Study of charmonium production using decays to hadrons with the LHCb

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QCD – Old Challenges and New Opportunities

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Charmonia production in the NRQCD

1. prompt hadroproduction
2. from b-decays, inclusive
3. exclusive production

Experimentally can be separated by pseudo- decay time $t_z = \frac{z_{SV} - z_{PV}}{c}$

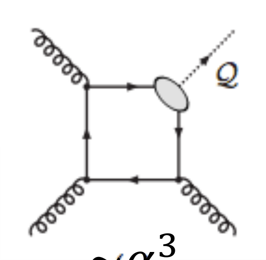
- **NRQCD. Major assumptions:**
  1. **Factorization**.
     Charmonia production includes two **independent** processes:
     - $c\bar{c}$ pair creation -> short distance process
       - treated **perturbatively**
     - *independent* hadronisation -> long distance matrix elements **(LDME)**
       - non-perturbative
  2. **Universality.**
     LDME are the same for both prompt production and production in b-decays
  3. **Heavy quark spin symmetry (HQSS)**
- Other theoretical approaches:
  - Color evaporation model (CEM)
  - Fragmentation
  - kt – factorization

NRQCD is the most powerful tool to predict charmonia production

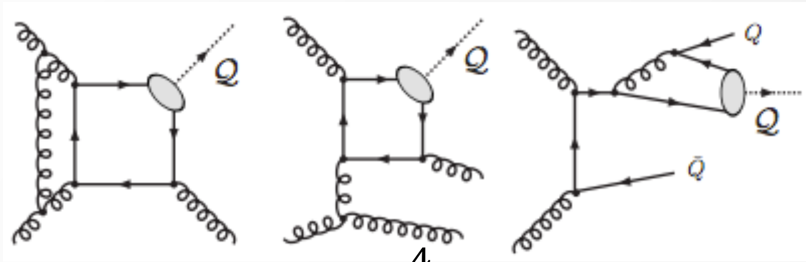
Charmonia production in the NRQCD

- Cross section factorizes: $d\boldsymbol{\sigma}_{A+B\to H+X} = \sum_n d\boldsymbol{\sigma}_{A+B\to Q\bar{Q}(n)+X} \times \langle \mathcal{O}^H(\boldsymbol{n})\rangle$
- **2 production mechanisms:**

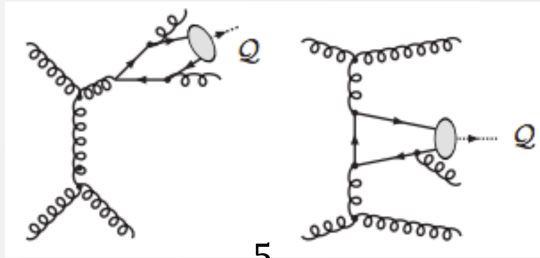
- Color Singlet (CS)



$\sim\alpha_s^3$

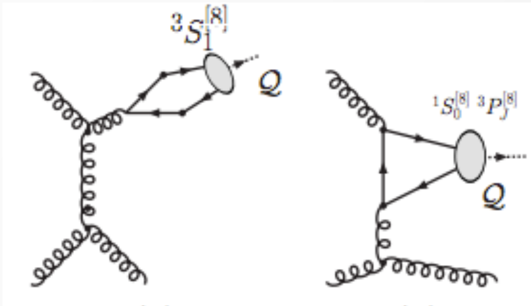


$\sim\alpha_s^4$



$\sim\alpha_s^5$

- Color Octet (CO)



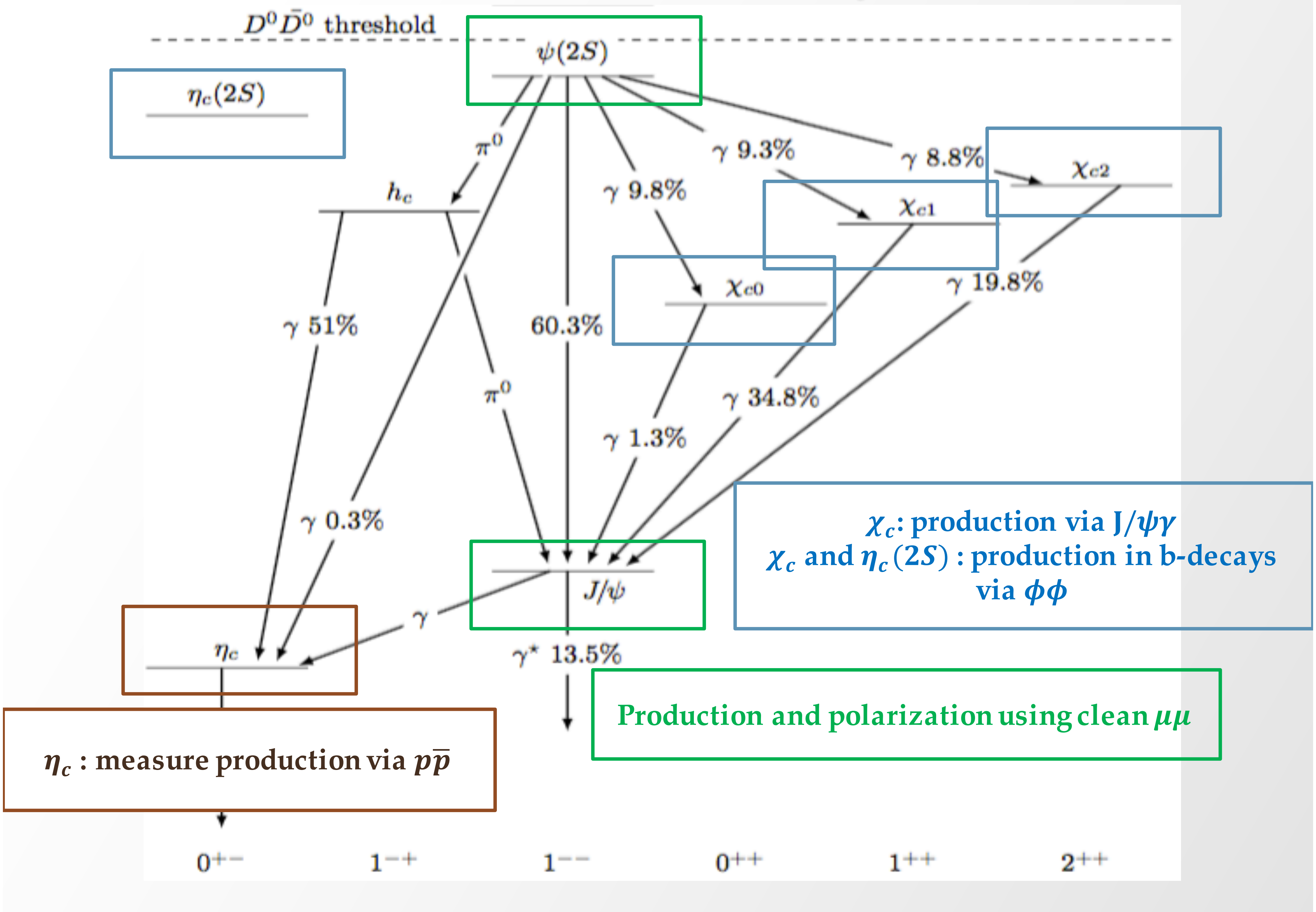
$\sim\alpha_s^3$

→ P_T - behavior (from perturbative part) respective to each LDME

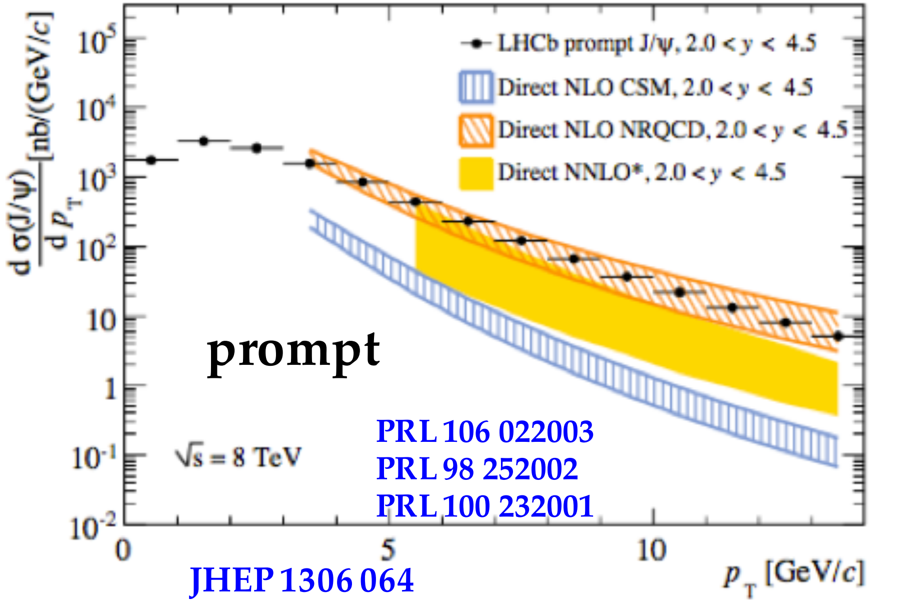
- **Spin-symmetry for LDMEs:**
  links between the CS and CO matrix elements of **different charmonia states**

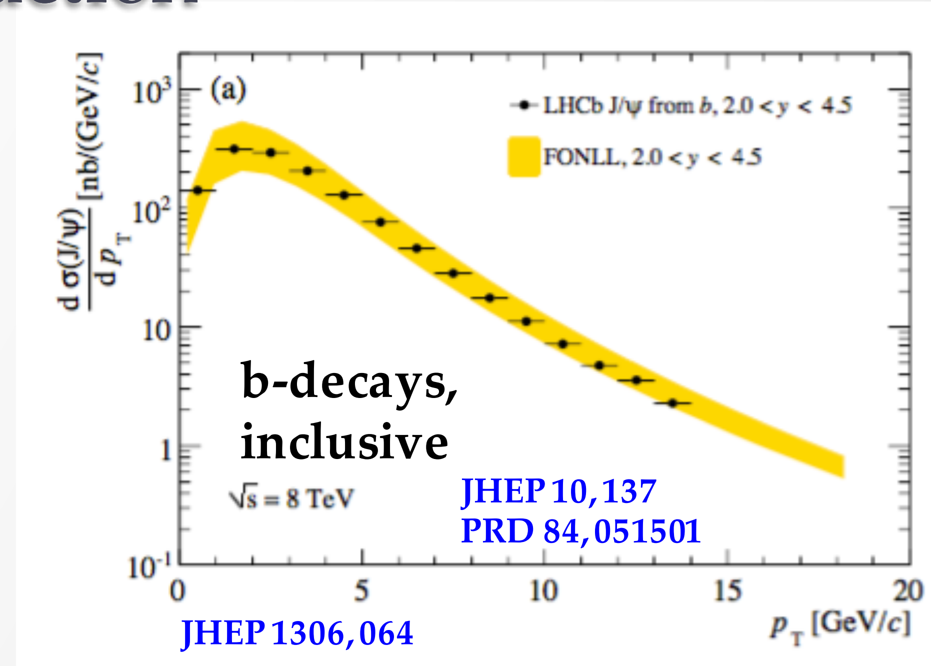
$$\langle O_1^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_1^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_8^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^3S_1)\rangle = \langle O_8^{J/\psi}(^1S_0)\rangle,$$
$$\langle O_8^{\eta_c}(^1P_1)\rangle = 3\langle O_8^{J/\psi}(^3P_0)\rangle.$$

Charmonium family



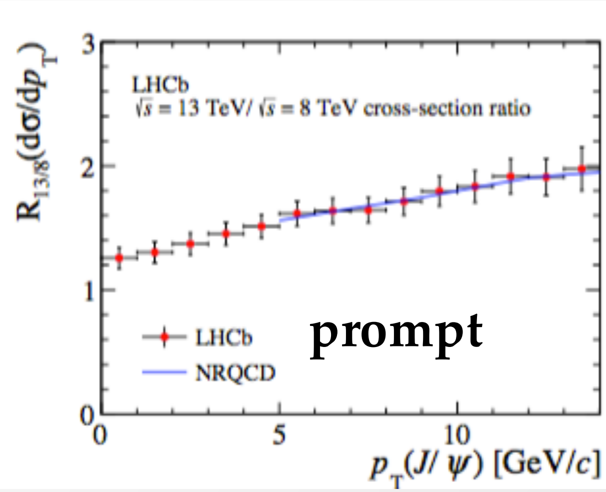
J/ψ production

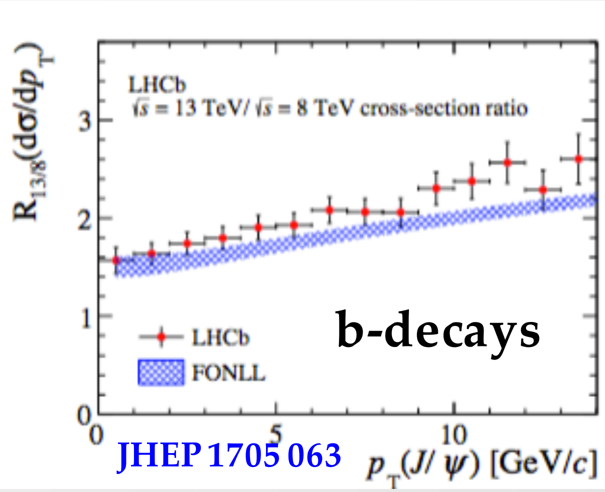




- Measurements of Tevatron and LHC (CDF, CMS, ATLAS, LHCb) experiments are in agreement
- Could not be described by CS NLO and NNLO -> motivation to investigate CO
- **Described by NRQCD NLO, dominated by CO contributions**

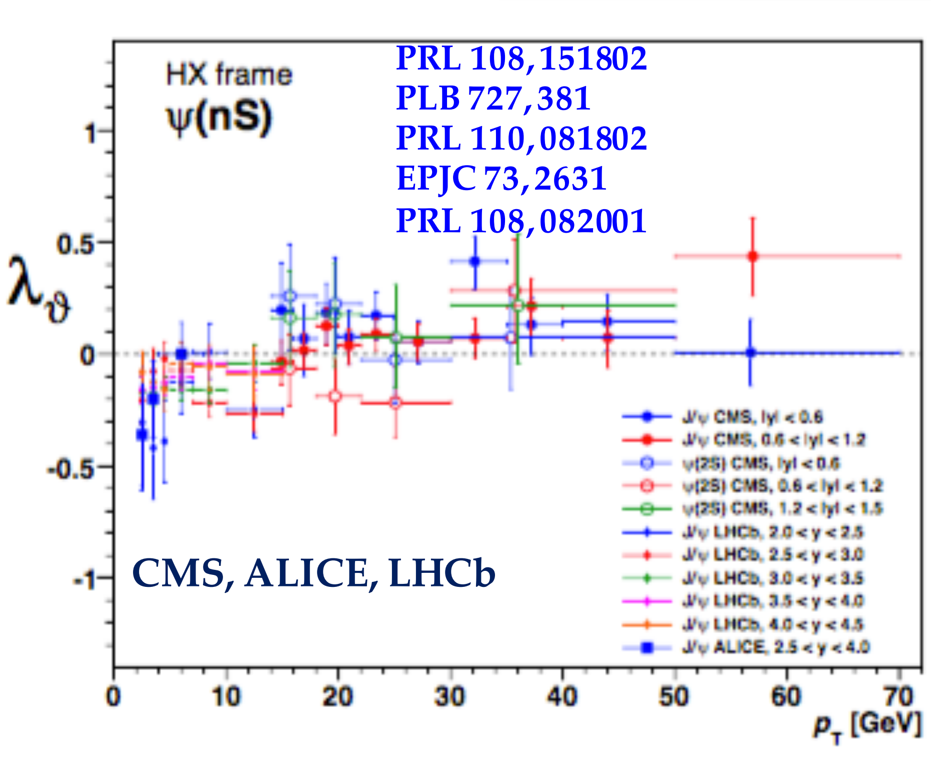
Ratio of 13 TeV/ 8 TeV production:
- Systematic uncertainties cancelled
- b-decays : theory prediction is slightly below than what was measured

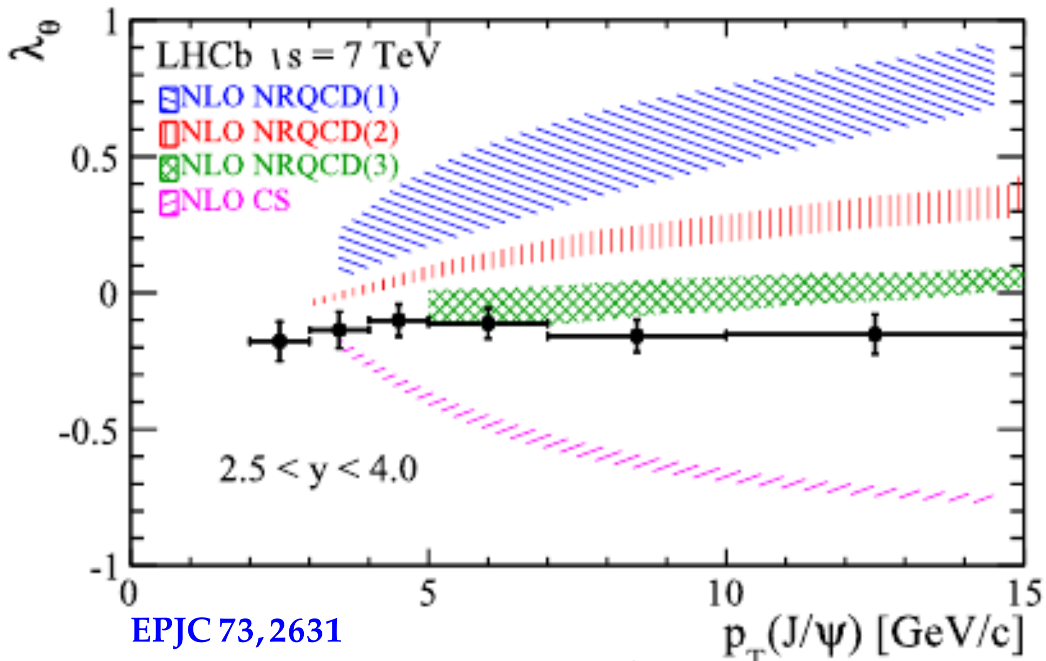




J/ψ (and $\psi(2S)$) polarization

PRL 108,172002
PRL 110,042002
PRL 108,242004



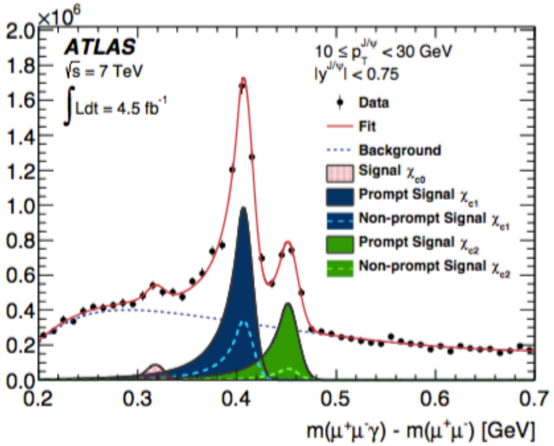


$$\frac{dN}{dCos\theta} \sim 1 + \lambda_\theta Cos^2\theta$$

***J/ψ* polarization:**

- Measurements of Tevatron and LHC experiment are in agreement between
- CO predicts strong polarization
- **Large CS contribution is needed**

χ_c prompt production

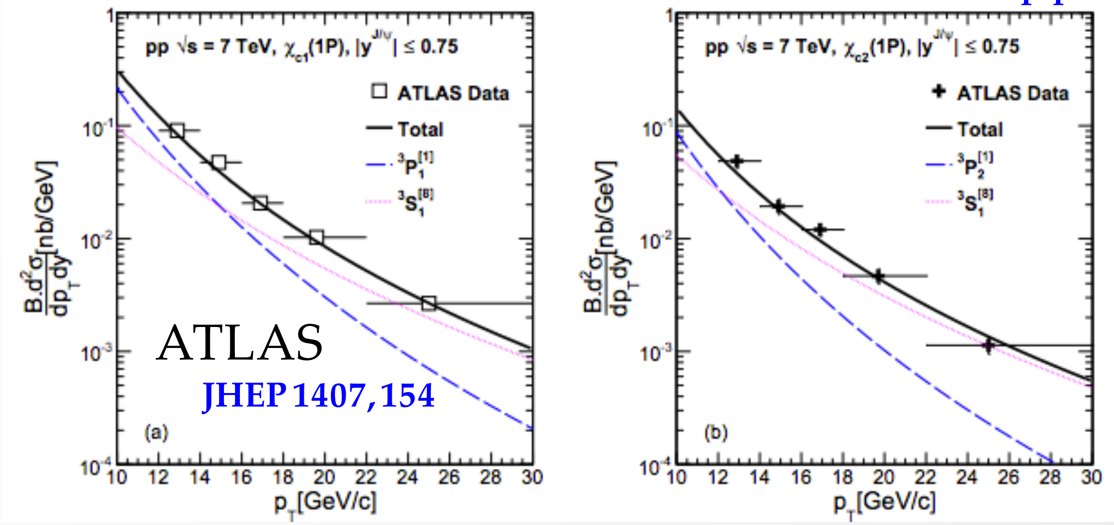


JHEP 1407, 154

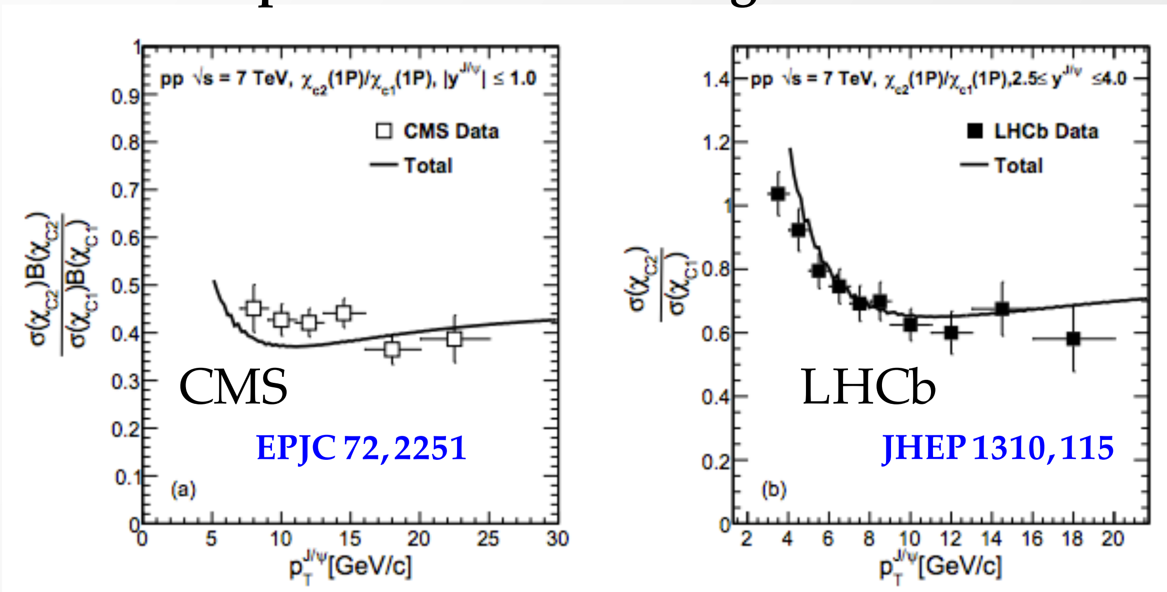
using $\chi_c \to J/\psi\,\gamma$ *decay*

- **NRQCD fit for absolute production:**

arXiv:1606.08265v2 [hep-ph]



- **More precise when looking for ratio:**

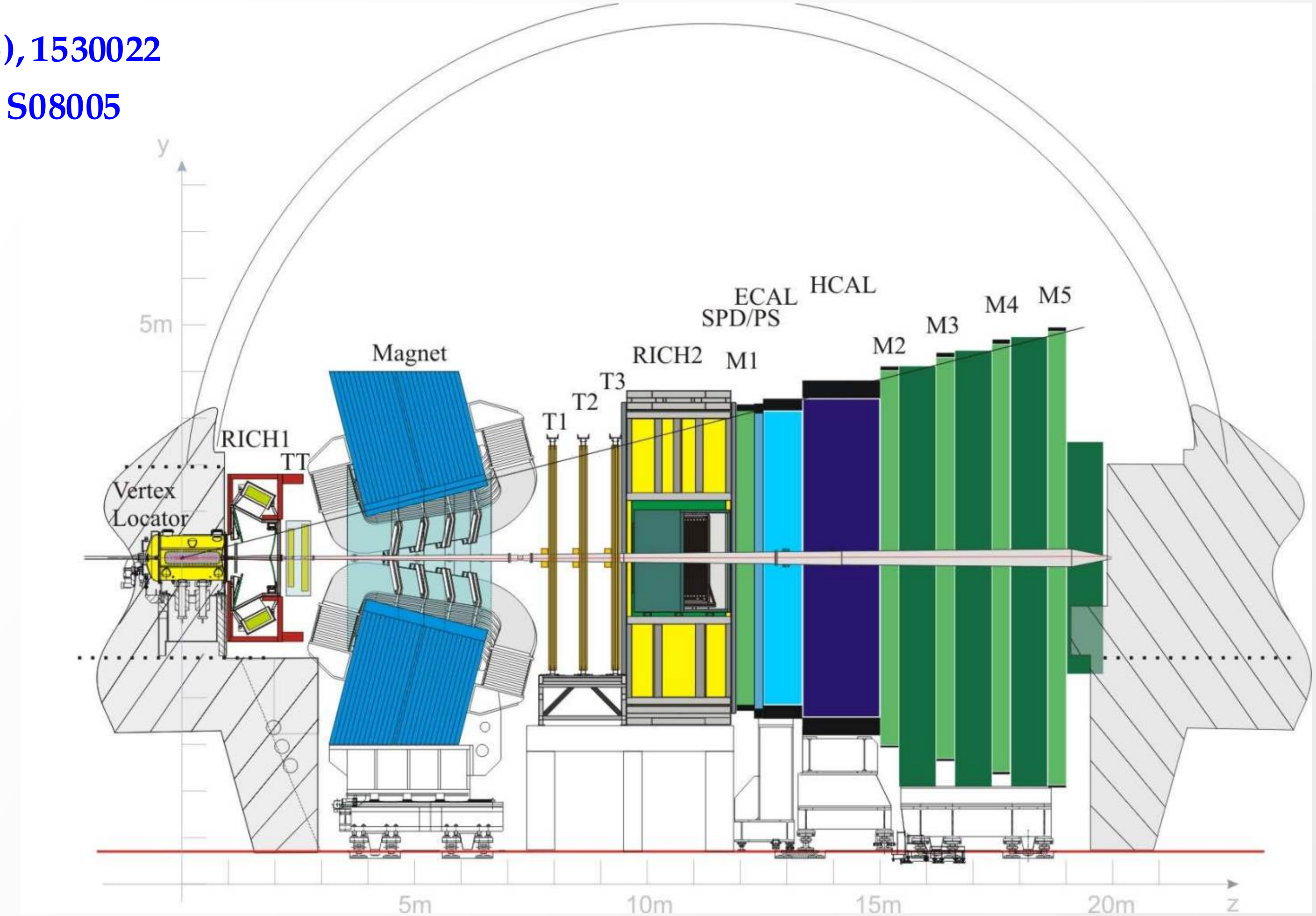


-> CO LDME extracted from fit

LHCb detector

IJMPA30 (2015), 1530022

JINST 3 (2008) S08005



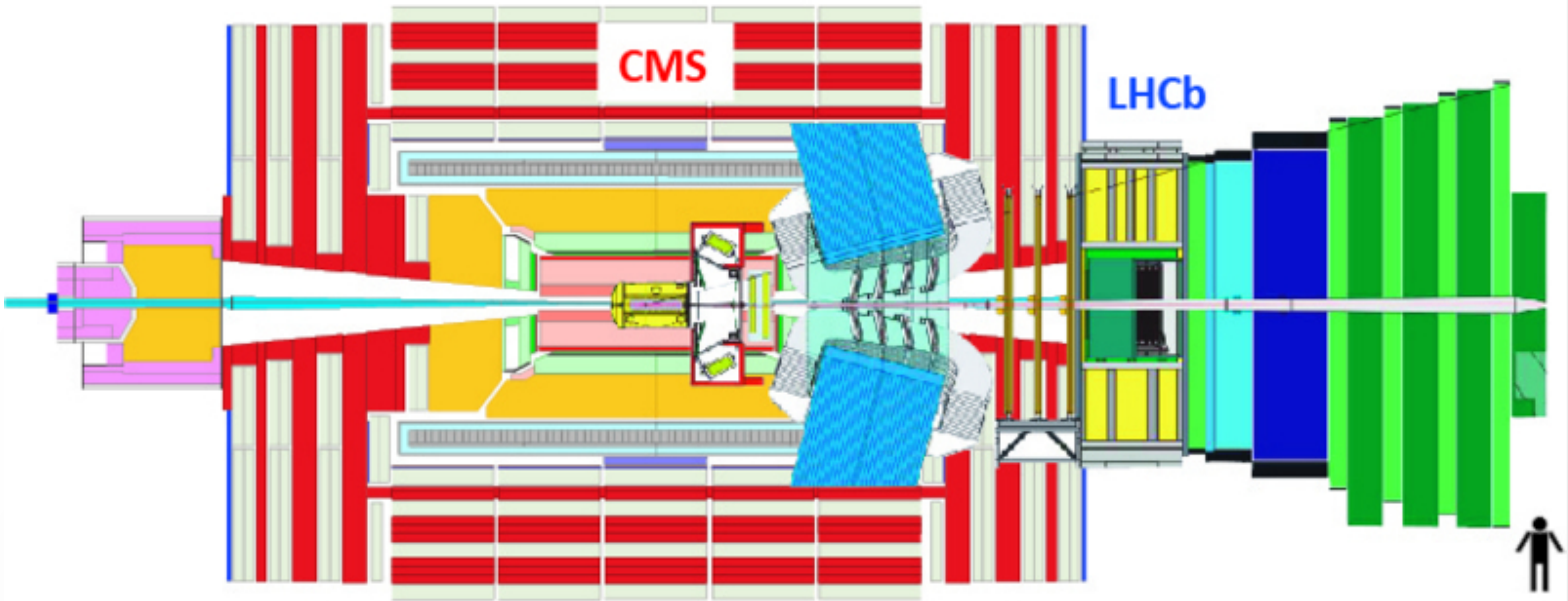
Important for **charmonia production studies via their decays to hadrons:**

- Precise vertex reconstruction with VELO
- Powerful charge particle ID by RICH detectors
- Robust trigger

LHCb detector

IJMPA30 (2015), 1530022

JINST 3 (2008) S08005



Important for **charmonia production studies via their decays to hadrons:**

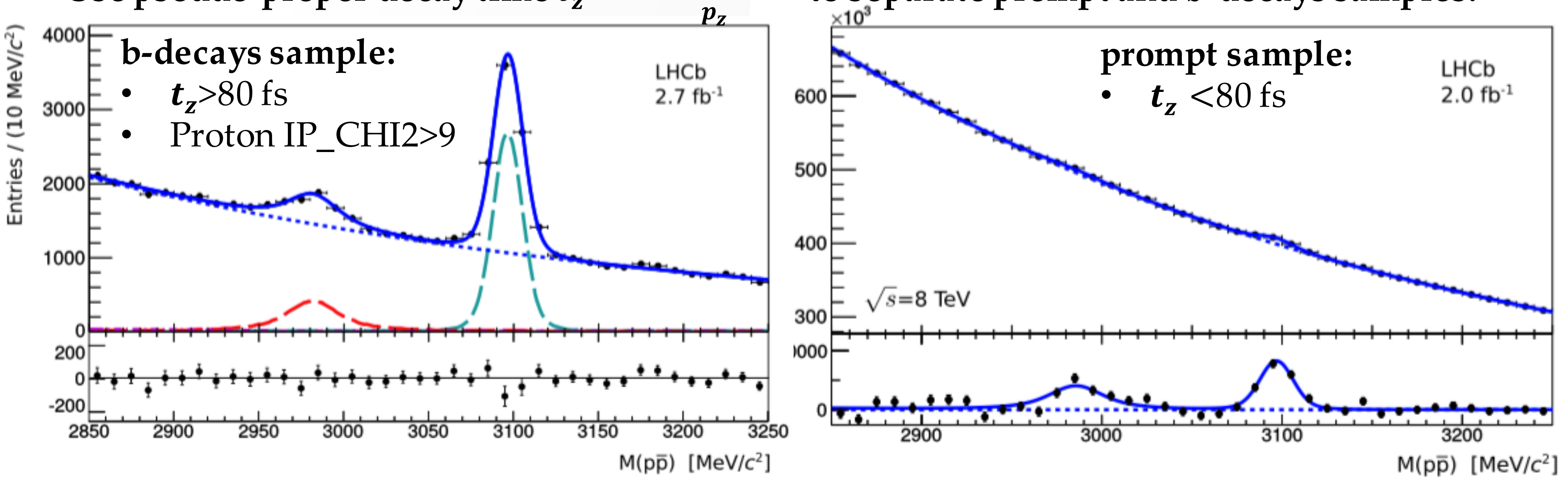
- Precise vertex reconstruction with VELO
- Powerful charge particle ID by RICH detectors
- Robust trigger

- **Covers complementary to ATLAS and CMS p_t and η range**

η_c production measurement via $\eta_c \to p\bar{p}$ at $\sqrt{s} = 7{,}8\ TeV$

EPJC 75 (2015) 311

- **Most of the selection performed at trigger level**
- **Use pseudo-proper decay time $t_z = \frac{(z_{SV}-z_{PV})M_{c\bar{c}}}{p_z}$ to separate prompt and b-decays samples:**

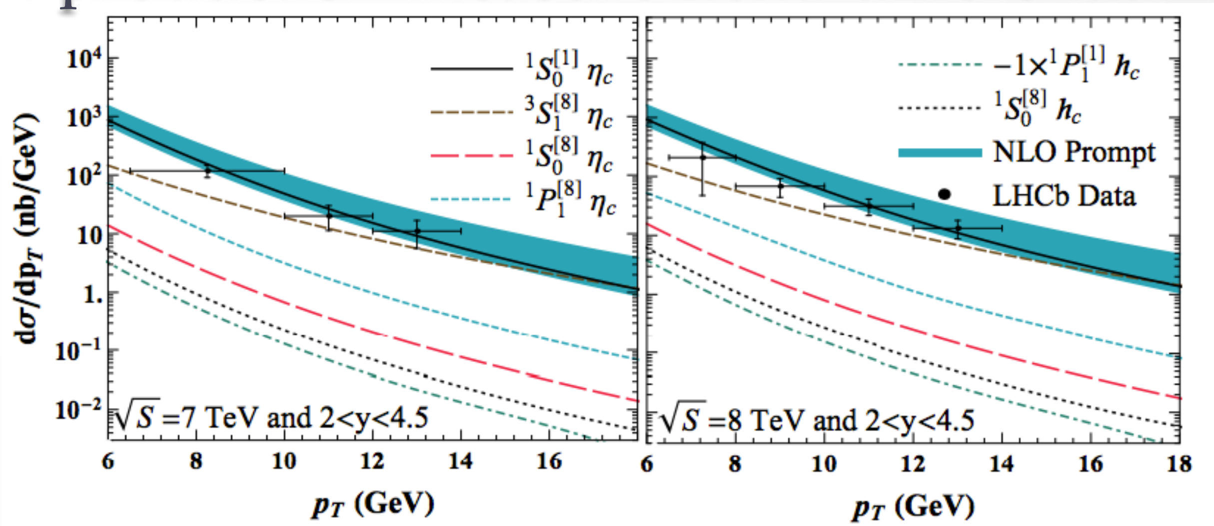


- Measurement of $M(\eta_c)$, $\Gamma(\eta_c)$
- **First measurement of $BR(b \to \eta_c X)$**

- Challenging background conditions
- Use masses, $\Gamma(\eta_c)$ and resolution from b-decays sample
- **First measurement of η_c hadroproduction**

	$\sqrt{s} = 7\text{TeV}$	$\sqrt{s} = 8\text{TeV}$
$\sigma_{\eta_c}/\sigma_{J/\psi}$ **(prompt, PT>6.5 GeV)**	$1.74\ \pm 0.29_{stat} \pm 0.28_{syst} \pm\ 0.18$	$1.60\ \pm 0.29_{stat} \pm 0.25_{syst} \pm\ 0.17$
$\frac{BR(b \to \eta_c X)}{BR(b \to J/\psi X)}$	$0.421 \pm 0.055 \pm 0.022 \pm 0.045$	

η_c prompt production measurement: differential cross-section

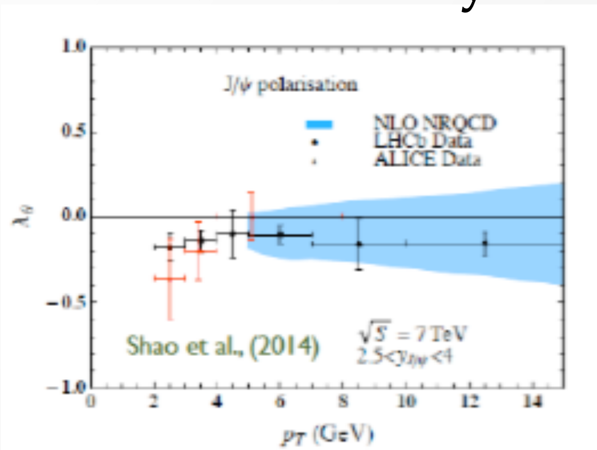


EPJC 75, 311
PRL 114 (2015) 092005

- Described by four LDMEs linked to J/ψ LDMEs by HQSS
- The only successful fit of theoretical prediction to p_t-differential production measurement by **Han, Ma, Meng, Shao, Chao PRL 114 (2015) 092005**
- CS contribution already saturates the yields $\rightarrow$ constrain CO LDME:

$$0 \leq \langle \mathcal{O}^{\eta_c}(^3S_1^{[8]}) \rangle \leq 1.46 \times 10^{-2}\ \text{GeV}^3$$
$$\Downarrow$$
$$0 \leq \langle \mathcal{O}^{J/\psi}(^1S_0^{[8]}) \rangle \leq 1.46 \times 10^{-2}\ \text{GeV}^3$$

➔Reduce the uncertainty from CO LDMEs :



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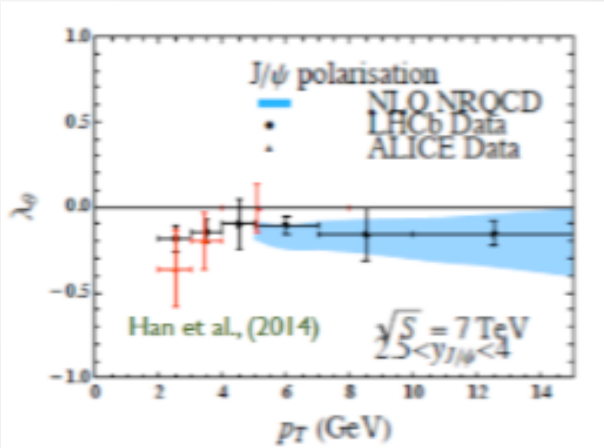


More precise measurement is needed

J/ψ and η_c production in inclusive b-decays

Barsuk, Kou, Usachov LAL-17-051

- From **EPJC 75 (2015) 311** and **PDG:**

$$\frac{\mathcal{B}(b \to \eta_c(1S)^{direct} X)}{\mathcal{B}(b \to J/\psi^{direct} X)} = 0.691 \pm 0.090 \pm 0.024 \pm 0.103$$

- Relation between LDME from HQSS:

$$\langle O_1^{\eta_c}({}^1S_0)\rangle = \frac{1}{3}\langle O_1^{J/\psi}({}^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}({}^1S_0)\rangle = \frac{1}{3}\langle O_8^{J/\psi}({}^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}({}^3S_1)\rangle = \langle O_8^{J/\psi}({}^1S_0)\rangle,$$
$$\langle O_8^{\eta_c}({}^1P_1)\rangle = 3\langle O_8^{J/\psi}({}^3P_0)\rangle.$$

- Branching fractions calculated in **Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003**

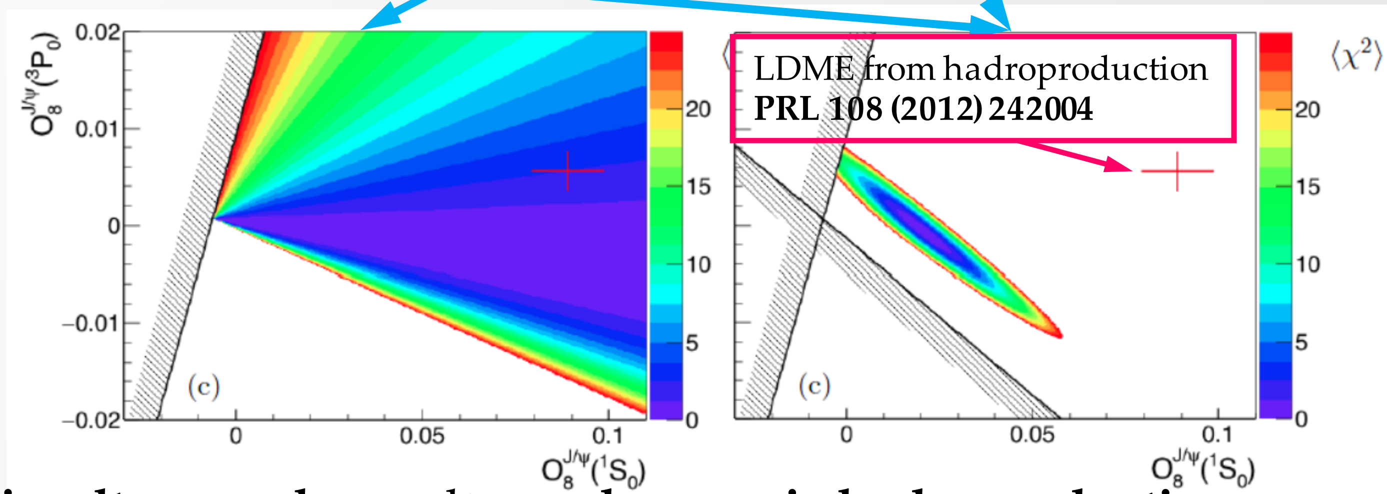
- **Fit two LDMEs to measurements**

- Consecutively fix two remaining LDME from **Chao et al., PRL 108 (2012) 242004**

$$\langle O_8^{J/\psi}({}^3S_1)\rangle = 0.003\ \mathrm{GeV}^3$$
$$\langle O_8^{J/\psi}({}^3S_1)\rangle = 1.16\ \mathrm{GeV}^3$$

$$\frac{\mathcal{B}(b \to \eta_c(1S)^{direct} X)}{\mathcal{B}(b \to J/\psi^{direct} X)}$$

$$\mathcal{B}(b \to J/\psi^{direct} X)$$



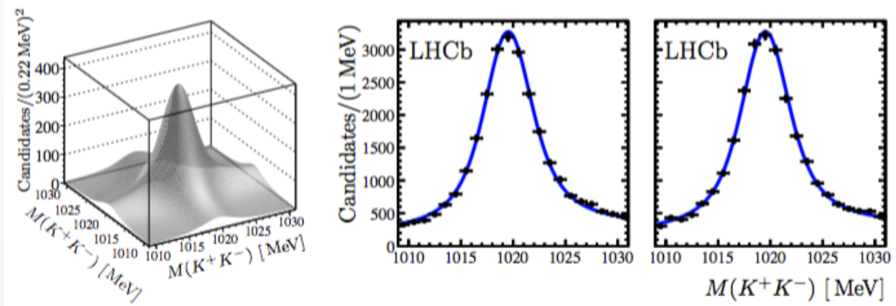
- Constrain theory using **simultaneously** results on **charmonia hadroproduction and** on **charmonia from b-inclusive decays**

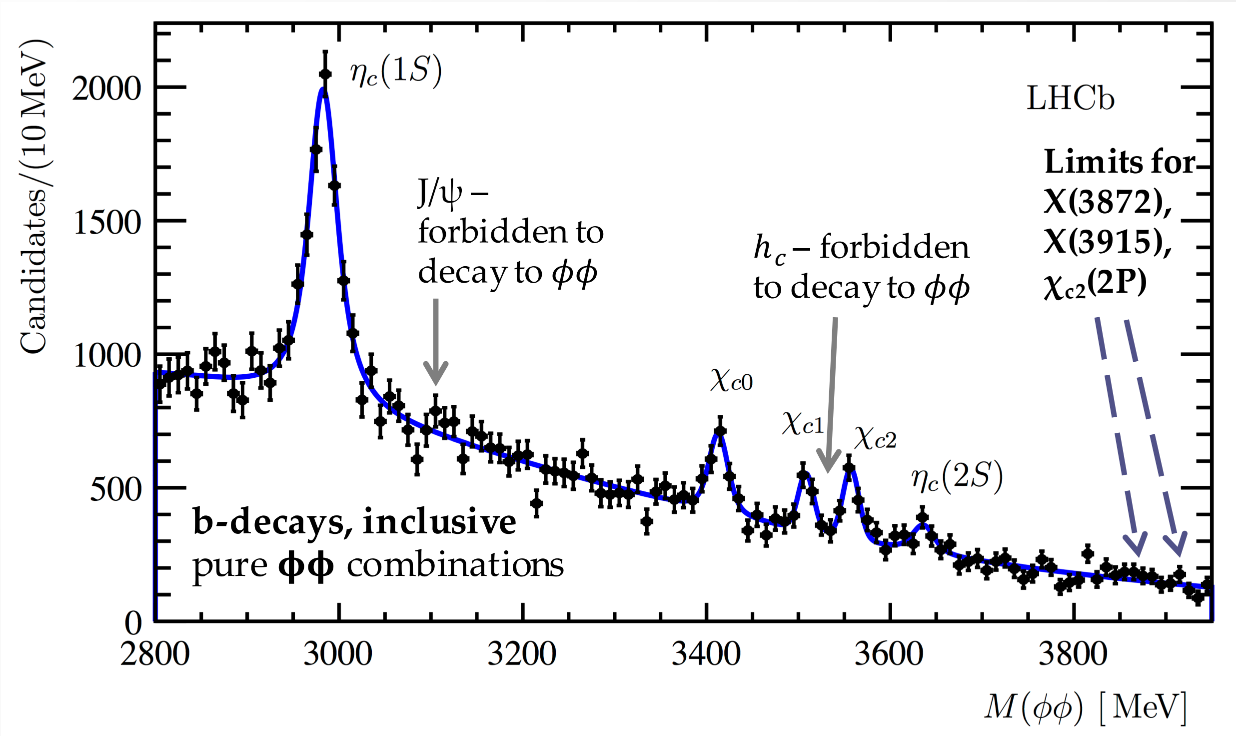
χ_c and $\eta_c(2S)$ production in inclusive b-decays using $\phi\phi$ at $\sqrt{s} = 7{,}8\ TeV$

EPJC 77 (2017), 609

- Powerful test of NRQCD factorization, universality of LDME and heavy quark spin symmetry assumptions
- Aiming at constraining LDMEs simultaneously by prompt and b-decays measurements

- 2D fit of $M(K^+K^-{}_1)\times M(K^+K^-{}_2)$ in bins of $M(KKKK)$ to select true $\phi\phi$ combinations



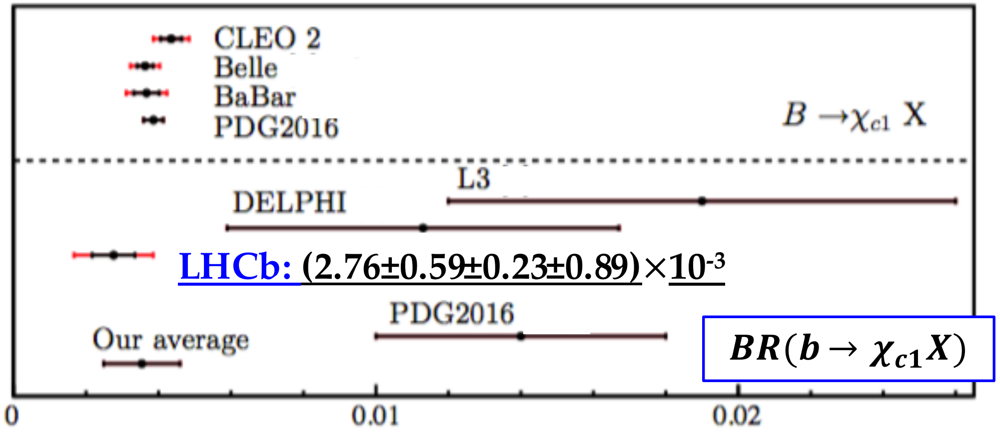


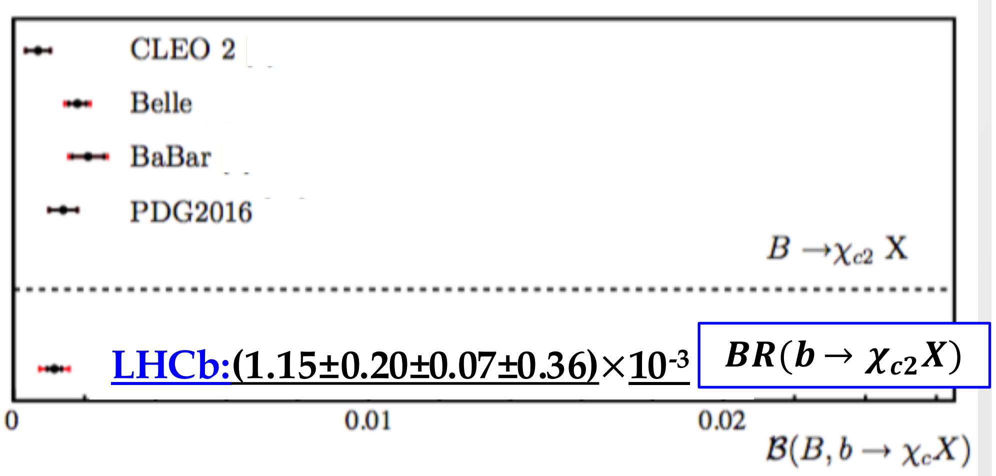
- χ_c and $\eta_c(2S)$ production rates measured using previously measured BR$(b \to \eta_c(1S)X)$

χ_c and $\eta_c(2S)$ production in inclusive b-decays using $\phi\phi$ at $\sqrt{s} = 7{,}8\ TeV$

EPJC 77 (2017), 609

- First measurement of χ_{c0} production in inclusive b-decays
  $\boldsymbol{BR(b \to \chi_{c0}X)} = (3.02\pm0.47\pm0.23\pm0.94)\times10^{-3}$
- The most precise measurements of $\boldsymbol{BR(b \to \chi_{c1}X)}$ and $\boldsymbol{BR(b \to \chi_{c2}X)}$
- $\boldsymbol{BR(b \to \chi_{c1}X)}$ and $\boldsymbol{BR(b \to \chi_{c2}X)}$ are in agreement with measurements at B-factories

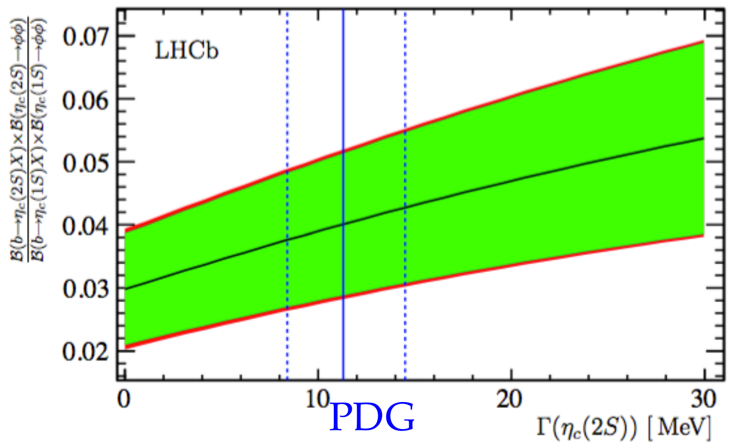




- First measurement of $\eta_c(2S)$ production in inclusive b-decays; first evidence of $\eta_c(2S) \longrightarrow \phi\phi$

$$\frac{BR(b \to \eta_c(2S)X)\,BR(\eta_c(2S) \to \phi\phi)}{BR(b \to \eta_c(1S)X)\,BR(\eta_c(1S) \to \phi\phi)} = 0.040 \pm 0.011 \pm 0.004$$ **(3.7σ significance)**

$\eta_c(2S)$ production as a function of assumed $\Gamma[\eta_c(2S)]$



➜ ***first step to measure $\eta_c(2S)$ hadroproduction***

χ_c and $\eta_c(2S)$ production in inclusive b-decays using $\phi\phi$ at $\sqrt{s} = 7{,}8\ TeV$

Barsuk, Kou, Usachov LAL-17-051

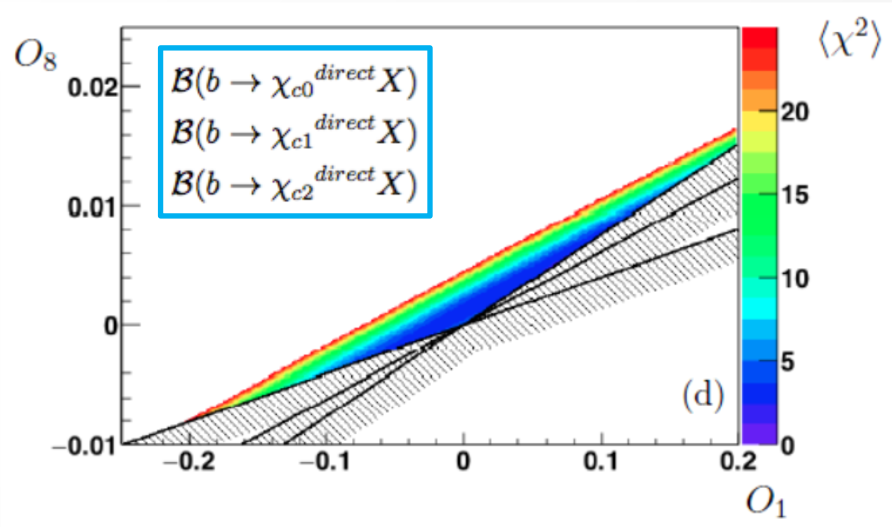
- From **EPJC 77 (2017), 609** and **PDG:**

$$\mathcal{B}(b \to \chi_{c0}{}^{direct} X) = (2.74 \pm 0.47 \pm 0.23 \pm 0.94_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c1}{}^{direct} X) = (2.49 \pm 0.59 \pm 0.23 \pm 0.89_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c2}{}^{direct} X) = (0.89 \pm 0.20 \pm 0.07 \pm 0.36_{\mathcal{B}}) \times 10^{-3}$$

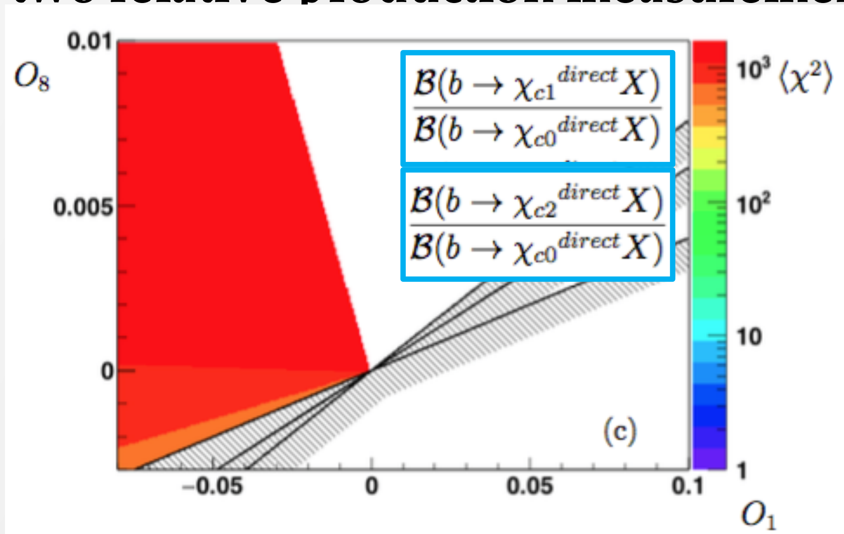
- Relation between LDME from HQSS:
- Branching fractions calculated in **Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003**

$$O_1 \equiv \langle O_1^{\chi_{c0}}(^3P_0)\rangle/m_c^2,$$
$$O_8 \equiv \langle O_8^{\chi_{c0}}(^3S_1)\rangle,$$
$$\langle O_1^{\chi_{cJ}}(^3P_J)\rangle/m_c^2 = (2J+1)O_1,$$
$$\langle O_8^{\chi_{cJ}}(^3S_1)\rangle = (2J+1)O_8.$$

1. Fit two LDMEs to three measurements:



2. Discrepancy when fitting two LDMEs to two relative production measurements:



- *to constrain theory using* ***simultaneously*** *results on* ***charmonia hadroproduction and*** *on* ***charmonia from b-inclusive decays***

Status of charmonia production measurements

	Prompt hadroproduction	$BR(B^0 \mid B^{\pm} \mid b-baryons \to (c\bar{c})X)$	$BR(B^0 \mid B^{\pm} \to (c\bar{c})X)$
$\eta_c(1S)$	LHCb - $p\bar{p}$	$(4.88 \pm 0.96)\times10^{-3}$ LHCb - $p\bar{p}$	-
J/ψ	LHCb, ATLAS, CMS -$\mu\mu$	$(1.16 \pm 0.10)\times10^{-3}$ LEP - ll	$(1.094 \pm 0.032)\times10^{-2}$ direct : $(7.8 \pm 0.4)\times10^{-3}$ BABAR, CLEO - ll
χ_{c0}	-	$(1.66 \pm 0.26 \pm 0.13 \pm 0.40B)\times10^{-3}$ LHCb -$\phi\phi$	-
χ_{c1}	ATLAS, LHCb, CMS -$J/\psi\gamma$	$(1.4 \pm 0.4)\times10^{-2}$ LEP - $J/\psi\gamma$ $(1.41 \pm 0.30 \pm 0.12 \pm 0.36B)\times10^{-3}$ LHCb -$\phi\phi$	$(3.86 \pm 0.27)\times10^{-3}$ direct: $(3.24 \pm 0.25)\times10^{-3}$ BABAR, Belle, CLEO -$J/\psi\gamma$
h_c	-	-	-
χ_{c2}	ATLAS, LHCb, CMS -$J/\psi\gamma$	$(0.63 \pm 0.11 \pm 0.05 \pm 0.15B)\times10^{-3}$ LHCb -$\phi\phi$	$(1.4 \pm 0.4)\times10^{-3}$ direct: $(1.65 \pm 0.31)\times10^{-3}$ BABAR, Belle -$J/\psi\gamma$
$\eta_c(2S)$	-	LHCb -$\phi\phi$ BR($\eta_c(2S) \to \phi\phi$) was not measured	-
$\psi(2S)$	LHCb, ATLAS, CMS -$\mu\mu$	$(2.83 \pm 0.29)\times10^{-3}$ LHCb, CMS - $\mu\mu$	$(3.07 \pm 0.21)\times10^{-3}$ BABAR, CLEO - ll

Conclusions and prospects

- J/ψ and $\psi(2S)$ prompt and b-decays production and polarization were measured using clean $\mu\mu$ channel at LHC
- $\chi_{c1,2}$ prompt production was measured using $J/\psi\,\gamma$

→ *Other charmonium states production have to be investigated using hadronic channels*

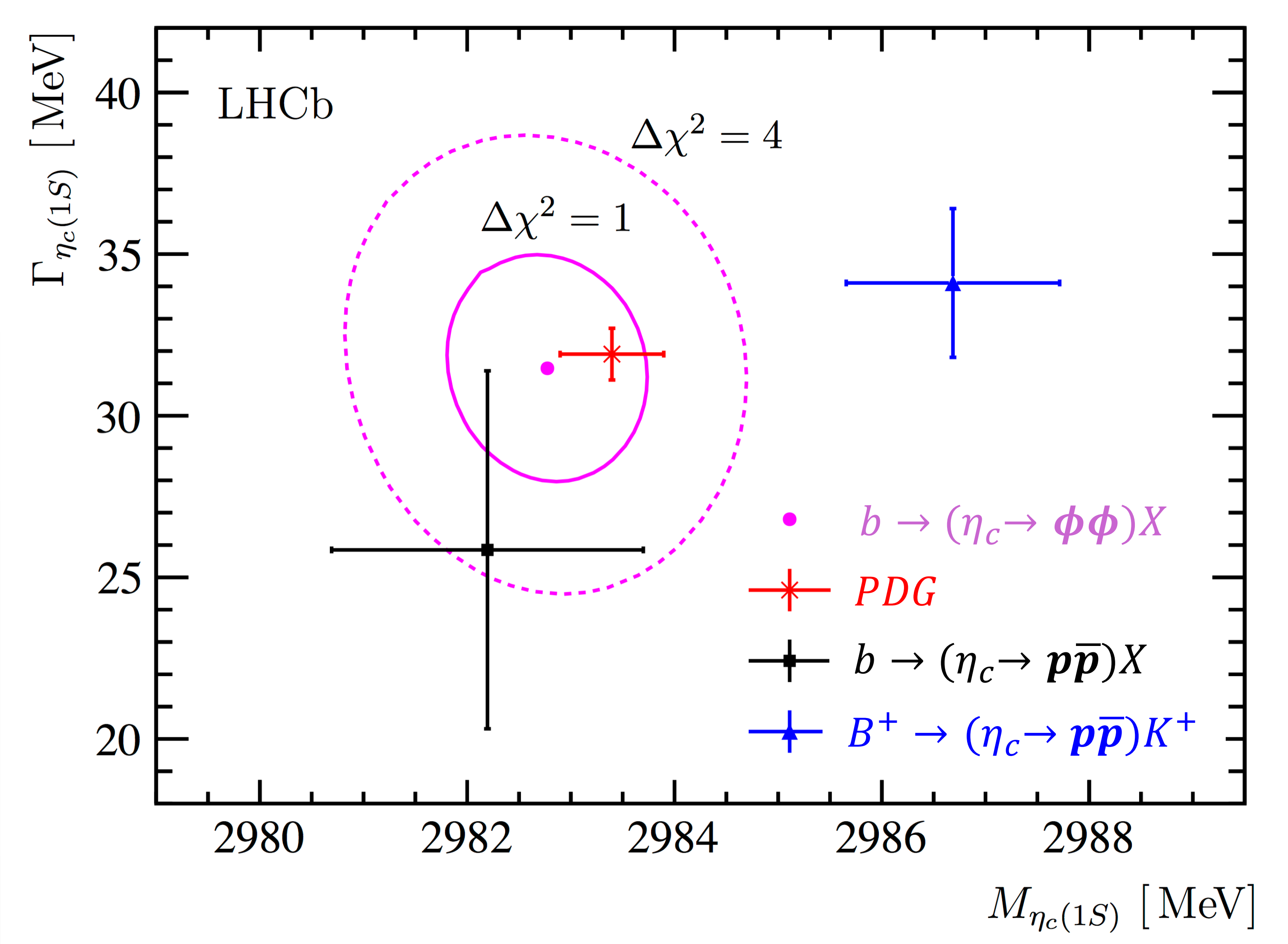
- η_c production was measured **for the first time** using $\eta_c \to p\bar{p}$
- CS contribution saturates η_c prompt production => limit for CO LDME
- $\chi_{c0,1,2}$ production in b-decays was measured at LHCb using $\phi\phi$.
  → Current theoretical prediction does not match to measured relative χ_c production

→ *To constrain theory using* ***simultaneously*** *results on* ***charmonia hadroproduction and*** *on* ***charmonia from b-inclusive decays***

- $\eta_c(2S)$ production in b-decays was measured at LHCb using $\phi\phi$ for the first time

- *No measurements for h_c and $\eta_c(2S)$ prompt production*
- *Other promising final states to investigate: $p\bar{p}\pi^+\pi^-$, $\Lambda\Lambda$, $\Xi\Xi$, $\Sigma\Sigma$*

Spectroscopy with η_c decays to hadrons



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PLB 769, 305

- General agreement with world average
- Similar to PDG precision expected for η_c mass with Run II data

Decays of charmonia

	$\mu\mu$	$J/\psi\,\gamma$	$p\bar{p}$	$\phi\phi$	$p\bar{p}\pi^+\pi^-$	$\phi\phi\pi^+\pi^-$	$\phi f_0(980)$	$\phi f_2(1545)$	baryons
$\eta_c(1S)$	forb.	-	0.15%	0.18%	0.5%				~0.1%
J/ψ	6%	-	0.2%	forb.	0.6%		0.03%	~0.1%	~0.1%
χ_{c0}	forb.	1.3%	0.02%	0.08%					~0.04%
χ_{c1}	forb.	34%	0.01%	0.04%	0.05%				~0.01%
h_c	forb.		?	forb.	?				?
χ_{c2}	forb.	19%	0.1%	0.01%	0.1%				~0.01%
$\eta_c(2S)$	forb.		?	?	?	?			?
$\psi(2S)$	0.8%		0.03%	forb.	0.06%				~0.02%

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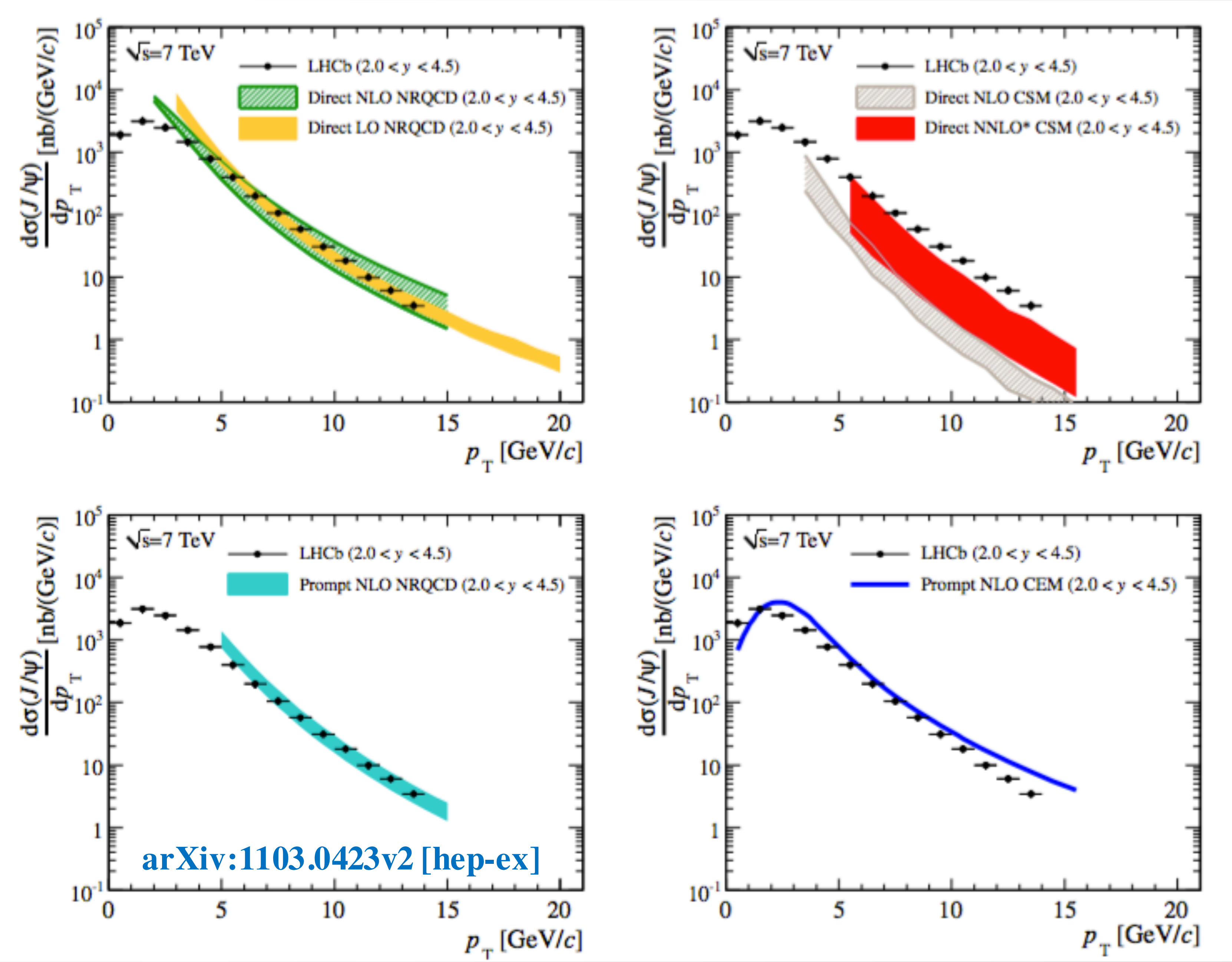
J/ψ prompt production vs different theory models



$BR(b \to \eta_c X)$ compare to theory

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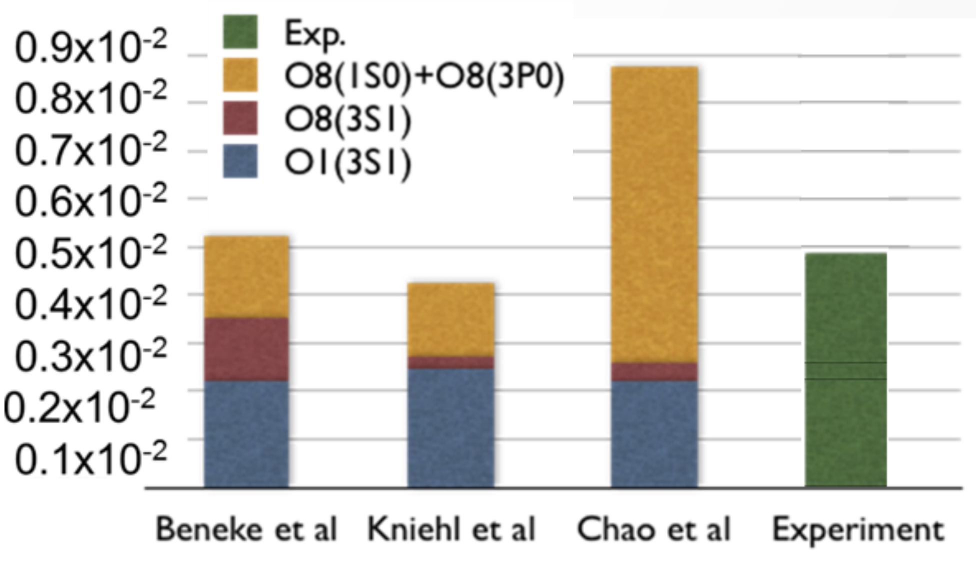
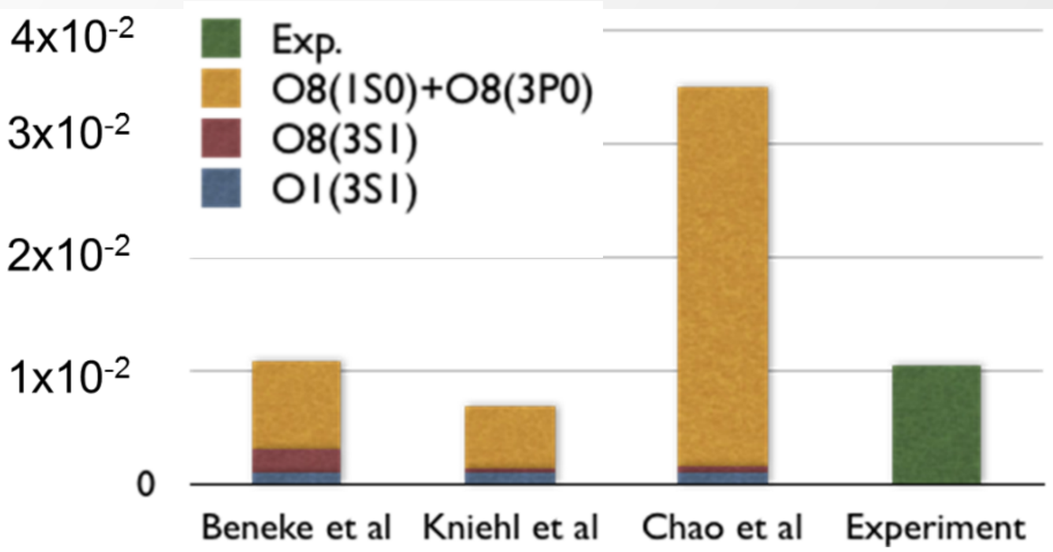


$BR(b \to J/\psi X)$ compare to theory:



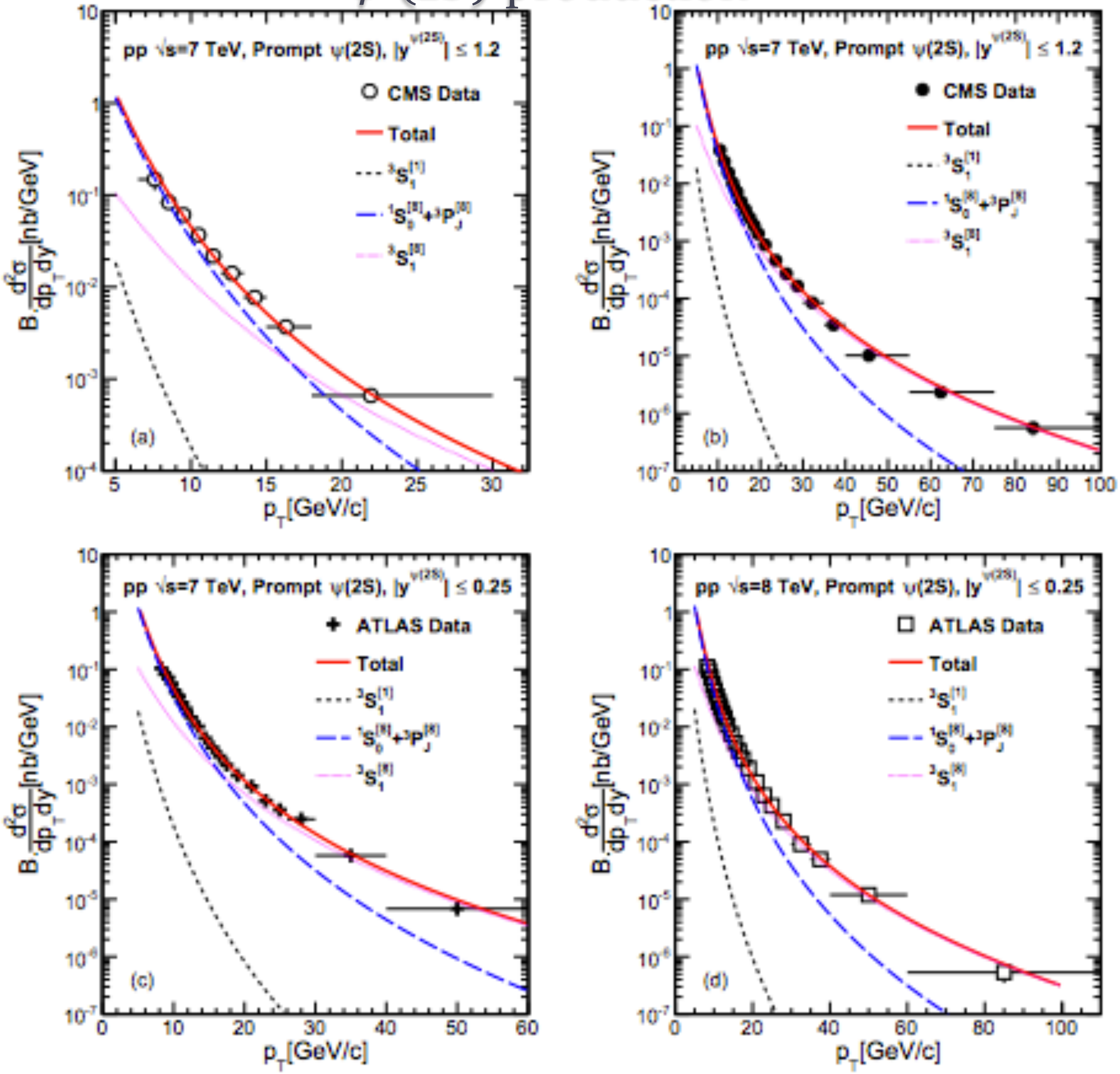
$BR(b \to (c\bar{c})X)$ from theory including HQSS relations

$$\mathcal{B}(B \to J/\psi\, X) = 7.54 \cdot 10^{-4} \langle O_1^{J/\psi}(^3S_1)\rangle + 0.195 \langle O_8^{J/\psi}(^3S_1)\rangle + 0.342 \left[\langle O_8^{J/\psi}(^1S_0)\rangle + \frac{3.10}{m_c^2} \langle O_8^{J/\psi}(^3P_0)\rangle \right],$$

$$\mathcal{B}(B \to \eta_c(1S) X) = 8.33 \cdot 10^{-4} \langle O_1^{J/\psi}(^3S_1)\rangle + 0.114 \langle O_8^{J/\psi}(^3S_1)\rangle + 0.195 \left[\langle O_8^{J/\psi}(^1S_0)\rangle - \frac{0.720}{m_c^2} \langle O_8^{J/\psi}(^3P_0)\rangle \right].$$

$$\mathcal{B}(B \to \chi_{c0} X) = -0.0148\ O_1 + 0.195\ O_8,$$
$$\mathcal{B}(B \to \chi_{c1} X) = -0.0234\ O_1 + 0.585\ O_8,$$
$$\mathcal{B}(B \to \chi_{c2} X) = -0.0600\ O_1 + 0.975\ O_8.$$

$\psi\ (2S)$ production



INCLUSIVE CHARMONIUM PRODUCTION

- Test the consistence in J/ψ production