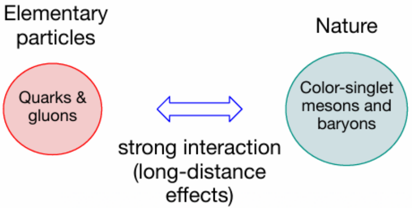
Heavy Hadron Spectroscopy

Standard Model at the LHC 2025

Simon Ghizzo
University & INFN Genova
on behalf of the CMS and LHCb collaborations

7 Apr. 2025

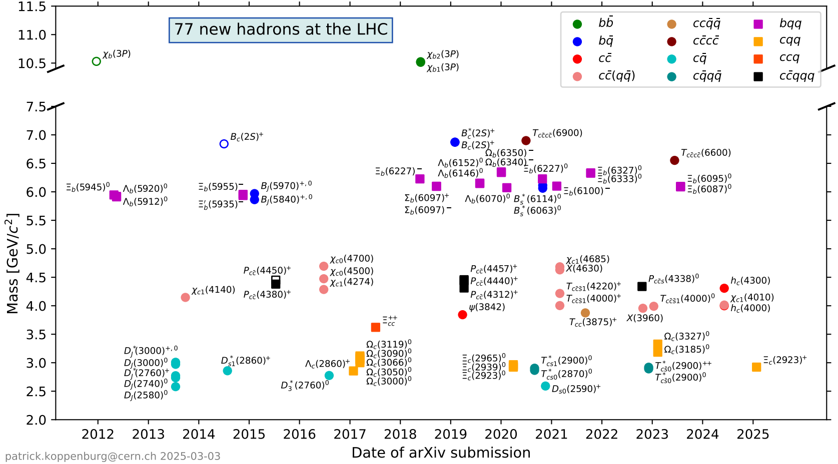
Physical motivations and analysis techniques



- Insight into a not yet fully understood corner of the SM $\rightarrow$ confinement
- How are quarks bound inside the hadrons?
- Is the diquark a building block of the hadrons?
- Nature of exotic hadrons?
  Tightly bound states, Hadronic molecules, $q\bar{q}g$ hybrids, Glueball, Mixture?

- Mass fit $\rightarrow$ To extract properties of states, M and Γ but not J^P
- Amplitude analysis $\rightarrow$ To measure J^P, mass, width and account for reflections

New hadrons at LHC



https://koppenburg.ch/particles.html

Selected recent results from CMS and LHCb

- Spectroscopy of conventional hadrons
  - LHCb Observation of a new charmed baryon decaying to $\Xi_c^+\pi^-\pi^+$ [LHCb-PAPER-2024-055]
  - LHCb Observation of the doubly-charmed-baryon decay $\Xi_{cc}^{++} \to \Xi_c^0\pi^+\pi^+$ [LHCb-PAPER-2024-053]
  - LHCb Observation of muonic Dalitz decays of χ_b mesons and precise spectroscopy of hidden-beauty states [JHEP 10 (2024) 122]
- Spectroscopy of exotic hadrons
  - LHCb Probing the nature of the $\chi_{c1}(3872)$ state using radiative decays [LHCb-PAPER-2024-015]
  - LHCb Search for the $B_c^+ \to \chi_{c1}(3872)\pi^+$ decay [LHCb-PAPER-2024-050]
  - LHCb Observation of the open-charm tetraquark state $T_{cs0}^{*0}(2870)$ in the $B^- \to D^-D^0K_s$ decay [LHCb-PAPER-2024-040]
  - LHCb [NOT DISCUSSED] Study of $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ in $B \to D^{(*)}D_s^+\pi^+\pi^-$ decays [LHCb-PAPER-2024-033]
  - CMS Observation of a family of all-charm tetraquark candidates at the LHC [CMS-PAS-BPH-24-003]

LHCb detector

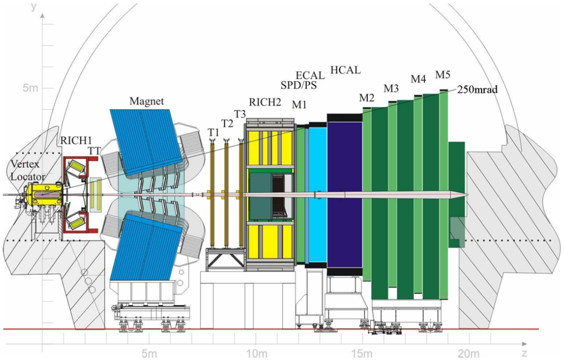
VELO: vertex detector, IP resolution of $15 + 29/p_T\ \mu$m

Tracking: momentum resolution of $\sigma_p/p \sim 0.5 - 1\%$ for 20-200 GeV

Particle ID: from calorimeters, muon chambers and RICH ($\text{PID}(K \to K) \sim 95\%$ @misID rate$(\pi \to K) \sim 5\%$)

Hardware trigger: from calorimeters and muon chambers, $\sim 90\%$ efficiency

The LHCb Collaboration et al 2008 JINST 3 S08005
Int. J. Mod. Phys. A 30, 1530022 (2015)

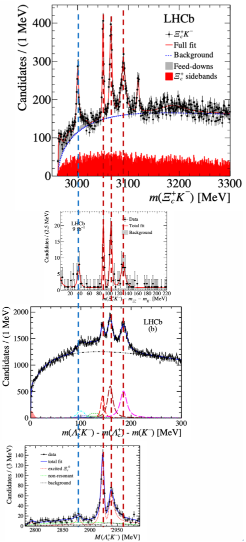


LHCb detector during Run1 and Run2

Spectroscopy of conventional hadrons

Excited Ξ_c^0 and Ω_c^0 states

- Fifteen singly charmed baryon with $L = 0$, hundreds when considering excitations.
- Modelled as a heavy quark interacting with a light diquark.
- Universal mass difference?
  $m(\Omega_c(3050)^0 - m(\Xi_c(2923)^0) \simeq 125\ MeV$
  $m(\Omega_c(3065)^0 - m(\Xi_c(2939)^0) \simeq 125\ MeV$
  $m(\Omega_c(3090)^0 - m(\Xi_c(2965)^0) \simeq 125\ MeV$
- Is $\Xi_c(2880)$ the SU(3) partner of the $\Omega_c(3000)$?
- Where is the partner of $\Omega_c(3120)$?



$\Omega_c^{**0} \rightarrow \Xi_c^+ K-$

Phys. Rev. Lett. 118, 182001 (2017)

$\Omega_b^- \rightarrow \Xi_c^+ K^- \pi^-$

Phys.Rev.D 104 (2021) 9, L091102

$\Xi_c^{**0} \rightarrow \Lambda_c^+ K^-$

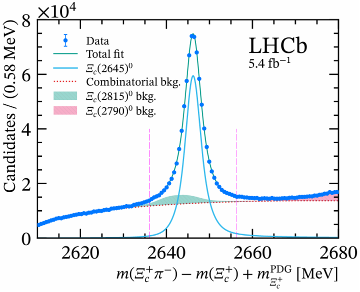
10.1103/PhysRevLett.124.222001

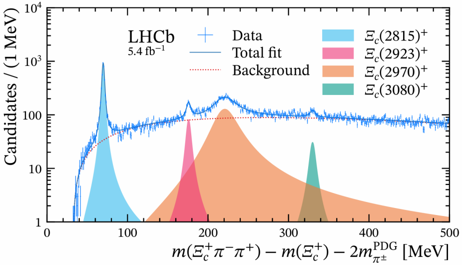
$B^- \rightarrow \Lambda_c^+ \Lambda_c^- K^-$

Physical Review D 108, 012020 (2023)

New charmed baryon decaying to $\Xi_c^+\pi^-\pi^+$ [LHCb-PAPER-2024-055]

- Excited Ξ_c^+ states reconstructed via the intermediate decay $\Xi_c(2645)^0\pi^+$, with $\Xi_c(2645)^0 \to \Xi_c^+\pi^-$ and $\Xi_c^+ \to pK^-\pi^+$
- Four excited Ξ_c^+ states observed with high significance
- First observation of $\Xi_c(2923)^+$ with significance 10 σ, consistent with isospin partner of $\Xi_c(2923)^0$
- New decay mode $\Xi_c(3080)^+ \to \Xi_c(2645)^0\pi^+$ with significance 5.4 σ





New charmed baryon decaying to $\Xi_c^+\pi^-\pi^+$ [LHCb-PAPER-2024-055]

- Masses and widths measured for the four observed states

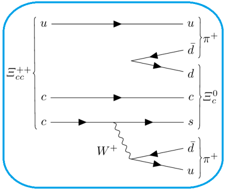
State	Mass [MeV]	Γ [MeV]
$\Xi_c(2815)^+$	$2816.65 \pm 0.03_{\text{stat}} \pm 0.03_{\text{syst}} \pm 0.23_{\text{ext}}$	$2.07 \pm 0.08_{\text{stat}} \pm 0.12_{\text{syst}}$
$\Xi_c(2923)^+$	$2922.8 \pm 0.3_{\text{stat}} \pm 0.5_{\text{syst}} \pm 0.2_{\text{ext}}$	$5.3 \pm 0.9_{\text{stat}} \pm 1.4_{\text{syst}}$
$\Xi_c(2970)^+$	$2968.6 \pm 0.5_{\text{stat}} \pm 0.5_{\text{syst}} \pm 0.2_{\text{ext}}$	$31.7 \pm 1.7_{\text{stat}} \pm 1.9_{\text{syst}}$
$\Xi_c(3080)^+$	$3076.8 \pm 0.7_{\text{stat}} \pm 1.3_{\text{syst}} \pm 0.2_{\text{ext}}$	$6.8 \pm 2.3_{\text{stat}} \pm 0.9_{\text{syst}}$

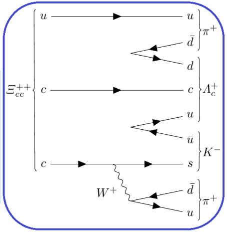
- No signal of $\Xi_c(2940)^+$
- Widths of $\Xi_c(2970)^+$ and $\Xi_c(2965)^0$ not consistent
  - Two different excited states and not isospin partners

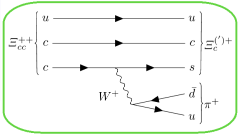
State	Mass [MeV]	Γ [MeV]
$\Xi_c(2965)^0$	$2964.88 \pm 0.26_{\text{stat}} \pm 0.14_{\text{syst}} \pm 0.14_{\text{ext}}$	$14.1 \pm 0.9_{\text{stat}} \pm 1.3_{\text{syst}}$
$\Xi_c(2970)^+$	$2968.6 \pm 0.5_{\text{stat}} \pm 0.5_{\text{syst}} \pm 0.2_{\text{ext}}$	$31.7 \pm 1.7_{\text{stat}} \pm 1.9_{\text{syst}}$

Doubly-charmed-baryon decay $\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+$ [LHCb-PAPER-2024-053]

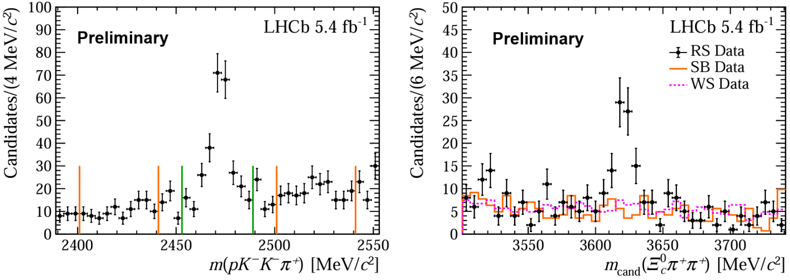
- Doubly charmed baryon Ξ_{cc}^{++} observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum by LHCb in 2017 [Phys.Rev.Lett.119,112001(2017)]
- Only three decay modes observed so far, additional measurements essential to better understand the decay dynamics of doubly charmed baryons
- $\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+$ mediated by the same $c \to s u \bar{d}$ weak transition of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \to \Xi_c^{(\prime)+} \pi^+$







- Significant structure can be seen in the $\Xi_c^0 \pi^+ \pi^+$ invariant mass distribution at a mass of approximately 3620 MeV$/c^2$
- No significant structure in the wrong-sign sample or in the sample with Ξ_c^0 candidates in the mass sidebands ($[2401, 2441] \cup [2501, 2541]$ MeV/c^2)

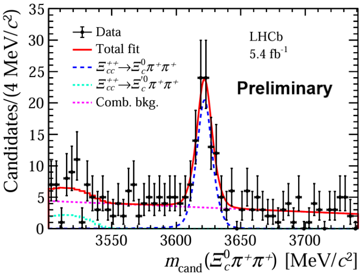


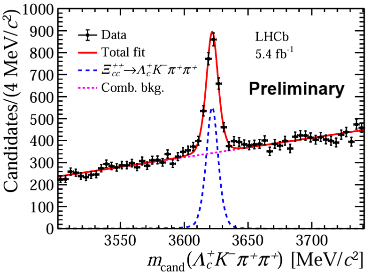
The significance of the $\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+$ signal is estimated to be above 10 σ

Most of the systematics cancel in the ratio of branching fractions

$$\mathcal{R} = \frac{B(\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+) \times B(\Xi_c^0 \to pK^- K^- \pi^+)}{B(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times B(\Lambda_c^+ \to pK^- \pi^+)} = 0.105 \pm 0.014_{\text{stat}} \pm 0.007_{\text{syst}}$$

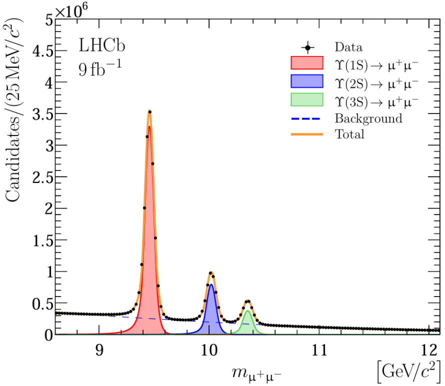
$$\frac{B(\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+)}{B(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} = 1.37 \pm 0.18_{\text{stat}} \pm 0.09_{\text{syst}} \pm \boxed{0.35_{\text{ext}}}$$





Spectroscopy of hidden-beauty states

[JHEP 10 (2024) 122]



Binned extended maximum-likelihood fit for very large data sample (bin width = 1 MeV)

- Experimental knowledge of hidden beauty states is still more limited compared to the charmonium system
- First observation of the muonic Dalitz decays of the $\chi_{b1}(1P)$, $\chi_{b2}(1P)$, $\chi_{b1}(2P)$, and $\chi_{b2}(2P)$ mesons to the $\Upsilon(1S)$ state and measurement of the masses
- Decay modes $\Upsilon(3S) \to (\Upsilon(2S) \to \mu^+\mu^-)\pi^+\pi^-$ and $\Upsilon(2S) \to (\Upsilon(1S) \to \mu^+\mu^-)\pi^+\pi^-$ to make precise measurements of the Υ masses and mass splittings

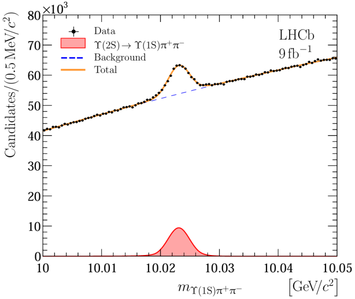
Spectroscopy of hidden-beauty states

[JHEP 10 (2024) 122]

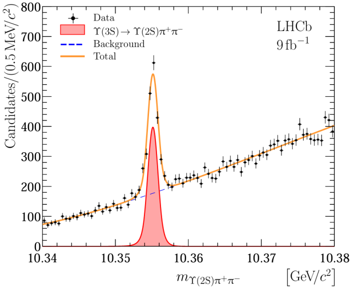
$$m_{\Upsilon(1S)} = 9460.37 \pm 0.01_{\text{stat}} \pm 2.85_{\text{syst}} \text{ MeV}/c^2$$
$$m_{\Upsilon(2S)} = 10023.28 \pm 0.03_{\text{stat}} \pm 0.12_{\text{syst}} \pm 0.09_{\text{ext}} \text{ MeV}/c^2$$
$$m_{\Upsilon(3S)} = 10355.28 \pm 0.03_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.48_{\text{ext}} \text{ MeV}/c^2$$

$$m_{\Upsilon(1S)_{PDG}} = 9460.4 \pm 0.1 \text{ MeV}/c^2$$
$$m_{\Upsilon(2S)_{PDG}} = 10023.4 \pm 0.5 \text{ MeV}/c^2$$
$$m_{\Upsilon(3S)_{PDG}} = 10355.1 \pm 0.5 \text{ MeV}/c^2$$

- Competitive and in agreement with PDG



$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$



$\Upsilon(3S) \to \Upsilon(2S)\pi^+\pi^-$

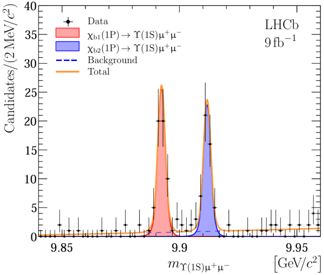
Bin width = 100 keV

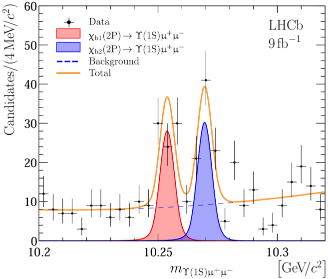
Spectroscopy of hidden-beauty states [JHEP 10 (2024) 122]

- Performed separately for the $\chi_b(1P)$ and $\chi_b(2P)$ regions
- Significance above 5σ for all the states

$$m_{\chi_{b1}(1P)} = 9892.50 \pm 0.26_{\text{stat}} \pm 0.10_{\text{syst}} \pm 0.10_{\text{ext}}\ \text{MeV}/c^2$$
$$m_{\chi_{b2}(1P)} = 9911.92 \pm 0.29_{\text{stat}} \pm 0.11_{\text{syst}} \pm 0.10_{\text{ext}}\ \text{MeV}/c^2$$
$$m_{\chi_{b1}(2P)} = 10253.97 \pm 0.75_{\text{stat}} \pm 0.22_{\text{syst}} \pm 0.09_{\text{ext}}\ \text{MeV}/c^2$$
$$m_{\chi_{b2}(2P)} = 10269.67 \pm 0.67_{\text{stat}} \pm 0.22_{\text{syst}} \pm 0.09_{\text{ext}}\ \text{MeV}/c^2$$

- Most precise measurements of $\chi_{b1}(1P)$

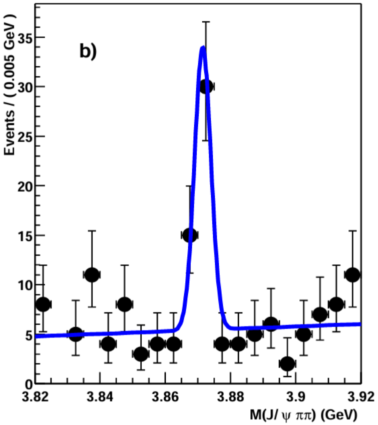




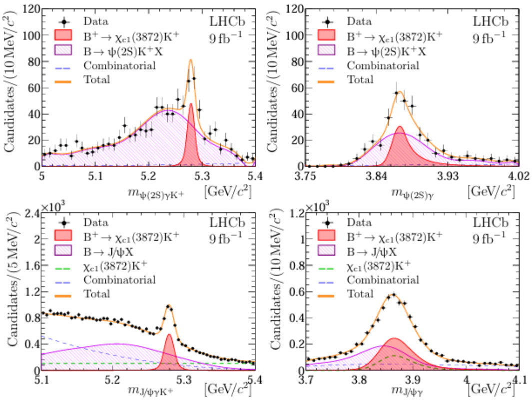
Spectroscopy of exotic hadrons

First exotic candidate: $\chi_{c1}(3872)$

- $\chi_{c1}(3872)$ first exotic charmonium-like state observed by Belle in 2003 in $B^+ \to J/\psi\pi^+\pi^- K^+$ decay [Phys.Rev.Lett.91:262001,2003]
- Quantum numbers $J^{PC} = 1^{++}$, mass close to the $D\bar{D}^*$ threshold, surprisingly narrow width
- **Its nature still under debate:** conventional $\chi_{c1}(2^3P_1)$, DD^* molecular state, tetraquark, hybrid, vector glueball, or mixed?



Radiative decays of $\chi_{c1}(3872)$ [LHCb-PAPER-2024-015]

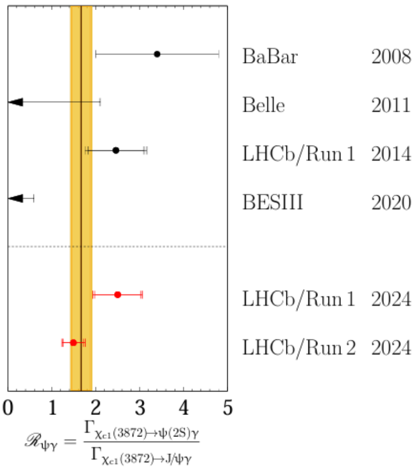


- $\chi_{c1}(3872) \to \psi(2S)\gamma$ and $\chi_{c1}(3872) \to J/\psi\gamma$ used to probe the nature of the $\chi_{c1}(3872)$
- $\chi_{c1}(3872) \to \psi(2S)\gamma$ observed for the first time using the decay $B^+ \to \chi_{c1}(3872)K^+$ at 4.8 σ (6.0 σ) in Run1 (Run2)

$$\mathcal{R}_{\psi\gamma} = \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}} = 1.67 \pm 0.21_{\text{stat}} \pm 0.12_{\text{syst}} \pm 0.04_{\text{ext}}$$

Radiative decays of $\chi_{c1}(3872)$ [LHCb-PAPER-2024-015]

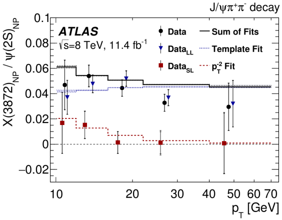
- As a general rule, $\mathcal{R}\psi\gamma \gtrsim 1$ is expected if the $\chi_{c1}(3872)$ state has a dominant conventional charmonium component, whereas a pure $D\bar{D}^*$ molecular hypothesis would predict $\mathcal{R}_{\psi\gamma} \ll 1$
- The measured ratio strongly indicates a sizeable compact charmonium or tetraquark component within the $\chi_{c1}(3872)$ state [PhysRevD 75,014005]
- Pure molecular $D\bar{D}^*$ hypothesis is questionable, but small admixture of $c\bar{c}$ component is sufficient to explain the data [PhysLettB 2015 0213]

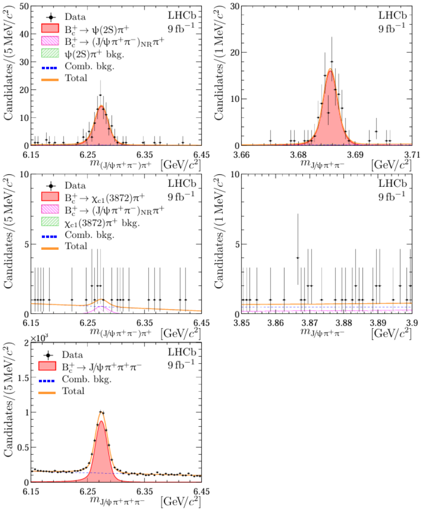


Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$ decay

[LHCb-PAPER-2024-050]

- Enhancement of $\chi_{c1}(3872)$ production interpretation from ATLAS measurement of the production cross-section in pp collisions [JHEP 01 (2017)117]
- Search for the decay $B_c^+ \to \chi_{c1}(3872)\pi^+$ with $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$
- Using the normalization channel: $B_c^+ \to \psi(2S)\pi^+$



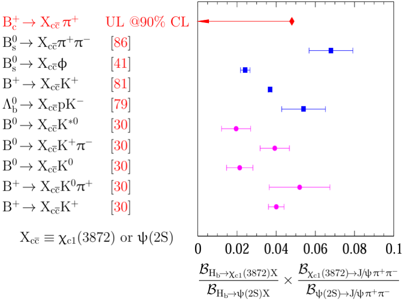


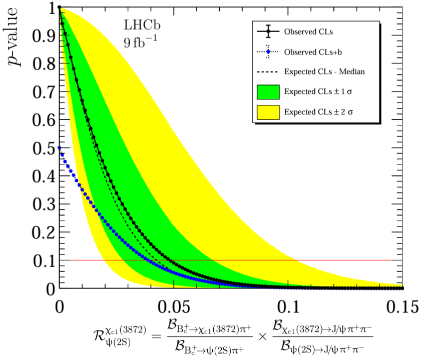
Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$ decay

No $B_c^+ \to \chi_{c1}(3872)\pi^+$ decay mode observed as signal.

Limit at 90% (95%) CL is set using the CLs method:

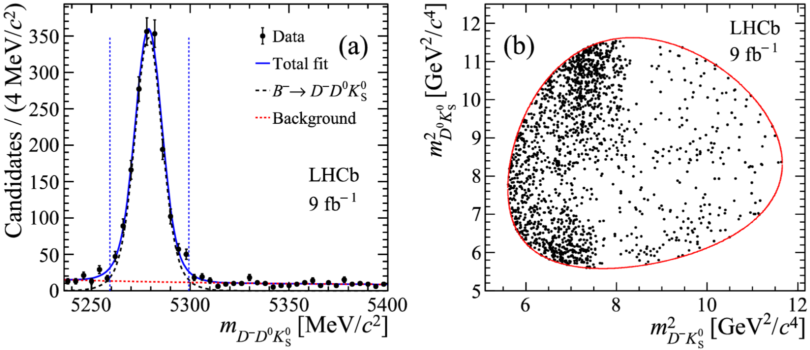
$$\mathcal{R}^{\chi_{c1}(3872)}_{\psi(2S)} = \frac{B(B_c^+ \to \chi_{c1}(3872)\pi^+)}{B(B_c^+ \to \psi(2S)\pi^+)} \times \frac{B(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{B(\psi(2S) \to J/\psi\pi^+\pi^-)} < 0.05\,(0.06)$$





[86], [41], [81], [79], [30]

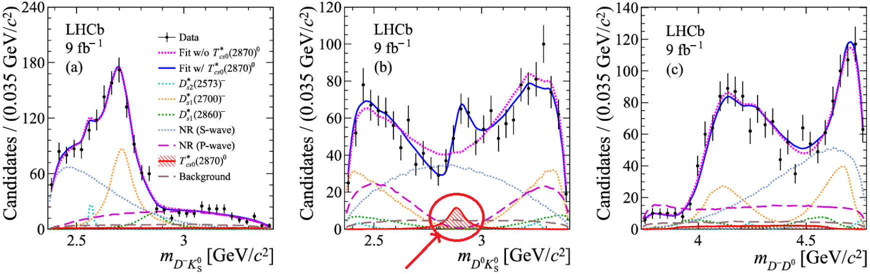
- Amplitude analysis of the $B^- \to D^- D^0 K^0_s$ decay
- Spin-0 open-charm tetraquark $T^{*0}_{cs0}(2870)$ observed in the $D^0 K^0$ final state for the first time
- Significance of 5.3 σ



Open-charm tetraquark in $B^- \to D^- D^0 K_s$ decay [LHCb-PAPER-2024-040]

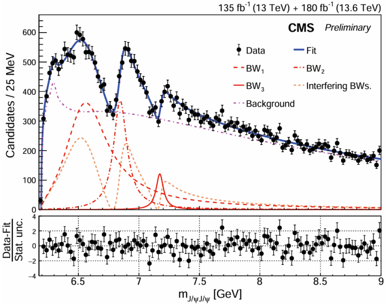
- Mass, width, spin-parity and flavor content consistent with those of the $T^{*0}_{cs0}(2870)$ observed in the $B^- \to D^- D^+ K^-$ decay [Phys.Rev.D102, 112003 (2020)]
- No significant T^{*0}_{cs} states with $J^P = 1^-$ or charmonium-like tetraquarks observed

$$m(T^{*0}_{cs0}(2870)) = 2883 \pm 11_{\text{stat}} \pm 8_{\text{syst}}\ \text{MeV}/c^2$$
$$\Gamma(T^{*0}_{cs0}(2870)) = 87^{+22_{\text{stat}}}_{-47_{\text{stat}}} \pm 17_{\text{syst}}\ \text{MeV}$$
$$\text{FF}(T^{*0}_{cs0}(2870) \to D^0 K^0_S) = (2.6 \pm 1.2_{\text{stat}} \pm 0.4_{\text{syst}})\%$$



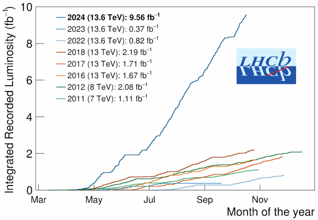
Observation of a family of all-charm tetraquark candidates @CMS [CMS-PAS-BPH-24-003]

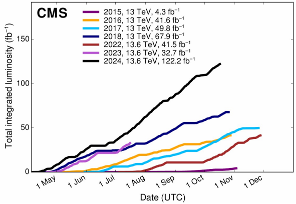
- Extension of study on three structures, $X(6600)$, $X(6900)$, and $X(7100)$ in the $J/\psi\, J/\psi$ channel [Science Bulletin 65 (2020) 1983]
- All three structures established with a significance well above 5 σ
- Interference among the three structures implies common J^{PC} $\rightarrow$ family of states?



Conclusions

- Analysing new Run 3 data right now
- Increased integrated luminosity, improved detector, better sensitivity to exotics (higher efficiency hadronic trigger)
- More investigation of observed states:
  - Confirm states in different channels
  - Measure J^P, study lineshape and resonance parameters
- Many new states to explore:
  - Search for *bc* tetraquarks and pentaquark with beauty
  - Search for exotic flavour multiplets



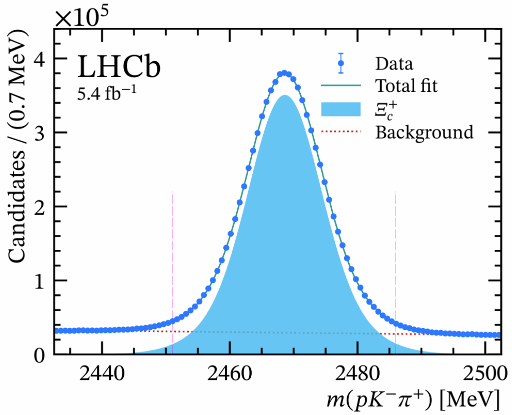


New significant results expected soon!

Thanks for the attention!!!

Backup

New charmed baryon decaying to $\Xi_c^+\pi^-\pi^+$



Contribution	$\Xi_c(2815)^+$ m	$\Xi_c(2815)^+$ Γ	$\Xi_c(2923)^+$ m	$\Xi_c(2923)^+$ Γ	$\Xi_c(2970)^+$ m	$\Xi_c(2970)^+$ Γ	$\Xi_c(3080)^+$ m	$\Xi_c(3080)^+$ Γ
RBW	0.00	0.02	0.09	1.12	0.15	0.55	0.02	0.68
Interference	0.00	0.01	0.53	0.70	0.44	1.05	1.26	0.65
Resolution	0.00	0.12	0.00	0.11	0.01	0.04	0.00	0.08
Background	0.00	0.01	0.01	0.32	0.11	1.51	0.04	0.08
Mom. scale	0.02	—	0.05	—	0.07	—	0.10	—
Energy loss	0.02	—	0.02	—	0.02	—	0.02	—
Sel. bias	0.02	—	0.02	—	0.02	—	0.02	—
Total syst.	0.03	0.12	0.54	1.36	0.48	1.92	1.27	0.95
Stat.	0.03	0.08	0.28	0.87	0.46	1.68	0.72	2.28

Doubly-charmed-baryon decay $\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+$

Table 1: Yields and efficiencies of the signal and normalisation channels. The uncertainties on the yields are statistical only; the uncertainties on the efficiencies include only the contribution from the limited size of the simulation sample.

Category	N_{sig}	N_{norm}	ε_{sig} $[\times 10^{-4}]$	$\varepsilon_{\text{norm}}$ $[\times 10^{-4}]$
TIS	62 ± 9	1279 ± 55	1.159 ± 0.023	2.547 ± 0.090
exTOS	21 ± 6	461 ± 34	0.286 ± 0.011	0.624 ± 0.034

Source	TIS(%)	exTOS(%)
Fit model	1.1	1.1
Simulation sample size	4.2	6.6
Ξ_{cc}^{++} lifetime	1.0	1.0
Kinematic correction	1.2	1.2
Decay dynamics	2.0	2.0
Tracking	1.5	1.5
Particle identification	1.4	1.4
Hardware trigger	—	9.0
Hit error parametrisation	0.5	0.5
BDT efficiency correction	4.4	4.4
Total	7.0	12.5

Spectroscopy of hidden-beauty states

Parameter		Value
$N_{\Upsilon(1S)}$	$[10^3]$	$14\,609.3 \pm 6.7$
$N_{\Upsilon(2S)}$	$[10^3]$	$3\,729.1 \pm 3.2$
$N_{\Upsilon(3S)}$	$[10^3]$	$1\,827.9 \pm 2.3$
$m_{\Upsilon(1S)}$	$[\text{MeV}/c^2]$	$9\,460.37 \pm 0.01$
$m_{\Upsilon(2S)} - m_{\Upsilon(1S)}$	$[\text{MeV}/c^2]$	562.71 ± 0.04
$m_{\Upsilon(3S)} - m_{\Upsilon(2S)}$	$[\text{MeV}/c^2]$	331.77 ± 0.07

Table 1. Parameters of interest, yields N_Υ, masses and mass differences, from the fit to the dimuon mass spectra. The uncertainties are statistical only.

Source of systematic	Uncertainty $[\text{MeV}/c^2]$		
	$m_{\Upsilon(1S)}$	$m_{\Upsilon(2S)} - m_{\Upsilon(1S)}$	$m_{\Upsilon(3S)} - m_{\Upsilon(2S)}$
Momentum scale	2.8	0.17	0.10
Energy loss correction	0.02	—	—
Radiative corrections	0.13	0.03	0.03
Fit model	0.35	0.10	0.02
Sum in quadrature	2.85	0.20	0.10

Table 2. Systematic uncertainties on the measurement of the $\Upsilon(1S)$ mass and mass differences from the analysis of the dimuon mass spectrum.

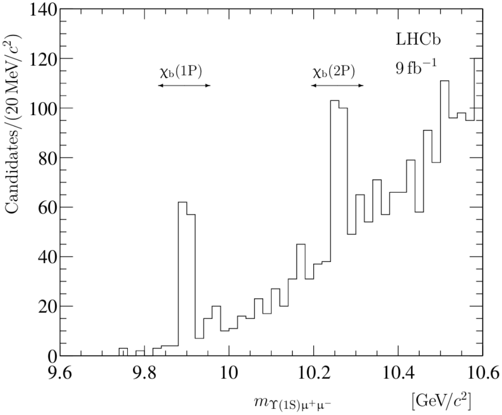
Parameter		Value
$N_{\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-}$	$[10^3]$	88.55 ± 1.05
$N_{\Upsilon(3S)\to\Upsilon(2S)\pi^+\pi^-}$	$[10^3]$	1.46 ± 0.05
$m_{\Upsilon(2S)}$	$[\text{MeV}/c^2]$	$10\,023.25 \pm 0.03$
$m_{\Upsilon(3S)}$	$[\text{MeV}/c^2]$	$10\,355.28 \pm 0.03$

Table 3. Values for the parameters of interest, yields N and masses, from the fits to the $\Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\pi^+\pi^-$ mass spectra. Uncertainties are statistical only.

Source of systematic	Uncertainty $[\text{keV}/c^2]$		
	$m_{\Upsilon(2S)}$	$m_{\Upsilon(3S)}$	$m_{\Upsilon(3S)} - m_{\Upsilon(2S)}$
Momentum scale	120	33	87
Energy loss correction	20	20	—
Radiative corrections	3	2	1
Fit model	8	2	6
Sum in quadrature	122	39	89

Table 4. Systematic uncertainties on the measurement of the $\Upsilon(2S)$ and $\Upsilon(3S)$ mass parameters, and the mass difference from the analysis of the $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(3S) \to \Upsilon(2S)\pi^+\pi^-$ decays.

Spectroscopy of hidden-beauty states



Source of systematic	Uncertainty [keV/c^2]					
	$m_{\chi_{b1}(1P)}$	$m_{\chi_{b2}(1P)}$	$m_{\chi_{b1}(2P)}$	$m_{\chi_{b2}(2P)}$	$\delta m_{\chi_b(1P)}$	$\delta m_{\chi_b(2P)}$
Momentum scale	99	106	214	218	7	4
Energy loss correction	20	20	20	20	—	—
Radiative corrections	7	8	13	13	1	—
Fit model	4	3	4	2	6	2
Natural width	—	—	10	10	—	—
Sum in quadrature	101	109	215	219	9	4

Parameter		PDG'24 [57]	Recalculated
$m_{\chi_{b1}(1P)}$	[MeV/c^2]	$9\,892.78 \pm 0.26 \pm 0.31$	$9\,892.92 \pm 0.33 \pm 0.50$
$m_{\chi_{b2}(1P)}$	[MeV/c^2]	$9\,912.21 \pm 0.26 \pm 0.31$	$9\,912.35 \pm 0.29 \pm 0.50$
$m_{\chi_{b1}(2P)}$	[MeV/c^2]	$10\,255.46 \pm 0.22 \pm 0.50$	
$m_{\chi_{b2}(2P)}$	[MeV/c^2]	$10\,268.65 \pm 0.22 \pm 0.50$	
$\delta m_{\chi_b(1P)}$	[MeV/c^2]	19.10 ± 0.25	19.42 ± 0.44
$\delta m_{\chi_b(2P)}$	[MeV/c^2]	13.10 ± 0.24	

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

Reference		$\mathscr{R}_{\psi\gamma}$	
T. Barnes and S. Godfrey	[67]	5.8	$c\bar{c}$
T. Barnes, S. Godfrey and S. Swanson	[69]	2.6	$c\bar{c}$
F. De Fazio	[84]	(1.64 ± 0.25)	$c\bar{c}$
B.-Q. Li and K. T. Chao	[85]	1.3	$c\bar{c}$
Y. Dong *et al.*	[86]	$1.3 - 5.8$	$c\bar{c}$
A. M. Badalian *et al.*	[87]	(0.8 ± 0.2)	$c\bar{c}$
J. Ferretti, G. Galata and E. Santopinto	[88]	6.4	$c\bar{c}$
A. M. Badalian, Yu. A. Simonov and B. L. G. Bakker	[89]	2.4	$c\bar{c}$
W. J. Deng *et al.*	[90]	1.3	$c\bar{c}$
F. Giacosa, M. Piotrowska and S. Goito	[71]	5.4	$c\bar{c}/\nu c$
E. S. Swanson	[81]	0.38 %	$D\bar{D}^*$
Y. Dong *et al.*	[86]	0.33 %	$D\bar{D}^*$
D. P. Rathaud and A. K. Rai	[91]	0.25	$D\bar{D}^*$
R. F. Lebed and S. R. Martinez	[92]	0.33 %	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	[93]	3.6 %	$D\bar{D}^*$
F.-K. Guo *et al.*	[82]	$0.21(g_2'/g_2)^2$	$D\bar{D}^*$
D. A.-S. Molnar, R. F. Luiz and R. Higa	[83]	$2 - 10$	$D\bar{D}^*$
E. Cincioglu *et al.*	[94]	< 4	$D\bar{D}^*$
S. Takeuchi, M. Takizawa and K. Shimizu	[95]	$1.1 - 3.4$	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	[93]	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$

Table 2: Yields for the fit components determined from the simultaneous extended unbinned maximum-likelihood fit. Uncertainties are statistical only. The last row shows the statistical significance of the $B^+ \to (\chi_{c1}(3872) \to \psi(2S)\gamma) K^+$ signal.

Parameter		Data-taking period Run 1	Run 2
$\psi(2S)\gamma K^+$			
$N_{B^+ \to (\chi_{c1}(3872) \to \psi(2S)\gamma)K^+}$		40 ± 8	63 ± 10
$N_{B \to \psi(2S)K^+X}$		567 ± 24	885 ± 29
N_{comb}		55 ± 17	132 ± 19
$J/\psi\gamma K^+$			
$N_{B^+ \to (\chi_{c1}(3872) \to J/\psi\gamma)K^+}$	$[10^3]$	0.43 ± 0.03	1.69 ± 0.05
$N_{B \to J/\psi X}$	$[10^3]$	3.61 ± 0.11	18.72 ± 0.26
$N_{\chi_{c1}(3872)K^+}$	$[10^3]$	1.18 ± 0.06	5.53 ± 0.23
N_{comb}	$[10^3]$	4.05 ± 0.11	17.46 ± 0.21
$\mathscr{S}_{\chi_{c1}(3872) \to \psi(2S)\gamma}$		5.3σ	6.7σ

Source	Data-taking period Run 1 [%]	Run 2 [%]
Fit model		
Signal and combinatorial background	${}^{+5.7}_{-0.1}$	${}^{+4.4}_{-2.0}$
$B \to \psi(2S)K^+X$ background		
Parameterisation	${}^{+1.6}_{-4.9}$	${}^{+5.0}_{-2.9}$
Composition	0.9	1.9
Simulation sample size	4.2	4.3
Additional components	${}^{+0.6}_{-4.4}$	${}^{+1.2}_{-2.6}$
B^+ meson kinematics	< 0.1	< 0.1
Track reconstruction	< 0.1	< 0.1
Photon reconstruction	1.1	1.1
Kaon identification	1.0	1.3
Trigger	1.1	1.1
Data-simulation (dis)agreement	1.0	${}^{+1.0}_{-1.5}$
Simulation sample size for efficiency	2.3	1.4
Total	${}^{+8.0}_{-9.2}$	${}^{+8.7}_{-7.9}$

Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$ decay

Table 1: Parameters of interest obtained from the simultaneous unbinned extended maximum-likelihood fit. In addition to statistical sources, the uncertainties also account for a systematic component due to the inclusion of $\varepsilon^{\chi_{c1}(3872)}_{\psi(2S)}$ in the fit.

Parameter		Value
$N_{B_c^+ \to J/\psi\pi^+\pi^+\pi^-}$		5049 ± 91
$N_{B_c^+ \to \psi(2S)\pi^+}$		96 ± 11
$\mathcal{R}^{\chi_{c1}(3872)}_{\psi(2S)}$	[%]	$-0.1^{+2.5}_{-2.1}$
$m_{B_c^+}$	[MeV/c^2]	6274.15 ± 0.21
$m_{\psi(2S)}$	[MeV/c^2]	3686.05 ± 0.27
$\delta m_{X_{c\bar{c}}}$	[MeV/c^2]	185.54 ± 0.06
$f_{B_c^+}$		1.118 ± 0.021
$f_{X_{c\bar{c}}}$		1.048 ± 0.004

Table 2: Relative systematic uncertainties (in %) for the efficiency ratio of the $B_c^+ \to \chi_{c1}(3872)\pi^+$ and $B_c^+ \to \psi(2S)\pi^+$ decays. The total uncertainty is calculated as the quadratic sum of individual contributions.

Source	$\sigma\left(\varepsilon^{\chi_{c1}(3872)}_{\psi(2S)}\right)$ [%]
B_c^+ production spectra	< 0.1
Track reconstruction	0.2
Pion identification	0.1
Trigger efficiency	1.1
Data-simulation difference	0.8
$\chi_{c1}(3872)$ and $\psi(2S)$ decay models	1.5
Size of simulated samples	0.2
Sum in quadrature	2.0

Open-charm tetraquark in $B^- \to D^- D^0 K_s$ decay

Source	Mass [MeV/c^2]	Width [MeV]	FF [%]
f_s	0.9	1.7	0.06
Background PDF	0.6	2.1	0.09
Efficiency	0.6	3.2	0.11
Blatt–Weisskopf radii	1.2	0.6	0.02
D_{sJ}^{*-} masses and widths	4.0	1.7	0.01
Fit with $D_{s3}^{*}(2860)^-$	0.3	2.5	0.05
Fit with $T_{cs1}^{*}(2900)^0$	4.2	15.7	0.34
D^-–K_S^0 K-matrix model	5.0	2.1	0.04
Total	8	17	0.4

Table 2: Measurements of the relative rates of decays into the $D^0\overline{K}^0$ and D^+K^- final states for $T_{cs0}^*(2870)^0$ and $T_{cs1}^*(2900)^0$ states, $R_{\mathrm{I}}(T_{cs0}^*(2870)^0)$ and $R_{\mathrm{I}}(T_{cs1}^*(2900)^0)$, and the double fit fraction ratio $R_{\mathrm{FF}}(D^0\overline{K}^0)/R_{\mathrm{FF}}(D^+K^-)$. The first, second and third uncertainties are statistical, systematic, and due to the external inputs of $B^- \to D^-D^+K^-$ and $B^- \to D^-D^0K_S^0$ branching fractions, respectively.

Observable	Result
$R_{\mathrm{I}}(T_{cs0}^*(2870)^0)$	$3.3 \pm 1.1 \pm 1.1 \pm 1.1$
$R_{\mathrm{I}}(T_{cs1}^*(2900)^0)$	$0.15 \pm 0.15 \pm 0.05 \pm 0.05$
$R_{\mathrm{FF}}(D^0\overline{K}^0)/R_{\mathrm{FF}}(D^+K^-)$	$0.044 \pm 0.035 \pm 0.020$

Observation of a family of all-charm tetraquark candidates @CMS

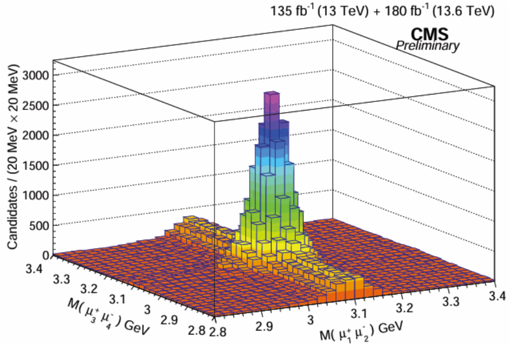


Figure 2: The two dimensional distribution of the double-dimuon masses for the final selection of $J/\psi J/\psi$ events in the 6–15 GeV four-muon mass range for the Run 2+3 data. The two $\mu^+\mu^-$ pairs are ordered by their total transverse momentum (p_T).