Quarkonium production at the Tevatron and the LHC

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NRQCD factorization

The cross section for inclusive quarkonium production is expressed as a sum of products of short-distance coefficients and long-distance matrix elements:

\[ \sigma[Q] = \sum_n \hat{\sigma}_\Lambda[Q \bar{Q}(n)] \langle \mathcal{O}^Q(n) \rangle_\Lambda \]

**SD coefficients**

many recent works have been devoted to improving their accuracy, i.e. by computing higher-order corrections in \( \alpha_s \)

**LD matrix elements**

for the color-octet, no theoretical tool to constrain the LDME’s other than the power counting rules in \( v \)
Quarkonium production can also proceed via the decay of heavier hadrons (feed-down)

For \( J/\psi \) production at the Tevatron:

- **b-hadron decays:**
  - \( b \rightarrow J/\psi + X \) accounts for 10% of the inclusive production rate at \( p_T = 1.5 \) GeV (increasing to 45% at \( p_T = 20 \) GeV) \([CDF\ collaboration, 04]\)
  - \( TH: \ FONLL\ scheme \ [Cacciari, Greco, Nason],\ good\ agreement\ between\ th.\ and\ exp.\)

- **feed-down from charmonium states:**
  - \( \psi(2S) \rightarrow J/\psi \pi \pi \) and \( \chi_c \rightarrow J/\psi \gamma \) accounts for 35% of the prompt production rate \([CDF\ collaboration, 97]\)
  - \( TH:\ NRQCD\ calculation\ recently\ extended\ at\ NLO \ [Ma, Wang, Chao]\)

In this talk: focus on direct \( J/\psi \) or \( \psi(2S) \) hadroproduction
Th. status of direct J/ψ production at the Tevatron I: 9 years ago

- Color-octet dominance:
  - LO + fragmentation color-singlet channels undershoot the CDF data by more than an order of magnitude.
  - Color-octet contributions fitted to the data describe well the shape in \( p_T \), and the values of the CO LDME’s agree with the power counting rules in \( v \).
  - Similar situation for prompt \( \psi(2S) \) production
More recent results have challenged the previous picture. At large $p_T$, the production is dominated by $g^* \rightarrow ^3S_1^{[8]}$, which leads to transverse polarization in the c.m. helicity frame. This prediction may be affected by perturbative and non-perturbative corrections. NLO correction has little impact on the pheno very small correction to the polarization [also investigated in the frag. approx: Ma 95, Beneke & Rothstein 96, Braaten & Lee, 00].
Color-singlet channel: th. vs exp. (update)

• NLO correction:
  Campbell, Maltoni, Tramontano, 07
  Artoisenet, Lansberg, Maltoni, 07
  Gong, Wang, 08:

• huge enhancement at large $p_T$.
• large th. unc., mainly from variations of the scales $\rightarrow$ size of higher-order corrections?
  (see talk by J.-P. Lansberg)

• Fragmentation approach at large $p_T$:

  • leading $p_T$ component:
    $\leftrightarrow$ single-parton fragmentation
    [Braaten, Yuan, 93]

  • next-to-leading $p_T$ component
    $\leftrightarrow$ charm-quark pair fragmentation
    [Kang, Qiu, Sterman, in preparation]

New channels at $\alpha_s^4$:

$pp \rightarrow ^3S_1^{[1]} + gg$
What can we learn from the first LHC data?

- **observable:** $p_T$ spectrum associated with $J/\psi$ production
  - $\sigma^{tot}$: large th. uncertainties since dominated by low $p_T$
  - polarization: measurements require sample with large statistics
- **calculation scheme:** NRQCD at leading order in $\alpha_s$
  - QCD correction to color-octet channels have negligible impact on the pheno (at least for the S-wave) [Gong, Wang, 08]
  - QCD corrections to the color-singlet yield might have a large impact on the phenomenology, but current th. uncertainties are very large

This scheme provides a test of the color-octet dominance picture for a different collision energy and over a wider $p_T$ range
Additional ingredient:

* resummation of \( [\alpha_s \log (m_c/p_T)]^n \) to all order in \( \alpha_s \) by solving the DGLAP equation for the evolution fragmentation function \( d_{g\rightarrow c\bar{c}8}(3S_1)(z, \mu) \)

based on a calculation by Maltoni & Petrelli

* The short-distance coefficient for the color-octet \( 3S_1 \) is expressed as

\[
d\hat{\sigma}_8(3S_1) = d\hat{\sigma}_8^{FO}(3S_1) \frac{d\hat{\sigma}_{g\rightarrow c\bar{c}8}(3S_1)(\mu_{fr} = M_T)}{d\hat{\sigma}_{g\rightarrow c\bar{c}8}(3S_1)(\mu_{fr} = 2m_c)}
\]

includes both the evolution and the effects from the finite mass of the charm quark
Impact of the evolution

* decrease of the differential rate by a factor 2 at $p_T=25$ GeV

* large uncertainties from the variations of $\mu_{fr}$
Theoretical uncertainties

- **scales:** 
  \[ M_T / 2 < \mu_r, \mu_f, \mu_{fr} < 2M_T \]

- **charm-quark mass:** 
  \[ m_c = 1.5 \pm 0.1 \text{ GeV} \]

→ results in a large uncertainty on the normalization of the NRQCD short-distance coefficients

We repeat the fit to the CDF data for each set of input parameters (any change in the normalization of the SD coefficients is reabsorbed into the color-octet LDME’s)
Predicted $p_T$ spectrum at the LHC

- th. & exp. uncertainties combined in quadrature

\[ \frac{d\sigma}{dp_T} (\text{nb}/\text{GeV}) \]

$|y|<2.4$

- factor $\approx 2$ of uncertainty in the normalization of the production rate

- analogous prediction for the forward region

- the $p_T$ spectrum can be effectively described by a LO Monte Carlo generator such as Pythia or MadOnia with an appropriate choice of the LDME’s
I presented a prediction for direct $J/\psi$ production rate at the LHC. Comparison with the data would provide a test of the color-octet dominance. The same approach can be followed for the prompt production of $\psi(2S)$.