

First complete study of hadroproduction of $\Upsilon + J/\psi$

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Outline

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- Introduction

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- The frame of Calculation

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- 4 Many quarkonium associated production processes, such as $J/\psi + W$, $J/\psi + Z$, $J/\psi + charm$, $\Upsilon + charm$ and $J/\psi + J/\psi$, seems to be dominant by Double-Parton Scattering (DPS).
- 5 However, one should keep in mind that before concluding for DPS dominance, one should always carefully examine the Single-Parton Scattering (SPS) contributions.

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$$\begin{aligned} R &= \sum_n F_n \langle \mathcal{O}(n) \rangle \\ F_n &= F_n^0 (1 + c_1 \alpha_s + c_2 \alpha_s^2 + \dots) \\ \langle \mathcal{O}(n) \rangle &\propto v^{d_n} \end{aligned} \tag{1}$$

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- 5 The approximated Loop-Induced (LI) contribution in CSM at $\mathcal{O}(\alpha_S^6)$ was estimated in Ref. Likhoded:2015zna with in the specific limit $\hat{s} \gg |\hat{t}| \gg m_{\psi, \Upsilon}^2$, where \hat{s} and \hat{t} are the

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- 2 The ψ production from b-hadron decay are excluded by D0.
- 3 We present the first complete study of the simultaneous production of prompt ψ and Υ mesons by including all leading contributions, at order $\mathcal{O}(\alpha_S^6)$ or equivalent.

The frame of Calculation

The SPS cross section

In general, the SPS cross section for the simultaneous production of charmonium \mathcal{C} and bottomonium \mathcal{B} in non-relativistic limit can be written as

$$\sigma(h_1 h_2 \rightarrow \mathcal{C} + \mathcal{B} + X) = \sum_{a,b,n_1,n_2} f_{a/h_1} \otimes f_{b/h_2} \quad (2)$$

$$\otimes \hat{\sigma}(ab \rightarrow c\bar{c}[n_1] + b\bar{b}[n_2] + X) \langle O^{\mathcal{C}}(n_1) \rangle \langle O^{\mathcal{B}}(n_2) \rangle, \quad (3)$$

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- 3 $\hat{\sigma}(ab \rightarrow c\bar{c}[n_1] + b\bar{b}[n_2] + X)$ is the perturbatively calculable short-distance coefficient for the simultaneous production of the charm-quark pair in the Fock state n_1 and the bottom-quark pair in the Fock state n_2 .

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- 3 In the following, we will consider all the contributions which can compete with the $\mathcal{O}(\alpha_S^6)$ CSM ones for $\alpha_S \sim v^2 \sim \sqrt{\alpha}$.

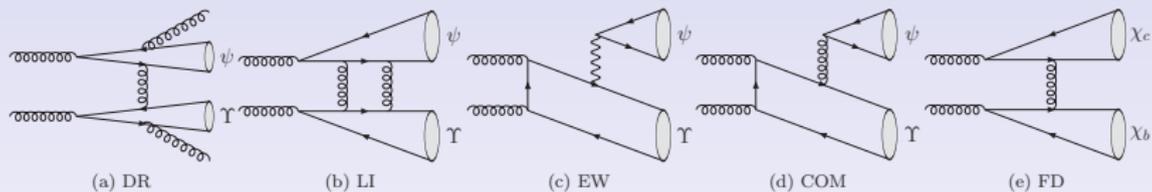
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- 4 Besides the possible DPS contribution, there are 5 relevant classes of production mechanisms, which are summarized in Table.

Order of SPS

Label	HELAC-ONIA 2.0 syntax	First order
DR	$g g > cc\sim(3S11) bb\sim(3S11) g g$	$\mathcal{O}(\alpha_S^6)$
LI	addon 8	$\mathcal{O}(\alpha_S^6)$
EW	$p p > cc\sim(3S11) bb\sim(3S11)$	$\mathcal{O}(\alpha_S^2 \alpha^2)$
INTER	addon 8	$\mathcal{O}(\alpha_S^4 \alpha)$
COM	$g g > jpsi y(1s)$	$\mathcal{O}(\alpha_S^4 v_c^i v_b^j), i + j \geq 4$

Feynman Diagram of SPS



DPS

- 1 Besides the SPSs, the DPS ψ and Υ are produced separately in two partonic scattering processes.

$$\sigma^{\text{DPS}}(h_1 h_2 \rightarrow \mathcal{C} + \mathcal{B} + X) = \frac{\sigma(h_1 h_2 \rightarrow \mathcal{C} + X) \sigma(h_1 h_2 \rightarrow \mathcal{B} + X)}{\sigma_{\text{eff}}}, \quad (4)$$

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- 4 It can be conservatively thought as the lower-limit value of σ_{eff} if one assumes the universality of σ_{eff} . We use a data-driven procedure as input for the single quarkonium production cross sections.

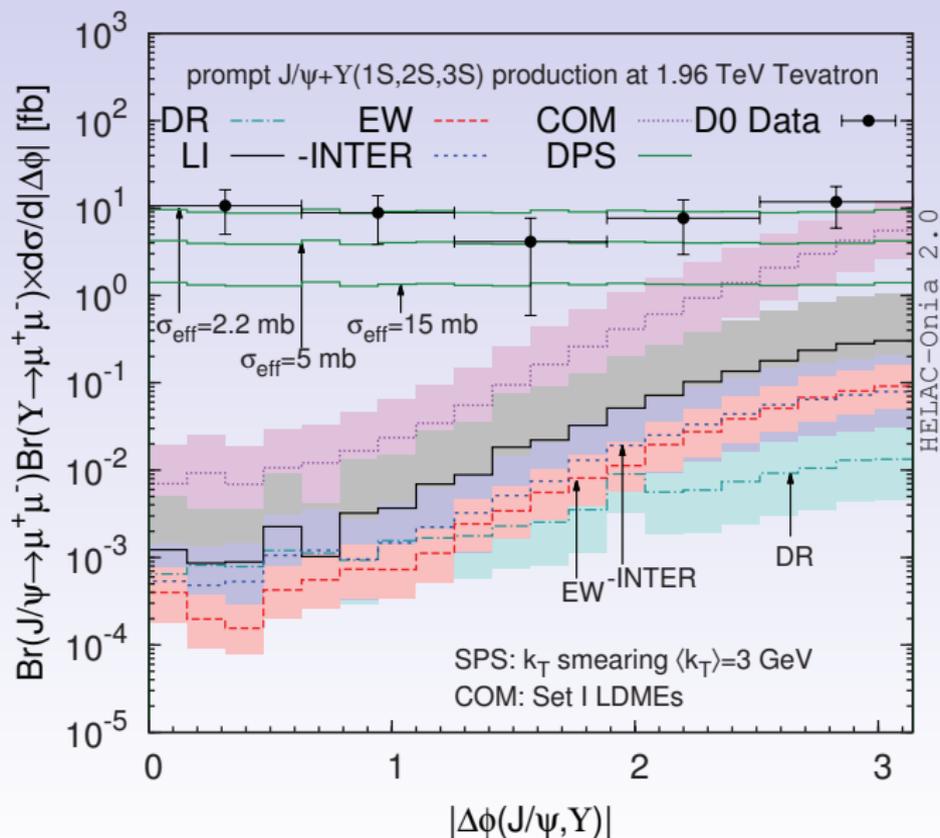
Numerical Result

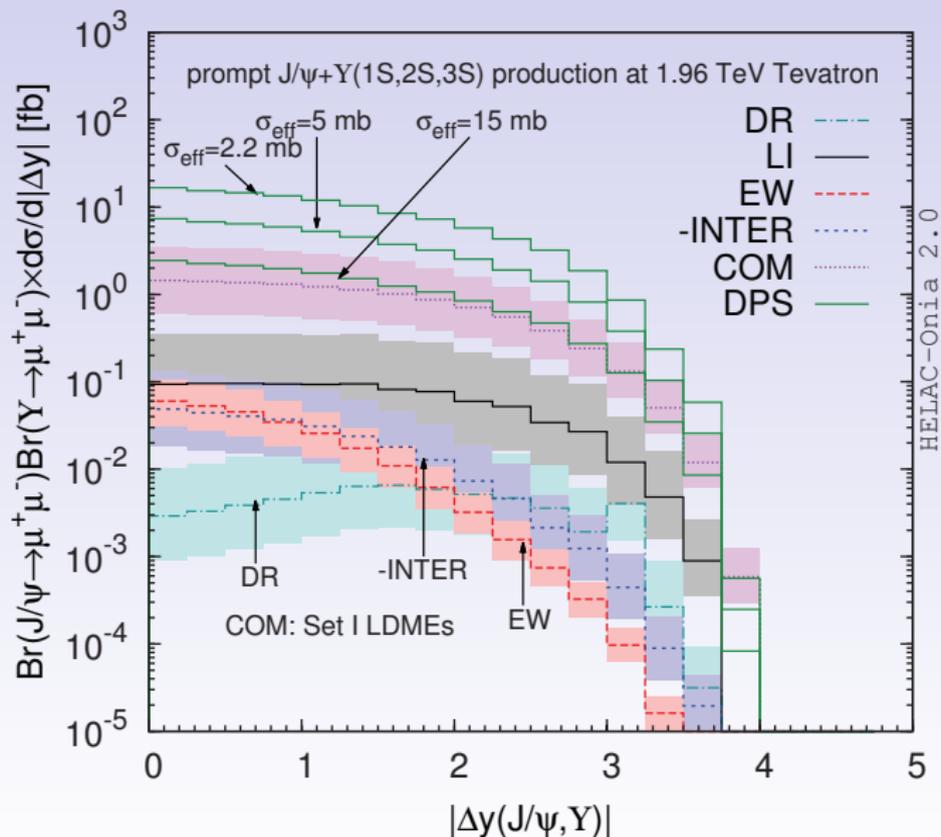
Direct SPS cross sections @ D0 in fb

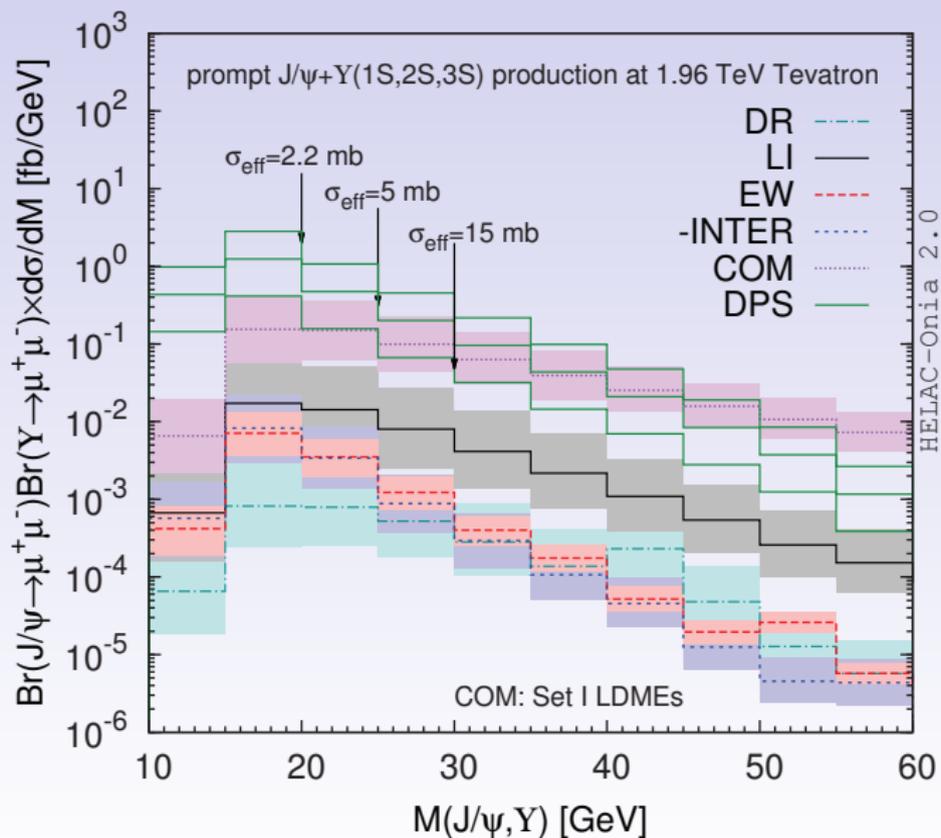
		J/ψ	$\psi(2S)$
DR	$\Upsilon(1S)$	$3.58^{+233\%}_{-66.4\%} \pm 4.4\%$	$2.34^{+233\%}_{-66.4\%} \pm 4.4\%$
	$\Upsilon(2S)$	$1.78^{+233\%}_{-66.4\%} \pm 4.4\%$	$1.17^{+233\%}_{-66.4\%} \pm 4.4\%$
	$\Upsilon(3S)$	$1.36^{+233\%}_{-66.4\%} \pm 4.4\%$	$0.894^{+233\%}_{-66.4\%} \pm 4.4\%$
LI	$\Upsilon(1S)$	$56.2^{+264\%}_{-70.2\%} \pm 4.7\%$	$36.8^{+264\%}_{-70.2\%} \pm 4.7\%$
	$\Upsilon(2S)$	$28.0^{+264\%}_{-70.2\%} \pm 4.7\%$	$18.4^{+264\%}_{-70.2\%} \pm 4.7\%$
	$\Upsilon(3S)$	$21.4^{+264\%}_{-70.2\%} \pm 4.7\%$	$14.0^{+264\%}_{-70.2\%} \pm 4.7\%$
EW	$\Upsilon(1S)$	$15.8^{+75.4\%}_{-46.4\%} \pm 4.6\%$	$10.4^{+75.4\%}_{-46.4\%} \pm 4.6\%$
	$\Upsilon(2S)$	$7.90^{+75.4\%}_{-46.4\%} \pm 4.6\%$	$5.18^{+75.4\%}_{-46.4\%} \pm 4.6\%$
	$\Upsilon(3S)$	$6.04^{+75.4\%}_{-46.4\%} \pm 4.6\%$	$3.96^{+75.4\%}_{-46.4\%} \pm 4.6\%$
INTER	$\Upsilon(1S)$	$-16.6^{+162\%}_{-62.0\%} \pm 4.8\%$	$-10.9^{+162\%}_{-62.0\%} \pm 4.8\%$
	$\Upsilon(2S)$	$-8.29^{+162\%}_{-62.0\%} \pm 4.8\%$	$-5.43^{+162\%}_{-62.0\%} \pm 4.8\%$
	$\Upsilon(3S)$	$-6.34^{+162\%}_{-62.0\%} \pm 4.8\%$	$-4.15^{+162\%}_{-62.0\%} \pm 4.8\%$
COM	$\Upsilon(1S)$	$409^{+138\%}_{-56.7\%} \pm 4.4\%$	$174^{+138\%}_{-56.8\%} \pm 4.4\%$
	$\Upsilon(2S)$	$135^{+139\%}_{-57.0\%} \pm 4.4\%$	$57.6^{+139\%}_{-57.1\%} \pm 4.4\%$
	$\Upsilon(3S)$	$197^{+137\%}_{-56.6\%} \pm 4.4\%$	$84.1^{+138\%}_{-56.7\%} \pm 4.4\%$

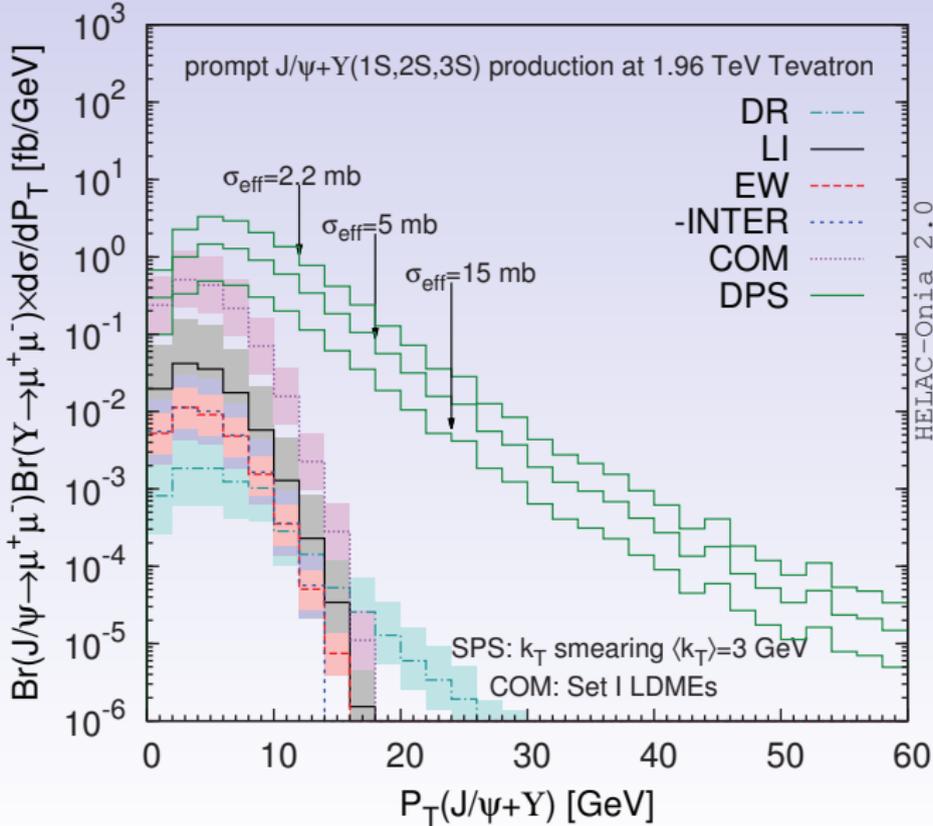
SPS cross sections @ D0 & LHCb

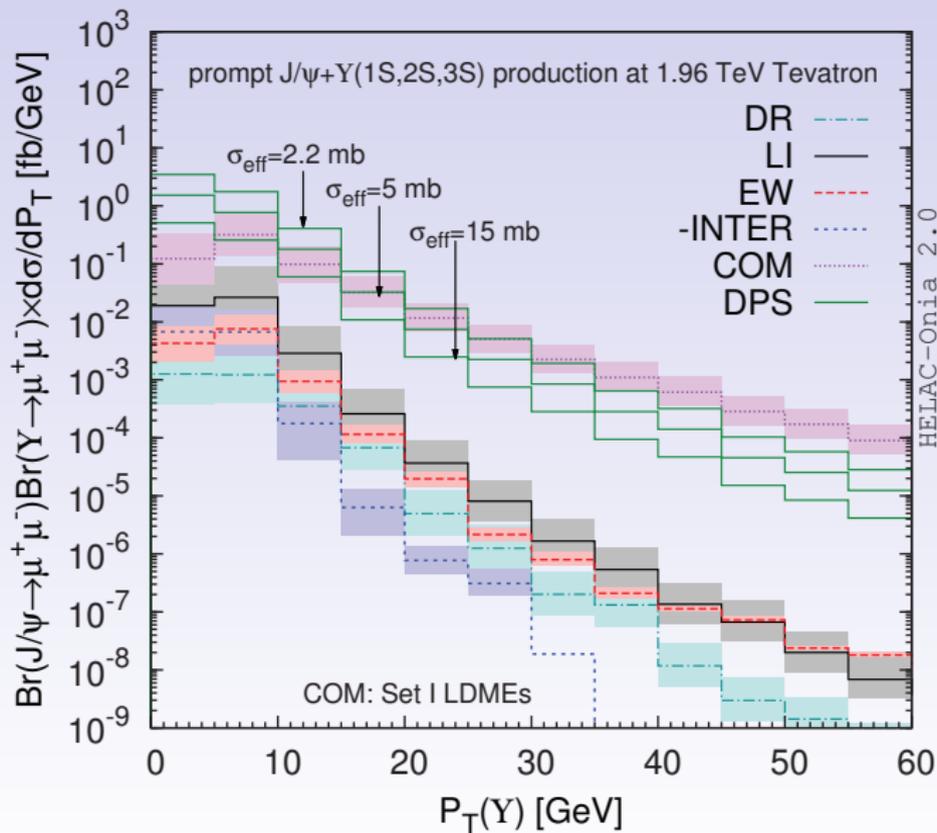
exp.	CSM				Set I
	DR	LI	EW	INTER	
D0: $27 \pm 42.2\%$	$0.0146^{+233\%}_{-66.6\%}$	$0.229^{+264\%}_{-70.4\%}$	$0.065^{+75.5\%}_{-46.6\%}$	$-0.068^{+162\%}_{-62.2\%}$	$2.96^{+135\%}_{-56.2\%}$
LHCb	$0.255^{+391\%}_{-79.7\%}$	$6.05^{+436\%}_{-82.2\%}$	$1.71^{+135\%}_{-65.2\%}$	$-3.23^{+262\%}_{-75.9\%}$	$38.8^{+238\%}_{-73.0\%}$

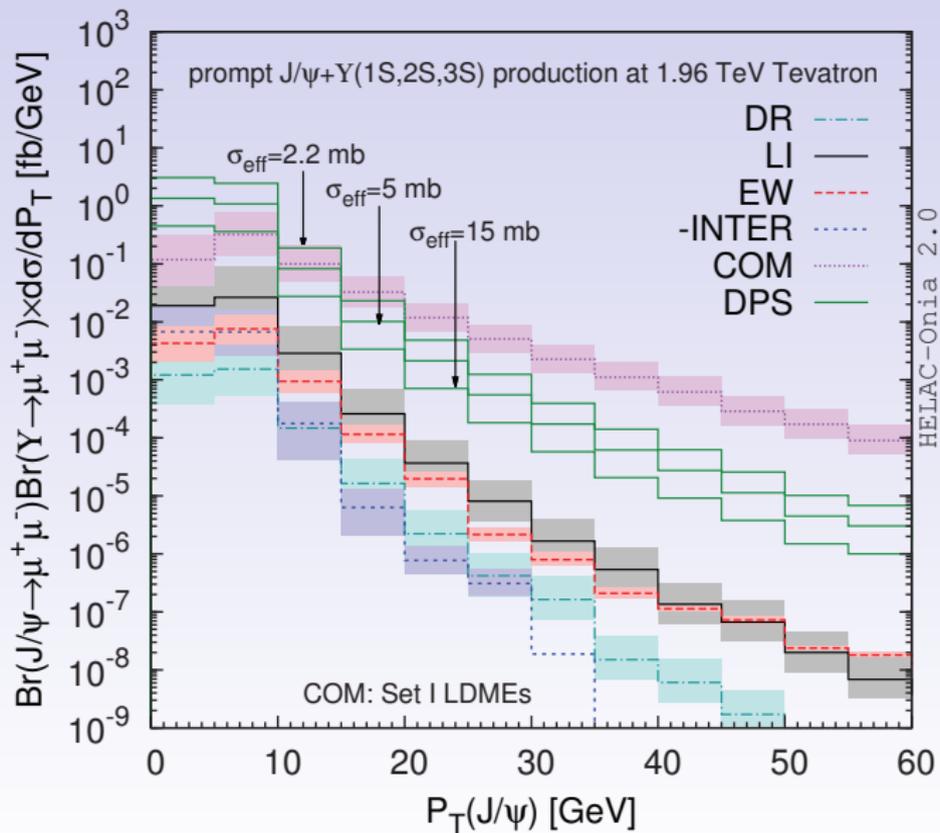


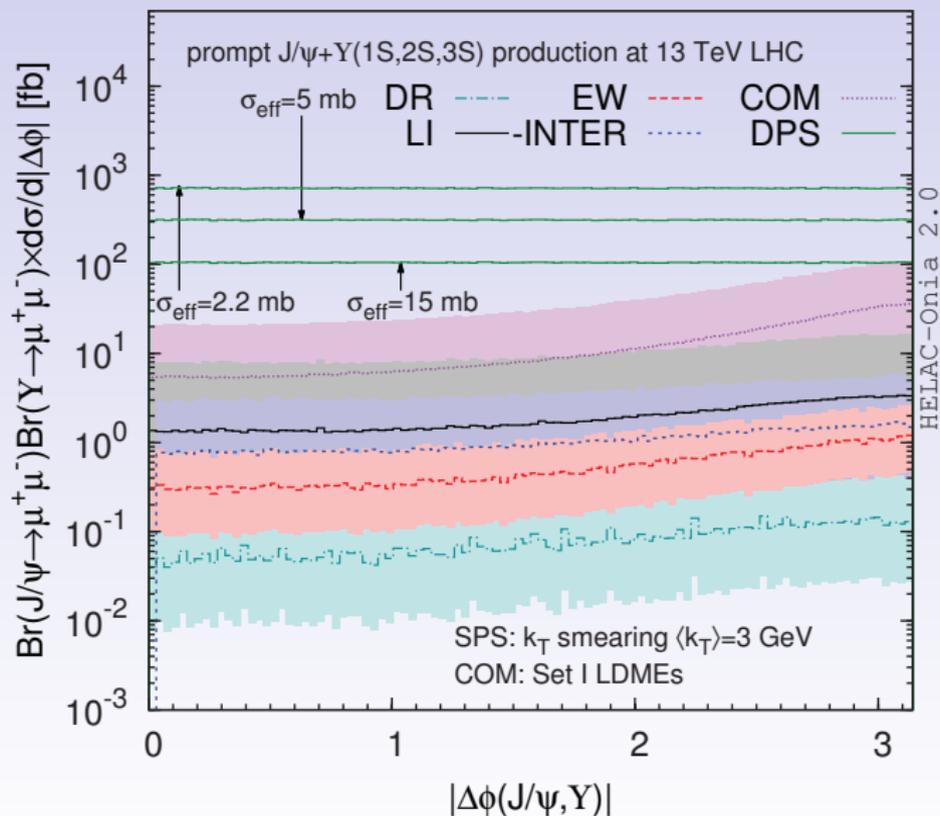


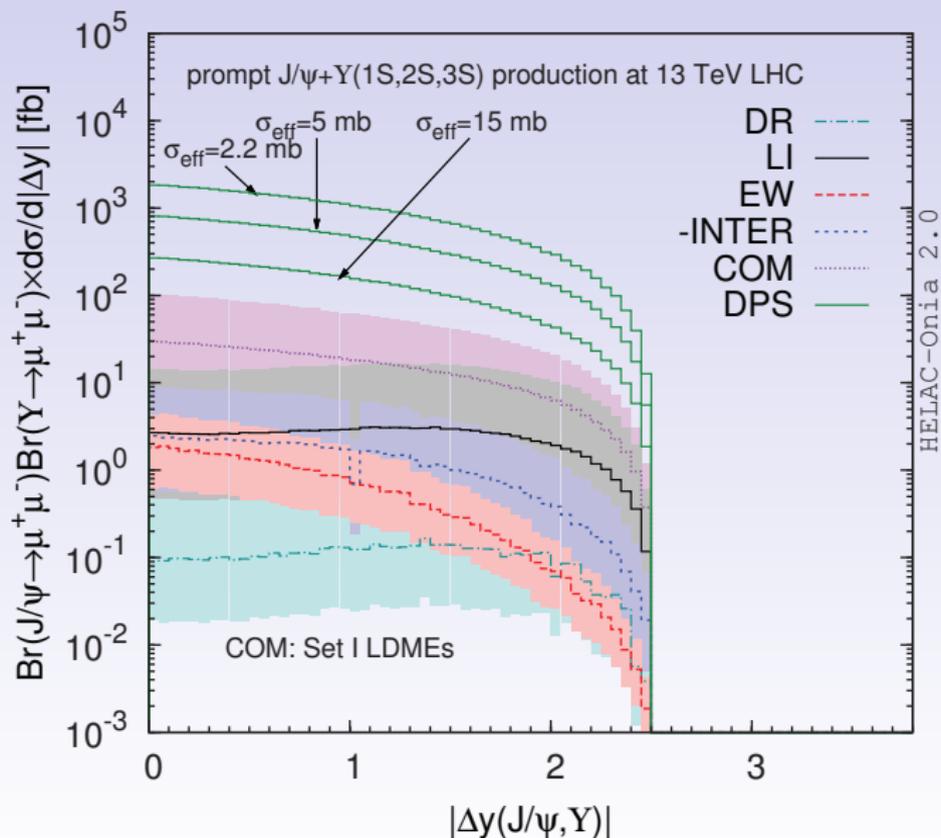


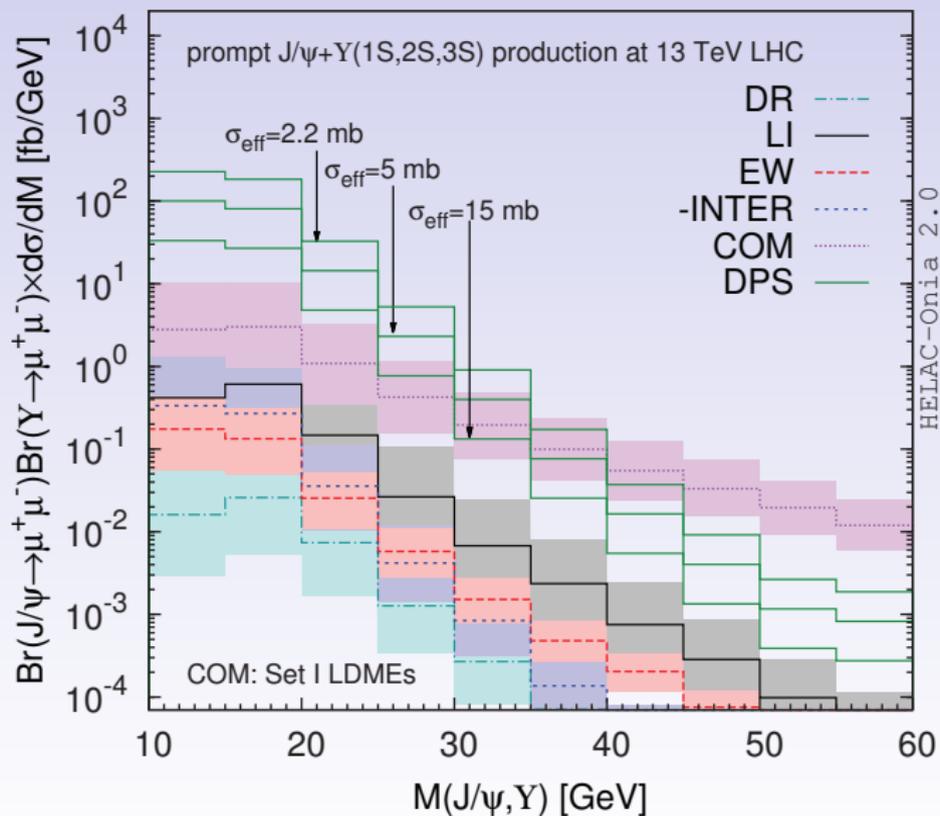


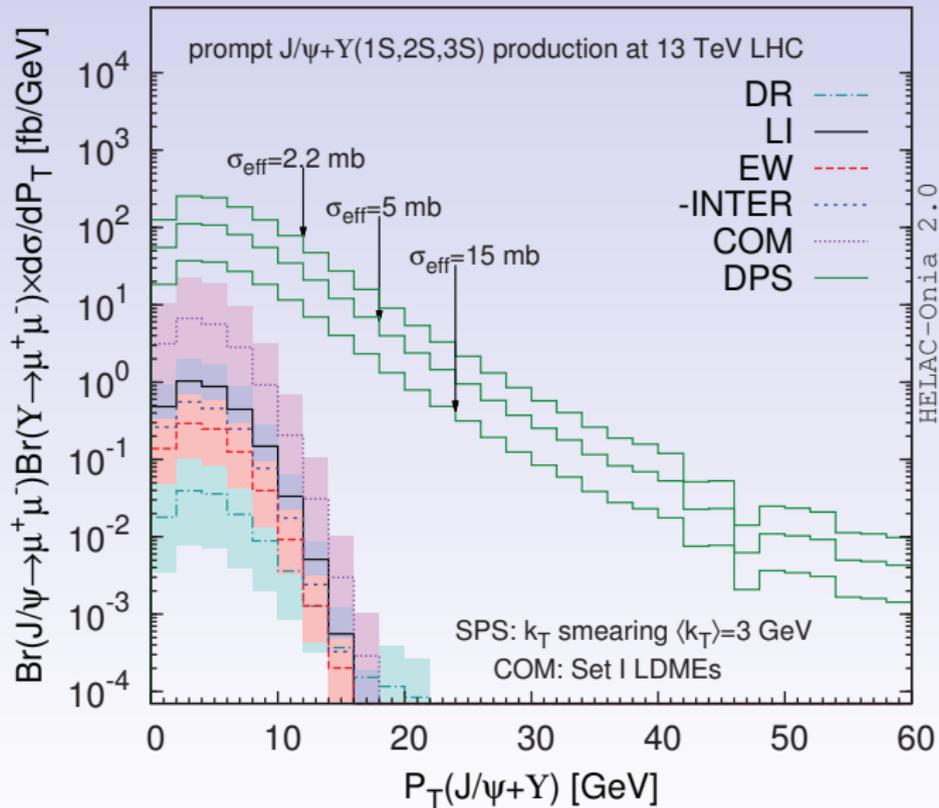


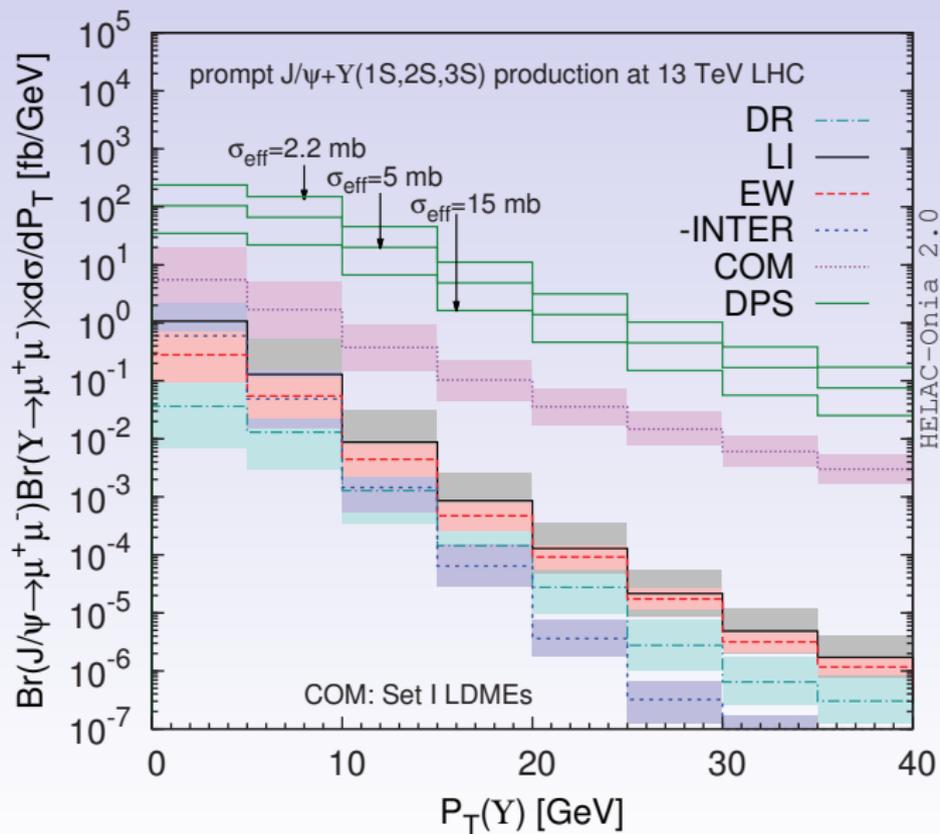


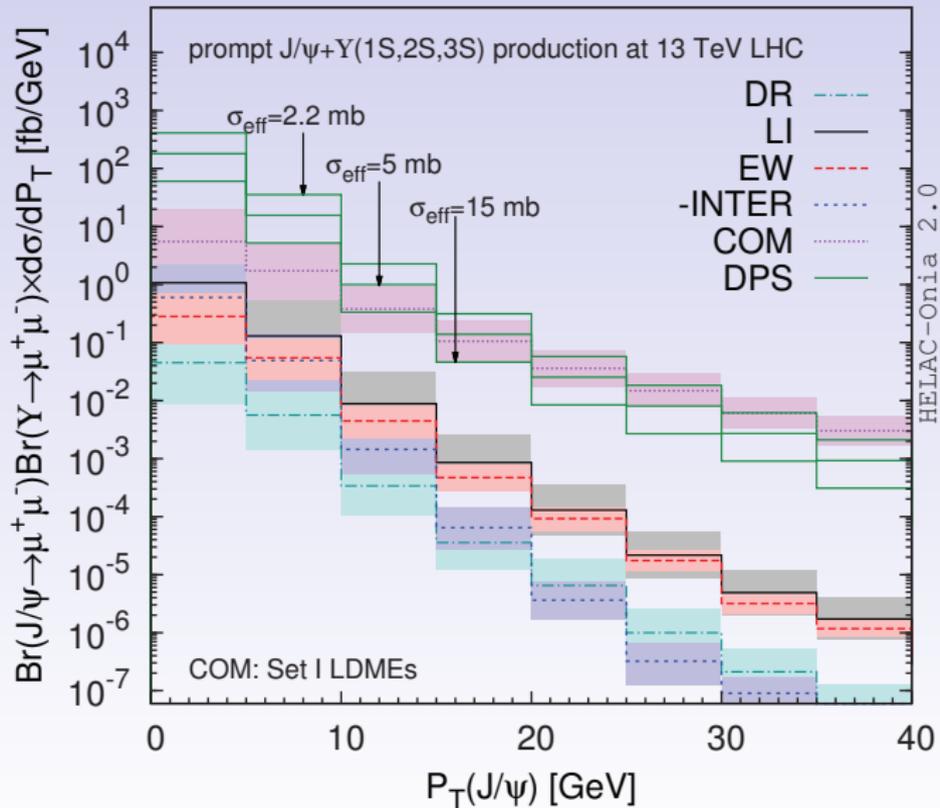












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- ③ Finally, we also present our predictions of prompt J/ψ and Υ production at the LHCb.

Thanks!

