PRODUCTION OF FORWARD CHARM AND NEUTRINOS, AND UNINTEGRATED GLUON DISTRIBUTIONS AT VERY SMALL x*

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In this presentation, we discussed production of charm quarks and antiquarks, D mesons, and neutrinos/antineutrinos in forward and very forward directions. Gluon–gluon fusions, intrinsic charm, and recombination mechanisms were included. The gluon–gluon contribution, as well as the intrinsic charm contribution, were calculated in the $k_{\rm t}$ and hybrid factorization, while the recombination contribution in the standard collinear approach. Different unintegrated gluon distributions from the literature were used. We compared the results of our calculations for D mesons with the LHCb data for different rapidity intervals. The best description was achieved for the Martin–Ryskin–Watt (MRW) uPDF. We presented also energy distributions for forward electron, muon, and tau neutrinos to be measured at the LHC by the currently operating FASERν experiment, as well as by future experiments such as FASERν2 or FLArE, proposed very recently by the Forward Physics Facility project. At very forward directions, the intrinsic charm and recombination contributions become very important. We presented also neutrino energy fluxes including the above-mentioned processes. For electron and muon neutrinos, intrinsic charm and recombination mechanisms lead to similar production rates and their separation seems rather impossible. On the other hand, for $\nu_\tau + \bar{\nu}_\tau$ neutrino flux, the recombination is further reduced making the measurement of the IC contribution very attractive.

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1. Introduction

The dominant mechanism of charm production is gluon–gluon fusion. At high energy, this mechanism is known to dominate at midrapidity. On the

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other hand, the mechanism of the forward production is not well known. In this presentation, two new mechanisms are considered:

(a) Intrinsic charm-induced mechanism,

(b) Recombination mechanism.

Both mechanisms cannot be predicted from first principles. The results depend on some model parameters. The FASERν project [1] will study the forward production of different kinds of neutrinos in proton–proton collisions at the LHC. Can such data provide new information on the not well known mechanisms? We will show the energy distributions of such neutrinos also here. This project is important for the production of high-energy neutrinos in the Earth's atmosphere (IceCube).

2. Sketch of the formalism

In Fig. 1, we present the diagrams showing the $k_{\rm t}$-factorization approach (see *e.g.* [2]) for $c\bar{c}$ production (left panel) and the hybrid approach [3] for the intrinsic charm contribution (right panel).

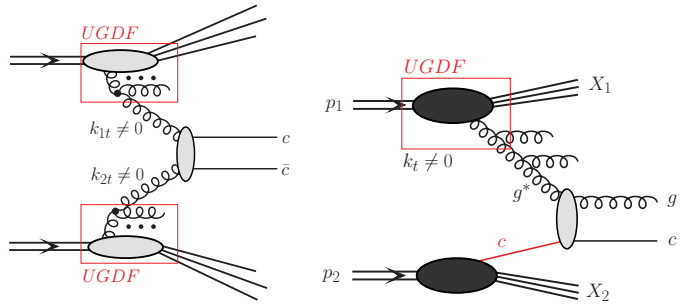

Fig. 1. The $k_{\rm t}$-factorization approach for $c\bar{c}$ production (left) and the hybrid approach for the intrinsic charm contribution (right).

The cross section in the $k_{\rm t}$-factorization approach is written as

$$\frac{{\rm d}\sigma(pp \to c\bar{c}\,X)}{{\rm d}y_1\,{\rm d}y_2\,{\rm d}^2p_{1,{\rm t}}\,{\rm d}^2p_{2,{\rm t}}} = \int \frac{{\rm d}^2k_{1,{\rm t}}}{\pi}\frac{{\rm d}^2k_{2,{\rm t}}}{\pi}\frac{1}{16\pi^2(x_1x_2s)^2}\,\overline{\left|\mathcal{M}^{\rm off-shell}_{g^*g^*\to c\bar{c}}\right|^2}$$
$$\times\,\delta^2\left(\vec{k}_{1,{\rm t}}+\vec{k}_{2,{\rm t}}-\vec{p}_{1,{\rm t}}-\vec{p}_{2,{\rm t}}\right)\,\mathcal{F}_g\left(x_1,k^2_{1,{\rm t}},\mu^2\right)\,\mathcal{F}_g\left(x_2,k^2_{2,{\rm t}},\mu^2\right)\,, \qquad (1)$$

where $\mathcal{F}_g(x_1,k^2_{1,{\rm t}},\mu^2)$ and $\mathcal{F}_g(x_2,k^2_{2,{\rm t}},\mu^2)$ are the gluon uPDFs for both colliding hadrons, and $\mathcal{M}^{\rm off-shell}_{g^*g^*\to c\bar{c}}$ is the off-shell matrix element.

The longitudinal momentum fractions are calculated as

$$\begin{aligned} x_1 &= \frac{m_{1,\mathrm{t}}}{\sqrt{s}} \exp(+y_1) + \frac{m_{2,\mathrm{t}}}{\sqrt{s}} \exp(+y_2)\,, \\ x_2 &= \frac{m_{1,\mathrm{t}}}{\sqrt{s}} \exp(-y_1) + \frac{m_{2,\mathrm{t}}}{\sqrt{s}} \exp(-y_2)\,, \end{aligned} \tag{2}$$

where $m_{i,\mathrm{t}} = \sqrt{p_{i,\mathrm{t}}^2 + m_c^2}$ is the quark/antiquark transverse mass.

The intrinsic charm component is calculated in the hybrid approach as it was done in Refs. [4–6]. In this approach, the differential cross section for $pp \to gcX$ via $g^*c \to gc$ mechanism reads

$$\mathrm{d}\sigma_{pp\to gcX} = \int \mathrm{d}^2k_\mathrm{t} \int \frac{\mathrm{d}x_1}{x_1} \int \mathrm{d}x_2\, \mathcal{F}_{g^*}\left(x_1, k_\mathrm{t}^2, \mu^2\right) c\left(x_2, \mu^2\right)\, \mathrm{d}\hat{\sigma}_{g^*c\to gc}\,, \tag{3}$$

where $\mathcal{F}_{g^*}(x_1, k_\mathrm{t}^2, \mu^2)$ is the unintegrated gluon distribution in one proton and $c(x_2, \mu^2)$ a collinear charm quark PDF in the second one. Here, we take the intrinsic charm distributions in the proton obtained according to the BHPS model [7]. The $\mathrm{d}\hat{\sigma}_{g^*c\to gc}$ is the hard partonic cross section obtained from a gauge-invariant tree-level off-shell amplitude.

The recombination components shown in Fig. 2 are calculated in the collinear approach as it was done in Ref. [8]. The differential cross section for production of Dc final state reads

$$\begin{aligned} \frac{\mathrm{d}\sigma}{\mathrm{d}y_1 \mathrm{d}y_2 \mathrm{d}^2p_\mathrm{t}} &= \frac{1}{16\pi^2 \hat{s}^2} \Big[x_1 q_1\left(x_1, \mu^2\right)\, x_2 g_2\left(x_2, \mu^2\right) \overline{|\mathcal{M}_{qg\to Dc}(s,t,u)|^2} \\ &\quad + x_1 g_1\left(x_1, \mu^2\right)\, x_2 q_2\left(x_2, \mu^2\right) \overline{|\mathcal{M}_{gq\to Dc}(s,t,u)|^2} \Big]\,. \end{aligned} \tag{4}$$

Above, y_1 is the rapidity of the D meson and y_2 the rapidity of the associated c quark or $\bar{c}$ antiquark.

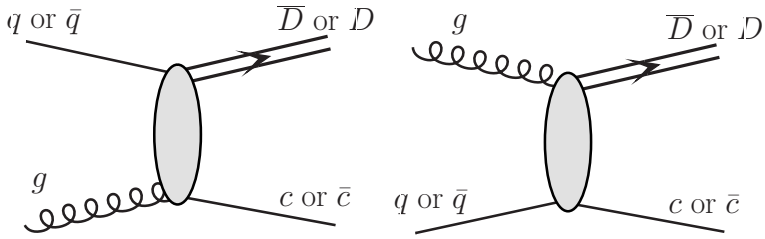

Fig. 2. Schematic diagrams for the recombination.

The matrix element squared in (4) can be written as

$$\overline{|\mathcal{M}_{qg\to Dc}(s,t,u)|^2} = \overline{\left|\mathcal{M}_{qg\to(\bar{c}q)^n c}\right|^2}\,\rho\,, \tag{5}$$

where n enumerates quantum numbers of the $\bar{c}q$ system $n \equiv {}^{2J+1}L$. The matrix elements were calculated by Braaten, Jia, Mehen [9–11] and ρ can be interpreted as a probability to form a real meson. For illustration, as our default set, we shall take $\rho = 0.1$, but the precise number should be adjusted to experimental data on $D^0/\bar{D}^0$ production asymmetry. We shall return to this point in the conclusion section. The factorization scale in the calculation is taken as $\mu^2 = p_{\rm t}^2 + \frac{m_{{\rm t},D}^2 + m_{{\rm t},c}^2}{2}$.

3. Selected results

In Fig. 3, we show some examples of transverse momentum (left) and rapidity (right) distributions for $D^0 + \bar{D}^0$. The calculation was performed within the $k_{\rm t}$-factorization approach. In these calculations, the unintegrated gluon densities from the MRW-MMHT2014nlo model [12] were used. Rather good agreement with the data was achieved. In Ref. [13], we showed also distributions for more forward rapidities.

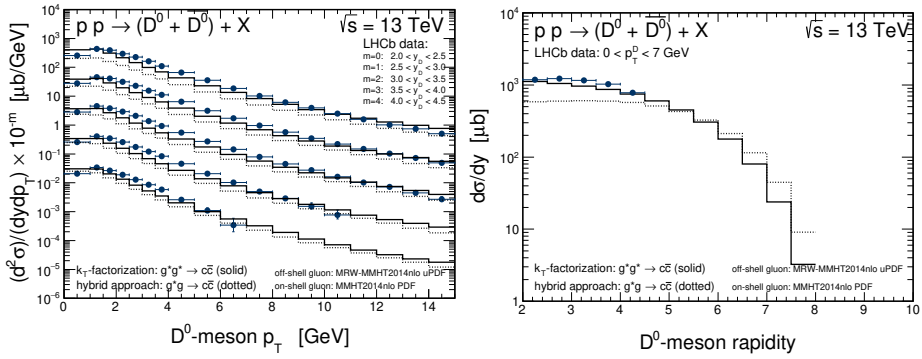

Fig. 3. An example for the D^0 production for the LHCb kinematics.

Below, we show also energy distributions of neutrinos (plus antineutrinos) coming from semileptonic decays of D mesons (see Figs. 4 and 5). As a reference, we show also the result of conventional component (decays of light mesons). In general, the decays of D mesons populate regions of larger neutrino energies. This is particularly true for intrinsic charm and recombination contributions. While for the electron neutrinos/antineutrinos the intrinsic charm and recombination contributions are of a similar order for the tau neutrinos/antineutrinos, the recombination contribution is much

smaller. This makes the measurement of tau neutrinos particularly promising in the context of searches for intrinsic charm. In Ref. [13], we show also the distribution of muon neutrinos/antineutrinos. There, the pion decay contribution is large which makes the searches for IC rather difficult.

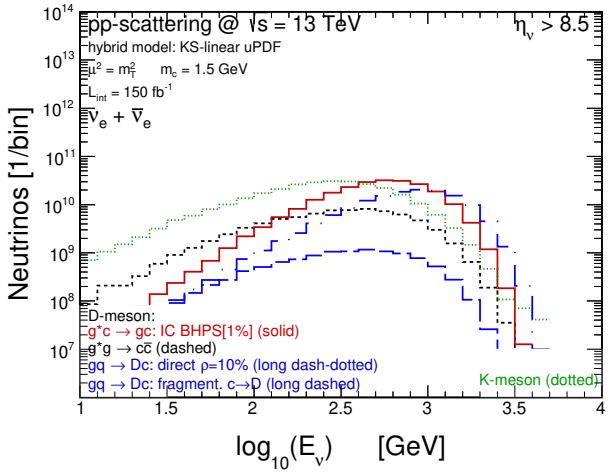

Fig. 4. Energy distribution of ν_e neutrinos.

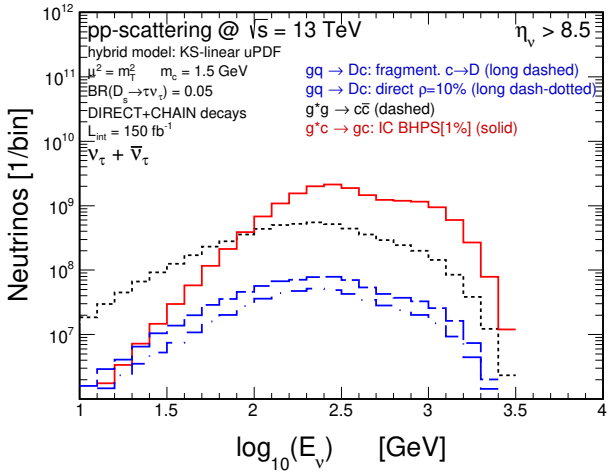

Fig. 5. Energy distribution of ν_τ neutrinos.

4. Conclusions

Here, we have discussed production of charmed quarks, mesons, and associated neutrinos/antineutrinos in proton–proton collisions. We have considered gluon–gluon fusion, intrinsic charm, and recombination contributions. Some parameters of the intrinsic charm model and recombination were fixed

from previous studies. The recombination parameter $\rho = 0.1$ is almost consistent with recent studies of asymmetry between the D^0 and $\bar{D}^0$ production in fixed target $p + {}^{20}$Ne collisions [14].

We have calculated transverse momentum distributions of $D^0 + \bar{D}^0$ for different bins of meson rapidities. The results of the calculations have been compared to the LHCb experimental data. A very good agreement has been achieved for the Martin–Ryskin–Watt unintegrated gluon distribution. In the original paper [13] we presented also results for the Kutak–Sapeta unintegrated gluon distributions.

We have also presented energy distributions of neutrinos/antineutrinos from the decay of D mesons including all considered contributions. At the large neutrino energies, the intrinsic charm and recombination contributions play an important role. While for electron neutrinos/antineutrinos both intrinsic charm and recombination contributions are crucial, for tau neutrinos/antineutrinos, one has unique dominance of intrinsic charm contribution. This makes the measurement of tau neutrinos particularly valuable in searches for an intrinsic charm component.

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