Complete NRQCD prediction for prompt double J/ψ hadroproduction

Zhiguo He

II. Institut für Theoretische Physik, Universität Hamburg

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Outline

1. Background
   - "J/ψ polarization puzzle"
   - Double J/ψ production
2. LO NRQCD Prediction
   - Theoretical framework
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3. Summary

Single J/ψ polarization puzzle

- Since the J/ψ meson was discovered in 1974, it has been an ideal laboratory to probe both perturbative and non-perturbative aspects of QCD because of its non-relativistic nature.
- After 20 years of the introduction of the NRQCD factorization formalism by Bodwin,Bratten, and Lapage in 1995, "the J/ψ polarization puzzle" has not been resolved yet.
- By far, the short-distance coefficients (SDCs) @ QCD NLO were obtained by three groups independently. However, the theoretical describtions depend very much on the chosen long-distance matrix elements (LDMEs).
- All these LDME sets are challenged by the η_c production data.
- See Mathias Butenschoen's talk in detail.

Double J/ψ production from theoretical point of view

- In double J/ψ production, the hadronization of charm quark pair takes twice. Therefore, it provides an particularly sensitive test on NRQCD hypothesis.
- The double J/ψ production also provides an additional crucial constrain on the J/ψ LDMEs.
- It is believed that double J/ψ can be produced also through double parton scattering (DPS) processes, which helps to extract the parameters in DPS (Kom, et al. 2011, Baranov, et al. 2013).

Theoretical study of double quarkonium production I

- Studying the double J/ψ production was first proposed by Barger, et al. in 1996, in which the $2(c\bar{c}(^3S_1^{[8]}))$ CO contribution (CO^*) was studied.
- Later, it is found that the CS $2(c\bar{c}(^3S_1^{[1]}))$ channel contributes (CS^*)predominately to the hadroproduction rate (Qiao 2002).
- Practical calculation showed that the LO CO^* contribution takes over the LO CS^* contribution at high p_t, for example at $p_t = 16$ GeV at 7 TeV LHC (Ko, et al. 2011).
- NLO QCD corrections to the CS^* channel are obtained by Sun et al.(arXiv:1404.4042).

Theoretical study of double quarkonium production II

- The relativistic corrections to both the CS* and CO* channels have also been studied (Li, et al. 2013).
- Production of double heavy quarkonia other than double J/ψ are also studied, such as, double η_c (Li, ea al. 2009), $J/\psi + \Upsilon$ (Ko, et al. 2011), $J/\psi + \eta_c + X$ (Lansberg, et al. 2013)
- Investigation of SPS+DPS contribution to double quarkonium production @LHC and after@LHC has also been performed (Lansberg et al. 2015).
- The double quarkonium production also is studied in the framework of k_t factorization (Baranov,et al. 2015, see the talk in details).
- and more ....

Double J/ψ production experimental measurements

- Double J/ψ is first measured by LHCb Collaboration at 7 TeV in the rapidity range of $2.0 < y^{J/\psi} < 4.5$ and $p_T^{J/\psi} < 10\text{GeV}$ for each J/ψ (PLB 707,52).
- It is also measured by D0 Collaboration at 1.96 TeV with $p_T^{J/\psi} > 4\text{GeV}$ and $|\eta^{J/\psi}| < 2.0$, where the single parton scatting (SPS) and DPS contributions are discriminated (PRD90, 111101).
- At LHC, the CMS Collaboration measure double J/ψ production in details with cut condition (JHEP 09 (2014) 094):

$$\begin{aligned} & p_T^{J/\psi} > 4.5 \text{ GeV} && \text{if} \quad 1.43 < y^{J/\psi} < 2.2, \\ & 4.5 \text{ GeV} < p_T^{J/\psi} < 6.5 \text{ GeV} && \text{if} \quad 1.2 < y^{J/\psi} < 1.43, \\ & p_T^{J/\psi} > 6.5 \text{ GeV} && \text{if} \quad y^{J/\psi} < 1.2. \end{aligned} \tag{1}$$

- Very recently the D0 Collaboration measure $J/\psi + \Upsilon$ production at Tevatron for the first time (PRL116, 082002).

NRQCD factorization formalism

NRQCD factorization formula for prompt double J/ψ production

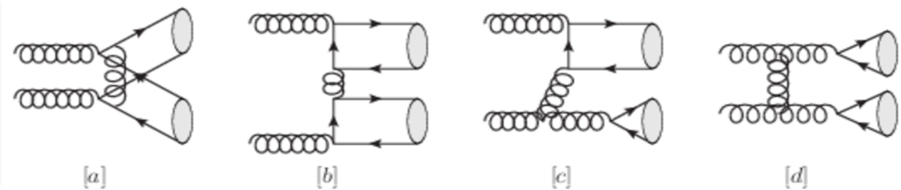
$$d\sigma(AB \to 2J/\psi + X) = \sum_{i,j,m,n,H_1,H_2} \int dx_1 dx_2$$
$$\times f_{i/A}(x_1) f_{j/B}(x_2) d\hat{\sigma}(ij \to c\bar{c}(m) c\bar{c}(n) + X)$$
$$\times \langle \mathcal{O}^{H_1}(m) \rangle \mathrm{Br}(H_1 \to J/\psi + X) \times \langle \mathcal{O}^{H_2}(n) \rangle \mathrm{Br}(H_2 \to J/\psi + X), (2)$$

At LO, $J/\psi + \chi_c$ sub-processes are forbidden because of the charge conjugation conservation, so there are in all $7 \times 8/2 - 3 = 25$ sub-processes needed to be calculated.

Note

The $q\bar{q}$ process is highly supperssed, so we only focus on the gluon-gluon fusion process.

The topological properties of the Feynman diagrams



4-type of Feynman diagrams:

- a) Non-fragmentation type-I
- b) Non-fragmentation type-II
- c) Single fragmentation like
- d) Double fragmentation like

Power counting for each channel at large p_T

According to the scaling $d\sigma/dp_T^2 \propto 1/p_T^N$ and the topological properties of the Feynman diagrams, the partonic sub-processes can also be divided into 4 categories:

1. NNLP-I, with $N = 8$, including $m = {}^3S_1^{[1]}$ and $n = {}^3S_1^{[1,8]}, {}^1S_0^{[8]}, {}^3P_J^{[8]}$;
2. NNLP-II, with $N = 8$, too, including $m, n = {}^1S_0^{[8]}, {}^3P_J^{[8]}, {}^3P_J^{[1]}$;
3. NLP, with $N = 6$, including $m = {}^3S_1^{[8]}$ and $n = {}^1S_0^{[8]}, {}^3P_J^{[8]}, {}^3P_J^{[1]}$; and
4. LP, with $N = 4$, including $m = n = {}^3S_1^{[8]}$.

Note

While the NNLP-I and NNPL-II subprocesses exhibit the same p_T scaling, they differ by the topologies of the respective Feynman diagrams. In the latter case, these are the diffraction-like ones as in Fig. (b), which allow for large values of $|\Delta y|$ and thus for an enhancement of the cross section at large values of J/ψ pair invariant mass $m_{J/\psi J/\psi}$.

The p_t and v^2 behaviors for each channel

- Together with the velocity scaling rule of NRQCD LDMEs and assuming that the branch function is also of v^2 order, we can obtain the p_T and v^2 scaling of $d\sigma/dp_T^2$ for the relevant pairings (m,n) of $c\bar{c}$ Fock states of each $gg \to c\bar{c}(m)c\bar{c}(n)$ channel.

(m,n)	${}^3S_1^{[1]}$	${}^3S_1^{[8]}$	${}^1S_0^{[8]}$	${}^3P_J^{[8]}$	${}^3P_J^{[1]}$
${}^3S_1^{[1]}$	$1/p_T^8$	v^4/p_T^8	v^3/p_T^8	v^4/p_T^8	0
${}^3S_1^{[8]}$	—	v^8/p_T^4	v^7/p_T^6	v^8/p_T^6	v^8/p_T^6
${}^1S_0^{[8]}$	—	—	v^6/p_T^8	v^7/p_T^8	v^7/p_T^8
${}^3P_J^{[8]}$	—	—	—	v^8/p_T^8	v^8/p_T^8
${}^3P_J^{[1]}$	—	—	—	—	v^8/p_T^8

The numerical inputs

Corresponding LDMEs in units of GeV^3 (Braaten, et al. 2000)

$\mathcal{O}^{J/\psi}({}^3S_1^{[1]})$=1.16, $\mathcal{O}^{J/\psi}({}^3S_1^{[8]})$=3.9 $\times$ 10^{-3}, $M_{3.4}^{J/\psi}({}^1S_0^{[8]})$=6.6 $\times$ 10^{-2}, $\mathcal{O}^{\psi'}({}^3S_1^{[1]})$=0.758, $\mathcal{O}^{\psi'}({}^3S_1^{[8]})$=3.7 $\times$ 10^{-3}, $M_{3.5}^{\psi'}({}^3S_1^{[1]})$=7.8 $\times$ 10^{-3}, $\mathcal{O}^{\chi_{c0}}({}^3P_0^{[1]})/m_c^2$=4.77 $\times$ 10^{-2}, and $\mathcal{O}^{\chi_{c0}}({}^3S_1^{[8]})$=1.9 $\times$ 10^{-3}.

PDF, α_s and scale settings

One-Loop running of α_s^4 with Λ^4=192 MeV, and CTEQ5L pdf.

$\mu_r = \mu_f = m_T = \sqrt{(4m_c)^2 + p_T^2}$.

Branch functions from higher states to J/ψ (PDG2012)

$\mathrm{Br}(\chi_{c1} \to J/\psi\gamma) = 33.9\%$, $\mathrm{Br}(\chi_{c2} \to J/\psi\gamma) = 19.2\%$, and $\mathrm{Br}(\psi' \to J/\psi + X) = 60.9\%$.

General features of numerical results

- Among the NNLP-I subprocesses, compared to the CS^* no kinematic enhancements are found in other channels, so the other channels are all suppressed at least by $\mathcal{O}(v^3)$.
- Although the p_T scalings of the NNLP-II subprocesses is the same as the NNLP-I ones, the SDCs of these channels can be 50–200 times larger than that of the CS^*.
- The contribution of the NLP subprocesses can also excceed that of the CS^* channel.
- The CS^* channel contributes predominately in low invariant mass region, when $m_{J/\psi J/\psi}$ is much larger than 2 $m_{J/\psi}$, the contribution of the NNLP-II, NLP,LP subprocesses can be orders of magnitude larger than that of the CS^* channel.
- From the identical-boson symmetry and $J/\psi + \chi_{cJ}$ suppression, the relative importance of the χ_{cJ} ($\psi(2S)$) feed-down contribution is reduced (enhanced) compared to single J/ψ production case.

NRQCD predictions meet LHCb data I

The measured cross section

$$\sigma_{\rm tot}^{\rm LHCb} = (5.1 \pm 1.0 \pm 1.1)\ \text{nb}. \qquad (3)$$

LO CS*+CO* prediction

$$\sigma_{\rm tot}^{*} = 12.2^{+4.8}_{-3.8}\ \text{nb}. \qquad (4)$$

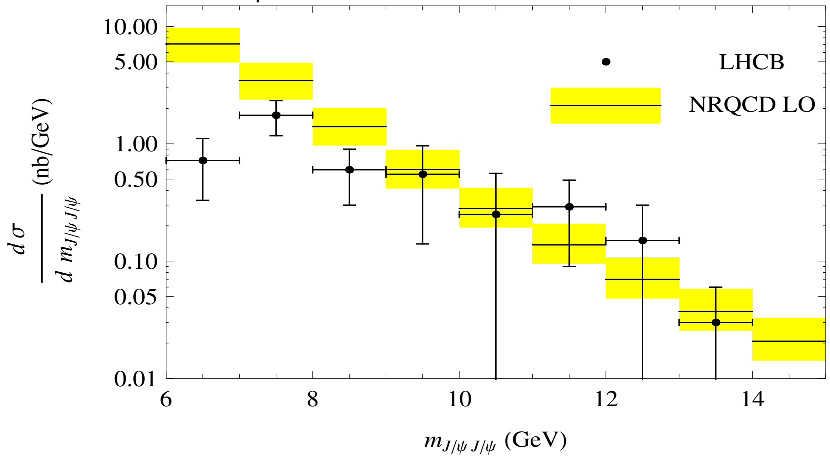
Complete LO prediction

$$\sigma_{\rm tot} = 13.2^{+5.2}_{-4.1}\ \text{nb}, \qquad (5)$$

which is about 2.6 times larger than the LHCb result.

NRQCD predictions meet LHCb data II

- The invariant mass spectrum:



NRQCD prediction meets D0 data

The measured cross section

$$\sigma^{\rm D0}_{\rm SPS} = (70 \pm 6 \pm 22)\ {\rm fb}, \quad \sigma^{\rm D0}_{\rm DPS} = (59 \pm 6 \pm 22)\ {\rm fb}. \tag{6}$$

LO CS* prediction

$$\sigma^*_{\rm tot} = 51.9\ \text{fb}. \tag{7}$$

- Complete LO result can enhance that of the LO CS* by around 28%, which yields a nice agreement between NRQCD and D0 measurement.

NRQCD preditions meet CMS measurements I

The measured cross section

$$\sigma_{\text{tot}}^{\text{CMS}} = (1.49 \pm 0.07 \pm 0.13) \text{ nb.} \quad (8)$$

LO CS*+CO* prediction

$$\sigma_{\text{tot}}^{*} = 0.10^{+0.05}_{-0.03} \text{ nb.} \quad (9)$$

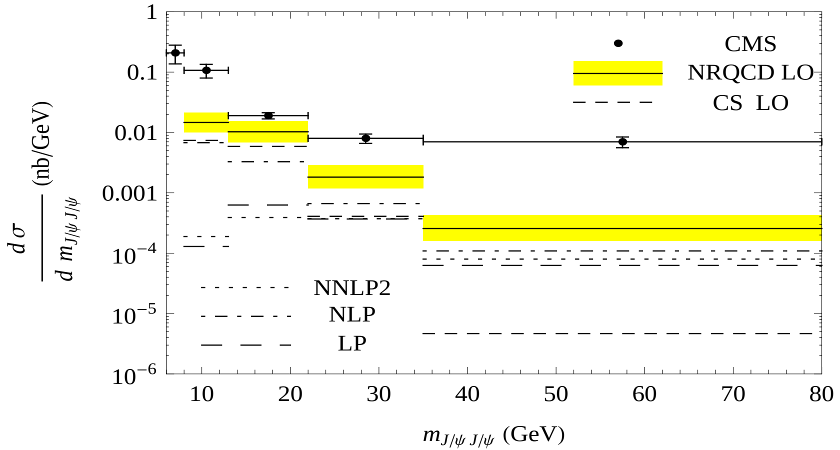
Complete LO prediction

$$\sigma_{\text{tot}} = 0.15^{+0.08}_{-0.05} \text{ nb.} \quad (10)$$

NLO CS* prediction (arXiv:1404.4042)

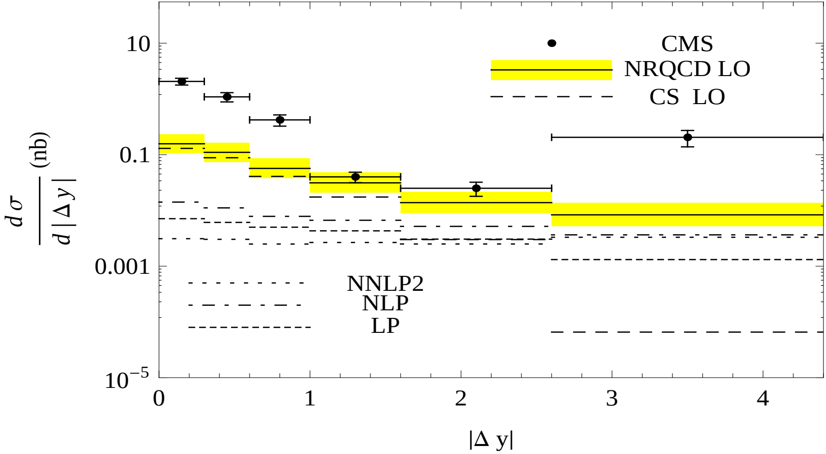
$$\sigma_{\text{CS}}^{*} = 0.98 \pm 0.16 \text{ nb.} \quad (11)$$

- The invariant mass spectrum:



NRQCD preditions meet CMS measurements III

- The $|\Delta y|$ distribution ($m_{J/\psi J/\psi} = 2\sqrt{4m_c^2 + p_T^2}Cosh(\Delta y)$):



In Summary

- The double J/ψ hadroproduction is first complete studied within NRQCD factorization formulism, which include all the possible combinations of CS and CO channels and the contribution of χ_{cJ} and $\psi(2S)$ mesons feed-down as well.
- The NRQCD prediction agrees well with the D0 data.
- The NRQCD prediction is about 2.6 times larger than the LHCb measurements, where the difference comes from the threshold region.
- There are orders of magnitude discremte between NRQCD predictions and CMS measurements in large invariant mass and $|\Delta y|$ bins.

Thank you !