Double prompt J/ψ production at hadron collider

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Frontier of QCD: Opportunities and Challenges
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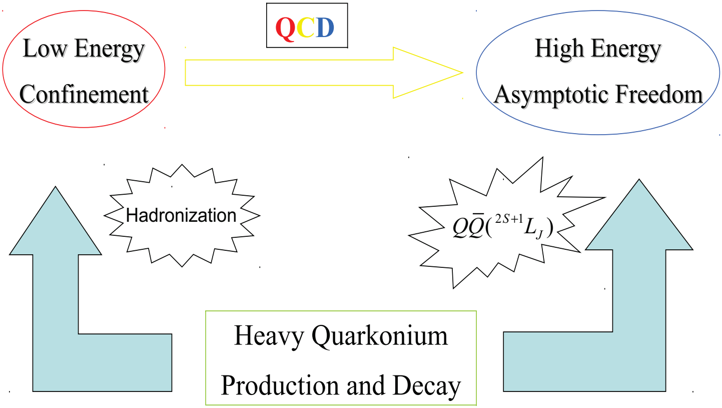
Outline

What is heavy quarkonium?

- Heavy quarkonium is one of the simplest QCD bound state constituted by heavy quark pair $Q\bar{Q}$.



J/ψ and Υ are ideal candidates for their large leptonic branching functions!

Non-relativistic QCD factorization

- Besides Λ_{QCD}, there are 3 relevant energy scales, which are well separated, $m_Q v^2 \ll m_Q v \ll m_Q$.
- NRQCD factorization formula:

$$\sigma(A+B \to J/\psi + X) = \sum_n \hat{\sigma}(A+B \to c\bar{c}(n) + X) \times \langle \mathcal{O}(n) \rangle^{J/\psi},$$

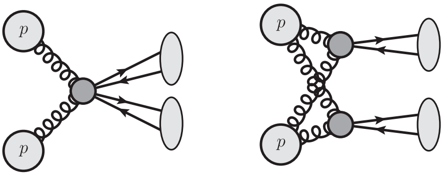
where $\hat{\sigma}$ is the short-distance coefficients and $\langle \mathcal{O}(n) \rangle^{J/\psi}$ is the long-distance matrix element.

The challenge of NRQCD:

1. The LDMEs for J/ψ production have not yet been pinned down.
2. For J/ψ production in e^+e^- annihilation, and η_c meson hadroproductin, the color singlet model itself can well describe the experimental measurements.

Why double J/ψ production

- In double J/ψ production, the hadronization of charm quark pair takes twice. Therefore, it provides an particularly sensitive test on NRQCD hypothesis and also an additional crucial constraint on its LDMEs.
- It is believed that double J/ψ can be produced also through double parton scattering (DPS) mechanism, which can help to extract the parameters in DPS (Kom, et al. 2011, Baranov, et al. 2013).
- Schematic representation of SPS (left) and DPS (right) to 2 prompt J/ψ hadroproduction:



Theoretical study of double J/ψ hadroproduction

- The double J/ψ production was first proposed by Barger, et al. in 1996, in which the $2(c\bar{c}(^3S_1^{[8]}))$ contribution was studied.
- Later, it is found that the CS $2(c\bar{c}(^3S_1^{[1]}))$ channel contributes predominately to the total cross section. (Qiao 2002)
- The complete LO NRQCD calculation including χ_c feed down were obtained by He and Kniehl in 2015.
- In 2013, Li, et al. calculated the relativistic corrections to $2(c\bar{c}(^3S_1^{[1]}))$ and $2(c\bar{c}(^3S_1^{[8]}))$ channels.
- The next-to leading order QCD corrections to the $2(c\bar{c}(^3S_1^{[1]}))$ channel is obtained by Sun et al. in 2016.
- Investigation of SPS+DPS contribution to double quarkonium production @LHC was also performed. (Lansberg et al. 2015)
- And more ...

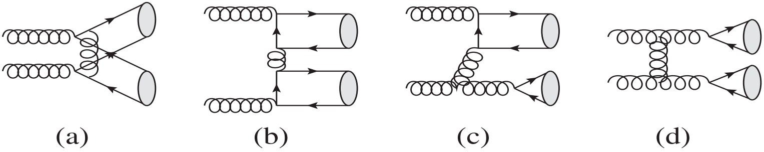
Experimental measurements for double J/ψ hadroproduction

- 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 $p_T^{J/\psi} < 10$GeV updated recently at 13 TeV LHC (LHCb 2012,2017).
- It is also measured by D0 Collaboration at 1.96 TeV with $p_T^{J/\psi} > 4$GeV and $|\eta^{J/\psi}| < 2.0$, where the single parton scatting (SPS) and DPS contributions are discriminated (D0 2014).
- The CMS Collaboration measure double J/ψ production in details with cut condition shown in page 10 of this talk (CMS 2014).
- The double J/ψ production in central rapidity range $|y^{J/\psi}| < 2.1$ with higher cut on J/ψ p_T ($p_T^{J/\psi} > 8.5$GeV) was measured by ATLAS Collaboration at 8 TeV LHC (ATLAS 2017).

- NRQCD factorization formula for 2 prompt J/ψ production:

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

- 4 different topological Feynman diagrams: a) Non-fragmentation type-I,b) Non-fragmentation type-II ,c) Single fragmentation like d) Double fragmentation like

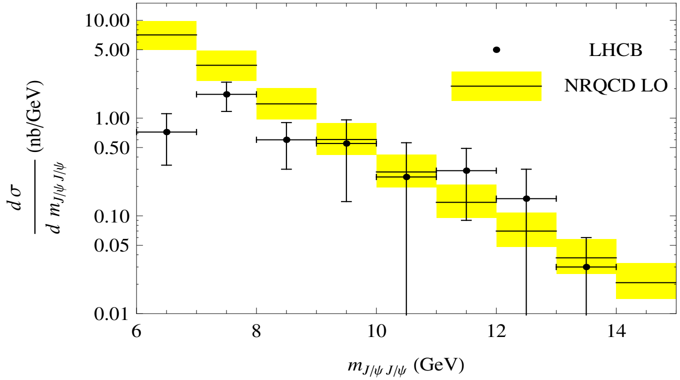


NRQCD predictions meet LHCb measurements

- Total cross section:

$$\sigma^{\mathrm{LHCb}} = (5.1 \pm 1.0 \pm 1.1)\ \mathrm{nb}, \sigma^{\mathrm{LO}}_{\mathrm{NRQCD}} = 13.2^{+5.2}_{-4.1}\ \text{nb}.$$

- The invariant mass spectrum:



- Total cross section for D0 measurement:

$$\sigma_{\rm SPS}^{\rm D0} = (70 \pm 6 \pm 22)\ {\rm fb}, \sigma_{\rm DPS}^{\rm D0} = (59 \pm 6 \pm 22)\ {\rm fb},$$
$$\sigma_{\rm NRQCD}^{\rm LO} = 49.4^{+34.1}_{-19.6}\ {\rm fb}.$$

- The CMS kinematic cut condition:

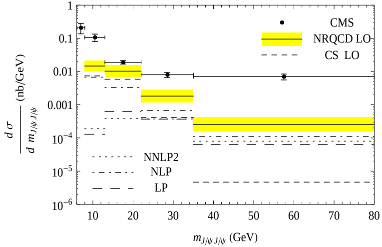
$$\begin{aligned} &p_T^{J/\psi} > 4.5\ {\rm GeV} && \text{if} \quad 1.43 < |y^{J/\psi}| < 2.2, \\ &4.5\ {\rm GeV} < p_T^{J/\psi} < 6.5\ {\rm GeV} && \text{if} \quad 1.2 < |y^{J/\psi}| < 1.43, \\ &p_T^{J/\psi} > 6.5\ {\rm GeV} && \text{if} \quad |y^{J/\psi}| < 1.2. \end{aligned}$$

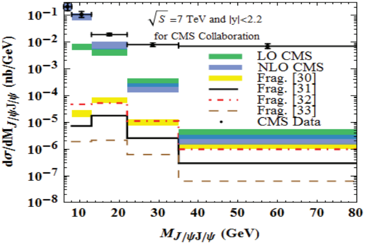
- Total cross section for CMS measurement:

$$\sigma^{\rm CMS} = (1.49 \pm 0.07 \pm 0.13)\ {\rm nb}$$
$$\sigma_{\rm NRQCD}^{\rm LO} = 0.15^{+0.08}_{-0.05}\ {\rm nb}, \sigma_{\rm CS}^{\rm NLO} = 0.98 \pm 0.16\ {\rm nb}.$$

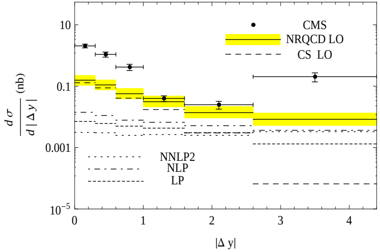
NRQCD preditions meet CMS measurements II

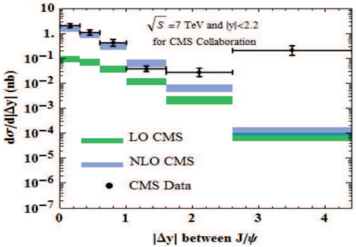
- The $m_{\psi\psi}$ spectrum from LO NRQCD (left) and NLO CS (right):





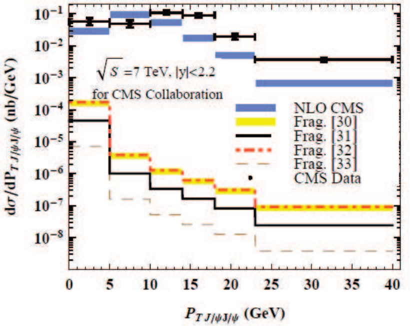
- The $|\Delta Y|$ spectrum from LO NRQCD (left) and NLO CS (right):





Why higher order corrections are important

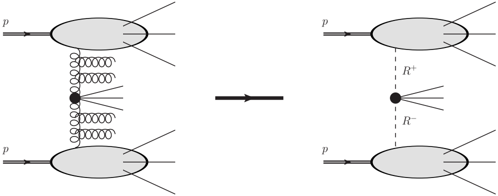
- The $p_T^{\psi\psi}$ distribution of CMS measurements indicates the predominant contribution comes from the $2 \to 3$ processes in CPM calculation.
- $p_T^{\psi\psi}$ spectrum:



However, the complete NLO QCD corrections are much more complicated, in particular, we found for 2 P-wave case un-canceled infrared divergence will violate conventional NRQCD factorization. (He et al. 2018)

The parton Reggeization approach

- These difficulties can be partially overcome by the k_T factorization, however, the formalism of old-k_T factorization is not gauge invariant.
- In fact, the characteristic scale $\mu \approx \sqrt{(4m_c)^2 + (p_T^{\psi\psi})^2}$ satisfies $\Lambda_{QCD} \ll \mu \ll \sqrt{S}$ implying accessing the high-energy Regge limit.
- In such regmime, a gauge invariant result can be obtained through Reggeization of the amplitude, in which NLO QCD corrections is embodied by the $\mathbf{p}_T$ un-integrated PDF.
- shematic representation of the parton Reggeization:



Topological properties of the Feynman diagrams

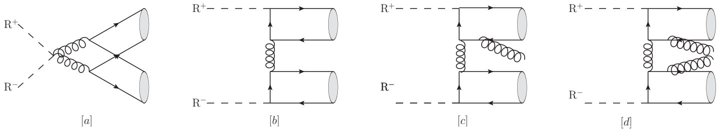


FIG. 1: Typical Feynman diagrams for $R^+R^- \to c\bar{c}(m)c\bar{c}(n)$ (a) non-t-channel gluon exchange type, (b) t-channel gluon exchange type at α_s LO, (c) t-channel gluon exchange type at α_s NLO, (d) t-channel gluon exchange type at α_s NNLO.

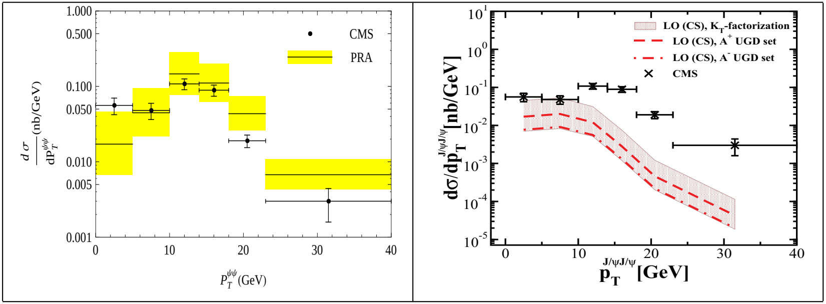
3-categories of partonic subprocesses:

1. LT, including $m = {}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[1,8]}$ and $n = {}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[1,8]}$.
2. NLT, including $m = {}^3S_1^{[1]}$ and $n = {}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[1,8]}$.
3. NNLT, including $m = {}^3S_1^{[1]}$ and $n = {}^3S_1^{[1]}$.

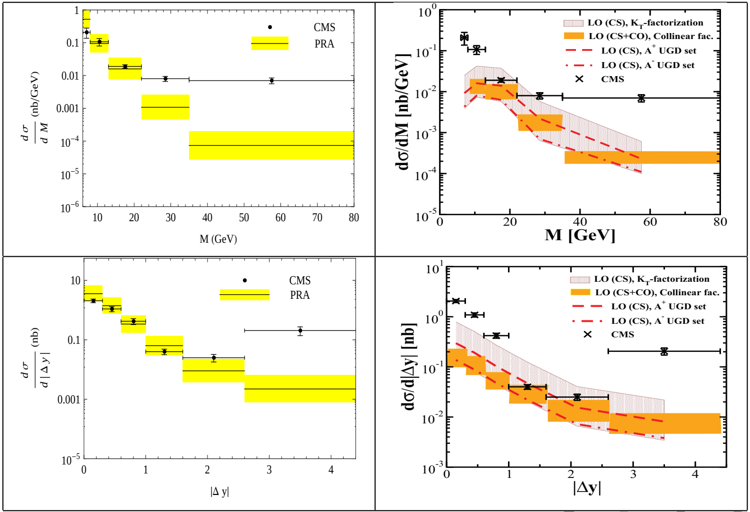
- Total cross section:

$$\sigma^{\mathrm{CMS}} = (1.49 \pm 0.07 \pm 0.13)\,\mathrm{nb},\ \sigma^{\mathrm{PRA}}_{\mathrm{LO}} = 1.68^{+1.32}_{-0.78}\,\mathrm{nb},$$
$$\sigma^{\mathrm{CPM}}_{\mathrm{LO}} = 0.15^{+0.08}_{-0.05}\,\mathrm{nb},\ \sigma^{\mathrm{CPM}}_{\mathrm{NLO(CS)}} = 0.98 \pm 0.16\,\mathrm{nb}.$$

- The $p_T^{\psi\psi}$ distribution predicted by PRA and k_T factorization:



- The invariant mass(up) and $|\Delta y|$ distribution (up) predicted by PRA and k_T factorization:



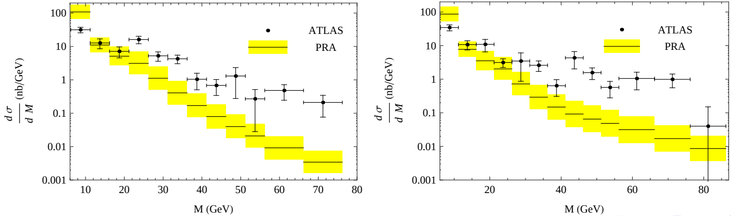
Comparison with ATLAS data I

- ATLAS further separated the rapidity region of the sub-leading J/ψ into $|y(J/\psi_2)| < 1.05$ and $1.05 < |y(J/\psi_2)| < 2.1$.
- Total cross section:

$$\sigma(pp \to J/\psi J/\psi + X) = \begin{cases} 82.2 \pm 8.3\,(\text{stat}) \pm 6.3\,(\text{syst}) \pm 0.9\,(\text{BF}) \pm 1.6\,(\text{lumi})\ \text{pb}, & \text{for } |y| < 1.05, \\ 78.3 \pm 9.2\,(\text{stat}) \pm 6.6\,(\text{syst}) \pm 0.9\,(\text{BF}) \pm 1.5\,(\text{lumi})\ \text{pb}, & \text{for } 1.05 \le |y| < 2.1. \end{cases}$$

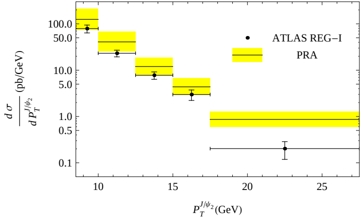
$$\sigma^{\text{PRA}}_{\text{ATLAS}} = \begin{cases} 133.6^{+89.6}_{-52.2}\ \text{pb, for} |y(J/\psi_2)| < 1.05 \\ 105.2^{+73.8}_{-41.6}\ \text{pb, for} 1.05 < |y(J/\psi_2)| < 2.1 \end{cases}$$

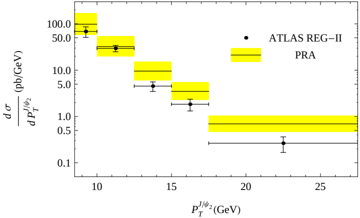
- The invariant mass $M = m_{\psi\psi}$ distribution:



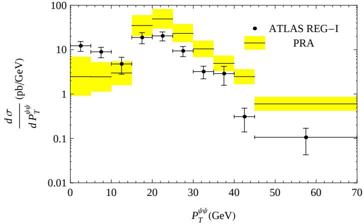
Comparison with ATLAS data II

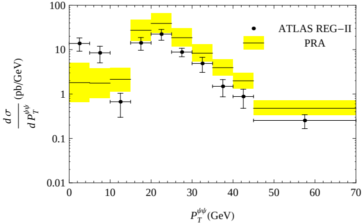
- The $p_T(J/\psi_2)$ distribution:





- The $p_T^{J/\psi J/\psi}$ distribution:

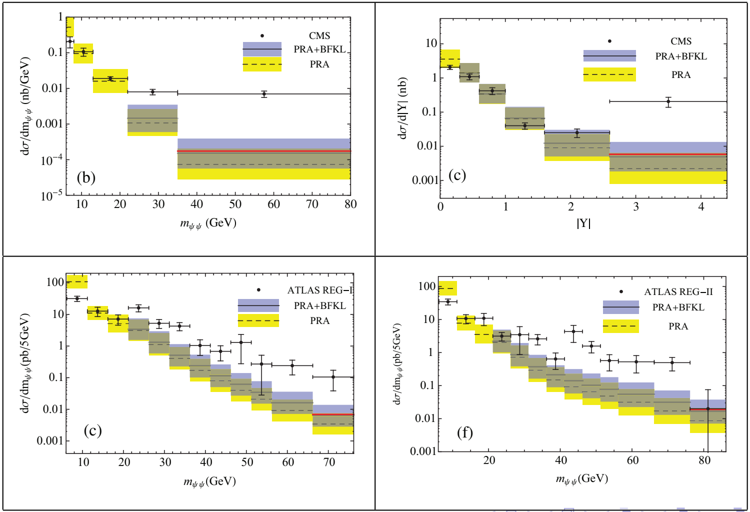




Higher order corrections

- In LO CPM calculation, $m_{\psi\psi} = 2\sqrt{4m_c^2 + (p_T^{J/\psi})^2}\cosh(|\Delta y|/2)$, and we found in LO PRA calculation, the $m_{\psi\psi}$ distribution at large $m_{\psi\psi}$ and $|Y|$ distribution at large $|Y|$ are strongly correlated.
- In such regions, the LT contribution is predominant, which is about 90% in the last $|Y|$ bin of CMS measurements.
- t channel gluon exchange sub-process will receive large logarithmic corrections of type $(\alpha_s \ln|s/t|)^n$, which can be resummed by BFKL resummation formalism.
- For the NLT sub-processes, the α_s suppression may be compensated by the CS LDME.

- The $m_{\psi\psi}$ and $|Y|$ distributions after BFKL resummation and partial NLO (NLO*) QCD corrections to NLT (red solid line):



Summary and outlook

- Firstly, the complete NRQCD predictions to double prompt J/ψ hadroproduction is calculated, and the effect due to t-channel gluon exchange is found to be huge.
- Secondly, we implement PRA and BFKL resummation to take into account higher order QCD effect.
- The experimental data obtained by CMS and ATLAS Collaborations can all be well described except for large $m_{\psi\psi}$ and $|Y|$ region.
- We think the σ_{eff} in DPS can be extracted only after all possible large SPS contribution is included.

Thank you!

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

$\mathcal{O}^{J/\psi}({}^3S_1^{[1]})$=1.16, $\mathcal{O}^{J/\psi}({}^3S_1^{[8]})$=$3.9\times10^{-3}$, $M_{3.4}^{J/\psi}({}^1S_0^{[8]})$=$6.6\times10^{-2}$,
$\mathcal{O}^{\psi'}({}^3S_1^{[1]})$=0.758, $\mathcal{O}^{\psi'}({}^3S_1^{[8]})$=$3.7\times10^{-3}$, $M_{3.5}^{\psi'}({}^3S_1^{[1]})$=$7.8\times10^{-3}$,
$\mathcal{O}^{\chi_{c0}}({}^3P_0^{[1]})/m_c^2$=$4.77\times10^{-2}$, and $\mathcal{O}^{\chi_{c0}}({}^3S_1^{[8]})$=$1.9\times10^{-3}$.

PDF, α_s and scale settings

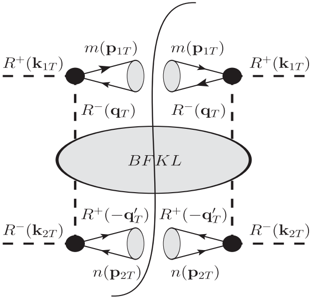
One-Loop running of α_s^4 with Λ^4=192 MeV, and CTEQ5L pdf.
$\mu_r=\mu_f=m_T=\sqrt{(4m_c)^2+p_T^2}$.

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
$\mathrm{Br}(\psi'\to J/\psi+X)=60.9\%$.

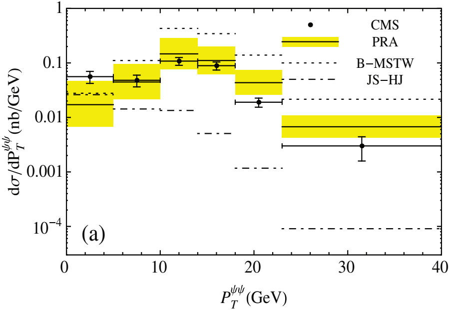
BFKL resummation II

- The above formula can be understood via the diagram:



Constraint on unPDFs:

- The unPDF set can also be generated from other schemes, like Blümlein and Jung-Salam schemes.



Only the unPDF set generated by KMR scheme can describe the data!