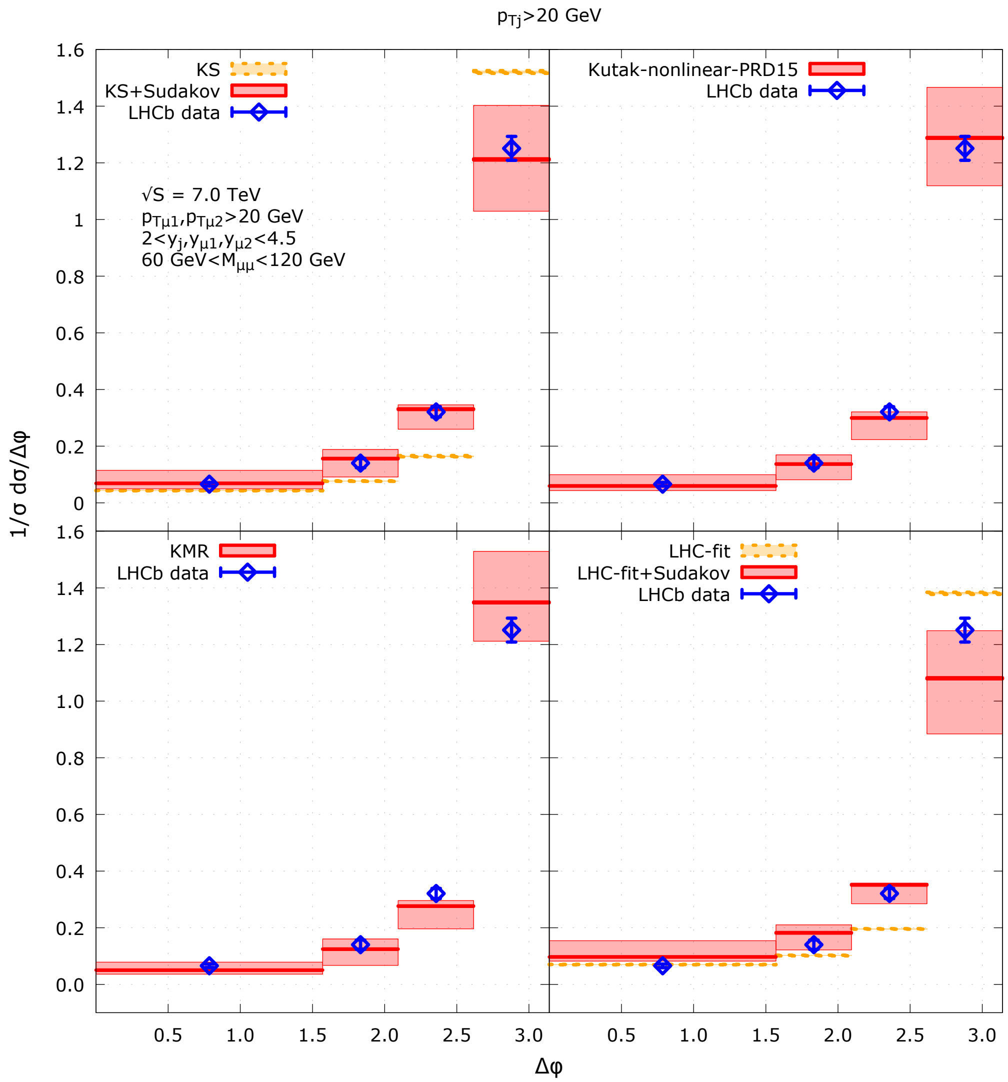

Figure 3: Azimuthal decorrelations for $p_{T\,j} > 20\,\mathrm{GeV}$ normalized to the total cross section.

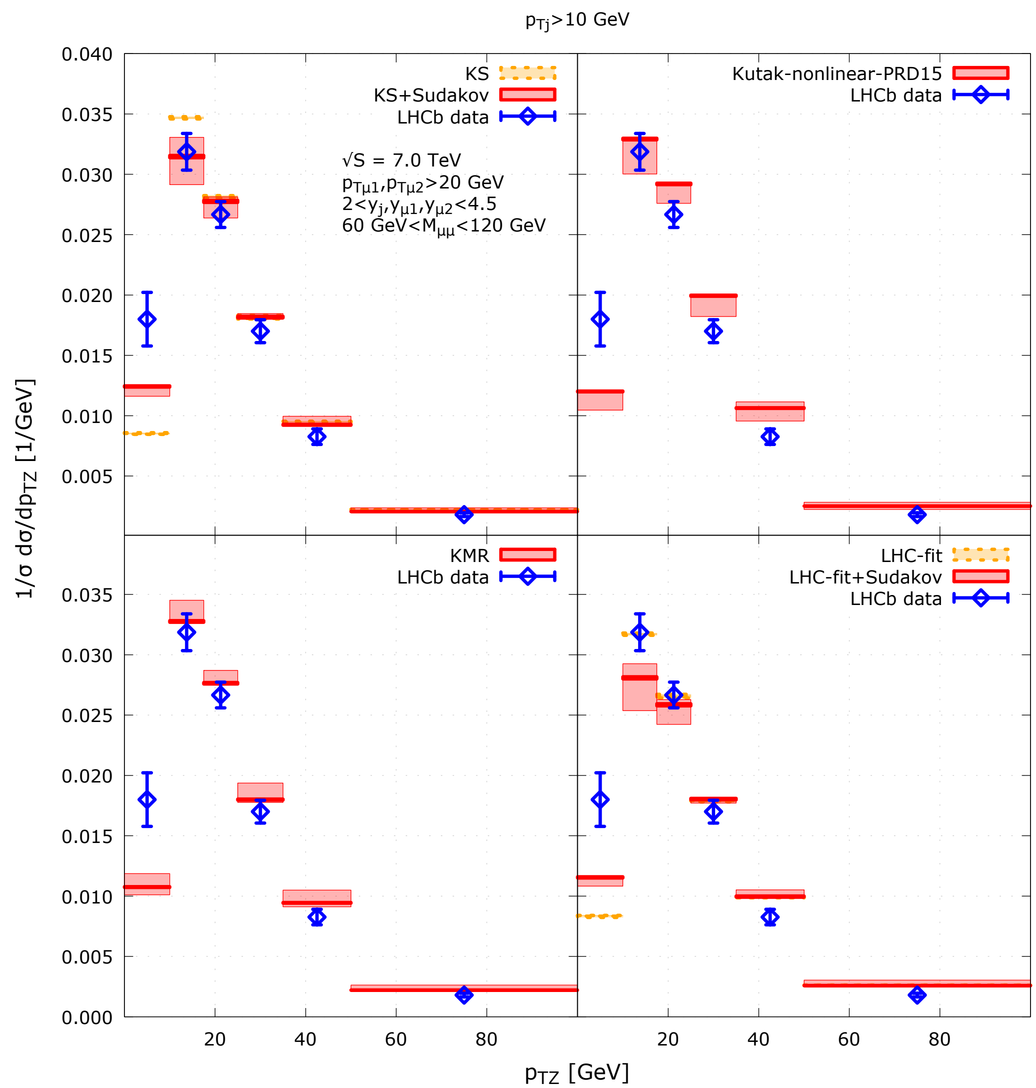

Figure 4: Transverse momentum spectrum for Z_0-boson for $p_{T\,j} > 10\,\mathrm{GeV}$ normalized to the total cross section.

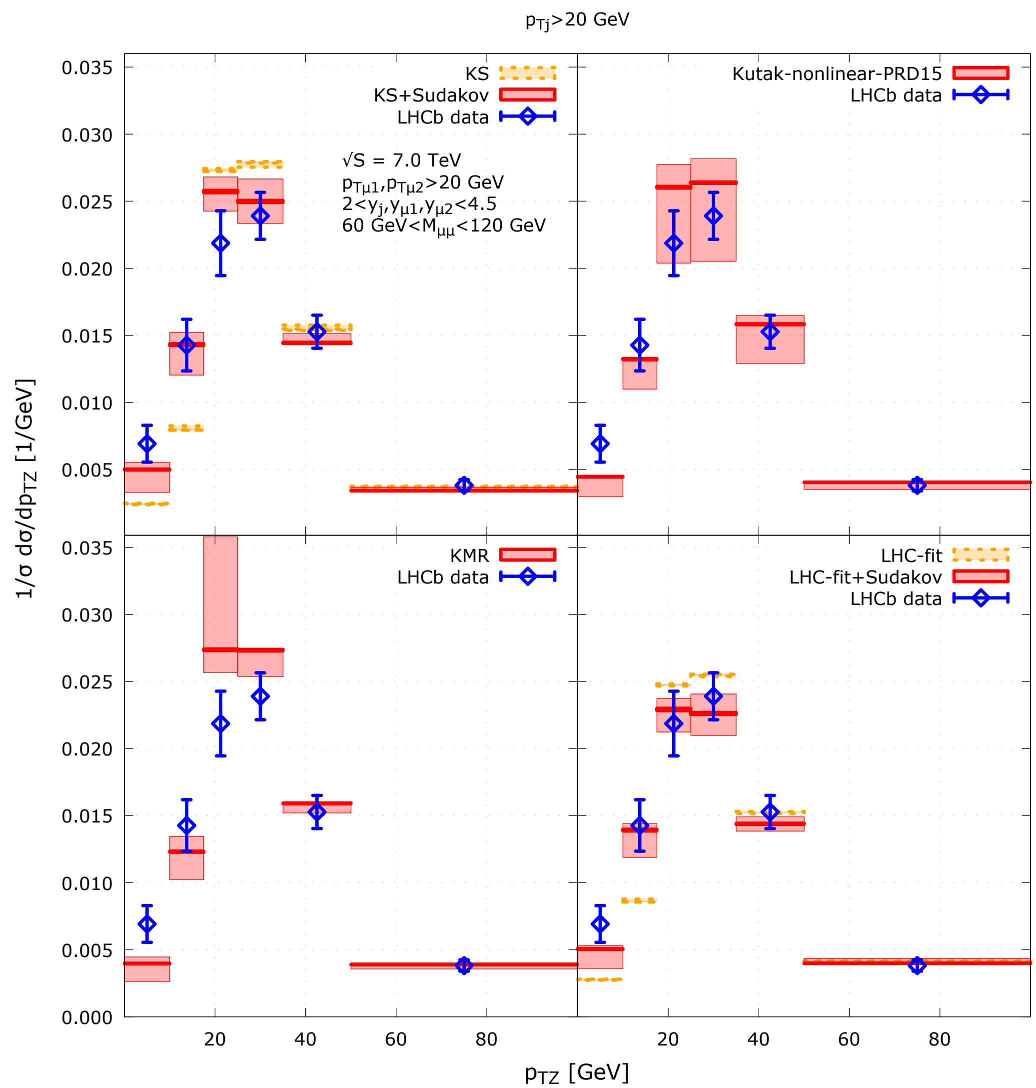

Figure 5: Transverse momentum spectrum for Z_0-boson for $p_{T\,j} > 20\,\text{GeV}$ normalized to the total cross section.

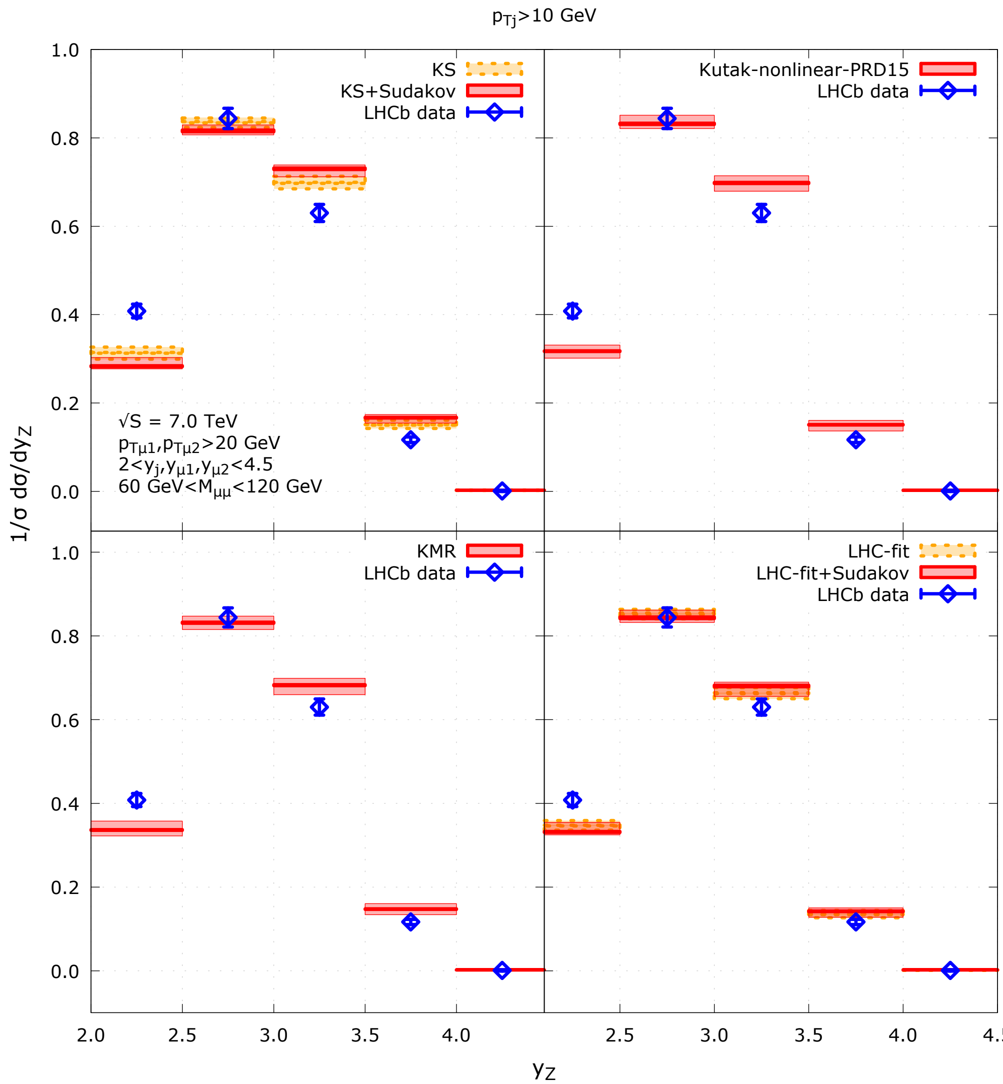

Figure 6: Rapidity spectrum of Z_0-boson for $p_{T\,j} > 10\,\text{GeV}$ normalized to the total cross section.

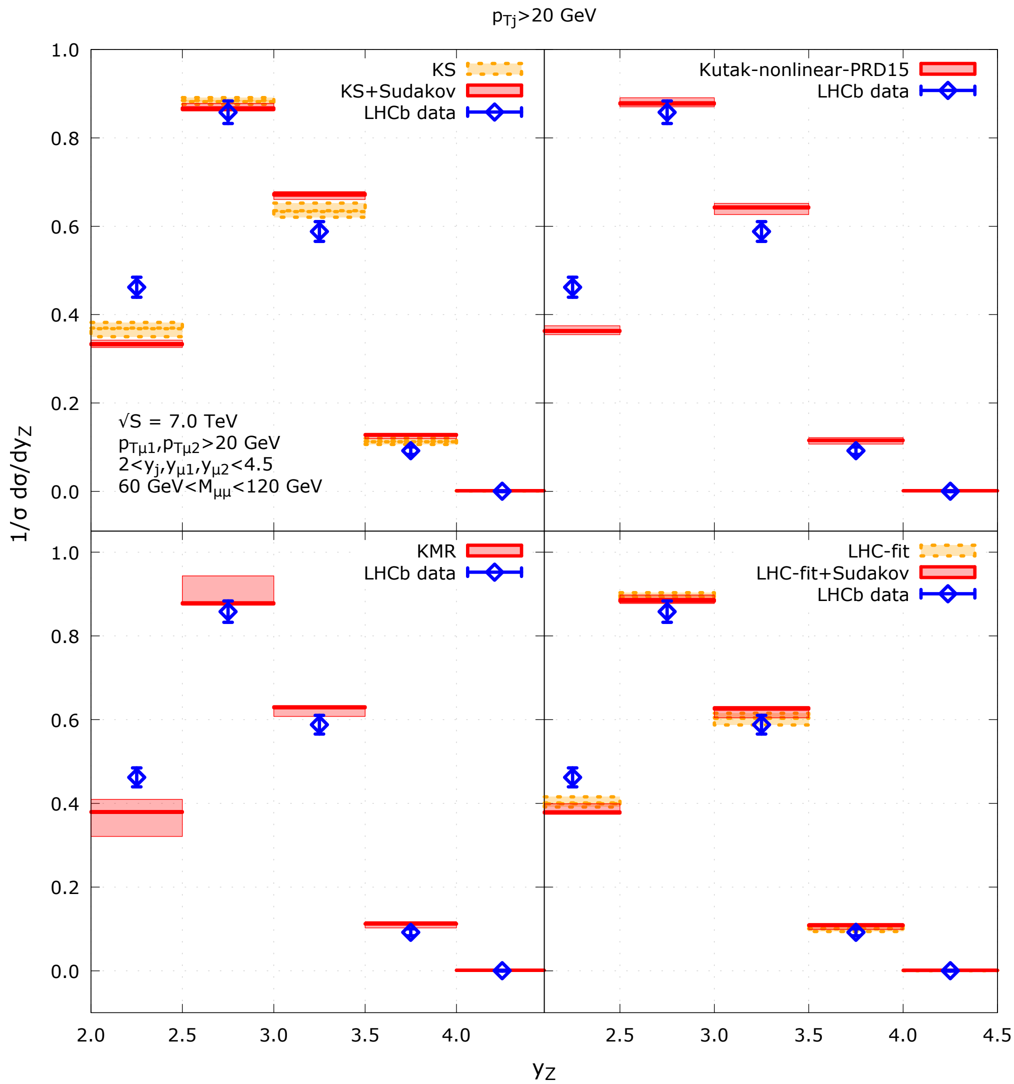

Figure 7: Rapidity spectrum of Z_0-boson for $p_{T\,j} > 20\,\mathrm{GeV}$ normalized to the total cross section.

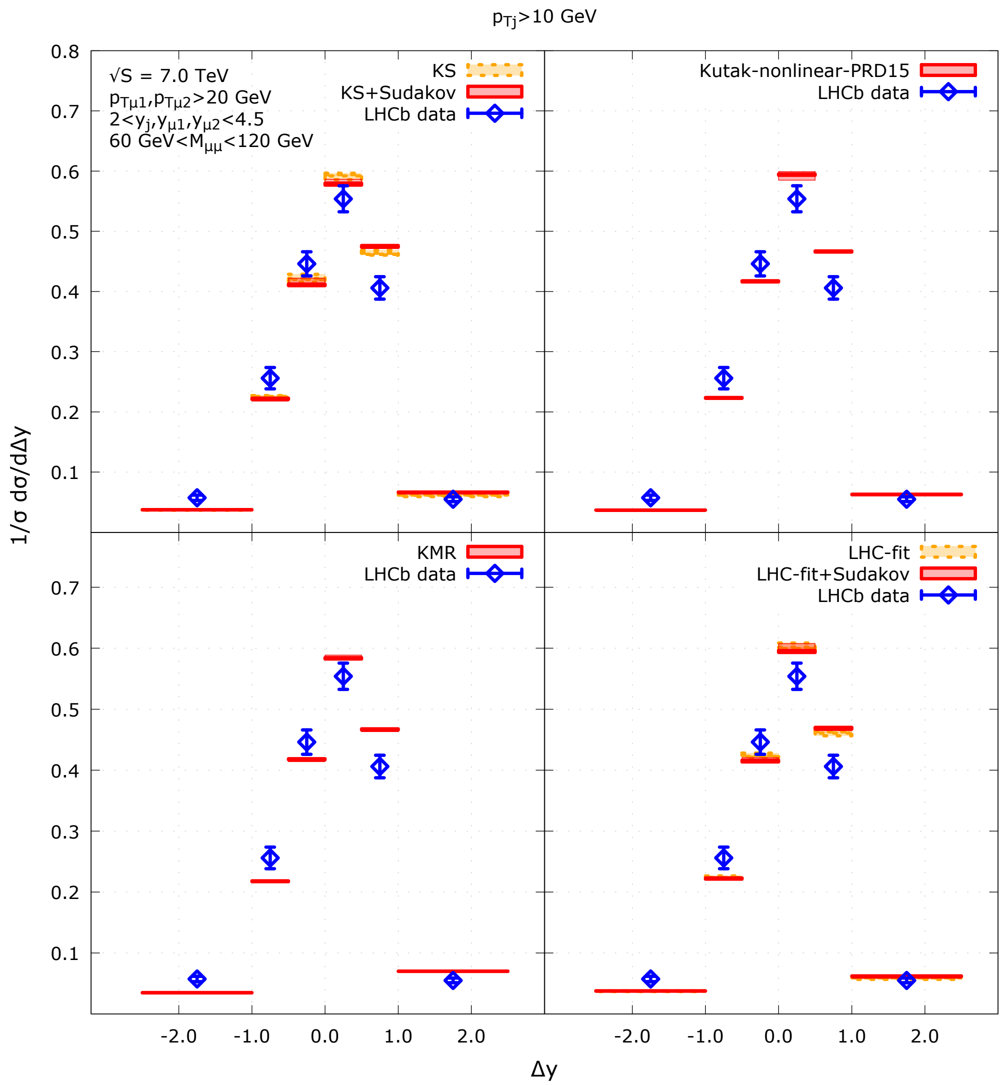

Figure 8: Differential cross section as a function of rapidity separation between the Z_0-boson and the jet for $p_{T\,j} > 10\,\text{GeV}$ normalized to the total cross section.

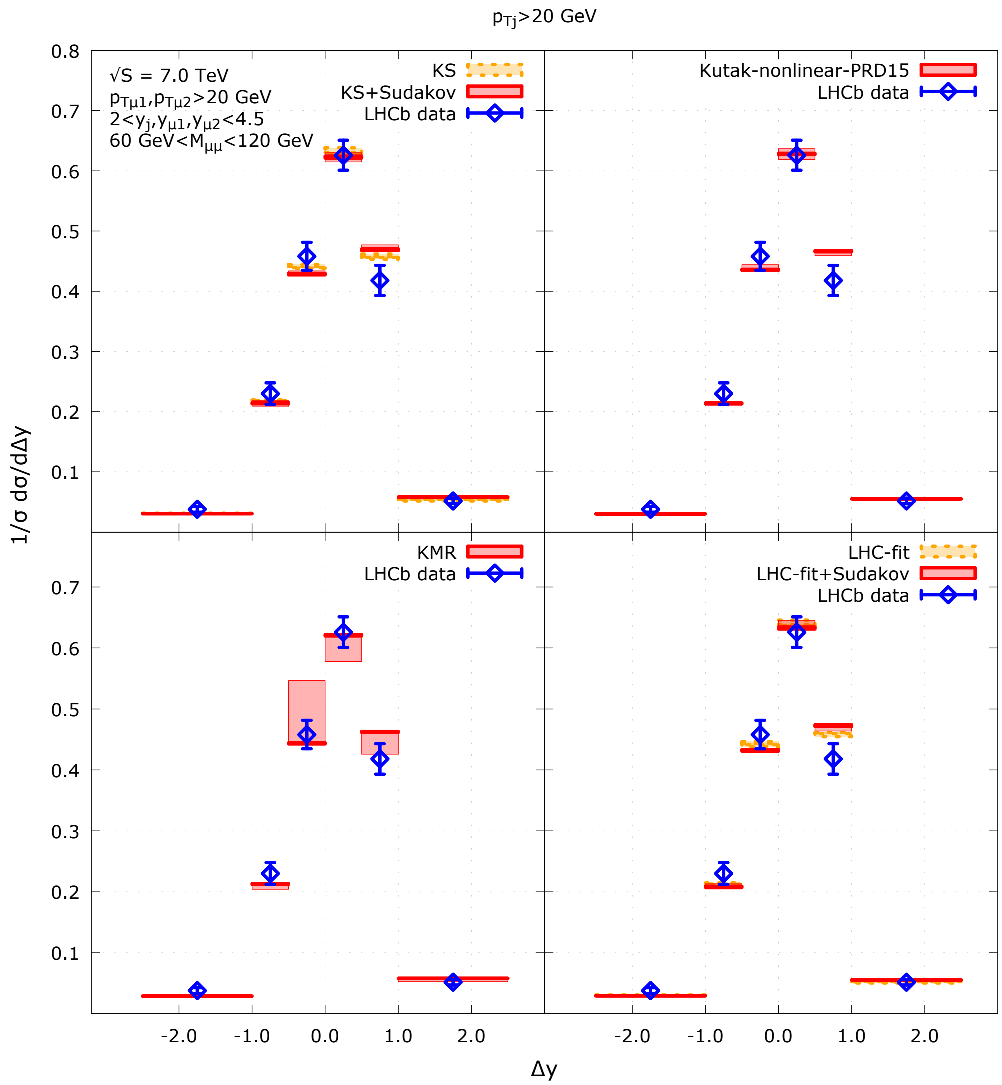

Figure 9: Differential cross section as a function of rapidity separation between the Z_0-boson and the jet for $p_{T\,j} > 20\,\mathrm{GeV}$ normalized to the total cross section.

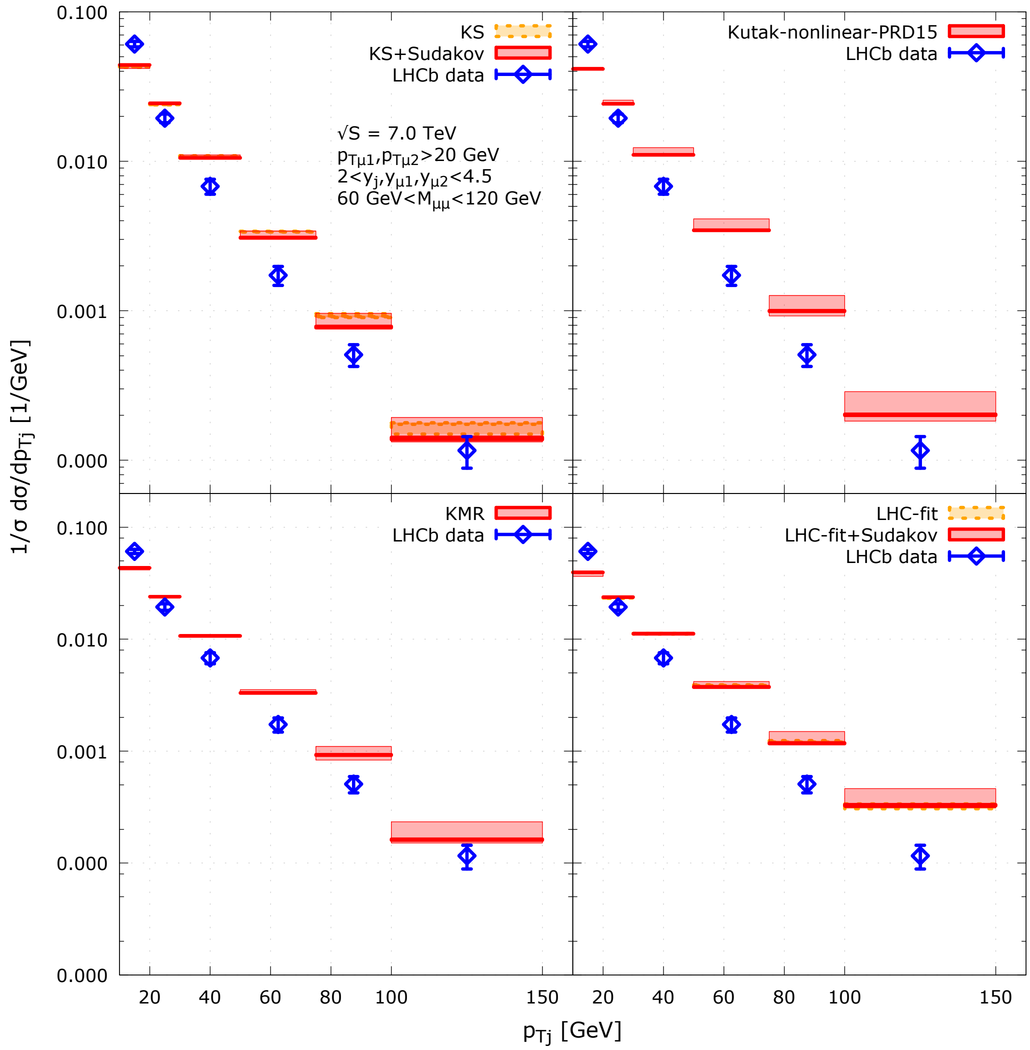

Figure 10: Transverse momentum spectrum of the jet normalized to the total cross section.