Production of η_c mesons at energy of the SPD NICA within generalized parton model and with various models of hadronization

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Outline

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2. Factorization approaches: CPM, TMD, GPM and PRA
3. Hadronization mechanisms: CSM, NRQCD and ICEM
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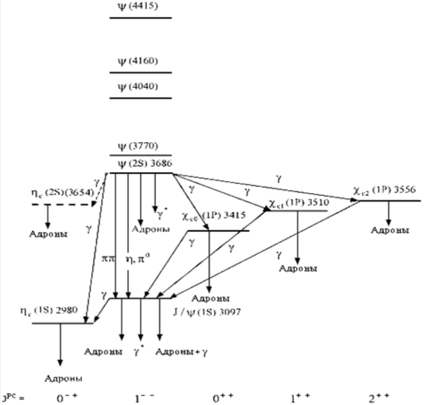
Introduction

$\eta_c = c\bar{c}[^1S_0]$, $M(\eta_c) = 2.981$ GeV, $\Gamma = 29.7$ MeV



$$Br(\eta_c \to p\bar{p}) = 1.4 \times 10^{-3}$$

$$Br(\eta_c \to \Lambda\bar{\Lambda}) = 9.4 \times 10^{-4}$$

$$Br(\eta_c \to K\bar{K}\pi) = 7.2 \times 10^{-2}$$

$$\boxed{Br(\eta_c \to \gamma\gamma) = 1.78 \times 10^{-4}}$$

Factorization approaches: CPM, TMD and GPM

Hard (factorization) scale $\mu_F \sim M$
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 $p_T \sim \mu_F$

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

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

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

Factorization approaches: PRA

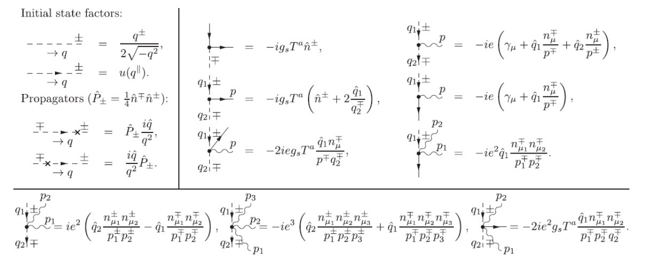
Parton Reggeization Approach

Parton Reggeization Approach (PRA) is based on High-Energy Factorization (HEF)

$$d\sigma(p+p\to H+X)=\sum_{i,j=Q,\bar{Q},R}\int\frac{dx_1}{x_1}\int\frac{d^2\vec{q}_{1T}}{\pi}\Phi_i^p(x_1,t_1,\mu^2)\times$$
$$\times\int\frac{dx_2}{x_2}\int\frac{d^2\vec{q}_{2T}}{\pi}\Phi_j^p(x_2,t_2,\mu^2)d\hat{\sigma}(i+j\to H+X)$$

$q^\mu_{1,2}=x_{1,2}P^\mu_{1,2}+q^\mu_{1,2T}, q_{1,2T}\neq 0, q^2_{1,2}=-\vec{q}^{\,2}_{1,2T}=q^2_{1,2T}=t_{1,2}$

- There is transverse momentum dependence, but initial partons are off-mass-shell instead of TMD factorization.
- For PRA amplitudes we can use effective gauge-invariance field theory with specific Feynman rules instead recover asymptotics of QCD amplitude on $s\to\infty$. This EFT is known as Lipatov's field theory.



Hadronization mechanisms: NRQCD and CSM

Basic idea - small relative momentum of $q\bar{q}$-pair, which can be neglected

Fock states can be decomposed into a series according to the small relative velocity parameter v. For instance, J/ψ-meson series is:

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

For η_c it gives

$$|\eta_c >= \mathcal{O}(v^0)|c\bar{c}[^1S_0^{(1)}] > +\mathcal{O}(v^1)|c\bar{c}[^1P_1^{(8)}]g > +\mathcal{O}(v^2)|c\bar{c}[^3S_1^{(1,8)}]g > +\mathcal{O}(v^2)|c\bar{c}[^1S_0^{(1,8)}]gg > + \dots$$

In **Color Singlet Model** (CSM) it's using only leading term of NRQCD series (singlet) without taking others terms (octets).

LDMEs

Long-Distance Matrix Elements defines transition of $q\bar{q}$ pair into final quarkonium. Singlet LDMEs connected with squared wave function as

$$< \mathcal{O}^H[c\bar{c}^{(1)}] >= 2N_c(2J+1)|\Psi(0)|^2$$

There is symmetry of LDMEs between J/ψ and η_c final states:

- $< \mathcal{O}^{\eta_c}[^1S_0^{(1)}|^1S_0^{(8)}] >= \frac{1}{3} < \mathcal{O}^{J/\psi}[^3S_1^{(1)}|^3S_1^{(8)}] >$
- $< \mathcal{O}^{\eta_c}[^3S_1^{(8)}] >=< \mathcal{O}^{J/\psi}[^1S_0^{(8)}] >$
- $< \mathcal{O}^{\eta_c}[^1P_1^{(8)}] >= 3 < \mathcal{O}^{J/\psi}[^3P_0^{(8)}] >$

Factorisation of η_c production in CSM from $c\bar{c}$ pair is presented in the form:

$$\hat{\sigma}(a+b \to c\bar{c}[13S_0^{1,8}] \to \eta_c) = \hat{\sigma}(a+b \to c\bar{c}[^1S_0^{1,8}])\frac{<\mathcal{O}^H[^1S_0^{(1,8)}]>}{N_{col}N_{pol}}$$

For singlet $N_{col} = 2N_c = 6, N_{pol} = 2J+1 = 1$. For octet $N_{col} = N_c^2 - 1$

Transformation into colorless charmonium

Amplitude of $c\bar{c}$ production can be obtained using projector on corresponds spin states

$$\Pi_1^\alpha = \frac{1}{\sqrt{8m_c^3}}\left(\frac{\hat{p}}{2} - \hat{q} - m_c\right)\gamma^\alpha\left(\frac{\hat{p}}{2} + \hat{q} + m_c\right)$$

where $\hat{p} = \gamma^\alpha p_\alpha$, p^α — 4-momenta of $c\bar{c}$-pair, $\hat{q} = \gamma^\alpha q_\alpha$, q_α — relative 4-momenta of quarks ,M — quarkonium mass, $m_c = M/2$ — mass of c-quark.
After convolution of amplitude with projector q is assumed **to be zero**.

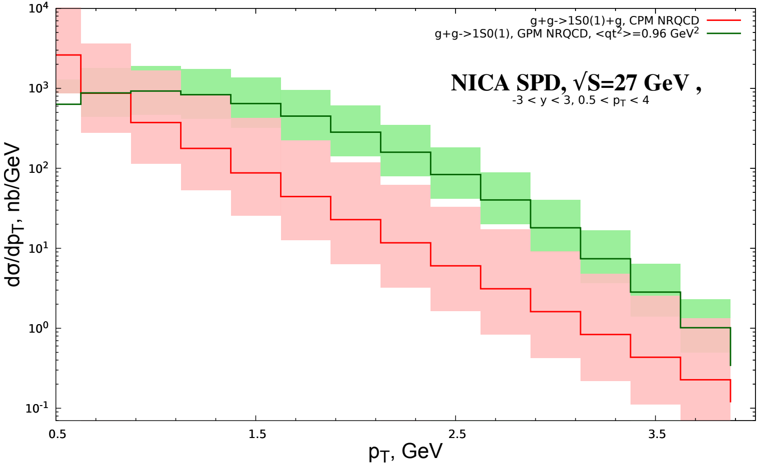
In Color Evaporation Model, heavy quark pair is produced perturbatively with definite spin and color quantum numbers and color of pair "evaporates"to transform into quarkonium

In the **Improved Color Evaporation Model** (ICEM) cross section of quarkonium state can be presented in form:

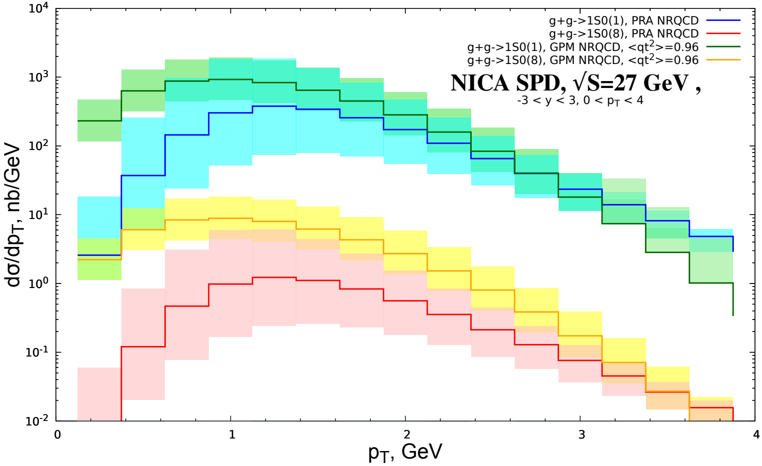
$$\hat{\sigma}(J/\psi) = \hat{\sigma}(c\bar{c} : M_{\eta_c} < s < 4m_D^2) f_c^{\eta_c}$$

when charmonium momentum is distinguished from the momentum of a quark pair through relation $p_T^{\eta_c} = \frac{M_{\eta_c}}{M_{c\bar{c}}} p_T^{c\bar{c}}$
f_c can be found from fit of experimental data. V. A. Saleev and A. A. Chernyshev showed that f_c depends on energy: $\mathbf{F_c = 0.2}$ at energy 27 GeV of SPD NICA

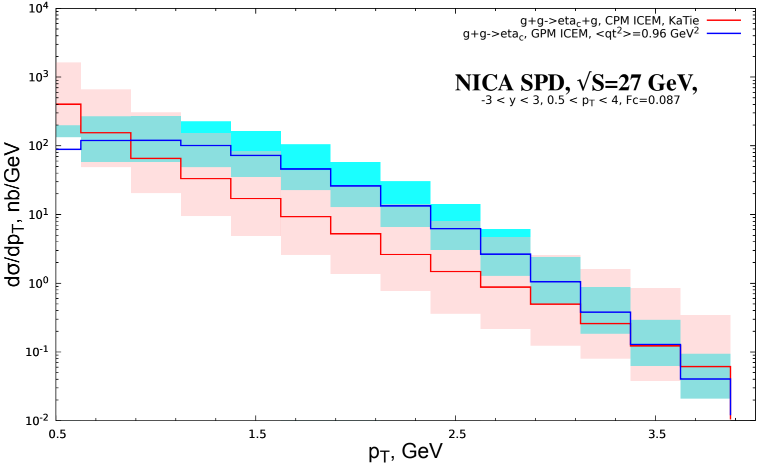
Comparison of differential cross-section of η_c-production at NICA in GPM and CPM within NRQCD



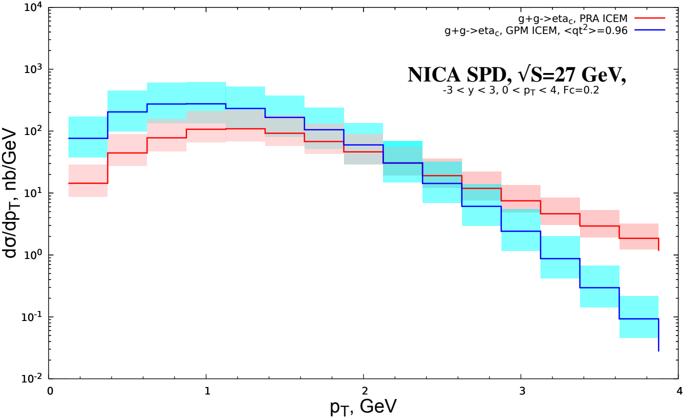
Comparison of differential cross-section of η_c-production at NICA in GPM and PRA within NRQCD



Comparison of differential cross-section of η_c-production at NICA in GPM and CPM within ICEM



Comparison of differential cross-section of η_c-production at NICA in GPM and PRA within ICEM



Conclusions

- CSM is approximately 80 % of NRQCD with CO NMEs taking accordingly HQS rules.
- PRA predictions for NICA are smaller by factor 2 than results within GPM used parameters obtained by fitting J/ψ data for the relevant energies.
- There is a good agreement between LO CPM, LO GPM and LO PRA calculations using both hadronization models NRQCD and ICEM.
- New experimental data is needed to answer some questions about NRQCD and ICEM phenomenology for η_c production case.

Thank you for your attention!