Probe triple partons interaction through three quarkonia associated production at LHC

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Based on Hua-Sheng Shao, YJZ, PRL122(2019)192002/Arxiv:1902.04949

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Introduction

SPS, DPS, and TPS

SPS, DPS, and TPS

1. Single parton scattering (SPS) / Double-parton scattering (DPS): involve one / two partons in each hadron colliding.
2. Triple-parton scattering (TPS): involve three partons in each hadron colliding. TPS are absent due to their more complicated final states and much fewer yields.

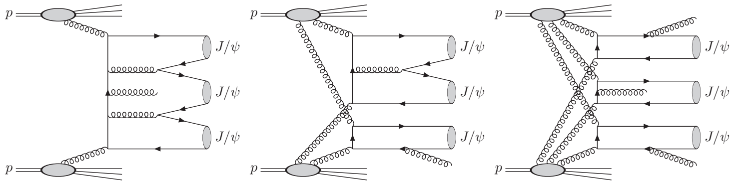

Figure: SPS/DPS/TPS triple J/ψ production at SPPC

MPI

MPI

1. The cross sections of MPI are either strongly model dependent or assuming no correlation between MPI.
2. We assume no correlation between MPI.
3. The DPS studies at the LHC and Tevatron suggest that no correlation assumption is a rather good approximation.
4. A N-parton scattering (NPS) cross-section (1708.07519)

$$\sigma^{\mathrm{NPS}}_{f_1\cdots f_N} = \frac{m}{N!}\frac{\prod_{i=1}^{N}\sigma^{\mathrm{SPS}}_{f_i}}{(\sigma_{\mathrm{eff,N}})^{N-1}}, \tag{1}$$

NPS

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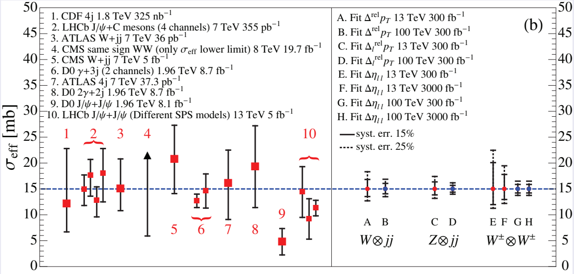
2. The factor $\frac{m}{N!}$: the indistinguishable final state symmetry.
3. $\sigma^{\mathrm{SPS}}_{f_i}$: the SPS cross section of producing final state f_i.
4. $\sigma_{\mathrm{eff,N}}$: the effective cross section, which should be determined by experiments.
5. The DPS and TPS cases correspond to $N = 2$ and $N = 3$.
6. Ref. 1612.05582 derives $\sigma_{\mathrm{eff,3}} = (0.82 \pm 0.11) \times \sigma_{\mathrm{eff,2}}$.

$\sigma_{\mathrm{eff},2}$ and heavy quarkonium (1710.06315, 1811.07474)

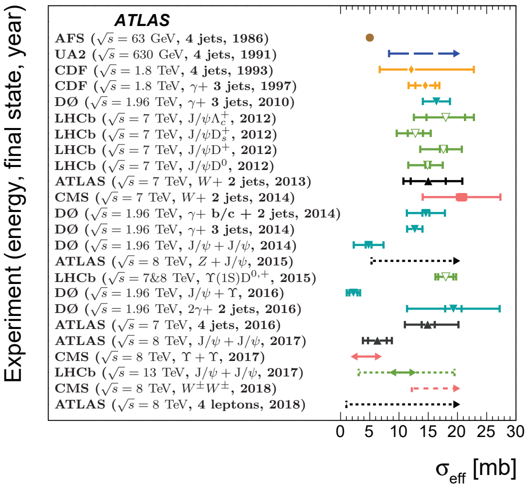
$\sigma_{\mathrm{eff},2}$

1. $\sigma_{\mathrm{eff},2}$ ∼10 mb: extracted from the quarkonium data.
2. $\sigma_{\mathrm{eff},2}$ ∼15 mb: extracted from the weak gauge boson data.
3. However, it is still far from being conclusive in view of the remaining large uncertainties.

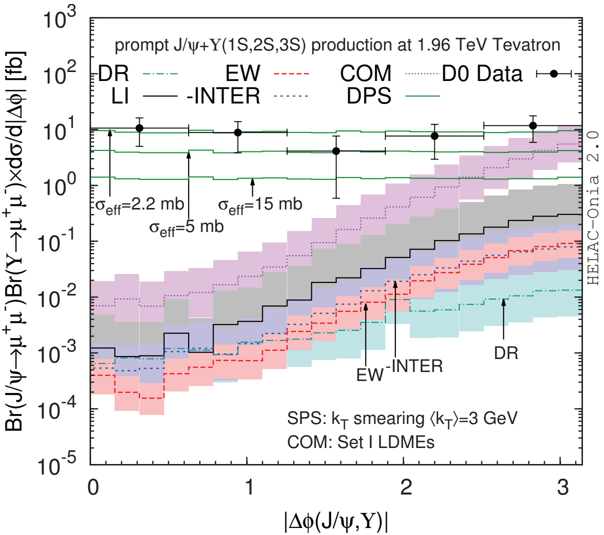


σ_{eff}^{DPS}, Atlas, 1811.11094

DPS and W, Z



dphi @ D0, Shao, YJZ, 1605.03061



Double parton scattering Picture (Enterria, Snigirev, 1708.07519)

DPS

$$\mathrm{P}^{DPS}_{pp\to ab} = \mathrm{P}^{SPS}_{pp\to a} \times \mathrm{P}^{SPS}_{pp\to b} = \frac{\sigma(pp\to a+X)}{\sigma^{inel}(pp)} \times \frac{\sigma(pp\to b+X)}{\sigma^{inel}(pp)} \quad (3)$$

Then $\sigma^{nPS}_{eff} \sim \sigma^{inel}(pp)$. But $\sigma^{inel}(pp) \sim 30-50\,\mathrm{mb}$ and $\sigma^{DPS}_{eff} \sim 10-15\,\mathrm{mb}$.

TPS

TPS (1612.05582, 1703.07163, 1710.1152)

TPS theoretical studies in literature are limited to open heavy-flavor productions so far. The complete study including SPS and DPS is not available.

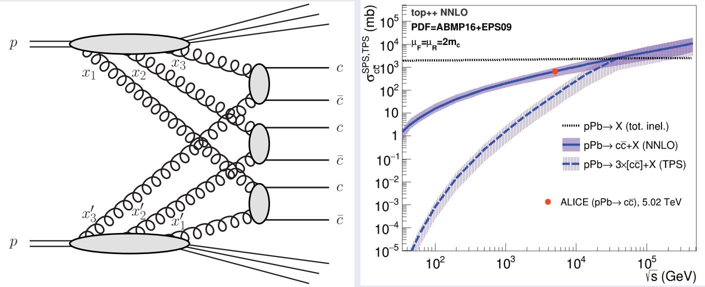
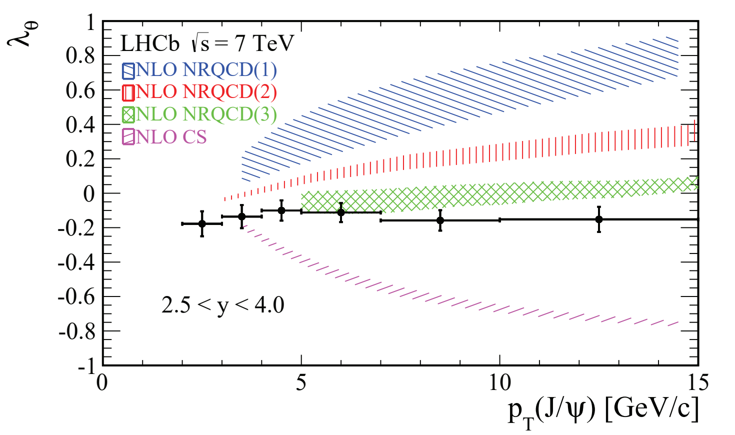


Figure: TPS of $pP_b \to c\bar{c} + c\bar{c} + c\bar{c}$ (PRL118, 122001).

Quarkonium productions

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



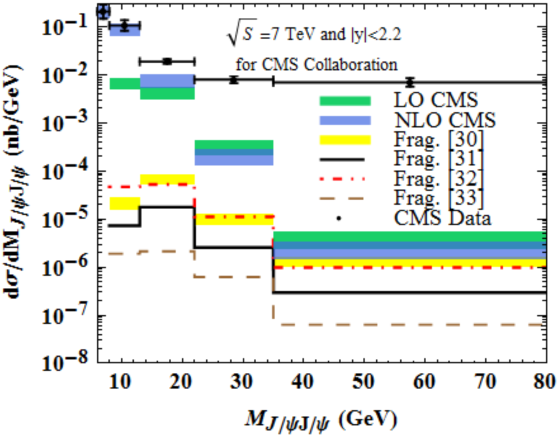
CO LDMEs, 1212.2037

	Butenschoen, Kniehl[18]	Gong, Wang, Wan, Zhang[53]	Chao, Ma, Shao, Wang, Zhang[52] default set	set 2	set 3
$\langle \mathcal{O}^{J/\psi}(^3S_1^{[1]})\rangle$	1.32 GeV^3	1.16 GeV^3	1.16 GeV^3	1.16 GeV^3	1.16 GeV^3
$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$	0.0497 GeV^3	0.097 GeV^3	0.089 GeV^3	0	0.11 GeV^3
$\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$	0.0022 GeV^3	−0.0046 GeV^3	0.0030 GeV^3	0.014 GeV^3	0
$\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle$	−0.0161 GeV^5	−0.0214 GeV^5	0.0126 GeV^5	0.054 GeV^5	0
$\langle \mathcal{O}^{\psi'}(^3S_1^{[1]})\rangle$		0.758 GeV^3			
$\langle \mathcal{O}^{\psi'}(^1S_0^{[8]})\rangle$		−0.0001 GeV^3			
$\langle \mathcal{O}^{\psi'}(^3S_1^{[8]})\rangle$		0.0034 GeV^3			
$\langle \mathcal{O}^{\psi'}(^3P_0^{[8]})\rangle$		0.0095 GeV^5			
$\langle \mathcal{O}^{\chi_0}(^3P_0^{[1]})\rangle$		0.107 GeV^5			
$\langle \mathcal{O}^{\chi_0}(^3S_1^{[8]})\rangle$		0.0022 GeV^3			

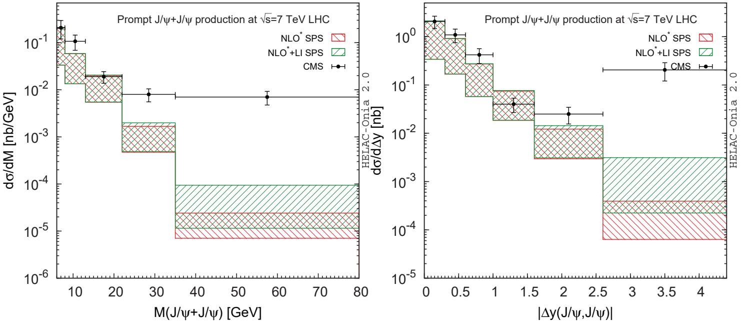
Double J/ψ, Lansberg, Shao, 1410.8822

	Energy and quarkonium cuts	$\sigma_{\text{exp.}}$	$\sigma_{\text{LO}}^{\text{SPS,prompt}}$	$\sigma_{\text{NLO}^{(\star)}}^{\text{SPS,prompt}}$	$\sigma^{\text{DPS,prompt}}$	χ^2
LHCb	$\sqrt{s} = 7$ TeV, $P_T^{\psi_{1,2}} < 10$ GeV, $2 < y_\psi < 5$ [34]	18 ± 5.3 pb	41^{+51}_{-24} pb	46^{+58}_{-27}	$31^{+11}_{-6.3}(^{+24}_{-15})$ pb	$0.5 - 1.2$
D0	$\sqrt{s} = 1.96$ TeV, $P_T^{\psi_{1,2}} > 4$ GeV,	SPS: 70 ± 23 fb	53^{+57}_{-27} fb	170^{+340}_{-110} fb	–	–
	$\lvert\eta_\psi\rvert < 2.0$ [12] (+ μ cuts in caption)	DPS: 59 ± 23 fb	–	–	$44^{+16}_{-9.1}(^{+7.5}_{-5.1})$ fb	$0.06 - 0.5$
CMS	$\sqrt{s} = 7$ TeV, $P_T^{\psi_{1,2}} > 6.5 \to 4.5$ GeV depending on $\lvert y_{\psi_{1,2}}\rvert \in [0, 2.2]$ (see the caption) [35]	5.25 ± 0.52 pb	$0.35^{+0.26}_{-0.17}$ pb	$1.5^{+2.2}_{-0.87}$ pb	$0.69^{+0.24}_{-0.14}(^{+0.039}_{-0.027})$ pb	$1.09 - 1.14$
ATLAS	$\sqrt{s} = 7$ TeV, $P_T^{\psi_{1,2}} > 5$ GeV and $\lvert y_{\psi_{1,2}}\rvert < 2.1$ (+ μ cuts in the caption) [48]	–	$6.4^{+4.3}_{-2.6}$ fb	36^{+49}_{-20} fb	$19^{+6.8}_{-4.0}(^{+2.2}_{-1.6})$ fb	N/A

Double J/ψ at CMS, Sun, Han, Chao, 1404.4042



Double J/ψ at CMS, Lansberg, Shao, Yamanaka, YJZ 1906.10049



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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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)

Quarkonium associated production

Quarkonium associated production at hadron colliders

1. $\sigma(J/\psi + c\bar{c})@\alpha_s^4$: Artoisenet, Lansberg, Maltoni, 0703129.

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2. $\sigma(\Upsilon + 3jets)@\alpha_s^5$: Artoisenet, Campbell, Lansberg, Maltoni, Tramontano, 0806.3282.

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3. $\sigma(B_{ccc} + \bar{c} + \bar{c} + \bar{c})@\alpha_s^6$: Chen, Wu, 1106.0193.

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3. $\sigma(B_{ccc} + \bar{c} + \bar{c} + \bar{c})@\alpha_s^6$: Chen, Wu, 1106.0193.
4. $\sigma(J/\psi + J/\psi + J/\psi + g)@\alpha_s^7$: Shao, YJZ, 1902.04949 ....

The frame of Calculation

Total triple J/ψ hadroproduction cross sections

DPS and TPS cross sections

We will use the following concrete formula:

$$\begin{aligned} &\sigma^{\rm DPS}(pp \to J/\psi J/\psi J/\psi + X) \\ = &\ \frac{\sigma^{\rm SPS}(pp \to J/\psi J/\psi + X)\sigma^{\rm SPS}(pp \to J/\psi + X)}{\sigma_{\rm eff,2}}, \\ &\sigma^{\rm TPS}(pp \to J/\psi J/\psi J/\psi + X) \\ = &\ \frac{1}{6}\frac{\left[\sigma^{\rm SPS}(pp \to J/\psi + X)\right]^3}{(\sigma_{\rm eff,3})^2} \end{aligned} \tag{4}$$

to calculate DPS and TPS cross sections.

I

n total, there are three different SPS cross sections, i.e., those

SPS cross sections

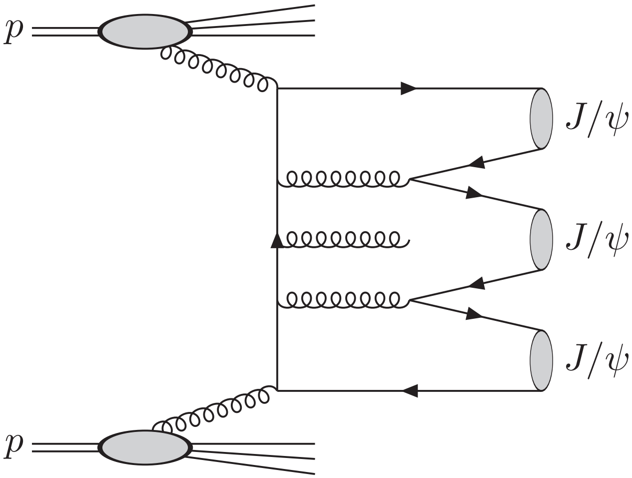
Hadron and Parton level cross sections

$$\sigma(h_1 h_2 \to \mathcal{J}\mathcal{J}\mathcal{J}) = \sum_{a,b} f_{a/h_1} \otimes f_{b/h_2} \otimes \hat{\sigma}(ab \to \mathcal{C} + \mathcal{J} + \mathcal{J} + X). \qquad (5)$$

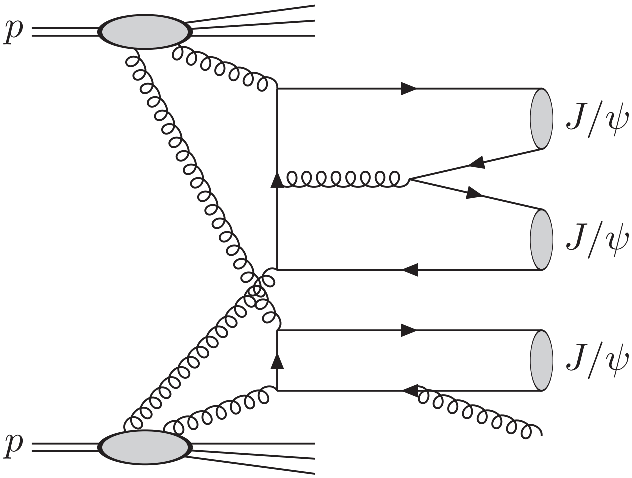
Parton level cross section

$$d\hat{\sigma}(ab \to \mathcal{J}\mathcal{J}\mathcal{J}) = \sum_{n_1,n_2,n_2} \hat{\sigma}(ab \to c\bar{c}[n_1]c\bar{c}[n_2]c\bar{c}[n_3] + X) \langle O^{\mathcal{J}}(n_1)\rangle\langle O^{\mathcal{J}}(n_2)\rangle\langle O^{\mathcal{J}}(n_3)\rangle \qquad (6)$$

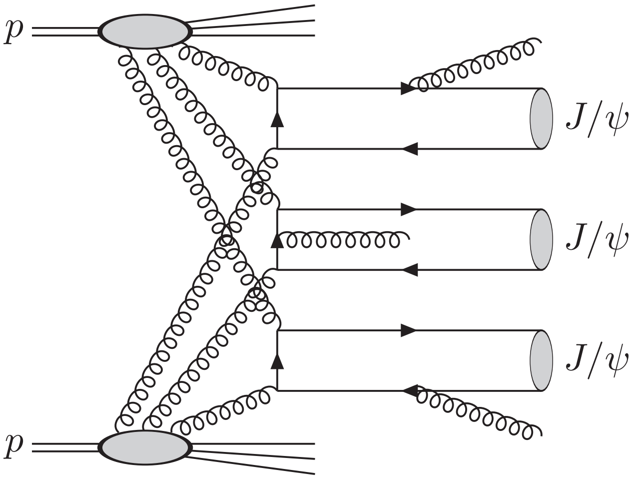
One of 28774 Feynman Diagrams of SPS



Feynman Diagrams of DPS



Feynman Diagrams of TPS



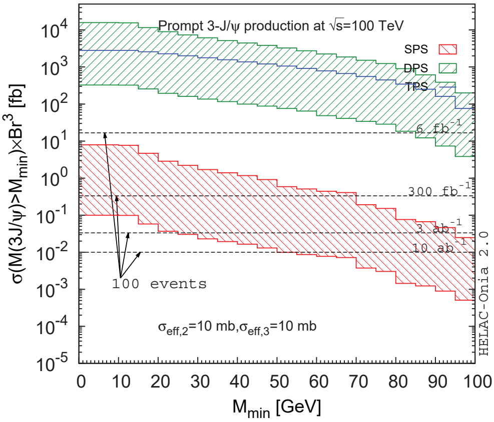
Numerical Result

SPS cross sections with $p_T(J/\psi) > 2\mathrm{GeV}$

σ^{SPS}	Order	14 TeV	100 TeV
$J/\psi + X$	α_s^3	72 ± 1 μb	300 ± 8 μb
$J/\psi J/\psi + X$	α_s^4	67 ± 2 nb	343 ± 13 nb
$J/\psi J/\psi J/\psi + X$	α_s^7	1 ± 0.6 pb	4.2 ± 3.2 pb

$\sigma(J/\psi J/\psi J/\psi + X)$	Order	14 TeV	CMS @ 14 TeV	100 TeV
TPS	α_s^9	620 ± 20 pb	45 ± 1.5 pb	45000 ± 1500 pb
DPS	α_s^7	480 ± 20 pb	35 ± 1.5 nb	10000 ± 1000 pb
SPS	α_s^7	1 ± 0.6 pb	0.07 ± 0.04 pb	4.2 ± 3.2 pb

Triple J/ψ production at 100 TeV SPPC



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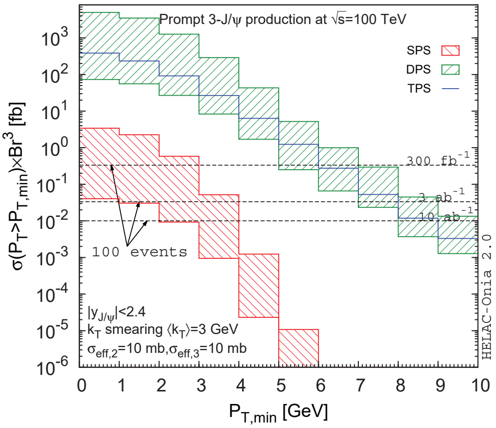
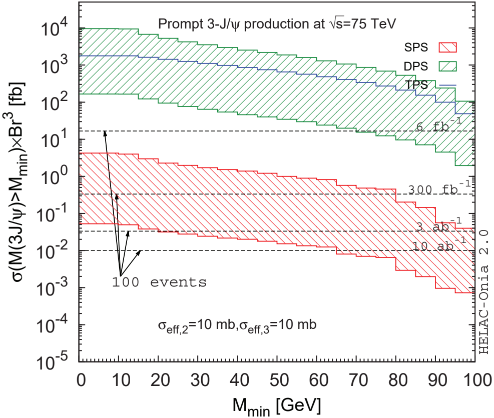
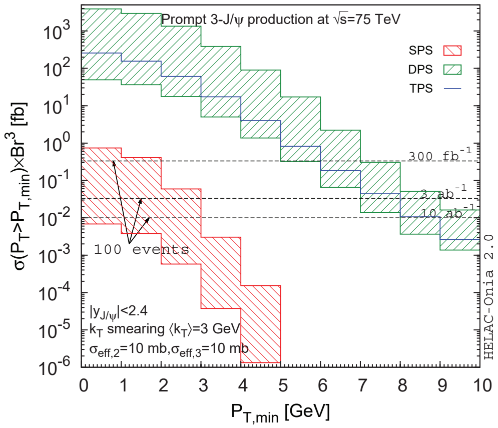


$J/\psi + J/\psi + J/\psi + X$

Triple J/ψ production at 75 TeV SPPC



Triple J/ψ production at 75 TeV SPPC



$J/\psi J/\psi J/\psi + X$ at CMS/Atlas

Search TPS at CMS/Atlas

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2. $Br[J/\psi\to\mu^{+}\mu^{-}]=0.059$.

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2. $Br[J/\psi\to\mu^+\mu^-]=0.059$.
3. Number of events for $3J/\psi(\mu^+\mu^-)$ with $p_T(J/\psi)>2\ \mathrm{GeV}$ is about 2700 ± 72 , which is 1500 ± 50 from TPS and 1200 ± 50 from DPS.

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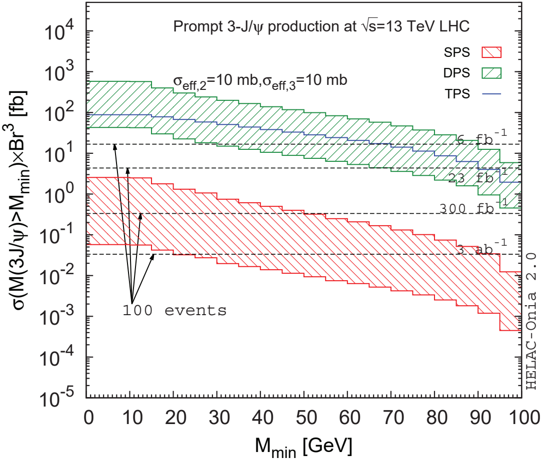
4. We can introduce cut of phase space to distinguish SPS, DPS, and TPS contributions.

Triple J/ψ production at LHC



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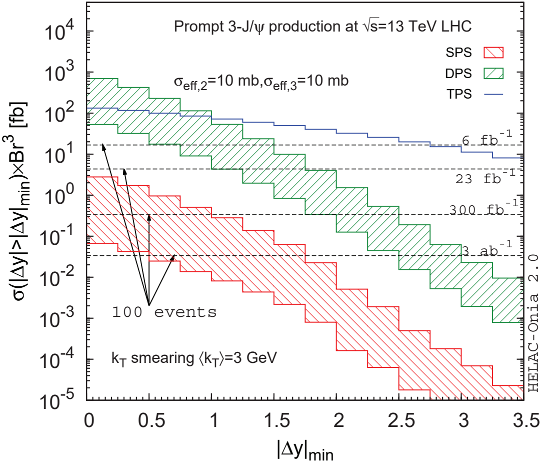

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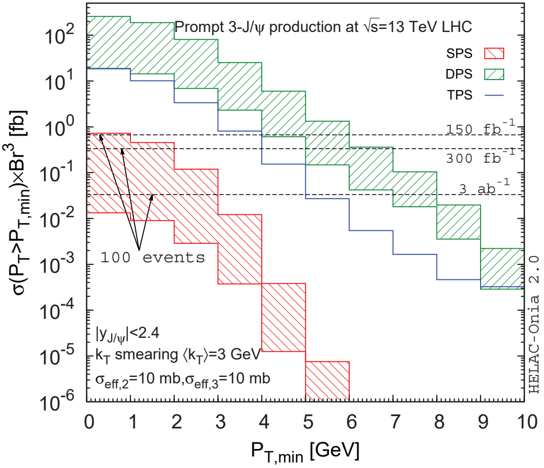

Numerical Result for $\Upsilon + J/\psi + \phi$

Υ, J/ψ, ϕ at LHCb

1. $\sigma(\Upsilon) \sim 0.20$ μb (1804.09214), $\sigma(J/\psi) \sim 15$ μb (1509.00771), and $\sigma(\phi) \sim 3$ mb (1107.3935).

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

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5. TPS $\Upsilon + J/\psi + \phi$: about $\frac{\sigma[\Upsilon]\sigma[J/\psi]\sigma[\phi]}{(\sigma_{eff}^{TPS})^2} \sim 100\ \mathrm{pb}$ for $\sigma_{eff}^{TPS} \sim 10$ 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 $Br[\phi \to K^+K^-] = 0.5$.

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3. Number of events for $\Upsilon(\mu^+\mu^-) + J/\psi(\mu^+\mu^-) + \phi(K^+K^-)$ with $p_T(\phi) > 2$ GeV is about 440.
4. We can introduce cut to suppress SPS and DPS contributions.

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

$\Upsilon + J/\psi + \phi$ at Atlas/CMS

1. $\sigma(\Upsilon) \sim 0.6$ μb (1211.7255), $\sigma(J/\psi) \sim 50$ μb (1104.3038), and $\sigma(\phi) \sim 6$ mb (1402.6162).

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2. We have gotten $\sigma^{SPS}[\Upsilon + J/\psi] \sim 100$ pb in 1605.03061.
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5. TPS $\Upsilon + J/\psi + \phi$: about $\frac{\sigma[\Upsilon]\sigma[J/\psi]\sigma[\phi]}{(\sigma_{eff}^{TPS})^2} \sim 2\ \mathrm{nb}$ for $\sigma_{eff}^{TPS} \sim 10$ mb.

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

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4. We can introduce cut to suppress SPS and DPS contributions.

Summary

We have performed the first analysis of simultaneous production of $J/\psi + J/\psi + J/\psi$ and $\Upsilon + J/\psi + \phi$ from SPS/DPS/TPS contributions at LHC.

Our work shows that it is in fact most probably dominated by TPS and DPS contributions.

Finally, we show that $J/\psi + J/\psi + J/\psi$ and $\Upsilon + J/\psi + \phi$ production at LHC may be studied by experimenters.

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,

$$\sigma^{\mathrm{NPS}}_{hh'\to a_1\ldots a_n} = \left(\frac{m}{n!}\right) \sum_{i_1,..,i_n,i'_1,..,i'_n} \int \Gamma^{i_1\ldots i_n}_{h}(x_1,..,x_n;\mathbf{b_1},..,\mathbf{b_n};Q_1^2,..,Q_n^2)$$

$$\times\, \hat{\sigma}^{i_1 i'_1}_{a_1}(x_1,x'_1,Q_1^2)\cdots\hat{\sigma}^{i_n i'_n}_{a_n}(x_n,x'_n,Q_n^2) \tag{7}$$

$$\times\, \Gamma^{i'_1\ldots i'_n}_{h'}(x'_1,\ldots,x'_n;\mathbf{b_1}-\mathbf{b},\ldots,\mathbf{b_n}-\mathbf{b};Q_1^2,\ldots,Q_n^2)$$

$$\times\, dx_1\ldots dx_n\, dx'_1,\ldots,dx'_n\, d^2b_1,\ldots,d^2b_n\, d^2b.$$

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,

$$\Gamma_h^{i_1 \ldots i_n} = D_h^{i_1 \ldots i_n}(x_1, .., x_n; Q_1^2, .., Q_n^2) f(\mathbf{b_1}) \ldots f(\mathbf{b_n}) \quad (8)$$

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

$$D_h^{i_1 \ldots i_n}(x_1, .., x_n; Q_1^2, .., Q_n^2) = D_h^{i_1}(x_1; Q_1^2) \cdots D_h^{i_n}(x_n; Q_n^2) \quad (9)$$

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

The cross sections of n-particle associated production

Then we can get

$$\sigma^{nPS}_{hh'\to a_1\ldots a_n} = \left(\frac{m}{n!}\right) \frac{\sigma^{SPS}_{hh'\to a_1} \cdots \sigma^{SPS}_{hh'\to a_n}}{\left(\sigma^{nPS}_{eff}\right)^{n-1}}, \quad (10)$$

σ_{eff}^{nPS}

$$\left(\frac{1}{\sigma^{nPS}_{eff}}\right)^{n-1} = \int d^2b\, T^n(\mathbf{b}) \quad (11)$$