Correlation observables in $\Upsilon + D$ associated production at the LHC within the parton Reggeization approach

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Outline

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   - Factorization formula for the PRA
2. Associated production of $\Upsilon(1S)$ and $D^{0/+}$ mesons at the LHCb
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Motivation: SPS vs DPS

- A study of correlation observables (such as $\Delta\varphi$ and Δy) is a sensitive tool for probing so-called Double Parton Scattering (DPS) mechanism. Another way to test DPS is investigating at high energies the total cross-section of the process, for which contribution of Single Parton Scattering (SPS) is as small as possible, due to suppression by high power of α_s.
- Recently in [Aaij R. et al. [LHCb Collaboration], JHEP 07 (2016) 052] different spectra of associated $\Upsilon(1S) + D$ production at $\sqrt{S} = 7$ and 8 TeV have been presented. Theoretical predictions for that process within SPS [A. V. Berezhnoy, A. K. Likhoded, Int. J. Mod. Phys. A 30 (2015) 1550125.] had given a small value of total cross-section while the experimental result had been at least 10 times more. So that had been interpreted as a clear signal of DPS mechanism.
- But due to low hard scales the SPS cross-section could receive unexpectedly large higher-order QCD corrections. Moreover, at low-x plenty of phase space is available for emission of additional relatively hard partons, what can mimic the behaviour of DPS, thus weakening the case for DPS-dominance in this process.

Sketch of the Parton Reggeization Approach (PRA)

Model process and Sudakov's decomposition

We can derive the factorization formula in PRA, considering the following auxilliary hard subprocess:

$$g(p_1) + g(p_2) \to g(k_1) + \mathcal{Y}(P_\mathcal{A}) + g(k_2), \tag{1}$$

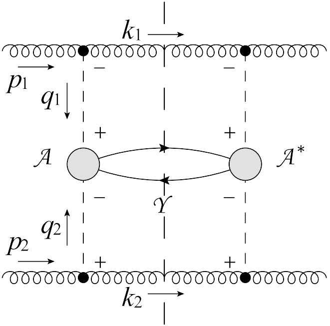
where $p_1^2 = p_2^2 = k_1^2 = k_2^2 = 0$, $M_\mathcal{A}^2 = P_\mathcal{A}^2$.
We use the Sudakov (light-cone) components of any four-momentum k:

$$k^\mu = \frac{1}{2}\left(k^+ n_-^\mu + k^- n_+^\mu\right) + k_T^\mu,$$

where $n_\pm^\mu = \left(n^\pm\right)^\mu = (1, 0, 0, \mp 1)^\mu$, $n_\pm^2 = 0$, $n_+ n^- = 2$, $k^\pm = k_\pm = (n_\pm k) = k^0 \pm k^3$, $n_\pm k_T = 0$, so that $p_1^- = p_2^+ = 0$ and $s = (p_1 + p_2)^2 = p_1^+ p_2^- > 0$. Then the dot-product of two four-vectors k and q in this notation is equal to:

$$(kq) = \frac{1}{2}\left(k^+ q_- + k^- q_+\right) - \mathbf{k}_T \mathbf{q}_T.$$

Multi-Regge Kinematics (MRK)



The limit of **Multi-Regge Kinematics** (MRK) for the subprocess (1) is defined as:

$$\Delta y_1 = y(k_1) - y(P_{\mathcal{A}}) \gg 1, \; \Delta y_2 = y(P_{\mathcal{A}}) - y(k_2) \gg 1, \tag{2}$$

$$\mathbf{k}_{T1}^2 \sim \mathbf{k}_{T2}^2 \sim M_{T\mathcal{A}}^2 \sim \mu^2 \ll s, \tag{3}$$

where rapidity for the four-momentum k is equal to $y(k) = \log\left(k^+/k^-\right)/2$.
MRK limit of QCD amplitudes can be obtained using **Lipatov's EFT for MRK processes in QCD** [L. N. Lipatov, Nucl. Phys. B **452**, 369 (1995)].

The field content of the effective theory.

Light-cone derivatives:

$$x^{\pm} = n^{\pm} x = x^0 \pm x^3, \ \partial_{\pm} = 2\frac{\partial}{\partial x^{\mp}}$$

Lagrangian of the effective theory $L = L_{kin} + \sum_y \left(L_{QCD} + L_{ind}\right)$, $v_\mu = v_\mu^a t^a$, $\left[t^a, t^b\right] = f^{abc} t^c$. The rapidity space is sliced into the subintervals, corresponding to the groups of final-state particles, close in rapidity. Each subinterval in rapidity $(1 \ll \eta \ll Y)$ has it's own set of QCD fields:

$$L_{QCD} = -\frac{1}{2} tr \left[G_{\mu\nu}^2\right], \ G_{\mu\nu} = \partial_\mu v_\nu - \partial_\nu v_\mu + g\left[v_\mu, v_\nu\right].$$

Different rapidity intervals communicate via the gauge-invariant fields of Reggeized gluons $(A_{\pm} = A_{\pm}^a t^a)$ with the kinetic term:

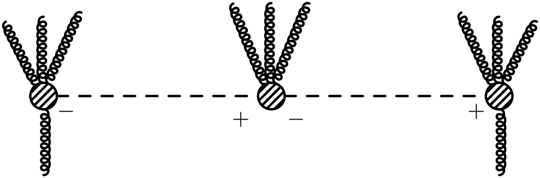
$$L_{kin} = -\partial_\mu A_+^a \partial^\mu A_-^a,$$

and the kinematical constraint:

$$\partial_- A_+ = \partial_+ A_- = 0 \Rightarrow$$

$$A_+ \text{ has } k_- = 0 \text{ and } A_- \text{ has } k_+ = 0.$$

The effective action for high energy processes in QCD.



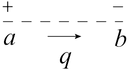
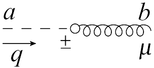
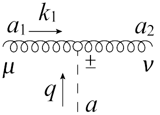
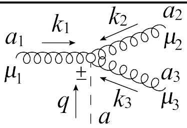
Particles and Reggeons interact via *induced interactions*:

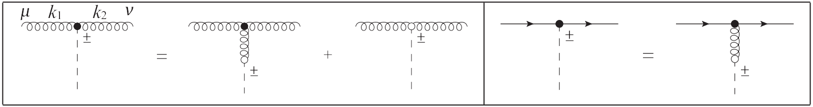
$$L_{ind} = - \operatorname{tr}\left\{ \frac{1}{g}\partial_+ \left[P\exp\left(-\frac{g}{2}\int\limits_{-\infty}^{x^-} dx'^- v_+(x') \right) \right] \cdot \partial_\sigma \partial^\sigma A_-(x) + \right.$$
$$\left. + \frac{1}{g}\partial_- \left[P\exp\left(-\frac{g}{2}\int\limits_{-\infty}^{x^+} dx'^+ v_-(x') \right) \right] \cdot \partial_\sigma \partial^\sigma A_+(x) \right\}$$

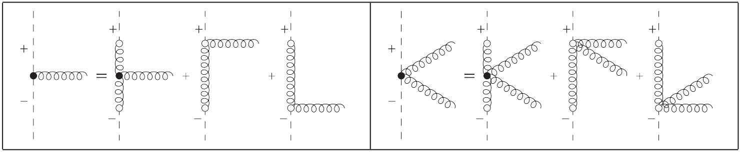
Wilson lines lead to the infinite chain of the induced vertices:

$$L_{ind} = \operatorname{tr}\left\{ \left[v_+ - g v_+ \partial_+^{-1} v_+ + g^2 v_+ \partial_+^{-1} v_+ \partial_+^{-1} v_+ - ... \right] \partial_\sigma \partial^\sigma A_- + \right.$$
$$\left. + \left[v_- - g v_- \partial_-^{-1} v_- + g^2 v_- \partial_-^{-1} v_- \partial_-^{-1} v_- - ... \right] \partial_\sigma \partial^\sigma A_+ \right\}$$

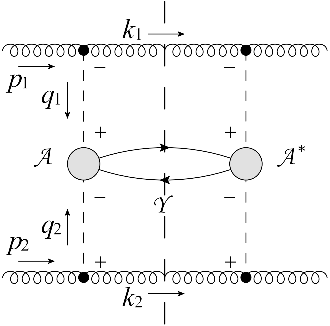
Feynman rules

 $= \frac{-i\delta_{ab}}{2q^2}$	 $= (-iq^2)\, n^{\mp}_{\mu}\, \delta_{ab}$
	$g_s f_{aa_1a_2} \left(n^{\mp}_{\mu} n^{\mp}_{\nu}\right) \frac{q^2}{k_1^{\mp}}$
	$i g_s^2 \left(n^{\mp}_{\mu_1} n^{\mp}_{\mu_2} n^{\mp}_{\mu_3}\right) \frac{q^2}{k_3^{\mp}} \left[\frac{f_{aba_1} f_{ba_2a_3}}{k_1^{\mp}} + \frac{f_{aba_2} f_{ba_1a_3}}{k_2^{\mp}} \right]$





Factorization formula for the PRA



In the MRK-limit we obtained the following formula in k_T**-factorized form** [A. V. Karpishkov, M. A. Nefedov, V. A. Saleev, Phys. Rev. D **96** (2017) 096019]:

$$d\sigma = \int_0^1 \frac{dx_1}{x_1} \int \frac{d^2\mathbf{q}_{T1}}{\pi} \Phi_g(x_1, t_1, \mu^2) \int_0^1 \frac{dx_2}{x_2} \int \frac{d^2\mathbf{q}_{T2}}{\pi} \Phi_g(x_2, t_2, \mu^2) \cdot d\hat{\sigma}_{\mathrm{PRA}},$$

where the partonic cross-section in PRA is given by:

$$d\hat{\sigma}_{\mathrm{PRA}} = \frac{\overline{|\mathcal{A}_{PRA}|^2}}{2Sx_1x_2} \cdot (2\pi)^4 \delta\left(\frac{1}{2}\left(q_1^+ n_- + q_2^- n_+\right) + q_{T1} + q_{T2} - P_{\mathcal{A}}\right) d\Phi_{\mathcal{A}}.$$

Nonintegrated Parton Distribution Functions (nPDFs)

The tree-level “unintegrated PDFs” (unPDFs) are:

$$\tilde{\Phi}_g(x,t,\mu^2) = \frac{1}{t}\frac{\alpha_s}{2\pi}\int\limits_x^1 dz\ P_{gg}(z)\frac{x}{z}f_g\left(\frac{x}{z},\mu^2\right),$$

which have the collinear divergence at $t_{1,2} \to 0$ and infrared (IR) divergence at $z_{1,2} \to 1$. It regularizes at $z_{1,2} < 1 - \Delta_{KMR}(t_{1,2},\mu^2)$, where $\Delta_{KMR}(t,\mu^2) = \sqrt{t}/(\sqrt{\mu^2}+\sqrt{t})$, and $\mu^2 \sim M_{T\mathcal{A}}^2$.
The collinear singularity is regularized by the Sudakov formfactor:

$$T_i(t,\mu^2) = \exp\left[-\int\limits_t^{\mu^2}\frac{dt'}{t'}\frac{\alpha_s(t')}{2\pi}\sum_{j=q,\bar{q},g}\int\limits_0^1 dz\ z\cdot P_{ji}(z)\theta\left(1-\Delta_{KMR}(t',\mu^2)-z\right)\right].$$

The final form of our unPDF is:

$$\Phi_i(x,t,\mu^2) = T_i(t,\mu^2)\frac{\alpha_s(t)}{2\pi}\sum_{j=q,\bar{q},g}\int\limits_x^1 dz\ P_{ij}(z)\frac{x}{z}f_j\left(\frac{x}{z},\mu^2\right)\theta\left(1-\Delta_{KMR}(t,\mu^2)-z\right).$$

The KMR unPDF satisfies the following normalization condition:

$$\int\limits_0^{\mu^2} dt\ \Phi_i(x,t,\mu^2) = xf_i(x,\mu^2).$$

Ingredients of the parton Reggeization approach

1. Factorization formula in the Regge limit of QCD:

$$d\sigma = \int_0^1 \frac{dx_1}{x_1} \int \frac{d^2\mathbf{q}_{T1}}{\pi} \Phi_g(x_1, t_1, \mu^2) \int_0^1 \frac{dx_2}{x_2} \int \frac{d^2\mathbf{q}_{T2}}{\pi} \Phi_g(x_2, t_2, \mu^2) \cdot d\hat{\sigma}_{\rm PRA}.$$

2. Unintegrated parton distribution functions in KMR model:

$$\Phi_i(x, t, \mu^2) = T_i(t, \mu^2) \frac{\alpha_s(t)}{2\pi} \sum_{j=q,\bar{q},g} \int_x^1 dz\, P_{ij}(z) \frac{x}{z} f_j\left(\frac{x}{z}, \mu^2\right) \theta\left(1 - \Delta_{KMR}(t, \mu^2) - z\right).$$

3. Partonic amplitudes with initial-state reggeized quarks and gluons in the Lipatov's EFT:

$$L = L_{kin} + \sum_y \left(L_{QCD} + L_{ind}\right).$$

Associated production of $\Upsilon(1S)$ and $D^{0/+}$ mesons at the LHCb

Basics of NRQCD factorization

The NRQCD framework [G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. D **51**, 1125 (1995)] describes heavy quarkonia in terms of Fock state decompositions. In case of orthoquarkonium state the wave function can be written as power series expansion in the velocity parameter $v \sim 1/\ln M_Q$:

$$|\mathcal{H}\rangle = \mathcal{O}(v^0)|Q\bar{Q}[^3S_1^{(1)}]\rangle + \mathcal{O}(v)|Q\bar{Q}[^3P_J^{(8)}]g\rangle + \mathcal{O}(v^2)|Q\bar{Q}[^1S_0^{(8)}]g\rangle \quad (4)$$

$$+\mathcal{O}(v^2)|Q\bar{Q}[^3S_1^{(1,8)}]gg\rangle + \ldots \quad (5)$$

In the NRQCD effects of short and long distances are separated, and then the cross-section of heavy-quarkonium production via a partonic subprocess $a + b \to \mathcal{H} + X$ can be presented in a factorized form:

$$d\hat{\sigma}(a + b \to \mathcal{H} + X) = \sum_n d\hat{\sigma}(a + b \to Q\bar{Q}[n] + X) \times \langle \mathcal{O}^{\mathcal{H}}[n] \rangle, \quad (6)$$

where n denotes the set of quantum numbers of the $Q\bar{Q}$ pair, and its nonperturbative transitions into $\mathcal{H}$ is described by the NMEs $\langle \mathcal{O}^{\mathcal{H}}[n] \rangle$.
In the general case, the partonic cross-section of quarkonium production from the $Q\bar{Q}$ Fock state $n =^{2S+1} L_J^{(1,8)}$ has the form:

$$d\hat{\sigma}(a + b \to Q\bar{Q}[^{2S+1}L_J^{(1,8)}] \to \mathcal{H}) = d\hat{\sigma}(a + b \to Q\bar{Q}[^{2S+1}L_J^{(1,8)}]) \times \frac{\langle \mathcal{O}^{\mathcal{H}}[^{2S+1}L_J^{(1,8)}] \rangle}{N_{col} N_{pol}},$$

where $N_{col} = 2N_c$ for color-singlet state, $N_{col} = N_c^2 - 1$ for color-octet state, and $N_{pol} = 2J + 1$.

Amplitude of specified state

The definition of partonic cross-section of $Q\bar{Q}[^{2S+1}L_J^{(1,8)}]$ production is following:

$$d\hat{\sigma}(a+b \to Q\bar{Q}[^{2S+1}L_J^{(1,8)}]) = \frac{1}{2x_1x_2S}\overline{|\mathcal{A}(a+b \to Q\bar{Q}[^{2S+1}L_J^{(1,8)}])|^2}d\Phi. \quad (7)$$

The projectors on spin-zero and spin-one states:

$$\Pi_0 = \frac{1}{8m^3}\left(\frac{\hat{p}}{2} - \hat{q} - m\right)\gamma^5\left(\frac{\hat{p}}{2} + \hat{q} + m\right), \Pi_1^\alpha = \frac{1}{8m^3}\left(\frac{\hat{p}}{2} - \hat{q} - m\right)\gamma^\alpha\left(\frac{\hat{p}}{2} + \hat{q} + m\right).$$

The projectors on color-singlet and color-octet states:

$$C_1 = \frac{\delta_{ij}}{\sqrt{N_c}}, \; C_8 = \sqrt{2}T^a_{ij},$$

respectively, where T^a with $a = 1, \cdots, N_c^2 - 1$ are the generators of the color gauge group $SU(N_c)$.
For example, the amplitude of $Q\bar{Q}$ production in state $^3S_1^{(1,8)}$ is:

$$\mathcal{A}(a+b \to Q\bar{Q}[^3S_1^{(1,8)}]) = Tr[C_{1,8}\Pi_1^\alpha \times \mathcal{A}(a+b \to Q\bar{Q})\varepsilon_\alpha(p)]_{q=0},$$

where $\varepsilon_\alpha(p)$ is the polarization 4-vector of a spin-one particle with momentum p^μ and mass $M = p^2$. And the polarization sum then is:

$$\sum_{J_z}\varepsilon_\alpha(p)\varepsilon^*_{\alpha'}(p) = \mathcal{P}_{\alpha\alpha'}(p) = -g_{\alpha\alpha'} + \frac{p_\alpha p'_\alpha}{M^2}.$$

Fragmentation approach

In the fragmentation approach [B. Mele, P. Nason, 1991], the cross-section of the inclusive production of D-meson is related with the partonic cross-section as follows:

$$\frac{d\sigma}{dp_T dy}\left(p+p\to D^{0/+}(p)+X\right)=\sum_a\int\limits_0^1\frac{dz}{z}D^{0/+}(z,\mu^2)\frac{d\hat{\sigma}}{dp_T dy}\left(p+p\to a(p/z)+X\right)$$

where $D^{0/+}(z,\mu^2)$-fragmentation function for the meson $D^{0/+}$. In our calculations we use the LO set of FFs BKK05 by [B. A. Kniehl, G. Kramer *et. al.*] fitted on the e^+e^- annihilation data.
In case of direct production of $\Upsilon(1S)$ we take into account the following partonic subprocesses:

$$\mathcal{R}(q_1)+\mathcal{R}(q_2) \to \Upsilon(1S)(p_1)+g(k)\,[\to D(p_2)]\,, \quad (8)$$
$$\mathcal{R}(q_1)+\mathcal{R}(q_2) \to \Upsilon(1S)(p_1)+c(k)[\to D(p_2)]+\bar{c}(p_3), \quad (9)$$

where $q_1^2=-\mathbf{q}_{T1}^2=-t_1$, $q_2^2=-\mathbf{q}_{T2}^2=-t_2$.
But we add also contribution of feed-down decays into ground state of bottomonium:

$$\mathcal{R}(q_1)+\mathcal{R}(q_2) \to \Upsilon(3S,2S)(p_1)+g(k)\,[\to D(p_2)]\,, \quad (10)$$
$$\mathcal{R}(q_1)+\mathcal{R}(q_2) \to \chi_{b_J}(2P,1P)(p_1)+g(k)\,[\to D(p_2)]\,. \quad (11)$$

Leading PRA subprocesses in $\Upsilon(1S) + D$ production

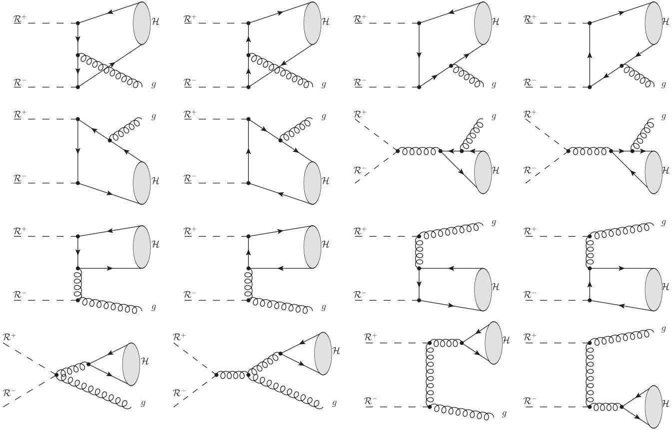
At the quark level we consider following PRA subprocesses:

$$\mathcal{R} + \mathcal{R} \rightarrow b\bar{b}[^3S_1^{(1,8)}] + g\,[\rightarrow D]\,, \quad (12)$$

$$\mathcal{R} + \mathcal{R} \rightarrow b\bar{b}[^3P_{0,1,2}^{(1)}] + g\,[\rightarrow D]\,, \quad (13)$$

$$\mathcal{R} + \mathcal{R} \rightarrow b\bar{b}[^3S_1^{(1,8)}] + c[\rightarrow D] + \bar{c}. \quad (14)$$

Here we show diagramms for the subprocesses (12) and (13):



LHCb data of $\Upsilon(1S) + D^0$ production, $2.0 < y_{\Upsilon(D)} < 4.5$, $\sqrt{S} = 7$ TeV

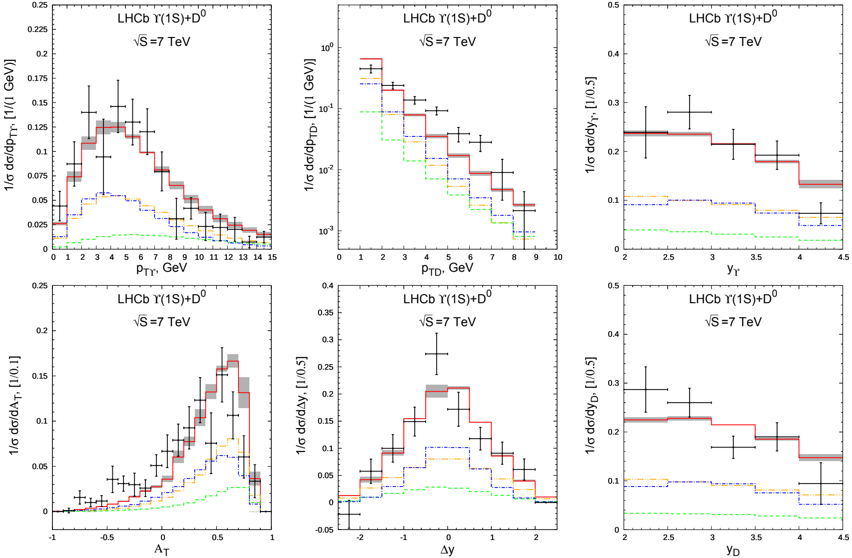


Figure 1 : $p_{T\Upsilon}$, p_{TD}, y_Υ, $\mathcal{A}_T$, Δy and y_D spectra of $\Upsilon(1S)D^0$ pair. LHCb data are from [LHCb Collab. R. Aaij *et al.*, JHEP **1607**, 052 (2016)].

LHCb data of $\Upsilon(1S) + D^0$ production, $2.0 < y_{\Upsilon(D)} < 4.5$, $\sqrt{S} = 7$ TeV

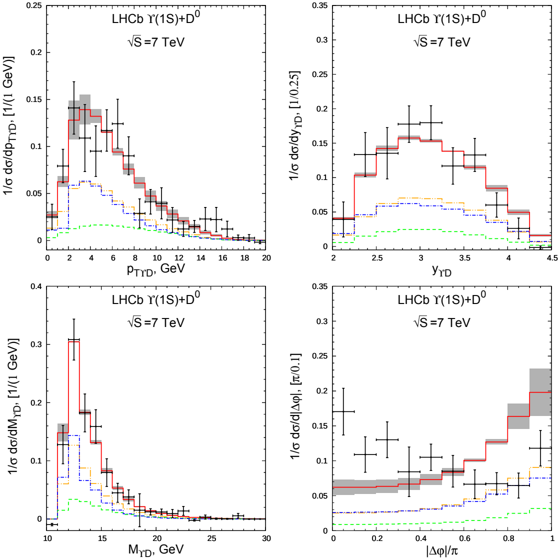


Figure 2 : $p_{T\Upsilon D}$, $y_{\Upsilon D}$, $M_{\Upsilon D}$ and $\Delta\phi$ spectra of $\Upsilon(1S)D^0$ pair. LHCb data are from [LHCb Collab. R. Aaij *et al.*, JHEP **1607**, 052 (2016)].

The total cross sections of $\Upsilon(1S)D^{0/+}$ production at the LHCb

Kinematical region:
$2.0 < y_\Upsilon < 4.5$, $0 < p_{T\Upsilon} < 15$ GeV/c, $2.0 < y_D < 4.5$, $1 < p_{TD} < 20$ GeV/c

$\sqrt{S} = 7$ TeV	$B_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}$, pb	$B_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}$, pb
Direct contributions:	51	20
$R + R \to \Upsilon[^3S_1^{(1)}] + g$	37	15
$R + R \to \Upsilon[^3S_1^{(8)}] + g$	14	5
Sum of feed-down contributions	40	16
Total cross section, LO PRA	91^{+48}_{-41}	36^{+19}_{-16}
$R + R \to \Upsilon[^3S_1^{(1)}] + c + \bar{c}$	14	5
$R + R \to \Upsilon[^3S_1^{(8)}] + c + \bar{c}$	6	3
Total cross section, experiment	155 ± 28	82 ± 24

$\sqrt{S} = 8$ TeV	$B_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}$, pb	$B_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}$, pb
Direct contributions:	61	24
$R + R \to \Upsilon[^3S_1^{(1)}] + g$	44	18
$R + R \to \Upsilon[^3S_1^{(8)}] + g$	17	6
Sum of feed-down contributions	49	19
Total cross section, LO PRA	108^{+56}_{-48}	42^{+22}_{-19}
$R + R \to \Upsilon[^3S_1^{(1)}] + c + \bar{c}$	16	6
$R + R \to \Upsilon[^3S_1^{(8)}] + c + \bar{c}$	8	3
Total cross section, experiment	250 ± 39	80 ± 21

Conclusions

- Using **ReggeQCD** model-file for **FeynArts** we obtained matrix elements of $\mathcal{RR} \to \Upsilon[{}^3S_1^{(1,8)}] + g$, $\mathcal{RR} \to \Upsilon[{}^3P_{0,1,2}^{(1)}] + g$ and calculated different spectra of $\Upsilon(1S) + D^{0/+}$ production.
- We have found a good agreement with LHCb data for various normalized differential distributions, except for the case of spectra on azimuthal angle differences at the small $\Delta\varphi$ values.
- In the mentioned above kinematical region the total cross-section in our Single Parton Scattering model accounts for more than one half of observed cross-section, thus dramatically shrinking the room for Double Parton Scattering mechanism.

For more details see our recent paper [Karpishkov A. V., Nefedov M. A., Saleev V. A., *Evidence in favor of Single Parton Scattering mechanism in Υ and D associated production at the LHC*, Phys. Rev. D **99**, 096021 (2019)].

Thank you for your attention!