中国科学院大学

University of Chinese Academy of Sciences


# Measurement of X(3872) production in pp collisions at LHCb

The 7th China LHC Physics Workshop

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**UCAS**

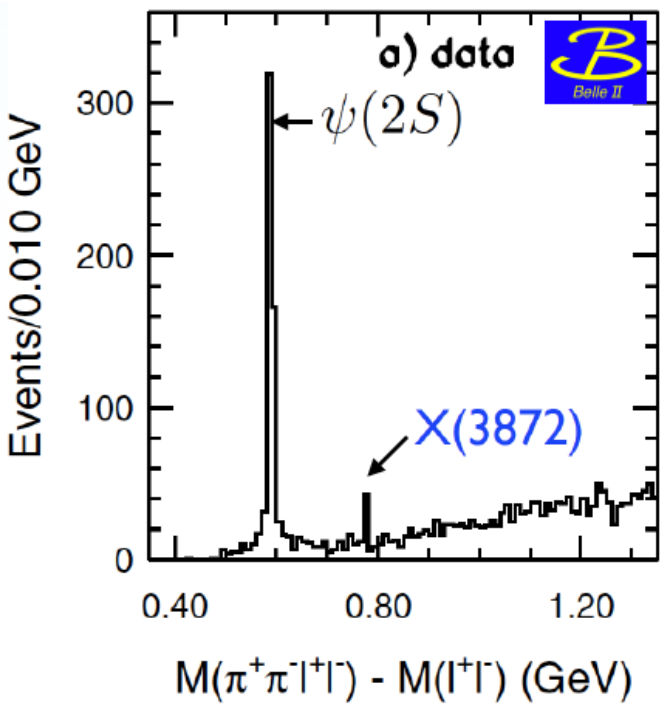
25-28 Nov 2021, Nanjing, China

# Introduction of X(3872)

- **Discovered by Belle in 2003**

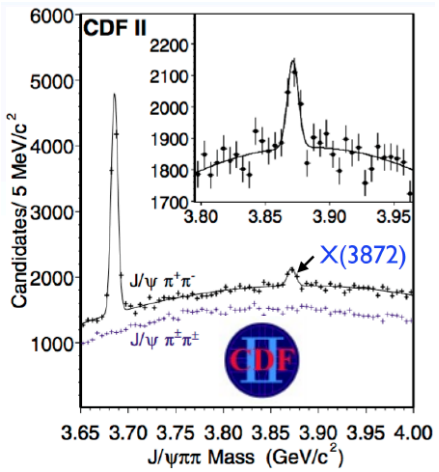
**PRL 91 262001 (2003)**

$$B^+ \to K^+ X$$
$$X \to J/\psi \pi^+ \pi^-$$

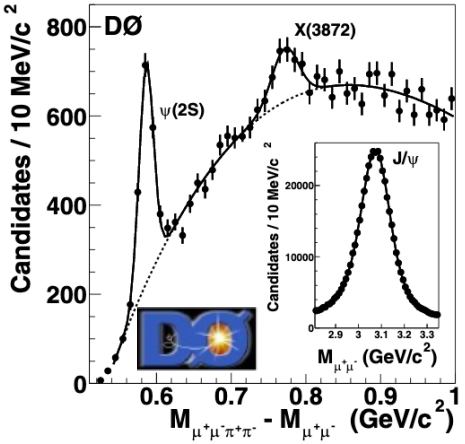



- **Confirmed by CDF, Babar and D0**

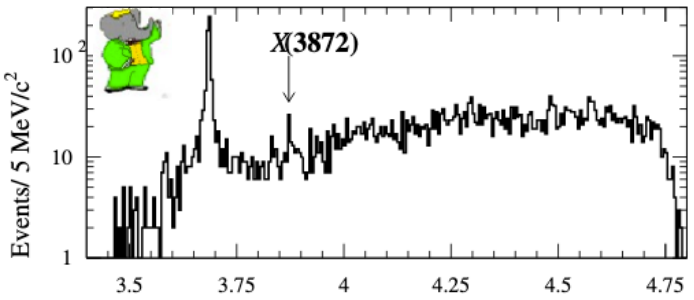
**PRL 91 072001 (2004)**




**PRL 93 162002 (2004)**




**PRD 71 071103 (2005)**



# Introduction of X(3872)

## What We Know

- Mass: very close to $\boldsymbol{D^0\bar{D}^{*0}}$threshold

  M = 3871.65±0.06 MeV

  $E_X = M_X - (M_{D^{*0}}+M_{D0}) = (-0.07 \pm 0.12)$ MeV

- Width: very narrow: 1.19±0.21 MeV — **LHCb, JHEP 08 (2020) 123, PRD 102 092005 (2020)**

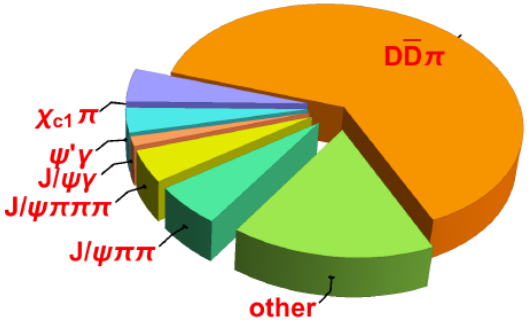
- Quantum numbers: $J^{PC} = 1^{++}$ — **LHCb, PRL 110 222001 (2013)**

- Seven observed decay modes:

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

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

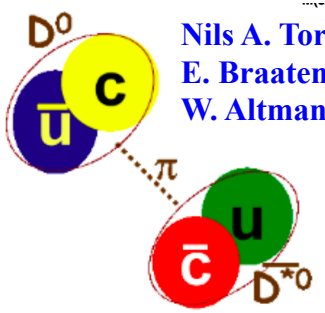
**BaBar, PRL 124 (2020) 152001**



# Introduction of X(3872)

## What is the X(3872) ?

➢ $D^0\bar{D}^{*0}$molecule




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)

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

➢ 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)

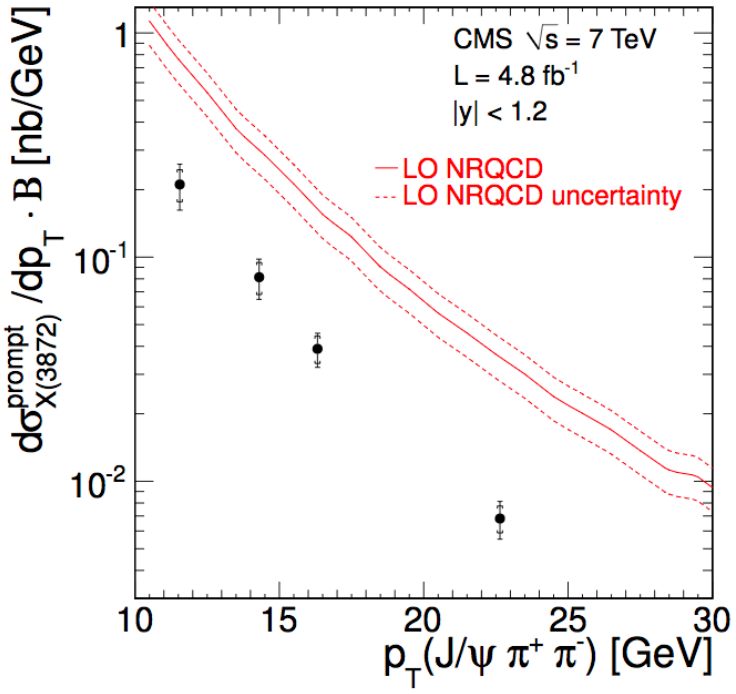
So many explanations reflect the structure of X(3872) is still unclear.

# Introduction of X(3872)

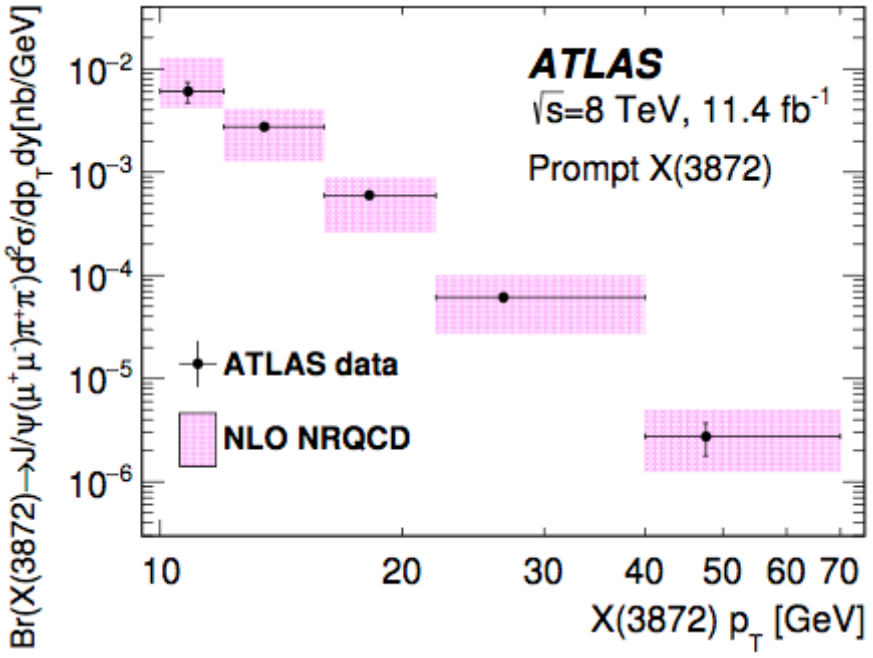
- **CMS measurement show** $\left(\frac{d\sigma}{dPt}\right)$ $<$ NRQCD **prediction for** $D^0\bar{D}^{*0}$**molecule.**

- **ATLAS results consistent with NLO NRQCD prediction for** $\chi_{c1}(2P)$-$D^0\bar{D}^{*0}$.

JHEP 04 (2013) 154



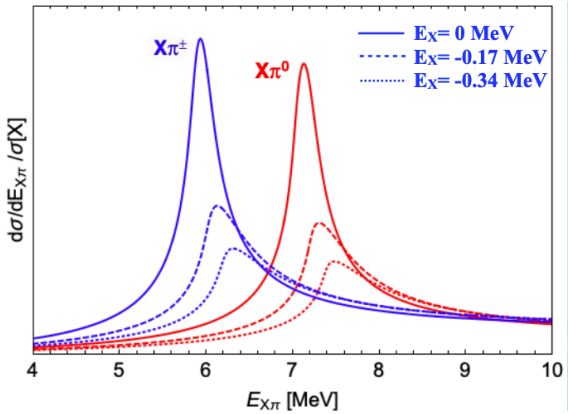

JHEP 01 (2017) 117



# Introduction of X(3872)

If the X(3872) is a $D^0\bar{D}^{*0}$molecule

- Creation of $D^{*+}\bar{D}^{*0}$ at short distance.
- $D^{*+}\bar{D}^{*0}$ scttering into $X\pi^+$.
- Triangle singularity produces a narrow peak in $X\pi^+$ invariant mass peak near 6.1 MeV above $X\pi^+$ threshold.




L.-P. He, and K. Ingles, PRD 100, 094006 (2019) and PRD 100, 0774028 (2019)

D0 collaboration measured the prompt and non-prompt production of $X\pi^+$.

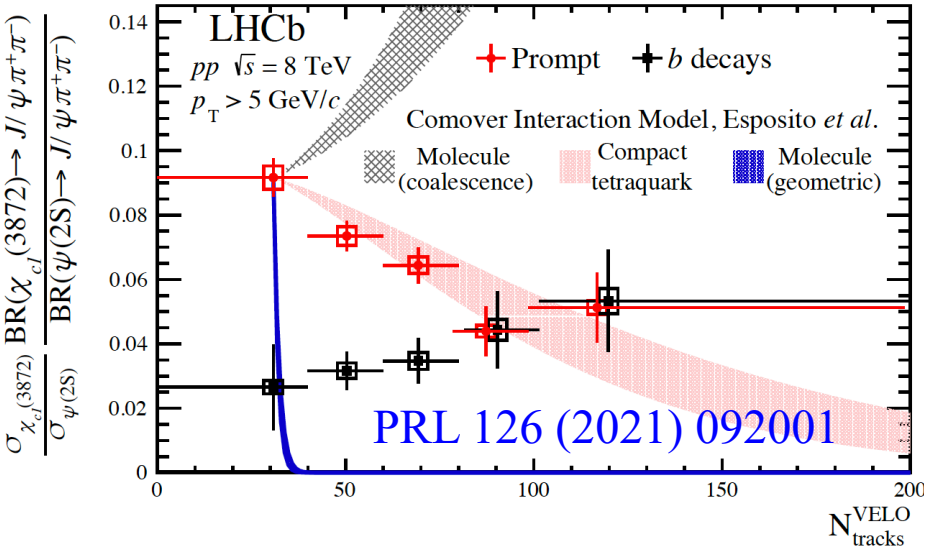
| | Observed events | Expected events |
|---|---|---|
| prompt | 12±16 | 245±730 |
| non-prompt | 25±12 | 30±90 |

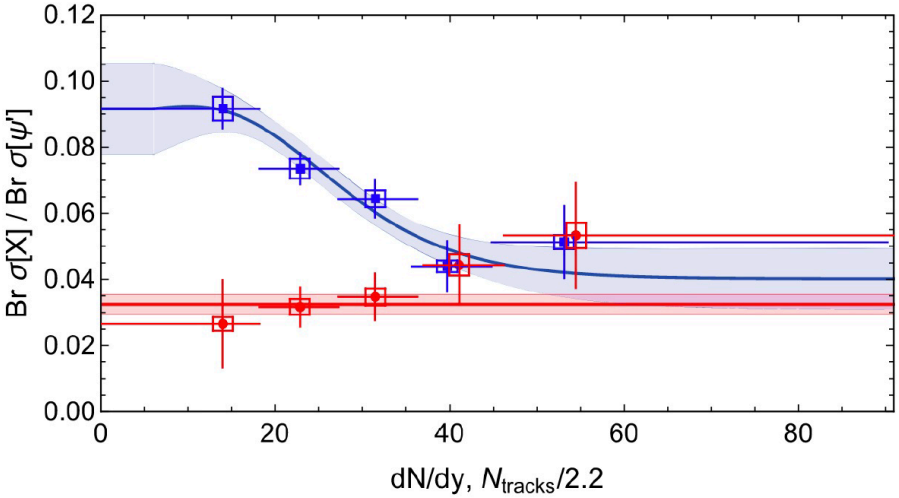
PRD 102, 072005 (2020)

Prompt: no evidence for the production of $X\pi^+$.
Non-prompt: consistent with predictions in $2\sigma$.

# Introduction of X(3872)

LHCb measured X(3872) production versus multiplicity



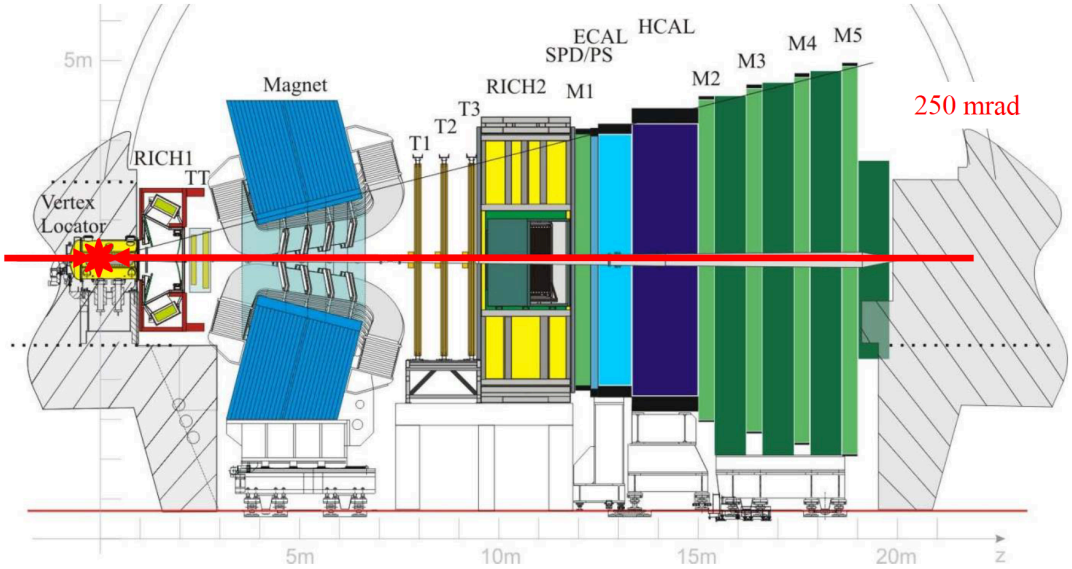

E. Braaten, L-P He, J. Jang et al. PRD 103, L071901 (2021)

- Comover Interaction Model is used to calculate these observables.
  A. Capella et al. PRL 85(2000) 2080]
  E.G. Ferreiro PLB 749(2015) 98
- Promptly produced X(3872) and ψ(2S) hadrons interact with other produced particles, with a breakup cross-section $\sigma_{br}$ that is determined by their radius and binding energy.
- The compact tetraquark matching the measured trend. A. Esposito, E. G. Ferreiro et al. EPJC 81 (2021) 669

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

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

# LHCb detector




Int. J. Mod. Phys A 30, 1530022 (2015)

- Designed for precision measurements in b, c flavor sectors.
- It covers a pseudo-rapidity range of $2 < \eta < 5$.
- Run1: $\mathcal{L} = 3.0$ fb$^{-1}$ from $pp$ collision at 7 TeV (2011) and 8 TeV (2012) in the center-of-mass-energy.
- Run2: $\mathcal{L} = 6.0$ fb$^{-1}$ from $pp$ collision at 13 TeV (2015-2018) in the center-of-mass-energy.

# Overview

- 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 $J/\psi \to \mu^+\ \mu^-$

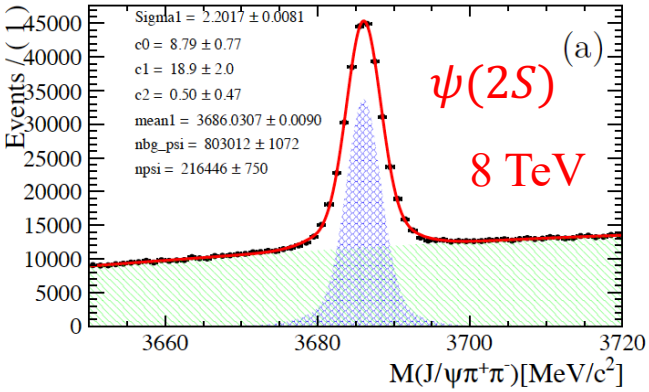
$$\frac{\sigma_{X(3872)} \cdot B(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma_{\psi(2S)} \cdot B(\psi(2S) \to J/\psi\pi^+\pi^-)} = \frac{N_{sig}}{N_{con}} \cdot \frac{\varepsilon_{con}}{\varepsilon_{sig}}$$

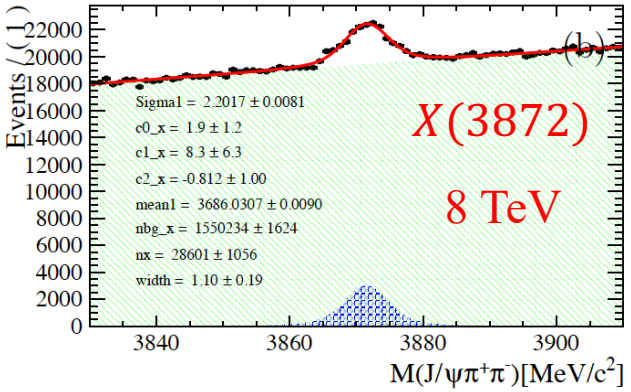
Dataset:

Data:
Run1: 2012 pp data at 8 TeV
Run2: 2016+2017+2018 data at 13 TeV

Run 1 + Run 2
the expected number of X(3872) increases by a factor of 400

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



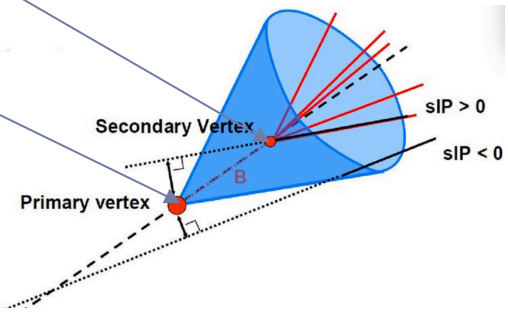
# Cross-section determination

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

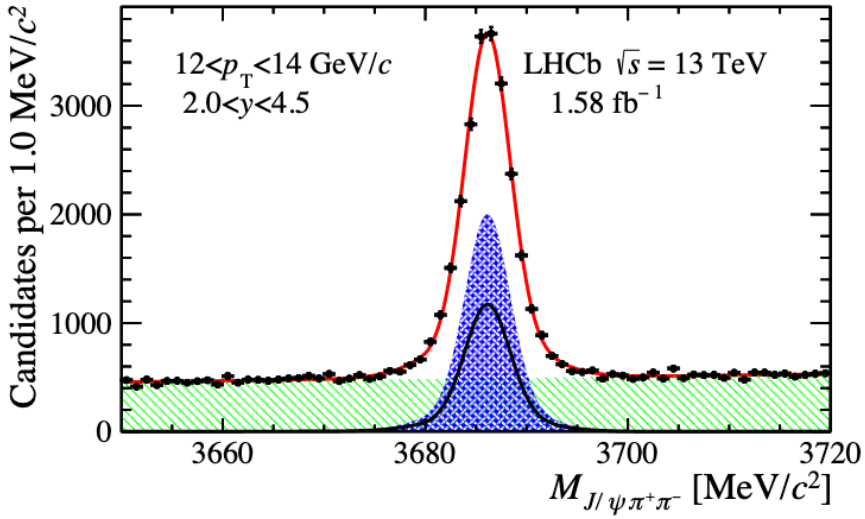
Extract from data  from MC

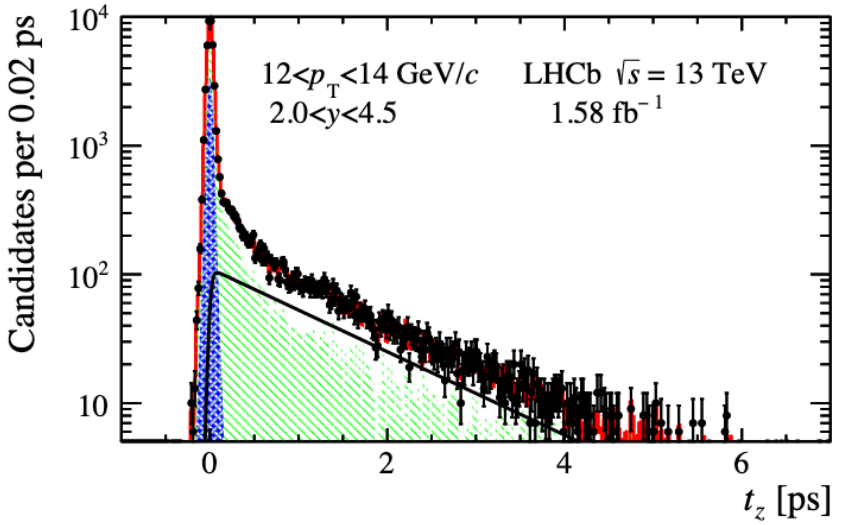
- To determinate the cross-section ratio, need to know the number of prompt X(3872) and $\psi(2S)$ , and the contribution from b-hadron decay in each $p_T$ bin.
- Pseudo-proper decay time $t_z = \frac{(z_{decay} - z_{PV})M}{p_z}$
  - prompt: decay immediately
  - b-decay: have a longer life time, decay at the SV, follows an exponential function

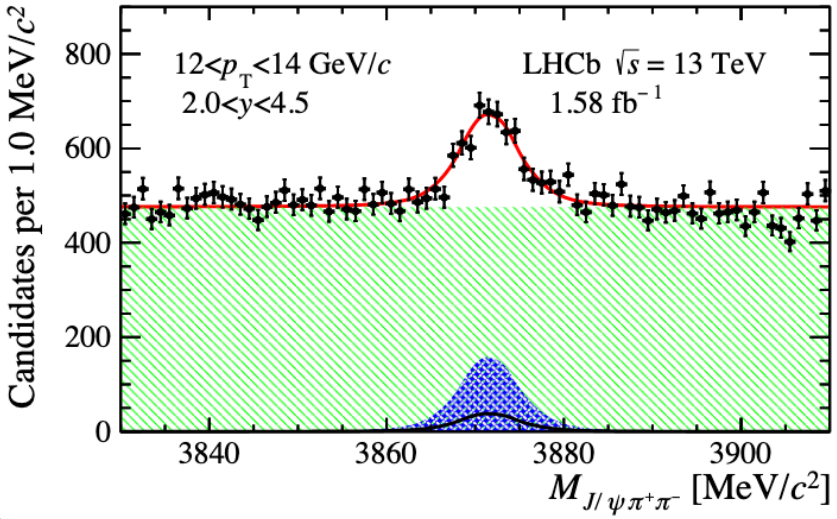
separate the prompt and b-decay components

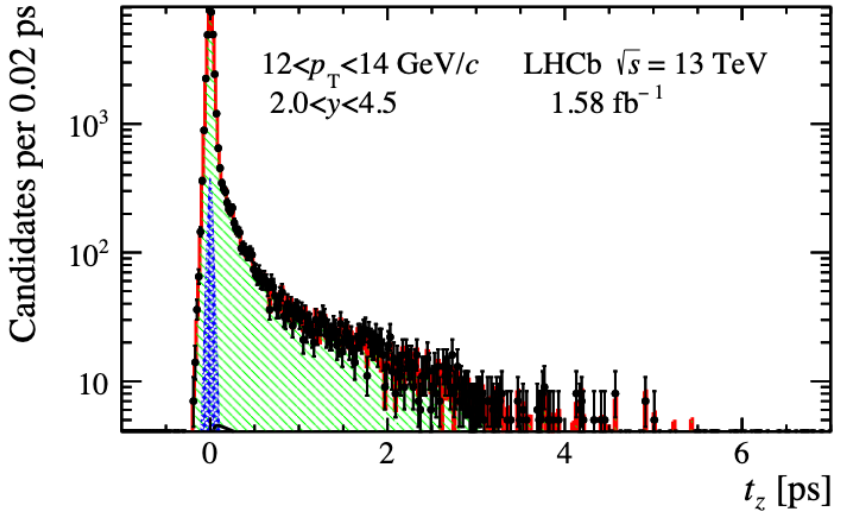


# Extract signal yield



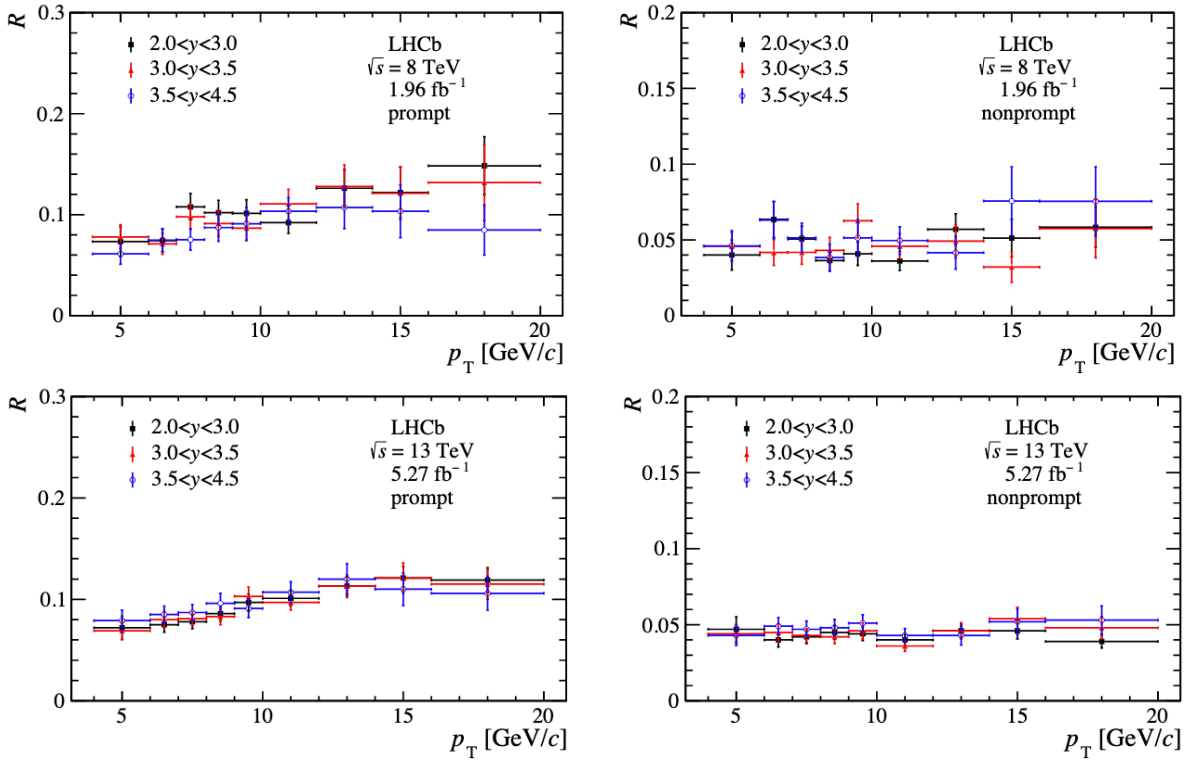
# X(3872) production

arXiv:2109.07360

The double-differential cross-section of X(3872) relative to $\psi(2S)$ are measured for 8TeV, and 13TeV.

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.

# X(3872) production

arXiv:2109.07360

Integrated over the kinematic range $4 < p_T < 20$ GeV/c and $2.0 < y < 4.5$.

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

8 TeV

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

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

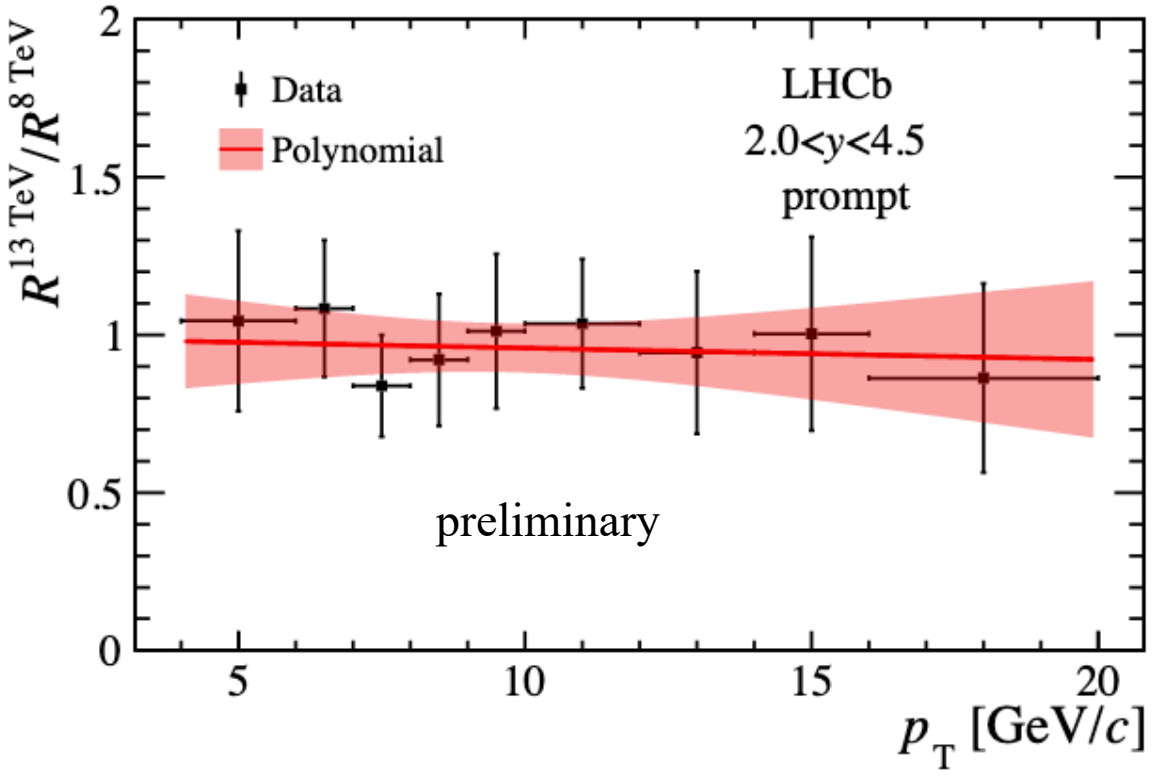
13 TeV

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

# X(3872) production

arXiv:2109.07360

The double ratio cross-section of X(3872) relative to $\psi(2S)$ between 13 TeV and 8 TeV as a function of $p_T$ integrated over 2.0 < y < 4.5.




- A first-order polynomial $(a_0 + a_1 p_T)$ is used to fit the double ratio.
- The $a_0$ consistent with one, the $a_1$ consistent with zero.
- Have no dependence on $p_T$ and center-of-mass energy.

# X(3872) production

arXiv:2109.07360

LHCb, EPJC 80(2020) 185

Take the cross-section of $\psi(2S)(\rightarrow \mu^+\mu^-)$ as input.

The measured cross-section times branching fractions as a function of $p_T$ for

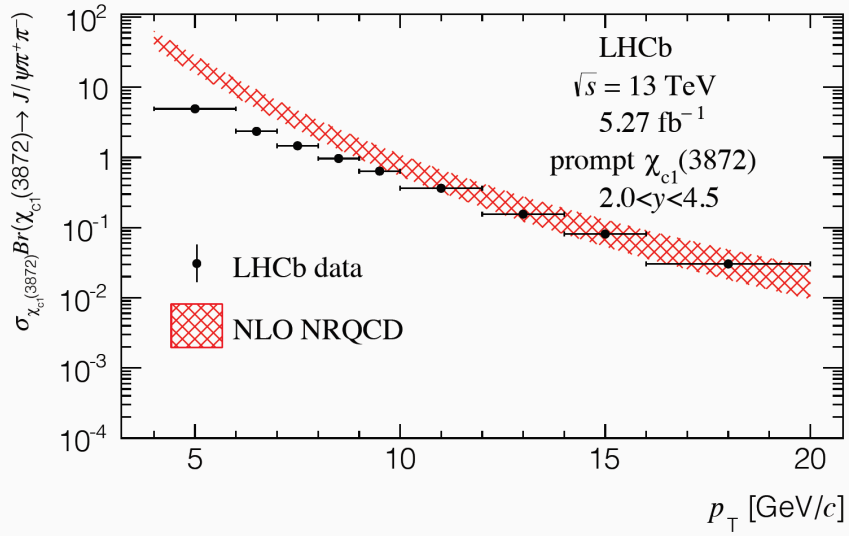
- prompt X(3872) compared to NLO NRQCD predictions,

NRQCD prediction:

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

$$\frac{d\sigma}{dp_T} = k \cdot \mathcal{O} <^3 P_1^{[1]} > (d\sigma(^3P_1^{[1]}) + r \cdot d\sigma(^3S_1^{[8]}))/m_c^2$$

- Include color-singlet and color-octet contribution.
- $k = 0.014$ and $r = 0.26$ are extracted by fitting the CMS data.

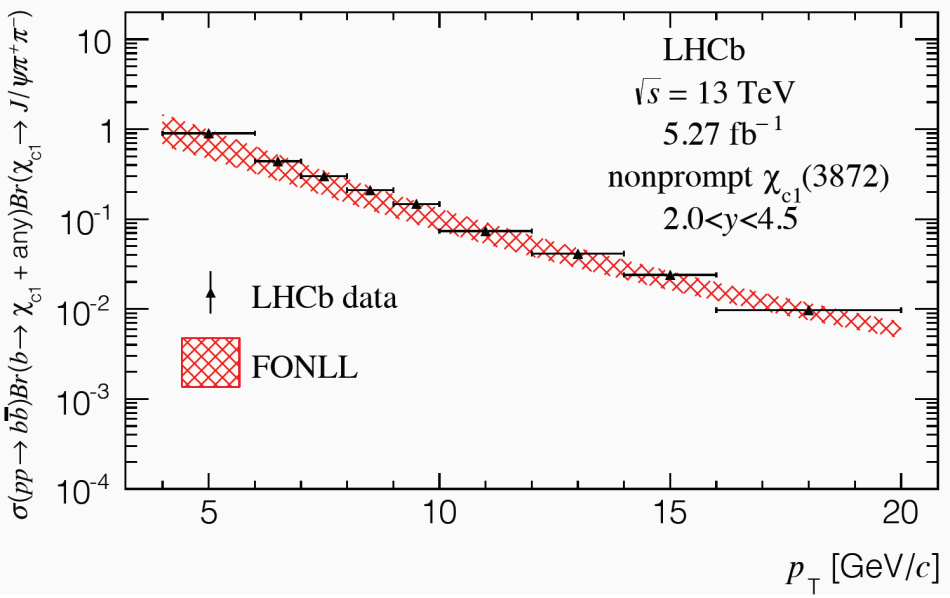



- The prompt production is consistent with NLO NRQCD in the $p_T$ > 10 GeV/c region.
- Might be $\boldsymbol{\chi_{c1}(2P) - D^0\bar{D}^{*0}}$, produced through $\boldsymbol{\chi_{c1}(2P)}$ component.

# X(3872) production

arXiv:2109.07360

- b-decay X(3872) compared to FONLL predictions.




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

The non-prompt production is consistent with FONLL predictions.

# Summary

- The nature of the X(3872) still continues to puzzle us.
- The double-differential cross-section of X(3872) relative to $\psi(2S)$ are measured.
- X(3872) prompt production in pp collision at 13 TeV favor $\chi_{c1}(2P) - D^0\overline{D^{*0}}$ interpretation.

Thanks!