$J/\psi + \Upsilon$ production at hadron colliders and double parton scattering

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Outline

Based on HuaSheng Shao, YJZ, PRL 117 (2016) 062001 (1605.03061)

Introduction

Quarkonium productions

Heavy quarkonium production at colliders have been studied by several groups

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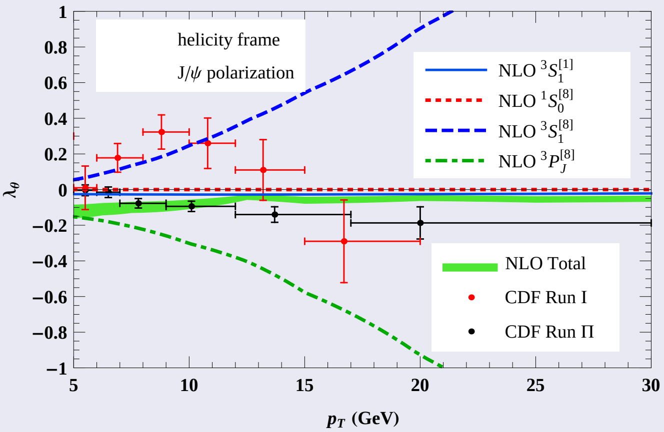
- Cong-Feng Qiao group
- Jian-Xiong Wang group
- ...

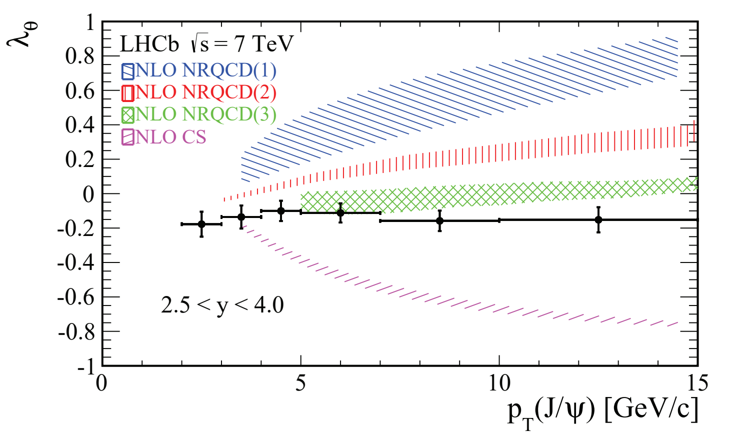
Quarkonium productions

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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2. $J/\psi + charm$ and $\Upsilon + charm$ (LHCb, arXiv:1205.0975, 1510.05949)

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2. $J/\psi + charm$ and $\Upsilon + charm$ (LHCb, arXiv:1205.0975, 1510.05949)
3. $J/\psi + J/\psi$ (D0, arXiv:1406.2380; CMS, arXiv:1406.0484)

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2. $J/\psi + \mathit{charm}$ and $\Upsilon + \mathit{charm}$ (LHCb, arXiv:1205.0975, 1510.05949)
3. $J/\psi + J/\psi$ (D0, arXiv:1406.2380; CMS, arXiv:1406.0484)
4. $\Upsilon + J/\psi$ (D0, arXiv:1511.02428)

Double parton scattering and Single parton scattering

However, one should keep in mind that before concluding for DPS dominance, one should always carefully examine the Single-Parton Scattering (SPS) contributions.

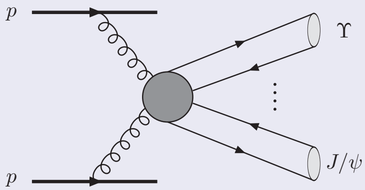


Figure: SPS and DPS of $pp \to J/\psi + \Upsilon + X$.

Double parton scattering

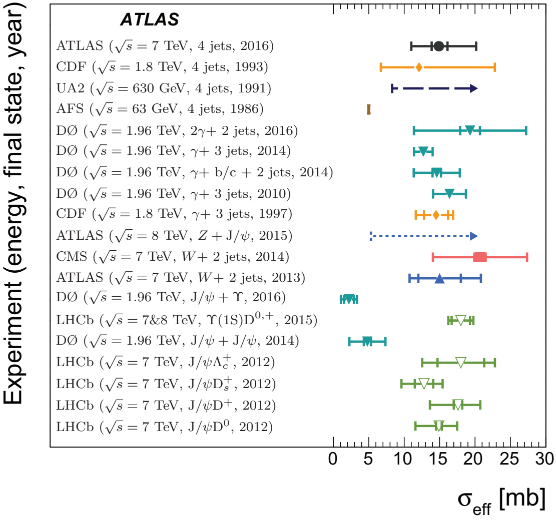
Cross section of Double parton scattering

$$\sigma^{AB}_{DPS} = \frac{1}{1+\delta_{AB}} \frac{\sigma^A \sigma^B}{\sigma_{eff}} \quad (1)$$

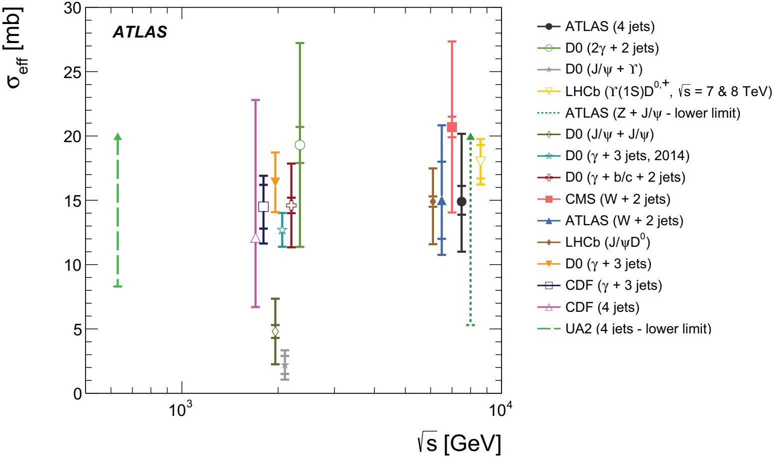
σ_{eff} (1306.3763)

$$\frac{1}{\sigma_{eff}} = \frac{\int \frac{d^2\vec{\Delta}}{(2\pi)^2} D_{h1}(x_1, x_2, Q_1^2, Q_2^2; \vec{\Delta}) D_{h2}(x_3, x_4, Q_1^2, Q_2^2; -\vec{\Delta})}{D_{h1}(x_1, Q_1^2) D_{h1}(x_2, Q_2^2) D_{h2}(x_3, Q_1^2) D_{h2}(x_4, Q_2^2)} \quad (2)$$

σ_{eff} (arXiv:1608.01857)



σ_{eff} (arXiv:1608.01857)



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

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

$$\sigma_{D0}^{J/\psi+\Upsilon} = 27 \pm 9 \pm 7 \text{ fb} \quad (3)$$

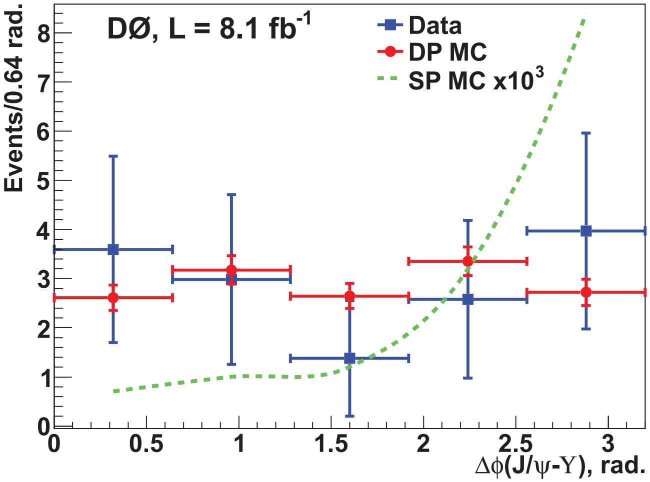
Ignore the SPS contribution

$$\sigma_{DPS}^{J/\psi+\Upsilon} = \sigma_{D0}^{J/\psi+\Upsilon} = \frac{\sigma^{J/\psi}\sigma^{\Upsilon}}{\sigma_{eff}} \quad (4)$$

σ_{eff}

$$\sigma_{eff} = 2.2 \pm 0.7 \pm 0.9 \text{ mb} \quad (5)$$

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

$$\sigma(h_1h_2 \to \mathcal{C} + \mathcal{B} + X) = \sum_{a,b} f_{a/h_1} \otimes f_{b/h_2} \otimes \hat{\sigma}(ab \to \mathcal{C} + \mathcal{B} + X). \quad (6)$$

Parton level cross section

$$d\hat{\sigma}(ab \to \mathcal{C} + \mathcal{B} + X) = \sum_{n_1,n_2} \hat{\sigma}(ab \to c\bar{c}[n_1] + b\bar{b}[n_2] + X) \langle O^{\mathcal{C}}(n_1)\rangle\langle O^{\mathcal{B}}(n_2)\rangle \quad (7)$$

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

$$
\begin{aligned}
v_b^2 &\sim v_c^2 \sim 0.1 - 0.3 \\
\alpha_S &\sim 0.2 \\
\alpha_S &\sim v_c^2 \sim v_b^2 \qquad (8)
\end{aligned}
$$

QED

J^{PC} Of J/ψ or Υ are 1^{--}

QED contributions may be important too.

α

$$\begin{aligned} \alpha &\sim 0.008 \\ \alpha_S &\sim \sqrt{\alpha} \end{aligned} \tag{9}$$

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

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 $i + j \geq 4$

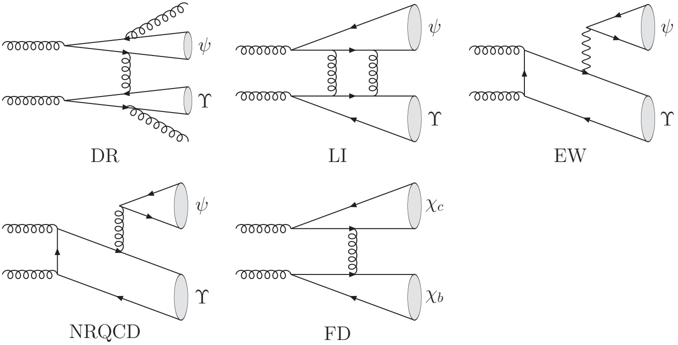
Feeddown for $\chi_{c,b}$

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



Numerical Result

Direct SPS cross sections @ D0 in fb

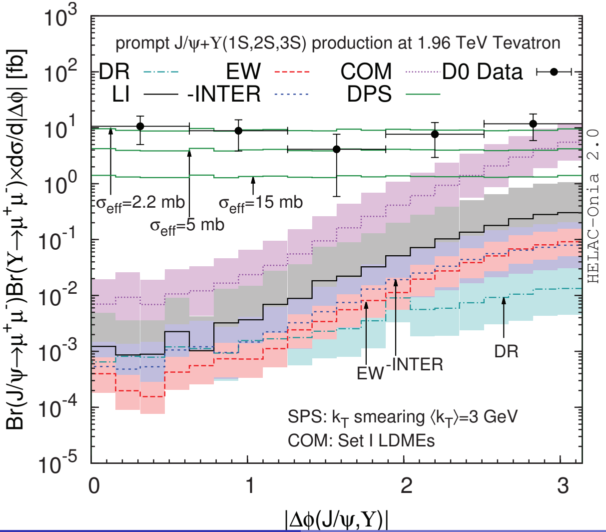
		J/ψ	$\psi(2S)$
DR	$\Upsilon(1S)$	$3.58^{+233\%}_{-66.4\%} \pm 4.4\%$	$2.34^{+233\%}_{-66.4\%} \pm 4.4\%$
	$\Upsilon(2S)$	$1.78^{+233\%}_{-66.4\%} \pm 4.4\%$	$1.17^{+233\%}_{-66.4\%} \pm 4.4\%$
	$\Upsilon(3S)$	$1.36^{+233\%}_{-66.4\%} \pm 4.4\%$	$0.894^{+233\%}_{-66.4\%} \pm 4.4\%$
LI	$\Upsilon(1S)$	$56.2^{+264\%}_{-70.2\%} \pm 4.7\%$	$36.8^{+264\%}_{-70.2\%} \pm 4.7\%$
	$\Upsilon(2S)$	$28.0^{+264\%}_{-70.2\%} \pm 4.7\%$	$18.4^{+264\%}_{-70.2\%} \pm 4.7\%$
	$\Upsilon(3S)$	$21.4^{+264\%}_{-70.2\%} \pm 4.7\%$	$14.0^{+264\%}_{-70.2\%} \pm 4.7\%$
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

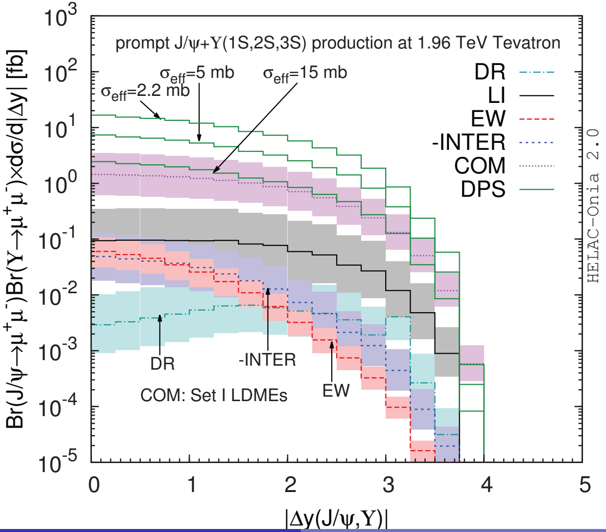
Experiment	CSM				COM			
	DR	LI	EW	INTER	Set I	Set II	Set III	Set IV
D0: $27 \pm 42.2\%$	$0.0146^{+233\%}_{-66.6\%}$	$0.229^{+264\%}_{-70.4\%}$	$0.065^{+75.5\%}_{-46.6\%}$	$-0.068^{+162\%}_{-62.2\%}$	$2.96^{+135\%}_{-56.2\%}$	$1.41^{+160\%}_{-77.6\%}$	$1.80^{+143\%}_{-58.0\%}$	$0.418^{+144\%}_{-58.3\%}$
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.

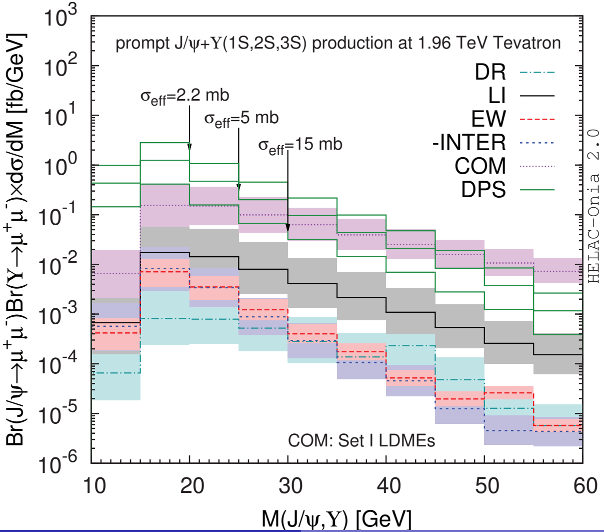
dphi @ D0


prompt J/ψ+Υ(1S,2S,3S) production at 1.96 TeV Tevatron
DR
EW
COM
D0 Data
LI
-INTER
DPS
σeff=2.2 mb
σeff=5 mb
σeff=15 mb
EW
-INTER
DR
SPS: kT smearing ⟨kT⟩=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)|

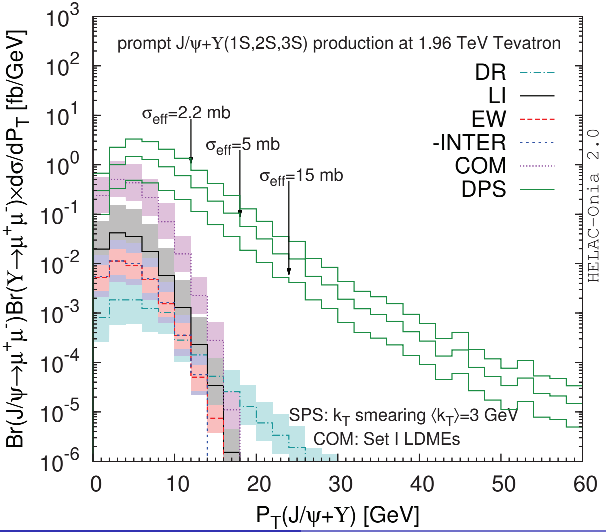
dy @ D0


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)|

dM @ D0

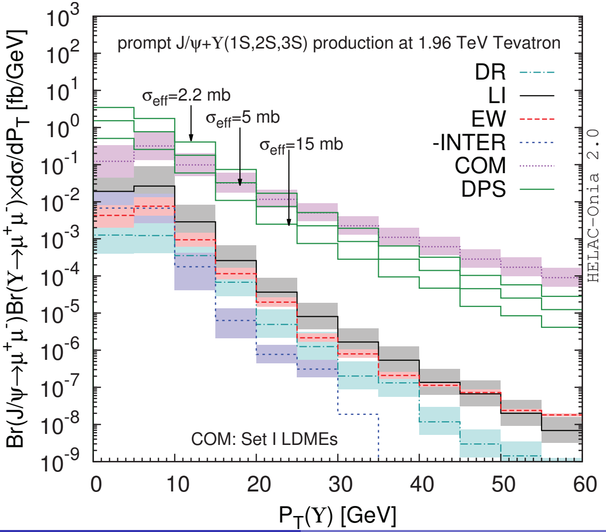

prompt J/ψ+Υ(1S,2S,3S) production at 1.96 TeV Tevatron
DR
LI
EW
-INTER
COM
DPS
σ_eff=2.2 mb
σ_eff=5 mb
σ_eff=15 mb
COM: Set I LDMEs
HELAC-Onia 2.0
Br(J/ψ→μ+μ-)Br(Υ→μ+μ-)×dσ/dM [fb/GeV]
M(J/ψ,Υ) [GeV]
10
20
30
40
50
60
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6

dPt @ D0

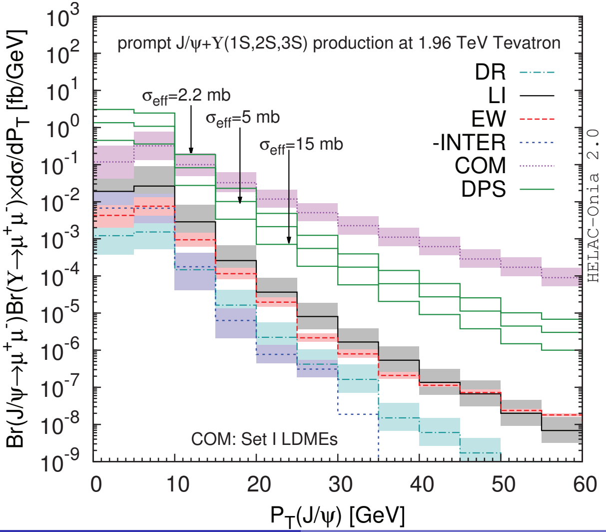


prompt J/ψ+Υ(1S,2S,3S) production at 1.96 TeV Tevatron
DR
LI
EW
-INTER
COM
DPS
σeff=2.2 mb
σeff=5 mb
σeff=15 mb
SPS: kT smearing ⟨kT⟩=3 GeV
COM: Set I LDMEs
HELAC-Onia 2.0
Br(J/ψ→μ+μ-)Br(Υ→μ+μ-)×dσ/dPT [fb/GeV]
PT(J/ψ+Υ) [GeV]

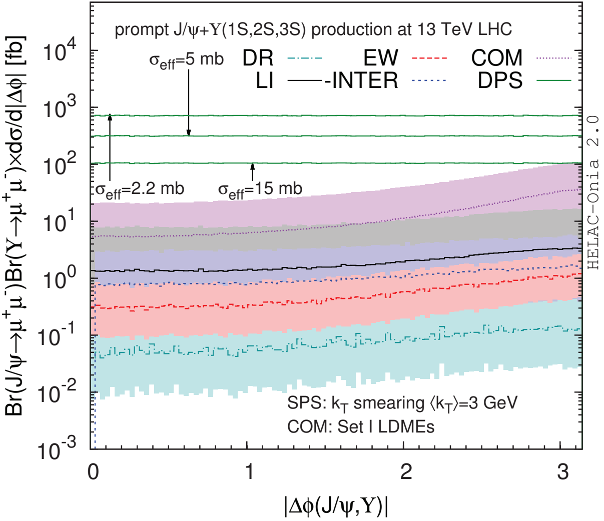
dptY @ D0


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(Υ) [GeV]
0
10
20
30
40
50
60
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

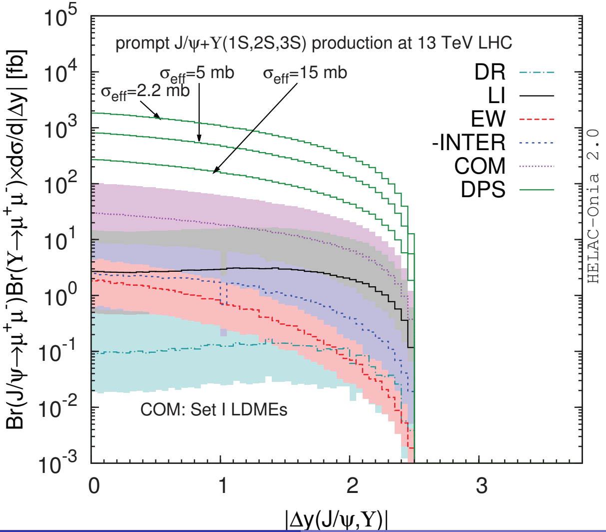
dptpsi @ D0


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
$Br(J/\psi\to\mu^+\mu^-)Br(\Upsilon\to\mu^+\mu^-)\times d\sigma/dP_T$ [fb/GeV]
$P_T(J/\psi)$ [GeV]

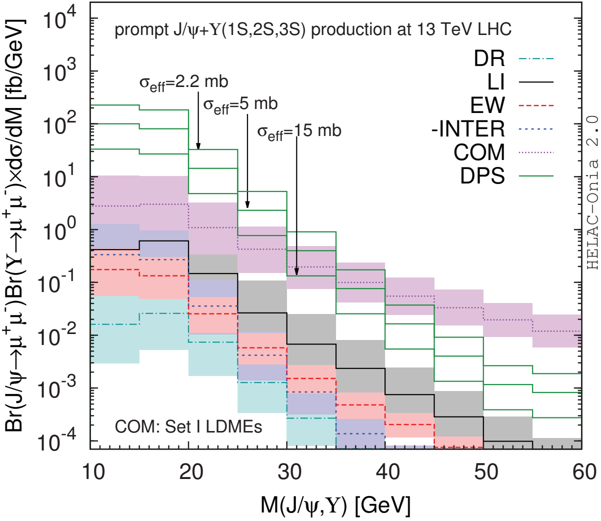
dphi @ LHCB


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 ⟨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)|
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
0
1
2
3

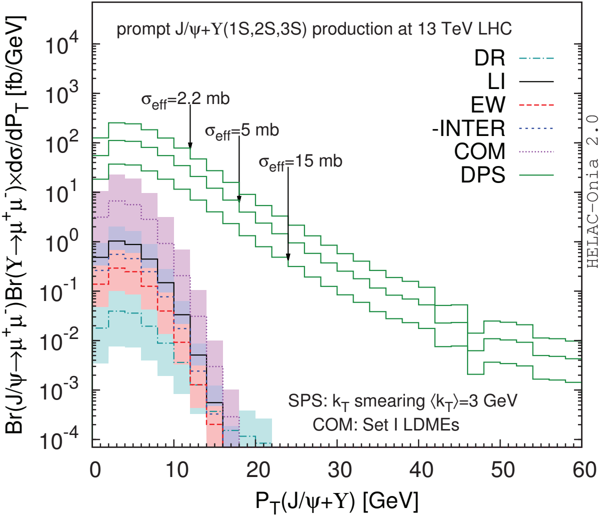
dy @ LHCB


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/d|Δy| [fb]
|Δy(J/ψ,Υ)|

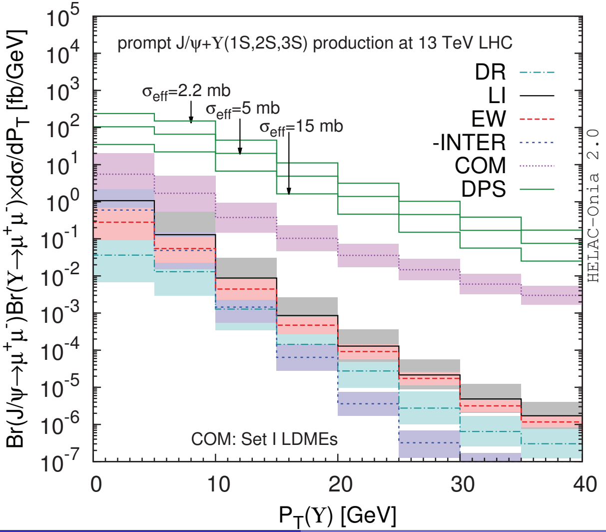
dM @ LHCB


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
COM: Set I LDMEs
HELAC-Onia 2.0
Br(J/ψ→μ+μ-)Br(Υ→μ+μ-)×dσ/dM [fb/GeV]
M(J/ψ,Υ) [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

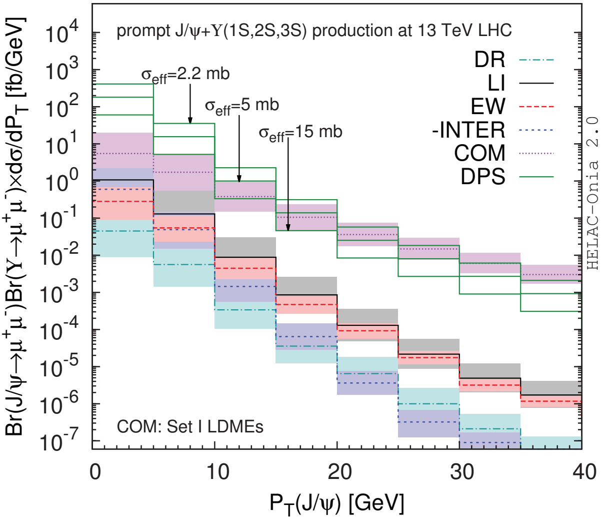
dPt @ LHCB


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]
0
10
20
30
40
50
60
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4

dptY @ 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
HELAC-Onia 2.0
COM: Set I LDMEs
Br(J/ψ→μ+μ-)Br(Υ→μ+μ-)×dσ/dPT [fb/GeV]
PT(Υ) [GeV]

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
HELAC-Onia 2.0
COM: Set I LDMEs
Br(J/ψ→μ+μ-)Br(Υ→μ+μ-)×dσ/dPT [fb/GeV]
PT(J/ψ) [GeV]

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 also present our predictions of prompt J/ψ and Υ production at the LHCb.