LHCb实验上的奇特强子态的研究

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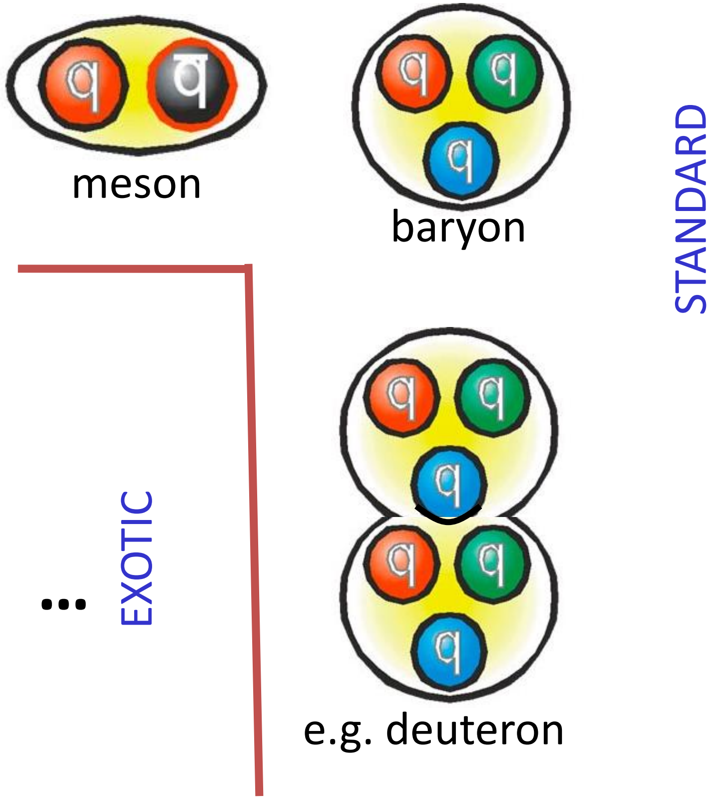
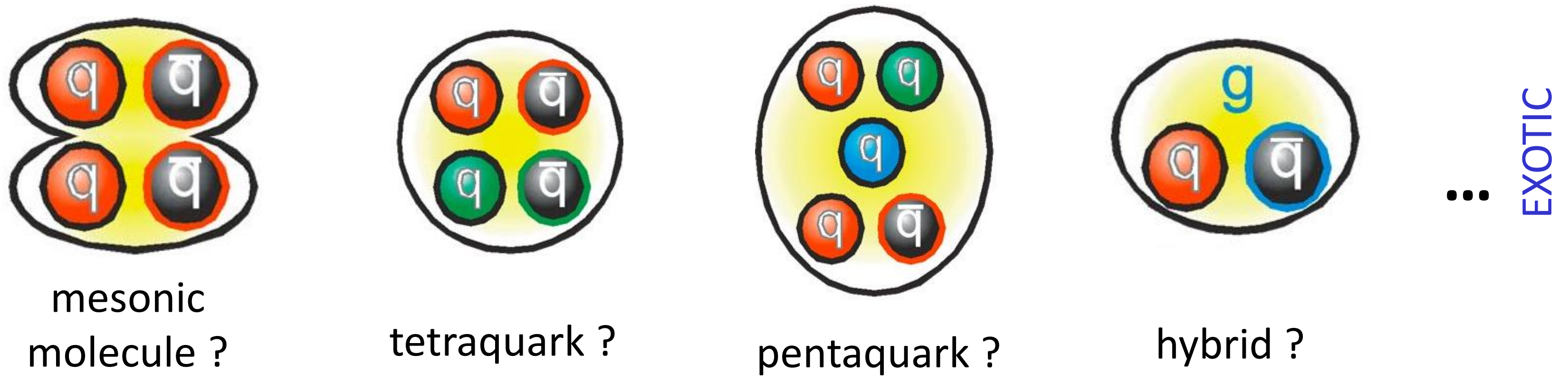
Introduction

- QCD describing strong interaction between quarks and gluons is not well understood due to its non-perturbative nature at low energy scale
- Hadron spectroscopy provides opportunities to test QCD and its effective models
  - e.g. lattice QCD, diquark model, potential model …
- Exotic hadrons provide unique probe to QCD
  - Predicted in quark model
  - Recent results show strong evidence for their existence





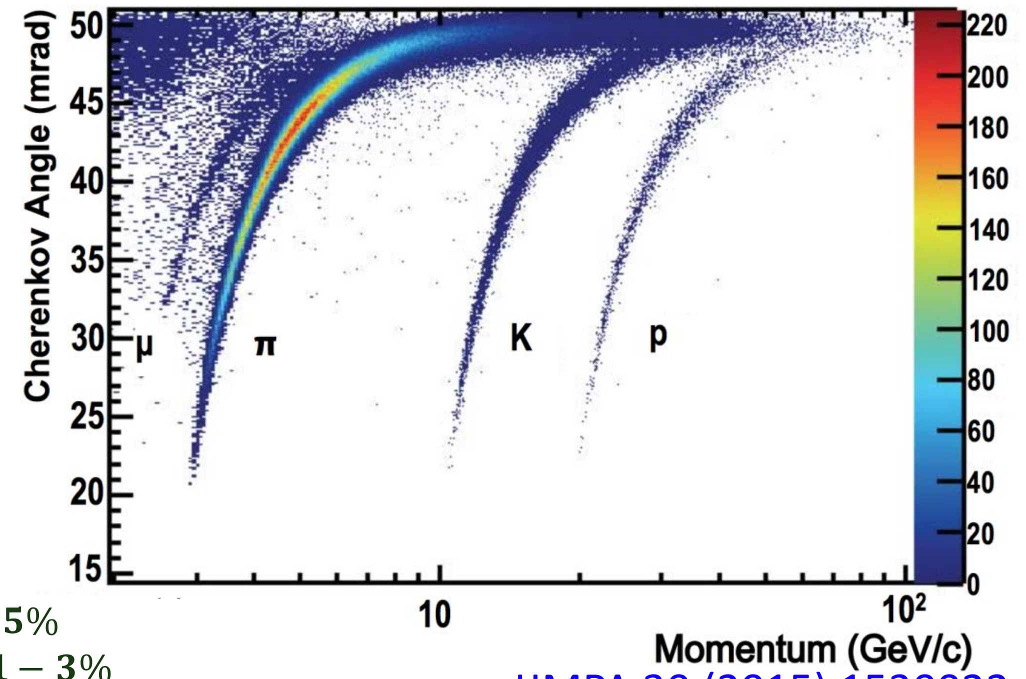
Advantages for spectroscopy study at LHCb

- Large statistics in LHCb acceptance
  - $\sim 6 \times 10^4$ $b\bar{b}$ per second @ 13 TeV
  - $\sim 20 \times$ yield for $c\bar{c}$ compared to $b\bar{b}$

- All kinds of hadrons can be produced
  - $\Lambda_b, \Xi_b, \Sigma_b, \Omega_b, B_s$ …

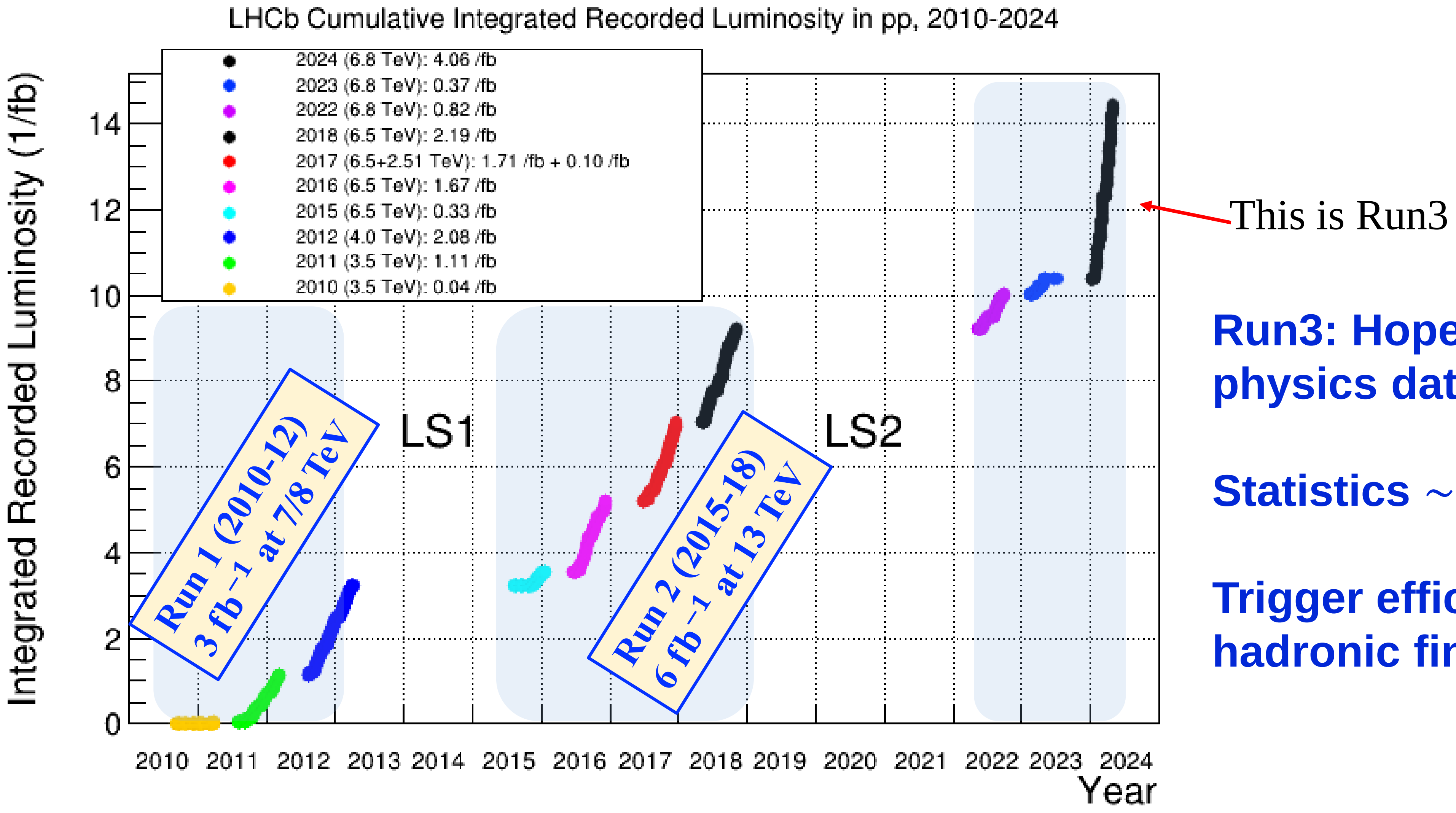
- Dedicated design of detector
  - Powerful particle identification
    - RICH $K-\pi$ separation: $\epsilon(K\to K)\sim 95\%$ mis-ID $\epsilon(\pi\to K)\sim 5\%$
      Muon ID: $\epsilon(\mu\to\mu)\sim 97\%$ mis-ID $\epsilon(\pi\to\mu)\sim 1-3\%$
  - Good momentum, mass resolution
    - Momentum: $\Delta p/p = 0.4\sim 0.6\%$ $(5 - 100\ \mathrm{GeV}/c)$
      Mass : $\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B\to J/\psi X$ (constrainted $m_{J/\psi}$)
  - Very precise vertex resolution
    - $\sigma_{\mathrm{IP}} = 20\mu\mathrm{m}$ to detect long-lived *D* and *B* decays

PID from Cherenkov



IJMPA 30 (2015) 1530022

LHCb collected luminosity



Run3: Hope to collect ~15 fb^{-1} physics data in 2024&2025

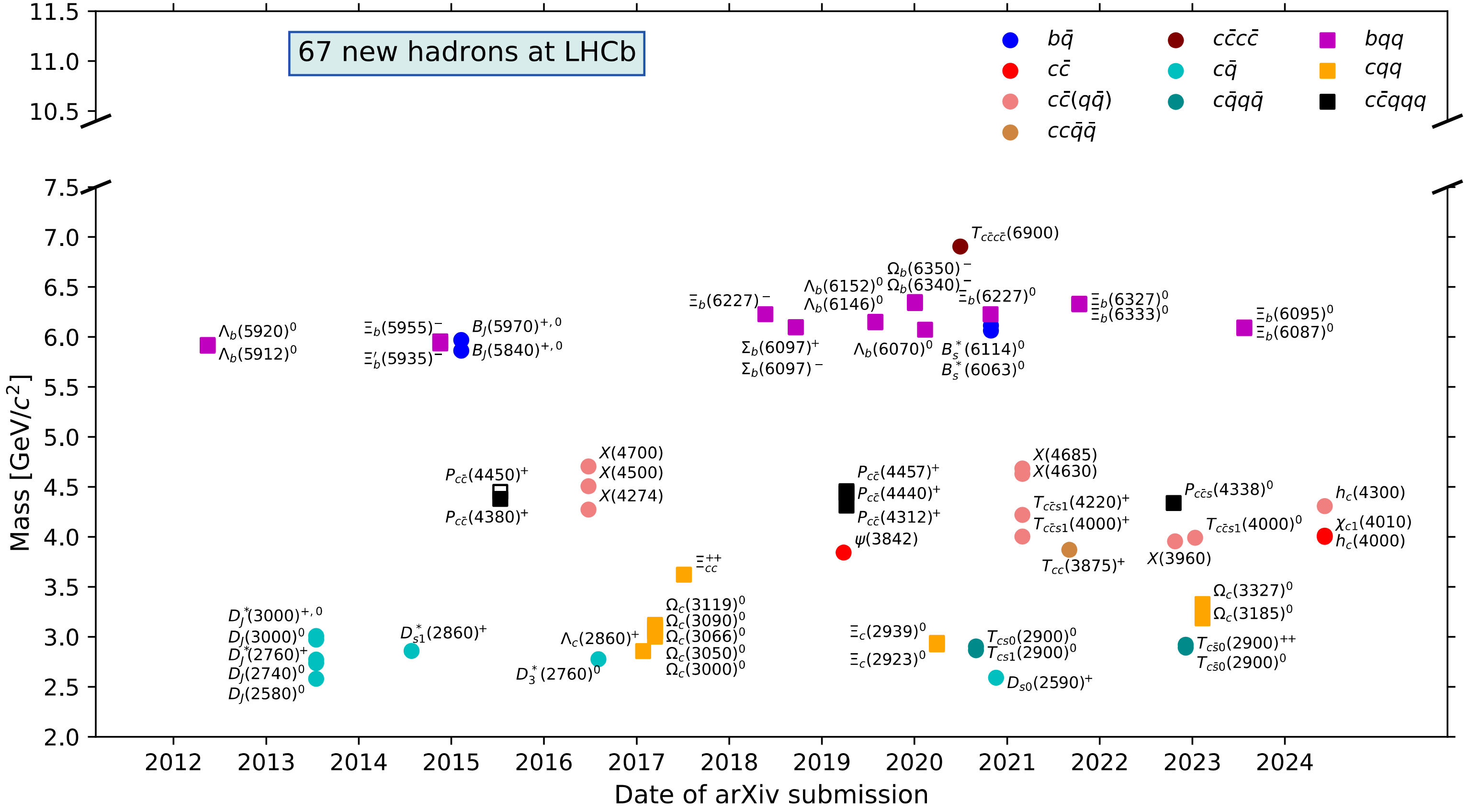
Statistics ~ 2 × run1+2

Trigger efficiency 2 × for hadronic final state

New particles in a glance

- 67 new hadrons discovered by LHCb!

https://www.nikhef.nl/~pkoppenb/particles.html



Exotic hadron naming convention: PDG2024 $Z_c \to T^{(*)}_{c\bar{c}J}$ $Z_{cs} \to T^{(*)}_{c\bar{c}\bar{s}J}$ $P_c \to P_{c\bar{c}}$

Selected topics

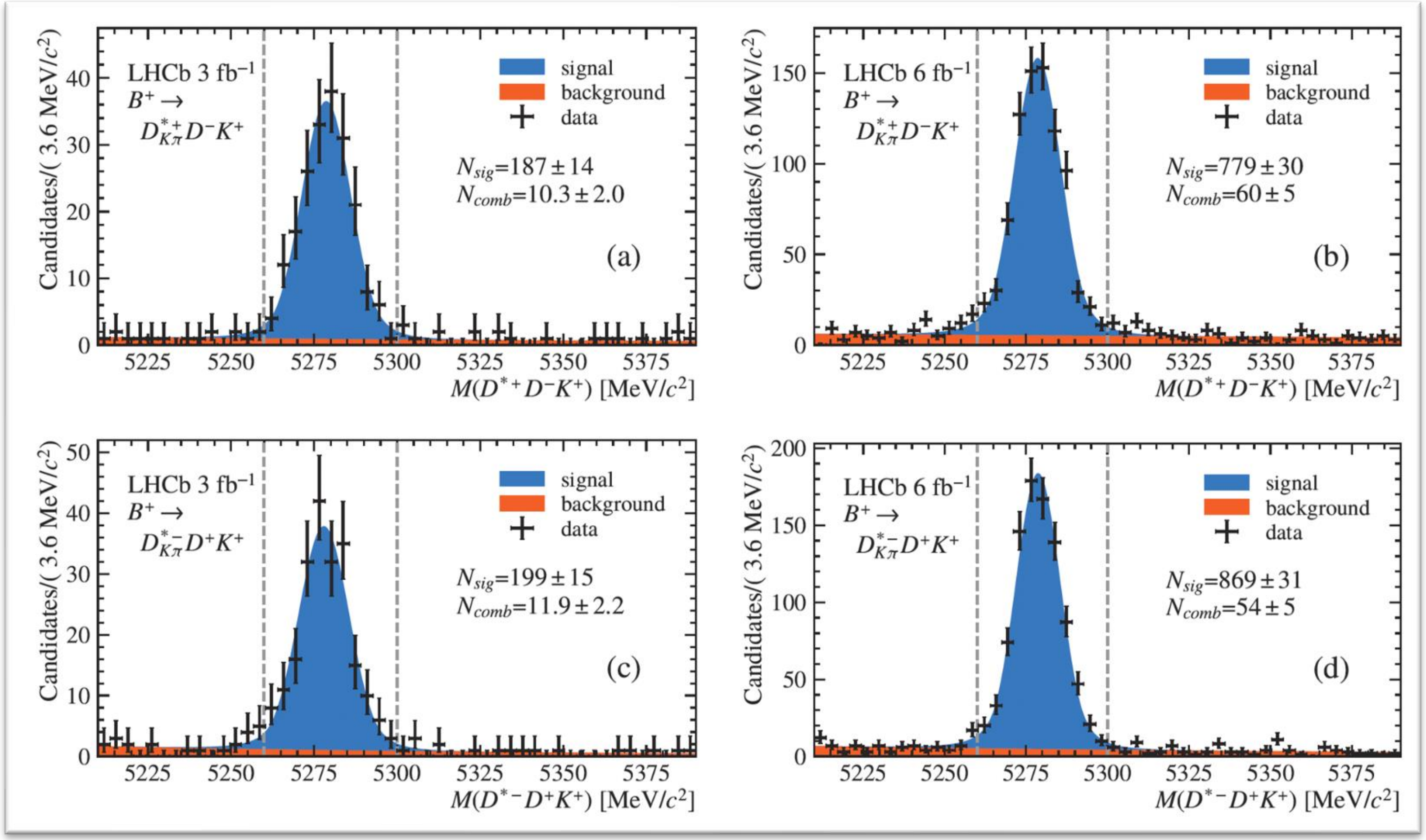
- Amplitude analysis of $B^+ \to D^{*\pm}D^{\mp}K^+$ [arXiv: 2406.03156]
- Exotic $J/\psi\phi$ resonances in diffractive processes in pp collisions [arXiv: 2407.14301]
- Amplitude analysis of $B^+ \to \psi(2S)K^+\pi^+\pi^-$ [arXiv: 2407.12475]
- Study of radiative decays of $\chi_{c1}(3872)$ [arXiv: 2406.17006]

- Amplitude analysis of $B^+ \to D^{*-}D_s^+\pi^+$ [arXiv: 2405.00098]
- Observation of $\Lambda_b^0 \to D^+D^-\Lambda$ [arXiv: 2403.03586]
- Search for prompt production of pentaquarks in open charm final states [arXiv: 2404.07131]
- Observation of $\Lambda_b^0 \to \Sigma_c^{(*)++}D^{(*)-}K^-$ [arXiv: 2404.19510]

$B^+ \to D^{*\pm} D^{\mp} K^+$: signal yields

[arXiv: 2406.03156]

- Using the full LHCb dataset of $9\ \text{fb}^{-1}$: $D^{*-} \to \overline{D}^0(\to K^+\pi^- \,\&\, K^+\pi^-\pi^-\pi^+)\pi^-$



✓ $B^+ \to D^{*+} D^- K^+$: **966**

✓ $B^+ \to D^{+} D^{*-} K^+$: **1068**

$B^+ \to D^{*\pm}D^{\mp}K^+$: amplitude analysis

- Amplitudes of $B^+ \to R(D^{*+}D^-)K^+$ and $B^+ \to R(D^+D^{*-})K^+$ linked by ***C*-parity**
  ⇒ allowing determination of *C*-parities of R resonances

$$\mathcal{A}(x) = \frac{1+d}{2}\left\{\sum_{j\in R(D^{*\pm}D^{\mp})} c_j A_j(x) + \sum_{k\in R(D^{*-}K^+,\ D^+K^+)} c_k A_k(x)\right\} \Leftarrow B^+ \to D^+D^{*-}K^+$$

$$+ \frac{1-d}{2}\left\{\sum_{j\in R(D^{*\pm}D^{\mp})} C_j \times c_j A_j(x) + \sum_{l\in R(D^{*+}K^+,\ D^-K^+)} c_l A_l(x)\right\} \Leftarrow B^+ \to D^{*+}D^-K^+$$

✓ $d = 1$ for $B^+ \to D^+D^{*-}K^+$; $d = -1$ for $B^+ \to D^{*+}D^-K^+$

☐ R resonances with $J^P = 1^+$: S-wave & D-wave

$$f_{R,S/D}(m) = \frac{\gamma_{S/D}}{m_0^2 - m^2 - i m_0[\gamma_S^2\Gamma_S(m) + \gamma_D^2\Gamma_D(m)]}$$

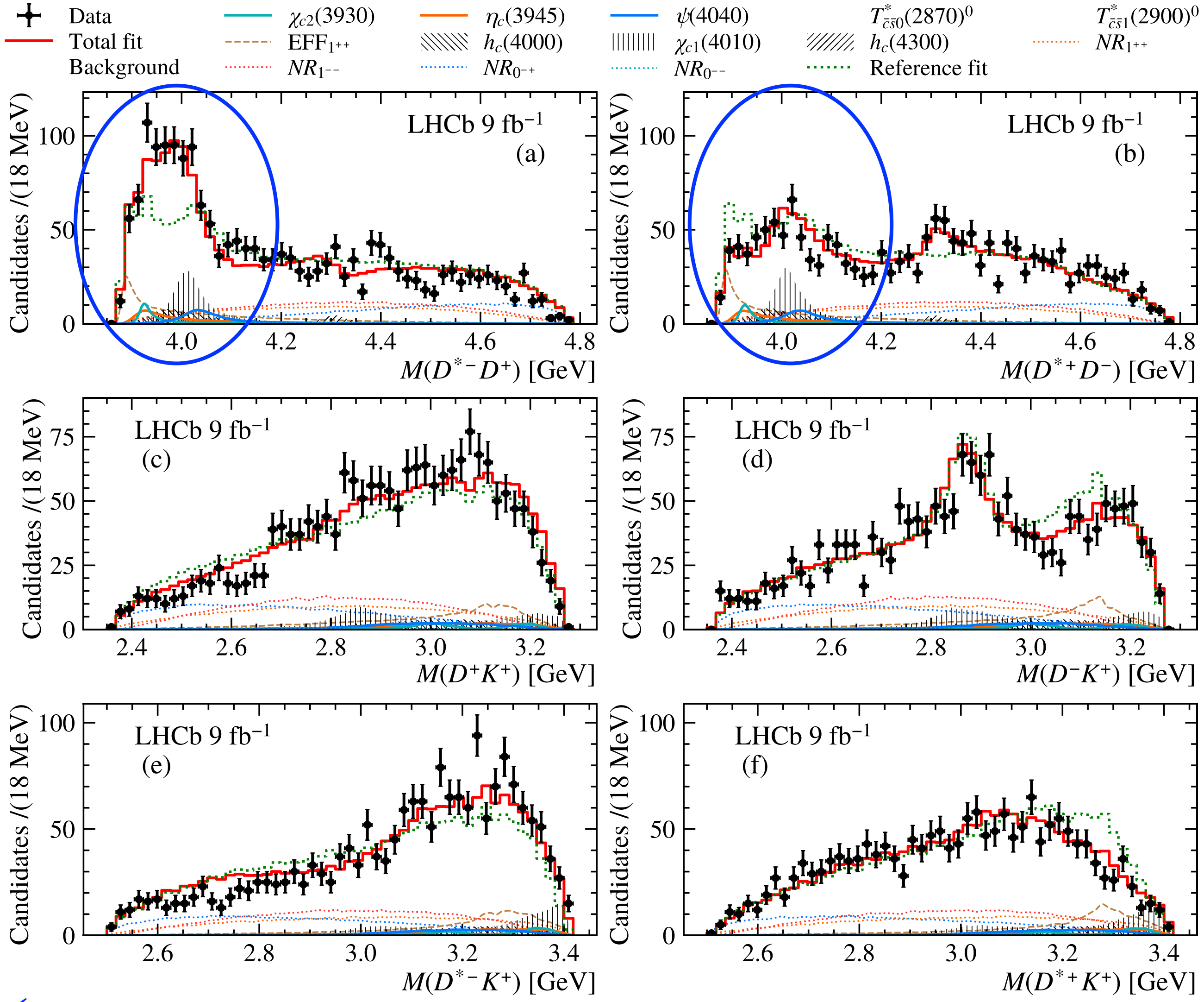
☐ Other resonances: Breit-Wigner

☐ Nonresonant contributions to $D^{*\pm}D^{\mp}$:
$f_R(m) = e^{(\alpha+\beta i)(m^2-m_0^2)}$ for $NR_{0^{-+}}$; otherwise $f_R(m) = 1$

$B^+ \to D^{*\pm} D^{\mp} K^+$: fit results

[arXiv: 2406.03156]

- All components in baseline fit have significance $> 5\sigma$

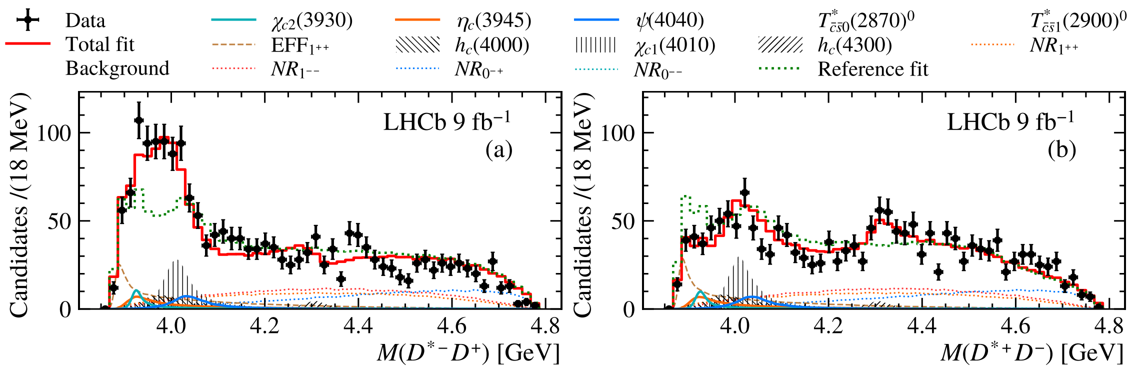


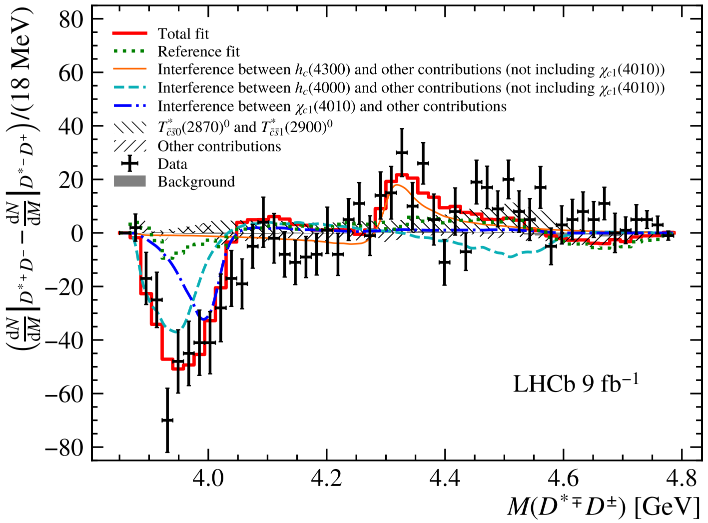
Component	$J^{P(C)}$
$\mathrm{EFF}_{1^{++}}$	1^{++}
$\eta_c(3945)$	0^{-+}
$\chi_{c2}(3930)$ †	2^{++}
$h_c(4000)$	1^{+-}
$\chi_{c1}(4010)$	1^{++}
$\psi(4040)$ †	1^{--}
$h_c(4300)$	1^{+-}
$T^*_{\bar{c}\bar{s}0}(2870)^0$ †	0^+
$T^*_{\bar{c}\bar{s}1}(2900)^0$ †	1^-
$\mathrm{NR}_{1^{--}}(D^{*\mp}D^\pm)$	1^{--}
$\mathrm{NR}_{0^{--}}(D^{*\mp}D^\pm)$	0^{--}
$\mathrm{NR}_{1^{++}}(D^{*\mp}D^\pm)$	1^{++}
$\mathrm{NR}_{0^{-+}}(D^{*\mp}D^\pm)$	0^{-+}

*Fit fractions in paper

✓clear different interference behaviors

$B^+ \to D^{*\pm} D^{\mp} K^+$: $D^{*\pm} D^{\mp}$ system





- Four charmonium(-like) are observed decaying to $D^{*\pm}D^{\mp}$
- At lease three of them are first observation

Component	$J^{P(C)}$
$\mathrm{EFF}_{1^{++}}$	1^{++}
$\chi_{c2}(3930)^{\dagger}$	2^{++}
$\psi(4040)^{\dagger}$	1^{--}
$\mathrm{NR}_{1^{--}}(D^{*\mp}D^{\pm})$	1^{--}
$\mathrm{NR}_{0^{--}}(D^{*\mp}D^{\pm})$	0^{--}
$\mathrm{NR}_{1^{++}}(D^{*\mp}D^{\pm})$	1^{++}
$\mathrm{NR}_{0^{-+}}(D^{*\mp}D^{\pm})$	0^{-+}

	This work		$c\bar{c}$ prediction [34]	
X(3940)?	$\eta_c(3945)$	$J^{PC} = 0^{-+}$	$\eta_c(3S)$	$J^{PC} = 0^{-+}$
	$m_0 = 3945^{+28}_{-17}{}^{+37}_{-28}$	$\Gamma_0 = 130^{+92}_{-49}{}^{+101}_{-70}$	$m_0 = 4064$	$\Gamma_0 = 80$
new	$h_c(4000)$	$J^{PC} = 1^{+-}$	$h_c(2P)$	$J^{PC} = 1^{+-}$
	$m_0 = 4000^{+17}_{-14}{}^{+29}_{-22}$	$\Gamma_0 = 184^{+71}_{-45}{}^{+97}_{-61}$	$m_0 = 3956$	$\Gamma_0 = 87$
	$\chi_{c1}(4010)$	$J^{PC} = 1^{++}$	$\chi_{c1}(2P)$	$J^{PC} = 1^{++}$
	$m_0 = 4012.5^{+3.6}_{-3.9}{}^{+4.1}_{-3.7}$	$\Gamma_0 = 62.7^{+7.0}_{-6.4}{}^{+6.4}_{-6.6}$	$m_0 = 3953$	$\Gamma_0 = 165$
	$h_c(4300)$	$J^{PC} = 1^{+-}$	$h_c(3P)$	$J^{PC} = 1^{+-}$
	$m_0 = 4307.3^{+6.4}_{-6.6}{}^{+3.3}_{-4.1}$	$\Gamma_0 = 58^{+28}_{-16}{}^{+28}_{-25}$	$m_0 = 4318$	$\Gamma_0 = 75$

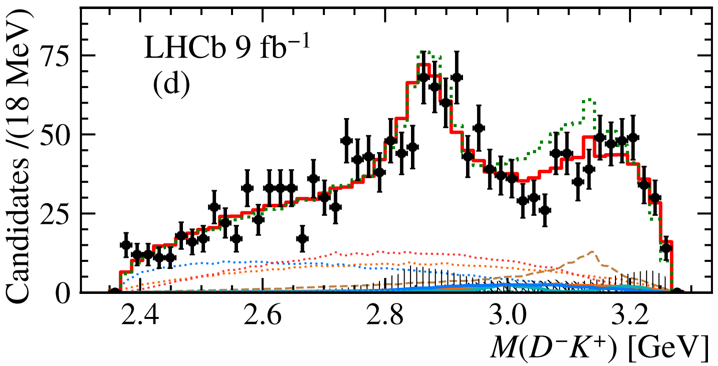
GI model
hep-ph/0505002

- Significances for those charmonium(-like) states >6.1σ
- J^{PC} for each state is determined to be >5.7σ better than other hypotheses
- $\chi_{c1}(4010)$ could be the partner of $\chi_{c1}(3872)$

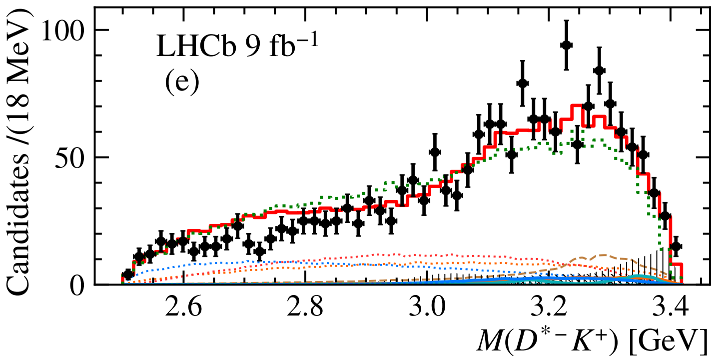
$B^+ \to D^{*\pm}D^{\mp}K^+$: $T^*_{\bar{c}\bar{s}}$ states

[arXiv: 2406.03156]

➢ $B^+ \to D^{*+}D^-K^+$



➢ $B^+ \to D^{*-}D^+K^+$



	Property	This work		Previous work $(B^+ \to D^+D^-K^+)$
11σ $X_0(2900)$	$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$		2866 ± 7
	$T^*_{\bar{c}\bar{s}0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	2σ ↔	57 ± 13
9.2σ $X_1(2900)$	$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$		2904 ± 5
	$T^*_{\bar{c}\bar{s}1}(2900)^0$ width [MeV]	$92 \pm 16 \pm 16$		110 ± 12
	$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})$	$(4.5\,^{+0.6}_{-0.8}\,^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$		$(1.2 \pm 0.5) \times 10^{-5}$
	$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})$	$(3.8\,^{+0.7}_{-1.0}\,^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$		$(6.7 \pm 2.3) \times 10^{-5}$
	$\frac{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})}{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	↔	0.18 ± 0.05

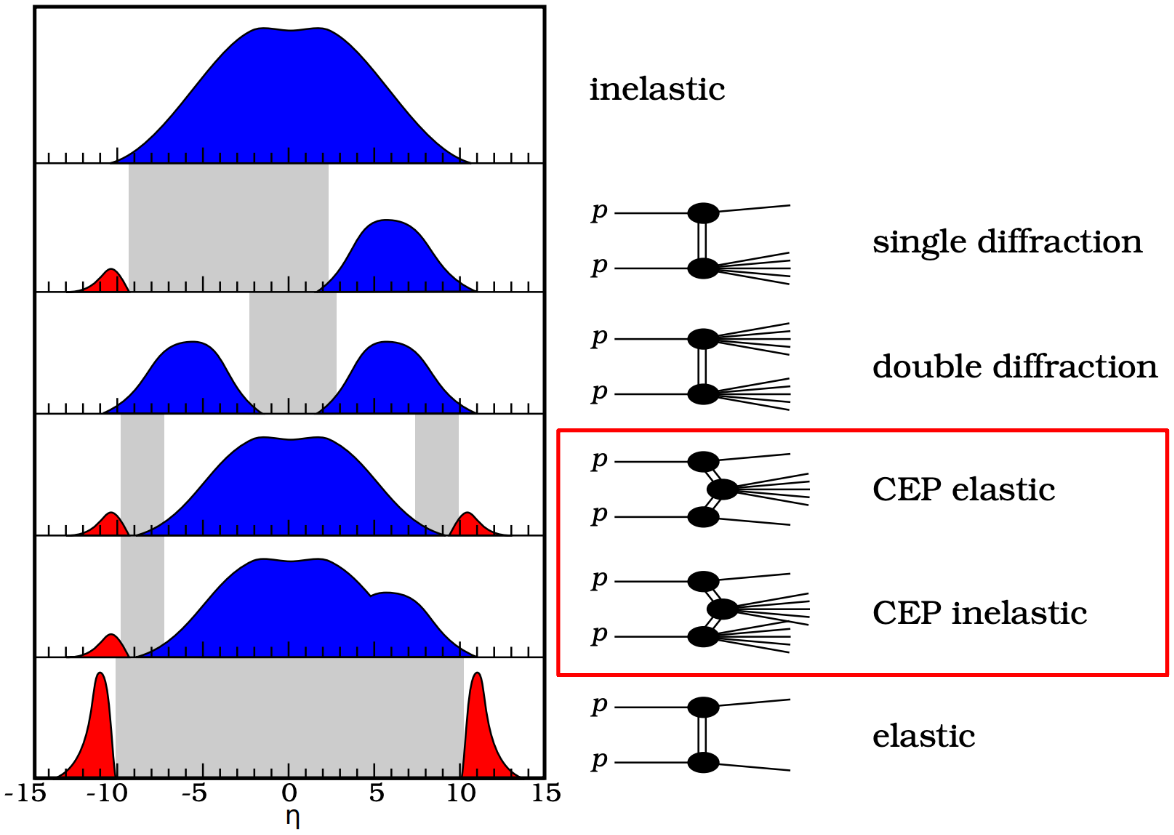
[PRL 125 (2020) 242001]
[PRD 102 (2020) 112003]

✓$T^*_{\bar{c}\bar{s}0}(2870)^0 \to D^{*-}K^+$ forbidden

✓$\mathcal{B}(T^*_{\bar{c}\bar{s}1}(2900)^0 \to D^{*-}K^+)/\mathcal{B}(T^*_{\bar{c}\bar{s}1}(2900)^0 \to D^-K^+) < 0.21$ @ 95% CL

Central exclusive production (CEP)

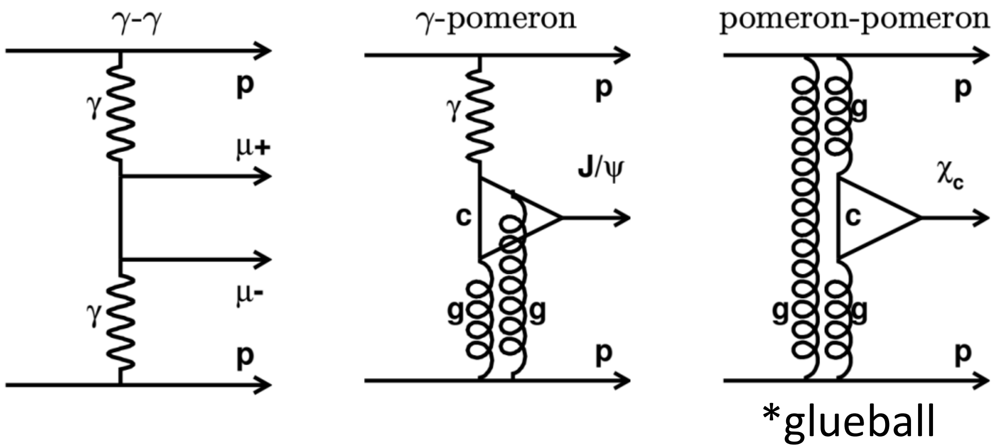
- Study *J/ψϕ resonances in CEP*



✓ Experimentally clean even @LHC

✓ Spin-parity option narrowed down

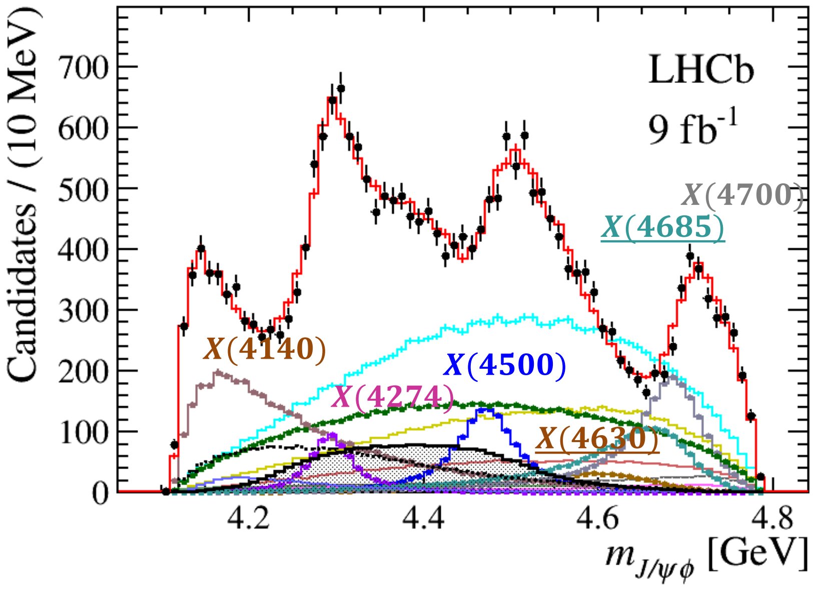
✗ Much smaller rate



X in $B^+ \to J/\psi\phi K^+$

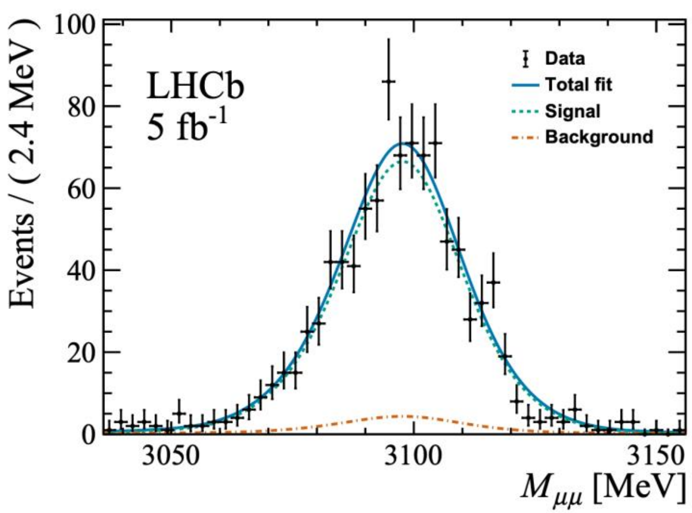
[PRL 127 (2021) 082001]

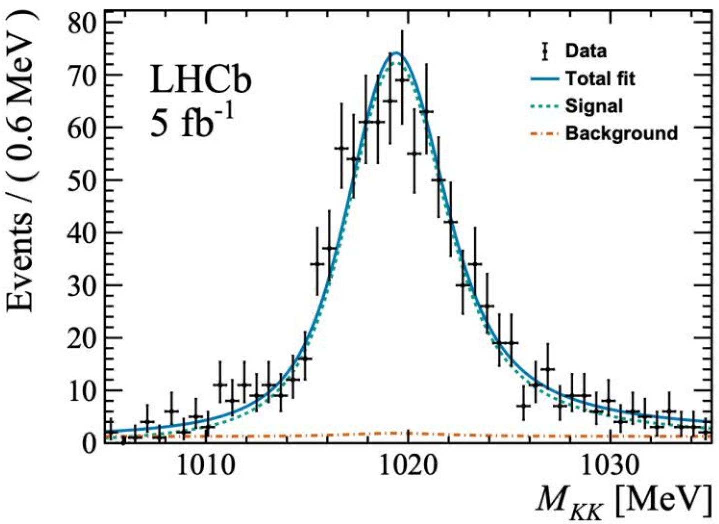
$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+18}_{-110}$	$174 \pm 27\,^{+134}_{-73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5\,^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6\,^{+10}_{-8}$	$5.6 \pm 0.7\,^{+2.4}_{-0.6}$
$X(4700)$	17 (18)	$4694 \pm 4\,^{+16}_{-3}$	$87 \pm 8\,^{+16}_{-6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3\,^{+8}_{-10}$
$X(4140)$	13 (16)	$4118 \pm 11\,^{+19}_{-36}$	$162 \pm 21\,^{+24}_{-49}$	$17 \pm 3\,^{+19}_{-6}$
$X(4274)$	18 (18)	$4294 \pm 4\,^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5\,^{+0.8}_{-0.4}$
$X(4685)$	15 (15)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$	$7.2 \pm 1.0\,^{+4.0}_{-2.0}$
All $Z_{cs}(1^+)$				$25 \pm 5\,^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$



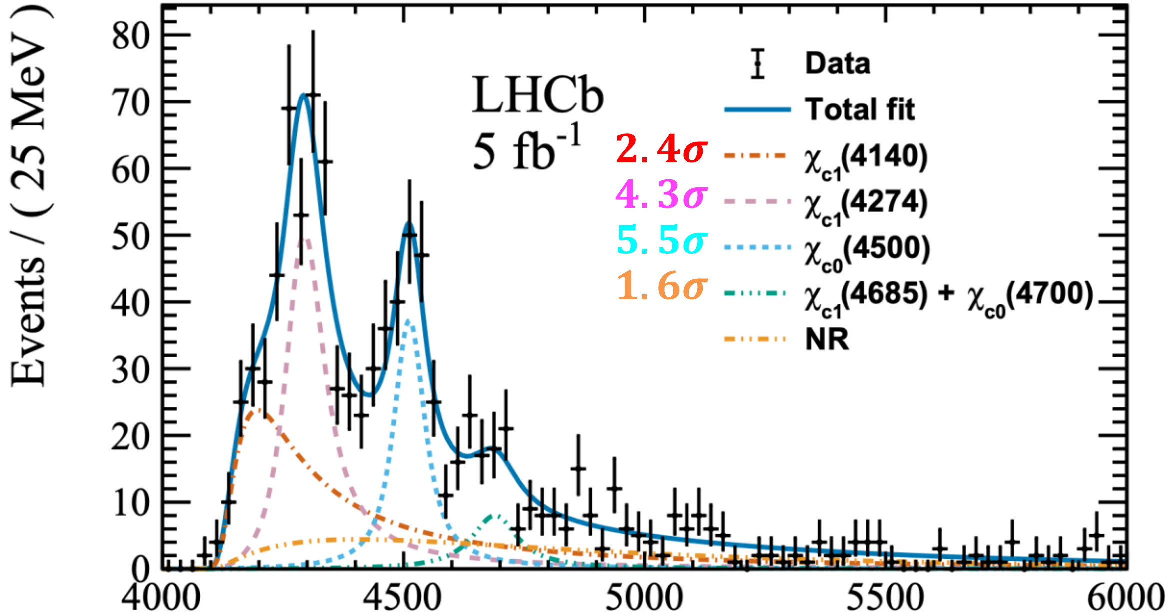
$X \to J/\psi\phi$ in CEP

[arXiv: 2407.14301]



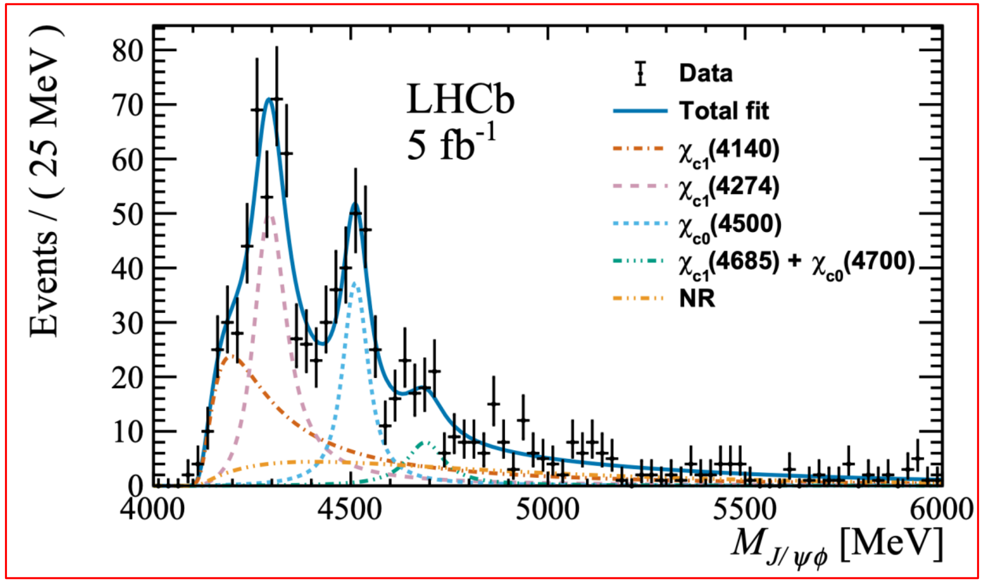


$N = 989$
purity $= (93.0 \pm 0.5)\%$

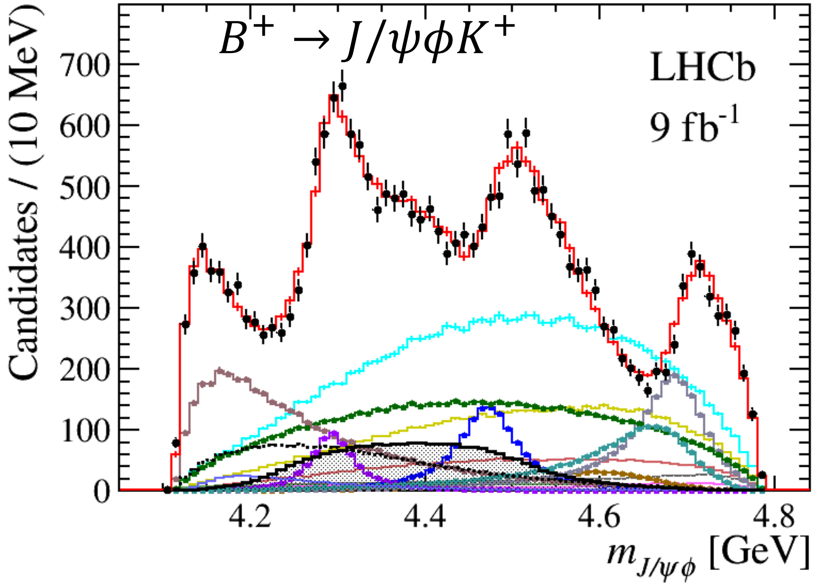


First exotic hadron measurement in CEP!

[arXiv: 2407.14301]



[PRL 127 (2021) 082001]



- Mass & width measurements: slightly higher mass of $X(4500)$

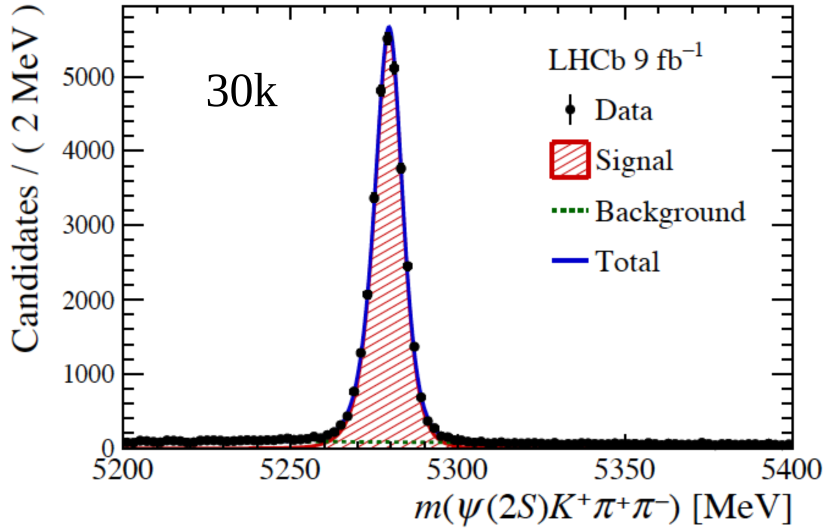
Parameter (MeV)	This Letter	Ref. [12]
$M_{\chi_{c1}(4274)}$	$4298 \pm 6 \pm 9$	$4294 \pm 4^{+3}_{-6}$
$\Gamma_{\chi_{c1}(4274)}$	$92^{+22}_{-18} \pm 57$	$53 \pm 5 \pm 5$
$M_{\chi_{c0}(4500)}$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$4474 \pm 3 \pm 3$
$\Gamma_{\chi_{c0}(4500)}$	$65^{+20}_{-16} \pm 32$	$77 \pm 6^{+10}_{-8}$

- Cross-section measurements:

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

$B^+ \to \psi(2S)K^+\pi^+\pi^-$: amplitude analysis [arXiv: 2407.12475]

- Can study $K^+\pi^+\pi^-$ system, crucial for NP studies of $B \to K\pi\pi(\gamma/\mu\mu)$
- Can also study charmonium-like exotic states
- With ~1000 signal decays, Belle only studied the $K^+\pi^+\pi^-$ system [PRD 83 (2011) 032005]
- LHCb performed the first full amplitude analysis on this decay
- Baseline fit contributions
  - 6 K'^+ states
  - 11 exotic states: most are very broad
  - Exotic states improve $\chi^2_{7\mathrm{D}}/\mathrm{ndf}$ from 2.05 to 1.21

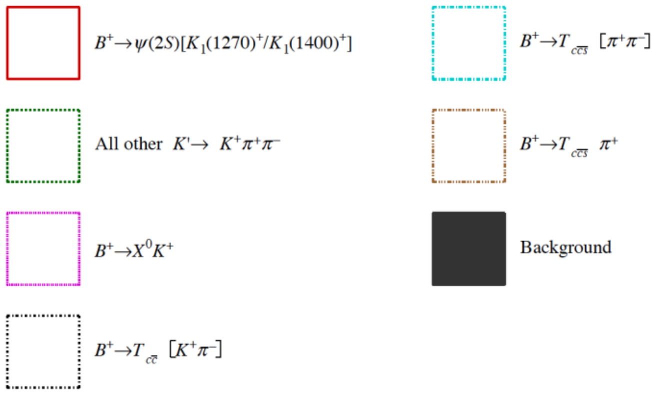


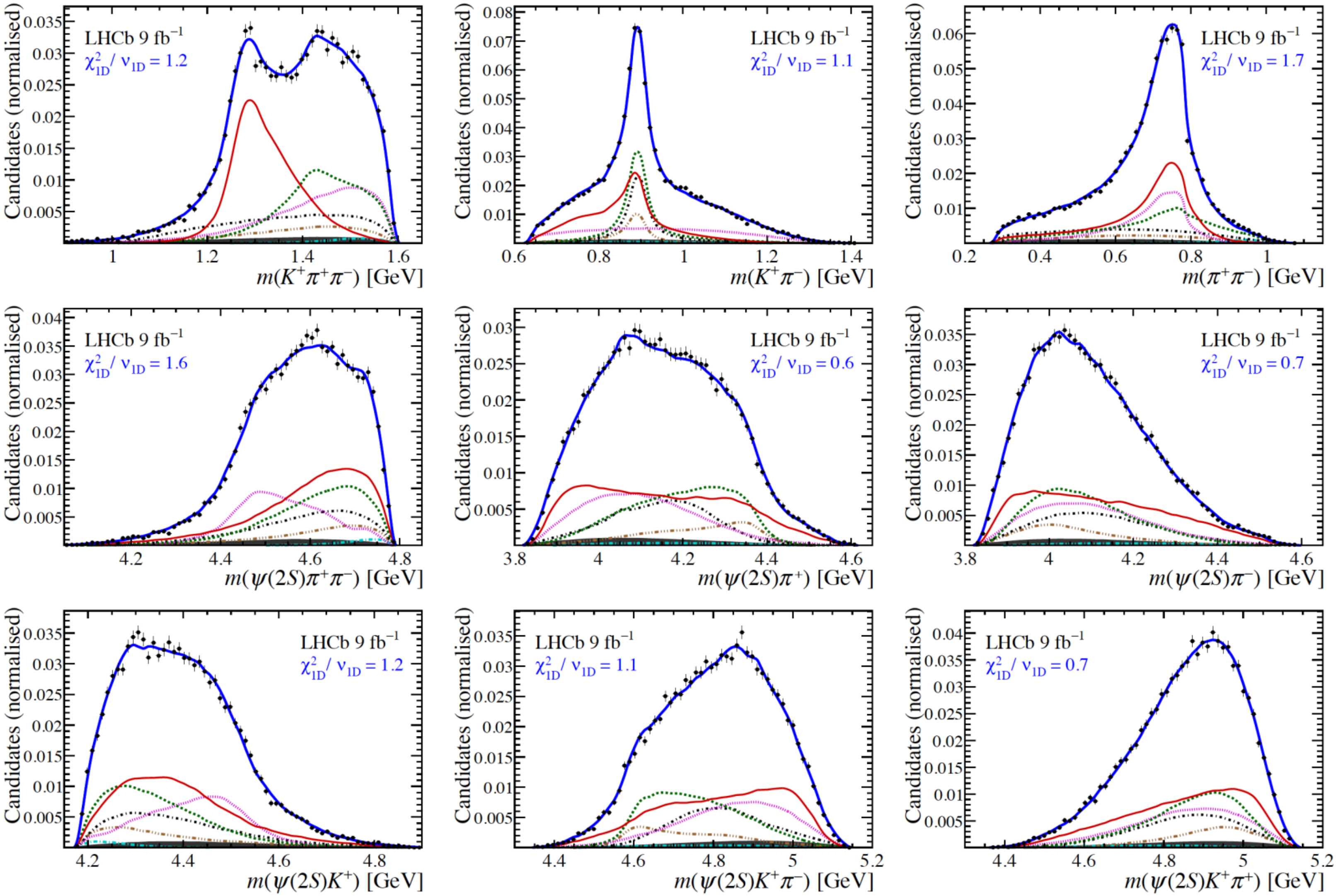
Decay channel	Fit fraction [%]
$B^+ \to \chi_{c0}(4475)K^+$	$18.45 \pm 1.31 \pm 2.92$
$B^+ \to \psi(2S)\,K^*(1680)^+$	$8.15 \pm 1.31 \pm 3.51$
$B^+ \to \psi(2S)\,K_1(1270)^+$	$7.60 \pm 0.85 \pm 1.35$
$B^+[P] \to \psi(2S)\,K_1(1270)^+$	$7.52 \pm 0.60 \pm 1.08$
$B^+[D] \to \psi(2S)\,K_1(1270)^+$	$6.81 \pm 0.45 \pm 1.18$
$B^+ \to \psi(2S)\,K_1(1400)^+$	$5.78 \pm 0.62 \pm 0.92$
$B^+ \to \psi(2S)\,K(1460)^+$	$5.26 \pm 0.48 \pm 0.87$
$B^+[P] \to T_{c\bar{c}1}(4200)^+\,K^*(892)^0$	$4.60 \pm 0.54 \pm 2.17$
$B^+ \to T_{c\bar{c}\bar{s}1}(4600)^0\pi^+$	$4.42 \pm 0.98 \pm 2.17$

......

Fit projections

- Fit quality is acceptable, 7D $\chi^2/\mathrm{ndf} = 1.21$
- Resonances are generally broad





Exotic contributions

- 4 $X^0 \to \psi(2S)\pi^+\pi^-$ states are identified
  - Main decay mode is $\boldsymbol{\psi(2S)\rho^0}$
  - Similar but broader that the states observed in $B^+ \to \boldsymbol{J/\psi\phi}K^+$
  - They might not be the same, $\psi(2S)\rho^0$ has I=1, $J/\psi\phi$ has I=0

Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	Res. PDG	m_0 [MeV]	Γ_0 [MeV]
$\chi_{c0}(4475)$	0^+	$4475\pm 7\pm12$	$231\pm19\pm32$	$\chi_{c0}(4500)$	4474 ± 4	77^{+12}_{-10}
$\chi_{c1}(4650)$	1^+	$4653\pm14\pm27$	$227\pm26\pm22$	$\chi_{c1}(4685)$	4684^{+15}_{-17}	126 ± 40
$\chi_{c0}(4710)$	0^+	$4710\pm 4\pm5$	$64\pm 9\pm10$	$\chi_{c0}(4700)$	4694^{+16}_{-5}	87^{+18}_{-10}
$\eta_{c1}(4800)$	1^-	$4785\pm37\pm119$	$457\pm93\pm157$	$X(4630)$	4626^{+24}_{-110}	174^{+140}_{-80}
$T^*_{c\bar{c}1}(4055)^+$	1^-	4054 (fixed)	45 (fixed)	$T_{c\bar{c}}(4055)^+$	4054 ± 3.2	45 ± 13
$T_{c\bar{c}1}(4200)^+$	1^+	$4257\pm11\pm17$	$308\pm20\pm32$	$T_{c\bar{c}1}(4200)^+$	4196^{+35}_{-32}	370^{+100}_{-150}
$T_{c\bar{c}1}(4430)^+$	1^+	$4468\pm21\pm80$	$251\pm42\pm82$	$T_{c\bar{c}1}(4430)^+$	4478^{+15}_{-18}	181 ± 31
$T_{c\bar{c}\bar{s}1}(4600)^0$	1^+	$4578\pm10\pm18$	$133\pm28\pm69$			
$T_{c\bar{c}\bar{s}1}(4900)^0$	1^+	$4925\pm22\pm47$	$255\pm55\pm127$			
$T^*_{c\bar{c}\bar{s}1}(5200)^0$	1^-	$5225\pm86\pm181$	$226\pm76\pm374$			
$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	$T_{c\bar{c}\bar{s}1}(4000)^+$	4003^{+7}_{-15}	131 ± 30

States in $B^+ \to J/\psi\phi K^+$

Exotic contributions

- 3 $T_{c\bar{c}}^{(*)} \rightarrow \psi(2S)\pi$ states are identified
  - Confirmed $\boldsymbol{Z_c(4430)}^+$ seen in $\bar{B}^0 \rightarrow \psi(2S)\pi^+K^-$
  - Confirmed $\boldsymbol{Z_c(4200)}^+$ seen in $\bar{B}^0 \rightarrow J/\psi\pi^+K^-$, and $J^P = 1^+$ is determined for the 1st time
  - $T_{c\bar{c}}(4055)^+$ seen in $e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$ is also needed

Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	Res. PDG	m_0 [MeV]	Γ_0 [MeV]
$\chi_{c0}(4475)$	0^+	$4475 \pm 7 \pm 12$	$231 \pm 19 \pm 32$	$\chi_{c0}(4500)$	4474 ± 4	77^{+12}_{-10}
$\chi_{c1}(4650)$	1^+	$4653 \pm 14 \pm 27$	$227 \pm 26 \pm 22$	$\chi_{c1}(4685)$	4684^{+15}_{-17}	126 ± 40
$\chi_{c0}(4710)$	0^+	$4710 \pm 4 \pm 5$	$64 \pm 9 \pm 10$	$\chi_{c0}(4700)$	4694^{+16}_{-5}	87^{+18}_{-10}
$\eta_{c1}(4800)$	1^-	$4785 \pm 37 \pm 119$	$457 \pm 93 \pm 157$	$X(4630)$	4626^{+24}_{-110}	174^{+140}_{-80}
$T^*_{c\bar{c}1}(4055)^+$	1^-	4054 (fixed)	45 (fixed)	$T_{c\bar{c}}(4055)^+$	4054 ± 3.2	45 ± 13
$T_{c\bar{c}1}(4200)^+$	1^+	$4257 \pm 11 \pm 17$	$308 \pm 20 \pm 32$	$T_{c\bar{c}1}(4200)^+$	4196^{+35}_{-32}	370^{+100}_{-150}
$T_{c\bar{c}1}(4430)^+$	1^+	$4468 \pm 21 \pm 80$	$251 \pm 42 \pm 82$	$T_{c\bar{c}1}(4430)^+$	4478^{+15}_{-18}	181 ± 31
$T_{c\bar{c}\bar{s}1}(4600)^0$	1^+	$4578 \pm 10 \pm 18$	$133 \pm 28 \pm 69$			
$T_{c\bar{c}\bar{s}1}(4900)^0$	1^+	$4925 \pm 22 \pm 47$	$255 \pm 55 \pm 127$			
$T^*_{c\bar{c}\bar{s}1}(5200)^0$	1^-	$5225 \pm 86 \pm 181$	$226 \pm 76 \pm 374$			
$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	$T_{c\bar{c}\bar{s}1}(4000)^+$	4003^{+7}_{-15}	131 ± 30

Exotic contributions

- 3 new $T_{c\bar{c}\bar{s}} \to \psi(2S)K\pi$ states are observed
- $\psi(2S)K$ mass above $Z_{cs}(4000)^+$, only tail of $Z_{cs}(4000)^+$ can contribute

Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	Res. PDG	m_0 [MeV]	Γ_0 [MeV]
$\chi_{c0}(4475)$	0^+	$4475\pm 7\pm12$	$231\pm19\pm32$	$\chi_{c0}(4500)$	4474 ± 4	77^{+12}_{-10}
$\chi_{c1}(4650)$	1^+	$4653\pm14\pm27$	$227\pm26\pm22$	$\chi_{c1}(4685)$	4684^{+15}_{-17}	126 ± 40
$\chi_{c0}(4710)$	0^+	$4710\pm 4\pm5$	$64\pm 9\pm10$	$\chi_{c0}(4700)$	4694^{+16}_{-5}	87^{+18}_{-10}
$\eta_{c1}(4800)$	1^-	$4785\pm37\pm119$	$457\pm93\pm157$	$X(4630)$	4626^{+24}_{-110}	174^{+140}_{-80}
$T^*_{c\bar{c}1}(4055)^+$	1^-	4054 (fixed)	45 (fixed)	$T_{c\bar{c}}(4055)^+$	4054 ± 3.2	45 ± 13
$T_{c\bar{c}1}(4200)^+$	1^+	$4257\pm11\pm17$	$308\pm20\pm32$	$T_{c\bar{c}1}(4200)^+$	4196^{+35}_{-32}	370^{+100}_{-150}
$T_{c\bar{c}1}(4430)^+$	1^+	$4468\pm21\pm80$	$251\pm42\pm82$	$T_{c\bar{c}1}(4430)^+$	4478^{+15}_{-18}	181 ± 31
$T_{c\bar{c}\bar{s}1}(4600)^0$	1^+	$4578\pm10\pm18$	$133\pm28\pm69$			
$T_{c\bar{c}\bar{s}1}(4900)^0$	1^+	$4925\pm22\pm47$	$255\pm55\pm127$			
$T^*_{c\bar{c}\bar{s}1}(5200)^0$	1^-	$5225\pm86\pm181$	$226\pm76\pm374$			
$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	$T_{c\bar{c}\bar{s}1}(4000)^+$	4003^{+7}_{-15}	131 ± 30

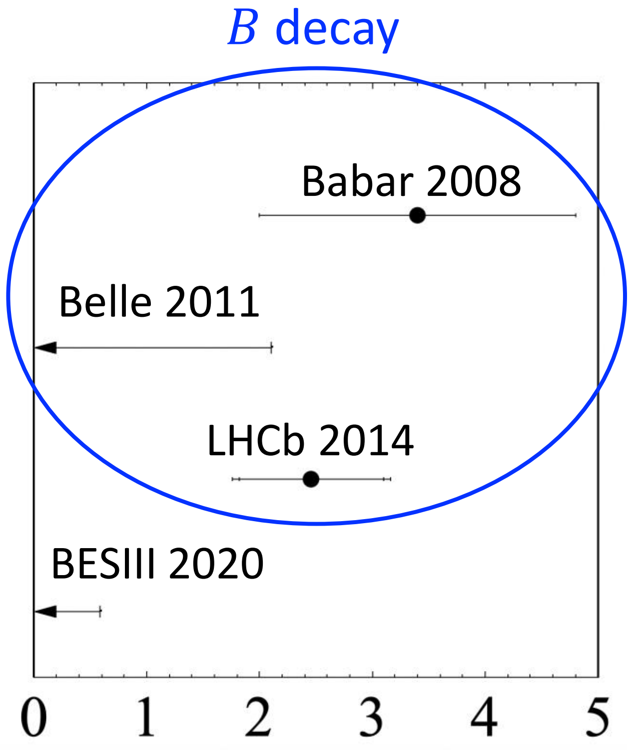
new

Radiative decays of $\chi_{c1}(3872)$

[arXiv: 2406.17006]

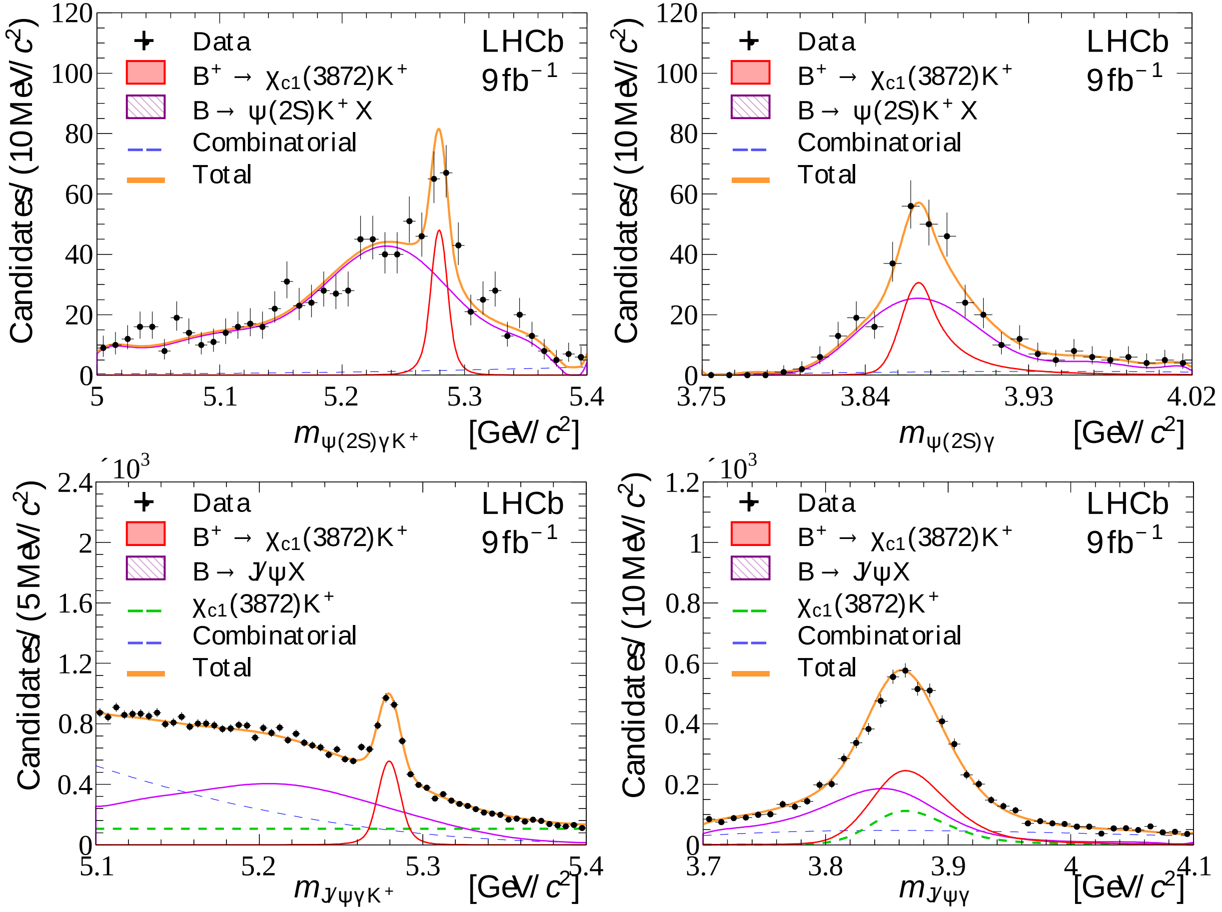
- Nature of $\chi_{c1}(3872)$ still under debate, while study of radiative decays provides a way to probe it
- Only evidence of $\chi_{c1}(3872) \to \psi(2S)\gamma$ was seen experimentally before

Reference			$\mathscr{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$	
T. Barnes and S. Godfrey	$\gtrsim 1$	[67]	5.8	$c\bar{c}$
T. Barnes, S. Godfrey and S. Swanson		[69]	2.6	$c\bar{c}$
F. De Fazio		[84]	(1.64 ± 0.25)	$c\bar{c}$
B.-Q. Li and K. T. Chao		[85]	1.3	$c\bar{c}$
Y. Dong *et al.*		[86]	$1.3 - 5.8$	$c\bar{c}$
A. M. Badalian *et al.*		[87]	(0.8 ± 0.2)	$c\bar{c}$
J. Ferretti, G. Galata and E. Santopinto		[88]	6.4	$c\bar{c}$
A. M. Badalian, Yu. A. Simonov and B. L. G. Bakker		[89]	2.4	$c\bar{c}$
W. J. Deng *et al.*		[90]	1.3	$c\bar{c}$
F. Giacosa, M. Piotrowska and S. Goito		[71]	5.4	$c\bar{c}/\nu c$
E. S. Swanson	$\ll 1$	[81]	0.38 %	$D\bar{D}^*$
Y. Dong *et al.*		[86]	0.33 %	$D\bar{D}^*$
D. P. Rathaud and A. K. Rai		[91]	0.25	$D\bar{D}^*$
R. F. Lebed and S. R. Martinez		[92]	0.33 %	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa		[93]	3.6 %	$D\bar{D}^*$
F.-K. Guo *et al.*		[82]	$0.21(g_2'/g_2)^2$	$D\bar{D}^*$
D. A.-S. Molnar, R. F. Luiz and R. Higa	mixed	[83]	$2 - 10$	$D\bar{D}^*$
E. Cincioglu *et al.*		[94]	< 4	$D\bar{D}^*$
S. Takeuchi, M. Takizawa and K. Shimizu		[95]	$1.1 - 3.4$	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa		[93]	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$



Radiative decays of $\chi_{c1}(3872)$ (cont.)

- Update at LHCb using $B^+ \to \chi_{c1}(3872)K^+$ decay with 9 fb^{-1} Run1+Run2 data



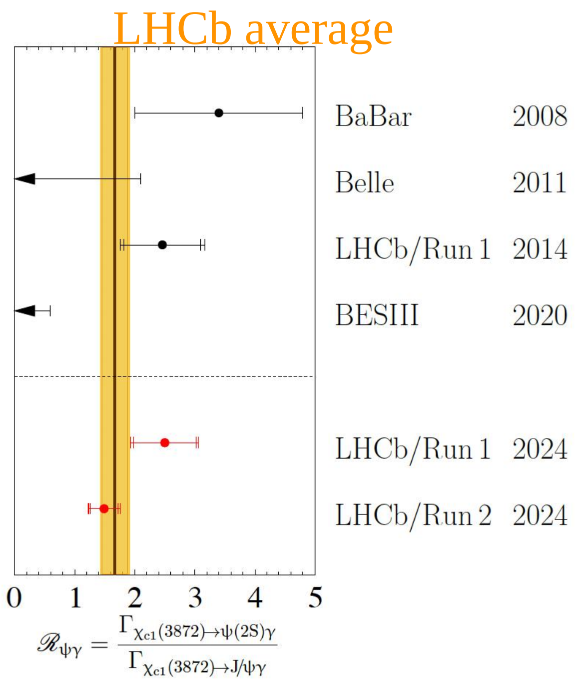
$$\mathscr{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04 \quad (15\%)$$

LHCb meets theory workshop

$$\chi_{c1}(3872) \to \psi(2S)\gamma$$

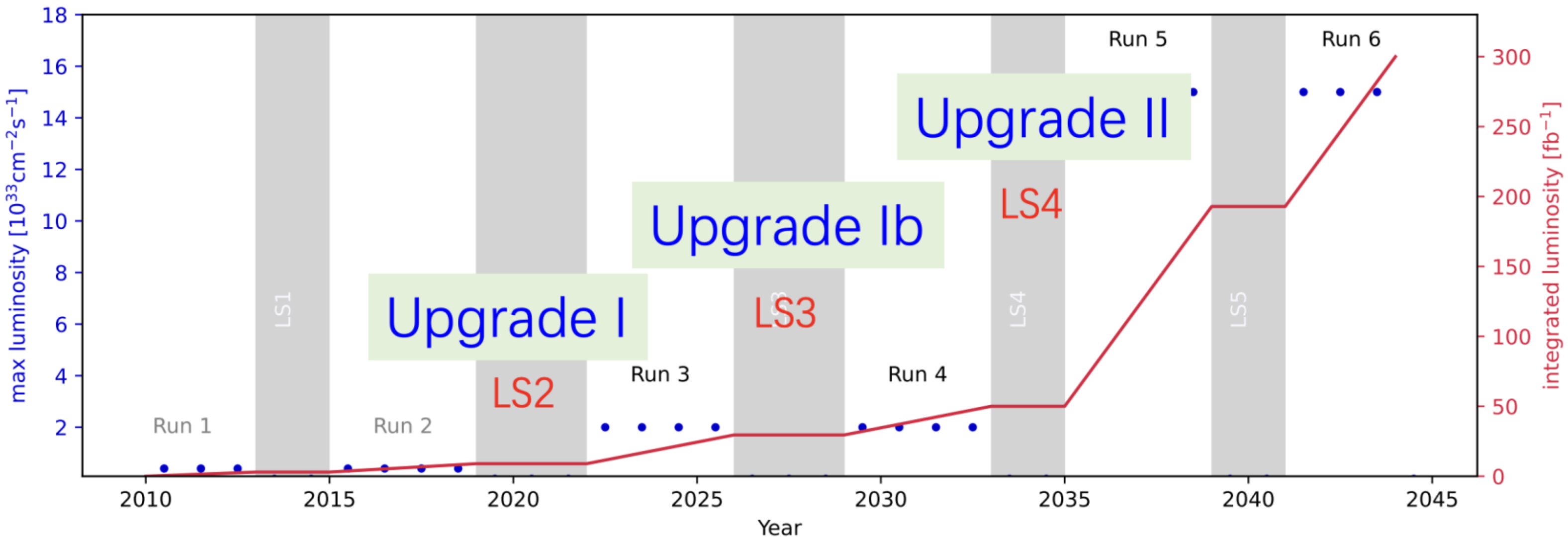
Run1: $N = 40 \pm 8$; $\mathbf{5.3\sigma}$

Run2: $N = 63 \pm 10$; $\mathbf{6.7\sigma}$



Summary and prospects

- LHCb keeps making important contributions to heavy hadron spectroscopy, both for conventional or exotic hadrons
- In Run 3, the upgraded LHCb detector and an improved software-only trigger system will be implemented



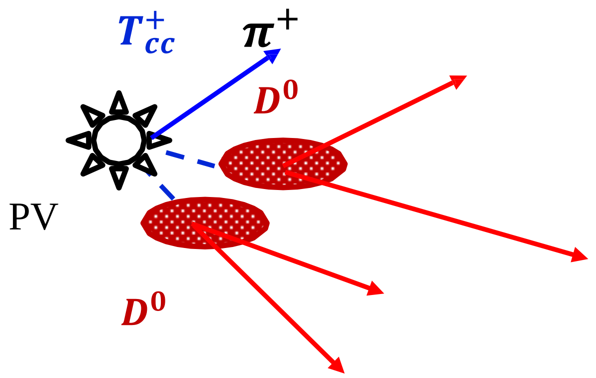
More exciting results are to come!
More data, more chances & challenges!

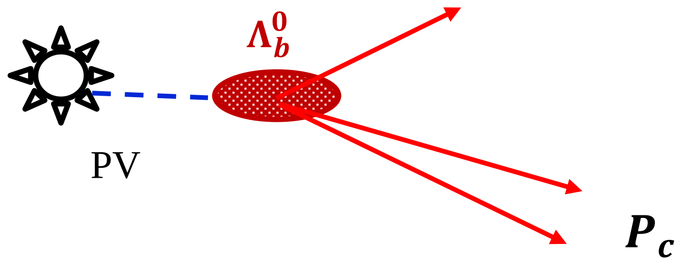
BACKUP

Two methods for spectroscopy

- Direct production in pp collisions
  - Combine a heavy flavour hadron with one or more light particles
  - Pros: High statistics, in principle can study all states
  - Cons: Large combinatorial background, hard to determine J^P

- Production by a heavier particle decay
  - Usually with amplitude analysis
  - Pros: Low background, Better determination of J^P
  - Cons: Low cross-section, limited mass range

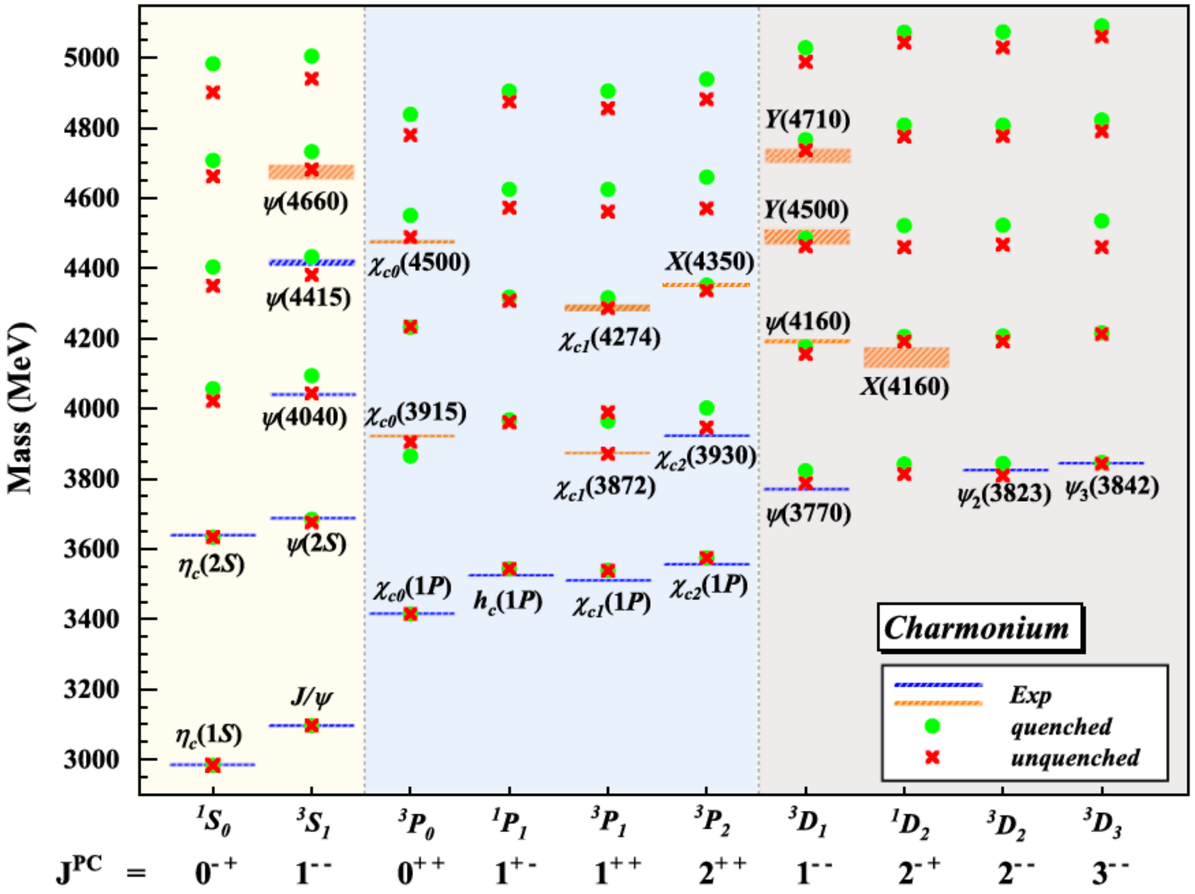




Charmonia in an unquenched quark model

Experiment results		Thereotical predictions		
		GI	Unquenched	states
$\eta_c(3945)$	$m_0 = 3945^{+28+37}_{-17-28}$	4064	4022	$\eta_c(3S)$
0^{-+}	$\Gamma_0 = 130^{+92+101}_{-49-70}$	80	62	
$h_c(4000)$	$m_0 = 4000^{+17+29}_{-14-22}$	3956	3961	$h_c(2P)$
1^{+-}	$\Gamma_0 = 130^{+92+101}_{-49-70}$	87	66	
$\chi_{c1}(4010)$	$m_0 = 4012.5^{+3.6+4.1}_{-3.9-3.7}$	3953	3990	$\chi_{c1}(2P)$
1^{++}	$\Gamma_0 = 62.7^{+7.0+6.4}_{-6.4-6.6}$	165	60	
$h_c(4300)$	$m_0 = 4307.3^{+6.4+3.3}_{-6.6-4.1}$	4318	4307	$h_c(3P)$
1^{+-}	$\Gamma_0 = 58^{+28+28}_{-16-25}$	75	25	

arXiv: 2312.10296



The LHCb Experiment

- LHCb is a dedicated flavour physics experiment at the LHC
  - $>10^4 \times$ larger b production rate than the B factories @ Υ(4S)
  - Access to all b-hadrons: B^+, B^0, B_s^0, B_c^+, b-baryons
- Can also study hadron spectroscopy and exotic states
- Acceptance optimised for forward $b\bar{b}$ production

> ➢ All results based on full or part of run-1 and run-2 datasets

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