NRQCD predictions of double J/ψ hadroproduction beyond LO

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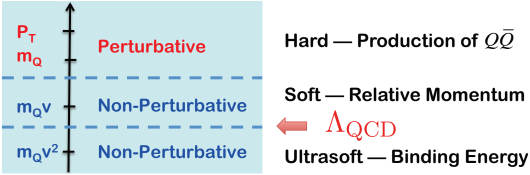
Outline

1. Introduction
2. NLO QCD corrections to double J/ψ hadroproduction
3. Relativistic effect in double J/ψ hadroproduction
4. Conclusion and summary

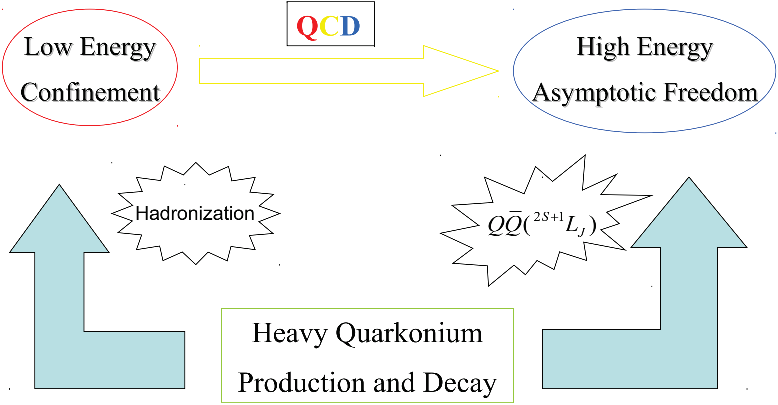
What is heavy quarkonium?

- Heavy quarkonium is one of the simplest QCD bound state constituted by heavy quark pair $Q\bar{Q}$ ($\Lambda_{QCD} \ll m_Q$).
- It is labeled by the spectroscopic notation $n^{2S+1}L_J$.
  - Its parity $P = (-1)^{L+1}$.
  - Its charge conjugation parity $C = (-1)^{L+S}$.
- There are 3 typical energy scales besides Λ_{QCD}:



- It is an approximately non-relativistic system:
  - Charmonium: $v_c^2 \approx 0.23 \ll 1$
  - Bottomonium: $v_b^2 \approx 0.08 \ll 1$

Quarkonium production–The ideal laboratory to probe QCD



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

Factorization of heavy quarkonium production

- The general factorization formalism:

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

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

Color Singlet Model

- Short Distance Part: The produced $Q\bar{Q}$ pair shares **the same quantum number** as the heavy meson.
- Long Distance Part: The non-relativistic wave function or its derivatives at origin.
- Non-factorizable in production and decay: S-wave relativistic corrections, P-wave at v^2 LO.

NRQCD Factorization formalism

NRQCD Factorization

- Short Distance Part: The produced $Q\bar{Q}$ pair can be **any possible quantum numbers**, even in **color octet**.
- Long Distance Part: The relative size of contribution from each Fock state obeys velocity scaling rules.
- The infrared divergence is absorbed into the NLO QCD corrections to the long distance matrix elements.

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 the LHC.

New features in quarkonium pair hadroproduction

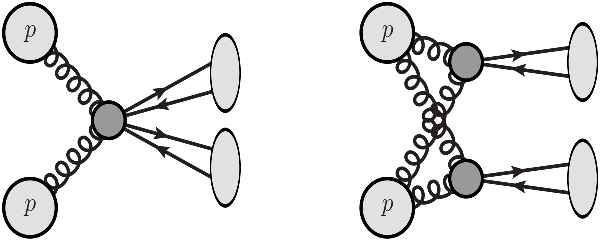
1. Kinematically, it can be viewed as a gluon-gluon fusion type "Drell-Yan" process.
2. To test NRQCD factorization or other models, and to provide crucial constraint on the long-distance matrix elements. (Barger et al. 1996)
3. Help to improve the NRQCD factorization formalism for double P-wave production. (He et al. 2018)
4. 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)

Production mechanism of double quarkonium states

- Multi-final states can be produced through single parton scattering (SPS) or double parton scattering (DPS).



Schematical representation of SPS (left) and DPS (right) for a proton-proton collision. (Figure from Phys. Rev. D 95, 034029)

- The key parameter in DPS is σ_{eff}, which is supposed to be universal.

Experimental Status of hadroproduction

Table: The summary experimental measurements

Experiment	$\sqrt{s}$	states	kinematic condition
D0	1.96 TeV	$J/\psi + J/\psi$	$p_T^{J/\psi} > 4.0\text{GeV}, \lvert\eta^{J/\psi}\rvert < 2$
LHCb	7 TeV	$J/\psi + J/\psi$	$P_T^{J/\psi} < 10\text{GeV}$ $2.0 < y^{J/\psi} < 4.5$
	13 TeV	$J/\psi + J/\psi$	$P_T^{J/\psi} < 10(14)\text{GeV}$ $2.0 < y^{J/\psi} < 4.5$
		$J/\psi + \psi(2S)$	
CMS	7 TeV	$J/\psi + J/\psi$	$p_T^{J/\psi} > 4.5\text{GeV}, \lvert y^{J/\psi}\rvert < 2.2$
ATLAS	8 TeV	$J/\psi + J/\psi$	$p_T^{J/\psi} > 8.5\text{GeV}, \lvert y^{J/\psi}\rvert < 2.1$
ALICE	13 TeV	$J/\psi + J/\psi$	$p_T^{J/\psi} > 0\text{GeV}, 2.5 < y^{J/\psi} < 4.0$

Rich observables

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

Theoretical study of quarkonium pair hadroproduction

- The J/ψ pair production was first proposed by Barger, et al. in 1996, in which the $2(c\bar{c}(^3S_1^{[8]}))$ contribution was studied.
- In 2002, Qiao found that the $2(c\bar{c}(^3S_1^{[1]}))$ channel contributes predominately to the total cross section.
- Baranov calculated the J/ψ pair production in $\mathrm{k_T}$ factorization approach in 2011.
- The NLO QCD corrections to the $2(c\bar{c}(^3S_1^{[1]}))$ channel was obtained by Sun et al. in 2014 and was updated in 2023.
- The complete LO NRQCD calculation including χ_c feed down were obtained by He and Kniehl in 2015.
- In 2019, He et al. studied the J/ψ pair production in the parton reggeization approach (PRA) with high-energy resummation.
- In 2023, the NLO QCD corrections to $2(c\bar{c}(^1S_0^{[8]}))$ channel was obtained by Sun.

NRQCD predictions @ D0 1.96 TeV

- The fiducial cross sections reported by D0 Collaborations:

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

- The CSM predictions in LO (Qiao and Sun 2013) , $\mathrm{k_T}$ factorization (Baranov 2013) and NLO^* calculations (Lansberg and Shao 2013):

$$\sigma^{\mathrm{SPS}}_{\mathrm{D0,fid}} = 51.9\ \mathrm{fb}, \sigma^{\mathrm{SPS,kT}}_{\mathrm{D0,fid}} = 55.1^{+28.5\ +31.0}_{-15.6\ -17.0}\ \mathrm{fb}, \sigma^{\mathrm{SPS,NLO^*}}_{\mathrm{D0,fid}} = 90^{+180}_{-50}\ \mathrm{fb}.$$

- LO NRQCD predictions (He et al. 2021):

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

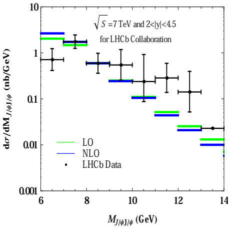
The D0 conclusion depended on the SPS inputs. When complete NRQCD calculation is taken into account their conclusion might change.

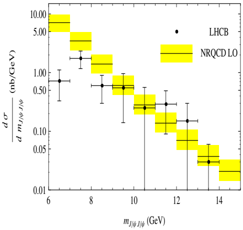
NRQCD predictions @ LHCb 7 TeV

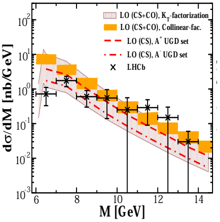
- Total cross section (nb): CSM predictions at QCD NLO (Sun et al. 2016) and complete LO NRQCD (He, Kniehl 2015)

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

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







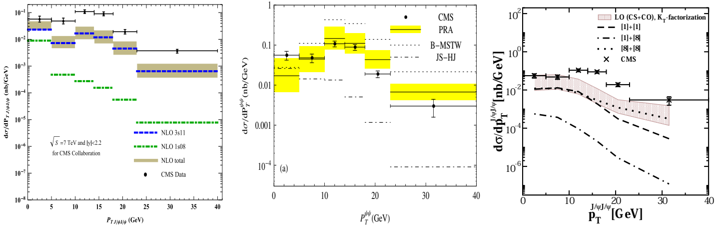
The theoretical predictions near threshold region strongly depend on the choice of m_c.

NRQCD predictions @ CMS 7 TeV I

- Total cross section (nb): NLO CSM (Sun eta al. 2023), complete LO NRQCD (He, Kniehl 2015), PRA (He et al. 2019)

CMS	LO CSM	NLO CSM	LO NRQCD	PRA
1.49 ± 0.07	0.048	0.18	$0.15^{+0.08}_{-0.05}$	$1.68^{+1.32}_{-0.78}$

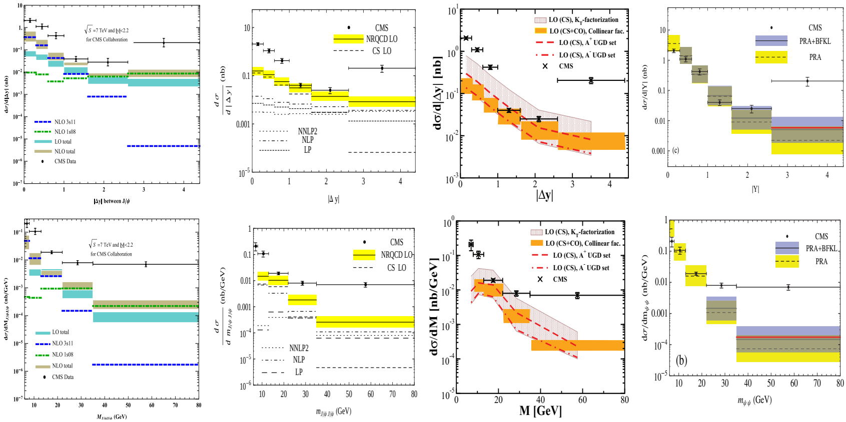
- The J/ψ pair $\mathrm{p_T}$ distribution including prediction of $\mathrm{k_T}$ factorization (Baranov and Rezaeian 2016):



Different way of generating the $\mathrm{k_T}$ dependent PDF could lead to complete different predictions.

NRQCD predictions @ CMS 7 TeV II

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



T-channel gluon exchange effect is significant and BKFL resummation can further enlarge fixed order calculations by a factor of 2.

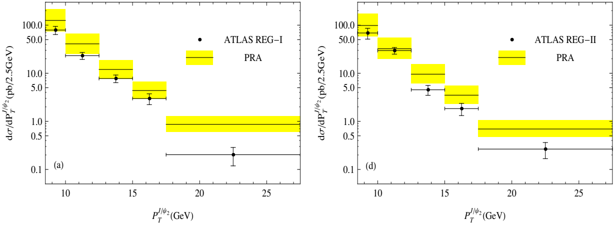
NRQCD predictions @ ATLAS 8 TeV I

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

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

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

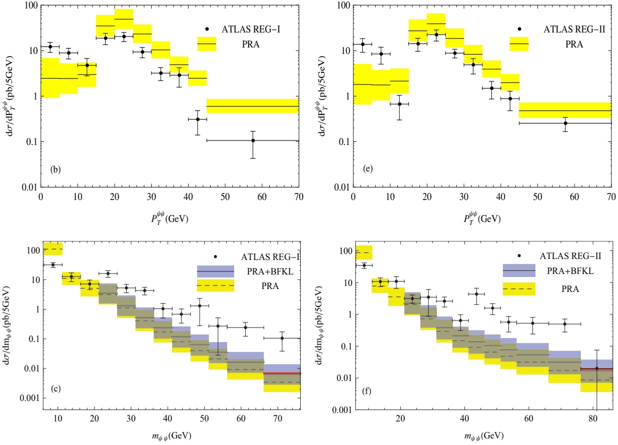
- p_T distribution of single J/ψ



PRA predictions agree fairly well with ATLAS measurements.

NRQCD predictions @ ATLAS 8 TeV II

- $\mathrm{p_T}$ and invariant mass distributions of the J/ψ pair:



SPS can not account for the invariant mass distribution in the upper bins.

Why shall we re-calculate the NLO QCD corrections?

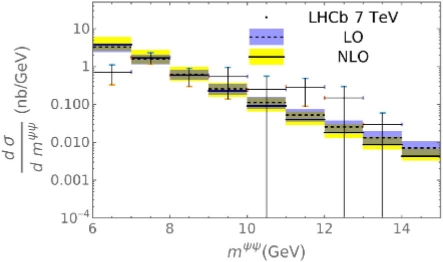
- Theoretically, the NLO QCD corrections become much more complicated when bound states are involved.
- In single J/ψ production, almost all channels were evaluated by more than one group.
- We calculated the NLO QCD corrections to the CS $gg \to 2c\bar{c}(^3S_1^{[1]})$.
- We found agreement upon adjusting inputs and eliminating a minor inconsistency in the paper of Sun et al. .
- We presented an up-to-date comparison with the latest LHC measurements.

CS NLO(α_s) @ LHCb 7 TeV

- Total cross section:

$$\sigma^{\rm Tot}_{\rm LHCb} = (5.1 \pm 1.0 \pm 1.1)\ \rm nb,$$
$$\sigma^{\rm LO}_{\rm CS} = 6.02^{+1.56}_{-1.59}\ \rm nb, \sigma^{\rm NLO}_{\rm CS} = 6.46^{+3.99}_{-2.01}\ \rm nb.$$

- The K-factor of total cross section is about 1.07.
- The invariant mass spectrum of the J/ψ pair:



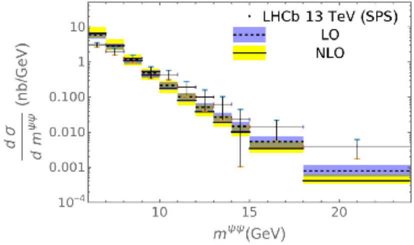
- The NLO QCD corrections near threshold region are positive, and become negative as $m^{\psi\psi}$ increases.

CS NLO(α_s) @ LHCb 13 TeV I

- Total cross section:

$$\sigma^{\rm Tot}_{\rm LHCb} = (16.36 \pm 0.28 \pm 0.88)\ \rm nb,\ \sigma^{\rm SPS}_{\rm LHCb} = (7.9 \pm 1.2 \pm 1.1)\ \rm nb,$$
$$\sigma^{\rm LO}_{\rm CS} = 10.9^{+1.4}_{-2.5}\ \rm nb, \sigma^{\rm NLO}_{\rm CS} = 11.4^{+5.8}_{-3.2}\ \rm nb.$$

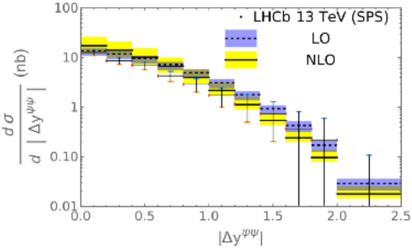
- The K-factor of total cross section is only about 1.05.
- The invariant mass spectrum of the J/ψ pair:



- When $m^{\psi\psi} > 15$GeV, the CS contribution tends to underestimate the LHCb measurements leaving room for CO contribution.

CS NLO(α_s) @ LHCb 13 TeV II

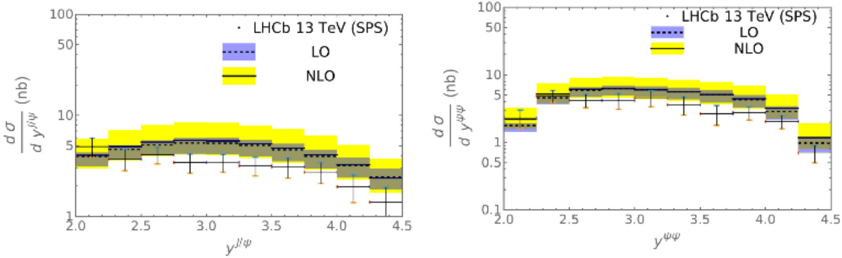
- The $|\Delta y^{\psi\psi}|$ distribution of the J/ψ pair:



- The NLO QCD corrections barely shift the LO predictions for $|\Delta y^{\psi\psi}| < 1$ region.
- When $|\Delta y^{\psi\psi}| > 1$, the NLO QCD corrections result in a reduction from 30% to 40%.
- Unlike the invariant mass spectrum, in the last bin there is no room for CO contribution.

CS NLO(α_s) @ LHCb 13 TeV III

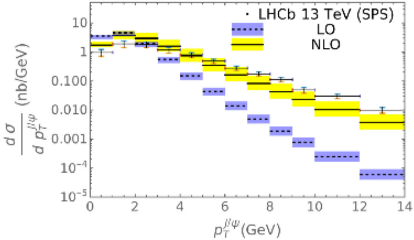
- The rapidity distributions of single J/ψ (left) and J/ψ pair (right):



- The tiny effect of NLO QCD corrections are almost uniform in the whole region of $2.0 < y^{\psi}(y^{\psi\psi}) < 4.5$.
- In most bins, the central values of CS predictions lie slightly above the experimental data.
- CS predictions can reasonably well describe the data within errors.

CS NLO(α_s) @ LHCb 13 TeV IV

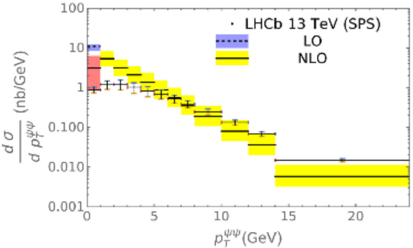
- The p_T distribution of single J/ψ:



- The LO prediction is about 3.7 times larger than LHCb measurements in the first bin, while falls off by more than 2 orders of magnitude in the last bin.
- The NLO QCD corrections bring about -51% decrease and 61 times increase in the first and last bins.
- The NLO QCD corrections greatly moderate the conflict!

CS NLO(α_s) @ LHCb 13 TeV V

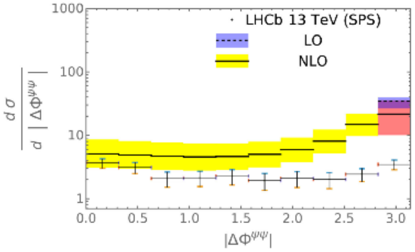
- The p_T distribution of J/ψ pair:

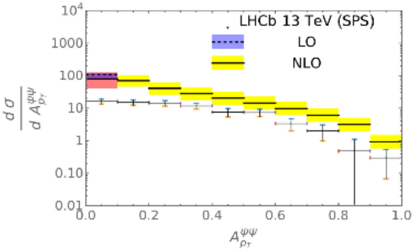


- In collinear parton model (CPM), only the $2 \to 3$ real corrections contribute when $p_T^{\psi\psi} \neq 0$.
- In small $p_T^{\psi\psi}$ region, perturbation theory is spoiled due to soft, hard-collinear gluons, and quarks radiation.
- Yet, as the value of $p_T^{\psi\psi}$ becomes larger, the NLO prediction falls off faster than experimental data.

CS NLO(α_s) @ LHCb 13 TeV VI

- The $|\Delta\Phi^{\psi\psi}|$ (left) and $A_{p_T}^{\psi\psi}$ (right) distributions of J/ψ pair:





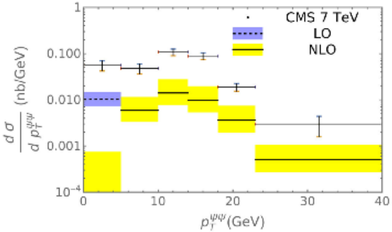
- At LO, $|\Delta\Phi^{\psi\psi}| = \pi$, $A_{p_T}^{\psi\psi} = 0$, so near these end point regions, perturbative results are not reliable too.
- The NLO predictions tends to agree with experimental data away from the end point regions.
- Small p_T resummation approach can improve the results obtained in fixed-order computation.

CS NLO(α_s) @ CMS 7 TeV I

- Total cross section:

$$\sigma_{\rm CMS} = (1.49 \pm 0.07 \pm 0.13)\ {\rm nb},$$
$$\sigma_{\rm CS}^{\rm LO} = 0.052^{+0.020}_{-0.016}\ {\rm nb}, \sigma_{\rm CS}^{\rm NLO} = 0.147^{+0.136}_{-0.061}\ \text{nb}.$$

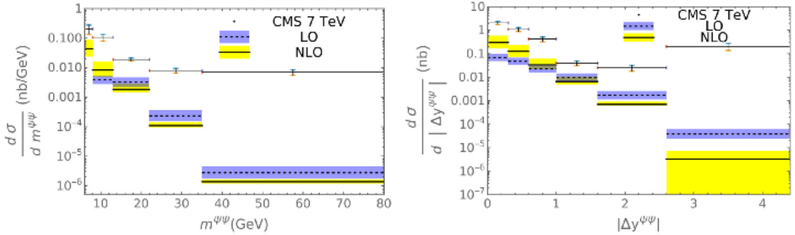
- The CS predictions at QCD NLO are about 10 times smaller than CMS data, even though the K-factor is about 2.8.
- The p_T spectrum of the J/ψ pair:



- The CSM predictions lie below the CMS data in the whole $p_T^{\psi\psi}$ range.

CS NLO(α_s) @ CMS 7 TeV II

- The $m^{\psi\psi}$ (left) and $|\Delta y^{\psi\psi}|$ (right) distributions of J/ψ pair:



- The CS contribution at QCD NLO can describe none of the data in experimental bins too.
- The NLO QCD corrections improve theoretical predictions in $m^{\psi\psi} < 13$ GeV and $|\Delta y^{\psi\psi}| < 1$ regions.
- In the residual bins, NLO QCD corrections turn to be negative and lead to 50% and 90% reduction in the last bin, respectively.

CS NLO(α_s) @ ATLAS 8 TeV I

- Total cross section:

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

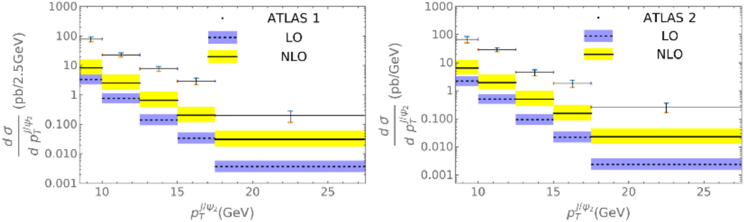
$$\sigma_{\rm CS}^{\rm LO} = \begin{cases} 2.97^{+1.42}_{-0.96}\ \text{pb}, & \text{for} |y(J/\psi_2)| < 1.05 \\ 1.98^{+0.97}_{-0.65}\ \text{pb}, & \text{for} 1.05 < |y(J/\psi_2)| < 2.1 \end{cases}$$

$$\sigma_{\rm CS}^{\rm NLO} = \begin{cases} 8.61^{+7.87}_{-3.56}\ \text{pb}, & \text{for} |y(J/\psi_2)| < 1.05 \\ 6.64^{+6.36}_{-2.82}\ \text{pb}, & \text{for} 1.05 < |y(J/\psi_2)| < 2.1 \end{cases}$$

- The K-factor are about 2.9 and 3.4 in central and non-central regions.
- However, the same as CMS case, CS contributions are still about 1 order of magnitude smaller than ATLAS measurements.

CS NLO(α_s) @ ATLAS 8 TeV II

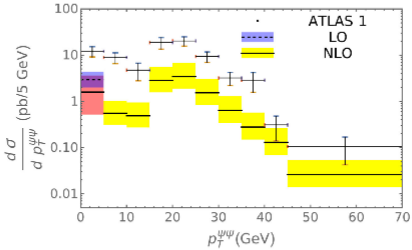
- The p_T distribution of the soft J/ψ in central (left) and forward (right) y^{ψ_2} regions:

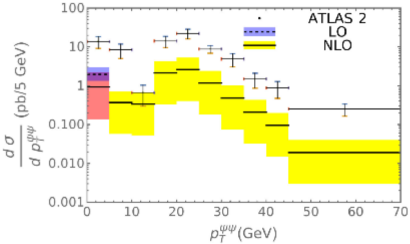


- The LO predictions systematically underestimate the ATLAS measurements by upto 2 orders of magnitude.
- The K-factors range from 2.5 and 2.9 in the first bins to 8.5 and 9.8 in the last bins.

CS NLO(α_s) @ ATLAS 8 TeV III

- The p_T distribution of J/ψ pair in central (left) and forward (right) y^{ψ_2} regions:

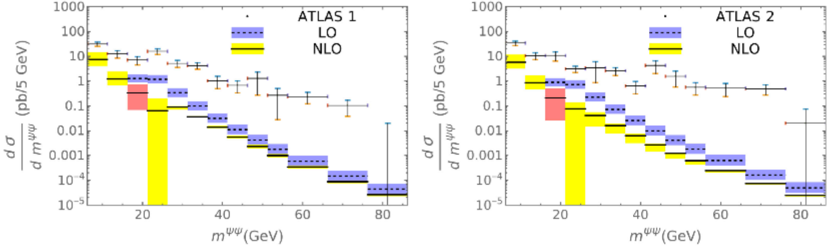




- The CS predictions at QCD NLO nicely reproduce the shapes of $p_T^{\psi\psi}$ distribution similar to CMS case.
- Incidentally, there is agreement within errors in the last two and third bins of the central and forward y^{ψ_2} regions, respectively.

CS NLO(α_s) @ ATLAS 8 TeV IV

- The J/ψ pair invariant mass distributions in central (left) and forward (right) y^{ψ_2} regions:



- The LO predictions show up from the third bin due to kinematics cut, and that is why the NLO results are negative in the third bin.
- From the fourth bins onward, the NLO QCD corrections are negative, ranging from $-95\%(-90\%)$ in the fourth bin to $-40\%(-50\%)$ in the last bins of central (forward) y^{ψ_2} region.

Why do we need the relativistic corrections?

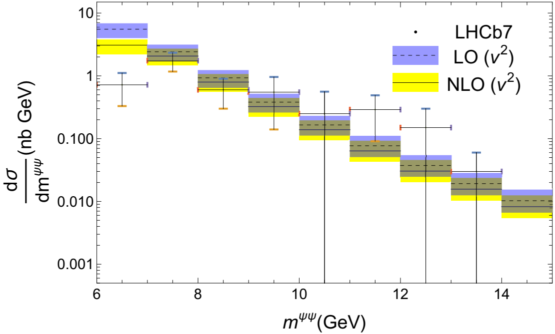
- Theoretically, $v_c^2 \approx \alpha_s(2m_c)$ for charmonium.
- The NLO v^2 corrections played an important role to resolve the large discrepancy of double charmonium (He et al. 2007) and single J/ψ (He et al. 2010, Jia 2010) production in e^+e^-.
- For prompt J/ψ photo- and hadroproduction, the relativistic corrections have considerable influence on both yield and polarization. (He and Kniehl 2014,2015)
- In relativistic quark model calculation, the total cross sections of double J/ψ hadroproduction lie significantly below LHCb measurements. (Martynenko and Trunin 2012)
- Near threshold region, the NRQCD predictions strongly depended on the choice of m_c. (Li et al. 2013)

CS NLO(v^2) @ LHCb 7 TeV I

- NLO v^2 corrections render 32% reduction to prompt cross section:

$$\sigma_{\mathrm{LHCb}}^{\mathrm{Tot}} = (5.1 \pm 1.0 \pm 1.1)\ \mathrm{nb},$$
$$\sigma_{\mathrm{CS}}^{\mathrm{LO}} = 9.60^{+2.57}_{-2.73}\ \mathrm{nb},\ \sigma_{\mathrm{CS}}^{\mathrm{NLO(v^2)}} = 6.55^{+1.92}_{-1.89}\ \mathrm{nb}$$

- The J/ψ pair invariant mass distribution:



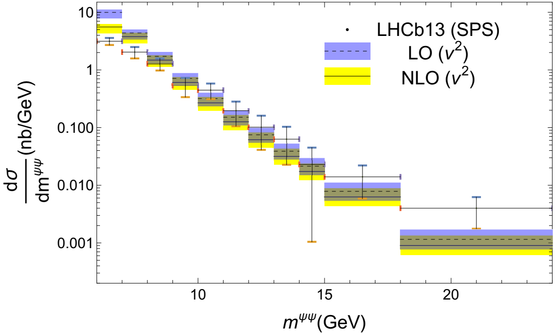
- The NLO v^2 contribution is -34% in direct production and -60% in $\psi(2S)$ feed-down, which lead to a total 45% reduction in the first bin.

CS NLO(v^2) @ LHCb 13 TeV I

- NLO total cross section: Conclusion similar to 7 TeV

$$\sigma^{\rm Tot}_{\rm LHCb} = (16.36 \pm 0.28 \pm 0.88)\ {\rm nb},\ \sigma^{\rm SPS}_{\rm LHCb} = (7.9 \pm 1.2 \pm 1.1)\ {\rm nb},$$
$$\sigma^{\rm LO}_{\rm CS} = 17.43^{+2.44}_{-3.98}\ {\rm nb},\ \sigma^{\rm NLO(v^2)}_{\rm CS} = 12.02^{+1.98}_{-2.81}\ {\rm nb}$$

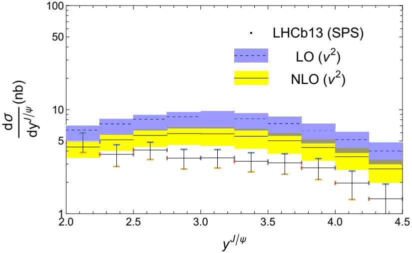
- The J/ψ pair invariant mass distribution:

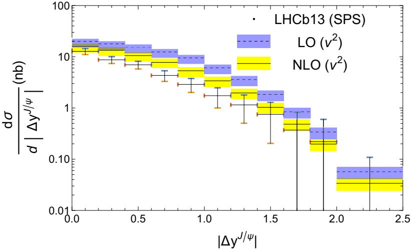


- The v^2 corrections are all negative, they are about -44% in the first bin and -20% in the last bin.

CS NLO(v^2) @ LHCb 13 TeV II

- The $y^{J/\psi}$ (left) and $|\Delta y^{\psi\psi}|$ (right) distributions:





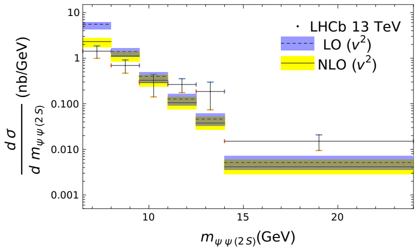
- The NLO v^2 corrections are constantly about -31% in all $y^{J/\psi}$ bins.
- The NLO v^2 corrections result in a reduction from 20% in the first bin to 40% in the last bin for $|\Delta y^{\psi\psi}|$ distribution.

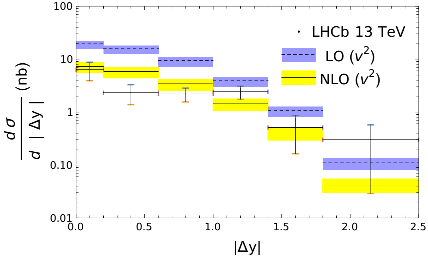
CS NLO(v^2) @ LHCb 13 TeV III

- NLO v^2 corrections leads to -65% reduction to $J/\psi + \psi(2S)$ total cross section.

$$\sigma^{\rm Tot}_{\rm LHCb} = (4.49 \pm 0.71 \pm 0.26)\ {\rm nb},$$
$$\sigma^{\rm LO}_{\rm CS} = 16.23^{+2.17}_{-3.67}\ {\rm nb},\ \sigma^{\rm NLO(v^2)}_{\rm CS} = 5.93^{+1.21}_{-1.44}\ {\rm nb}$$

- The distributions of J/ψ and $\psi(2S)$ invariant mass (left) and $|\Delta y|$ (right):



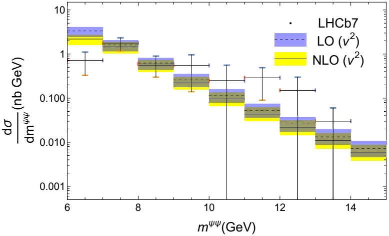


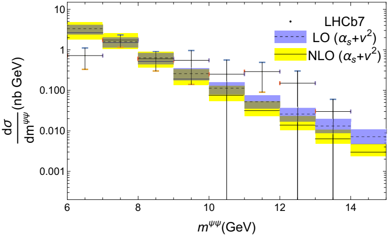
CS NLO($\alpha_s + v^2$) @ LHCb 7 TeV

- NLO $\alpha_s + v^2$ corrections leads to -16% reduction to direct double J/ψ total cross section.

$$\sigma_{\rm LHCb}^{\rm Tot} = (5.1 \pm 1.0 \pm 1.1)\ \rm nb,$$
$$\sigma_{\rm CS}^{\rm LO} = 6.02^{+1.56}_{-1.59}\ \rm nb,\ \sigma_{\rm CS}^{\rm NLO(\alpha_s+v^2)} = 5.04^{+3.70}_{-1.62}\ \rm nb$$

- The NLO v^2 (left) and $\alpha_s + v^2$(left) corrections to invariant mass spectrum:



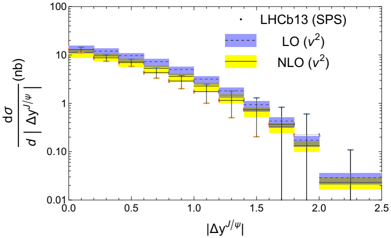


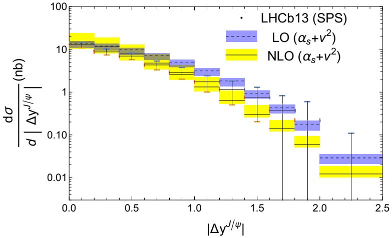
CS NLO($\alpha_s + v^2$) @ LHCb 13 TeV I

- NLO $\alpha_s + v^2$ corrections leads to -18% reduction to direct double J/ψ total cross section.

$$\sigma^{\mathrm{SPS}}_{\mathrm{LHCb}} = (7.9 \pm 1.2 \pm 1.1)\ \mathrm{nb},$$
$$\sigma^{\mathrm{LO}}_{\mathrm{CS}} = 10.9^{+1.4}_{-2.5}\ \mathrm{nb},\ \sigma^{\mathrm{NLO}(\alpha_s+v^2)}_{\mathrm{CS}} = 8.9^{+5.6}_{-2.7}\ \mathrm{nb}$$

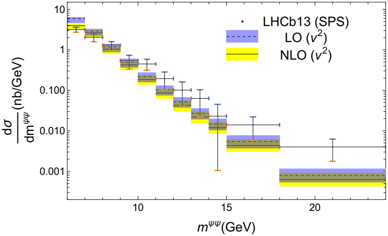
- The NLO v^2 (left) and $\alpha_s + v^2$(left) corrections to $|\Delta y^{\psi\psi}|$ distribution:

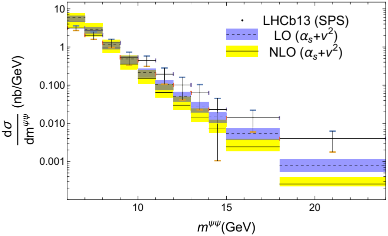




CS NLO($\alpha_s + v^2$) @ LHCb 13 TeV II

- The NLO v^2 (left) and $\alpha_s + v^2$(left) corrections to invariant mass spectrum:





- The NLO α_s and v^2 joint corrections are negative in the whole region of J/ψ pair invariant spectrum.
- In the last bin the corrections can reach -68% leaving more room for CO contribution.

Conclusion and summary

1. The NLO QCD and relativistic corrections are important to understand the mechanism of J/ψ pair hadroproduction.
2. In LHCb case, the CS contribution can account for most of the experimental measurements although some resummation techniques are needed to improve theoretical predictions.
3. In CMS and ATLAS cases, the CS contribution are far below the experimental measurements, which indicates the CO contribution may play an important role to fill the large discrepancies.
4. Much more theoretical effort are still needed to explain the experimental measurements.

Thank you!

Back up

Setup of Numerical predictions

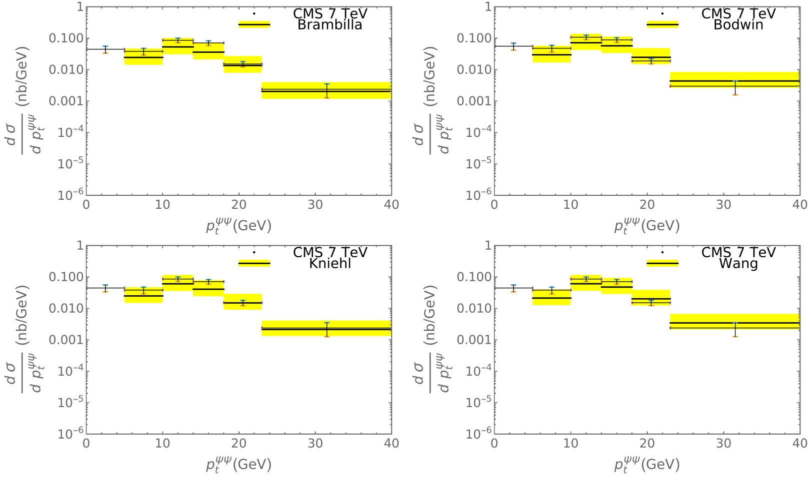
- We choose LO CTEQ6L PDFs, and one-loop running of α_s, $\mu_r = \mu_f = (\sqrt{(p_T^{\psi_1})^2 + 4m_c^2} + \sqrt{(p_T^{\psi_2})^2 + 4m_c^2})/2$.
- We by hand remove 20% contribution from $\psi(2S)$ feeddown.
- We investigate predictions of 4 group with the LDMEs listed below.

Table: The LDMEs in unit of GeV^3 for S-wave and GeV^5 for P-wave

	Brambilla	Bodwin	Kniehl	Wang
$\langle \mathcal{O}^{J/\psi}(^3S_1^{[1]}) \rangle$	1.16	1.16	1.32	1.16
$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]}) \rangle$	-0.00204	0.099	0.0304	0.097
$\langle \mathcal{O}^{J/\psi}(^3P_J^{[8]}) \rangle$	0.0429	0.011	-0.0091	-0.0214
$\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]}) \rangle$	0.0106	0.011	0.0016	-0.0046

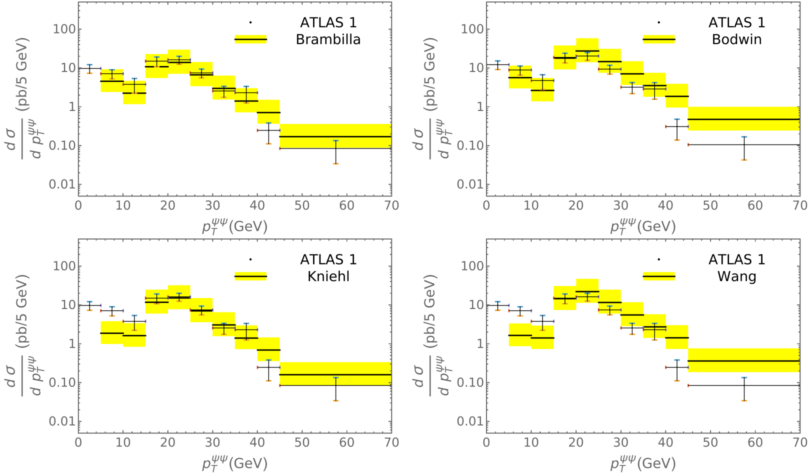
Numerical predictions for 7 TeV CMS

- All groups' predictions can describe the experimental data.



Numerical predictions for 8 TeV ATLAS central

- All groups' predictions can describe the experimental data except for Bodwin and Wang's.



Numerical predictions for 8 TeV ATLAS forward

- All groups' predictions can describe the experimental data.