Production of η_c mesons at high energy in proton-proton collisions

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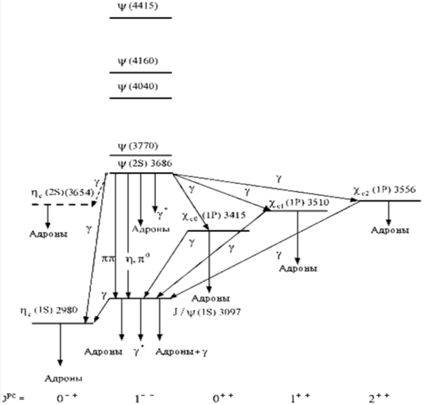
Outline

Introduction

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



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

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

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

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

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.

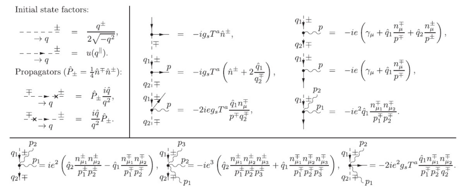
For details:

- M. A. Nefedov, V. A. Saleev and A. V. Shipilova, Dijet azimuthal decorrelations at the LHC in the parton Reggeization approach,// Phys. Rev. D **87** (2013) no.9, 094030
- A.V. Karpishkov, M.A. Nefedov and V.A. Saleev, $B\bar{B}$ angular correlations at the LHC in the parton Reggeization approach merged with higher-order matrix elements // Phys. Rev. D 96, 096019 (2017)
- M.A. Nefedov and V.A. Saleev, High-energy factorization for the Drell-Yan process in pp and $p\bar{p}$ collisions with new unintegrated PDFs // Phys. Rev. D 102, 114018 (2020)

Amplitudes in PRA

Lipatov's field theory

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.



ReggeQCD

Model-file ReggeQCD _ flv.mod was developed by Nefedov M.A. and Saleev V.A. for PRA calculations in FeynCalc with using of FeynArts in Wolfram Mathematica.

Automated amplitude generation with Reggeized quarks using ReggeQuarks.

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For details:

- E.N. Antonov, L.N. Lipatov, E.A. Kuraev and I. O. Cherednikov, Feynman rules for effective Regge action // Nucl. Phys. B 721, 111 (2005)
- M.A. Nefedov, V.A. Saleev, Diphoton production at the Tevatron and the LHC in the NLO approximation of the parton Reggeization approach // Phys. Rev. D 92, 094033 (2015)

PRA: Unintegrated PDFs with exact normalization

Tree-level UPDF contains a collinear divergence

Standard definition in BFKL formalism is used to resolve this divergence:

$$\Phi_i(x,t,\mu^2) = \frac{d}{dt}\left[T_i(t,\mu^2,x)\tilde{f}_i(x,t)\right]$$

We ask **exact equivalence** between last ones and following (KMRW) prescription

$$\Phi_i(x,t,\mu_Y^2) = \frac{\alpha_S(t)}{2\pi}\frac{T_i(t,\mu^2,x)}{t}\sum_{j=q,\bar{q},g}\int_x^1 dz P_{ij}(z)\tilde{f}_j(\tfrac{x}{z},t)\theta(\Delta(t,\mu_Y^2)-z)$$

and Sudakov form-factor

$$T_i(q_T,\mu) = Exp\left(-\int_t^{\mu^2}\frac{dt'}{t'}\frac{\alpha_S(t')}{2\pi}(\tau_i(t',\mu^2)) + \Delta\tau_i(t',mu^2,x)\right)$$

with $\tau_i(t,\mu^2) = \sum_j \int_0^1 dz z P_{ji}(z)\theta(\Delta(t,\mu^2)-z)$ and

$\Delta\tau_i(t,\mu^2,x) = \sum_j \int_0^1 dz \theta(z-\Delta(t,\mu^2))\Big[zP_{ji}(z) - \frac{F_j(\frac{x}{z},t)}{F_i(x,t)}P_{ij}(z)\theta(z-x)$

For details:

- M.A. Kimber, A.D. Martin and M.G. Ryskin, Unintegrated parton distributions and prompt photon hadroproduction // Eur.Phys.J.C12:655-661 (2000)
- M.A. Nefedov and V.A. Saleev, High-Energy Factorization for Drell-Yan process in pp and $p\bar{p}$ collisions with new Unintegrated PDFs // Phys. Rev. D 102 (2020)

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:

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

For details:

- G.T. Bodwin, E. Braaten, G. Peter Lepage, Rigorous QCD Analysis of Inclusive Annihilation and Production of Heavy Quarkonium // Phys. Rev. D 51, 1125 (1995)
- P. Cho, A.K. Lebovich, Color-octet quarkonia production // Phys. Rev. D 53, 150 (1996)

NRQCD: $q\bar{q}$ into quarkonium

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 $N_{col} = N_c^2 - 1$

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**.

For details:

- B.A. Kniehl, D.V. Vasin and V.A. Saleev Charmonium Production at High Energy in the k_T -Factorization Approach // Phys. Rev. D73 074022 (2006)
- B.A. Kniehl, V. Saleev, D. V. Vasin, Bottomonium production in the Regge limit of QCD // Phys. Rev. D 74, 014024 (2006)

Hadronization mechanisms: CEM and ICEM

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:

- $F_c = 0.02$ at big energies as 7,8 or 13 TeV
- $F_c = 0.07$ at PHENIX energy (200 GeV)
- $F_c = 0.2$ at energy 27 GeV of SPD NICA

For details:

- Y. Ma, R. Vogt, Quarkonium production in an improved color evaporation model // Phys. Rev. D 94,114029 (2016)
- A. A. Chernyshev and V. A. Saleev, Single and pair J/ψ production in the improved color evaporation model using the parton Reggeization approach, Phys. Rev. D 106 (2022) no.11, 114006

η_c production in pp-collisions

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2019-214
LHCb-PAPER-2019-024
5 March 2020

Measurement of the $\eta_c(1S)$ production cross-section in pp collisions at $\sqrt{s} = 13\,\text{TeV}$

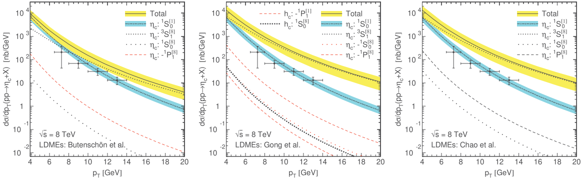
LHCb collaboration†

- LHCb 7 TeV, 8 TeV, 13 TeV - **There are experimental data only for 7 TeV, 8 TeV**
- ATLAS 7 TeV, 8 TeV, 13 TeV
- PHENIX 200 GeV
- SPD NICA 27 GeV

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:

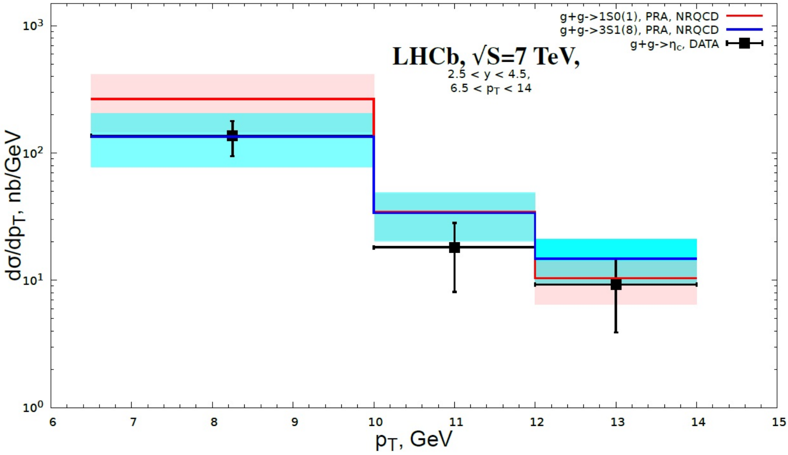
- CS-model $({}^1S_0^{(1)})$ describes LHCb data! CO-contrs. lead to significant overshoot. $\Rightarrow$ **HQSS-relations fail!**
- **Feeddown from h_c is negligible**

η_c production in CPM and GPM within framework of CSM

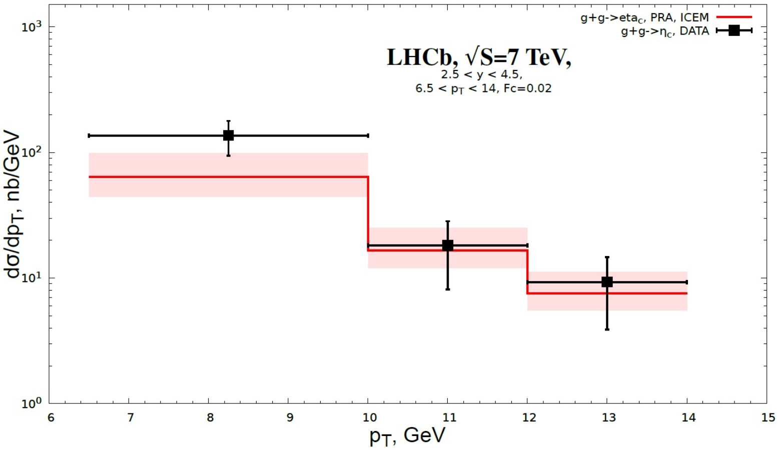
Analysis of η_c production in the NLO at the LHC leads to following conclusions:

- 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 not 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.

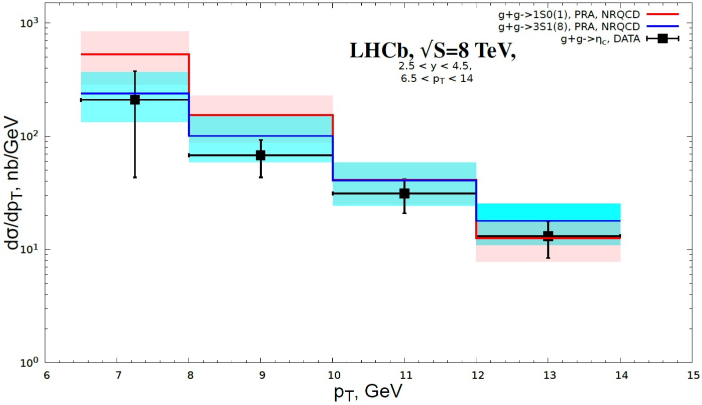
Comparison with LHCb data at the 7 Tev within NRQCD



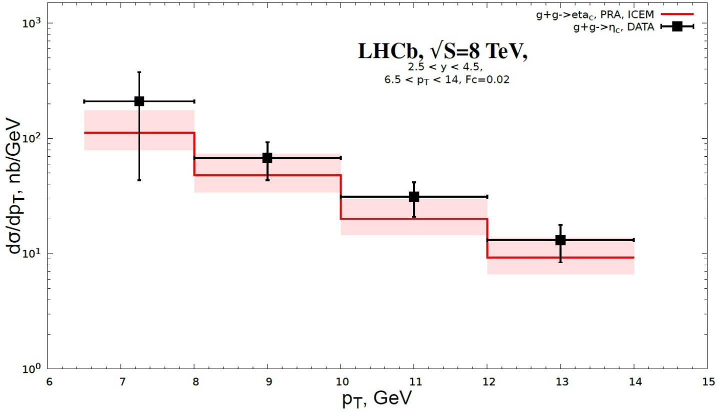
Comparison with LHCb data at the 7 Tev within ICEM



Comparison with LHCb data at the 8 Tev within NRQCD



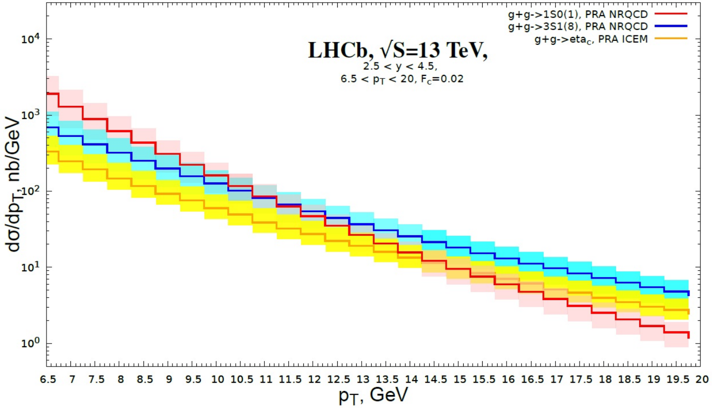
Comparison with LHCb data at the 8 Tev within ICEM



Predictions for LHCb at the 13 TeV

Total cross-section

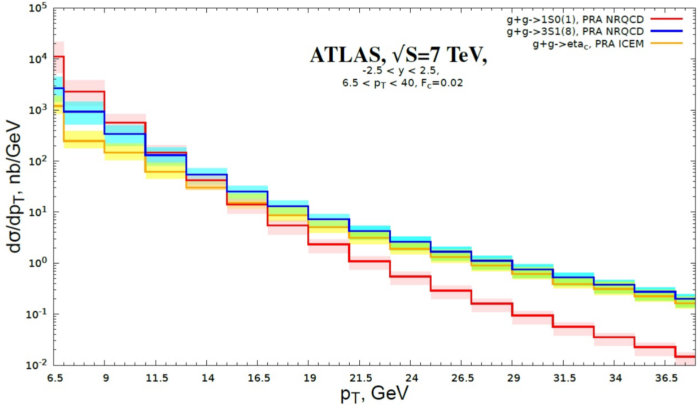
- PRA ICEM: $\sigma_{tot} = 0.95\,\mu b$
- PRA CSM: $\sigma_{tot} = 15.1\,\mu b$
- PRA NRQCD: $\sigma_{tot} = 19.5\,\mu b$



Predictions for ATLAS at the 7 TeV

Total cross-section

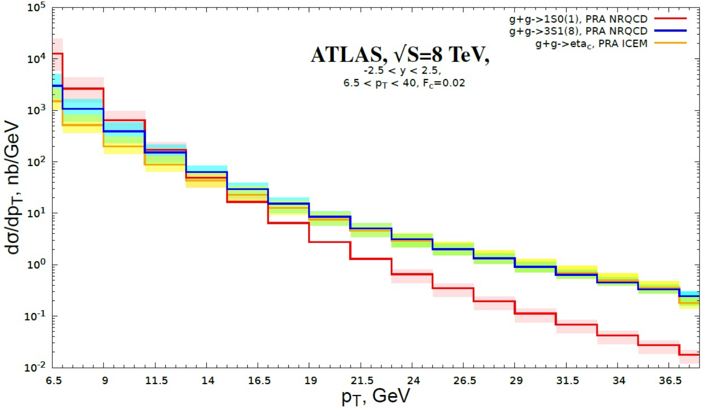
- PRA ICEM: $\sigma_{tot} = 0.5\,\mu b$
- PRA CSM: $\sigma_{tot} = 8.1\,\mu b$
- PRA NRQCD: $\sigma_{tot} = 11.2\,\mu b$



Predictions for ATLAS at the 8 TeV

Total cross-section

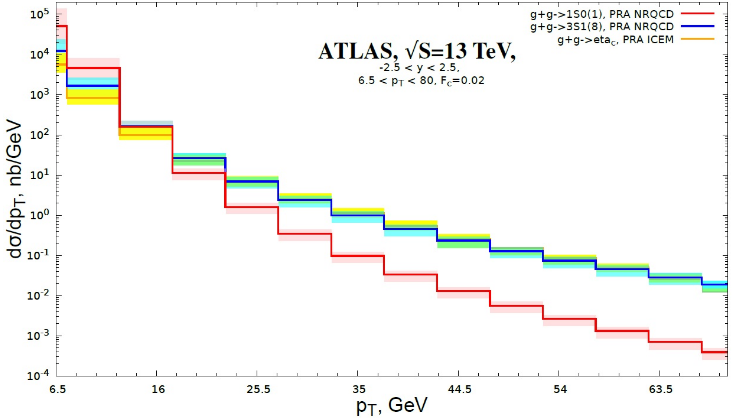
- PRA ICEM: $\sigma_{tot} = 0.6\,\mu b$
- PRA CSM: $\sigma_{tot} = 9.3\,\mu b$
- PRA NRQCD: $\sigma_{tot} = 12.3\,\mu b$



Predictions for ATLAS at the 13 TeV

Total cross-section

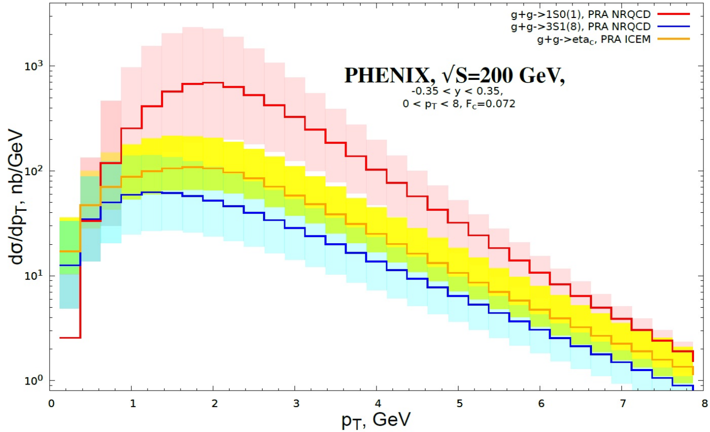
- PRA ICEM: $\sigma_{tot} = 1.1\,\mu b$
- PRA CSM: $\sigma_{tot} = 15.02\,\mu b$
- PRA NRQCD: $\sigma_{tot} = 18.9\,\mu b$



Predictions for PHENIX

Total cross-section

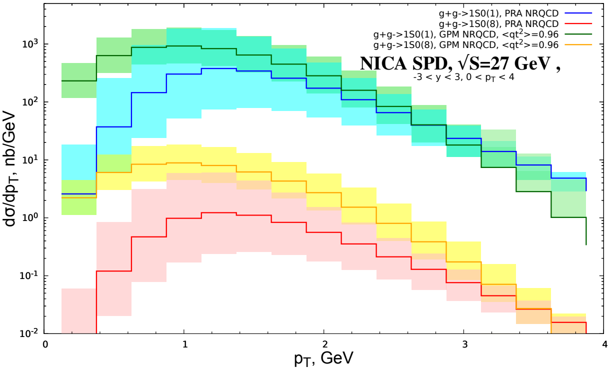
- PRA ICEM: $\sigma_{tot} = 0.2\,\mu b$
- PRA CSM: $\sigma_{tot} = 1.4\,\mu b$
- PRA NRQCD: $\sigma_{tot} = 1.6\,\mu b$



Predictions for SPD NICA within NRQCD

Total cross-section

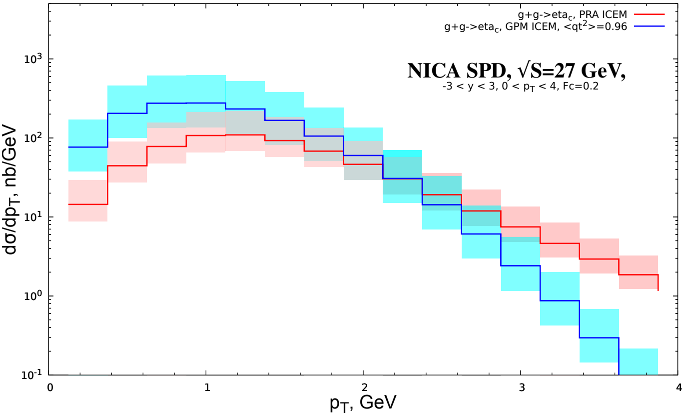
- PRA CSM: $\sigma_{tot} = 0.48\,\mu b$
- PRA NRQCD: $\sigma_{to} = 0.49\,\mu b$
- GPM CSM: $\sigma_{tot} = 1.3\,\mu b$
- GPM NRQCD: $\sigma_{tot} = 1.31\,\mu b$



Predictions for SPD NICA within ICEM

Total cross-section

- PRA ICEM: $\sigma_{tot} = 0.16\,\mu b$
- GPM ICEM: $\sigma_{tot} = 0,37\,\mu b$



Conclusions

- PRA calculations confirmed conclusions obtained in the NLO CPM. CSM is enough to describe η_c production at the LHC.
- CSM is approximately 80 % of NRQCD with CO NMEs taking accordingly HQS rules.
- PRA ICEM approximately 2 times less than data , and lies below CSM when $f_{\eta_c} = f_{J/\psi}$.
- 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.
- The predicted total cross section of η_c production is approximately from 0.5 μb to 1,3 μb

Thank you for your attention!