Associated production of $J/\psi + \gamma$ at the energy of SPD NICA

L. Alimov[1], V. Saleev[1,2]

[1] Samara National Research University
[2] Joint Institute for Nuclear Research

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Outline

1. Introduction
2. Factorization approaches: CPM, TMD, and GPM
3. Hadronization mechanisms: CSM, NRQCD and CEM
4. $J/\psi+\gamma$ production in CPM and GPM within framework of CSM
5. Predictions at the energy of SPD NICA

Introduction

$J/\psi = c\bar{c}[^3S_1]$, $M(J/\psi) = 3.097$ GeV, $\Gamma = 92.9$ keV

$$\Gamma(J/\psi \to \mu^+\mu^-) = 5.55 \text{ keV}$$

$$Br(J/\psi \to \mu^+\mu^-) = 5.9 \times 10^{-2}$$

Introduction

- Up to now we deal with charmonium puzzles: J/ψ polarization, double J/ψ, ...
- Test of perturbative QCD, $M_\psi >> \Lambda_{QCD}$
- Test of heavy quark hadronization mechanism: NRQCD, CSM and CEM
- Tools for study gluon structure of proton, including helicity structure functions.
- Study of J/ψ production motivates a lot of new theoretical works about factorization, resummation and evolution ...

Factorization approaches: CPM, TMD, and GPM

Hard (factorization) scale $\mu_F \sim M_\psi$
Intrinsic parton transverse momentum $< q_T^2 > \sim 1$ GeV^2

- **Collinear parton model:** $q_{1,2T} << p_T$ and $\mu_F = M_T \geq M$

$$\sigma(pp \to \eta_c X) = \int dx_1 \int dx_2 f_g(x_1, \mu_F) f_g(x_2, \mu_F) \hat{\sigma}(g + g \to \eta_c + g)$$

- **TMD PM** by Collins, Soper, Stermann: $q_{1,2T} \sim p_T$ and $p_T << \mu_F$

$$\sigma(pp \to \eta_c X) = \int dx_1 d^2 q_{1T} \int dx_2 d^2 q_{2T} F_g(x_1, q_{1T}, \mu_F, \mu_Y) \times$$

$$\times F_g(x_2, q_{2T}, \mu_F, \mu_Y) \hat{\sigma}(g + g \to \eta_c)$$

- **Generalized parton model:** $q_{1,2T} \sim p_T$ and $p_T \sim \mu_F$

$$\sigma(pp \to \eta_c X) = \int dx_1 d^2 q_{1T} \int dx_2 d^2 q_{2T} F_g(x_1, q_{1T}, \mu_F) \times$$

$$\times F_g(x_2, q_{2T}, \mu_F) \hat{\sigma}(g + g \to \eta_c)$$

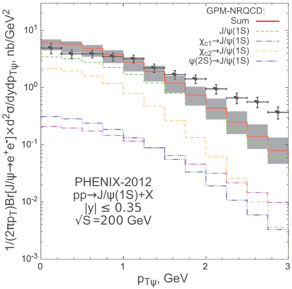
$$F_g(x, q_T, \mu_F) = f_g(x, \mu_F) \times \exp(-q_T^2 / < q_T^2 >)/(\pi < q_T^2 >)$$

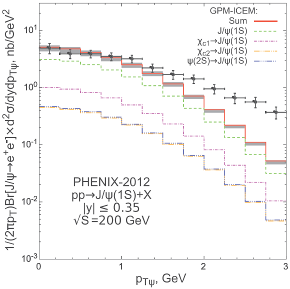
Hadronization mechanisms: CSM, NRQCD and CEM

- Color Singlet Model (CSM): only $c\bar{c}-$pairs with matched quantum number of the charmonium, ${}^3S_1^{(1)}$ for $J/\psi-$meson.
- Non-relativistic QCD (NRQCD): all $c\bar{c}-$pairs of different color and spin sates fragmenting with different probabilities long distance matrix elements (LDME)
- Color Evaporation Model (CEM): all $c\bar{c}-$pairs with mass less than $D\bar{D}$ threshold. One hadronization parameter for each charmonium is used.

J/ψ production in CPM and GPM within framework of CSM

J/ψ production at the PHENIX





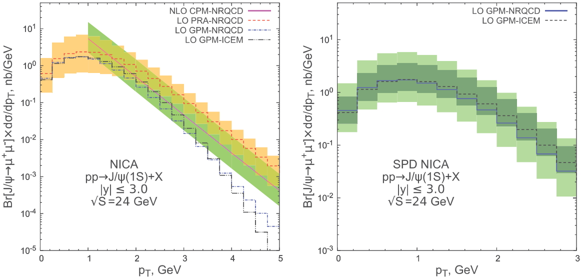
J/ψ production in CPM and GPM within framework of CSM

J/ψ production at the PHENIX leads to following conclusions:

- Color octet LDMEs are not needed at low energy and small p_T. Color singlet LDME $< \mathcal{O}[^3S_1^{(1)}] >$ can be calculated in potential model, $(|\Psi(0)|^2)$, or extracted decay width $\Gamma(J/\psi \to \mu^+\mu^-)$.
- In process $g + g \to J/\psi + \gamma$, final state is colorless and we can neglect final-state interactions with soft (Glauber) gluons, which destroy hard-soft factorization.

J/ψ production in CPM and GPM within framework of CSM

J/ψ production at the SPD NICA



$J/\psi + \gamma$ production in CPM and GPM within framework of CSM

CPM for $p_T \geq M$

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

GPM for $p_T < M$. There is no reduction to $2 \to 1$ subprocess in CSM

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

For prompt J/ψ production we include following contributions:

$$g + g \to \psi(2S) + \gamma, \qquad \psi(2S) \to J/\psi X$$

$$g + g \to \chi_{c1} + \gamma, \qquad \chi_{c1} \to J/\psi X$$

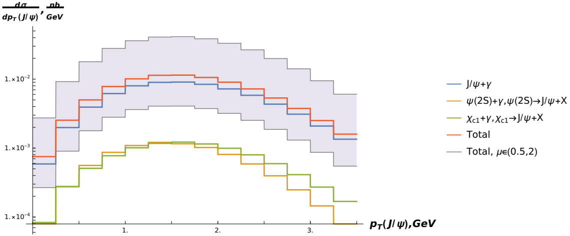
Processes of the following order

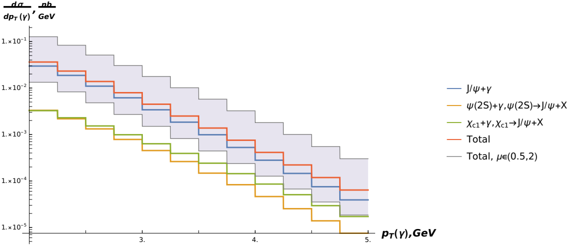
$$g + g \to J/\psi + g(\to \gamma)$$

$$g + g \to \chi_{cj} + g(\to \gamma), \chi_{cj} \to J/\psi X, j = 1, 2, 3$$

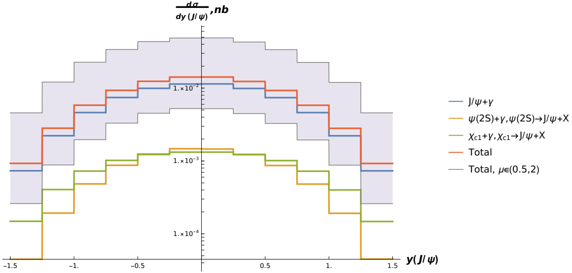
$$g + g \to \psi(2S) + g(\to \gamma), \psi(2S) \to J/\psi X$$

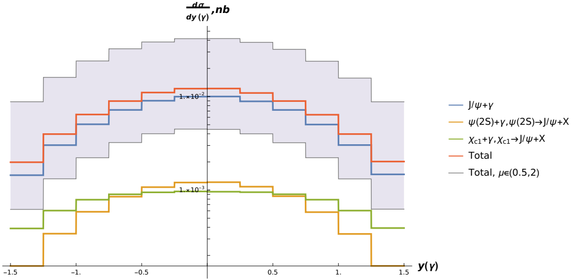
$J/\psi + \gamma$ production in CPM and GPM within framework of CSM



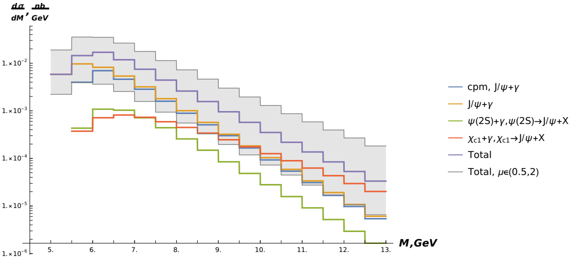


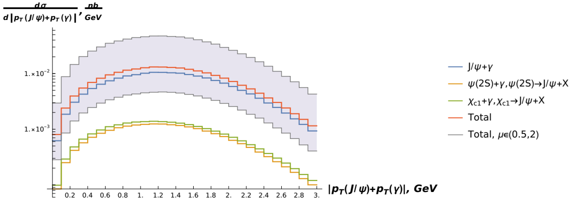
$J/\psi + \gamma$ production in CPM and GPM within framework of CSM



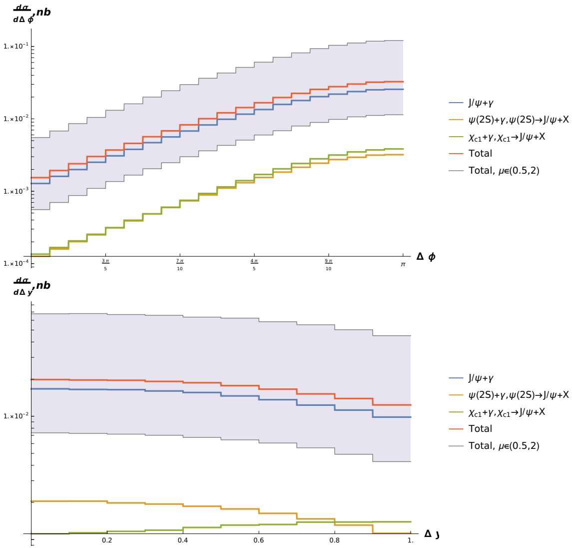


$J/\psi + \gamma$ production in CPM and GPM within framework of CSM

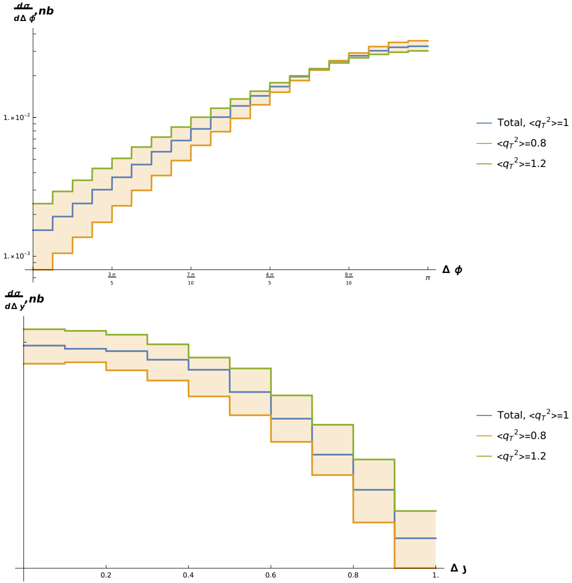




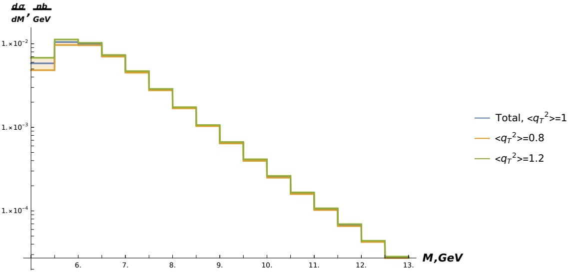
$J/\psi + \gamma$ production in CPM and GPM within framework of CSM

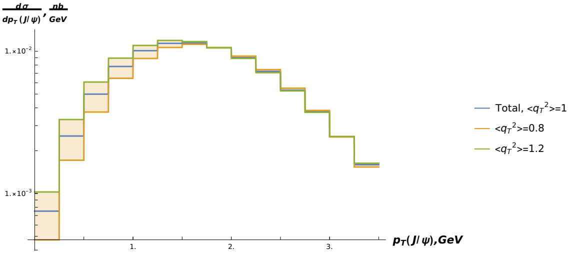


$J/\psi + \gamma$ production in CPM and GPM within framework of CSM

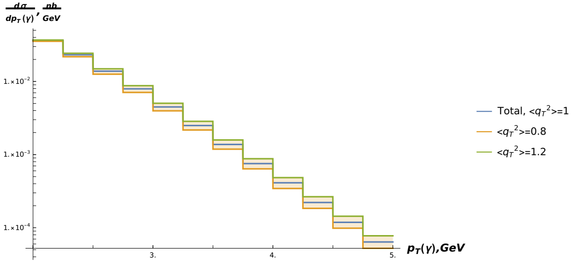


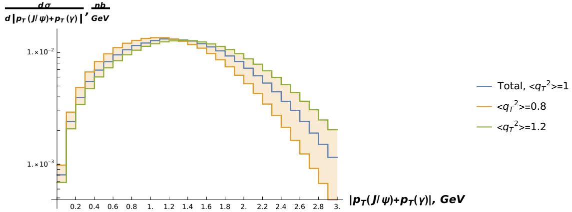
$J/\psi + \gamma$ production in CPM and GPM within framework of CSM



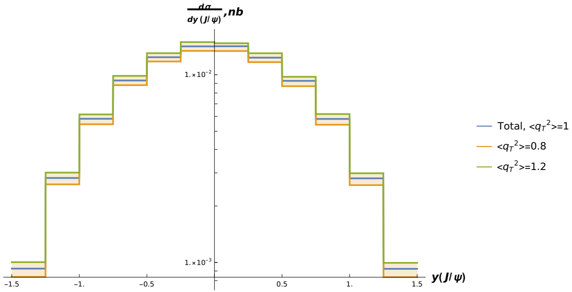


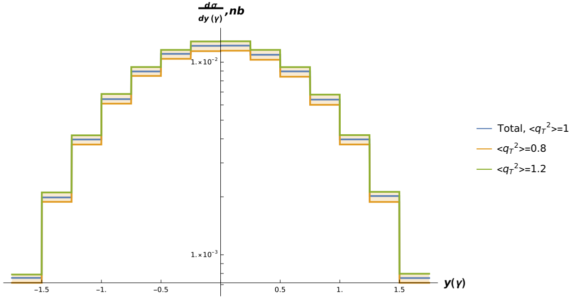
$J/\psi + \gamma$ production in CPM and GPM within framework of CSM





$J/\psi + \gamma$ production in CPM and GPM within framework of CSM





Conclusions

- We estimate cross section of associated $J/\psi + \gamma$ production at the energy of SPD NICA as 5.7×10^{-3} nb, where $p_{T\psi} \in [0, 6]$ GeV, $|y_\psi, y_\gamma| \in [0, 3]$ and $p_{T\gamma} \in [2, 6]$ GeV.
- We calculate J/ψ and γ transverse momentum and rapidity spectra, as well as azimuthal angle difference and rapidity difference spectra in GPM+CSM approach.
- The factorization-scale choice uncertainty is found as large, about factor 2.
- We test dependence of obtained results as function of average intrinsic transverse momentum of gluon, $< q_T^2 >$.

Thank you for your attention!