Energy scan and beam polarization as a tools to study heavy quarkonium production mechanism

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Outline

- Short theoretical introduction: NRQCD-factorization and Color-Evaporation model
- Status of NRQCD+LO PRA predictions for low energies (COMPASS, NICA), NA-3 problem
- CEM vs. NRQCD-factorization. Beam polarization as a tool to distinguish production models

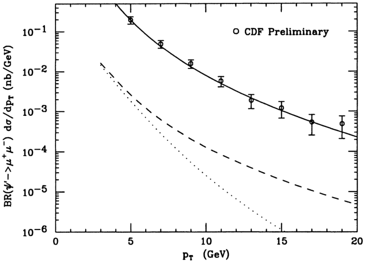
A bit of history

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 $|R^{(k)}(0)|^2$, ($k = 0, 1, ...$) 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**.

- **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 ${}^3P_J^{(8)} = O(v^2)$ and ${}^3S_1^{(8)}$, ${}^1S_0^{(8)}$, contribute at $O(v^4)$.

NRQCD and Color-Evaporation model

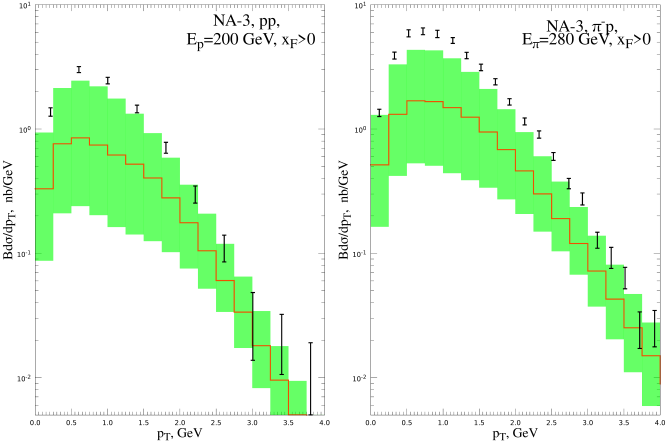
To solve above-mentioned problems, two approaches have been proposed: **NRQCD-factorization** and **Color-Evaporation Model**.

- 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*
- 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.

Both models are well-defined to all orders in α_s, but NRQCD-factorization is viewed as more "rigorous" approach by the community.

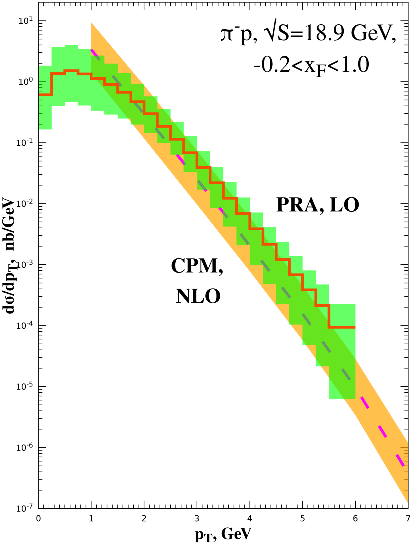
Both models are rather successful in description of p_T-spectra at high energies. The polarization issue is complicated and requires separate talk...

Situation at low energies: NA-3 problem



- LO PRA [M.N., V.A.S.] predictions with LDMEs well-describing high-energy data under-estimate the cross-section in pp amd πp-collisions at $\sqrt{S} = 19 - 23$ GeV.
- The fraction of $q\bar{q}$-initiated subprocesses ($q\bar{q} \to^3 S_1^{(8)}$) is very low: $\sim 1\%$ of total cross-section.

Situation at low energies: COMPASS



- LO PRA [M.N., V.A.S.] and NLO CPM [Kniehl, Butenshön] predictions with NRQCD-factorization agree with each-other
- However PRA predictions will probably underestimate COMPASS data, since they do not agree with NA-3 data

NRQCD prediction is robust

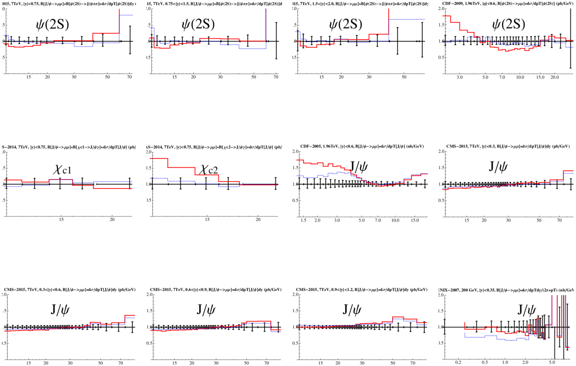
Many options had been tried to improve situation with NA-3 data:

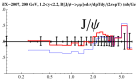
- Various LDME fit strategies: use/not-use HQSS-relations between LDMEs; allow negative color-octet LDMEs; fit color-singlet LDMEs as well.
- LO vs. "NLO" formulas for KMRW UPDF, different input PDF sets (MSTW, CT18, GRV LO/NLO for pion).
- On/off kinematic shift in cascade decays $X_1 \to X_2$: $p_{T2} = p_{T1} \times M_{X_2}/M_{X_1}$.
- fixed quark mass prescription in the short-distance part vs. $m_Q = M_X/2$ prescription.

In all cases LDMEs change in such a way that prediction for prompt-J/ψ spectrum stays the essentially same.

Example: m_Q-dependence

Fit of high-energy data (ATLAS, CMS, CDF, PHENIX):





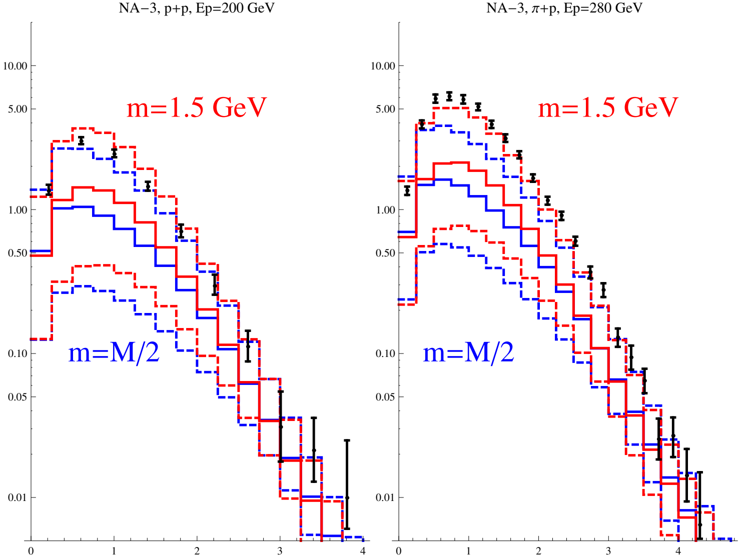
χ^2/d.o.f.=1.44934

χ^2/d.o.f.=2.65076

LO, mQ=1.5 GeV:	LO, mQ=M/2:
oJψ3S18=0.00170806±0.0000185009	oJψ3S18=0.00157612±0.0000169744
oJψ1S08=0±0.00153448	oJψ1S08=0±0.00118435
oJψ3P08=0.00714443±0.000206544	oJψ3P08=0.0121518±0.000245038
ψ2S3S18=0.000927456±0.00002685	ψ2S3S18=0.00109943±0.00004909
oψ2S1S08=0±0.00136388	oψ2S1S08=0±0.0009566
ψ2S3P08=0.000371047±0.00016073	oψ2S3P08=0.0100972±0.000434641
χc13S18=0.000595678±0.000078324	oχc13S18=0.0021449±0.000122563
oχc23S18=0±0.000497784	χc23S18=0.000843343±0.00019379

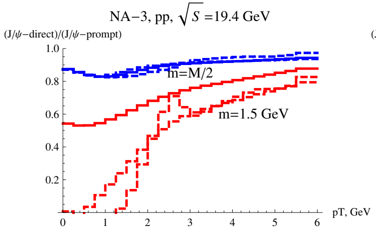
Example: m_Q-dependence

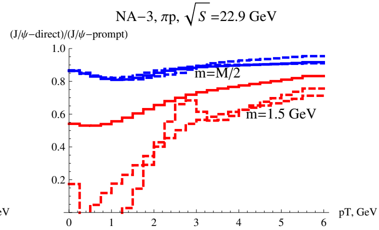
Predictions of both fits for NA-3 data are essentially the same:



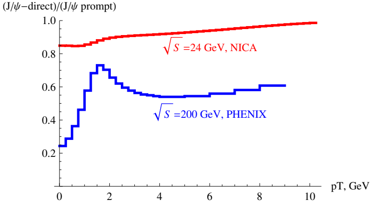
Example: m_Q-dependence

What changes is the fraction of prompt J/ψ produced directly:





In $m_Q = M_X/2$-model this fraction is energy-dependent:



while in fixed m_Q-model it is approximately constant ($\simeq 60\%$).

Suggestion I: Energy scan as a tool

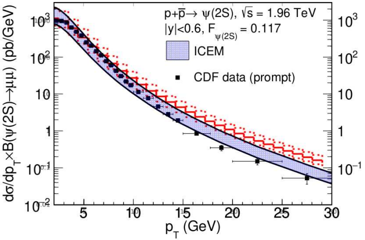
- NRQCD-factorization predictions in LO of PRA and NLO of CPM agree well. But LO PRA under-estimates NA-3 data. Large NNLO mcorrections? Threshold logarithms ($\ln(1-z)$)?
- **It is important to study observables beyond prompt J/ψ to discriminate production models.**
- Fixed-m_Q model = "factorization picture" between $Q\bar{Q}$-production and hadronization, while $m_Q = M/2$-model $\Rightarrow$ more complicated interplay between hard subprocess and hadronization. Which of them is correct?
- Two models predict different $\sigma_{(\text{direct}-J/\psi)}/\sigma_{(J/\psi)}$ or $\sigma_{(J/\psi \text{ from decays})}/\sigma_{(J/\psi)}$. But these observables are experimentally challenging.
- Energy-dependence of the ratios:

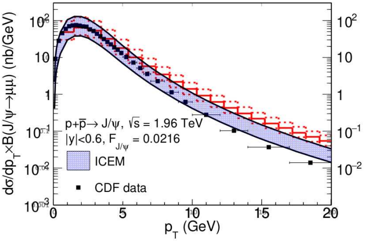
$$\frac{d\sigma_{\psi(2S)}/dp_T}{d\sigma_{J/\psi}/dp_T}, \ \frac{d\sigma_{\chi_{cJ}}/dp_T}{d\sigma_{J/\psi}/dp_T},$$

probes the same physics.

ICEM calculation

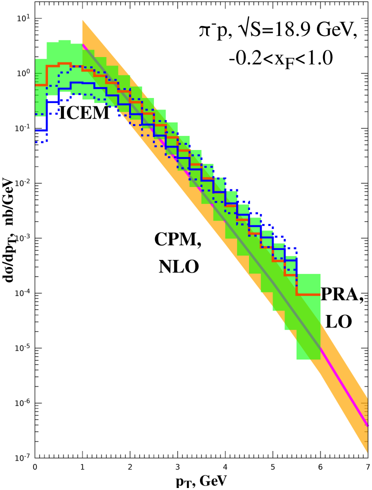
Results of [R.Vogt, et al.] where reproduced with our UPDF (KMRW UPDF derived from MSTW-08 LO PDF set instead of CCFM UPDF by [Jung, Hauptmann, 2016]). The same F_X-probabilities as in the paper where used:





ICEM calculation

Calculation for COMPASS kinematics basically coincides with PRA-NRQCD result:



So there could be no sharp distinction between NRQCD and ICEM predictions for un-polarized cross-section.

Suggestion II: Polarized beam as a tool

Beam polarization can be used as a handle to distinguish two models.
Idea is to measure the polarization-asymmetry for the p_T-spectra of J/ψ and $D\bar{D}$-pairs:

$$A_{J/\psi \text{ or } D\bar{D}}(p_T) = \frac{d\sigma_+/dp_T(p_T) - d\sigma_-/dp_T(p_T)}{d\sigma_+/dp_T(p_T) + d\sigma_-/dp_T(p_T)}.$$

Prediction:

- **In NRQCD** the weights of various $Q\bar{Q}$ states is very different $\Rightarrow$ $\boxed{A_{J/\psi}^{\text{NRQCD}}(p_T) \neq A_{D\bar{D}}(p_T)}$.
- **In CEM** all L, S states contribute equally $\Rightarrow$ $\boxed{A_{J/\psi}^{\text{CEM}}(p_T) \simeq A_{D\bar{D}}(p_T)}$.
- Transverse spin asymmetry is useful as well.
- Unfortunately, radiative corrections will dilute the difference and make $A_{J/\psi}(p_T) \to A_{D\bar{D}}(p_T)$ ("decoherence"), the effect of this should be estimated.

Conclusions

- Heavy quarkonium production at low enegries can become (yet another) challenge for NRQCD-factorization
- LO PRA and NLO CPM calculations agree but probably will under-estimate the data
- It is important to study not only J/ψ but also χ_{cJ} and $\psi(2S)$-cross-sections as function of energy to discriminate various models
- Beam-polarization asymmetry for J/ψ and $D\bar{D}$-production can be used to discriminate between NRQCD and ICEM. Calculations are in progress...

Thank you for your attention!