Triple J/ψ Production at Hadronic Colliders

Yu-Jie Zhang

Beihang Univeisity

2019.11.09-10 Peking University

Based on Hua-Sheng Shao, YJZ, PRL122(2019)192002

November 9, 2019

Outline

Introduction

Quarkonium productions at B factories

Puzzle of J/ψ productions at B factories, Liu, He, KTC, PLB557(2003)45

1. Belle data (hep-ex/0205104):
   $\sigma[e^+e^- \to J/\psi + \eta_c] \times Br_{\eta_c}[> 2charged] = 33 \pm 12\ fb$
2. Theoretical prediction: $\sigma[e^+e^- \to J/\psi + \eta_c] = 5 \pm 1\ fb$

NLO of J/ψ productions at B factories

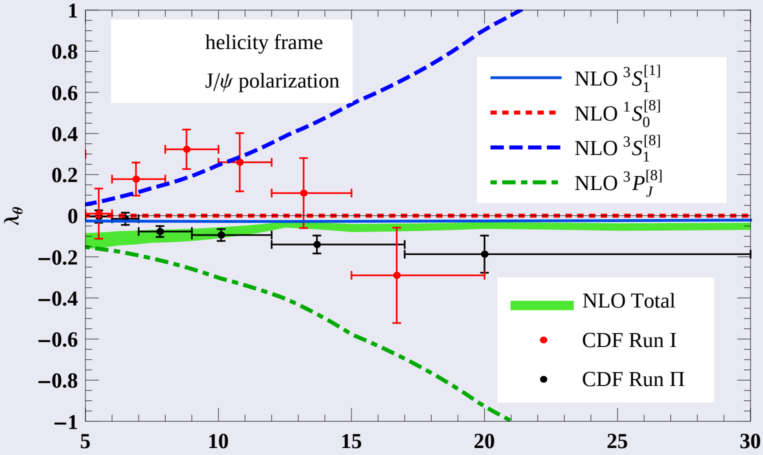
1. Zhang, Gao, KTC, PRL(2006); Gong, Wang, PRD(2008): $\sigma[J/\psi + \eta_c] = 18\ fb$; He, Fan, KTC, PRD(2010); Feng, Jia, Sang, 1901.08447
2. Zhang, KTC, PRL96(2006)092001; Gong, Wang, PRD77(2008)054028: $\sigma[e^+e^- \to J/\psi + c\bar{c}] = 0.5pb$
3. Ma, Zhang, KTC, PRL102 (2009) 162002; Gong, Wang, PRL102(2009)162003: $\sigma[e^+e^- \to J/\psi + gg] = 0.3\ pb$

Quarkonium productions

Quarkonium production have been studied by

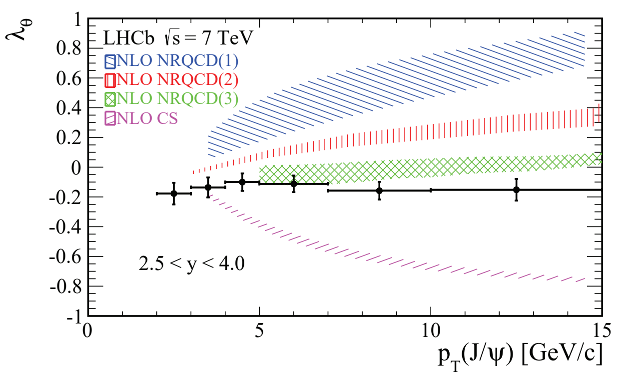
1. Kuang-Ta Chao group
2. Yu-Qi Chen group
3. Yu Jia group
4. B. A. Kniehl group
5. Cong-Feng Qiao group
6. Jian-Xiong Wang group
7. ...

NLO J/ψ polarization at CDF, KTC, Ma, Shao, Wang, Zhang, PRL108(2012) 242004



Quarkonium productions

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



CO LDMEs, 1212.2037

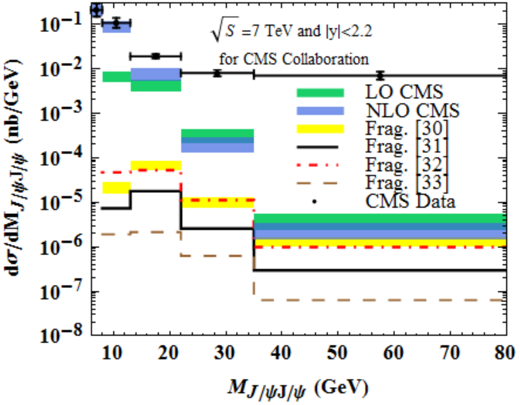
	Butenschoen, Kniehl[18]	Gong, Wang, Wan, Zhang[53]	Chao, Ma, Shao, Wang, Zhang[52] default set	set 2	set 3
$\langle\mathcal{O}^{J/\psi}(^3S_1^{[1]})\rangle$	1.32 GeV^3	1.16 GeV^3	1.16 GeV^3	1.16 GeV^3	1.16 GeV^3
$\langle\mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$	0.0497 GeV^3	0.097 GeV^3	0.089 GeV^3	0	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			

J/ψ production and polarization at LHC

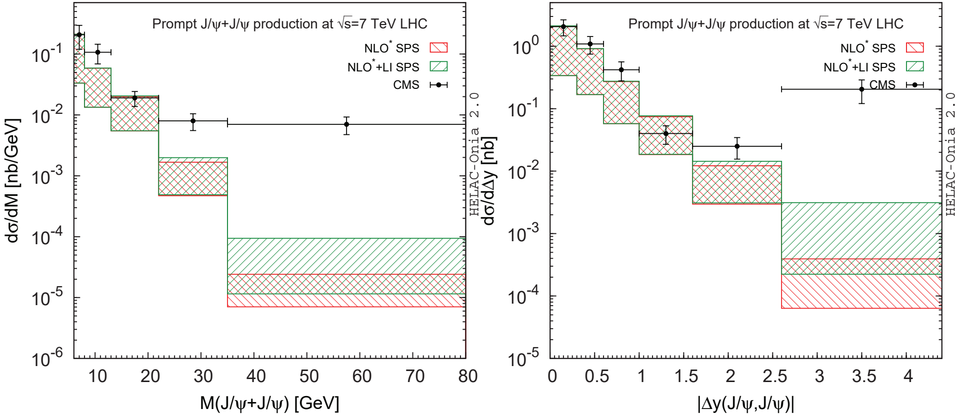
KTC Group, PRL106(2011), 108(2012), 112(2014), 114(2015)

1. Production and polarization prediction is confirmed by Atlas/CMS: 1307.6070, 1404.7035, 1502.04155, 1603.02913, 1709.03089, ...
2. Physics picture is confirmed by Bodwin, et al., PRL113(2014)022001
3. Physics picture is confirmed CMS: 1910.01686
4. CERN Courier 2015 March: the cross-section measurements are actually found to agree with the polarization data, indicating that the bound-state formation through coloured $^1S_0$ pre-resonance is dominant (Bodwin et al. 2014, Chao et al. 2012, Faccioli et al. 2014)

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



2 J/ψ, Lansberg, Shao, Yamanaka, YJZ 1906.10049, He's talk in tomorrow



Double parton correlation in proton (Enterria, Snigirev, 1708.07519)

Single-parton Scattering with $\sigma^{inel}(pp) \sim 30 - 50$ mb

$$\mathrm{P}^{SPS}_{pp\to a} = \frac{\sigma(pp \to a + X)}{\sigma^{inel}(pp)}, \quad (1)$$

Double parton scattering, but $\sigma^{DPS}_{eff} \sim 10 - 15$ mb

$$\begin{aligned} \mathrm{P}^{DPS}_{pp\to ab} &= \mathrm{P}^{SPS}_{pp\to a} \times \mathrm{P}^{SPS}_{pp\to b} \\ \sigma^{DPS}(pp \to a + X) &= \frac{\sigma(pp \to a + X)\sigma(pp \to b + X)}{\sigma^{DPS}_{eff}} \end{aligned} \quad (2)$$

SPS, DPS, and TPS

1. Single-/Double-/Triple-parton scattering (SPS/DPS/TPS): 1/2/3 partons from proton.
2. $\sigma^{TPS} : \sigma^{DPS}\sigma^{SPS} \sim \Lambda^4_{QCD} : \Lambda^2_{QCD} : 1$

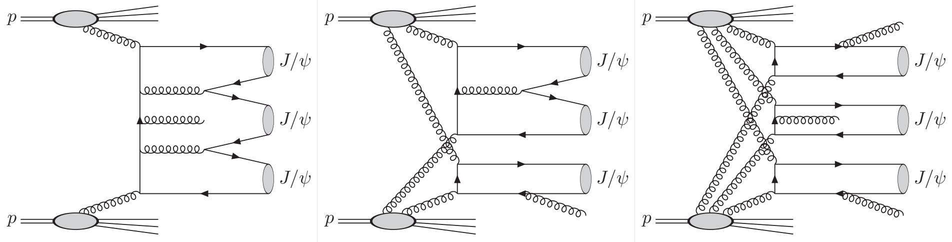


Figure: SPS/DPS/TPS triple J/ψ production at SPPC

Multi-parton correlation

Multi-parton correlation (MPI)

1. The cross sections of Multi-parton correlation 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)

$$\sigma^{\mathrm{NPS}}_{f_1\cdots f_N} = \frac{m}{N!}\frac{\prod_{i=1}^{N}\sigma^{\mathrm{SPS}}_{f_i}}{(\sigma_{\mathrm{eff,N}})^{N-1}}, \quad (3)$$

N-parton scattering

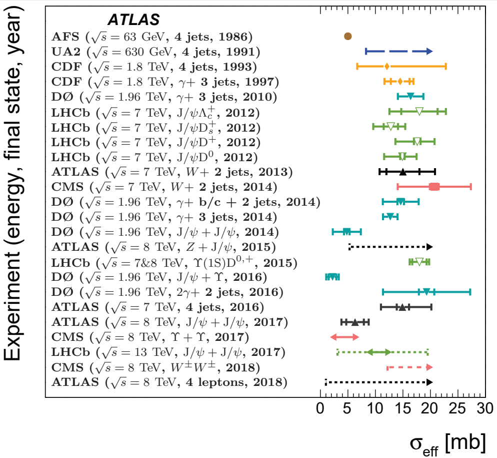
1. A N-parton scattering (NPS) cross-section (1708.07519)

$$\sigma^{\mathrm{NPS}}_{f_1\cdots f_N} = \frac{m}{N!}\frac{\prod_{i=1}^{N}\sigma^{\mathrm{SPS}}_{f_i}}{(\sigma_{\mathrm{eff,N}})^{N-1}}, \tag{4}$$

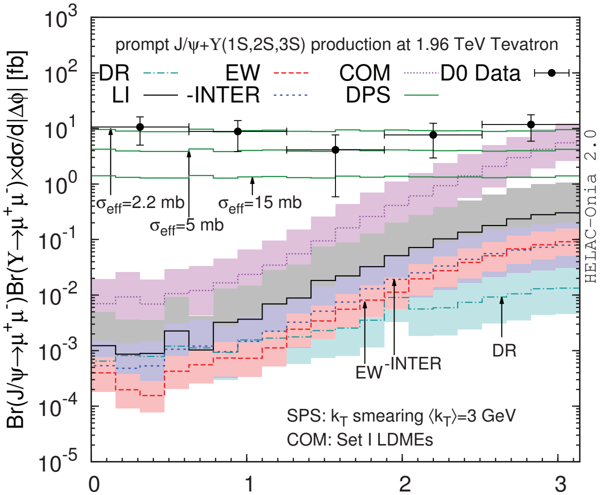
2. The factor $\frac{m}{N!}$: the indistinguishable final state symmetry.
3. $\sigma^{\mathrm{SPS}}_{f_i}$: the SPS cross section of producing final state f_i.
4. $\sigma_{\mathrm{eff,N}}$: the effective cross section, which should be determined by experiments.
5. The DPS and TPS cases correspond to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

Multiparton scattering

σ_{eff}^{DPS} and heavy quarkonium, 1811.11094



dphi @ D0, Shao, YJZ, PRL117 (2016) 062001



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.

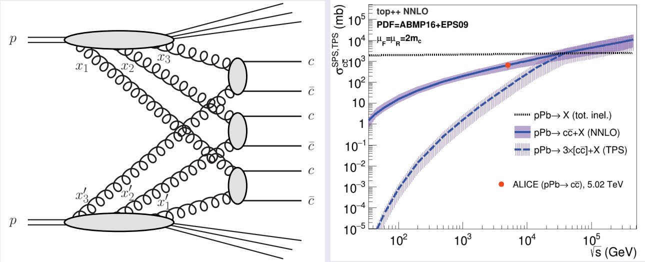


Figure: TPS of $pP_b \to c\bar{c} + c\bar{c} + c\bar{c}$ (PRL118, 122001).

The frame of Calculation

Total triple J/ψ hadroproduction cross sections

DPS and TPS cross sections

We will use the following concrete formula:

$$\begin{aligned}
&\sigma^{\mathrm{DPS}}(pp \to J/\psi J/\psi J/\psi + X) \\
= &\frac{\sigma^{\mathrm{SPS}}(pp \to J/\psi J/\psi + X)\sigma^{\mathrm{SPS}}(pp \to J/\psi + X)}{\sigma_{\mathrm{eff},2}}, \\
&\sigma^{\mathrm{TPS}}(pp \to J/\psi J/\psi J/\psi + X) \\
= &\frac{1}{6}\frac{\left[\sigma^{\mathrm{SPS}}(pp \to J/\psi + X)\right]^3}{(\sigma_{\mathrm{eff},3})^2}
\end{aligned} \quad (5)$$

to calculate DPS and TPS cross sections.

SPS cross sections

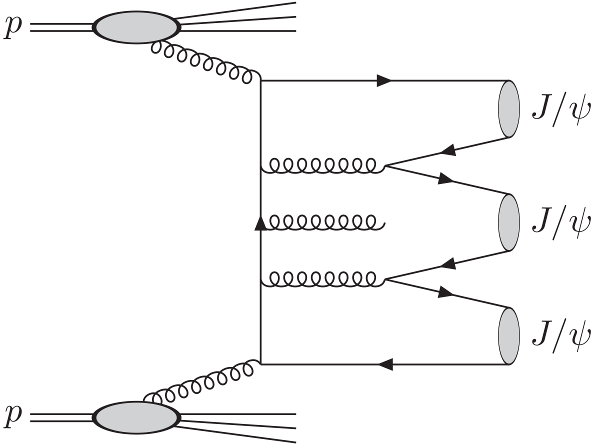
Hadron and Parton level cross sections

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

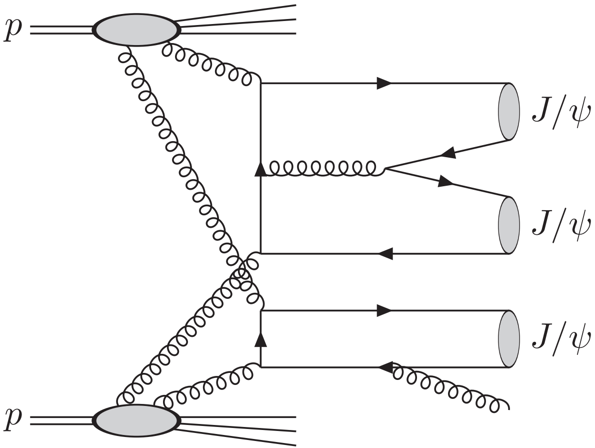
Parton level cross section

$$d\hat{\sigma}(ab \to \mathcal{J}\mathcal{J}\mathcal{J}) = \sum_{n_1,n_2,n_2} \hat{\sigma}(ab \to c\bar{c}[n_1]c\bar{c}[n_2]c\bar{c}[n_3] + X) \langle O^{\mathcal{J}}(n_1)\rangle\langle O^{\mathcal{J}}(n_2)\rangle\langle O^{\mathcal{J}}(n_3)\rangle \tag{7}$$

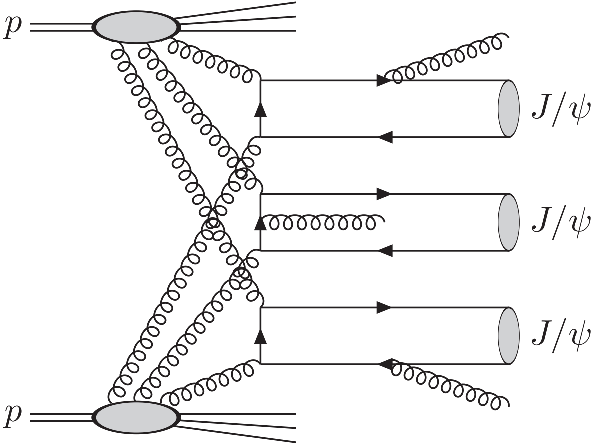
One of 28774 Feynman Diagrams of SPS



Feynman Diagrams of DPS



Feynman Diagrams of TPS



Numerical Result

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

σ^{SPS}	Order	14 TeV	100 TeV
$J/\psi + X$	α_s^3	$72 \pm 1\ \mu\text{b}$	$300 \pm 8\ \mu\text{b}$
$J/\psi J/\psi + X$	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

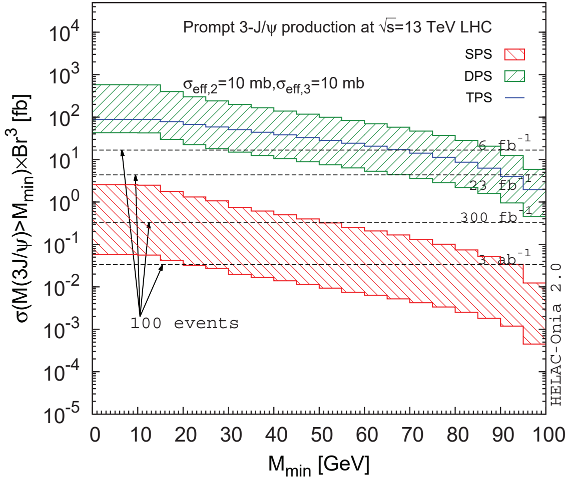
$\sigma(J/\psi J/\psi J/\psi + X)$	Order	14 TeV	CMS @ 14 TeV	100 TeV
TPS	α_s^9	620 ± 20 pb	45 ± 1.5 pb	45000 ± 1500 pb
DPS	α_s^7	480 ± 20 pb	35 ± 1.5 nb	10000 ± 1000 pb
SPS	α_s^7	1 ± 0.6 pb	0.07 ± 0.04 pb	4.2 ± 3.2 pb

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

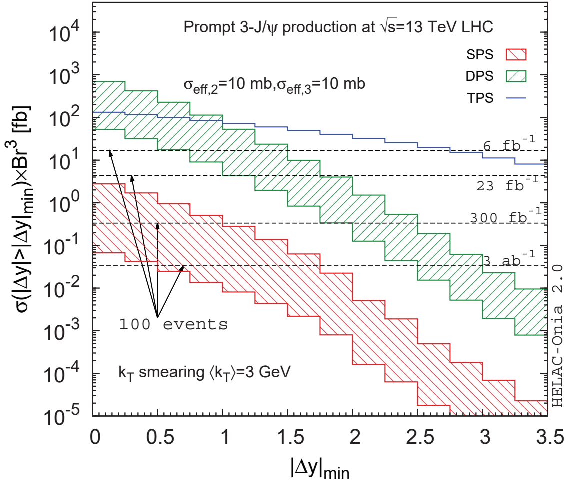
Search TPS at CMS/Atlas

1. Integrated luminosity of CMS/Atlas is about $160\ \text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV.
2. $Br[J/\psi \to \mu^+\mu^-] = 0.059$.
3. Number of events for $3J/\psi(\mu^+\mu^-)$ with $p_T(J/\psi) > 2$ GeV is about 2700 ± 72 , which is 1500 ± 50 from TPS and 1200 ± 50 from DPS.
4. We can introduce cut of phase space to distinguish SPS, DPS, and TPS contributions.

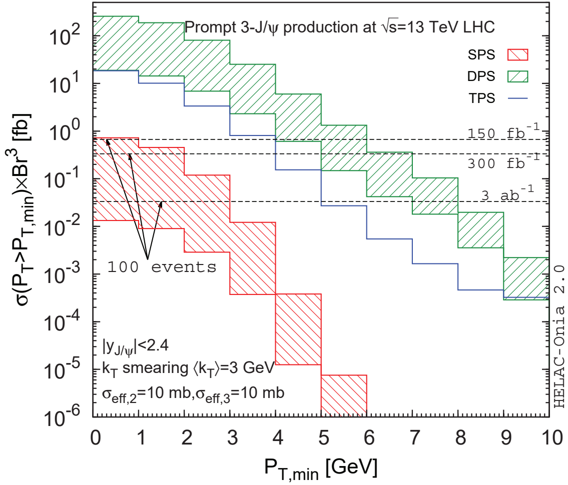
Triple J/ψ production at LHC



Triple J/ψ production at LHC



Triple J/ψ production at LHC



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

Υ, J/ψ, ϕ at LHCb

1. $\sigma(\Upsilon) \sim 0.20\ \mu$b (1804.09214), $\sigma(J/\psi) \sim 15\ \mu$b (1509.00771), and $\sigma(\phi) \sim 3$ mb (1107.3935).
2. We have gotten $\sigma^{SPS}[\Upsilon + J/\psi] \sim 10$ pb in 1605.03061.
3. SPS $\Upsilon + J/\psi + \phi$: $\mathcal{O}(\alpha_s^9)$, very small.
4. DPS $\Upsilon + J/\psi + \phi$: about $3 \times \sigma^{SPS}[\Upsilon + J/\psi]\frac{\sigma[\phi]}{\sigma_{eff}^{DPS}} \sim$ 10 pb for $p_T(\phi) > 2$ GeV and $\sigma_{eff}^{DPS} \sim 10$ mb.
5. TPS $\Upsilon + J/\psi + \phi$: about $\frac{\sigma[\Upsilon]\sigma[J/\psi]\sigma[\phi]}{(\sigma_{eff}^{TPS})^2} \sim$ 100 pb for $\sigma_{eff}^{TPS} \sim 10$ mb.
6. Number of events for $\Upsilon(\mu^+\mu^-) + J/\psi(\mu^+\mu^-) + \phi(K^+K^-)$ with $p_T(\phi) > 2$ GeV is about 440.

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,

$$\begin{aligned}\sigma^{\mathrm{NPS}}_{hh'\to a_1\ldots a_n} = & \left(\frac{m}{n!}\right) \sum_{i_1,..,i_n,i'_1,..,i'_n} \int \Gamma_h^{i_1\ldots i_n}(x_1,..,x_n;\mathbf{b_1},..,\mathbf{b_n};Q_1^2,..,Q_n^2) \\ & \times \hat{\sigma}_{a_1}^{i_1 i'_1}(x_1,x'_1,Q_1^2)\cdots\hat{\sigma}_{a_n}^{i_n i'_n}(x_n,x'_n,Q_n^2) \\ & \times \Gamma_{h'}^{i'_1\ldots i'_n}(x'_1,\ldots,x'_n;\mathbf{b_1}-\mathbf{b},\ldots,\mathbf{b_n}-\mathbf{b};Q_1^2,\ldots,Q_n^2) \\ & \times dx_1\ldots dx_n\, dx'_1,\ldots,dx'_n\, d^2b_1,\ldots,d^2b_n\, d^2b. \end{aligned} \quad (8)$$

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,

$$\Gamma_h^{i_1 \dots i_n} = D_h^{i_1 \dots i_n}(x_1, .., x_n; Q_1^2, .., Q_n^2) f(\mathbf{b_1}) \dots f(\mathbf{b_n}) \quad (9)$$

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

$$D_h^{i_1 \dots i_n}(x_1, .., x_n; Q_1^2, .., Q_n^2) = D_h^{i_1}(x_1; Q_1^2) \cdots D_h^{i_n}(x_n; Q_n^2) \quad (10)$$

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

The cross sections of n-particle associated production

Then we can get

$$\sigma^{nPS}_{hh'\to a_1\ldots a_n} = \binom{m}{n!} \frac{\sigma^{SPS}_{hh'\to a_1} \cdots \sigma^{SPS}_{hh'\to a_n}}{\left(\sigma^{nPS}_{eff}\right)^{n-1}}, \tag{11}$$

σ_{eff}^{nPS}

$$\left(\frac{1}{\sigma^{nPS}_{eff}}\right)^{n-1} = \int d^2b \, T^n(\mathbf{b}) \tag{12}$$