Production and Decay of η_c States at LHCb

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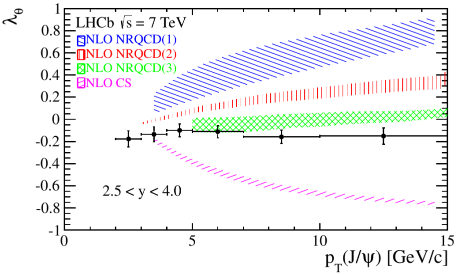
Charmonium Production at the LHC

- While charmonium production rates in pp collisions at LHC are well described by NLO NRQCD [EPJ C71(2011)1645] …
- … the small observed J/ψ polarisation is a puzzle
- Idea: Test NRQCD factorisation with η_c production data
  - LDMEs related by heavy quark symmetry

[EPJ C73(2013)2631]



- Previous charmonium production analyses: $\psi \rightarrow \mu\mu$
- This does not work for the η_c
- Radiative decays difficult to isolate in the hadronic environment at LHC

Charmonia in the $\mathrm{p\bar{p}}$ final state

[EPJ C75(2015)7,311]

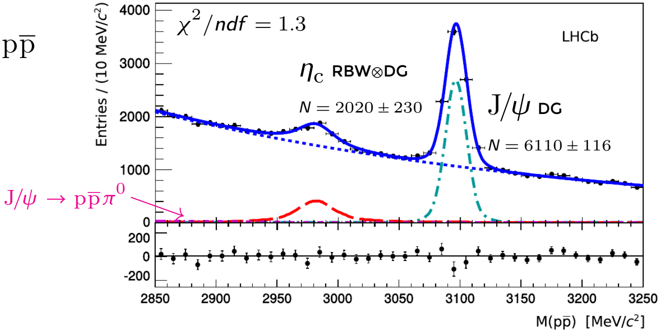
- Simultaneous decay channel for η_c and J/ψ?
- Idea: all charmonia decay into $\mathrm{p\bar{p}}$
- Use excellent tracking and PID capabilities at LHCb
- J/ψ as reference

- Datasets:
  - $0.7\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7\,\mathrm{GeV}/c^2$
  - $2\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{GeV}/c^2$

- Prompt production in pp collision
- and from B-decays
- $p_T(\mathrm{p\bar{p}}) > 6.5\,\mathrm{GeV}$
- $2.5 < y(\mathrm{p\bar{p}}) < 4.5$

$\mathrm{p\bar{p}}$ from displaced vertex

(pseudo decay time $t_z = \Delta z\, M/p_z > 80\,\mathrm{fs}$)



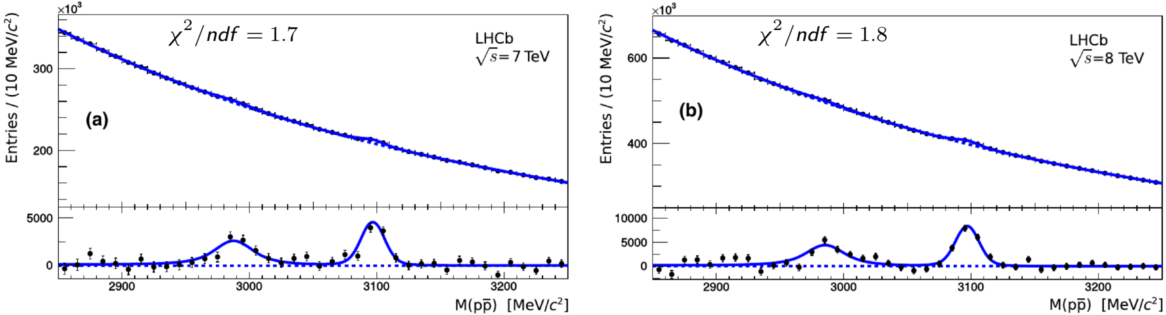
$$\Delta M_{J/\psi,\eta_c} = 114.7 \pm 1.5 \pm 0.1\,\mathrm{MeV}/c^2$$

$$\Gamma_{\eta_c(1S)} = 25.8 \pm 5.2 \pm 1.9\,\mathrm{MeV}/c^2$$

$$N^b_{\eta_c(1S)}/N^b_{J/\psi} = 0.302 \pm 0.039 \pm 0.015$$

pseudo decay time $t_z = \Delta z \, M/p_z < 80$ fs

line shapes taken from previous fit of from-B sample



cross-feed between prompt and from-B samples determined in MC and corrected (few %)

$$\left(N^P_{\eta_c(1S)}/N^P_{J/\psi}\right)_{7\,\text{TeV}} = 1.24 \pm 0.21 \pm 0.20$$

$$\left(N^P_{\eta_c(1S)}/N^P_{J/\psi}\right)_{8\,\text{TeV}} = 1.14 \pm 0.21 \pm 0.18$$

Results for η_c (1S)

[EPJ C75(2015)7,311]

Inclusive branching fraction

Using the the PDG average of the branching fractions into $\mathrm{p\bar{p}}$

$$\mathcal{B}(b \to \eta_c(1S)X)/\mathcal{B}(b \to \mathrm{J}/\psi X) = 0.421 \pm 0.055 \pm 0.025 \pm 0.045_{\mathcal{B}}$$

and of $\mathcal{B}(b \to \mathrm{J}/\psi X) = (1.16 \pm 0.10)\%$

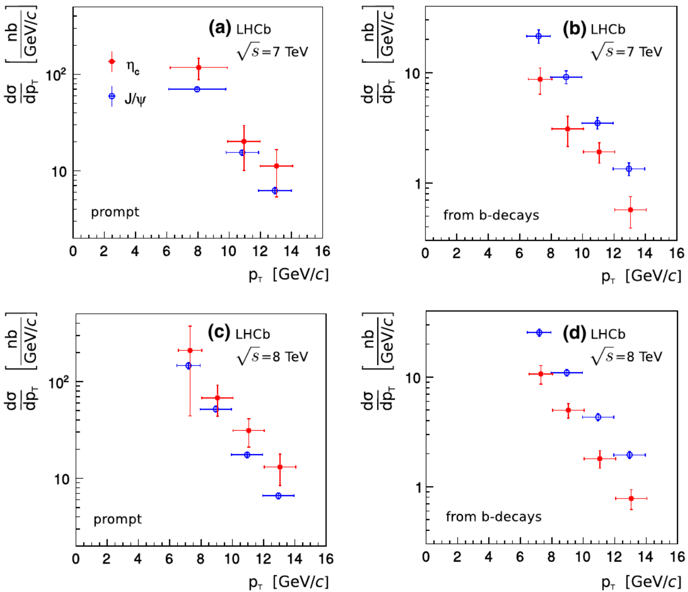
$$\boxed{\mathcal{B}(b \to \eta_c(1S)X) = (4.88 \pm 0.64 \pm 0.29 \pm 0.67_{\mathcal{B}}) \times 10^{-3}}$$

η_c production cross sections $p_T > 6.5$ GeV $2.5 < y < 4.5$

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
$\sigma_{\eta_c(1S)}/\sigma_{\mathrm{J}/\psi}$	$1.74 \pm 0.29 \pm 0.28 \pm 0.18_{\mathcal{B}}$	$1.60 \pm 0.29 \pm 0.25 \pm 0.17_{\mathcal{B}}$
$\sigma_{\eta_c(1S)}$	$0.52 \pm 0.09 \pm 0.08 \pm 0.06\,\mu$b	$0.59 \pm 0.11 \pm 0.09 \pm 0.08\,\mu$b

p_T dependence of η_c production

[EPJ C75(2015)7,311]

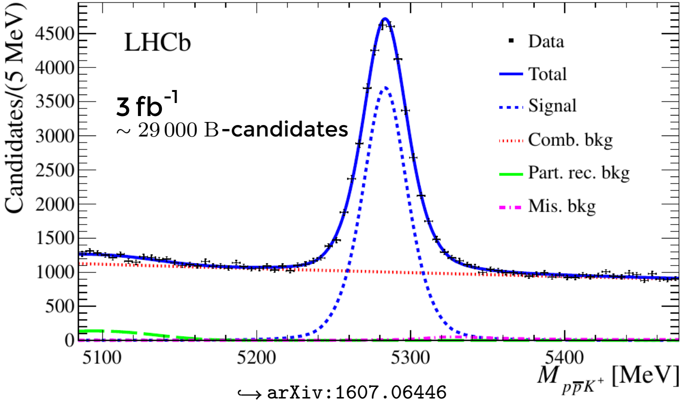


Implications for NRQCD see following talk by Zhiguo He

What about other charmonia in the $\mathrm{p\bar{p}}$ channel?

NEW

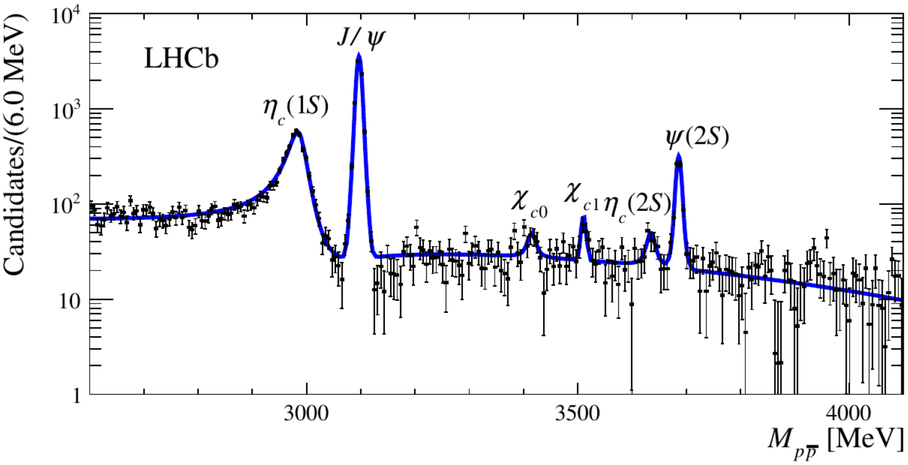
Use the clean decay $\mathrm{B^+ \to p\bar{p}K^+}$ as a source:



$\hookrightarrow$ arXiv:1607.06446

Selection optimized for $\mathrm{B^+ \to \chi_{c1}(1P)K^+}$ yield

Background subtracted spectrum:



Search for narrow charmonia: $p\bar{p}$ fit model ↪ arXiv:1607.06446

State	Parametrisation	Signal Yield	
$\eta_c(1S)$+non res.	rel. BW+gaussian + interference	11246 ± 119	
J/ψ	double gaussian	6721 ± 93	
$\chi_{c0}(1P)$	rel. BW+gaussian	84 ± 22	
$\chi_{c1}(1P)$	gaussian	95 ± 16	
η_c (2S)	rel. BW+gaussian	106 ± 22	first obs. 6.0σ
ψ (2S)	double gaussian	588 ± 30	
ψ (3770)	rel. BW+gaussian	-6 ± 9	
$X(3872)$	gaussian	-14 ± 8	

- $\eta_c(1S)$ allowed to interfere with $\ell = 0$ $p\bar{p}$ non-resonant component (phase-space distribution)
- $\chi_{c0}(1P)$,$\chi_{c1}(1P)$,$X(3872)$ and ψ (3770) masses fixed to PDG values

$$\Delta M_{J/\psi,\eta_c(1S)} = 110.2 \pm 0.5 \pm 0.9 \text{ MeV}$$

$$\Delta M_{\psi(2S),\eta_c(2S)} = 52.5 \pm 1.7 \pm 0.6 \text{ MeV}$$

$$\Gamma_{\eta_c(1S)} = 34.0 \pm 1.9 \pm 1.3 \text{ MeV}$$

Results on $\eta_c(2S)$, $\psi(3770)$ and $X(3872)$ ↪ arXiv:1607.06446 subm. to PLB

First observation of $\eta_c(2S) \to p\bar{p}$ with a significance of 6.0σ

$$\frac{\mathcal{B}(B^+ \to \eta_c(2S)K^+) \times \mathcal{B}(\eta_c(2S) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} = (1.58 \pm 0.33 \pm 0.09) \times 10^{-2}$$

using PDG average for $\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})$

$$\mathcal{B}(B^+ \to \eta_c(2S)K^+) \times \mathcal{B}(\eta_c(2S) \to p\bar{p}) = (3.47 \pm 0.72 \pm 0.20 \pm 0.16_{\mathcal{B}}) \times 10^{-8}$$

Upper limits at $90(95)$% confidence levels

$$\frac{\mathcal{B}(B^+ \to \psi(3770)K^+) \times \mathcal{B}(\psi(3770) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 9(10) \times 10^{-2}$$

$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 0.20(0.25) \times 10^{-2}$$

Summary

- Inclusive branching fraction $\mathcal{B}(b \to \eta_c(1S)X)$ [EPJ C75(2015)7,311]
- η_c (1S) prompt production cross section in pp collisions
- Provides crucial tests for NLO NRQCD calculations

  e.g. [PRL114(2015)092004] [PRL114(2015)092005] [PRL114(2015)092006]

- First observation of the decay $\eta_c(2S) \to \mathrm{p\overline{p}}$ [arXiv:1607.06446 subm. to PLB]
- $\psi(3770)$ and $X(3872) \to \mathrm{p\overline{p}}$ not observed.

  Set limits will be important input for future $\mathrm{p\overline{p}}$ collider experiments

- $\Delta M_{\mathrm{J}/\psi,\eta_c}$ and $\Gamma_{\eta_c(1S)}$ in agreement with world averages

  measurements do not depend on knowledge of radiative transition line shape

Backup

Fit to $\mathrm{p}\,\overline{\mathrm{p}}$ production spectra

- Detector resolution modelled by double Gaussian (common mean)
- Relative resolutions from simulation
- Width of narrow Gaussian for J/ψ left floating in fit
- Natural width of η_{c} (relativistic Breit-Wigner) determined in fit

- Exponential background parametrisation for $\mathrm{p}\,\overline{\mathrm{p}}$ from B
- 3rd order polynomial for prompt $\mathrm{p}\,\overline{\mathrm{p}}$
- Efficiencies differ by less than 0.5% between η_{c} and J/ψ