Role of initial state gluon emissions in double J/ψ production at central rapidities

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Outline

- Introduction
- Color singlet contribution
- Fragmentation contribution
- DPS
- Comparison with ATLAS data
- Summary

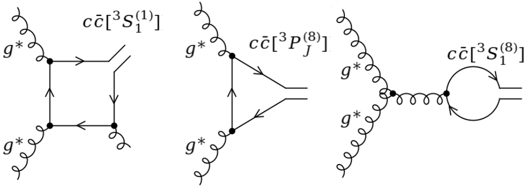
Introduction

- **Non-relativistic QCD** (NRQCD):

$$\sigma(pp \to J/\psi + X) = \sum_n \sigma(pp \to c\bar{c}(^{2S+1}L_J^{(a)}) + X)\langle \mathcal{O}^{J/\psi}[n]\rangle$$

- $\sigma(pp \to c\bar{c}(^{2S+1}L_J^{(a)}) + X)$ is the cross section of production unbound $c\bar{c}$ pair at the Fock state $n =^{2S+1} L_J^{(a)}$ with definite spin S, orbital angular momentum L, total angular momentum J and color representation a (color singlet (CS) (1) and color octet (CO) (8)) - can be calculated in the framework of pQCD

- **LDME** (long distance matrix element or nonperturbative matrix element) $\langle \mathcal{O}^{J/\psi}[n]\rangle$ corresponds to transition from unbound state to the physical J/ψ meson - nonperturbative part.



- Expansion of S-wave charmonia ψ in a small parameter v of a quarks relative motion:

$$|\psi\rangle = O(v^0)|c\bar{c}[^3S_1^{(1)}]\rangle + O(v^1)|c\bar{c}[^3P_J^{(8)}]g\rangle + O(v^2)|c\bar{c}[^3S_1^{(1,8)}]gg\rangle + Q(v^2)|c\bar{c}[^1S_0^{(8)}]g\rangle$$

- Total amplitude $\mathcal{A}(\mathcal{H})$ of charmonia production can be obtained from the amplitude $\mathcal{A}(q)$ of quark production at the intermediate Fock state integrated with charmonia wave function:

$$\mathcal{A}(\mathcal{H}) = \int \frac{d^3q}{(2\pi)^3}\mathcal{A}(q)\Psi^{(a)}(q) = \mathcal{A}|_{q=0}\int \frac{d^3q}{(2\pi)^3}\Psi^{(a)}(q) + + \left(\frac{\partial\mathcal{A}}{\partial q^\mu}\right)\bigg|_{q=0}\int \frac{d^3q}{(2\pi)^3}q^\mu\Psi^{(a)}(q) + ...,$$

where

$$\int \frac{d^3q}{(2\pi)^3}\Psi^{(a)}(q) = \frac{1}{\sqrt{4\pi}}\mathcal{R}^{(a)}(0), \int \frac{d^3q}{(2\pi)^3}q^\mu\Psi^{(a)}(q) = -i\epsilon^\mu(L_z)\frac{\sqrt{3}}{\sqrt{4\pi}}\mathcal{R}'^{(a)}(0)$$

k_T-factorization approach

- Cross section in k_T-factorization approach:

$$d\sigma(pp \to J/\psi + X) = \sum_n \int dx_1\, dx_2 \sum_{i,j} d^2\overrightarrow{k}_{\perp 1} d^2\overrightarrow{k}_{\perp 2} f_i(x_1, \overrightarrow{k}^2_{\perp 1}\mu^2) f_j(x_2, \overrightarrow{k}^2_{\perp 2}\mu^2)\cdot$$
$$\cdot d\widehat{\sigma}(i^* + j^* \to c\bar{c}(^{2S+1}L_J^{(a)}) + X)\langle \mathcal{O}^{J/\psi}[n]\rangle$$

- $f_{i,j}(x_{1,2}, \overrightarrow{k}_{\perp 1,2}, \mu^2)$ - TMD gluon distribution functions (TMD PDF) in a proton obeying the BFKL or CCFM evolution equation

- $d\widehat{\sigma}(i^* + j^* \to J/\psi + Z/W)$ - off-shell partonic cross section

- We see certain technical advantages in the ease of including higher-order pQCD radiative corrections (namely, the leading-logarithm part of NLO + NNLO + ... terms corresponding to real gluon emissions) in the form of transverse momentum dependent (TMD, or unintegrated) gluon density in a proton

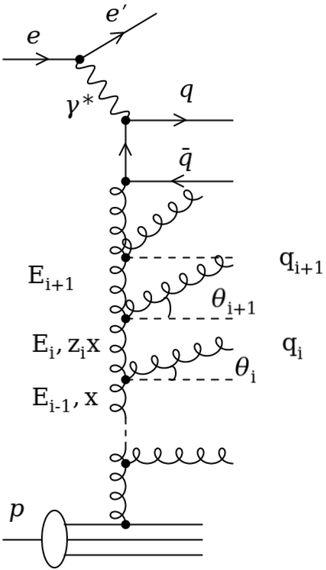
- We use the k_T-factorization approach with CCFM-evolved (Catani, Ciafaloni, Fiorani, Marchesini) Transverse Momentum Dependent (TMD) gluon densities

- Simultaneous description for all of the available LHC data on the entire charmonia and bottomonia families were achieved within NRQCD [Phys.Rev.D.100.114021 (2019); Eur.Phys.J.C 80 (2020) 11, 1022; Eur.Phys.J.C 79 (2019) 10, 830; Eur.Phys.J.C 80 (2020) 5, 486; Eur.Phys.J.C 81 (2021) 12, 1085]. Possible solution of polarization problem [Phys.Rev.D.93.054037 (2016)].

J/ψ pair production in NRQCD formalizm

- Direct test for mechanisms of creation bound heavy quark states.
- Progress in NRQCD evaluation of prompt $J/\psi + J/\psi$ production:
  complete LO calculations of CS and CO contributions [Phys. Rev. Lett. 115.022002 (2015)];
  NLO corrections for CS contributions [Phys. Rev. D 94.074033 (2016)];
  partial NLO* corrections for CS and CO [Phys. Rev. Lett. 111.122001 (2013)].
- Differential cross sections at the LO are significantly enhanced by the NLO terms.
- Unfortunately, theoretical predictions are demonstrated sizeable discrepancies with the latest experimental data of ATLAS [Eur. Phys. J. C 77, 76 (2017)] and CMS [JHEP 09, 094 (2014)] Collaborations, especially at large $m(J/\psi, J/\psi)$ and $\Delta y(J/\psi, J/\psi)$.
- Possible solutions: inclusion of high order corrections and/or new contributions

CCFM evolution and multiple gluon radiation



- CCFM evolution equation at the leading logarithmic approximation:

$$f_g(x, \mathbf{k}_T^2, q^2) = f_g(x, \mathbf{k}_T^2, q_0^2)\,\Delta_s(q, q_0) + \\ + \int dz \int \frac{dq'^2}{q'^2}\Theta(q - zq') \times \\ \times \Delta_s(q, zq')\tilde{P}_{gg}(z, q', \mathbf{k}_T) f_g(x/z, \mathbf{k}'^2_T, q'^2),$$

- Radiated gluons obey the angular ordering:

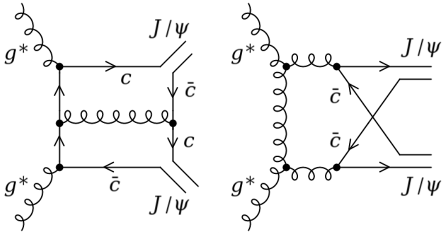
$$q > z_n q_n > z_{n-1} q_{n-1} > ... > q_1 > q_0,$$

- **Multiple gluon radiation** can serve as a source for J/ψ production via fragmentation mechanisms, because gluons have the non-zero p_T

Motivation and goals

- We consider the new contributions to the prompt $J/\psi + J/\psi$ production based on the fragmentation of gluons and charm quarks: $g \to J/\psi$ and $c \to J/\psi$. We can expect a sizeable contribution from multiple gluon radiation
- Recently we found that contributions of **multiple gluon radiation** to the cross section of double J/ψ production are very important [Eur. Phys. J. C80,1046 (2020)]. The multiple gluon radiation can be taken into account using the CCFM evolution equation.
- A sizeable contributions from **multiple gluon radiation** for $J/\psi + Z/W^{\pm}$ processes were observed [Phys. Rev. D 104 (2021) 3, 034018]
- Additional fragmentation contributions in DPS mechanism is expected to be important for double J/ψ production.
- **Our goal is to investigate a role of fragmentation mechanisms to the prompt $J/\psi + J/\psi$ production**

Color singlet contribution to the J/ψ pair production



(a)

- Typical diagrams of prompt-prompt J/ψ pair production at the LO QCD $\mathcal{O}(\alpha_s^4)$

$$g^* + g^* \to c\bar{c}[^3S_1^{(1)}] + c\bar{c}[^3S_1^{(1)}] \qquad (\sim 1/p_T^8)$$

- We take into consideration LO off-shell (depending on the initial gluons transverse momenta) production amplitude of gluon-gluon subprocesses
- Cross section can be written:

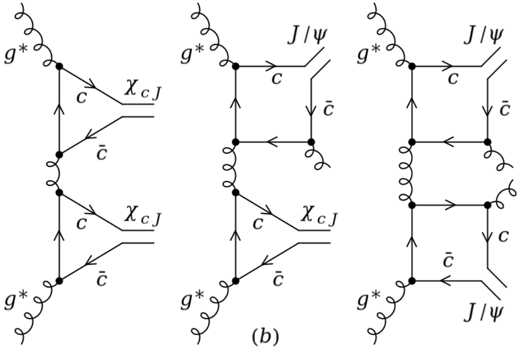
$$\sigma(pp \to J/\psi J/\psi + X) = \int \frac{1}{16\pi(x_1 x_2 s)^2} |\bar{\mathcal{A}}(g^* g^* \to J/\psi J/\psi|^2 \times$$

$$\times f_g(x_1, k_{1T}^2, \mu^2) f_g(x_2, k_{2T}^2, \mu^2) dk_{1T}^2 dk_{2T}^2 dp_{1T}^2 dy_1 dy_2 \frac{d\phi_1}{2\pi} \frac{d\phi_2}{2\pi} \frac{d\psi_1}{2\pi}$$

where $f_g(x, k_T^2, \mu^2)$ is the TMD gluon density in a proton

- Amplitudes $\mathcal{A}$ are calculated by S.P.Baranov [Phys. Rev. D 84, 054012 (2011)]

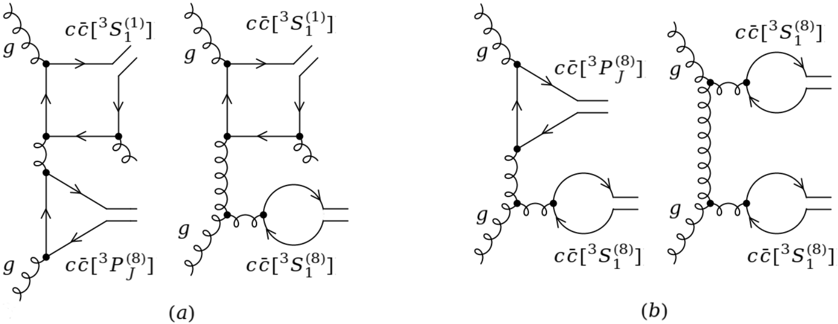
Color singlet contribution to the J/ψ pair production



- Additional subleading CS subprocesses at $\mathcal{O}(\alpha_s^4 - \alpha_s^6)$

$$g^* + g^* \to c\bar{c}[^3P_J^{(1)}] + c\bar{c}[^3P_J^{(1)}]$$
$$g^* + g^* \to c\bar{c}[^3P_J^{(1)}] + c\bar{c}[^3S_1^{(1)}] + g$$
$$g^* + g^* \to c\bar{c}[^3S_1^{(1)}] + c\bar{c}[^3S_1^{(1)}] + g + g$$

Color octet-singlet contribution to the J/ψ pair production



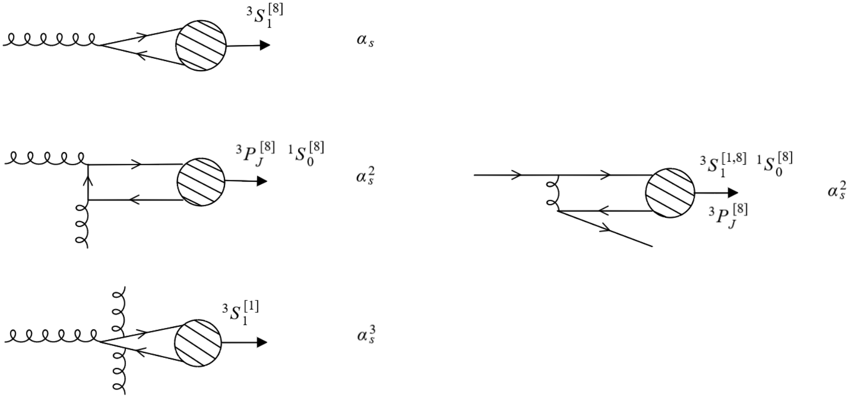
- CS-CO and CO-CO contributions starts to dominate with increasing p_T

$$g^* + g^* \to c\bar{c}[^3S_1^{(1)}] + c\bar{c}[^3P_J^{(8)}] + g \qquad (\sim 1/p_T^8)$$
$$g^* + g^* \to c\bar{c}[^3S_1^{(1)}] + c\bar{c}[^3S_1^{(8)}] + g \qquad (\sim 1/p_T^6)$$
$$g^* + g^* \to c\bar{c}[^3P_J^{(8)}] + c\bar{c}[^3S_1^{(8)}] \qquad (\sim 1/p_T^6)$$
$$g^* + g^* \to c\bar{c}[^3S_1^{(8)}] + c\bar{c}[^3S_1^{(8)}] \qquad (\sim 1/p_T^4)$$

- Fragmentation function in NRQCD formalism at the starting scale $\mu_0^2 = m_{\mathcal{H}}^2$:

$$D_a^{\mathcal{H}}(z, \mu_0^2) = \sum_n d_a^n(z, \mu_0^2)\langle \mathcal{O}^{\mathcal{H}}[n]\rangle$$

- Typical diagrams of gluons and charm quarks fragmentation into charmonium



Charmonium $\mathcal{H}$ production via fragmentation

- We consider contributions to the FFs:

$$J/\psi, \psi' \quad \Longleftrightarrow \quad \begin{cases} g \to c\bar{c}[^3S_1^{(8)}] \\ g \to c\bar{c}[^3P_J^{(8)}] + g \\ c \to c\bar{c}[^3S_1^{(1)}] + c \end{cases} \qquad \chi_{cJ} \quad \Longleftrightarrow \quad \begin{cases} g \to c\bar{c}[^3P_J^{(1)}] + g \\ g \to c\bar{c}[^3S_1^{(8)}] \\ c \to c\bar{c}[^3P_J^{(1)}] + c \end{cases}$$

- **LO DGLAP evolution equation** $\Rightarrow$ FFs $\mathcal{D}_c^{\mathcal{H}}(z, \mu^2)$ and $\mathcal{D}_g^{\mathcal{H}}(z, \mu^2)$ at the any scale μ^2:

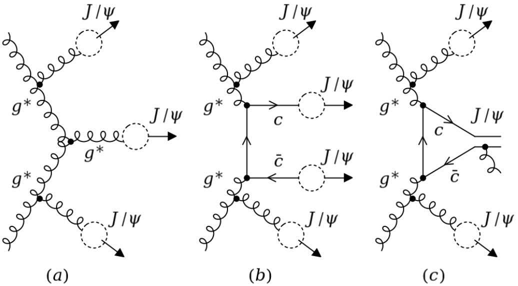
$$\frac{d}{d \ln \mu^2} \begin{pmatrix} \mathcal{D}_c^{\mathcal{H}} \\ \mathcal{D}_g^{\mathcal{H}} \end{pmatrix} = \frac{\alpha_s(\mu^2)}{2\pi} \begin{pmatrix} P_{cc} & P_{gc} \\ P_{cg} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} \mathcal{D}_c^{\mathcal{H}} \\ \mathcal{D}_g^{\mathcal{H}} \end{pmatrix},$$

where P_{ab} standard LO DGLAP splitting function

- Single charmonia production cross section via fragmentation mechanism can be written:

$$\frac{d\sigma(pp \to \mathcal{H} + X)}{dp_T} = \int \frac{d\sigma(pp \to g^*)}{dp_T^{(g^*)}} D_g^{\mathcal{H}}(z, \mu^2)\, \delta(z - p/p^{(g^*)})\, dz$$
$$+ \int \frac{d\sigma(pp \to c\bar{c})}{dp_T^c} D_c^{\mathcal{H}}(z, \mu^2)\, \delta(z - p/p^c)\, dz$$

Fragmentation contribution to the J/ψ pair production



- For the initial hard processes, we consider:

$$g^* + g^* \to g^*, \quad g^* + g^* \to c + \bar{c}, \quad g^* + g^* \to q + \bar{q}$$

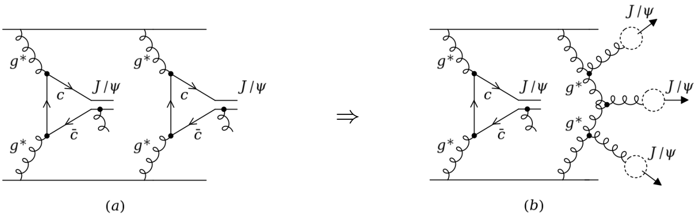
$$g^* + g^* \to c\bar{c}\left[\,^3P_J^{(1,8)}\right], \quad g^* + g^* \to c\bar{c}\left[\,^3S_1^{(1)}\right] + g,$$

- Circles denote the possible channels of $g \to J/\psi$ and $c \to J/\psi$ fragmentation
- Double charmonia production cross section can be written as:

$$\sigma(pp \to \mathcal{H} + \mathcal{H}' + X) = \sum_a \int \sigma(pp \to \mathcal{H}' + X)\mathcal{D}_a^{\mathcal{H}}(z, \mu^2)\,\delta\left(z - \frac{p^{\mathcal{H}}}{p^{\,a}}\right) dz$$

$$+ \sum_{a,b} \iint \sigma(pp \to g^*/c\bar{c}/q\bar{q})\,\mathcal{D}_a^{\mathcal{H}}(z, \mu^2)\mathcal{D}_b^{\mathcal{H}'}(z', \mu'^{\,2})\,\delta\left(z - \frac{p^{\mathcal{H}}}{p^{\,a}}\right)\,\delta\left(z' - \frac{p^{\mathcal{H}'}}{p^{\,b}}\right) dz\, dz'$$

DPS contribution to the J/ψ pair production



- Calculation of DPS:

$$\sigma_{\rm DPS}(pp \to \mathcal{H} + \mathcal{H}' + X) = \frac{1}{2}\frac{\sigma_1(pp \to \mathcal{H} + X)\cdot\sigma_2(pp \to \mathcal{H}' + X)}{\sigma_{\rm eff}}$$

- Example of DPS J/ψ pair production in conventional calculation scheme (left) and modified DPS J/ψ pair production with fragmentation mechanism (right)
- Direct production of $g^*g^* \to J/\psi$ via ${}^3S_1^{[8]}$ intermediate state can be replaced by the $g^*g^* \to g^*$ (or $g^*g^* \to c\bar{c}$) with subsequent fragmentation to the J/ψ with additional multiple gluon radiation
- For direct J/ψ pair production:

$$[{}^3S_1^{(1,8)},\, {}^3P_J^{(8)}] \times [{}^3S_1^{(1,8)},\, {}^3P_J^{(8)}] \Rightarrow [g,\, c,\, {}^3S_1^{(1)},\, {}^3P_J^{(8)}] \times [g,\, c,\, {}^3S_1^{(1)},\, {}^3P_J^{(8)}]$$

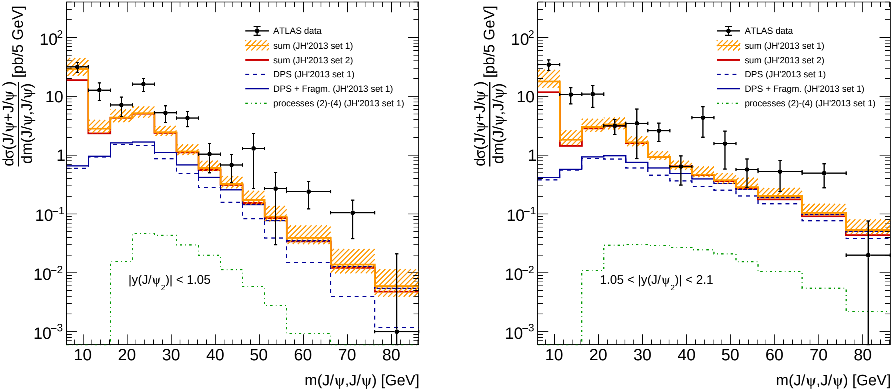
We used:

- **JH'2013 set1 and set2 TMD gluon densities**; Monte Carlo event generator CASCADE
- Additional fragmentation mechanism $g \to \chi_c(^3P_J^{[1]}) + g$ based on fragmentation function calculated by S.P. Baranov (Eur. Phys. J. Plus 136 (2021) 8, 836)
- **numerical solution of DGLAP evolution of FFs** with appropriate LDME's $\langle \mathcal{O}^{\mathcal{H}}[n] \rangle$ (list of used LDME for JH'2013 set1: $\langle \mathcal{O}^{J/\psi}[^3S_1^{(1)}] \rangle = 1.16$ GeV^3, $\langle \mathcal{O}^{\psi'}[^3S_1^{(1)}] \rangle = 0.7038$ GeV^3, $\langle \mathcal{O}^{\chi_{c1}}[^3P_1^{(1)}] \rangle = 0.95$ GeV^5, $\langle \mathcal{O}^{\chi_{c2}}[^3P_2^{(1)}] \rangle = 0.49$ GeV^5, $\langle \mathcal{O}^{J/\psi}[^3S_1^{(8)}] \rangle = 0.0012$ GeV^3, $\langle \mathcal{O}^{\psi}[^3S_1^{(8)}] \rangle = 0.0011$ GeV^3, $\langle \mathcal{O}^{\chi_{c0}}[^3S_1^{(8)}] \rangle = 0.00012$ GeV^3, $\langle \mathcal{O}^{J/\psi}[^3P_0^{(8)}] \rangle = 0.024$ GeV^5, $\langle \mathcal{O}^{\psi}[^3P_J^{(8)}] \rangle = 0.015$ GeV^5 (see [Phys. Rev. D 100.114021 (2019)] for more information about fitting procedure)
- Effective cross section $\sigma_{\text{eff}} = 13.8$ mb for DPS was obtained from the best description of LHCb data of J/ψ pair production (see more in [Eur. Phys. J. C 80,1046 (2020)])

Selection criteria:

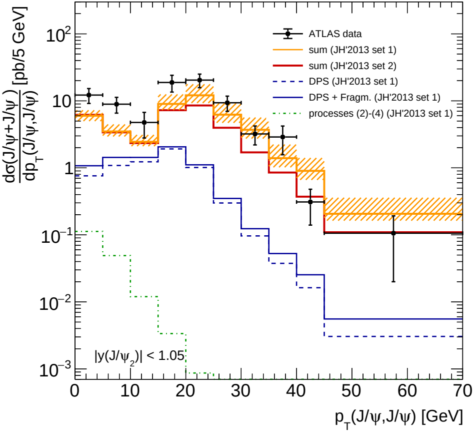
- $J/\psi + J/\psi$: $p_T(J/\psi) > 8.5$ GeV, $|y(J/\psi)| < 2.1$, trigger muons $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.3$, muons $p_T(\mu) > 2.5$ GeV, $|\eta(\mu)| < 2.3$

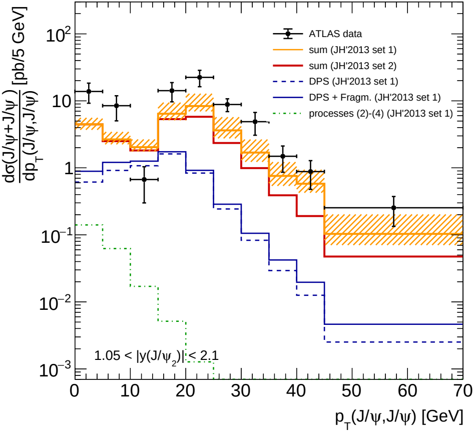
Comparison with ATLAS data



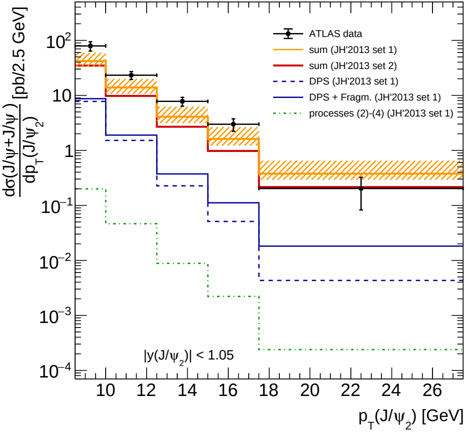
- Contributions from modified DPS, modified DPS + fragmentation and sum of all contributions (modified DPS + fragmentation + color singlet)
- (2)-(4) processes include the $g^*g^* \to \chi_c + \chi_c$, $g^*g^* \to \chi_c + J/\psi + g$ and $g^*g^* \to J/\psi + J/\psi + g + g$
- Shaded bands represents the scale uncertainties.

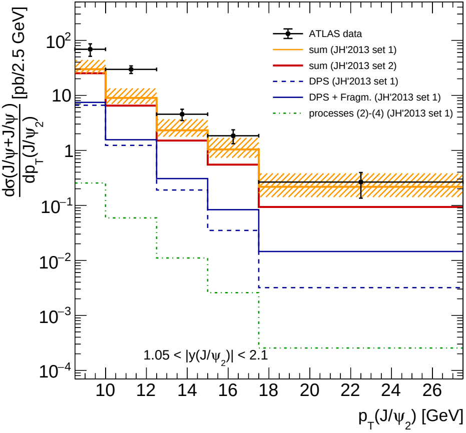
Comparison with ATLAS data



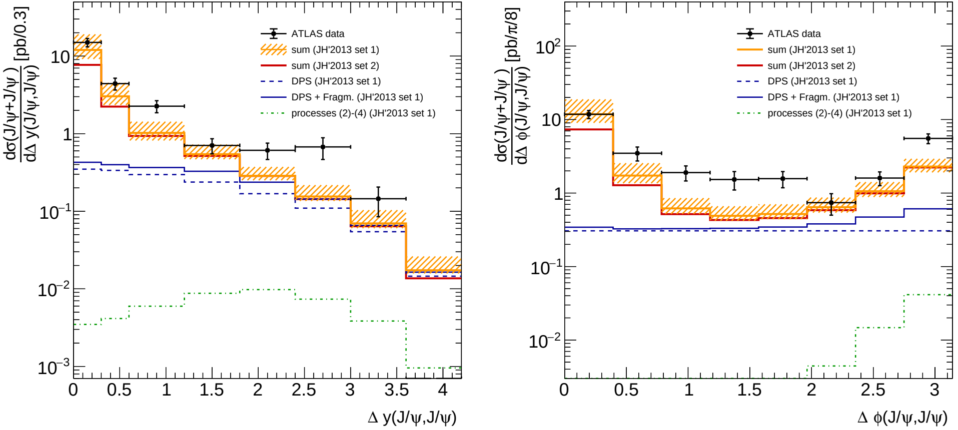


Comparison with ATLAS data

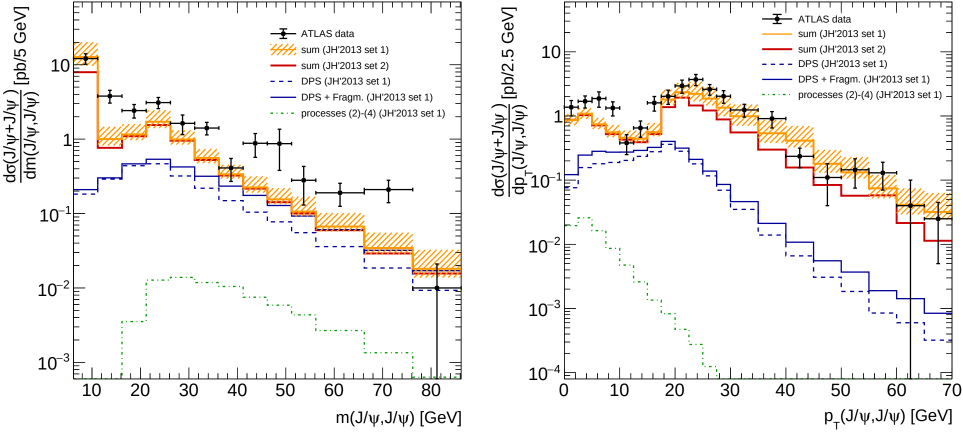




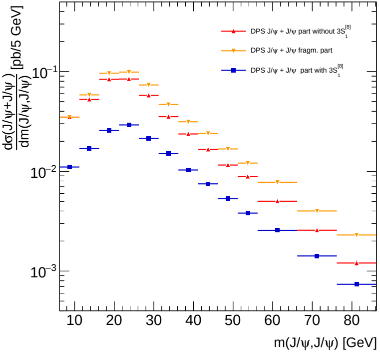
Comparison with ATLAS data

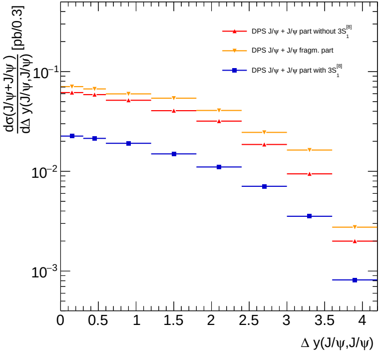


Comparison with ATLAS data



Fragmentation in DPS





- $[{}^3S_1^{(1)}, {}^3P_J^{(8)}] \times [{}^3S_1^{(1)}, {}^3P_J^{(8)}]$ (red) contributions are same in both schemes of calculations
- Second part $[{}^3S_1^{(8)}] \times [{}^3S_1^{(1)}, {}^3P_J^{(8)}, {}^3S_1^{(8)}]$ (blue) and it's modification $[g, c] \times [{}^3S_1^{(1)}, {}^3P_J^{(8)}, g, c]$ (orange) (with fragmentation contribution)
- Modified part of DPS with fragmentation mechanism increases the total and differential cross section by 2 times

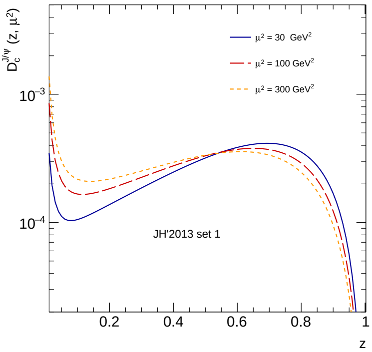
Summary

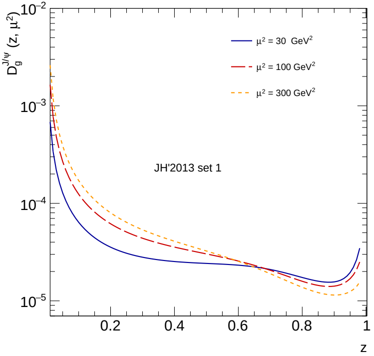
- We compare our predictions of $J/\psi + J/\psi$ production calculated within the k_T-factorization approach with latest ATLAS data at $\sqrt{s} = 8$ TeV.
- We take into account the effects of the multiple gluon radiation in the initial state.
- Fragmentation contributions of multiple initial gluon emissions to the J/ψ pair production are very important at large invariant masses $m(J/\psi, J/\psi)$ and rapidity separation $|\Delta y(J/\psi, J/\psi)|$.
- Implementation of fragmentation mechanism to the DPS increases by two times the total and differential cross section in comparison with conventional scheme of calculations.

Thank you for your attention

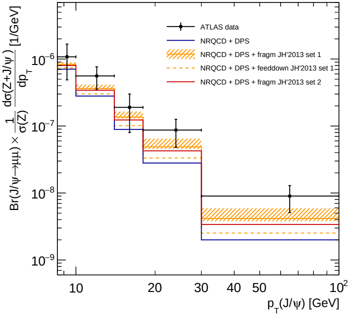
Backup

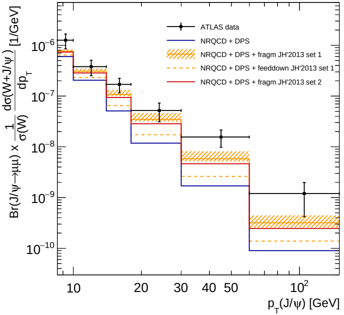
Evolution of fragmentation functions





$Z/W^{\pm} + J/\psi$ production

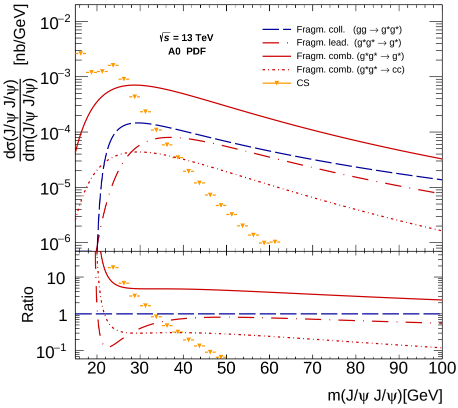




- Fragmentation contributions to the J/ψ production are remarkably important, especially at large transverse momenta (at $p_T^{J/\psi} \geq$ 20-30 GeV it gives approximately the same contribution as NLO NRQCD + DPS) [Phys. Rev. D 104 (2021) 3, 034018]

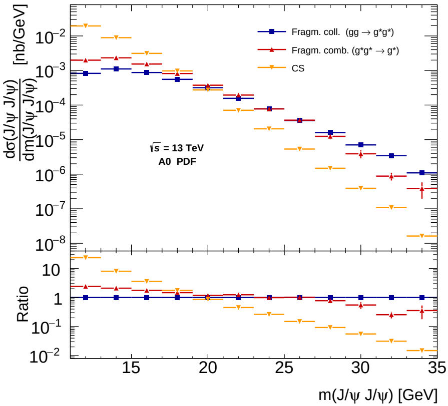
Effects of multiple gluon radiation in ATLAS, CMS kinematics

- See [Eur. Phys. J. C80,1046 (2020)] for details.
- Selection criteria: $p_T(J/\psi) > 10$ GeV for both produced mesons (such cuts are close to those in ATLAS and CMS analysis)
- Fragm. coll.: collinear calculation in LO
- Fragm. lead.: calculation in framework of k_T-factorization approach, where J/ψ mesons are originated from gluon produced in hard subprocess and leading gluon in cascade
- Fragm. comb.: calculation in framework of k_T-factorization approach with all combinatorial contributions from cascade gluons
- CS: color singlet J/ψ pair production in framework of k_T-factorization approach (box diagrams)

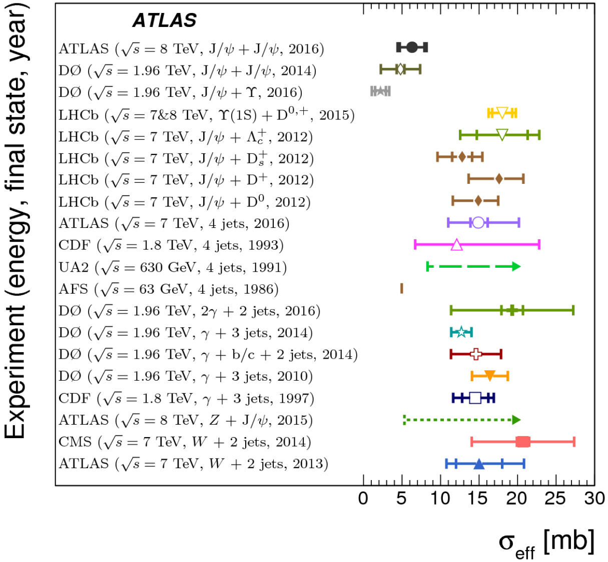


Effects of multiple gluon radiation in LHCb kinematics

- See [Eur. Phys. J. C80,1046 (2020)] for details.
- Selection criteria: 4.5 $< p_T(J/\psi) <$ 10 GeV and 2 $< y(J/\psi) <$ 4.5 for both produced mesons
- Cascade gluon fragmentations give a small contribution to the forward J/ψ pair production
- Only CS mechanism and DPS give a significant contribution to the J/ψ production in the forward rapidity region



DPS σ_{eff}



DPS σ_{eff} extraction from LHCb data

- See [Eur. Phys. J. C80,1046 (2020)] for details.
- Double J/ψ production at forward rapidities can be used to determine the DPS σ_{eff}.
- We tried to extract σ_{eff} from avaliable LHCb data $\sqrt{s} = 7$ TeV [Phys. Lett. B707, 52 (2012)] and $\sqrt{s} = 13$ TeV [JHEP 06, 047 (2017)] by considering the CS and DPS contributions.
- Selection criteria: $p_T(J/\psi) < 10$ GeV, $m(J/\psi, J/\psi) < 15$ GeV and $2 < y(J/\psi) < 4.5$

- Calculation of DPS

$$\sigma_{DPS} = \frac{1}{2}\frac{\sigma^2(pp \to J/\psi + X)}{\sigma_{\text{eff}}}$$

  with inclusion of feeddown contribution from radiative χ_c and ψ'
- $\sigma_{\text{eff}} = 17.5 \pm 4.1$ mb for A0 gluon density
  $\sigma_{\text{eff}} = 13.8 \pm 0.9$ mb for JH'2013 set 2 gluon density
- Results are compatible with many other estimations based on essentially different final states.