NLO J/ψ production with the Color Evaporation Model

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HEP 2023

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Quarkonia production

Color-evaporation model (CEM); 1977; Fritzsch, Halzen:

Numerous non-perturbative gluon emissions $\Rightarrow$ quantum states of the $Q\bar{Q}$ and H can be different

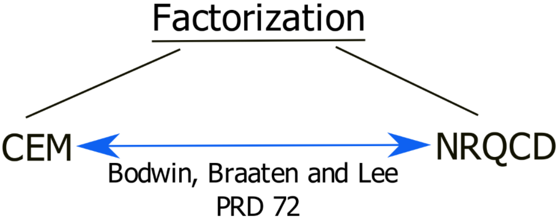
Color-singlet model (CSM); ∼1980; Chang, Berger and Jones, Baier and Ruckl:

Quantum state of the pair does not evolve between its production and its hadronisation.

Color-octet mechanism (COM) **and NRQCD** 1997; Bodwin, Braaten, and Lepage.

- All based on the factorization (hypothesis) of the cross section into short-distance coefficients and long-distance functions. Factorization not always explicitly stated.

Quarkonia production: factorization point of view



Includes CS and CO contributions

Just one LDME

EFT: expansion parameter v

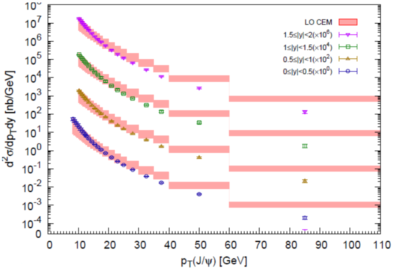
Includes CS and CO contributions

Several LDMEs

- The difference between CEM and NRQCD is non-perturbative.

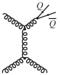
The fact. formalism includes a fragmentation contribution $i \to H$.

CEM at NLO



Lansberg, Phys.Rept. 889 (2020) 1-106

Main issue: Spectrum too hard. Due to NLO contributions $gg \to gQ\bar{Q}$



Our main goals:

1. Solve this issue
2. Compare with LO results obtained with the k_t-factorization formalism $\to$ contrains on unintegrated PDFs (UPDFs).

Proposed solution

NLO calculations + **timelike parton shower (TPS)**

- The starting scale for parton showers is usually $Q_{ini} \sim p_t$, with p_t the HQ transverse momentum
- Larger $p_t \Rightarrow$ longer shower $\Rightarrow$ more energy loss by the $Q\bar{Q} \Rightarrow$ softer spectrum

Consequence for NRQCD:

- The diagram responsable for the too-hard spectrum is also present in NRQCD
- Changes induced by the timelike shower will modify the value of the extracted LDMEs
- Could solve some of the tensions in LDMEs' fits (e.g., between differential cross section and polarization data or between different sets)

Kang, Ma, Qiu, and Sterman: Absence of resummation of $\ln(pt^2/m_Q^2)$ could affect the LDMEs' fits *PRD , Vol. 90, No. 3* .

Our framework

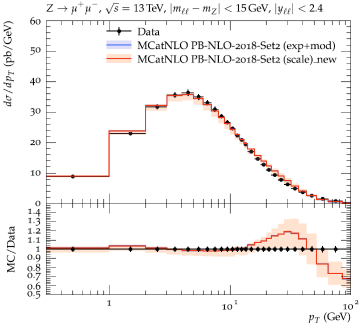
1. k_t-factorization (LO diagrams do contribute) with PB UPDFs:

$$\frac{d\sigma}{dx_1 dx_2 d^2p_t} = \int^{\sim s} d^2k_{1t} d^2k_{2t} F_i(x_1, k_{1t}^2; \mu^2) F_j(x_2, k_{2t}^2; \mu^2) \hat{\sigma}_{ij}(\hat{s}, k_{1t}^2, k_{2t}^2, p_t^2, \mu^2)$$

2. NLO cross section for $Q\bar{Q}$ with Madgraph5_aMC@NLO (fixed-flavor-number scheme, $n_f = 3$, $m_c = 1.3$ GeV)

3. Timelike parton shower with PYTHIA6 (through CASCADE3)

Framework used for Drell-Yan data, *Bermudez Martinez et al., Eur. Phys. J. C (2020) 80:598.*



J/ψ production mechanism

Color-evaporation model (CEM):

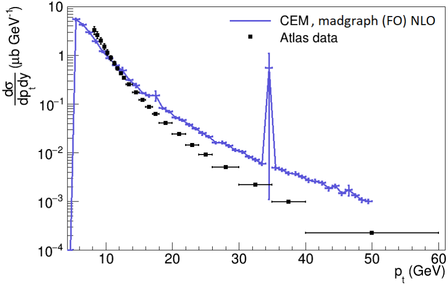
$$d\sigma = F_{J/\psi} \int_{2m_c}^{2m_{D^0}} \frac{d\sigma}{dm_{c\bar{c}}} dm_{c\bar{c}}$$

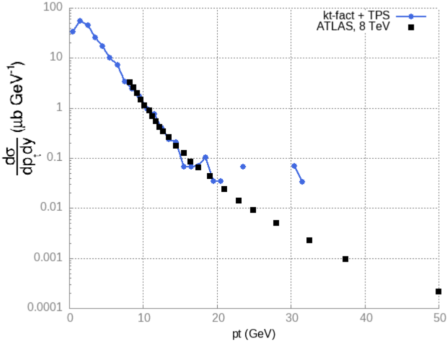
Improved-color-evaporation model (ICEM):
Ma and Vog, Phys. Rev. D 94, 114029 ; Cheung and Vogt, Phys. Rev. D 96, 054014, Phys. Rev. D 98, 114029.

$$\frac{d\sigma}{d^3P_{J/\psi}} = F_{J/\psi} \int_{m_{J/\psi}}^{2m_{D^0}} \frac{d\sigma(Q\bar{Q}+X)}{dm_{c\bar{c}}d^3p} dm_{c\bar{c}} d^3p \delta^3 \left(\vec{P_{J/\psi}} - \frac{m_{J/\psi}}{m_{c\bar{c}}} \vec{p} \right)$$

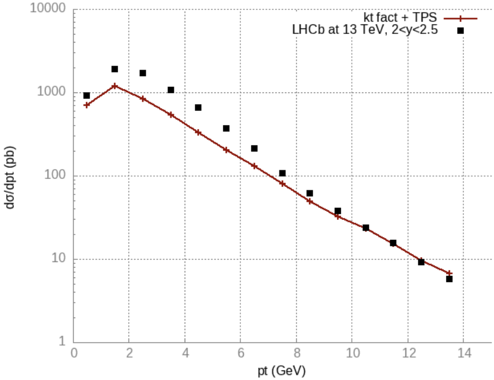
- $F_{J/\psi}$ expected to be universal
- We use $F_{J/\psi} = 0.014$, *Lansberg, Phys.Rept. 889 (2020) 1-106*

Preliminary results at medium and large p_t





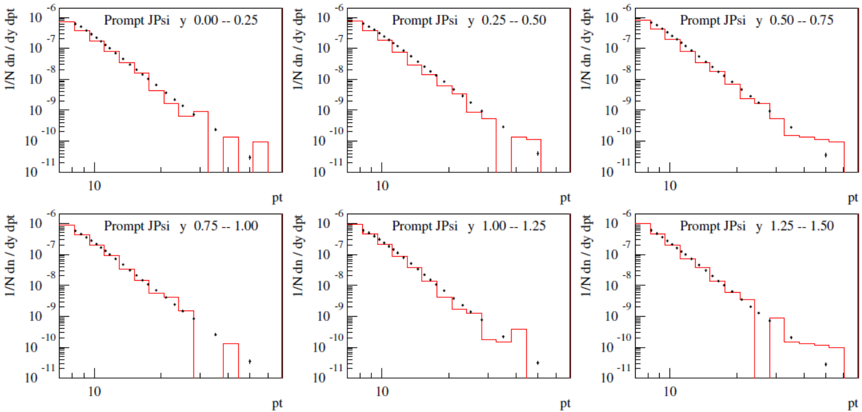
Preliminary results at small p_t



Parton-branching UPDFs play an important role at $p_t \lesssim 5 m_C$.

Same conclusion with EPOS 3

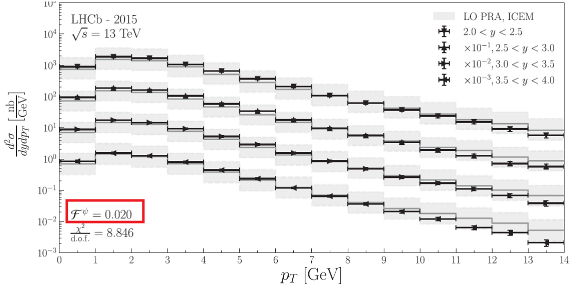
- EPOS 3 event generator: Generates realistic events
- The framework is different but has a **timelike cascade**

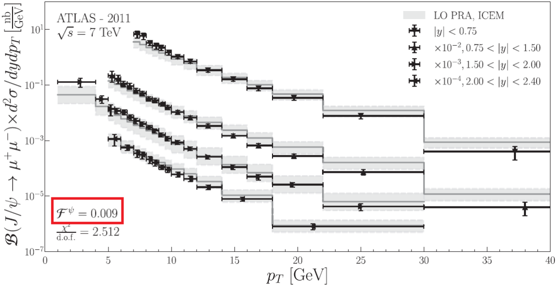


ATLAS data at 8 TeV, *Eur. Phys. J. C (2016) 76:283.*

Comparison with LO k_t factorization

Chernyshev, Saleev, PRD 106, 114006 (2022)





Too-hard spectrum: KMR UPDFs is probably not the best choice!

Final remark (factorization formalism)

Qiu, Sterman and Watanabe, arXiv:2211.12648v1 (2022)

$$\frac{\partial}{\partial \ln \mu^2} D_{f\to H}(z,\mu^2) = \frac{\alpha_s(\mu)}{2\pi} \sum_{f'} \int_z^1 \frac{dz'}{z'} P_{f\to f'}\left(\frac{z}{z'}\right) D_{f'\to H}(z',\mu^2)$$
$$+ \frac{\alpha_s^2(\mu)}{\mu^2} \sum_{\kappa} \int_z^1 \frac{dz'}{z'} P_{f\to [Q\bar{Q}(\kappa)]}\left(\frac{z}{z'}\right) D_{[Q\bar{Q}(\kappa)]\to H}\left(z',\mu^2\right)$$

$$\frac{\partial}{\partial \ln \mu^2} D_{[Q\bar{Q}(\kappa)]\to H}(z,\mu^2) = \frac{\alpha_s(\mu)}{2\pi} \sum_{n} \int_z^1 \frac{dz'}{z'} P_{[Q\bar{Q}(n)]\to [Q\bar{Q}(\kappa)]}\left(\frac{z}{z'}\right) D_{[Q\bar{Q}(n)]\to H}(z',\mu^2)$$

- Energy loss in the transition $Q\bar{Q}(n) \to Q\bar{Q}(\kappa)$
- The TPS approximately implement this equation
- A numerical code and analytical solution will be soon released by Qiu, Sterman and Watanabe
- Difficulties in the description of low-p_t data $\Rightarrow$ matching with FO NRQCD calculations

Conclusion

- Color Evaporation Model at NLO + TPS seems in agreement with data.
- Consequences of NLO + resummation of $\log(p_t^2/m_Q^2)$ for the extraction of LDMEs?
- Both $d\sigma(J/\psi)/dp_t$ and $F_{J/\psi}$ give interesting contrains on UPDFs.

Thank you for your attention