Triple prompt J/ψ hadroproduction as a hard probe of multiple-parton scatterings

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2nd FCPPL Quarkonium Production workshop @ THU

Based on Hua-Sheng Shao, YJZ, 1902.04949

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Outline

Introduction

Heavy Quarkonium Physics

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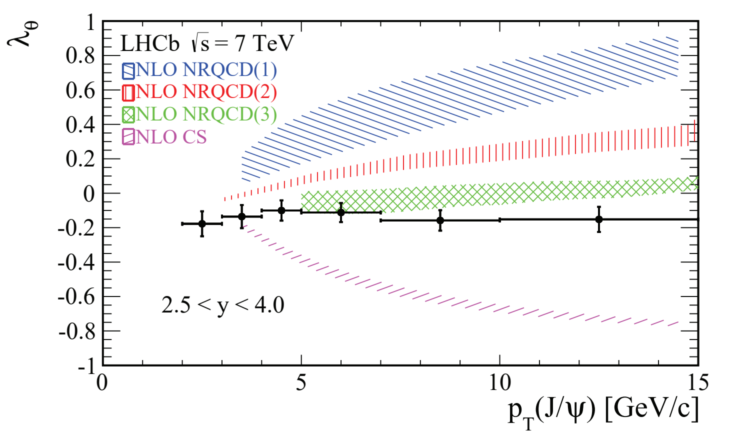
5. Double-parton scattering (DPS), triple-parton scattering (TPS)

Quarkonium productions

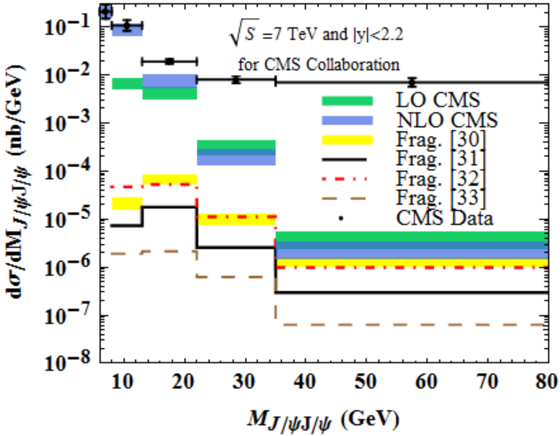
NLO J/ψ at LHCb, Chao/Wang/Kniehl, 1506.03981



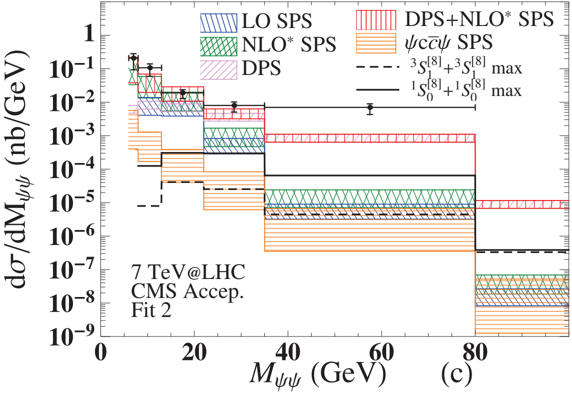
CO LDMEs, 1212.2037

	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 at CMS, Sun, Han, Chao, 1404.4042



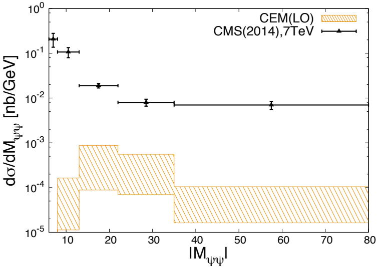
Double J/ψ at CMS, Lansberg, Shao, 1410.8822

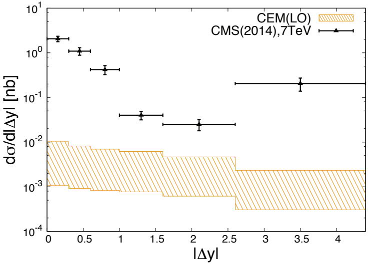


Double J/ψ, Lansberg, Shao, 1410.8822

	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 in the color evaporation model (CEM), Yamanaka, Lansberg, Shao, Zhang 1808.09884, 1811.07474





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

Single parton scattering(SPS), double parton scattering(DPS), and triple-parton scattering (TPS)

SPS, DPS, TPS

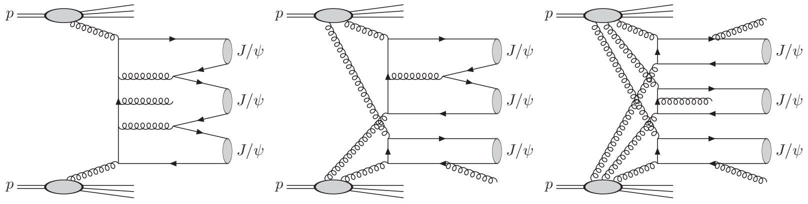


Figure: SPS (α_s^7), DPS (α_s^7) , and TPS (α_s^9) of $pp \to 3J/\psi + X$.

DPS and TPS, 1708.07519

DPS

$$\sigma^{DPS}_{pp\to a+b+X} = \frac{1}{1+\delta_{ab}} \frac{\sigma(pp\to a+X)\times\sigma(pp\to b+X)}{\sigma_{eff,2}} \quad (1)$$

TPS

In particular, the TPS has never been observed yet by any experiment.

$$\sigma^{DPS}_{pp\to a+b+c+X} = \frac{1}{(1+\delta_{ab}+\delta_{ac}+\delta_{bc}-\delta_{ab}\delta_{ac}\delta_{bc})!} \times \frac{\sigma(a+X)\times\sigma(b+X)\times\sigma(c+X)}{\sigma^2_{eff,3}} \quad (2)$$

$\sigma_{eff,3} = (0.82 \pm 0.11) \times \sigma_{eff,2}$ is drive after a global survey of

Triple parton scattering

TPS

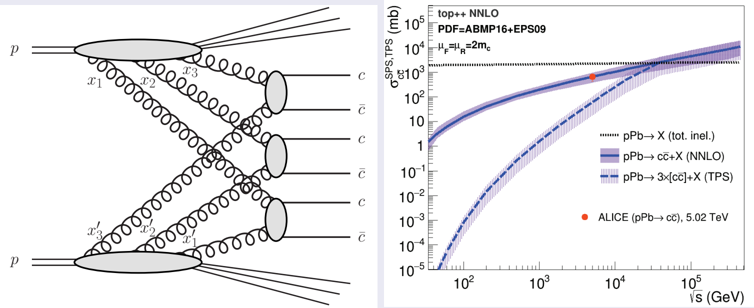


Figure: TPS of $pP_b \to c\bar{c} + c\bar{c} + c\bar{c}$ (PRL118, 122001).

Double parton scattering Picture (Enterria, Snigirev, 1708.07519)

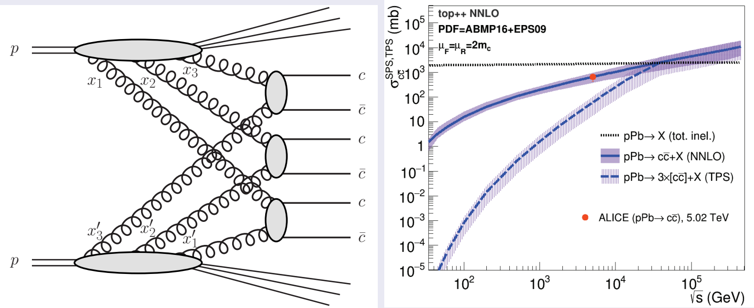
DPS

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

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

Triple parton scattering

TPS



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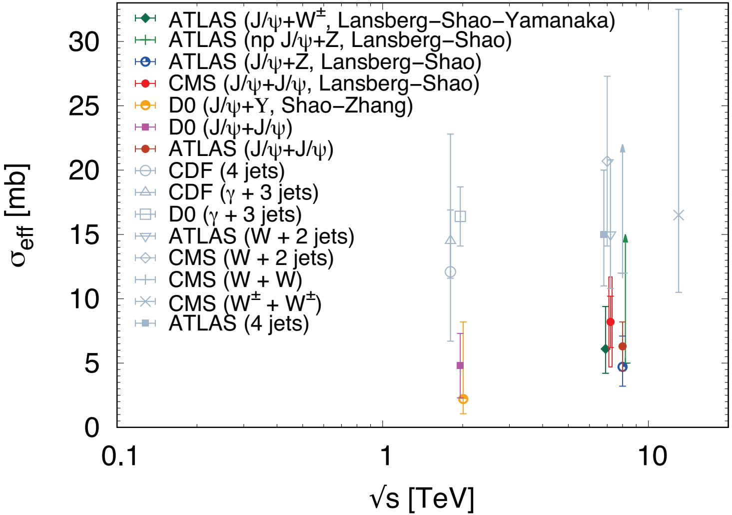
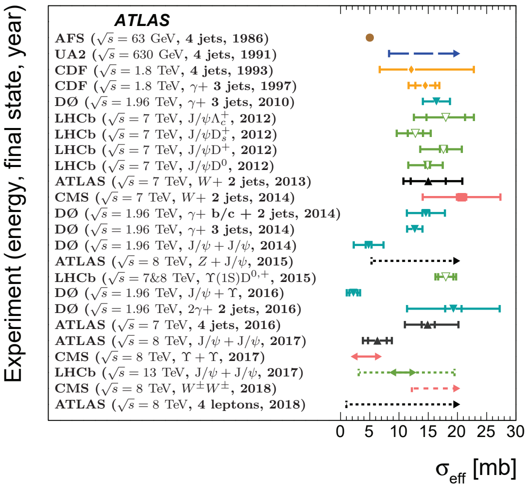
σ_{eff}^{DPS} (Yamanaka, Lansberg, Shao, Zhang, 1811.07474)

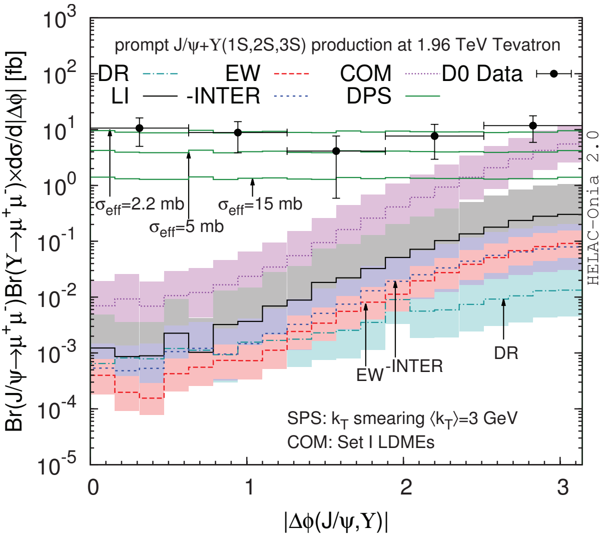


σ_{eff}^{DPS}, Atlas, 1811.11094

DPS and W, Z



$J/\psi + \Upsilon$ @ D0, Shao, Zhang, 1605.03061



Quarkonium associated production

Quarkonium associated production at hadron colliders

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5. $\sigma(\Upsilon + J/\psi)@\alpha_s^6$, Shao, Zhang, 1605.03061.
6. $\sigma(J/\psi + J/\psi + J/\psi + g)@\alpha_s^7$, Shao, Zhang, 1902.04949.

The frame of Calculation

Cross sections

Hadron and Parton level cross sections

$$\sigma(h_1 h_2 \to \mathcal{J}\mathcal{J}\mathcal{J}) = \sum_{a,b} f_{a/h_1} \otimes f_{b/h_2} \otimes \hat{\sigma}(ab \to \mathcal{C} + \mathcal{J} + \mathcal{J} + X). \quad (4)$$

Parton level cross section

$$d\hat{\sigma}(ab \to \mathcal{J}\mathcal{J}\mathcal{J}) = \sum_{n_1,n_2,n_2} \hat{\sigma}(ab \to c\bar{c}[n_1]c\bar{c}[n_2]c\bar{c}[n_3] + X) \langle O^{\mathcal{J}}(n_1)\rangle\langle O^{\mathcal{J}}(n_2)\rangle\langle O^{\mathcal{J}}(n_3)\rangle \quad (5)$$

DPS and TPS cross sections of $3J/\psi$

$$\sigma^{\rm DPS}(pp \to 3J/\psi + X) = \frac{\sigma^{\rm SPS}(J/\psi J/\psi + X)\sigma^{\rm SPS}(J/\psi + X)}{\sigma_{\rm eff,2}},$$
$$\sigma^{\rm TPS}(pp \to 3J/\psi + X) = \frac{1}{6}\frac{\left(\sigma^{\rm SPS}(pp \to J/\psi + X)\right)^3}{(\sigma_{\rm eff,3})^2}. \quad (6)$$

Therefore, we have to calculate three different SPS cross sections for one, two and three J/ψ production in proton-proton collisions, Lansberg, Shao, 1504.06531.

SPS cross sections for one and two J/ψ production

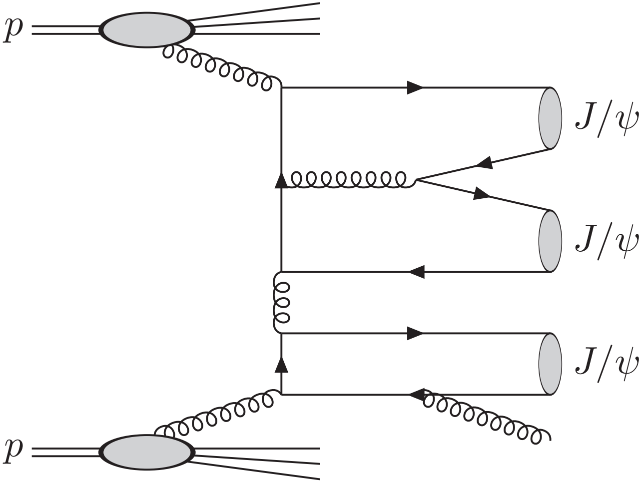
SPS cross sections for J/ψ

We will use the data-driven approach to fit the matrix element of the single J/ψ production with the precise experimental data, Lansberg, Shao, 1410.8822.

SPS cross sections for $J/\psi J/\psi$

We will use partial NLO result of double J/ψ SPS part by including infrared-safe real emission diagrams only (Lansberg, Shao, 1410.8822), which shows a reasonable agreement with the complete NLO calculation (Sun, Han, Chao, 1404.4042).

One of 28774 Feynman Diagrams of SPS cross sections for $J/\psi J/\psi J/\psi$

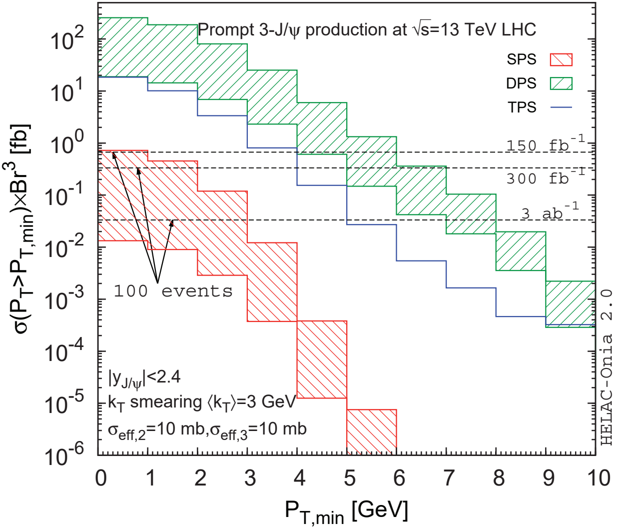


Numerical Result of $J/\psi J/\psi J/\psi + X$

Cross sections of $J/\psi J/\psi J/\psi$

		inclusive	$2.0 < y_{J/\psi} < 4.5$	$\lvert y_{J/\psi}\rvert < 2.4$
13 TeV	SPS	$0.41^{+2.4}_{-0.34} \pm 0.0083$	$(1.8^{+11}_{-1.5} \pm 0.18) \times 10^{-2}$	$(8.7^{+56}_{-7.5} \pm 0.098) \times 10^{-2}$
	DPS	$(190^{+501}_{-140}) \times \frac{10\ \text{mb}}{\sigma_{\text{eff},2}}$	$(7.0^{+18}_{-5.1}) \times \frac{10\ \text{mb}}{\sigma_{\text{eff},2}}$	$(50^{+140}_{-37}) \times \frac{10\ \text{mb}}{\sigma_{\text{eff},2}}$
	TPS	$130 \times \left(\frac{10\ \text{mb}}{\sigma_{\text{eff},3}}\right)^2$	$1.3 \times \left(\frac{10\ \text{mb}}{\sigma_{\text{eff},3}}\right)^2$	$18 \times \left(\frac{10\ \text{mb}}{\sigma_{\text{eff},3}}\right)^2$
27 TeV	SPS	$0.46^{+2.9}_{-0.39} \pm 0.022$	$(3.2^{+22}_{-2.8} \pm 0.21) \times 10^{-2}$	$(5.8^{+39}_{-5.1} \pm 0.29) \times 10^{-2}$
	DPS	$(560^{+2900}_{-480}) \times \frac{10\ \text{mb}}{\sigma_{\text{eff},2}}$	$(19^{+97}_{-16}) \times \frac{10\ \text{mb}}{\sigma_{\text{eff},2}}$	$(120^{+630}_{-100}) \times \frac{10\ \text{mb}}{\sigma_{\text{eff},2}}$
	TPS	$570 \times \left(\frac{10\ \text{mb}}{\sigma_{\text{eff},3}}\right)^2$	$5.0 \times \left(\frac{10\ \text{mb}}{\sigma_{\text{eff},3}}\right)^2$	$57 \times \left(\frac{10\ \text{mb}}{\sigma_{\text{eff},3}}\right)^2$
75 TeV	SPS	$0.59^{+4.4}_{-0.52} \pm 0.016$	$(3.0^{+25}_{-2.7} \pm 0.23) \times 10^{-2}$	$(7.2^{+63}_{-6.5} \pm 0.38) \times 10^{-2}$
	DPS	$(1900^{+11000}_{-1600}) \times \frac{10\ \text{mb}}{\sigma_{\text{eff},2}}$	$(57^{+340}_{-50}) \times \frac{10\ \text{mb}}{\sigma_{\text{eff},2}}$	$(310^{+2000}_{-270}) \times \frac{10\ \text{mb}}{\sigma_{\text{eff},2}}$
	TPS	$3900 \times \left(\frac{10\ \text{mb}}{\sigma_{\text{eff},3}}\right)^2$	$27 \times \left(\frac{10\ \text{mb}}{\sigma_{\text{eff},3}}\right)^2$	$260 \times \left(\frac{10\ \text{mb}}{\sigma_{\text{eff},3}}\right)^2$
100 TeV	SPS	$1.1^{+8.4}_{-1.0} \pm 0.044$	$(4.5^{+33}_{-4.0} \pm 0.72) \times 10^{-2}$	$(36^{+290}_{-32} \pm 1.8) \times 10^{-2}$
	DPS	$(3400^{+19000}_{-2900}) \times \frac{10\ \text{mb}}{\sigma_{\text{eff},2}}$	$(100^{+550}_{-86}) \times \frac{10\ \text{mb}}{\sigma_{\text{eff},2}}$	$(490^{+3000}_{-430}) \times \frac{10\ \text{mb}}{\sigma_{\text{eff},2}}$
	TPS	$6500 \times \left(\frac{10\ \text{mb}}{\sigma_{\text{eff},3}}\right)^2$	$45 \times \left(\frac{10\ \text{mb}}{\sigma_{\text{eff},3}}\right)^2$	$380 \times \left(\frac{10\ \text{mb}}{\sigma_{\text{eff},3}}\right)^2$

Cross sections of $J/\psi J/\psi J/\psi$



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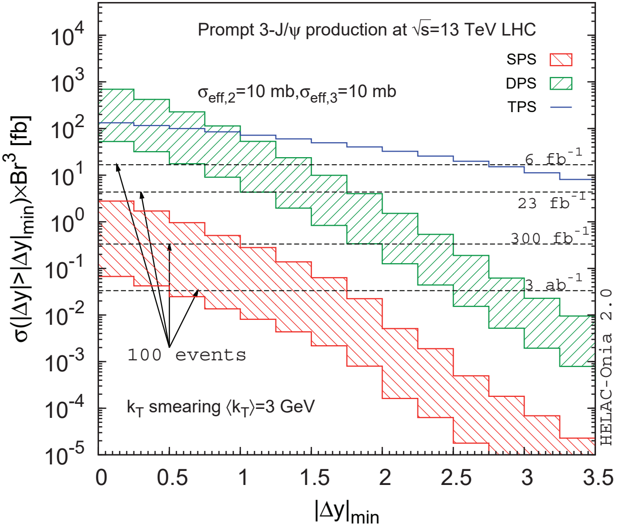

Summary

We performed a first complete theoretical study of $3J/\psi$ by including SPS, DPS and TPS contributions.

The prompt $3J/\psi$ is a very clean process to probe TPS and therefore the possible triple-parton correlations in a proton.

Although the process is rare, LHC Run2 is already more than enough to measure this process.

Finally, the minimal rapidity gap among $3J/\psi$s is a very useful observable to separate the TPS events from DPS and SPS.

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,

$$\sigma^{\rm NPS}_{hh'\to a_1\ldots a_n} = \left(\frac{m}{n!}\right) \sum_{i_1,..,i_n,i'_1,..,i'_n} \int \Gamma_h^{i_1\ldots i_n}(x_1,..,x_n;\mathbf{b_1},..,\mathbf{b_n};Q_1^2,..,Q_n^2) \times \hat{\sigma}_{a_1}^{i_1 i'_1}(x_1,x'_1,Q_1^2)\cdots\hat{\sigma}_{a_n}^{i_n i'_n}(x_n,x'_n,Q_n^2) \times \Gamma_{h'}^{i'_1\ldots i'_n}(x'_1,\ldots,x'_n;\mathbf{b_1}-\mathbf{b},\ldots,\mathbf{b_n}-\mathbf{b};Q_1^2,\ldots,Q_n^2) \times dx_1\ldots dx_n\, dx'_1,\ldots,dx'_n\, d^2b_1,\ldots,d^2b_n\, d^2b. \quad (7)$$

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,

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

2. We can get hadron-hadron overlap function $T(\mathbf{b}) = \int f(\mathbf{b_1})f(\mathbf{b_1}-\mathbf{b})d^2b_1$, where $1 = \int T(\mathbf{b})d^2b$.
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

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

σ^{nPS}_{eff}

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