Recent LHCb Results on Hadron Spectroscopy and Exotic States

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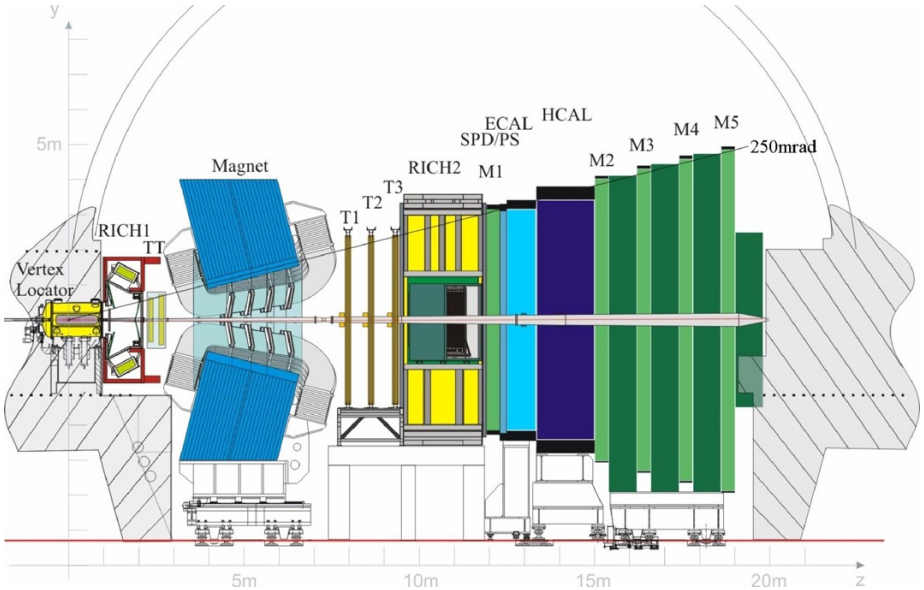
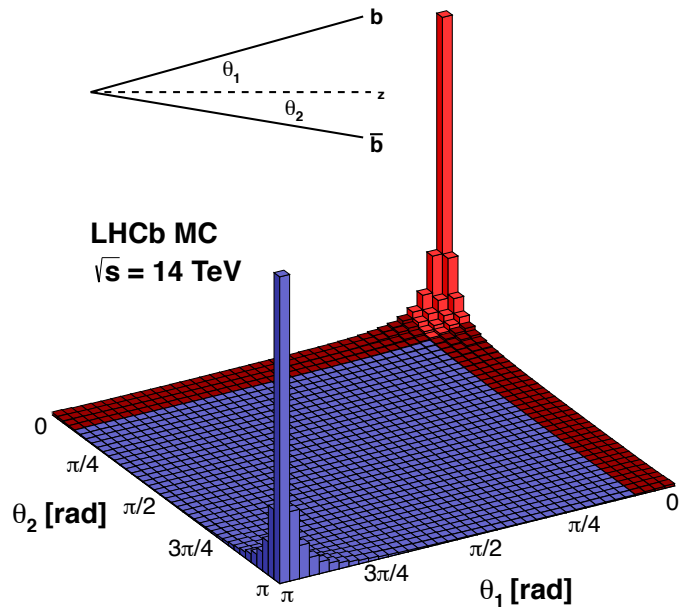
Spectroscopy at LHCb

The LHCb Detector

- LHCb is a single-arm spectrometer in the forward region $(2 < \eta < 5)$ at the LHC.
- Optimised for studying b (and c) decays which are boosted in the forward region.



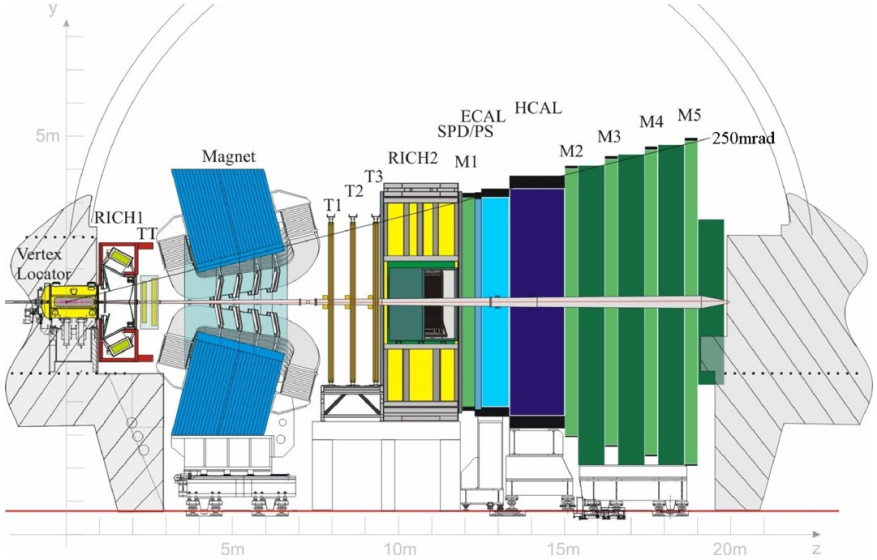
LHCb cross-section



Boosting of $b\bar{b}$ pair

The LHCb Detector

- Good tracking and particle identification performance.

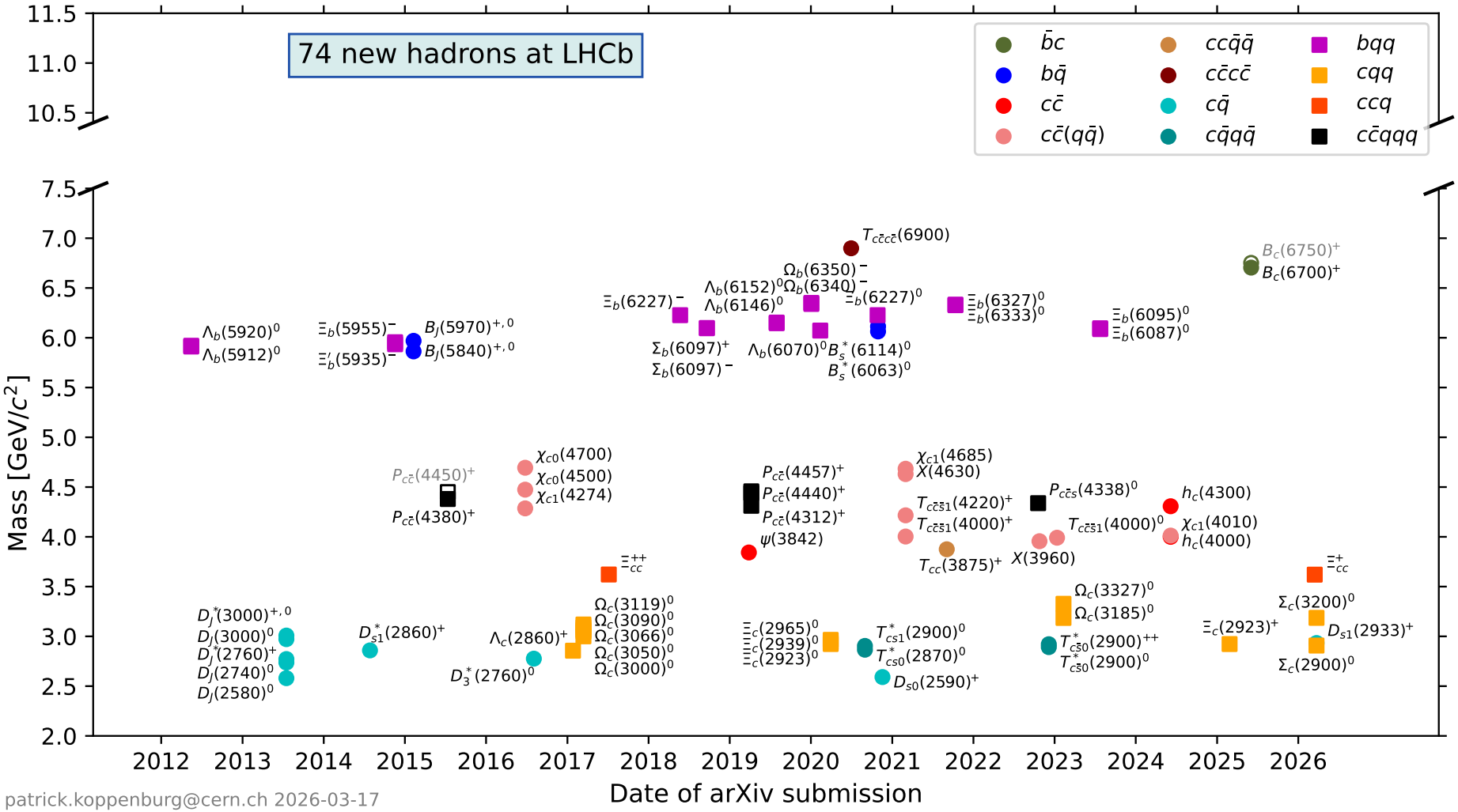


- VELO and T stations.
  - Momentum resolution $\sigma_p/p \approx 0.5 - 1\%$.
  - IP resolution $(15 + 29/p_T\ [\text{GeV}])\mu m$.
- Muon, RICH, ECAL and HCAL.
  - $\epsilon(e) \sim 90\%$, $e \to h$ misID $\sim 5\%$.
  - $\epsilon(K) \sim 95\%$, $\pi \to K$ misID $\sim 5\%$.
  - $\epsilon(\mu) \sim 97\%$, $\pi \to \mu$ misID $\sim 1 - 3\%$.

清華大學 Tsinghua University LHCb

Recent Spectroscopy Results

- LHCb has a strong record of spectroscopy results.



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Recent Spectroscopy Results

- Conventional
  - $\Xi_c(2923)^+$ and $\Xi_c(2939)^+$ in $B^0 \to \Lambda_c^+ \bar{\Lambda_c}^- K_s^0$.
  - $D_{s1}(2933)^+$ in $B^0 \to D^+ D^- K^+ \pi^-$.
  - $\Sigma_c(2800)^0$, $\Sigma_c(2900)^0$,$\Sigma_c(3200)^0$ in $B^- \to \Lambda_c^+ \bar{p} \pi^-$.
  - $B_c(1P)^+$ in $B_c^+ \gamma$ spectroscopy.
  - Ξ_{cc}^+ discovery covered by Xuhao. I want to add that predicted $\tau(\Xi_{cc}^+) \sim$ detector resolution.
- Exotic
  - $\Lambda_b \to \Lambda_c^+ D_s^- K^+ K^-$.
  - $\chi_c(3872) \to J/\psi \mu^+ \mu^-$.
  - $T_{c\bar{c}}(4430)^+$ in $B^+ \to \psi(2S) K_s^0 \pi^+$.
  - Amplitude analysis of $B^0 \to \eta_c K^+ \pi^-$.

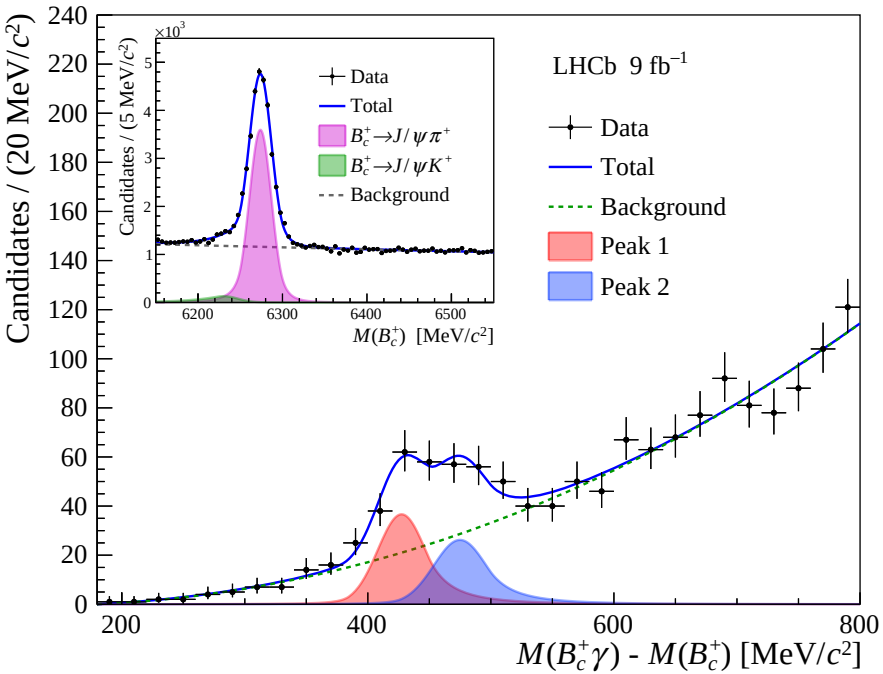
Conventional Spectroscopy

$B_c(1P)^+ \to B_c^+\gamma$

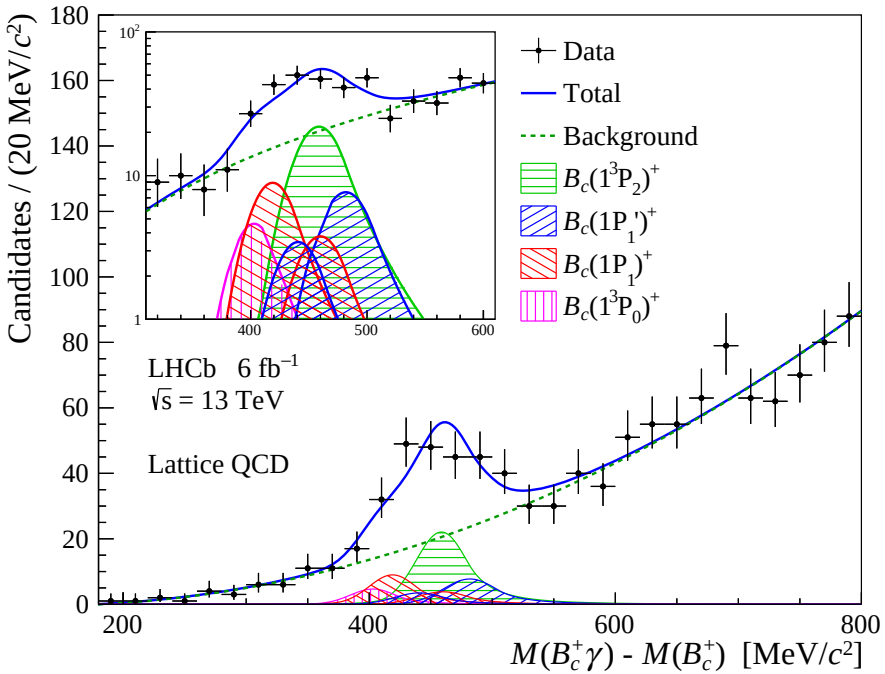
PRD 112 (2025) 11, 112003

PRL 135 (2025) 23, 231902

- Search for orbitally excited $B_c(1P)^+$ via $B_c^+\gamma$.
- Experimental data can resolve a two-peak structure, with
  - $M_1 = 6704.8 \pm 5.5(\text{stat}) \pm 2.8(\text{syst}) \pm 0.3(B_c^+)$ MeV
  - $M_2 = 6752.4 \pm 9.5(\text{stat}) \pm 3.1(\text{syst}) \pm 0.3(B_c^+)$ MeV
- Attempted fits with 6 peak theory models:



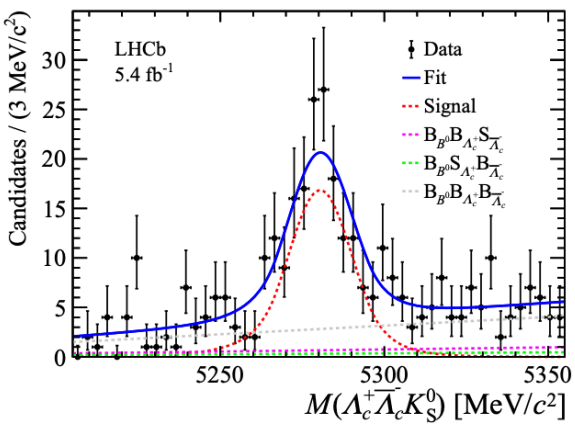
Empirical Model

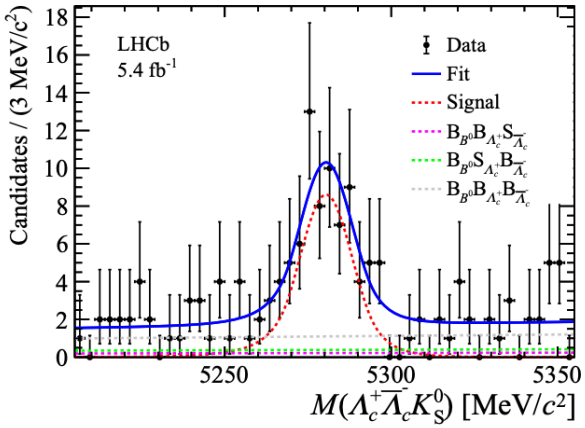


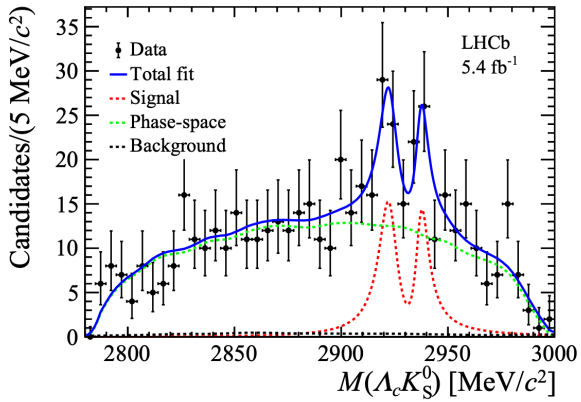
Theory: Best Fit

$B^0 \to \Lambda_c^+ \bar{\Lambda}_c^- K_s^0$ LHCb-PAPER-2025-072 in preparation

- Isospin partner of $B^+ \to \Lambda_c^+ \bar{\Lambda}_c^- K^+$ seen by Belle (EPJC 78 (2018) 3, 252), BaBar (PRD 77 (2008) 031101) and LHCb (PRD 108 (2023) 012020).
  - BaBar and Belle reported $\Xi_c(2930)$.
  - PRL 124 (2020) 22, 222001: LHCb analysis of $\Xi_c' \to \Lambda_c^+ K^-$ found two peaks, $\Xi_c(2923)$ and $\Xi_c(2939)$. Resolved $\Xi_c(2930)$?
- 210 $B^0 \to \Lambda_c^+ \bar{\Lambda}_c^- K_s^0$ signal events.
- Significances: 3.9σ double peak vs no resonance hypotheses, 1.7σ double peak vs single peak hypotheses.







- Previously observed $D_{s0}(2590)^+$ at $m(K^+\pi^-) < 750$ MeV in this decay mode. PRL 126 (2021) 12, 122002
- Perform amplitude analysis over full phase space.
- Require a new $D_{s1}(2933)^+$ state with $> 10\sigma$ significance.
  - $M = 2933^{+6+4}_{-5-3}$ MeV, $\Gamma = 72^{+18+7}_{-12-10}$ MeV.
  - $J^P = 1^+$ favored over 0^-, 1^+, $2^\pm$ by $> 5\sigma$.
- Compatible with conventional $D_s(2P_1')^+$ state.

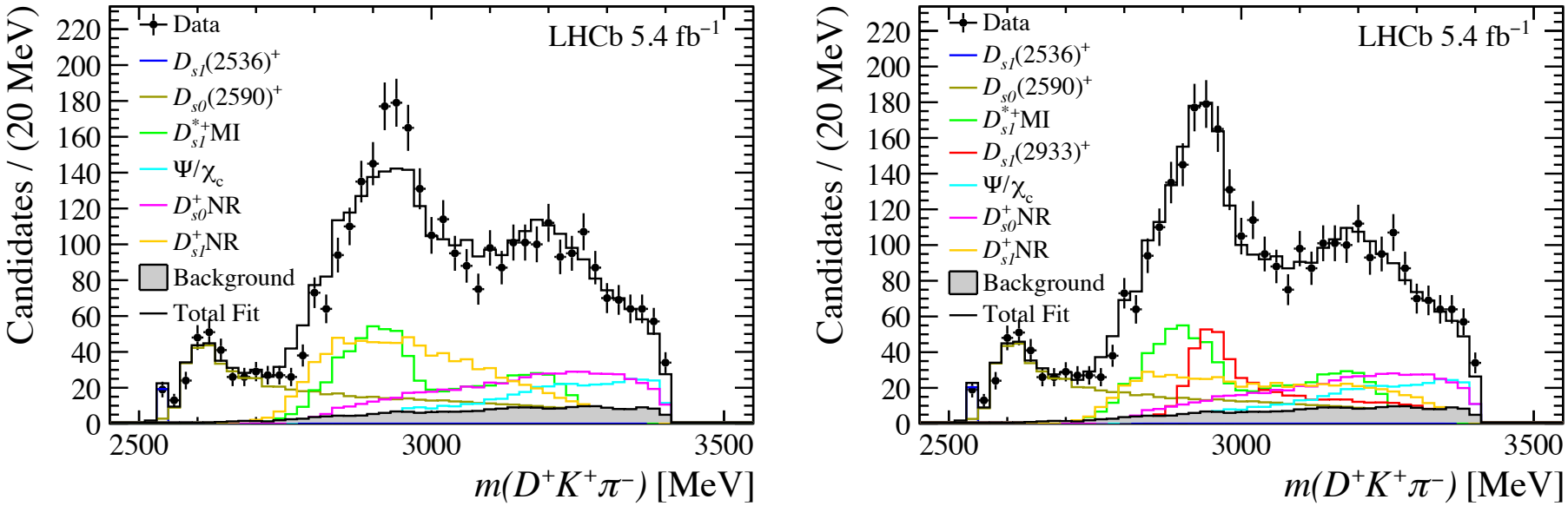
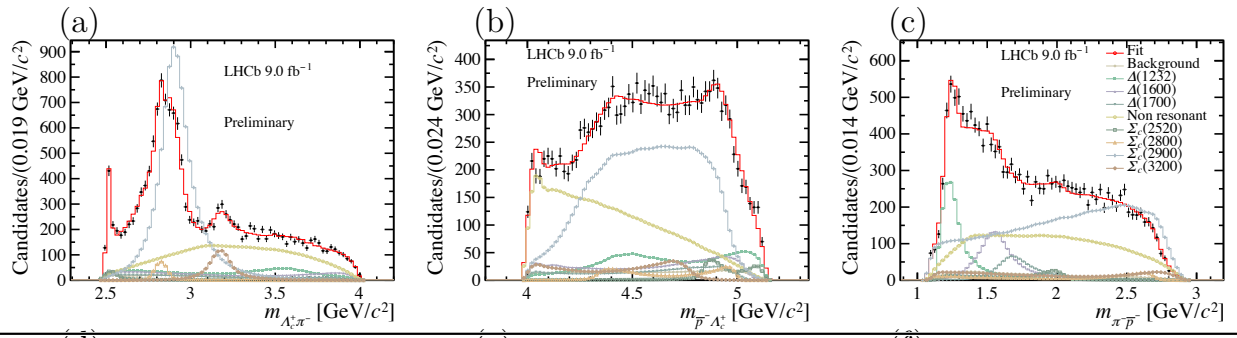


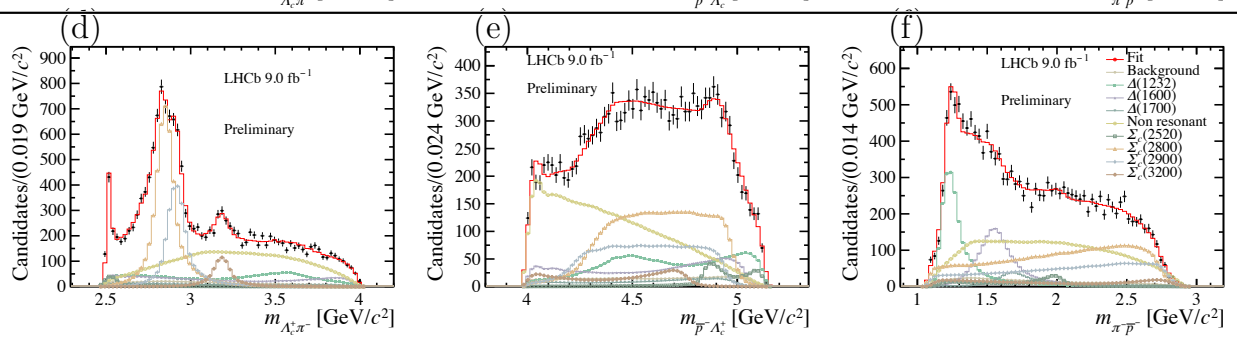
Figure: Without (left) and with (right) $D_{s1}(2933)^+$ in the fit.

- $\Sigma_c(2800)$ observation by Belle (PRL 94 (2005) 122002), but BaBar analysis (PRD 78 (2008) 112003) of $B^- \to \Lambda_c^+ \bar{p}\pi^-$ measured an inconsistent mass. Mixing or multiple states?
- LHCb amplitude analysis of $B^- \to \Lambda_c^+ \bar{p}\pi^-$ favors $\Sigma_c(2800)^0$, $\Sigma_c(2900)^0$ and $\Sigma_c(3200)^0$.
  - Two peak $\Sigma_c(2800)$-$\Sigma_c(2900)$ favored over single peak by 7.5σ.
  - $\Sigma_c(3200)^0$ observed with 12.0σ.

Group A



Group B



- Masses and widths categorized as Group A and Group B.
  - Each group contains multiple spin-parity permutations, but measured masses and widths are similar.
  - Preferred J^P is $3/2^+$, $1/2^-$, $3/2^-$ for Group A.
  - Preferred J^P is $1/2^-$, $1/2^+$, $3/2^-$ for Group B.
- $\mathcal{R}$ is fit fraction relative to $B^- \to \Sigma_c(2455)\bar{p}$.

Parameter	Group A	Group B
$m_{\Sigma_c(2800)^0}[\mathrm{GeV}/c^2]$	$2.8192 \pm 0.0060 \pm 0.0020$	$2.8483 \pm 0.0037 \pm 0.0055$
$\Gamma_{\Sigma_c(2800)^0}[\mathrm{GeV}]$	$0.0326 \pm 0.0068 \pm 0.0080$	$0.0990 \pm 0.0072 \pm 0.0209$
$m_{\Sigma_c(2900)^0}[\mathrm{GeV}/c^2]$	$2.9077 \pm 0.0048 \pm 0.0087$	$2.9143 \pm 0.0032 \pm 0.0081$
$\Gamma_{\Sigma_c(2900)^0}[\mathrm{GeV}]$	$0.1754 \pm 0.0082 \pm 0.0225$	$0.0921 \pm 0.0061 \pm 0.0234$
$m_{\Sigma_c(3200)^0}[\mathrm{GeV}/c^2]$	$3.1859 \pm 0.0059 \pm 0.0144$	$3.1898 \pm 0.0054 \pm 0.0107$
$\Gamma_{\Sigma_c(3200)^0}[\mathrm{GeV}]$	$0.1331 \pm 0.0176 \pm 0.0267$	$0.1001 \pm 0.0154 \pm 0.0323$
$\mathcal{R}(\Sigma_c(2800)^0)$	$0.09 \pm 0.02 \pm 0.05$	$0.86 \pm 0.07 \pm 0.42$
$\mathcal{R}(\Sigma_c(2900)^0)$	$1.68 \pm 0.07 \pm 0.29$	$0.50 \pm 0.04 \pm 0.19$
$\mathcal{R}(\Sigma_c(3200)^0)$	$0.21 \pm 0.03 \pm 0.05$	$0.17 \pm 0.03 \pm 0.05$
$\mathcal{R}(\Sigma_c(2520)^0)$	$0.09 \pm 0.01 \pm 0.02$	$0.11 \pm 0.01 \pm 0.03$
$\mathcal{R}((\Lambda_c^+\pi^-)_{\mathrm{NR\,S-wave}})$	$2.19 \pm 0.14 \pm 0.22$	$2.23 \pm 0.11 \pm 0.30$

Exotic Spectroscopy

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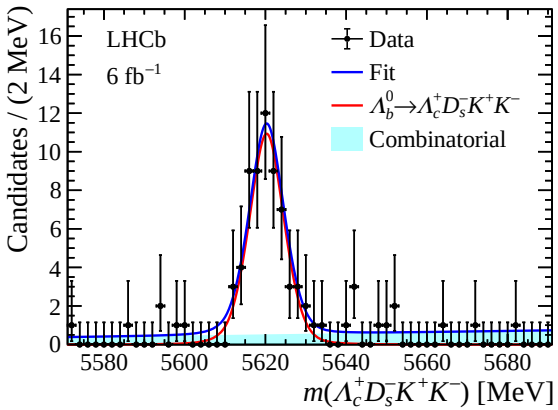
$\Lambda_b \to \Lambda_c^+ D_s^- K^+ K^-$

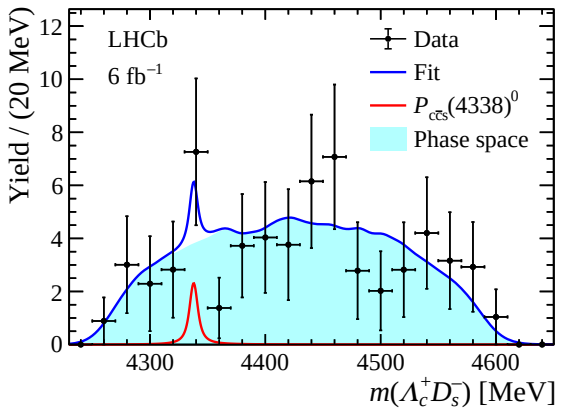
PRD 112 (2025) 5, 052013

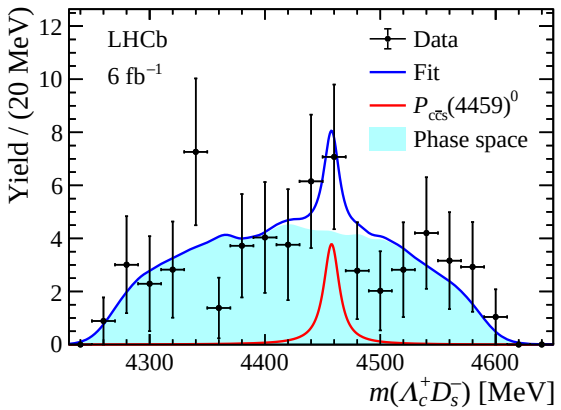
- Search for $P_{c\bar{c}s}$ near $\Xi_c D_s^{(*)}$ thresholds in $\Lambda_c^+ D_s^-$ system.
  - $B^- \to J/\psi \Lambda \bar{p}$: $P_{c\bar{c}s}(4338)$, $> 15\sigma$, PRL 131, 031901 (2023).
  - $\Xi_b^- \to J/\psi \Lambda K^-$: $P_{c\bar{c}s}(4459)$, 3.1σ, Sci.Bull. 66 (2021) 1278-1287.
- Measured relative branching fraction:

$$\frac{\mathcal{B}(\Lambda_b \to \Lambda_c^+ D_s^- K^+ K^-)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ D_s^-)} = 0.0141 \pm 0.0019 \pm 0.0012$$

- No sensitivity to $P_{c\bar{c}s}$ in $m(\Lambda_c^+ D_s^-)$. Potential improvement in Run 3 with software triggers.





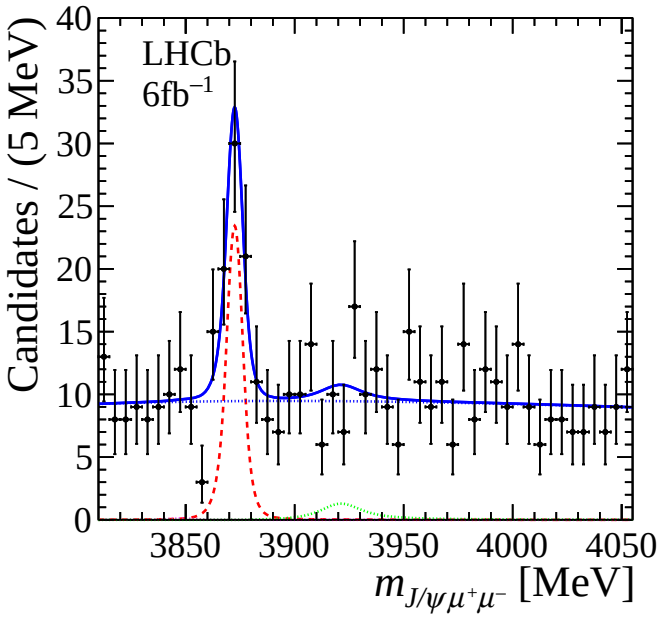


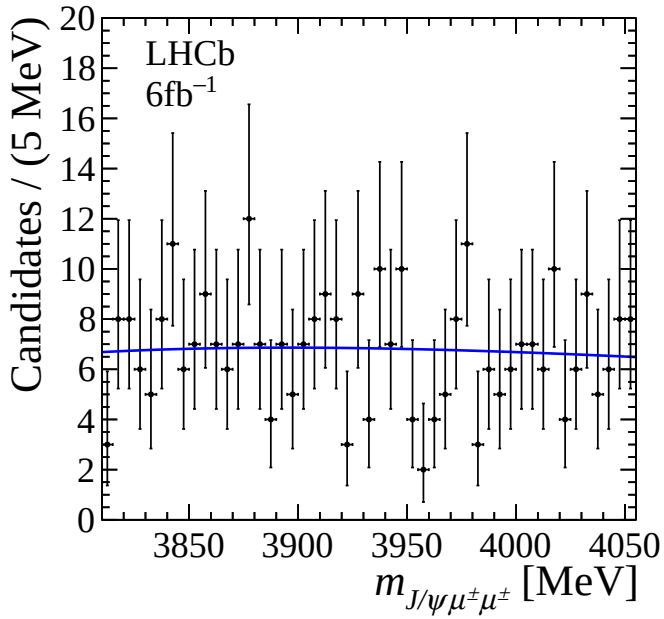
$\chi_{c1}(3872) \to J/\psi\mu^+\mu^-$

LHCb-PAPER-2025-043

- Probe internal structure of $\chi_{c1}(3872)$.
  - Photon pole dominates at low $m_{\mu\mu}$.
  - ρ and ω contributes at high $m_{\mu\mu}$.
- Study secondary vertex $\chi_{c1}(3872)$ (from b decays).
- Measure branching fraction relative to $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$:

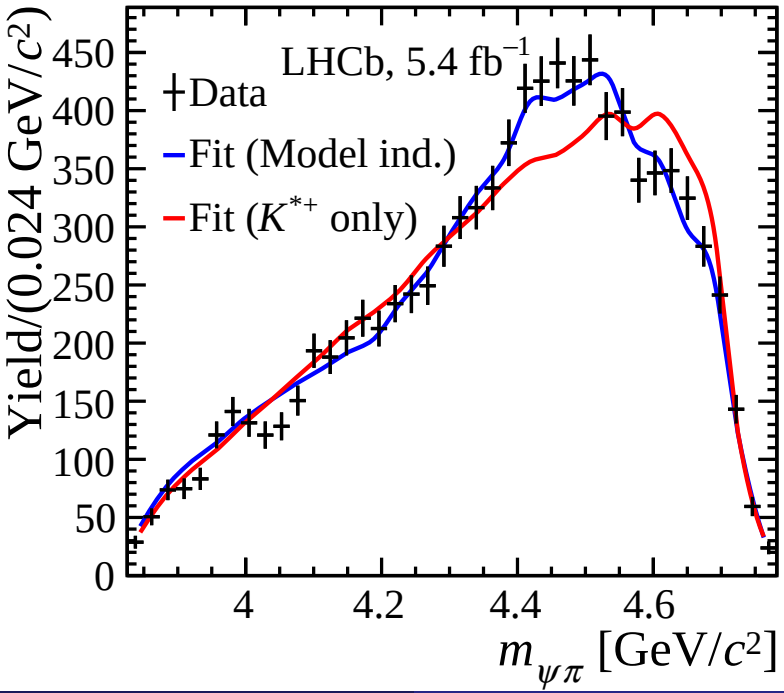
$$\mathcal{R} = \frac{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\mu^+\mu^-)}{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)} = (1.64 \pm 0.32 \pm 0.05) \times 10^{-3}.$$

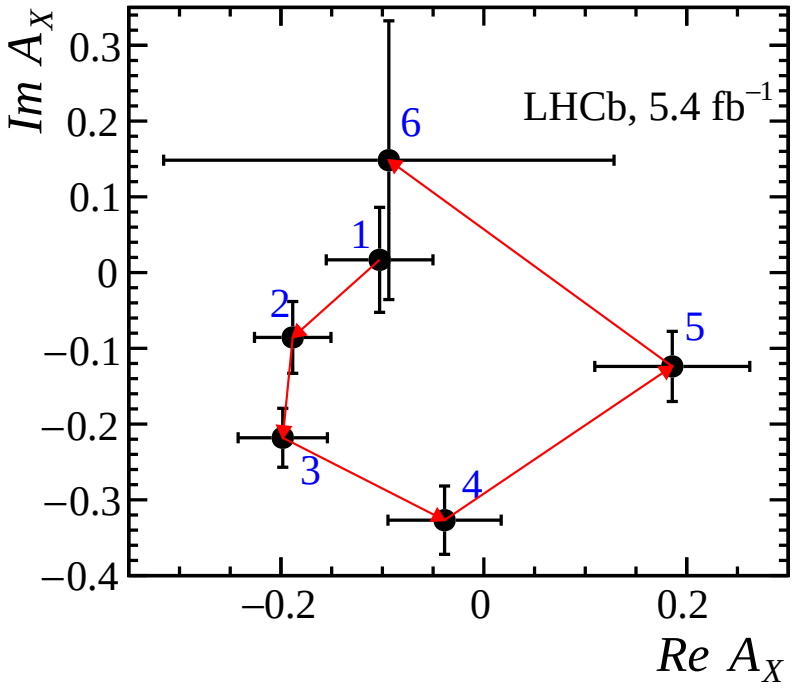




$B^+ \to \psi(2S)K^0_s\pi^+$ Amplitude Analysis arXiv:2511.20428

- Isospin partner of $B^0 \to \psi(2S)K^+\pi^-$, $T_{c\bar{c}}(4430)^-$ seen by Belle (PRL 100 (2008) 142001) and LHCb (PRL 112 (2014) 22, 222002).
- Fitting $B^+ \to \psi(2S)K^0_s\pi^+$ with only K^{*+} resonances cannot describe the data in $m(J/\psi\pi^+)$ well.
- A model independent cubic spline with $L = 0$ shows a circular loop, supporting the existence of a resonance.





$B^+ \to \psi(2S)K^0_S\pi^+$ Amplitude Analysis arXiv:2511.20428

- Breit-Wigner $T_{c\bar{c}}(4430)^+$ consistent with previous LHCb results:
  - $M = 4.452 \pm 0.016^{+0.055}_{-0.033}$ GeV, $\quad \Gamma = 0.174 \pm 0.019^{+0.083}_{-0.020}$ GeV.
  - $J^P = 1^+$ is favored by 6σ over $0^-, 1^-, 2^-, 2^+$.
- Molecular hypothesis modelled with Flatté parameterization:

$$F = \frac{1}{m_f^2 - m^2 - i(\rho_1 g_1^2 + \rho_2 g_2^2)}$$

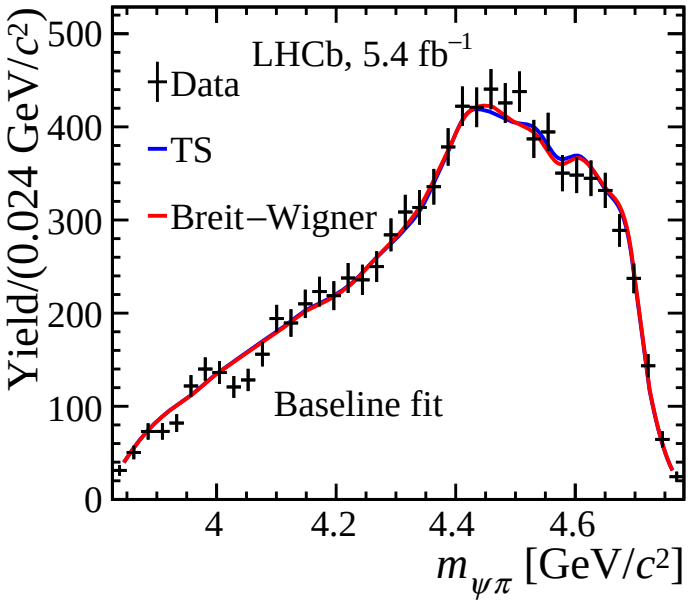
  - With channel $1 = \psi(2S)\pi^+$ and channel $2 = \bar{D}_1^*(2600)^0 D^+$:

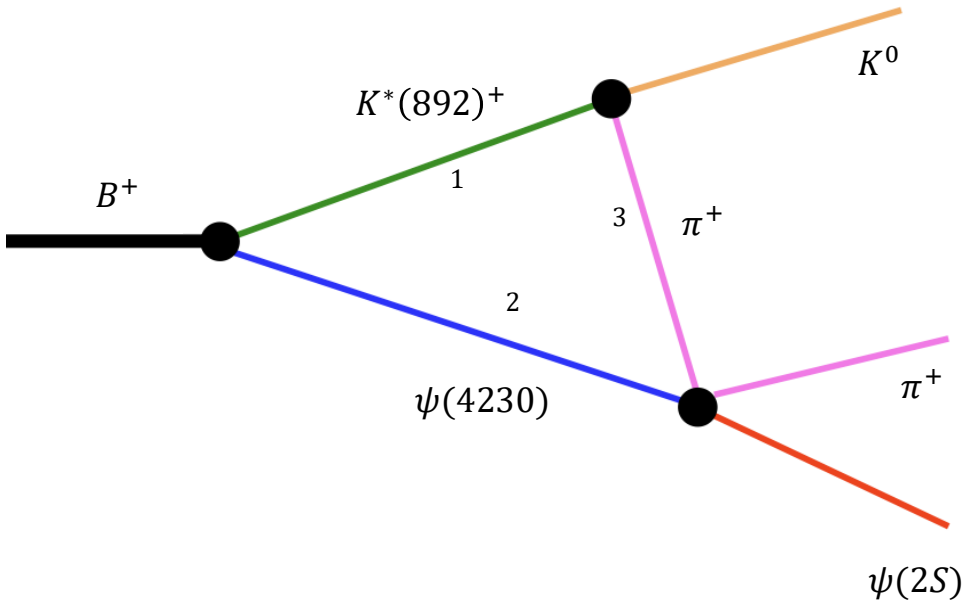
$$g_1 = 1.58 \pm 0.17^{+0.05}_{-0.82} \text{ GeV}, \quad g_2 = 0.00 \pm 1.78 \pm 2.81 \text{ GeV}.$$

  - $|g_1/g_2| < 6.8$ at 95% confidence level, constraining $\bar{D}_1^*(2600)^0 D^+$ coupling to $T_{c\bar{c}1}(4430)^+$.

$B^+ \to \psi(2S)K^0_S\pi^+$ Amplitude Analysis arXiv:2511.20428

- Triangle singularity model of PRD 100 (2019) 5, 051502 can describe the data as well as Breit-Wigner.
  - Arise from rescattering of $\psi(4230)\pi^+ \to \psi(2S)\pi^+$ in $B^+ \to \psi(4230)K^*(892)^+$.
  - However, this implies a large $B^+ \to \psi(4230)K^*(892)^+$ branching fraction, which can be seen in other decay modes.
- Current dataset is statistically insensitive to distinguish between triangle singularity and Breit-Wigner models.





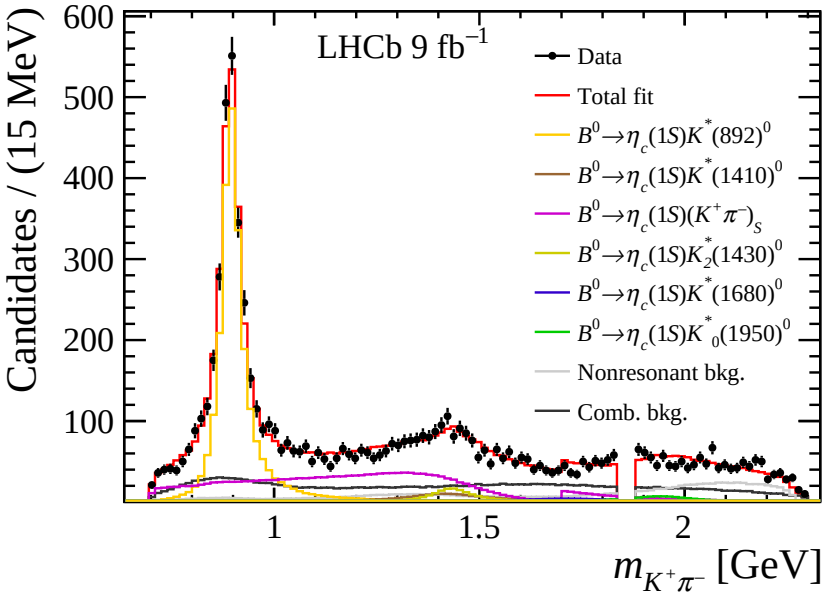
$B^0 \to \eta_c K^+ \pi^-$ Amplitude Analysis

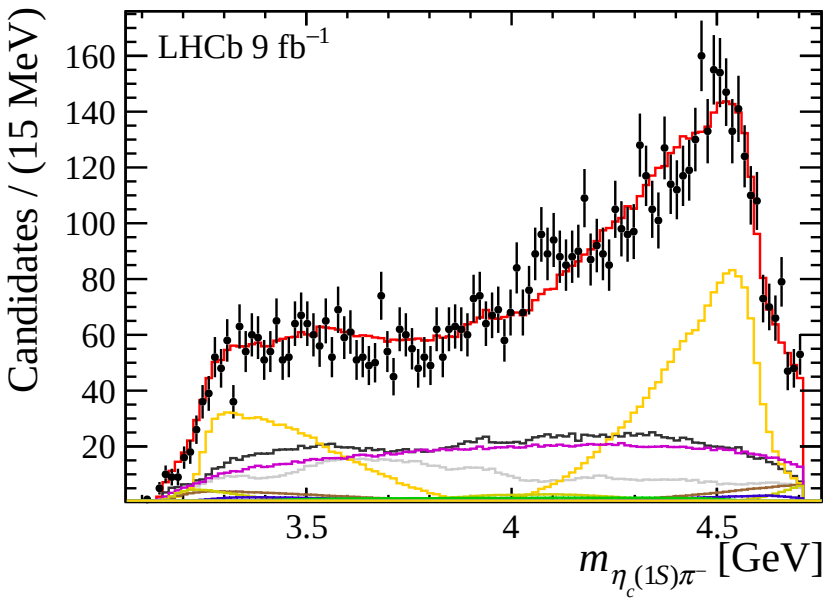
arXiv:2509.03133

- Previous analysis with LHCb Run 1 + 2016 data ($4.7\ \text{fb}^{-1}$) found an evidence for $T_{c\bar{c}}(4100)^-$: EPJC 78 (2018) 12, 1019

$$M = 4096 \pm 20^{+18}_{-22}\ \text{MeV}, \quad \Gamma = 152 \pm 58^{+60}_{-35}\ \text{MeV}.$$

- This update uses the entire LHCb Run 1 + 2 dataset ($9\ \text{fb}^{-1}$).



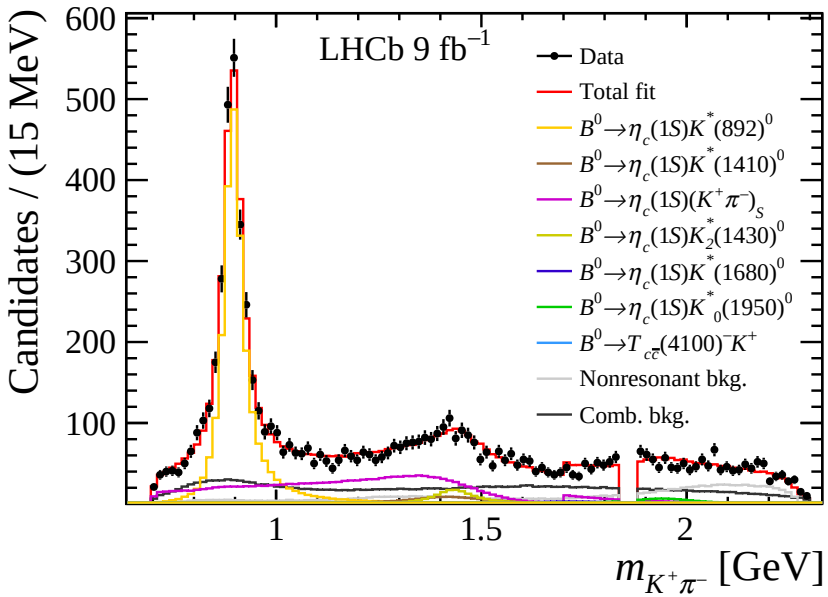


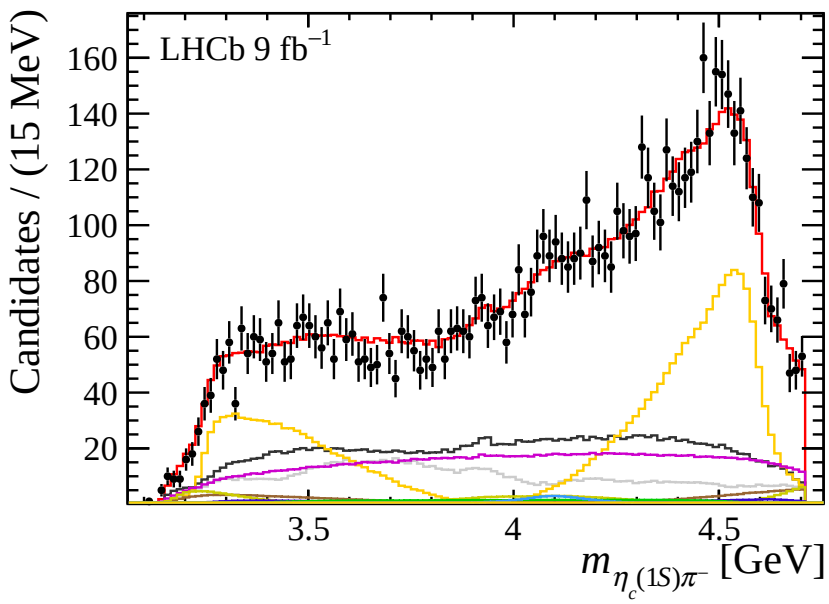
Baseline model only has K^* resonances.

$B^0 \to \eta_c K^+ \pi^-$ Amplitude Analysis

arXiv:2509.03133

- $T_{c\bar{c}}(4100)^-$ component with $J^P = 1^-$ has 3.6σ significance.
- Background parametrization systematic reduces this to 2.5σ.
  - Supersedes previous results: no evidence of exotic candidates in $B^0 \to \eta_c K^+ \pi^-$ decays with Run 1 + 2 LHCb dataset.

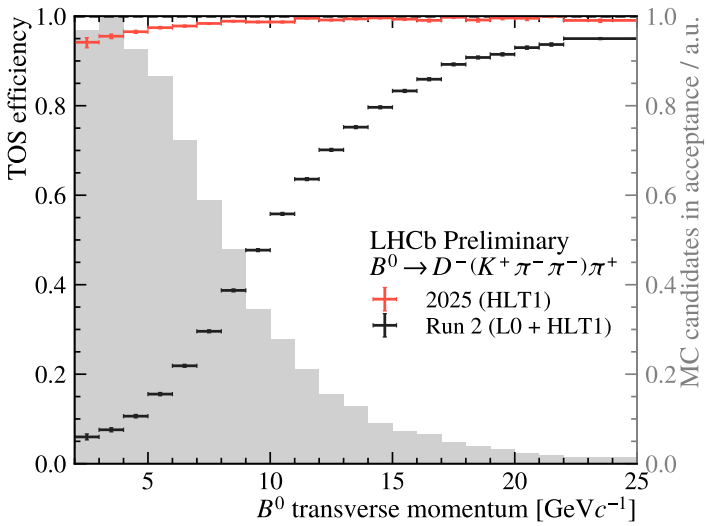


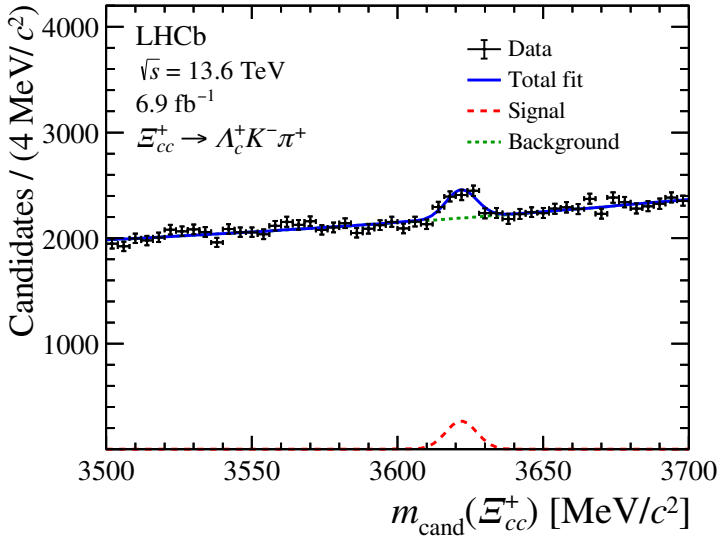


Extended model with $T_{c\bar{c}}(4100)^-$.

Summary and Future Prospects

Summary and Future Prospects





LHCB-FIGURE-2025-015 LHCb-PAPER-2026-009 in preparation

- LHCb has a rich physics program of hadron spectroscopy:
  - Studies of conventional hadrons from b decays (excited $Sigma_c$, D_s, Ξ_c) or radiative transitions of excited b decays (excited B_c).
  - Studies of exotic $\chi_{c1}(3872)$, $T_{c\bar{c}}$, $P_{c\bar{c}s}$ from b decays.
- Expect more to come with Upgraded Run 3 detector!
  - Software triggers $2-3\times$ more efficient on hadronic b decays.
  - Ξ_{cc}^+ discovery with $4\times$ more efficient triggers in Run 3.