Introduction

- The effective Lagrangian of NRQCD
  - expansion in $1/m$ and $\alpha_s(m)$
  - $d\sigma_{A+B\to H+X} = \sum_n \boxed{d\sigma_{A+B\to Q\bar{Q}(n)+X}} \times \boxed{\langle\mathcal{O}^H(n)\rangle}$
- Factorisation assumption
  - $c\bar{c}$ pair production at $E \sim m_Q$ (treated perturbatively)
  - independent hadronisation at $E \sim m_Q v$ guided by long-distance matrix elements (LDME)
- Two production mechanisms:
  - colour-singlet (CS)
  - colour-octet (CO)

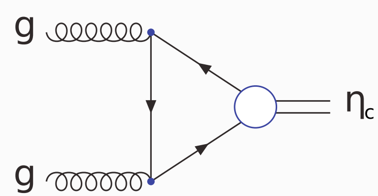
Spin symmetry relations:

$$\langle\mathcal{O}_1^{\eta_c}(^1S_0)\rangle = 1/3\langle\mathcal{O}_1^{J/\psi}(^3S_1)\rangle$$
$$\langle\mathcal{O}_8^{\eta_c}(^1S_0)\rangle = 1/3\langle\mathcal{O}_8^{J/\psi}(^3S_1)\rangle$$
$$\langle\mathcal{O}_8^{\eta_c}(^3S_1)\rangle = \langle\mathcal{O}_8^{J/\psi}(^1S_0)\rangle$$
$$\langle\mathcal{O}_8^{\eta_c}(^1P_1)\rangle = 3\langle\mathcal{O}_8^{J/\psi}(^3P_0)\rangle$$

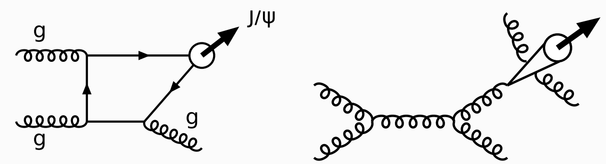
[N. Brambilla *et al.* [Quarkonium Working Group Collaboration], hep-ph/0412158.]

Slides prepared by M.Teklishyn

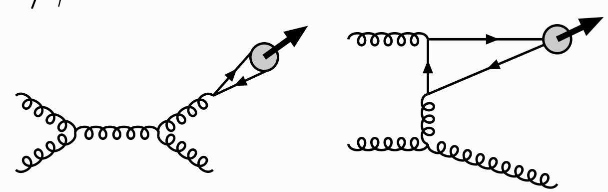
- η_c hadroproduction at LO
  [F. Maltoni and A. D. Polosa, Phys. Rev. D **70** (2004) 054014]



- J/ψ colour-singlet [M. Kramer, 1, Prog. Part. Nucl. Phys. **47** (2001) 141]



- J/ψ colour-octet



$$\frac{d\hat{\sigma}(gg\to\eta_Q g)}{dp_T} = |R(0)|^2\frac{d\hat{\sigma}(gg\to Q\bar{Q}[^1S_0^{[1]}]g)}{dp_T} + \langle O_S\rangle\frac{d\hat{\sigma}(gg\to Q\bar{Q}[^3S_1^{[8]}]g)}{dp_T} + \langle O_P\rangle\frac{d\hat{\sigma}(gg\to Q\bar{Q}[^1P_1^{[8]}]g)}{dp_T},$$

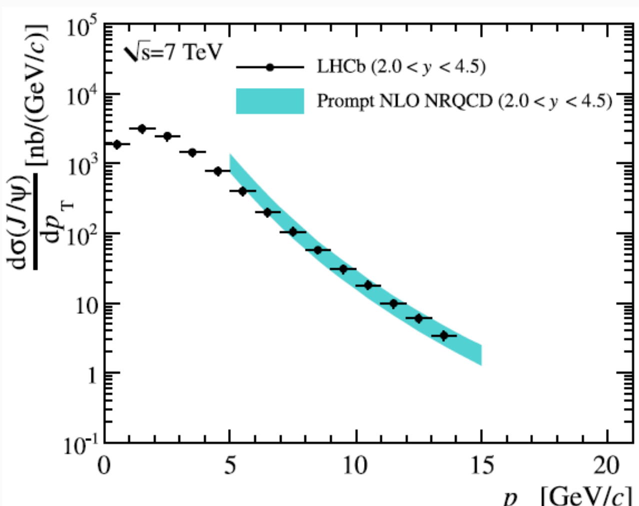
Likhoded et al.
arXive:1411.1247

J/ψ production studies at the LHCb experiment

- J/ψ production measurements by LHCb

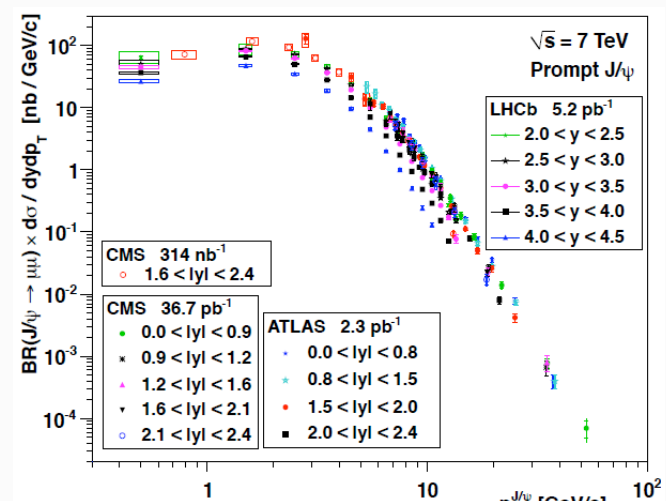
$\sqrt{s}$, TeV	data set	$\sigma_{J/\psi}$	$\sigma_{b\bar{b}} \times \mathcal{B}_{b\to J/\psi X}$
2.76	$71\ \text{nb}^{-1}$	$5.6 \pm 0.1 \pm 0.4\ \mu\text{b}$	$400 \pm 35 \pm 49\ \text{nb}$
7	$5.2\ \text{pb}^{-1}$	$10.52 \pm 0.04 \pm 1.40^{+1.64}_{-2.20}\ \mu\text{b}$	$1.14 \pm 0.01 \pm 0.16\ \mu\text{b}$
8	$18\ \text{pb}^{-1}$	$10.94 \pm 0.02 \pm 0.79\ \mu\text{b}$	$1.28 \pm 0.01 \pm 0.11\ \mu\text{b}$

- Differential J/ψ production at LHCb [LHCb, EPJC 71 (2011) 1645]:



- Observed J/ψ production is described by theory [Phys. Rev. Lett. **106** (2011) 042002]

- Result comparison with other experiments (by H. K. Wöhri)

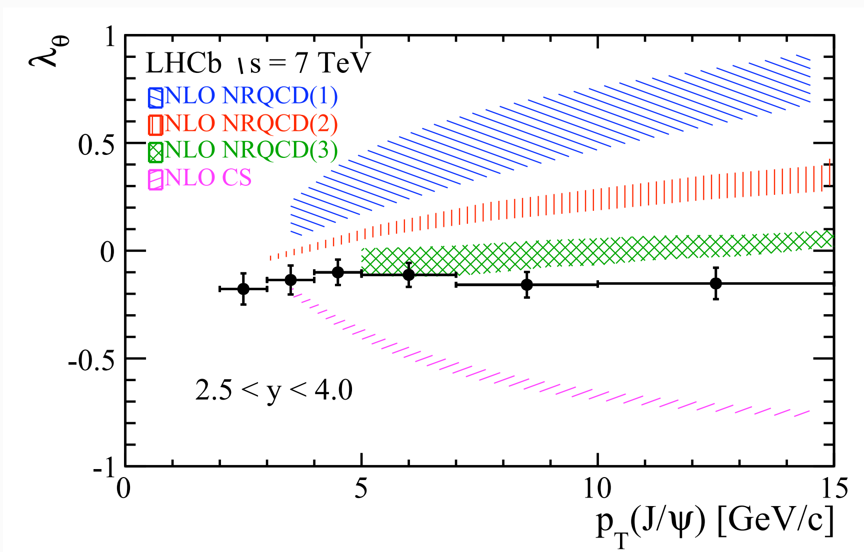


- Agreement between different LHC experiments

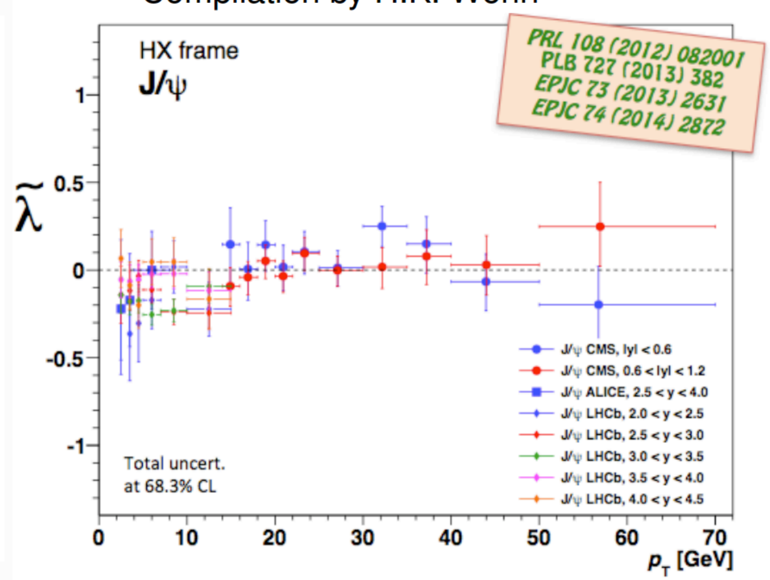
J/ψ polarisation puzzle

- CO predicts strong polarisation
- NLO NRQCD calculations, different selections of experimental data to determine non-perturbative matrix elements
  - NLO CS and NLO NRQCD(1) [M. Butenschoen and B. A. Kniehl, PRL 108 (2012) 172002]
  - NLO NRQCD(2) [B. Gong et al., PRL 110 (2013) 042002]
  - NLO NRQCD(3) [K.-T. Chao et al., PRL 108 (2012) 242004]

[Eur. Phys. J. C **73** (2013) 2631]



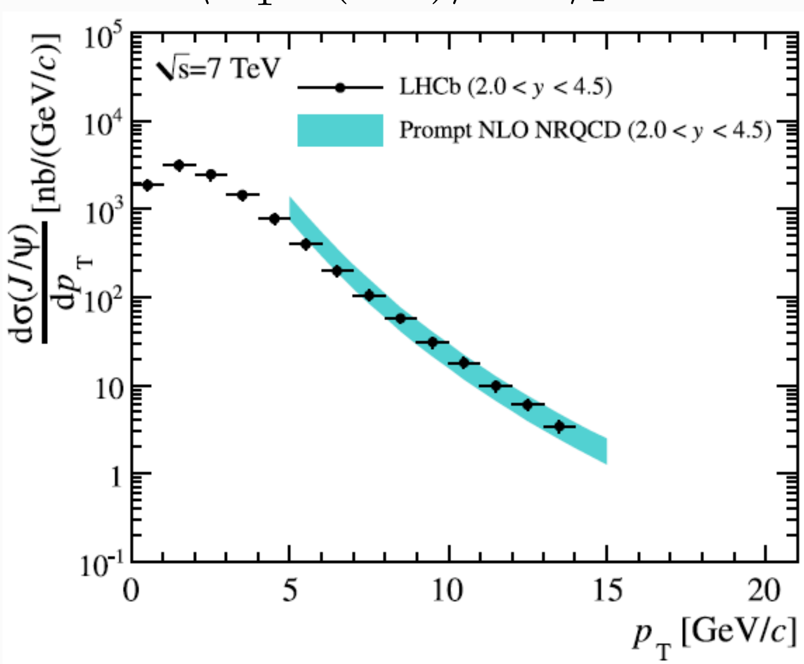
Compilation by H.K. Wöhri



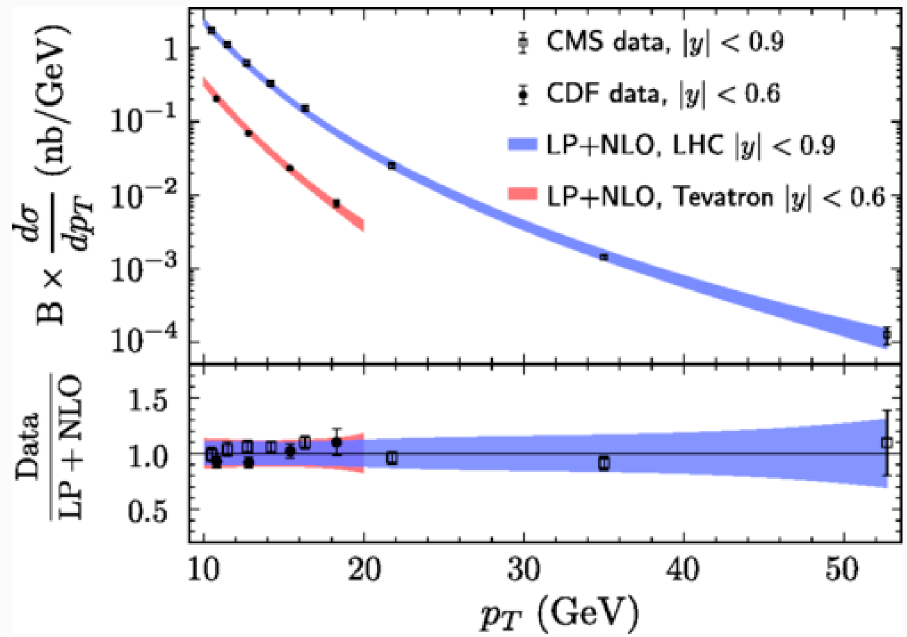
- Polarisation measurements are in agreement between experiments

J/ψ differential cross-section

- Differential J/ψ production at LHCb [LHCb, EPJC 71 (2011) 1645] is consistent with theoretical prediction [Phys. Rev. Lett. **106** (2011) 042002]
- At the NLO: arXiv:1411.7350 [hep-ph]
  - $\langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle \sim 1/p^4$
  - $\langle \mathcal{O}_8^{J/\psi}(^1S_0, {}^3P_J)\rangle \sim 1/p^6$
  - $\langle \mathcal{O}_1^{J/\psi}(^3S_1)\rangle \sim 1/p^6$



- Results from Tevatron and CMS are fitted with pure octet model [Phys. Rev. Lett. **113** (2014) 2, 022001]

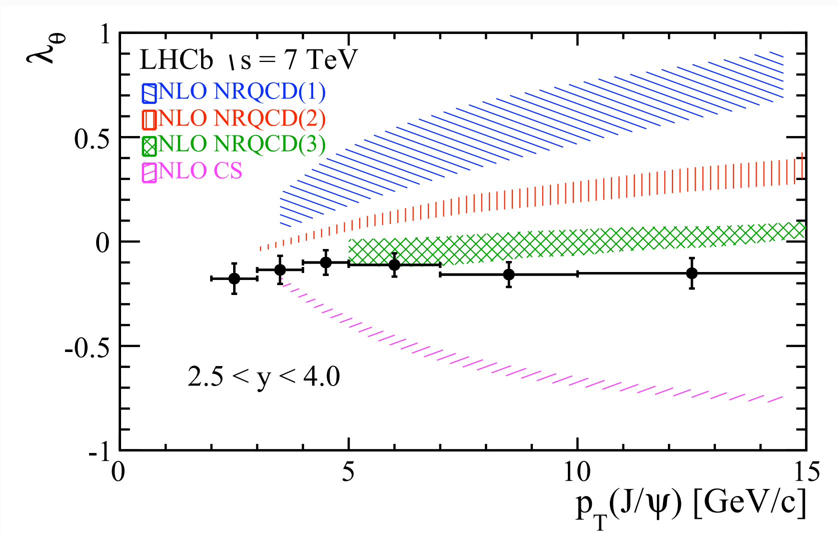


CO LDME from fit ($\times 10^{-2}$):

$$\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle = 0.099 \pm 0.022\,\mathrm{GeV}^3$$
$$\langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle = 0.011 \pm 0.010\,\mathrm{GeV}^3$$
$$\langle \mathcal{O}_8^{J/\psi}(^3P_0)\rangle = 0.011 \pm 0.010\,\mathrm{GeV}^5$$

J/ψ polarization puzzle

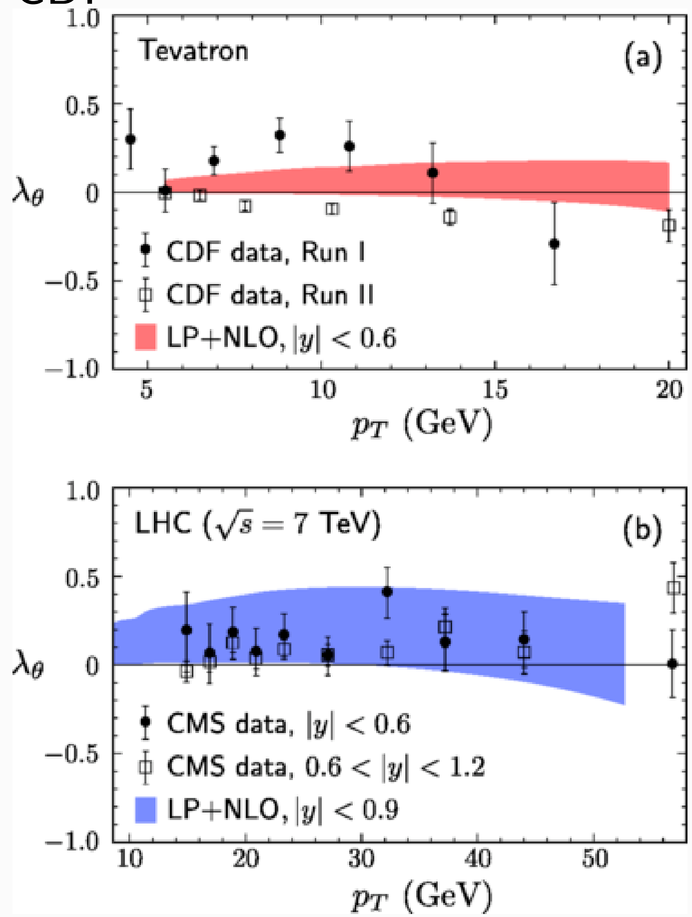
- CS predicts strong polarisation
- NLO NRQCD calculations
  1. [M. Butenschoen and B. A. Kniehl, PRL 108 (2012) 172002]
  2. [B. Gong et al., PRL 110 (2013) 042002]
  3. [K.-T. Chao et al., PRL 108 (2012) 242004]



[Eur. Phys. J. C **73** (2013) 2631]

- Large CO is needed
- $\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle$ can be obtained from η_c measurements:

- Polarization plots from CMS and CDF

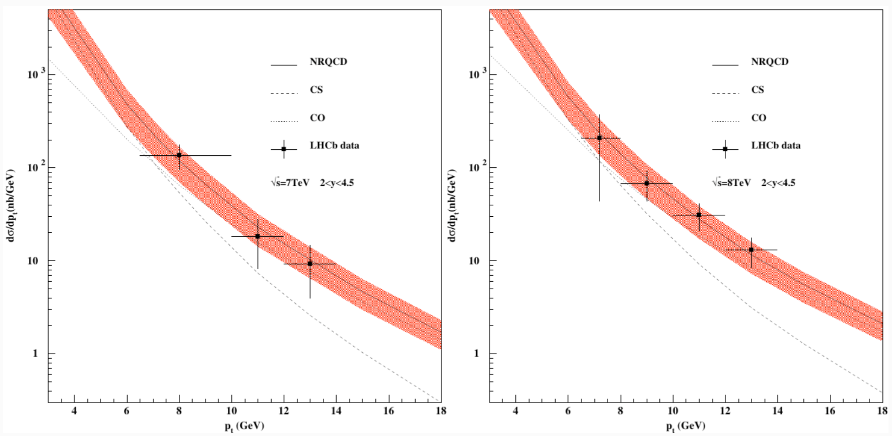


[Phys. Rev. Lett. **113** (2014) 2, 022001]

$$\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle = \langle \mathcal{O}_8^{\eta_c}(^3S_1)\rangle$$

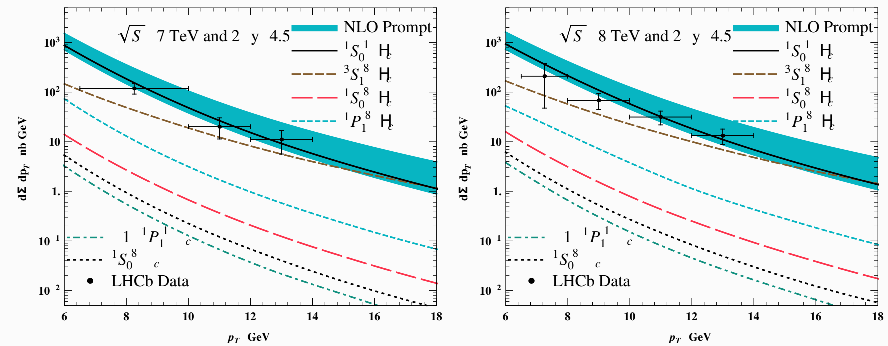
Fitting $\mathcal{O}_1^{\eta_c}(^1S_0)$ and $\mathcal{O}_8^{\eta_c}(^3S_1)$ from LHCb data

- $\mathcal{O}_1^{\eta_c}(^1S_0)$ and $\mathcal{O}_8^{\eta_c}(^3S_1)$ are fitted from prompt η_c differential cross-section
- other LDME contribute $< 2\%$



arXiv:1412.0508 [hep-ph]

$$\mathcal{O}_1^{\eta_c}(^1S_0) = (0.20 \pm 0.10)\,\mathrm{GeV}^3$$
$$\mathcal{O}_8^{\eta_c}(^3S_1) = (0.86 \pm 0.27) \times 10^{-2}\,\mathrm{GeV}^3$$



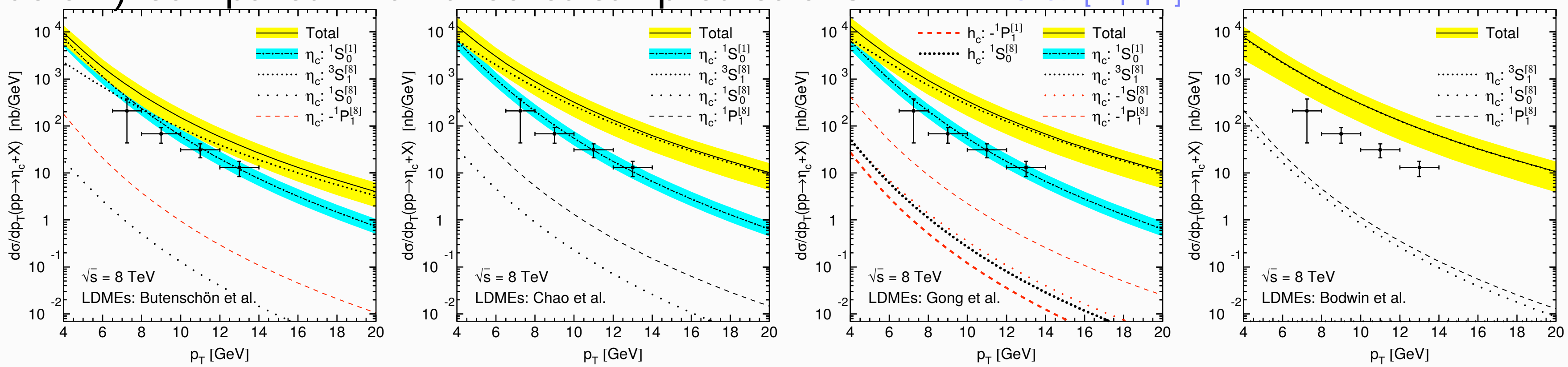
arXiv:1411.7350 [hep-ph]

- CS component is fixed to $\mathcal{O}_1^{\eta_c}(^1S_0) = 1/3\mathcal{O}_1^{J/\psi}(^3S_1) = 0.39\,\mathrm{GeV}^3$
- CO LDME from fit: $0 < \mathcal{O}_8^{\eta_c}(^3S_1) < 1.46 \times 10^{-2}\,\mathrm{GeV}^2$

Obtained $\mathcal{O}_8^{\eta_c}(^3S_1)$ values are ~ 10 times smaller than was predicted before

Description of the η_c differential cross-section

Recent LHCb results on η_c production arXiv:1409.3612 [hep-ex] ($\sqrt{s}$ =8 TeV on plots below) compared with theoretical predictions arXiv:1411.5287 [hep-ph]



	1	2	3	4
$\langle\mathcal{O}_1^{J/\psi}({}^3S_1)\rangle$	1.32	1.16	1.16	
$\langle\mathcal{O}_8^{J/\psi}({}^1S_0)\rangle$	0.0304 ± 0.0035	0.089 ± 0.0098	0.097 ± 0.009	0.099 ± 0.022
$\langle\mathcal{O}_8^{J/\psi}({}^3S_1)\rangle$	0.0016 ± 0.0005	0.0030 ± 0.012	-0.0046 ± 0.0013	0.011 ± 0.010
$\langle\mathcal{O}_8^{J/\psi}({}^3P_0)\rangle$	-0.0091 ± 0.0016	0.0126 ± 0.0047	-0.0214 ± 0.0056	0.011 ± 0.010

LDME from references below. $\langle\mathcal{O}^{\eta_c}_{1,8}(n)\rangle$ obtained with spin relations.

1. [M. Butenschoen and B. A. Kniehl, PRL 108 (2012) 172002]
2. [K.-T. Chao et al., PRL 108 (2012) 242004]
3. [B. Gong et al., PRL 110 (2013) 042002]
4. [G. T. Bodwin at al., Phys. Rev. Lett. **113** (2014) 2, 022001]

- $\langle\mathcal{O}_8^{J/\psi}({}^1S_0)\rangle$ is too large
- $\langle\mathcal{O}_8^{J/\psi}({}^1S_0)\rangle = \langle\mathcal{O}_8^{\eta_c}({}^3S_1)\rangle$ — can be fixed from η_c fit

Charmonia decays to the $p\bar{p}$ final state

- Many charmonium states decay to the $p\bar{p}$ final state
- Experimental data on charmonia mass, natural width and branching fraction of their decay to the $p\bar{p}$ final state

	mass, MeV	Γ, MeV	$\mathcal{B}_{c\bar{c}\to p\bar{p}} \times 10^{-3}$
η_c(1S)	2983.6 ± 0.9	32.2 ± 0.9	1.52 ± 0.16
J/ψ(1S)	3096.916 ± 0.011	negligible	2.120 ± 0.029
χ_{c0}(1S)	3414.75 ± 0.31	10.4 ± 0.6	0.213 ± 0.012
χ_{c1}(1P)	3510.66 ± 0.07	0.86 ± 0.5	0.073 ± 0.004
h_c(1P)	3525.67 ± 0.32	< 1	not seen
χ_{c2}(1P)	3556.20 ± 0.09	1.98 ± 0.11	0.071 ± 0.004
η_c(2S)	3638.9 ± 1.3	10 ± 4	< 0.29 @ 90%
ψ(2S)	3686.09 ± 0.04	negligible	0.275 ± 0.012
$\psi(3770)$	3773.15 ± 0.33	27.2 ± 1.0	not seen
X(3872)	3871.68 ± 0.17	< 1.2 @ 90%	not seen
X(3915)	3917.5 ± 2.7	27 ± 10	not seen

- The h_c meson branching fraction predicted by E. Kou [Phys. Rev. D **86** (2012) 034011]

$$\mathcal{B}_{h_c\to p\bar{p}} = (3.2 \pm 0.5) \times 10^{-3}$$