η_c-production at SPD NICA

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Outline

- Short theoretical introduction: NRQCD-factorization and Color-Evaporation model
- Measurement of η_c-production at LHCb, HQSS-puzzle
- Predictions for SPD-NICA

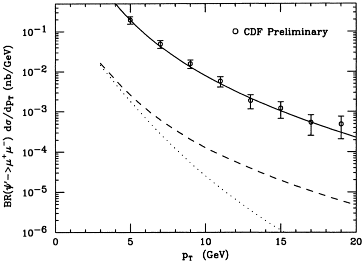
A bit of history

Historically, the first model of heavy-quarkonium production was the **color-singlet model**: *The production of state X_Q $(J/\psi, \chi_{cJ}, ..., \Upsilon(nS), \chi_{bJ}, ...)$ is dominated by production of* ***color-singlet*** *$Q\bar{Q}$-pair with L and S quantum numbers given by NR potential model for this state. Probability of hadronization is proportional to $|\Psi^{(k)}(0)|^2$, $(k = 0, 1, ...)$ from potential model.*

This model has two problems:

- Leads to a wrong shape of p_T-spectrum at high energies (Tevatron, LHC) both at LO and NLO of CPM and in k_T-factorization, which **under-estimates** the cross-section for $p_T > 10$ GeV by factor of 30 (*Tevatron $\psi(2S)$ puzzle*).
- Is **theoretically inconsistent at NLO for production of P-wave states:** In QCD, non-cancelling IR-divergences arise at NLO.

[Braaten, Fleming, 1994]



Dotted line – LO CPM color-singlet contribution. Solid line – ${}^3S_1^{(8)}$.

NRQCD and Color-Evaporation model

To solve above-mentioned problems, two approaches have been proposed: **NRQCD-factorization** and **Color-Evaporation Model**. Both models are well-defined to all orders in α_s, but NRQCD-factorization is viewed as more "rigorous" approach by the community.

- In **(Improved-)Color-Evaporation Model:** *all $Q\bar{Q}$ states with $M_X < M_{Q\bar{Q}} < 2M_{(\text{open flav. Q-meson})}$ hadronize to quarkonium X with the same probability – F_X, independent on $Q\bar{Q}$-quantum numbers*
- Optionally [Ma, Vogt, 2016] ICEM takes into account kinematic (soft-gluon recoil) corrections from the difference of masses $M_{Q\bar{Q}}$ and M_X using simple relation $p_T(X) = p_T(Q\bar{Q}) \times M_X/M_{Q\bar{Q}}$.
- ICEM can be viewed as NRQCD-factorization without velocity-scaling rules for probabilities F_X.

NRQCD and Color-Evaporation model

To solve above-mentioned problems, two approaches have been proposed: **NRQCD-factorization** and **Color-Evaporation Model**.

- **NRQCD-factorization:** *Different L, S and* **color** *states of $Q\bar{Q}$-pair hadronize to X with different "probability" –* **long-distance matrix element (LDME):** $\left\langle \mathcal{O}^X \left[{}^{2S+1}L_J^{(\text{color})} \right] \right\rangle$.
- LDME-s of states different from CSM-state are suppressed by powers of v^2 (~ 0.3 for J/ψ, ~ 0.1 for Υ) – *velocity-scaling rules for LDMEs*. E.g. for J/ψ and $\psi(2S)$: CSM$={}^3S_1^{(1)} = O(1)$ and ${}^3P_J^{(8)}$ and ${}^3S_1^{(8)}$, ${}^1S_0^{(8)}$, contribute up to $O(v^4)$.

Velocity-scaling rules and HQSS-relations

Velocity-scaling rules for LDMEs:

	${}^1S_0^{(1)}$	${}^3S_1^{(1)}$	${}^1S_0^{(8)}$	${}^3S_1^{(8)}$	${}^1P_1^{(1)}$	${}^3P_0^{(1)}$	${}^3P_1^{(1)}$	${}^3P_2^{(1)}$	${}^1P_1^{(8)}$	${}^3P_0^{(8)}$	${}^3P_1^{(8)}$	${}^3P_2^{(8)}$
η_c	1		v^4	v^3					v^4			
J/ψ		1	v^3	v^4						v^4	v^4	v^4
h_c			v^2		v^2							
χ_{c0}				v^2		v^2						
χ_{c1}				v^2			v^2					
χ_{c2}				v^2				v^2				

HQSS-relations between LDMEs of η_c and J/ψ:

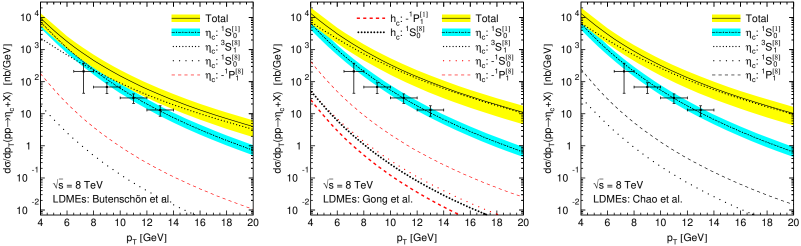
$$\left\langle \mathcal{O}^{\eta_c}\left[{}^1S_0^{(1/8)}\right]\right\rangle = \frac{1}{3}\left\langle \mathcal{O}^{J/\psi}\left[{}^3S_1^{(1/8)}\right]\right\rangle + O(v^2),$$

$$\left\langle \mathcal{O}^{\eta_c}\left[{}^3S_1^{(8)}\right]\right\rangle = \left\langle \mathcal{O}^{J/\psi}\left[{}^1S_0^{(8)}\right]\right\rangle + O(v^2),$$

$$\left\langle \mathcal{O}^{\eta_c}\left[{}^1P_1^{(8)}\right]\right\rangle = 3\left\langle \mathcal{O}^{J/\psi}\left[{}^3P_0^{(8)}\right]\right\rangle + O(v^2).$$

Test of HQSS-relations

[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 at SPD-NICA?

- If pure-CS picture of η_c-production is correct, then only gluon-induced process contributes at LO:

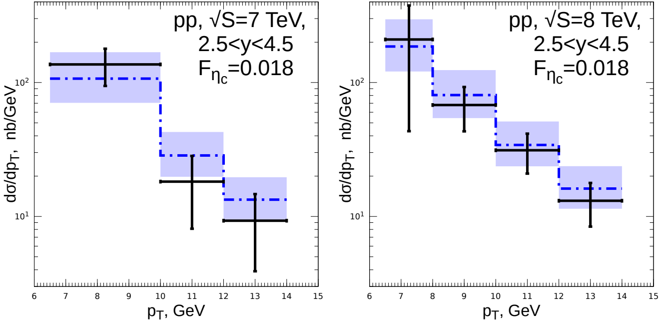
$$g + g \to c\bar{c}\left[{}^1S_0^{(1)}\right],$$

  and it has no free-parameters: $\left\langle \mathcal{O}^{\eta_c}\left[{}^1S_0^{(1)}\right]\right\rangle \propto |\Psi(0)|^2$.
- η_c is probably the only state for which TMD-factorization is valid [Eichevarria, 2019; Fleming, Markis, Mehen, 2019].
- LHCb has done measurement at high $\sqrt{S}$ and forward rapidity. **More measurements in other PS-regions needed to check CS hypothesis!**
- LHCb used $\eta_c \to p\bar{p}$-decay with $B = 1.45 \times 10^{-3}$. What about $\eta_c \to K\bar{K}\pi$ with $B = 7.3\%$? At lower energy comb. background is lower, right? However neutral pion...

We decided to estimate η_c p_T-spectrum in pp-collisions with $\sqrt{S} = 24$ GeV in ICEM and NRQCD (CS-model).

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}:

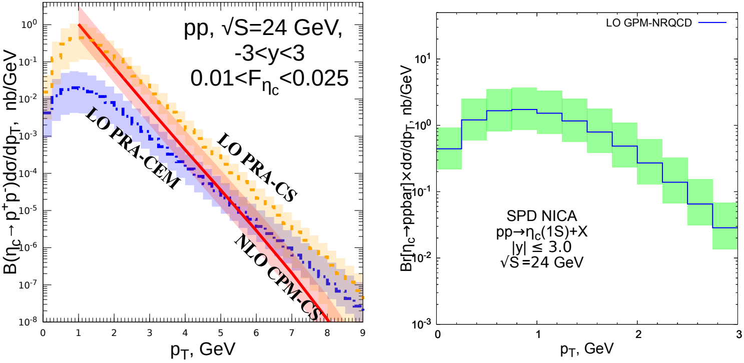


$$\Rightarrow \boxed{0.01 < F_{\eta_c} < 0.025}$$

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

Results for SPD-NICA

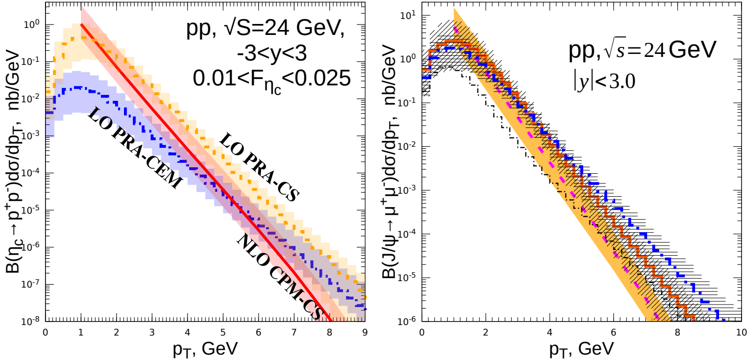
Predictions in NLO CPM CSM[Kniehl, Butenshön], LO PRA ICEM and LO PRA CSM shown in the left plot. Right plot – LO GPM CSM (with $\langle k_T \rangle = 1$ GeV). Cross-section$\times B(\eta_c \to p\bar{p})$:



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

Comparison with J/ψ

Predictions in NLO CPM CSM[Kniehl, Butenshön], LO PRA ICEM and LO PRA CSM shown in the left plot. Cross-section$\times B(\eta_c \to p\bar{p})$:



Cross section is ~ 0.1 compared with the J/ψ $\times B(J/\psi \to \mu^+\mu^-)$.

Outlook

- Any measurement of η_c production, even with large errors, is useful for development of heavy-quarkonium production theory
- If CS-model is valid $\Rightarrow$ η_c **is the golden probe for proton structure.** Couples to gluons, TMD-factorization is valid. One can study spin-asymmetries etc.
- $d\sigma/dp_T \times B(\eta_c \to p\bar{p}) \sim 1$ nb/GeV is obtained at $\sqrt{S} = 24$ GeV.
- Any hope to see this?

Thank you for your attention!