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Collider test of proton intrinsic charm in $\gamma(Z)+c(b)$ production by pp collisions

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We consider an observable very sensitive to the non-zero intrinsic charm (IC) contribution to the proton density. It is the ratio between the differential cross sections of the photon or Z-boson and c-jet production in the pp collision, $\gamma(Z)+c$, and the $\gamma(Z)$ and the b-jet production. It is shown that this ratio can be approximately flat or increasing at large $\gamma(Z)$ transverse momenta p_T and their pseudo-rapidities $1.5 < \eta < 2.4$ if the IC contribution is taken into account. On the contrary, in the absence of the IC this ratio decreases as p_T grows. We also present the ratios of the cross sections integrated over p_T as a function of the IC probability w. It is shown that these ratios are mostly independent on the theoretical uncertainties, and such predictions could therefore be much more promising for the search for the intrinsic charm signal at the LHC compared to the predictions on p_T-spectrta of photons or Z-bosons.

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1. Introduction

The hypothesis of the *intrinsic* (or valence-like) heavy quark component, the quark Fock state $|uudQ\bar{Q}\rangle$ [1]-[4] in a proton suggested by Brodsky with coauthors [1, 2] (BHPS model) is intensively discussed in connection with an opportunity to verify it experimentally, see [5] and the review [6] and references there in. Below we perform the calculations in two ways. Our main motivation is that it gives a better description of the Tevatron data compared to the NLO pQCD calculations [7], as it was claimed [8]-[10]. We apply this approach and the MC generator MCFM to the associated Z and heavy jet production to perform an independent cross-check of our results.[1].

2. Intrinsic charm density in a proton as a function of IC probability w

According to the BHPS model [1, 2], the charm density in a proton is the sum of the *extrinsic* and *intrinsic* charm densities,

$$xc(x,\mu_0^2) = xc_{ext}(x,\mu_0^2) + xc_{int}(x,\mu_0^2). \tag{2.1}$$

The *extrinsic*, or ordinary quarks and gluons are generated on a short-time scale associated with the large-transverse-momentum processes. Their distribution functions satisfy the standard QCD evolution equations. Contrariwise, the *intrinsic* quarks and gluons can be associated with a bound-state hadron dynamics and one believes that they have a non-perturbative origin. It was argued [2] that existence, for example, of *intrinsic* heavy quark pairs $c\bar{c}$ and $b\bar{b}$ within the proton state can be due to the gluon-exchange and vacuum-polarization graphs.

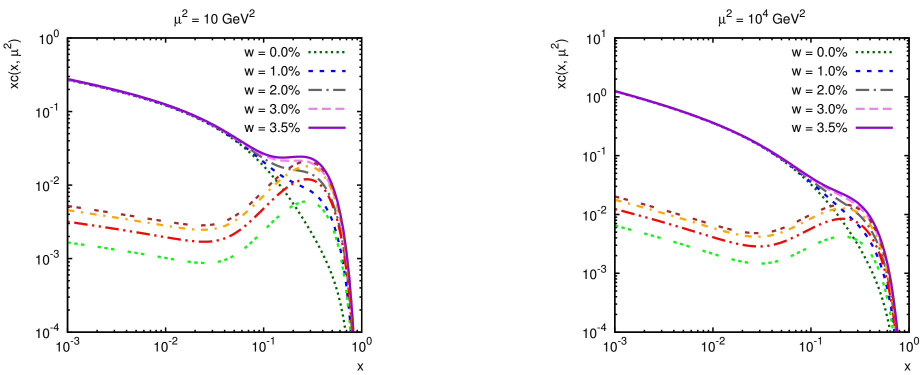

Figure 1: The charmed quark densities as a function of x and w at $\mu^2 = 10$ GeV^2 (left) and $\mu^2 = 10^4$ GeV^2 (right). The triple dashed line is the IC contriubion at $w = 1\%$, dash-double-dotted line corresponds to $w = 2\%$, dosh-dotted curve corresponds to $w = 3\%$ and double dashed corresponds to $w = 3.5$ %.

The charm density $xc(x,\mu^2)$ at an arbitrary scale μ^2 is calculated using the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations. Let us stress that both the intrinsic part xc_{int} and extrinsic one xc_{ext} depend on μ^2. In the general case, there is some mixing between two parts

[1]Unfortunately, the MCFM routine does not produce the prompt photon and heavy jet production cross sections.

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of Eq.(2.1) during the DGLAP evolution. However, such mixing is negligible [11], especially at large μ^2 and x. It can be seen from comparison of our calculations of charmed quark denspiies presented in Fig. (1), where this mixing was included within the CTEQ set, and Fig.(2) of [11], when the mixing between two parts of the charm density was neglected. Our results on the total charm density $xc(x,\mu^2)$ are in good agreement with the calculations of [11] at the whole kinematical region of x because at $x < 0.1$ the IC contribution xc_{int} is much smaller than the *extrinsic* one xc_{ext}. Therefore, one can apply the DGLAP evolution separately to the first part $xc_{ext}(x,\mu_0^2)$ and the second part $xc_{int}(x,\mu_0^2)$ of (2.1), as it was done in [11]. Such calculations were done by the CTEQ and CT14 groups at some fixed values of the IC probability w. Namely, the CTEQ group used $w = 1\%$ and $w = 3.5\%$, and CT14 used $w = 1\%$ and $w = 2\%$.

Taking into account that the IC probability w enters into (2.1) as a constant in front of the function dependent on x and μ^2, one can suggest a simple relation at any $w \leq w_{\max}$:

$$xc_{int}(x,\mu^2) = \frac{w}{w_{\max}} xc_{int}(x,\mu^2)|_{w=w_{\max}}. \tag{2.2}$$

Actually, that is the linear interpolation between two charm densities at the scale μ^2, obtained at $w = w_{\max}$ and $w = 0$. Later we adopt the charm distribution function from the CTEQ66M. We assume $w_{\max} = 3.5\%$ everywhere, which corresponds to the CTEQ66c1. Additionally, we performed the three-point interpolation of the charmed quark distributions (over $w = 0$, $w = 1\%$ and $w = 3.5\%$, which correspond to the CTEQ66M, CTEQ66c0 and CTEQ66c1 sets, respectively). These results differ from the ones based on (2.2) by no more than 0.5%, thus giving us the confidence in our starting point.

Below we apply the charmed quark density obtained by (2.1) and (2.2) to calculate the total and differential cross sections of associated prompt photon or Z boson and heavy flavor jet production, $\gamma(Z) + Q$, at the LHC conditions. Here Q means the c- or b-jet. The suggested procedure [12] to calculate $xc_{int}(x,\mu^2)$ at any $w \leq w_{\max}$ allows us to reduce significantly the time for the calculation of these observables.

3. Theoretical approaches to the associated $\gamma(Z) + Q$ production

As was mentioned above, we perform the numerical calculations of the associated $\gamma(Z) + Q$ production cross sections using the parton-level Monte Carlo event generator MCFM within the NLO pQCD as well as the k_T-factorization QCD approach. The MCFM is able to calculate the processes, that involve the gauge bosons Z or W (see [13, 14] for more information). In contrast to our early study of these processes [14] within the MCFM, we use this generator to calculate the differential and total cross sections of the $Z + c$ and $Z + b$ production in the pp collision and their ratio as a function w [12].

The k_T-factorization approach is based on the small-x Balitsky-Fadin-Kuraev-Lipatov (BFKL) gluon dynamics and provides solid theoretical grounds for the effects of the initial gluon radiation and the intrinsic parton transverse momentum. To improve the k_T-factorization predictions at high transverse momenta, we take into account some $\mathcal{O}(\alpha\alpha_s^2)$ contributions, namely $q\bar{q} \to VQ\bar{Q}$ and $qQ \to VqQ$ ones, where V denotes the photon or the Z boson. These contributions are significant

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at large x and therefore can be calculated in the usual collinear QCD factorization scheme. Thus, we rely on the combination of two techniques that is most suitable.

4. Results and discussion

Let us present the results of our calculations. They are presented in Figs. (2-5) It is important that the calculated ratios $\sigma(\gamma+c)/\sigma(\gamma+b)$ and $\sigma(Z+c)/\sigma(Z+b)$ can be used to determine the IC probability w from the future LHC data. Moreover, these ratios are practically independent of the uncertainties of our calculations: actually, the curves corresponded to the usual scale variations as described above coincide with each other (see Figs. 4 and 5). Therefore, we can recommend these observables as a test for the hypothesis of the IC component inside the proton.

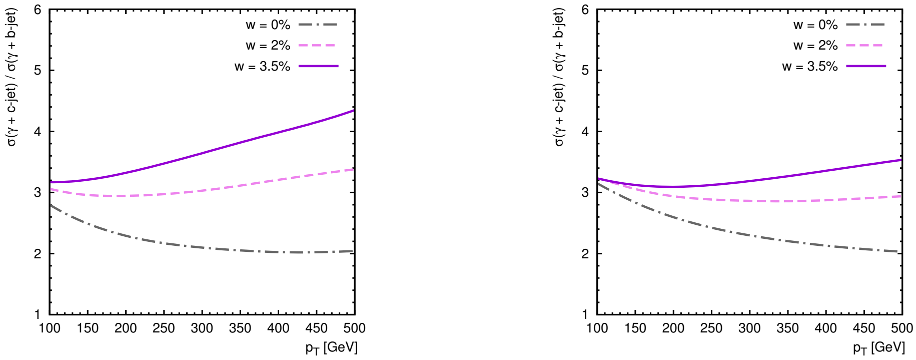

Figure 2: The cross section ratio of the $\gamma+c$ production to the $\gamma+b$ one in the pp collision calculated as a function of the photon transverse momentum p_T at $\sqrt{s}=8$ TeV (left) and $\sqrt{s}=13$ TeV (right) within the k_T-factorization approach.

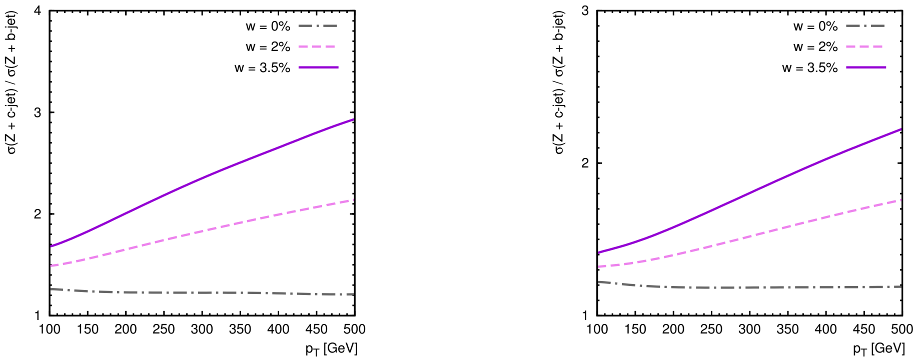

Figure 3: The cross section ratio of the $Z+c$ production to the $Z+b$ one in the pp collision calculated as a function of the Z boson transverse momentum p_T at $\sqrt{s}=8$ TeV (left) and $\sqrt{s}=13$ TeV (right) within the k_T-factorization approach.

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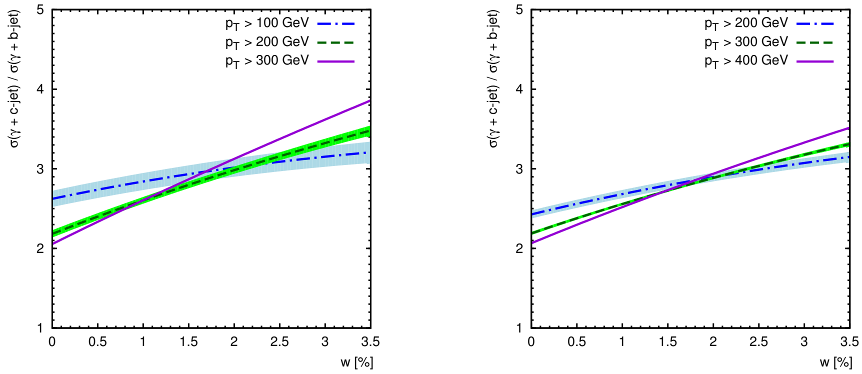

Figure 4: The ratios of the cross sections of the associated $\gamma + c$ and $\gamma + b$ production in the pp collision as a function of w integrated over the photon transverse momenta $p_T > p_T^{\rm min}$ for different $p_T^{\rm min}$ at $\sqrt{s} = 8$ TeV (left) and $\sqrt{s} = 13$ TeV (right). The calculations were done using the k_T-factorization approach. The bands correspond to the usual scale variation from 0.5μ to 2μ

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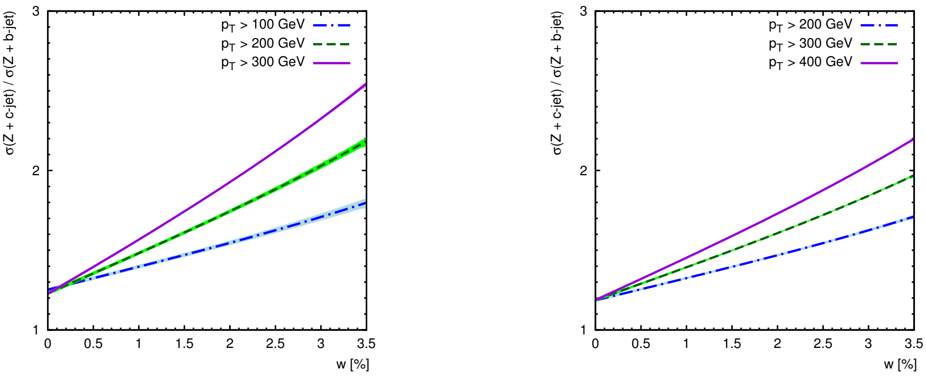

Figure 5: The ratios of the cross sections of the associated $Z + c$ and $Z + b$ production in the pp collision as a function of w integrated over the photon transverse momenta $p_T > p_T^{\rm min}$ for different $p_T^{\rm min}$ at $\sqrt{s} = 8$ TeV (left) and $\sqrt{s} = 13$ TeV (right). The calculations were done using the k_T-factorization approach. The bands correspond to the usual scale variation from 0.5μ to 2μ

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5. Conclusion

If the IC contributions are taken into account, the ratio $\sigma(\gamma + c)/\sigma(\gamma + b)$ as a function of the photon transverse momentum is approximately flat or increases at $p_T > 100$ GeV. The similar flat behavior of this ratio was observed in the $p\bar{p}$ annihilation at the Tevatron [8]-[10]. In the absence of the IC contributions this ratio decreases. Similarly, the ratio $\sigma(Z + c)/\sigma(Z + b)$ increases when the Z boson transverse momentum grows if the IC contribution is included and slowly decreases in the absence of the IC terms. We argued that the ratio of the cross sections $\gamma(Z) + c$ and $\gamma(Z) + b$ integrated over $p_T > p_T^{\rm min}$ with $p_T^{\rm min} \geq 100$ GeV can be used to determine the IC probability from the future LHC data. The advantage of the proposed ratios is that the theoretical uncertainties

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are very small, while the uncertainties for the p_T-spectra of photons or Z bosons produced in association with the c or b jets are large. Therefore, the search for the IC signal by analyzing the ratio $\sigma(\gamma/Z+c)/\sigma(\gamma/Z+b)$ can be more promising.

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