Production of $J/\psi$ quarkonia in color evaporation model based on $k_T$-factorization

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Heavy Flavours and Quarkonia at high energies

Heavy-flavours ⇒ open or hidden charm and beauty ⇒ study of QCD
- among the most important tools in high-energy $pp$, $pA$ and $AA$ collisions

Production of quarkonia is one of the most actively studied topics at the LHC
- the $J/\psi$, $\Psi'$, $\Upsilon$, $\Upsilon'$ and $\Upsilon''$ are the usually measured quarkonia
- the production of $J/\psi$ is a model case
- there was (still is) a disagreement related to the underlying production mechanism

There are essentially two theoretical approaches:
- non-relativistic QCD (NRQCD) approach based on collinear and/or $k_T$-factorization
- the color evaporation model (CEM)
Motivation behind Color Evaporation Model (CEM)

Why CEM?
- a lack of a complete NLO NRQCD computation
- unsolved problems:
  - simultaneous description of small and large $p_T$'s and size of color-octet contributions
  - description of quarkonium-associated-production channels and polarisation observables

The useful alternative:
Color Evaporation Model ⇒ can be seen as the application of the quark-hadron-duality principle to quarkonium production

Main advantages:
- simplicity of the model
- possible full NLO collinear computations
- useful application of $k_T$-factorization approach

In this approach one is using the perturbative calculation of $c\bar{c}$-pair production
- the $c\bar{c}$-pair by emitting a soft radiation goes to the color singlet state of a given spin and parity
- the emission is not explicit and everything is contained in a suitable renormalization of the $c\bar{c}$ cross section
Color Evaporation Model (CEM)

The cross section for $J/\psi$ production $\Rightarrow$ the $c\bar{c}$-pair cross section integrated over an invariant-mass region where its hadronization into a quarkonium is likely:

$$\frac{d\sigma_{J/\psi}(P_{J/\psi})}{d^3P_{J/\psi}} = F_{J/\psi} \int_{M_{J/\psi}}^{2M_D} d^3P_{c\bar{c}} \ dM_{c\bar{c}} \frac{d\sigma_{c\bar{c}}(M_{c\bar{c}},P_{c\bar{c}})}{dM_{c\bar{c}}d^3P_{c\bar{c}}} \delta^3(\vec{P}_{J/\psi} - \frac{M_{J/\psi}}{M_{c\bar{c}}} \vec{P}_{c\bar{c}})$$

- $F_{J/\psi}$ is the probability of the $c\bar{c} \rightarrow J/\psi$ which is fitted to the experimental data
- $M_{J/\psi}$ (or $M_D$) is the mass of $J/\psi$ (or $D$) and $M_{c\bar{c}}$ is the invariant mass of $c\bar{c}$-system

Improved version of the CEM:
- lower integration limit: $M_{J/\psi}$ instead of $2m_c$
- momentum relation: $\vec{P}_{J/\psi} = \frac{M_{J/\psi}}{M_{c\bar{c}}} \vec{P}_{c\bar{c}}$, where $\vec{P}_{c\bar{c}} = \vec{p}_c + \vec{p}_{\bar{c}}$

THEORY vs. DATA on prompt $J/\psi$:
- $p_T$ of $J/\psi$-meson directly calculated from the transverse momentum of the $c\bar{c}$-pair
- one can easily calculate also rapidity of $J/\psi$-meson
- numerical results corrected by the direct-to-prompt ratio equal to 0.62
- the two pQCD approaches available:
  - NLO collinear approximation
  - $k_T$-factorization approach
Charm cross section at high energies

- The leading-order (LO) partonic processes for $Q\bar{Q}$ production ⇒
  gluon-gluon fusion dominant at high energies

- Main classes of the next-to-leading order (NLO) diagrams:
  - pair creation with gluon emission
  - flavour excitation
  - gluon splitting

the observable of the interest ⇒ transverse momentum of the $c\bar{c}$-pair

collinear approach:
- $c\bar{c}$-pair transverse momentum is equal to zero at the LO
- the NLO diagrams are the LO for this quantity

$k_T$-factorization:
- nonzero $c\bar{c}$-pair transverse momentum can be obtained already at the LO
- some contributions beyond the NLO available
**$k_T$-factorization (high-energy factorization) approach**

**Off-shell initial state partons** $\Rightarrow$

**Initial transverse momenta explicitly included** $k_{1,t}, k_{2,t} \neq 0$

- Exact kinematics from the very beginning and additional hard dynamics coming from transverse momenta of incident partons
- Very efficient for less inclusive studies of kinematical correlations
- More exclusive observables, e.g. pair transverse momentum or azimuthal angle very sensitive to the incident transverse momenta

**Multi-differential cross section:**

$$
\frac{d\sigma}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t}} = \int \frac{d^2 k_{1,t}}{\pi} \frac{d^2 k_{2,t}}{\pi} \frac{1}{16 \pi^2 (x_1 x_2 s)^2} |M_{g^* g^* \rightarrow Q \bar{Q}}|^2 \\
\times \delta^2 \left( \vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t} \right) F_g(x_1, k_{1,t}^2, \mu) F_g(x_2, k_{2,t}^2, \mu)
$$

- $F_g(x, k_t^2, \mu)$ - (unintegrated) transverse momentum dependent PDFs
- The LO off-shell matrix elements $|M_{g^* g^* \rightarrow Q \bar{Q}}|^2$ available (analytic form)
- The higher-order matrix elements only at tree-level (KaTie Monte Carlo generator)
- Part of higher-order (real) corrections effectively included in uPDF

**Pair creation**
- with gluon emission

**Flavour excitation**
- Gluon splitting

**Final state radiation**

**Part of the proton**
Unintegrated parton distribution functions (uPDFs)

Most popular models:
- H. Jung et al. (CCFM, broad range of $x$)
- H. Jung et al. (DGLAP + Parton-Branching, broad range of $x$)
- Kimber-Martin-Ryskin (DGLAP-BFKL, broad range of $x$)
- Kwieciński-Martin-Staśto (BFKL-DGLAP, rather small $x$-values)
- Kutak-Staśto, Kutak-Sapeta (BK+saturation, only small $x$-values)

As a default set: Kimber-Martin-Ryskin (KMR) approach:
- calculated from collinear PDFs (most up-to-date PDF sets can be used)
- the unique feature: $k_t > \mu$ included $\Rightarrow$ hard emissions from the uPDF

For comparison: JH2013 uPDF (Jung-Hautmann, CCFM fits to HERA precision data)
- $k_t > \mu$ strongly suppressed (only soft extra emissions)
- a model that provides a good description of charm cross section beyond the single-particle spectra is crucial (especially in the region of small invariant masses)
Open charm meson

Theoretical computations:

$k_T$-factorization: $g^*g^* \rightarrow c\bar{c} + \text{uPDFs} + \text{Peterson FF for } c \rightarrow D^\pm$ transition

- Some sensitivity to the choice of the collinear PDF in the KMR calculations but only at small transverse momenta (CT14lo vs. MMHT2014lo)
- The JH-2013-set2 uPDF noticeably overestimates the data points at small $p_T$’s
- First two bins in $p_T$ ⇒ uncertain region ⇒ crucial for the rapidity distribution
- The LHCb open charm data well described with the KMR uPDF
Prompt $J/\psi$ meson

**Theoretical computations:**

ICEM + $k_T$-factorization: $g^* g^* \rightarrow c\bar{c} +$ uPDFs + $P_{J/\psi}$ for $c\bar{c} \rightarrow J/\psi$ transition

- the $P_{J/\psi}$ transition probability fitted to the $J/\psi$ $p_T$-distribution
- $p_T$ of $J/\psi \Rightarrow p_T$ of the $c\bar{c}$-pair $\Rightarrow$ very sensitive to the $k_t$-dependence of the uPDF
- very different results for the two uPDFs
- the JH-2013set2 uPDF completely fails for larger $p_T$'s of the $J/\psi$-meson
- the LHCb prompt $J/\psi$ data reasonably well described with the KMR uPDF
Prompt $J/\psi$ meson

Theoretical computations:

ICEM + $k_T$-factorization: $g^* g^* \to c\bar{c} + \text{KMR uPDFs} + P_{J/\psi}$ for $c\bar{c} \to J/\psi$ transition

- the improved CEM (our default) leads to the $p_T$-slope more supported by the data
- the $p_T$-slope sensitive to the choice of the renormalization/factorization scale
  $\Rightarrow$ the default set $\mu^2 = \frac{m_1^2 + m_2^2}{2}$ is the most favourable one
Prompt $J/\psi$ meson

Theoretical computations:

ICEM + $k_T$-factorization: $g^*g^* \rightarrow c\bar{c} + \text{KMR uPDFs} + P_{J/\psi}$ for $c\bar{c} \rightarrow J/\psi$ transition

- the typical uncertainty bands:
  - charm quark mass $\Rightarrow 1.2 < m_c < 1.5$ GeV
  - scales $\Rightarrow 0.5 < \frac{\mu}{m_T} < 2$

- the LHCb data described in the whole considered $p_T$ region with the KMR uPDF within the theoretical uncertainties
Prompt $J/\psi$ meson

different $\sqrt{s}$ and $y$

Theoretical computations:

$\text{ICEM} + k_T$-factorization: $g^* g^* \rightarrow c\bar{c} + \text{KMR uPDFs} + P_{J/\psi}$ for $c\bar{c} \rightarrow J/\psi$ transition

- we keep the $P_{J/\psi} = 0.018$ from the fits to the LHCb forward data
- the theoretical model reasonably works also when we go to
  - the midrapidity regime $\Rightarrow |y| < 0.9$ ALICE, CMS and $|y| < 0.75$ ATLAS
  - the lower collision energy $\Rightarrow \sqrt{s} = 1.96$ TeV at Tevatron
- very large $p_T$'s slightly overestimated
Prompt $J/\psi$ meson

**CCFM uPDFs**

### Why the JH-2013 uPDF does not work here?
- The observable very sensitive to the $k_t$-dependence in uPDFs
- This model does not allow for hard extra emissions during the uPDF evolution
- Only soft emissions $k_t < \mu$ are included
- The KMR uPDF has long tails in $k_t$'s and is able to produce large transverse momenta of the $c\bar{c}$-pair

### Our idea to improve the data description:

- We explicitly include the $g^*g^* \rightarrow gc\bar{c}$ mechanism at tree-level
- The calculations are done with the KaTie Monte Carlo generator
Prompt $J/\psi$ meson

**Theoretical computations:**

ICEM + $k_T$-factorization: $g^* g^* \rightarrow c\bar{c} +$ JH-2013 uPDF + $P_{J/\psi}$ for $c\bar{c} \rightarrow J/\psi$ transition

$+ g^* g^* \rightarrow gc\bar{c}$

- the description of the data of the same quality as for the KMR uPDF with the $2 \rightarrow 2$ calculations
- the $2 \rightarrow 3$ contribution is crucial for the calculations with the JH-2013 uPDF
- this conclusion may be important for the recent studies ⇒ V.Cheung, and R.Vogt, Phys.Rev.D98, 114029 (2018)
We have discussed how to extend the improved color evaporation model for production of $J/\psi$ meson to be used in the framework of $k_T$-factorization approach:

- Rapidity and transverse momentum distributions of $J/\psi$ mesons have been calculated and the normalization factors $P_{J/\psi}$, being a probability of $c\bar{c}$ soft transition to color singlet $S$ wave quarkonium, have been obtained.
- Different models of unintegrated PDFs have been used.
- For the first time, the higher-order contribution $g^*g^* \rightarrow gc\bar{c}$ with off-shell initial state partons has been included.
- A reasonable description of the prompt $J/\psi$ world data have been obtained.

Thank You for attention!