η_c Production at LHC and Implications for the Understanding of J/ψ Production

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Based on works done with:

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Outline

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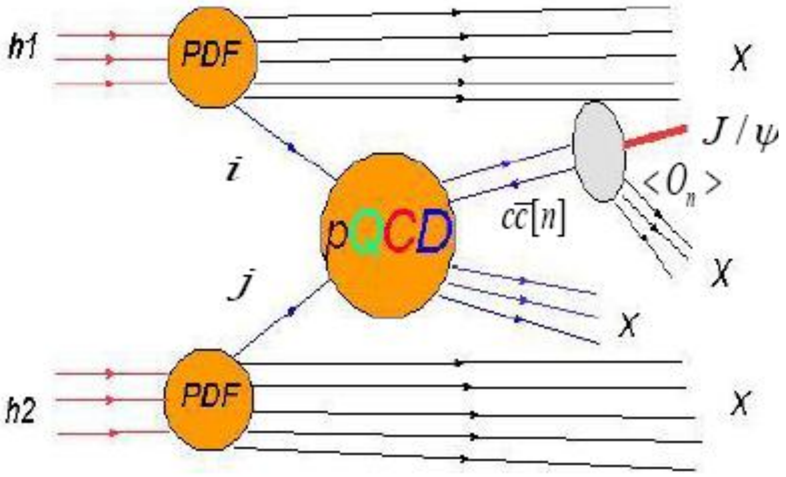
NRQCD factorization



NRQCD factorization: G. Bodwin *et al*. PRD. 51, 1125 (1995)

$$d\sigma_{s_z s_z} = \sum_{i,j,n} \iint dx_1 dx_2 G_{i/p} G_{j/p} \langle O_n^H \rangle d\sigma_{s_z s_z}^{i,j,n}$$

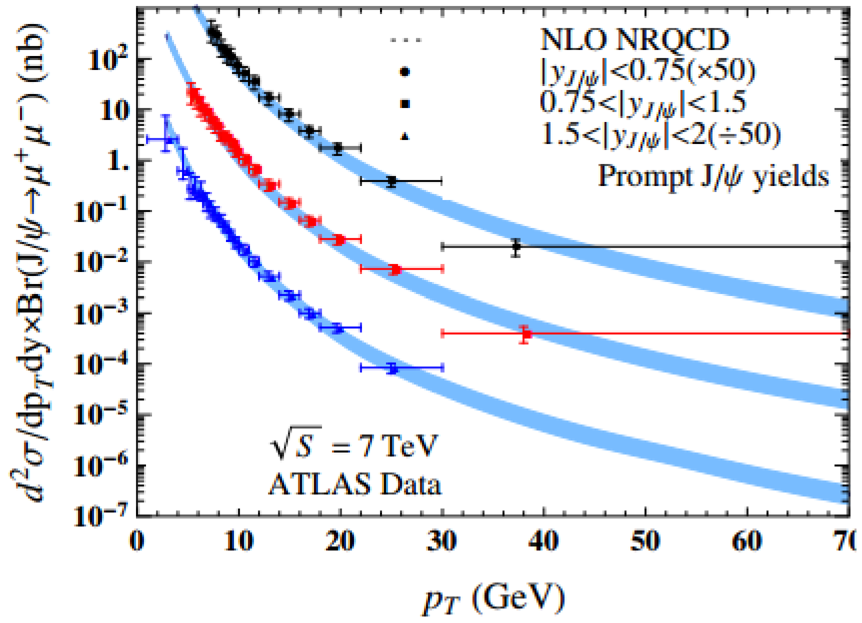
➢For the direct J/ψ production, four LDMEs are $\mathcal{O}^{J/\psi}\left({}^3S_1^{[1]}\right)$, $\mathcal{O}^{J/\psi}\left({}^3S_1^{[8]}\right)$, $\mathcal{O}^{J/\psi}\left({}^1S_0^{[8]}\right)$, $\mathcal{O}^{J/\psi}\left({}^3P_J^{[8]}\right)$.

The production is factorized into perturbative calculable short-distance coefficients and nonperturbative long-distance matrix elements(LDMEs).

The short-distance coefficients can be scaled by α_s and v. $v_c^2 \approx 0.23, v_b^2 \approx 0.08$.

J/ψ production and polarization

- Complete next-to-leading order(NLO) QCD corrections for J/ψ hadroproduction have been calculated by three groups independently. PRL 106, 042002(2011), PRL 106, 022003(2011), PRL 110, 042002(2013)



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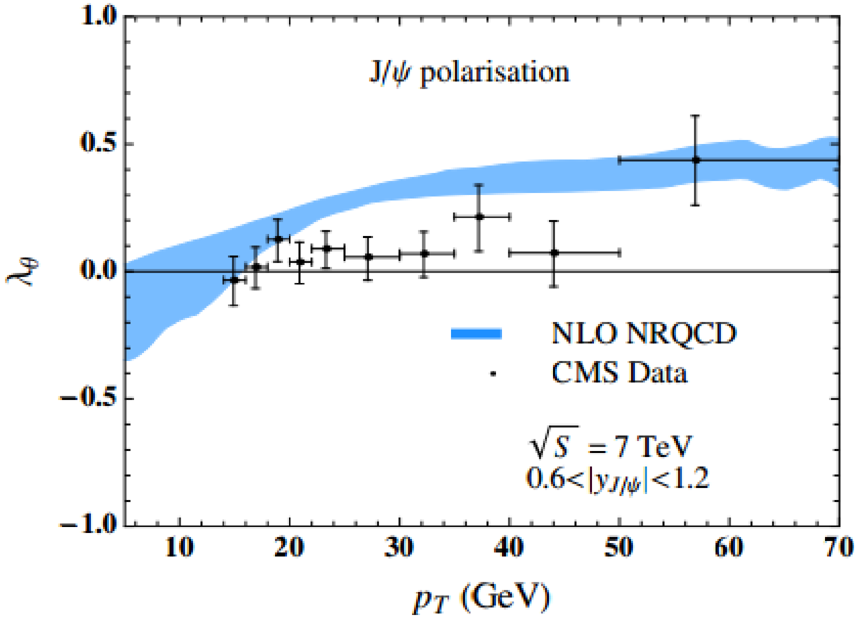

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- Our group find that J/ψ polarization can be explained by NLO NRQCD, whereas the other two groups concluded that NRQCD cannot explain the polarization data. PRL 106, 042002(2011)

J/ψ production and polarization

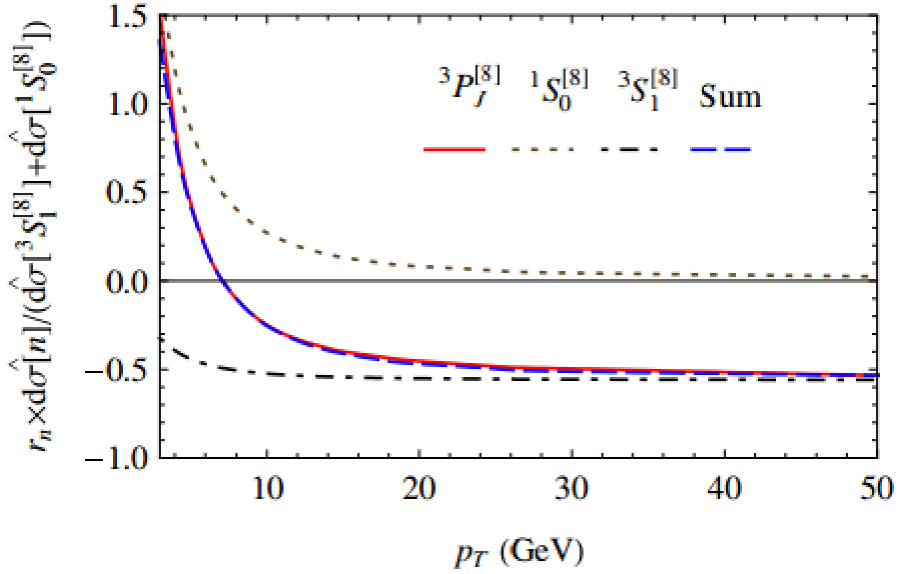
- P-wave CO Fock state decomposition:

$$\widehat{d\sigma}\left[\,{}^3P_J^{[8]}\right] = r_0\widehat{d\sigma}\left[\,{}^1S_0^{[8]}\right] + r_1\widehat{d\sigma}\left[\,{}^3S_1^{[8]}\right]$$

For CDF condition: $r_0 = 3.9, r_1 = -0.56$

- At $P_T > 7$ Gev, we find the P-wave Fock state decomposition with little uncertainties.
- Thus, we obtain two linearly combined LDMEs:

$$M_{0,r_0}^{J/\psi} = \left\langle \mathcal{O}^{J/\psi}\left(\,{}^1S_0^{[8]}\right)\right\rangle + \frac{r_0}{m_c^2}\left\langle \mathcal{O}^{J/\psi}\left(\,{}^3P_0^{[8]}\right)\right\rangle$$
$$M_{1,r_1}^{J/\psi} = \left\langle \mathcal{O}^{J/\psi}\left(\,{}^3S_1^{[8]}\right)\right\rangle + \frac{r_1}{m_c^2}\left\langle \mathcal{O}^{J/\psi}\left(\,{}^3P_0^{[8]}\right)\right\rangle$$



PRL 106, 042002(2011)

$$M_0 = (7.4 \pm 1.9) \times 10^{-2}\mathrm{GeV}^3, M_1 = (0.05 \pm 0.02) \times 10^{-2}\mathrm{GeV}^3$$

J/ψ production and polarization

- The M_1' in the transverse component is:

$$M_1' = \left\langle \mathcal{O}^{J/\psi}\left({}^3S_1^{[8]}\right)\right\rangle - \frac{0.52}{m_c^2}\left\langle \mathcal{O}^{J/\psi}\left({}^3P_0^{[8]}\right)\right\rangle$$

- Furtherly, we find that the transversely polarized cross section for direct J/ψ is almost proportional to M_1'.

Since the of M_1' or M_1 is much smaller than that of M_0 , we expect that the polarizations will be dominated by M_0 at least in the intermediate P_T region, which tends to give unpolarized results.

Note: The expectation is independent of the exact values of three CO LDMEs of J/ψ, as long as M_0 and M_1 are fixed.

η_c production

- For the direct η_c production, four LDMEs are $\mathcal{O}^{\eta_c}\left({}^1S_0^{[1]}\right)$, $\mathcal{O}^{\eta_c}\left({}^3S_1^{[8]}\right)$, $\mathcal{O}^{\eta_c}\left({}^1S_0^{[8]}\right)$, $\mathcal{O}^{\eta_c}\left({}^1P_1^{[8]}\right)$.
- The dominant feeddown contribution through $h_c \to \eta_c\gamma$ contains two other LDMEs $\mathcal{O}^{h_c}\left({}^1P_1^{[1]}\right)$ and $\mathcal{O}^{h_c}\left({}^1S_0^{[8]}\right)$.

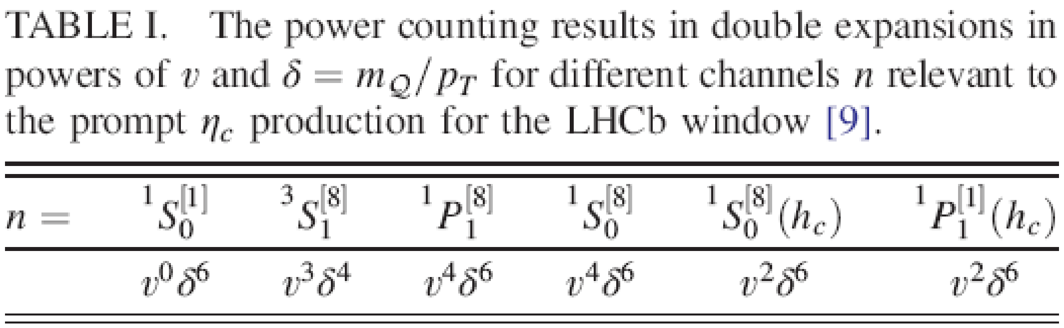


TABLE I. The power counting results in double expansions in powers of v and $\delta = m_Q/p_T$ for different channels n relevant to the prompt η_c production for the LHCb window [9].

$n =$	${}^1S_0^{[1]}$	${}^3S_1^{[8]}$	${}^1P_1^{[8]}$	${}^1S_0^{[8]}$	${}^1S_0^{[8]}(h_c)$	${}^1P_1^{[1]}(h_c)$
	$v^0\delta^6$	$v^3\delta^4$	$v^4\delta^6$	$v^4\delta^6$	$v^2\delta^6$	$v^2\delta^6$

PRL 114, 092005(2015)

We find that only the ${}^3S_1^{[8]}$ channel behaves as P_T^{-4}, while all other channels behave as P_T^{-6}.

As a result, only the ${}^1S_0^{[1]}$ and ${}^3S_1^{[8]}$ channels give the leading contributions in combined power counting.

Relationship between J/ψ and η_c production

- Heavy quark Spin Symmetry (HQSS)

$$\left\langle \mathcal{O}^{\eta_c}\left({}^1S_0^{[1]}\right)\right\rangle = \left\langle \mathcal{O}^{J/\psi}\left({}^3S_1^{[1]}\right)\right\rangle/3$$

$$\left\langle \mathcal{O}^{\eta_c}\left({}^3S_1^{[8]}\right)\right\rangle = \left\langle \mathcal{O}^{J/\psi}\left({}^1S_0^{[8]}\right)\right\rangle$$

$$\left\langle \mathcal{O}^{\eta_c}\left({}^1S_0^{[8]}\right)\right\rangle = \left\langle \mathcal{O}^{J/\psi}\left({}^3S_1^{[8]}\right)\right\rangle/3$$

$$\left\langle \mathcal{O}^{\eta_c}\left({}^1P_1^{[8]}\right)\right\rangle = 3\left\langle \mathcal{O}^{J/\psi}\left({}^3P_0^{[8]}\right)\right\rangle$$

$$\left\langle \mathcal{O}^{h_c}\left({}^1S_0^{[8]}\right)\right\rangle = 3\left\langle \mathcal{O}^{\chi_{c0}}\left({}^3S_1^{[8]}\right)\right\rangle$$

$$\left\langle \mathcal{O}^{h_c}\left({}^1P_1^{[1]}\right)\right\rangle = 3\left\langle \mathcal{O}^{\chi_{c0}}\left({}^3P_0^{[1]}\right)\right\rangle$$

- We use the CTEQ6M parton distribution for NLO calculations and use HeLAC-Onia to calculate the hard noncollinear part of real correction. *Comput. Phys. Commun. 184 (2013) pp. 2562-2570*

- The charm-quark mass is set to be $m_c =$ 1.5 GeV, the renormalization, factorization, and NRQCD scales are $\mu_r = \mu_f = \sqrt{P_T^2 + 4m_c^2}$ and $\mu_\Lambda = m_c$.

- Thanks to LHCb data, we can determine η_c production LDMEs. *Eur. Phys. J. C75 (2015) 7, 311*

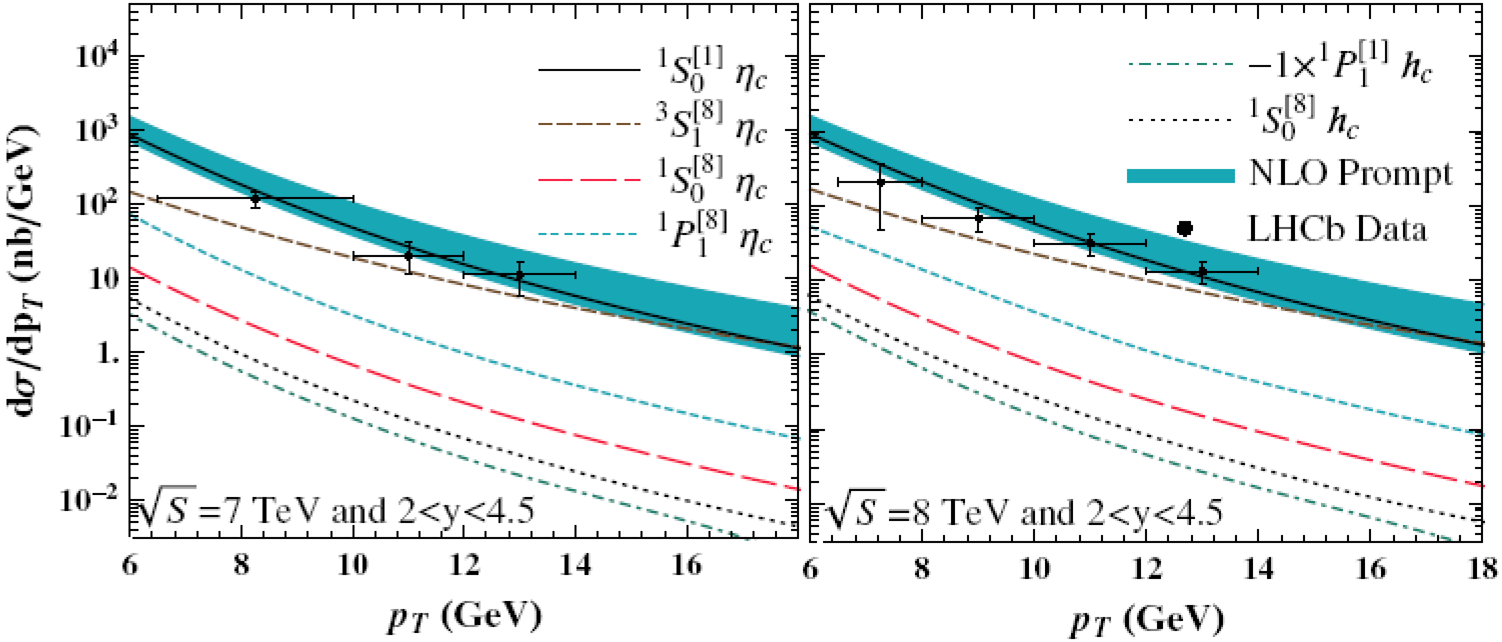
η_c production

We find that the LHCb data are almost saturated by the contribution from the CS channel.

Phys.Rev.D52:1726-1728,1995

Is there any contribution from the ${}^3S_1^{[8]}$ channel ?? Yes!

There are large uncertainties of the data. The slope of data is different from the contribution of ${}^1S_0^{[1]}$ channel.



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The value of CS LDME is not exact, but with at least an uncertainty of order $v^2 \sim 0.3$ because of modeling of potential, relativistic corrections, HQSS broken, and so on.

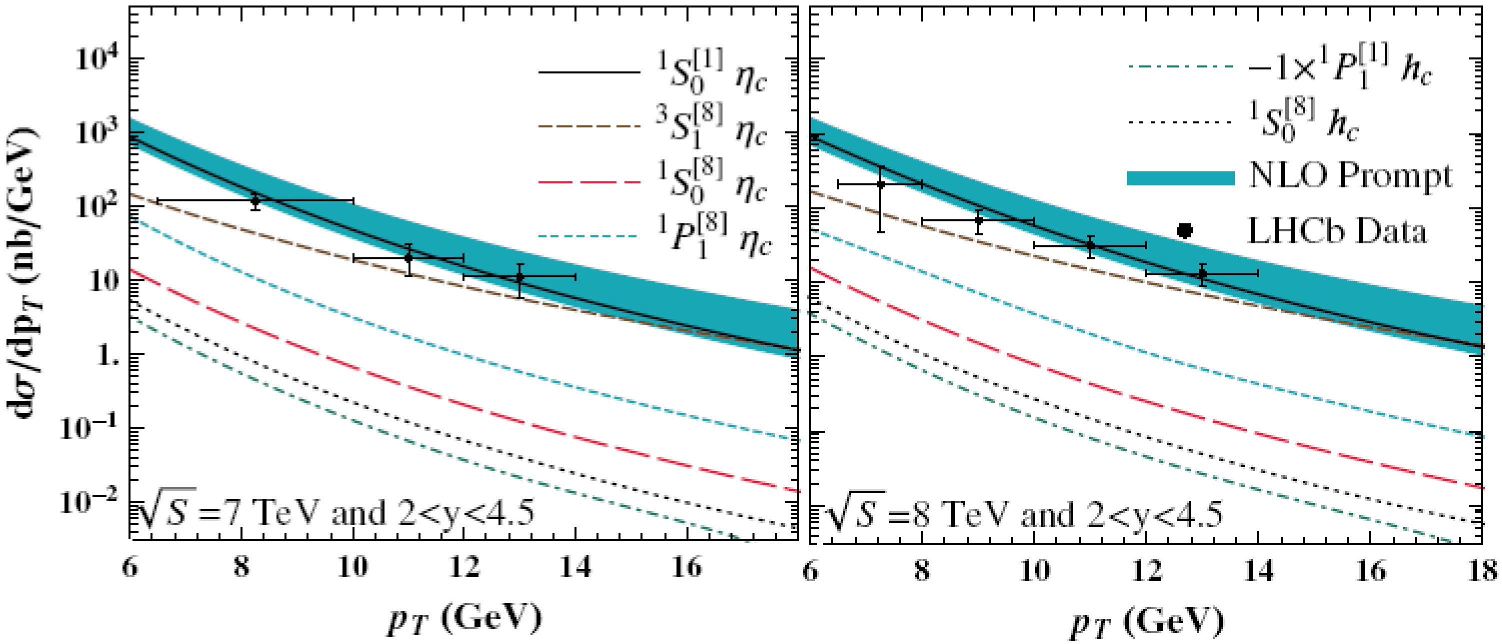
η_c production

Although it is hard at present to determine the exact value of $\mathcal{O}^{\eta_c}\left({}^3S_1^{[8]}\right)$ due to the large uncertainties from both data and theory.

We can give a safe upper bound for $\mathcal{O}^{\eta_c}\left({}^3S_1^{[8]}\right)$ by letting the data be saturated by ${}^3S_1^{[8]}$ channel.

$$\mathcal{O}^{\eta_c}\left({}^3S_1^{[8]}\right) = (1.46 \pm 0.20) \times 10^{-2}\mathrm{GeV}^3$$

$$\boxed{0 < \mathcal{O}^{\eta_c}\left({}^3S_1^{[8]}\right) < 1.46 \times 10^{-2}\mathrm{GeV}^3}$$



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η_c production

By using the HQSS and M_0 and M_1, we can constrain all other CO LDMEs of J/ψ and η_c.

$$\left\langle \mathcal{O}^{\eta_c}\left({}^1S_0^{[1]}\right)\right\rangle = \left\langle \mathcal{O}^{J/\psi}\left({}^3S_1^{[1]}\right)\right\rangle/3 = 0.39\ \mathrm{GeV}^3$$

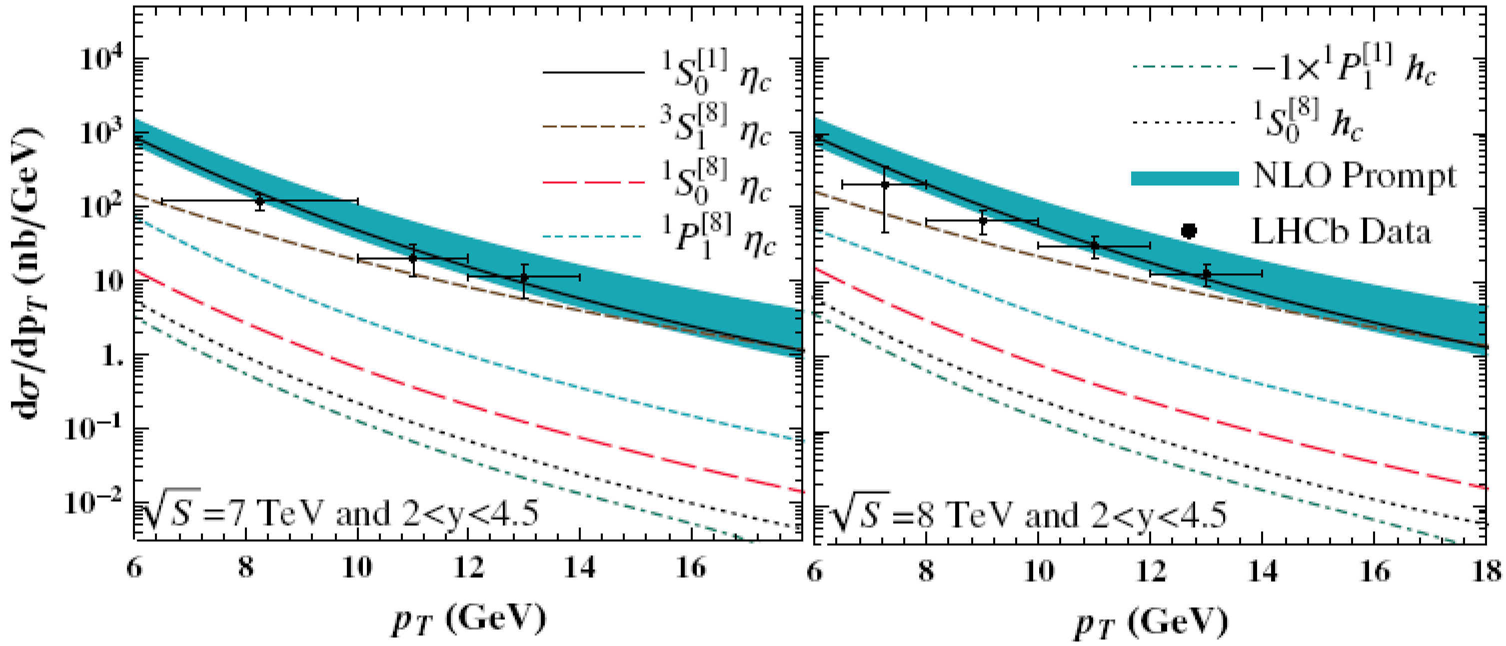
$$\left\langle \mathcal{O}^{\eta_c}\left({}^3S_1^{[8]}\right)\right\rangle = \left\langle \mathcal{O}^{J/\psi}\left({}^1S_0^{[8]}\right)\right\rangle = \frac{0.0146}{2}\ \mathrm{GeV}^3$$

$$\left\langle \mathcal{O}^{\eta_c}\left({}^1S_0^{[8]}\right)\right\rangle = \left\langle \mathcal{O}^{J/\psi}\left({}^3S_1^{[8]}\right)\right\rangle/3 = \frac{0.01}{3}\ \mathrm{GeV}^3$$

$$\left\langle \mathcal{O}^{\eta_c}\left({}^1P_1^{[8]}\right)\right\rangle = 3\left\langle \mathcal{O}^{J/\psi}\left({}^3P_0^{[8]}\right)\right\rangle = 3 \times 0.017 \times 2.25\ \mathrm{GeV}^5$$

$$\left\langle \mathcal{O}^{h_c}\left({}^1S_0^{[8]}\right)\right\rangle = 3\left\langle \mathcal{O}^{\chi_{c0}}\left({}^3S_1^{[8]}\right)\right\rangle = 3 \times 0.27 \times \frac{3 \times 0.075}{4\pi \times 2.25}\ \mathrm{GeV}^3$$

$$\left\langle \mathcal{O}^{h_c}\left({}^1P_1^{[1]}\right)\right\rangle = 3\left\langle \mathcal{O}^{\chi_{c0}}\left({}^3P_0^{[1]}\right)\right\rangle = 3 \times \frac{3 \times 0.075}{4\pi}\ \mathrm{GeV}^5$$



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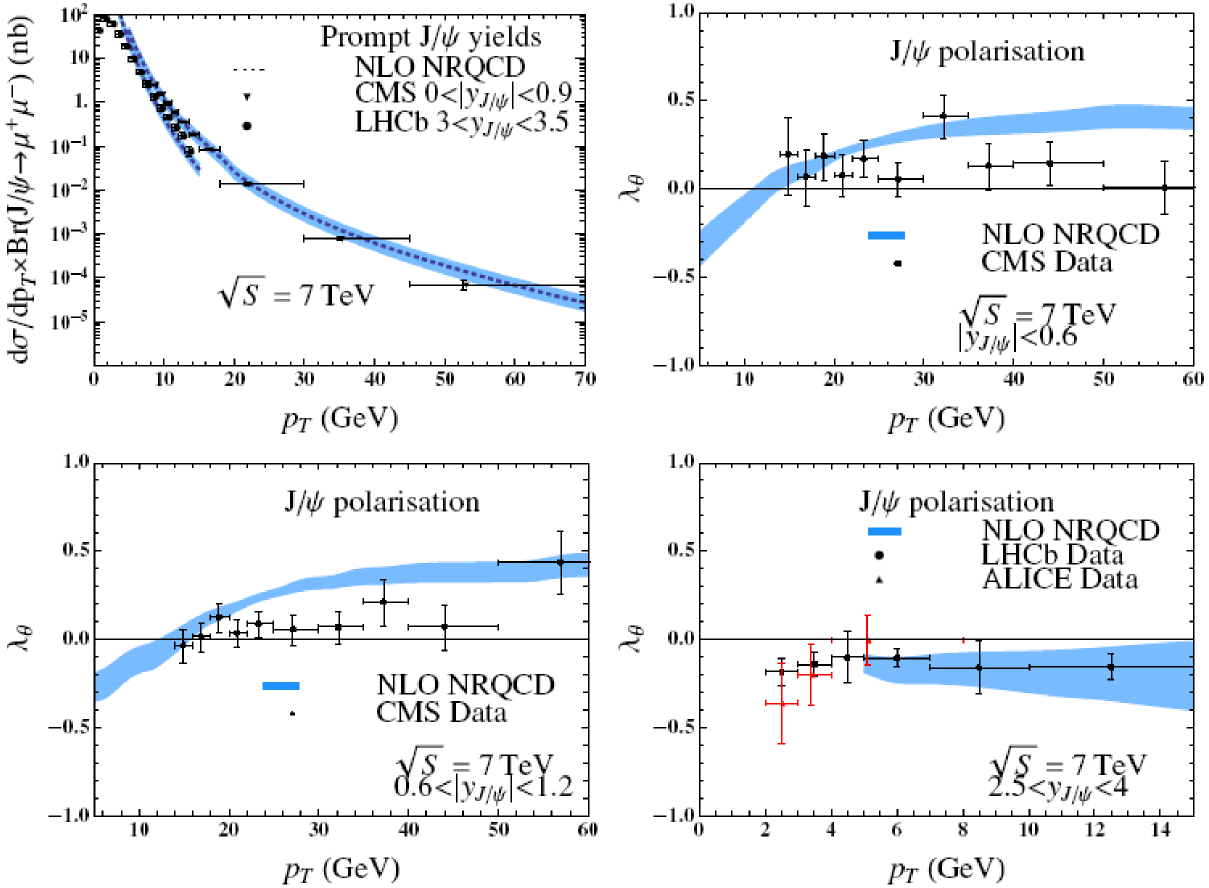
We find that the CS channel is larger than the others by 1 or 2 orders of magnitude. Thus, the upper bound of the value of $\mathcal{O}^{\eta_c}\left({}^3S_1^{[8]}\right)$ will not be changed even when these new contributions are taken into account.

Updated J/ψ production



PRL 114, 092005(2015)

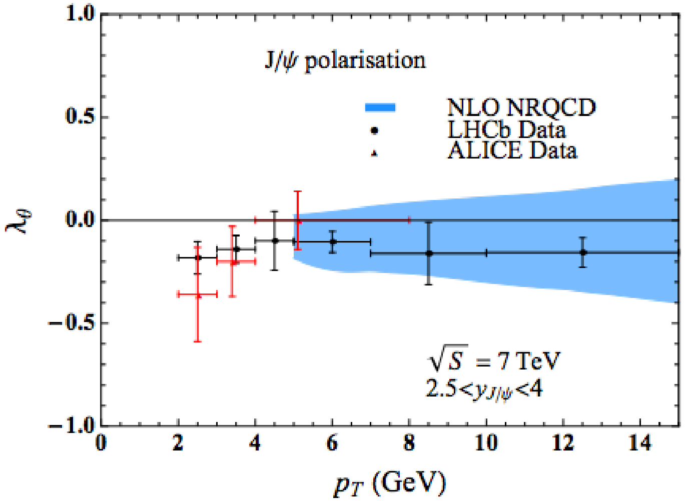
By using LHCb data and HQSS, we constrain the three CO LDMEs for J/ψ.

$$0 < \mathcal{O}^{J/\psi}\left({}^1S_0^{[8]}\right) < 1.46 \times 10^{-2}\mathrm{GeV}^3$$

It is better to update our predictions for both yields and polarizations of J/ψ prompt production.

Note: The new predictions for CMS window are almost unchanged, because the predictions for yield are only sensitive to LDMEs M_0 and M_1, and for polarizations are only sensitive to M_1'.

Updated J/ψ production



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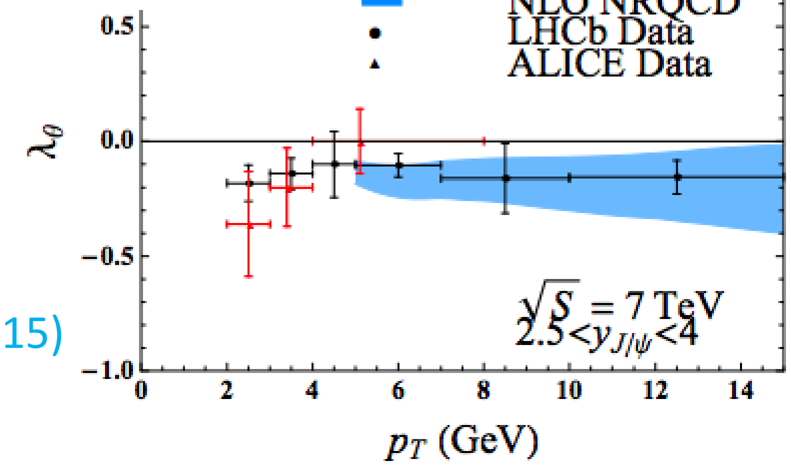

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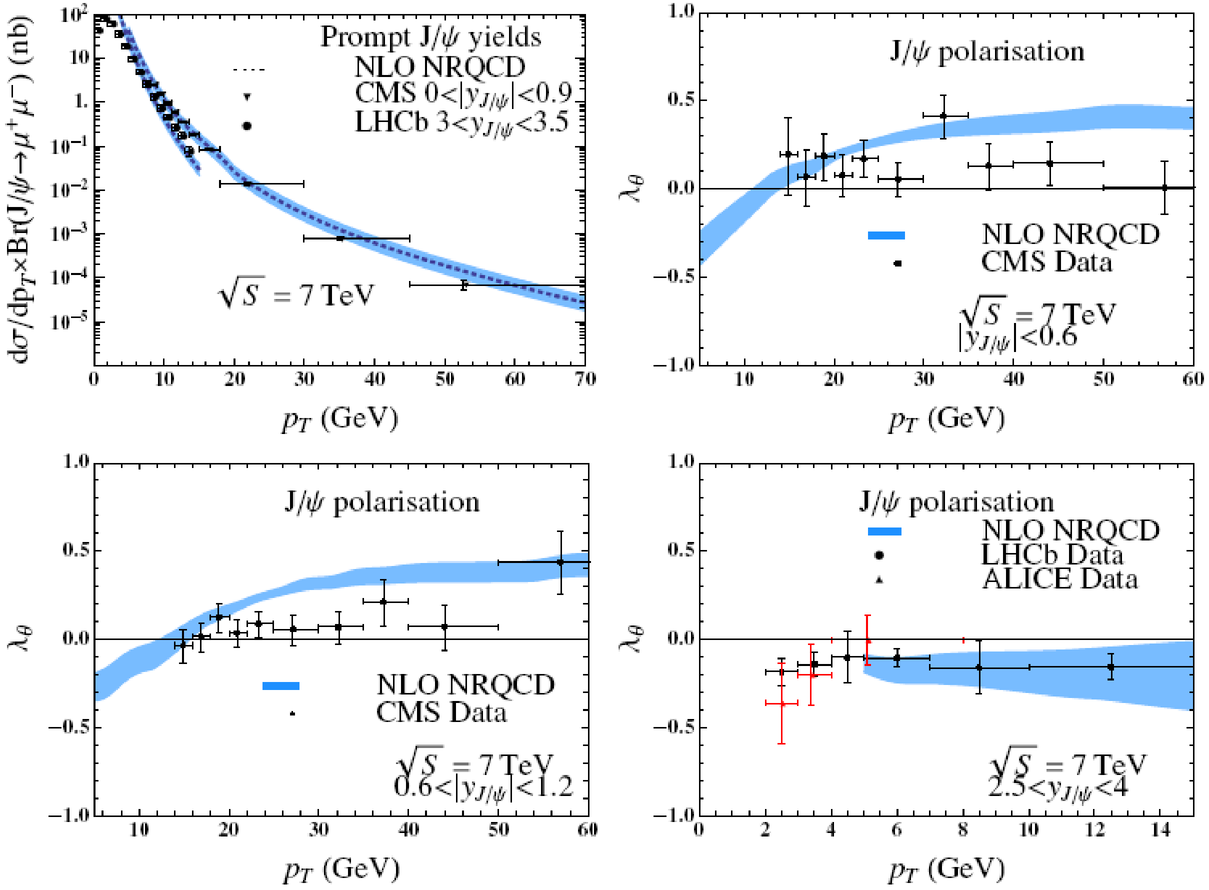
Note: Our new prediction of the polarization for LHCb window tends to be more longitudinally polarized.

- Because r_1 in the forward rapidity interval is smaller than that in the central rapidity interval, the relatively large and positive $\mathcal{O}^{J/\psi}\left({}^3P_0^{[8]}\right)$, will imply that the transversely polarized component of the cross section should be further reduced in forward rapidity interval, compared with the central one.

$$M_{0,r_0}^{J/\psi} = \left\langle \mathcal{O}^{J/\psi}\left({}^1S_0^{[8]}\right)\right\rangle + \frac{r_0}{m_c^2}\left\langle \mathcal{O}^{J/\psi}\left({}^3P_0^{[8]}\right)\right\rangle$$

$$M_{1,r_1}^{J/\psi} = \left\langle \mathcal{O}^{J/\psi}\left({}^3S_1^{[8]}\right)\right\rangle + \frac{r_1}{m_c^2}\left\langle \mathcal{O}^{J/\psi}\left({}^3P_0^{[8]}\right)\right\rangle$$

Updated J/ψ production



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Note: The $\chi^2/d.o.f$. Values for polarization data 13/10 and 22/10 for the CMS data with $0 < |y| < 0.6$ and $0.6 < |y| < 1.2$ and 1.2/2 for the LHCb data.

Although the agreement between our predictions and CMS polarizations data is not very good, it is tolerable considering the large experimental and theoretical uncertainties. In particular, the current CMS data still suffer form large statistical fluctuations.

${}^1S_0^{[8]}$ dominance and HQSS

- The upper bound of $\left\langle \mathcal{O}^{J/\psi}\left({}^1S_0^{[8]} \right) \right\rangle$ by fitting the LHCb data is 0.0146.
  - However, many other NLO NRQCD fits in the literature disagree with our results along with HQSS.

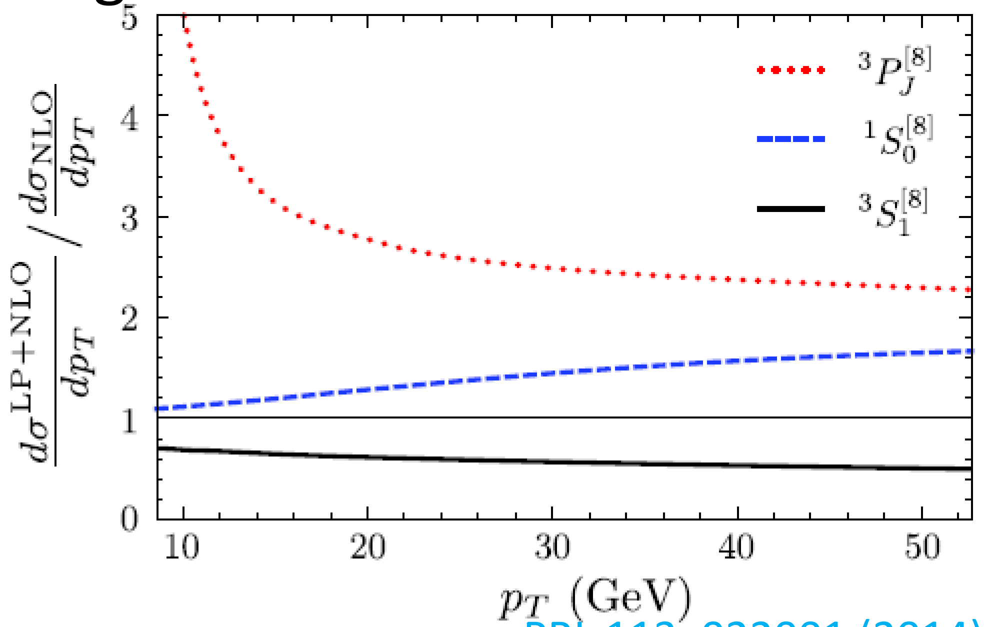
M.Butenschon *et al*. PRL, 106, 022003 (2011)	0.0304+-0.0035
B. Gong *et al*. PRL 110, 042002 (2013)	0.097+-0.009
G. T. Bodwin *et al*. PRL 113, 022001 (2014)	0.099+-0.022

  - The authors PLB 736, 98 (2014) argued that ${}^1S_0^{[8]}$ will dominate the J/ψ production and $\left\langle \mathcal{O}^{J/\psi}\left({}^1S_0^{[8]} \right) \right\rangle$ should be at least larger than 0.07 GeV^3.

Note: By saturating LHCb data, we give a very safe upper bound for $\left\langle \mathcal{O}^{J/\psi}\left({}^1S_0^{[8]} \right) \right\rangle$.

${}^1S_0^{[8]}$ dominance and HQSS

- May the contradiction with these NLO NRQCD indicate that HQSS is broken or there are still some theoretical problems to be clarified, if LHCb data are reliable??
- If HQSS is good, a natural way to resolve the contradiction could be that the NNLO correction for NLP contribution is significant.
- We conjecture that it is mainly this extra LP contribution that the theoretical curve of the ${}^3P_J^{[8]}$ channel, and results in a ${}^1S_0^{[8]}$ dominance conclusion. *See Y.-Q. Ma's talk.*



PRL 113, 022001 (2014)

Summary and Outlook

- Within NLO NRQCD, we demonstrate that ${}^1S_0^{[1]}$ and ${}^3S_1^{[8]}$ channels are essential for the η_c production at LHC.
- By comparing with the LHCb data, we find the η_c production tends to be saturated by contributions from CS channel.
- With HQSS relation, we update our predictions for J/ψ yield and polarization production.
- We conclude that the prompt production of η_c and J/ψ can be understood in the same theoretical framework.
- In order to test rigorously the validation of HQSS for charmonium production, it is necessary to calculate complete both LP and NLP corrections to the same order in α_s.