Prompt double J/ψ hadroproduction

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Outline

1. Background
   - "J/ψ polarization puzzle"
   - Double J/ψ production
2. LO NRQCD Prediction
   - Theoretical framework
   - Comparison between NRQCD predictions and experimental data
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.
- 20 years after the introduction of the NRQCD factorization formalism by Bodwin, Braaten, and Lapage in 1995, the "J/ψ polarization puzzle" has not been resolved yet.
- The short-distance coefficients (SDCs) @ QCD NLO were obtained by three groups independently. However, the theoretical description depends very much on the chosen long-distance matrix elements (LDMEs).
- All these LDME sets are challenged by the η_c production data.
- See my talk and round-table discussion as of yesterday for details.

Double J/ψ production from theoretical point of view

- In double J/ψ production, the hadronization of charm quark pairs takes place twice. Therefore, this provides a particularly sensitive test of the NRQCD hypothesis.
- The double J/ψ production also provides an additional crucial constrain on the J/ψ LDMEs.
- It is believed that J/ψ pairs 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 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 was found that the CS $2(c\bar{c}(^3S_1^{[1]}))$ channel (CS*) contributes predominately to the hadroproduction rate (Qiao 2002).
- Explicit 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, et 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 thereafter has also been performed (Lansberg, et al. 2015).
- Double quarkonium production was also studied in the k_T factorization framework (Baranov, et al. 2015).

Double J/ψ production experimental measurements

- Double J/ψ production was first measured by the LHCb Collaboration at 7 TeV in the rapidity range of $2.0 < y^{J/\psi} < 4.5$ and $p_T^{J/\psi} < 10$ GeV for each J/ψ [PLB707(2012)52].
- It was also measured by the D0 Collaboration at 1.96 TeV with $p_T^{J/\psi} > 4$ GeV and $|\eta^{J/\psi}| < 2.0$, where the SPS and DPS contributions were discriminated [PRD90(2014)R111101].
- At LHC, the CMS Collaboration measured double J/ψ production in details with cut condition [JHEP09(2014)094]:

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

- Very recently, the D0 Collaboration measured $J/\psi + \Upsilon$ production at the Tevatron for the first time [PRL116(2016)082002].

NRQCD factorization formalism

NRQCD factorization formula for prompt double J/ψ production

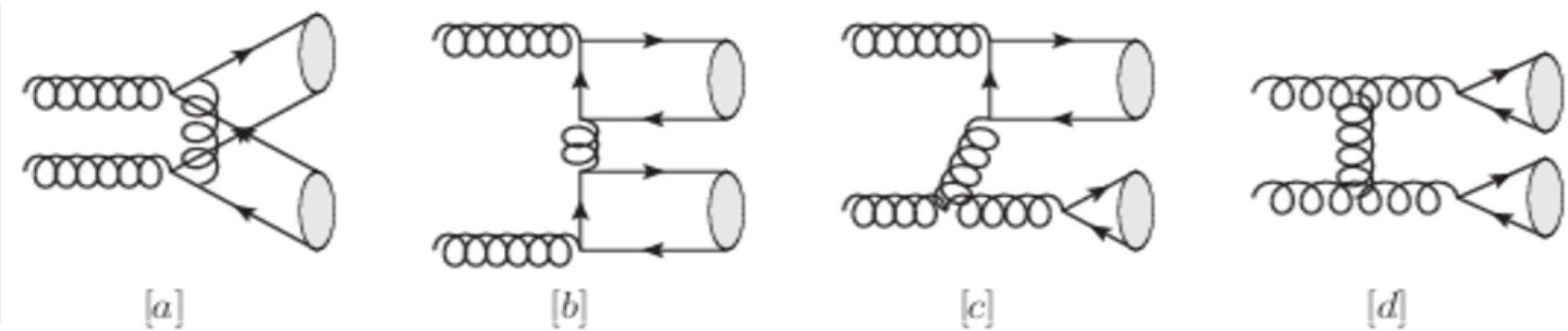
$$d\sigma(AB \to 2J/\psi + X) = \sum_{i,j,m,n,H_1,H_2} \int dx_1 dx_2$$
$$\times f_{i/A}(x_1) f_{j/B}(x_2) d\hat{\sigma}(ij \to c\bar{c}(m) c\bar{c}(n) + X)$$
$$\times \langle \mathcal{O}^{H_1}(m) \rangle \mathrm{Br}(H_1 \to J/\psi + X) \times \langle \mathcal{O}^{H_2}(n) \rangle \mathrm{Br}(H_2 \to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

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

Note

The $q\bar{q}$ process is highly suppressed, so we only focus on the gg 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

- Using the velocity scaling rules of NRQCD LDMEs and assuming that the branching fraction is also of order v^2, 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 $\alpha_s^{(4)}$ with $\Lambda^{(4)} = 192$ MeV, and CTEQ5L PDF.
$\mu_r = \mu_f = m_T = \sqrt{(4m_c)^2 + p_T^2}$.

Branching fractions 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 are 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 the low-$m_{J/\psi J/\psi}$ region. For $m_{J/\psi J/\psi} \gg 2m_{J/\psi}$, the contributions of the NNLP-II, NLP, and LP subprocesses can be orders of magnitude larger than that of the CS^* channel.
- From 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

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

LO CS*+CO* prediction

$$\sigma_{\rm tot}^{*} = 12.2^{+4.8}_{-3.8}\ {\rm nb}. \tag{4}$$

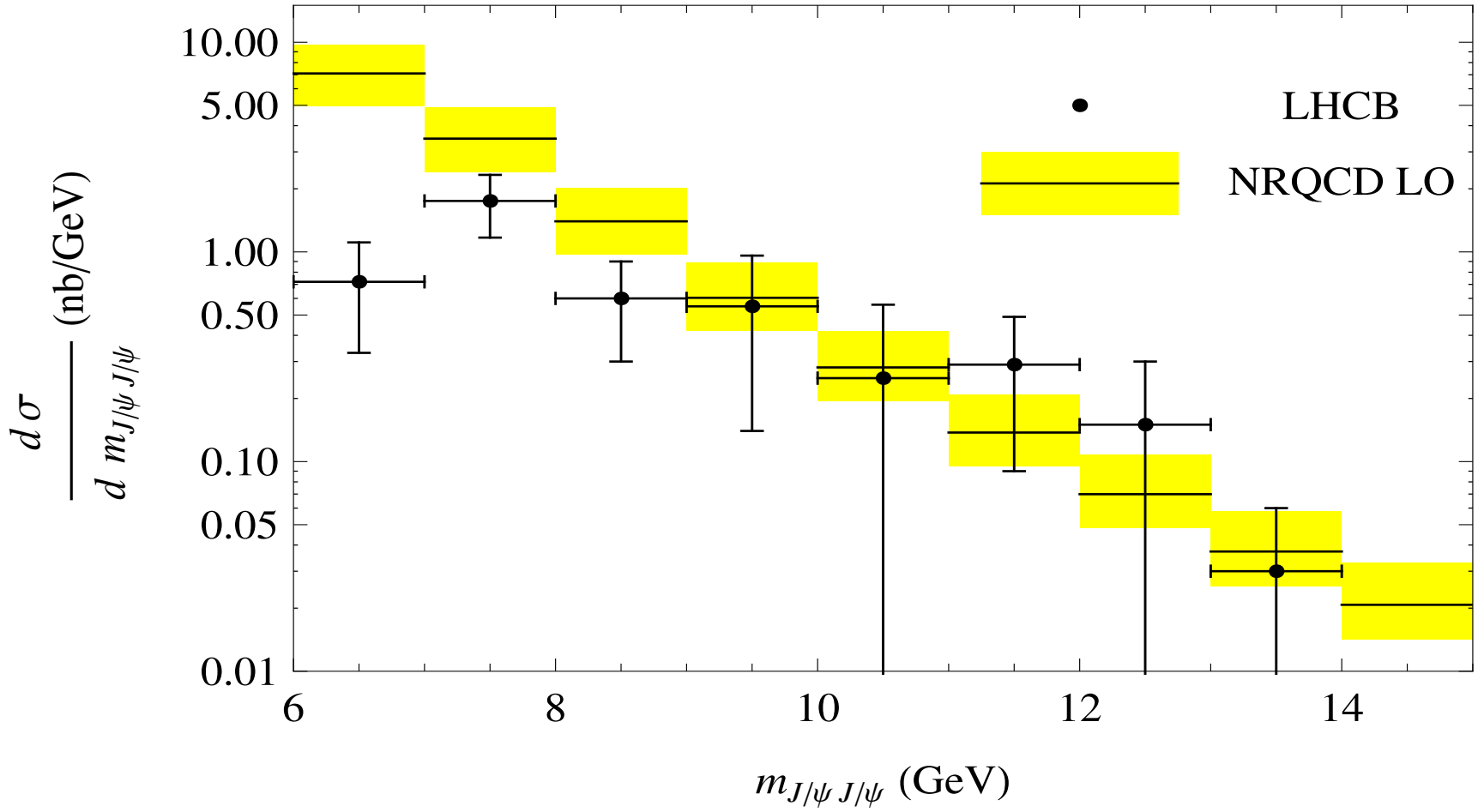
Complete LO prediction

$$\sigma_{\rm tot} = 13.2^{+5.2}_{-4.1}\ {\rm nb}, \tag{5}$$

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

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

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 predictions meet CMS measurements I

The measured cross section

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

LO CS*+CO* prediction

$$\sigma_{\rm tot}^{*} = 0.10^{+0.05}_{-0.03}\ {\rm nb}. \tag{9}$$

Complete LO prediction

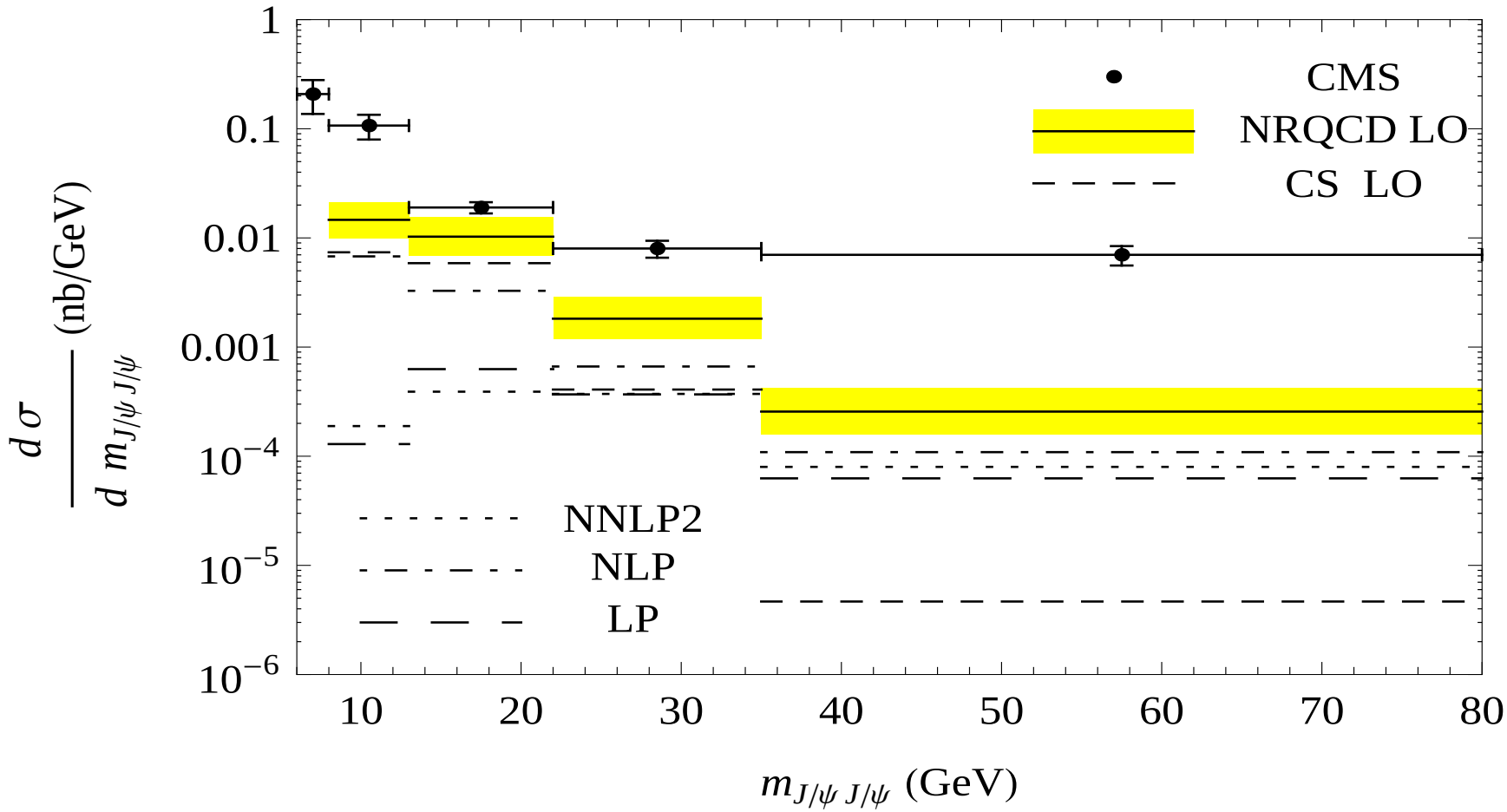
$$\sigma_{\rm tot} = 0.15^{+0.08}_{-0.05}\ {\rm nb}. \tag{10}$$

NLO CS* prediction (arXiv:1404.4042)

$$\sigma_{\rm CS}^{*} = 0.98 \pm 0.16\ {\rm nb}. \tag{11}$$

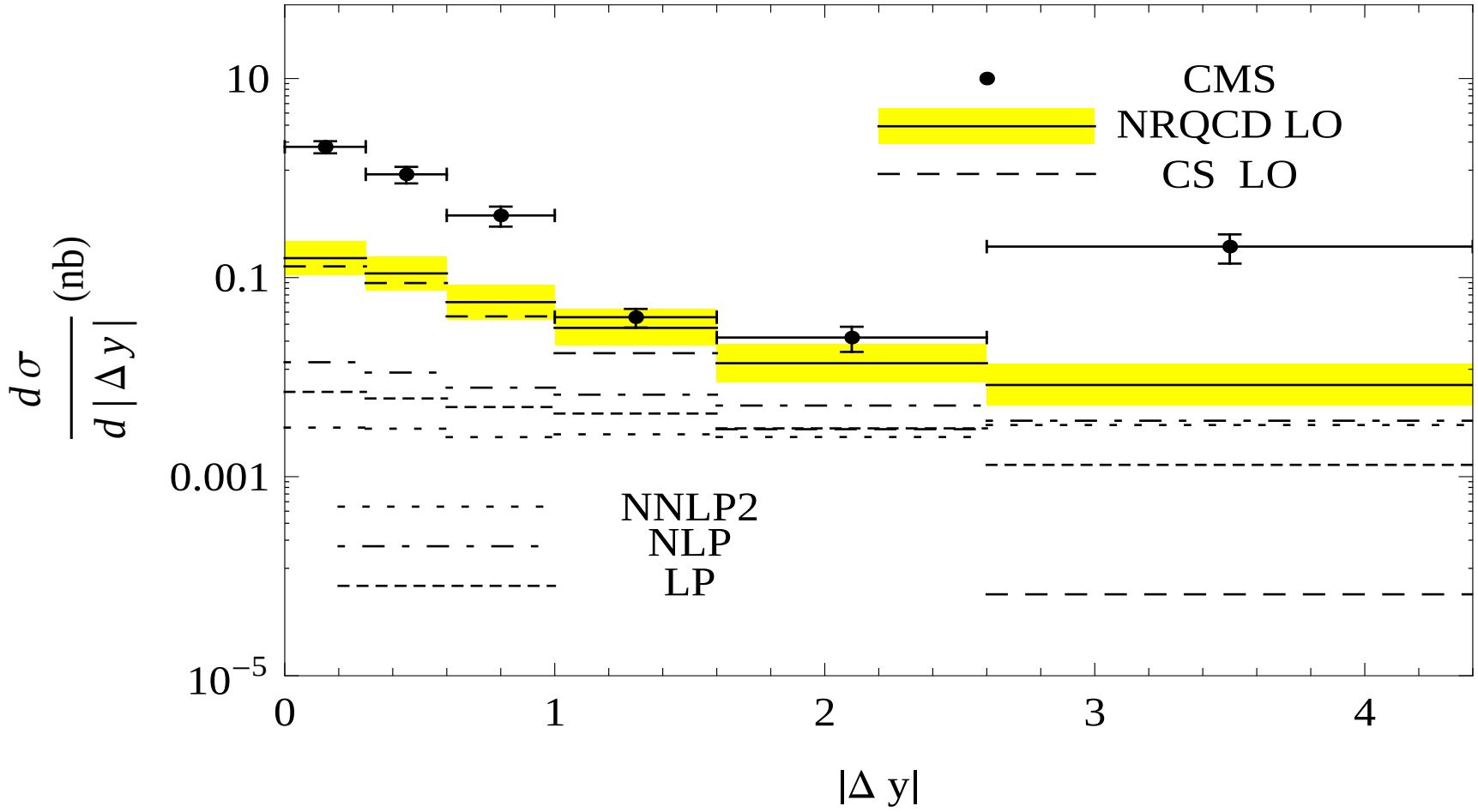
NRQCD preditions meet CMS measurements II

- 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

- Double J/ψ hadroproduction was for the first time completely studied within NRQCD factorization formalism, including all the possible combinations of CS and CO channels and the contribution of χ_{cJ} and $\psi(2S)$ 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 differences between NRQCD predictions and CMS measurements in large $m_{J/\psi J/\psi}$ and $|\Delta y|$ bins.

Thank you !