Production and two-photon decay of η_c at energy of SPD NICA

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Outline

1. Introduction
2. Factorization approaches: CPM, TMD, and GPM
3. Hadronization mechanisms: CSM, NRQCD and CEM
4. η_c production in CPM and GPM within framework of CSM
5. Predictions for energy of SPD NICA
6. Background process $pp \to \gamma\gamma X$
7. Estimations for S/B ratio
8. Conclusions

Introduction

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

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

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

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

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

Introduction

- There are only LHCb data for hadronic η_c production
- Test of perturbative QCD
- Test of heavy quark hadronization mechanism
- Tools for study gluon structure of proton
- Theoretically cleanest description

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 $p_T \sim \mu_F$

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

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

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

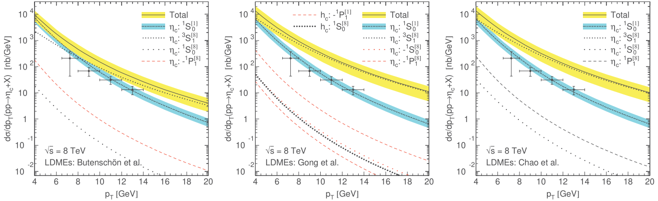
Hadronization mechanisms: CSM, NRQCD and CEM

- Color Singlet Model (CSM): only $c\bar{c}-$pairs with matched quantum number of the charmonium, ${}^1S_0^{(1)}$ for η_c-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

η_c production in CPM and GPM within framework of CSM

η_c production at the LHC

[Butenschön, Kniehl, He, 2014] Experimental data from [LHCb, 2014]: $pp \to \eta_c(\to p\bar{p}) + X$ with $\sqrt{S} = 7$ and 8 TeV.



Conclusions:

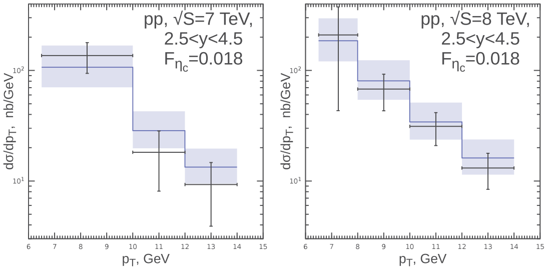
- CS-model $({}^1S_0^{(1)})$ describes LHCb data! CO-contrs. lead to significant overshoot. $\Rightarrow$ **HQSS-relations fail!**
- **Feeddown from h_c is negligible**

η_c production in CPM and GPM within framework of CSM

η_c production at the LHC

Description of LHCb data in ICEM+LO PRA

We use LO of Parton Reggeization Approach $(R_+(\mathbf{q}_{T1}) + R_-(\mathbf{q}_{T2}) \to c + \bar{c})$ to compute $c + \bar{c}$-production cross-section and tune F_{η_c}:



$$\Rightarrow \boxed{0.01 < F_{\eta_c} < 0.025}$$

For comparison, $F_{J/\psi} \simeq 0.02$.

η_c production in CPM and GPM within framework of CSM

η_c production at the LHC leads to following conclusions:

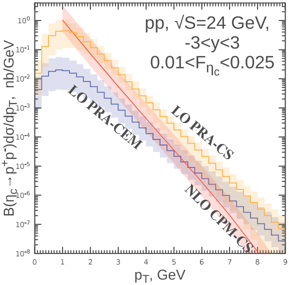
- Color singlet LDME $< \mathcal{O}[^1S_0^{(1)}] >$ can be calculated in a non-relativistic potential model ($|\Psi(0)|^2$), or extracted from the decay width $\Gamma(\eta_c \to \gamma\gamma)$. Color octet LDMEs are don't needed.
- Final state is colorless and we can neglect final-state interactions with soft (Glauber) gluons, which destroy hard-soft factorization. The η_c production in two-gluon fusion may be considered as "Drell-Yan" process, only for initial gluons.
- There is only direct production of η_c, contributions from high-mass states can be neglected.

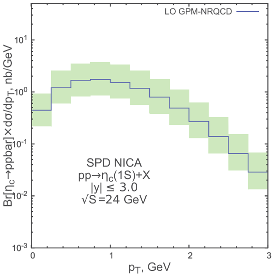
η_c production in CPM and GPM within framework of CSM

η_c production at the SPD NICA

Results for SPD-NICA

Predictions in NLO CPM CSM[Kniehl, Butenshön], LO PRA ICEM and LO PRA CSM shown in the left plot. Right plot – LO GPM CSM (with $\langle k_T \rangle = 1$ GeV). Cross-section$\times B(\eta_c \to p\bar{p})$:





LO PRA CSM: $\sigma \times B(\eta_c \to p\bar{p}) = 0.61^{+0.76}_{-0.43}$ nb.

η_c production in CPM and GPM within framework of CSM

CPM for $p_T \geq M$, $2 \to 2$ LO subprocess

$$g + g \to c\bar{c}[^1S_0^{(1)}] + g$$

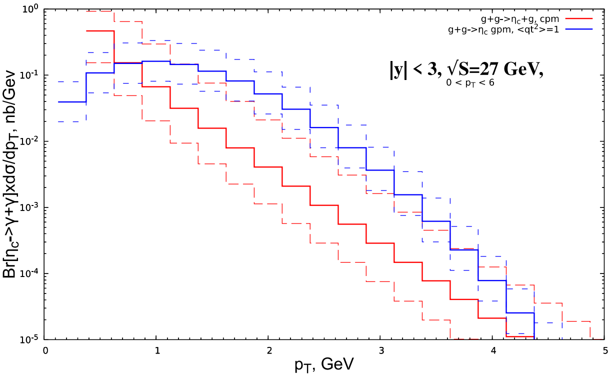
GPM for $p_T < M$, $2 \to 1$ LO subprocess

$$g + g \to c\bar{c}[^1S_0^{(1)}]$$

η_c production in CPM and GPM within framework of CSM

Total cross sections $|y| < 3, p_T > 0.5$

- $\sigma_{total} \times B(\eta_c \to \gamma\gamma) \simeq 0.071$ nb for CPM
- $\sigma_{total} \times B(\eta_c \to \gamma\gamma) \simeq 0.189$ nb for GPM



Background process $pp \to \gamma\gamma X$

Direct two-photon production

$$q + \bar{q} \to \gamma + \gamma$$

Fragmentation two-photon production

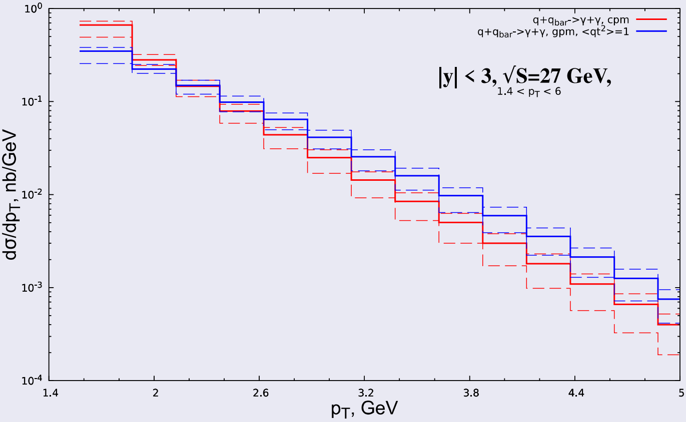
$$q + q \to q(\to \gamma) + q(\to \gamma)$$

$$g + g \to q(\to \gamma) + \bar{q}(\to \gamma)$$

$$q + g \to q(\to \gamma) + g(\to \gamma)$$

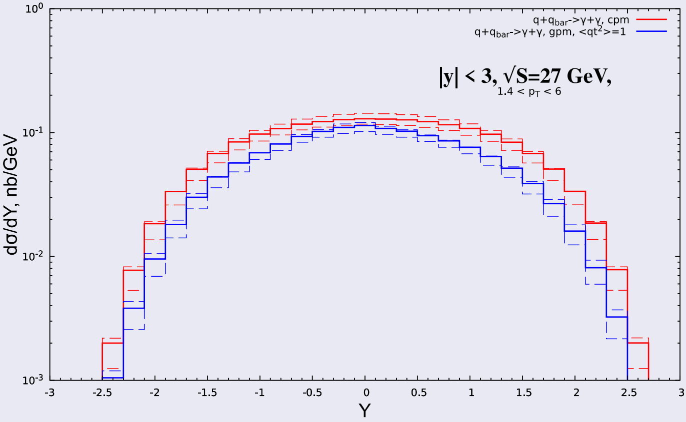
Background process $pp \to \gamma\gamma X$

Pair photon production at the SPD NICA



Background process $pp \to \gamma\gamma X$

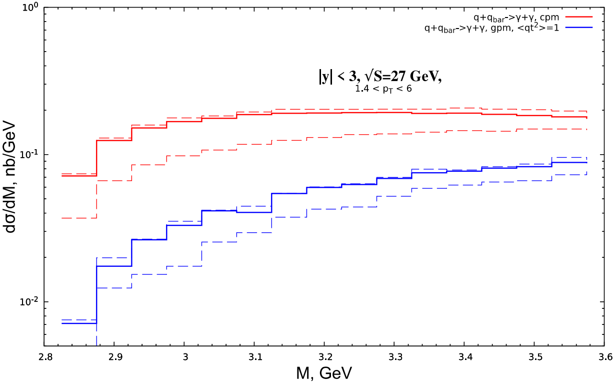
Pair photon production at the SPD NICA



Background process $pp \to \gamma\gamma X$

Total cross sections with transverse momentum cut $1.4 < p_T < 6$

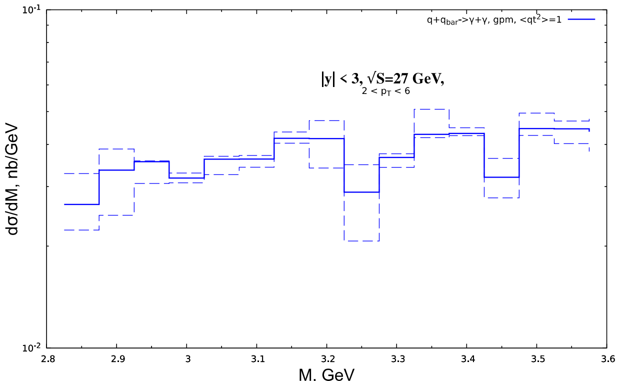
- $\sigma_{total} \simeq 1.286$ nb for CPM
- $\sigma_{total} \simeq 0.277$ nb for GPM



Background process $pp \to \gamma\gamma X$

Pair photon production with transverse momentum cut $2 < p_T < 6$

- There is invariant mass of photon pair minimum in LO CPM: $M_{min} = 4p_T^2 > M_{\eta_c}$
- In GPM-model $M_{min} \simeq 0$ so only it is useful
- $\sigma_{total} \simeq 0.053$ nb



Production and two-photon decay $pp \to \eta_c \to \gamma\gamma X$

Amplitude for $gg \to \eta_c \to \gamma\gamma$

$$A^{\alpha\beta\mu\nu} = f_{gg} f_{\gamma\gamma} \varepsilon^{\alpha\beta\alpha'\beta'} q_1^{\alpha'} q_2^{\beta'} \frac{i}{p^2 - M^2 + iM\Gamma} \varepsilon^{\mu\nu\mu'\nu'} k_1^{\mu'} k_2^{\nu'}$$

Structure constants from $\pi_0 \to g + g$ and $\pi_0 \to \gamma + \gamma$ decay widths

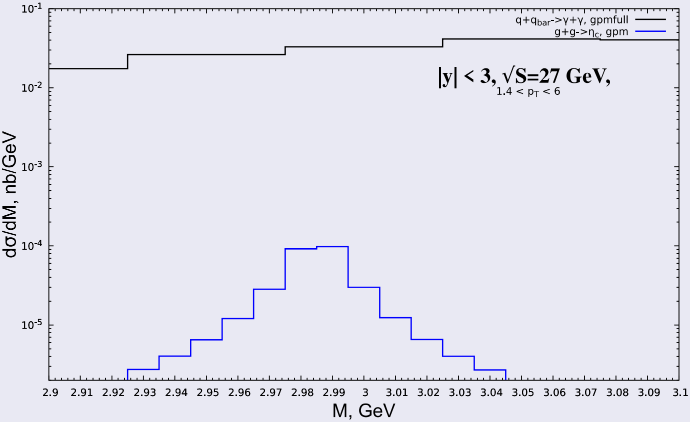
$$f_{\gamma\gamma} = \frac{96}{M^3} e^4 \alpha^2 \sqrt{\frac{\pi}{M}} |R(0)^2|, \quad f_{gg} = \frac{16}{9M^3} \alpha_s^2 \sqrt{\frac{\pi}{M}} |R(0)^2|$$

Square of amplitude

$$|\bar{A}|^2 = \frac{1}{256} \frac{M_0^8 f_{\gamma\gamma}^2 f_{gg}^2}{4(M^2 - M_0^2)^2 + M_0^2 \Gamma^2}$$

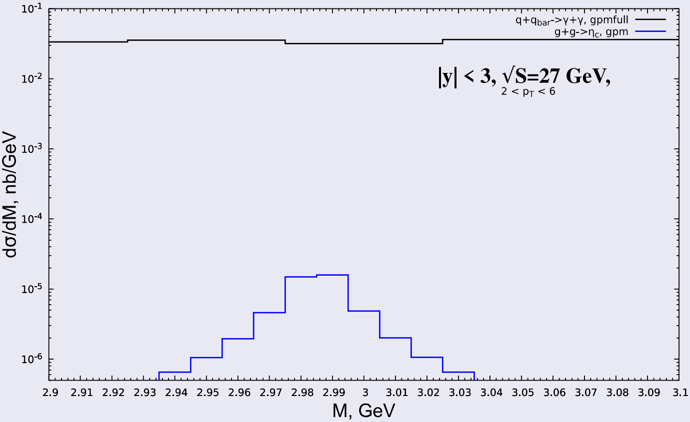
Estimations for S/B ratio

$pp \to \eta_c X \to \gamma\gamma X$ at the SPD NICA



Estimations for S/B ratio

$pp \to \eta_c X \to \gamma\gamma X$ at the SPD NICA



Estimations for S/B ratio

$pp \to \pi^0(\to \gamma\gamma) + \pi^0(\to \gamma\gamma)X$ at the SPD NICA

$$q + q \to q(\to \pi^0) + q(\to \pi^0)$$

$$g + g \to q(\to \pi^0) + \bar{q}(\to \pi^0)$$

$$q + g \to q(\to \pi^0) + g(\to \pi^0)$$

Fragmentation functions are taken from: J.F. Owens, E. Reya, M. Gluck, PRD18(1978)1501

$$D_u^{\pi^0}(z) = \frac{1}{2}\left(D_u^{\pi^+}(z) + D_u^{\pi^-}(z)\right)$$

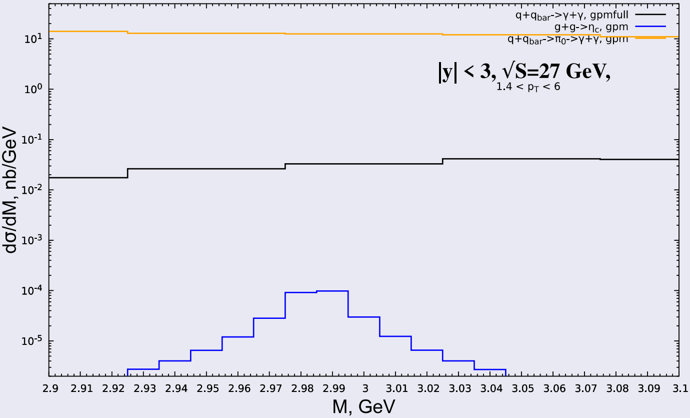
$$zD_u^{\pi^+}(z) = a\sqrt{z}(c - z) + \xi_\pi(1 - z)^2$$

$$zD_u^{\pi^-}(z) = \xi_\pi(1 - z)^2$$

$$zD_g^{\pi^0}(z) = C_\pi(1 - z)^{1.5}$$

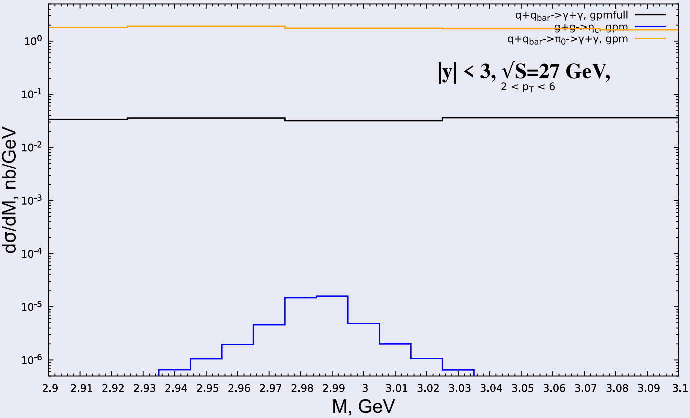
Estimations for S/B ratio

$pp \to \eta_c X \to \gamma\gamma X$ at the SPD NICA



Estimations for S/B ratio

$pp \to \eta_c X \to \gamma\gamma X$ at the SPD NICA



Conclusions

- $pp \to \pi^0\pi^0 X$ with $\pi^0 \to \gamma\gamma$ is main source of photon pairs with invariant mass in the range of $M \sim 3$ GeV.
- The S/B ratio for $pp \to \eta_c X \to \gamma\gamma$ to processes of prompt photon pair production $pp \to \gamma\gamma$ estimates as $\sim 10^{-3}$.
- There is dependence on photon transverse momenta ($p_{T\gamma,min}$) for S/B ratio.

Thank you for your attention!