



Recent results of the exotic states studies at LHCb

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LHCb detector



Data

- pp collisions
 - Run 1 (7, 8 TeV) + Run 2 (13 TeV) data, 9 fb⁻¹
- p-Pb and Pb-p data in 2016
 - ~32.3 nb⁻¹



LHCb Integrated Luminosity in p-Pb/Pb-p in 2016

https://lbgroups.cern.ch/online/OperationsPlots/index.htm

$\chi_{c1}(3872)$, aka X(3872)

- Discovered in 2003 by Belle collaboration
- First non-conventional state
 - its nature is still not clear



- Extensive studies at LHCb
 - mass and lineshape study: <u>PRD102 (2020) 092005</u>, <u>JHEP 08 (2020) 123</u>
 - determination of $J^{PC} = 1^{++} PRL 110 (2013) 222001, PRD92 (2015) 011102(R)$
 - production
 - inclusive production JHEP 01 (2022) 131
 - multiplicity dependence: <u>PRL 126 (2021) 092001</u> ~
 - $\Lambda_b \rightarrow \chi_{c1}(3872) p K^- JHEP 09 (2019) 028$
 - $B_{s}^{0} \rightarrow \chi_{c1}(3872) \oint \underline{JHEP \ 02 \ (2021) \ 024}$
 - decay
 - search for $\chi_{c1}(3872) \rightarrow p\overline{p}$ <u>PLB769 (2017) 305</u>
 - $\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$ <u>Nucl. Phys. B886 (2014) 665</u>



$\chi_{c1}(3872)$ production in pPb collisions

- The ratio of $\chi_{c1}(3872)$ and $\psi(2S)$
 - use $\psi(2S)$ as the conventional states for reference
- Check the dependence of system size
 - pp collisions
 - CMS results in Pb-Pb collisions (<u>Phys.</u> <u>Rev. Lett. 128 (2022) 032001</u>)

- $\sqrt{s} = 8.16 \text{ TeV}$
 - p-Pb: 12.5 nb (1.5 < y < 4)
 - Pb-p: 19.3 nb (-5 < y < -2)

LHCb-CONF-2022-001



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$\chi_{c1}(3872)$ production in pPb collisions

- The ratio increase with the system size
 - $\psi(2S)$ production is supressed in pA collisions
 - The ratio decrease with multiplicity in pp collisions
- Further measurement of the nuclear modification factor of $\psi(2S)$ and $\chi_{c1}(3872)$ are in progress

Measured value of *R*: p-Pb: 0.27 ± 0.08 ± 0.05 Pb-p: 0.36 ± 0.15 ± 0.11



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First observation of $B_s^0 \rightarrow \chi_{c1}(3872)\pi^+\pi^-$



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First observation of $B_s^0 \rightarrow \chi_{c1}(3872)\pi^+\pi^-$

- Large contribution from $f_0(980)$
- Simultaneous fit of the dipion mass spectra in both processes
 - S-wave Breit–Wigner for $f_0(1500)$

- $F(m) \propto mqp^3 \left| f \mathcal{A}_{f_0(980)}(m) + e^{i\varphi} \mathcal{A}_{f_0(1500)}(m) \right|^2$
- modified Flatté–Bugg amplitude for $f_0(980)$



ω contribution in $\chi_{c1}(3872)$ decay

- $\chi_{c1}(3872) \rightarrow J/\psi \rho^0$ violates isospin symmetry
- $\chi_{c1}(3872) \rightarrow J/\psi\omega$ measured by Belle, Babar and BESIII using $\omega \rightarrow \pi^+\pi^-\pi^0$
- $\pi^+\pi^-$ final state
 - Interference between ω and ρ^0
 - studied by CDF and Belle but large statistical uncertainties
- B⁺ $\rightarrow \chi_{c1}(3872)$ K⁺ decay
 - 6788 ± 117 signal



arXiv:2204.12597

ω contribution in $\chi_{c1}(3872)$ decay

- $m_{\pi\pi}$ spectrum from fits in $m_{\pi\pi}$ intervals
- Fit with K-matrix parametrization
 - For ρ^0 only model use Breit-Wigner

Total ω contribution: $(21.4\pm2.3\pm2.0)\%$ Exclude interference: $(1.9\pm0.4\pm0.3)\%$ Isospin violation ratio: 0.29 ± 0.04



arXiv:2204.12597

Discovery of $T^{\theta}_{\psi s1}(4000)^0 \rightarrow J/\psi K_s^0$

• Similar to the early study in B⁺ \rightarrow J/ $\psi \varphi K^+$ (<u>PRL 128 (2022) 082001</u>)

 $B^{0}(B^{+})$

d(u)

- two states were discovered in $J/\psi K^+$ system
- $T^{\theta}_{\psi s1}(4000)^+$, $T^{\theta}_{\psi s1}(4220)^+$
- $B^0 \rightarrow J/\psi \varphi K_s^0$ decay
 - 1866 ± 47 signal events



 $\frac{\overline{c}}{c} J/\psi$

 W^+

Discovery of $\overline{T^{\theta}}_{\psi s1}(4000)^0 \rightarrow J/\psi K_s^0$

- Isospin partner of $T^{\theta}_{\psi s1}(4000)^+$? (<u>PRL 128 (2022) 082001</u>)
- $T^{\theta}_{\psi s1}(4220)^{0}$ is constrained to $T^{\theta}_{\psi s1}(4220)^{+}$

New neutral state: $m = 3991^{+12+9}_{-10-17} \text{ MeV}$ $\Gamma = 105^{+29+17}_{-25-23} \text{ MeV}$



Discovery of $T^a_{C\overline{s}0}(2900)^0$ and $T^a_{C\overline{s}0}(2900)^{++}$

• In $B^0 \to \overline{D}{}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$

• ~4000 B^0 and 3750 B^+ selected



Discovery of $T^a_{C\overline{S}0}(2900)^0$ and $T^a_{C\overline{S}0}(2900)^{++}$

- In $B^0 \to \overline{D}{}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$
 - Isospin symmetry
- First observation of a doubly charged opencharm tetraquark

 $m = 2.908 \pm 0.011 \pm 0.020 \text{ GeV}$ $\Gamma = 0.136 \pm 0.023 \pm 0.011 \text{ GeV}$ $J^P = 0^+$



$X(3960) \rightarrow D_s^+ D_s^-$

- In B⁺ \rightarrow D_s⁺D_s⁻K⁺ decays
 - 360 ± 22 signal events



$X(3960) \rightarrow D_s^+ D_s^-$

- Flatte-like function for X(3960)
- $X_0(4140)$ is needed to describe the dip
 - $J^{PC} = 0^{++}$
 - significance 3.7σ

- $m = 3956 \pm 5 \pm 10 \text{ MeV}$ $\Gamma = 43 \pm 13 \pm 8 \text{ MeV}$ $J^{PC} = 0^{++}$
- might be a new Tetraquark or coupled channel effect $J/\psi \varphi \leftrightarrow D_s^+ D_s^-$



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Discovery of $P^{\Lambda}_{\psi s0}(4338)^0 \rightarrow J/\psi \Lambda$

- In $B^- \to J/\psi \Lambda \overline{p}$ decay
 - ~4400 signal events

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B⁻ mass:
m = 5279.44 \pm 0.05 \pm 0.07 \text{ MeV}
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- Most precise single measurement of the B⁻ mass to date
 - Thanks to the small Q-value of the decay!



Discovery of $P^{\Lambda}_{\psi s0}(4338)^0 \rightarrow J/\psi \Lambda$

- A new resonance is needed in the amplitude fit
- First pentaquark containing strange quark

$$m = 4338.2 \pm 0.7 \pm 0.4 \text{ MeV}$$

 $\Gamma = 7.0 \pm 1.2 \pm 1.3 \text{ MeV}$
 $J^{P} = \frac{1}{2}^{-7}$ preferred

arXiv:2210.10346 7/4/2023



Summary

- LHCb continue exploring the treasure in data
- New results about the $\chi_{c1}(3872)$ state
 - production in p-Pb collisions
 - ω contribution in $\chi_{c1}(3872)$ decay
 - new production mode in B_s decay: B_s $\rightarrow \chi_{c1}(3872)\pi^{+}\pi^{-}$
- New exotic states
 - $T^{\theta}_{\psi s1}(4000)^{0} [c \overline{c} s \overline{d}]$ -- isospin partner of $T^{\theta}_{\psi s1}(4000)^{+} [c \overline{c} s \overline{u}]$
 - $T^{a}_{c\overline{s}0}(2900)^{0} [c\overline{s}\overline{u}d]$ and $T^{a}_{c\overline{s}0}(2900)^{++}[c\overline{s}u\overline{d}]$
 - $X(3960)[C\overline{C}S\overline{S}]$
 - $P^{\Lambda}_{\psi s0}(4338)^{0}[c\overline{c}sud]$
- More studies on-going...stay tuned!



ω contribution in X(3872) decay



X(3960)



 $M(\overline{D}\pi) > 2.7 \,\mathrm{GeV}$





