Measurements of charmonia production in b-hadron inclusive decays in LHCb

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Mini-workshop on charmonium production at LHCb
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Introduction

- Test of **NRQCD factorization** framework
  - Universality assumption: long-distance hadronization of $c\bar{c}$ pair to charmonium is independent from the way $c\bar{c}$ pair was produced
    => **long-distance matrix elements (LDME) are the same for prompt and b-decays production**
  - Spin symmetry:
    => linked LDMEs parameters for $\mathbf{J/\psi}$ and $\boldsymbol{\eta_c}$**(1S)**
    => linked LDMEs parameters for $\boldsymbol{\chi_{c0,1,2}}$ and $\boldsymbol{h_c}$

- Powerful tests of FONLL using b → J/ψX
- Nice to measure production of other states

- Mass and natural width of $\boldsymbol{\eta_c(1S)}$
  The most precise measurements of mass and natural width of $\boldsymbol{\eta_c}$**(1S)** were performed using $\boldsymbol{\eta_c}$ **produced in radiative decays (PRL 108, 222002)**
  - > significant asymmetry in the lineshapes was observed **[PRD 73, 054005]**
  -> the most precise BES results shifted world average of $\boldsymbol{\Gamma(\eta_c(1S))}$ *by* $> 2\sigma$
- Properties of $\boldsymbol{\eta_c}$**(2S)** are not well studied

Decays of charmonia

	$\mu\mu$	$J/\psi\gamma$ $J/\psi\pi^+\pi^-$	$p\bar{p}$	$\phi\phi$	$p\bar{p}\pi^+\pi^-$	$\phi f_0(980)$	$\phi f_2(1545)$	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.		<0.015%	forb.	?			?
χ_{c2}	forb.	19%	0.1%	0.01%	0.1%			~0.01%
$\eta_c(2S)$	forb.		<0.1%	?	?			?
$\psi(2S)$	0.8%		0.03%	forb.	0.06%			~0.02%

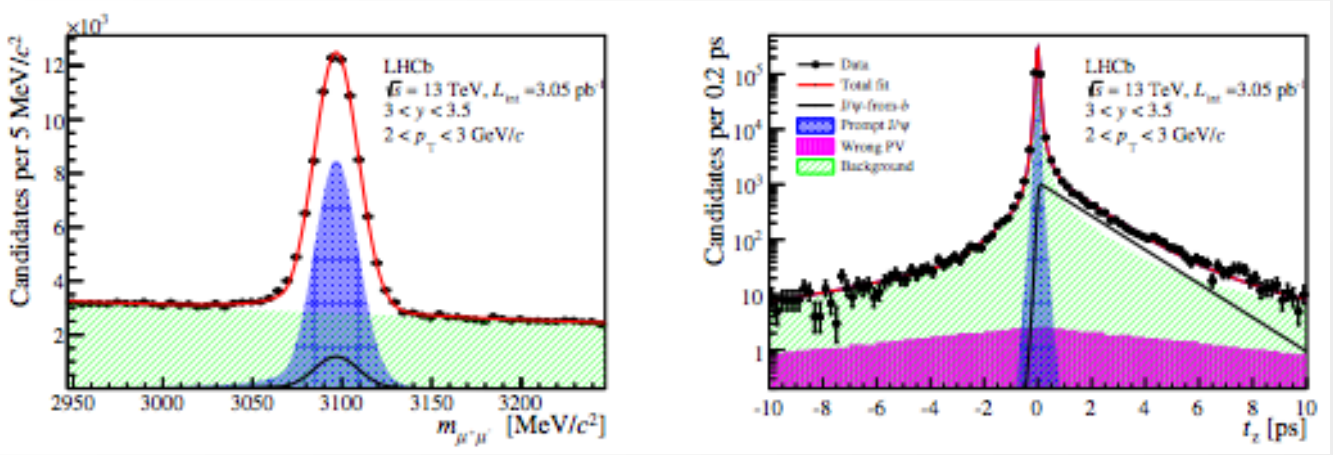
$\Lambda\Lambda$
$\Xi\Xi$
$\Sigma\Sigma$

- The most precise studies were performed for J/ψ (and $\psi(2S)$) using clean $\mu\mu$ channel
- χ_{c1} and χ_{c2} are accessed using $J/\psi\gamma$ channel
- Use charmonia decays to hadrons to measure production of other charmonium states ($\eta_c(1S)$, $\eta_c(2S)$, h_c?, χ_{c0})
  - *LHCb is well suited to measure charged hadron final states*

J/ψ production in inclusive b-decays

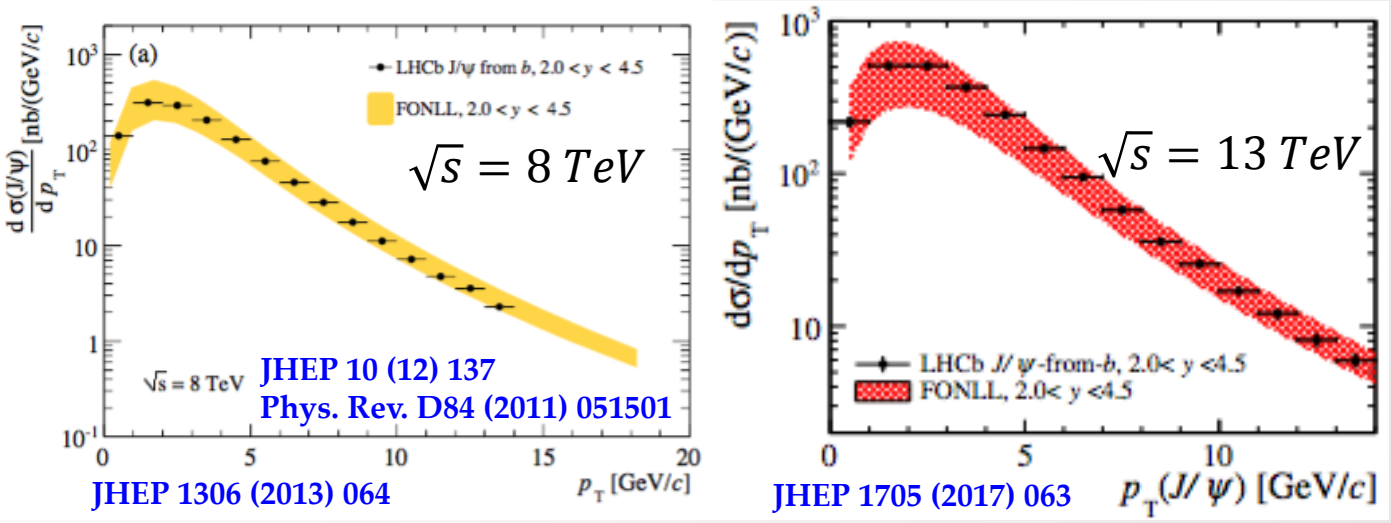
- Simultaneous **invariant mass** and **pseudo-proper decay time t_z** fit to separate prompt J/ψ and J/ψ from b-decays

$$t_z = \frac{(z_{SV} - z_{PV}) \times M_{J/\psi}}{p_z}$$



Results:

- Differential cross-section measurement described by FONLL prediction

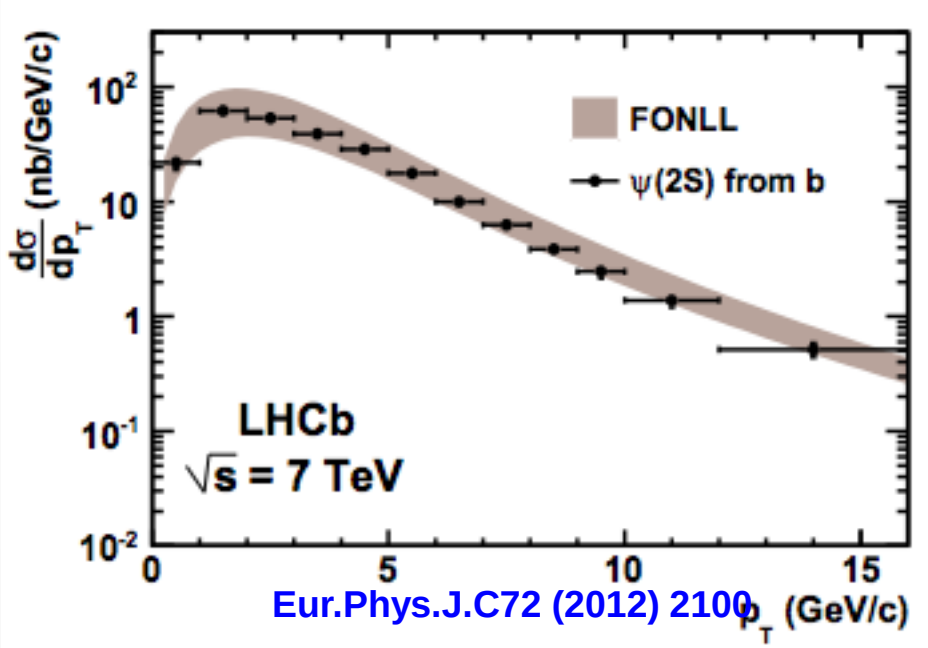


$\psi(2S)$ production in inclusive b-decays

- Simultaneous **invariant mass** and **pseudo-proper decay time** fit to separate prompt $\psi(2S)$ and $\psi(2S)$ from b-decays

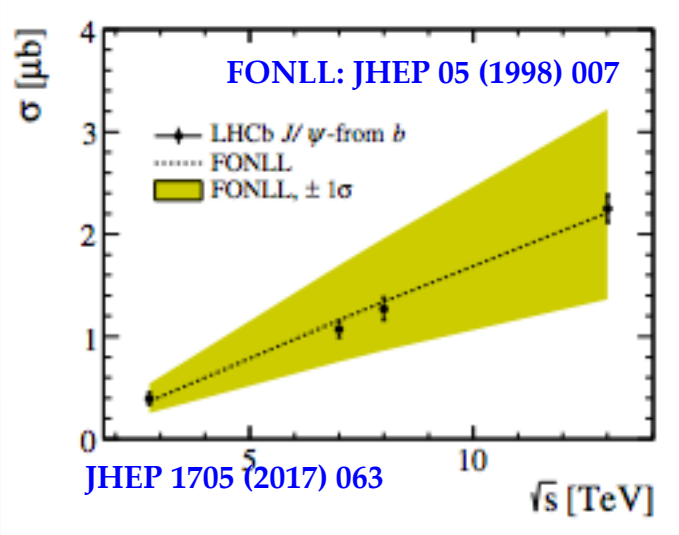
$$\frac{\mathcal{B}(b \to \psi(2S)X)}{\mathcal{B}(b \to J/\psi X)} = 0.235 \pm 0.005\ (\text{stat}) \pm 0.015\ (\text{syst}),$$

$$\mathcal{B}(b \to \psi(2S)X) = (2.73 \pm 0.06\ (\text{stat}) \pm 0.16\ (\text{syst}) \pm 0.24\ (\text{BF})) \times 10^{-3}$$

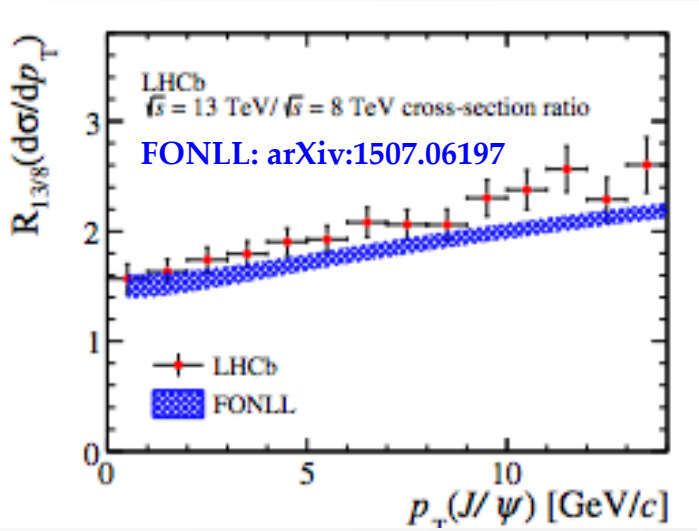


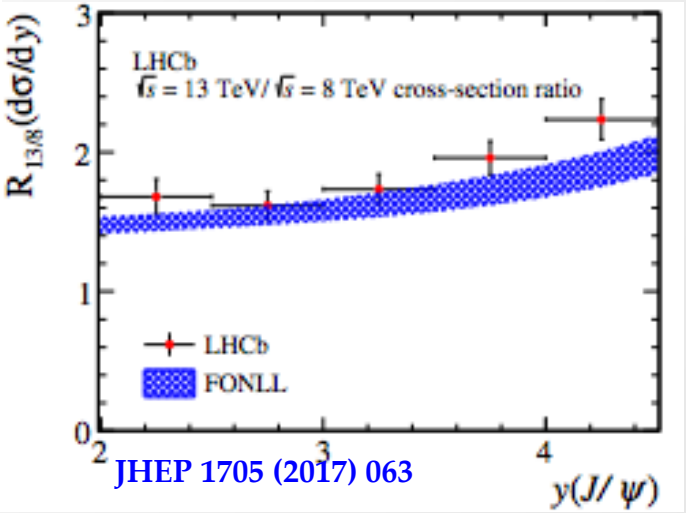
J/ψ production in inclusive b-decays

Measurements were performed for $\sqrt{s} = 2.76, 7, 8, 13\ TeV$



Ratio of 13 TeV/ 8 TeV production:
- Powerful test of FONLL: experimental and theoretical uncertainties partially cancel





$\eta_c(1S)$ production in inclusive b-decays using $p\bar{p}$ at $\sqrt{s} = 7{,}8\ TeV$

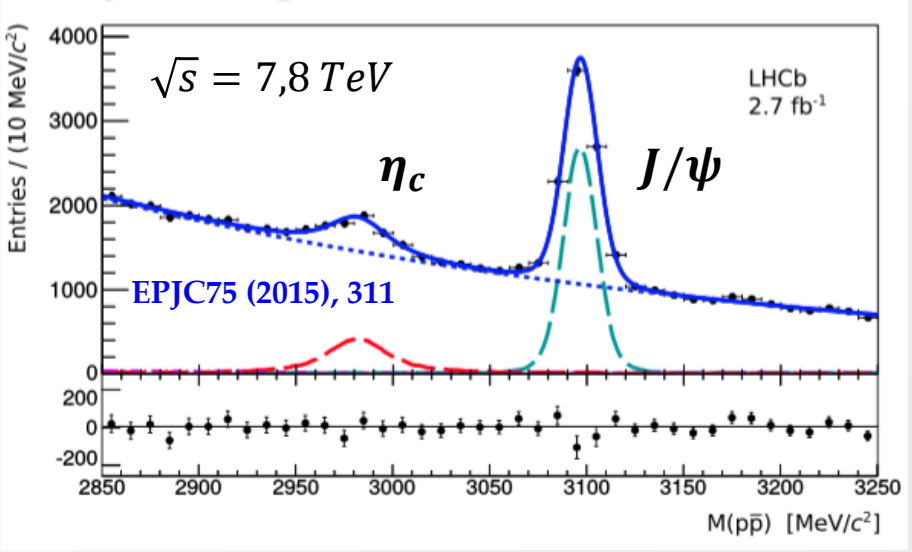
- Hadronic charmonia decays give access to non 1^{--} charmonia

Analysis:

- Normalization channel: $J/\psi \to p\bar{p}$
- Prompt and b-decays charmonia separated by t_z cut

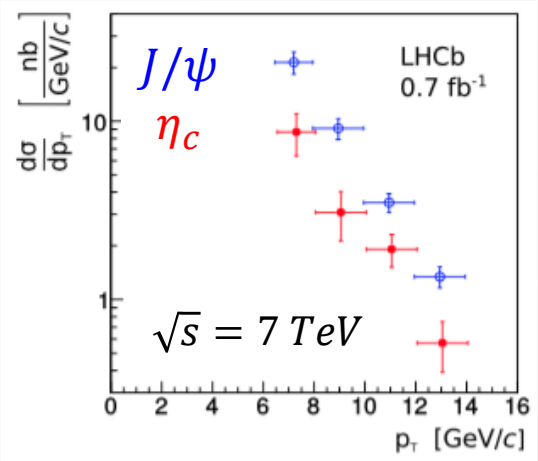
Results:

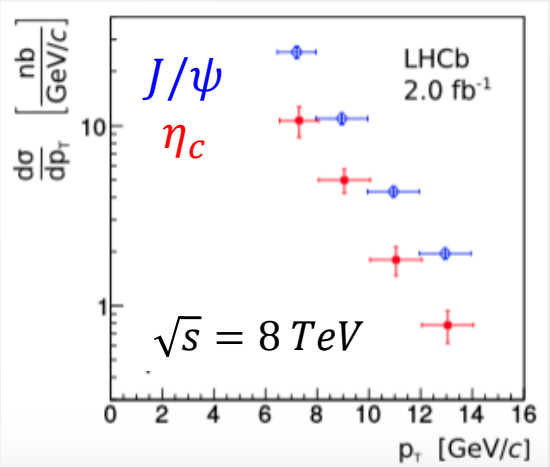
- First measurement of η_c production in inclusive b-decays:



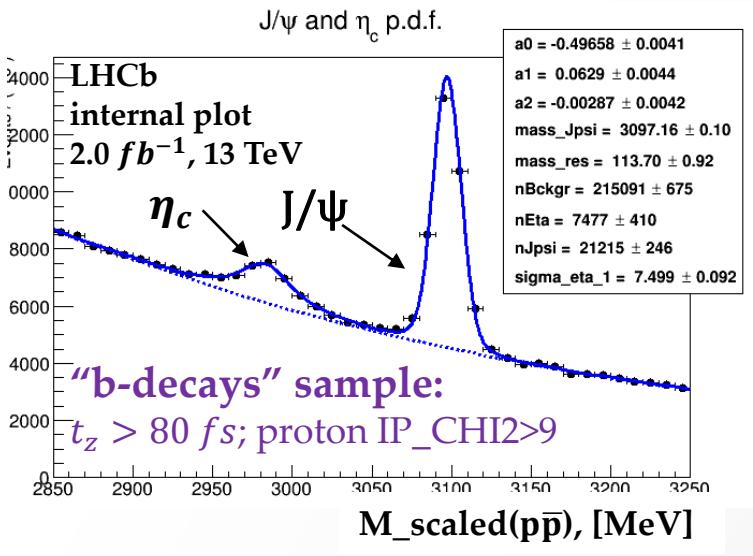
$$\mathcal{B}(b \to \eta_c(1S)X)/\mathcal{B}(b \to J/\psi X) = 0.421 \pm 0.055 \pm 0.025 \pm 0.045_{\mathcal{B}}$$
$$\mathcal{B}(b \to \eta_c(1S)X) = (4.88 \pm 0.64 \pm 0.29 \pm 0.67_{\mathcal{B}}) \times 10^{-3}$$

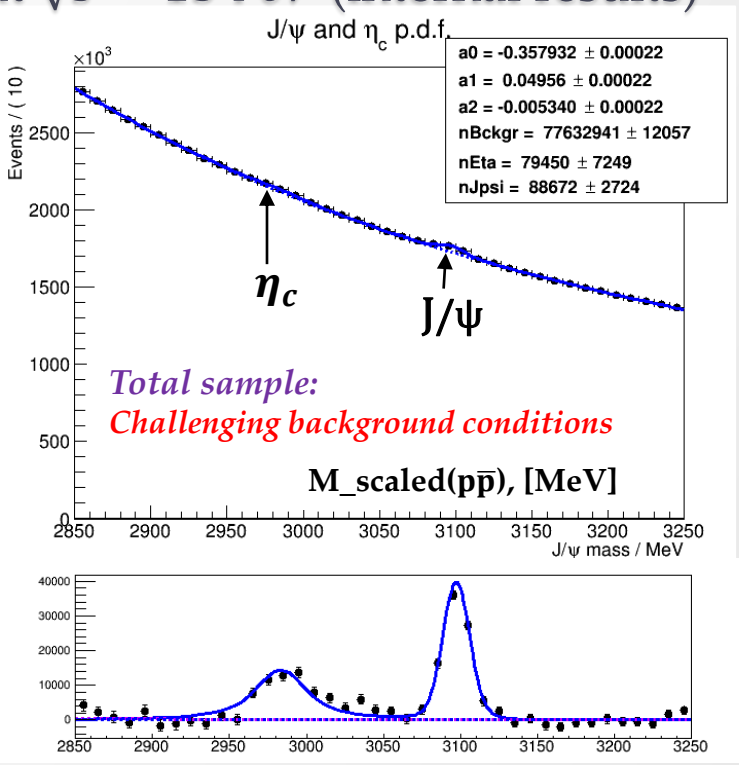
- Differential production cross-section:





$\eta_c(1S)$ production in inclusive b-decays using $p\bar{p}$ at $\sqrt{s} = 13\ TeV$ (internal results)

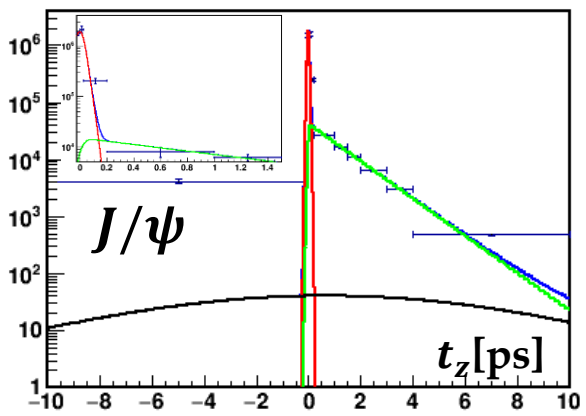


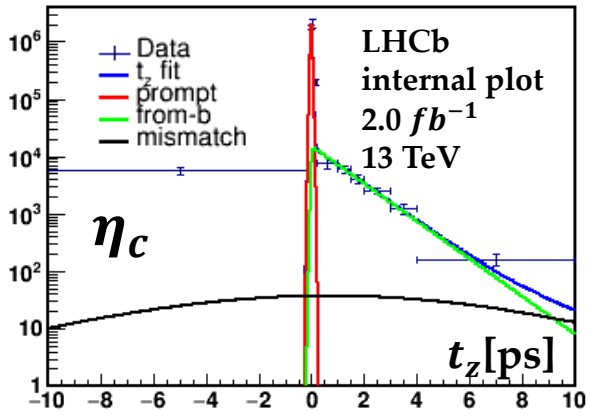


Strategy:

1. **Use "b-decays" sample to determine masses and resolution parameter**
2. **Perform invariant mass fit in bins of t_z**
3. **t_z fit to separate prompt from b-decays**
4. **Measure differential production in PT bins**

Simultaneous (J/ψ and η_c) χ^2integral t_z-fit:

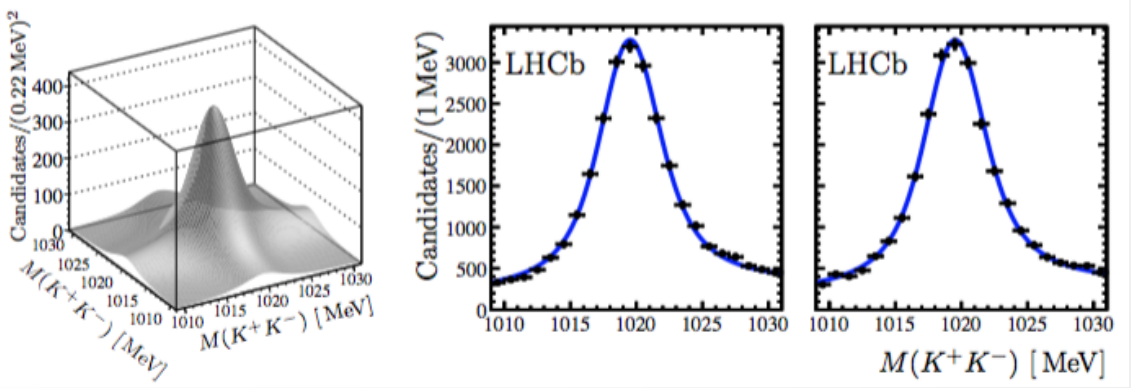




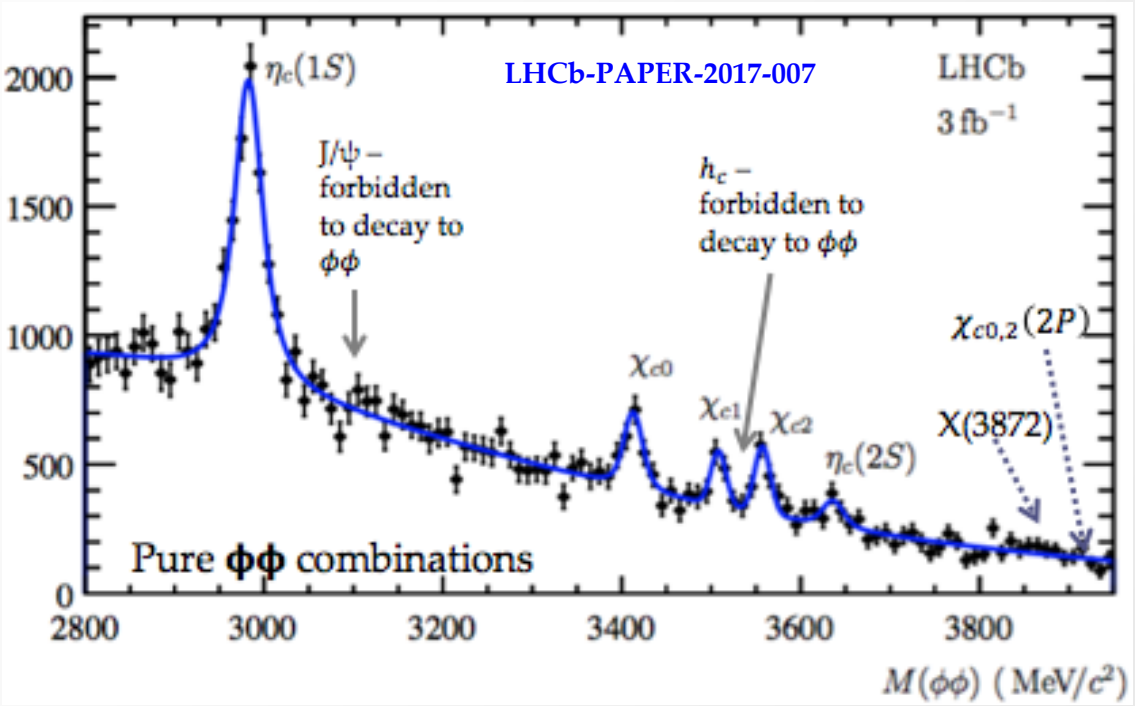
Agreement between Run I and Run II measurements

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

- Normalization channel: $\eta_c(1S) \to \phi\phi$
- Prompt charmonia removed by flight distance cut
- **2D fit of $M(K^+K^-_1) \times M(K^+K^-_2)$ in bins of $M(KKKK)$ to remove ϕKK and $KKKK$ backgrounds**

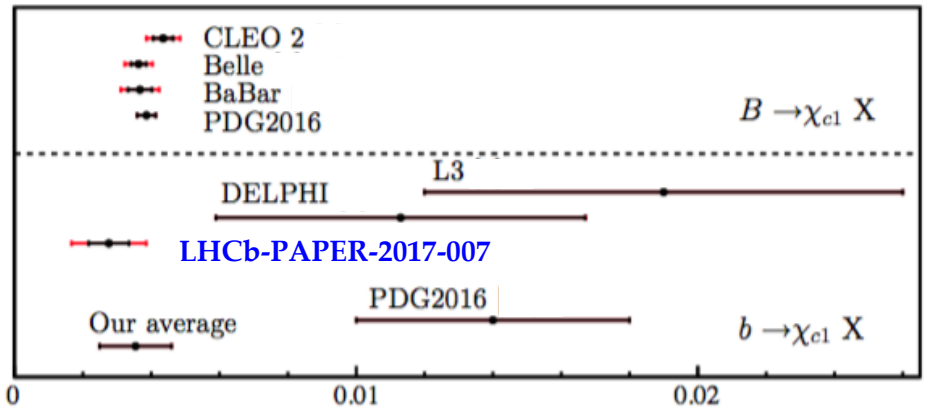


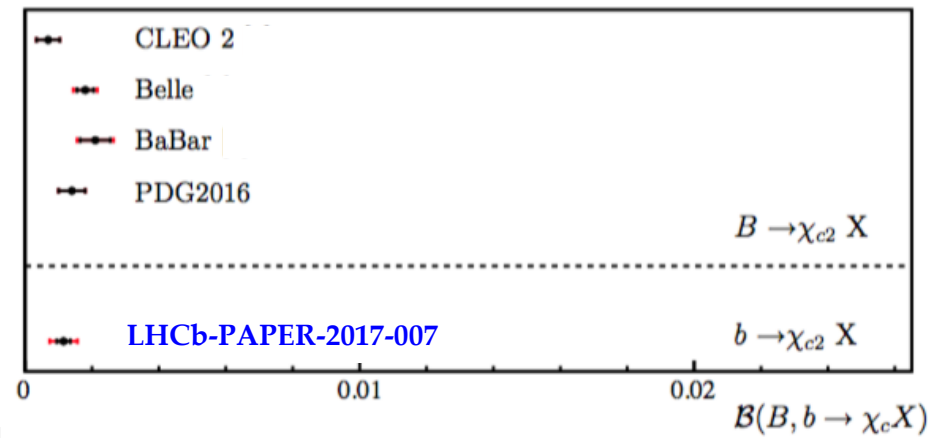
- Invariant mass spectrum of true $\phi\phi$ combinations:



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

- First measurement of χ_{c0} production in inclusive b-decays
- 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

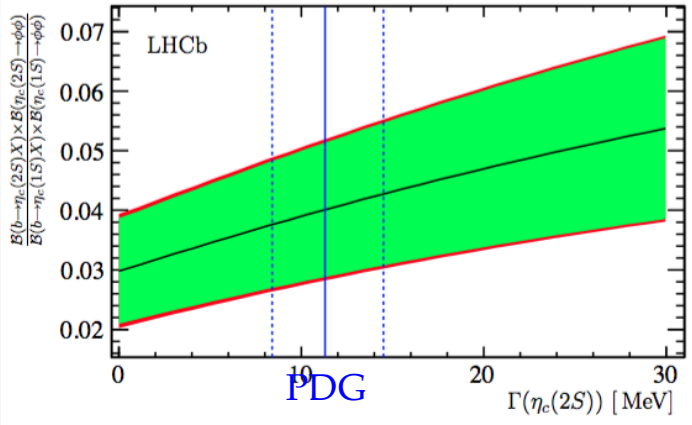




- First measurement of $\eta_c(2S)$ production in inclusive b-decays; first evidence of $\eta_c(2S) \longrightarrow \phi\phi$

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

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



PDG

Search for X(3872), X(3915) and $\chi_{c2}(2P)$ in inclusive b-decays using $\phi\phi$ at $\sqrt{s} = 7{,}8\ TeV$

- Bayessian upper limits on the X(3872), X(3915) and $\chi_{c2}(2P)$ production rates:

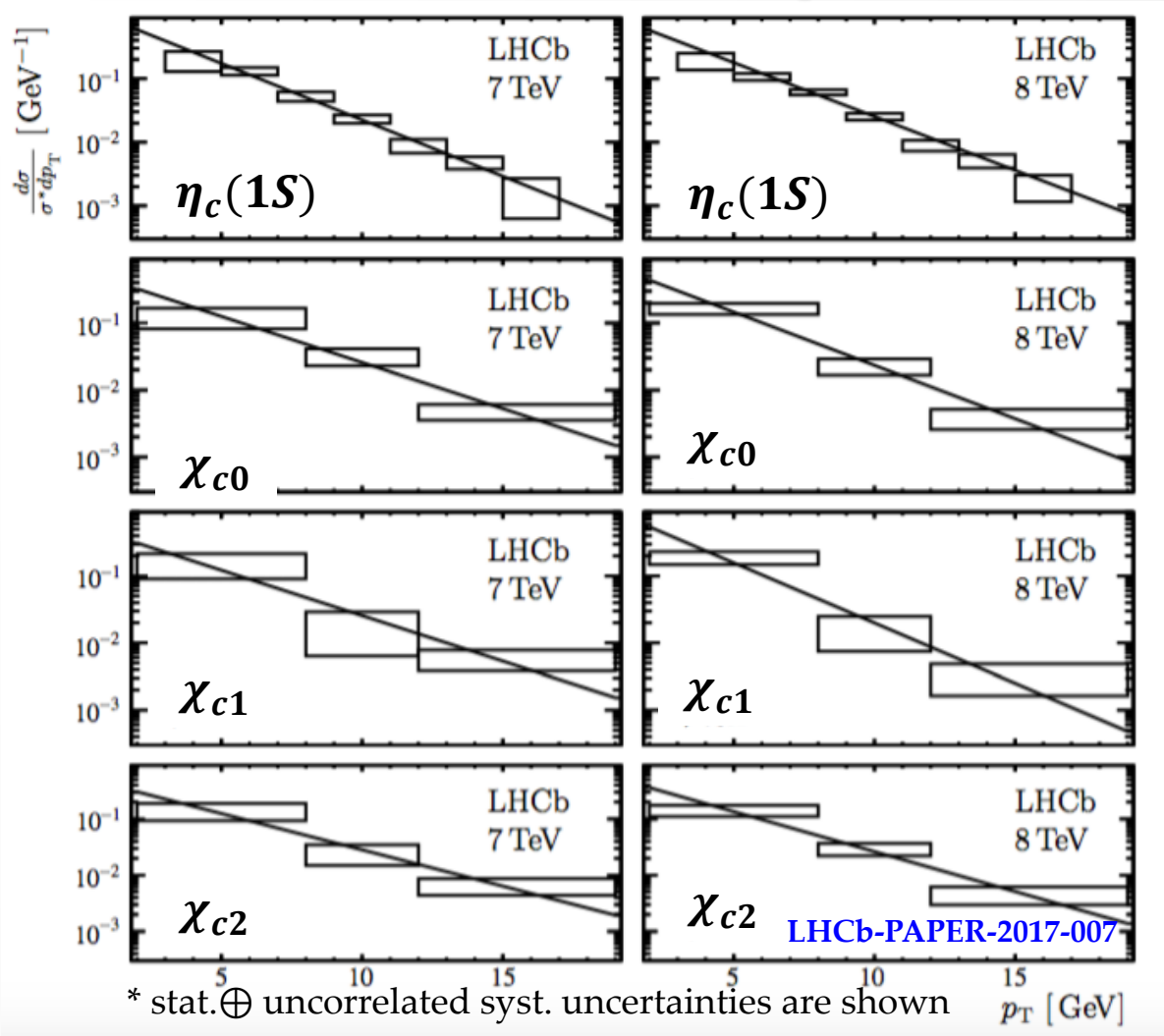
$$\frac{\mathcal{B}(b \to X(3872)X) \times \mathcal{B}(X(3872) \to \phi\phi)}{\mathcal{B}(b \to \chi_{c1}X) \times \mathcal{B}(\chi_{c1} \to \phi\phi)} < 0.39(0.34),$$
$$\frac{\mathcal{B}(b \to \chi_{c0}(2P)X) \times \mathcal{B}(\chi_{c0}(2P) \to \phi\phi)}{\mathcal{B}(b \to \chi_{c0}X) \times \mathcal{B}(\chi_{c0} \to \phi\phi)} < 0.14(0.12),$$
$$\frac{\mathcal{B}(b \to \chi_{c2}(2P)X) \times \mathcal{B}(\chi_{c2}(2P) \to \phi\phi)}{\mathcal{B}(b \to \chi_{c2}X) \times \mathcal{B}(\chi_{c2} \to \phi\phi)} < 0.20(0.16)$$

@ 90(95)% CL

$$\mathcal{B}(b \to X(3872)X) \times \mathcal{B}(X(3872) \to \phi\phi) < 4.5(3.9) \times 10^{-7},$$
$$\mathcal{B}(b \to \chi_{c0}(2P)X) \times \mathcal{B}(\chi_{c0}(2P) \to \phi\phi) < 3.1(2.7) \times 10^{-7},$$
$$\mathcal{B}(b \to \chi_{c2}(2P)X) \times \mathcal{B}(\chi_{c2}(2P) \to \phi\phi) < 2.8(2.3) \times 10^{-7}.$$

@ 90(95)% CL

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



* stat.⊕ uncorrelated syst. uncertainties are shown

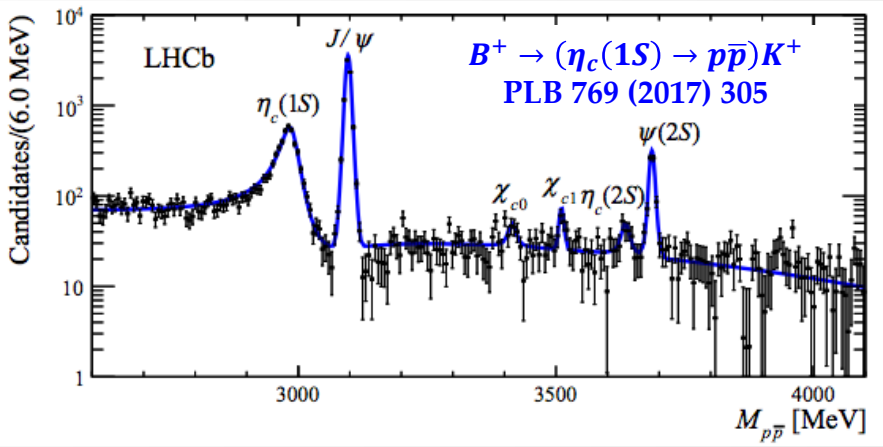
Exponential slopes of normalized differential prodcution cross-section are extracted:

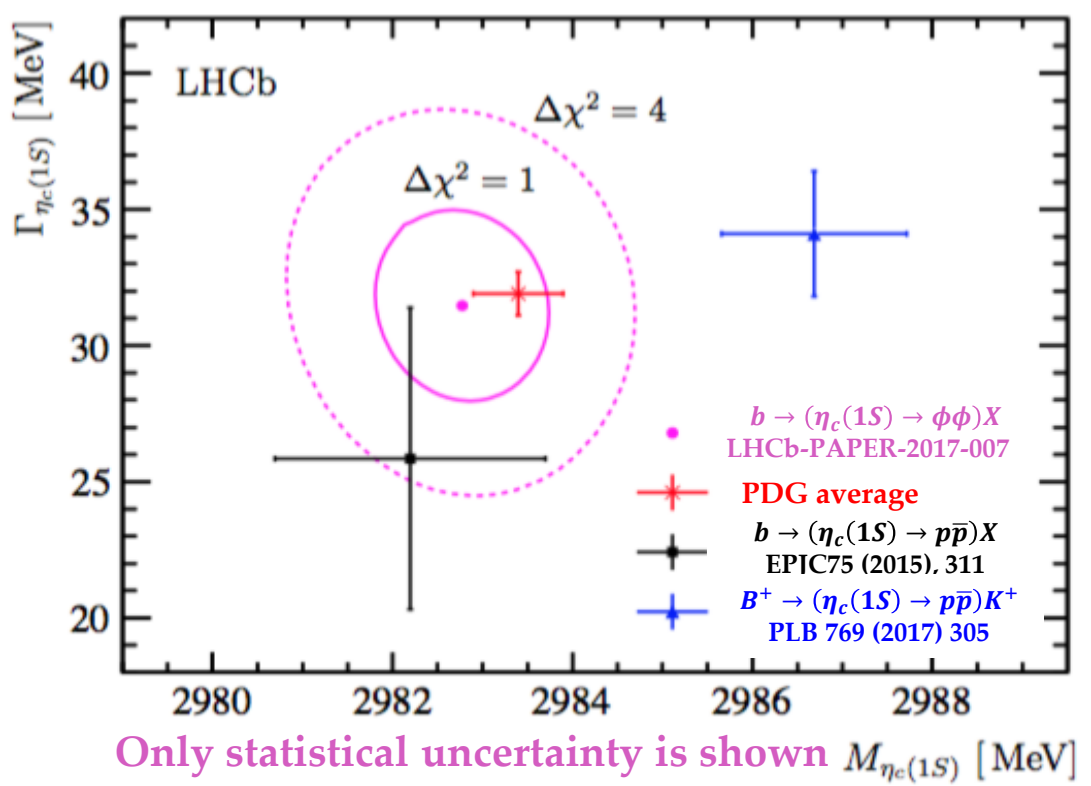
	$\eta_c(1S)$	χ_{c0}	χ_{c1}	χ_{c2}
$\sqrt{s} = 7\,\text{TeV}$	0.41 ± 0.02	0.32 ± 0.04	0.31 ± 0.06	0.30 ± 0.05
$\sqrt{s} = 8\,\text{TeV}$	0.39 ± 0.02	0.37 ± 0.04	0.41 ± 0.06	0.33 ± 0.04

Mass and natural width of $\eta_c(1S)$

LHCb measurements:

- $b \to (\eta_c(1S) \to p\bar{p})X$
- $b \to (\eta_c(1S) \to \phi\phi)X$
- **Another determination from exclusive $B^+ \to (\eta_c(1S) \to p\bar{p})K^+$ ➜**





Precision of η_c mass is competitive to PDG

Status of charmonia production measurements

	Prompt hadroproduction	$\boldsymbol{BR(B^0\|B^\pm\|b-baryons \to (c\bar{c})X)}$	$\boldsymbol{BR(B^0\|B^\pm \to (c\bar{c})X)}$ (B-factories)
$\boldsymbol{\eta_c}$(1S)	LHCb - $\boldsymbol{p\bar{p}}$	$(4.88 \pm 0.96) \times 10^{-3}$ LHCb - $\boldsymbol{p\bar{p}}$	-
$\boldsymbol{J/\psi}$	LHCb, ATLAS, CMS **-μμ**	$(1.16 \pm 0.10) \times 10^{-3}$ LEP **-** $\boldsymbol{ll}$	$(1.094 \pm 0.032) \times 10^{-2}$ direct : $(7.8 \pm 0.4) \times 10^{-3}$ BABAR, CLEO **-** $\boldsymbol{ll}$
$\boldsymbol{\chi_{c0}}$	-	$(3.02 \pm 0.47 \pm 0.23 \pm 0.94\text{B}) \times 10^{-3}$ LHCb **-**$\boldsymbol{\phi\phi}$	-
$\boldsymbol{\chi_{c1}}$	ATLAS, LHCb, CMS **-J/ψγ**	$(1.4 \pm 0.4) \times 10^{-2}$ LEP - **J/ψγ**	$(3.86 \pm 0.27) \times 10^{-3}$ direct: $(3.24 \pm 0.25) \times 10^{-3}$ BABAR, Belle, CLEO **-J/ψγ**
		$(2.76 \pm 0.59 \pm 0.23 \pm 0.89\text{B}) \times 10^{-3}$ LHCb **-**$\boldsymbol{\phi\phi}$	
h_c	-	-	-
$\boldsymbol{\chi_{c2}}$	ATLAS, LHCb, CMS **-J/ψγ**	$(1.15 \pm 0.20 \pm 0.07 \pm 0.36\text{B}) \times 10^{-3}$ LHCb **-**$\boldsymbol{\phi\phi}$	$(1.4 \pm 0.4) \times 10^{-3}$ direct: $(1.65 \pm 0.31) \times 10^{-3}$ BABAR, Belle **-J/ψγ**
$\boldsymbol{\eta_c}$(2S)	-	LHCb **-**$\boldsymbol{\phi\phi}$ BR$(\eta_c(2S) \to \phi\phi)$ was not measured	-
$\boldsymbol{\psi}$(2S)	LHCb, ATLAS, CMS **-μμ**	$(2.83 \pm 0.29) \times 10^{-3}$ LHCb, CMS **- μμ**	$(3.07 \pm 0.21) \times 10^{-3}$ BABAR, CLEO - $\boldsymbol{ll}$

Summary

- LHCb measured J/ψ production in inclusive b-decays in complementary PT and rapidity range to ATLAS and CMS
  - Differential cross-section is in agreement with FONLL prediction
  - The ratio $R_{13/8}$ is a powerful test of FONLL

- LHCb is well suited to measure hadronic final states to access non 1^{--} charmonia
  - First measurement of BR($b \to \eta_c X$) using $\eta_c \to p\bar{p}$
  - First measurement of BR($b \to \chi_{c0} X$), BR($b \to \eta_c(2S) X$) and the most precise BR($b \to \chi_{c1,2} X$) using decays to $\phi\phi$
  - Mass measurements for $\eta_c(1S)$

- Still no measurements of BR($b \to h_c X$)

- Determination of mass width and resolution for further prompt measurements
- Tempting to simultaneous constraint LDMEs by both prompt and b-decays measurements