Measurement of $\eta_c(1S)$ and X(3872) productions in pp collisions

The 6th China LHC Physics Workshop

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UCAS

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Introduction

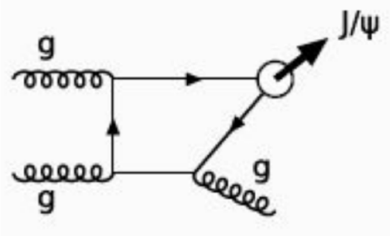
Charmonia production in the NRQCD

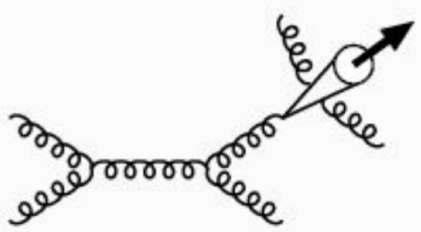
$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \times \langle O^H(n)\rangle$$

- $c\bar{c}$ production : short distance process
- Independent hadronization: Long Distance Matrix Elements (LDMEs)

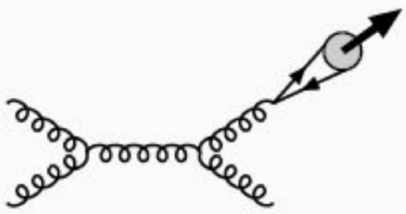
Two production mechanisms

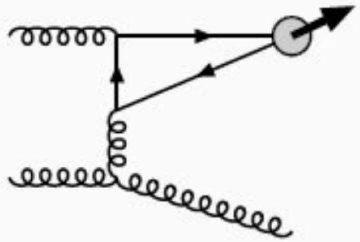
- Color Singlet (CS) : quantum numbers $c\bar{c}$ pair and charmonium match





- Color octet (CO) : quantum numbers $c\bar{c}$ pair in CO state are different from charmonium; soft gluons emitted at later stage of hadronization



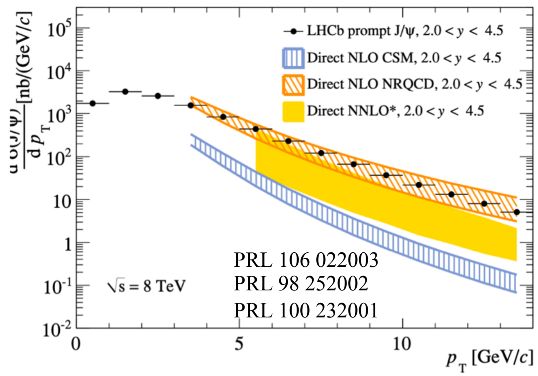


Spin-symmetry for LDMEs:
Links between the CS and CO matrix elements of different charmonia states
Simultaneous studying of $\eta_c(1S)$ and J/ψ.

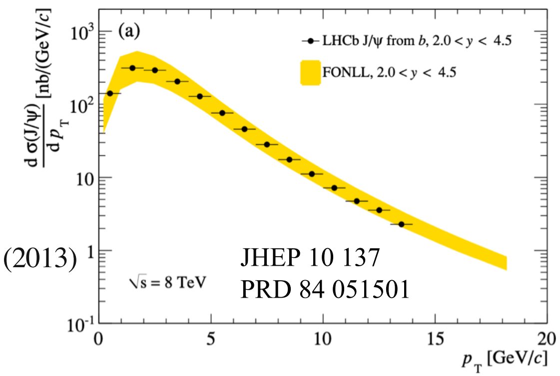
Introduction

J/ψ production and polarization at LHCb

Production:

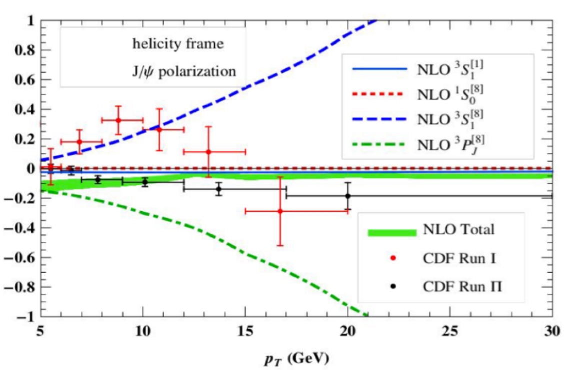


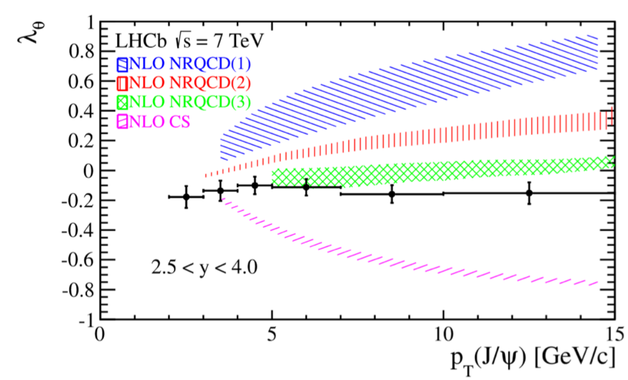
JHEP 06, 064, (2013)



- Measurements of LHC and Tevatron are in agreement
- CS NLO and NNLO could not describe prompt production
- NRQCD description dominates by CO contribution

Polarization:



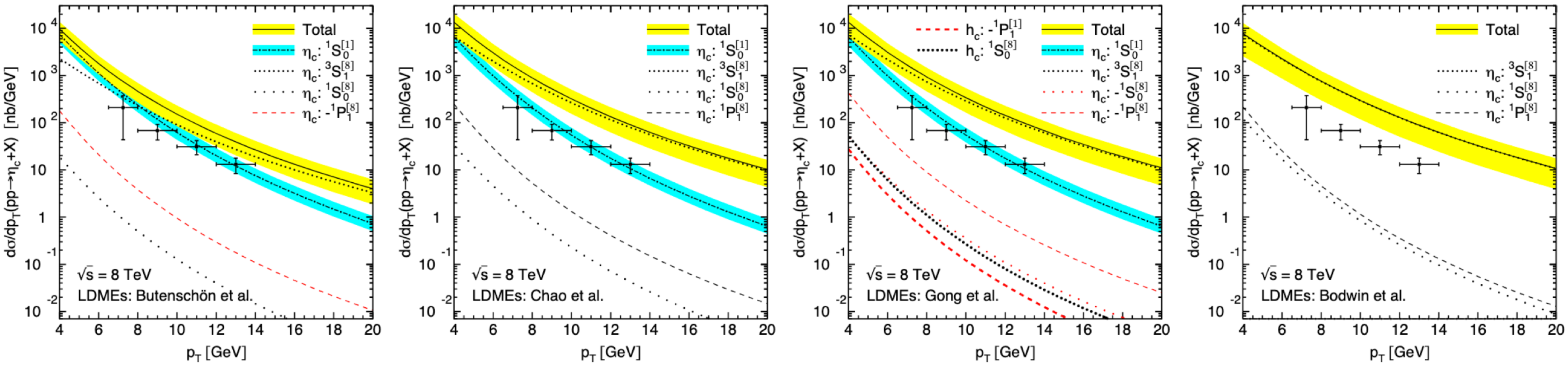


Eur. Phys. J. C 73, 2631, (2013)

- CO predicts strong polarization
- Large CS contribution is required

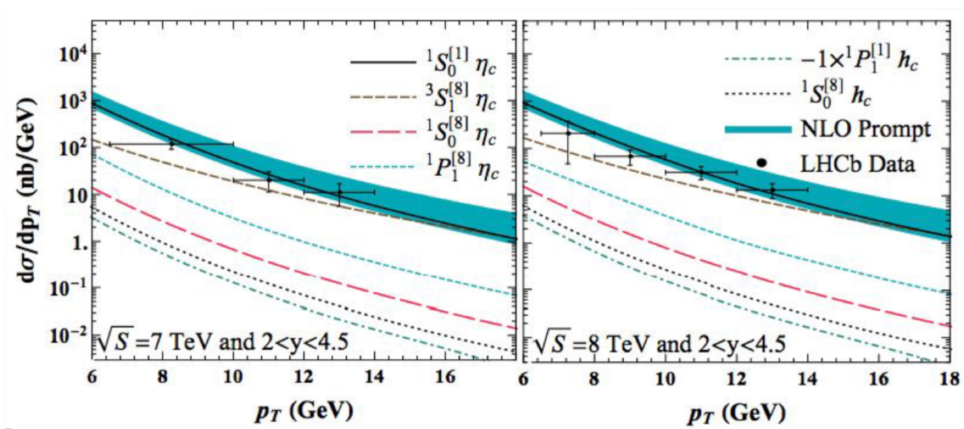
Introduction

$\eta_c(1S)$ production: Phys.Rev.Lett. 114 (2015) no.9, 092004



heavy-quark spin symmetry links J/ψ and $\eta_c(1S)$ LDMEs

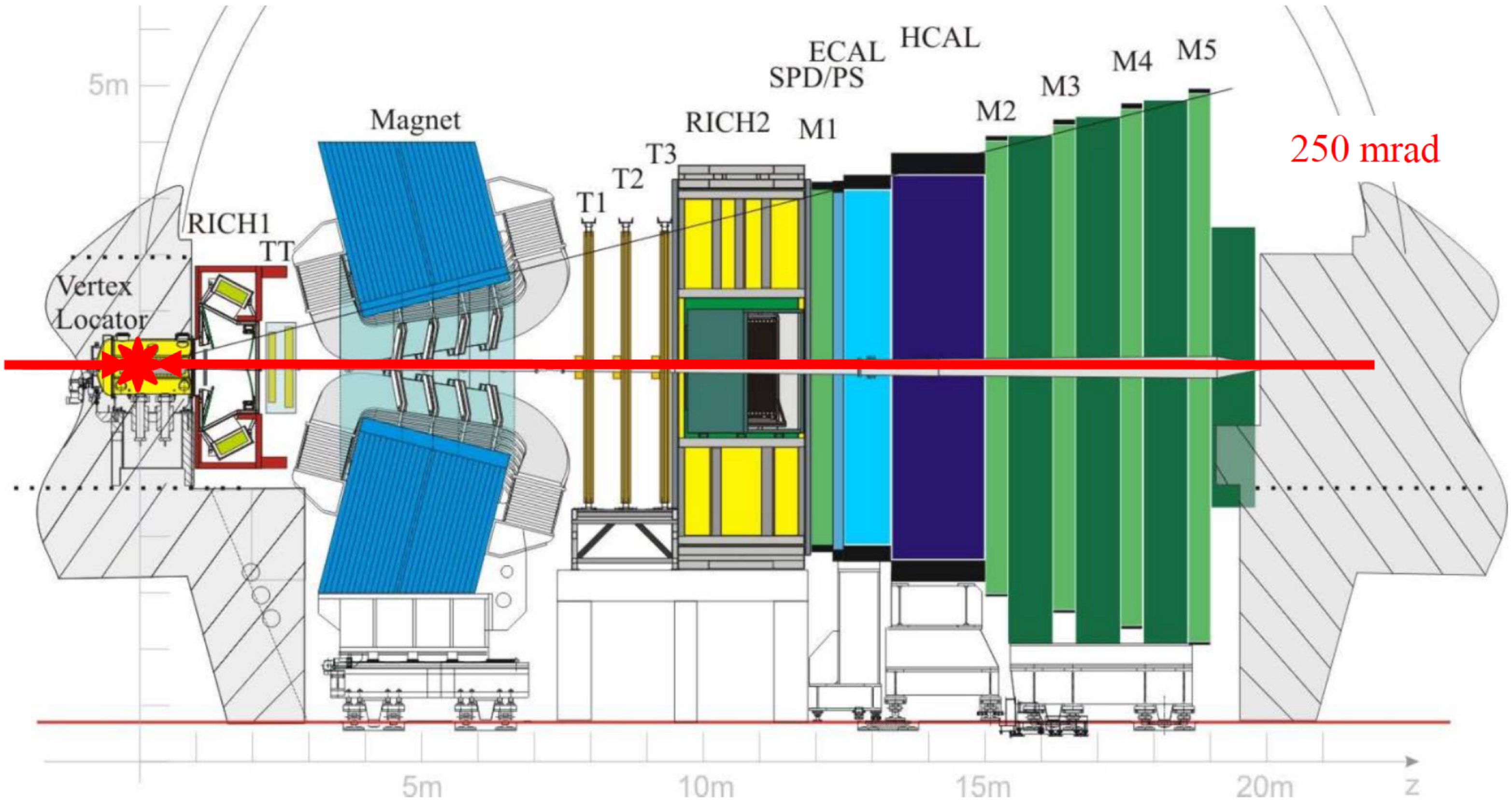
- Prompt η_c production should be described by theory simultaneously with J/ψ prompt production and polarization.
- Contrary to theory expectations, $\eta_c(1S)$ prompt production data entirely described by Color-Singlet contribution.
- PRL 114(2015), 092005 gives reasonable description for charmonium production.



Two large CO contributions cancel each other ⇒ hierarchy problem ⇒ Soft Gluon Fragmentation.

LHCb detector

- **Designed for precision measurements in *b*, *c* flavor sectors**
- **Acceptance: $2 < \eta < 5$**



1) precise vertex 2) precise tracking 3) powerful hadron ID

Overview

Eur. Phys. J. C80 (2020) 191

- Signal mode :$\eta_c(1S) \to p\bar{p}$
- Control mode :$J/\psi \to p\bar{p}$

$$\frac{\sigma_{\eta_c}^{\text{prompt }(b)}}{\sigma_{J/\psi}^{\text{prompt }(b)}} = \frac{N_{\eta_c}^{\text{prompt }(b)}}{N_{J/\psi}^{\text{prompt }(b)}} \times \frac{\epsilon_{J/\psi}}{\epsilon_{\eta_c}} \times \frac{\mathcal{B}_{J/\psi \to p\overline{p}}}{\mathcal{B}_{\eta_c \to p\overline{p}}}$$

Dataset:

Data:

Run II 2015-2016

2.0 fb^{-1} integrated luminosity

Full simulation MC are generated for $\eta_c(1S)$ and J/ψ to estimated the efficiency.

cross-section determination

$$\frac{\sigma_{\eta_c}^{\text{prompt }(b)}}{\sigma_{J/\psi}^{\text{prompt }(b)}} = \boxed{\frac{N_{\eta_c}^{\text{prompt }(b)}}{N_{J/\psi}^{\text{prompt }(b)}}} \times \boxed{\frac{\epsilon_{J/\psi}}{\epsilon_{\eta_c}}} \times \boxed{\frac{\mathcal{B}_{J/\psi\to p\overline{p}}}{\mathcal{B}_{\eta_c\to p\overline{p}}}}$$

Extract from data

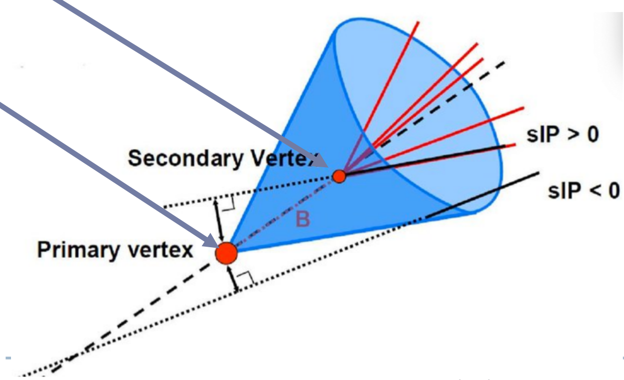
from MC: 1.00±0.02

From PDG:

$$\mathcal{B}_{J/\psi\to p\bar{p}} = (2.120 \pm 0.029) \times 10^{-3}$$
$$\mathcal{B}_{\eta_c\to p\bar{p}} = (1.50 \pm 0.16) \times 10^{-3}$$

- To determine the cross-section ratio, need to know the number of prompt J/ψ , $\eta_c(1S)$ and the contribution from b-hadron decay in each p_T bin.
- Pseudo-proper decay time $t_z = \frac{\Delta z \cdot M_{p\overline{p}}}{p_z}$

  separate the prompt and b-decay components
  - prompt: decay immediately
  - b-decay: have a longer life time, decay at the SV, follows an exponential function
- Two methods used to extract signal yields
  - t_z-cut method
  - t_z-fit method

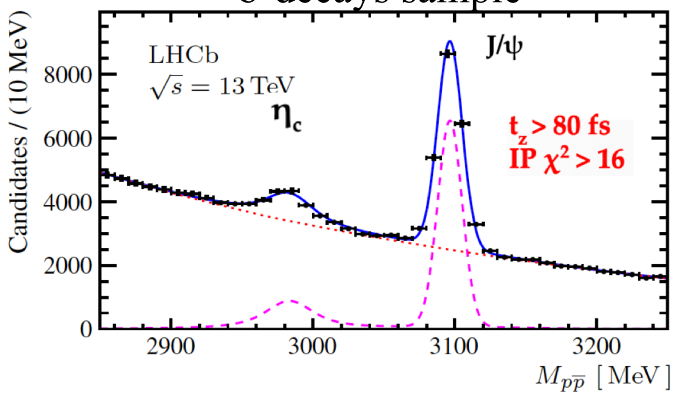


Invariant mass fit

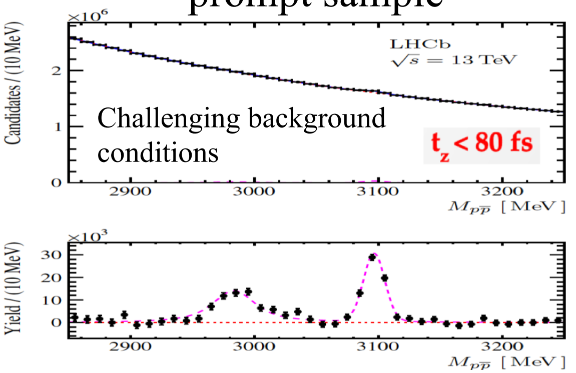
t_z-cut method

- split data to two samples and fit them simultaneously in p_T-bins

b-decays sample



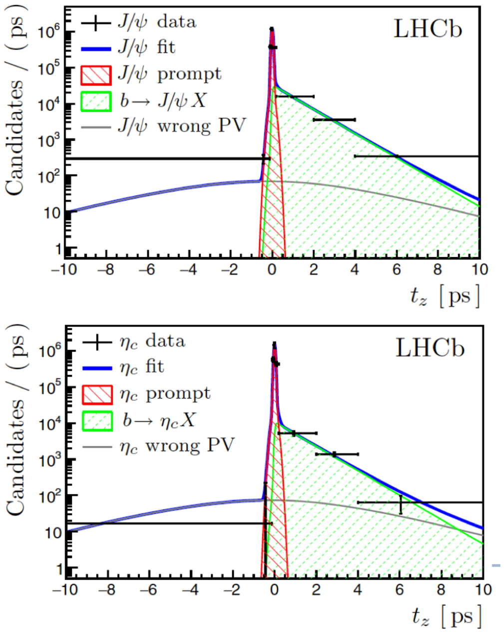
prompt sample



t_z-fit method

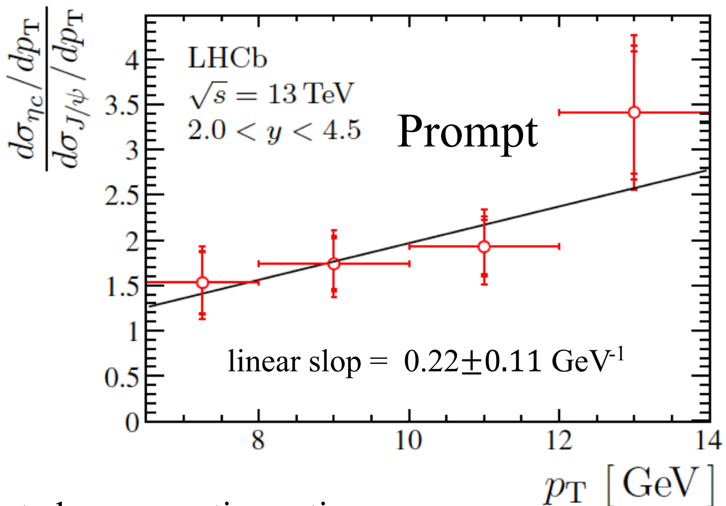
1. Simultaneous likelihood fit to $M(p\bar{p})$ in 28 bins of [p_T, $t_z = (z_d - z_p)\, M(p\bar{p})/p_z$];
   t_z= [-10,-0.125,-0.025,0.,0.2,2.,4.,10.] ps
   p_T=[6.5, 8, 10, 12, 14] GeV/c
   to extract charmonia yields.

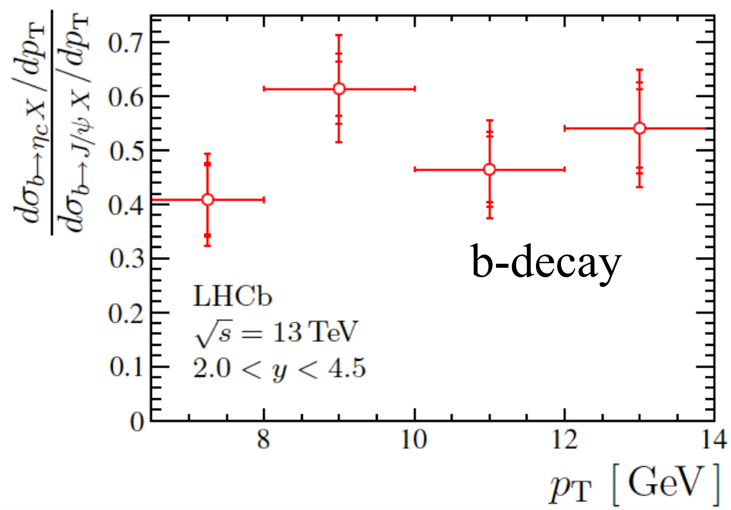
2. Simultaneous integral $\chi^2 t_z$ fit in p_T bins
   to separate prompt and from b-decays charmonia.



cross-section results

Differential production cross-sections for $\eta_c(1S)$ relative to J/ψ as a function of p_T





Integrated cross-section ratio:

$$\left(\sigma_{\eta_c}^{\text{prompt}}/\sigma_{J/\psi}^{\text{prompt}}\right)_{13\,\text{TeV}}^{6.5<p_T<14.0\,\text{GeV},\,2.0<y<4.5}$$

$$= 1.69 \pm 0.15_{\text{stat}} \pm 0.10_{\text{syst}} \pm 0.18_{\text{BR}}$$

Using $\sigma_{J/\psi}^{\text{prompt}} = 0.749 \pm 0.005 \pm 0.028 \pm 0.037$ μb as input. [JHEP 10, 172 (2015)].

$$\left(\sigma_{\eta_c}^{\text{prompt}}\right)_{13\,\text{TeV}}^{6.5<p_T<14.0\,\text{GeV},\,2.0<y<4.5}$$

$$= 1.26 \pm 0.11_{\text{stat}} \pm 0.08_{\text{syst}} \pm 0.14_{\text{BR}}\ \mu\text{b}$$

- The integrated cross-section of $\eta_c(1S)$ agreement with the color-singlet model prediction [Nucl.Phys.B114662, (2019)]
- A larger measured slope with respect to the prediction from [Nucl.Phys.B114662, (2019)] would indicate a possible color-octet contribution.

cross-section results

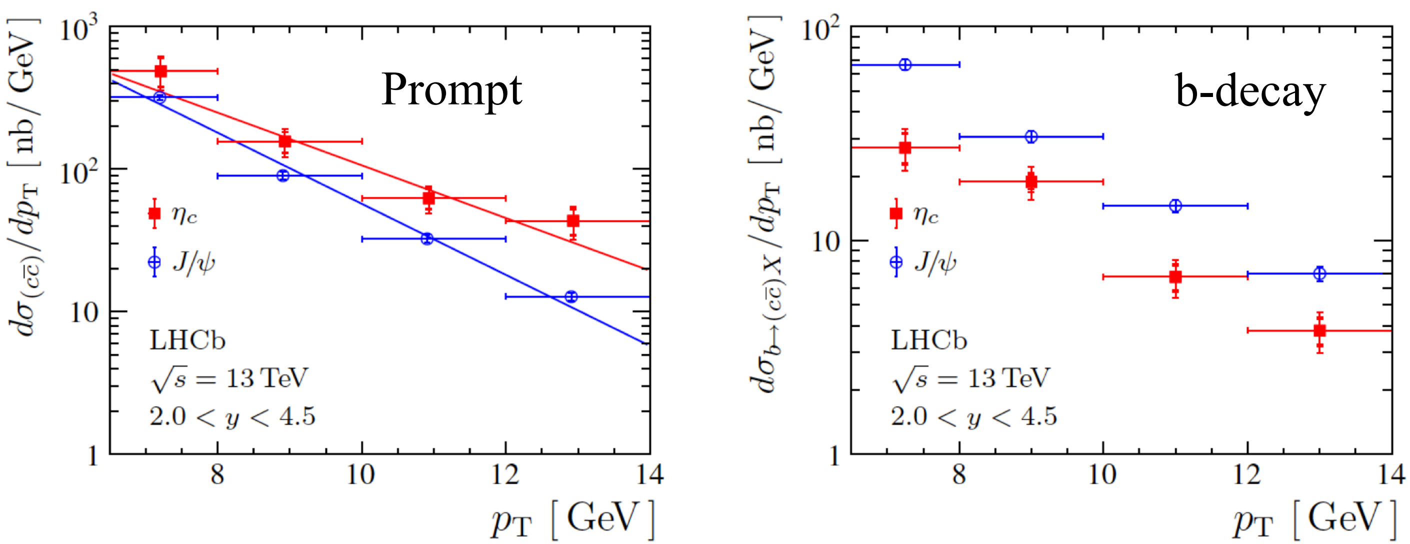
The relative $\eta_c(1S)$ inclusive branching fraction from b-hadron decays

$$\mathcal{B}_{b\to\eta_c X}/\mathcal{B}_{b\to J/\psi\, X} = 0.48 \pm 0.03_{\text{stat}} \pm 0.03_{\text{syst}} \pm 0.05_{\text{BR}}$$

which combined with $\mathcal{B}_{b\to J/\psi\, X} = 1.16 \pm 0.10\%$ [PDG 2018]

$$\mathcal{B}_{b\to\eta_c X} = (5.51 \pm 0.32_{\text{stat}} \pm 0.29_{\text{syst}} \pm 0.77_{\text{BR}}) \times 10^{-3}$$

The absolute $\eta_c(1S)$ and J/ψ differential production cross-sections

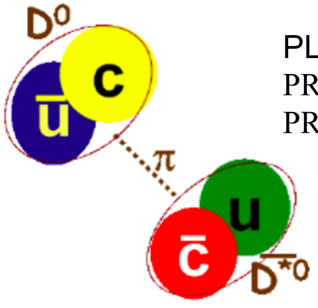


X(3872) production

Introduction

- X(3872) is an exotic meson discovered in 2003 by Belle [**Phys.Rev.Lett. 91 (2003) 262001**]
- $J^{PC} = 1^{++}$ confirmed by LHCb [**Phys.Rev. D 92 (2015) 011102(R)**]
- The nature of X(3872) still not clear.

Hadronic Molecule?



PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)

Mixture of states?

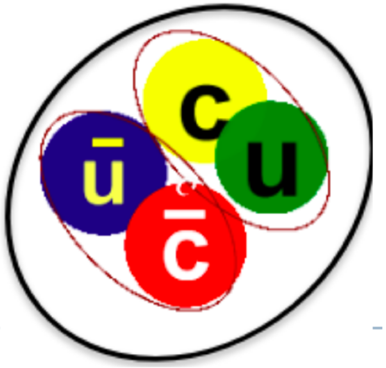
$$X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle$$

$$X = a\,|\chi'_{c1}\rangle + b\,|D\bar{D}^*\rangle$$

PLB 578 365 (2004)
PRD 96 074014 (2017)

Binding energy consistent with zero.
Radius ~7 fm.

Compact tetraquark?
Radius ~1 fm.



PRD 71, 014028 (2005)
PLB 662 424 (2008)

Introduction

New idea: Probe X(3872) via its interactions with the underlying event

- Promptly produced X(3872) and ψ(2S) can interact with other comoving particles produced at PV. These interactions can break apart formed/forming states, and these dissociation effects should depend on size/binding energy.

- A large body of work exists exploring these effects on conventional quarkonia in heavy ion collisions.

- X(3872) and ψ(2S) from b decays in vacuum do not have further interactions. Serves as control sample.

- Measure ratio of X(3872)/ψ(2S) as function of multiplicity. Gives direct comparison of possible medium effects between exotic and conventional state.

Overview

HCb-PAPER-2020-023 (arXiv:2009.06619) submitted to PRL

- Signal mode : $X(3872) \to J/\psi\pi^+\pi^-$ with $J/\psi \to \mu^+ \mu^-$
- Control mode : $\psi(2S) \to J/\psi\pi^+\pi^-$ with $J/\psi \to \mu^+ \mu^-$

$$\frac{\mathcal{B}[X(3872) \to J/\psi\,\pi^+\pi^-]}{\mathcal{B}[\psi(2S) \to J/\psi\,\pi^+\pi^-]} \times \frac{\sigma_{X(3872)}}{\sigma_{\psi(2S)}} = \frac{N_{X(3872)}}{N_{\psi(2S)}} \frac{\epsilon_{\psi(2S)}}{\epsilon_{X(3872)}}$$

Dataset:

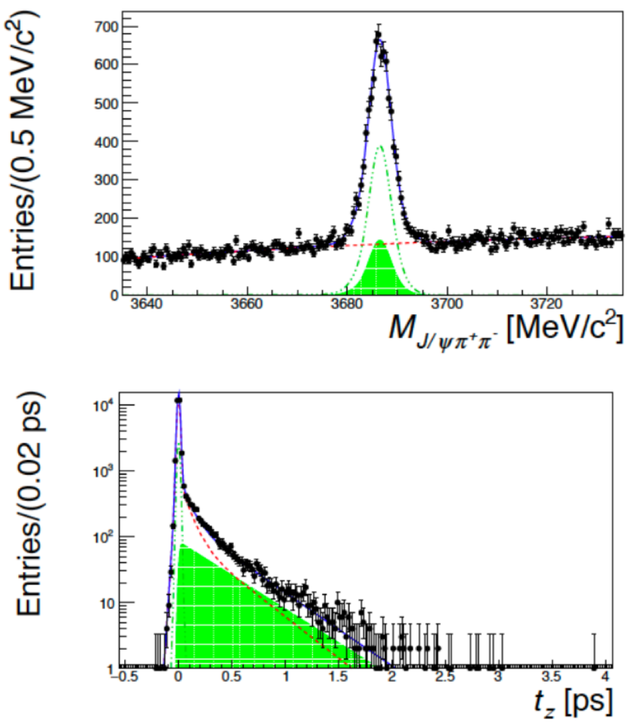
2012 pp data at 8 TeV
1.8 fb^{-1} integrated luminosity

Full simulation MC are generated for $X(3872)$ and $\psi(2S)$ used to estimated efficiency.

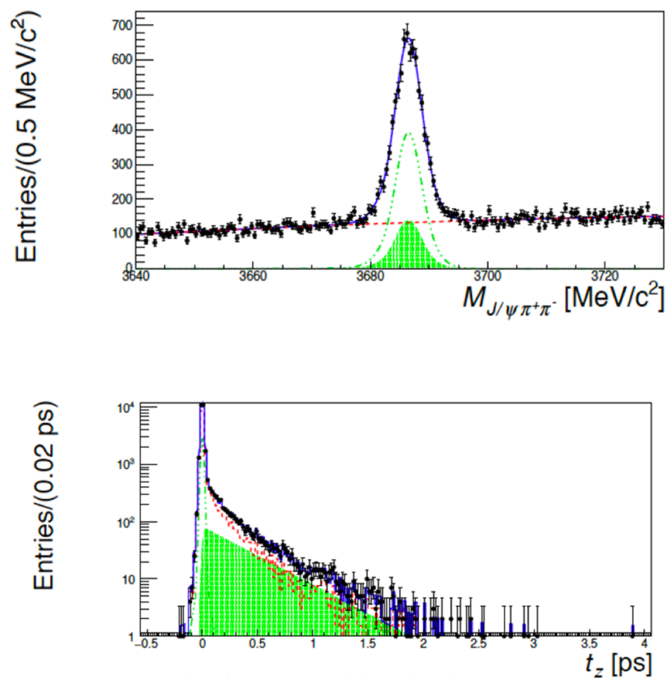
Extract signal yield

To separate the prompt and b-decay components.
Simultaneous fits of mass and proper time spectra, using two methods.

$$t_z = \frac{(z_{decay} - z_{PV})M}{p_z}$$



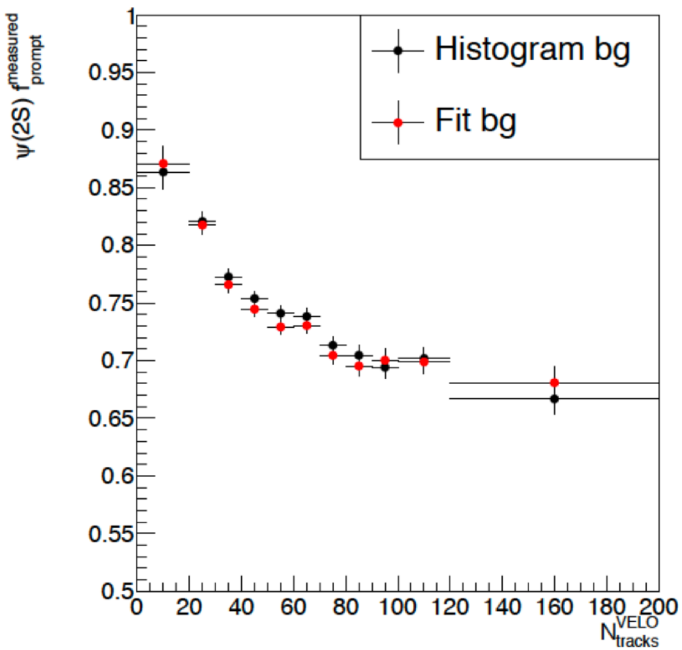
Method 1: use empirical functions to model proper time backgrounds, as in multiple previous LHCb papers

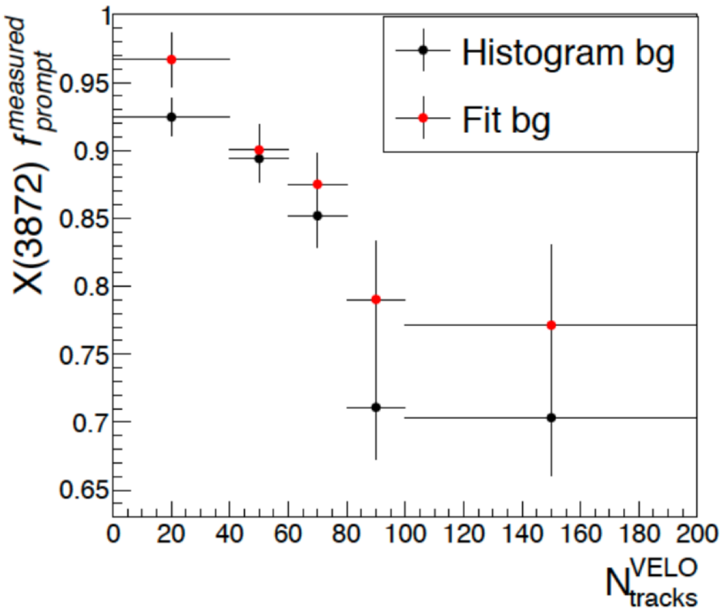


Method 2: use sideband t_z histograms to model proper time backgrounds

Extract signal yield

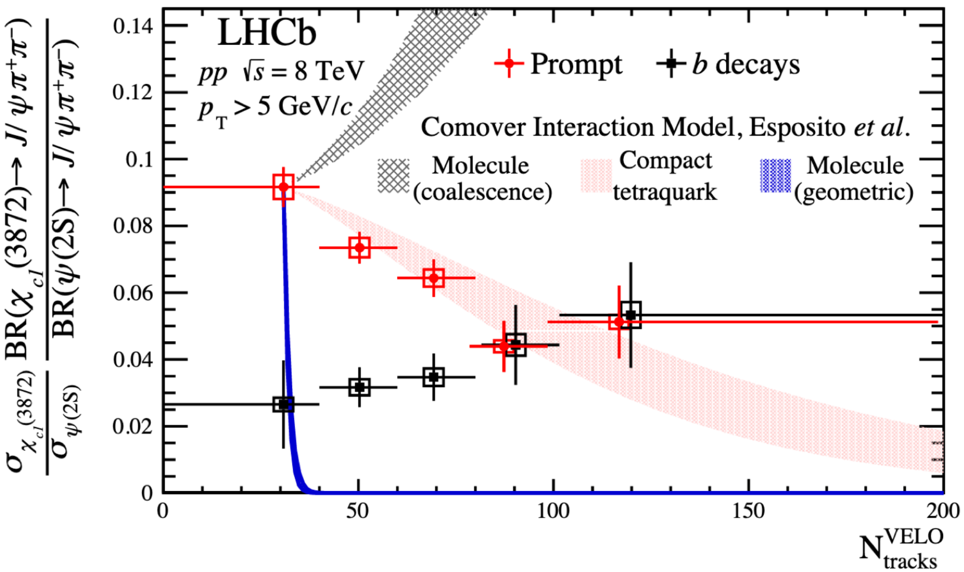
The fraction of prompt component.





Use average of two methods as central value, take difference between average and individual values as systematic uncertainty.

Results



Prompt ratio decreases with multiplicity:
prompt X(3872) is suppressed relative to prompt ψ(2S) in high multiplicity events. Fit w/straight line gives non-zero slope with 5σ significance

Non-prompt ratio consistent with constant:
b decays in vacuum unaffected by activity at vertex. Fit w/ straight line gives slope consistent with zero within 1.6σ

- Comover Interaction Model is used to calculate these observables.
  [Phys. Rev. Lett.85(2000) 2080]
  [Phys. Lett.B749(2015) 98]
  arXiv:2006.15044
- In this model, promptly produced X(3872) and ψ(2S) hadrons interact with other produced particles, with a breakup cross-section σ_{br} that is determined by their radius and binding energy.
- The compact tetraquark matching the measured trend.

Summary

- $\eta_c(1S)$ production
  - cross-sections for $\eta_c(1S)$ relative to J/ψ are measured
  - cross-sections for $\eta_c(1S)$ agreement with the colour-singlet model prediction
  - The relative/absolute $\eta_c(1S)$ inclusive branching fraction from b-hadron decays are measured.

- X(3872) production
  - cross-sections for X(3872) relative to $\psi(2S)$ as a function of charged particle multiplicity are measured.
  - The measurements consistent with compact tetraquark prediction.

Thanks!