η_c Production at the LHC Challenges Nonrelativistic-QCD Factorization

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Outline

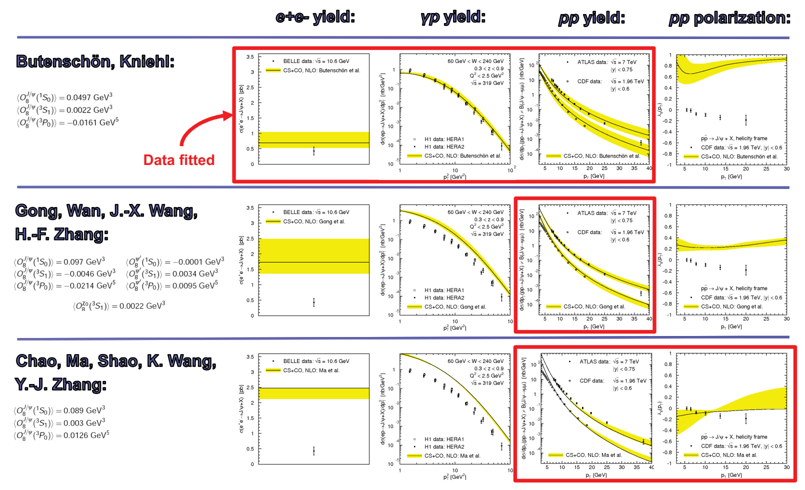
1. Background
   - "J/ψ polarization puzzle"
   - η_c hadroproduction
2. NRQCD Predictions @ QCD and v^2 NLO
   - Theoretical framework
   - Compare NRQCD predictions with LHCb measurements
   - Comparison with other calculations
3. Conclusion

Single J/ψ polarization puzzle-I

- After 20 years of the introduction of the NRQCD factorization formalism by Bodwin,Bratten, and Lapage in 1995, the long-standing "J/ψ polarization puzzle" has not been resolved yet.
- By far, the short-distance coefficients (SDCs) are known at QCD next-to-leading order (NLO) and v^2 subleading order for yield and polarization of all the relavent channels including χ_c feed-down contribution as well.
- Different sets of long-distance matrix elements (LDMEs) are obtained by fitting the SDCs @ QCD NLO to experimental data under different considerations, which lead to completely different conclusions.

Single J/ψ polarization puzzle-II

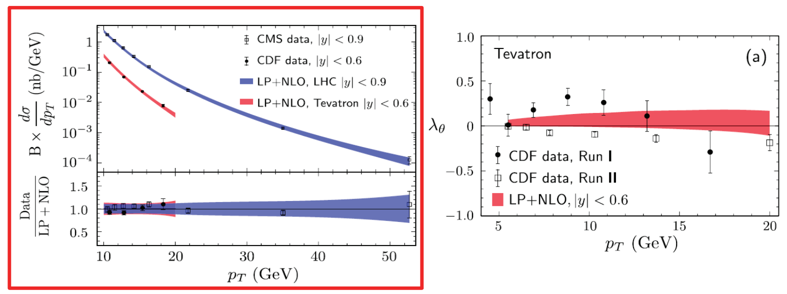
NRQCD predictions meet experimental data I



Single J/ψ polarization puzzle III

NRQCD predictions meet experimental data II

- The LDMEs are also determined independently by fitting the fragmentation calculation to J/ψ hadroproduction data (Bodwin et al. 2013) yielding that $\langle\mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle = \langle 0.099 \pm 0.022\ \mathrm{GeV}^3\rangle$, $\langle\mathcal{O}^{J/\psi}({}^3S_1^{[8]})\rangle = \langle 0.011 \pm 0.010\ \mathrm{GeV}^3\rangle$, $\langle\mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle = \langle 0.011 \pm 0.010\ \mathrm{GeV}^5\rangle$.



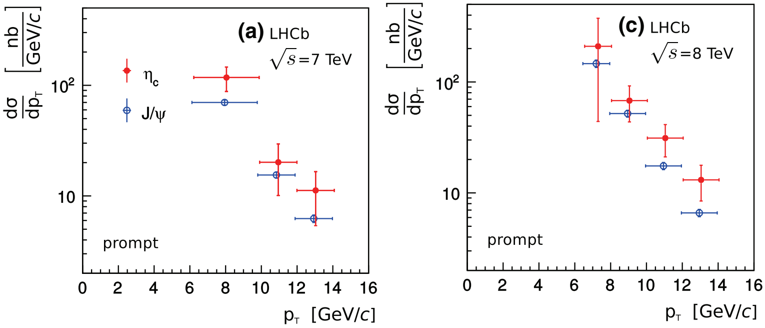
Why are we interested in prompt η_c hadroproduction?

- η_c is another quarkonium state with $J^{PC} = 0^{-+}$ other than J/ψ with $J^{PC} = 1^{--}$, which can provide a new test on NRQCD factorization.
- In NRQCD, η_c is related to J/ψ through the heavy quark spin symmetry(HQSS), so do the corresponding LDMEs in their production. For example,

$$
\begin{aligned}
\langle \mathcal{O}^{\eta_c}({}^1S_0^{[1,8]}) \rangle &= \frac{1}{3} \langle \mathcal{O}^{J/\psi}({}^3S_1^{[1,8]}) \rangle \\
\langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]}) \rangle &= \langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) \rangle \\
\langle \mathcal{O}^{\eta_c}({}^1P_1^{[8]}) \rangle &= 3 \langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]}) \rangle \\
\langle \mathcal{O}^{h_c}({}^1P_1^{[1]}/{}^1S_0^{[8]}) \rangle &= \langle \mathcal{O}^{\chi_{c0}}({}^3P_0^{[1]}/{}^3S_1^{[8]}) \rangle
\end{aligned}
$$

Its production provides an additional constrain on the LDMEs for J/ψ production.

- In 2014, the LHCb Collaboration manage to measure prompt η_c hadroproduction for the first time at center of mass energy of 7 TeV and 8 TeV LHC. (LHCb Collaboration, 2015)



- For details see Sebastian Neubert's talk.

NRQCD factorization formula for prompt η_c production up to v^2 subleading order:

$$
\begin{aligned}
d\sigma^{\eta_c}_{\text{prompt}} = & \sum_{n={}^1S_0^{[1]},{}^1S_0^{[8]},{}^3S_1^{[8]},{}^1P_1^{[8]}} \Big[d\sigma^{c\bar{c}[n]} \langle \mathcal{O}^{\eta_c}(n) \rangle \\
& + d\sigma^{c\bar{c}[n]}_{v^2} \langle \mathcal{P}^{\eta_c}(n) \rangle \Big] + \sum_{n={}^1P_1^{[1]},{}^1S_0^{[8]}} \Big[d\sigma^{c\bar{c}[n]} \langle \mathcal{O}^{h_c}(n) \rangle \\
& + d\sigma^{c\bar{c}[n]}_{v^2} \langle \mathcal{P}^{h_c}(n) \rangle \Big] \mathcal{B}(h_c \to \eta_c \gamma),
\end{aligned}
$$

where $d\sigma^{c\bar{c}[n]}$ are the Born SDCs including their $\mathcal{O}(\alpha_s)$ corrections, $d\sigma^{c\bar{c}[n]}_{v^2}$ contain their $\mathcal{O}(v^2)$ corrections, and $\langle \mathcal{Q}^h(n) \rangle$ with $\mathcal{Q} = \mathcal{O}, \mathcal{P}$ and $h = \eta_c, h_c$ are the appropriate LDMEs.

NRQCD factorization formalism-II

- The $\mathcal{O}(\alpha_s)$ SDC of $n = {}^1P_1^{[1]}$ is known. (Wang and Zhang, 2015)
- The $\mathcal{O}(\alpha_s)$ SDCs of $n = {}^1S_0^{[1]}$ and $n = {}^1P_1^{[8]}$ are new.
- The $\mathcal{O}(v^2)$ SDCs of $n = {}^1S_0^{[1]}$, $n = {}^1P_1^{[1]}$ and $n = {}^1P_1^{[8]}$ are new.

- The definitions of the new $P-$ wave four-fermion operators:

$$\mathcal{P}^{\eta_c}({}^1P_1^{[8]}) = \chi^\dagger \left(-\frac{i}{2}\overleftrightarrow{\mathbf{D}}^j\right) T^a \psi (a^\dagger_{\eta_c} a_{\eta_c})$$

$$\times \psi^\dagger T^a \left(-\frac{i}{2}\overleftrightarrow{\mathbf{D}}^j\right) \left(-\frac{i}{2}\overleftrightarrow{\mathbf{D}}\right)^2 \chi + \mathrm{H.c.},$$

$$\mathcal{P}^{h_c}({}^1P_1^{[1]}) = \chi^\dagger \left(-\frac{i}{2}\overleftrightarrow{\mathbf{D}}^j\right) \psi (a^\dagger_{h_c} a_{h_c})$$

$$\times \psi^\dagger \left(-\frac{i}{2}\overleftrightarrow{\mathbf{D}}^j\right) \left(-\frac{i}{2}\overleftrightarrow{\mathbf{D}}\right)^2 \chi + \mathrm{H.c.}.$$

- There are uncancelled IR singularities in $P-$ wave channels, which are absorbed into the $S-$ wave LDMEs at NLO via

$$\langle\mathcal{O}^h({}^1S_0^{[8]})\rangle(\mu_\lambda) = \langle\mathcal{O}^h({}^1S_0^{[8]})\rangle_0 - \frac{4\alpha_s(\mu_\lambda)}{3\pi m^2}\left(\frac{4\pi\mu^2}{\mu_\lambda^2}e^{-\gamma_E}\right)^\epsilon \times \frac{1}{\epsilon_{\rm IR}}\left[\frac{C_F}{2C_A}\langle\mathcal{O}^h({}^1P_1^{[1]})\rangle + \left(\frac{C_A}{4}-\frac{1}{C_A}\right)\langle\mathcal{O}^h({}^1P_1^{[8]})\rangle\right]$$

$$\langle\mathcal{O}^h({}^1S_0^{[1]})\rangle(\mu_\lambda) = \langle\mathcal{O}^h({}^1S_0^{[1]})\rangle_0 - \frac{4\alpha_s(\mu_\lambda)}{3\pi m^2}\left(\frac{4\pi\mu^2}{\mu_\lambda^2}e^{-\gamma_E}\right)^\epsilon \times \frac{1}{\epsilon_{\rm IR}}\frac{1}{2C_A}\langle\mathcal{O}^h({}^1P_1^{[8]})\rangle,$$

- The μ dependence of the LDMEs can be obtained by solving the operator evolution equation: $\mu_\lambda\frac{d}{d\mu_\lambda}\langle\mathcal{O}^h(n)\rangle_0 = 0$

Highlight in NLO v^2 corrections

- We implement the covariant spin projection method (Bodwin and Petreli, 2002) with the projector to all order of v^2:

$$\sum_{\lambda_1,\lambda_2} v(-q,\lambda_2)\bar{u}(q,\lambda_1)\left\langle \frac{1}{2},\lambda_1;\frac{1}{2},\lambda_2|0,0\right\rangle =$$

$$\frac{-1}{2\sqrt{2}(E_q+m_c)}\left(\frac{\not{P}}{2}-\not{q}-m_c\right)\times\gamma^5\frac{\not{P}+2E_q}{2E_q}\left(\frac{\not{P}}{2}+\not{q}+m_c\right),$$

$$\sum_{\lambda_1,\lambda_2} v(-q,\lambda_2)\bar{u}(q,\lambda_1)\left\langle \frac{1}{2},\lambda_1;\frac{1}{2},\lambda_2|1,\epsilon\right\rangle =$$

$$\frac{-1}{2\sqrt{2}(E_q+m_c)}\left(\frac{\not{P}}{2}-\not{q}-m_c\right)\times\not{\epsilon}\frac{\not{P}+2E_q}{2E_q}\left(\frac{\not{P}}{2}+\not{q}+m_c\right).$$

- The details of computation of relativistic corrections can be found in our recent work.(He and Kniehl,2014)

The numerical inputs

α_s, PDF, and scale settings

We adopt CTEQ6L1 (CTEQ6M) PDFs setting for LO (NLO) calculation with $\Lambda_{\mathrm{QCD}}^{n_f=4}$=215 MeV (326 MeV) for one-Loop (two-loop) running of $\alpha_s^{n_f}(\mu_r)$. The NRQCD factorization is set $\mu_\lambda = m_c = 1.5\mathrm{GeV}$, the renormalization and factorization scales are chosen $\mu_r = \mu_f = m_T = \sqrt{(2m_c)^2 + p_T^2}$.

h_c feed-down contribution

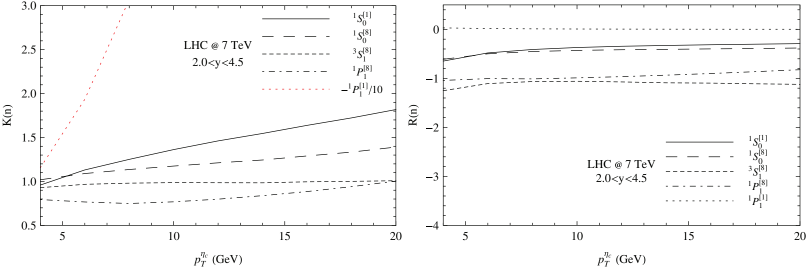
For those η_c from h_c feed-down, their p_T can be approximately estimated by $p_T^{\eta_c} = p_T^{h_c} \times m_{\eta_c}/m_{h_c}$ with $m_{\eta_c} = 2983.6$ MeV, $m_{h_c} = 3525.38$ MeV and $\mathrm{Br}(h_c \to \eta_c + X) = 51\%$ taken from PDG2014.

Note: Unlike J/ψ case, the $\eta_c(2S)$ feed-down contribution is negligible because of the small branching function.

- To study how large the NLO QCD and v^2 corrections, we define the K-factor and R-factor

$$K(n) = d\sigma_{\rm NLO}^{c\bar{c}[n]}/d\sigma_{\rm LO}^{c\bar{c}[n]},\, R(n) = d\sigma_{v^2}^{c\bar{c}[n]} m_c^2/d\sigma_{\rm NLO}^{c\bar{c}[n]}$$

- The K(n) and R(n) as function of $p_T^{\eta_c}$:



Sizes of NLO QCD and v^2 corrections-II

- In the ${}^1P_1^{[1]}$ case, the QCD correction is negtive, and the absolute value of $K-$factor is very large which is similar to the ${}^3P_J^{[1,8]}$ case.
- However, the SDC of ${}^1P_1^{[8]}$ still be positive @ QCD NLO.
- The $K(n)$ are of order 1 except for $n = {}^1P_1^{[1]}$.

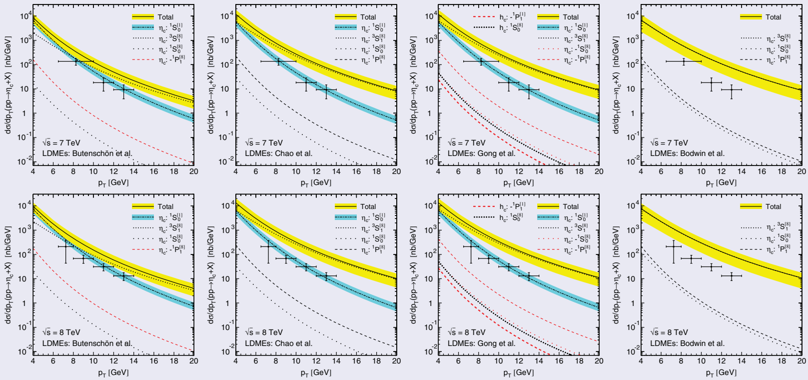
- The $R(n)$ are also of order 1 except for $n = {}^1P_1^{[1]}$, which indecates that the relativistic corrections are of relative order $\mathcal{O}(v^2)$.
- At 7 TeV LHC under LHCb setup, $R(n)$ are almost constant when $p_T^{\eta_c} > 7$ GeV.

- Firstly, we implement the HQSS to get the relavent LDMEs for η_c production from those determined in J/ψ production, and compare NRQCD predictions with LHCb data with

	Butenschoen, Kniehl [4]	Chao, Ma, Shao, Wang, Zhang [6]	Gong, Wan, Wang, Zhang [7]	Bodwin, Chung, Kim, Lee [8]
$\langle\mathcal{O}^{J/\psi}({}^3S_1^{[1]})\rangle/\mathrm{GeV}^3$	1.32	1.16	1.16	
$\langle\mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle/\mathrm{GeV}^3$	0.0304 ± 0.0035	0.089 ± 0.0098	0.097 ± 0.009	0.099 ± 0.022
$\langle\mathcal{O}^{J/\psi}({}^3S_1^{[8]})\rangle/\mathrm{GeV}^3$	0.0016 ± 0.0005	0.0030 ± 0.012	-0.0046 ± 0.0013	0.011 ± 0.010
$\langle\mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle/\mathrm{GeV}^5$	-0.0091 ± 0.0016	0.0126 ± 0.0047	-0.0214 ± 0.0056	0.011 ± 0.010
$\langle\mathcal{O}^{\chi_0}({}^3P_0^{[1]})\rangle/\mathrm{GeV}^5$			0.107	
$\langle\mathcal{O}^{\chi_0}({}^3S_1^{[8]})\rangle/\mathrm{GeV}^3$			0.0022 ± 0.0005	

- The v^2 corrections are treated to be uncertainties via relations $\langle\mathcal{P}^{\eta_c/h_c}(n)\rangle/m_c^2/\langle\mathcal{O}^{\eta_c/h_c}(n)\rangle$=0.23. (Bodwin et al.2008, Guo et al. 2011)

BREAKING OF NRQCD FACTORIZATION OR HQSS!



None of the four sets LDMEs can describe LHCb measurements. All the preditions are above the data.

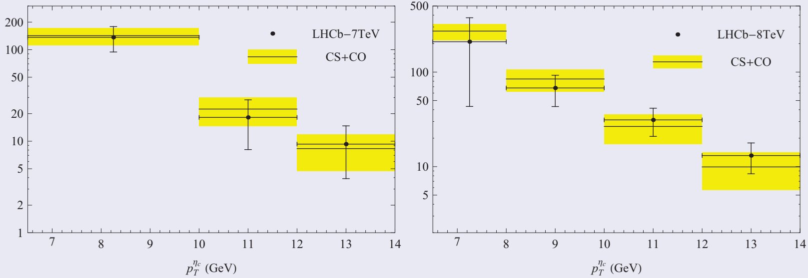
Approach II—New fit to η_c data-I

Setup of the fit

- Drop the h_c feed-down contribution for its enormous suppression as shown in above figure.
- Drop the contribution of ${}^1S_0^{[8]}$ and ${}^1P_1^{[8]}$ channels.
- Fit the CS LDME to η_c 2-photon and inclusive decays with $\alpha = 1/137$, $\alpha_s(2m_c) = 0.26$, $\Gamma(\eta_c) = (32.3 \pm 1.0)MeV$ and $\mathrm{Br}(\eta_c \to \gamma\gamma) = (1.57 \pm 0.12) \times 10^{-4}$
- Only need to fit the ${}^3S_1^{[8]}$ channel contribution.
- At v^2 subleading order, only the combination $\langle \bar{\mathcal{O}}^{\eta_c}({}^3S_1^{[8]}) \rangle = \langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]}) \rangle - 1.1 \langle \mathcal{P}^{\eta_c}({}^3S_1^{[8]}) \rangle / m_c^2$ can be obtained.

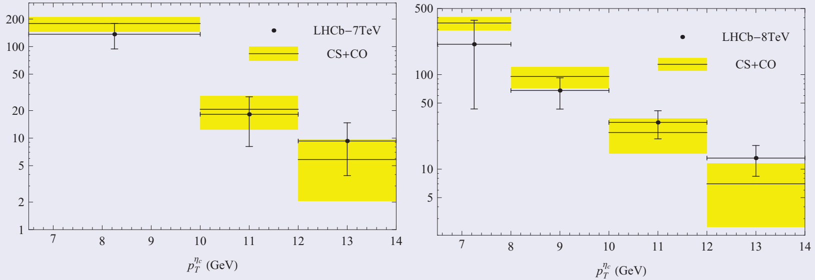
Results at v^2 LO

- With $\langle \mathcal{O}^{\eta_c}(^1S_0^{[1]}) \rangle = (0.24 \pm 0.02)\ \mathrm{GeV}^3$ (fit to 2-photon data) as input, we get a very nice fit to LHCb data with $\chi^2/\mathrm{d.o.f} = 1.4/6$ yielding $\langle \mathcal{O}^{\eta_c}(^3S_1^{[8]}) \rangle = (3.3 \pm 2.3 \pm 4.0) \times 10^{-3}\ \mathrm{GeV}^3$.



Results at v^2 NLO

- With $\langle \mathcal{O}^{\eta_c}(^1S_0^{[1]})\rangle = (0.50 \pm 0.009)\ \mathrm{GeV}^3$, $\langle \mathcal{P}^{\eta_c}(^1S_0^{[1]})\rangle / m_c^2 = (0.14 \pm 0.005)\ \mathrm{GeV}^3$ as input, we get a good fit to LHCb data resulting $\langle \bar{\mathcal{O}}^{\eta_c}(^3S_1^{[8]})\rangle = (-6.6 \pm 4.4) \times 10^{-3}\ \mathrm{GeV}^3$.



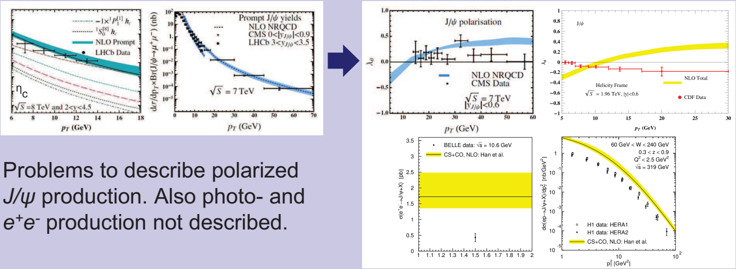
Approach II—New fit to η_c data-IV

- After setting CS contribution equal to zero, and assuming that the contribution of the other channels is positive, we get the upper bound of $\langle\bar{\mathcal{O}}^{\eta_c}(^3S_1^{[8]})\rangle$ to be $(1.5 \pm 0.2^{+0.3}_{-0.4}) \times 10^{-2}\ \mathrm{GeV}^3$.
- If we further set $\frac{\langle\mathcal{P}^{\eta_c}(^3S_1^{[8]})\rangle}{m_c^2\langle\mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle} \approx \mathcal{O}(v^2) = 0.23$, we get that $\langle\mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle < (1.9 \pm 0.3^{+0.4}_{-0.5}) \times 10^{-2}\ \mathrm{GeV}^3$.
- The HQSS is found to be hold in CS case after fitting the CS LDMEs in J/ψ decay and comparing them with those in η_c decay.
- We then implement the HQSS, and get the upper bound of $\langle\mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$ to be $(1.9 \pm 0.3^{+0.4}_{-0.5}) \times 10^{-2}\ \mathrm{GeV}^3$.

The above value is much smaller than any of the previous results from directly fitting to J/ψ data!

- In Han et al. work, only the NLO QCD corrections are studied, and a similar constrain on $\langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]}) \rangle$ is obtained. With the help HQSS, this new constrain is applied to update their predictions on J/ψ polarization. (Shao et al., 2015)

Han, Ma, Meng, Shao, Chao (2014): "Fit" high-p_T η_c and J/ψ pp yield:



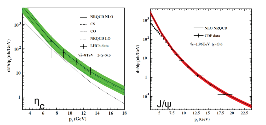
Problems to describe polarized J/ψ production. Also photo- and e^+e^- production not described.

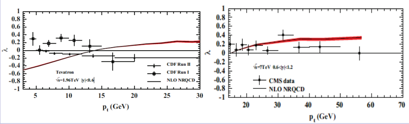
Compare with work of Zhang, Sun, Sang, Li

- Zhang et al. do a similar work as Han et al., but fit the CS LDME for η_c production. They get a similar conclusion as Han et al.

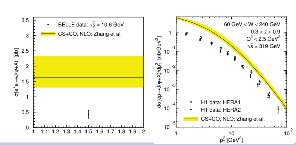
Zhang, Sun, Sang, Li (2014):

Similar, but color singlet $\langle O^{\eta_c}({}^1S_0^{[1]})\rangle$ independently fitted in fit!





- Also: Photo- and e⁺e⁻ production not described:



Note: Neither of the two group take into account the relativistic effect or treat it properly.

In Conclusion

- The η_c production at LHC is studied within the framework of NRQCD factorization at NLO of both α_s and v^2.
- We find that the CS contribution itself can explain the data well, which leaves a small room to CO contribution indecating a small value of $\langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]}) \rangle$ and $\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) \rangle$ if we preserve the HQSS.
- A small value of $\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) \rangle$ may not describe J/ψ polarization data which requires a relative large value of it.
- We, therefore, conclude that whether the HQSS or the universality of the LDMEs is in question or there may be another important ingredient to current NLO NRQCD analyses has so far been overlooked.

Thank you !