Heavy Quarkonium Associated Production and Multi-parton Interaction

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Outline

Introduction

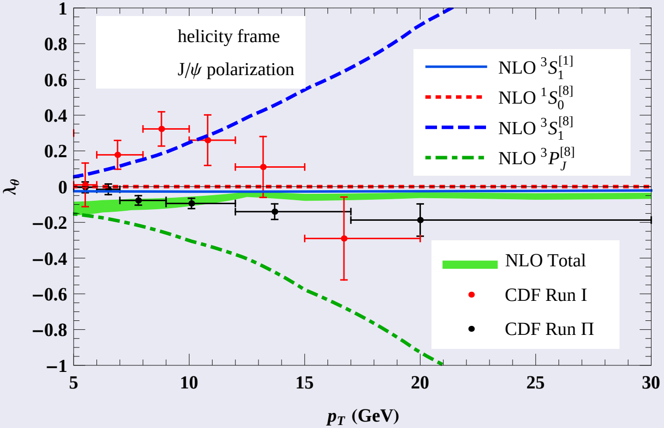
Quarkonium productions

Quarkonium production have been studied by

1. Kuang-Ta Chao group
2. Yu Jia group
3. B. A. Kniehl group
4. Cong-Feng Qiao group
5. Jian-Xiong Wang group
6. ...

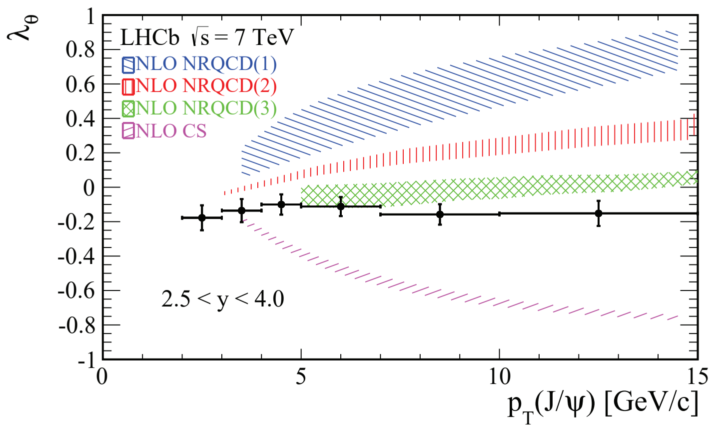
Quarkonium productions

NLO J/ψ polarization at CDF, arXiv:1201.2675



Quarkonium productions

NLO J/ψ at LHCb, Chao/Wang/Kniehl, 1506.03981



Quarkonium production and double parton scattering

Many quarkonium associated production processes seems to be dominant by Double-Parton Scattering (DPS).

1. $J/\psi + W$ and $J/\psi + Z$, (ATLAS, arXiv:1401.2831, 1412.6428)

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3. $J/\psi + J/\psi$ (D0, arXiv:1406.2380; CMS, arXiv:1406.0484)

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4. $\Upsilon + J/\psi$ (D0, arXiv:1511.02428)

Multi parton scattering

The inclusive cross section to produce *n* hard particles in hadronic colliders is a convolution of generalized *n*-parton distribution functions (PDF) and elementary partonic cross sections summed over all involved partons,

$$
\begin{aligned}
&\sigma^{\mathrm{NPS}}_{hh'\to a_1\ldots a_n} = \\
&\left(\frac{m}{n!}\right) \sum_{i_1,..,i_n,i'_1,..,i'_n} \int \Gamma_h^{i_1\ldots i_n}(x_1,..,x_n;\mathbf{b_1},..,\mathbf{b_n};Q_1^2,..,Q_n^2) \\
&\times \hat{\sigma}_{a_1}^{i_1 i'_1}(x_1,x'_1,Q_1^2)\cdots\hat{\sigma}_{a_n}^{i_n i'_n}(x_n,x'_n,Q_n^2) \\
&\times \Gamma_{h'}^{i'_1\ldots i'_n}(x'_1,\ldots,x'_n;\mathbf{b_1}-\mathbf{b},\ldots,\mathbf{b_n}-\mathbf{b};Q_1^2,\ldots,Q_n^2) \\
&\times dx_1\ldots dx_n\, dx'_1,\ldots,dx'_n\, d^2b_1,\ldots,d^2b_n\, d^2b.
\end{aligned}
\tag{1}
$$

Double parton scattering and Single parton scattering

SPS and DPS

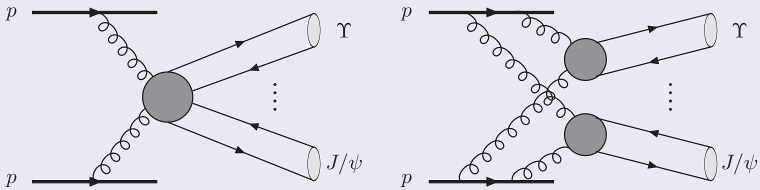


Figure: SPS and DPS of $pp \to J/\psi + \Upsilon + X$.

Triple parton scattering

TPS

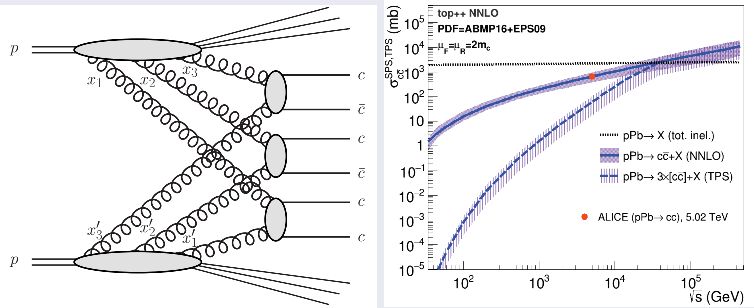


Figure: TPS of $pp \to c\bar{c} + c\bar{c} + c\bar{c}$ (PRL118, 122001).

The *n*-parton distribution function (1708.07519)

It encodes all the 3D structure information of the hadron.

1. Assumption 1: the n-PDF are factored in terms of longitudinal and transverse components,

$$\Gamma_h^{i_1 \dots i_n} = D_h^{i_1 \dots i_n}(x_1, .., x_n; Q_1^2, .., Q_n^2) f(\mathbf{b_1}) \dots f(\mathbf{b_n}) \qquad (2)$$

2. We can get hadron-hadron overlap function $T(\mathbf{b}) = \int f(\mathbf{b_1}) f(\mathbf{b_1} - \mathbf{b}) d^2 b_1$, where $1 = \int T(\mathbf{b}) d^2 b$.
3. Assumption 2: the longitudinal components reduce to the product of independent single PDF

$$D_h^{i_1 \dots i_n}(x_1, .., x_n; Q_1^2, .., Q_n^2) = D_h^{i_1}(x_1; Q_1^2) \cdots D_h^{i_n}(x_n; Q_n^2) \qquad (3)$$

The cross sections and σ_{eff}^{nPS} (1708.07519)

The cross sections of *n*-particle associated production

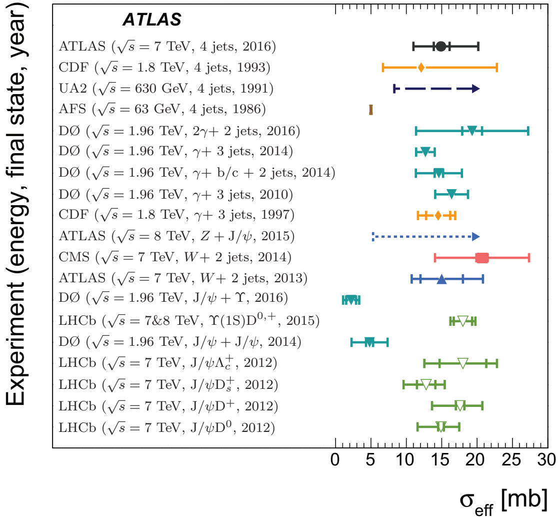
Then we can get

$$\sigma^{nPS}_{hh'\to a_1\ldots a_n} = \left(\frac{m}{n!}\right)\frac{\sigma^{SPS}_{hh'\to a_1}\cdots\sigma^{SPS}_{hh'\to a_n}}{\left(\sigma^{nPS}_{eff}\right)^{n-1}}, \tag{4}$$

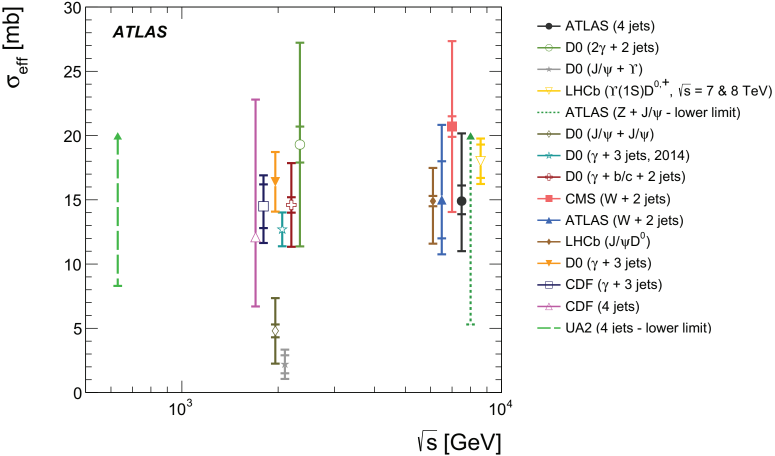
σ_{eff}^{nPS}

$$\left(\frac{1}{\sigma^{nPS}_{eff}}\right)^{n-1} = \int d^2b\, T^n(\mathbf{b}) \tag{5}$$

σ_{eff}^{DPS} (arXiv:1608.01857)



σ_{eff}^{DPS} (arXiv:1608.01857)



Prompt $J/\psi + \Upsilon$ @ D0

Prompt $J/\psi + \Upsilon(1S, 2S, 3S)$ @ D0 (arXiv:1511.02428)

$$\sigma_{D0}^{J/\psi+\Upsilon} = 27 \pm 9 \pm 7 \text{ fb} \tag{6}$$

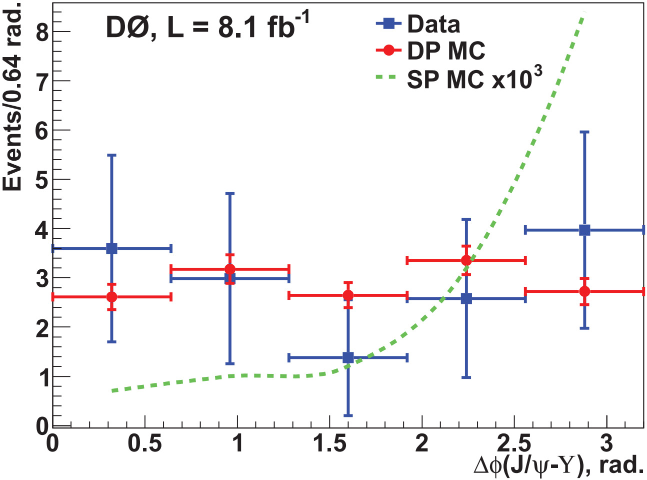
Ignore the SPS contribution

$$\sigma_{DPS}^{J/\psi+\Upsilon} = \sigma_{D0}^{J/\psi+\Upsilon} = \frac{\sigma^{J/\psi}\sigma^{\Upsilon}}{\sigma_{eff}} \tag{7}$$

σ_{eff}

$$\sigma_{eff} = 2.2 \pm 0.7 \pm 0.9 \text{ mb} \tag{8}$$

The distribution of the azimuthal angle between the $J/\psi + \Upsilon$



Color-Singlet contributions of $J/\psi + \Upsilon$

Color-Singlet contributions

Unlike J/ψ-pair or Υ-pair production, neither $\mathcal{O}(\alpha_S^4)$ nor $\mathcal{O}(\alpha_S^5)$ contributions survive in Color-Singlet Model (CSM).

The approximated Loop-Induced (LI) contribution

The approximated Loop-Induced (LI) contribution in CSM at $\mathcal{O}(\alpha_S^6)$ was estimated in Ref. (arXiv:1503.00246) with in the specific limit $\hat{s} \gg |\hat{t}| \gg m^2_{\psi,\Upsilon}$, where $\hat{s}$ and $\hat{t}$ are the Mandelstam variables.

Color-Octet contributions of $J/\psi + \Upsilon$

Color-Octet contributions

The process is a golden observable to probe the so-called Color-Octet Mechanism (COM) (arXiv:1007.3095)

Color-Octet contributions at $\sqrt{s} = 115$ GeV

The Color Octet (CO) contribution were predicted for AFTER@LHC energies $\sqrt{s} = 115$ GeV (arXiv:1504.06531) with HELAC-Onia (arXiv:1212.5293, 1507.03435).

Hadroproduction of $\Upsilon + J/\psi$

SPS contributions were absence

However, the exact calculations of the complete SPS contributions were absence in the literature.

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

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

Cross sections

Hadron and Parton level cross sections

$$\sigma(h_1 h_2 \to \mathcal{C} + \mathcal{B} + X) = \sum_{a,b} f_{a/h_1} \otimes f_{b/h_2} \otimes \hat{\sigma}(ab \to \mathcal{C} + \mathcal{B} + X). \tag{9}$$

Parton level cross section

$$d\hat{\sigma}(ab \to \mathcal{C} + \mathcal{B} + X) = \sum_{n_1, n_2} \hat{\sigma}(ab \to c\bar{c}[n_1] + b\bar{b}[n_2] + X) \langle O^{\mathcal{C}}(n_1)\rangle \langle O^{\mathcal{B}}(n_2)\rangle \tag{10}$$

Matrix elements

Fock States Of J/ψ

$$\begin{aligned} |J/\psi\rangle &= \mathcal{O}(1)|c\bar{c}(^3S_1^{[1]})\rangle + \mathcal{O}(v_c^2)|c\bar{c}(^3S_1^{[8]})gg\rangle \\ &+ \mathcal{O}(v_c^2)|c\bar{c}(^3P_J^{[1,8]})g\rangle + \mathcal{O}(v_c^2)|c\bar{c}(^1S_0^{[8]})g\rangle + \ldots . \end{aligned}$$

v^2

$$\begin{aligned} v_b^2 &\sim v_c^2 \sim 0.1 - 0.3 \\ \alpha_S &\sim 0.2 \\ \alpha_S &\sim v_c^2 \sim v_b^2 \end{aligned} \quad (11)$$

QED

J^{PC} Of J/ψ or Υ are 1^{--}

QED contributions may be important too.

α

$$\begin{aligned} \alpha &\sim 0.008 \\ \alpha_S &\sim \sqrt{\alpha} \end{aligned} \tag{12}$$

$\mathcal{O}(\alpha_S^6)$

Color Singlet

The $\mathcal{O}(\alpha_S^4)$ and $\mathcal{O}(\alpha_S^5)$ contributions to $\Upsilon + \psi$ direct production in CSM vanish because of P-parity and C-parity conservation.

Color Octet

$\mathcal{O}(\alpha_S^4 v_c^i v_b^j) \leq \mathcal{O}(\alpha_S^6)$ with $i + j \geq 4$

EW

$\mathcal{O}(\alpha_S^2 \alpha^2) \leq \mathcal{O}(\alpha_S^6)$ with $i + j \geq 4$

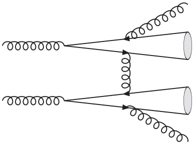
Feeddown for $\chi_{c,b}$

$\mathcal{O}(\alpha_S^4 v_c^i v_b^j) \leq \mathcal{O}(\alpha_S^6)$ with $i + j \geq 4$

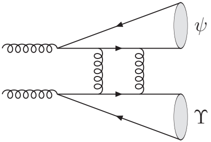
Order of SPS

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

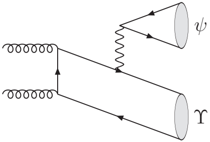
Feynman Diagram of SPS



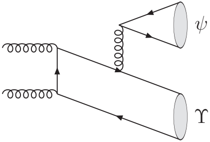
DR



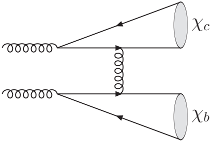
LI



EW



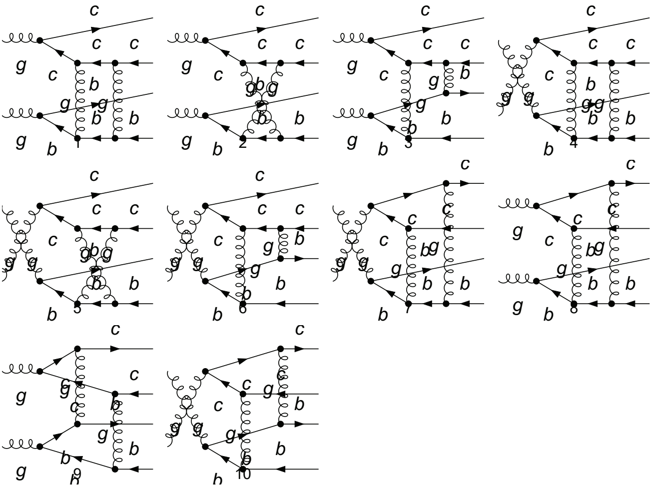
NRQCD



FD

Loop Induced Contributions

Feynman Diagram



Loop induced contributions of $J/\psi + \Upsilon$

Tree contributions is 0

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The Loop-Induced (LI) contributions are UV and IR finite

1. The amplitude can be calculated in $D = 4$ directly.
2. The gluon mass is introduced to test IR divergence.
3. The momentum and polarization vector can be written in $D = 4$ directly.
4. ...

Momentum for IR and UV finite amplitude

Momentum of $g(k_1)g(k_2) \to J/\psi(p_1) + \Upsilon(p_2)$

$$\begin{aligned} k_1 &= \{\frac{\sqrt{s}}{2}, 0, 0, \frac{\sqrt{s}}{2}\} \\ k_2 &= \{\frac{\sqrt{s}}{2}, 0, 0, -\frac{\sqrt{s}}{2}\} \\ p_1 &= \{E_1, 0, p \times \sin\theta, p \times \cos\theta\} \\ p_2 &= \{E_2, 0, -p \times \sin\theta, -p \times \cos\theta\} \end{aligned} \tag{13}$$

Momentum and polarization vector of $g(k_1)g(k_2)$

Momentum of $g(k_1)g(k_2)$

$$\begin{aligned} k_1 &= \{\frac{\sqrt{s}}{2}, 0, 0, \frac{\sqrt{s}}{2}\} \\ k_2 &= \{\frac{\sqrt{s}}{2}, 0, 0, -\frac{\sqrt{s}}{2}\} \end{aligned} \tag{14}$$

Polarization of $g(k_1)g(k_2)$

$$\begin{aligned} \epsilon_1(k_1) &= \epsilon_2(k_2) = \{0, 1, 0, 0\} \\ \epsilon_2(k_1) &= \epsilon_1(k_2) = \{0, 0, 1, 0\} \end{aligned} \tag{15}$$

Momentum and polarization of $J/\psi(p_1) + \Upsilon(p_2)$

Momentum of $J/\psi(p_1) + \Upsilon(p_2)$

$$\begin{aligned} p_1 &= \{E_1, 0, p \times \sin\theta, p \times \cos\theta\} \\ p_2 &= \{E_2, 0, -p \times \sin\theta, -p \times \cos\theta\} \end{aligned} \quad (16)$$

Polarization of $J/\psi(p_1) + \Upsilon(p_2)$

$$\begin{aligned} \epsilon_L(p_1) &= 1/m_J\{p, 0, E_1\sin\theta, E_1\cos\theta\} \\ \epsilon_L(p_2) &= 1/m_\Upsilon\{p, 0, -E_2\sin\theta, -E_2\cos\theta\} \\ \epsilon_{T1}(p_1) &= \epsilon_{T1}(p_2) = \{0, 1, 0, 0\} \\ \epsilon_{T2}(p_1) &= \epsilon_{T2}(p_2) = \{0, 0, -\cos\theta, \sin\theta\} \end{aligned} \quad (17)$$

Amplitude

Amplitude of $g(k_1, 1)g(k_2, 1) \to J/\psi(p_1, L) + \Upsilon(p_2, L)$

- Cololor factor can be calculated diagram by diagram. It can be considered as a global factor.

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- The scalar product of $k_1,\ k_2,\ p_1,\ p_2$ and polarization vector can be expressed by $s,\ m_J,\ m_\Upsilon,\ E_1,\ p,\ \theta$.

Amplitude

Amplitude of $g(k_1,1)g(k_2,1)\rightarrow J/\psi(p_1,L)+\Upsilon(p_2,L)$

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- Loop integrate.

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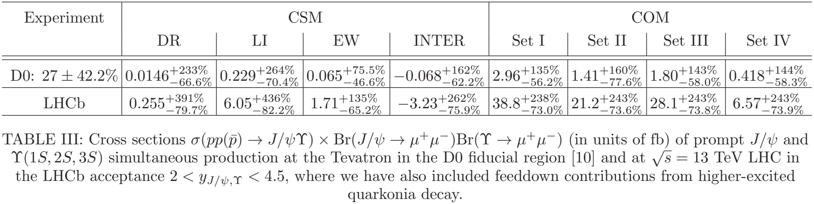
- Loop integrate.
- Amplitude can be expressed by $s,\ m_J,\ m_\Upsilon,\ E_1,\ p,\ \theta$.
- Simplify the amplitude

Numerical Result of $\Upsilon + J/\psi$

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	$\Upsilon(1S)$	$409^{+138\%}_{-56.7\%} \pm 4.4\%$	$174^{+138\%}_{-56.8\%} \pm 4.4\%$
	$\Upsilon(2S)$	$135^{+139\%}_{-57.0\%} \pm 4.4\%$	$57.6^{+139\%}_{-57.1\%} \pm 4.4\%$
	$\Upsilon(3S)$	$197^{+137\%}_{-56.6\%} \pm 4.4\%$	$84.1^{+138\%}_{-56.7\%} \pm 4.4\%$

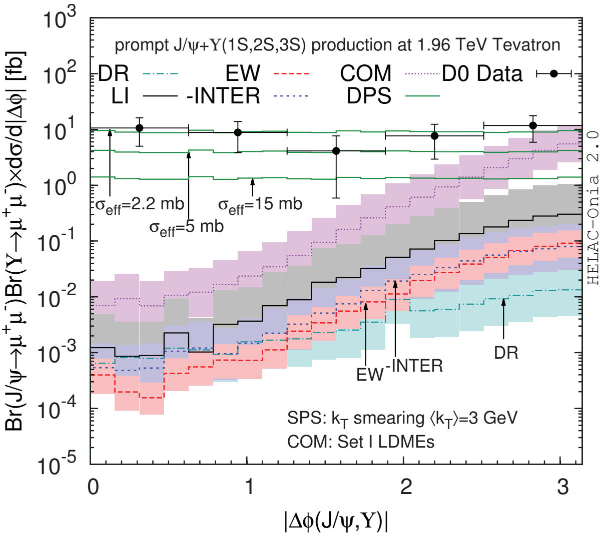
SPS cross sections @ D0 & LHCb



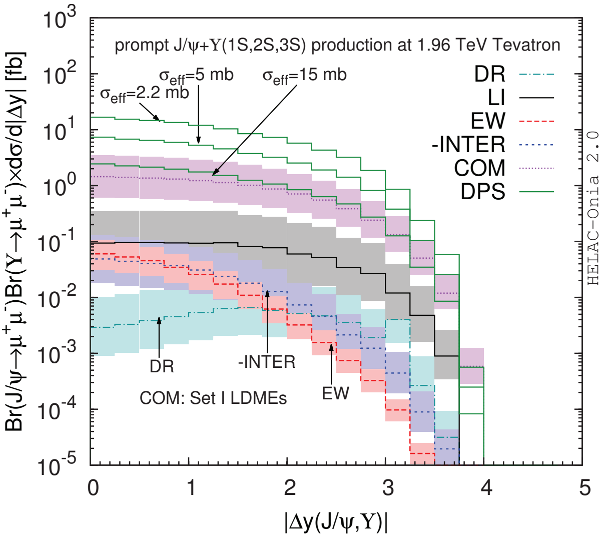
Experiment	CSM				COM			
	DR	LI	EW	INTER	Set I	Set II	Set III	Set IV
D0: $27 \pm 42.2\%$	$0.0146^{+233\%}_{-66.6\%}$	$0.229^{+264\%}_{-70.4\%}$	$0.065^{+75.5\%}_{-46.6\%}$	$-0.068^{+162\%}_{-62.2\%}$	$2.96^{+135\%}_{-56.2\%}$	$1.41^{+160\%}_{-77.6\%}$	$1.80^{+143\%}_{-58.0\%}$	$0.418^{+144\%}_{-58.3\%}$
LHCb	$0.255^{+391\%}_{-79.7\%}$	$6.05^{+436\%}_{-82.2\%}$	$1.71^{+135\%}_{-65.2\%}$	$-3.23^{+262\%}_{-75.9\%}$	$38.8^{+238\%}_{-73.0\%}$	$21.2^{+243\%}_{-73.6\%}$	$28.1^{+243\%}_{-73.8\%}$	$6.57^{+243\%}_{-73.9\%}$

TABLE III: Cross sections $\sigma(pp(\bar{p}) \to J/\psi\Upsilon) \times \mathrm{Br}(J/\psi \to \mu^+\mu^-)\mathrm{Br}(\Upsilon \to \mu^+\mu^-)$ (in units of fb) of prompt J/ψ and $\Upsilon(1S, 2S, 3S)$ simultaneous production at the Tevatron in the D0 fiducial region [10] and at $\sqrt{s} = 13$ TeV LHC in the LHCb acceptance $2 < y_{J/\psi,\Upsilon} < 4.5$, where we have also included feeddown contributions from higher-excited quarkonia decay.

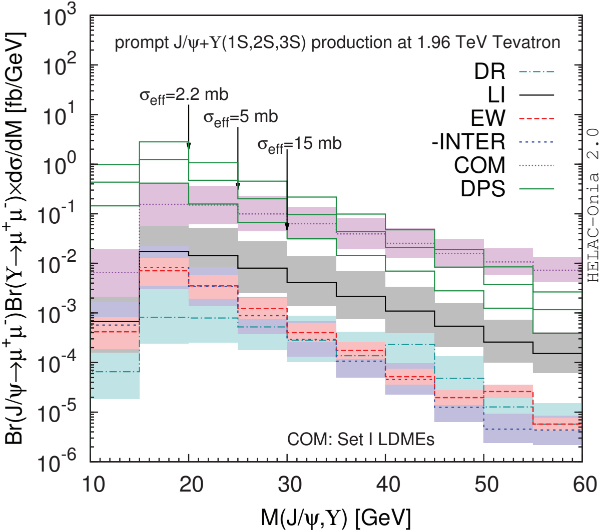
dphi @ D0


prompt J/ψ+Υ(1S,2S,3S) production at 1.96 TeV Tevatron
DR
EW
COM
D0 Data
LI
-INTER
DPS
σ_eff=2.2 mb
σ_eff=5 mb
σ_eff=15 mb
EW
-INTER
DR
SPS: k_T smearing ⟨k_T⟩=3 GeV
COM: Set I LDMEs
HELAC-Onia 2.0
Br(J/ψ→μ+μ-)Br(Υ→μ+μ-)×dσ/d|Δφ| [fb]
|Δφ(J/ψ,Υ)|
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
0
1
2
3

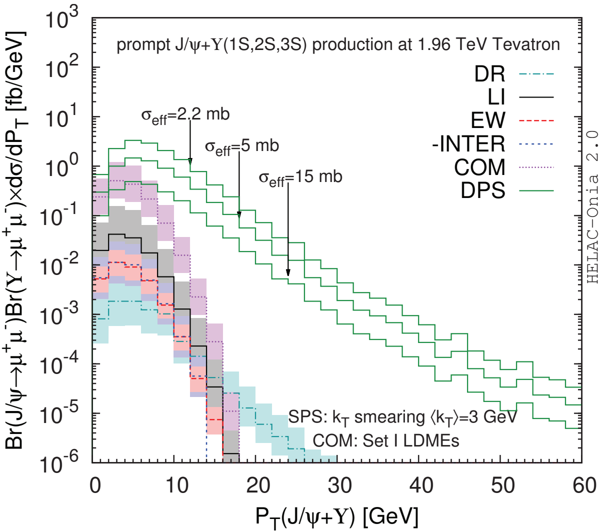
dy @ D0


prompt J/ψ+Υ(1S,2S,3S) production at 1.96 TeV Tevatron
σeff=2.2 mb
σeff=5 mb
σeff=15 mb
DR
LI
EW
-INTER
COM
DPS
DR
-INTER
EW
COM: Set I LDMEs
HELAC-Onia 2.0
Br(J/ψ→μ+μ-)Br(Υ→μ+μ-)×dσ/d|Δy| [fb]
|Δy(J/ψ,Υ)|
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
0
1
2
3
4
5

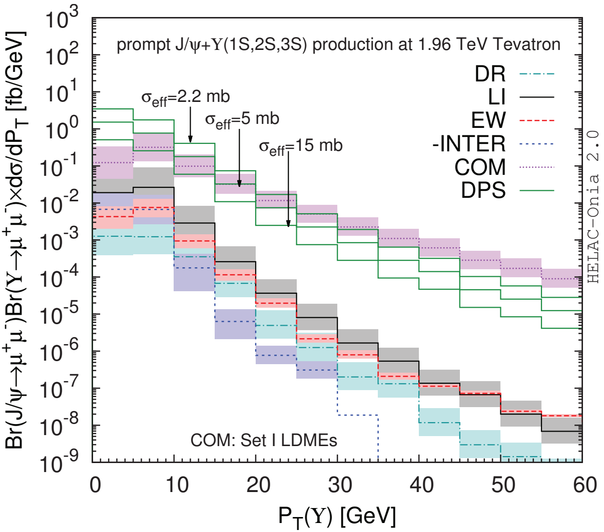
dM @ D0


prompt J/ψ+Υ(1S,2S,3S) production at 1.96 TeV Tevatron
DR
LI
EW
-INTER
COM
DPS
σeff=2.2 mb
σeff=5 mb
σeff=15 mb
COM: Set I LDMEs
HELAC-Onia 2.0
Br(J/ψ→μ+μ-)Br(Υ→μ+μ-)×dσ/dM [fb/GeV]
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10
20
30
40
50
60
M(J/ψ,Υ) [GeV]

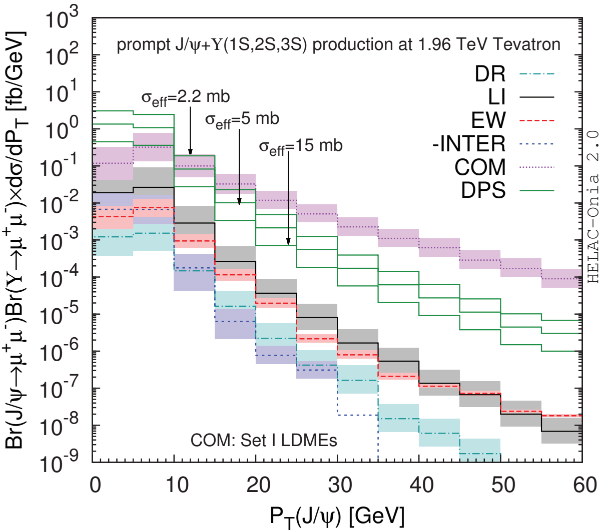
dPt @ D0


prompt J/ψ+Υ(1S,2S,3S) production at 1.96 TeV Tevatron
DR
LI
EW
-INTER
COM
DPS
σeff=2.2 mb
σeff=5 mb
σeff=15 mb
SPS: kT smearing ⟨kT⟩=3 GeV
COM: Set I LDMEs
HELAC-Onia 2.0
Br(J/ψ→μ+μ-)Br(Υ→μ+μ-)×dσ/dPT [fb/GeV]
PT(J/ψ+Υ) [GeV]
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0
10
20
30
40
50
60

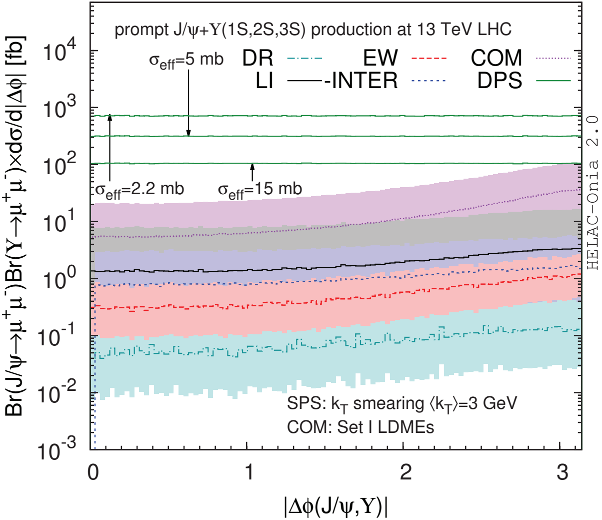
dptY @ D0


prompt J/ψ+Υ(1S,2S,3S) production at 1.96 TeV Tevatron
DR
LI
EW
-INTER
COM
DPS
σ_eff=2.2 mb
σ_eff=5 mb
σ_eff=15 mb
COM: Set I LDMEs
HELAC-Onia 2.0
Br(J/ψ→μ+μ-)Br(Υ→μ+μ-)×dσ/dP_T [fb/GeV]
P_T(Υ) [GeV]
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
0
10
20
30
40
50
60

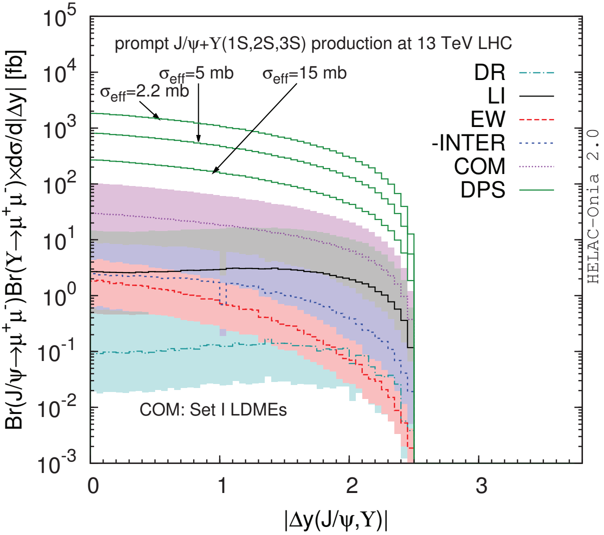
dptpsi @ D0


prompt J/ψ+Υ(1S,2S,3S) production at 1.96 TeV Tevatron
DR
LI
EW
-INTER
COM
DPS
σeff=2.2 mb
σeff=5 mb
σeff=15 mb
COM: Set I LDMEs
HELAC-Onia 2.0
Br(J/ψ→μ+μ-)Br(Υ→μ+μ-)×dσ/dPT [fb/GeV]
PT(J/ψ) [GeV]
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
0
10
20
30
40
50
60

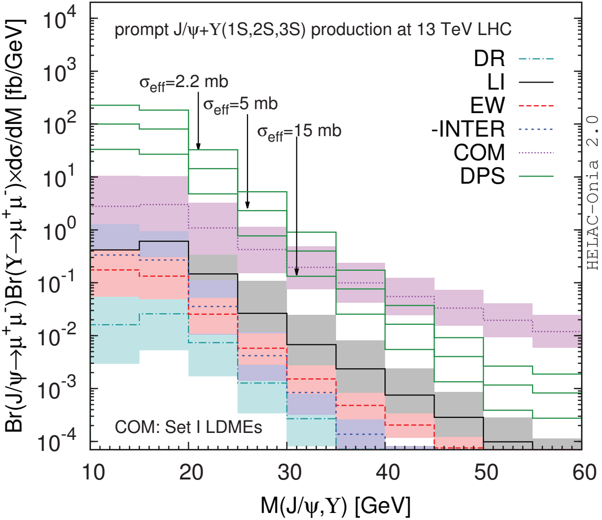
dphi @ LHCB


prompt J/ψ+Υ(1S,2S,3S) production at 13 TeV LHC
σ_{eff}=5 mb
DR
EW
COM
LI
-INTER
DPS
σ_{eff}=2.2 mb
σ_{eff}=15 mb
SPS: k_T smearing $\langle k_T \rangle$=3 GeV
COM: Set I LDMEs
HELAC-Onia 2.0
$\mathrm{Br}(J/\psi\to\mu^+\mu^-)\mathrm{Br}(\Upsilon\to\mu^+\mu^-)\times d\sigma/d|\Delta\phi|$ [fb]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
1
2
3
$|\Delta\phi(J/\psi,\Upsilon)|$

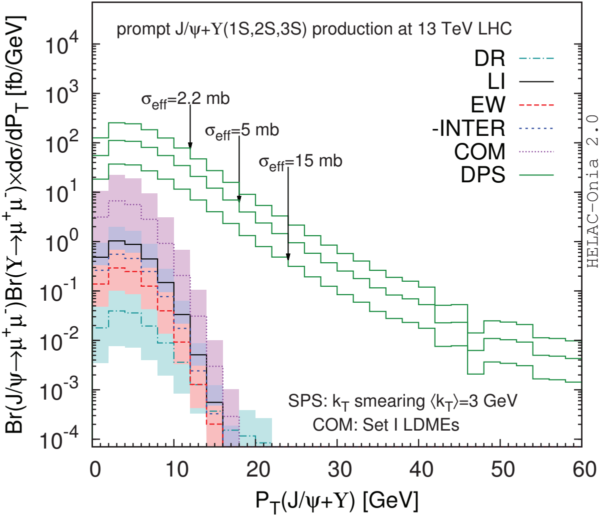
dy @ LHCB


prompt J/ψ+Υ(1S,2S,3S) production at 13 TeV LHC
σ_eff=2.2 mb
σ_eff=5 mb
σ_eff=15 mb
DR
LI
EW
-INTER
COM
DPS
HELAC-Onia 2.0
COM: Set I LDMEs
Br(J/ψ→μ+μ-)Br(Υ→μ+μ-)×dσ/d|Δy| [fb]
|Δy(J/ψ,Υ)|
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
0
1
2
3

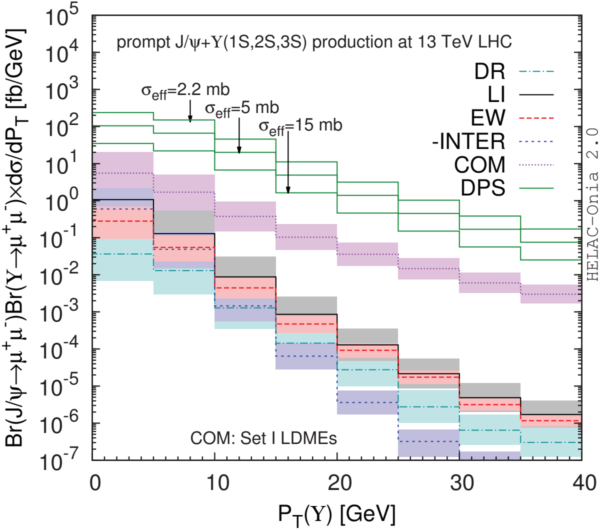
dM @ LHCB


prompt J/ψ+Υ(1S,2S,3S) production at 13 TeV LHC
σ_eff=2.2 mb
σ_eff=5 mb
σ_eff=15 mb
DR
LI
EW
-INTER
COM
DPS
COM: Set I LDMEs
HELAC-Onia 2.0
Br(J/ψ→μ⁺μ⁻)Br(Υ→μ⁺μ⁻)×dσ/dM [fb/GeV]
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10
20
30
40
50
60
M(J/ψ,Υ) [GeV]

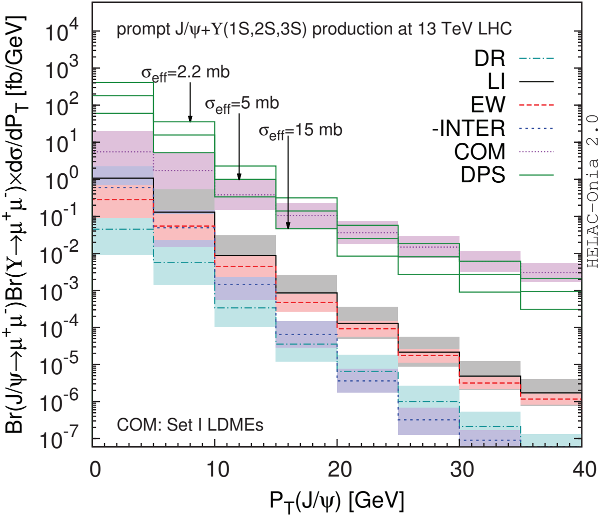
dPt @ LHCB


prompt J/ψ+Υ(1S,2S,3S) production at 13 TeV LHC
DR
LI
EW
-INTER
COM
DPS
σeff=2.2 mb
σeff=5 mb
σeff=15 mb
SPS: kT smearing ⟨kT⟩=3 GeV
COM: Set I LDMEs
HELAC-Onia 2.0
Br(J/ψ→μ+μ-)Br(Υ→μ+μ-)×dσ/dPT [fb/GeV]
PT(J/ψ+Υ) [GeV]
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
0
10
20
30
40
50
60

dptY @ LHCB


prompt J/ψ+Υ(1S,2S,3S) production at 13 TeV LHC
σ_{eff}=2.2 mb
σ_{eff}=5 mb
σ_{eff}=15 mb
DR
LI
EW
-INTER
COM
DPS
COM: Set I LDMEs
HELAC-Onia 2.0
$Br(J/\psi \to \mu^+\mu^-)Br(\Upsilon \to \mu^+\mu^-) \times d\sigma/dP_T$ [fb/GeV]
$P_T(\Upsilon)$ [GeV]
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
10
20
30
40

dptpsi @ LHCB


prompt J/ψ+Υ(1S,2S,3S) production at 13 TeV LHC
σeff=2.2 mb
σeff=5 mb
σeff=15 mb
DR
LI
EW
-INTER
COM
DPS
COM: Set I LDMEs
HELAC-Onia 2.0
Br(J/ψ→μ+μ-)Br(Υ→μ+μ-)×dσ/dPT [fb/GeV]
PT(J/ψ) [GeV]
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
0
10
20
30
40

Numerical Result of $\Upsilon + J/\psi + \phi$

Numerical Result for $\Upsilon + J/\psi + \phi$

SPS cross section of $\Upsilon,\ J/\psi,\ \phi$ at LHCb

1. We can get the inclusive cross sections of $\Upsilon,\ J/\psi,\ \phi$ at $\sqrt{s} = 13$ TeV at LHCb, it 0.2(15) μb for $\Upsilon(J/\psi)$, and the cross sections is 0.6 mb for $p_T(\phi) > 2$ GeV.

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2. With the NLO(LO) LDMEs, $\sigma^{SPS}[\Upsilon + J/\psi] \sim 8(24)$ pb, then $\sigma^{SPS}[\Upsilon + J/\psi] \sim \sqrt{\sigma[\Upsilon]\sigma[J/\psi]} \times \alpha_s^3$ and $\alpha_s \sim 0.16(0.23)$ (1605.03061).

Numerical Result for $\Upsilon + J/\psi + \phi$

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3. SPS $\Upsilon + J/\psi + \phi$: $\mathcal{O}(\alpha_s^9)$, very small.

Numerical Result for $\Upsilon + J/\psi + \phi$

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3. SPS $\Upsilon + J/\psi + \phi$: $\mathcal{O}(\alpha_s^9)$, very small.
4. DPS $\Upsilon + J/\psi + \phi$: about $3 \times \sigma^{SPS}[\Upsilon + J/\psi]\frac{\sigma[\phi]}{\sigma_{eff}^{DPS}} \sim 1.4$ pb for $p_T(\phi) > 2$ GeV and $\sigma_{eff}^{DPS} \sim 10$ mb.

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3. SPS $\Upsilon + J/\psi + \phi$: $\mathcal{O}(\alpha_s^9)$, very small.
4. DPS $\Upsilon + J/\psi + \phi$: about $3 \times \sigma^{SPS}[\Upsilon + J/\psi]\frac{\sigma[\phi]}{\sigma_{eff}^{DPS}} \sim$ 1.4 pb for $p_T(\phi) > 2$ GeV and $\sigma_{eff}^{DPS} \sim 10$ mb.
5. TPS $\Upsilon + J/\psi + \phi$: about $\frac{\sigma[\Upsilon]\sigma[J/\psi]\sigma[\phi]}{(\sigma_{eff}^{TPS})^2} \sim$ 28 pb for $p_T(\phi) > 2$ GeV and $\sigma_{eff}^{TPS} \sim 8$ mb.

Search for TPS in $\Upsilon + J/\psi + \phi$ at LHCb

Estimate the number of events

1. $Br[\Upsilon(J/\psi) \to \mu^+\mu^-] = 0.024(0.06)$ and $Br[\phi \to K^+K^-] = 0.5$.

Search for TPS in $\Upsilon + J/\psi + \phi$ at LHCb

Estimate the number of events

1. $Br[\Upsilon(J/\psi) \to \mu^+\mu^-] = 0.024(0.06)$ and $Br[\phi \to K^+K^-] = 0.5$.
2. Integrated luminosity of LHCb is about 4 fb^{-1} at $\sqrt{s} = 13$ TeV.

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Estimate the number of events

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2. Integrated luminosity of LHCb is about 4 fb^{-1} at $\sqrt{s} = 13$ TeV.
3. Number of events for $\Upsilon(\mu^+\mu^-) + J/\psi(\mu^+\mu^-) + \phi(K^+K^-)$ with $p_T(\phi) > 2\ \mathrm{GeV}$ is about 80.

Search for TPS in $\Upsilon+J/\psi+\phi$ at LHCb

Estimate the number of events

1. $Br[\Upsilon(J/\psi)\to\mu^+\mu^-]=0.024(0.06)$ and $Br[\phi\to K^+K^-]=0.5$.
2. Integrated luminosity of LHCb is about $4\ \mathrm{fb}^{-1}$ at $\sqrt{s}=13$ TeV.
3. Number of events for $\Upsilon(\mu^+\mu^-)+J/\psi(\mu^+\mu^-)+\phi(K^+K^-)$ with $p_T(\phi)>2\ \mathrm{GeV}$ is about 80.
4. We can introduce cut to suppress SPS and DPS contributions.

Numerical Result for $\Upsilon + J/\psi + \phi$ at CMS/Atlas

SPS cross section of $\Upsilon,\ J/\psi,\ \phi$ at CMS/Atlas

1. We can get the inclusive cross sections of $\Upsilon,\ J/\psi,\ \phi$ at $\sqrt{s} = 13$ TeV at CMS/Atlas, it $0.4,\ 30,\ 1200\ \mu$b for $p_T(\phi) > 2$ GeV.

4. $Br[\Upsilon(J/\psi) \to \mu^+\mu^-] = 0.024(0.06)$ and $Br[\phi \to K^+K^-] = 0.5$.

Numerical Result for $\Upsilon + J/\psi + \phi$ at CMS/Atlas

SPS cross section of $\Upsilon,\ J/\psi,\ \phi$ at CMS/Atlas

1. We can get the inclusive cross sections of $\Upsilon,\ J/\psi,\ \phi$ at $\sqrt{s} = 13$ TeV at CMS/Atlas, it $0.4,\ 30,\ 1200\ \mu$b for $p_T(\phi) > 2$ GeV.
2. SPS and DPS are very small.

4. $Br[\Upsilon(J/\psi) \to \mu^+\mu^-] = 0.024(0.06)$ and $Br[\phi \to K^+K^-] = 0.5$.
5. Integrated luminosity of LHCb is about 40 fb^{-1} at $\sqrt{s} = 13$ TeV.

Numerical Result for $\Upsilon + J/\psi + \phi$ at CMS/Atlas

SPS cross section of $\Upsilon,\ J/\psi,\ \phi$ at CMS/Atlas

1. We can get the inclusive cross sections of $\Upsilon,\ J/\psi,\ \phi$ at $\sqrt{s} = 13$ TeV at CMS/Atlas, it $0.4,\ 30,\ 1200\ \mu$b for $p_T(\phi) > 2$ GeV.
2. SPS and DPS are very small.
3. TPS $\Upsilon + J/\psi + \phi$: about $\frac{\sigma[\Upsilon]\sigma[J/\psi]\sigma[\phi]}{(\sigma_{eff}^{TPS})^2} \sim$ 200 pb for $p_T(\phi) > 2$ GeV and $\sigma_{eff}^{TPS} \sim 8$ mb.
4. $Br[\Upsilon(J/\psi) \to \mu^+\mu^-] = 0.024(0.06)$ and $Br[\phi \to K^+K^-] = 0.5$.
5. Integrated luminosity of LHCb is about 40 fb^{-1} at $\sqrt{s} = 13$ TeV.
6. Number of events for $\Upsilon(\mu^+\mu^-) + J/\psi(\mu^+\mu^-) + \phi(K^+K^-)$ with $p_T(\phi) > 2$ GeV is about 6000.

Numerical Result for $\Upsilon + J/\psi + \phi$ at CMS/Atlas

SPS cross section of $\Upsilon,\ J/\psi,\ \phi$ at CMS/Atlas

1. We can get the inclusive cross sections of $\Upsilon,\ J/\psi,\ \phi$ at $\sqrt{s} = 13$ TeV at CMS/Atlas, it $0.4,\ 30,\ 1200\ \mu$b for $p_T(\phi) > 2$ GeV.
2. SPS and DPS are very small.
3. TPS $\Upsilon + J/\psi + \phi$: about $\frac{\sigma[\Upsilon]\sigma[J/\psi]\sigma[\phi]}{(\sigma_{eff}^{TPS})^2} \sim 200\ \mathrm{pb}$ for $p_T(\phi) > 2$ GeV and $\sigma_{eff}^{TPS} \sim 8$ mb.
4. $Br[\Upsilon(J/\psi) \to \mu^+\mu^-] = 0.024(0.06)$ and $Br[\phi \to K^+K^-] = 0.5$.
5. Integrated luminosity of LHCb is about $40\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV.
6. Number of events for $\Upsilon(\mu^+\mu^-) + J/\psi(\mu^+\mu^-) + \phi(K^+K^-)$ with $p_T(\phi) > 2\ \mathrm{GeV}$ is about 6000.

Summary

We have performed the first complete analysis of simultaneous production of prompt ψ and Υ mesons including all leading SPS contributions.

Our work shows that it is in fact most probably dominated by DPS contributions for D0 data.

Finally, we show that $\Upsilon + J/\psi + \phi$ at LHC is dominated by TPS. It may be studied by experimenters.