Hardon Spectroscopy at LHCb

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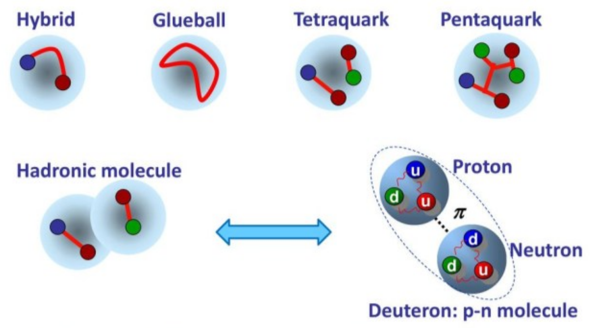
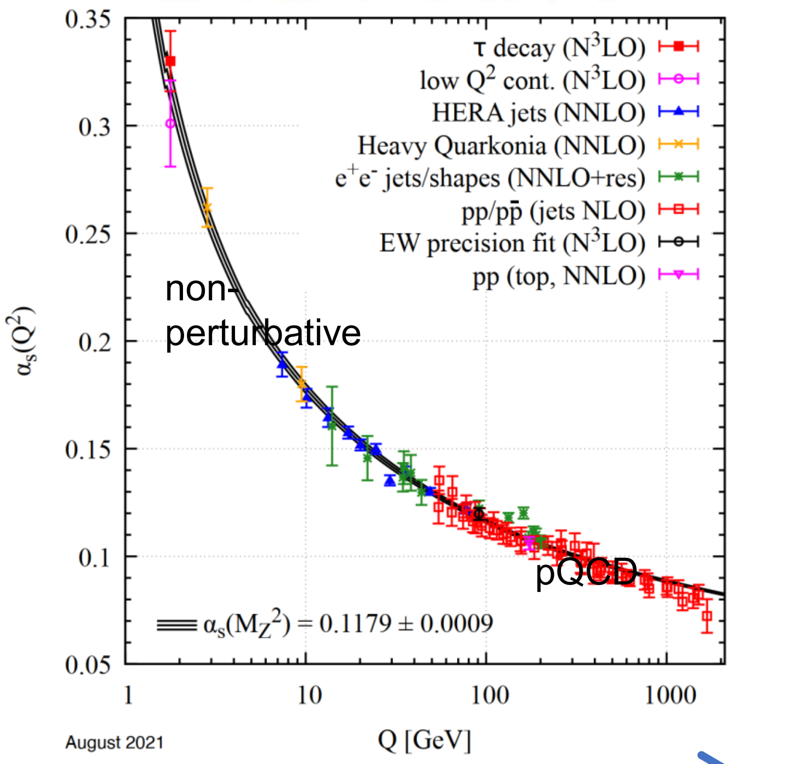
About hadron spectroscopy

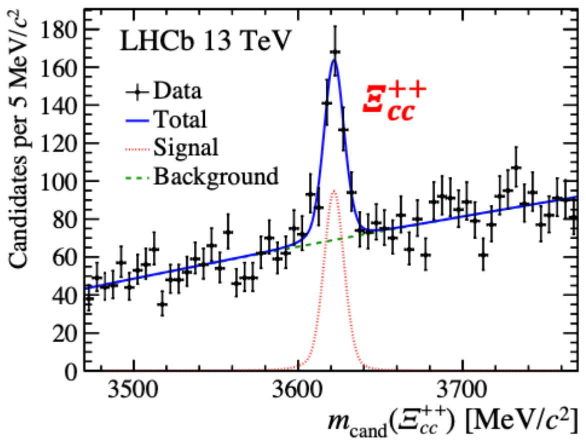
- QCD shows non-perturbative behavior at the energy scale of nuclei and hadrons.
- Spectroscopy of conventional hadrons (mesons and baryons) enriched in the past decades.
- Exotics are predicted since 1960s but first observed until 2003.
    - In the last 20 years, many new exotic candidates have been discovered in e^+e^- collision and hadron collision experiments.
- Experimental study of hadron spectroscopy can:
    - test the theory model → understand internal structure and production mechanism
    - provide inputs for theory → improve the precision and extensibility



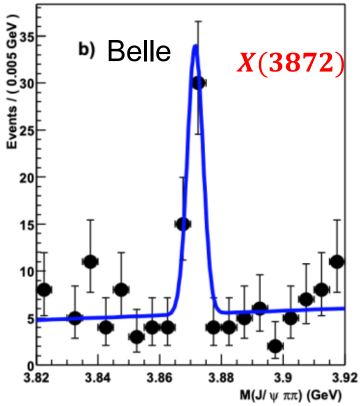


Lower energy (10^{-15} m scale)

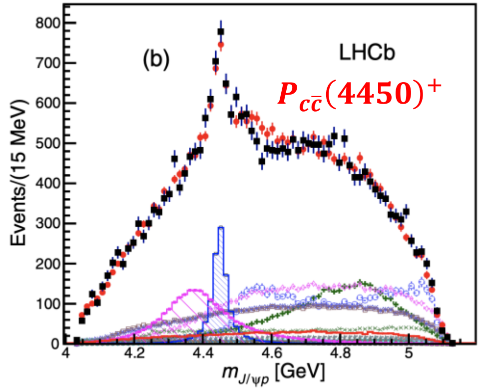
higher energy (10^{-18} m scale)



PRL117(2017) 112001



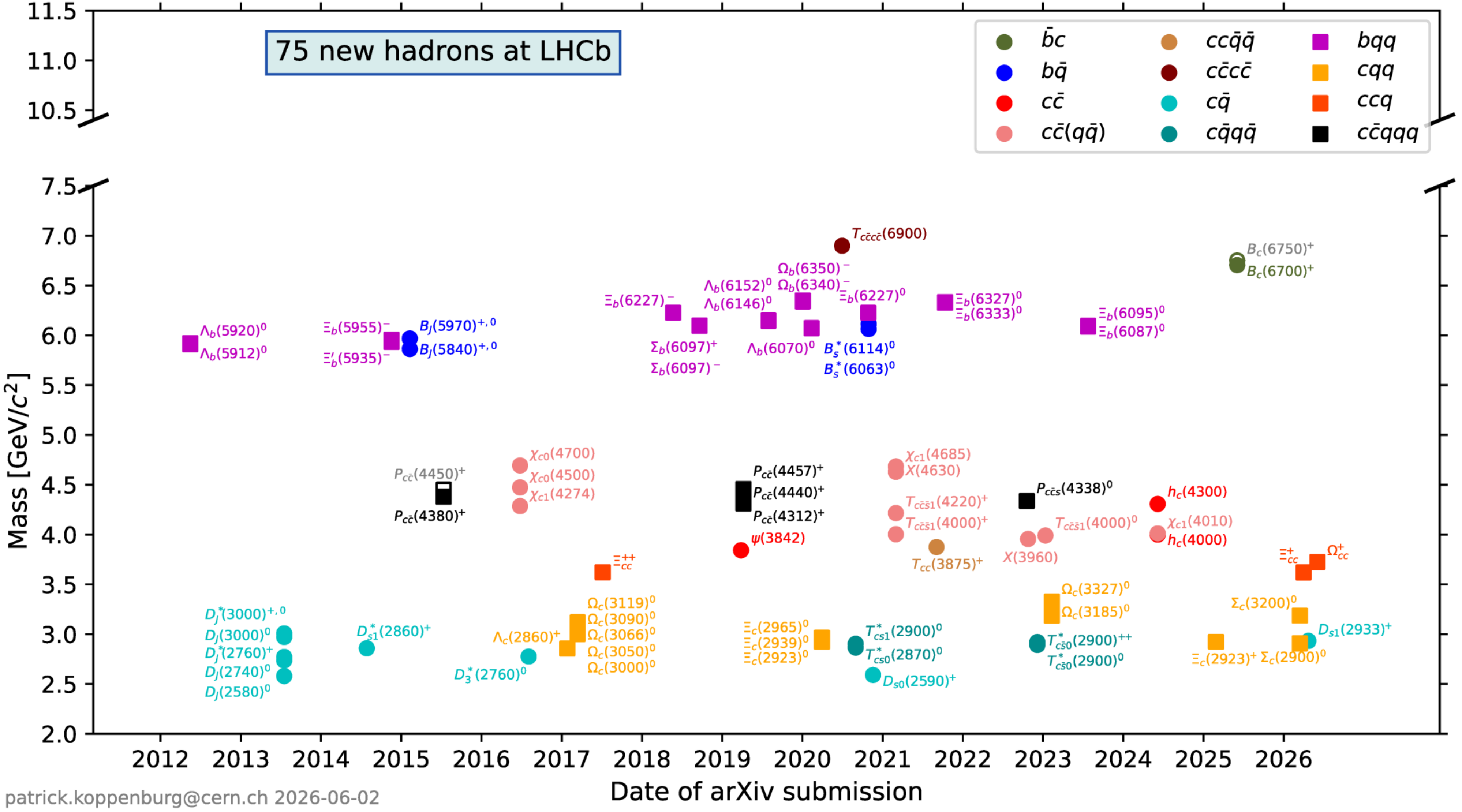
PRL 91 (2003) 262001



PRL115(2015)072001

Hadrons discovered by LHCb

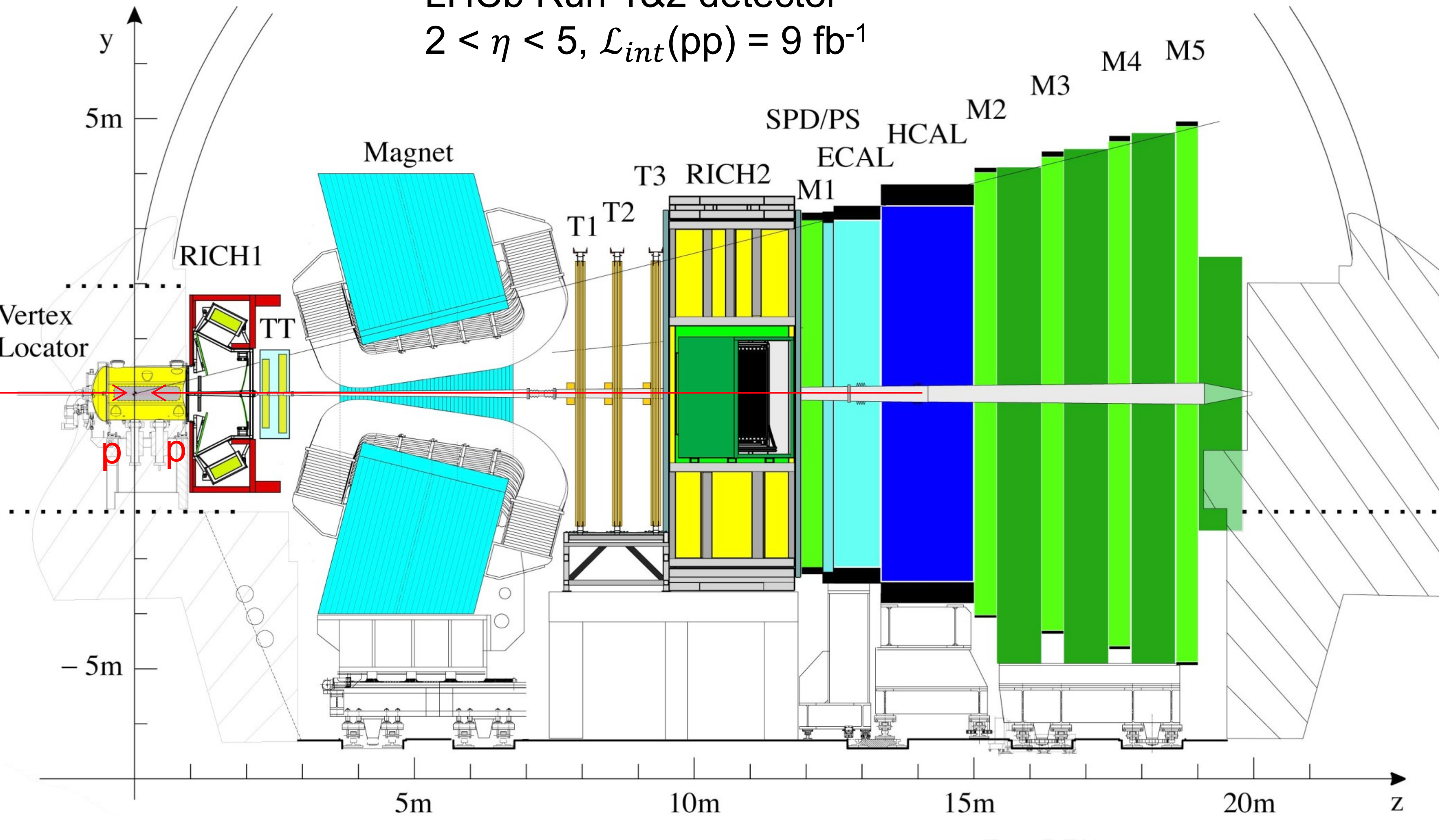
https://www.koppenburg.ch/particles.html



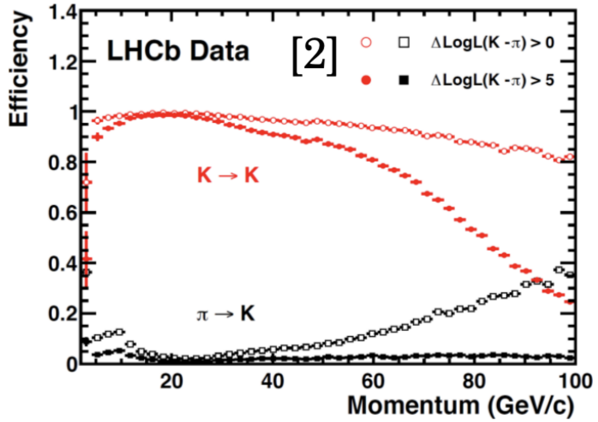
LHCb detector

- Single-arm, forward. Specifically designed for heavy-flavour physics.

LHCb Run 1&2 detector
$2 < \eta < 5$, $\mathcal{L}_{int}(pp) = 9\ \mathrm{fb}^{-1}$



- Excellent tracking and vertexing
  - $\sigma(p)/p < 1\%$ @ $\epsilon_{\mathrm{track}} > 96\%$
  - $\sigma(\mathrm{IP}) = (15 + 29/p_T)\ \mu m$
- Excellent PID
  - $\epsilon_{\mathrm{PID}}(K) \approx 95\%$ @ $\mathrm{MisID}(\pi \to K) \approx 5\%$
  - $\epsilon_{\mathrm{PID}}(\mu) \approx 97\%$ @ $\mathrm{MisID}(\pi \to \mu) \approx 3\%$



JINST3 (2008) S08005
IJMPA 30 (2015) 1530022

New results covered by this talk

- Conventional states and related:

Ξ_{cc}^{+} PRL 137, 021902 (2026)
Ω_{cc}^{+} LHCb-PAPER-2026-022 in preparation

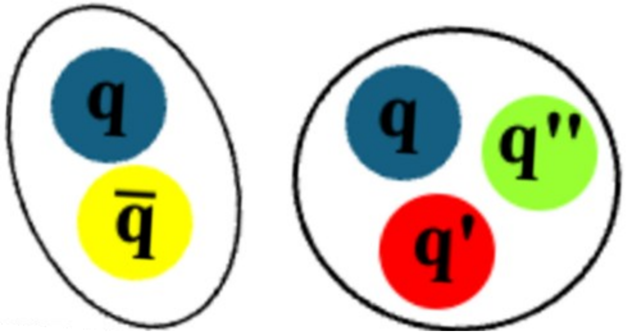
  - Observation of doubly charmed baryons: Ξ_{cc}^{+} and Ω_{cc}^{+}

See the talk on tomorrow (by Jibo) : 《LHCb上双重味重子实验研究》

  - Observation of $D_{s1}(2933)^{+}$ in $B^{+} \rightarrow D^{+}D^{-}K^{+}\pi^{-}$ decays — arXiv:2604.21257
  - Observation of new excited Σ_c^0 states in the $B^{-} \rightarrow \Lambda_c^{+}\overline{p}\,\pi^{-}$ decay — arXiv:2607.10595

- Exotic states and related:
  - Observation of the decay $\chi_{c1}(3872) \rightarrow J/\psi\mu^{+}\mu^{-}$ — PRD 113, 072019 (2026)
  - Amplitude analysis of $B^{0} \rightarrow \eta_c(1S)K^{+}\pi^{-}$ decays — EPJC 86 537 (2026)
  - Observation and investigation of the $T_{c\bar{c}1}(4430)^{+}$ structure in $B^{+} \rightarrow \psi(2S)K_S^0\pi^{+}$decays — PRD 113, L071101 (2026)

Red: Analysis mainly completed by Chinese groups/people.



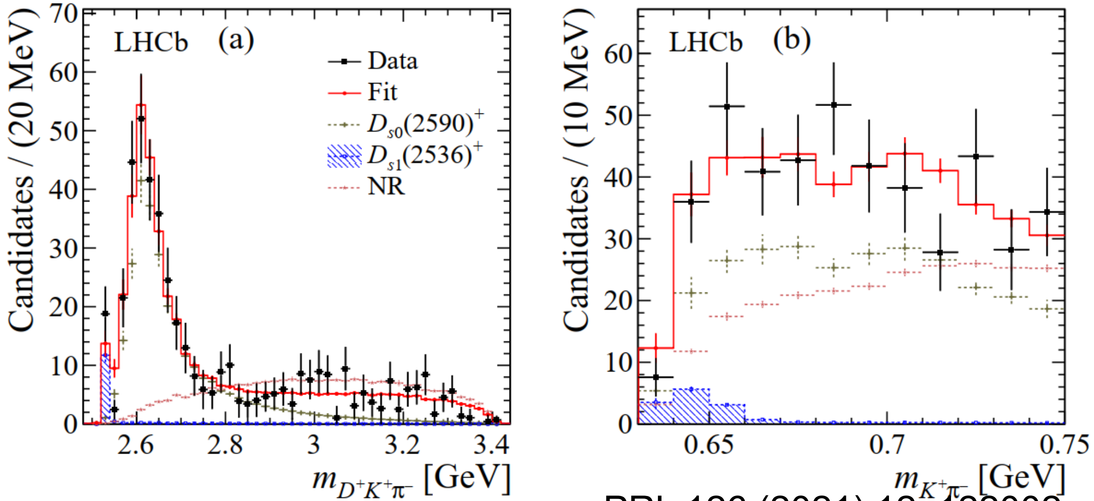
Conventional spectroscopy

Observation of $D_{s1}(2933)^+$ in $B^+ \to D^+D^-K^+\pi^-$ decays

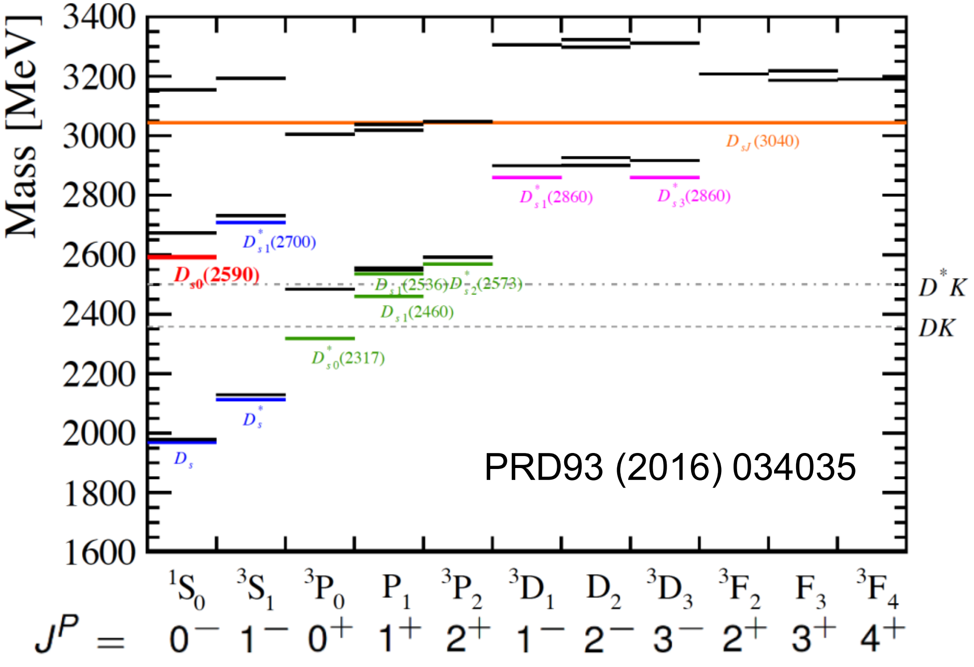
https://arxiv.org/abs/2604.21257

- The $D_s^{(*)+}$ spectrum is complicated:
  - Several predicted states (below 3.1GeV) haven't yet been observed
  - $D_{s0}(2317)$ and $D_{s1}(2460)$ puzzle
- The D_s^{*+} search benefits from using the $D^+K^+\pi^-$ (inc. D^+K^{*0}) final state
  - can access both natural $(0^+, 1^-, ...)$ and unnatural $(0^-, 1^+, ...)$ J^P configurations
  - No π^0 or γ, benefit from good PID of charged tracks
- Previous study ($m_{K^+\pi^-} < 0.75$ GeV):
  - $D_{s0}(2590)^+$ $J^P = 0^-$ observed

$m_R = 2591 \pm 6 \pm 7$ MeV
$\Gamma_R = 89 \pm 16 \pm 12$ MeV



PRL 126 (2021) 12, 122002

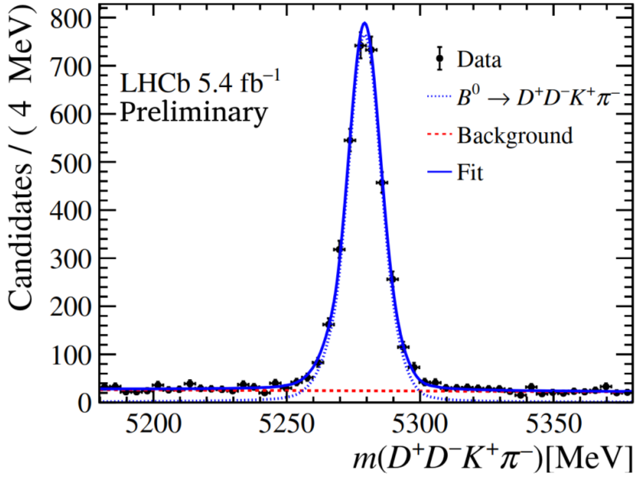


spectrum of $c\bar{s}$ mesons

Observation of $D_{s1}(2933)^+$ in $B^+ \to D^+D^-K^+\pi^-$ decays

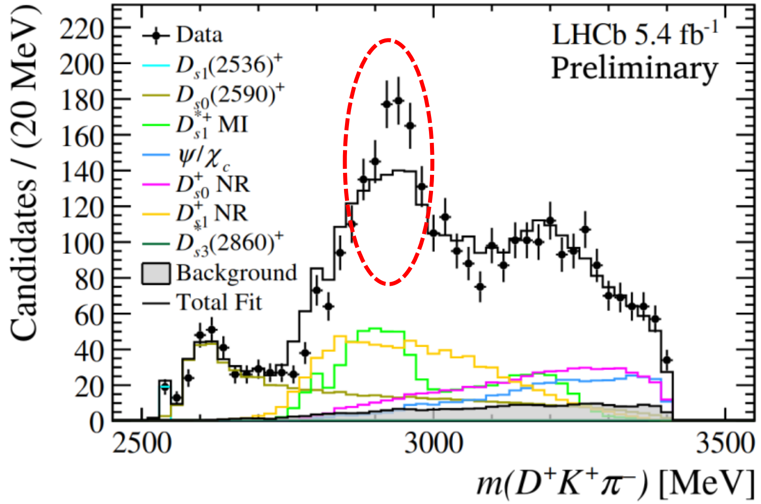
https://arxiv.org/abs/2604.21257

- This study: same dataset but full phase space region (no cut on $m_{K\pi}$)
  - Full 4D amplitude analysis

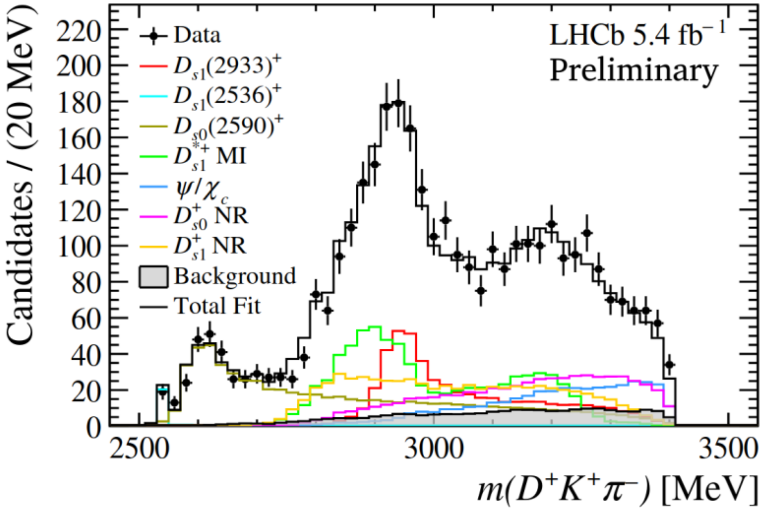


~3260 $B^\pm$ signal

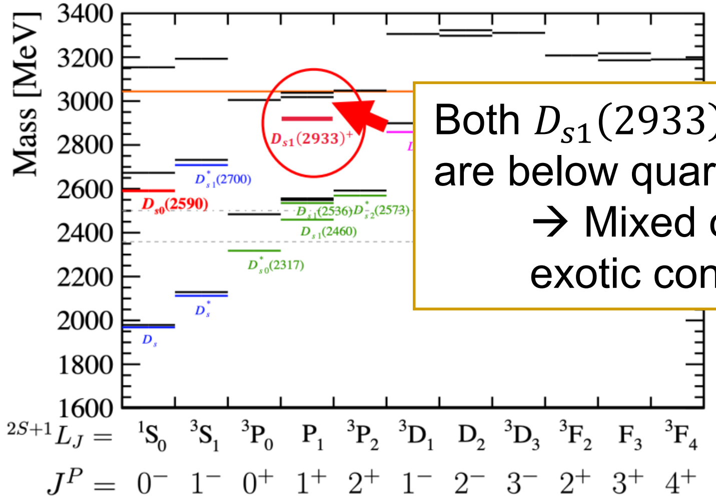
Only known K^* and D_s^* and ψ/χ_c do not correctly describe the data



Add a new state $D_{s1}(2933)^+$



- About the new $D_{s1}(2933)^+$ state:
  - $m = 2933^{+6}_{-5}(\text{stat})^{+4}_{-3}(\text{syst})$ MeV
  - $\Gamma = 72^{+18}_{-12}(\text{stat})^{+7}_{-10}(\text{syst})$ MeV
  - Significance > 10σ
  - $J^P = 1^+$ preferred by 5σ
  - Candidate for the conventional $D_s(2P')$ state
- $D_{s0}(2590)^+$mass and width consistent with previous measurements



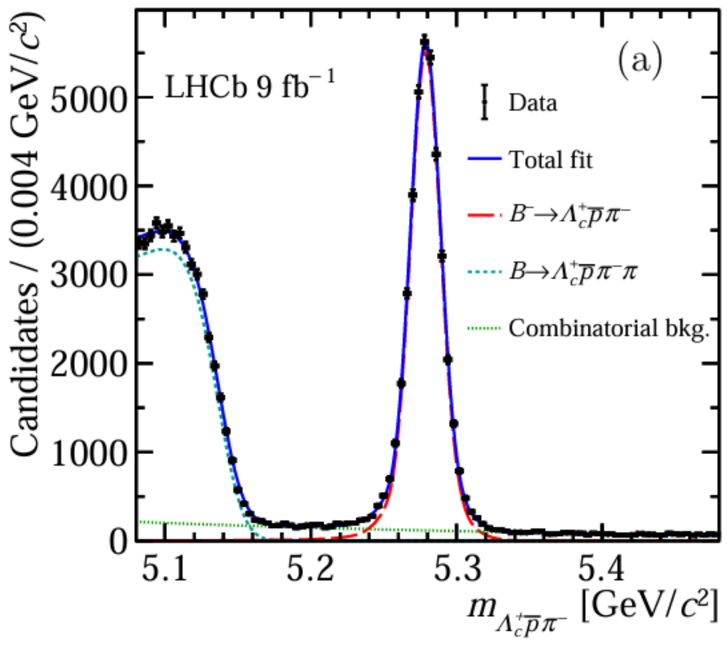
Both $D_{s1}(2933)^+$ and $D_{s0}(2590)^+$ are below quark-model prediction
→ Mixed of conventional and exotic contribution?

Observation of new excited Σ_c^0 states in the $B^- \to \Lambda_c^+ \bar{p}\, \pi^-$ decay

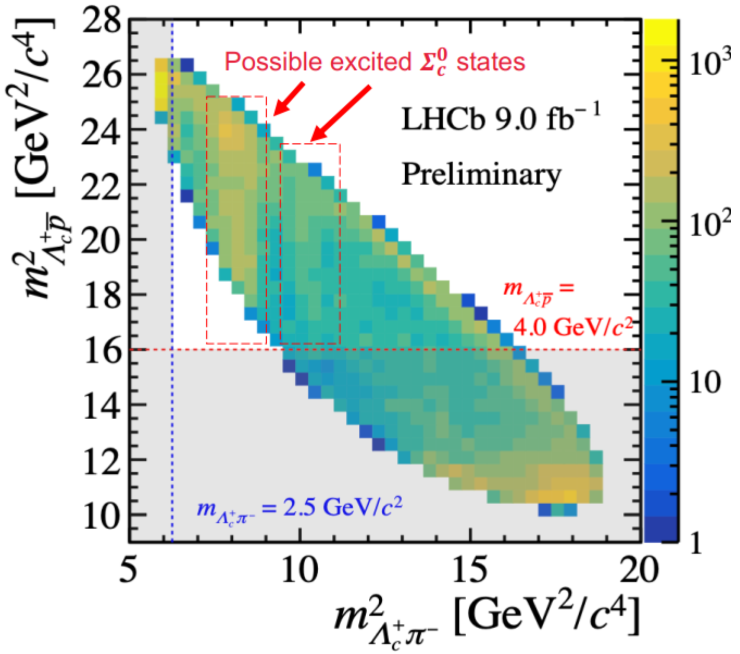
arXiv:2607.10595

Fit Parameter	BaBar	Belle
m_R (GeV/c^2)	2.846 ± 0.008	$2.802^{+0.004}_{-0.007}$
Γ_R (MeV)	86^{+33}_{-22}	61^{+28}_{-18}

- Excited charmed baryons:
  - $\Sigma_c^0(2800)$ reported by Belle and BaBar is inconsistent
    PRL94 (2005) 122002, PRD 78 112003
- This work: search for Σ_c^0 in the $\Lambda_c^+\pi^-$ system of the $B^- \to \Lambda_c^+\bar{p}\pi^-$ decay using LHCb Run 1+2 data



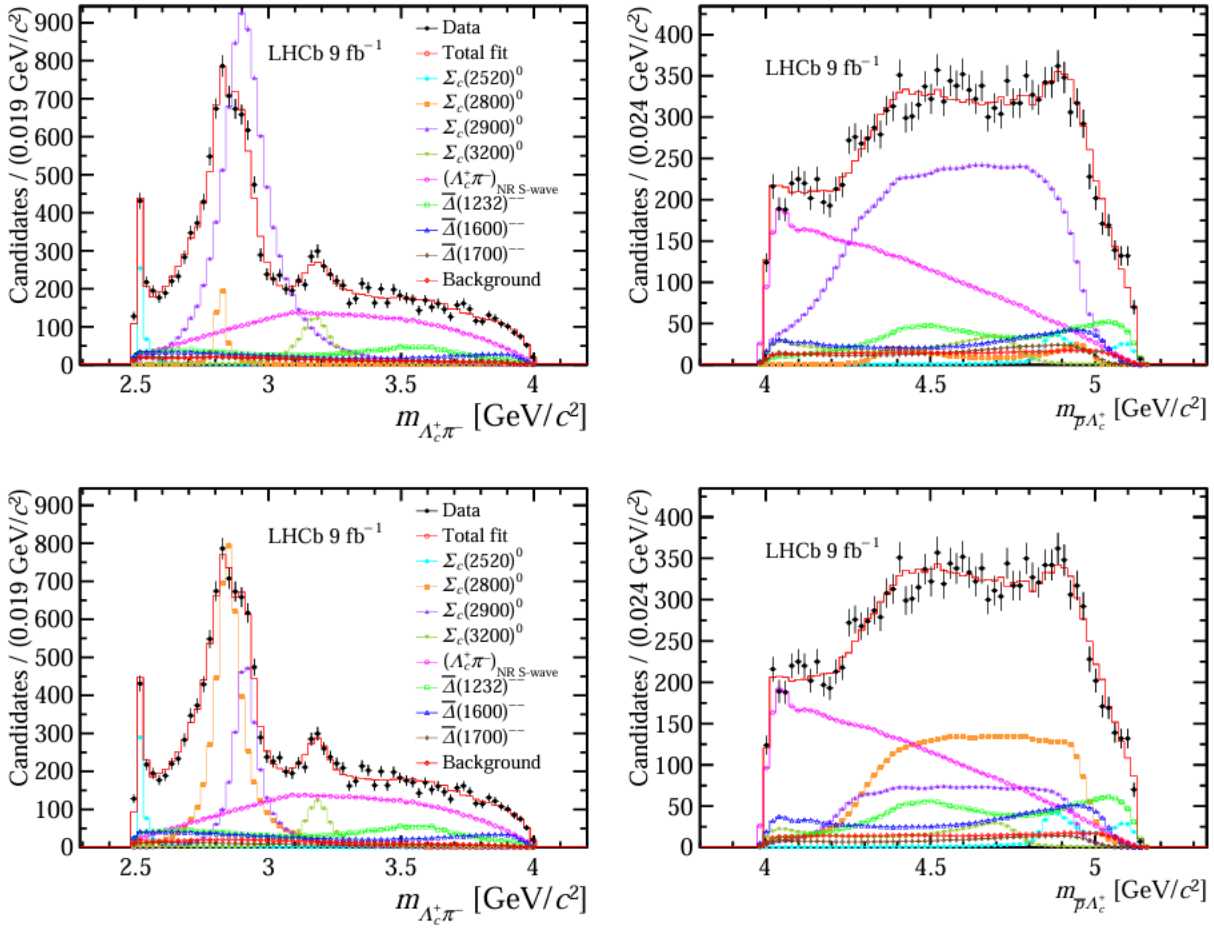
$\sim 3.7 \times 10^4$ signal



Data in red dashed square:
Used in the amplitude fit

Observation of new excited Σ_c^0 states in the $B^- \to \Lambda_c^+ \overline{p}\, \pi^-$ decay

- In addition to $\Sigma_c(2520)^0$ and $\Sigma_c(2800)^0$, two new states $\Sigma_c^0(2900)$ and $\Sigma_c^0(3200)$ are found.
- Two solution groups show identically fit quality but exhibit significant differences.



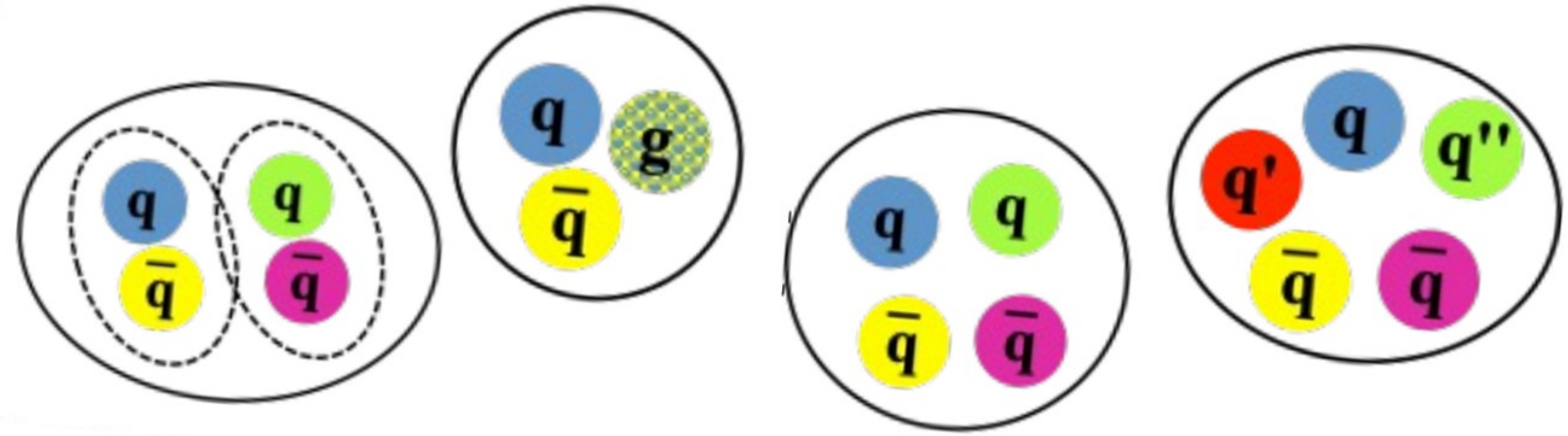
Parameter	Group A	Group B
$m_{\Sigma_c(2800)^0}\,[\text{GeV}/c^2]$	$2.819 \pm 0.006 \pm 0.002$	$2.848 \pm 0.004 \pm 0.006$
$\Gamma_{\Sigma_c(2800)^0}\,[\text{GeV}]$	$0.033 \pm 0.007 \pm 0.008$	$0.099 \pm 0.007 \pm 0.021$
$m_{\Sigma_c(2900)^0}\,[\text{GeV}/c^2]$	$2.908 \pm 0.005 \pm 0.009$	$2.914 \pm 0.003 \pm 0.008$
$\Gamma_{\Sigma_c(2900)^0}\,[\text{GeV}]$	$0.175 \pm 0.008 \pm 0.023$	$0.092 \pm 0.006 \pm 0.023$
$m_{\Sigma_c(3200)^0}\,[\text{GeV}/c^2]$	$3.186 \pm 0.006 \pm 0.014$	$3.190 \pm 0.005 \pm 0.011$
$\Gamma_{\Sigma_c(3200)^0}\,[\text{GeV}]$	$0.133 \pm 0.018 \pm 0.027$	$0.100 \pm 0.015 \pm 0.032$
$\mathcal{R}(\Sigma_c(2520)^0)$	$0.09 \pm 0.01 \pm 0.02$	$0.11 \pm 0.01 \pm 0.03$
$\mathcal{R}(\Sigma_c(2800)^0)$	$0.09 \pm 0.02 \pm 0.05$	$0.86 \pm 0.07 \pm 0.42$
$\mathcal{R}(\Sigma_c(2900)^0)$	$1.68 \pm 0.07 \pm 0.29$	$0.50 \pm 0.04 \pm 0.19$
$\mathcal{R}(\Sigma_c(3200)^0)$	$0.21 \pm 0.03 \pm 0.05$	$0.17 \pm 0.03 \pm 0.05$
$\mathcal{R}((\Lambda_c^+\pi^-)_{\text{NR S-wave}})$	$2.19 \pm 0.14 \pm 0.22$	$2.23 \pm 0.11 \pm 0.30$

For $\Sigma_c(2800)^0$:

- Solution A consistent with the Belle
- Solution B consistent with the BABAR

➔ Need further investigation!

arXiv:2607.10595



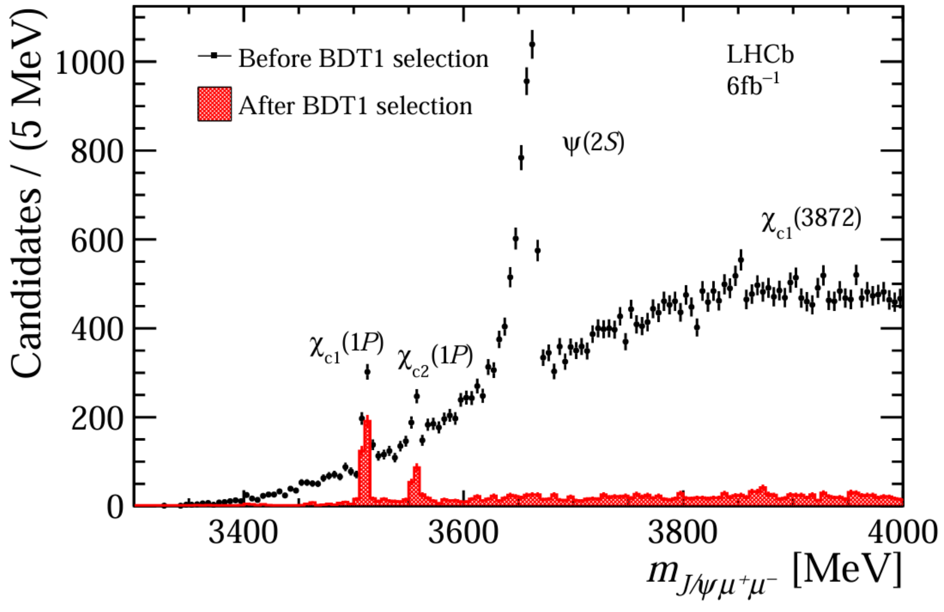
Exotic spectroscopy

Observation of the decay $\chi_{c1}(3872) \rightarrow J/\psi\mu^+\mu^-$

PRD 113, 072019 (2026)

- $\chi_{c1}(3872)$ is well-established in many experiments
  - Nature of $\chi_{c1}(3872)$ remains investigation: exotic (molecule? compact?) or a mixture of charmonium and exotic
- Study of $\chi_{c1}(3872) \rightarrow J/\psi\mu^+\mu^-$ has several possible contributions:
  - Virtual photon at low $m_{\mu\mu}$ → related to the radiative decay of $\chi_{c1}(3872)$
  - Higher $m_{\mu\mu}$ region → ρ or ω contribution may exist
  - Simultaneously searching for $\chi_{c0}(3915)$

$$\mathcal{R} \equiv \frac{\mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi\mu^+\mu^-)}{\mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-)} = \frac{N_{\mu^+\mu^-}\,\epsilon_{\pi^+\pi^-}\,\epsilon^{\mathrm{Corr}}_{\mathrm{PID}}}{N_{\pi^+\pi^-}\,\epsilon_{\mu^+\mu^-}\,\epsilon^{\mathrm{Corr}}_{\mathrm{BDT1}}\,\epsilon^{\mathrm{Corr}}_{\mathrm{BDT2}}}$$



- Full Run1 & Run2 data (3fb^{-1} + 6fb^{-1})
- Machine-learning based selection:
  - BDT1: reject the pion → muon misidentification
  - BDT2: reject the J/ψ – dimuon random combination

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

PRD 113, 072019 (2026)

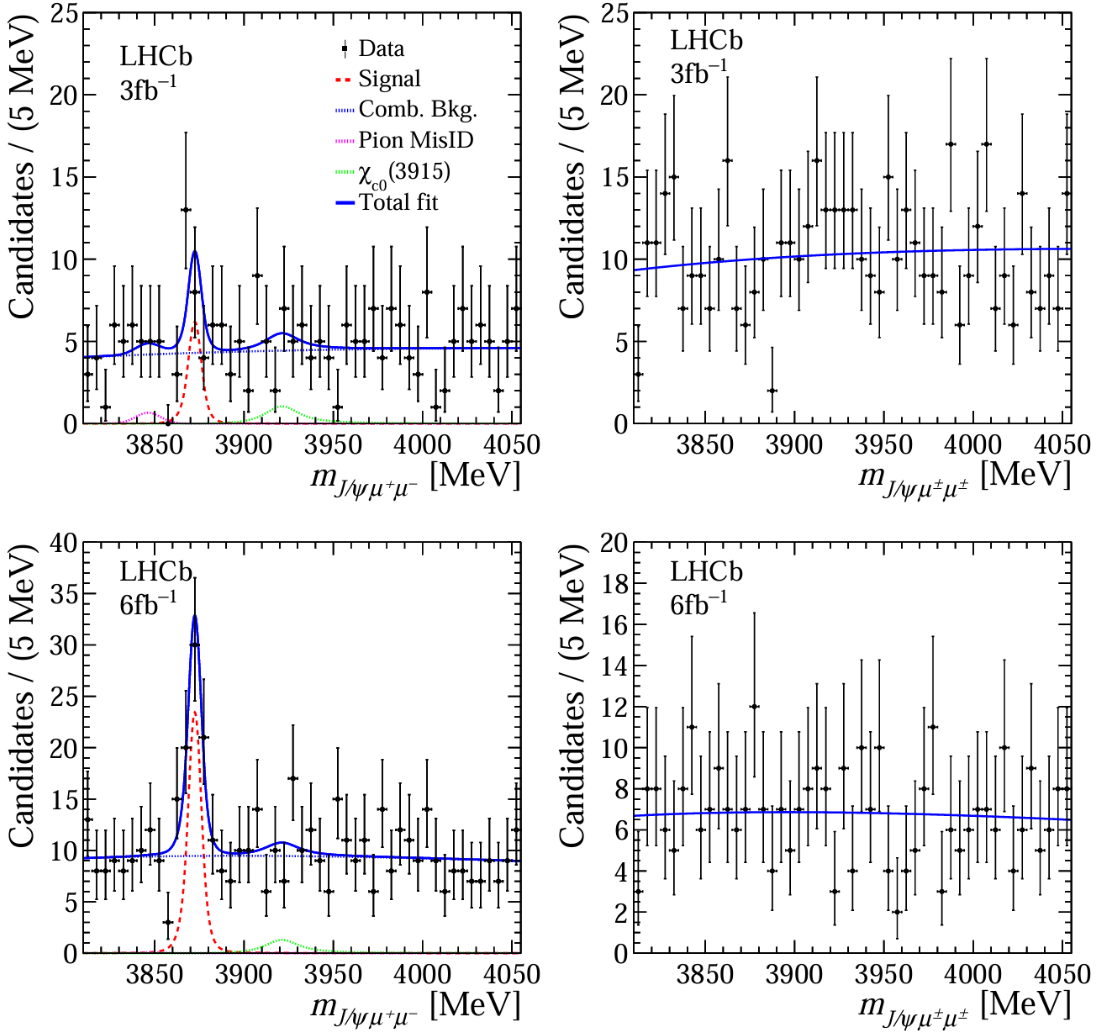
- 60 ± 11 $\chi_{c1}(3872)$ signals: significance $> 6\sigma$
- 14 ± 14 $\chi_{c0}(3915)$: not observed
- Relative branching fraction:

$$\mathcal{R} = (1.68 \pm 0.32 \pm 0.05) \times 10^{-3}$$

- Quoting the lasted $\mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)$,

$$\mathcal{B}(\chi_{c1}(3872) \to J/\psi\mu^+\mu^-) = (7.2 \pm 2.7) \times 10^{-5}$$

- Not enough statistic to disentangle contribution from virtual photon and ρ or ω



Opposite-sign dimuon

Same-sign dimuon

Amplitude analysis of $B^0 \to \eta_c(1S)K^+\pi^-$ decays

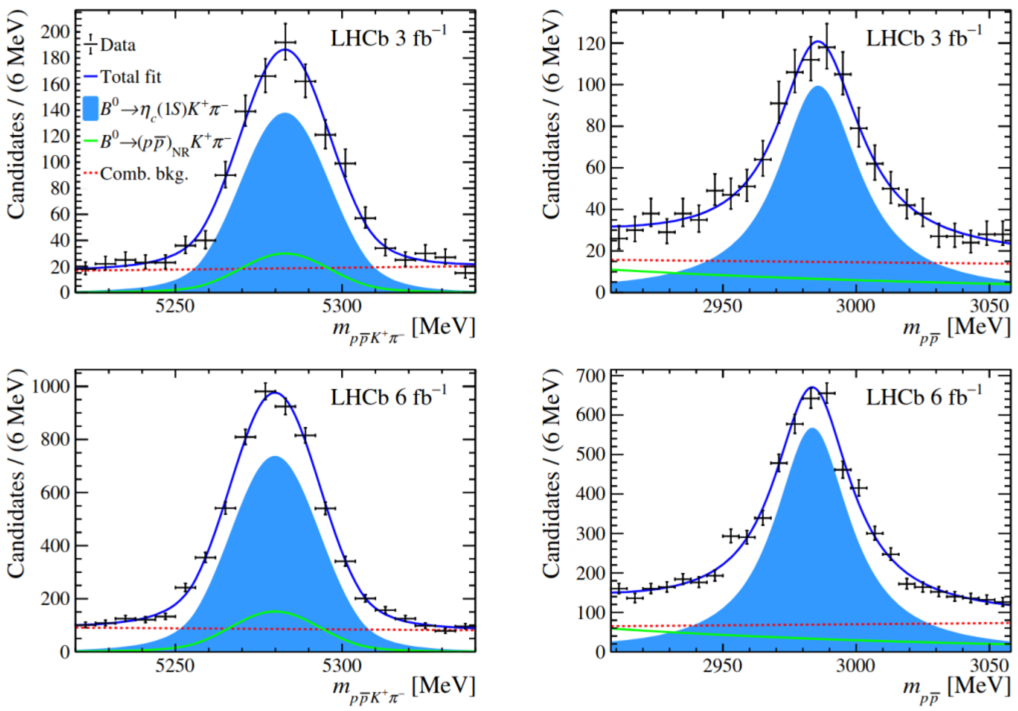
EPJC 86 537 (2026)

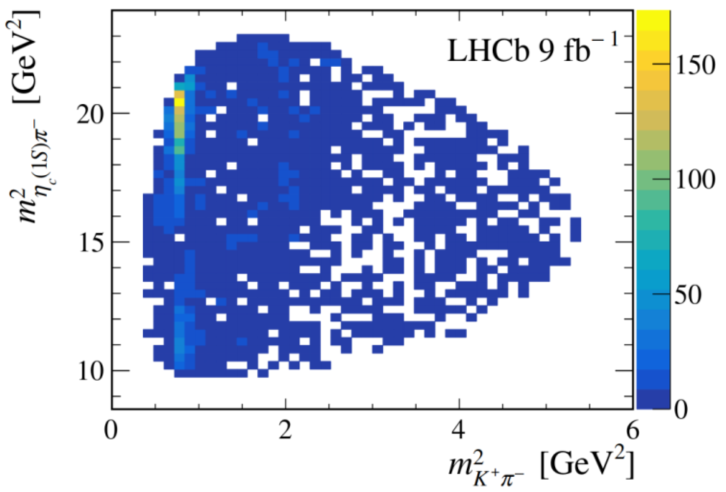
- Evidence of $T_{c\bar{c}}(4100)$ found in $\eta_c\pi^-$ by LHCb (using Run 1 + 2016)
  - Improved analysis using full Run1 & Run2

EPJC 78 1019 (2018)

- 2D fit on $m(p\bar{p}K^+\pi^-), m(p\bar{p})$
  - 5038 $B^0/\bar{B}^0$ signal
  - sPlot technique to determine the background lineshape

  ➔ to be used in amplitude analysis





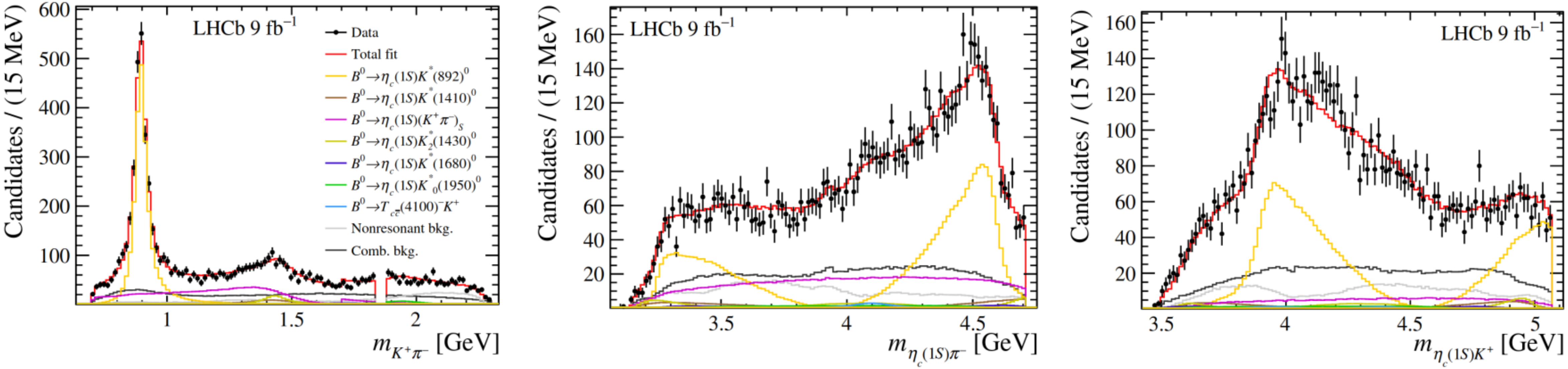
Baseline model: Low mass $K^+\pi^-$-S wase

- K^* LASS model

Amplitude analysis of $B^0 \to \eta_c(1S)K^+\pi^-$ decays

EPJC 86 537 (2026)

- Extended model: Add a $T_{c\bar{c}}(4100)$ in $\eta_c\pi^-$, fit quality improved
  - Properties from the default fit in agreement with old results $m = 4106 \pm 23$ MeV, $\Gamma = 506 \pm 166$ MeV
  - However, the significance becomes <3σ after considering systematical uncertainties.
- Comments:
  - The old result is superseded. No contribution from $T_{c\bar{c}}(4100)$ in this data.



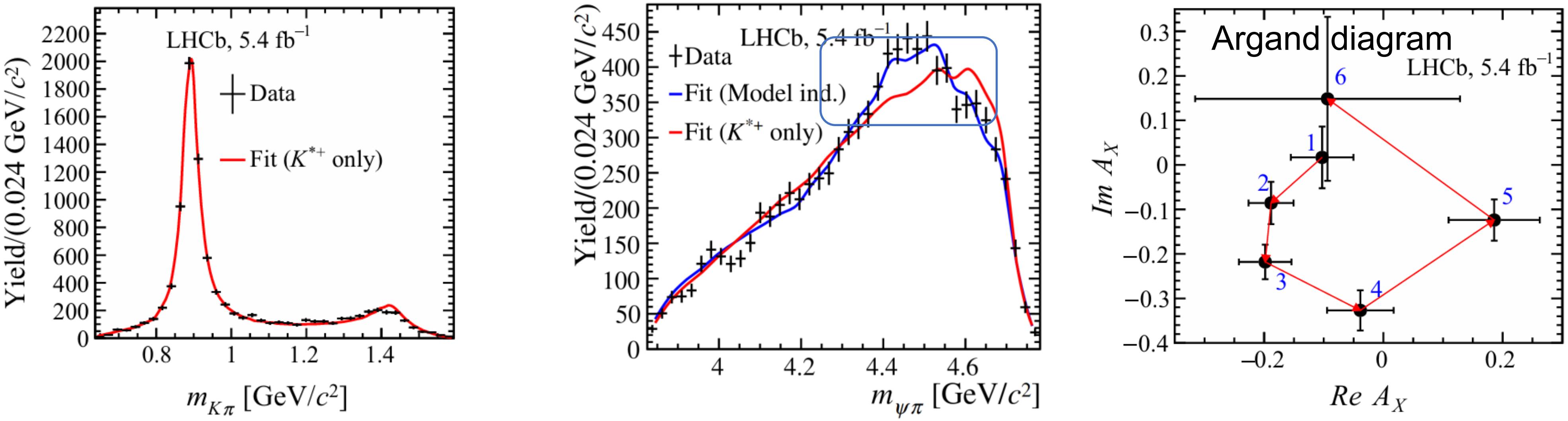
- Branching fraction: $\mathcal{B}(B^0 \to \eta_c K^+\pi^-) = (5.82 \pm 0.20 \pm 0.23 \pm 0.55) \times 10^{-4}$

$T_{c\bar{c}1}(4430)^+$ in $B^+ \to \psi(2S) K_S^0 \pi^+$ decays

PRD 113, L071101 (2026)

- About $T_{c\bar{c}1}(4430)^+$
  - Discovered by Belle in 2007 in $B^{+,0} \to K^{0,-} \pi^+ \psi(2S)$ PRL 100 (2008) 142001
  - Confirmed by LHCb $J^P = 1^+$ in B^0 decays. PRL12 (2014) 22, 222002
- 4-dimensional amplitude analysis of $B^+ \to \psi(2S) \pi^+ K_S^0$ decays

Red curve: Amplitude fit result with only K^* contributions



K*-only model cannot describe the data – more structures in $m_{\psi\pi^+}$ needed

→ Model-independent fit gives a circular phase shift as $m_{\psi\pi}$ increases.

→ Not a statistical fluctuation but physical states/effects.

$T_{c\bar{c}1}(4430)^+$ in $B^+ \to \psi(2S)K_S^0\pi^+$ decays

PRD 113, L071101 (2026)

Model-dependent investigation:

Structure modelled as a genuine state

Relativistic Breit-Wigner parametrization

$m(\mathrm{GeV}/c^2)$	$\Gamma(\mathrm{GeV})$	J^P
$4.452 \pm 0.016^{+0.055}_{-0.033}$	$0.174 \pm 0.019^{+0.083}_{-0.020}$	1^+

Properties consistent with $T_{c\bar{c}1}(4430)^+$ state

Furthermore, assuming $T_{c\bar{c}1}(4430)^+$ is $\bar{D}_1^*(2600)^0 D^+$ hadronic molecule

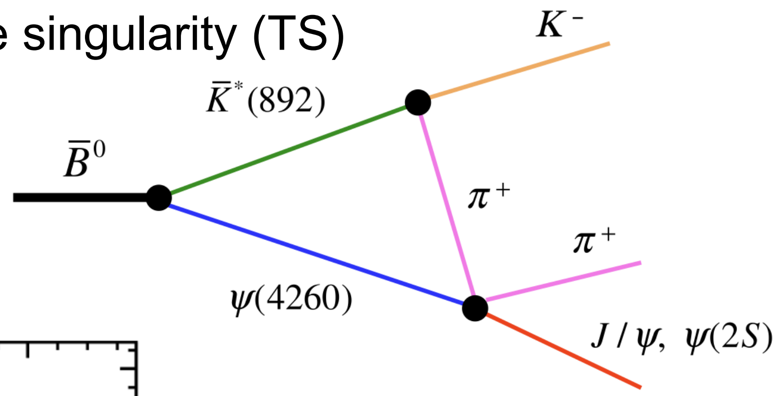
$$F = \frac{1}{m_0^2 - m^2 - i(\rho_1 g_1^2 + \rho_2 g_2^2)}$$

g_1: $T_{c\bar{c}1}(4430)^+ \to \psi(2S)\pi^+$
g_2: $T_{c\bar{c}1}(4430)^+ \to \bar{D}_1^*(2600)^0 D^+$

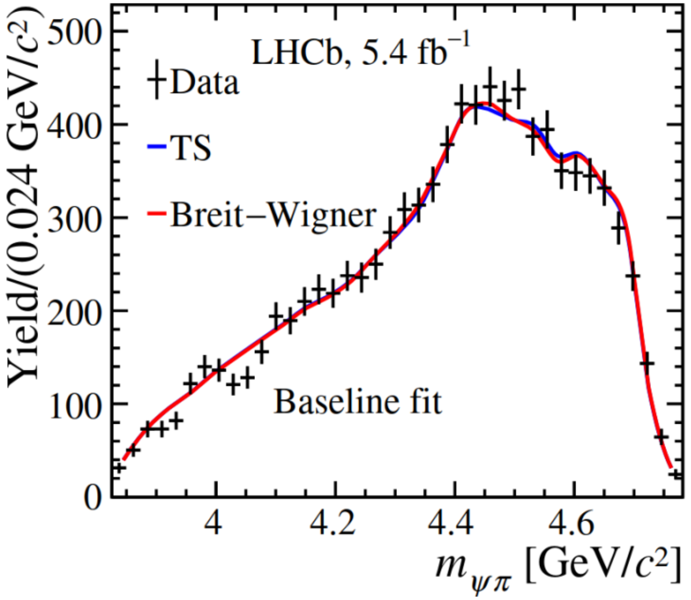
Result: $|g_2/g_1| < 6.8$ in 95% CL

Structure modelled as a triangle singularity

Triangle singularity (TS)



PRD 100 (2019) 051502

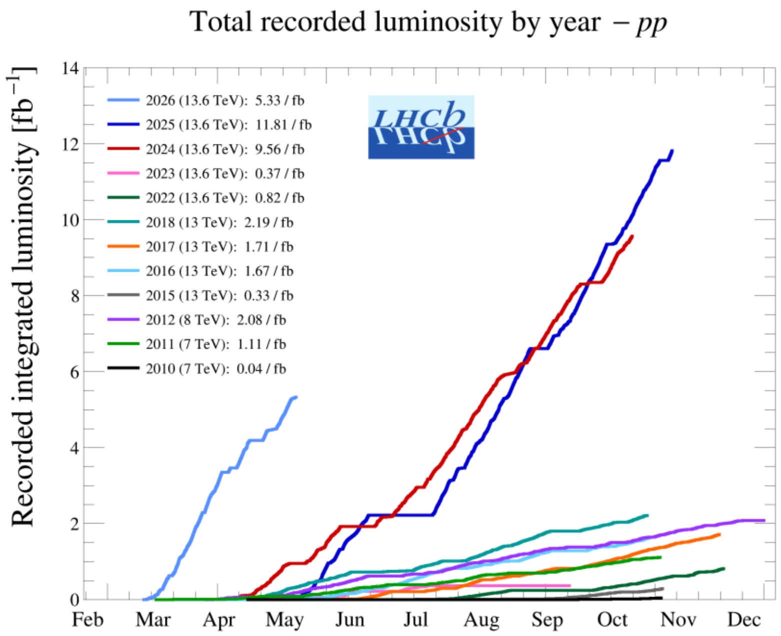


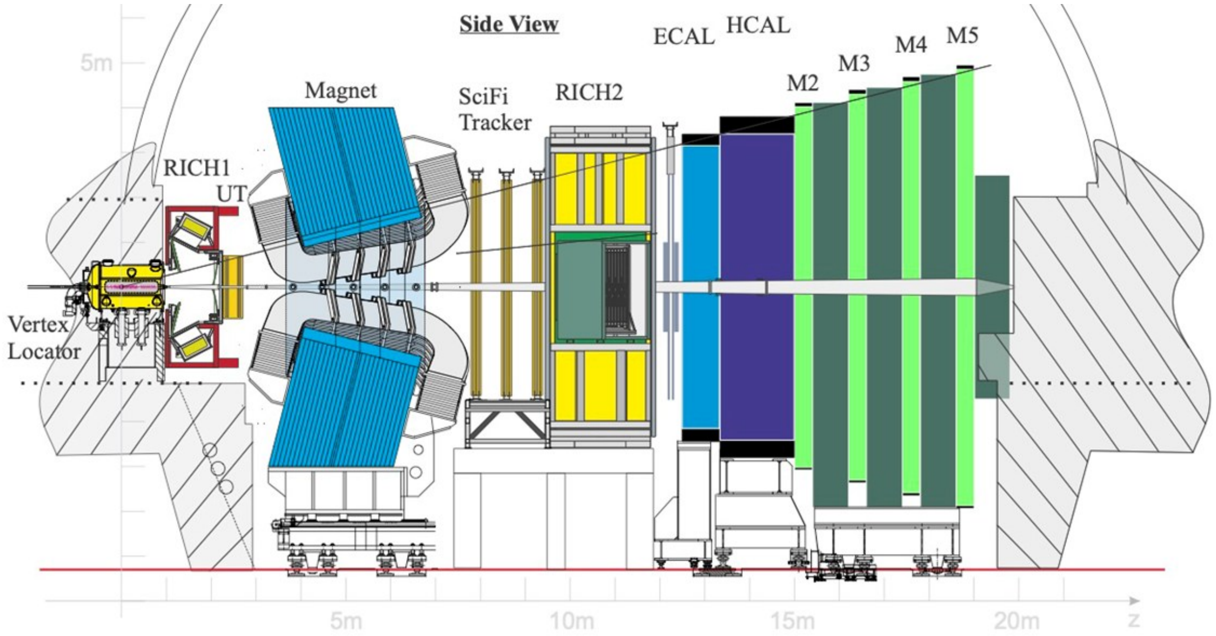
- Potential description of data,
- More precise measurement needed to determine the nature of the structure

PRD 113, L071101 (2026)

Summary and prospects

- Run1&2: Hadron spectroscopy is one of the leading topics and highlights of LHCb!
- Run3: Upgraded detector & Higher statistics (~25 fb^{-1}) further boosts the spectroscopy studies:
    - Search for more conventional excited states
    - Search for new decay modes of observed exotic hadrons
    - Determine J^P and other properties of multiquark states
    - ……





JINST 19 (2024) P05065

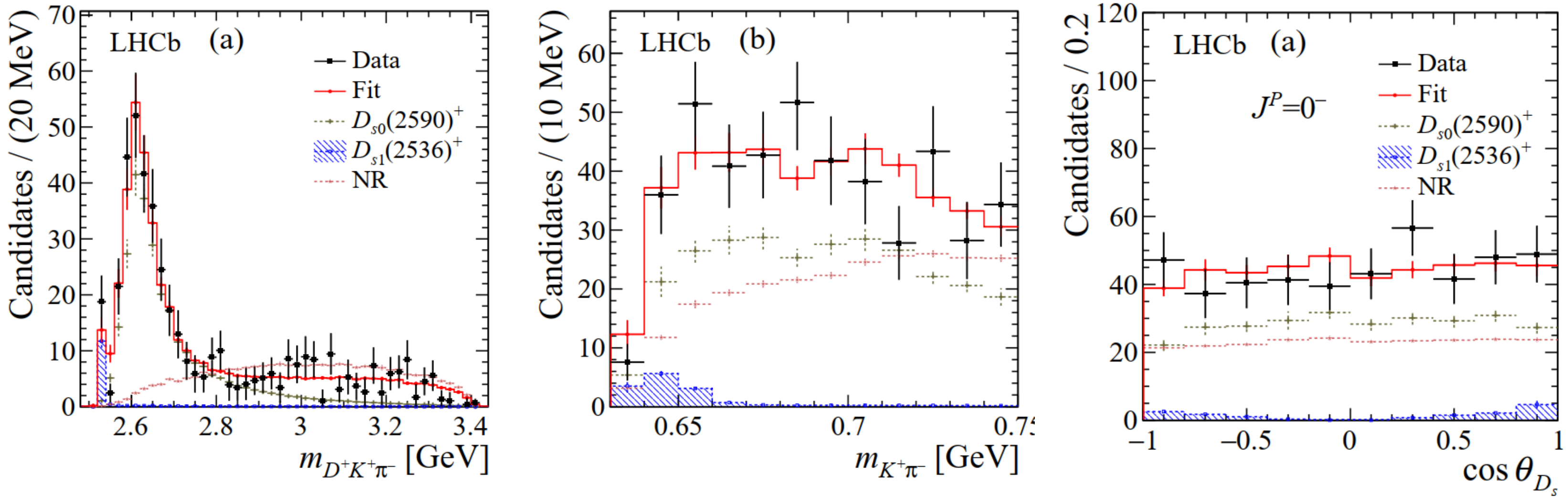
Thanks for your listening!

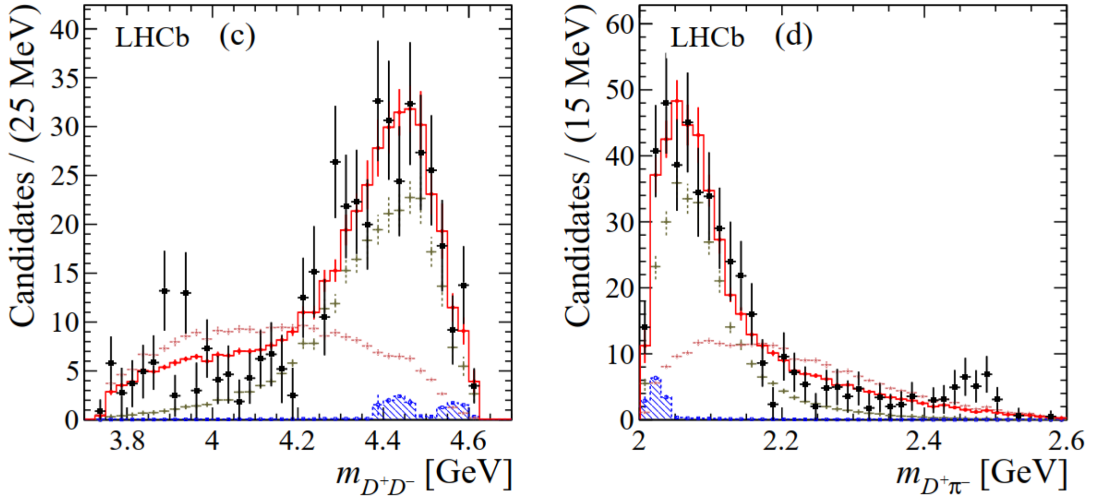
Backup

Study of the $B^0 \to D^+D^-K^+\pi^-$ decay (previous)

- Fit results

PRL 126 (2021) 12, 122002





- Systematics

Source	m_R [MeV]	Γ_R [MeV]
$D_{s0}(2590)^+$ width model	6.1	8.0
$D_{s1}(2536)^+$ mass shape	0.3	4.3
$K^+\pi^-$ mass shape	2.7	2.6
Blatt-Weisskopf factor	0.7	3.4
Including $c\bar{c}$ resonances	1.1	5.4
$D^+\pi^-$ resonance veto	2.4	2.1
Simulation correction	0.2	1.1
Momentum calibration	0.5	0.4
Total	7.2	11.7

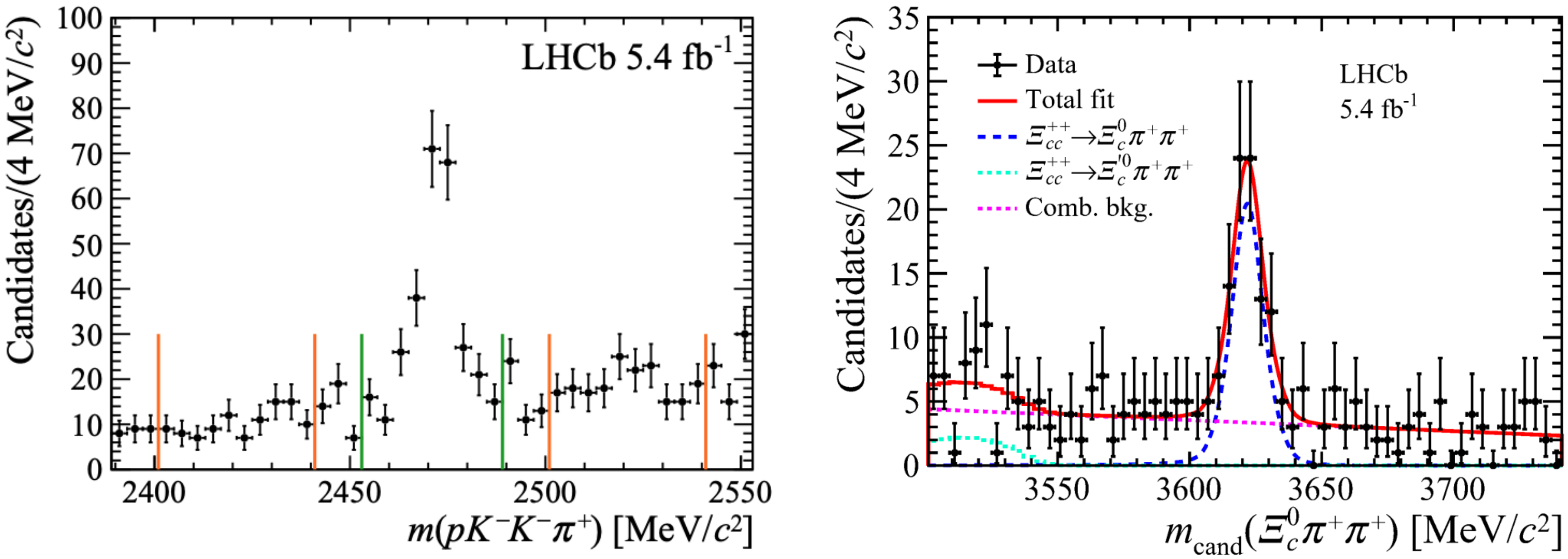
- $m_R = 2591 \pm 6 \pm 7$ MeV
- $\Gamma_R = 89 \pm 16 \pm 12$ MeV
- $J^P = 0^-$
- While 1^+ and 2^- are rejected by >10σ

	Fit fraction $(\times 10^{-2})$
$D_{s0}(2590)^+$	63 ± 9 (stat) ± 9 (syst)
$D_{s1}(2536)^+$	3.9 ± 1.4 (stat) ± 0.8 (syst)
NR	51 ± 11 (stat) ± 19 (syst)
D_{s0}^+–NR	-18 ± 18 (stat) ± 24 (syst)
D_{s1}^+/D_{s0}^+	6.1 ± 2.4 (stat) ± 1.4 (syst)

Observation of the decay $\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+$

arXiv:2504.05063, Submitted to JHEP

- Measurements of additional Ξ_{cc}^{++} decay modes provide essential information to better understand the decay dynamics of doubly charmed baryons.

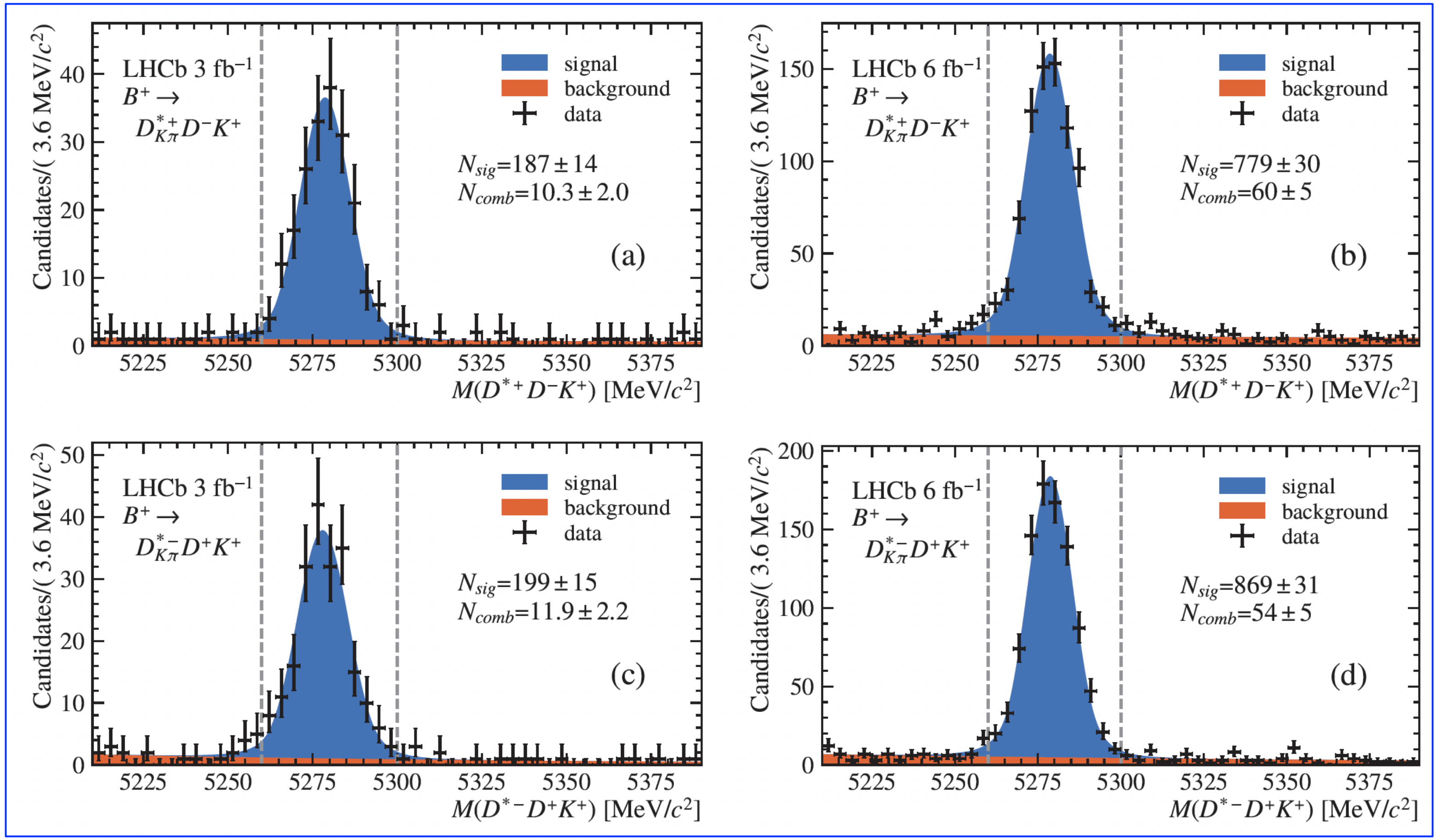


$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} = 1.37 \pm 0.18(\text{stat}) \pm 0.09(\text{syst}) \pm 0.35(\text{ext})$$

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

[PRL 133 (2024) 131902]

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



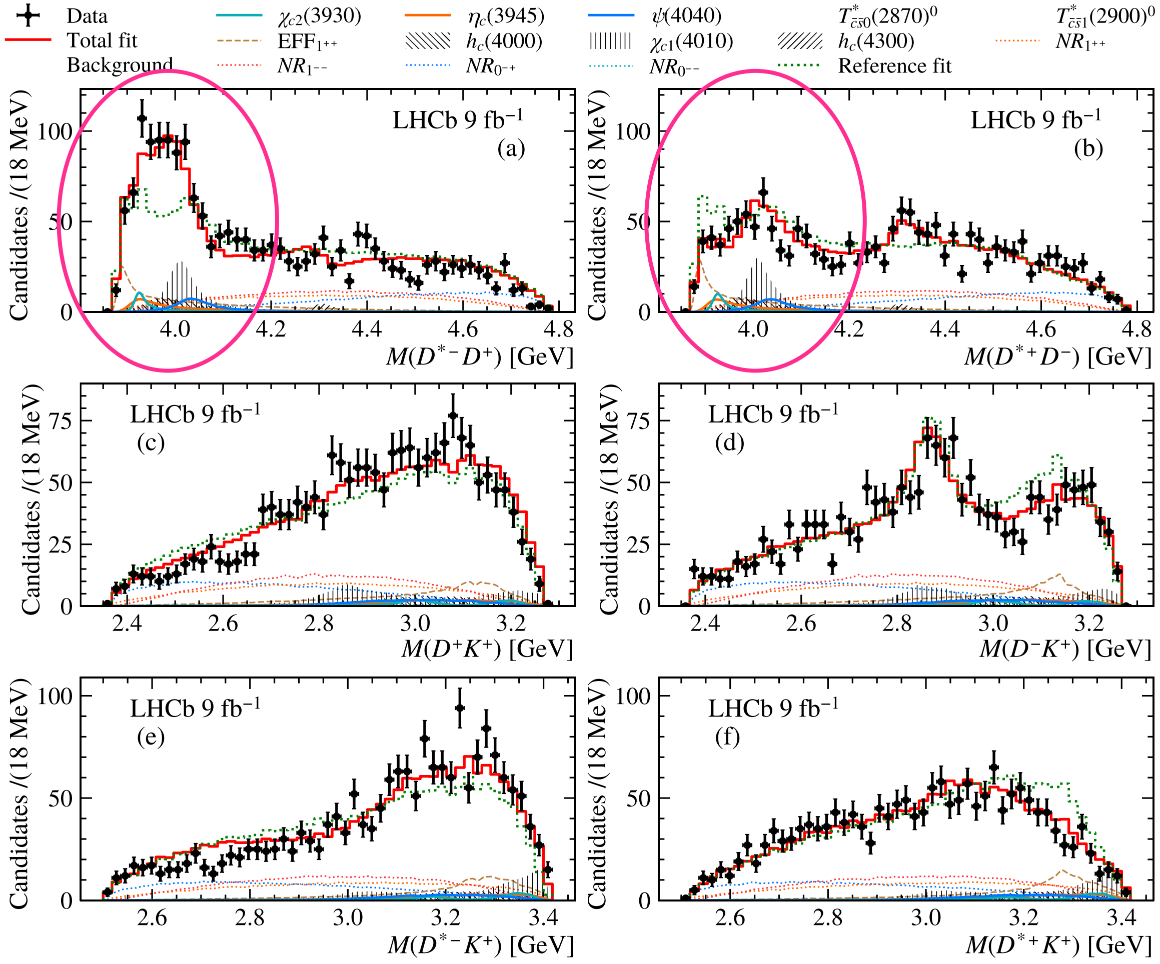
✓ $B^+ \to D^{*+} D^- K^+$: **966**

✓ $B^+ \to D^+ D^{*-} K^+$: **1068**

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

[PRL 133 (2024) 131902]

- Amplitudes of $R \to D^{*+}D^-$ and $R \to D^{*-}D^+$ linked by ***C*-parity**
  $\Rightarrow$ allowing determination of *C*-parities of R resonances



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

$D^{*\pm}D^{\mp}$ system

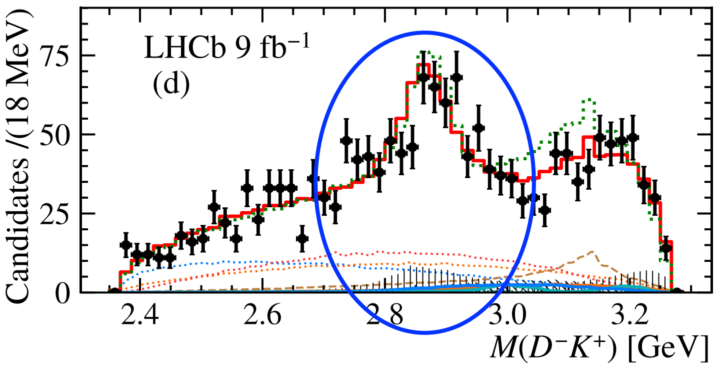
- Four charmonium(-like) states are observed decaying to $D^*\overline{D}$ for >6.1σ
- At least the three of them are new
- J^{PC} for each state is determined for >5.7σ

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

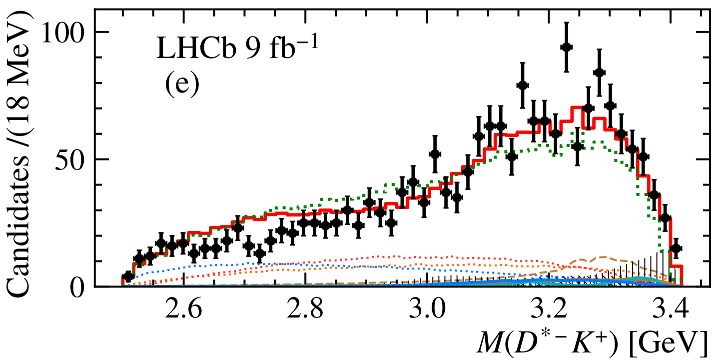
$B^+ \to D^{*\pm} D^{\mp} K^+$: $T^*_{\bar{c}\bar{s}}$ states

[PRL 133 (2024) 131902]

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



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



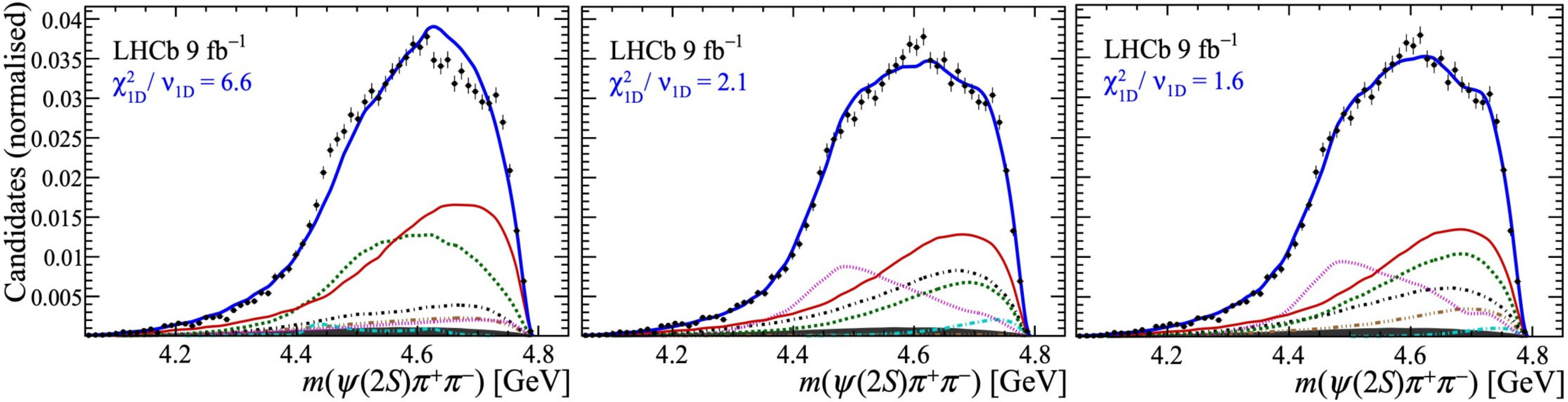
	Property	This work		Previous work
11σ	$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$		2866 ± 7
	$T^*_{\bar{c}\bar{s}0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	2σ	57 ± 13
9.2σ	$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$		2904 ± 5
	$T^*_{\bar{c}\bar{s}1}(2900)^0$ width [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

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

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" $\to \psi(2S)\pi\pi, \psi(2S)\pi$ or $\psi(2S)K$

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

$T_{c\bar{c}\bar{s}1}(4600)^0 \to \psi(2S)K\pi$
$T_{c\bar{c}\bar{s}1}(4900)^0 \to \psi(2S)K\pi$
$T^*_{c\bar{c}\bar{s}1}(5200)^0 \to \psi(2S)K\pi$(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

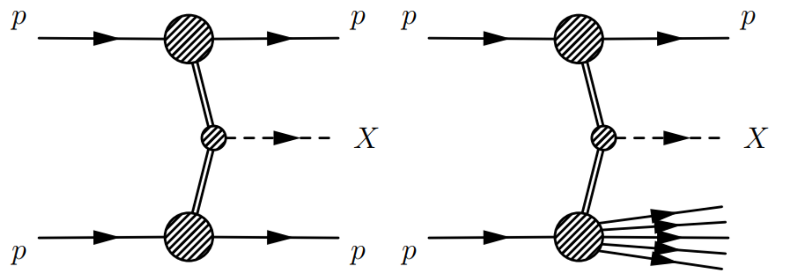
  - Four $X^0/\chi_{c0} \to \psi(2S)\pi^+\pi^-$ are identified and the shows some similarities to previously observed $J/\psi\phi$ resonances
  - In $\psi(2S)\pi^\pm$ system, $T_{c\bar{c}1}(4430)^\pm$ is confirmed, J^P of $T_{c\bar{c}1}(4200)^\pm$is determined to be 1^+
  - Cascade exotics decays $X^0 \to T^{\pm}_{c\bar{c}1}\pi^\mp$ 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 $B^0 \to [J/\psi K^0_s]\phi$

Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	$\Delta(-2\ln\mathcal{L})$	$\Delta N_{\rm par}$	Sign. [σ]
$\chi_{c0}(4475)$	0^+	$4475\pm 7\pm12$	$231\pm19\pm32$	675	6	>20 (19)
$\chi_{c1}(4650)$	1^+	$4653\pm14\pm27$	$227\pm26\pm22$	286	6	15 (13)
$\chi_{c0}(4710)$	0^+	$4710\pm 4\pm5$	$64\pm 9\pm10$	255	6	14 (10)
$\eta_{c1}(4800)$	1^-	$4785\pm37\pm119$	$457\pm93\pm157$	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^+	$4257\pm11\pm17$	$308\pm20\pm32$	842	16	>20 (>20)
$T_{c\bar{c}1}(4430)^+$	1^+	$4468\pm21\pm80$	$251\pm42\pm82$	305	10	15 (8)
$T_{c\bar{c}\bar{s}1}(4600)^0$	1^+	$4578\pm10\pm18$	$133\pm28\pm69$	287	8	15 (12)
$T_{c\bar{c}\bar{s}1}(4900)^0$	1^+	$4925\pm22\pm47$	$255\pm55\pm127$	177	4	12 (8)
$T^*_{c\bar{c}\bar{s}1}(5200)^0$	1^-	$5225\pm86\pm181$	$226\pm76\pm374$	149	6	10 (8)
$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	597	4	>20 (14)

Stat only

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

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

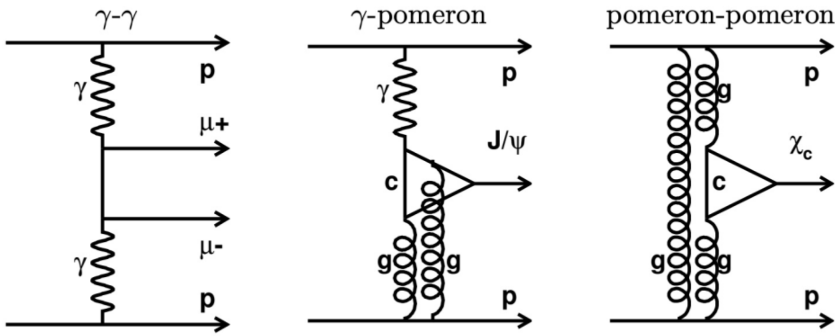


Elastic CEP   Inelastic CEP

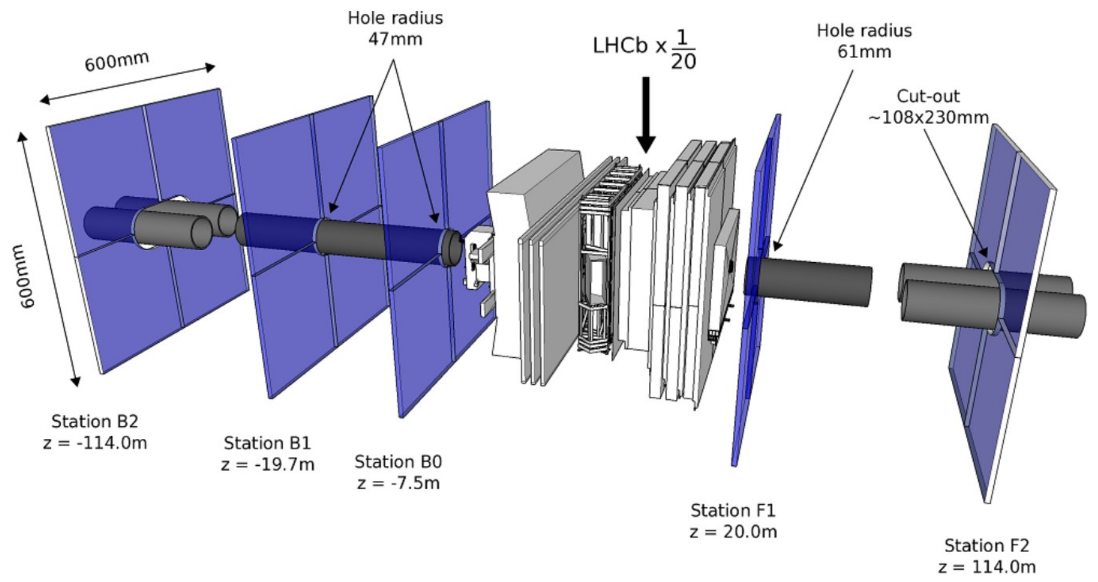
- Low-activity
- Specific kinematics

→ Lower background

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

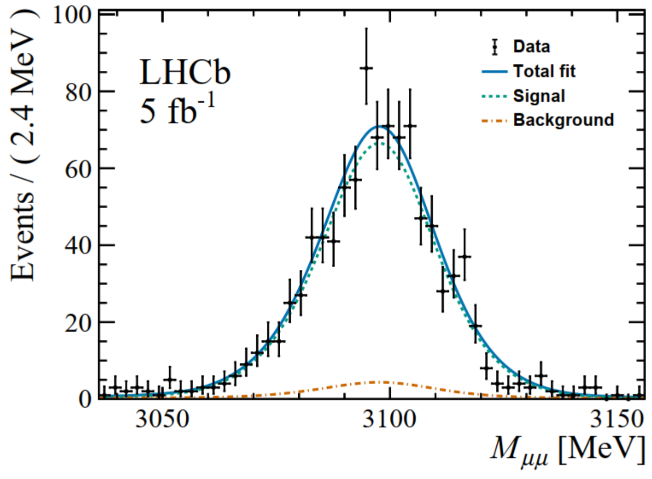


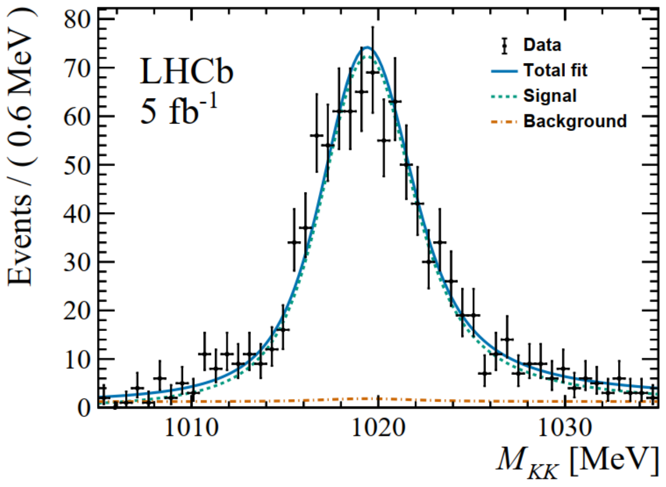
*glueball



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

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

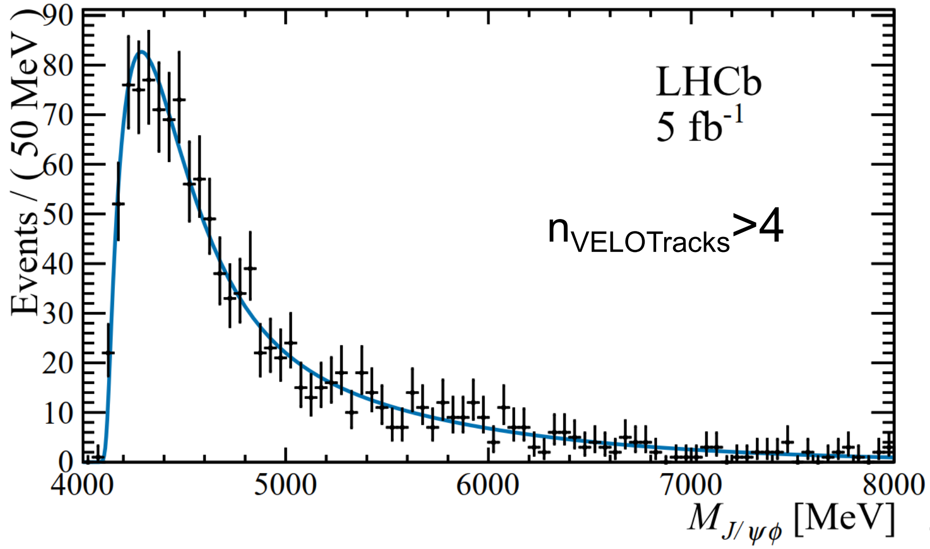




Purity ~ 93%

PRL 134 (2025) 3, 031902

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

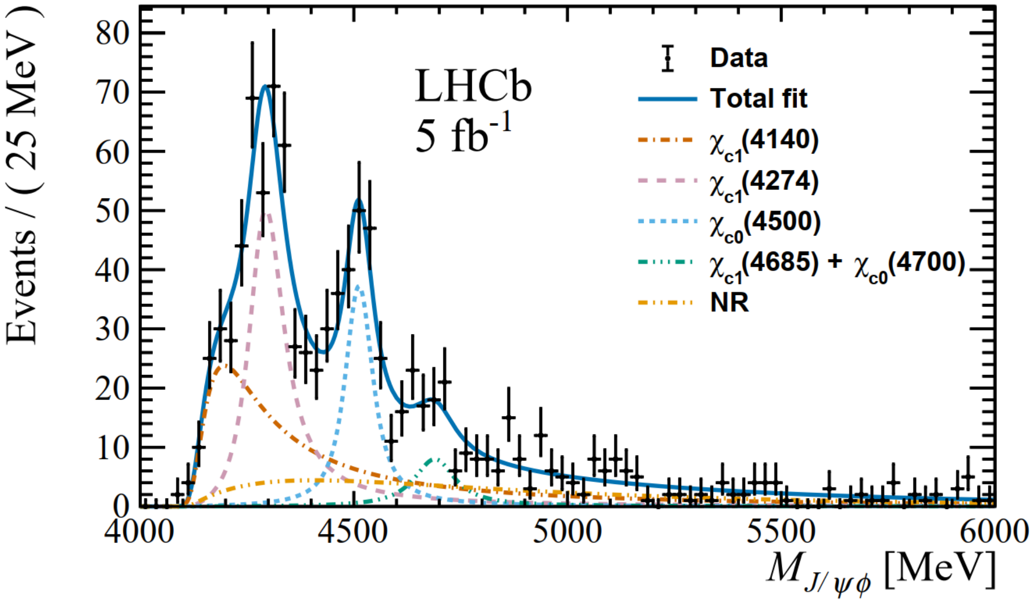


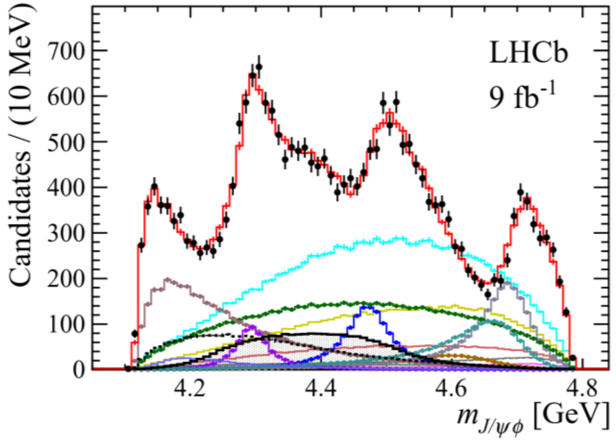
Zan REN

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:

$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4140)} = (0.80 \pm 0.15 \pm 0.28)\ \text{pb},$$

$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4274)} = (0.73 \pm 0.08 \pm 0.17)\ \text{pb},$$

$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\rm eff}^{\chi_{c0}(4500)} = (0.42^{+0.09}_{-0.08} \pm 0.06)\ \text{pb},$$

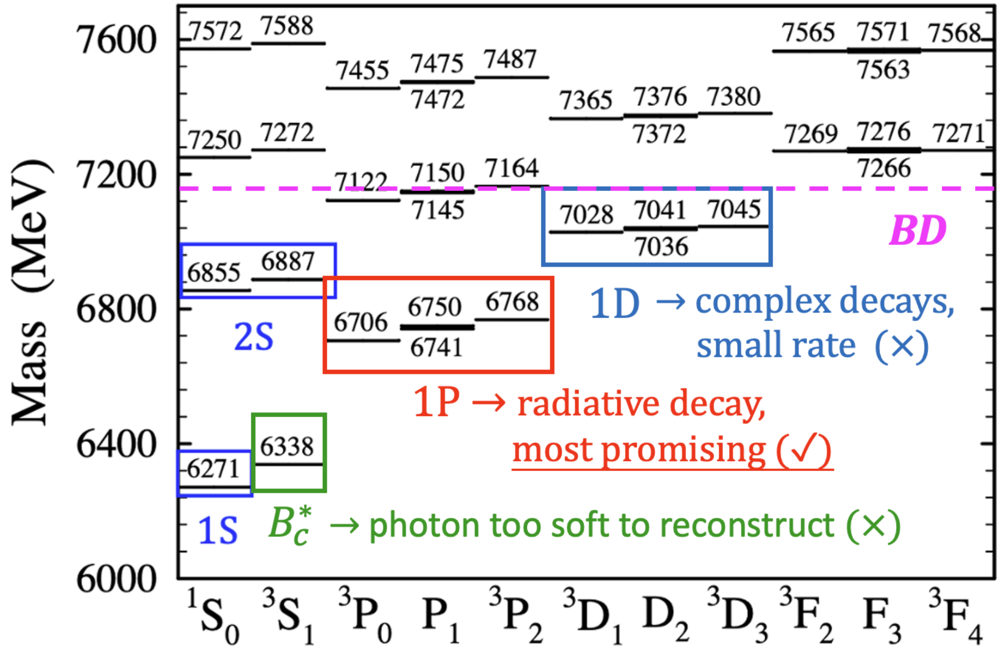
$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} \pm 0.06)\ \text{pb},$$

$$\sigma_{\rm NR} \times \mathcal{B}_{\rm eff}^{\rm NR} = (0.43^{+0.24}_{-0.18} \pm 0.20)\ \text{pb},$$

Observation of the orbitally excited B_c^+ states

- The B_c^+ meson family is the only mesons composed of two different heavy quarks $(\bar{b}c)$
- Despite its ground state, only the 2S excitations have been observed at the LHC PRL 113 (2014) 212004
- The 1P excited states are predicted to decay solely via radiative transitions
  - most likely to be the next excitations to be observed, with predicted masses in the range of $(340, 520)$ MeV
  - four states are expected, leading to six peaks due to unreconstructed photons from B_c^* decays

PRD 70 (2004) 054017



$$(L=1)\otimes(S=0,1)\begin{cases} S=0 \;\rightarrow\; \boxed{1^1P_1} \\ S=1 \;\rightarrow\; 1^3P_0,\ 1^3P_1,\ 1^3P_2 \end{cases}$$

mixing

Four physical states

$$1^3P_0,\ 1^3P_2\quad \begin{pmatrix} 1P_1' \\ 1P_1 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 1^1P_1 \\ 1^3P_1 \end{pmatrix}$$

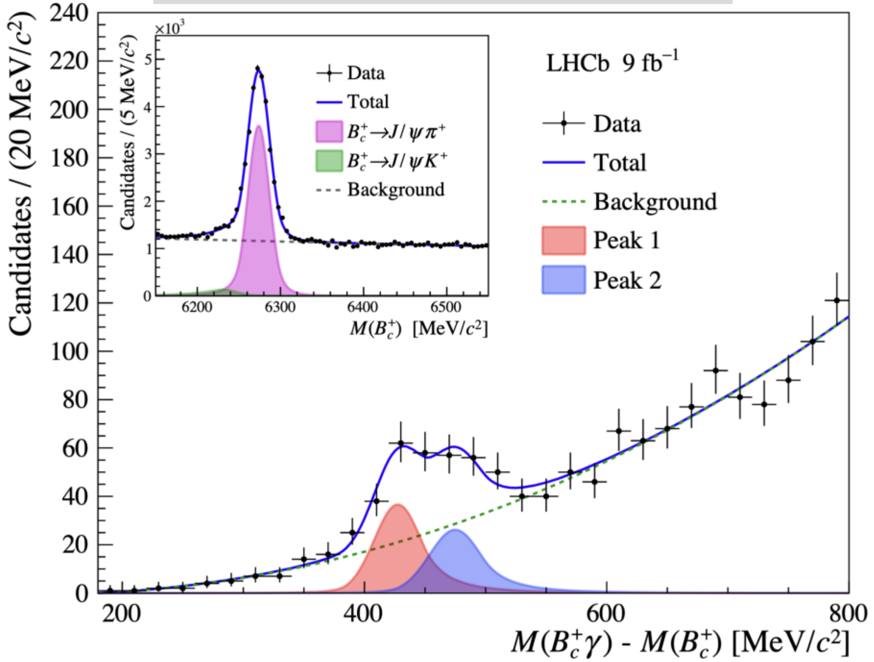
States	1^3P_0	$1P_1$	$1P_1'$	1^3P_2
Decays	$B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^+\gamma$ $B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^+\gamma$ $B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^{*+}(\to B_c^+\gamma)\gamma$
#peaks	1	2	2	1

Observation of the orbitally excited B_c^+ states

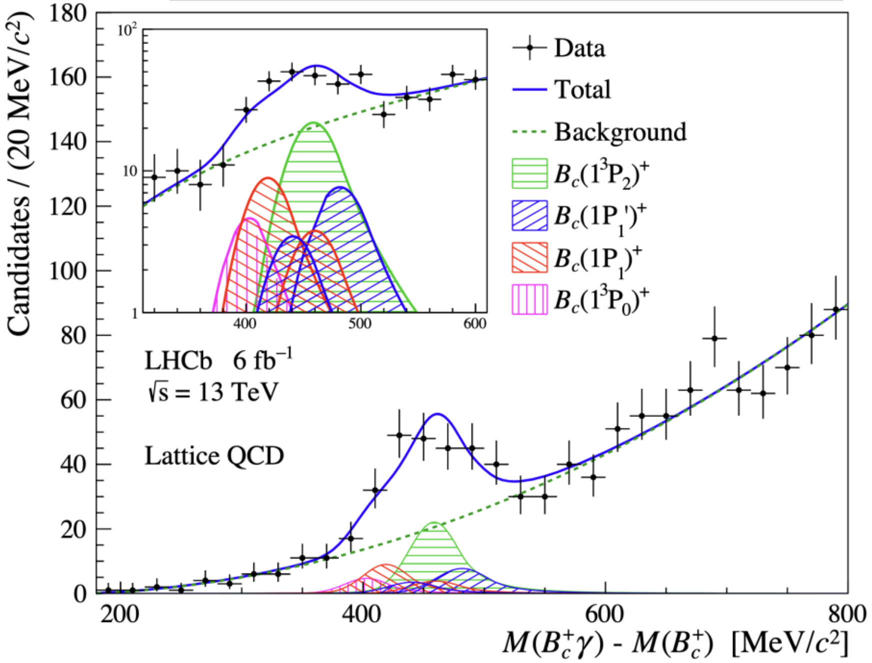
- $B_c(1P)^+ \to B_c^+\gamma$, where $B_c^+ \to J/\psi\ (\to \mu^+\mu^-)\pi^+$ and photon reconstructed from calorimeter
- A pronounced wide peaking structure is seen within the predicted mass range (significance $> 7\sigma$)
- The visible width exceed the expectation of single-peak interpretation ⇒ a minimal effective **two-peak** model used
- By fixing the peak positions and relative yields to theory, different theoretical models were investigated ⇒ all generally good
- The relative production rate, representing the fraction of B_c^+ comes from $B_c(1P)^+$ is determined using the LQCD model

$$R = \frac{N(B_c(1P)^+ \to B_c^+\gamma)}{N(B_c^+)} \cdot \frac{\varepsilon(B_c^+)}{\varepsilon(B_c(1P)^+ \to B_c^+\gamma)} = 0.20 \pm 0.03 \pm 0.02 \pm 0.03$$ (choice of theoretical models)

arXiv:2507.02149, Submitted to PRL



arXiv:2507.02142, Submitted to PRD

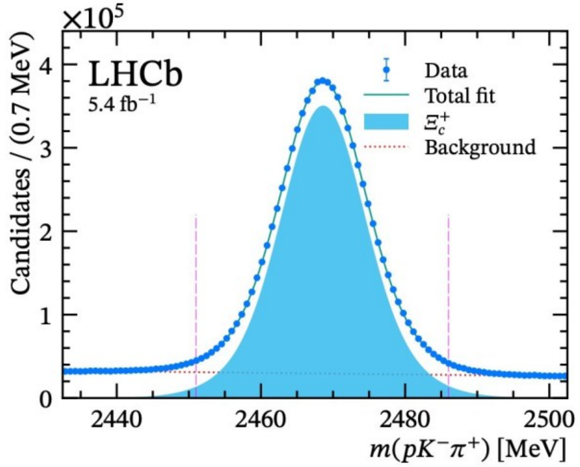


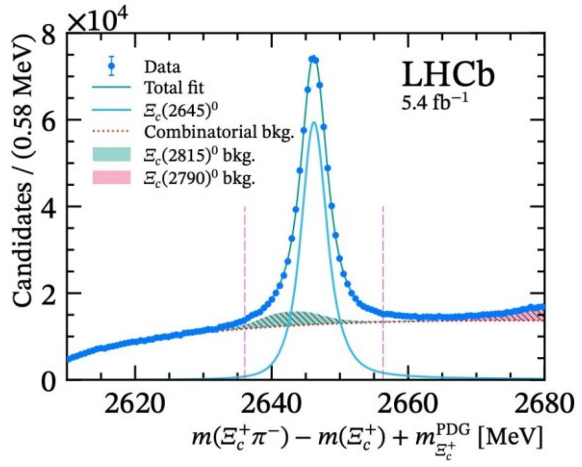
Observation of $\Xi_c(2923)^+$ decaying to $\Xi_c^+ \pi^- \pi^+$

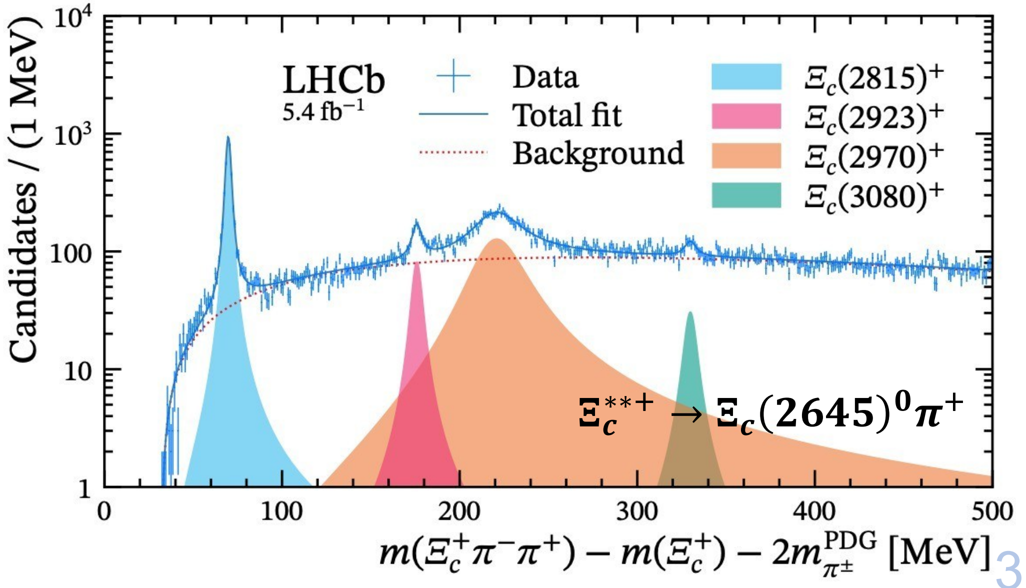
arXiv: 2502.18987, Submitted to PRL

- Four peaks with high significance
  - $\Xi_c(2923)^+$
    - observed for the first time
  - $\Xi_c(3080)^+$
    - seen in this decay mode for the first time
  - $\Xi_c(2970)^+$ with ~30 MeV width
    - confirms different to $\Lambda_c K \pi$ peak

$$m[\Xi_c(2815)^+] = 2816.65 \pm 0.03 \pm 0.03 \pm 0.23\,\mathrm{MeV},$$
$$\Gamma[\Xi_c(2815)^+] = 2.07 \pm 0.08 \pm 0.12\,\mathrm{MeV},$$
$$m[\Xi_c(2923)^+] = 2922.8 \pm 0.3 \pm 0.5 \pm 0.2\,\mathrm{MeV},$$
$$\Gamma[\Xi_c(2923)^+] = 5.3 \pm 0.9 \pm 1.4\,\mathrm{MeV},$$
$$m[\Xi_c(2970)^+] = 2968.6 \pm 0.5 \pm 0.5 \pm 0.2\,\mathrm{MeV},$$
$$\Gamma[\Xi_c(2970)^+] = 31.7 \pm 1.7 \pm 1.9\,\mathrm{MeV},$$
$$m[\Xi_c(3080)^+] = 3076.8 \pm 0.7 \pm 1.3 \pm 0.2\,\mathrm{MeV},$$
$$\Gamma[\Xi_c(3080)^+] = 6.8 \pm 2.3 \pm 0.9\,\mathrm{MeV},$$



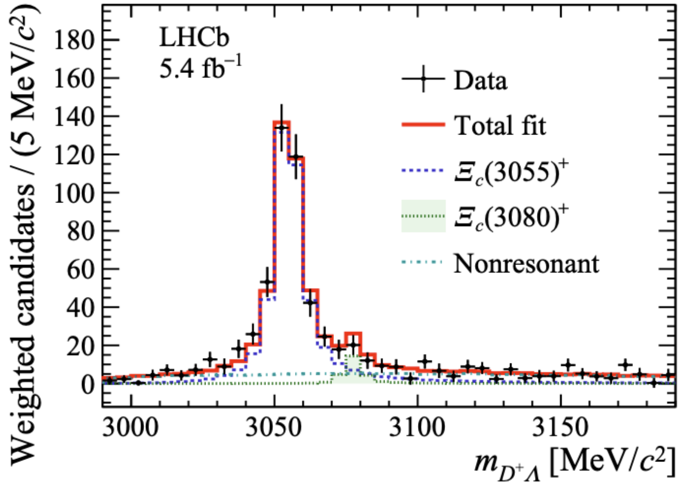


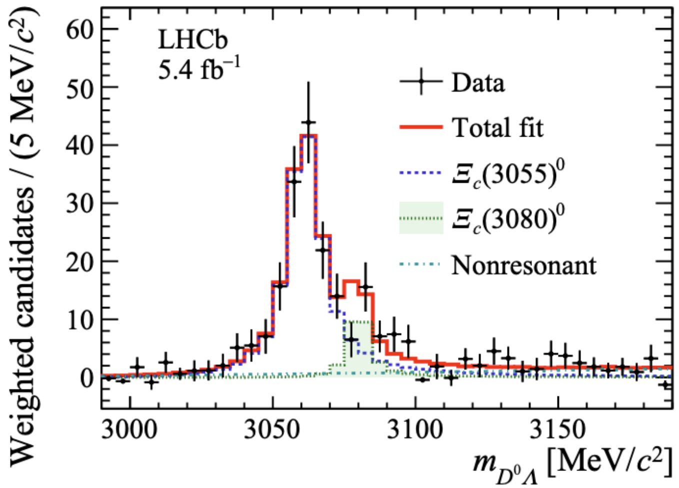


First determination of the spin-parity of $\Xi_c(3055)^{+,0}$

PRL 134 (2025) 081901

- Study $\Xi_c^{**+(0)}$ in the $\Xi_b^{0(-)} \to D^{+(0)}\Lambda\pi^+$ processes
  - Dominated by $\Xi_c(3055)^{+(0)} \to D^{+(0)}\Lambda$ contributions
  - Using LHCb Run2 dataset of 5.4 fb^{-1}
- $\Xi_c(3055)^+$ and $\Xi_c(3055)^0$ observed, first time in Ξ_b decays
- Evidence of $\Xi_c(3080)^{+(0)}$, significance $4.4(3.6)\sigma$
- Mass, width of $\Xi_c(3055)$, relative branching fraction
- $R_{\mathfrak{B}} = Br(\Xi_c(3080)) \,/\, Br(\Xi_c(3055))$ measured



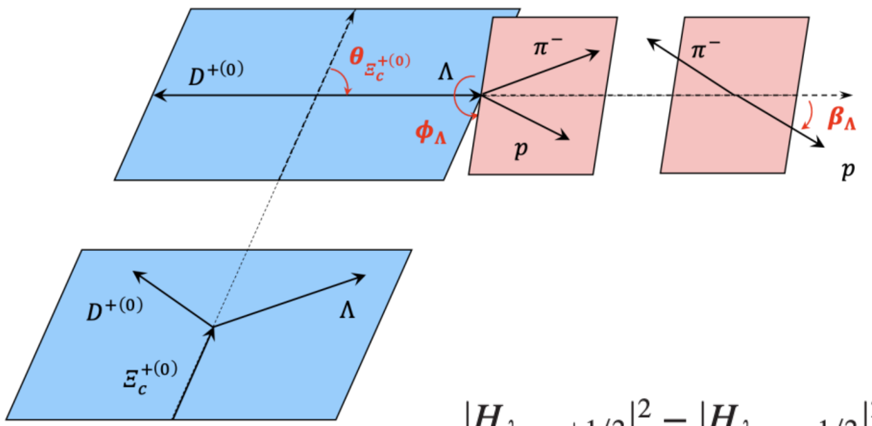


Quantity	$\Xi_c(3055)^+$	$\Xi_c(3055)^0$
m [MeV/c^2]	$3054.52 \pm 0.36 \pm 0.17$	$3061.00 \pm 0.80 \pm 0.23$
Γ [MeV/c^2]	$8.01 \pm 0.76 \pm 0.34$	$12.4 \pm 2.0 \pm 1.1$
$R_{\mathcal{B}}$	$0.045 \pm 0.023 \pm 0.006$	$0.14 \pm 0.06 \pm 0.04$

First determination of the spin-parity of $\Xi_c(3055)^{+,0}$

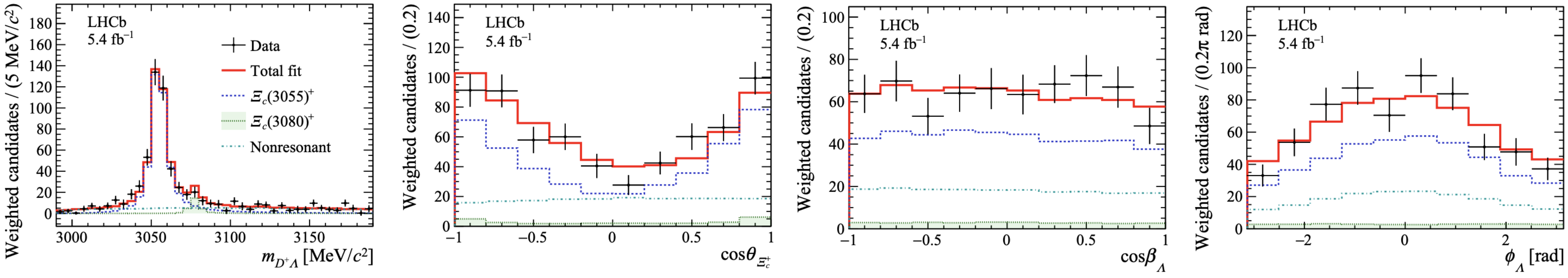
PRL 134 (2025) 081901

- $\Xi_b^{0(-)} \to \Xi_c^{**+(0)}(\to D\Lambda(\to p\pi))\pi^-$ amplitude analysis
  - 4-dimensional fit to $m(D\Lambda)$, helicity angles θ, β, ϕ
  - J^P of $\Xi_c(3055)^{+(0)}$ determined to be $\mathbf{3/2^+}$ for the first time
    - $6.5(3.5)\sigma$ significance w.r.t. other hypotheses
    - $5/2^+$ of $\Xi_c(3080)^{+(0)}$ also favored, but not significant
  - Decay parameter $\alpha_{\Xi_b \to \Xi_c(3055)\pi^-}$ (up-down asymmetry)
    - Consistent with maximal parity violation
    - Indicates the light quarks are spectating in $b \to c$ transition



$$\alpha \equiv \frac{|H_{\lambda_{\Xi_b^0}=+1/2}|^2 - |H_{\lambda_{\Xi_b^0}=-1/2}|^2}{|H_{\lambda_{\Xi_b^0}=+1/2}|^2 + |H_{\lambda_{\Xi_b^0}=-1/2}|^2},$$

- Identified $\Xi_c(3055)$ as the first D-wave, λ-mode excitation of the Ξ_c triplet

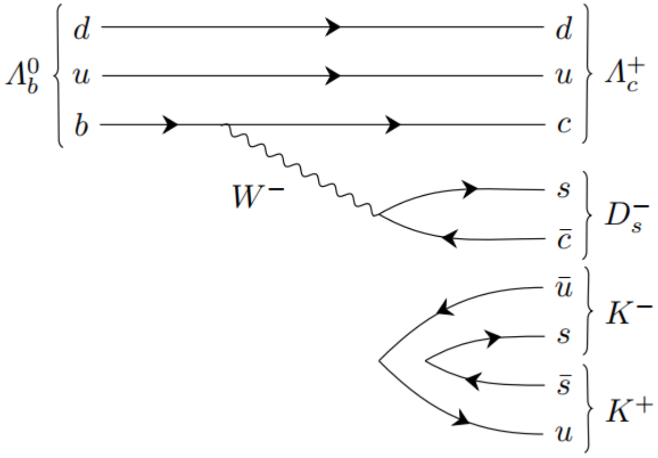


Observation of $\Lambda_b^0 \to \Lambda_c^+ D_s^- K^+ K^-$ decay and search for pentaquarks

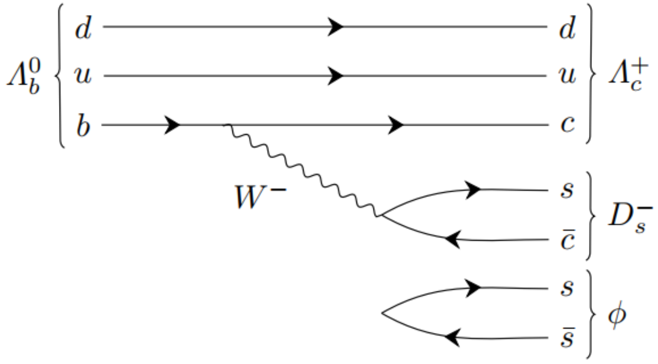
PRL 131 (2023) 031901

Sci. Bull. 66 (2021) 1278

- $P_{c\bar{c}s}$ observed in $B^- \to J/\psi \Lambda \bar{p}$ and evidence in $\Xi_b^- \to J/\psi \Lambda K^-$ decays



(a) The nonresonant K^+K^- process

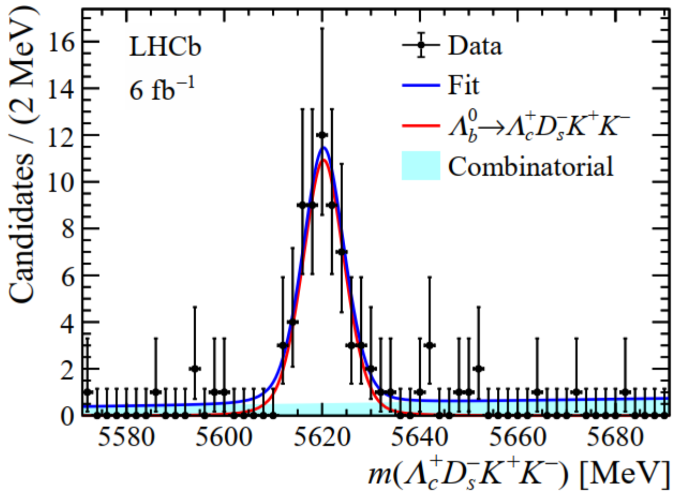


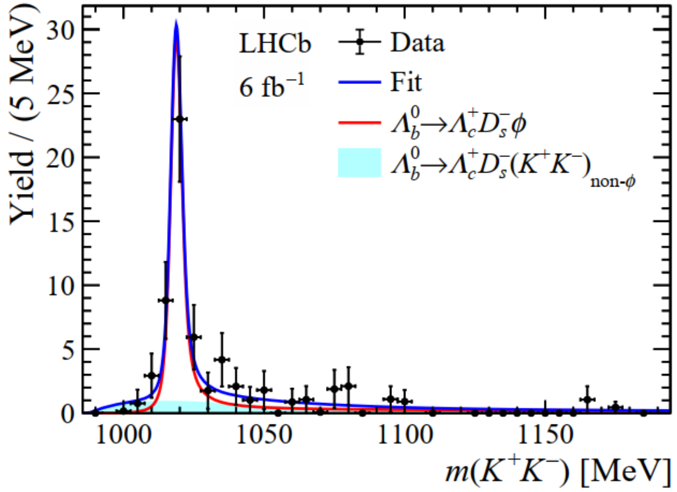
(b) The ϕ-dominated process

arXiv:2507.10713,
Submitted to PRD

- Cut & MVA based selection
  - 61 ± 8 Λ_b^0 decays
  - Dominated by $\phi \to K^+K^-$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^- K^+ K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.0141 \pm 0.0019 \pm 0.0012$$



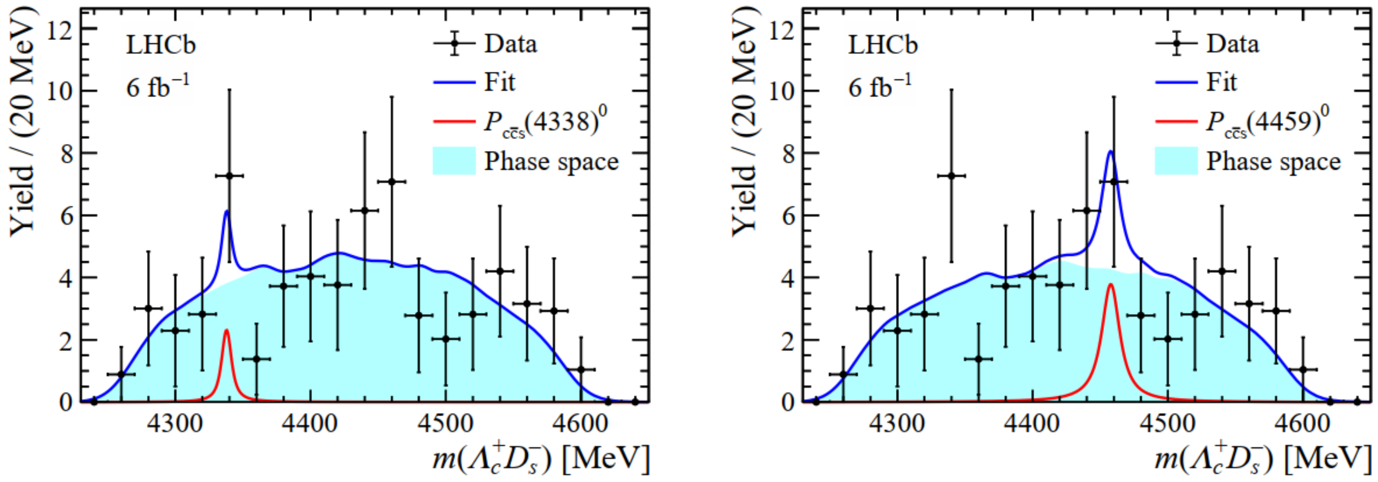


Observation of $\Lambda_b^0 \to \Lambda_c^+ D_s^- K^+ K^-$ decay and search for pentaquarks

- The relative $P_{c\bar{c}s}$ contributions (fit fractions) derived from fit to background-subtracted data.

$$\mathcal{R}_{P^0_{c\bar{c}s}} \equiv \frac{\mathcal{B}\left(\Lambda_b^0 \to P_{c\bar{c}s} K^+ K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^- K^+ K^-\right)} \cdot \mathcal{B}\left(P^0_{c\bar{c}s} \to \Lambda_c^+ D_s^-\right)$$

- Widths and masses for $P^0_{c\bar{c}s}$ states are Gaussian with the means and uncertainties constrained to their known value. PRL 131 (2023) 031901 Sci. Bull. 66 (2021) 1278



$$\Gamma(m) = \Gamma_0 \cdot \frac{q(m, m_{J/\psi}, m_\Lambda)}{q(m_0, m_{J/\psi}, m_\Lambda)} \cdot \frac{m_0}{m}$$

$$\mathcal{P}_{\rm sig}(m|m_0,\Gamma_0) = \frac{|{\rm BW}(m|m_0,\Gamma_0)|^2 \cdot p_{\Lambda_b^0}(m)\, q_{P_{c\bar{c}s}}(m)}{\mathcal{N}}$$

arXiv:2507.10713, Submitted to PRD

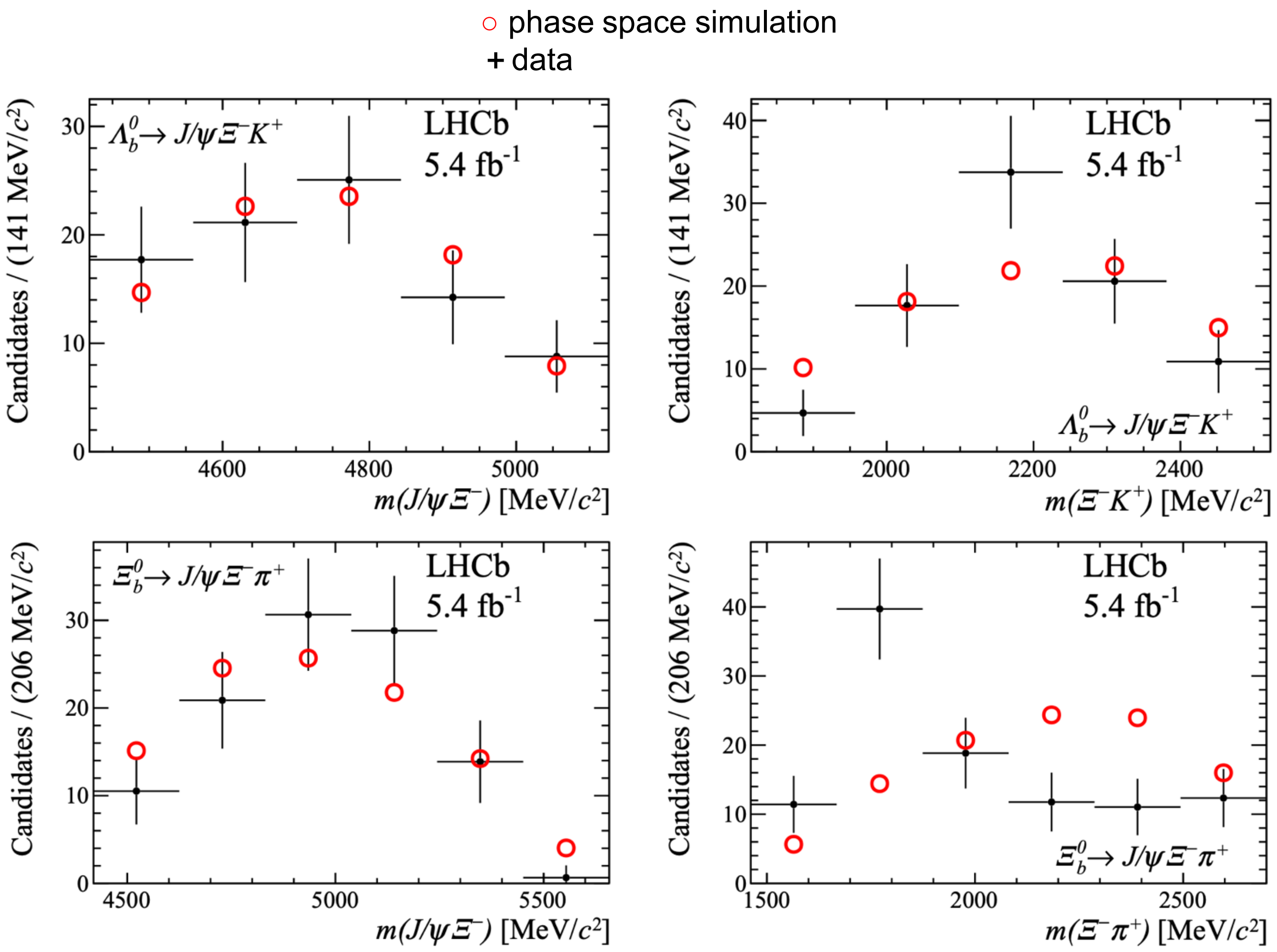
- Upper limits on 95% (90%) CLs:
  - $\mathcal{R}_{P_{c\bar{c}s}(4338)^0} < 0.12\ (0.10)$ and $\mathcal{R}_{P_{c\bar{c}s}(4459)^0} < 0.20\ (0.17)$

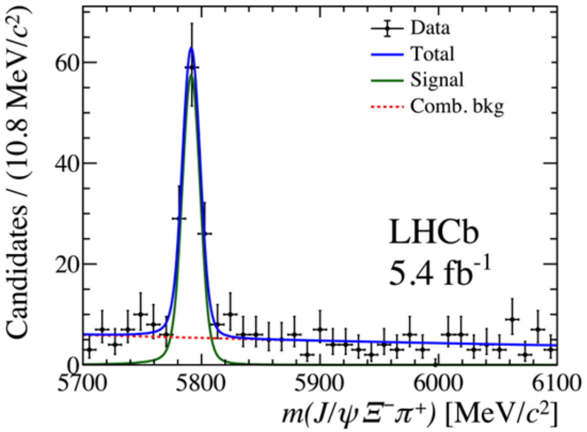
Branching fractions of $\Lambda_b{}^0(\Xi_b^0) \to J/\psi\Xi^- K^+(\pi^+)$

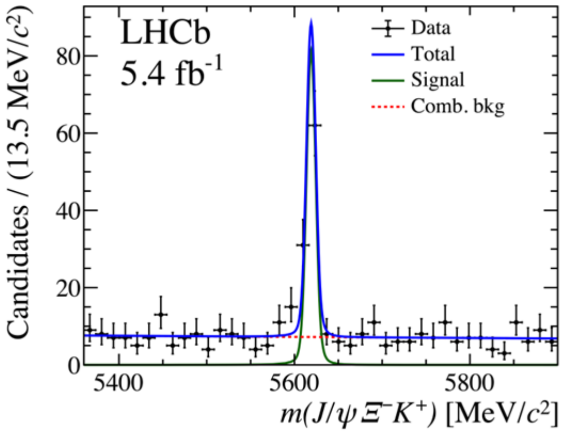
- Motivation: $P_{c\bar{c}}(J/\psi p)[c\bar{c}uud] \to P_{c\bar{c}s}(J/\psi\Lambda)[c\bar{c}sud] \to P_{c\bar{c}ss}(J/\psi\Xi^-)[c\bar{c}ssd]$
- First observation of $\Xi_b^0 \to J/\psi\Xi^-\pi^+$
- Branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0\to J/\psi\Xi^- K^+)}{\mathcal{B}(\Lambda_b^0\to J/\psi\Lambda)} = (1.17 \pm 0.14 \pm 0.08) \times 10^{-2}$$

$$\frac{\mathcal{B}(\Xi_b^0\to J/\psi\Xi^-\pi^+)}{\mathcal{B}(\Xi_b^0\to J/\psi\Xi^-)} = (11.9 \pm 1.4 \pm 0.6) \times 10^{-2}$$







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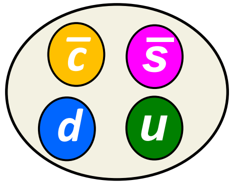
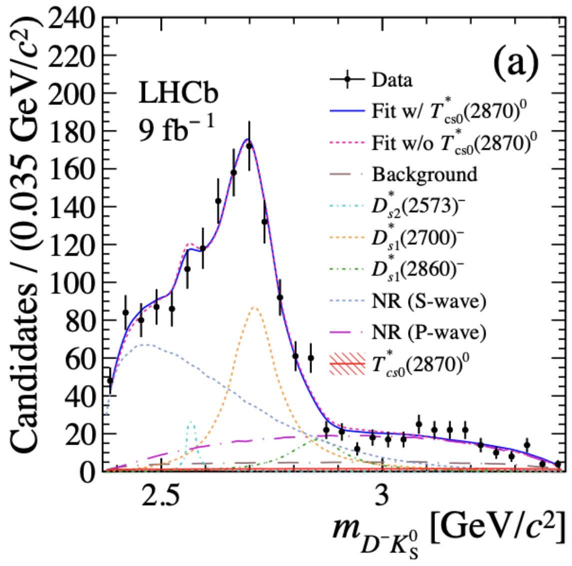
Observation of $T^*_{cs0}(2870)^0$ in $B^- \to D^- D^0 K^0_S$

- Amplitude analysis of $B^- \to D^- D^0 K^0_S$ found $T^*_{cs0}(2870)^0$, but no $T^*_{cs1}(2900)^0$ decaying to $D^0 K^0_S$
- $T^*_{cs0}(2870)^0$
  - Significance of 5.3 σ
  - $m = 2883 \pm 11 \pm 8$ MeV
  - $\Gamma = 87^{+22}_{-47} \pm 17$ MeV



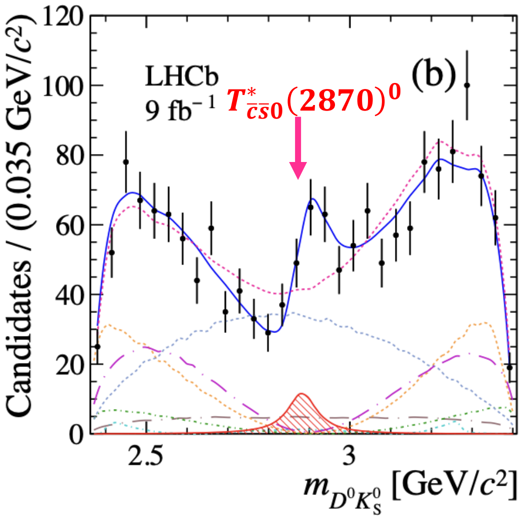


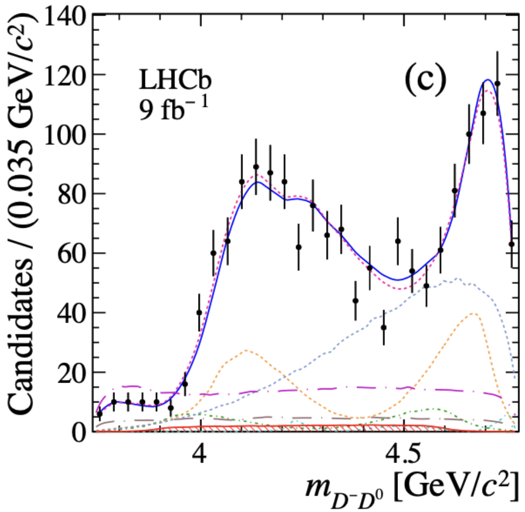
- Branching ratio $R_{\rm I}(T^{*0}_{cs}) = \dfrac{\mathcal{B}(B^- \to D^- D^0 \overline{K}^0)\mathrm{FF}(T^{*0}_{cs} \to D^0 K^0_S)}{\mathcal{B}(B^- \to D^- D^+ K^-)\mathrm{FF}(T^{*0}_{cs} \to D^+ K^-)}$

$$\frac{T^*_{cs0}(2870)^0 \to D^0 \overline{K}^0}{T^*_{cs0}(2870)^0 \to D^+ K^-} = \mathbf{3.3 \pm 1.1 \pm 1.1 \pm 1.1(\mathcal{B})}$$

- $$\frac{T^*_{cs1}(2900)^0 \to D^0 \overline{K}^0}{T^*_{cs1}(2900)^0 \to D^+ K^-} = \mathbf{0.15 \pm 0.15 \pm 0.05 \pm 0.05(\mathcal{B})}$$

Isospin symmetry: these two ratios should be 1





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