# Charm fragmentation and associated $J/\psi + Z/W^{\pm}$ production at the LHC

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based on arXiv:2105.13035

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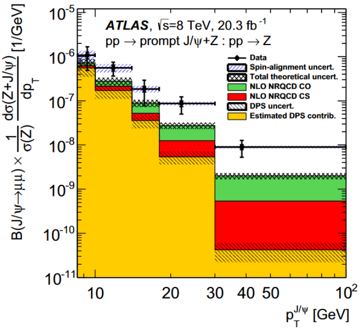
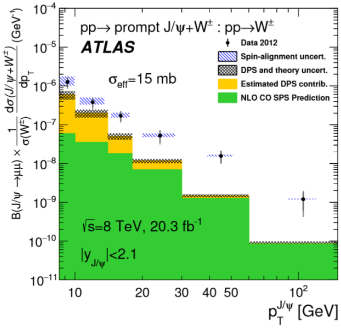
# Introduction

- **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 $J/\psi$ 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 ath the LO are significantly enhanced by the NLO corrections.




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 $J/\psi$ 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**

- One can expect a sizeable contribution from **multiple gluon radiation** originated during the QCD evolution. The multiple gluon radiation can be taken into account using the CCFM evolution equation. Recently we found that contribution of multiple gluon radiation to the cross section of double $J/\psi$ production are very important [Eur. Phys. J. C80,1046 (2020)]

- **Our goal is to investigate a role of multiple gluon fragmentation to the prompt $J/\psi + Z/W^{\pm}$ production**

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

# $k_T$-factorization approach

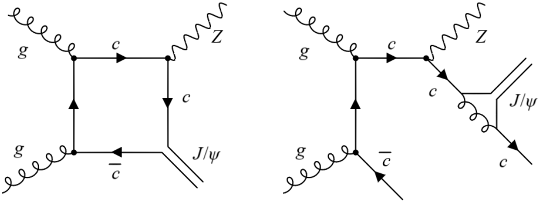
- Cross section in $k_T$-factorization approach:

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

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

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

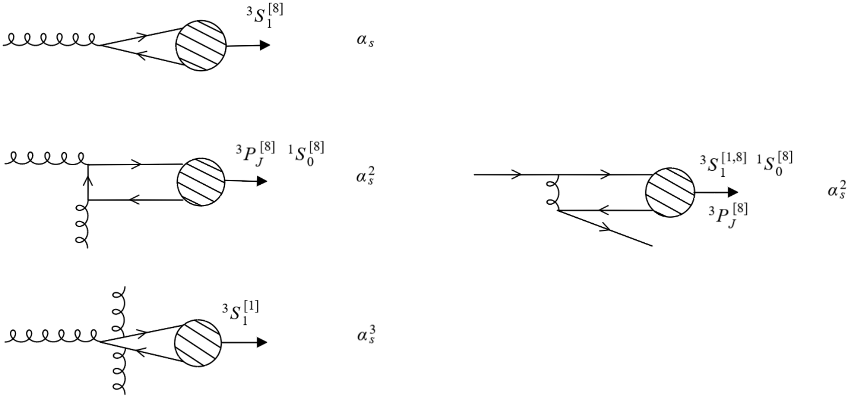



- Examples of Feynman diagram taken into account in the NRQCD calculations (left panel) and diagram of charm excitation followed by the c-quark fragmentation to $J/\psi$ (right panel)
- Since the charm quark contribution can be obtained via gluon splitting ($g \to q_s \bar{q}_s$) for CCFM evolved gluon 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 $\mathcal{H}$

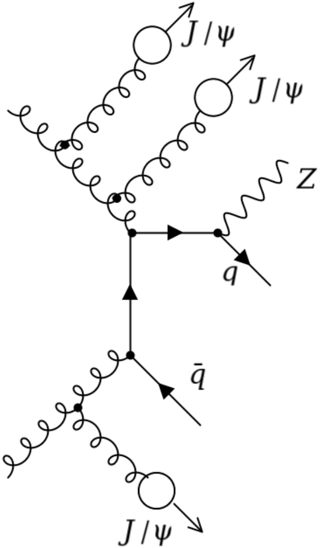
- We consider not only the direct production of $J/\psi$ but also the feeddown contribution from radiative decay of $\psi' \to J/\psi X$ and $\chi_{cJ} \to J/\psi\gamma$
- Typical diagrams of gluons and charm quarks fragmentation into charmonium
- Fragmentation function in NRQCD formalism at the starting scale $\mu_0^2 = m_{\mathcal{H}}^2$:

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

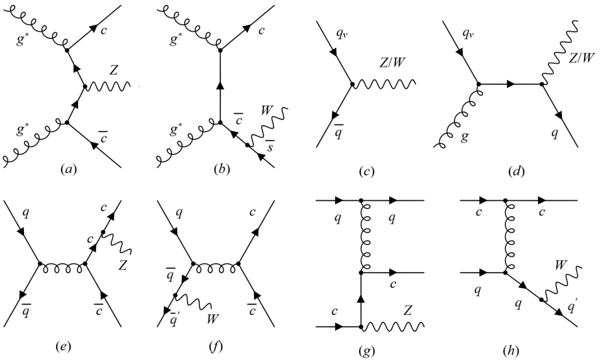


# Multiple gluon radiation

- Another contributions 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 $J/\psi$ 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)

# $J/\psi$ 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 $\chi_{cJ}$. 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 $\mu^2$

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

where $P_{ab}$ standard LO DGLAP splitting function

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

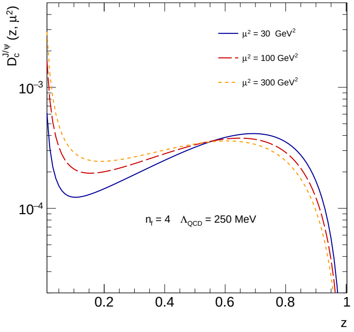
$$\frac{d\sigma(pp \to J/\psi + Z/W)}{dp_T} = \int dz\, \frac{d\widehat{\sigma}(pp \to c + Z)}{dp_T^c} D_c^{J/\psi}(z,\mu^2)\delta(z - \frac{p}{p^c})$$

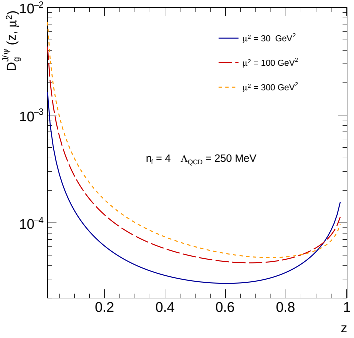
# Evolution of FFs

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

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

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



# Modelling events

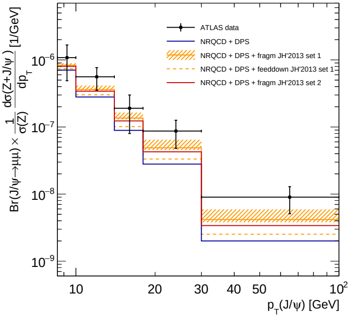
We used:

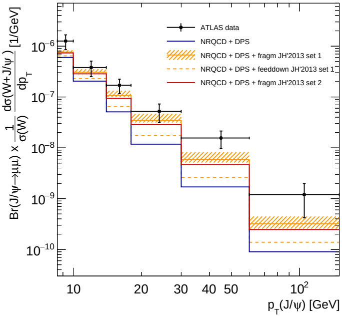
- **JH'2013 set1 and set2 TMD gluon densities** for numerical calculations of gluon-gluon fusion subprocesses in $k_T$-factorization approach; Monte Carlo event generator CASCADE for reconstruction of CCFM initial gluon emissions
- **MMHT2014LO PDF** for numerical calculation of quark-involved subprocesses 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 $\nu$: $p_T > 20$ GeV, $|\eta| < 2.4$

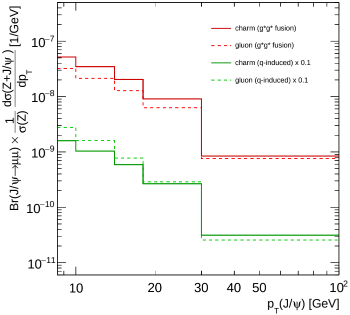
# Comparison with ATLAS data

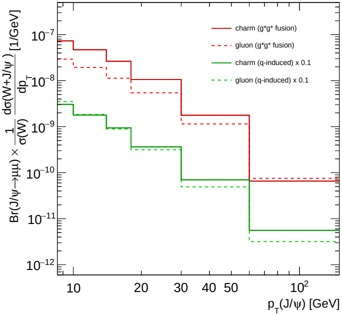



- Contribution from considered subprocesses with their subsequent parton fragmentation into $J/\psi$ mesons are remarkably important, especially at large transverse momenta (at $p_T^{J/\psi} \geq$ 20-30 GeV it gives approximately the same contribution as NLO NRQCD + DPS)
- Feeddown contribution from radiative decay of $\psi', \chi_{cJ}$ 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 $J/\psi$ 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 $\psi', \chi_{cJ}$ 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 and experimental results on the $J/\psi + Z/W^{\pm}$