Progress on Hadron Spectroscopy Studies at LHCb

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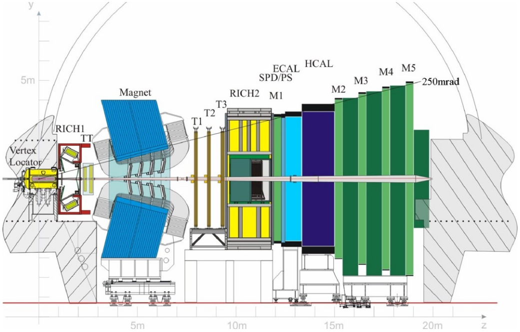
第 6 届 LHCb 前沿物理研讨会, 26/05/24

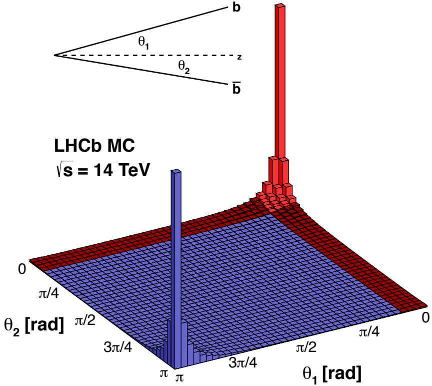
Spectroscopy at LHCb

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 IJMPA 30 (2015) 07, 1530022

- Why is LHCb good for spectroscopy? **Tracking** and **PID**:

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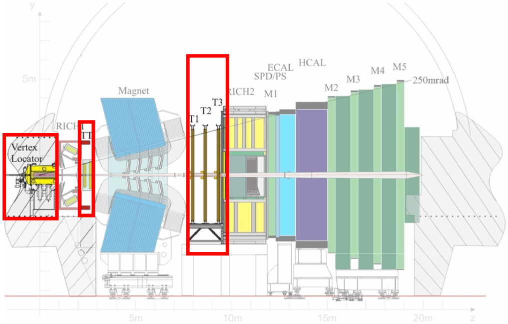

- VELO and T stations.
  - Momentum resolution $\sigma_p/p \approx 0.5 - 1\%$.
  - IP resolution $(15 + 29/p_T\ [\text{GeV}])\mu m$.

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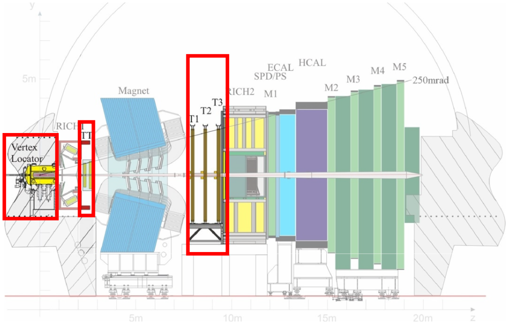

- `VELO` and `T` stations.
  - Momentum resolution $\sigma_p/p \approx 0.5 - 1\%$.
  - `IP` resolution $(15 + 29/p_T\ [\text{GeV}])\mu m$.
- **Good mass resolution** driven by:
  - Momentum resolution from trackers.
  - Vertex resolution from silicon pixel vertex detector.

The LHCb Detector IJMPA 30 (2015) 07, 1530022

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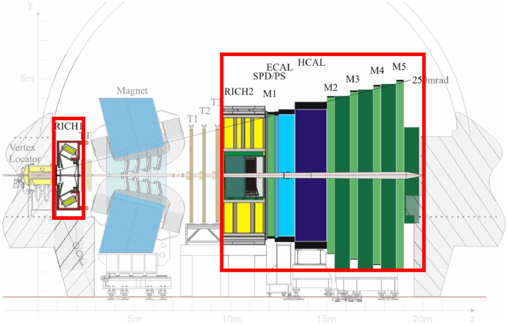

- Muon, RICH, ECAL and HCAL.
  - $\epsilon(e) \sim 90\%$, $e \to h$ misID $\sim 5\%$.
  - $\epsilon(K) \sim 95\%$, $\pi \to K$ misID $\sim 5\%$.
  - $\epsilon(\mu) \sim 97\%$, $\pi \to \mu$ misID $\sim 1-3\%$.

The LHCb Detector IJMPA 30 (2015) 07, 1530022

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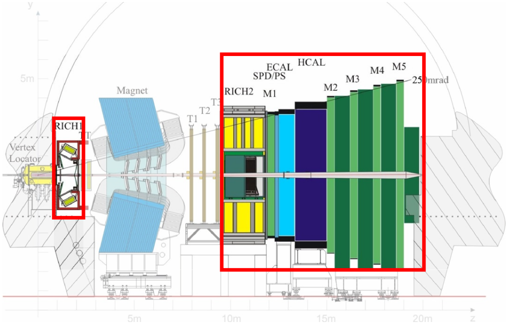

- Muon, RICH, ECAL and HCAL.
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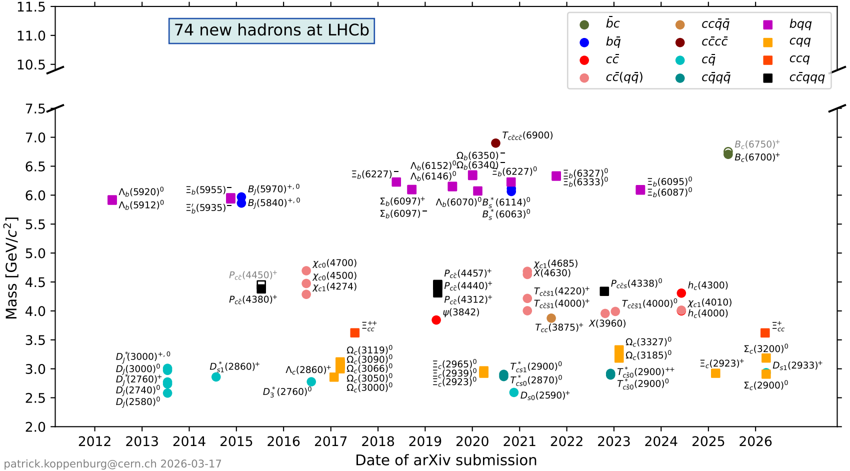
  - $\epsilon(\mu) \sim 97\%$, $\pi \to \mu$ misID $\sim 1 - 3\%$.
- **Good particle identification**:
  - Identify final state particles with high signal-to-background ratio, e.g. $\chi_{c1}(3872) \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$.

Recent Spectroscopy Results

- LHCb has a strong record of spectroscopy results. **74 hadrons at LHCb!**



Recent Spectroscopy Results

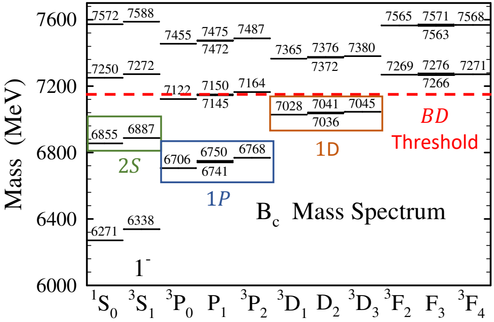
- Conventional:
  - $B_c(1P)^+$ in $B_c^+\gamma$ spectroscopy.
  - $D_{s1}(2933)^+$ in $B^0 \to D^+D^-K^+\pi^-$.
  - $\Sigma_c(2800)^0$, $\Sigma_c(2900)^0$,$\Sigma_c(3200)^0$ in $B^- \to \Lambda_c^+\bar{p}\pi^-$.
  - Ξ_{cc}^+ discovery covered by Jibo He.
- Exotic:
  - $T_{c\bar{c}}(4430)^+$ in $B^+ \to \psi(2S)K_s^0\pi^+$.
  - Amplitude analysis of $B^0 \to \eta_c K^+\pi^-$.

Conventional Spectroscopy

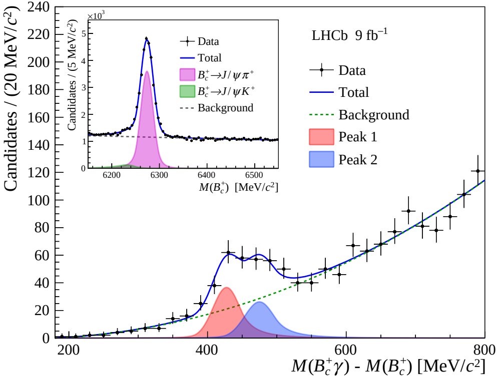
$B_c(1P)^+ \to B_c^+\gamma$

PRD 112 (2025) 11, 112003, PRL 135 (2025) 23, 231902

- B_c^+ is the only weakly decaying meson with two heavy quarks.
  - Like heavy $c\bar{c}$ and $b\bar{b}$ quarkonia, its production can be predicted by NRQCD.
- Unlike $Q\bar{Q}$, excited B_c^+ decay radiatively or via light hadrons below BD threshold.
  - Search for **orbitally excited** $B_c(1P)^+$ states via $B_c^+\gamma$.

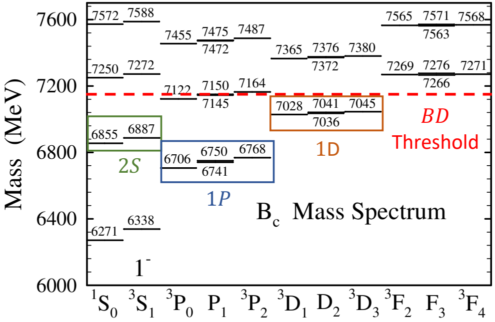


PRD 70 (2004) 054017

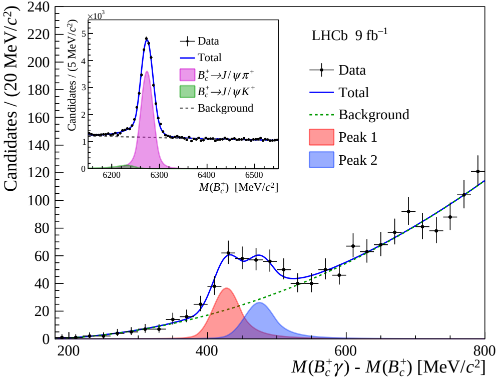


$B_c(1P)^+ \to B_c^+\gamma$ PRD 112 (2025) 11, 112003, PRL 135 (2025) 23, 231902

- Observation of $B_c(1P)^+ \to B_c^+\gamma$ decays, global significance 8σ, **local** 7σ.
- Experimental data can fitted with **effective two-peak model**:
  - $M_1 = 6704.8 \pm 5.5(\text{stat}) \pm 2.8(\text{syst}) \pm 0.3(B_c^+)$ MeV
  - $M_2 = 6752.4 \pm 9.5(\text{stat}) \pm 3.1(\text{syst}) \pm 0.3(B_c^+)$ MeV



PRD 70 (2004) 054017



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

PRD 112 (2025) 11, 112003, PRL 135 (2025) 23, 231902

- There are **four $B_c(1P)^+$ states**, but **six possible peaks** due to missing photons in $B_c^{*+} = B_c(1^3S_1)^+$. Explained elegantly from Liupan's CERN Seminar.

$B_c(1P)^+$ states

$$L = 1 \otimes S = \begin{cases} 0 \Rightarrow 1^1P_1 \\ 1 \Rightarrow \mathbf{1^3P_0} \quad 1^3P_1 \quad \mathbf{1^3P_2} \end{cases}$$

$\to B_c^+\gamma$: peak in $B_c^+\gamma$ mass spectrum

$\to B_c^{*+}(\to B_c^+\not{\gamma})\gamma$: peak in $B_c^+\gamma$ mass spectrum but shifted downwards by

$$\delta M = M(B_c^{*+}) - M(B_c^+)$$

mixing

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 1^1P_1 \\ 1^3P_1 \end{pmatrix} = \begin{pmatrix} \mathbf{1P_1'} \\ \mathbf{1P_1} \end{pmatrix} \begin{cases} \to B_c^+\gamma \\ \to B_c^{*+}(\to B_c^+\not{\gamma})\gamma \end{cases}$$

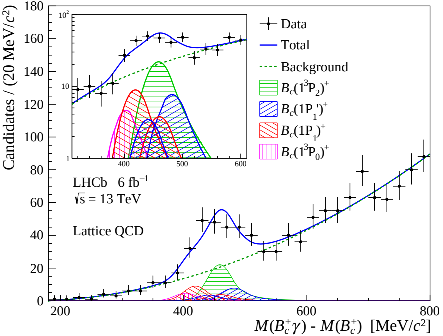
four states → **six peaks**

States	1^3P_0	$1P_1$	$1P_1'$	1^3P_2
Decays	$B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^+\gamma$ $B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^+\gamma$ $B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^{*+}(\to B_c^+\gamma)\gamma$
#peaks	1	2	2	1

2025/5/27 Liupan An 11/33

- Tested various theory models predicting the 6-peak $B_c(1P)^+$ spectrum.
  - All of them give ***p*-values of $15-90\%$**.
- Relative production rate of excited $B_c(1P)^+$ to ground state B_c^+ **consistent with `BcVegPy` prediction of $0.17-0.19$**:

$$R = 0.20 \pm 0.03(\text{stat}) \pm 0.03(\text{theory})$$

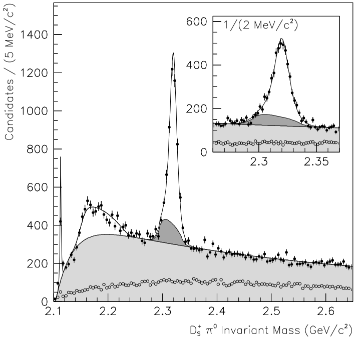


	δM	$M(1^3P_0)$	$M(1P_1)$	$M(1P_1')$	$M(1^3P_2)$	θ [°]
Lattice QCD [1]	41	6727	6743	6765	6783	33.4
GKLT [5]	64	6683	6717	6729	6743	17.1
GJ [6]	61	6689	6738	6757	6773	25.6
FUII [7]	55	6701	6737	6760	6772	28.5
EFG [8]	62	6699	6734	6749	6762	20.4
GI [9]	67	6706	6741	6750	6768	22.4
EQ [10]	54	6693	6731	6739	6759	18.7
LLLLGZ [11]	55	6714	6757	6776	6787	35.5
WWLC [12]	55	6705	6739	6748	6762	32.2
LTFWP [13]	53	6712	6770	6761	6783	−24.3
LLWL [14]	67	6701	6745	6754	6773	35.2
HZ [15]	63	6707	6751	6786	6802	55.0

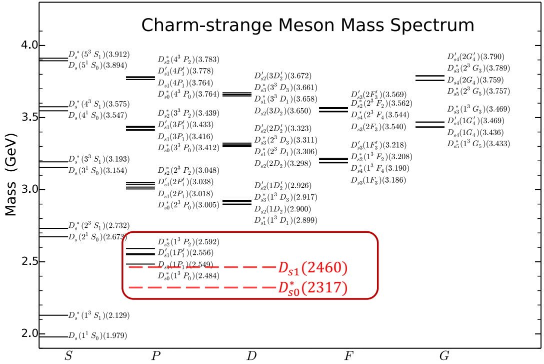
D_s^+ Quark Model

PRD 93 (2016) 3, 034035

- $D_{s0}^*(2317)^+ \to D_s^+\pi^0$ $(J^P = 0^+)$ and $D_{s1}(2460)^+ \to D_s^+\gamma$ $(J^P = 1^+)$ are about ~ 100 **MeV$/c^2$ below** predicted quark model masses. PLB 568 (2003) 254-260
  - Predictions $D_{s0}^*(2484)^+$ and $D_{s1}(2549)^+$.
- Possible explanations include exotic tetraquarks.



BaBar: PRD 74 (2006) 032007



- PRL 126 (2021) 12, 122002 observed $D_{s0}(2590)^+$ in this decay mode with amplitude analysis over **partial** $m(K^+\pi^-) < 750$ **MeV** data.
- New $D_{s1}(2933)^+$ at $> 10\sigma$ significance in **full phase space** amplitude analysis.
  - $M = 2933^{+6+4}_{-5-3}$ 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.

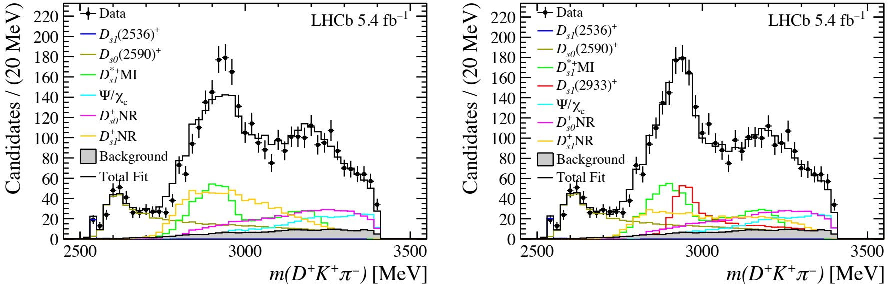
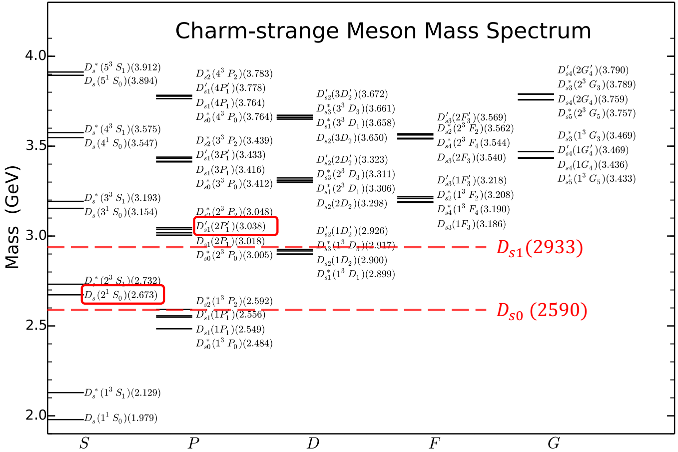


Figure: Without (left) and with (right) $D_{s1}(2933)^+$ in the fit.

Back To D_s^+ Quark Model

PRD 93 (2016) 3, 034035

- Like the $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$, excited D_{sJ}^+ states found in $B^0 \to D^+D^-K^+\pi^-$ are also below expected quark model masses.



- Measured $D_{s0}(2590)^+$, predicted $D_{s0}(2673)^+$.
- Measured $D_{s1}(2933)^+$, predicted $D_{s1}(3038)^+$ or $D_{s1}(3018)^+$.
- Are they non-conventional resonances?

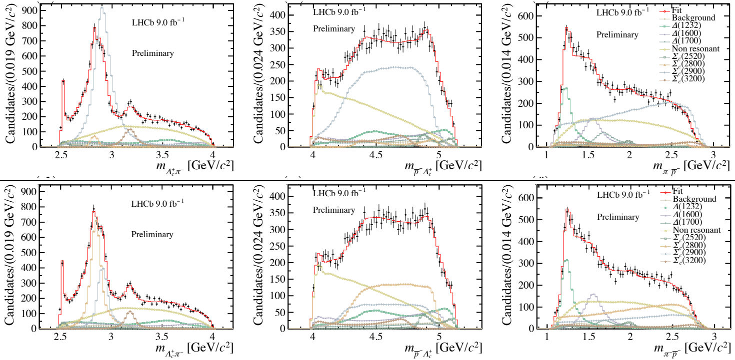
$B^- \to \Lambda_c^+ \bar{p} \pi^-$

LHCb-PAPER-2026-001 in preparation

- Belle observed $\Sigma_c(2800)^0$ (PRL 94 (2005) 122002) but BaBar reported an **inconsistent mass** (PRD 78 (2008) 112003) in $B^- \to \Lambda_c^+ \bar{p} \pi^-$ decays.
- New LHCb amplitude analysis of $B^- \to \Lambda_c^+ \bar{p} \pi^-$ favors **three** Σ_c^0:
  - **Two peak** $\Sigma_c(2800)^0$-$\Sigma_c(2900)^0$ 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

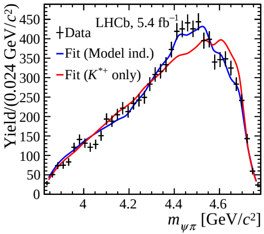
$B^+ \to \psi(2S) K_s^0 \pi^+$ Amplitude Analysis

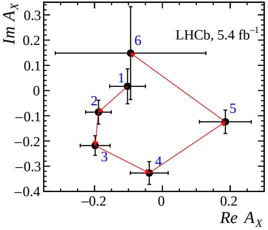
arXiv:2511.20428

- Isospin partner of $B^0 \to \psi(2S) K^+ \pi^-$, $T_{c\bar{c}}(4430)^- \to \psi(2S)\pi$ seen by Belle (PRL 100 (2008) 142001). $J^P = 1^+$ confirm by LHCb (PRL 112 (2014) 22, 222002).

	M (MeV)	Γ (MeV)
Belle[a]	$4485 \pm 22\,^{+28}_{-11}$	$200\,^{+41}_{-46}\,^{+26}_{-35}$
LHCb	$4475 \pm 7\,^{+15}_{-25}$	$172 \pm 13\,^{+37}_{-34}$

[a]Updated analysis: PRD (2009) 031104





- Isospin partner of $B^0 \to \psi(2S) K^+ \pi^-$.
- Fitting $B^+ \to \psi(2S) K_s^0 \pi^+$ with only $K^{*+} \to K_S^0 \pi^+$ 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 (BW) $T_{c\bar{c}}(4430)^+$ model **consistent with previous LHCb results**:
  - $M = 4.452 \pm 0.016^{+0.055}_{-0.033}$ GeV, $\Gamma = 0.174 \pm 0.019^{+0.083}_{-0.020}$ 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 $2 = \bar{D}_1^*(2600)^0 D^+$:

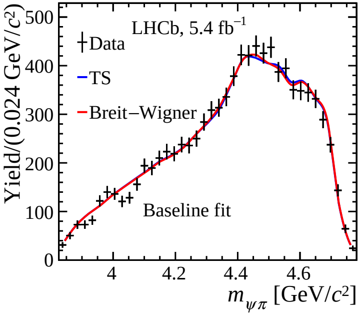
$$g_1 = 1.58 \pm 0.17^{+0.05}_{-0.82}\ \text{GeV}, \quad g_2 = 0.00 \pm 1.78 \pm 2.81\ \text{GeV}.$$

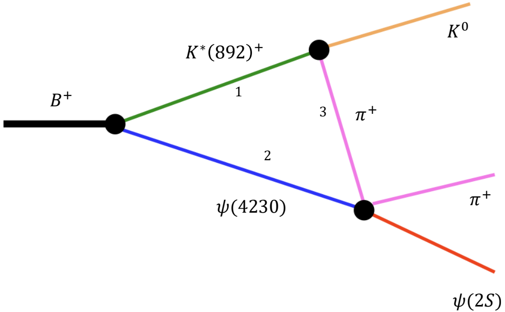
  - $|g_1/g_2| < 6.8$ at 95% confidence level, constraining $\bar{D}_1^*(2600)^0 D^+$ channel coupling to $T_{c\bar{c}1}(4430)^+$.

$B^+ \to \psi(2S) K_s^0 \pi^+$ Amplitude Analysis

arXiv:2511.20428

- **Triangle singularity** (PRD 100 (2019) 5, 051502) models data as well as BW.
  - 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 limited**: cannot distinguish between triangle singularity and Breit-Wigner models.





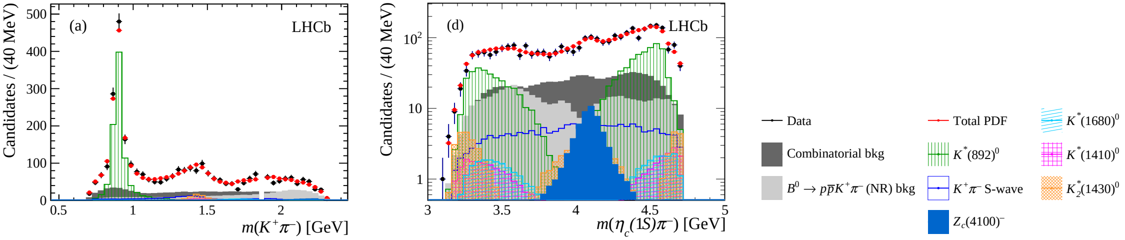
$B^0 \to \eta_c K^+ \pi^-$ Amplitude Analysis

EPJC 78 (2018) 12, 1019 (superseded)

- **Previous** LHCb amplitude analysis of $B^0 \to \eta_c K^+ \pi^-$ with LHCb Run 1 + 2016 data (4.7 fb^{-1}) found a 3.2σ **evidence** for $T_{c\bar{c}}(4100)^-$:

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

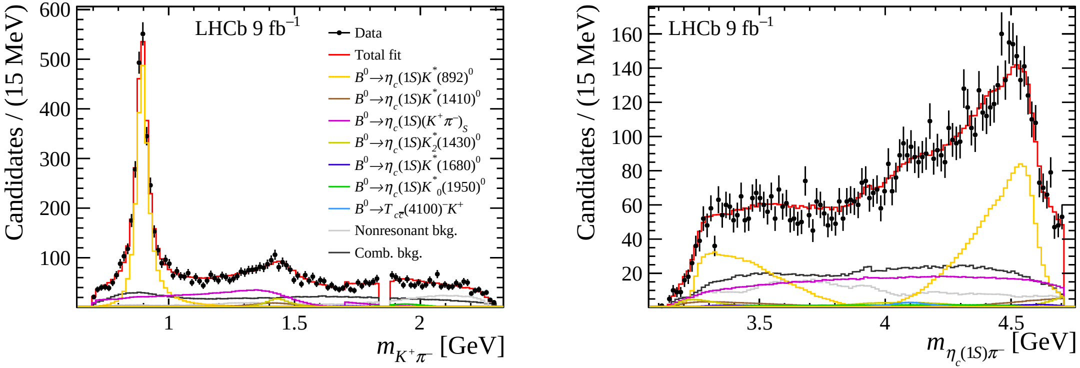
- Cannot distinguish between $J^P = 0^+$ or 1^-.
- Theory interpretation includes diquark-antidiquark and hadrocharmonium.



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

arXiv:2509.03133

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



Summary and Future Prospects

Summary and Future Prospects LHCB-FIGURE-2025-015, JINST 19 (2024) 05, P05065

- LHCb has a rich physics program of hadron spectroscopy:
  - Studies of **conventional hadrons** from b decays (excited Σ_c, D_s) or decays of **excited b hadrons** ($B_c(1P)^+ \to B_c^+\gamma$).
  - Studies of **exotic $T_{c\bar{c}}$ hadrons** from b decays.

Summary and Future Prospects LHCB-FIGURE-2025-015, JINST 19 (2024) 05, P05065

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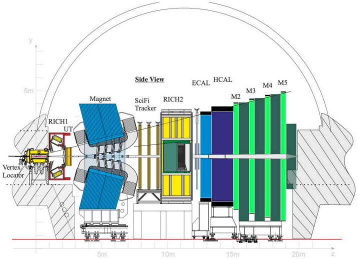
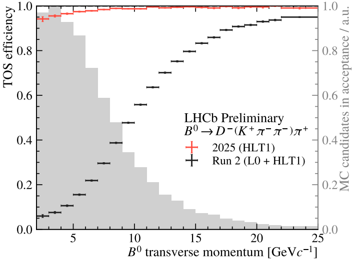
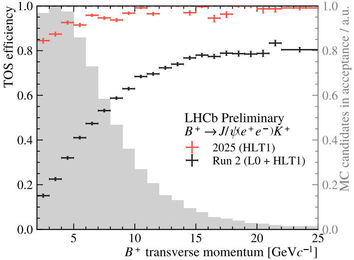






- Expect more to come with **Upgraded Run 3 detector**!
  - Software triggers $2-3\times$ **more efficient** on hadronic b decays.
  - Ξ_{cc}^+ discovery with $2.5\times$ more efficient triggers in Run 3.

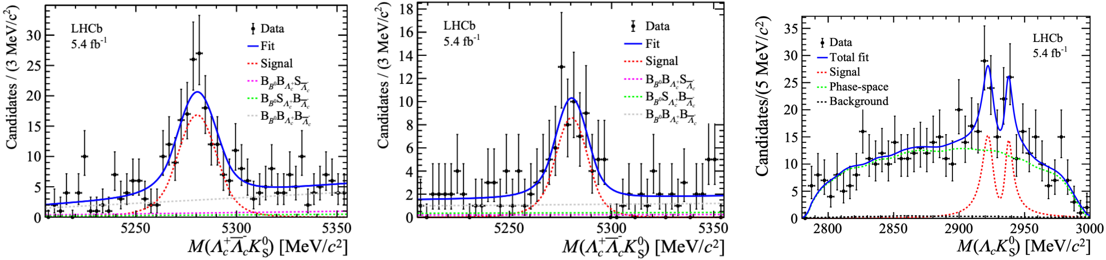
Backup

Not Covered

- Due to time constraints, I will not cover a few recent results.
  - They are available in the backup.
- Conventional:
  - Study of $\Xi_c(2923)^+$ and $\Xi_c(2939)^+$ in $B^0 \to \Lambda_c^+ \bar{\Lambda}_c^- K_s^0$.
- Exotic:
  - First observation of $\Lambda_b \to \Lambda_c^+ D_s^- K^+ K^-$.
  - First observation of $\chi_c(3872) \to J/\psi \mu^+ \mu^-$.

$B^0 \to \Lambda_c^+ \bar{\Lambda}_c^- K_s^0$

- 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 analaysis of $\Xi_c' \to \Lambda_c^+ K^-$ found two peaks, $\Xi_c(2923)$ and $\Xi_c(2939)$. Resolved $\Xi_c(2930)$?
- With 210 $B^0 \to \Lambda_c^+ \bar{\Lambda}_c^- K_s^0$ signal events: 3.9σ double peak vs no resonance hypotheses, 1.7σ double peak vs single peak hypotheses.



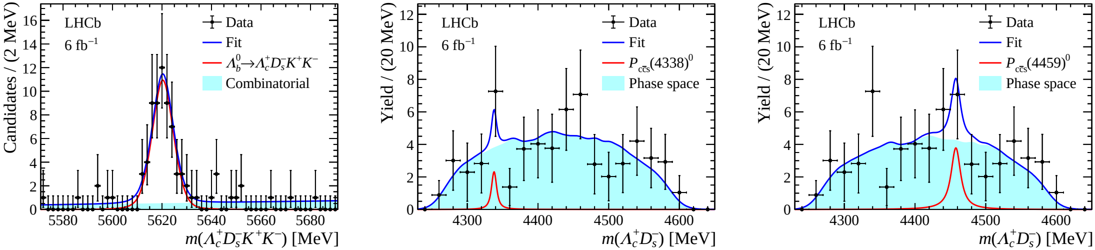
$\Lambda_b \to \Lambda_c^+ D_s^- K^+ K^-$

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:

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

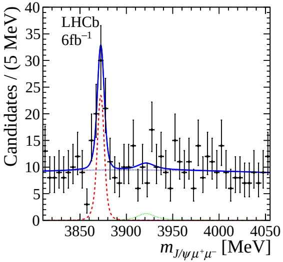
- No sensitivity to $P_{c\bar{c}s}$ in $m(\Lambda_c^+ D_s^-)$. Potential improvement in Run 3.

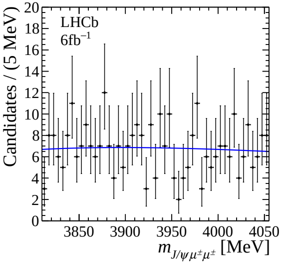


$\chi_{c1}(3872) \to J/\psi\mu^+\mu^-$

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

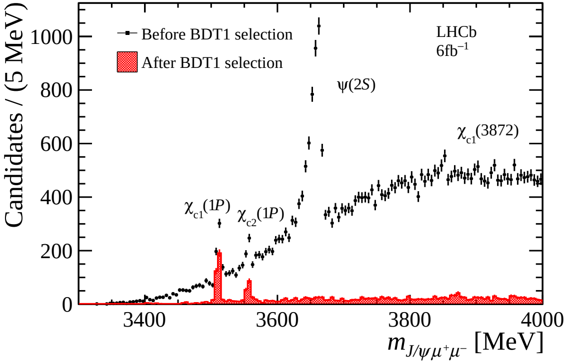
$$\mathcal{R} = \frac{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\mu^+\mu^-)}{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)} = (1.64 \pm 0.32 \pm 0.05) \times 10^{-3}.$$





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

- Experimentally, background dominated by pions decay in-flight $\pi^+ \to \mu^+\nu_\mu$ from $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$.
  - Suppressed by BDT, $\psi(2S) \to J/\psi\pi^+\pi^-$ peak disappears.



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

- Run 1 results shown below.