Revisiting the production of J/ψ pairs at the LHC

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

based on Eur. Phys. J. C. 80 (2020) 11, 1046

Resummation, Evolution, Factorization 2020
11 December 2020

Introduction

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

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

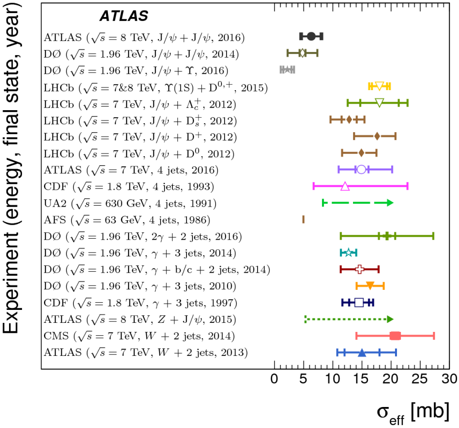
- Progress in NRQCD evaluation of prompt double J/ψ production: complete LO calculations [Phys. Rev. Lett. 115, 022002 (2015)], relativistic corrections [JHEP 07, 051 (2013)] and partial tree-level NLO contributions [Phys. Rev. D 94, 074033 (2016); Phys. Rev. Lett. 111, 122001 (2013)]

- Predictions have sizeable discrepancies with the latest CMS [JHEP 09, 094 (2014)] and ATLAS [Eur. Phys. J. C 77, 76 (2017)] data, especially at large invariant mass $m(J/\psi, J/\psi)$ and rapidity separation $\Delta y(J/\psi, J/\psi)$ of the J/ψ pairs (underestimations by the NRQCD predictions up to 10 times).

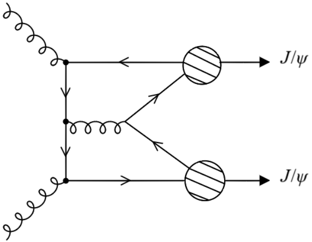
Introduction

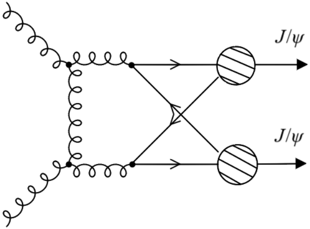
- At large invariant mass $m(J/\psi, J/\psi)$ the processes with large angular separation between the J/ψ mesons could play a role. One of such processes: quark and gluon fragmentations. Contribution of $g^* \to c\bar{c}[^3S_1^{[8]}]$ intermediate state behaves as $1/p_T^4$ and determine the single J/ψ production at high p_T
- One can expect a sizeble contribution from **multiple gluon radiation** originated during the QCD evolution. The multiple gluon radiation can be taken into account using the CCFM evolution equation
- **Our goal is to investigate a role of multiple gluon fragmentation to the double J/ψ production**
- We use the k_T-factorization approach with CCFM-evolved Transverse Momentum Dependent (TMD) gluon densities

- DPS mechanism is expected to be important for double J/ψ production af foward rapidities
- The typical value of σ_{eff} extracted from experinemtal data are 12 - 20 mb. Estimations for processes with double quarkonia give lower value (at 2-3 times)
- **Our second goal is to investigate DPS in double J/ψ production**



Color singlet contribution to J/ψ pair production





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

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

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

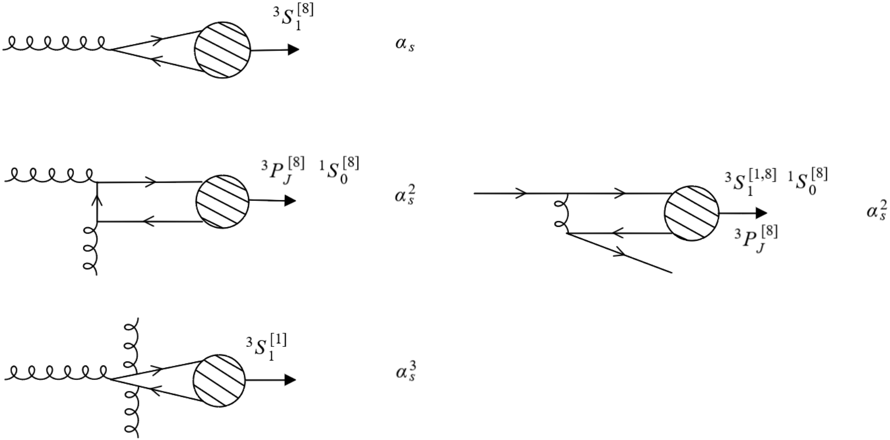
where $f_g(x, k_T^2, \mu^2)$ is the TMD gluon density in a proton

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

Color octet contribution to the J/ψ pair production

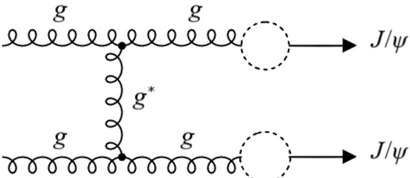
- Typical fragmentation diagrams of gluons and charm quarks into charmonium
- Fragmentation function in NRQCD formalism at the starting scale $\mu_0^2 = m_{J/\psi}^2$:

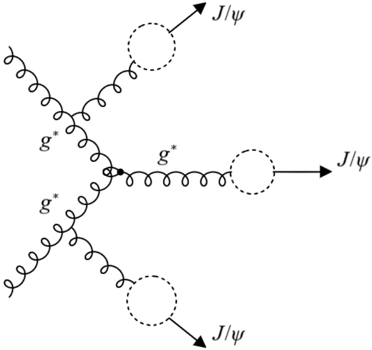
$$D_a^{J/\psi}(z, \mu_0^2) = \sum_n d_a^n(z, \mu_0^2) \langle \mathcal{O}^{J/\psi}[n] \rangle$$



k_T-factorization vs collinear

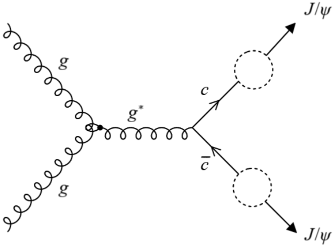
- Typical diagram (upper) of double J/ψ production via fragmentation, which correspond to collinear LO QCD $gg \longrightarrow gg$ subprocess
- One diagram (lower) with multiple gluon radiation in the initial state, which correspond to $g^*g^* \longrightarrow g^*$ subprocess in k_T-factorization approach
- Initial gluon cascade can be described by the CCFM evolution equation
- Dotted circles denote the possible channels of partons fragmentation into J/ψ mesons

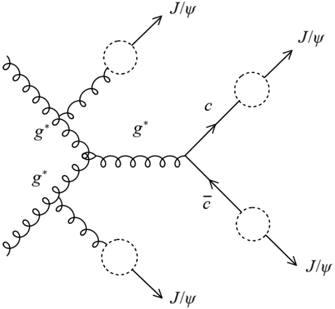




k_T-factorization vs collinear

- Typical diagram (upper) of double J/ψ production via fragmentation, which correspond to collinear LO QCD $gg \longrightarrow c\bar{c}$ subprocess
- Typical diagram (lower) with multiple gluon radiation in the initial state, which correspond to $g^* g^* \longrightarrow c\bar{c}$ subprocess in k_T-factorization approach
- Dotted circles denote the possible channels of partons fragmentation into J/ψ mesons





J/ψ production via fragmentation

- We took only LO contributions to the FFs, $D_g^{J/\psi}({}^3S_1^{[8]})$ and $D_c^{J/\psi}({}^3S_1^{[1]})$. Charm fragmentation into octet color states supressed due to color factor.
- LO DGLAP evolution equation $\Rightarrow$ FFs $D_c^{J/\psi}(z,\mu^2)$ and $D_g^{J/\psi}(z,\mu^2)$ 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 single J/ψ production via fragmentation can be written:

$$\sigma(pp \to J/\psi + X) = \int dz\, \widehat{\sigma}(pp \to ab) D_{a/b}^{J/\psi}(z,\mu^2)$$

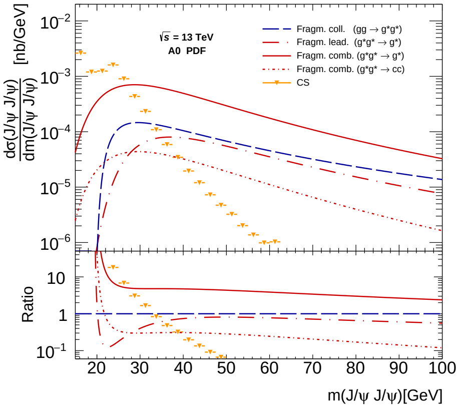
Modelling events

We used:

- In k_T-factorization:
  $\hookrightarrow$ A0 and JH'2013 set 2 TMD gluon densities for numerical calculations of CS and CO contributions in k_T-factorization approach;
  $\hookrightarrow$ fragmentation: $g^*g^* \to g^*$ and $g^*g^* \to c\bar{c}$
- In collinear calculations:
  $\hookrightarrow$ PDF MMHT2014LO
  $\hookrightarrow$ fragmentation: $gg \to gg$ and $gg \to c\bar{c}$
- Monte Carlo event generator CASCADE for reconstruction of CCFM initial gluon emissions
- numerical solution of DGLAP evolution of FFs with appropriate LDME's $\langle \mathcal{O}^{J/\psi}[n] \rangle$ (see [Phys. Rev. D 100, 114021 (2019)])

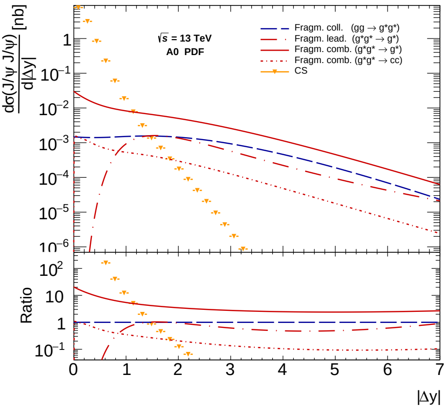
Analysis similar to ATLAS, CMS

- 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)



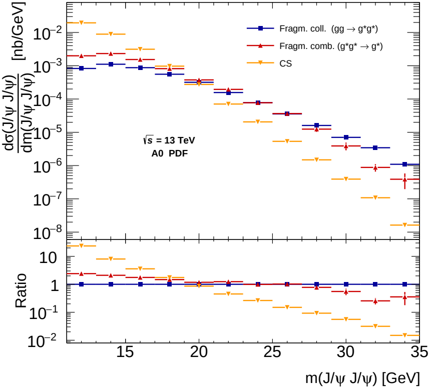
Analysis similar to ATLAS, CMS

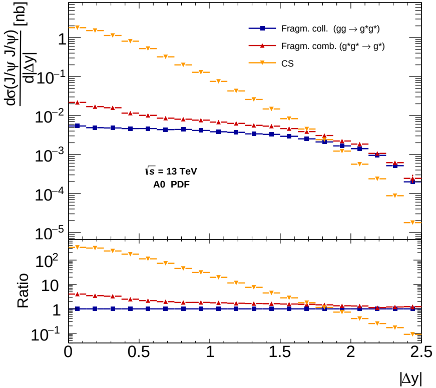
- Cascade gluon fragmentations play a dominant role at large invariant masses $m(J/\psi, J/\psi) \geq 25$ GeV and $|\Delta y(J/\psi, J/\psi)| > 1$ for A0 gluon density
- Correct accounting for these combinatorial contributions can help to fill the discrepancy between NRQCD estimations (including CS and CO contributions) and ATLAS, CMS experimental data at large $m(J/\psi, J/\psi)$



Analysis similar to LHCb

- 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} extraction from LHCb data

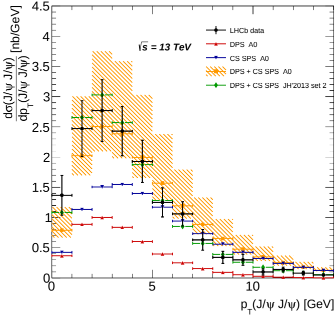
- Double J/ψ production at forward rapidities can be used to determine the DPS σ_{eff}.
- We tried to extract σ_{eff} from avaliable LHCb data $\sqrt{s} = 7$ TeV [Phys. Lett. B707, 52 (2012)] and $\sqrt{s} = 13$ TeV [JHEP 06, 047 (2017)] by considering the CS and DPS contributions.
- Selection criteria: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

- Calculation of DPS

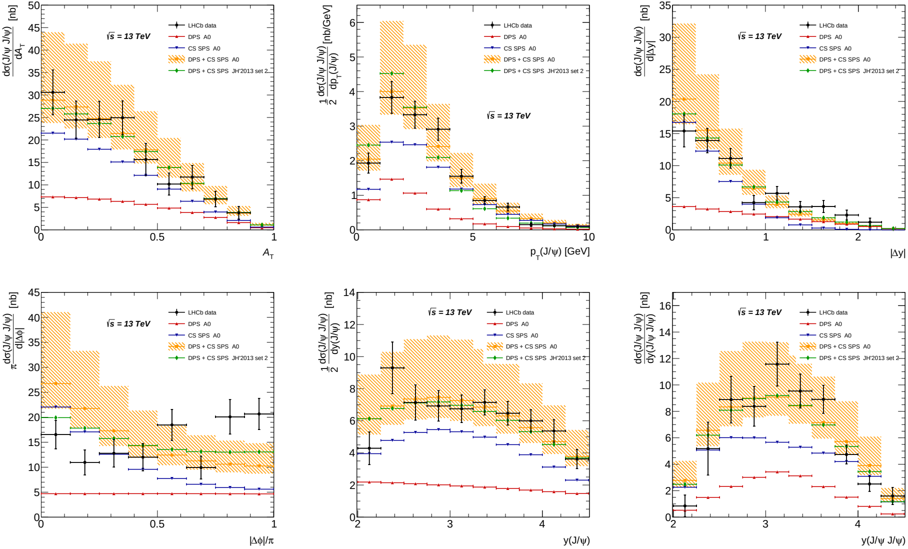
$$\sigma_{DPS} = \frac{1}{2}\frac{\sigma^2(pp \to J/\psi + X)}{\sigma_{eff}}$$

with inclusion of feeddown contribution from radiative χ_c and ψ'

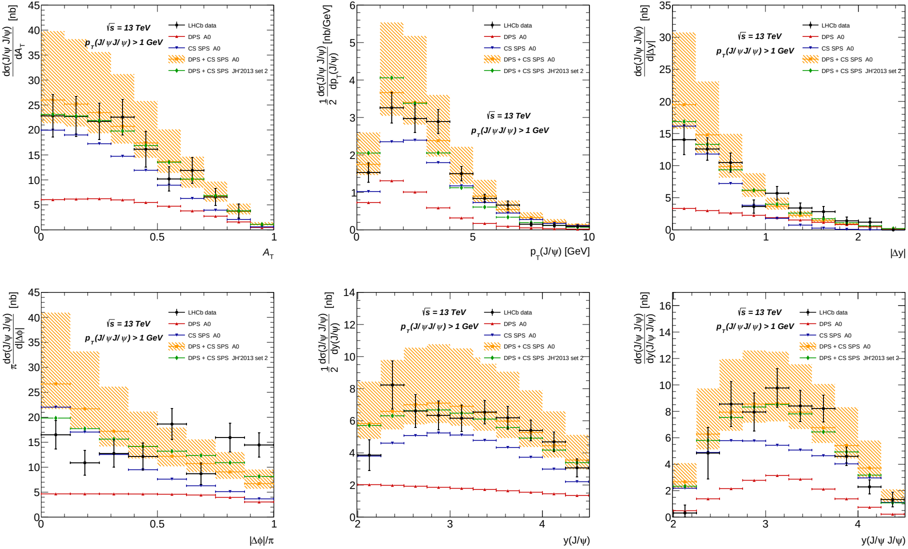
- $\sigma_{eff} = 17.5 \pm 4.1$ mb for A0 gluon density $\sigma_{eff} = 13.8 \pm 0.9$ mb for JH'2013 set 2 gluon density
- Results are compatible with many other estimations based on essentially different final states.



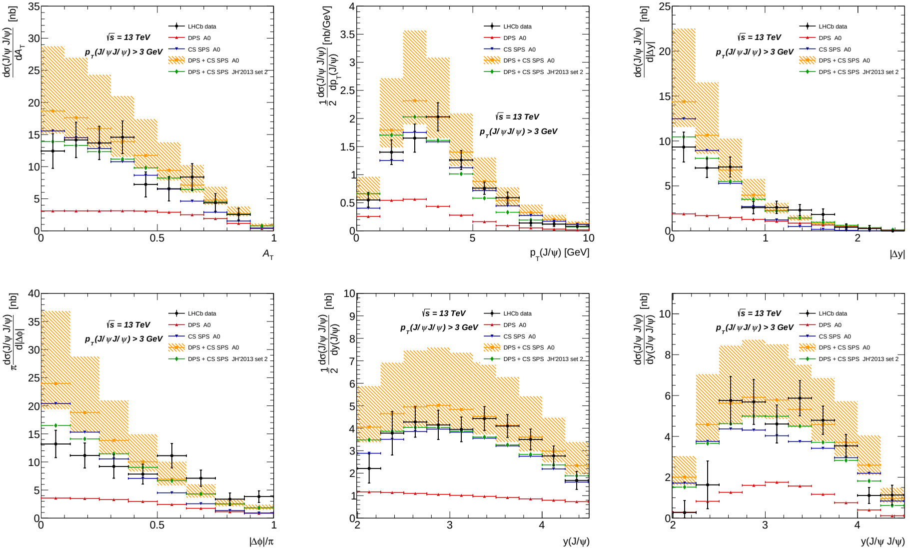
LHCb data: inclusive



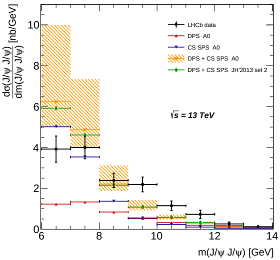
LHCb data: $p_T(J/\psi, J/\psi) > 1$ GeV

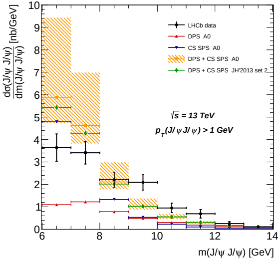


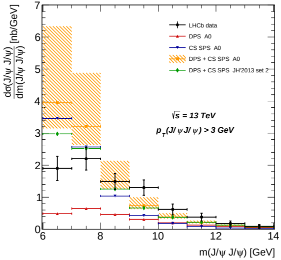
LHCb data: $p_T(J/\psi, J/\psi) > 3$ GeV

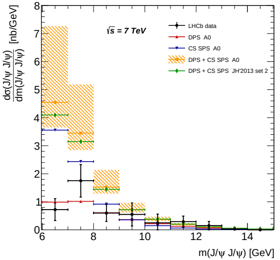


LHCb data: $m(J/\psi, J/\psi)$









Summary

- Combinatorial contributions of multiple initial gluon emissions to the J/ψ pair production plays a dominant role at large invariant masses $m(J/\psi, J/\psi) \geq 25$ GeV and $|\Delta y(J/\psi, J/\psi)| > 1$
- Correct accounting for these contributions to J/ψ pair production in framework of the k_T-factorization approach increases by few times cross section compared with collinear calculations in LO QCD.
- This effect is essential for ATLAS and CMS kinematics, but, in principle, can be neglected for LHCb analysis
- To accurate calculation of double J/ψ production for comparison with recent ATLAS and CMS data it is necessary to include not only the full combinatorial fragmentation contributions, CS box and DPS, but the series of processes with single fragmentation and feeddown contributions from radiative decay of χ_c and ψ'. This work in progress.
- DPS effective cross section $\sigma_{eff} = 17.5 \pm 4.1$ mb and $\sigma_{eff} = 13.8 \pm 0.9$ mb (for A0 and JH'2013 set 2 gluon densities correspondingly) extracted from LHCb data on the J/ψ pair mesons production are compatible with many other estimations based on essentially different final states.

Thank you for your attention!

Backup

Single J/ψ production

- The probability for two quarks to form a meson is described by the bound state function $\Psi(q)$ where q momentum of the relative motion $c\bar{c}$. Bound states can be presented as Fock states $n =^{2S+1} L_J[a]$ with definite spin S, orbital angular momentum L, total angulr momentum J and color representation a (color singlet (CS) $[1]$ and color octet (CO) $[8]$)
- Total amplitude $\mathcal{A}$ of J/ψ production can be obtained as multiplication of partonic subprocess amplitude $A(q)$ $g^*g^* \to c\bar{c}$ with the wave function $\Psi(q)$

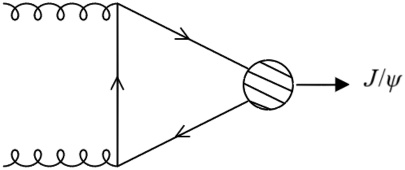
  $$\mathcal{A} \sim \int d^3q A(q)\Psi^{[n]}(q) = \int d^3q (A|_{q=0}\Psi^{[n]}(q) + q^\mu(\partial A/\partial q^\mu)|_{q=0}\Psi^{[n]}(q) + ...)$$

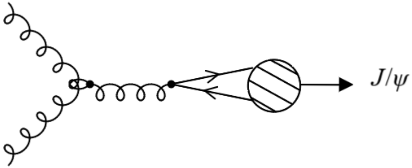
  where first term contributes to S-waves only and vanishes for P-waves. Second term contributes only for P-waves
- LDME's (NME) are long distant nonperturbative matrix elements $\langle \mathcal{O}^{J/\psi}[n] \rangle$

  $$\int d^3q \Psi^{[n]}(q) \sim \langle \mathcal{O}^{J/\psi}[^{2S+1}S_J] \rangle^{1/2} \text{ for S-waves}$$

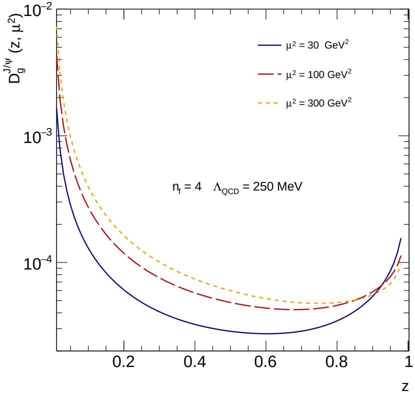
  $$\int d^3q q^\mu \Psi^{[n]}(q) \sim \langle \mathcal{O}^{J/\psi}[^{2S+1}P_J] \rangle^{1/2} \text{ for P-waves}$$
- Their values are extracted from single prompt J/ψ production data (depends on the TMD PDF choice only)

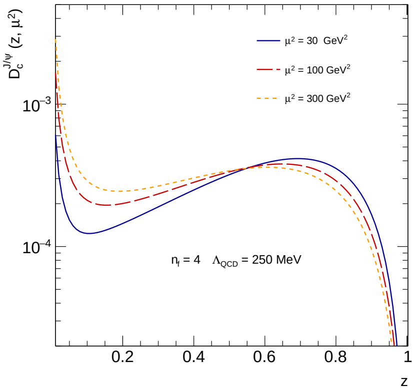
Single J/ψ production with k_T-factorization approach



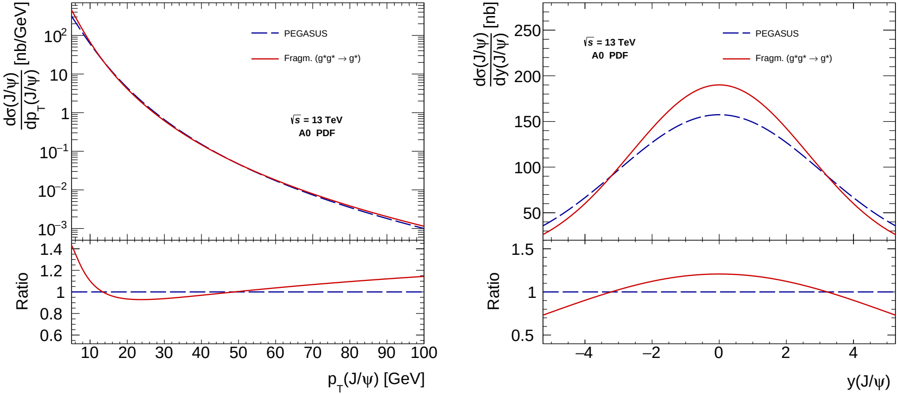


Fragmentation functions

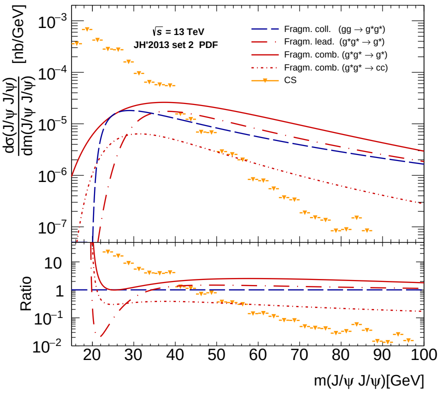


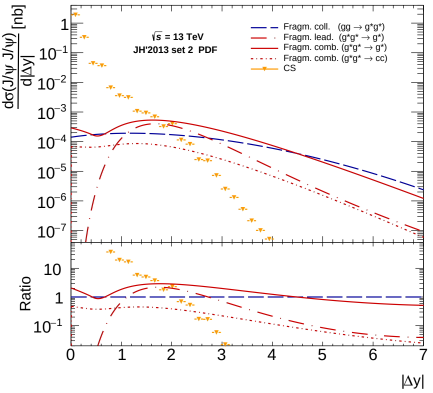


Single J/ψ production in color octet channel $g \to {}^3S_1^{[8]}$



Analysis similar to ATLAS, CMS





Analysis similar to LHCb