Role of parton fragmentation for associated J/ψ production at high energies

S.P. Baranov, A.V. Lipatov, A.A. Prokhorov

based on Phys.Rev.D 104 (2021) 3, 034018

Resummation, Evolution, Factorization Workshop 2021
19 November 2021

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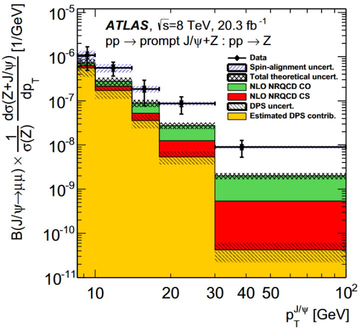
Introduction

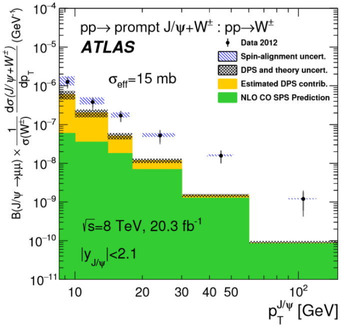
- **Non-relativistic QCD** (NRQCD):

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

- $\widehat{\sigma}(pp \to c\bar{c}(^{2S+1}L_J^{[n]}) + X)$ 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) $\langle \mathcal{O}^{J/\psi}[n]\rangle$ corresponds to transition from unbound state to the physical J/ψ meson - nonperturbative part.
- Progress in NRQCD evaluation of prompt $J/\psi + Z/W^{\pm}$ production: complete NLO calculations [Phys. Rev. D66, 114002 (2002)], [Phys. Rev. D83, 014001 (2011)], [JHEP02, 071 (2011)]; differential cross sections at the LO are significantly enhanced by the NLO corrections.

Introduction





Complete NLO NRQCD predictions with the double parton scattering (DPS) underestimate the latest ATLAS [Eur.Phys.J.C. 75, 229 (2015)] and ATLAS [J.High.Energ.Phys. 2020,95 (2020)] data by the factor 2 - 10 (depending on the J/ψ transverse momentum).

Motivation and goals

- We consider the new contributions to the prompt $J/\psi + Z/W^{\pm}$ production: **flavor excitation subprocesses** (charm for Z boson and strange for W) followed by the subsequent **charm fragmentation**, $c \to J/\psi + c$. **Our goal is to estimate such contributions**
- Recently we found that contribution 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. One can expect a sizeable contribution from **multiple gluon radiation** for $J/\psi + Z/W^{\pm}$ processes.
- **Our goal is to investigate a role of multiple gluon fragmentation to the prompt $J/\psi + Z/W^{\pm}$ production**

k_T-factorization approach

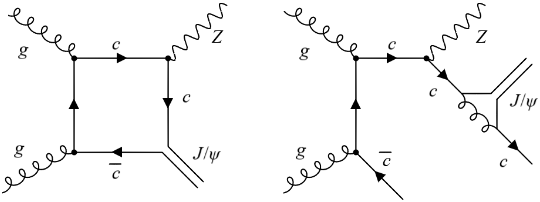
- We use the k_T-factorization approach with CCFM-evolved (Catani, Ciafaloni, Fiorani, Marchesini) Transverse Momentum Dependent (TMD) gluon densities
- Cross section in k_T-factorization approach:

$$d\sigma(pp \to J/\psi + Z/W) = \int dx_1\, dx_2 \sum_{i,j} d^2\overrightarrow{k}_{\perp 1} d^2\overrightarrow{k}_{\perp 2} f_i(x_1, \overrightarrow{k}^2_{\perp 1}\mu^2) f_j(x_2, \overrightarrow{k}^2_{\perp 2}\mu^2)$$

$$\cdot d\widehat{\sigma}(i^* + j^* \to J/\psi + Z/W)$$

- $f_{i,j}(x_{1,2}, \overrightarrow{k}_{\perp 1,2}, \mu^2)$ - TMD parton 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

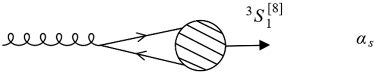
Flavor excitation

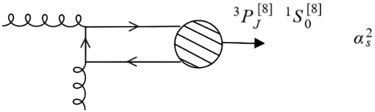


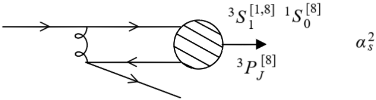
- Examples of Feynman diagram taken into account in the NRQCD calculations (left panel) and diagram of **charm excitation followed by the c-quark fragmentation to J/ψ** (right panel)
- Since the charm quark contribution can be obtained via gluon splitting ($g \to q_s\bar{q}_s$) for CCFM evolved gluon densities, the processes of flavor excitation: $g + c \to Z + c$, $g + s \to W^- + c$ turn to gluon-gluon fusion $g + g \to Z + c + \bar{c}$, $g + g \to W^- + c + \bar{s}$
- Gluon-gluon fusion followed by the fragmentation $c \to J/\psi + c$

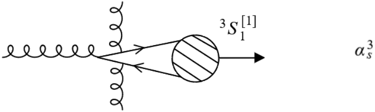
Fragmentation to the charmonium $\mathcal{H}$

- We consider not only the direct production of J/ψ but also the feeddown contribution from radiative decay of $\psi' \to J/\psi X$ and $\chi_{cJ} \to J/\psi\gamma$
- 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



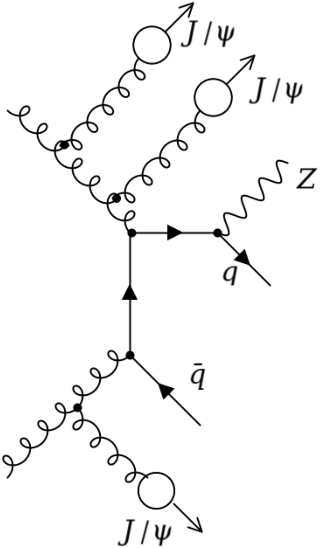




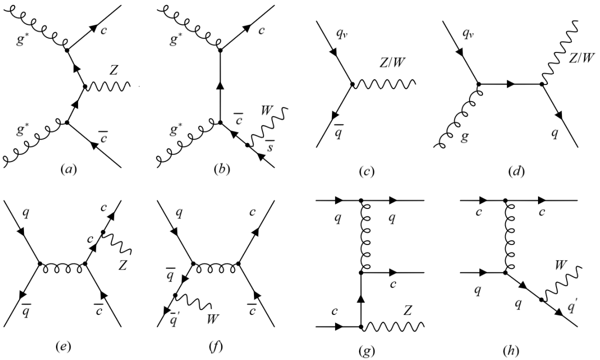


Multiple gluon radiation

- Additional contribution comes from **multiple initial gluon radiation** that accompanies the Z/W production
- Initial gluon cascade can be described by the CCFM evolution equation
- Subprocesses $g + g \to Z + q + \bar{q}$, $g + g \to W + q + \bar{q}'$ give additional contribution via fragmentation $g \to cc(^3S_1^{[8]}) \to J/\psi$
- Circles on the plot denote the possible channels of partons fragmentation into J/ψ mesons



List of considered subprocesses



- Gluon-gluon fusion (a)-(b) are calculated in k_T-factorization approach QCD. The initial multiple gluon radiation can be taken into account using the CCFM evolved gluon densities
- Quark-involved subprocesses (c)-(h) are calculated in collinear QCD. The initial multiple gluon radiation are reconstructed with PYTHIA routine. Subprocesses (c)-(d) involve only valence quarks (sea quark effectively included in gluon-gluon fusion)

J/ψ production via fragmentation

- We took only **LO contributions to the FFs**: $D_g^{\mathcal{H}}({}^3S_1^{[8]})$ and $D_c^{\mathcal{H}}({}^3S_1^{[1]})$ for $J/\psi, \psi'$; $D_g^{\mathcal{H}}({}^3S_1^{[8]})$ and $D_c^{\mathcal{H}}({}^3P_J^{[1]})$ for χ_{cJ}. Charm fragmentation into octet color states supressed due to color factor.

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

$$\frac{d}{d\log\mu^2}\begin{pmatrix} D_c \\ D_g \end{pmatrix} = \frac{\alpha_s(\mu^2)}{2\pi}\begin{pmatrix} P_{cc} & P_{gc} \\ P_{cg} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} D_c \\ D_g \end{pmatrix}$$

where P_{ab} standard LO DGLAP splitting function

- Cross section of $J/\psi + Z/W$ production via charm fragmentation can be written:

$$\frac{d\sigma(pp \to J/\psi + Z/W)}{dp_T} = \int dz\, \frac{d\widehat{\sigma}(pp \to c + Z/W)}{dp_T^c} D_c^{J/\psi}(z, \mu^2)\delta(z - \frac{p}{p^c})$$

Modelling events

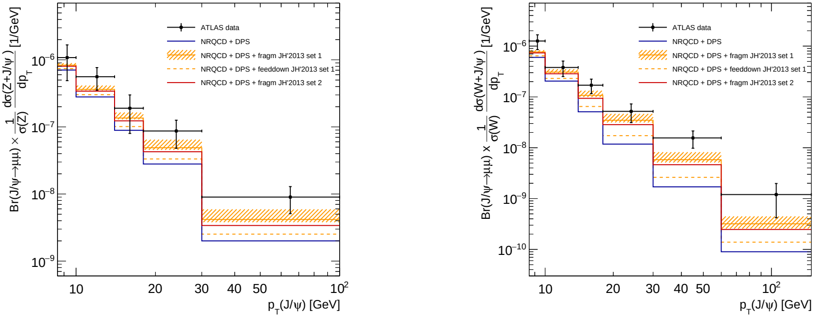
We used:

- **JH'2013 set1 and set2 TMD gluon densities** for numerical calculations of gluon-gluon fusion subprocesses in k_T-factorization approach; Monte Carlo event generator CASCADE for reconstruction of CCFM initial gluon emissions
- **MMHT2014LO PDF** for numerical calculation of quark-involved subprocesses in collinear QCD; PYTHIA routine for initial gluon emissions
- **numerical solution of DGLAP evolution of FFs** with appropriate LDME's $\langle \mathcal{O}^{\mathcal{H}}[n] \rangle$ (list of used LDME: $\langle \mathcal{O}^{J/\psi}[^3S_1^{(1)}] \rangle = 1.16$ GeV^3, $\langle \mathcal{O}^{\psi'}[^3S_1^{(1)}] \rangle = 0.7038$ GeV^3, $\langle \mathcal{O}^{\chi_{c1}}[^3P_1^{(1)}] \rangle = 0.2$ GeV^5, $\langle \mathcal{O}^{\chi_{c2}}[^3P_2^{(1)}] \rangle = 0.0496$ GeV^5, $\langle \mathcal{O}^{J/\psi,\psi'}[^3S_1^{(8)}] \rangle = 0.0012$ GeV^3, $\langle \mathcal{O}^{\chi_{c0}}[^3S_1^{(8)}] \rangle = 0.0004$ GeV^3)

Selection criteria:

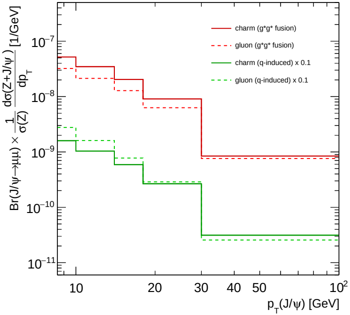
- $J/\psi + Z$: $p_T(J/\psi) > 8.5$ GeV, $|y(J/\psi)| < 2.1$, $M(Z) = 81 \div 101$ GeV
  lead l: $p_T > 25$ GeV,$|\eta| < 2.5$; sublead l: $p_T > 15$ GeV, $|\eta| < 2.5$
- $J/\psi + W$: $p_T(J/\psi) > 8.5$ GeV, $|y(J/\psi)| < 2.1$,
  $m_T(W^{\pm}) = \sqrt{2p_T^l p_T^{\nu}[1 - cos(\phi^l - \phi^{\nu})]} > 40$ GeV
  muon l: $p_T > 25$ GeV, $|\eta| < 2.4$; neutrino ν: $p_T > 20$ GeV, $|\eta| < 2.4$

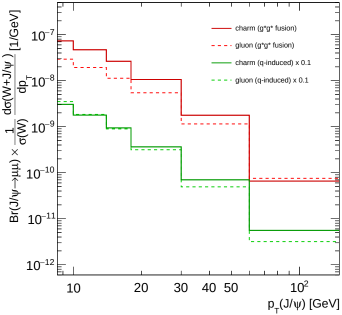
Comparison with ATLAS data



- Contribution from considered subprocesses with their subsequent parton fragmentation into J/ψ mesons **(fragmnetation contribution)** 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)
- Feeddown contribution from radiative decay of ψ', χ_{cJ} also play the significant role (about 30% of the estimated direct contribution at the wide $p_T^{J/\psi}$ range).
- Shaded bands represents the scale uncertainties.

Role of the multiple gluon radiation





- We consider the two qualitatively different sources of parton fragmentation into the J/ψ meson: **fragmentation of charm quarks**, originated in the hard interaction, and **fragmentation of gluons**, originated as a result of initial QCD evolution of parton densities
- In both cases of gluon-gluon fusion and quark-involved subprocesses the fragmentation of multiple gluon emission noticeably enhances the charm fragmentation and provides a sensible growth of the total and differential cross sections (especially at the region of high $p_T^{J/\psi}$)

Summary

- We investigated the role of new partonic subprocesses which yet have never been considered in the literature, namely, flavor (charm or strangeness) excitation subprocesses followed by the charm fragmentation $c \to J/\psi + c$.
- We take into account the effects of the multiple quark and gluon radiation in the initial and final states.
- Contributions from multiple gluon emissions noticeably enhance the charm fragmentation (especially at the region of high $p_T^{J/\psi}$).
- Accounting for the feeddown contribution from radiative decay of ψ', χ_{cJ} also play a significant role (about 30% of the estimated direct contribution at the wide $p_T^{J/\psi}$ range).
- Considered new contributions are remarkably important and significantly reduce the gap between the theoretical predictions and experimental results for the $J/\psi + Z/W^{\pm}$

Backup

Evolution of FFs

$$D^{J/\psi}_{init\,g}(z,\mu_0^2) = \frac{a_s(\mu_0^2)\pi}{8m^3_{J/\psi}}\delta(1-z)$$

$$D^{J/\psi}_{init\,c}(z,\mu_0^2) = \frac{a_s^2(\mu_0^2)}{m^3_{J/\psi}}\frac{16z(1-z)^2}{243(2-z)^6}(5z^4-32z^3+72z^2-32z+16)$$

[Bernd. A.Kniehl, Gustav Kramer Phys.Rev.D. 56, 5820, (1997)]