Study of the exotic state production at LHCb

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Exotic states

- Many hadronic states observed with possible internal structures beyond normal mesons and baryons

- Being found via charmonium decay modes
  — $J/\psi\,\pi^+$: $Z_c(3900)^+, Z_c(4200)^+$
  — $J/\psi\,p$: $P_c(4312)^+, P_c(4440)^+, P_c(4457)^+$
  — $J/\psi\,\phi$: $X(4140), X(4274)$
  — $J/\psi\,\pi^+\pi^-$: $X(3872)$, Y(4260)
  — $\psi(2S)\pi^-$: $Z(4430)^-$
  — $J/\psi\ J/\psi$: $X(6900)$

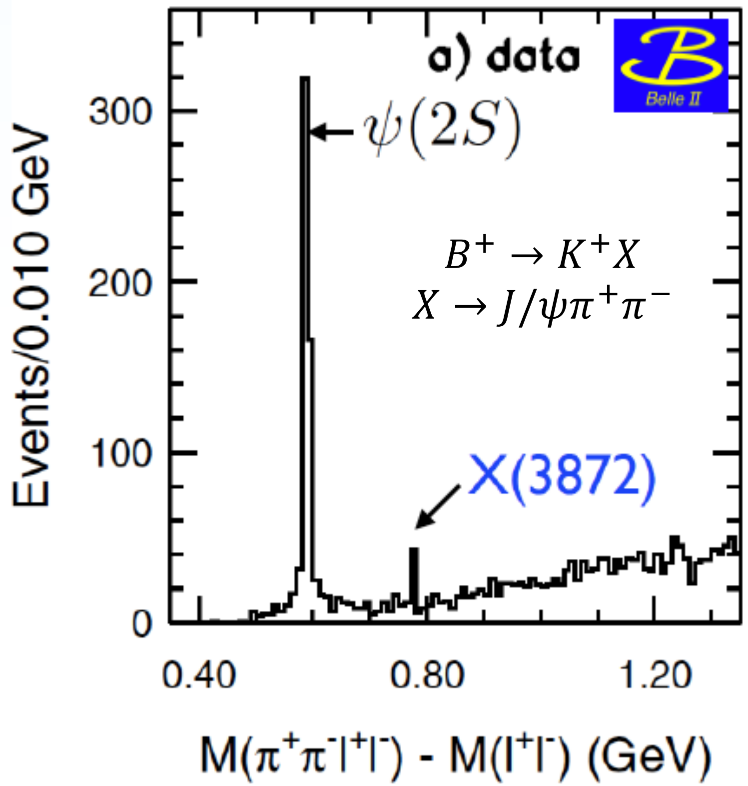
- The nature of exotics states still not clear

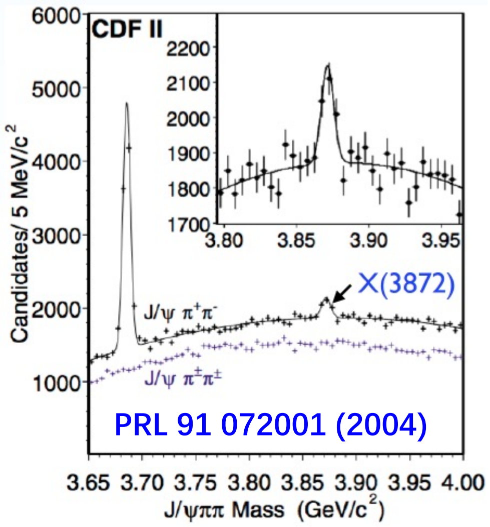
- The production measurement is a good probe:
  - Comparing with the pure charmonium states
  - Testing the theoretical estimations based on different models and hypotheses

Observation of X(3872)

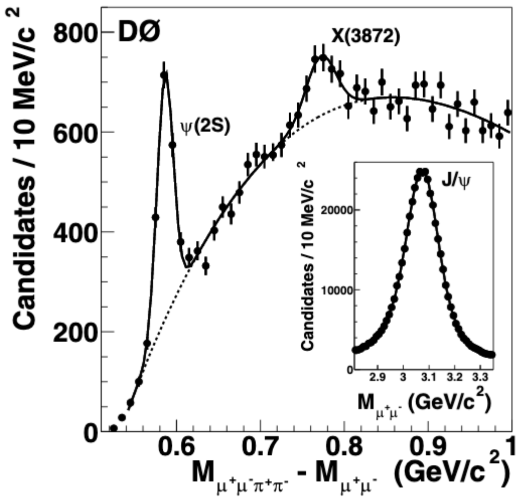
- The first exotic state X(3872) was first observed by Belle in 2003 and then confirmed by CDF, Babar and D0
- The mass of X(3872) is a little bit below than the $D^0\overline{D}^{*0}$ threshold

PRL 91 262001 (2003)

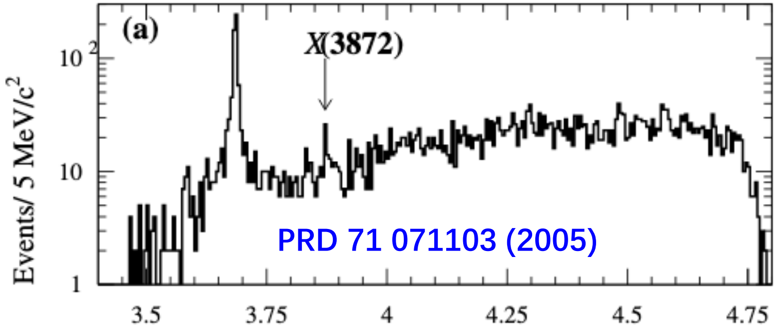




PRL 91 072001 (2004)



PRL 93 162002 (2004)



PRD 71 071103 (2005)

Study of X(3872)

- The mass of X(3872) is a little bit below than the $D^0\overline{D}^{*0}$ threshold
  M = 3871.65±0.06 MeV, Γ = 1.19±0.21 MeV
  M(X)-M($D^0\overline{D}^{*0}$) = -0.07±0.12 MeV

- $J^{PC} = 1^{++}$

Belle, PRL 107 091803 (2011)

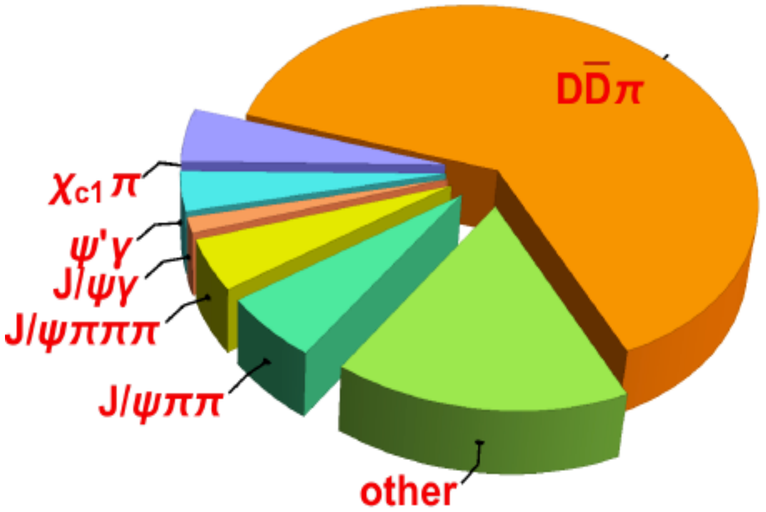
LHCb, PRL 110 222001 (2013)

- Seven observed decay modes:

$$J/\psi\pi^+\pi^-, J/\psi\pi^+\pi^-\pi^0, J/\psi\gamma, \psi(2S)\gamma, \chi_{c1}\pi^0, D^0\bar{D}^0\gamma, D^0\bar{D}^0\pi^0$$

$$Br(X \to J/\psi\,\pi^+\pi^-) = (4.1 \pm 1.3)\%$$

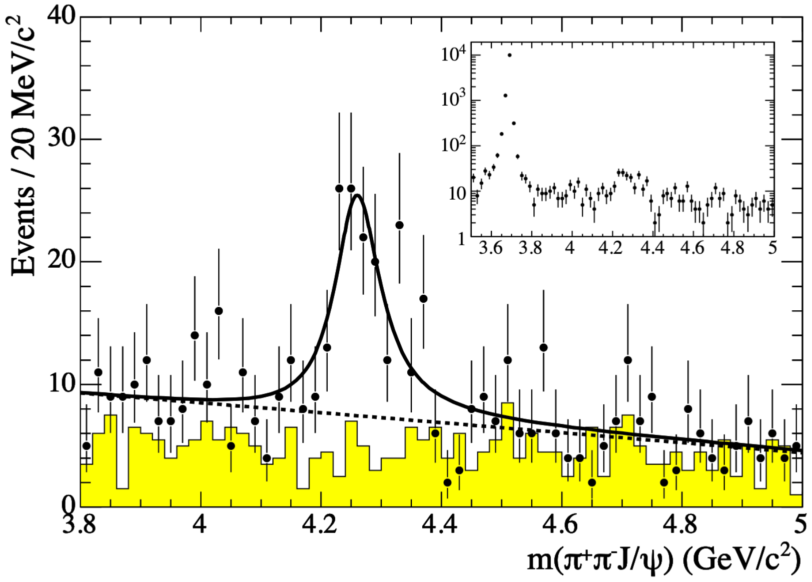
Babar, PRL 124 (2020) 152001

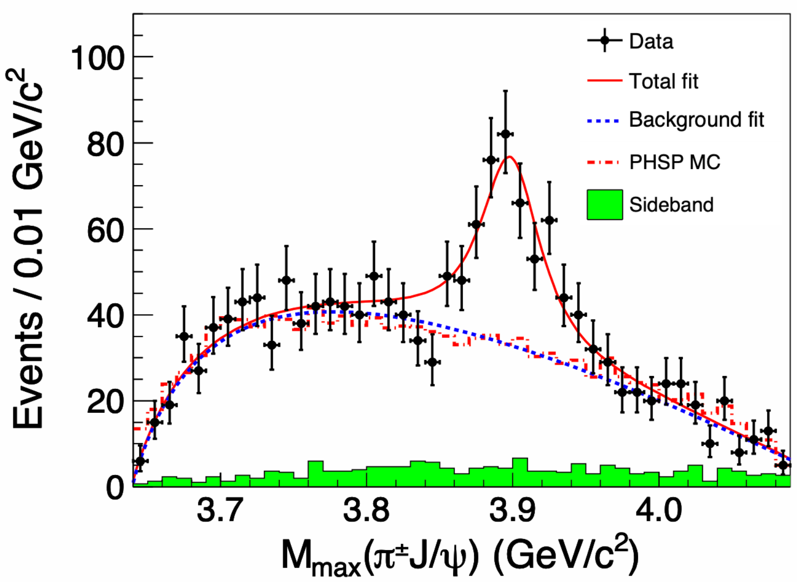


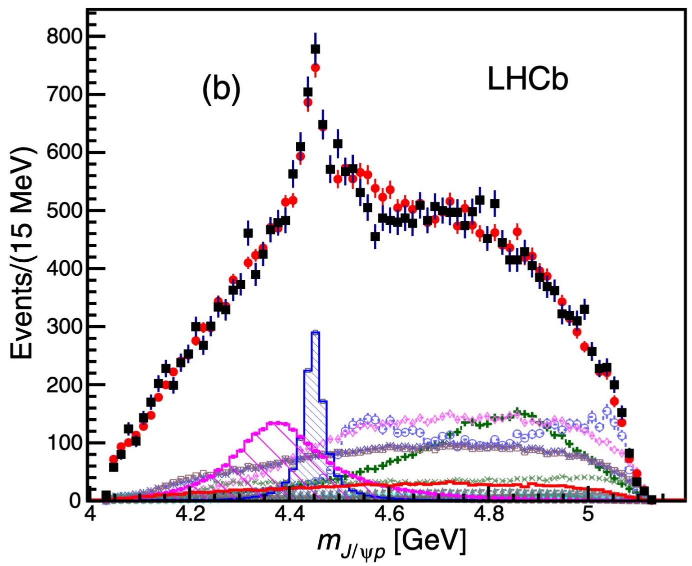
- Significantly observed in **hadron collisions**, **b-hadron decays** and $\boldsymbol{e^+e^-}$ **annihilation**

YZ & P_c states

- Y(4260): $e^+e^- \to \gamma_{ISR} J/\psi\, \pi^+\pi^-$, Y $\to J/\psi\, \pi^+\pi^-$ first observed by BaBar, vector state $J^{PC} = 1^{--}$ only from $\boldsymbol{e^+e^-}$ **annihilation**
- $Z_c(3900)^+$: $e^+e^- \to J/\psi\, \pi^+\pi^-$, $Z \to J/\psi\, \pi^+$ first observed in BESIII, isospin multiplet only from $\boldsymbol{e^+e^-}$ **annihilation**
- $P_c(4450)^+$: $pp \to \Lambda_b^0$ + anything, $\Lambda_b^0 \to P_c K$, $P_c \to J/\psi\, p$ first observed in LHCb, pentaquark only from **b-hadron decays**

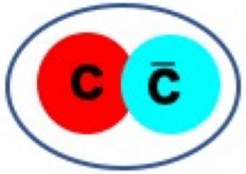




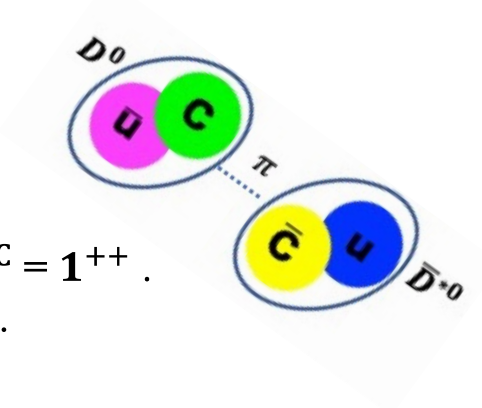


Nature of X(3872)

- There are many hypotheses for the internal structure of X(3872)
- $c\bar{c}$ charmonium



- $D^0\bar{D}^{*0}$ molecule:
  - Mass is close to $\boldsymbol{D^0\bar{D}^{*0}}$threshold.
  - S-wave coupling to $\boldsymbol{D^0\bar{D}^{*0}}$ favor $\mathbf{J^{PC} = 1^{++}}$.
  - Binding energy consistent with zero.
    Radius ~10 fm.

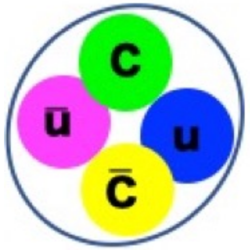


Nils A. Tornqvist PLB 590 209 (2004)
E. Braaten, M. Lu PRD 77 014029 (2008)
W. Altmannshofer, S Gori et al. PRD 100 0115029 (2019)

- Mixture of states $X = a|\chi'_{c1}\rangle + b|D\bar{D}^*\rangle$

T. E Browder, S. Pakvasa et al. PLB 578 365 (2004)
C. Meng, H. Han et al. PRD 96 074014 (2017)

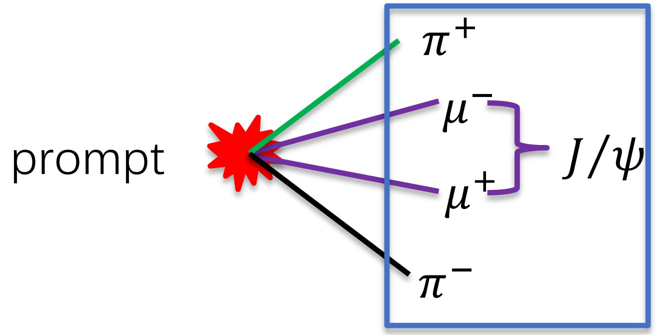
- Compact tetraquark
  Radius ~1 fm.

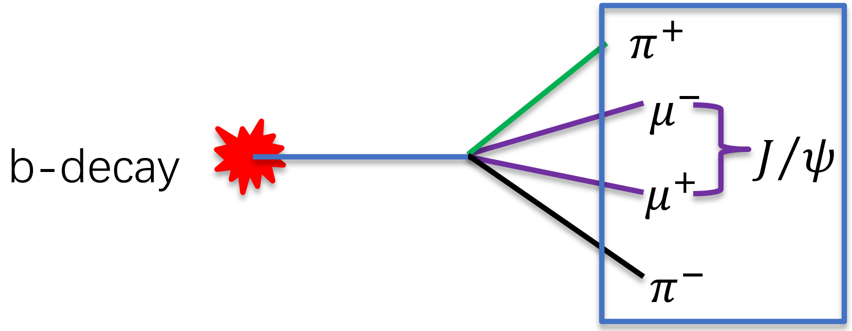


L. Maiani, F. Piccinini et al. PRD 71, 014028 (2005)
G. ‘t Hooft, G. Isidori et al. PLB 662 424 (2008)

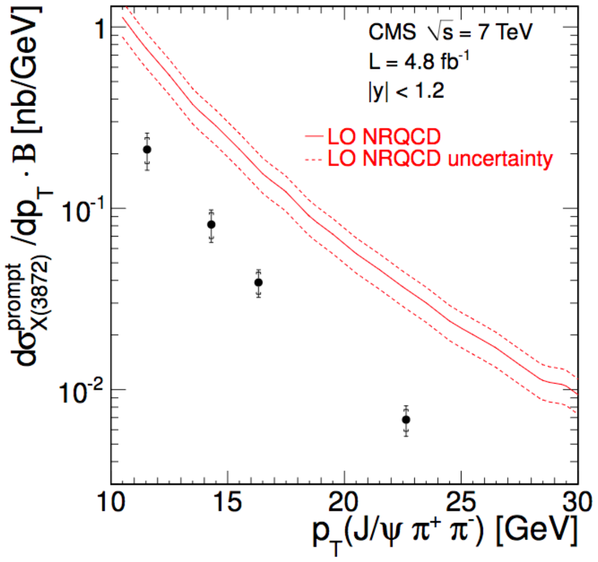
Production measurement of X(3872)

- Two different production mechanisms in experiments

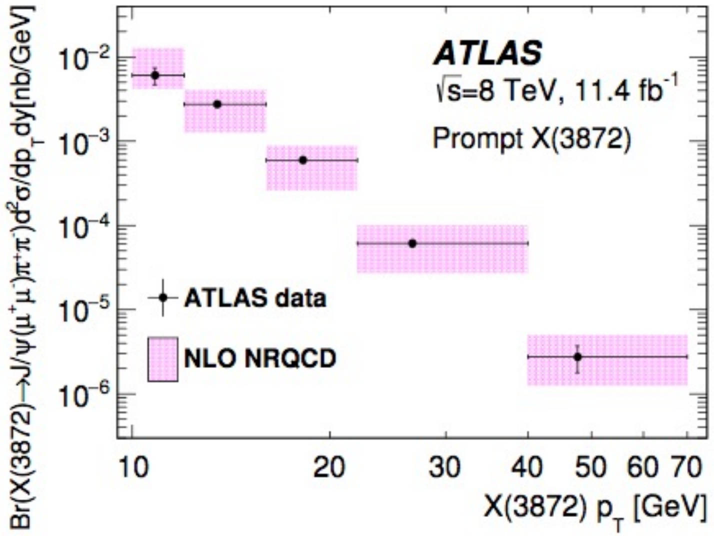




- CMS measurement show $\left(\frac{d\sigma}{dPt}\right)$ $<$ NRQCD prediction based on $D^0\bar{D}^{*0}$ molecule.
- ATLAS results consistent with NLO NRQCD prediction for $\chi_{c1}(2P)$-$D^0\bar{D}^{*0}$.



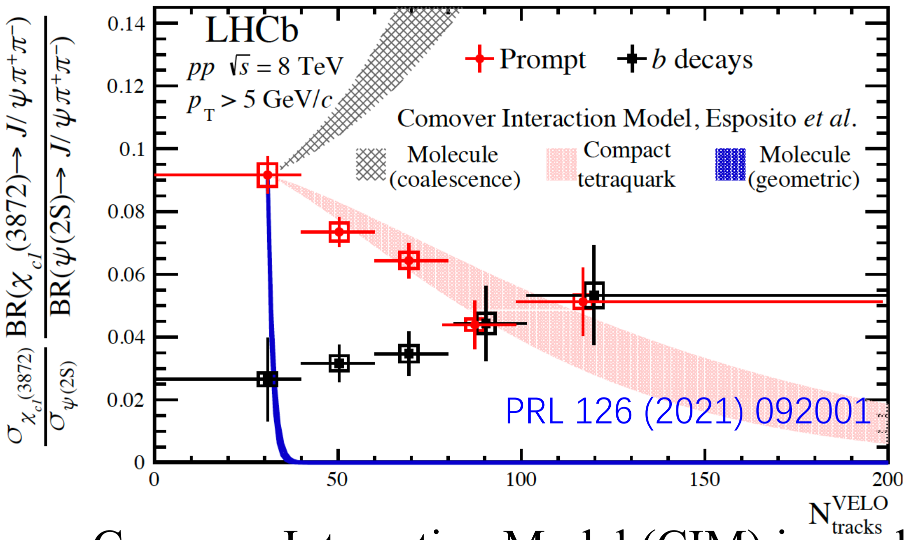
JHEP 04 (2013) 154

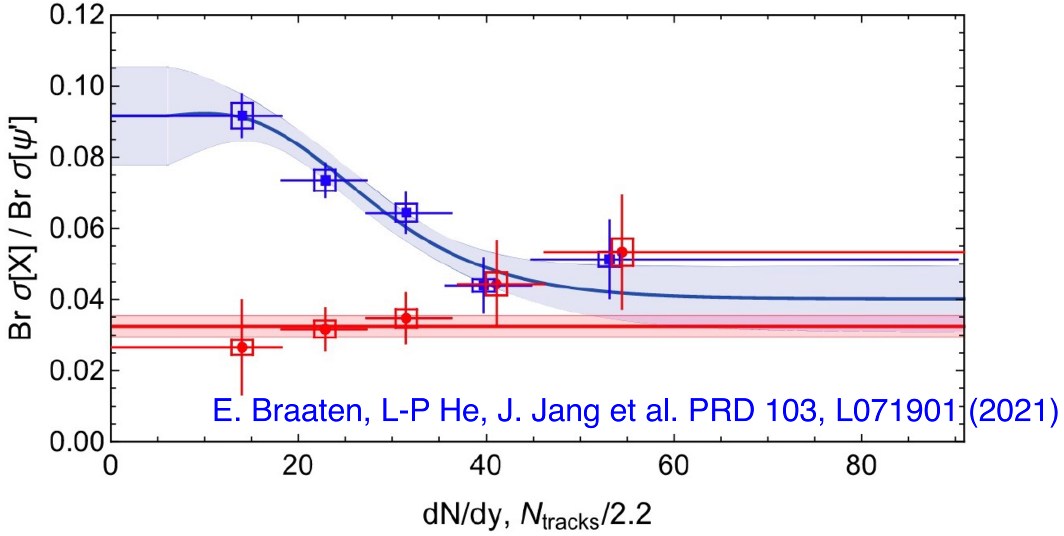


JHEP 01 (2017) 117

Production measurement of X(3872)

- LHCb measured the promptly production of X(3872) versus multiplicity





Comover Interaction Model (CIM) is used to calculate these observables.

A. Capella et al. PRL 85(2000) 2080
E.G. Ferreiro PLB 749(2015) 98

Breakup cross section approximated as sum of cross section for molecule constituents

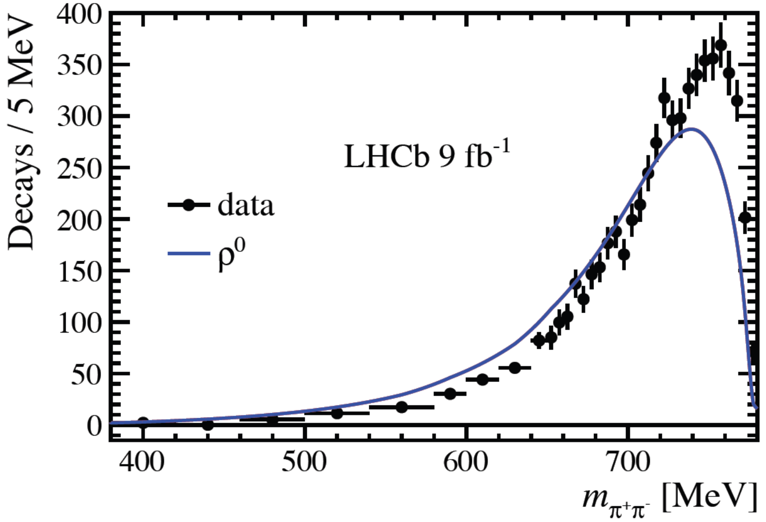
$$\sigma^{\rm inel}[\pi X] = \frac{1}{2}\left(\sigma[\pi D \to D\pi] + \sigma[\pi\bar{D} \to \bar{D}\pi] + \sigma[\pi D^* \to D^*\pi] + \sigma[\pi\bar{D}^* \to \bar{D}^*\pi]\right)$$

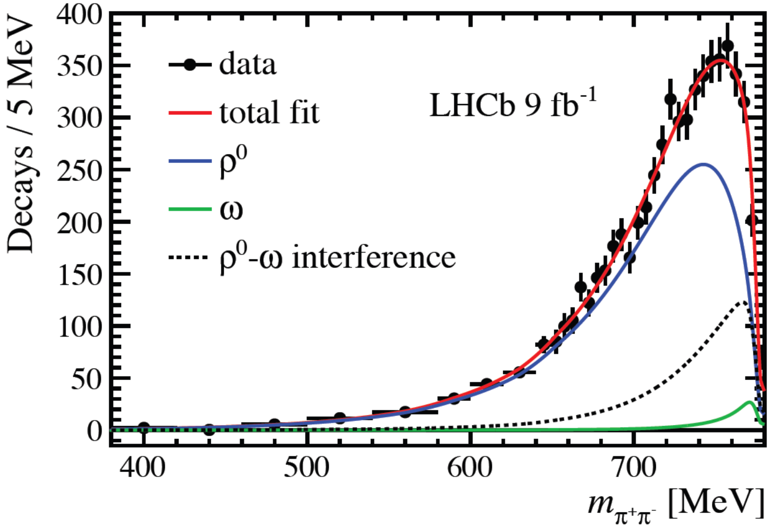
Promptly produced X(3872) and ψ(2S) hadrons interact with other produced particles, with a breakup cross-section σ_{br} that is determined and sensitive by their radius and binding energy.

Production measurement of X(3872)

- ϖ contribution in X(3872) $\rightarrow J/\psi\pi^+\pi^-$ was also measured by LHCb

arXiv:2204.12597





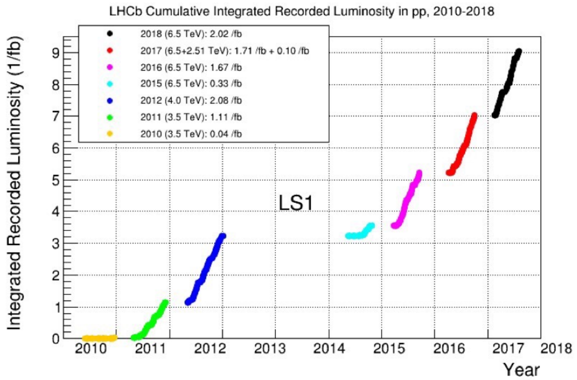
$$\frac{g_{\chi_{c1}(3872)\to\rho^0 J/\psi}}{g_{\chi_{c1}(3872)\to\omega J/\psi}} = \sqrt{\frac{\mathcal{B}(\omega\to\pi^+\pi^-)}{R_{\omega/\rho}{}^{0\prime}}} = 0.29 \pm 0.04.$$

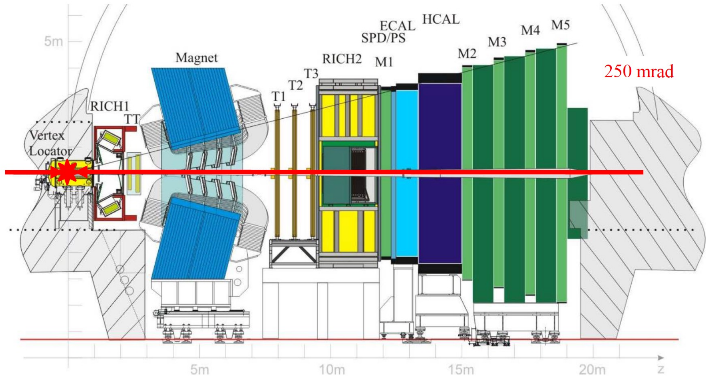
$$\frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = \sqrt{\frac{\mathcal{B}(\psi(2S)\to\pi^0 J/\psi)}{\mathcal{B}(\psi(2S)\to\eta J/\psi)}\frac{p_\eta{}^3}{p_{\pi^0}{}^3}} = 0.045 \pm 0.001$$

An order of magnitude larger than expected for pure $c\bar{c}$ states.

Analysis strategy

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





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

Data MC

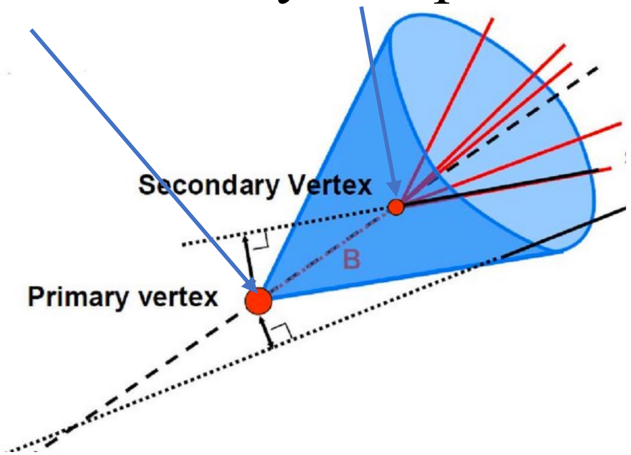
p_{T} bin boundaries [GeV/c]: 4, 6, 7, 8, 9, 10, 12, 14, 16, 20;

y bin boundaries: 2, 3, 3.5, 4.5.

- 2012, 8 TeV 2016+2017+2018, 13 TeV
- Using pseudo-proper decay time to separate the prompt and b-decay components

Run 1 + Run 2
the expected number of X(3872)
increases by a factor of 400
than the previous measurement in LHCb

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

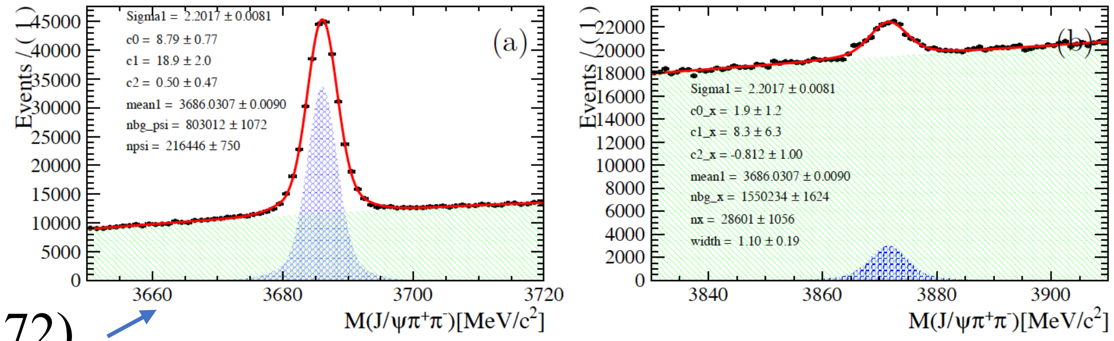


Signal extraction

- Mass-t_z simultaneous fit for each PT and y bins

- Mass

Signal: Two DSCBs for $\psi(2S)$ and BW $\otimes$ resolution for X(3872)



· Fix the ratio of the mass resolution for $\psi(2S)$ and X(3872) from MC

· Fix the mass of X(3872) to $M(\psi)$+185.49 MeV/c^2

· Gauss constrain is for width of X(3872) JHEP 08 (2020) 123

Background: Exponential function

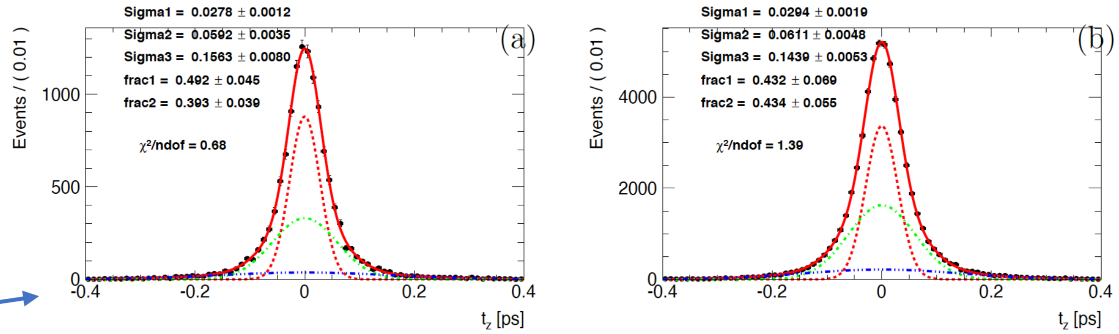
- t_z

Signal:

· Delta function for prompt

· Exponential function for b-decay

· Convoluted with tz resolution

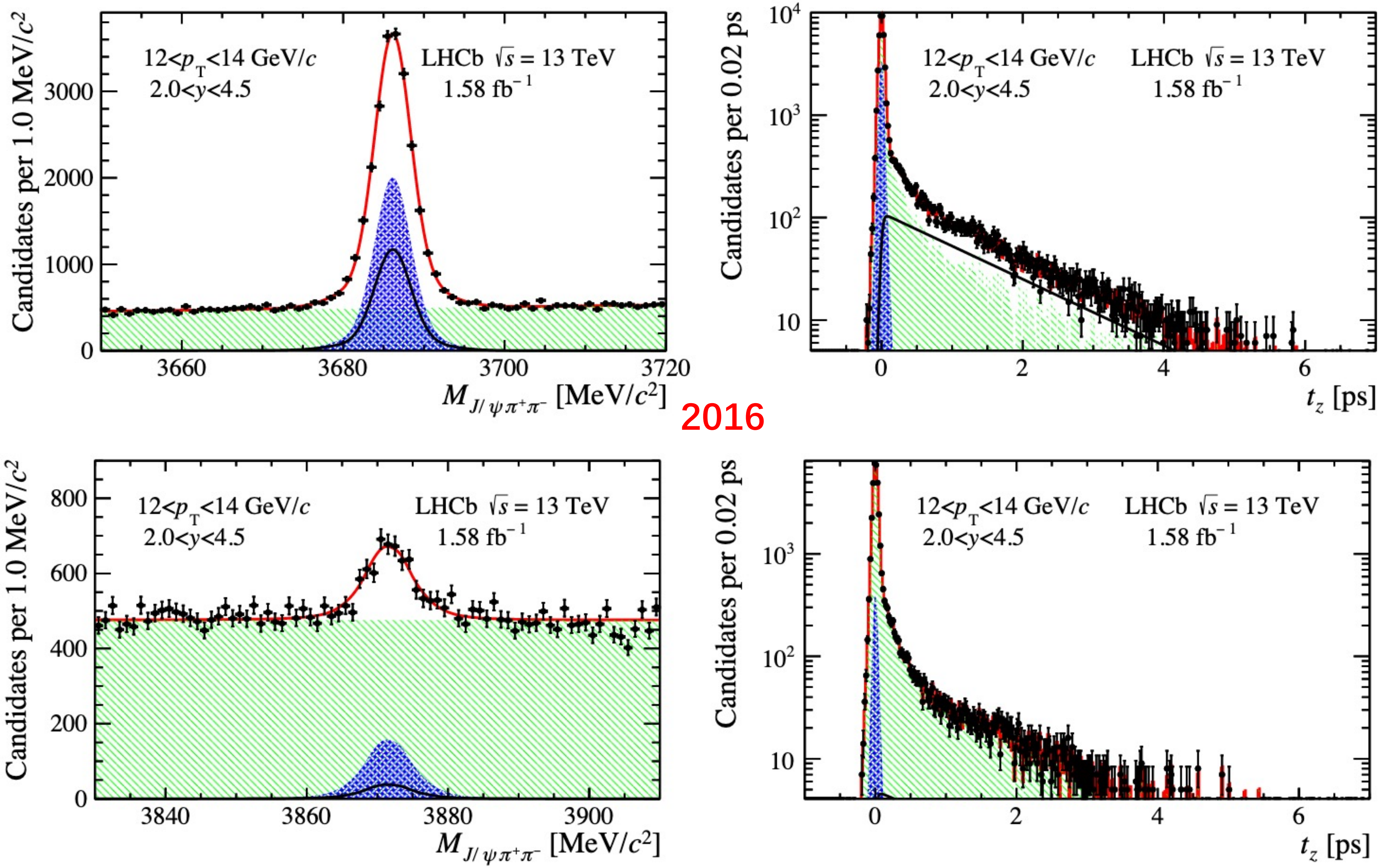


Background: combinatorial background

tz background distribution is extracted from the mass spectrum

Signal extraction

- Fit for 2016 dataset as an illustration

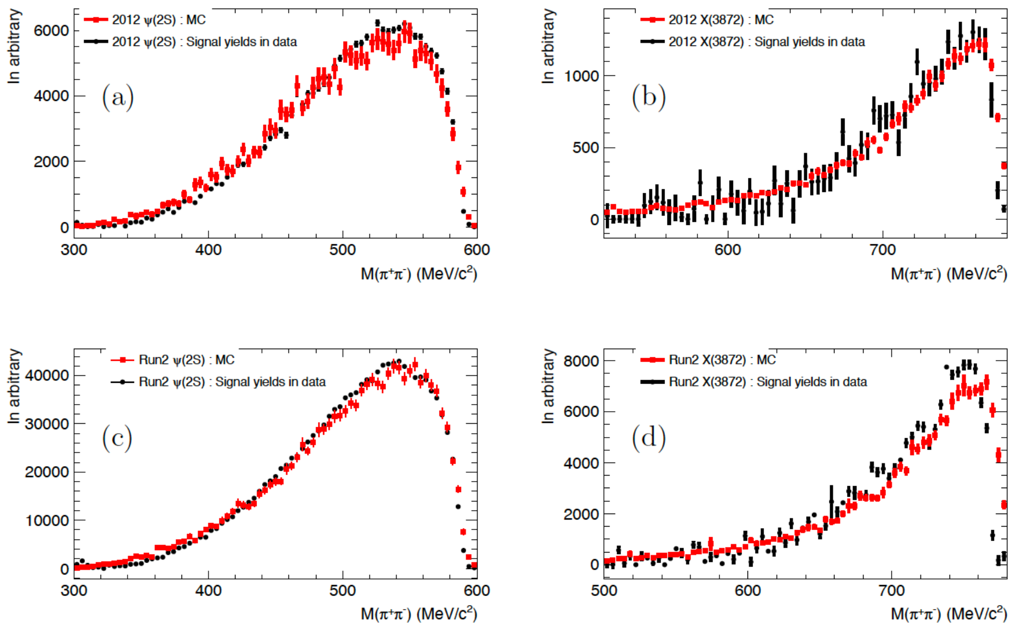


Effciency

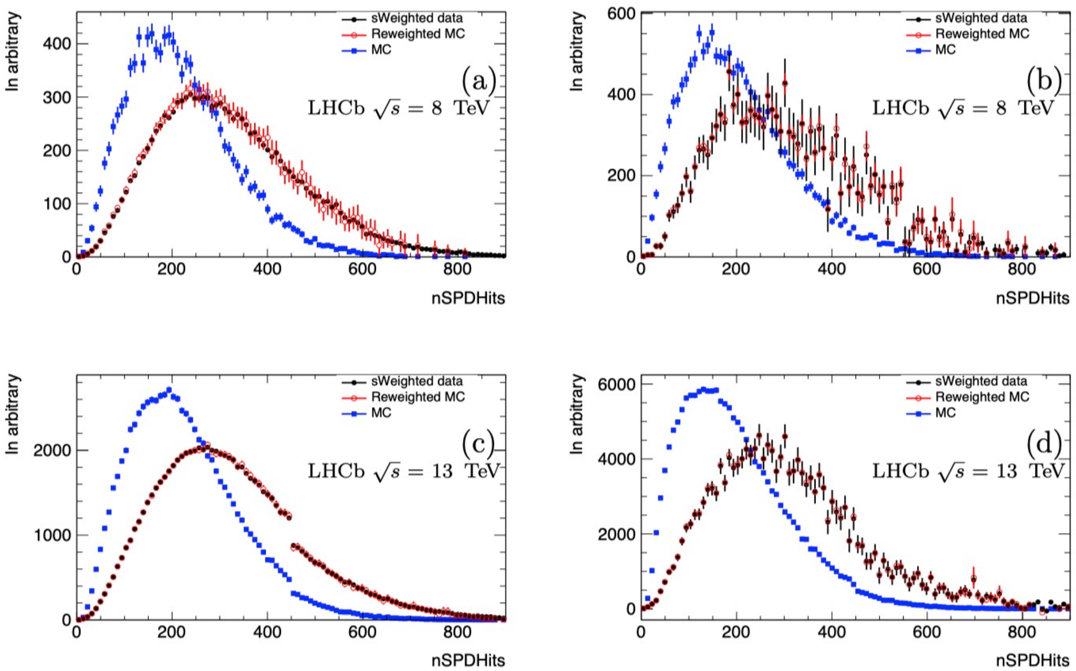
- The efficiency ratio factorized into three parts

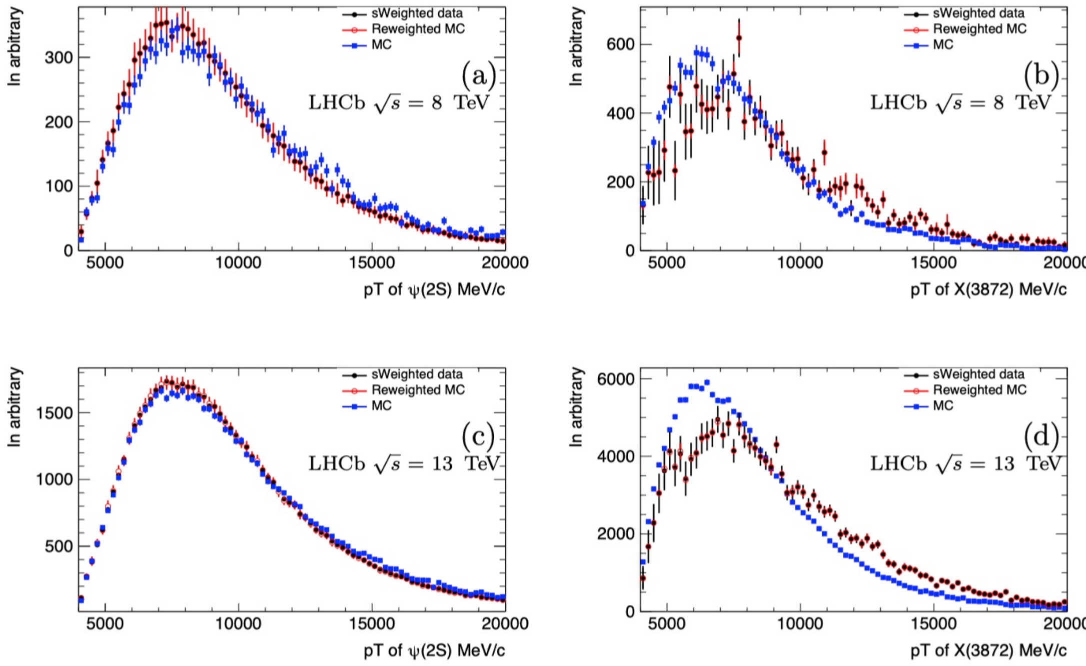
$$\frac{\epsilon_{\psi(2S)}}{\epsilon_{X(3872)}} = \frac{\epsilon^{\text{acc}}_{\psi(2S)}\,\epsilon^{\text{rec\&sel}}_{\psi(2S)}\,\epsilon^{\text{PID}}_{\psi(2S)}}{\epsilon^{\text{acc}}_{X(3872)}\,\epsilon^{\text{rec\&sel}}_{X(3872)}\,\epsilon^{\text{PID}}_{X(3872)}}$$

- Check the M($\pi^+\pi^-$) distribution in simulation



- The simulation samples are corrected to match the data

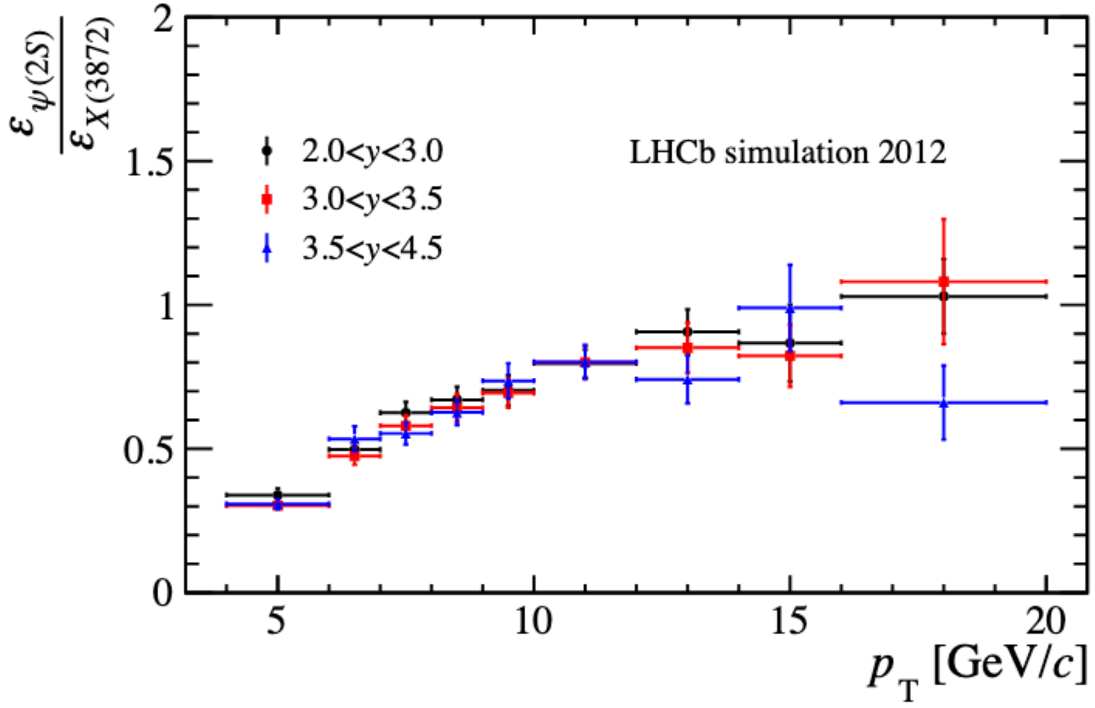


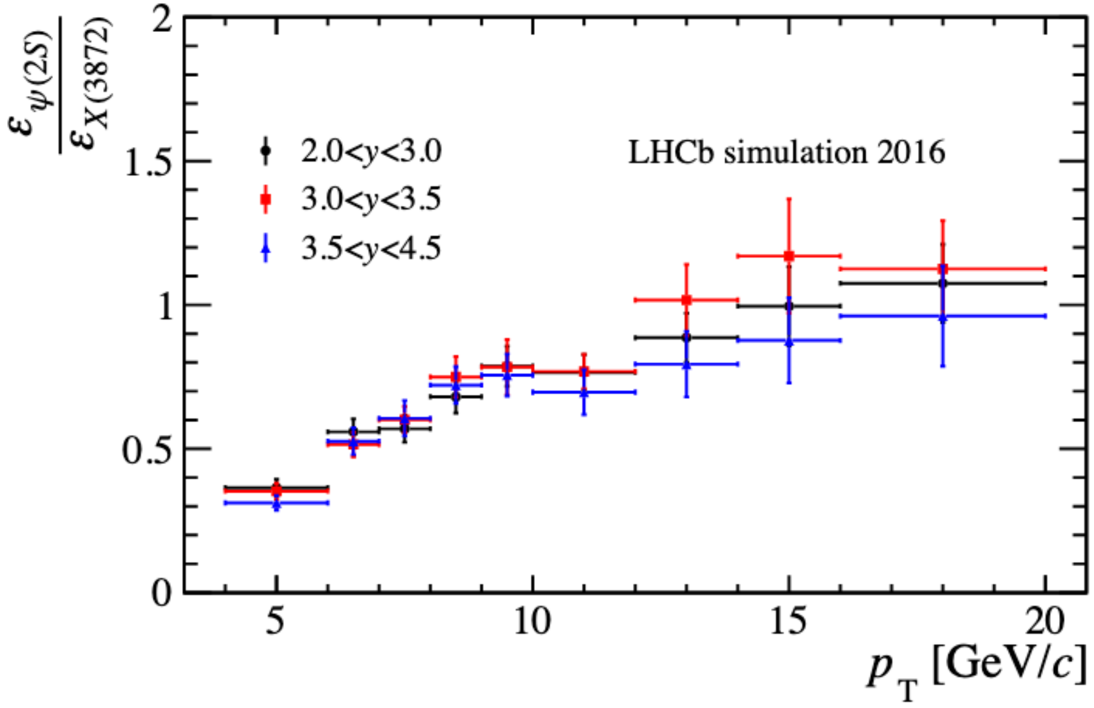


Effciency

- The efficiency ratio factorized into three parts

$$\frac{\epsilon_{\psi(2S)}}{\epsilon_{X(3872)}} = \frac{\epsilon^{\text{acc}}_{\psi(2S)}\epsilon^{\text{rec\&sel}}_{\psi(2S)}\epsilon^{\text{PID}}_{\psi(2S)}}{\epsilon^{\text{acc}}_{X(3872)}\epsilon^{\text{rec\&sel}}_{X(3872)}\epsilon^{\text{PID}}_{X(3872)}}$$





Systematic uncertainty

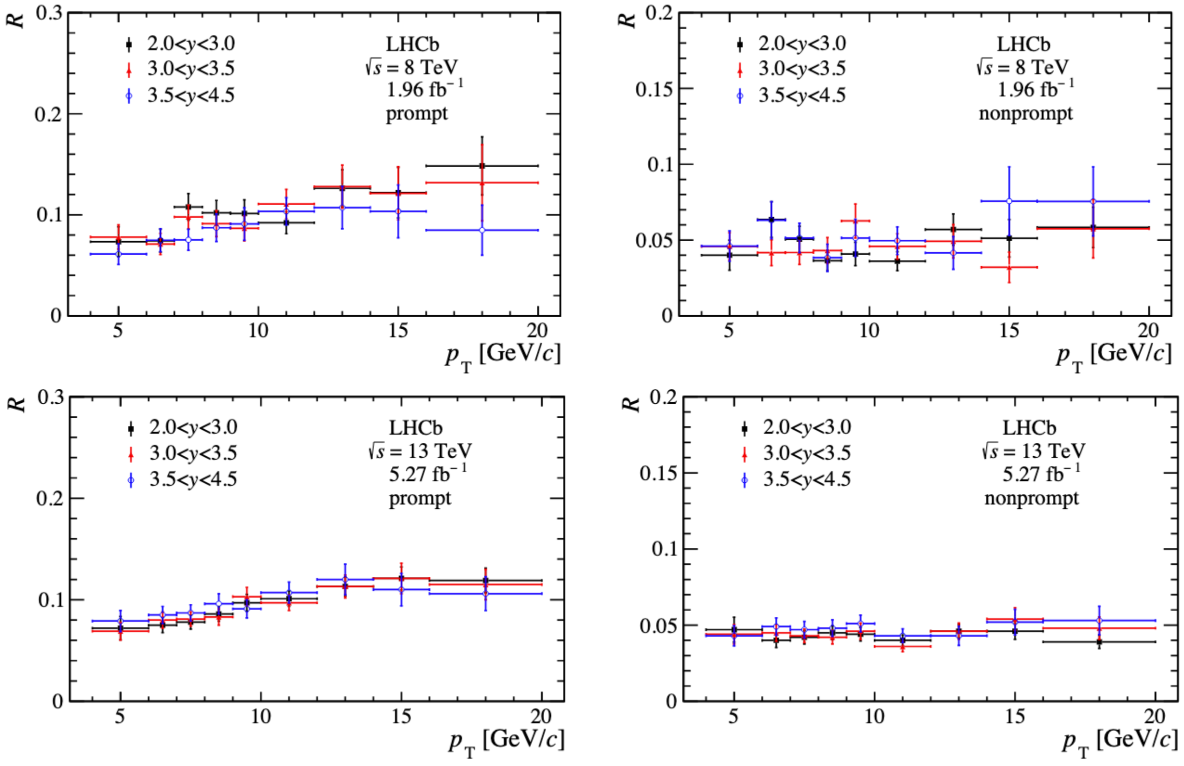
Sources		Systematic uncertainty (%)			
		8 TeV	13 TeV		
		2012	2016	2017	2018
Mass fit	Signal lineshape	0.6		2.3	
	Fraction of two F_{DSCB}	0.0–3.6		0.0–5.6	
	$\sigma_2^{\psi(2S)}/\sigma_1^{\psi(2S)}$	0.0–2.7		0.0–6.8	
	$\sigma_1^{\chi_{c1}(3872)}/\sigma_1^{\psi(2S)}$	0.2–3.6		0.2–5.1	
	$\sigma_2^{\chi_{c1}(3872)}/\sigma_2^{\psi(2S)}$	0.2–5.6		0.2–6.2	
	Background lineshape	0.0–1.5		0.0–3.7	
t_z fit	t_z resolution function	0.0–1.4	0.0–3.0	0.0–1.6	0.0–1.0
	Fixed mean of t_z resolution	0.0–0.4	0.0–1.0	0.0–0.8	0.0–0.6
	Wrong PV	0.0–2.8	0.0–4.1	0.0–3.6	0.0–1.8
	Backgrond shape	2.4		2.4	
	Fixed pseudo-lifetime	0.1–10.9	1.0–12.1	1.3–8.0	1.3–7.8
Tracking		0.1–0.7	0.1–0.2	0.1–1.4	0.1–1.0
Muon identification		0.0–6.1	0.0–1.8	0.0–1.8	0.0–1.5
Pion identification		0.1–6.7	0.0–0.4	0.0–0.9	0.0–0.3
Trigger thresholds		—	0.0–15.1	0.3–6.4	0.3–7.3
Simulation weighting		4.5–9.3	3.6–7.4	3.2–8.9	3.2–6.1
Global event requirements		0.5		1.9	
$M_{\pi^+\pi^-}$ spectrum		2.0		2.0	
Trigger efficiency		1.0		1.0	
Total systematic uncertainty		6.7–14.8	7.1–17.9	6.0–15.3	6.0–13.1
Total statistical uncertainty: prompt		7–17	5–19	6–31	5–13
Total statistical uncertainty: nonprompt		13–26	11–23	10–32	9–19

Double-differential cross-section

- Measured for 8 TeV and 13 TeV

8 TeV

13 TeV



- The prompt ratio increase as a function of p_T, showing that X(3872) production is enhanced relative to prompt $\psi(2S)$ in higher p_T region.
- This flat behavior of the non-prompt ratio is set by the b-decay branching ratios.

Integrated cross-section

- Integrated over $4 < p_T < 20$ GeV/c and $2.0 < y < 4.5$

$$R_\sigma^{\text{8TeV}} = \frac{\sigma(pp \to \chi_{c1}(3872) + \text{any}) \times \mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + \text{any}) \times \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}$$
$$= (7.6 \pm 0.5\,(\text{stat}) \pm 0.9\,(\text{syst})) \times 10^{-2}$$

$$R_B^{\text{8TeV}} = \frac{\mathcal{B}(b \to \chi_{c1}(3872) + \text{any}) \times \mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(b \to \psi(2S) + \text{any}) \times \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}$$
$$= (4.6 \pm 0.4\,(\text{stat}) \pm 0.5\,(\text{syst})) \times 10^{-2}$$

8 TeV

$$R_\sigma^{\text{13TeV}} = \frac{\sigma(pp \to \chi_{c1}(3872) + \text{any}) \times \mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + \text{any}) \times \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}$$
$$= (7.6 \pm 0.3\,(\text{stat}) \pm 0.6\,(\text{syst})) \times 10^{-2}$$

$$R_B^{\text{13TeV}} = \frac{\mathcal{B}(b \to \chi_{c1}(3872) + \text{any}) \times \mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(b \to \psi(2S) + \text{any}) \times \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}$$
$$= (4.4 \pm 0.2\,(\text{stat}) \pm 0.4\,(\text{syst})) \times 10^{-2}$$

13 TeV

- Results for b-decay is consistent with ATLAS results in ~1sigma

$$R_B = \frac{\mathcal{B}(B \to X(3872) + \text{any})\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B \to \psi(2S) + \text{any})\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (3.95 \pm 0.32(\text{stat}) \pm 0.08(\text{sys})) \times 10^{-2}$$

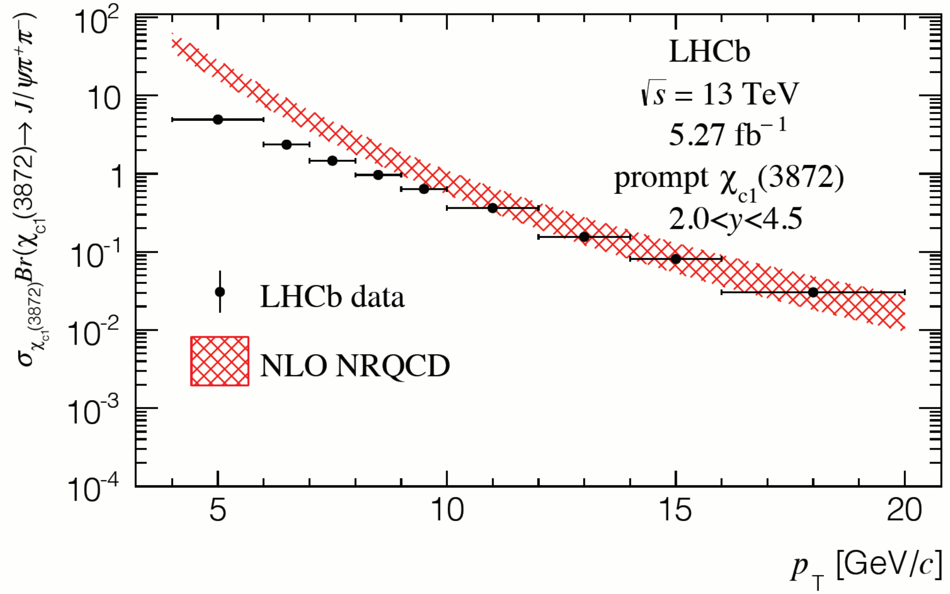
ATLAS, JHEP 01 117 (2017)

Discussion

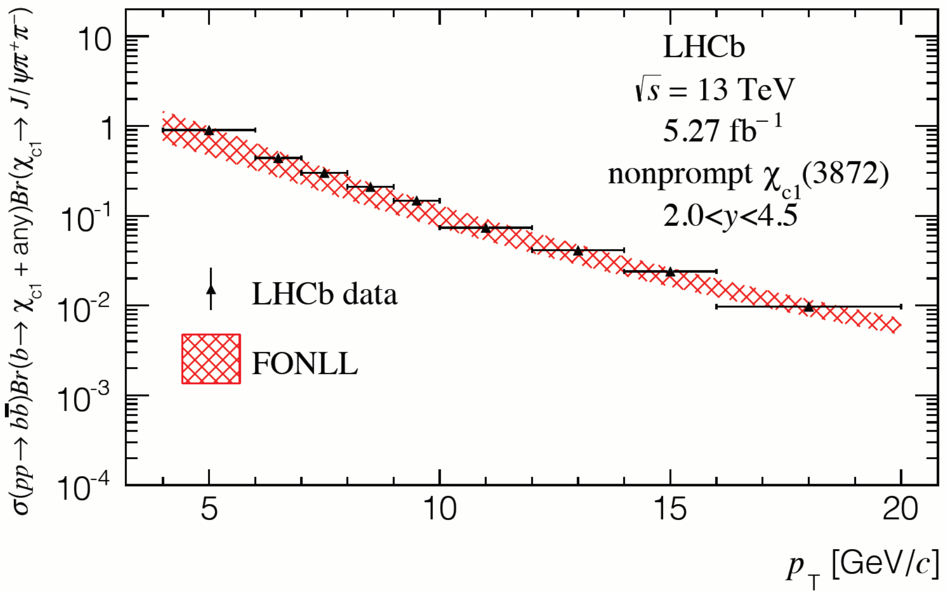
- The absolute cross-section of X(3872) could be calculated using the meausred cross-section of $\psi(2S)(\rightarrow \mu^+\mu^-)$ and the branching fraction of $\mathcal{B}(\psi(2S) \rightarrow J/\psi\pi^+\pi^-)$

- Prompt production compared to NLO NRQCD predictions, b-decay X(3872) compared to FONLL predictions

NRQCD: C. Meng, H. Han et al. PRD 96 (2017) 074014



FONLL: M. Cacciari, M. Greco et al. JHEP 05 (1998) 007
M. Cacciari, M. L. Mangano et al. EPJC 75 (2015) 610



- The prompt production is consistent with NLO NRQCD in the p_T > 10 GeV/c region.
- Favour $\boldsymbol{\chi_{c1}(2P) - D^0\bar{D}^{*0}}$ admixture.

Prospects

- The production measurement would provide useful information to understand exotic states
- Especially the **prompt production**, which could be compared with the theoretical calculation based on different hypothesis
- The inclusive study using J/ψ + track(s) would be a good approach to find new exotic states and measure production of the known states

— $J/\psi\,\pi^+$: $Z_c(3900)^+, Z_c(4200)^+$
— $J/\psi\,p$: $P_c(4312)^+, P_c(4440)^+, P_c(4457)^+$
— $J/\psi\,\phi$: $X(4140), X(4274)$
— $J/\psi\,\pi^+\pi^-$: $X(4312)$
— $\psi(2S)\pi^+$: $Z(4430)^+$
— $J/\psi\;J/\psi$: $X(6900)$