Production of J/ψ quarkonia in color evaporation model based on k_T-factorization

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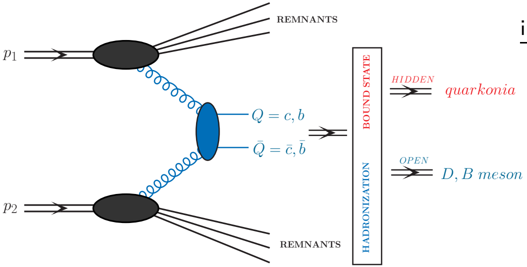
Heavy Flavours and Quarkonia at high energies

Heavy-flavours ⇒ open or hidden charm and beauty ⇒ study of QCD

- among the most important tools in high-energy *pp*, *pA* and *AA* collisions



in proton-proton interactions:

- important tests of our understanding of various aspects of QCD
- heavy quark mass ⇒ perturbative QCD
- open heavy meson ⇒ hadronization
- quarkonium bound state ⇒ non-perturbative aspects of QCD calculations

Production of quarkonia is one of the most actively studied topics at the LHC

- the J/ψ, Ψ', Υ, Υ' and Υ'' are the usually measured quarkonia
- the production of J/ψ 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)

Color Evaporation Model (CEM)

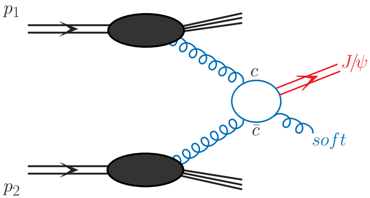
Why CEM?

- 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 $\Rightarrow$ can be seen as the application of the quark-hadron-duality principle to quarkonium production



- 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

main advantages:

- simplicity of the model
- possible full NLO collinear computations
- useful application of k_T-factorization approach

Color Evaporation Model (CEM)

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

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

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

Improved version of the CEM:

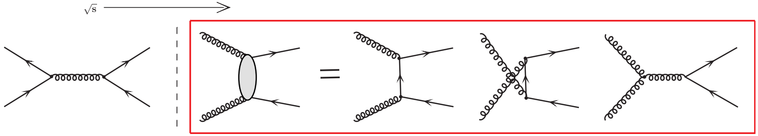
- lower integration limit: $M_{J/\psi}$ instead of $2m_c$
- momentum relation: $\vec{P}_{J/\psi} = \frac{M_{J/\psi}}{M_{c\bar{c}}} \vec{P}_{c\bar{c}}$, where $\vec{P}_{c\bar{c}} = \vec{p}_c + \vec{p}_{\bar{c}}$

THEORY vs. DATA on prompt J/ψ:

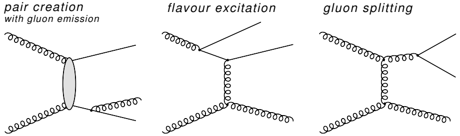
- p_T of J/ψ-meson directly calculated from the transverse momentum of the $c\bar{c}$-pair
- one can easily calculate also rapidity of J/ψ-meson
- numerical results corrected by the direct-to-prompt ratio equal to 0.62
- the two pQCD approaches available:
  - NLO collinear approximation
  - k_T-factorization approach

Charm cross section at high energies

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



- Main classes of the next-to-leading order (NLO) diagrams:



the NLO corrections of a special importance for charm production!

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

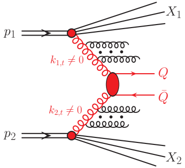
collinear approach:

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

k_T-factorizaton:

- 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 ⇒

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

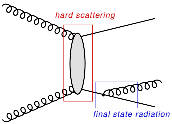
multi-differential cross section:

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \int \frac{d^2k_{1,t}}{\pi} \frac{d^2k_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{g^* g^* \to Q\bar{Q}}|^2}$$

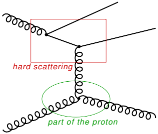
$$\times \quad \delta^2\left(\vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}\right) \mathcal{F}_g(x_1, k_{1,t}^2, \mu)\, \mathcal{F}_g(x_2, k_{2,t}^2, \mu)$$

- $\mathcal{F}_g(x, k_t^2, \mu)$ - (unintegrated) transverse momentum dependent PDFs
- the LO off-shell matrix elements $\overline{|\mathcal{M}_{g^* g^* \to Q\bar{Q}}|^2}$ 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

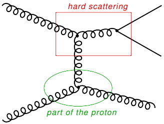
pair creation with gluon emission



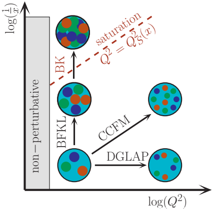
flavour excitation



gluon splitting



Unintegrated parton distribution functions (uPDFs)

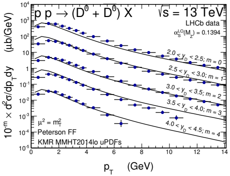


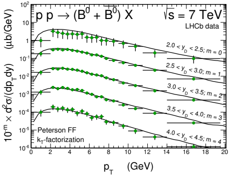
Most popular models:

- 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





k_T-factorization + KMR uPDF works very well for inclusive charm and bottom at the LHC (including correlation observables)

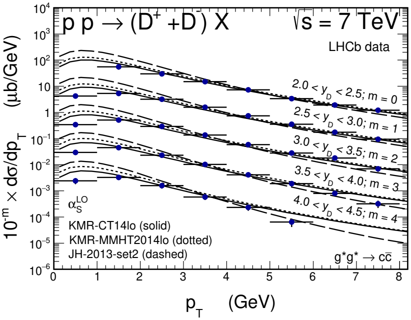
For comparison: JH2013 uPDF (Jung-Hautmann, CCFM fits to HERA precision data)
$k_t > \mu$ strongly suppressed (only soft extra emissions)

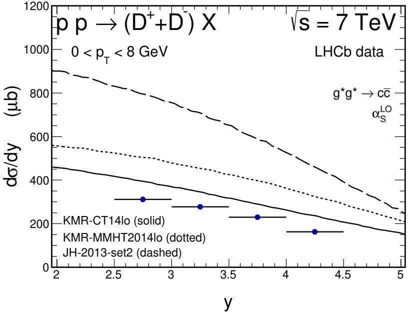
- a model that provides a good description of charm cross section beyond the single-particle spectra is crucial (especially in the region of small invariant masses)

Open charm meson — LHCb data

Theoretical computations:

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



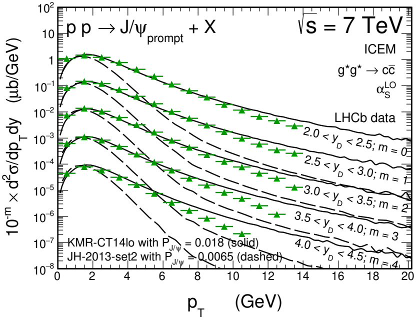


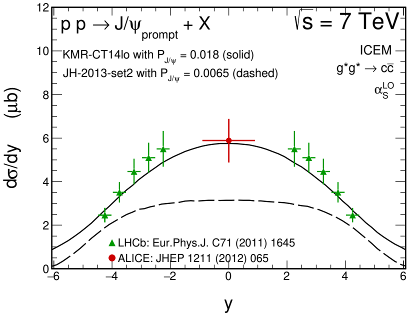
- some sensitivity to the choice of the collinear PDF in the KMR calculations but only at small transverse momenta (CT14lo vs. MMHT2014lo)
- the JH-2013-set2 uPDF noticeably overestimates the data points at small p_T's
- first two bins in p_T $\Rightarrow$ uncertain region $\Rightarrow$ crucial for the rapidity distribution
- the LHCb open charm data well described with the KMR uPDF

Prompt J/ψ meson LHCb data

Theoretical computations:

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



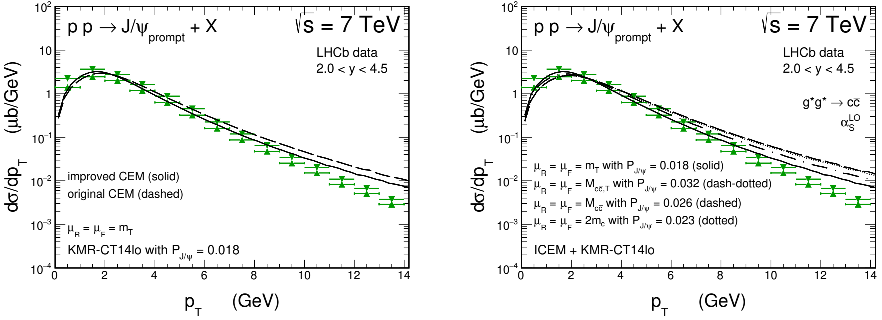


- the $P_{J/\psi}$ transition probability fitted to the J/ψ p_T-dsitribution
- p_T of J/ψ $\Rightarrow$ p_T of the $c\bar{c}$-pair $\Rightarrow$ very sensitive to the k_t-dependence of the uPDF
- very different results for the two uPDFs
- the JH-2013set2 uPDF completely fails for larger p_T's of the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

Prompt J/ψ meson — LHCb data

Theoretical computations:

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

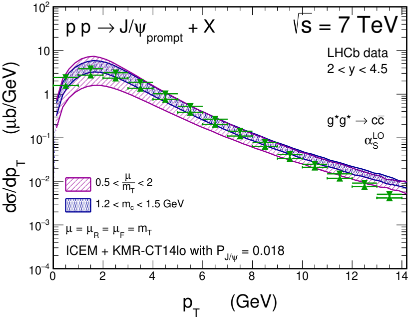


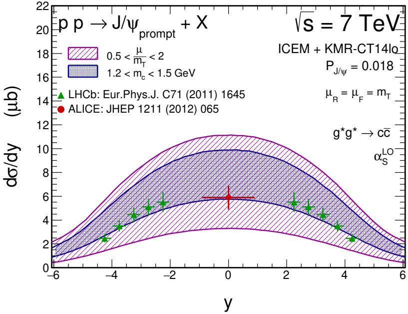
- the improved CEM (our default) leads to the p_T-slope more supported by the data
- the p_T-slope sensitive to the choice of the renormalizaton/factorization scale
  $\Rightarrow$ the default set $\mu^2 = \frac{m_{t1}^2 + m_{2t}^2}{2}$ is the most favourable one

Prompt J/ψ meson — LHCb data

Theoretical computations:

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



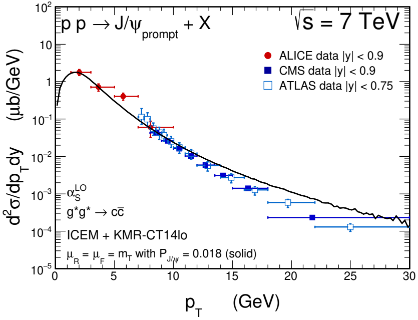


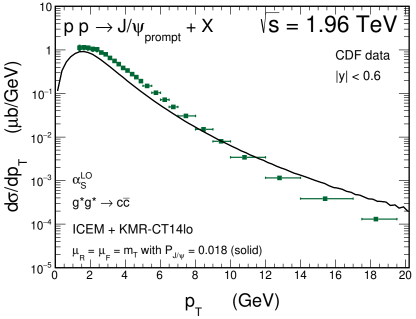
- the typical uncertainty bands:
  - charm quark mass $\Rightarrow 1.2 < m_c < 1.5$ GeV
  - scales $\Rightarrow 0.5 < \frac{\mu}{m_T} < 2$
- the LHCb data described in the whole considered p_T region with the KMR uPDF within the theoretical uncertainties

Prompt J/ψ meson — different $\sqrt{s}$ and y

Theoretical computations:

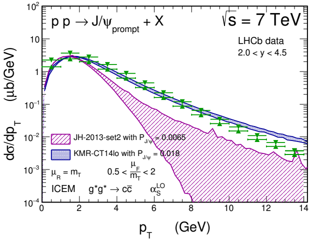
ICEM + k_T-factorization: $g^* g^* \to c\bar{c}$ + KMR uPDFs + $P_{J/\psi}$ for $c\bar{c} \to J/\psi$ transition





- 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

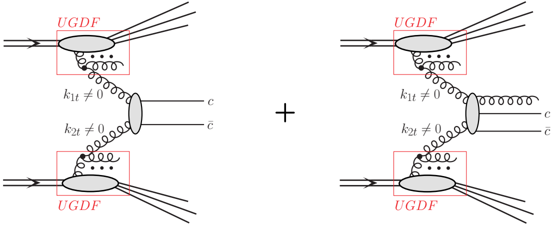
Prompt J/ψ meson CCFM uPDFs



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:



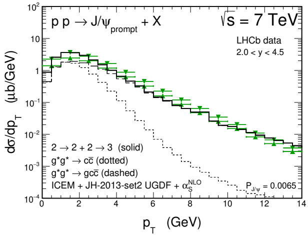
$\Rightarrow$ $(2 \to 2) + (2 \to 3)$
extra hard emission at the level of hard matrix elements

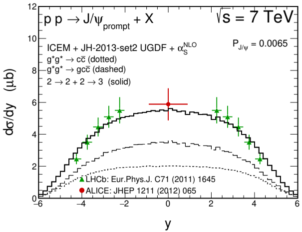
- we explicitly include the $g^* g^* \to g c\bar{c}$ mechanism at tree-level
- the calculations are done with the KaTie Monte Carlo generator

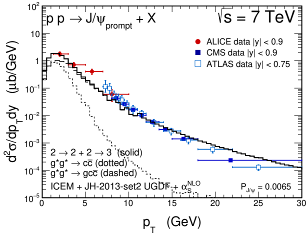
Prompt J/ψ meson — CCFM uPDFs

Theoretical computations:

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







- the description of the data of the same quality as for the KMR uPDF with the $2 \to 2$ calculations
- the $2 \to 3$ contribution is crucial for the calculations with the JH-2013 uPDF
- this conclusion may be important for the recent studies $\Rightarrow$ V.Cheung, and R.Vogt, Phys.Rev.D98, 114029 (2018)

Conclusions

We have discussed how to extend the improved color evaporation model for production of J/ψ meson to be used in the framework of k_T-factorization approach:

- rapidity and transverse momentum distributions of J/ψ 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 $g^* g^* \to g c\bar{c}$ with off-shell initial state partons has been included
- a reasonable description of the prompt J/ψ world data have been obtained

Thank You for attention!