Multi-quark states at LHCb

on behalf of LHCb Collaboration

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Crete, Greece

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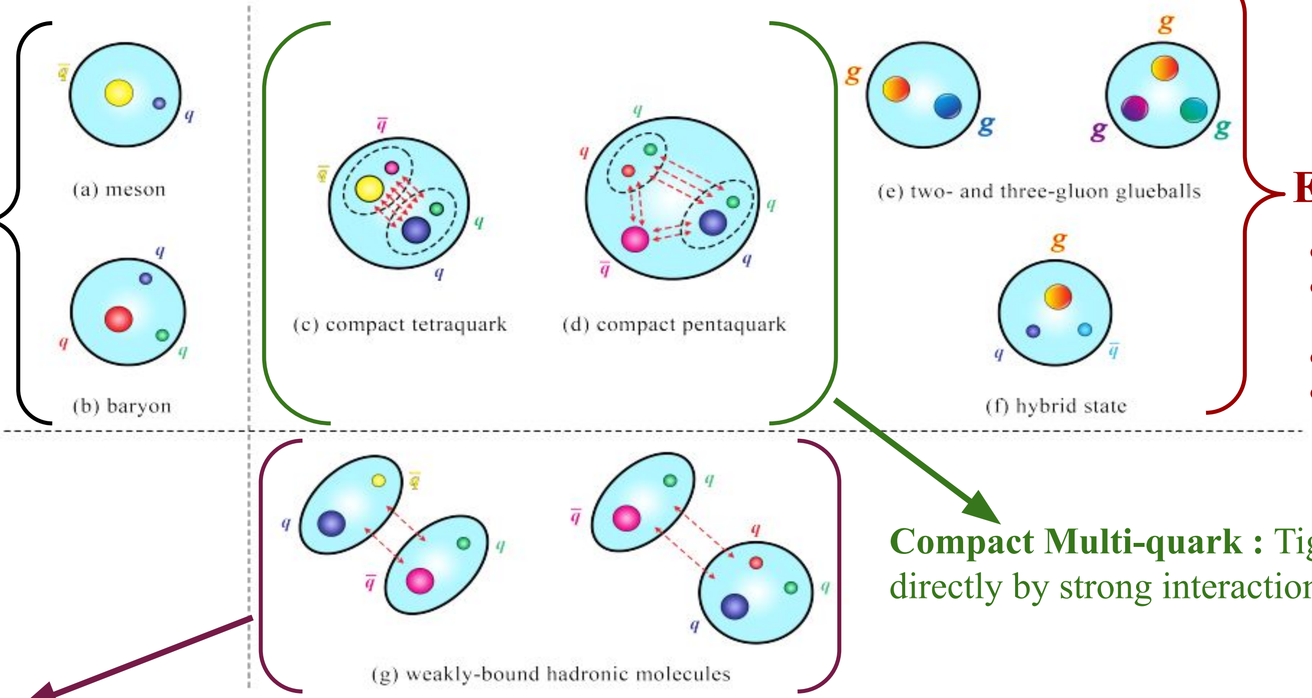
Multi-quark States

Conventional Hadrons

K, π, ρ, ω, p, n,...



Exotic Hadrons

- > 3 quarks
- Un-conventional quantum numbers
- Mass / width
- Production / decay

Compact Multi-quark : Tightly bound directly by strong interactions.

Hadronic Molecular : Weakly bound by residual strong interaction.

Rep. Prog. Phys. 86 026201(2023)

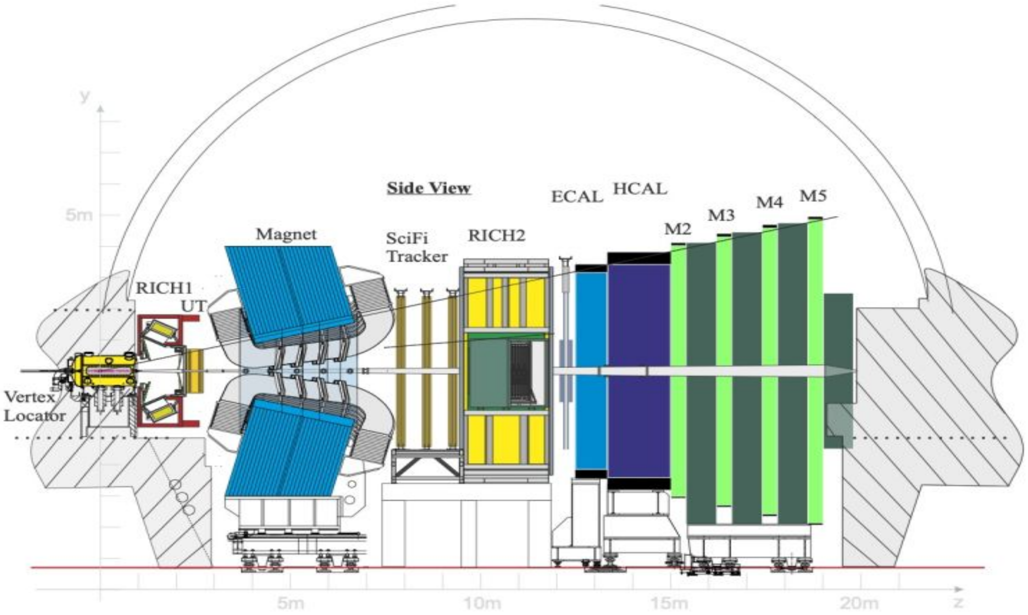
Charmonium States

- **Charmonium :** Any meson formed from a charm quark and its antiquark [$c\bar{c}$]
- **Charmonium spectrum** :
  - Conventional charmonium states : **$c\bar{c}$** (η_c(1S), J/Ψ(1S), Ψ(2S),...)
  - **$c\bar{c}$** + **other quarks** : above open charm threshold
- **Open charm states** : Either only c or only $\bar{c}$, non zero net charm content
  - Open-flavour tetraquarks: **$c\bar{s}ud$**
  - Doubly charm tetraquarks: **$c\bar{u}cd$**
- **Hidden charm states** : $c\bar{c}$ pairs, zero net charm content.
  - Fully charm tetraquarks: **$cc\bar{c}\bar{c}$**
  - Pentaquarks: **$c\bar{c}uud$, $c\bar{c}uds$**...

LHCb

arXiv:2305.10515

[JINST 3 (2008) S08005];
[IJMPA 30 (2015) 1530022]



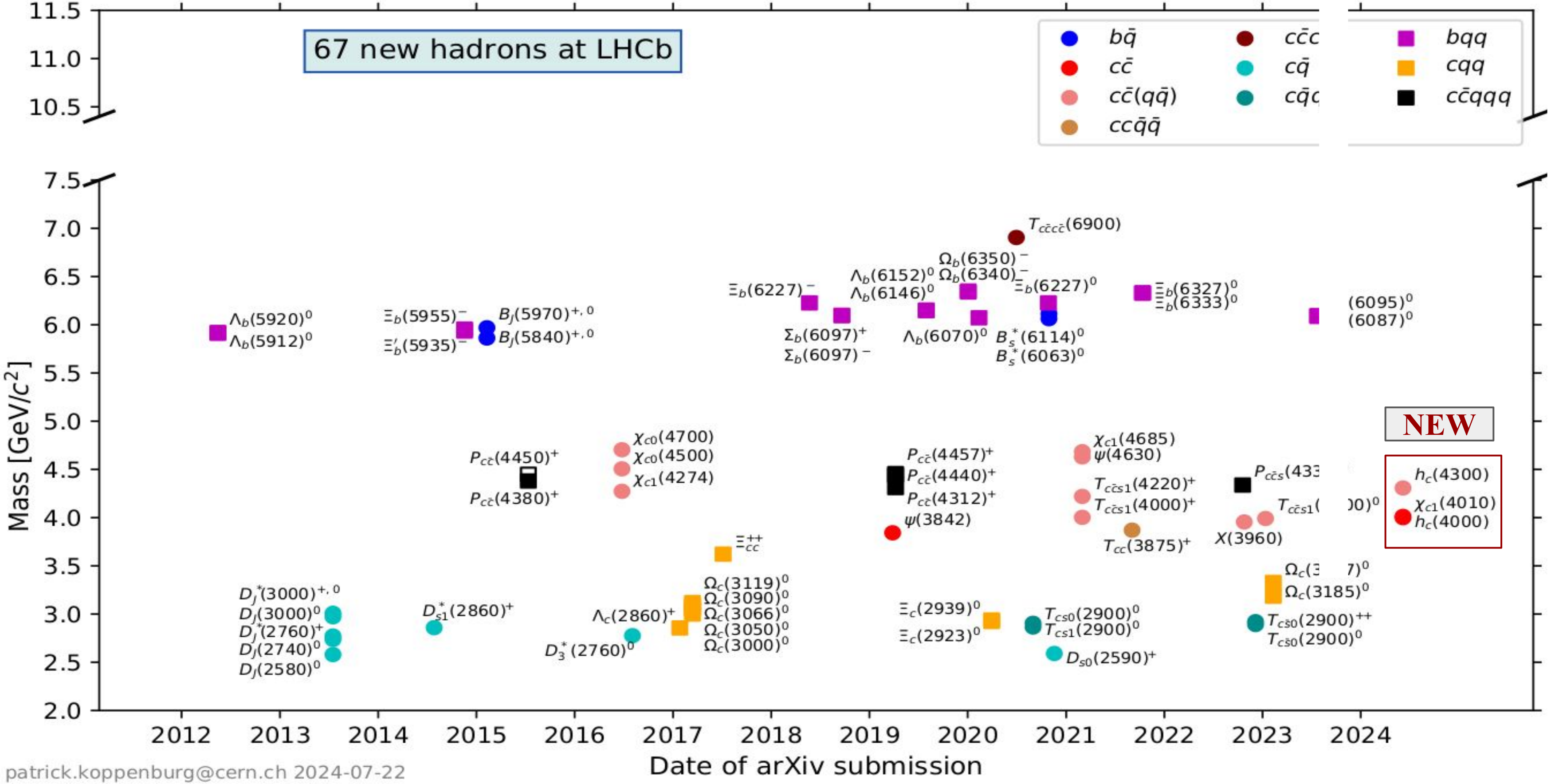
Hadron spectroscopy at LHCb

- **Largest data sample** of **b** and **c** hadrons
- Single arm forward spectrometer : $2 < \eta < 5$
- Impact parameter resolution : $\sigma_{IP} \approx 20\mu m$
- Momentum resolution $(\Delta P/P)$: $(0.5 - 1)\%$
- Efficient hadronic identification.
- PID separation K , p from π:
  - $(K \to K) \approx 95\%$ and
  - $(\pi \to K) \approx 5\%$
  - $(p \to p) \approx 95\%$ and
  - $(\pi \to p) \approx 5\%$

Run	Years	Lum. [fb^{-1}]	$\sqrt{s}$ [TeV]	$\sigma_{b\bar{b}}$ [μb]	$\sigma_{c\bar{c}}$ [μb]
1	2011-12	3.0	7,8	70	1400
2	2015-17	3.8	13	150	2400
2	2018	2.2	13		

- Excited open-flavour mesons, conventional charmonia and heavy baryons
- **Exotic heavy-hadron** spectroscopy

Multi-quark States and LHCb



Today's agenda

Pentaquarks decay to open-charm states :

- Observation of $\Lambda^0_b \to \Lambda^+_c \bar{D}^{(*)0} K^-$ and $\Lambda^0_b \to \Lambda^+_c D^*_s$ decays (EPJC 84 (2024) 575)
- First observation of $\Lambda^0_b \to \Sigma_c^{(*)++} D^{(*)-} K^-$ decays (Phys. Rev. D 110, L031104)

Charmed tetraquark states in B-decays :

- Observation of new charmonium(-like) states in $B^+ \to D^{*\pm} D^{\mp} K^+$ decays (arXiv:2406.03156)
- Probing the nature of the $\chi_{c1}(3872)$ state using radiative decays (arXiv:2406.17006)

Multiquark observations in p-p and p-Pb collisions :

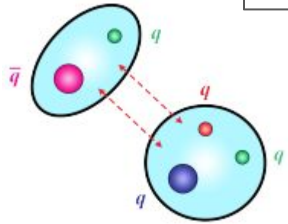
- Observation of exotic $J/\psi\phi$ resonances in diffractive processes in proton-proton collisions (arXiv:2407.14301)
- Modification of $\chi_{c1}(3872)$ and $\psi(2S)$ production in pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV (Phys. Rev. Lett. 132, 242301)

Pentaquarks decay to open- charm states

Observation of $\Lambda^0_b \to \Lambda^+_c \bar{D}^{(*)0} K^-$ and $\Lambda^0_b \to \Lambda^+_c D^{*-}_s$

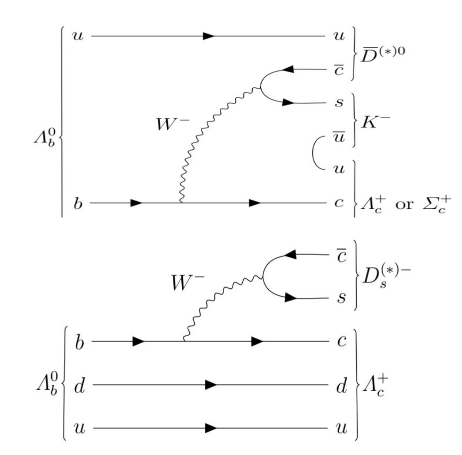
EPJC 84 (2024) 575

- Pentaquarks mass : charm-baryon & charm-meson thresholds.
- Previous observations : $[c\bar{c}]$ + light flavoured baryon
- P_c^+ ($\bar{c}$cuud) → $J/\Psi p$ ⇔ $\Lambda^+_c \bar{D}^{*0}$ and $\Lambda^+_c \bar{D}^0$ (open charm)
- No B.F predictions for 3 body double open-charm decays
- Pentaquark fit fraction :

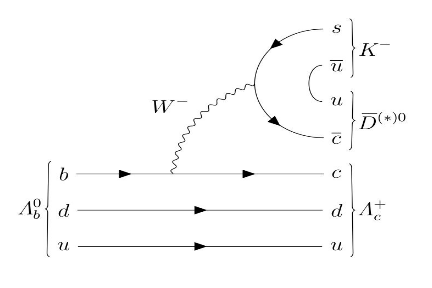


$$f_{\Lambda_c^+ \bar{D}^{(*)0}}(P_c^+) = f_{J/\psi p}(P_c^+) \cdot \frac{\mathcal{B}\left(\Lambda_b^0 \to J/\psi p K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-\right)} \cdot \frac{\mathcal{B}\left(P_c^+ \to \Lambda_c^+ \bar{D}^{(*)0}\right)}{\mathcal{B}\left(P_c^+ \to J/\psi p\right)}$$

$\Lambda^0_b \to \Lambda^+_c \bar{D}^{(*)0} K^-$



$\Lambda^0_b \to \Lambda^+_c D^{*-}_s$



Reconstruction :

- $\Lambda^+_c \to p K^- \pi^+$, $\bar{D}^0 \to K^+ \pi^-$, $D^-_s \to K^- K^+ \pi^+$

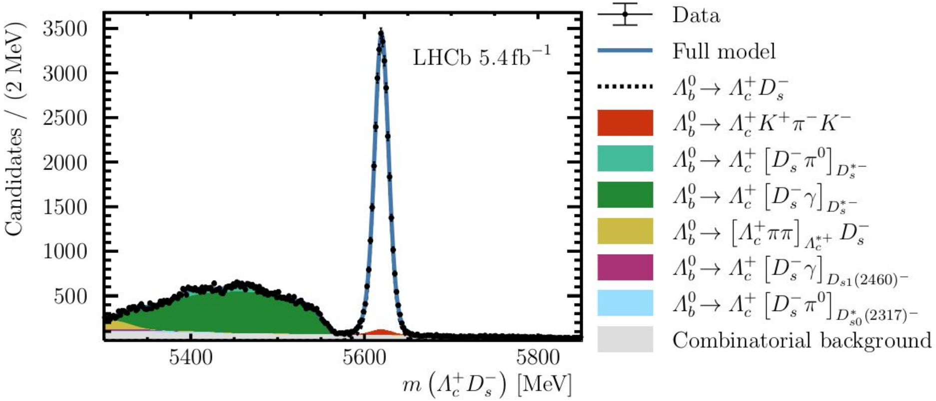
Backgrounds :

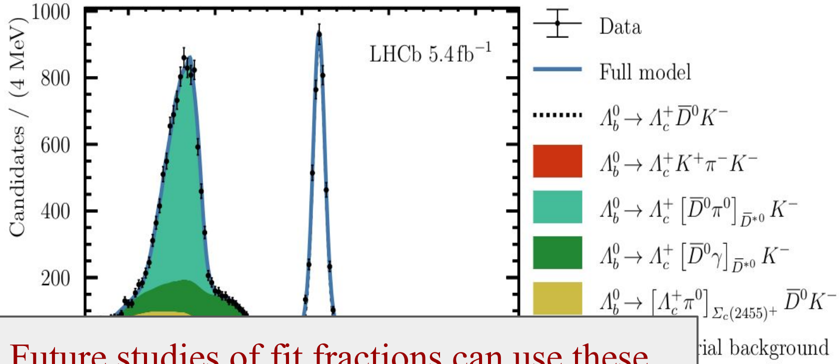
- Single charm/ charmless bkg : determined by **3D fit**
  - $\Lambda^0_b \to \Lambda^+_c K^- K^+ \pi^-$
- Partially reconstructed : **KDE** method
  - $\Lambda^0_b \to \Lambda^+_c [D^-_s \gamma/\pi^0]$
  - $\Lambda^0_b \to \Lambda^+_c K^- [\bar{D}^0 \gamma/\pi^0]$
  - $\Lambda^0_b \to [\Lambda^+_c \pi \pi] D^-_s$

Observation of $\Lambda^0_b \to \Lambda^+_c \overline{D}^{(*)0} K^-$ and $\Lambda^0_b \to \Lambda^+_c D^{*-}_s$

EPJC 84 (2024) 575

First observation with significance >> 5σ





Future studies of fit fractions can use these values to determine validity of different model predictions of P_c^+ branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.1908^{+0.0036+0.0016}_{-0.0034-0.0018} \pm 0.0038,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.589^{+0.018+0.017}_{-0.017-0.018} \pm 0.012,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 1.668 \pm 0.022^{+0.061}_{-0.055},$$

w.r.t. normalisation channel

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-)} = 0.152^{+0.032}_{-0.028},$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-)} = 0.049^{+0.011}_{-0.009},$$

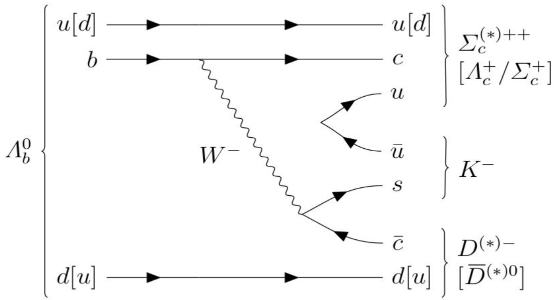
w.r.t. to the P_ψ observation channel

Observation of $\Lambda^0_b \to \Sigma_c^{(*)++} D^{(*)-} K^-$

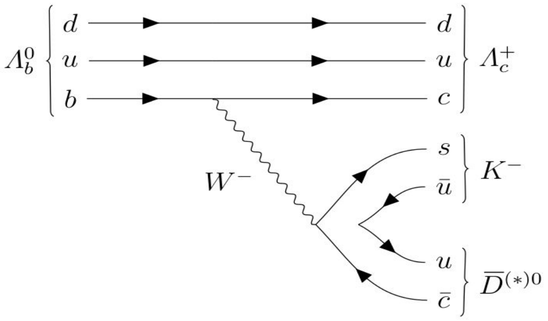
Phys. Rev. D 110, L031104)

- $P^N_\Psi(4380)^+$, $P^N_\Psi(4440)^+$, $P^N_\Psi(4457)^+$, $P^N_\Psi(4312)^+$ were observed in $\Lambda^0_b \to J/\Psi p K^-$.
- Molecular Models : predict substantial decay of P^N_Ψ with spin-parity $3/2^-$ to $\Sigma_c^{(*)}\bar{D}$.
- Reference channel : $\Lambda^0_b \to \Lambda^+_c \bar{D}^0 K^-$

Color suppressed but not forbidden



Color favoured



Reconstruction :

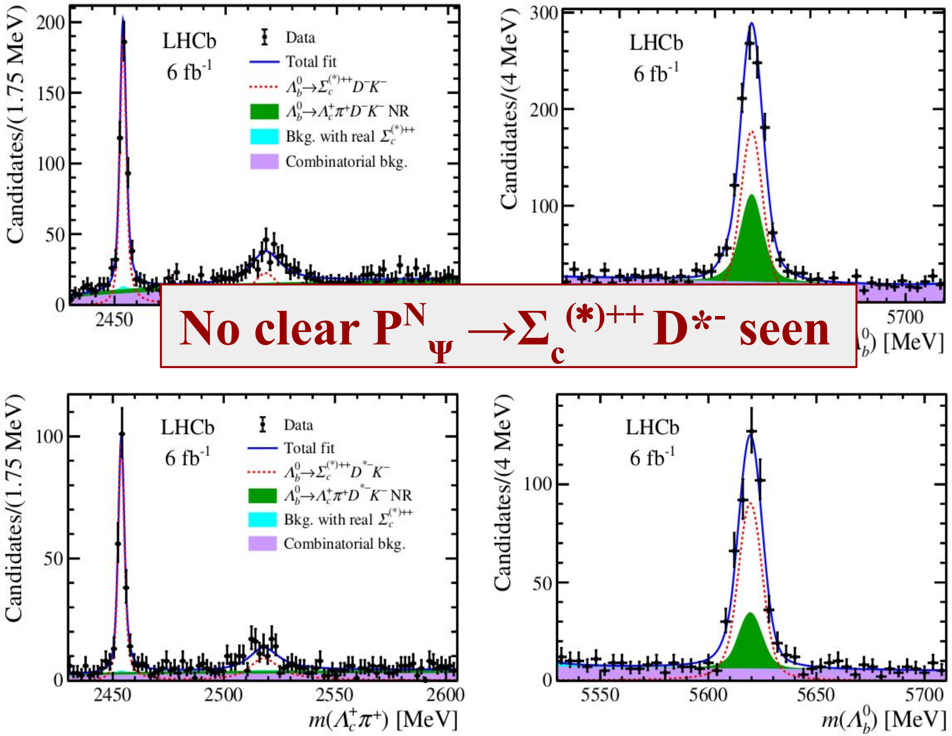
- $\Sigma_c^{(*)++} \to \Lambda^+_c \pi^+$
- $\Lambda^+_c \to p K^- \pi^+$
- $D^- \to K^+ \pi^- \pi^-$
- $D^{*-} \to \bar{D}^0 \pi^-$
- $\bar{D}^0 \to K^+ \pi^-$

Backgrounds :

- **Non-doubly charmed** backgrounds : separation between charmed hadron and Λ^0_b decay vertex utilised.
- **Mis-reconstructed** backgrounds :
  - $\Lambda^+_c \to (p\pi^+)_{\Lambda+c} K^-_{\Lambda 0b}$
- **Mis-identification** backgrounds :
  - $K^+ \to p$, $K^- \to \pi^-$, $\pi^+ \to p$

Observation of $\Lambda^0_b \to \Sigma_c^{(*)++} D^{(*)-} K^-$

Phys. Rev. D 110, L031104)



No clear $P^N_\Psi \to \Sigma_c^{(*)++} D^{*-}$ seen

Branching fractions wrt reference channel

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-\right)} = 0.282 \pm 0.016 \pm 0.016 \pm 0.005,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{*++} D^- K^-)}{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-)} = 0.460 \pm 0.052 \pm 0.028,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-)} = 2.261 \pm 0.202 \pm 0.129 \pm 0.046,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{*++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-)} = 0.896 \pm 0.137 \pm 0.066 \pm 0.018,$$

Significance :

- $\Lambda^0_b \to \Sigma_c^{++} D^- K^-$: **32 σ**
- $\Lambda^0_b \to \Sigma_c^{++} D^{*-} K^-$: **21 σ**
- $\Lambda^0_b \to \Sigma_c^{*++} D^- K^-$: **13 σ**
- $\Lambda^0_b \to \Sigma_c^{*++} D^{*-} K^-$: **9 σ**

Low statistics O(100) currently but future amplitude analysis with RUN 3 of these four decay modes will help constrain the characteristics of the three observed pentaquark candidates.

Charmed tetraquark in B-decays

New Charmonium like states in $B^+ \rightarrow D^{*\pm} D^{\mp} K^+$

arXiv:2406.03156

- First open charm $T^*_{cs0}(2900)^0$ & $T^*_{cs1}(2900)^0$ observed in $B^+ \rightarrow D^+ D^- K^+$ in $D^- K^+$
- C-parity conservation in strong decays $\Rightarrow$ equal resonant contribution to $D^{*+}D^-$ & $D^{*-}D^+$
- **Simultaneous amplitude analysis** : $B^+ \rightarrow D^{*+}D^-K^+$ & $B^+ \rightarrow D^{*-}D^+K^+$
- Resonance C-parity determined by linking decay amplitudes by C-parity.

Reconstruction :

- $D^- \rightarrow K^+ \pi^- \pi^-$
- $D^{*-} \rightarrow \bar{D}^0 \pi^-$
- $\bar{D}^0 \rightarrow K^+ \pi^-$, $K^+ \pi^- \pi^+ \pi^-$

Backgrounds :

BDT classifier used to reduce combinatorial background

Partial-wave Analysis : Helicity Formalism

Baseline fit model

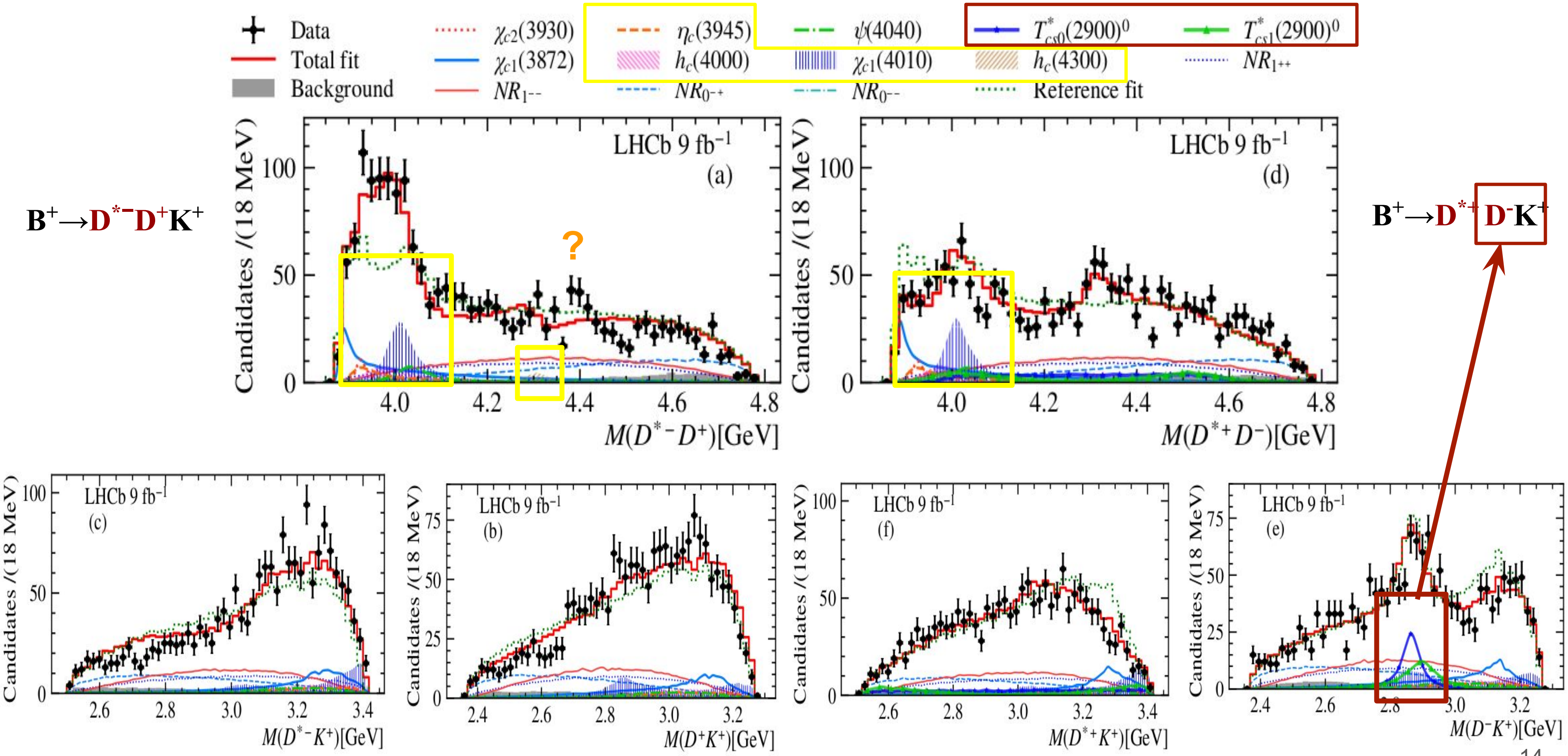
Component	$J^{P(C)}$	Fit fraction(%) $B^+ \to D^{*+}D^-K^+$	Fit fraction(%) $B^+ \to D^{*-}D^+K^+$	Branching fraction ($\times 10^{-4}$)
$\chi_{c1}(3872)^\dagger$	1^{++}	$10.9^{+2.3}_{-1.2}{}^{+1.6}_{-2.1}$	$9.9^{+2.1}_{-1.0}{}^{+1.4}_{-1.9}$	$0.74^{+0.16}_{-0.08}{}^{+0.11}_{-0.14} \pm 0.07$
$\eta_c(3945)$	0^{-+}	$3.4^{+0.5}_{-1.0}{}^{+1.9}_{-0.7}$	$3.1^{+0.5}_{-0.9}{}^{+1.7}_{-0.6}$	$0.23^{+0.04}_{-0.07}{}^{+0.13}_{-0.05} \pm 0.02$
$\chi_{c2}(3930)^\dagger$	2^{++}	$1.8^{+0.5}_{-0.4}{}^{+0.6}_{-1.2}$	$1.7^{+0.5}_{-0.4}{}^{+0.6}_{-1.1}$	$0.12^{+0.03}_{-0.03}{}^{+0.04}_{-0.08} \pm 0.01$
$h_c(4000)$	1^{+-}	$5.1^{+1.0}_{-0.8}{}^{+1.5}_{-0.8}$	$4.6^{+0.9}_{-0.7}{}^{+1.4}_{-0.7}$	$0.35^{+0.07}_{-0.05}{}^{+0.10}_{-0.05} \pm 0.03$
$\chi_{c1}(4010)$	1^{++}	$10.1^{+1.6}_{-0.9}{}^{+1.3}_{-1.6}$	$9.1^{+1.4}_{-0.8}{}^{+1.2}_{-1.4}$	$0.69^{+0.11}_{-0.06}{}^{+0.09}_{-0.11} \pm 0.06$
$\psi(4040)^\dagger$	1^{--}	$2.8^{+0.5}_{-0.4}{}^{+0.5}_{-0.5}$	$2.6^{+0.5}_{-0.4}{}^{+0.4}_{-0.5}$	$0.19^{+0.04}_{-0.03}{}^{+0.03}_{-0.03} \pm 0.02$
$h_c(4300)$	1^{+-}	$1.2^{+0.2}_{-0.5}{}^{+0.2}_{-0.2}$	$1.1^{+0.2}_{-0.5}{}^{+0.2}_{-0.2}$	$0.08^{+0.01}_{-0.03}{}^{+0.02}_{-0.01} \pm 0.01$
$T^*_{cs0}(2900)^{0\,\dagger}$	0^{+}	$6.5^{+0.9}_{-1.2}{}^{+1.3}_{-1.6}$	–	$0.45^{+0.06}_{-0.08}{}^{+0.09}_{-0.1} \pm 0.04$
$T^*_{cs1}(2900)^{0\,\dagger}$	1^{-}	$5.5^{+1.1}_{-1.5}{}^{+2.4}_{-1.6}$	–	$0.38^{+0.07}_{-0.10}{}^{+0.16}_{-0.11} \pm 0.03$
$\mathrm{NR}_{1^{--}}(D^{*\mp}D^{\pm})$	1^{--}	$20.4^{+2.3}_{-0.6}{}^{+2.1}_{-2.6}$	$18.5^{+2.1}_{-0.5}{}^{+1.9}_{-2.3}$	$1.39^{+0.16}_{-0.04}{}^{+0.14}_{-0.17} \pm 0.12$
$\mathrm{NR}_{0^{--}}(D^{*\mp}D^{\pm})$	0^{--}	$1.2^{+0.6}_{-0.1}{}^{+0.7}_{-0.6}$	$1.1^{+0.6}_{-0.1}{}^{+0.6}_{-0.5}$	$0.08^{+0.04}_{-0.01}{}^{+0.05}_{-0.04} \pm 0.01$
$\mathrm{NR}_{1^{++}}(D^{*\mp}D^{\pm})$	1^{++}	$17.8^{+1.9}_{-1.4}{}^{+3.6}_{-2.6}$	$16.1^{+1.7}_{-1.3}{}^{+3.3}_{-2.3}$	$1.21^{+0.13}_{-0.10}{}^{+0.24}_{-0.17} \pm 0.11$
$\mathrm{NR}_{0^{-+}}(D^{*\mp}D^{\pm})$	0^{-+}	$15.9^{+3.3}_{-1.2}{}^{+3.3}_{-3.3}$	$14.5^{+3.0}_{-1.1}{}^{+3.0}_{-3.0}$	$1.09^{+0.23}_{-0.08}{}^{+0.22}_{-0.23} \pm 0.09$

New Charmonium like states in $B^+ \to D^{*\pm} D^{\mp} K^+$

arXiv:2406.03156

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

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



New Charmonium like states in $B^+ \to D^{*\pm} D^{\mp} K^+$

arXiv:2406.03156

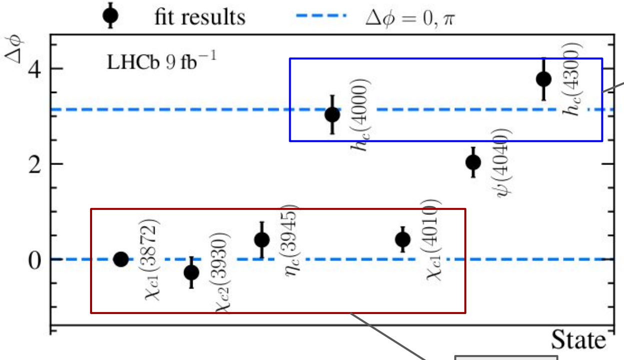
Confirmation of previously observed states

Property	This work	Previous work
$T^*_{cs0}(2900)^0$ mass (MeV) — 11 σ	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{cs0}(2900)^0$ width (MeV)	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{cs1}(2900)^0$ mass (MeV) — 9.2 σ	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{cs1}(2900)^0$ width (MeV)	$92 \pm 16 \pm 16$	110 ± 12
$\mathcal{B}(B^+ \to T^*_{cs0}(2900)^0 D^{(*)+})$	$(4.5\,^{+0.6}_{-0.8}\,^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
$\mathcal{B}(B^+ \to T^*_{cs1}(2900)^0 D^{(*)+})$	$(3.8\,^{+0.7}_{-1.0}\,^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
$\frac{\mathcal{B}(B^+ \to T^*_{cs0}(2900)^0 D^{(*)+})}{\mathcal{B}(B^+ \to T^*_{cs1}(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

Newly observed states

This work		
10 σ	$\eta_c(3945)$: $m_0 = 3945\,^{+28}_{-17}\,^{+37}_{-28}$	$J^{PC} = 0^{-+}$: $\Gamma_0 = 130\,^{+92}_{-49}\,^{+101}_{-70}$
9.16 σ	$h_c(4000)$: $m_0 = 4000\,^{+17}_{-14}\,^{+29}_{-22}$	$J^{PC} = 1^{+-}$: $\Gamma_0 = 184\,^{+71}_{-45}\,^{+97}_{-61}$
16.6 σ	$\chi_{c1}(4010)$: $m_0 = 4012.5\,^{+3.6}_{-3.9}\,^{+4.1}_{-3.7}$	$J^{PC} = 1^{++}$: $\Gamma_0 = 62.7\,^{+7.0}_{-6.4}\,^{+6.4}_{-6.6}$
6.4 σ	$h_c(4300)$: $m_0 = 4307.3\,^{+6.4}_{-6.6}\,^{+3.3}_{-4.1}$	$J^{PC} = 1^{+-}$: $\Gamma_0 = 58\,^{+28}_{-16}\,^{+28}_{-25}$

C-parity relationship test using χ_{c1} as reference



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

arXiv:2406.17006

- Measured cross section
- Transverse momentum
- Rapidity Spectra

→ **Conventional charmonium**

- Proximity to $D^0\bar{D}^{*0}$ threshold
- $J^{PC} = 1^{++}$
- Large coupling to $D^0\bar{D}^{*0}$

→ **$\bar{D}^0D^{*0}+D^0\bar{D}^{*0}$ Molecule**

- Radiative decays of $\chi_{c1}(3872)$ to $\Psi(2S)\gamma$ and $J/\Psi\gamma$

$$\mathscr{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$$

$\mathscr{R}_{\psi\gamma} \gtrsim 1$ — **Charmonium $\chi_{c1}(2P)$**

$\mathscr{R}_{\psi\gamma} \ll 1$ — **Molecular hypothesis**

$$\mathscr{R}_{\psi\gamma} = \frac{\mathcal{B}_{B^+\to(\chi_{c1}(3872)\to\psi(2S)\gamma)K^+}}{\mathcal{B}_{B^+\to(\chi_{c1}(3872)\to J/\psi\gamma)K^+}}$$

Reference		$\mathscr{R}_{\psi\gamma}$	
T. Barnes and S. Godfrey	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	$c\bar{c}/vc$
E. S. Swanson	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	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	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$

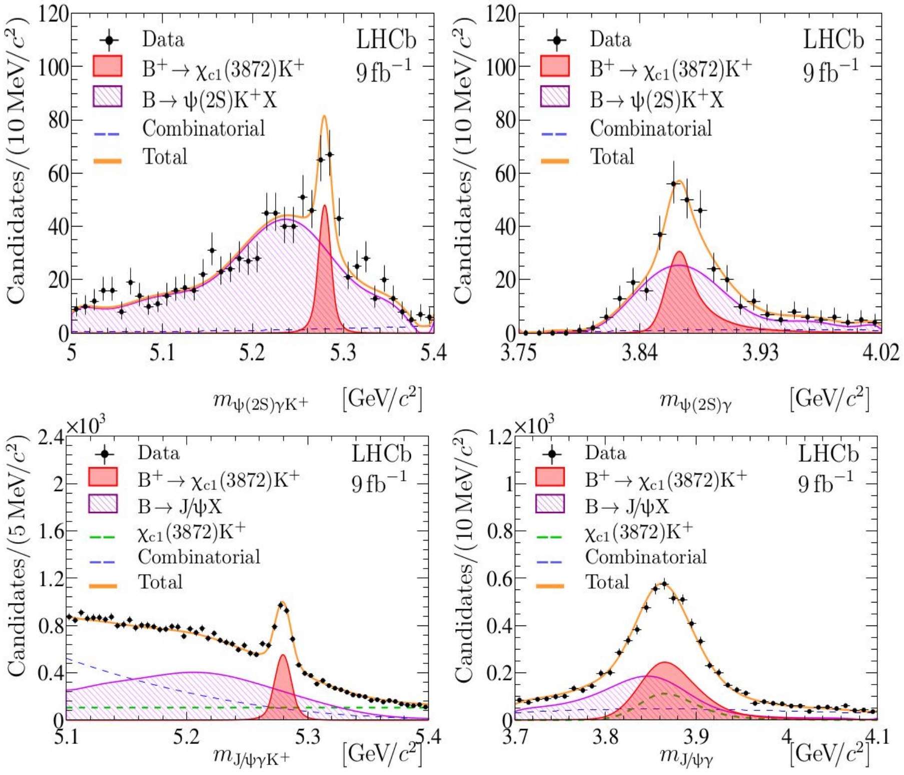
Compact tetraquark

Predictions for the ratio $R_{\psi\gamma}$ of radiative partial decay widths of the $\chi_{c1}(3872)$

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

arXiv:2406.17006

$B^+ \to (\chi_{c1}(3872) \to \Psi(2S)\gamma)K^+$



$B^+ \to (\chi_{c1}(3872) \to J/\Psi\gamma)K^+$

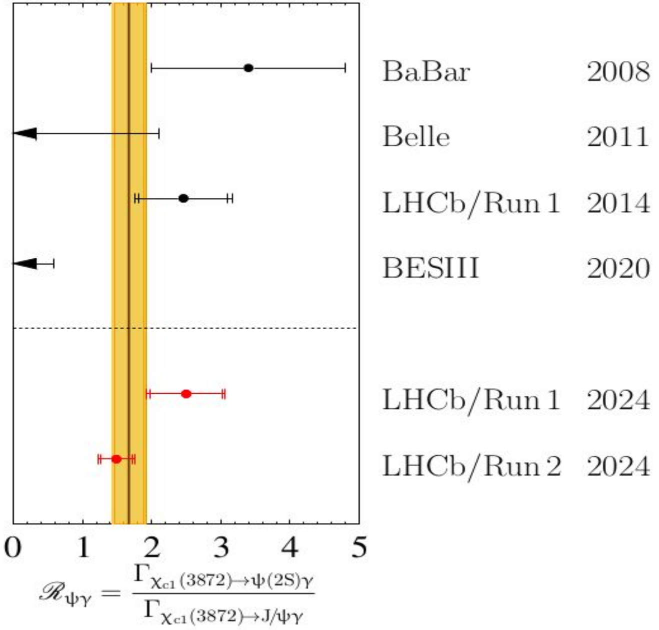
Strong indication of a sizeable compact component

$$\mathcal{R}_{\psi\gamma}^{\mathrm{Run\,1}} = 2.50 \pm 0.52\,^{+0.20}_{-0.23} \pm 0.06\,,$$

$$\mathcal{R}_{\psi\gamma}^{\mathrm{Run\,2}} = 1.49 \pm 0.23\,^{+0.13}_{-0.12} \pm 0.03\,,$$

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

Current status of experimental results

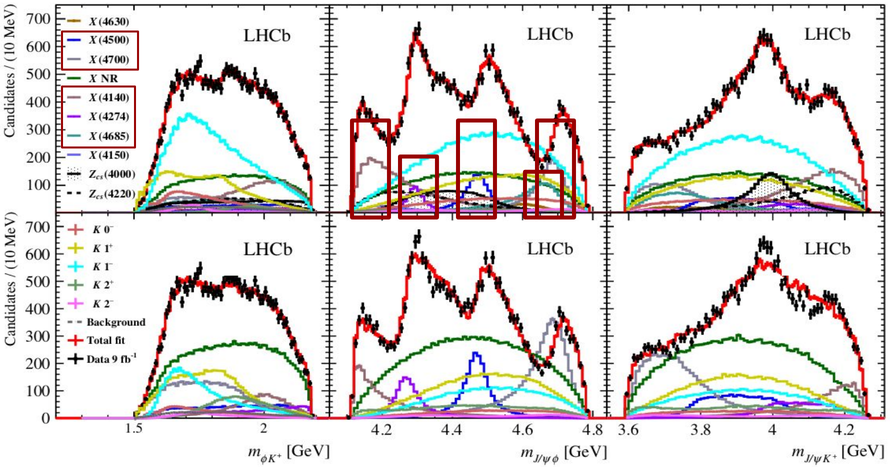


Observations in p-p and p-Pb collisions

Observation of exotic J/ψΦ resonances

arXiv:2407.14301

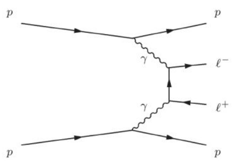
- 5 exotic candidates in J/ΨΦ invariant mass in $B^+ \to J/\Psi\Phi K^+$
- Production dominated by **pomeron-pomeron** processes in p-p collisions.
- First time : **$J/\Psi(\to\mu^+\mu^-)\Phi(\to K^+K^-)$** production cross section is measured in CEP processes.
- Production cross section measured for 5 resonant and 1 non resonant component.



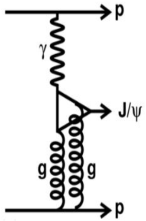
[PRL 127 (2021) 082001]

Central Exclusive Processes :

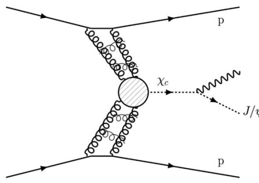
- Particles produced in regions large rapidity gaps $\Delta y \gtrsim 3$
- Incident beam : stay intact / may dissociate
- Generic rxn : $\mathbf{pp \to p^{(*)} + X + p^{(*)}}$
- **"+" :** rapidity gaps with no hadrons
- four-momentum transfer : carried by a virtual ***γ*** or a **pomeron**
- **Pomeron :** color singlet of gluons



γ-γ



γ-Pomeron



Pomeron-pomeron

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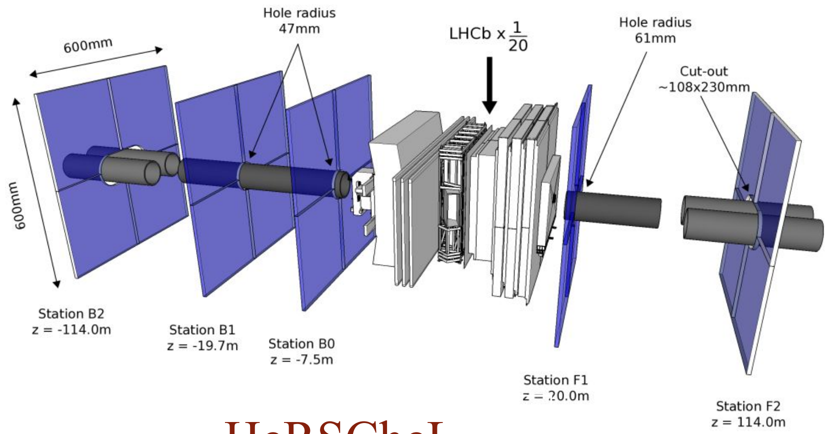
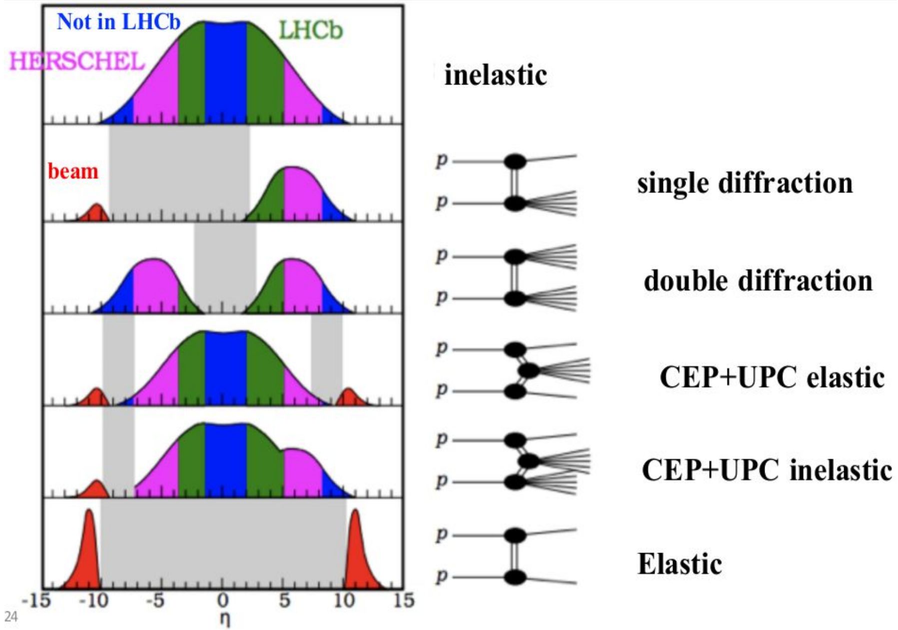


HeRSCheL

K. Carvalho Akiba et al 2018 JINST 13 P04017

- 989 J/ΨΦ candidates retained.
- J/ΨΦ modelled with 5 resonances as RBW convolved with gaussian.
- Small sample size : mass and width fixed for $\chi_{c1}(4140), \chi_{c1}(4685), \chi_{c1}(4700)$.
- $\chi_{c1}(4685), \chi_{c1}(4700)$ not resolved.



Rapidity range for different processes

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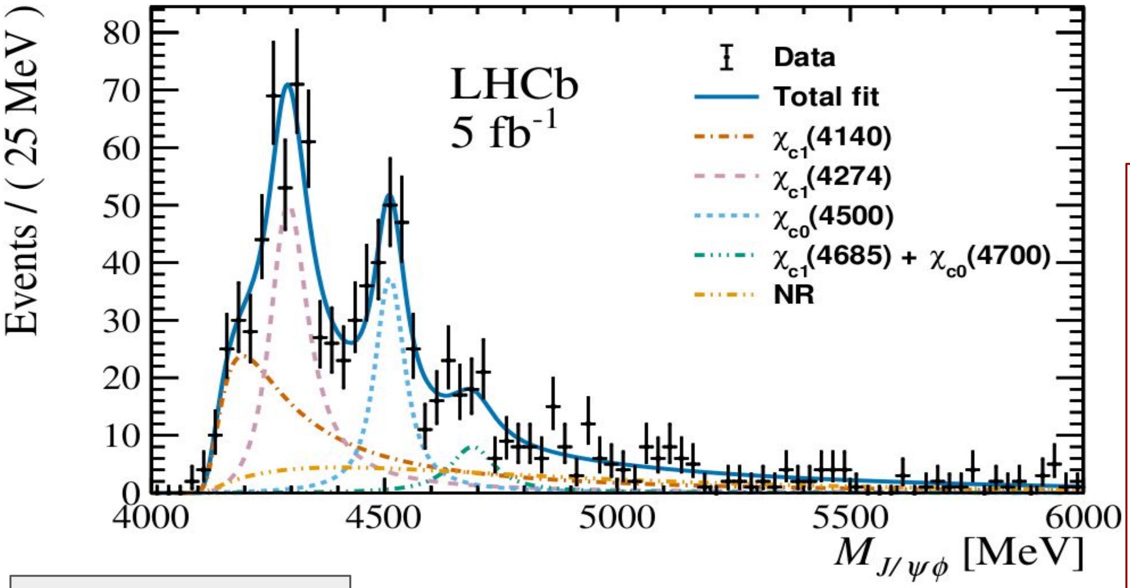


Cross-section measurement

$$\sigma_{J/\psi\phi} \times \mathcal{B}(J/\psi \to \mu^+\mu^-) \times \mathcal{B}(\phi \to K^+K^-) = (2.67 \pm 0.08 \pm 0.13 \pm 0.08)\ \text{pb},$$

$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4140)} = (0.85 \pm 0.16 \pm 0.30)\ \text{pb},$$

$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4274)} = (0.77^{+0.14}_{-0.13} \pm 0.18)\ \text{pb},$$

$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\text{eff}}^{\chi_{c0}(4500)} = (0.44^{+0.09}_{-0.08} \pm 0.07)\ \text{pb},$$

$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} \pm 0.06)\ \text{pb},$$

$$\sigma_{\text{NR}} \times \mathcal{B}_{\text{eff}}^{\text{NR}} = (0.46^{+0.25}_{-0.19} \pm 0.22)\ \text{pb},$$

Signal Significance

- $\chi_{c1}(4140)$: 2.4σ
- $\chi_{c1}(4274)$: 4.3σ
- $\chi_{c0}(4500)$: 5.5σ
- $\chi_{c1}(4685)$ + $\chi_{c1}(4700)$: 1.6σ

Mass & width measurement

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

Modification of χ_{c1}(3872) & Ψ(2S) production

Phys. Rev. Lett. 132, 242301

Prompt cross section ratio $\sigma\chi_{c1(3872)}/\sigma_{\Psi(2S)}$:

- In **p-p** collisions (LHCb): observed suppression attributed to breakup due to interaction with comoving particles.
- In **Pb-Pb** collisions (CMS) : enhancement observed, quark coalescence ⇒ production rate sensitive to hadronic structure ⇒ Tetraquark production should be enhanced.
- **Pb-p** collisions : test suppression and enhancement!

First measurement of prompt production of **χ_{c1}(3872) & Ψ(2S)** in **Pb-p** at $\sqrt{s_{NN}}$ **= 8.16 TeV**

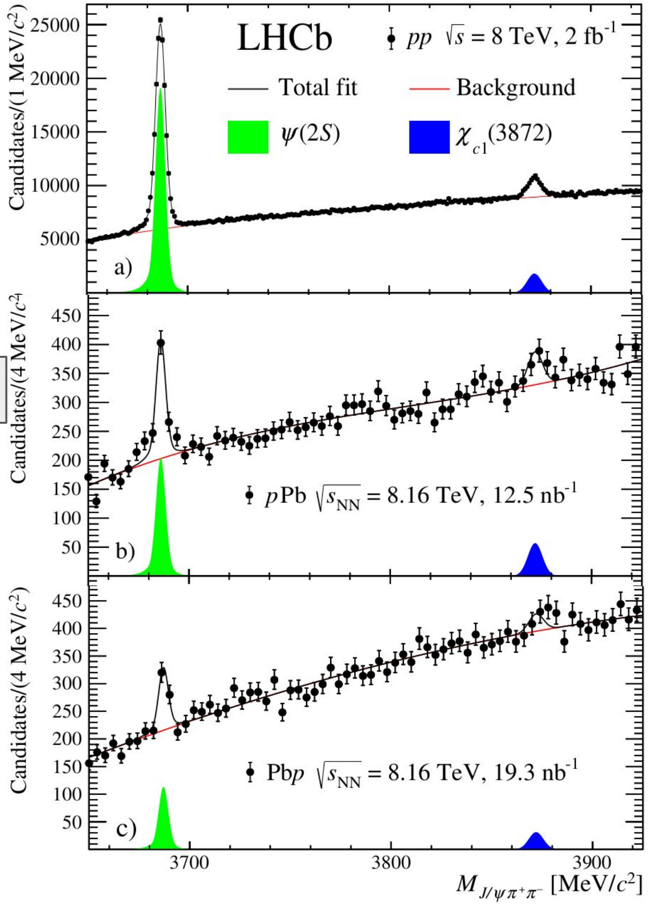
- $\sigma\chi_{c1(3872)}/\sigma_{\Psi(2S)}$ & Nuclear modification factor : $R_{pA}^{\chi_{c1}(3872)}$
- χ_{c1}(3872) & Ψ(2S) reconstructed from **$J/\psi\pi^+\pi^-$**

Dataset : Pb-p data 2016

- **Forward configuration (pPb) :** 1.5 <y< 4, L = 12.5 nb^{-1}
- **Backward configuration (Pbp) :** -5 <y< -2.5, L = 19.3 nb^{-1}

Highly enriched prompt data using pseudo- decay time t_z < 0.1 sec

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



Modification of $\chi_{c1}(3872)$ & $\Psi(2S)$ production

Phys. Rev. Lett. 132, 242301

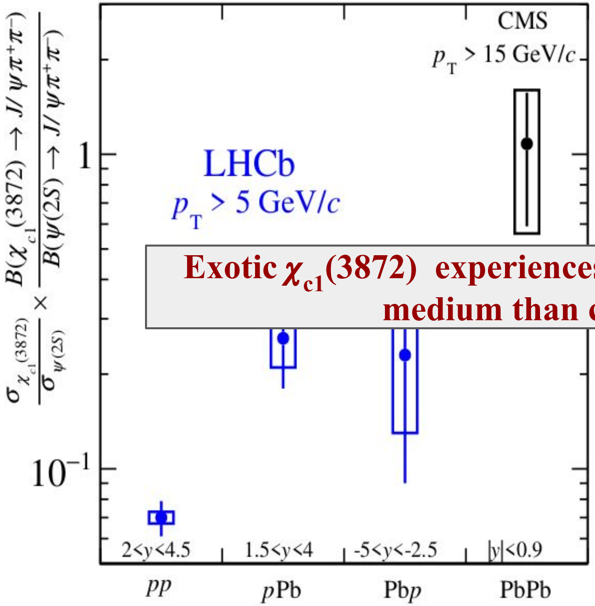
pPb data set :

- **χ_{c1}(3872)** yield : 129 ± 37
  Signal significance : 3.6 σ
- **Ψ(2S)** yield : 343 ± 32

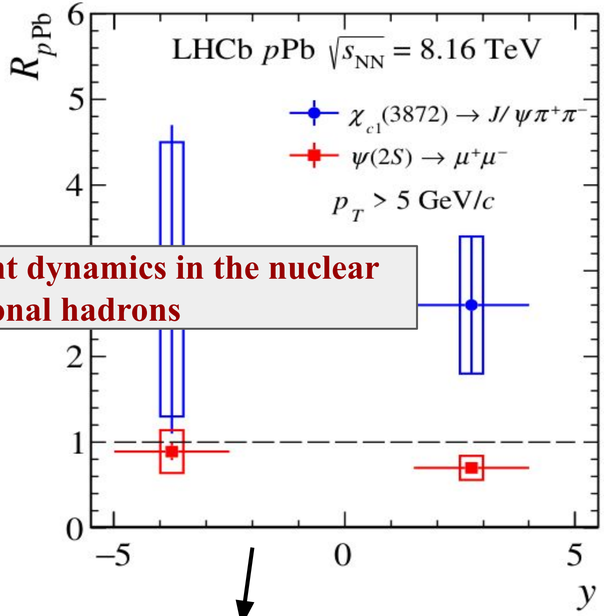
Pbp data set :

- **χ_{c1}(3872)** yield : 71 ± 39
  Signal significance : 1.9 σ
- **Ψ(2S)** yield : 191 ± 30

Cross section ratios



Nuclear modification factor



Exotic χ_{c1}(3872) experiences different dynamics in the nuclear medium than conventional hadrons

Increase in system size ⇒ increase ratio due to Ψ(2S) suppression in pA or higher densities leading to quark coalescence ⇒ high $\sigma_{\chi_{c1}(3872)}$

Number of nucleons in nuclear beam

$$R_{pA}^{\chi_{c1}(3872)} = \frac{\sigma_{pA}^{\chi_{c1}(3872)}}{\boxed{208} \times \sigma_{pp}^{\chi_{c1}(3872)}}$$

Enhancement in **χ_{c1}(3872)** production indicate **coalescence dominance** over suppression due to breakup

Future Prospects

Run3: ~15 fb^{-1} *pp* data (Statistics ~ 2× Run1&2) with 2 × Trigger efficiency

- Higher statistics of heavy hadron production will aid in exotics studies at LHCb.
- Full software trigger allows studies on fully-hadronic final states.
- Higher efficiency of the LHCb topological trigger increases sensitivity of spectroscopy studies.

Increased discovery potential!

- General idea : search for new decay modes and determine properties of new or previously observed multi-quark hadrons.
  - True nature of $\chi_{c1}(3872)$ is still a question, molecular ? compact?
  - Fully charmed tetraquark already observed, T_{bc} and T_{bb}?
  - Sexaquarks?
  - Exotic state production mechanisms?

More exciting future discoveries are positively expected!