



中国科学院大学
University of Chinese Academy of Sciences



Recent studies on exotic states at LHCb

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*on behalf of LHCb collaboration

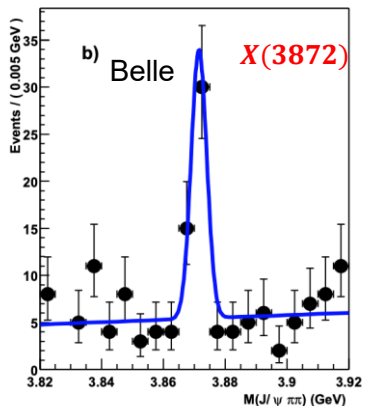
University of Chinese Academy of Sciences

July 23rd, 2026

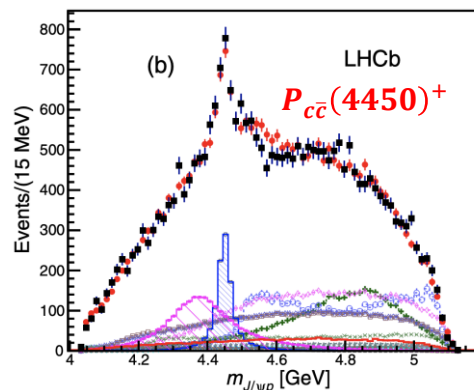
第十一届XYZ研讨会 @ 贵州民族大学

Hadron spectroscopy and exotics

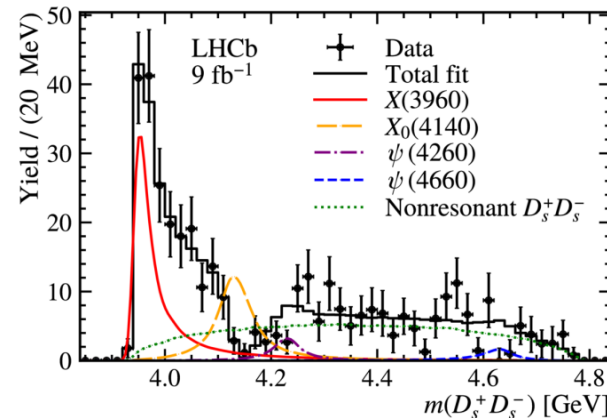
- QCD shows non-perturbative behavior at the energy scale of nuclei and hadrons.
- Spectroscopy of conventional hadrons (mesons and baryons) enriched in the past decades.
- Exotics are predicted since 1960s but first observed until 2003.
 - In the last 20 years, many new exotic candidates have been discovered in e^+e^- collision and hadron collision experiments.
 - Compact, Molecule, dynamic rescattering, ...



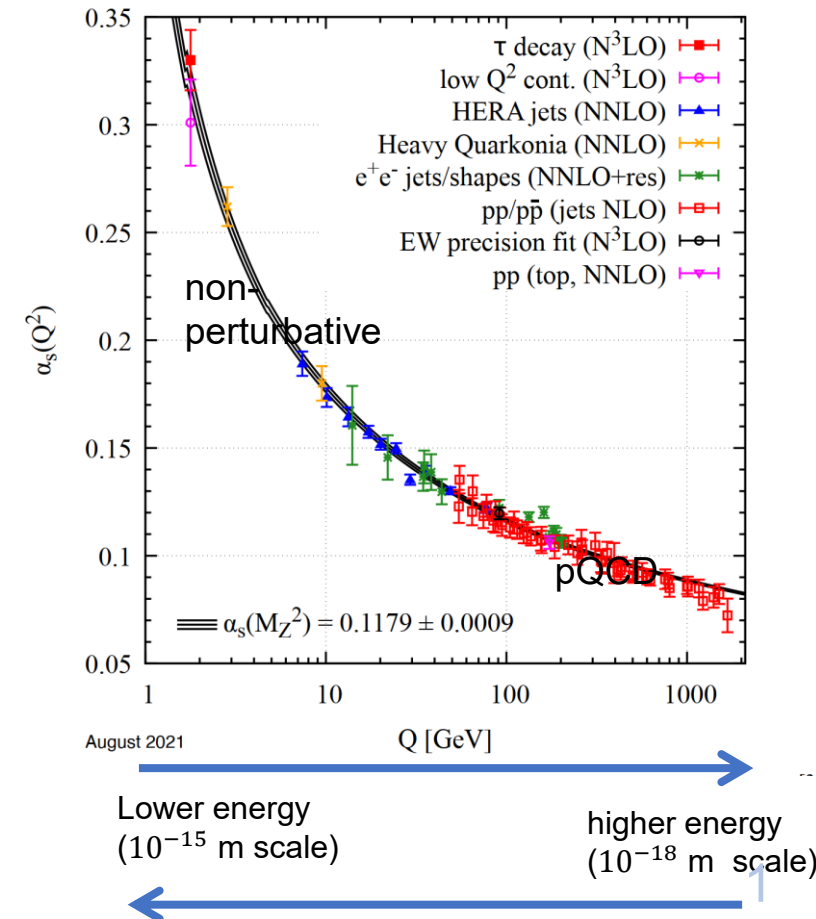
PRL 91 (2003) 262001



PRL115(2015)072001

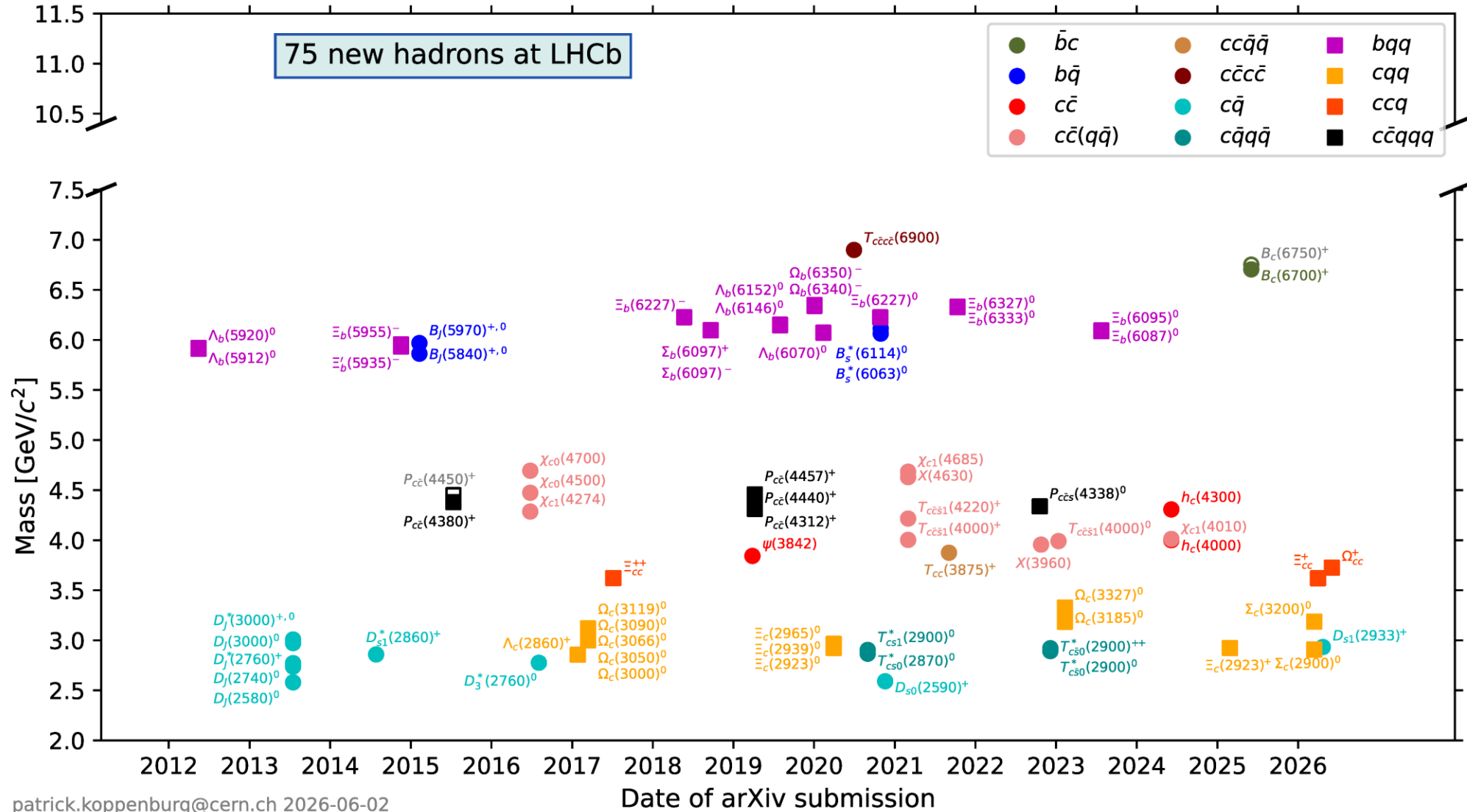


PRL 131 071901



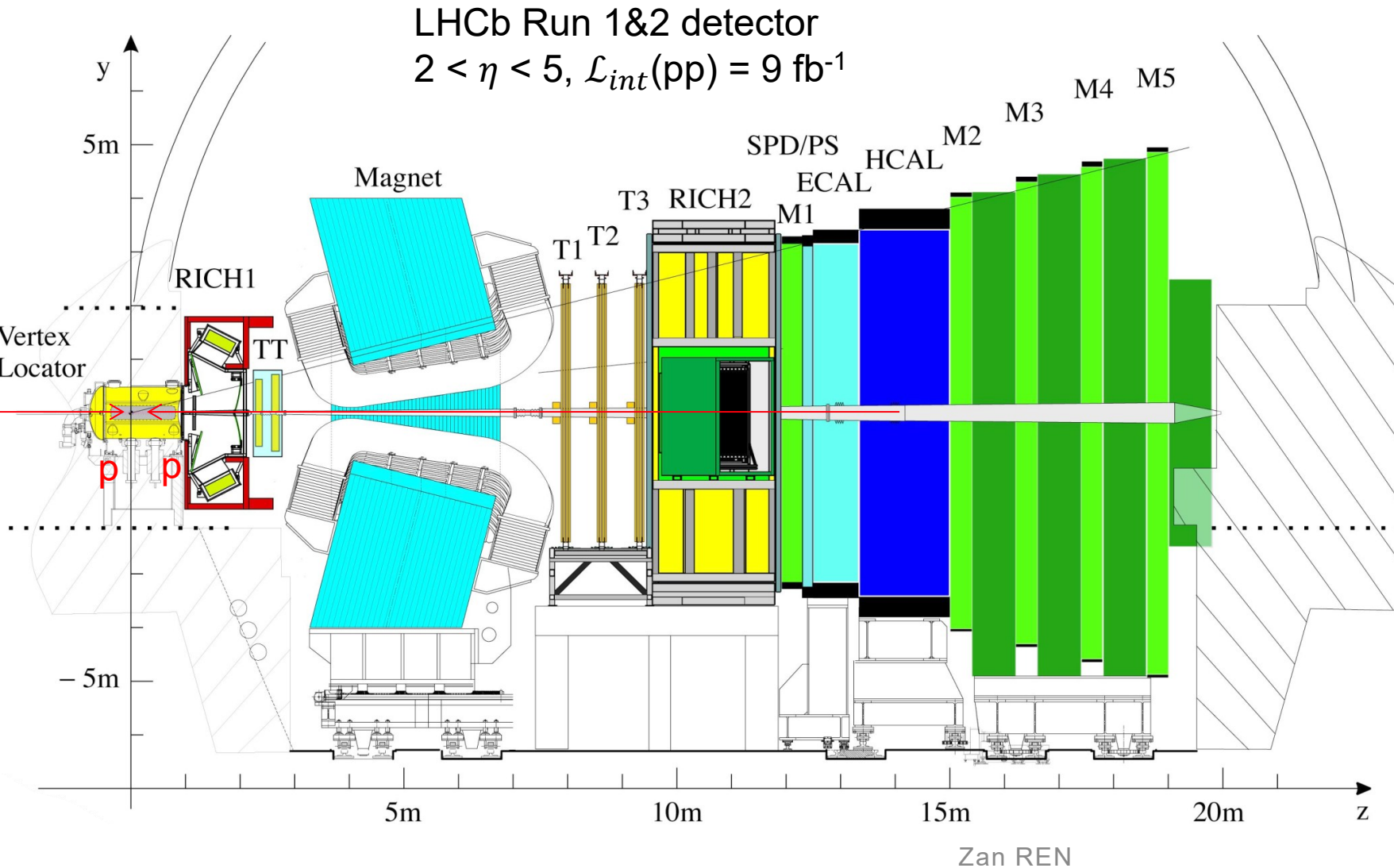
Hadrons discovered by LHCb

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

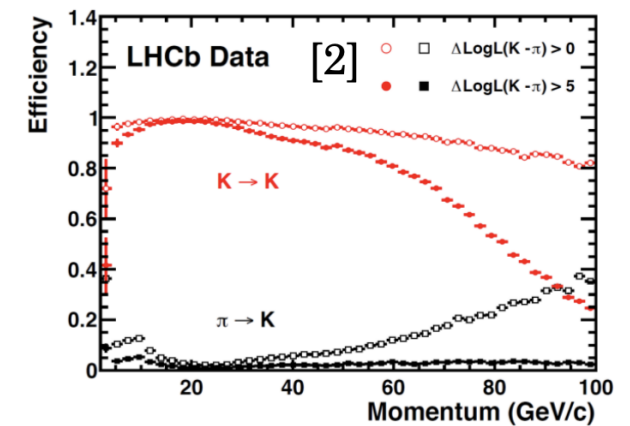


LHCb detector

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



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



JINST3 (2008) S08005
IJMPA 30 (2015) 1530022

New results covered by this talk

- Charmonia and tetraquark-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)

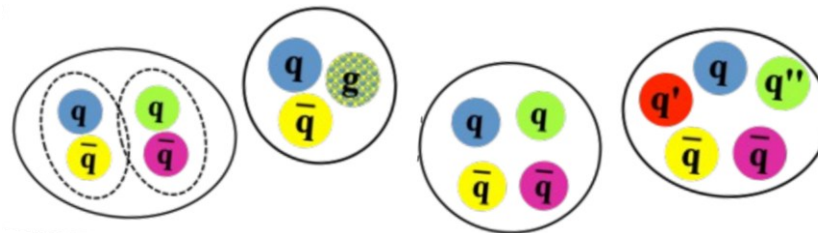
- Pentaquark-related:

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

PRD112 (2025) 052013

- Branching fractions of $\Lambda_b^0(\Xi_b^0) \rightarrow J/\psi \Xi^- K^+ (\pi^+)$ decays

EPJC 85 (2025) 812



Charmonia and tetraquark-related

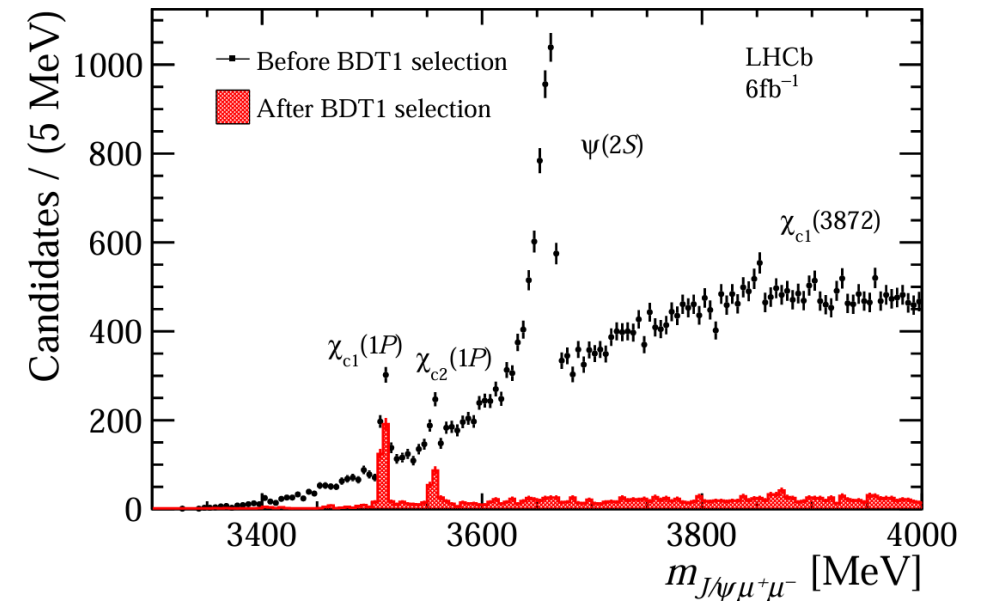
Observation of the decay $\chi_{c1}(3872) \rightarrow J/\psi \mu^+ \mu^-$

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 $m_{\mu\mu} \rightarrow$ related to the radiative decay of $\chi_{c1}(3872)$
 - Higher $m_{\mu\mu}$ region $\rightarrow \rho$ or ω contribution may exist
 - Simultaneously searching for $\chi_{c0}(3915)$

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

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



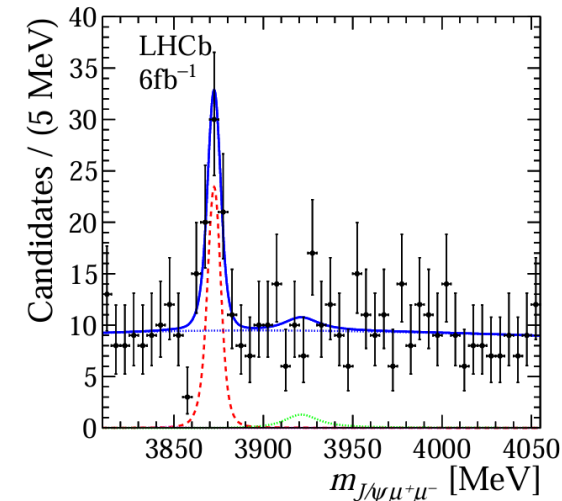
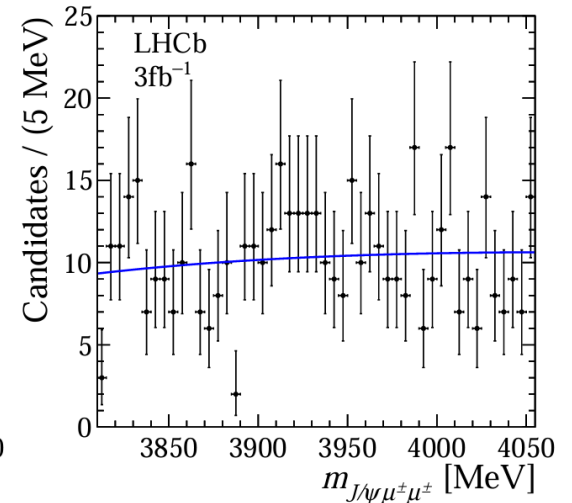
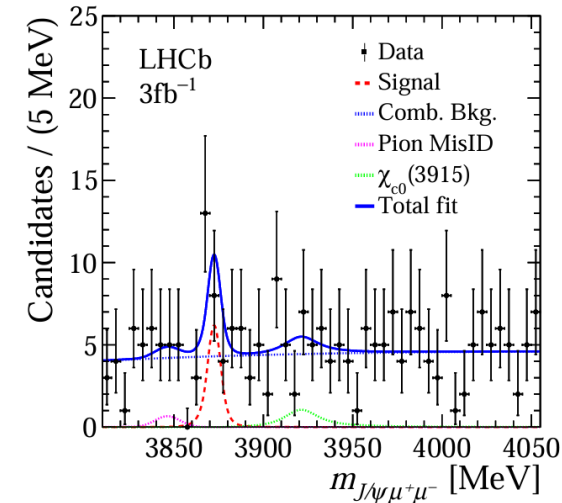
Observation of the decay $\chi_{c1}(3872) \rightarrow J/\psi \mu^+ \mu^-$

PRD 113, 072019 (2026)

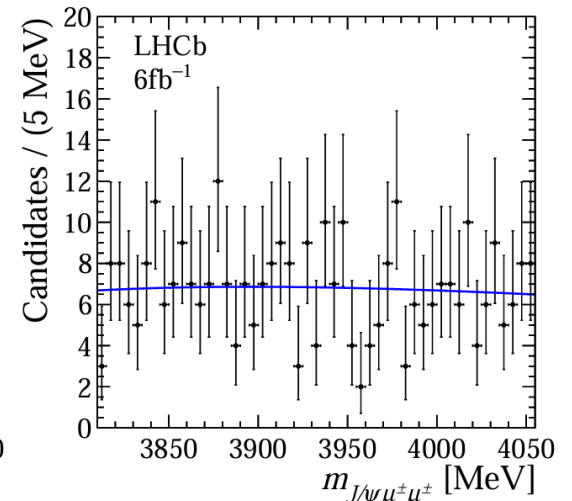
- 60 ± 11 $\chi_{c1}(3872)$ signals: significance $> 6\sigma$
- 14 ± 14 $\chi_{c0}(3915)$: not observed
- Relative branching fraction:

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

- Quoting the lasted $\mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-)$,
 $\mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi \mu^+ \mu^-)$
 $= (7.2 \pm 2.7) \times 10^{-5}$
- Not enough statistic to disentangle contribution from virtual photon and ρ or ω



Opposite-sign dimuon



Same-sign dimuon

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

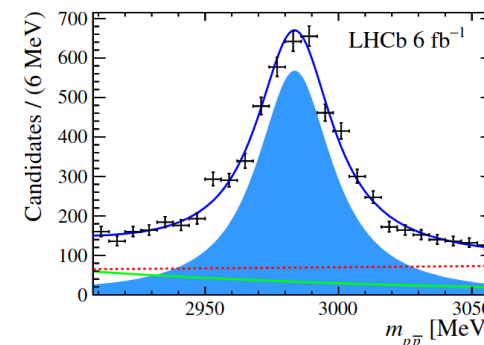
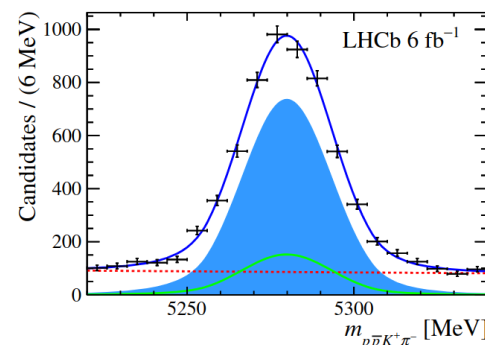
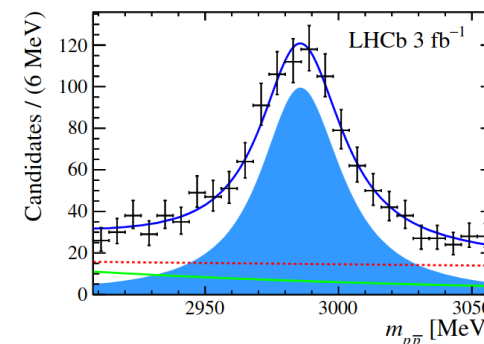
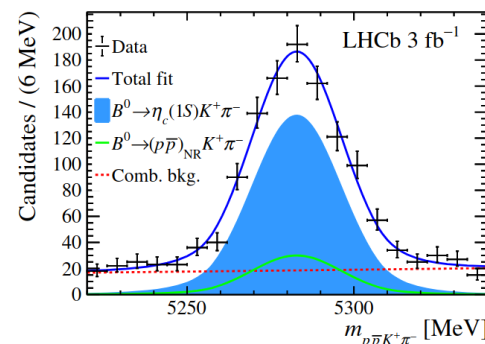
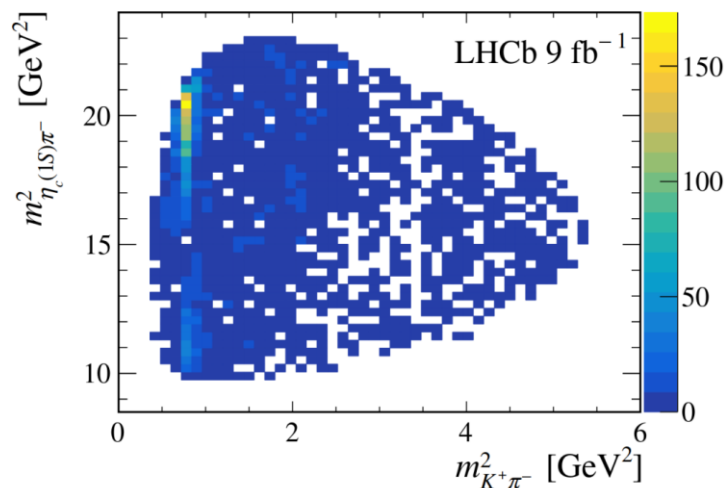
EPJC 78 1019 (2018)

- 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



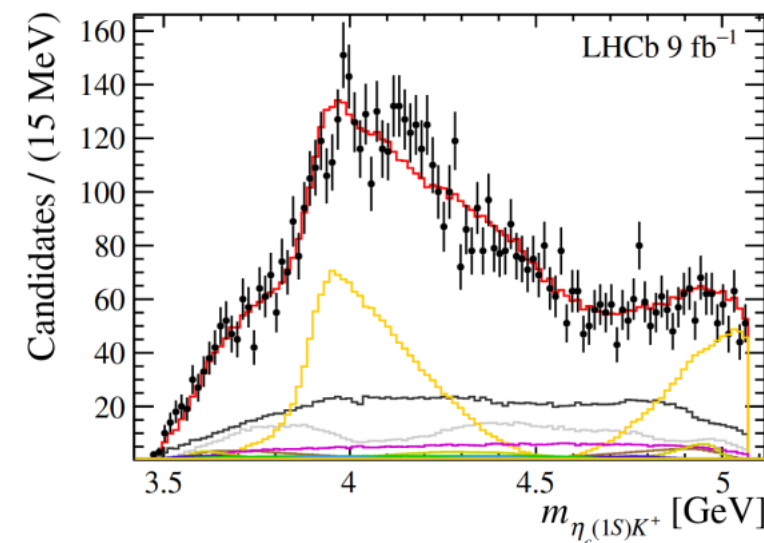
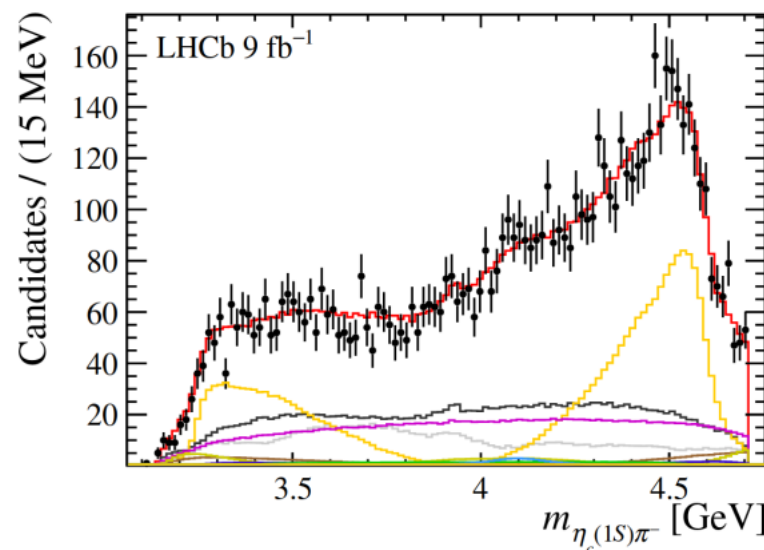
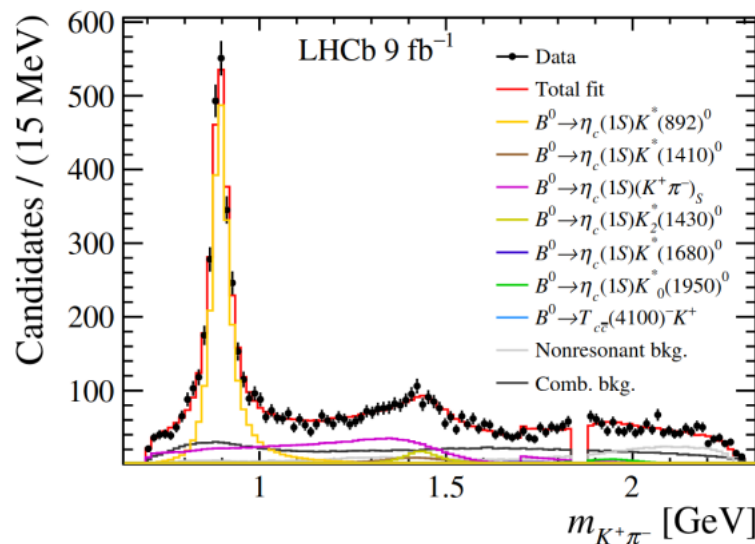
Baseline model: Low mass $K^+\pi^-$ -S wave

- K^* LASS model

Amplitude analysis of $B^0 \rightarrow \eta_c(1S)K^+\pi^-$ 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 $<3\sigma$ after considering systematical uncertainties.
- Comments:
 - The old result is superseded. No contribution from $T_{c\bar{c}}(4100)$ in this data.



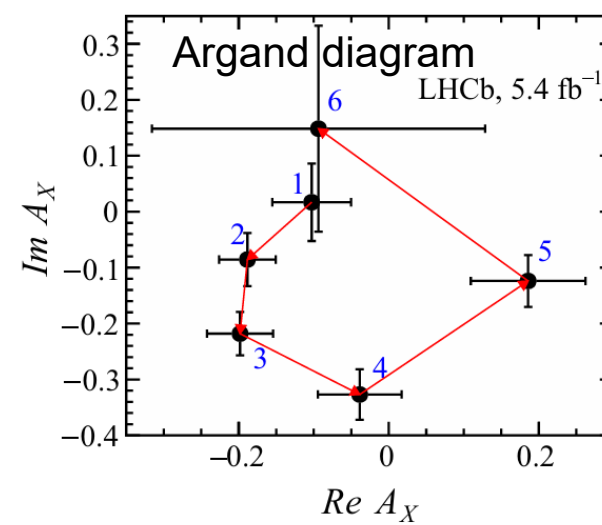
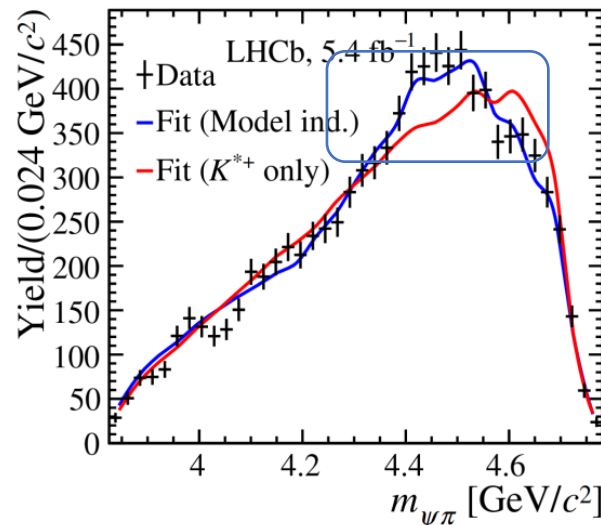
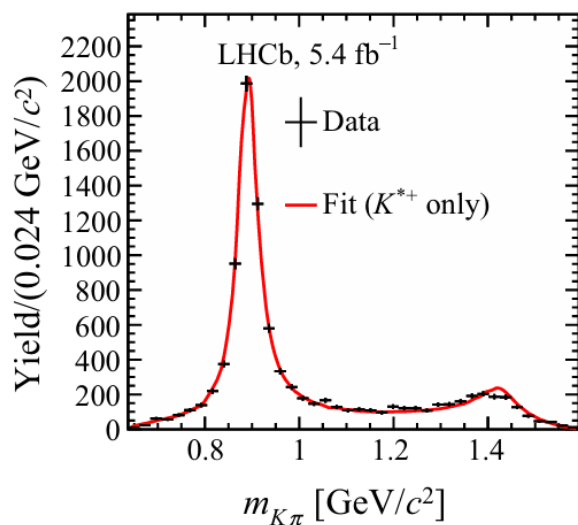
- Branching fraction: $\mathcal{B}(B^0 \rightarrow \eta_c K^+\pi^-) = (5.82 \pm 0.20 \pm 0.23 \pm 0.55) \times 10^{-4}$

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

PRD 113, L071101 (2026)

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

PRD 113, L071101 (2026)

Model-dependent investigation:

Structure modelled as a genuine state

Relativistic Breit-Wigner parametrization

$m(\text{GeV}/c^2)$	$\Gamma(\text{GeV})$	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

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

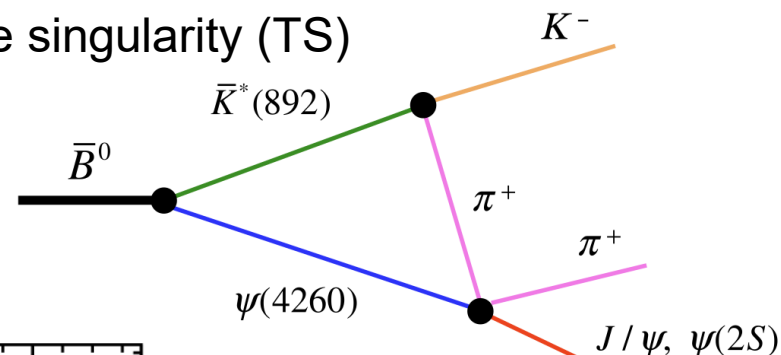
$$g_1: T_{c\bar{c}1}(4430)^+ \rightarrow \psi(2S)\pi^+$$

$$g_2: T_{c\bar{c}1}(4430)^+ \rightarrow \bar{D}_1^*(2600)^0 D^+$$

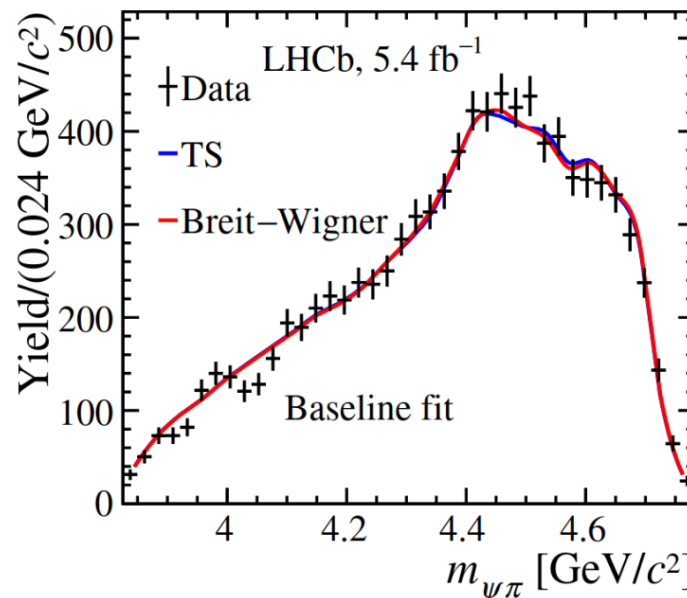
Result: $|g_2/g_1| < 6.8$ in 95% CL

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)

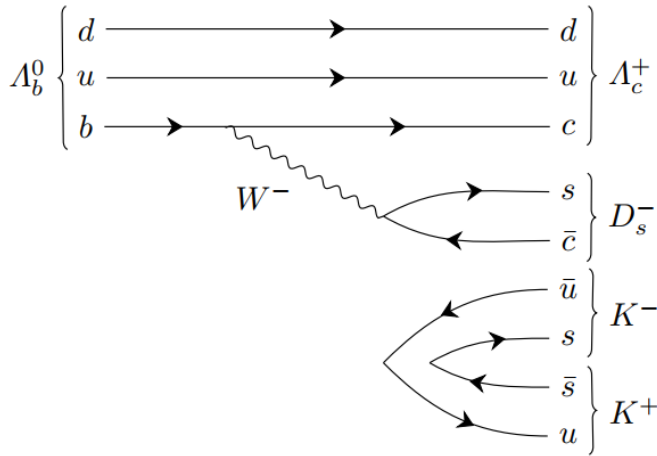
Pentaquark-related

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

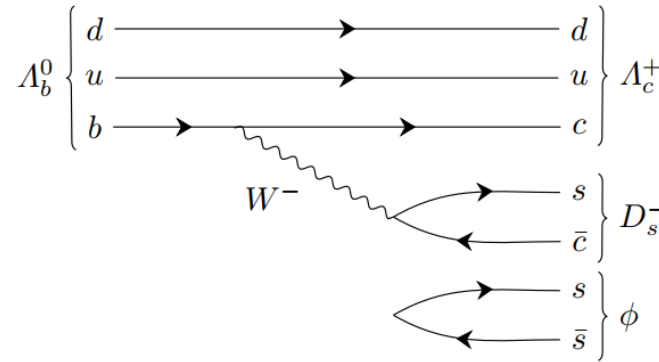
PRL 131 (2023) 031901

Sci. Bull. 66 (2021) 1278

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



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



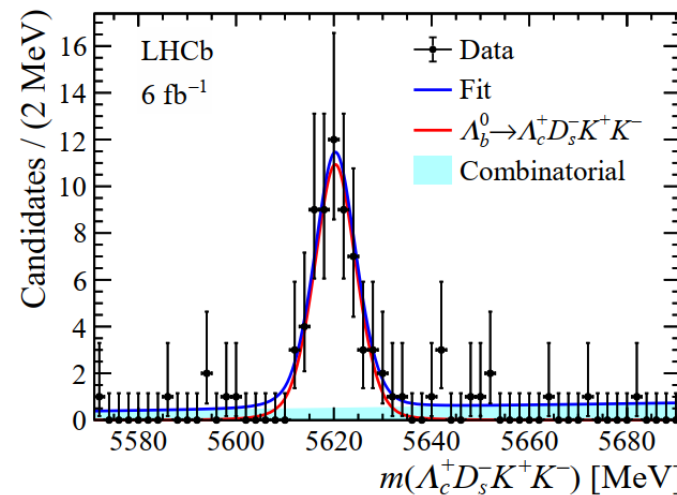
(b) The ϕ -dominated process

arXiv:2507.10713,
Submitted to PRD

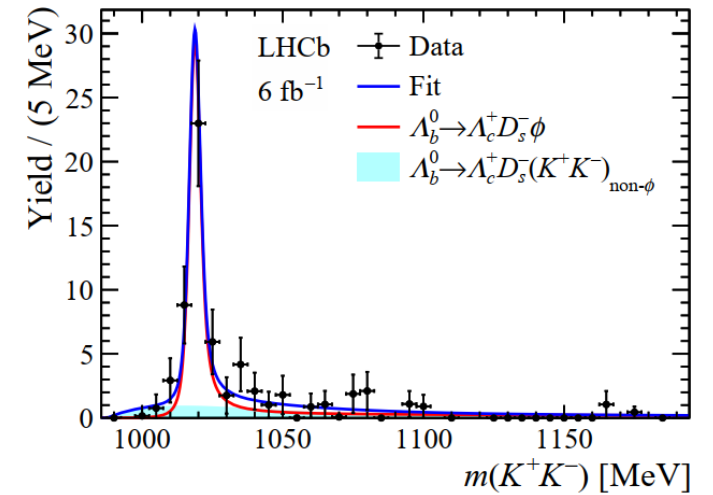
Cut & MVA based selection

- $61 \pm 8 \Lambda_b^0$ decays
- Dominated by $\phi \rightarrow K^+ K^-$

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



Zan REN



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

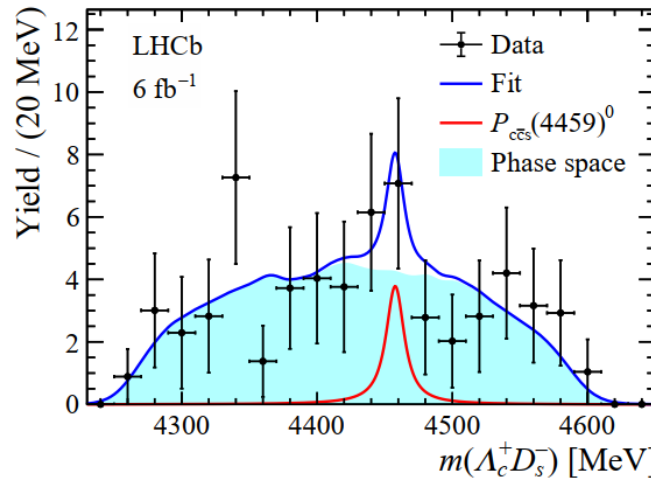
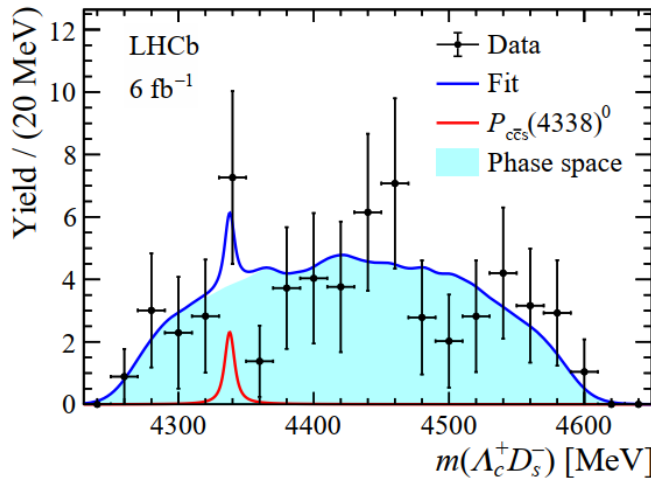
PRD112 (2025) 052013

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

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

- Widths and masses for $P_{c\bar{c}s}^0$ states are Gaussian with the means and uncertainties constrained to their known value.

PRL 131 (2023) 031901 Sci. Bull. 66 (2021) 1278



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

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

- Upper limits on 95% (90%) CLs:

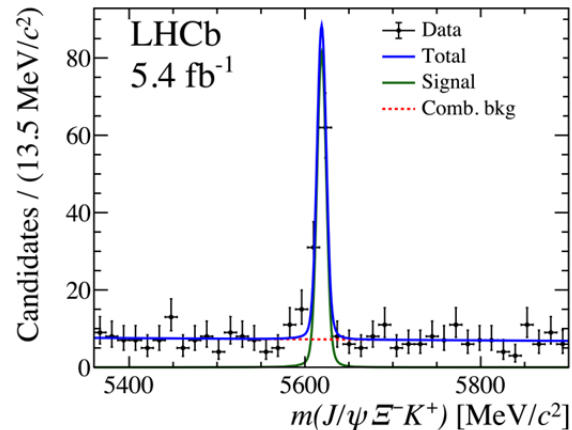
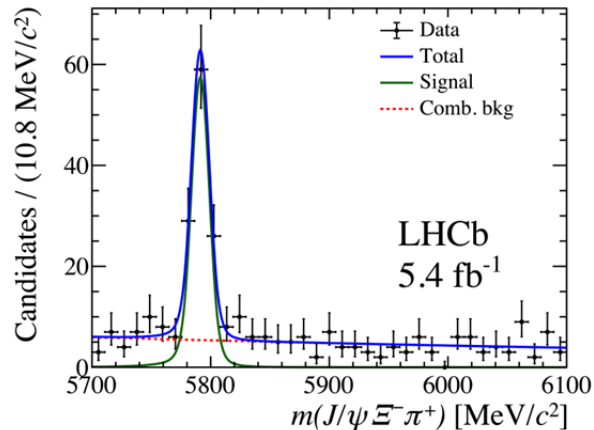
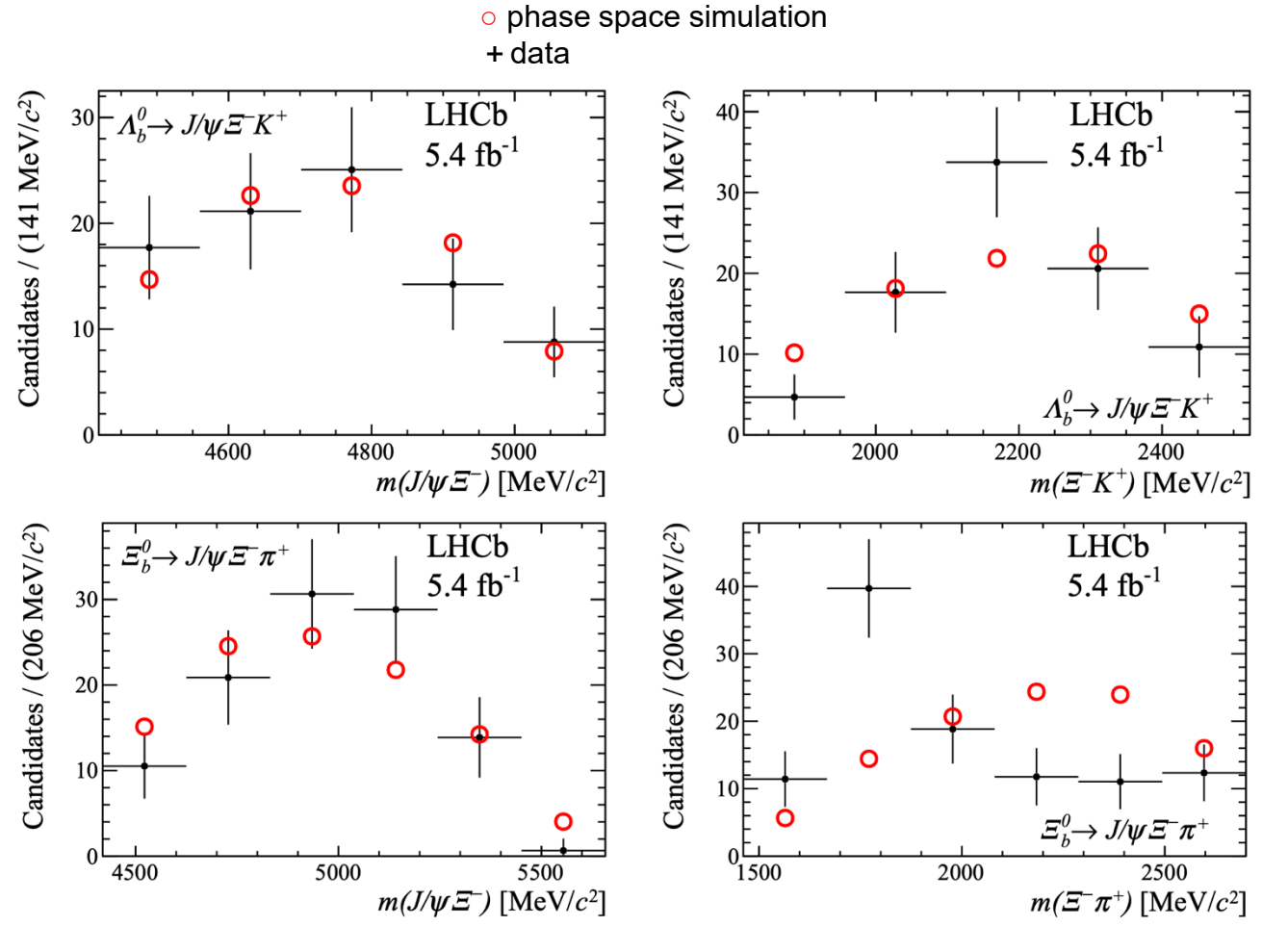
$$\mathcal{R}_{P_{c\bar{c}s}(4338)^0} < 0.12 \text{ (0.10)} \quad \text{and} \quad \mathcal{R}_{P_{c\bar{c}s}(4459)^0} < 0.20 \text{ (0.17)}$$

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

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

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

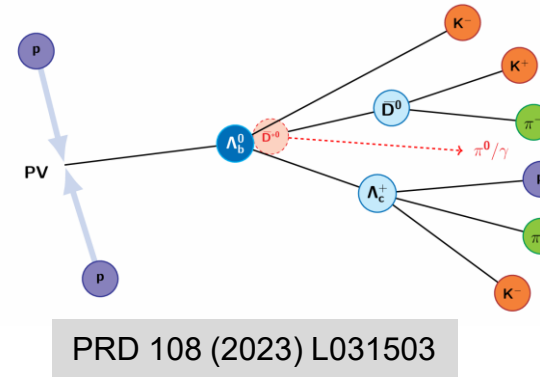
$$\frac{B(\Xi_b^0 \rightarrow J/\psi \Xi^- \pi^+)}{B(\Xi_b^0 \rightarrow J/\psi \Xi^-)} = (11.9 \pm 1.4 \pm 0.6) \times 10^{-2}$$



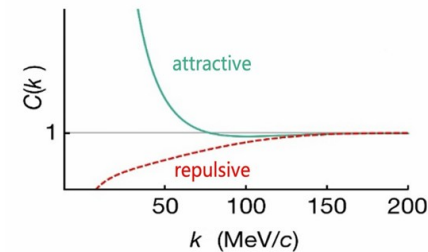
Progresses and prospects on pentaquark researches

- $\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^{(*)-} K^-$ Legendre moment analysis
- $\Lambda_b^0 \rightarrow \Lambda_c^+ D^{*0} K^-$ ECC (Extended Cone Closure)
 - Reconstruction for D^*
 - Recover the missing neutral particles by kinematic constraints
 - Can be applied for $\Lambda_b^0 \rightarrow \Sigma_c^+ \bar{D}^0 K^-$
- Femtoscopy study in $\Sigma_c^{++} D^-$ or $\Sigma_c^0 \bar{D}^0$
 - Help for determination of the spin of $P_{c\bar{c}}$
- $\Lambda_b^0 \rightarrow J/\psi p K^-$: amplitude analysis
 - Ongoing, delayed due to the complex amplitude:
 - Considering the coupled channels ($J/\psi p$ and $\Sigma_c^+ \bar{D}^0$)
 - Maybe publish a combined Run2 & Run3 result
- $B^- \rightarrow J/\psi \bar{p} \Lambda$, $\Xi_b^- \rightarrow J/\psi \Lambda K^-$:
 - Run 3 data analyses are ongoing ...

$$\langle Y_k^{U,j} \rangle = \sum_{l=1}^{N_j^{Data}} w_l P_k(h_l(\theta))$$



Correlation function



$C(k) > 1$: attractive

$C(k) = 1$: no interaction

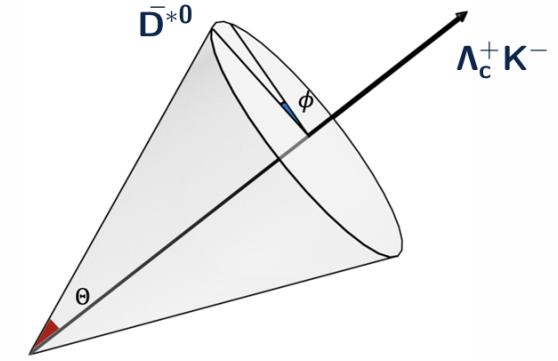
$C(k) < 1$: repulsive

$$C(k) = \xi(k) \frac{N_{same}(k)}{N_{mixed}(k)}$$

$\xi(k)$: corrections for experimental effect

$N_{same}(k)$: same-event distribution

$N_{mixed}(k)$: mixed-event distribution

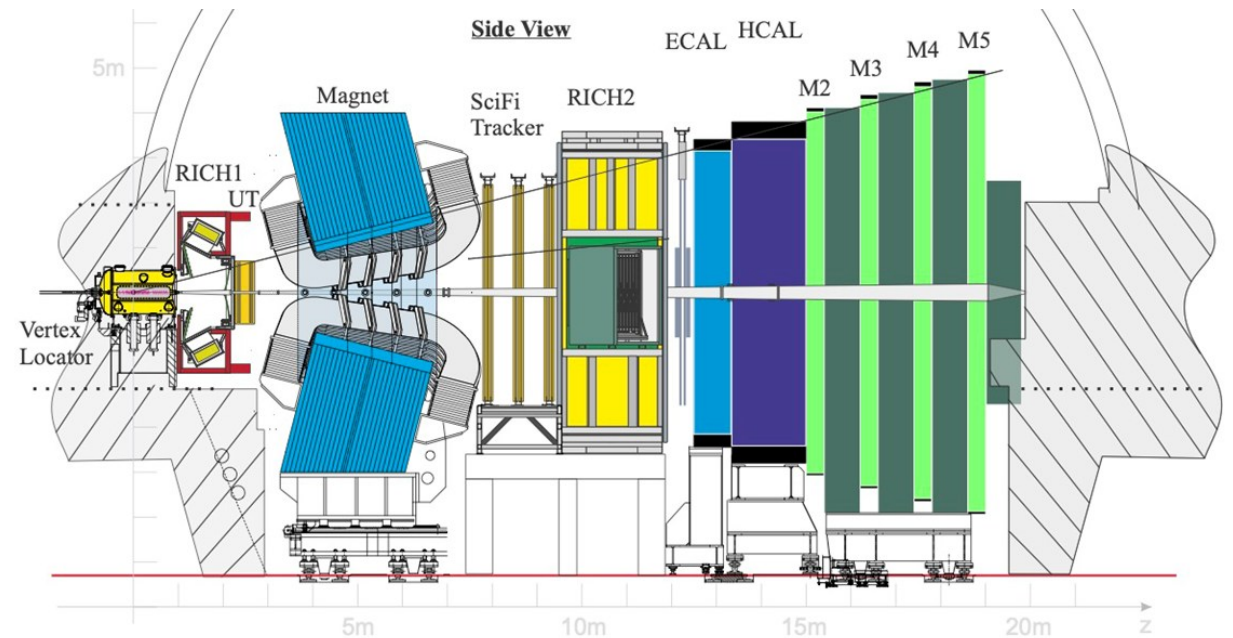
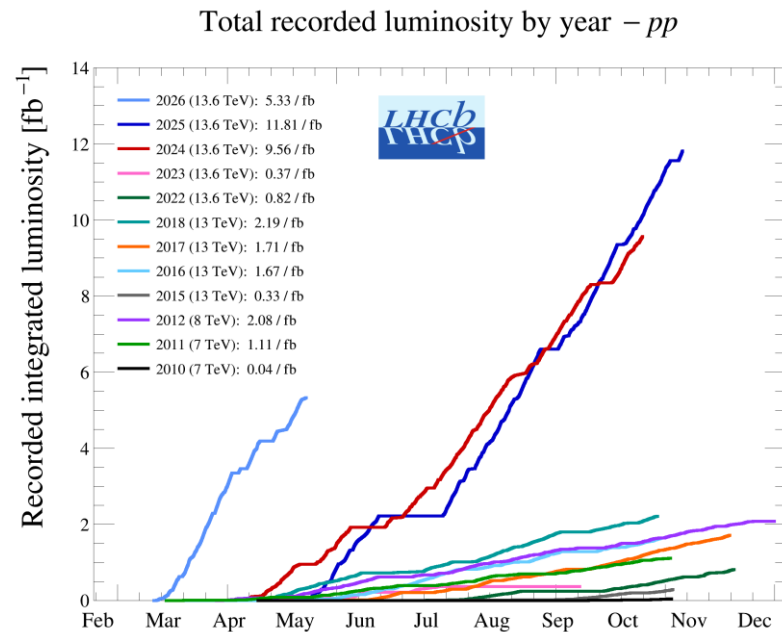


$$p_{\bar{D}^{*0}} = \sqrt{\left(\frac{m_{\bar{D}^{*0}}^2 - m_{\bar{D}^0}^2 - m_X^2}{2 \cdot m_{\bar{D}^0}} \right)^2 - m_X^2}$$

$$\cos \theta = \frac{m_{\bar{D}^{*0}}^2 + m_{\Lambda_c^+ K^-}^2 + 2 \cdot E_{\bar{D}^{*0}} \cdot E_{\Lambda_c^+ K^-} - m_{\Lambda_b^0}^2}{2 \cdot p_{\bar{D}^{*0}} \cdot p_{\Lambda_c^+ K^-}}$$

Summary and prospects

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





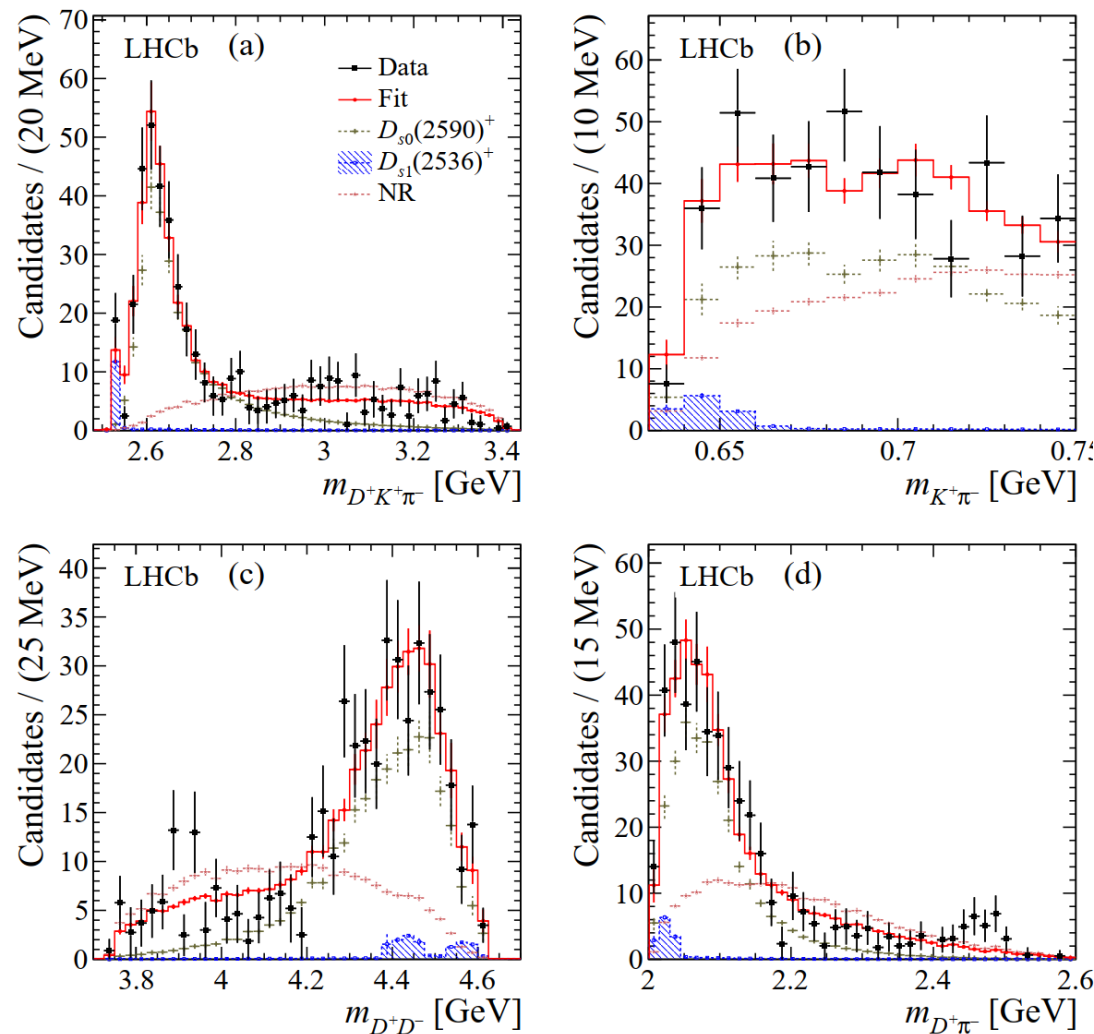
Thanks for your listening!

Backup

Study of the $B^0 \rightarrow D^+ D^- K^+ \pi^-$ 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

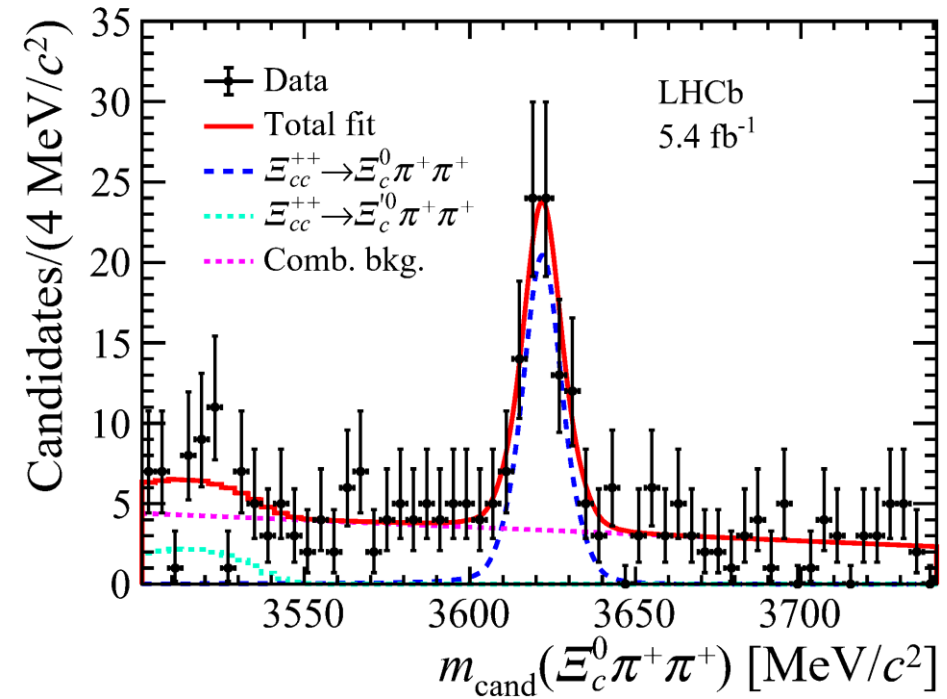
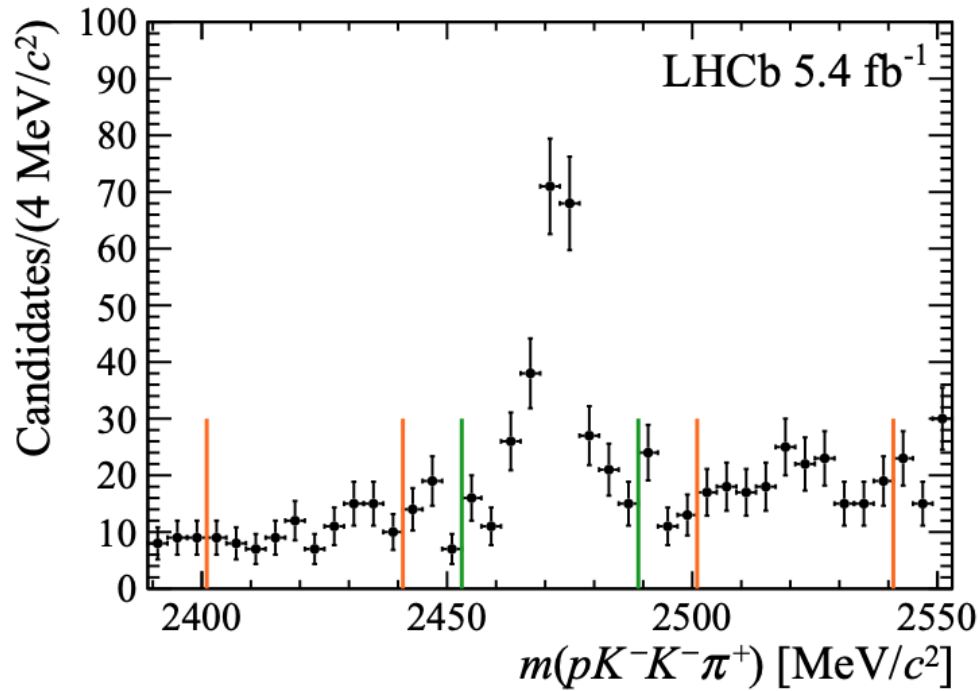
- $m_R = 2591 \pm 6 \pm 7$ MeV
- $\Gamma_R = 89 \pm 16 \pm 12$ MeV
- $J^P = 0^-$
- While 1^+ and 2^- are rejected by $>10\sigma$

	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)	
$D_{s0}^+ - \text{NR}$	-18	± 18 (stat)	± 24 (syst)	
D_{s1}^+ / D_{s0}^+	6.1	± 2.4 (stat)	± 1.4 (syst)	

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

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.

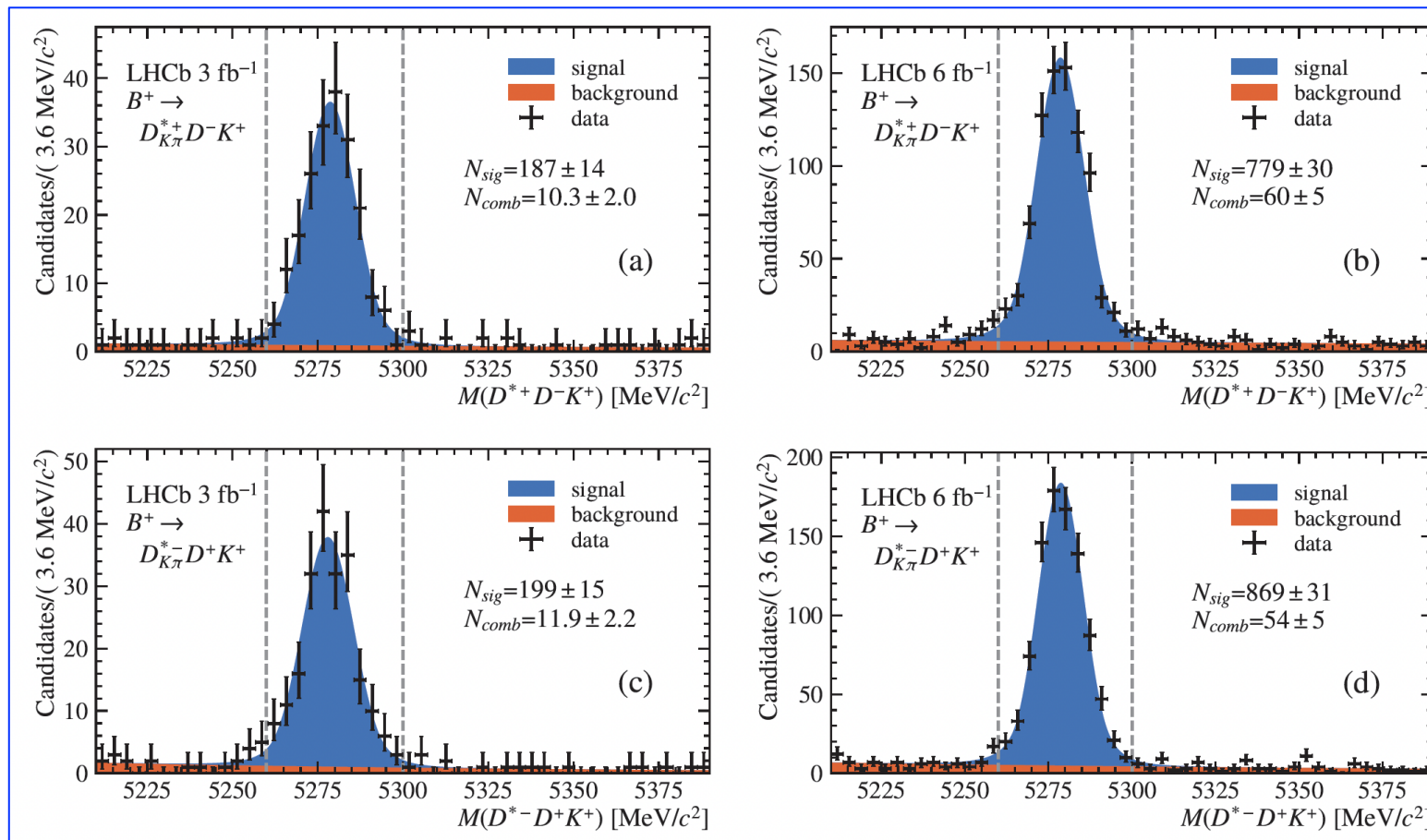


$$\frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^0 \pi^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)} = 1.37 \pm 0.18(\text{stat}) \pm 0.09(\text{syst}) \pm 0.35(\text{ext})$$

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

[PRL 133 (2024) 131902]

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

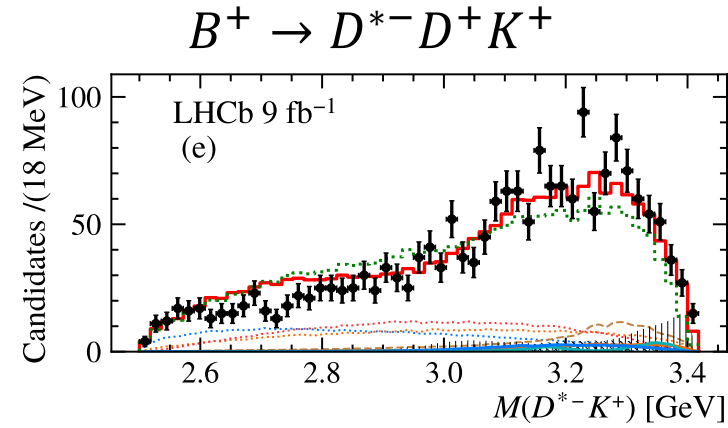
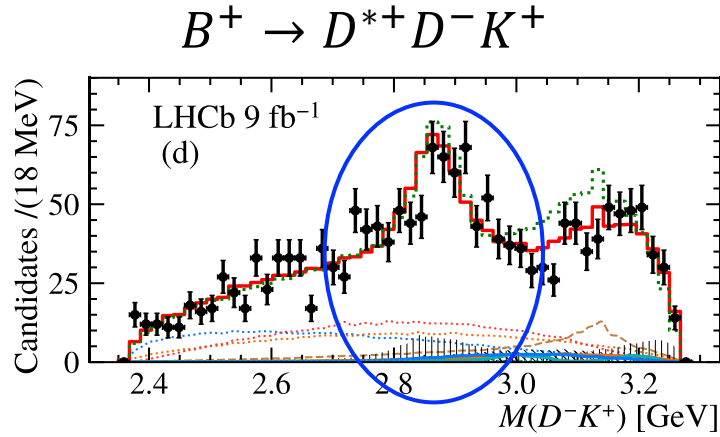


✓ $B^+ \rightarrow D^{*+} D^- K^+$: **966**

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

$B^+ \rightarrow D^{*\pm} D^{\mp} K^+ : T_{\bar{c}\bar{s}}^*$ states

[PRL 133 (2024) 131902]



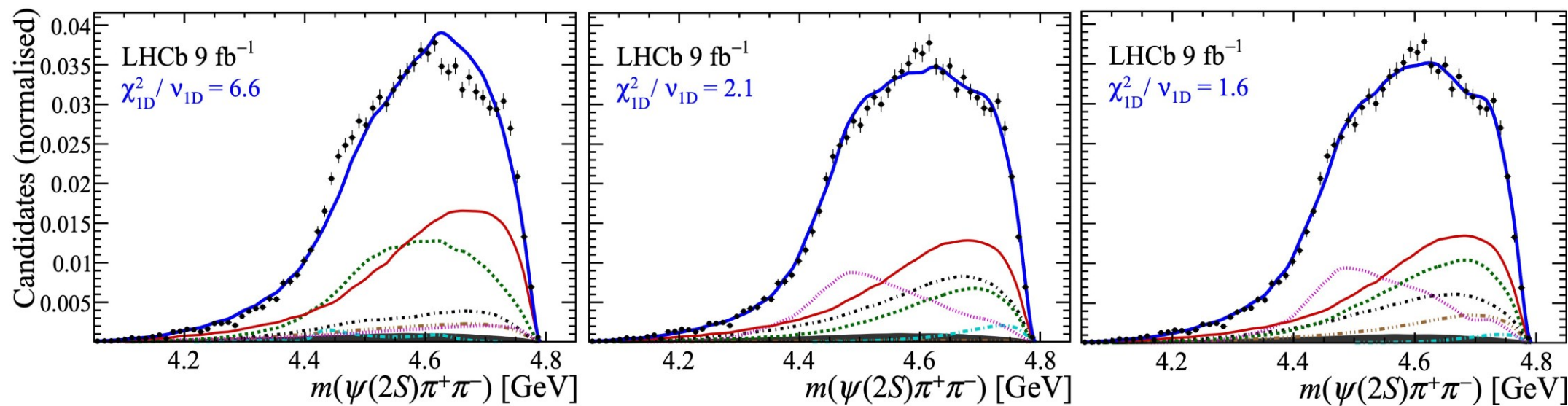
	Property	This work	Previous work
11σ	$T_{\bar{c}\bar{s}0}^*(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
	$T_{\bar{c}\bar{s}0}^*(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
9.2σ	$T_{\bar{c}\bar{s}1}^*(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
	$T_{\bar{c}\bar{s}1}^*(2900)^0$ width [MeV]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

✓ $T_{\bar{c}\bar{s}0}^*(2870)^0 \rightarrow D^{*-} K^+$ forbidden

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

Amplitude analysis of $B^+ \rightarrow \psi(2S)K^+\pi^+\pi^-$ decay

- 7D amplitude analysis, using a model-building algorithm to iteratively add contributions to the total amplitude.
- More than 30k $B^+ \rightarrow \psi(2S)K^+\pi^+\pi^-$ decays are observed with $> 97\%$ signal purity.



8 known excited $K' \rightarrow K\pi\pi$
 3 known excited $\psi^* \rightarrow \psi(2S)\pi\pi$
No exotic states

6 known excited $K' \rightarrow K\pi\pi$
 1 known excited $\psi^* \rightarrow \psi(2S)\pi\pi$
 8 “known” $\rightarrow \psi(2S)\pi\pi, \psi(2S)\pi$ or $\psi(2S)K$

6 known excited $K' \rightarrow K\pi\pi$
 1 known excited $\psi^* \rightarrow \psi(2S)\pi\pi$
8 “known” $\rightarrow \psi(2S)\pi\pi, \psi(2S)\pi$ or $\psi(2S)K$
+ 3 new exotic states

JHEP 01 (2025) 054

$T_{c\bar{c}s1}(4600)^0 \rightarrow \psi(2S)K\pi$
 $T_{c\bar{c}s1}(4900)^0 \rightarrow \psi(2S)K\pi$
 $T_{c\bar{c}s1}^*(5200)^0 \rightarrow \psi(2S)K\pi(\text{maybe})$

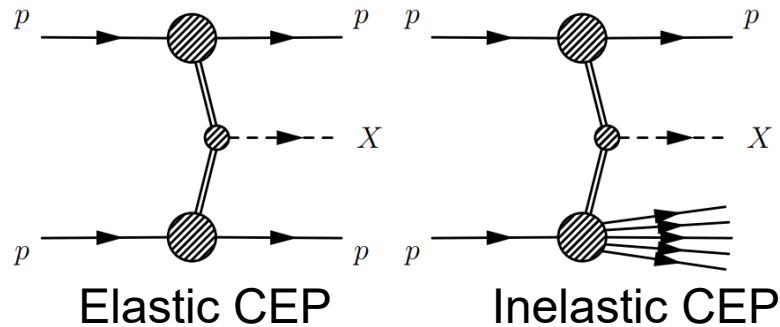
Amplitude analysis of $B^+ \rightarrow \psi(2S)K^+\pi^+\pi^-$ decay

- Interpretation of results is not straightforward: JHEP 01 (2025) 054
 - Four $X^0/\chi_{c0} \rightarrow \psi(2S)\pi^+\pi^-$ 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 $X^0 \rightarrow T_{c\bar{c}1}^\pm \pi^\mp$ observed
 - Hidden-charm exotics with minimal quark content $c\bar{c}\bar{s}d$: $T_{c\bar{c}\bar{s}1}(4600/4900)^0 \rightarrow \psi(2S)K^+\pi^-$, may be the radial excitations of $T_{c\bar{c}\bar{s}}(4000)^0$ in $B^0 \rightarrow [J/\psi K_S^0]\phi$

Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	$\Delta(-2 \ln \mathcal{L})$	ΔN_{par}	Sign. [σ]	Stat only
$\chi_{c0}(4475)$	0^+	$4475 \pm 7 \pm 12$	$231 \pm 19 \pm 32$	675	6	> 20 (19)	
$\chi_{c1}(4650)$	1^+	$4653 \pm 14 \pm 27$	$227 \pm 26 \pm 22$	286	6	15 (13)	
$\chi_{c0}(4710)$	0^+	$4710 \pm 4 \pm 5$	$64 \pm 9 \pm 10$	255	6	14 (10)	
$\eta_{c1}(4800)$	1^-	$4785 \pm 37 \pm 119$	$457 \pm 93 \pm 157$	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^+	$4257 \pm 11 \pm 17$	$308 \pm 20 \pm 32$	842	16	> 20 (> 20)	
$T_{c\bar{c}1}(4430)^+$	1^+	$4468 \pm 21 \pm 80$	$251 \pm 42 \pm 82$	305	10	15 (8)	
$T_{c\bar{c}\bar{s}1}(4600)^0$	1^+	$4578 \pm 10 \pm 18$	$133 \pm 28 \pm 69$	287	8	15 (12)	
$T_{c\bar{c}\bar{s}1}(4900)^0$	1^+	$4925 \pm 22 \pm 47$	$255 \pm 55 \pm 127$	177	4	12 (8)	
$T_{c\bar{c}\bar{s}1}^*(5200)^0$	1^-	$5225 \pm 86 \pm 181$	$226 \pm 76 \pm 374$	149	6	10 (8)	
$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	597	4	> 20 (14)	

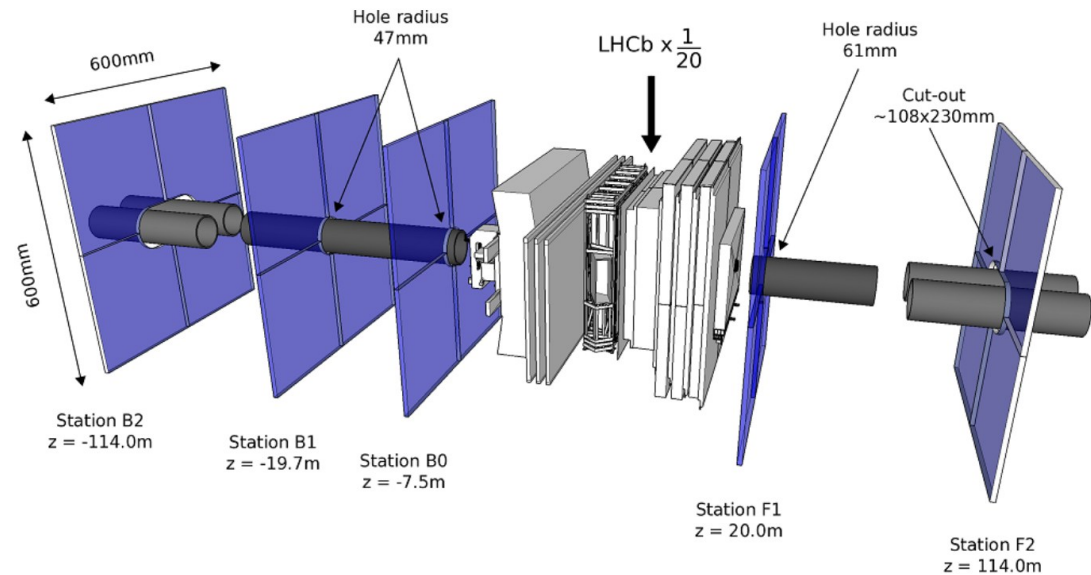
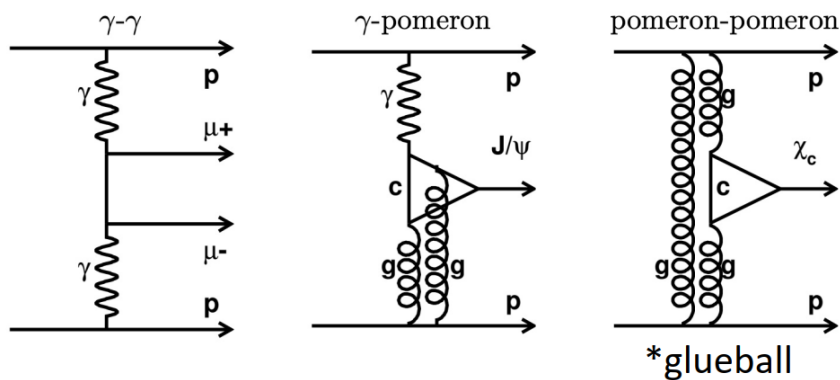
Study of exotic $J/\psi\phi$ resonances in CEP process

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



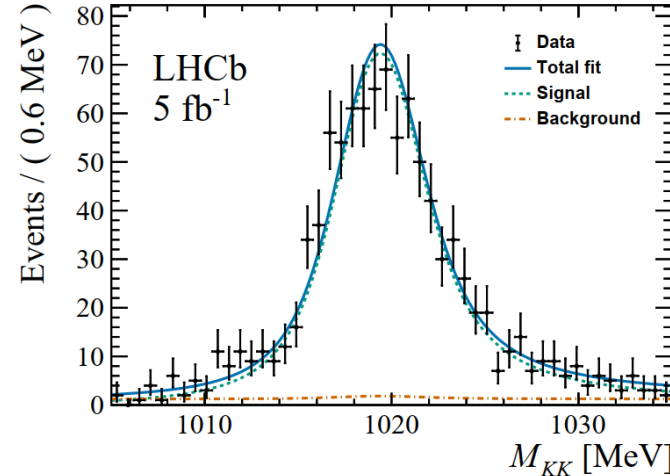
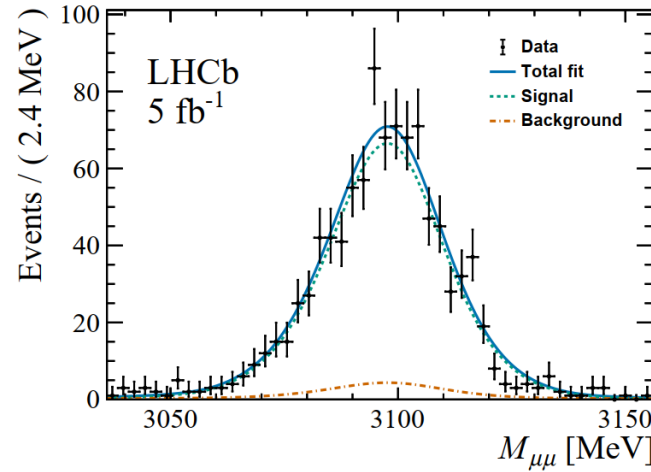
- Low-activity
- Specific kinematics $\rightarrow$ Lower background

HeRSChel (high-rapidity shower counters for LHCb)
 $\rightarrow$ Extend LHCb's sensitivity to $5 < |\eta| < 10$



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

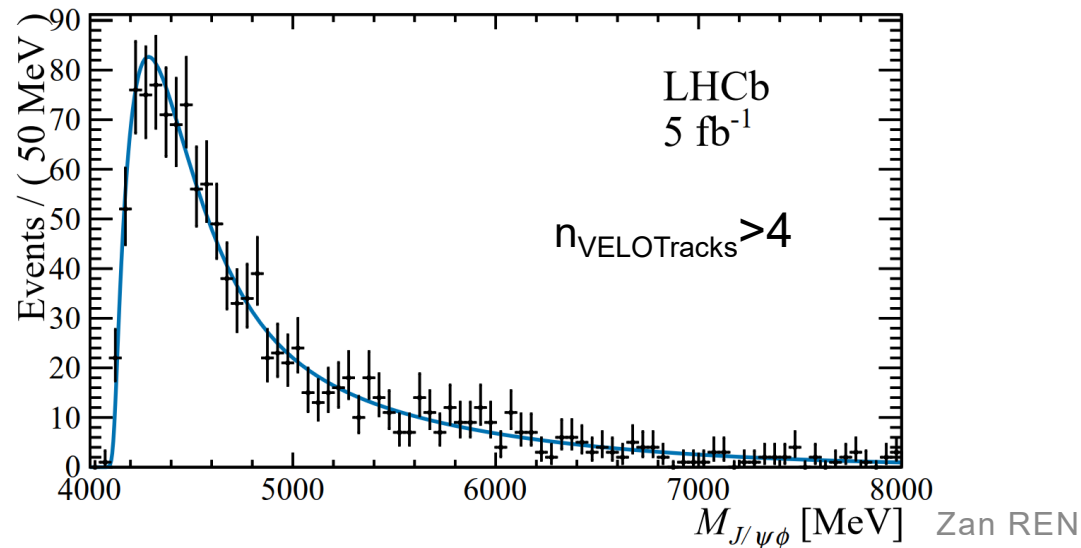
- Clean J/ψ and ϕ peaks: 2D fit on $m(\mu\mu), m(KK)$



Purity ~ 93%

PRL 134 (2025) 3, 031902

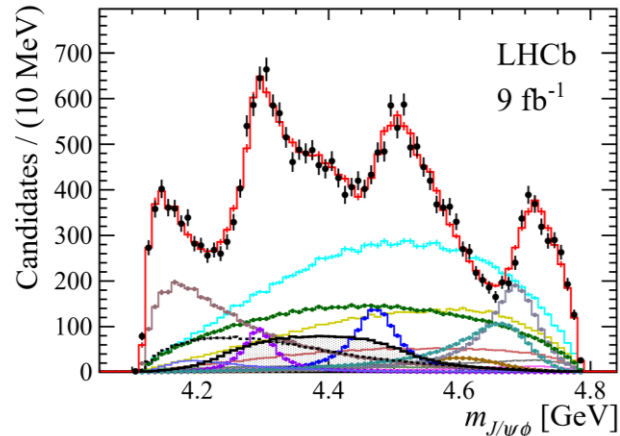
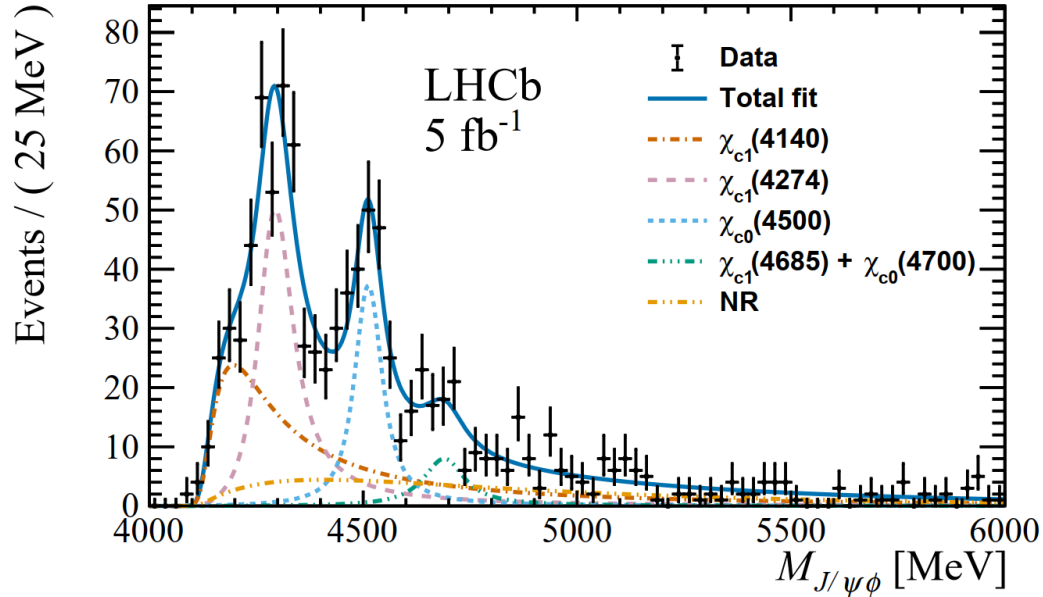
- Background lineshape: determined by dataset with inverted offline multiplicity requirement



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 $> 3\sigma$ 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:

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

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

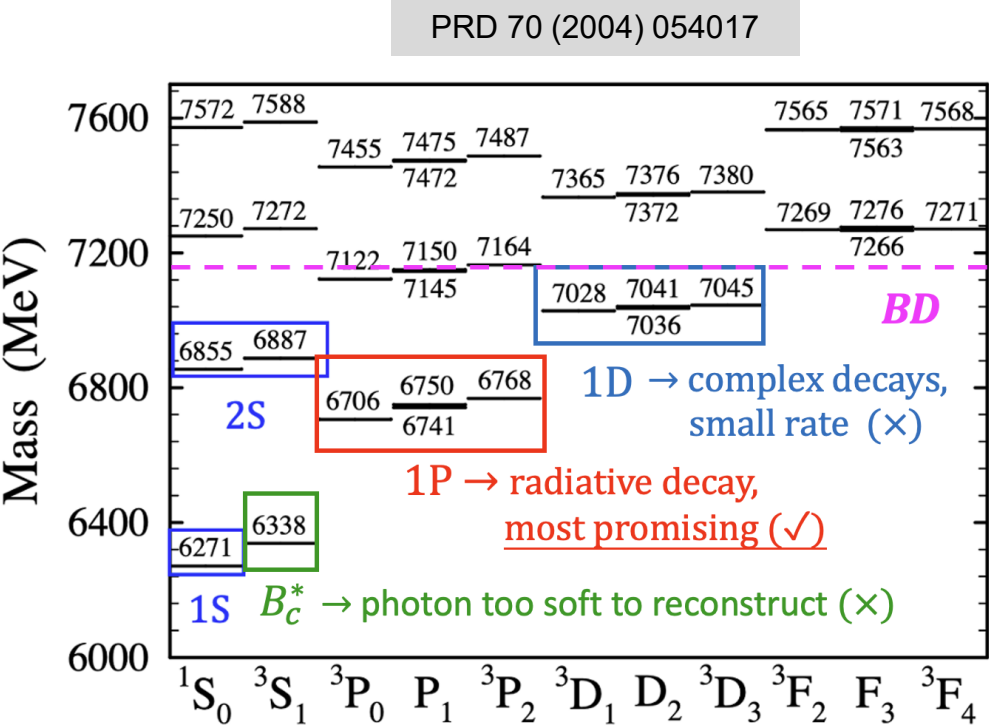
$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\text{eff}}^{\chi_{c0}(4500)} = (0.42^{+0.09}_{-0.08} \pm 0.06) \text{ pb},$$

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

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

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



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

Four physical states

mixing

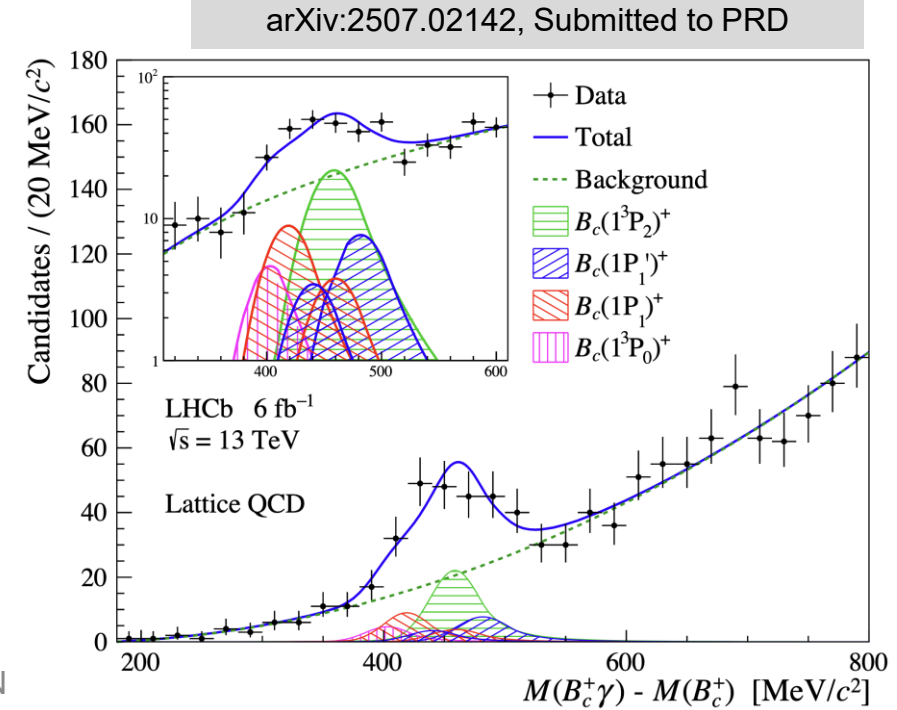
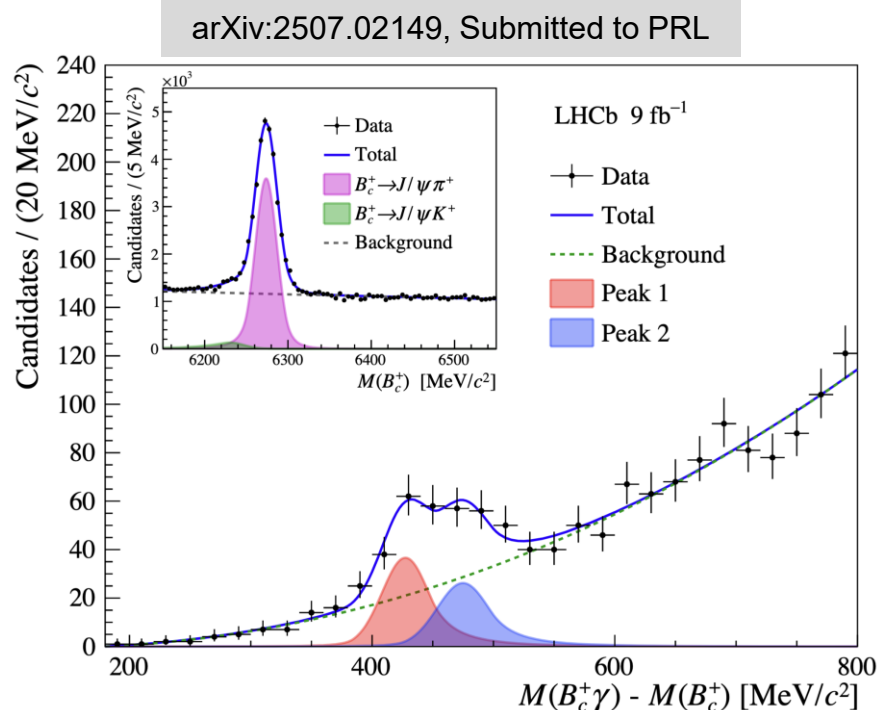
$1^3P_0, 1^3P_2 \begin{pmatrix} 1P'_1 \\ 1P_1 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} 1^1P_1 \\ 1^3P_1 \end{pmatrix}$

States	1^3P_0	$1P_1$	$1P'_1$	1^3P_2
Decays	$B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$	$B_c^+\gamma$	$B_c^+\gamma$	$B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$
		$B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$	$B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$	
#peaks	1	2	2	1

Observation of the orbitally excited B_c^+ states

- $B_c(1P)^+ \rightarrow B_c^+ \gamma$, where $B_c^+ \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) \pi^+$ 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 $\Rightarrow$ a minimal effective **two-peak** model used
- By fixing the peak positions and relative yields to theory, different theoretical models were investigated $\Rightarrow$ all generally good
- The relative production rate, representing the fraction of B_c^+ comes from $B_c(1P)^+$ is determined using the LQCD model

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



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

$$m[\Xi_c(2815)^+] = 2816.65 \pm 0.03 \pm 0.03 \pm 0.23 \text{ MeV},$$

$$\Gamma[\Xi_c(2815)^+] = 2.07 \pm 0.08 \pm 0.12 \text{ MeV},$$

$$m[\Xi_c(2923)^+] = 2922.8 \pm 0.3 \pm 0.5 \pm 0.2 \text{ MeV},$$

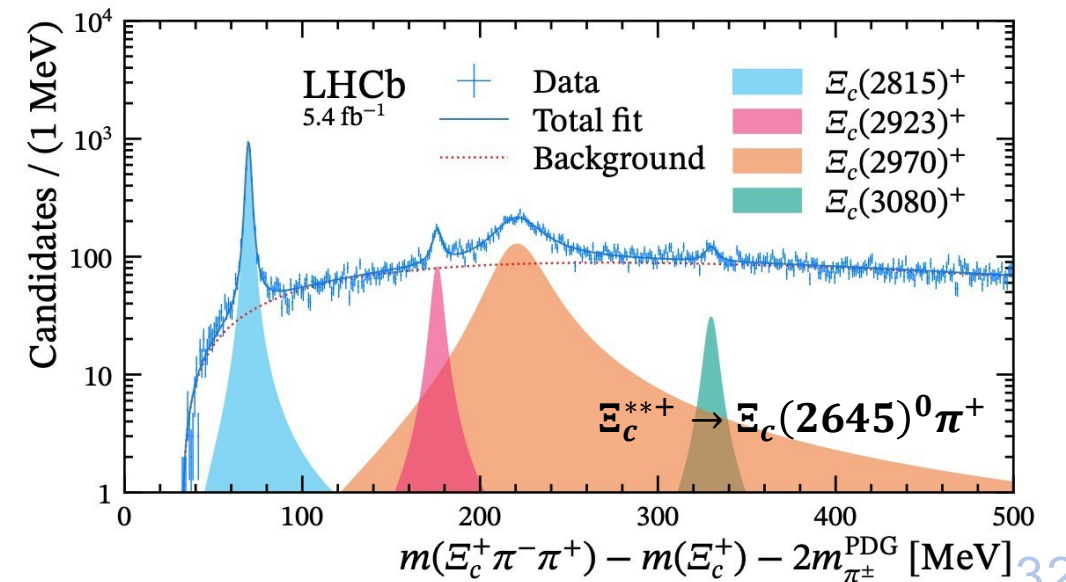
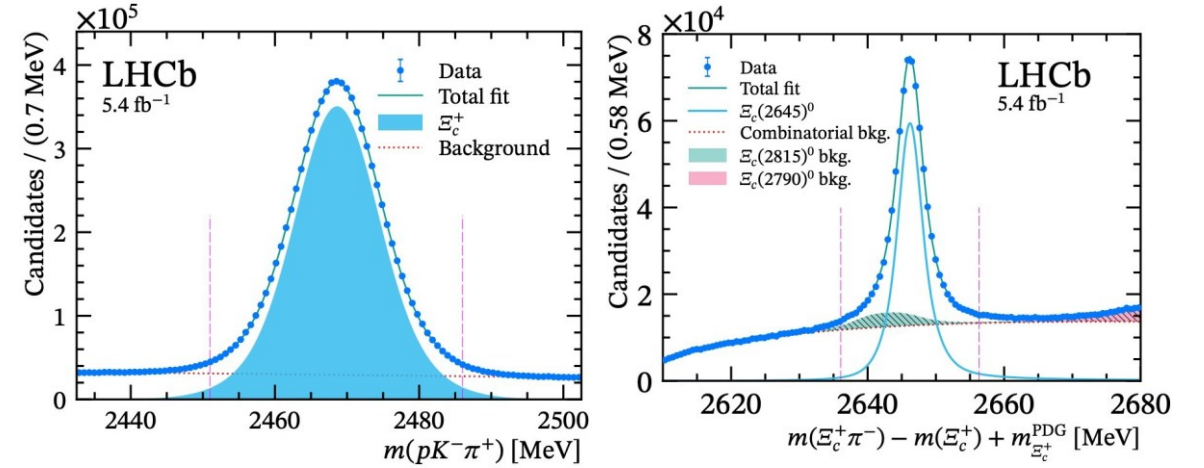
$$\Gamma[\Xi_c(2923)^+] = 5.3 \pm 0.9 \pm 1.4 \text{ MeV},$$

$$m[\Xi_c(2970)^+] = 2968.6 \pm 0.5 \pm 0.5 \pm 0.2 \text{ MeV},$$

$$\Gamma[\Xi_c(2970)^+] = 31.7 \pm 1.7 \pm 1.9 \text{ MeV},$$

$$m[\Xi_c(3080)^+] = 3076.8 \pm 0.7 \pm 1.3 \pm 0.2 \text{ MeV},$$

$$\Gamma[\Xi_c(3080)^+] = 6.8 \pm 2.3 \pm 0.9 \text{ MeV},$$

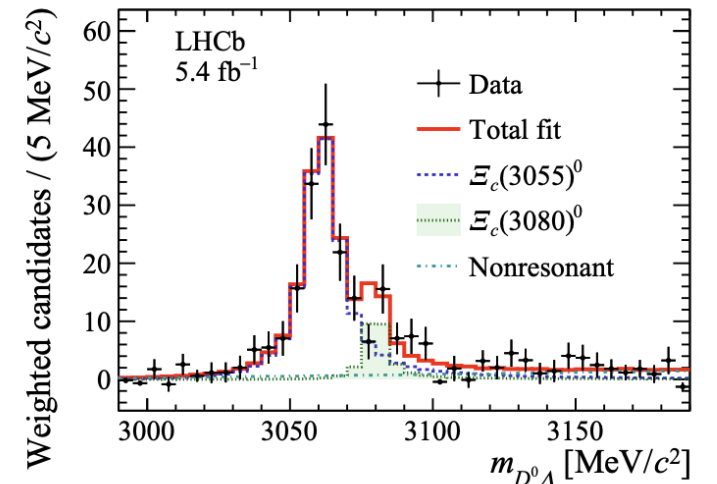
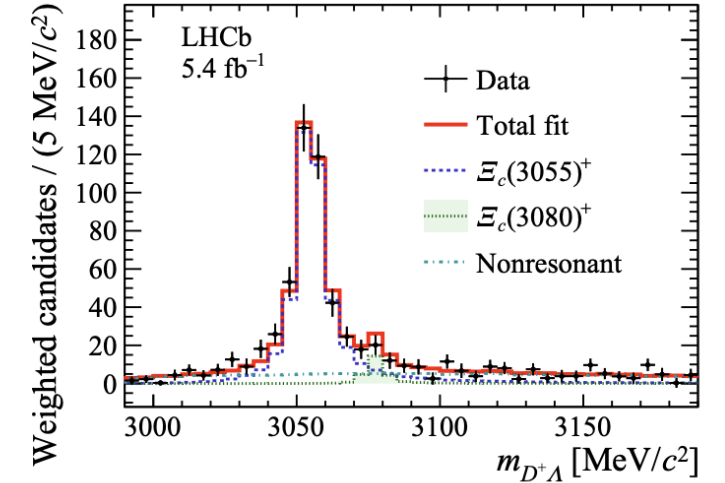


First determination of the spin-parity of $\Xi_c(3055)^{+,0}$

PRL 134 (2025) 081901

- Study $\Xi_c^{**+ (0)}$ in the $\Xi_b^{0 (-)} \rightarrow D^{+ (0)} \Lambda \pi^+$ processes
 - Dominated by $\Xi_c(3055)^{+ (0)} \rightarrow D^{+ (0)} \Lambda$ 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
- $R_{\mathcal{B}} = Br(\Xi_c(3080)) / Br(\Xi_c(3055))$ measured

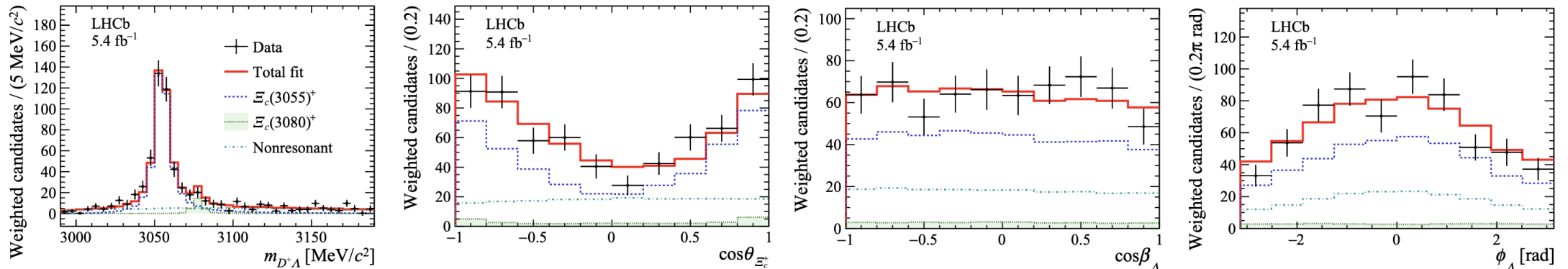
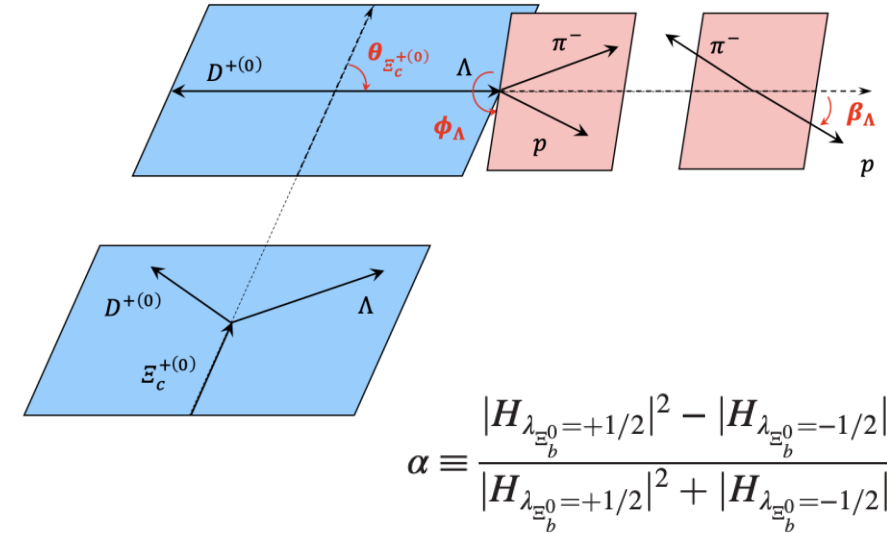
Quantity	$\Xi_c(3055)^+$	$\Xi_c(3055)^0$
$m [\text{MeV}/c^2]$	$3054.52 \pm 0.36 \pm 0.17$	$3061.00 \pm 0.80 \pm 0.23$
$\Gamma [\text{MeV}/c^2]$	$8.01 \pm 0.76 \pm 0.34$	$12.4 \pm 2.0 \pm 1.1$
$R_{\mathcal{B}}$	$0.045 \pm 0.023 \pm 0.006$	$0.14 \pm 0.06 \pm 0.04$



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

PRL 134 (2025) 081901

- $\Xi_b^{0(-)} \rightarrow \Xi_c^{*+ (0)} (\rightarrow D\Lambda(\rightarrow p\pi))\pi^-$ amplitude analysis
 - 4-dimensional fit to $m(D\Lambda)$, helicity angles θ, β, ϕ
 - J^P of $\Xi_c(3055)^{+(0)}$ determined to be $3/2^+$ 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 $\alpha_{\Xi_b \rightarrow \Xi_c(3055)\pi^-}$ (up-down asymmetry)
 - Consistent with maximal parity violation
 - Indicates the light quarks are spectating in $b \rightarrow c$ transition
- Identified $\Xi_c(3055)$ as the first D -wave, λ -mode excitation of the Ξ_c triplet

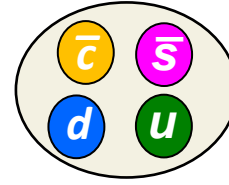


Observation of $T_{cs0}^*(2870)^0$ in $B^- \rightarrow D^- D^0 K_S^0$

- Amplitude analysis of $B^- \rightarrow D^- D^0 K_S^0$ found $T_{cs0}^*(2870)^0$, but no $T_{cs1}^*(2900)^0$ decaying to $D^0 K_S^0$

- $T_{cs0}^*(2870)^0$

- Significance of 5.3σ
- $m = 2883 \pm 11 \pm 8 \text{ MeV}$
- $\Gamma = 87_{-47}^{+22} \pm 17 \text{ MeV}$



- Branching ratio $R_I(T_{cs}^{*0}) = \frac{\mathcal{B}(B^- \rightarrow D^- D^0 \bar{K}^0) \text{FF}(T_{cs}^{*0} \rightarrow D^0 K_S^0)}{\mathcal{B}(B^- \rightarrow D^- D^+ K^-) \text{FF}(T_{cs}^{*0} \rightarrow D^+ K^-)}$

$$\frac{T_{cs0}^*(2870)^0 \rightarrow D^0 \bar{K}^0}{T_{cs0}^*(2870)^0 \rightarrow D^+ K^-} = 3.3 \pm 1.1 \pm 1.1 \pm 1.1(B)$$

$$\frac{T_{cs1}^*(2900)^0 \rightarrow D^0 \bar{K}^0}{T_{cs1}^*(2900)^0 \rightarrow D^+ K^-} = 0.15 \pm 0.15 \pm 0.05 \pm 0.05(B)$$

Isospin symmetry: these two ratios should be 1

