中国科学院大学
University of Chinese Academy of Sciences

LHCb

LHCb 实验上隐粲四夸克态的研究进展

中国科学院大学　任赞

第十届XYZ研讨会

2025年4月

湖南 · 长沙

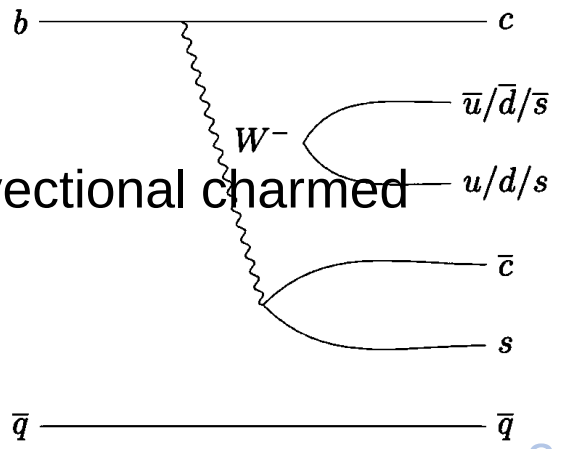
Searching for hidden-charmed tetraquarks at LHCb

- Via charmonia $(c\bar{c})$ + light hadron/photon in B hadron decays or prompt production.
  - E.g. $B^+ \to J/\psi\phi K^+$, $B^0 \to J/\psi\phi K_S^0$,…
  - The radiative decays of $\chi_{c1}(3872)$ in $B^+ \to \chi_{c1}(3872)K^+$
  - Amplitude analysis of $B^+ \to \psi(2S)K^+\pi^+\pi^-$ decay
  - Study of exotic $J/\psi\phi$ resonances in CEP process

Recent results included in this talk!

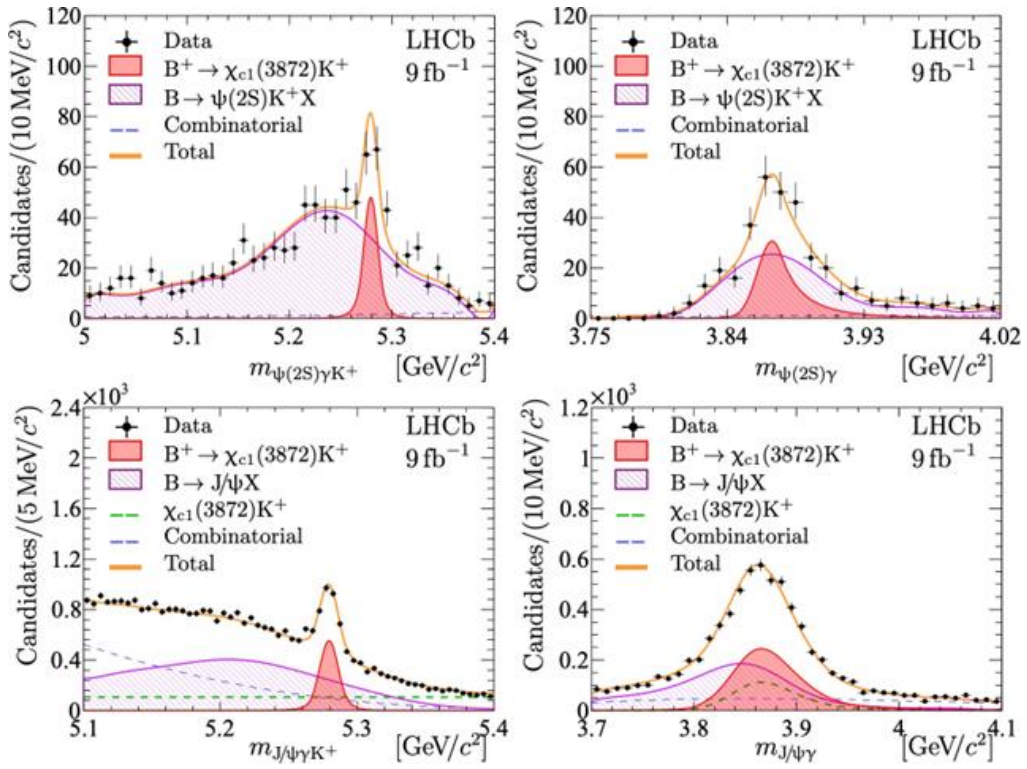
- Via B to $D_{(s)}^{*}\overline{D}_{(s)}^{(*)}h(h')$ decays
  - Hidden-charmed tetraquark in $D_{(s)}^{*}\overline{D}_{(s)}^{(*)}$ system
  - Also available for searching open-charmed tetraquarks and excited convectional charmed mesons in $\overline{D}_{(s)}^{(*)}h$ systems

➔ **See tomorrow's talk《LHCb上$B \to DDh$ 衰变的研究》by 朱琳萱**



The radiative decays of $\chi_{c1}(3872)$ in $B^+ \to \chi_{c1}(3872)K^+$

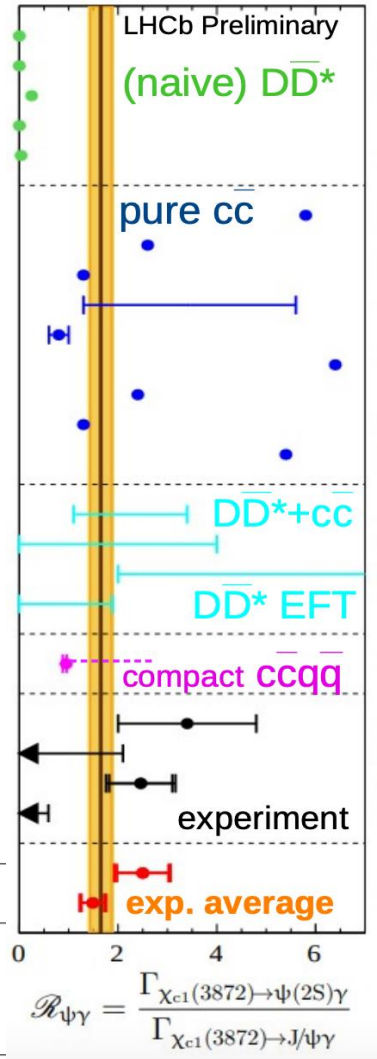
- The radiative decay of X(3872) provides an approach for distinguishing different interpretations of its nature.



1st observation of $\chi_{c1}(3872) \to \psi(2S)\gamma$

JHEP 11 (2024) 121

$\psi(2S)\gamma K^+$	Run 1	Run 2
$N_{B^+\to(\chi_{c1}(3872)\to\psi(2S)\gamma)K^+}$	40 ± 8	63 ± 10
$N_{B\to\psi(2S)K^+X}$	567 ± 24	885 ± 29
N_{comb}	55 ± 17	132 ± 19
Significance (incl. syst,)	4.8σ	6σ



E. S. Swanson
Y. Dong *et al.*
D. P. Rathaud and A. K. Rai
R. F. Lebed and S. R. Martinez
B. Grinstein, L. Maiani and A. D. Polosa

T. Barnes and S. Godfrey
T. Barnes, S. Godfrey and S. Swanson
B.-Q. Li and K. T. Chao
Y. Dong *et al.*
A. M. Badalian *et al.*
J. Ferretti, G. Galata and E. Santopinto
A. M. Badalian, Yu. A. Simonov and B. L. G. Bakker
W. J. Deng *et al.*
F. Giacosa, M. Piotrowska and S. Goito

S. Takeuchi, M. Takizawa and K. Shimizu
E. Cincioglu *et al.*
D. A.-S. Molnar, R. F. Luiz and R. Higa
F.-K. Guo *et al.*

B. Grinstein, L. Maiani and A. D. Polosa

BaBar	2008
Belle	2011
LHCb/Run 1	2014
BESIII	2020
LHCb/Run 1	2024
LHCb/Run 2	2024

The radiative decays of $\chi_{c1}(3872)$ in $B^+ \to \chi_{c1}(3872)K^+$

- The radiative decay of X(3872) provides an approach for distinguishing different interpretations of its nature.
- Measurement of the ratio
- $\mathcal{R}_{\psi\gamma} = \frac{\mathcal{B}(B^+ \to (\chi_{c1}(3872) \to \psi(2S)\gamma)K^+)}{\mathcal{B}(B^+ \to (\chi_{c1}(3872) \to J/\psi\gamma)K^+)} = \frac{\Gamma(\chi_{c1}(3872) \to \psi(2S)\gamma)}{\Gamma(\chi_{c1}(3872) \to J/\psi\gamma)}$

$$\mathcal{R}^{\text{Run 1}} = 2.50 \pm 0.52^{+0.20}_{-0.23} \pm 0.06$$
$$\mathcal{R}^{\text{Run 2}} = 1.49 \pm 0.23^{+0.13}_{-0.12} \pm 0.03$$
$$\mathcal{R}^{\text{Combined}} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$

Strongly suggest that X(3872) is not a pure $D\bar{D}^*$ molecule.
Contributions from compact component and/or mixture are nonnegligible

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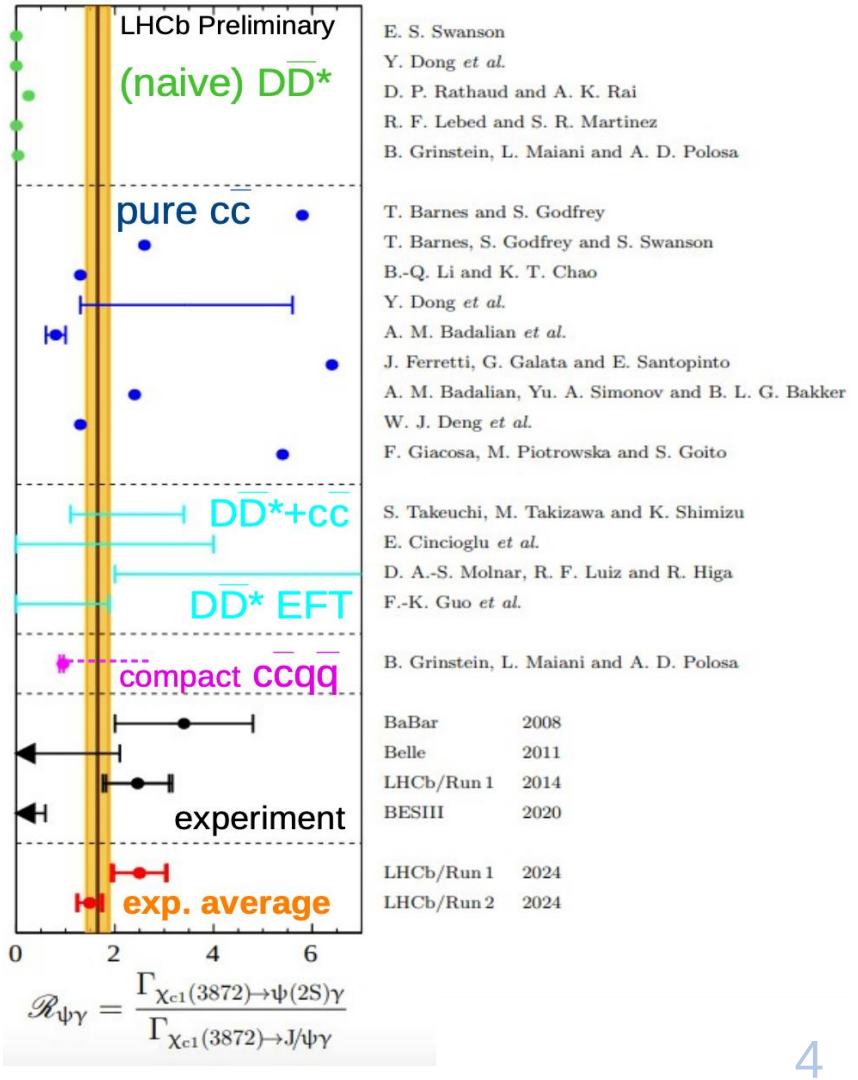
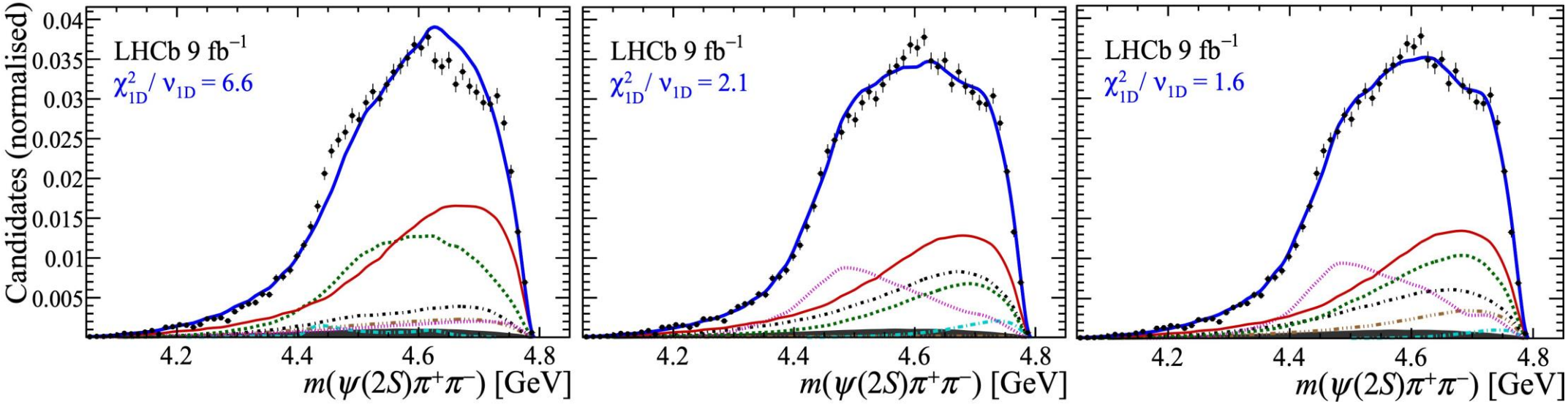


Amplitude analysis of $B^+ \to \psi(2S)K^+\pi^+\pi^-$ decay

- 7D amplitude analysis, using a model-building algorithm to iteratively add contributions to the total amplitude.
- More than 30k $B^+ \to \psi(2S)K^+\pi^+\pi^-$ decays are observed with > 97% signal purity.



8 known excited K′ → Kππ
3 known excited ψ* → ψ (2S)ππ
No exotic states

6 known excited K′ → Kππ
1 known excited ψ* → ψ (2S)ππ
8 "known" → $\psi(2S)\pi\pi, \psi(2S)\pi$ or $\psi(2S)K$

6 known excited K′ → Kππ
1 known excited ψ* → ψ (2S)ππ
8 "known" → $\psi(2S)\pi\pi, \psi(2S)\pi$ or $\psi(2S)K$
+ **3** new exotic states

$T_{c\bar{c}s1}(4600)^0 \to \psi(2S)K\pi$
$T_{c\bar{c}s1}(4900)^0 \to \psi(2S)K\pi$
$T^*_{c\bar{c}s1}(5200)^0 \to \psi(2S)K\pi$(maybe)

JHEP 01 (2025) 054

Amplitude analysis of $B^+ \to \psi(2S)K^+\pi^+\pi^-$ decay

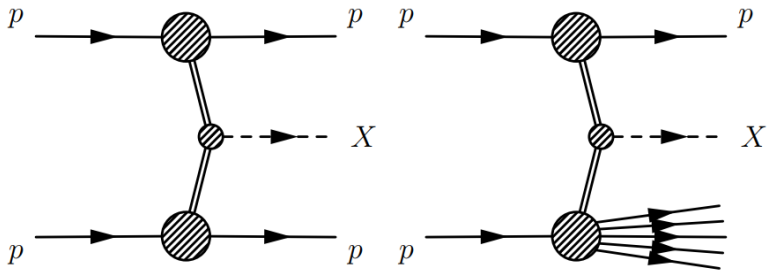
- Interpretation of results is not straightforward: JHEP 01 (2025) 054
  - Four $X^0/\chi_{c0} \to \psi(2S)\pi^+\pi^-$ are identified and the shows some similarities to previously observed $J/\psi\phi$ resonances
  - In $\psi(2S)\pi^\pm$ system, $T_{c\bar{c}1}(4430)^\pm$ is confirmed, J^P of $T_{c\bar{c}1}(4200)^\pm$is determined to be 1^+
  - Cascade exotics decays $X^0 \to T^\pm_{c\bar{c}1}\pi^\mp$ observed
  - Hidden-charm exotics with minimal quark content $c\bar{c}\bar{s}d$: $T_{c\bar{c}\bar{s}1}(4600/4900)^0 \to \psi(2S)K^+\pi^-$, may be the radial excitations of $T_{c\bar{c}\bar{s}}(4000)^0$ in $B^0 \to [J/\psi K^0_S]\phi$

Stat only

Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	$\Delta(-2\ln\mathcal{L})$	$\Delta N_{\rm par}$	Sign. [σ]
$\chi_{c0}(4475)$	0^+	4475± 7 ±12	231±19±32	675	6	$>$ 20 (19)
$\chi_{c1}(4650)$	1^+	4653±14±27	227±26±22	286	6	15 (13)
$\chi_{c0}(4710)$	0^+	4710± 4 ±5	64± 9 ±10	255	6	14 (10)
$\eta_{c1}(4800)$	1^-	4785±37±119	457±93±157	382	8	17 (12)
$T^*_{c\bar{c}1}(4055)^+$	1^-	4054 (fixed)	45 (fixed)	81	2	8 (7)
$T_{c\bar{c}1}(4200)^+$	1^+	4257±11±17	308±20±32	842	16	$>$ 20 ($>$ 20)
$T_{c\bar{c}1}(4430)^+$	1^+	4468±21±80	251±42±82	305	10	15 (8)
$T_{c\bar{c}\bar{s}1}(4600)^0$	1^+	4578±10±18	133±28±69	287	8	15 (12)
$T_{c\bar{c}\bar{s}1}(4900)^0$	1^+	4925±22±47	255±55±127	177	4	12 (8)
$T^*_{c\bar{c}\bar{s}1}(5200)^0$	1^-	5225±86±181	226±76±374	149	6	10 (8)
$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	597	4	$>$ 20 (14)

Study of exotic $J/\psi\phi$ resonances in CEP process

- CEP (central exclusive production) in pp collisions: $pp \rightarrow p + X + p$

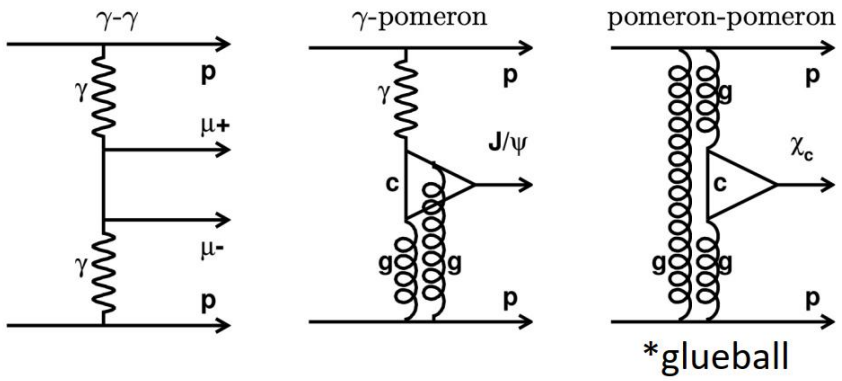


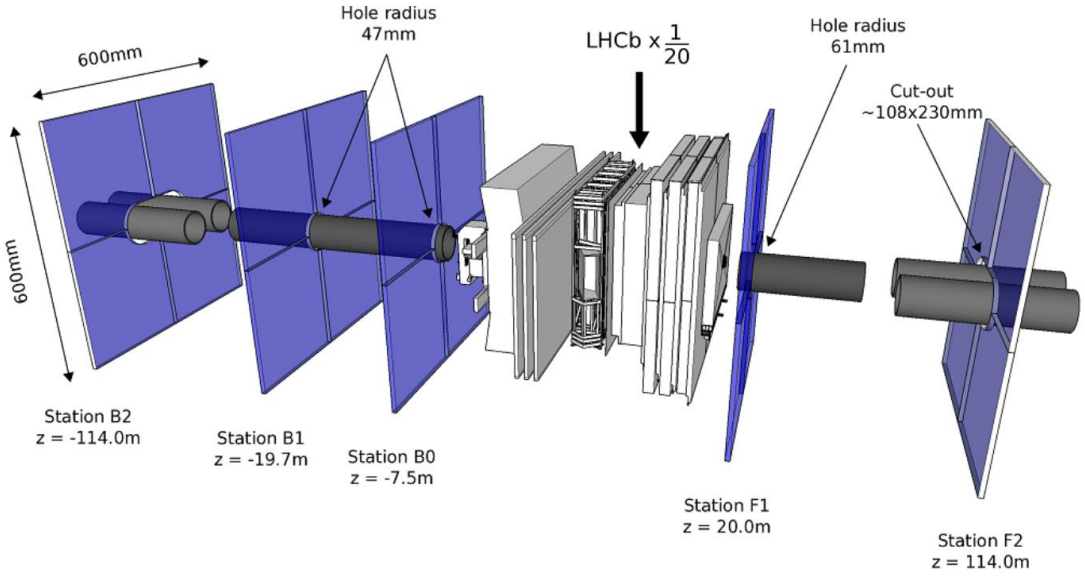
Elastic CEP Inelastic CEP

- Low-activity
- Specific kinematics

➡ Lower background

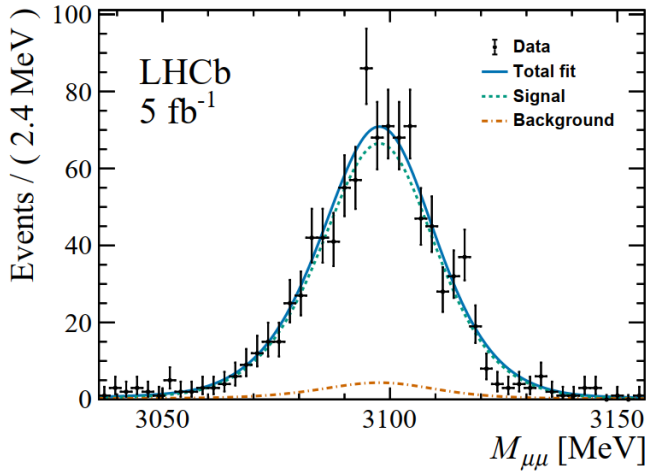
HeRSCheL (**h**igh-**r**apidity **s**hower **c**ounters for **L**HCb)
→ Extend LHCb's sensitivity to $5 < |\eta| < 10$

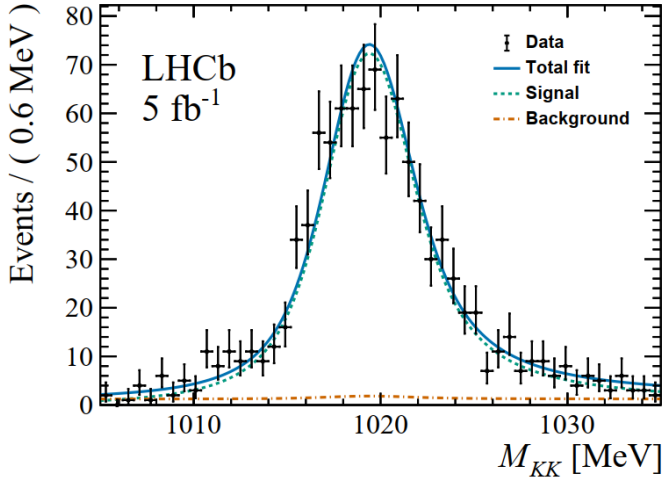




Study of exotic $J/\psi\phi$ resonances in CEP process

- Clean J/ψ and ϕ peaks: 2D fit on $m(\mu\mu), m(KK)$

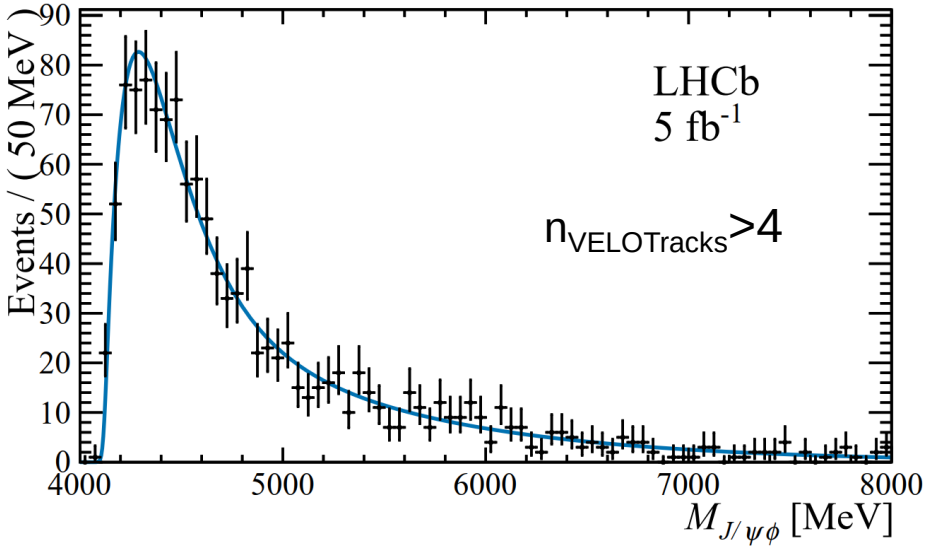




Purity ~ 93%

PRL 134 (2025) 3, 031902

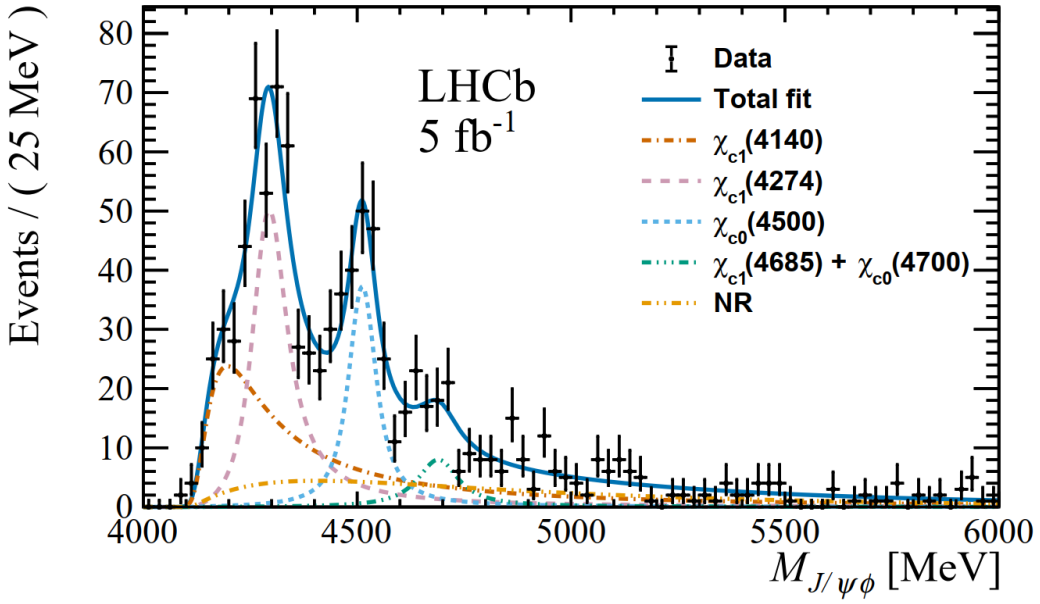
- Background lineshape: determined by dataset with inverted offline multiplicity requirement

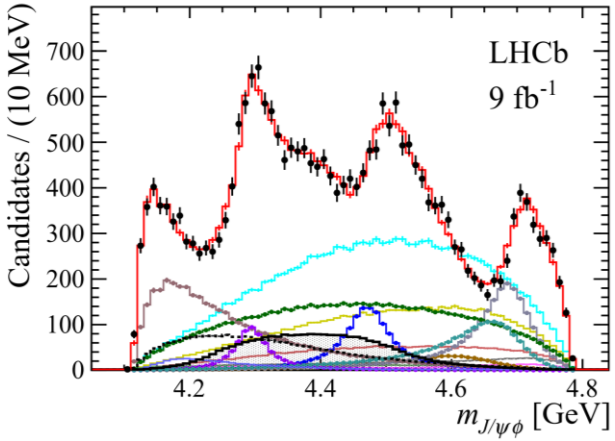


Study of exotic $J/\psi\phi$ resonances in CEP process

- Mass spectrum

PRL 134 (2025) 3, 031902





PRL 127 (2021) 082001

- Significance:
  - $\chi_{c1}(4140)$: 2.4
  - $\chi_{c1}(4274)$: 4.7
  - $\chi_{c0}(4500)$: 5.5
  - $\chi_{c1}(4685)$+$\chi_{c0}(4700)$:1.6
- Mass and width for peaks with a significance>3σ are measured:

Parameter [MeV]	Current analysis	Ref. [13]
$M_{\chi_{c1}(4274)}$	$4298 \pm 6 \pm 9$	$4294 \pm 4^{+3}_{-6}$
$\Gamma_{\chi_{c1}(4274)}$	$92^{+22}_{-18} \pm 57$	$53 \pm 5 \pm 5$
$M_{\chi_{c0}(4500)}$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$4474 \pm 3 \pm 3$
$\Gamma_{\chi_{c0}(4500)}$	$65^{+20}_{-16} \pm 32$	$77 \pm 6^{+10}_{-8}$

- Cross-sections:

$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4140)} = (0.80 \pm 0.15 \pm 0.28)\,{\rm pb},$$
$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4274)} = (0.73 \pm 0.08 \pm 0.17)\,{\rm pb},$$
$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\rm eff}^{\chi_{c0}(4500)} = (0.42^{+0.09}_{-0.08} \pm 0.06)\,{\rm pb},$$
$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} \pm 0.06)\,{\rm pb},$$
$$\sigma_{\rm NR} \times \mathcal{B}_{\rm eff}^{\rm NR} = (0.43^{+0.24}_{-0.18} \pm 0.20)\,{\rm pb},$$

Summary

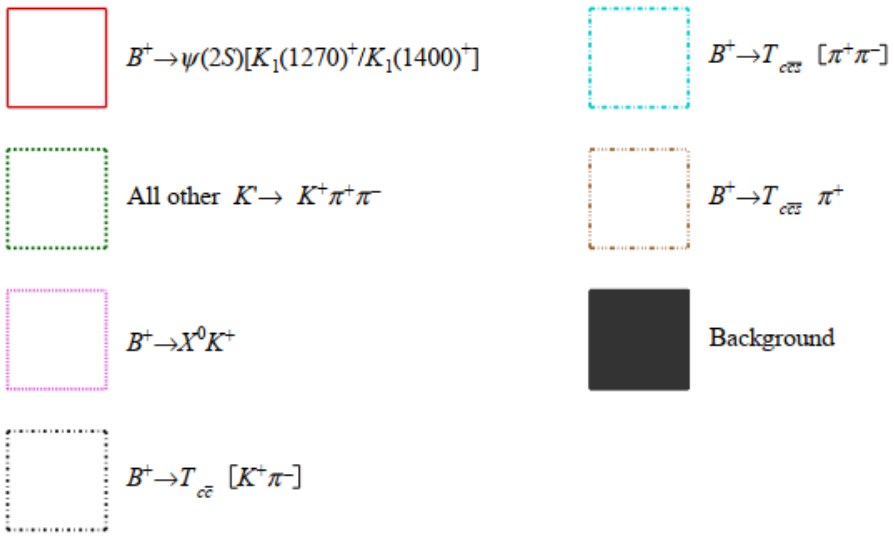
- First observation of the radiative decay $\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$ with significance 6
  → $\chi_{c1}(3872)$ has (at least some) compact component ?

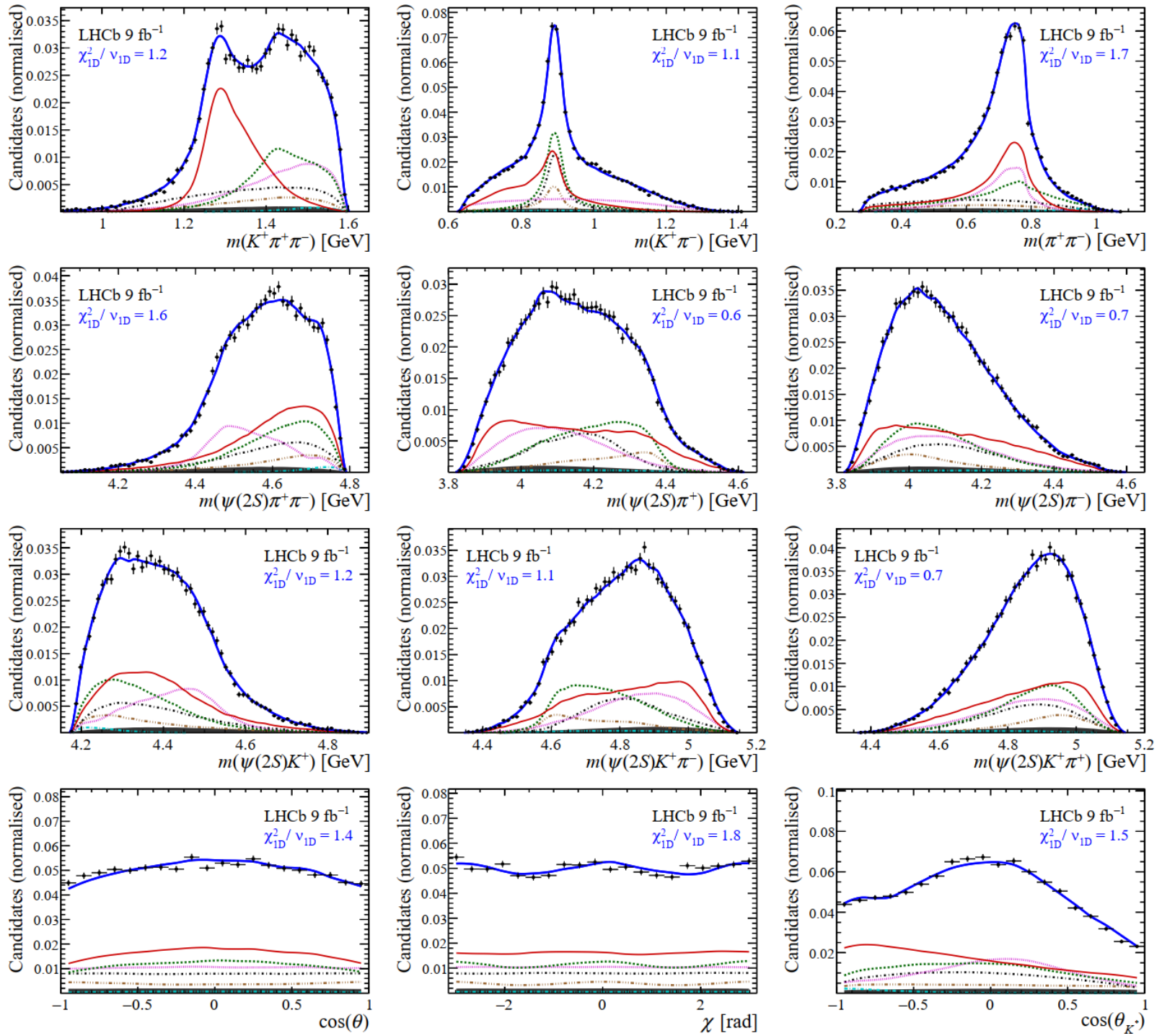
$$\boxed{\mathcal{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04}$$

- New tetraquarks found in $B^+ \rightarrow \psi(2S)K^+\pi^+\pi^-$ partial wave analysis
  - → $1^+T_{c\bar{c}s1}(4600/4900)^0 \rightarrow \psi(2S)K^+\pi^-$, may be the radial excitations of $T_{c\bar{c}s}(4000)^0$ in $B^0 \rightarrow [J/\psi K_s^0]\phi$
- First observation of exotics (in $J/\psi\phi$) in CEP data @ LHC!
  - May be a new experimental opportunities to study hadron spectroscopy

- LHCb Run3 will open more opportunities for exotic studies including the hidden-charmed tetraquarks.

Thanks!


$B^+ \to \psi(2S)[K_1(1270)^+/K_1(1400)^+]$
All other $K' \to K^+\pi^+\pi^-$
$B^+ \to X^0 K^+$
$B^+ \to T_{c\bar{c}}\ [K^+\pi^-]$
$B^+ \to T_{c\bar{c}s}\ [\pi^+\pi^-]$
$B^+ \to T_{c\bar{c}s}\ \pi^+$
Background


LHCb 9 fb^{-1}
$\chi^2_{1D}/\nu_{1D} = 1.2$
Candidates (normalised)
$m(K^+\pi^+\pi^-)$ [GeV]
LHCb 9 fb^{-1}
$\chi^2_{1D}/\nu_{1D} = 1.1$
$m(K^+\pi^-)$ [GeV]
LHCb 9 fb^{-1}
$\chi^2_{1D}/\nu_{1D} = 1.7$
$m(\pi^+\pi^-)$ [GeV]
LHCb 9 fb^{-1}
$\chi^2_{1D}/\nu_{1D} = 1.6$
$m(\psi(2S)\pi^+\pi^-)$ [GeV]
LHCb 9 fb^{-1}
$\chi^2_{1D}/\nu_{1D} = 0.6$
$m(\psi(2S)\pi^+)$ [GeV]
LHCb 9 fb^{-1}
$\chi^2_{1D}/\nu_{1D} = 0.7$
$m(\psi(2S)\pi^-)$ [GeV]
LHCb 9 fb^{-1}
$\chi^2_{1D}/\nu_{1D} = 1.2$
$m(\psi(2S)K^+)$ [GeV]
LHCb 9 fb^{-1}
$\chi^2_{1D}/\nu_{1D} = 1.1$
$m(\psi(2S)K^+\pi^-)$ [GeV]
LHCb 9 fb^{-1}
$\chi^2_{1D}/\nu_{1D} = 0.7$
$m(\psi(2S)K^+\pi^+)$ [GeV]
LHCb 9 fb^{-1}
$\chi^2_{1D}/\nu_{1D} = 1.4$
$\cos(\theta)$
LHCb 9 fb^{-1}
$\chi^2_{1D}/\nu_{1D} = 1.8$
χ [rad]
LHCb 9 fb^{-1}
$\chi^2_{1D}/\nu_{1D} = 1.5$
$\cos(\theta_{K^*})$

Decay channel	Fit fraction [%]
$B^+ \to \chi_{c0}(4475)K^+$	$18.45 \pm 1.31 \pm 2.92$
$B^+ \to \psi(2S)\, K^*(1680)^+$	$8.15 \pm 1.31 \pm 3.51$
$B^+ \to \psi(2S)\, K_1(1270)^+$	$7.60 \pm 0.85 \pm 1.35$
$B^+[P] \to \psi(2S)\, K_1(1270)^+$	$7.52 \pm 0.60 \pm 1.08$
$B^+[D] \to \psi(2S)\, K_1(1270)^+$	$6.81 \pm 0.45 \pm 1.18$
$B^+ \to \psi(2S)\, K_1(1400)^+$	$5.78 \pm 0.62 \pm 0.92$
$B^+ \to \psi(2S)\, K(1460)^+$	$5.26 \pm 0.48 \pm 0.87$
$B^+[P] \to T_{c\bar{c}1}(4200)^+\, K^*(892)^0$	$4.60 \pm 0.54 \pm 2.17$
$B^+ \to T_{c\bar{c}s1}(4600)^0\pi^+$	$4.42 \pm 0.98 \pm 2.17$
$B^+ \to K_2^*(1430)^+\psi(2S)$	$4.35 \pm 0.29 \pm 0.26$
$B^+ \to T_{c\bar{c}1}(4200)^+\, K^*(892)^0$	$4.02 \pm 0.88 \pm 1.01$
$B^+ \to T_{c\bar{c}1}(4430)^+\, [K^+\pi^-]_S$	$3.41 \pm 0.54 \pm 0.78$
$B^+ \to \eta_{c1}(4800)K^+$	$3.24 \pm 0.50 \pm 0.79$
$B^+ \to \chi_{c1}(4650)K^+$	$2.89 \pm 0.45 \pm 0.45$
$B^+[D] \to T_{c\bar{c}1}(4200)^+\, K^*(892)^0$	$2.78 \pm 0.33 \pm 0.61$
$B^+ \to T_{c\bar{c}s1}(4900)^0\pi^+$	$2.60 \pm 0.66 \pm 1.94$
$B^+[D] \to \rho(770)^0\, T_{c\bar{c}s1}(4000)^+$	$2.06 \pm 0.22 \pm 0.84$
$B^+ \to \psi(2S)\, K^*(1410)^+$	$1.79 \pm 0.35 \pm 0.74$
$B^+ \to \chi_{c0}(4710)K^+$	$1.73 \pm 0.28 \pm 0.40$
$B^+ \to T^*_{c\bar{c}s1}(5200)^0\pi^+$	$1.59 \pm 0.46 \pm 0.61$
$B^+ \to T_{c\bar{c}s1}(4000)^+\, [\pi^+\pi^-]_S$	$1.24 \pm 0.23 \pm 0.34$
$B^+ \to T_{c\bar{c}1}(4430)\, K^*(892)^0$	$0.75 \pm 0.43 \pm 2.24$
$B^+ \to \psi(4360)K^+$	$0.64 \pm 0.14 \pm 0.12$
$B^+ \to T^*_{c\bar{c}1}(4055)\, K^*(892)^0$	$0.52 \pm 0.10 \pm 0.11$
$B^+[P] \to \psi(2S)\, K_1(1400)^+$	$0.48 \pm 0.18 \pm 0.40$
Sum B^+	$102.69 \pm 4.40 \pm 7.41$

	J^{PC}	Mass (MeV)	width (MeV)	Significance (σ)
$X(4140)$	1^{++}	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	13
$X(4274)$	1^{++}	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	18
$X(4500)$	0^{++}	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	20
$X(4685)$	1^{++}	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	15
$X(4700)$	0^{++}	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	17