SPS contribution to double J/ψ hadroproduction

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Quarkonia as Tools
12.01.2023, Aussois,France

Outline

Factorization of heavy quarkonium production

- The general factorization formula:

$$\sigma_{(A+B\to quarkonium+X)} = \sum_n \int \sigma_{A+B\to(Q\bar{Q})_n+X} \times f[(Q\bar{Q})_n \to quarkonium]$$

- The models in market include color-singlet model (CSM), color evaporation model (CEM), and nonrelativistic QCD (NRQCD) factorization.

The challenges to NRQCD:

1. The long-standing J/ψ polarization puzzle.
2. The universality of the NRQCD LDMEs for J/ψ production up to QCD NLO.
3. The success of CSM to account for J/ψ production in e^+e^- annihilation, and η_c meson hadroproduction at LHC.

What can quarkonium pair hadroproduction tell us?

1. Kinematically, it can be viewed as a gluon-gluon fusion type "Drell-Yan" process.
2. To test the NRQCD factorization or other models, and to provide crucial constraint on the corresponding non-perturbative parameters. (Barger et al. 1996)
3. Help to improve the NRQCD factorization formula for double $P-$wave production. (He et al. 2018)
4. To study the transverse momentum dependent parton distribution function. (Lansberg et al. 2018)
5. To extract σ_{eff} for DPS process. (Kom, et al. 2011)

Other benefits

- To help to understand the new fully heavy tetraquark states ($Q\bar{Q}Q\bar{Q}$). (LHCb Collaboration 2020)

Experimental status on double J/ψ hadroproduction

Table: The summary of experimental measurements of quarkonium pair hadroproduction.

Collaboration	$\sqrt{s}$	kinematic cut condition
LHCb	7 TeV	$P_T^{J/\psi} < 10\text{GeV}$ $2.0 < y^{J/\psi} < 4.5$
	13 TeV	
D0	1.96 TeV	$p_T^{J/\psi} > 4.0\text{GeV}, \lvert\eta^{J/\psi}\rvert < 2$
CMS	7 TeV	$p_T^{J/\psi} > 4.5\text{GeV}, \lvert y^{J/\psi}\rvert < 2.2$ [1]
ATLAS	8 TeV	$p_T^{J/\psi} > 8.5\text{GeV}, 0 < \lvert y^{J/\psi}\rvert < 1.05$ $2.0 < y^{J/\psi} < 4.5$

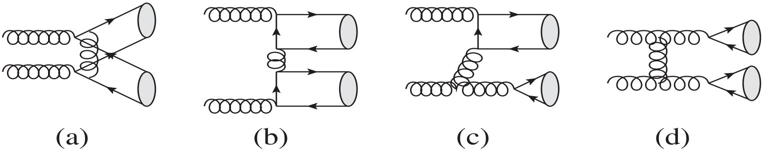
Very rich observables

- σ, $\frac{d\sigma}{dp_T^{\psi}}$, $\frac{d\sigma}{dy^{\psi}}$, $\frac{d\sigma}{dp_T^{\psi\psi}}$, $\frac{d\sigma}{dy^{\psi\psi}}$, $\frac{d\sigma}{dm^{\psi\psi}}$, $\frac{d\sigma}{d|\Delta y|}$, $\frac{d\sigma}{d|\Delta\phi|}$, $\frac{d\sigma}{d\mathcal{A}_T}$.

[1] The lower bound of $p_T^{J/\psi}$ depends on $y^{J/\psi}$

SPS contribution at LO

- Representative Feynman diagrams at LO:



4 different types of topological Feynman diagrams:

- a) Non-gluon fragmentation type I
- b) Non-gluon fragmentation type II
- c) One gluon fragmentation like
- d) Two gluons fragmentation like

The power counting for each channel at large p_T I

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 be divided into 4 categories:

1. NNLP-I, with $N = 8$, including $m = {}^3S_1^{[1]}$ and $n = {}^3S_1^{[1,8]}, {}^1S_0^{[8]}, {}^3P_J^{[1,8]}$;
2. NNLP-II, with $N = 8$, too, including $m, n = {}^1S_0^{[8]}, {}^3P_J^{[1,8]}$;
3. NLP, with $N = 6$, including $m = {}^3S_1^{[8]}$ and $n = {}^1S_0^{[8]}, {}^3P_J^{[1,8]}$; 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, the topology of Feynman diagrams are different. In the latter case, there are the diffraction-like ones as in Fig. (b), which can largely enhance the differential cross section in large $|\Delta y|$ and large $m_{J/\psi J/\psi}$ regions.

- Together with the scaling of LDMEs, the relative contributions each channel at QCD LO are:

(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

Note

The much more complicate power counting makes the theoretical predictions become more sensitive to the choice of LDMEs in NRQCD and can potentially result in large theoretical uncertainties.

Some general features in double J/ψ hadroproduction

1. The CS channel mainly contributes to total and differential cross sections at low p_T, small invariant mass, and small $|\Delta Y|$ regions.
2. The CO contribution are predominant in large $|\Delta Y|$ and invariant mass regions due to the existence of diffraction-like gluon exchange.
3. 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 hadroproduction case.
4. Near the threshold region, $\sigma \propto m_c^{-8}$, so the theoretical predictions are very sensitive to the choice of m_c value.
5. For some observables, for example $p_T^{\psi\psi}$ or $|\Delta\phi|$ distribution, QCD higher order contribution is necessary.

SPS contribution at higher order

- The relativistic corrections to double J/ψ hadroproduction was found to be ignorable for total cross section and become non-ignorable in large p_T region. (Li et al. 2013)
- The K-factors of the NLO QCD corrections to CS ${}^3S_1^{[1]} + {}^3S_1^{[1]}$ channel were about 1.2 in 7 TeV LHCb case and were about 12 in 8 TeV CMS case. (Sun et al. 2016)
- The complete NLO QCD corrections are much more complicated, in particular, there are un-canceled infrared divergence in double P-wave channel, which will violate the conventional NRQCD factorization. (He et al. 2018)
- The partial α_s^6 contribution from loop-induced subset of Feynman diagrams will overtake the NLO results in large $|\Delta y|$ and large invariant mass regions due to t-channel gluon exchange effect. (Lansberg et al. 2019)

SPS contribution with k_T dependent PDF

- Alternatively, k_T dependent PDF can effectively take into account initial state radiation effect at QCD NLO order.
- The approaches include k_T factorization, parton reggeization approach (PRA) or high energy factorization, and NLO^* approach.
- In such LO calculation, with a proper PDF set, the CS channel can fairly well describe the distributions of p_T in whole range, moderate invariant mass and small $|\Delta y|$ regions.
- The CO contribution although can be more than one order of magnitude higher in large invariant mass or large $|\Delta y|$ region, SPS predictions still lie far below the experimental data.

New power counting in large $|\Delta y|$ region

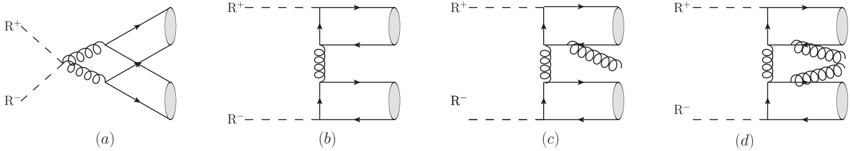
- In collinear parton model, at LO, $m_{\psi\psi}$ and $|\Delta y|$ are related through $m_{\psi\psi} = 2\sqrt{4m_c^2 + (p_T^{\psi})^2}\cosh(|\Delta y|/2)$.
- When initial parton carries k_T, the differential cross sections in large $m_{\psi\psi}$ and $|\Delta y|$ regions are still strongly correlated.
- In such regions, the channels including t-channel gluon exchange type Feynman diagrams contribute predominantly.
- Moreover, large logarithmic of type $(\alpha_s \ln|s/t|)^n$ will arise in the higher order QCD corrections, which can be resummed by BFKL resummation formalism.

3 categories of channels according to t-channel gluon exchange:

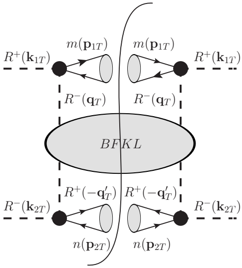
1. LT, including $m = {}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[1,8]}$ and $n = {}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[1,8]}$.
2. NLT, including $m = {}^3S_1^{[1]}$ and $n = {}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[1,8]}$.
3. NNLT, including $m = {}^3S_1^{[1]}$ and $n = {}^3S_1^{[1]}$.

BFKL resummation in high energy factorization

- Represent Feynman diagrams for LT (b), NLT (c) and NNLT (d) channels:



- Schematic representation of the BFKL resummation:



SPS contribution confront D0 @1.96 TeV

- The fiducial cross sections reported by D0 Collaborations:

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

- The CSM (Qiao and Sun 2013) and NRQCD (He et al. 2021) predictions at QCD LO:

$$\sigma^{\rm SPS,CSM}_{\rm D0,fid} = 51.9\ {\rm fb}, \sigma^{\rm SPS,NRQCD}_{\rm D0,fid} = 86.1^{+59.7}_{-34.0}\ {\rm fb}$$

- The $\rm k_T$ factorization (Baranov 2013) and $\rm NLO^*$ calculations (Lansberg and Shao 2013):

$$\sigma^{\rm SPS,k_T}_{\rm D0,fid} = 55.1^{+28.5}_{-15.6}{}^{+31,0}_{-17.0}\ {\rm fb}, \sigma^{\rm SPS,NLO^*}_{\rm D0,fid} = 90^{+180}_{-50}\ {\rm fb},$$

The conclusion of depended on the SPS input. When complete NRQCD calculation is taken into account, it might be changed.

SPS contribution confront D0 @1.96 TeV $J/\psi + \Upsilon$

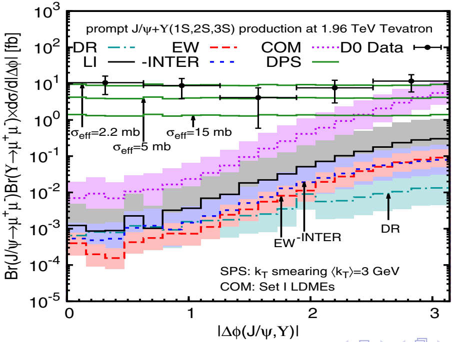
- The fiducial cross section reported by D0 Collaborations:

$$\sigma^{\rm SPS}_{\rm D0,fid} = 0 \text{ fb}, \sigma^{\rm DPS}_{\rm D0,fid} = (27 \pm 9 \pm 7) \text{ fb},$$

- LO NRQCD+ α_s^6 CSM+ QED (Shao and Zhang 2016):

$$\sigma^{\rm SPS}_{\rm D0,fid} = 2.96^{+4.00}_{-1.66} \text{ fb}$$

- The $|\Delta\phi|$ distribution:

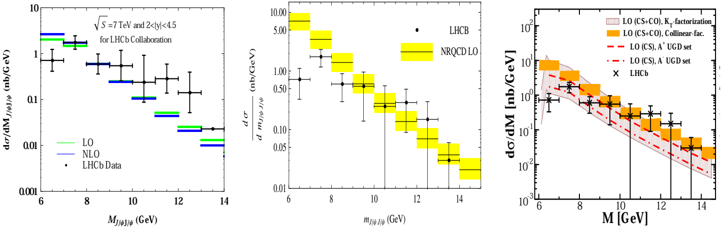


SPS contribution confront LHCb @ 7 TeV

- Total cross section (nb), NLO CSM (Sun et al. 2016) and LO NRQCD (He, Kniehl 2015) predictions:

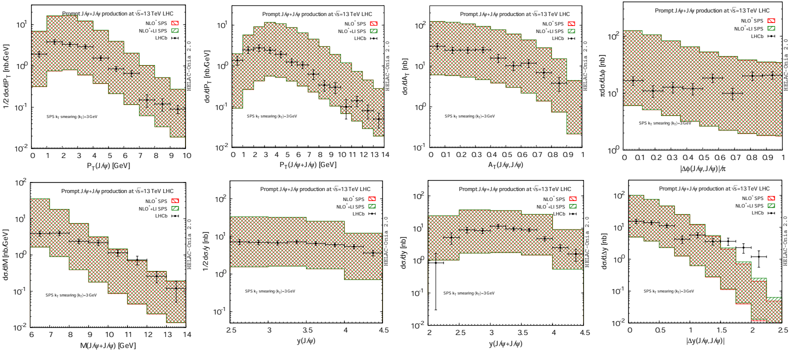
LHCb	LO CSM	NLO CSM	LO NRQCD
$5.1 \pm 1.0 \pm 1.1$	4.56 ± 1.13	$5.41^{+2.73}_{-1.14}$	$13.2^{+5.2}_{-4.1}$

- Invariant mass spectrum, NLO CSM, LO NRQCD, and $\mathrm{k_T}$(Baranov, Rezaeian 2016) predictions:



The SPS contribution from LO CS can well describe LHCb data except for near threshold region.

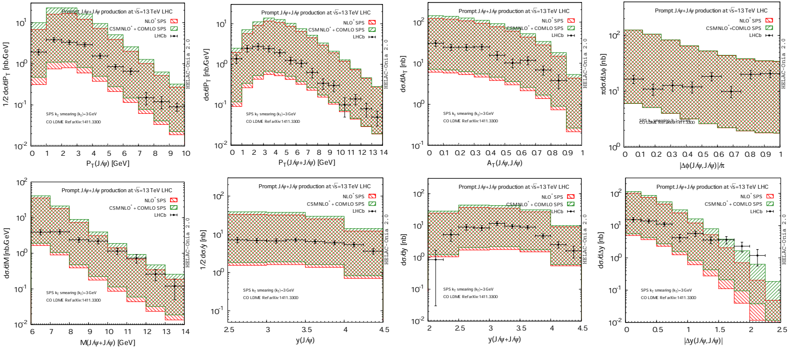
- Various differential cross sections, $\mathrm{NLO}^{*}+$ loop-induced CS predictions (Lansberg et al. 2019):



CS predictions with large theoretical uncertainties can cover LHCb data except for the upper $|\Delta y|$ bins.

SPS contribution confront LHCb @ 13 TeV II

- Various differential cross sections, LO CO+ $\mathrm{NLO}^{*}\mathrm{CS}$ predictions (Lansberg et al. 2019):



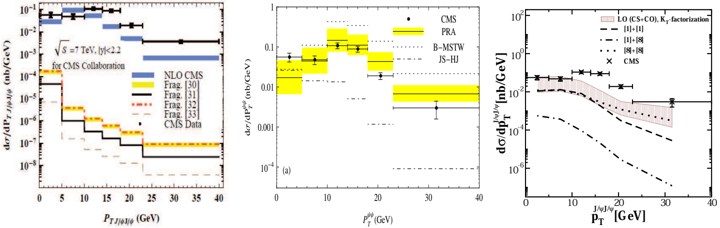
CO contribution remedies the discrepancy.

SPS contribution confront CMS @ 8 TeV I

- Total cross section (nb), NLO CSM (Sun eta al. 2016), LO NRQCD (He, Kniehl 2015) and PRA (He et al. 2019) predictions:

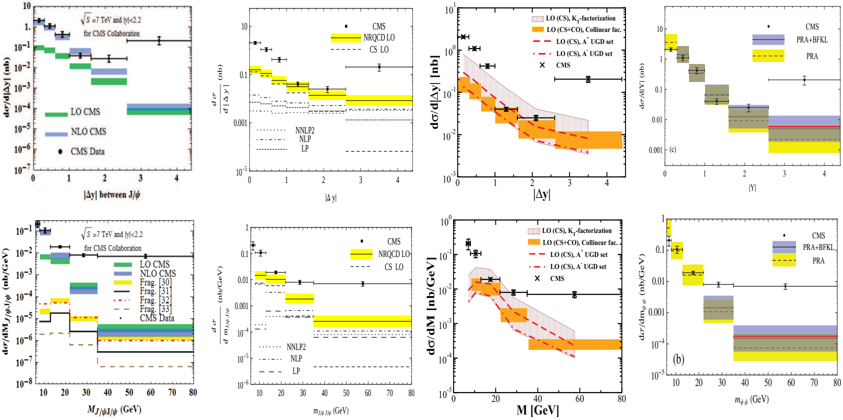
CMS	LO CSM	NLO CSM	LO NRQCD	PRA
1.49 ± 0.07	0.08 ± 0.02	0.93 ± 0.25	$0.15^{+0.08}_{-0.05}$	$1.68^{+1.32}_{-0.78}$

- J/ψ pair $\mathrm{p_T}$ distribution, $\mathrm{k_T}$ factorization (Baranov and Rezaeian 2016) and PRA predictions:



SPS contribution can describe CMS measurements with a proper scheme to generate $\mathrm{k_T}$ dependent PDFs in non-zero k_T approaches.

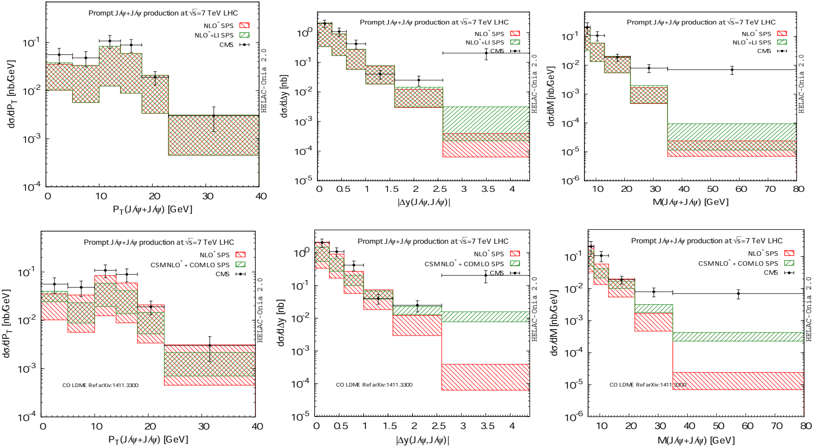
- $|\Delta y|$ and $m_{\psi\psi}$ distributions, NLO CSM, LO NRQCD, $\mathrm{k_T}$ and PRA predictions:



In the last bins, LT channel contribution is predominate and BKFL resummation can enhance fixed order results by a factor of 2.

SPS contribution confront CMS @ 8 TeV III

- $\mathrm{NLO}^{*}+$ loop-induced CS and LO CO+NLO^{*} CS predictions (Lansberg et al. 2019):



SPS contribution lies far below CMS data in the last $|\Delta y|$ and $m^{\psi\psi}$ bins.

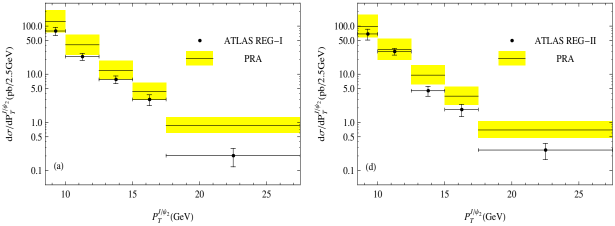
SPS contribution confront ATLAS @ 8 TeV I

- Total cross section, PRA (He et al. 2019) predictions:

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

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

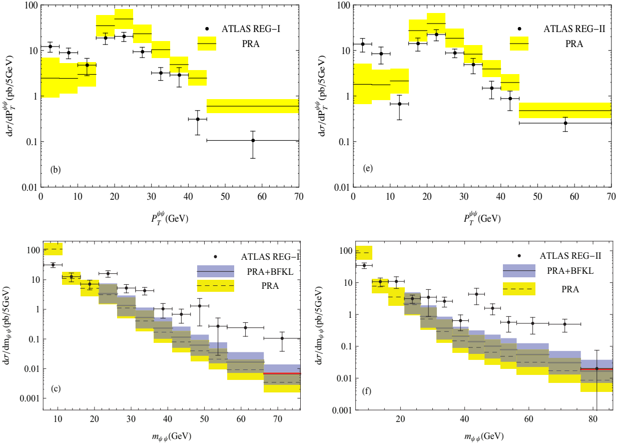
- p_T^{ψ} distribution, PRA predictions:



SPS can account for the total cross section and single J/ψ p_T distribution.

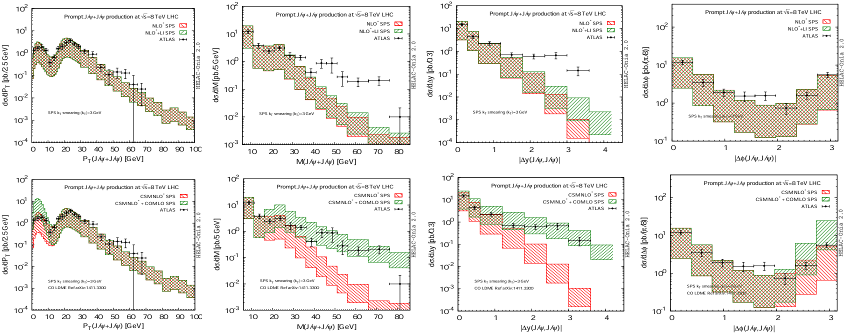
SPS contribution confront ATLAS @ 8 TeV II

- $p_T^{\psi\psi}$ and $m^{\psi\psi}$ distributions, PRA predictions:



For invariant mass spectrum, SPS preditions are much smaller than ATLAS measurement in the last few bins.

- Differential cross sections in fiducial: $\mathrm{CS\ NLO^{*} + LI}$, $\mathrm{NLO^{*}CS + CO}$ (Lansberg al et. 2019)



SPS contribution itself agree well with ATLAS measurements in fiducial with proper LDMEs set(7) in NRQCD.

Summary and Outlook

1. Quarkonium pair hadroproduction offers rich observables to understand the production mechanism of heavy quarkonium as well as the property of patron distribution inside proton.
2. For SPS contribution, the role of each channel in different kinematic region may be different due to different power counting rules.
3. More careful theoretical investigations are needed in both near and far away from threshold regions.
4. To compare theoretical predictions with experimental measurements, more detailed and precise data analysis would be welcomed.
5. A deep understanding of SPS contribution also helps to extract the value of σ_{eff} in DPS process.

Thank you!