LHCb实验重味强子谱学研究进展

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On behalf of the LHCb Collaboration

北京大学

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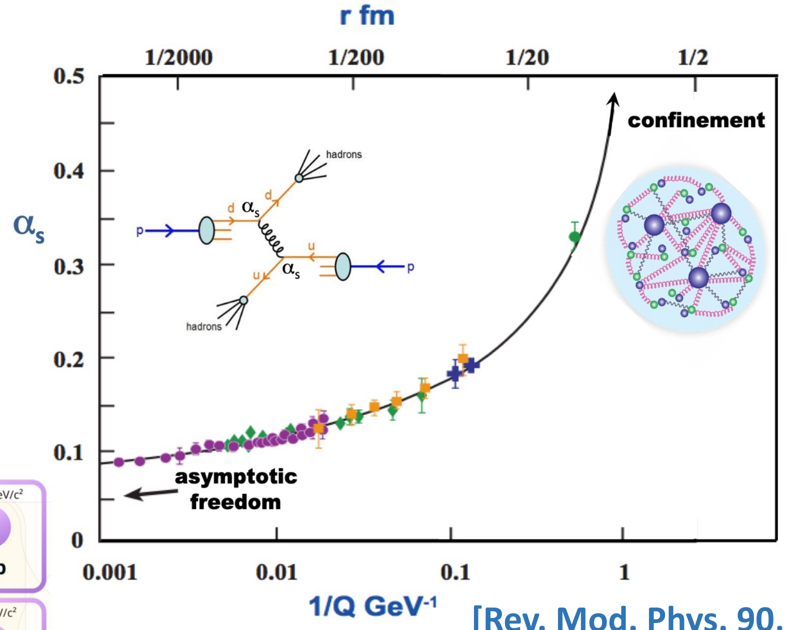
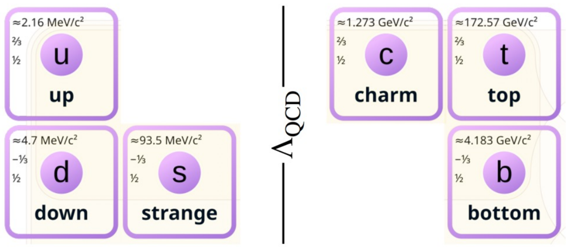
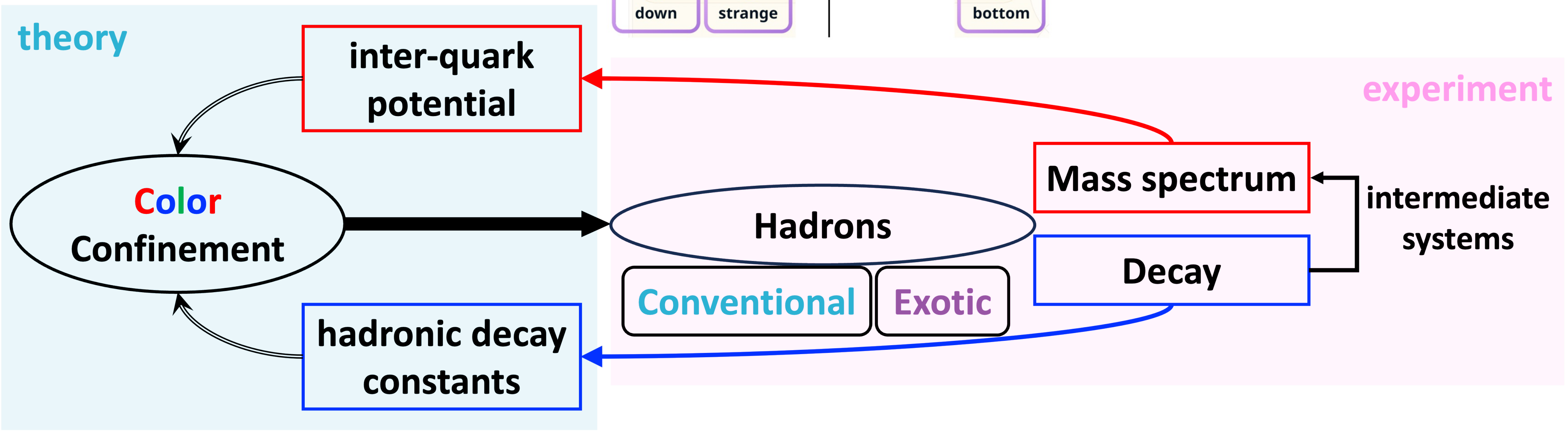
QCD and hadron spectroscopy

- ***QCD dilemma***: understanding the non-perturbative property of QCD at low-energy scale
  - ✓There are no rigorous, first-principle treatments except ***Lattice QCD***, whose application is yet limited
- ***Color confinement***: no analytic proof exists



[Rev. Mod. Phys. 90, 15003 (2018)]





LHCb experiment @ LHC

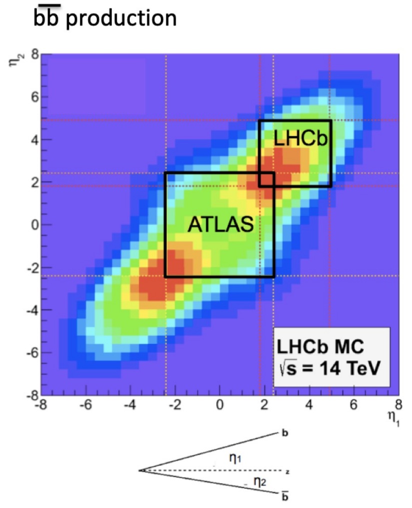
➢The LHCb experiment is one of the four large experiments at the ***LHC***, dedicated to ***heavy flavor physics***

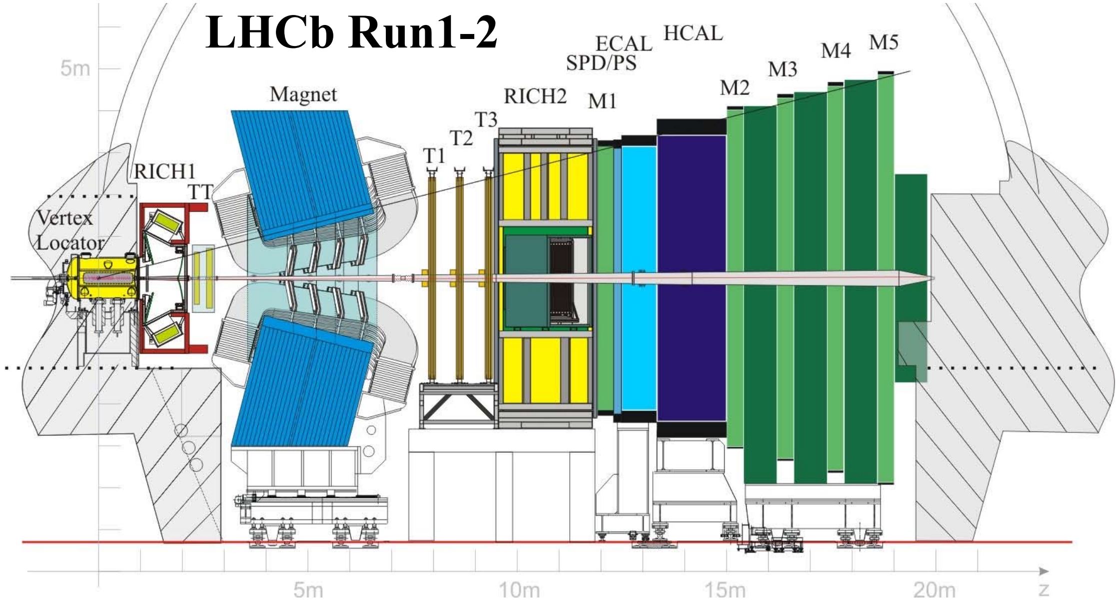
- ***Largest production cross-sections*** of b- and c-hadrons
  - ✓ $\sigma(b\bar{b}) \approx 500$ μb @ 13 TeV & $\sigma(c\bar{c}) \approx 20\times\sigma(b\bar{b})$

◆A ***single-arm forward spectrometer*** in $2 < \eta < 5$ to effectively cover the dominant kinematic region of heavy quark production

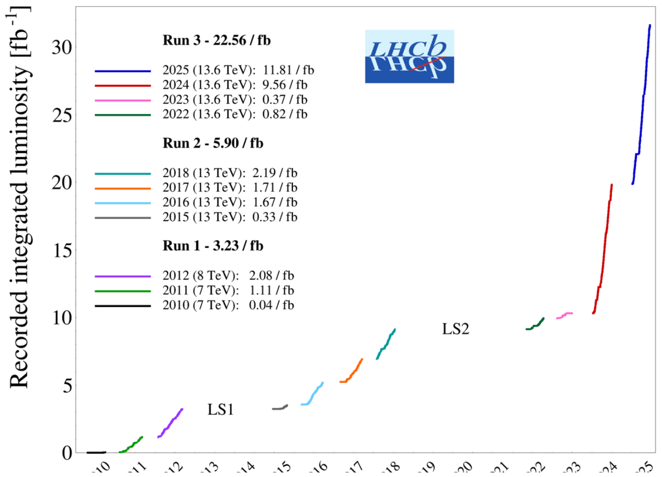
- ***Huge background*** contamination

◆Excellent ***vertexing***, ***tracking*** and ***particle identification (PID)*** performance allowing for effective detection and background suppression



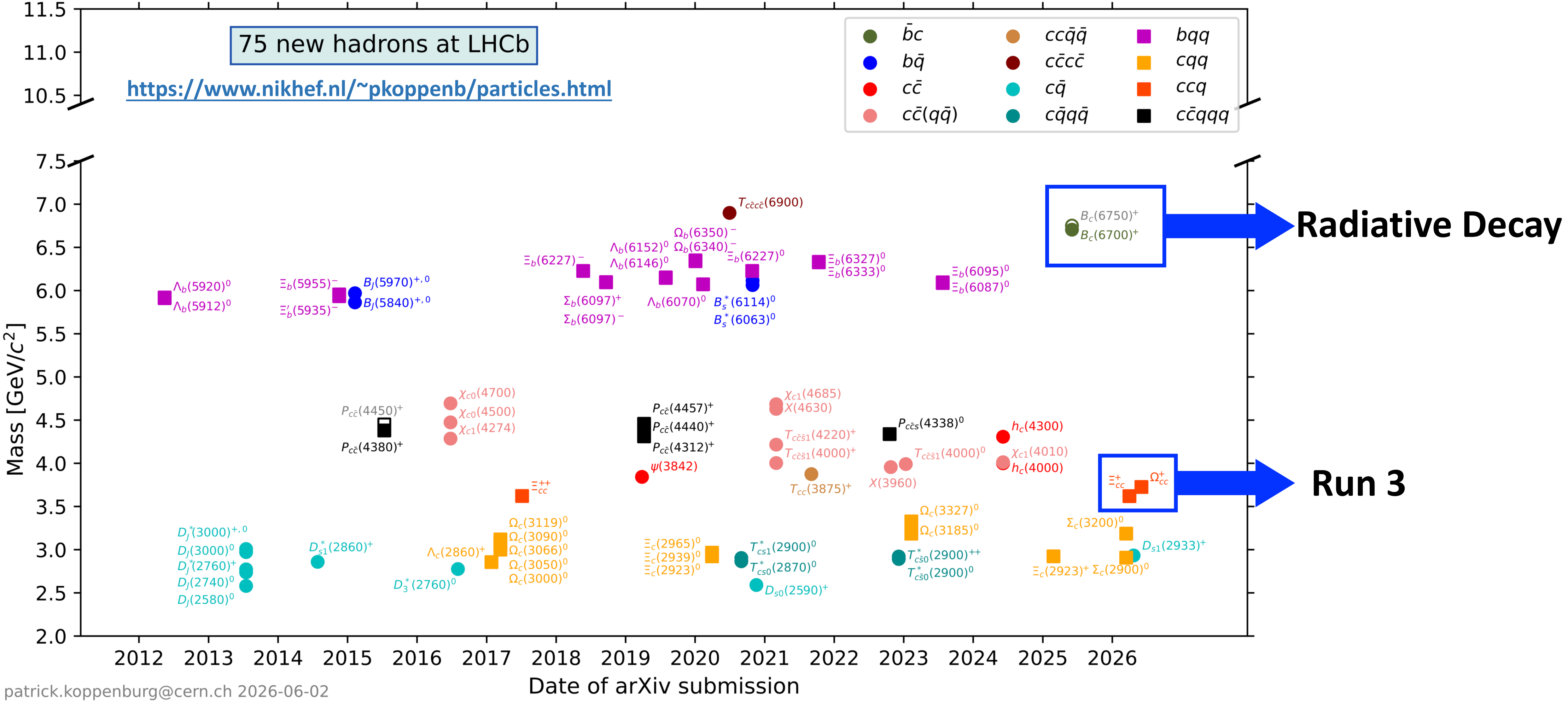


$\mathcal{L}_{\text{int}} = 9\ \text{fb}^{-1}$ @ Run1-2

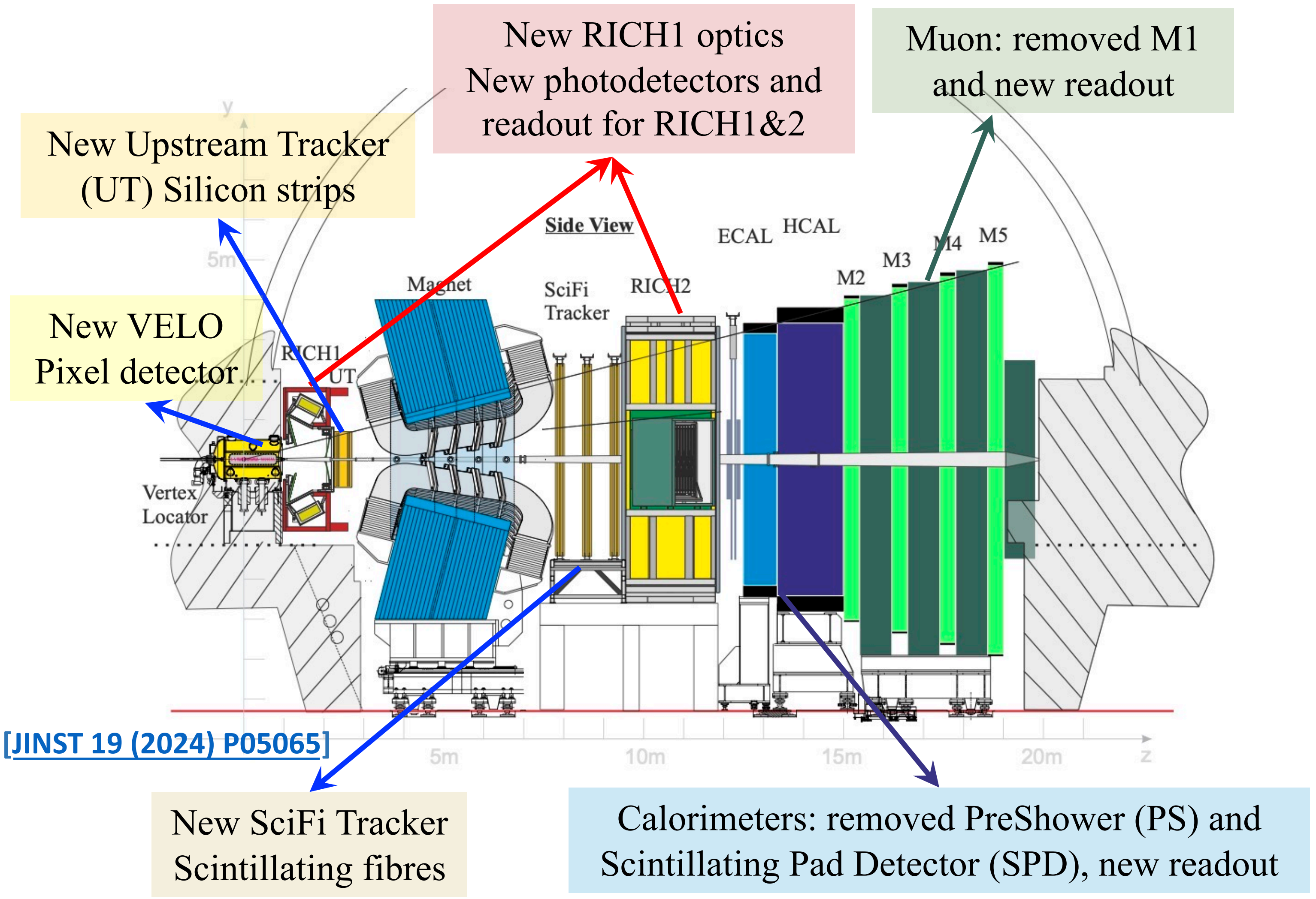


[JINST 3 (2008) S08005]
[IJMPA 30:07 (2015) 1530022]

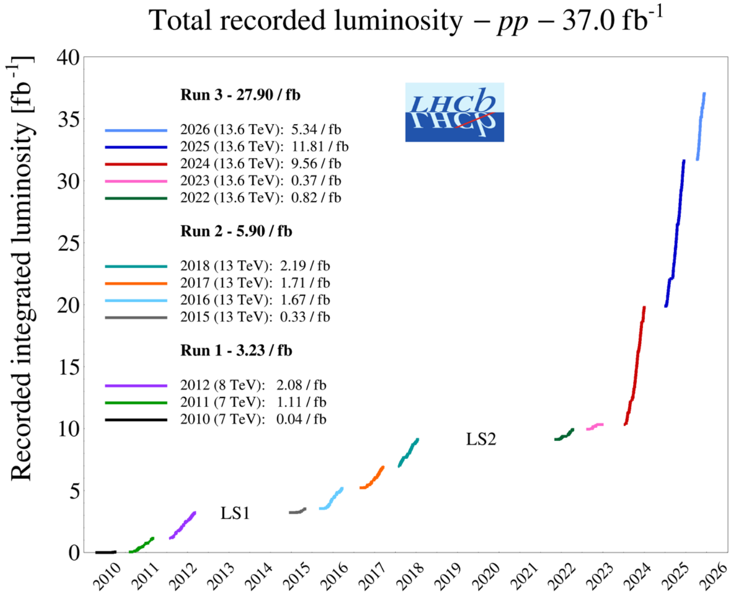
New hadrons at LHCb



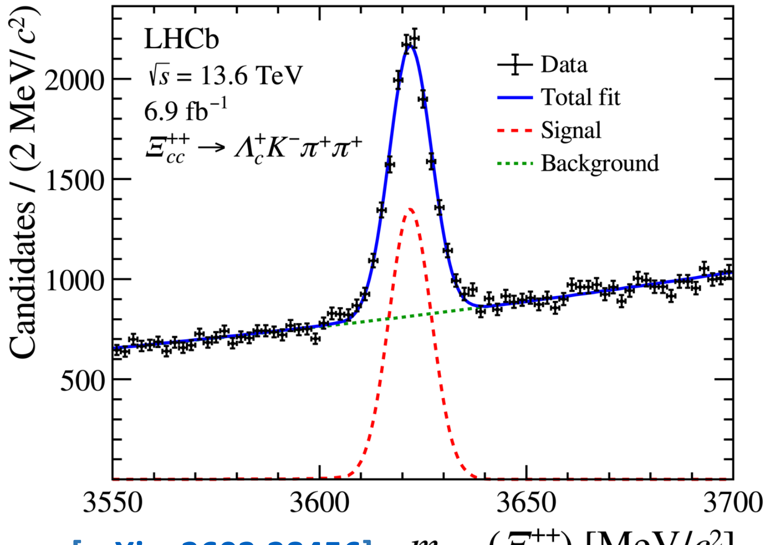
New dataset - Run3 of LHCb



[JINST 19 (2024) P05065]



✓ Ξ_{cc}^{++} yield/fb^{-1}: 285 @ Run2 → 1262 @ 2024



[arXiv: 2603.28456]

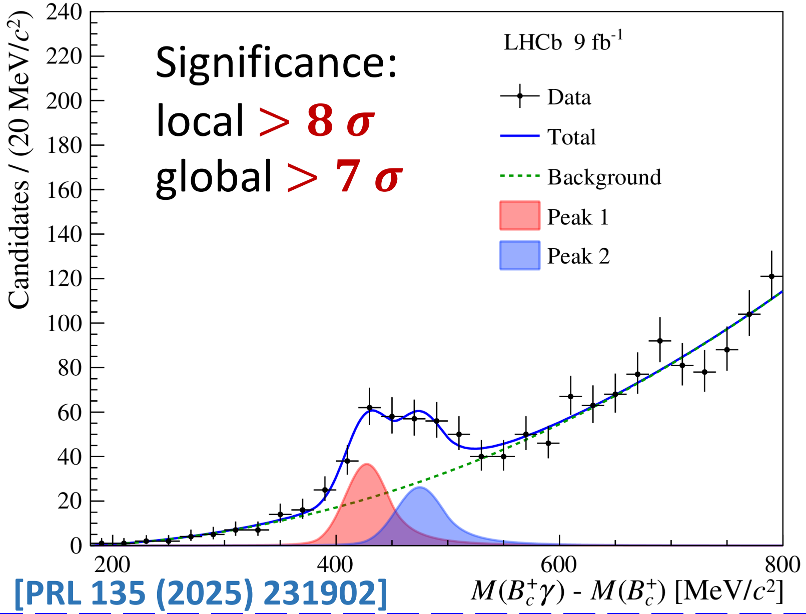
- **Luminosity**: 9 fb^{-1} @ Run 1-2 → **37 fb^{-1}** by Run 3
- **Software-only trigger**: efficiency of hadronic modes **×2 to 4**

Novel final states - neutral modes

➢ Although challenging, physics modes with ***neutral particles*** are accessible at LHCb

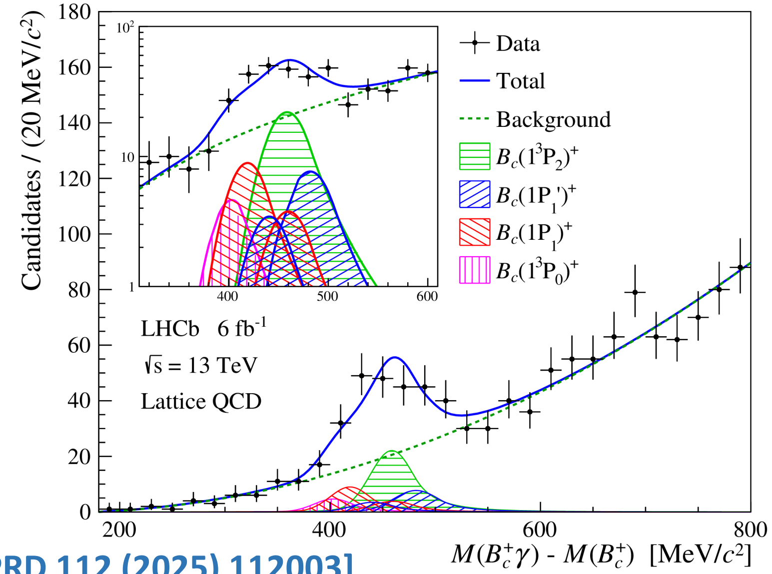
■ Observation of $B_c(1P)^+ \to B_c^+\gamma$

◆ **Theory-independent fit**



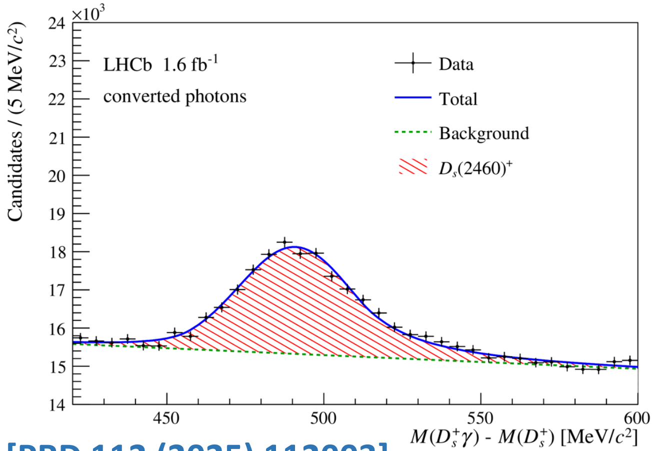
[PRL 135 (2025) 231902]

◆ **Theory-constrained fit**

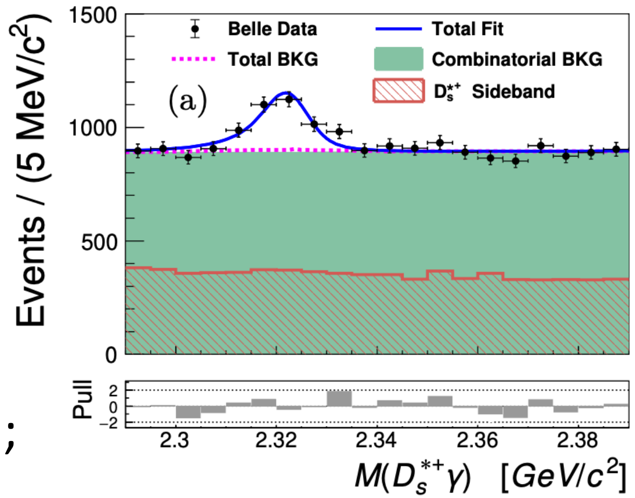


[PRD 112 (2025) 112003]

$D_{s1}(2460)^+ \to D_s^+\gamma$



[PRD 112 (2025) 112003]



✓To probe the properties of known states

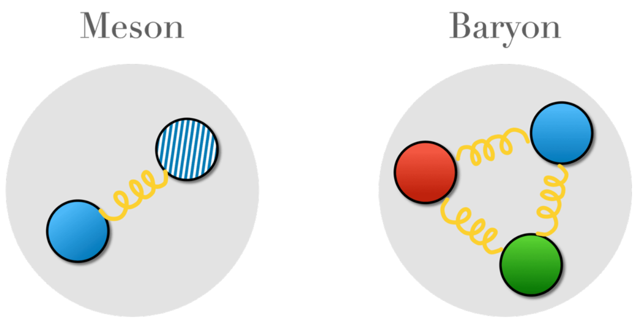
- $D_{s0}^*(2317)^+ \to D_s^{*+}\gamma$ observed at Belle&BelleII [PRL 136 (2026) 241901]

✓To explore new states with neutral modes

- a wide variety of possibilities: b-counterparts of $\chi_{c1}(3872)$ and $D_{s0}^*(2317)^+$; lower lying excited hadron states

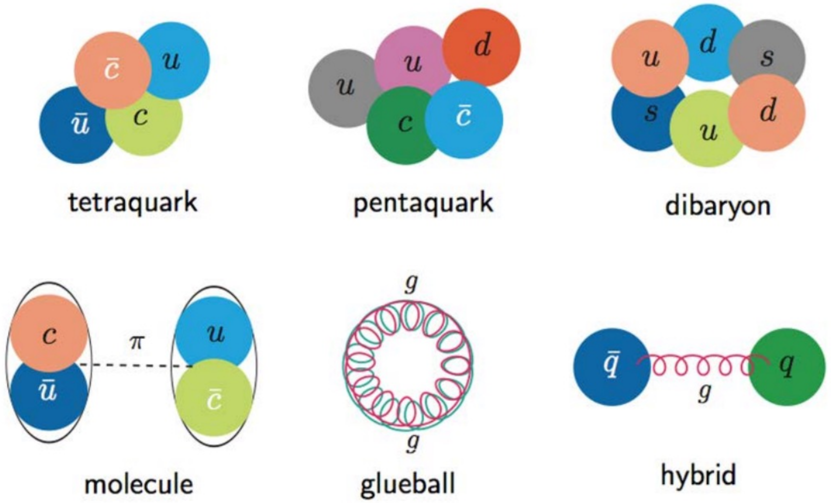
Selected recent results

Conventional Hadrons



- **Discovering new hadron species**
  - ✓ Observation of Ξ_{cc}^{+}
  - ✓ Observation of Ω_{cc}^{+}
- **Exploring excited hadron states**
  - ✓ Observation of excited Σ_c^0 in $B^- \to \Lambda_c^+ \bar{p} \pi^-$
- **Measuring hadron properties**

Exotic Hadrons



- **Chasing new exotic states**
  - ✓ Observation of $D_{s1}(2933)^+$ in $B^0 \to D^+ D^- K^+ \pi^-$
- **Decoding internal configurations**
  - ✓ Observation of $\chi_{c1}(3872) \to J/\psi \mu^+ \mu^-$
  - ✓ Study of $T_{c\bar{c}1}(4430)^+$ in $B^+ \to \psi(2S) K_S^0 \pi^+$
  - ✓ Amplitude analysis of $B^0 \to \eta_c(1S) K^+ \pi^-$

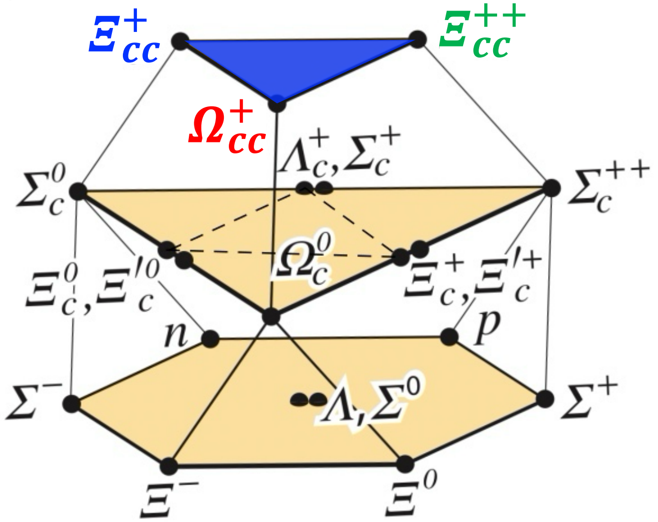
《LHCb实验上双粲重子的研究》by 童星昱

《LHCb实验上奇特强子态的研究》by 任赞

Conventional Hadrons

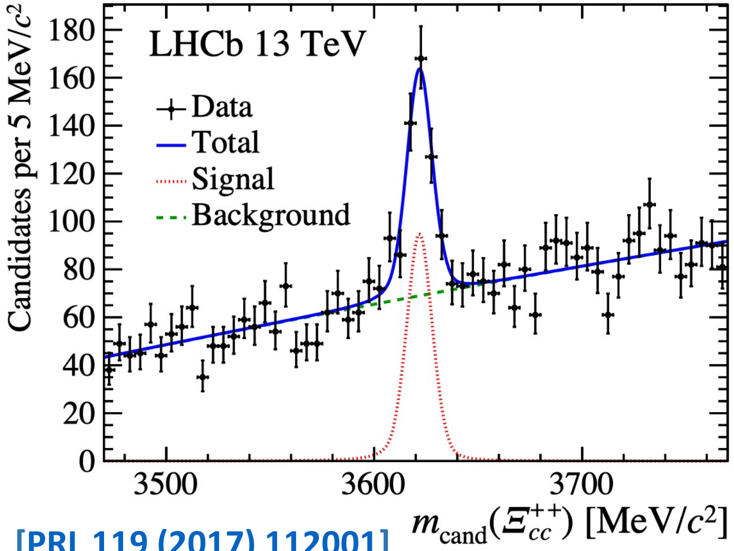
History of doubly charmed baryons

- Doubly charmed baryons remained a missing piece in baryon sector, until the firm observation of Ξ_{cc}^{++} in $\Lambda_c^+ K^- \pi^+ \pi^+$
- Search for Ξ_{cc}^{+} and Ω_{cc}^{+} with LHCb Run1&2 data yields no observation $\rightarrow$ larger statistic is essential



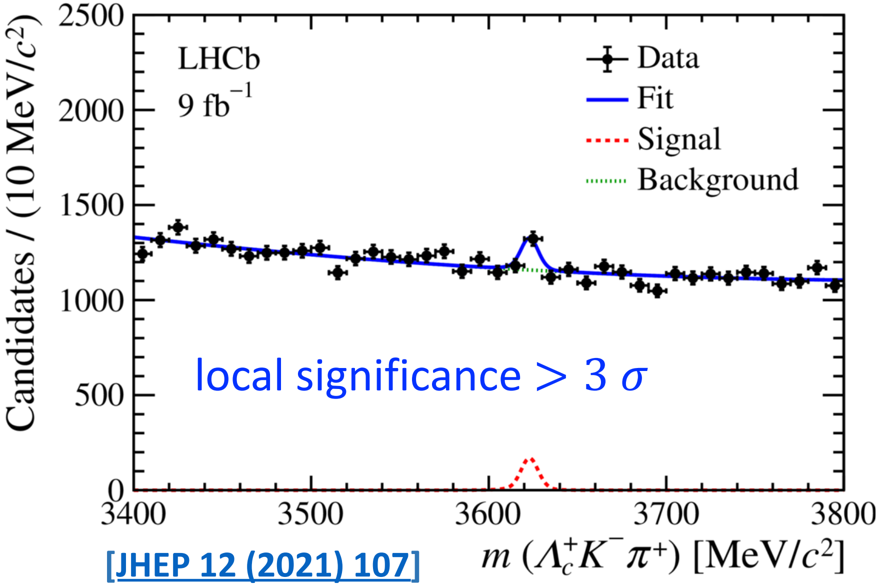
$$\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) > \tau(\Xi_{cc}^{+})$$
$$\sigma(\Xi_{cc}^{++}) \sim \sigma(\Xi_{cc}^{+}) \sim 3\times\sigma(\Omega_{cc}^{+})$$

Observation of Ξ_{cc}^{++}



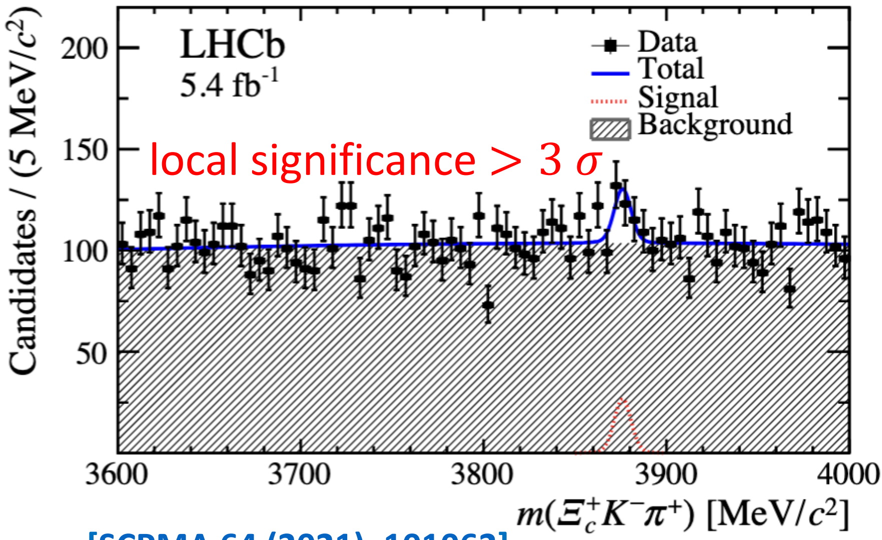
[PRL 119 (2017) 112001]

Search for $\Xi_{cc}^{+} \rightarrow \Lambda_c^+ K^- \pi^+$



[JHEP 12 (2021) 107]

Search for $\Omega_{cc}^{+} \rightarrow \Xi_c^+ K^- \pi^+$

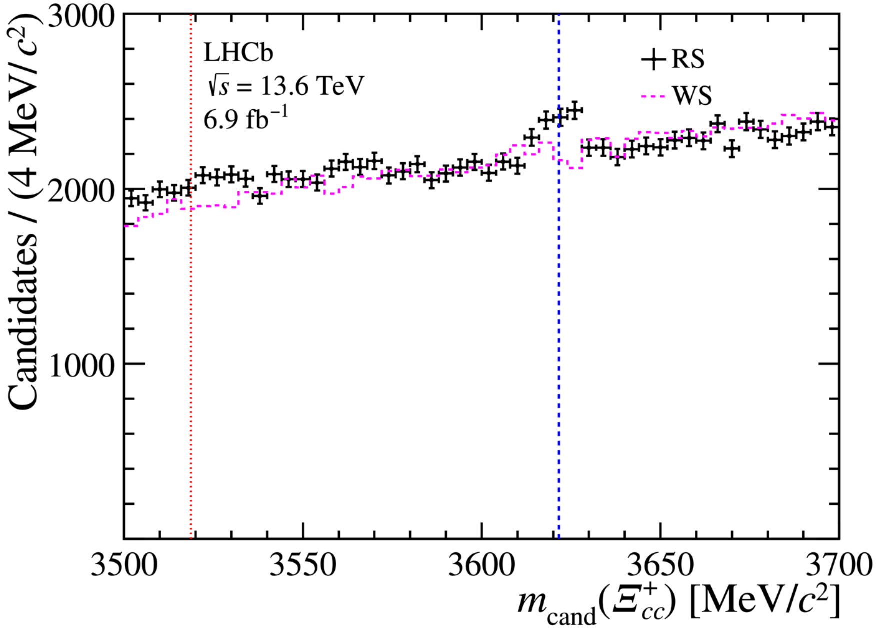


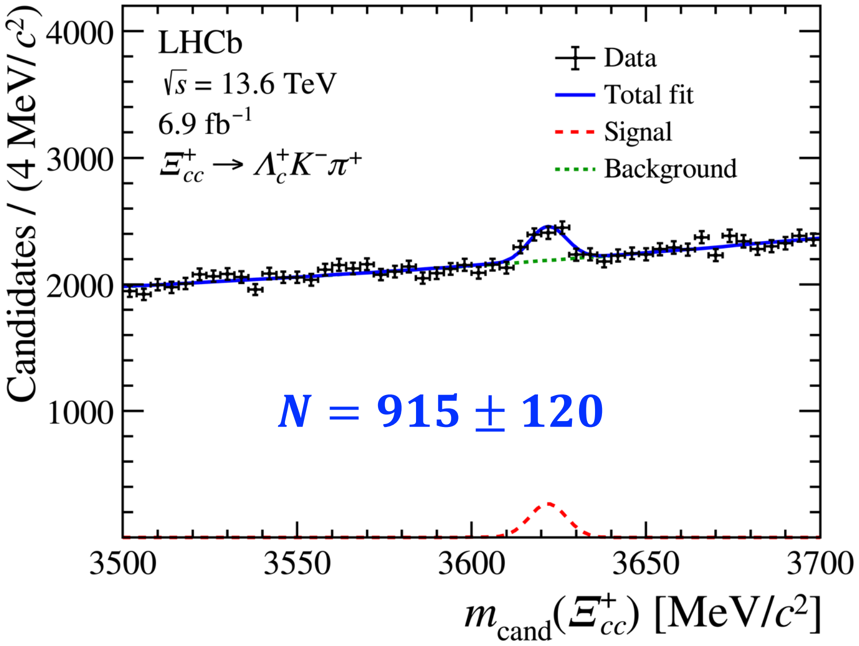
[SCPMA 64 (2021), 101062]

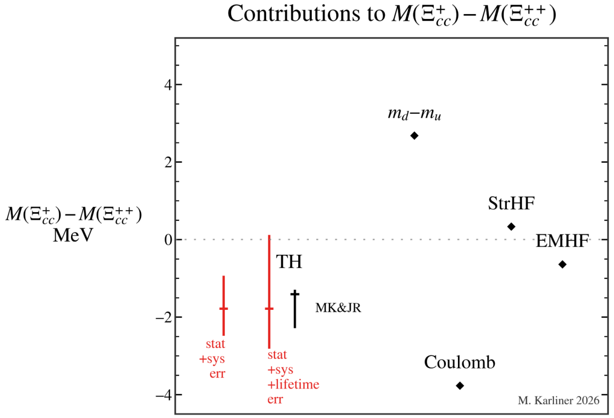
Observation of Ξ_{cc}^{+} at LHCb Run3

[PRL 137 (2026) 021902]

- **Dataset:** 6.9 fb^{-1} LHCb Run3 data collected in 2024
- **Decay chain:** $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+, \Lambda_c^+ \to p K^- \pi^+$
- **$\boldsymbol{\Xi_{cc}^{+}}$ is observed with statistical significance $> 7\ \sigma$** → **First new particle from LHCb Run3**, thanks to the enhanced capabilities of the upgraded LHCb detector and its trigger system







M. Karliner & J. Rosner [PRD 96 (2017) 3, 033004]

	$M_{\Xi_{cc}^{++}} - M_{\Xi_{cc}^{+}}$	$M_{\Xi_{bb}^{-}} - M_{\Xi_{bb}^{0}}$	$M_{\Xi_{bc}^{+}} - M_{\Xi_{bc}^{0}}$
EM	4.2 ± 2.3	4.0 ± 1.5	1.6 ± 1.1
Strong	-2.7 ± 1.5	2.3 ± 0.8	-2.5 ± 1.4
Total	1.5 ± 2.7	6.3 ± 1.7	-0.9 ± 1.8
Ref. [31]	2.3 ± 1.7	5.3 ± 1.1	-1.5 ± 0.9

[PLB 698 (2011) 251-255]

$$M(\Xi_{cc}^{+}) = 3619.97 \pm 0.83(\text{stats}) \pm 0.26(\text{syst})\ ^{+1.90}_{-1.30}(\tau)\ \text{MeV}/c^2$$
$$M(\Xi_{cc}^{+}) - M(\Xi_{cc}^{++}) = -1.77 \pm 0.84(\text{stat}) \pm 0.15(\text{syst})\ ^{+1.90}_{-1.30}(\tau)\ \text{MeV}/c^2$$

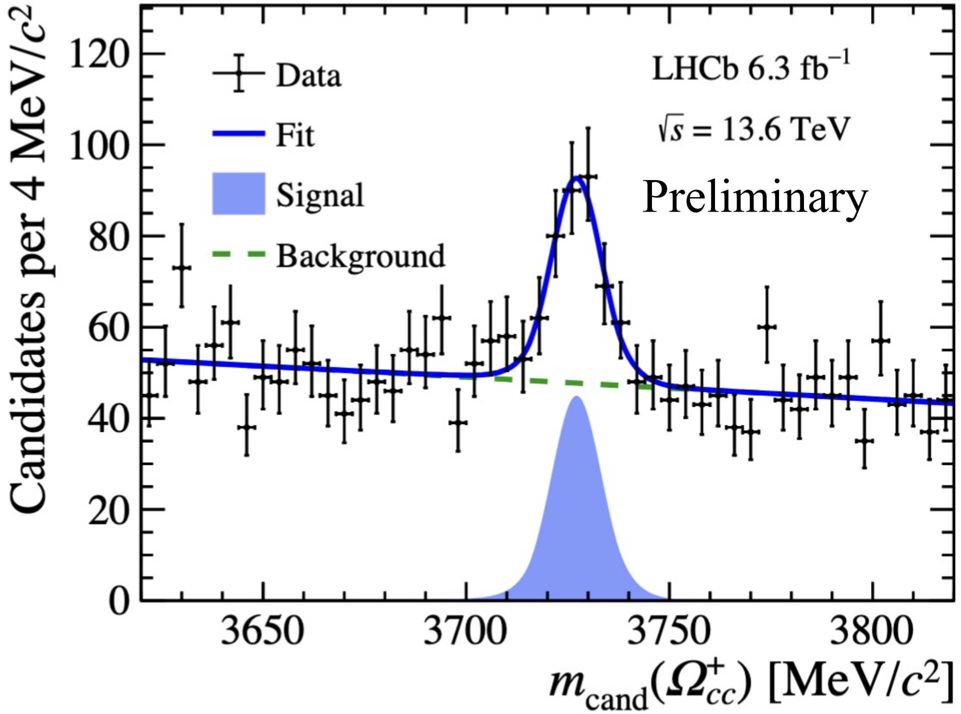
Observation of Ω_{cc}^{+} at LHCb Run3

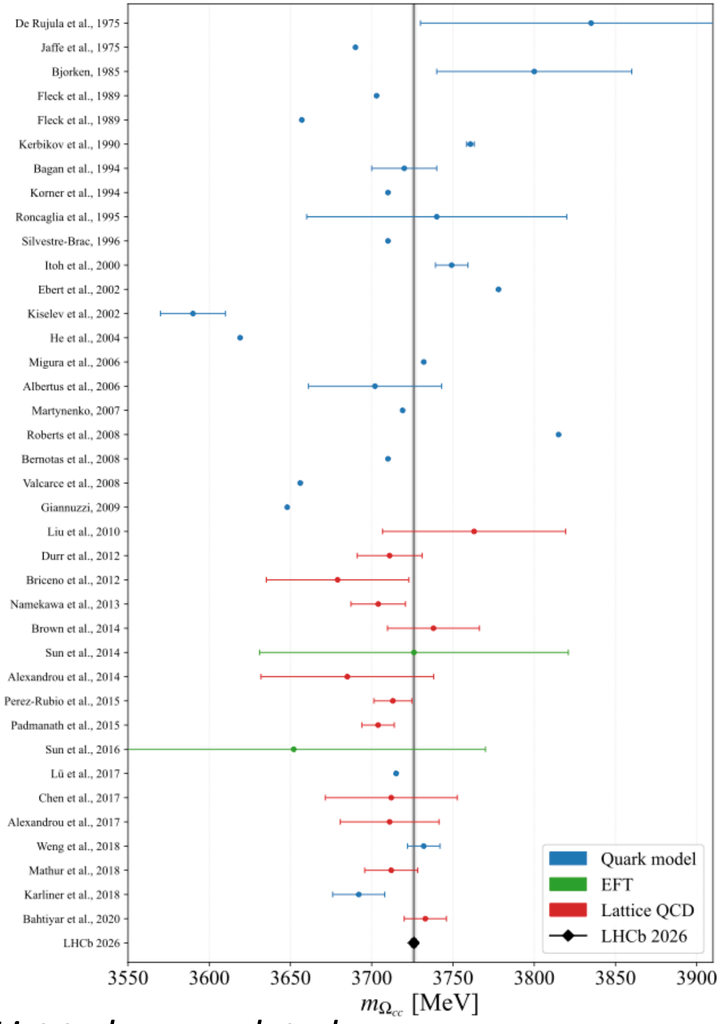
[LHCb-PAPER-2026-022]
in preparation

- **Dataset:** 6.3 fb^{-1} LHCb Run3 data collected in 2024
- **Decay chain:** $\Omega_{cc}^{+} \to \Omega_c^0\pi^+, \Omega_c^0 \to pK^-K^-\pi^+$ to exploit the large $\tau(\Omega_c^0)$~280 fs

- $\boldsymbol{\Omega_{cc}^{+}}$ **is observed at $> 8\,\sigma$**
  $\to$ **final piece of the $\mathrm{SU}(4)_f$ J = 1/2 20-plet**

$N = 184 \pm 24$





*List to be completed

$$M(\Omega_{cc}^{+}) = 3725.9 \pm 1.0(\mathrm{stat}) \pm 0.2(\mathrm{syst}) \pm 0.4(\tau) \pm 0.6(\mathrm{ext})\ \mathrm{MeV}/c^2$$
$$M(\Omega_{cc}^{+}) - M(\Xi_{cc}^{++}) = 104.3 \pm 1.0(\mathrm{stat}) \pm 0.2(\mathrm{syst}) \pm 0.4(\tau) \pm 0.5(\mathrm{ext})\ \mathrm{MeV}/c^2$$

Prospects on Ξ_{bc} and Ξ_{bb}

Ξ_{bc}

[arXiv:1808.08865]

✓Reference: $\sim 100\ B_c^+ \to J/\psi D_s^+$ with 3 fb^{-1}@7/8 TeV

$$N = \mathcal{L}\times\sigma\times\mathcal{B}\times\varepsilon$$

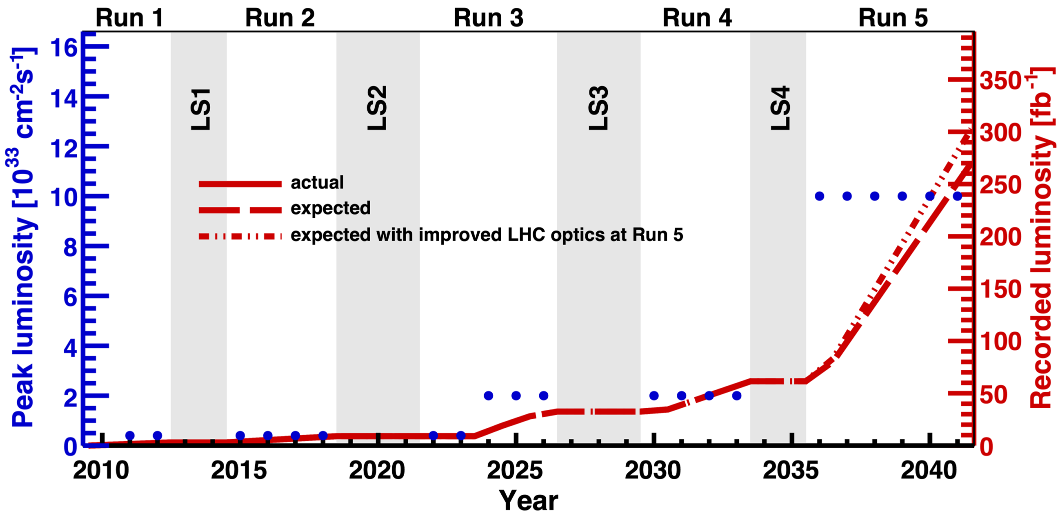
✓Assuming (with sizable uncertainties):

- $f_{\Xi_{bc}^+}/f_{B_c^+} \sim 0.2$
- $\mathcal{B}(\Xi_{bc}^+ \to J/\psi \Xi_c^+)/\mathcal{B}(B_c^+ \to J/\psi D_s^+) \sim 1$
- $\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)/\mathcal{B}(D_s^+ \to K^+K^-\pi^+) \sim 0.1$
- $\varepsilon_{\Xi_{bc}^+}/\varepsilon_{B_c^+} \sim 0.5$

$\Rightarrow \mathcal{O}(100)$ with 300 fb^{-1}@14 TeV

& combination of different modes

◆ **Promising to observe Ξ_{bc} in Run3/4**



Ξ_{bb}

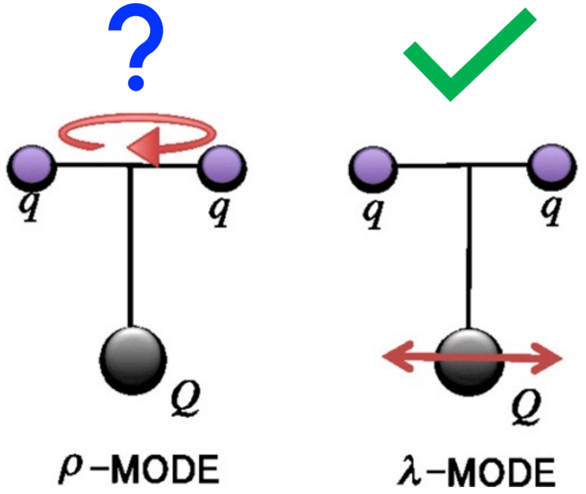
highly simplified!

Ξ_{cc}	$\to$	Ξ_{bc}	$\to$	Ξ_{bb}
~ 55 k		$\mathcal{O}(100)$		$\mathcal{O}(1)$

with 300 fb^{-1}@14 TeV

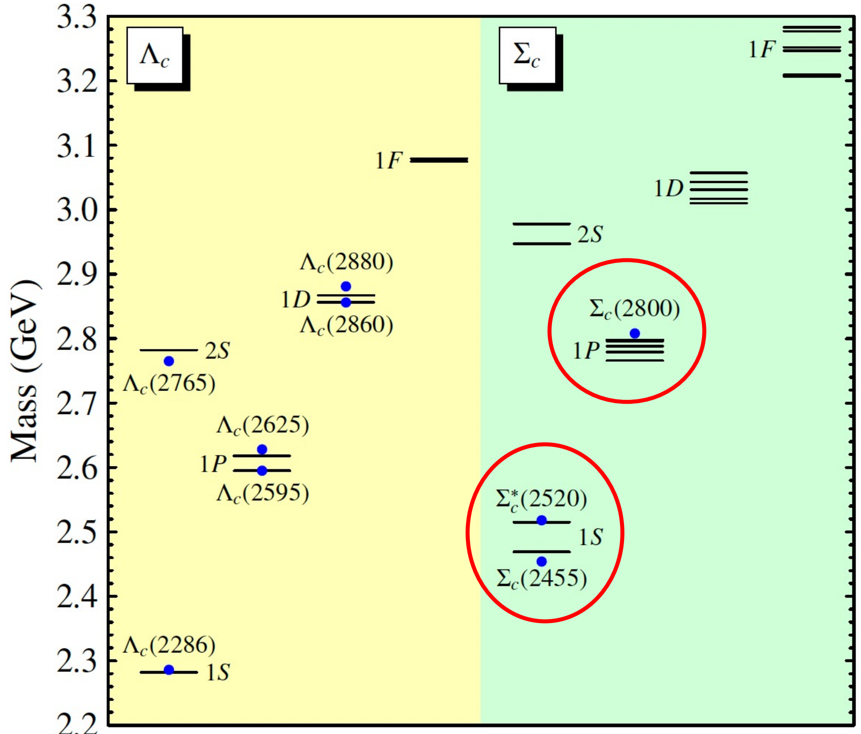
Σ_c spectroscopy

- Singly heavy baryons offer
  - ✓ a crucial testbed for ***Heavy Quark Effective Theory***
  - ✓ verification of ***diquark model***
- Based on heavy quark-light diquark $Q[qq]$ model, for λ-mode
  - ✓ Only 3 Σ_c states observed so far
  - ✓ Mass measurement of $\boldsymbol{\Sigma_c(2800)}$ at BaBar contradicts Belle result



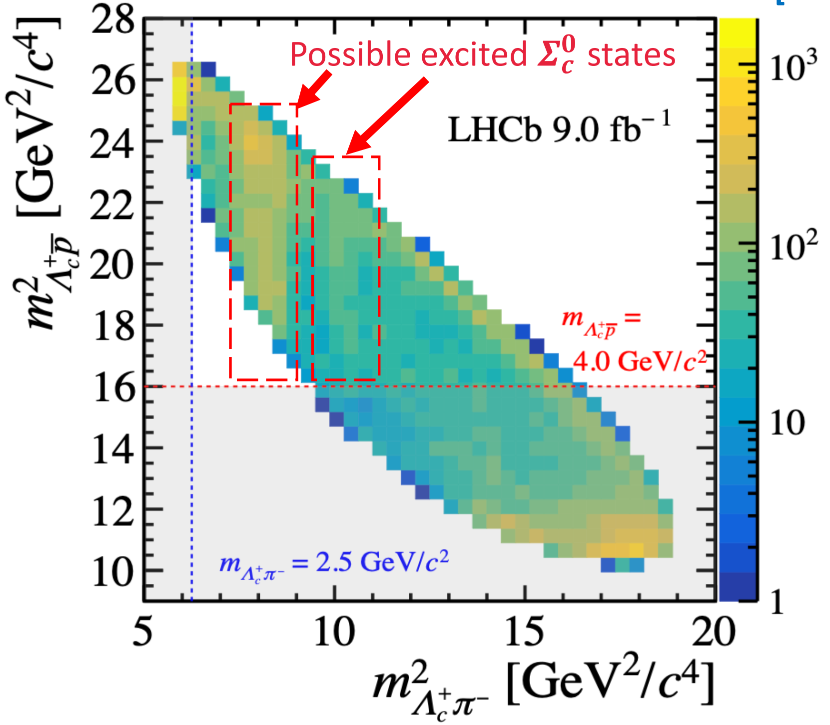
[PRD 92 (2015) 114029]

- Amplitude analysis of $B^- \to \Lambda_c^+ \bar{p} \pi^-$ with 9 fb^{-1} LHCb Run1+2 data in search for excited $\Sigma_c^0 \to \Lambda_c^+ \pi^-$



[PRD 108 (2023) 3, 034002]

[arXiv: 2607.10595]

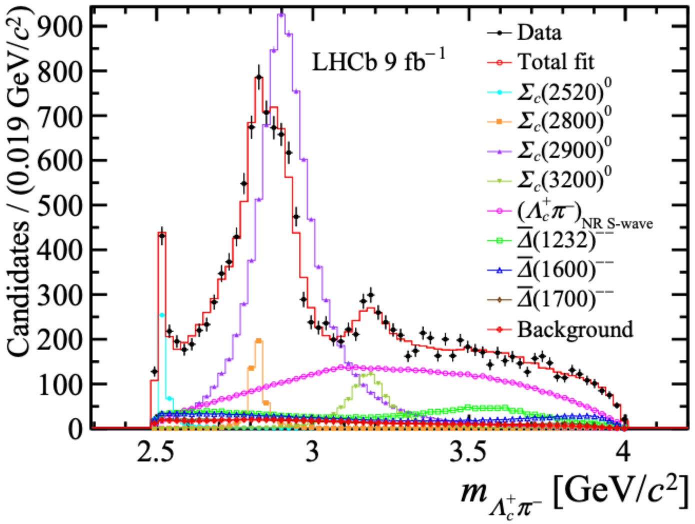


Observation of new excited Σ_c^0 states

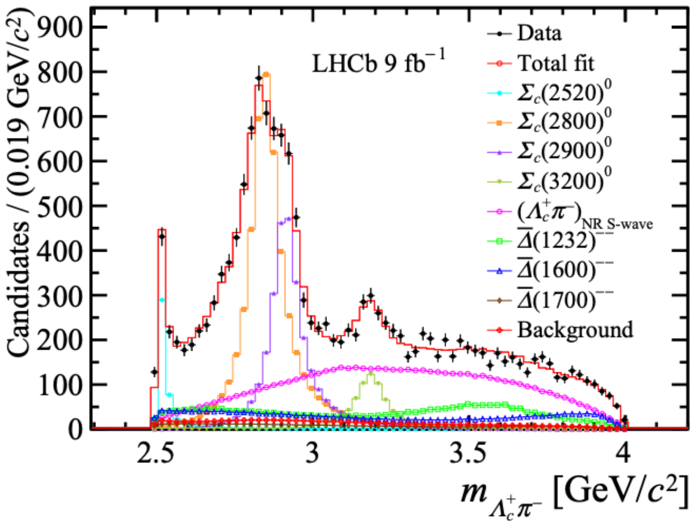
[arXiv: 2607.10595]

- J^P of $\Sigma_c(2520)^0$ firmly established to be $(3/2)^+$
- $\Sigma_c(2900)^0$ and $\Sigma_c(3200)^0$ newly observed → $\Sigma_c(2800)$ at BaBar resolved into $\Sigma_c(2800)^0$&$\Sigma_c(2900)^0$

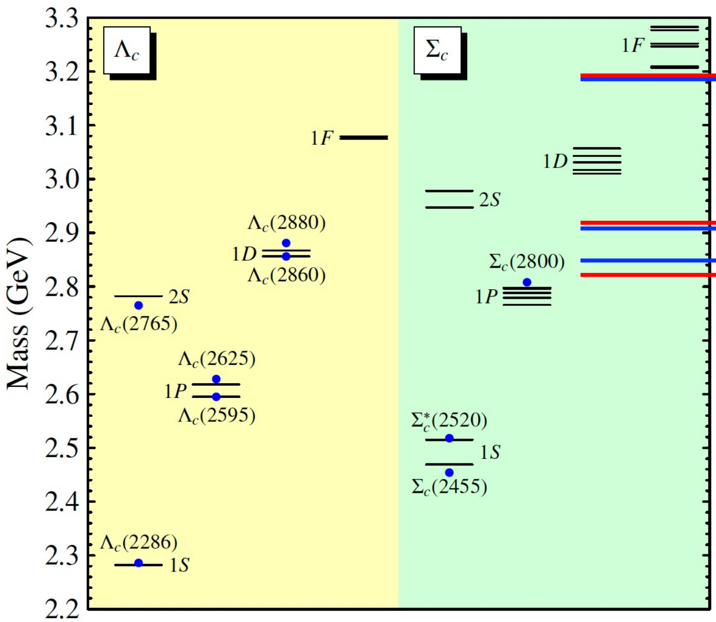
Group A



Group B



Parameter	Group A	Group B
$m_{\Sigma_c(2800)^0}$ [GeV/c^2]	$2.819 \pm 0.006 \pm 0.002$	$2.848 \pm 0.004 \pm 0.006$
$\Gamma_{\Sigma_c(2800)^0}$ [GeV]	$0.033 \pm 0.007 \pm 0.008$	$0.099 \pm 0.007 \pm 0.021$
$m_{\Sigma_c(2900)^0}$ [GeV/c^2]	$2.908 \pm 0.005 \pm 0.009$	$2.914 \pm 0.003 \pm 0.008$
$\Gamma_{\Sigma_c(2900)^0}$ [GeV]	$0.175 \pm 0.008 \pm 0.023$	$0.092 \pm 0.006 \pm 0.023$
$m_{\Sigma_c(3200)^0}$ [GeV/c^2]	$3.186 \pm 0.006 \pm 0.014$	$3.190 \pm 0.005 \pm 0.011$
$\Gamma_{\Sigma_c(3200)^0}$ [GeV]	$0.133 \pm 0.018 \pm 0.027$	$0.100 \pm 0.015 \pm 0.032$



[PRD 108 (2023) 3, 034002]

$\Sigma_c(3200)^0$: $2P$ or $3S$

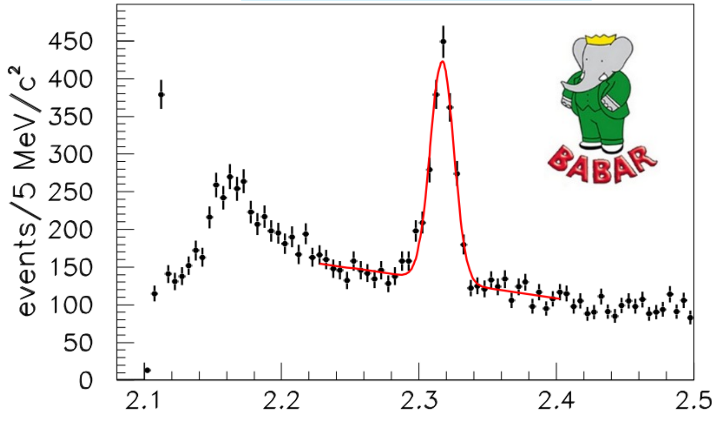
$\Sigma_c(2900)^0$: $2S$ or $1P$

$\Sigma_c(2800)^0$: $1P$ or $2S$

Exotic Hadrons

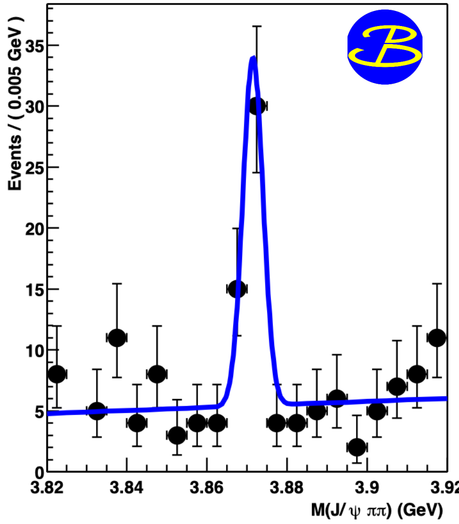
Renaissance of hadron spectroscopy

$D_{s0}^{*}(2317)^{+}$

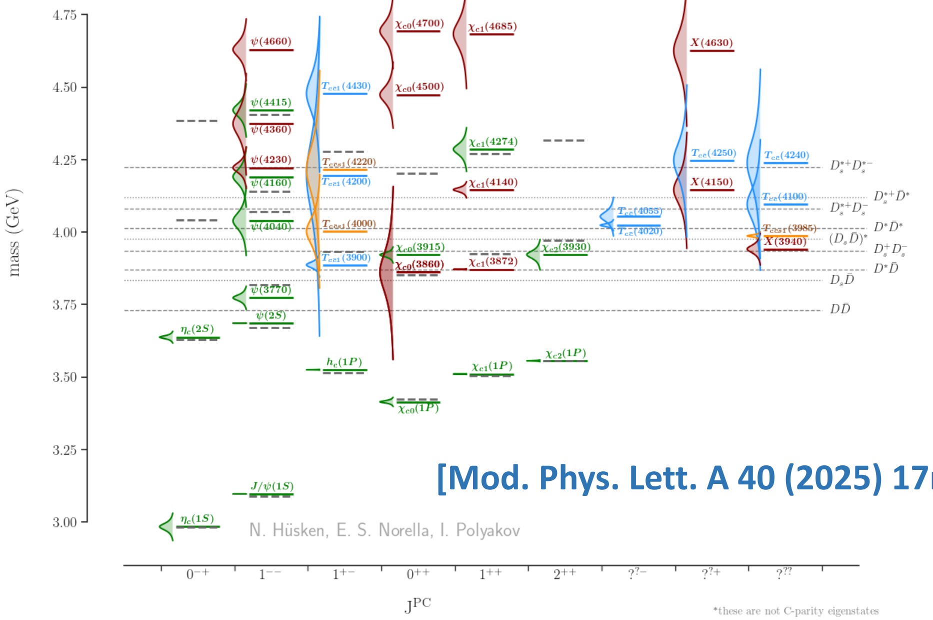


[PRL 90 (2003) 242001]

$\chi_{c1}(3872)$



[PRL 91 (2003) 262001]



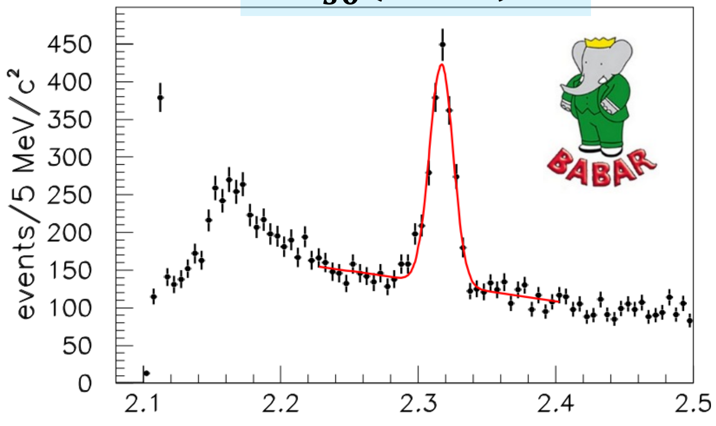
[Mod. Phys. Lett. A 40 (2025) 17n18, 2530002]

- ➢ $Q\bar{Q}q\bar{q}$
- ✓ X: Neutral, $J^{PC} \neq 1^{--}$
- ✓ Y: Neutral, $J^{PC} = 1^{--}$
- ✓ Z: Charged

At prod.	Charm		Beauty		Charm + Beauty	
$Q\bar{Q}$	$cq\bar{q}\bar{q}$	$c\bar{q}qqq/\bar{c}qqqq$	$bq\bar{q}\bar{q}$	$b\bar{q}qqq/\bar{b}qqqq$		
	$c\bar{c}q\bar{q}$	$c\bar{c}qqq$	$b\bar{b}q\bar{q}$	$b\bar{b}qqq$		
$Q\bar{Q}+Q\bar{Q}$	$cc\bar{q}\bar{q}$	$c\bar{q}cqq$	$bb\bar{q}\bar{q}$	$b\bar{q}bqq$	$bc\bar{q}\bar{q}$	$b\bar{c}qqq/\bar{b}cqqq$
	$cc\bar{c}\bar{q}$	$c\bar{c}cqq$	$bb\bar{b}\bar{q}$	$b\bar{b}bqq$	$bq\bar{c}\bar{q}$	$b\bar{q}cqq$
	$cc\bar{c}\bar{c}$		$bb\bar{b}\bar{b}$		......	

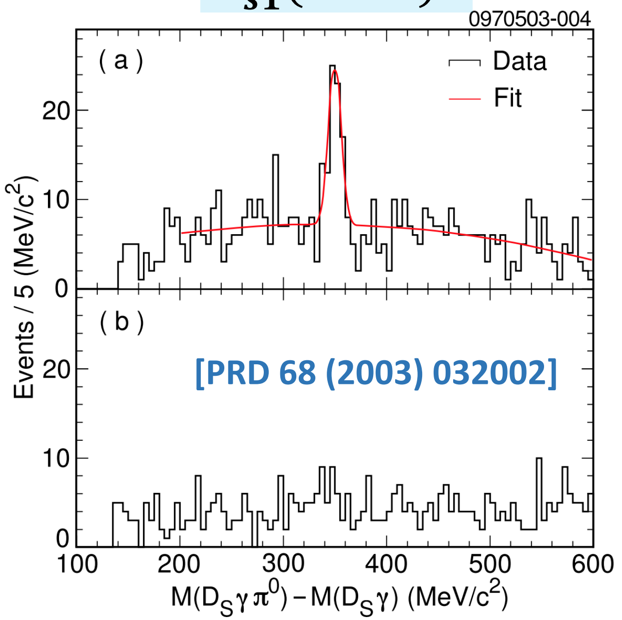
$D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$

$D_{s0}^*(2317)^+$

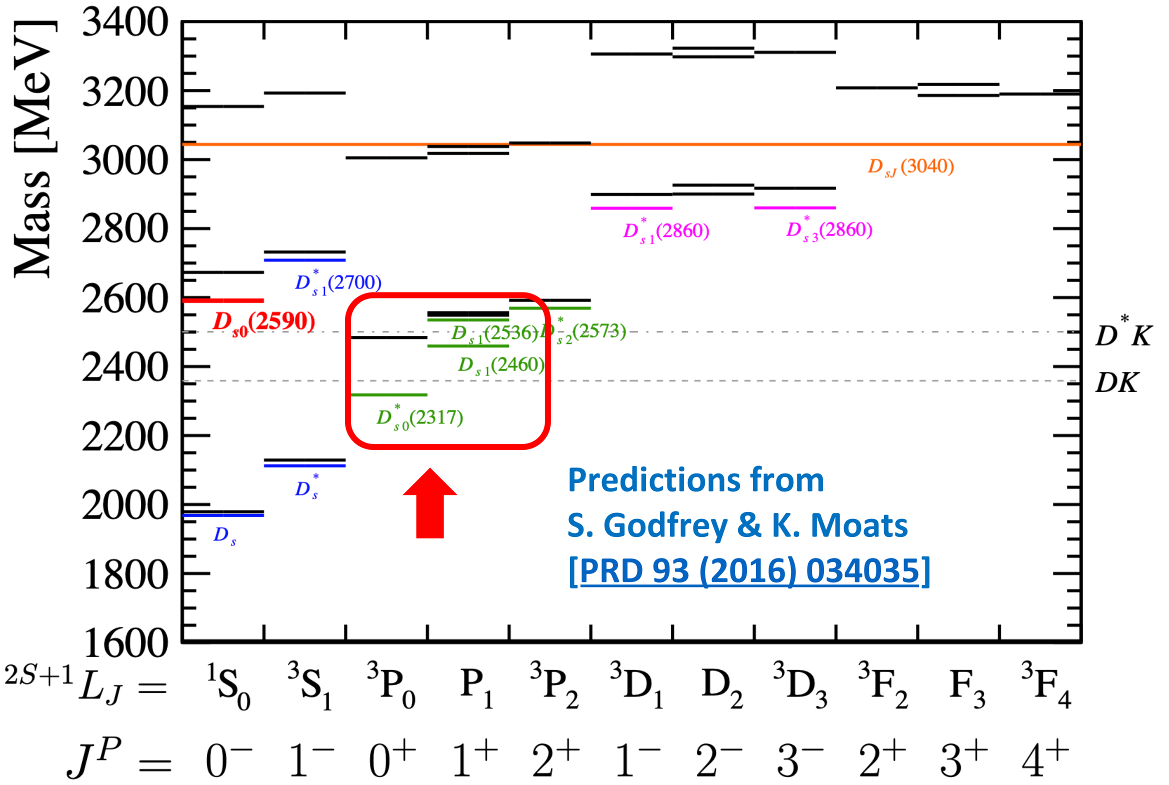


[PRL 90 (2003) 242001]

$D_{s1}(2460)^+$



[PRD 68 (2003) 032002]



Predictions from
S. Godfrey & K. Moats
[PRD 93 (2016) 034035]

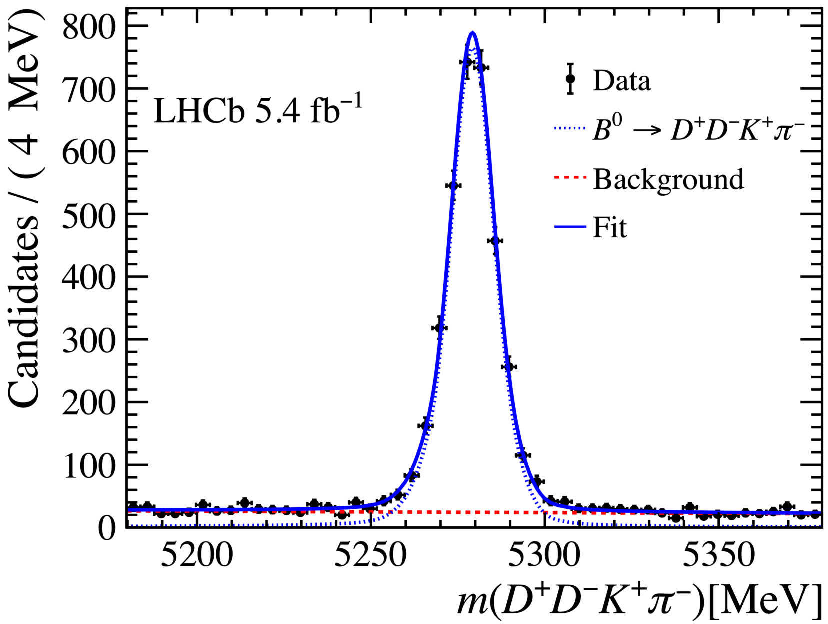
- $D_{s0}^*(2317)^\pm$ is a **paradigm breaker** in hadron spectroscopy
  - A 160 MeV mass deficit wrt quark potential model
- Its spin partner $D_{s1}(2460)^+$ exhibits a coherent mass anomaly
  - $m(D_{s0}^*(2317)^\pm) < m\big(D_0^*(2300)\big)$ i.e. $c\bar{u}/c\bar{d}$ heavier than $c\bar{s}$
  - $m(D_{s1}(2460)^\pm) - m(D_{s0}^*(2317)^\pm) \simeq m(D^*) - m(D)$
  - $D_{s0}^*(2317)^\pm$ decay ~100% through the isospin breaking mode $D_s^+\pi^0$

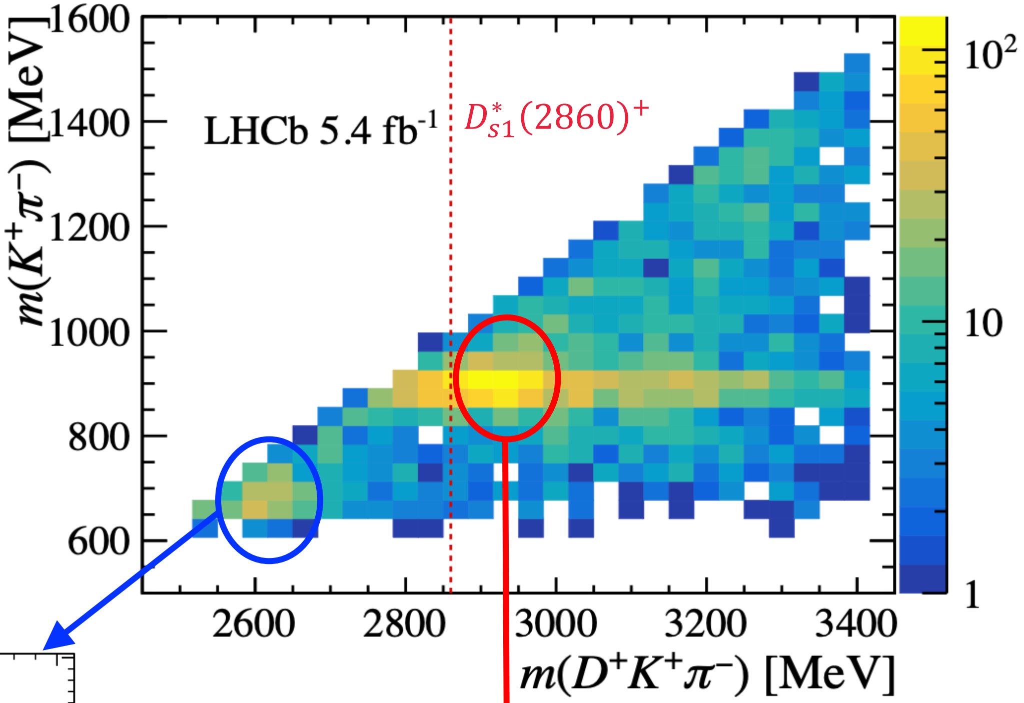
✓ (DK, D^*K) molecules?
✓ chiral partners of (D_s^+, D_s^{*+})?
✓ mixture?

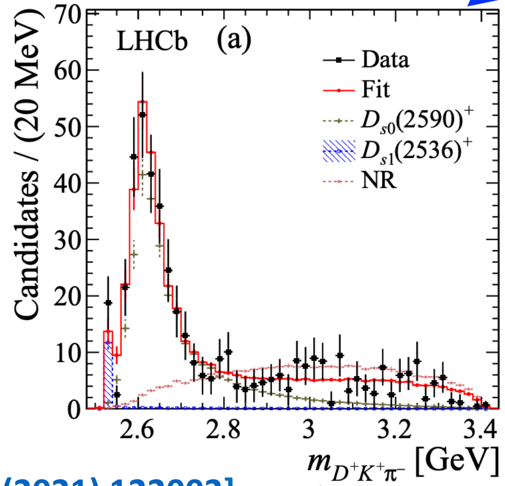
Search for excited D_s^+ in $B^0 \to D^+D^-K^+\pi^-$ [arXiv: 2604.21257]

- Search for excited D_s^+ performed in $B^0 \to D^+D^-K^+\pi^-$ with LHCb Run2 data

$\boldsymbol{N = 3264 \pm 62}$







✓ $D_{s0}(2590)^+$ observed in previous study with restricted phase-space region of $m(K^+\pi^-) < 750$ MeV

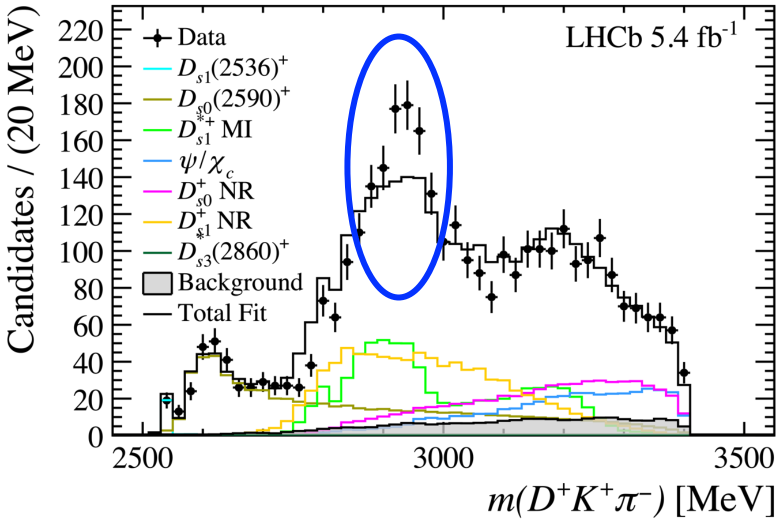
✓ Enhancement in the $K^*(892)$ region at $m(D^+K^+\pi^-) \approx 2950$ MeV hints for new excited D_s^+?

[PRL 126 (2021) 122002]

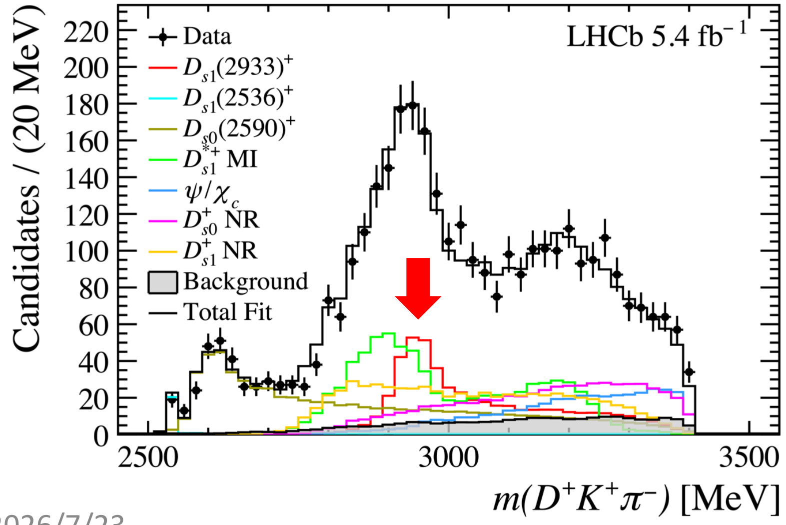
Observation of $D_{s1}(2933)^+$

[arXiv: 2604.21257]

Model without $D_{s1}(2933)^+$



Model with $D_{s1}(2933)^+$

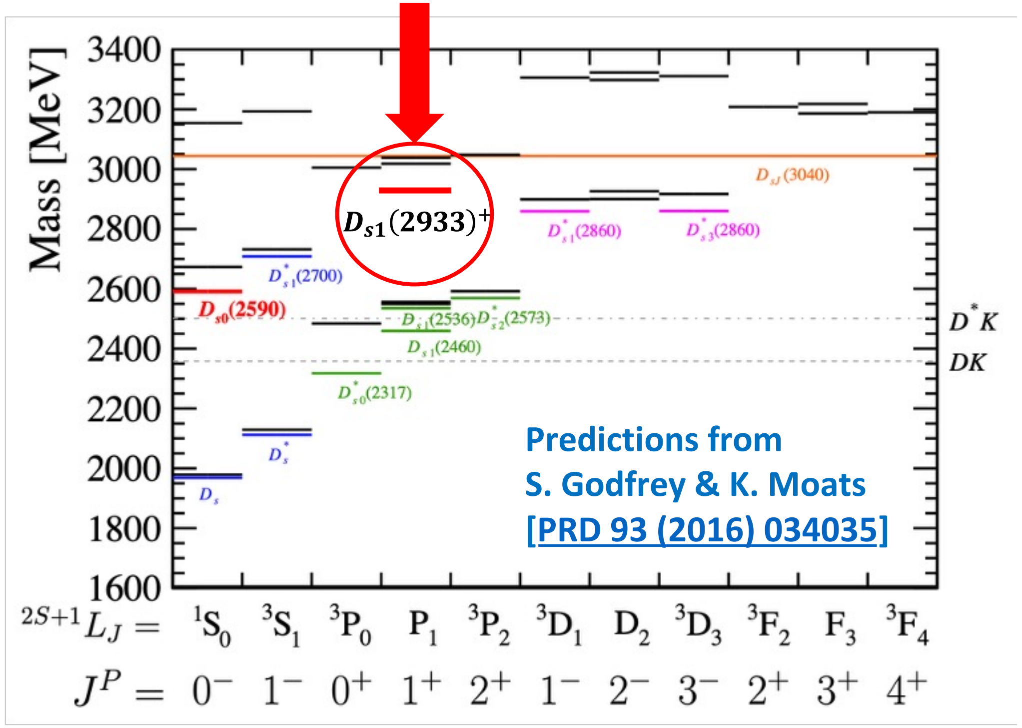


- A new $D_{s1}(2933)^+$ state is observed with significance $> \mathbf{10\ \sigma}$

$$M = 2933^{+6}_{-5}(\text{stat})\ ^{+4}_{-3}(\text{syst})\ \ \text{MeV}/c^2$$
$$\Gamma = 72^{+18}_{-12}(\text{stat})\ ^{+7}_{-10}(\text{syst})\ \ \text{MeV}$$

✓ $J^P = 1^+$ with other J^P assignments rejected at $> \mathbf{5\ \sigma}$

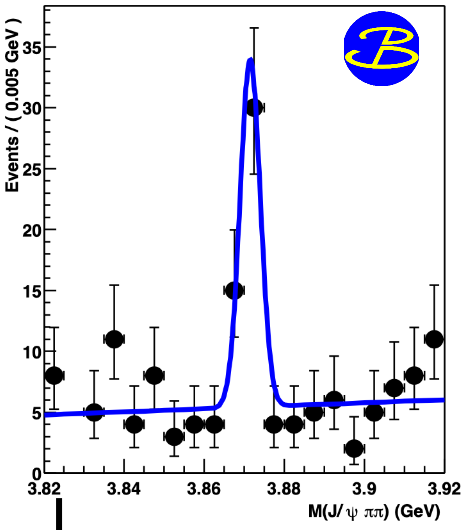
- First radial excitation of the P-wave D_s^+ states
  → mass lower than potential model predictions



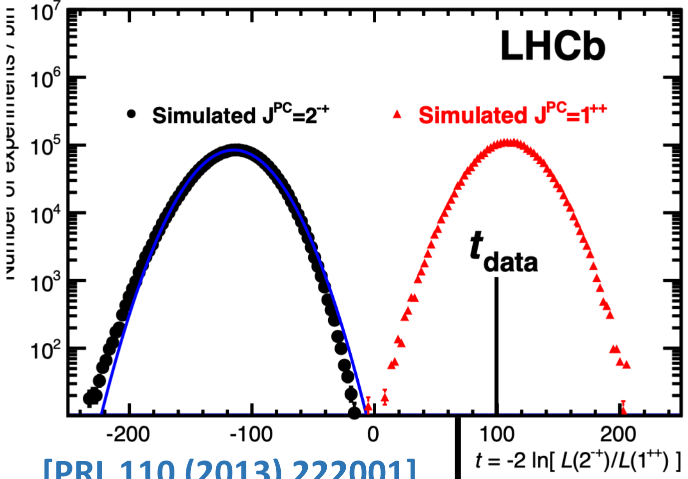
$\chi_{c1}(3872)$

$J^{PC} = 1^{++}$

[PRL 91 (2003) 262001]



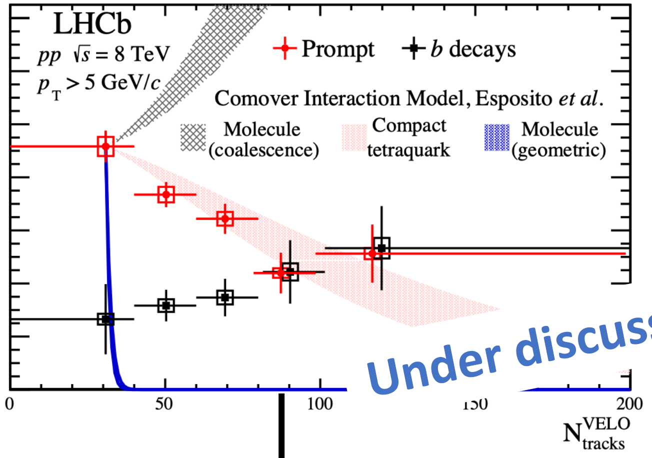
2003



[PRL 110 (2013) 222001]

2013

[PRL 126 (2021) 092001]



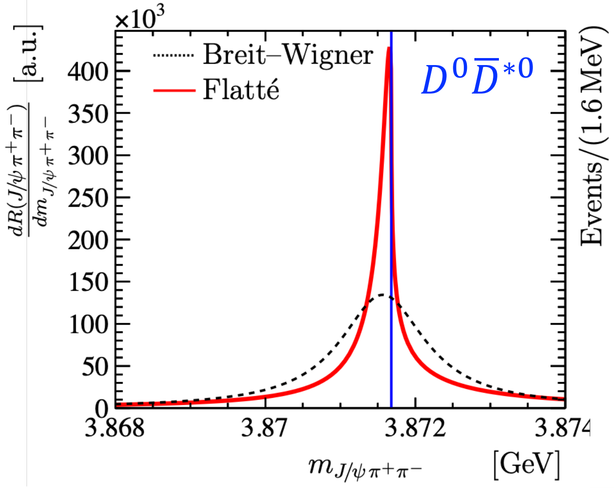
Under discussion

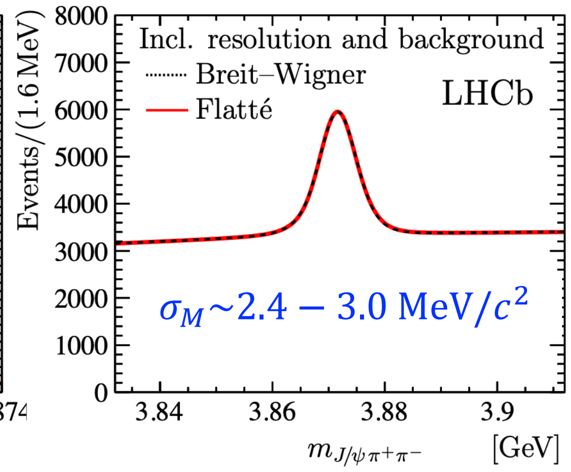
2020

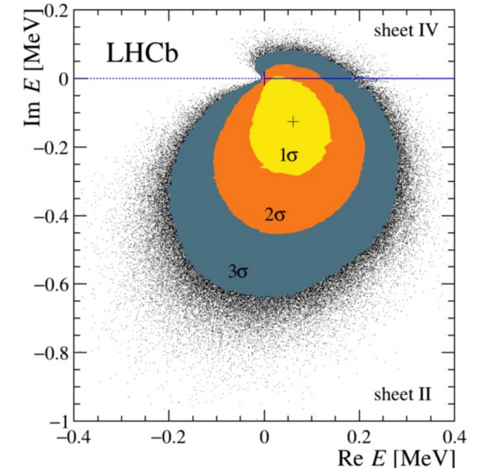
2021

- Intriguing properties:
  - ✓ Measured mass below prediction for $\chi_{c1}(2^3P_1)$
  - ✓ $\chi_{c1}(3872) \to J/\psi\rho$ is isospin violating
  - ✓ Mass extremely close to $D^0\bar{D}^{*0}$ threshold $3871.70 \pm 0.11\ \mathrm{MeV}/c^2$

[PRD 102 (2020) 092005]





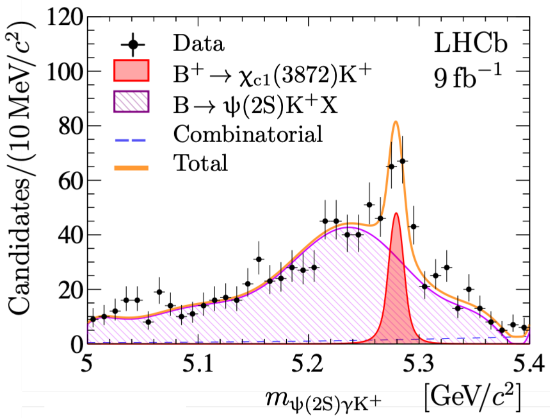


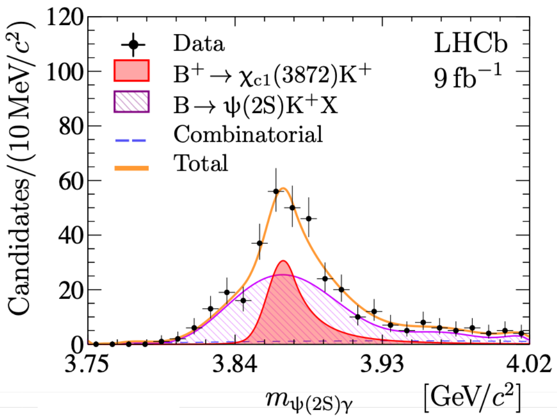
New decay of $\chi_{c1}(3872)$

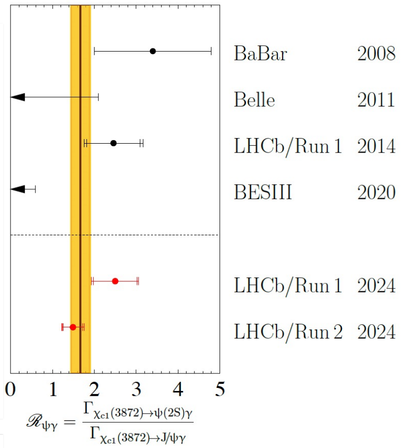
➢ Observation of the $\chi_{c1}(3872) \to J/\psi\mu^+\mu^-$ decay at LHCb using 9 fb^{-1} Run1+2 data

✓ At low $m_{\mu^+\mu^-}$, the virtual photon pole dominates the decay rate → radiative decay

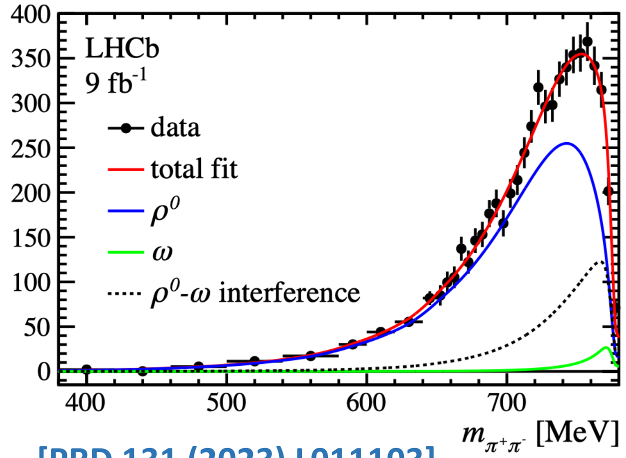
[JHEP 11 (2024) 121]



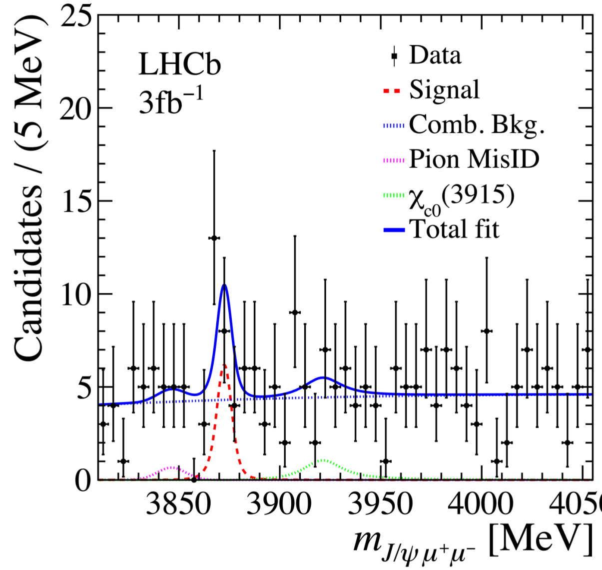


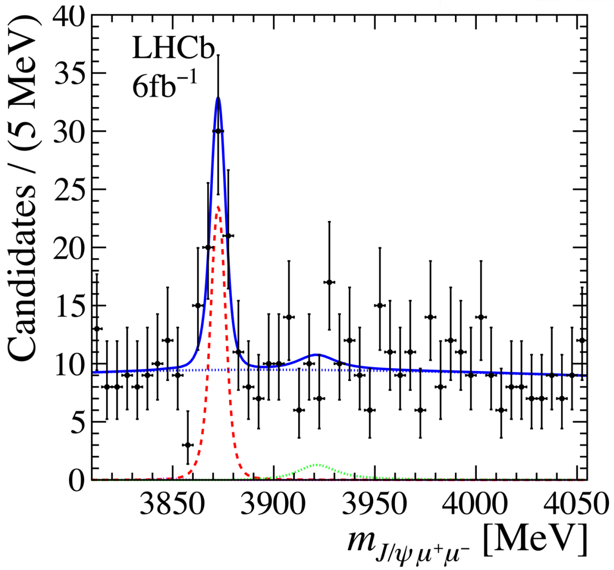


✓ At higher $m_{\mu^+\mu^-}$, to probe ρ^0 & ω contribution



[PRD 131 (2023) L011103]





✓ Signal significance $> \mathbf{6.5\,\sigma}$

$$\boxed{\frac{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\mu^+\mu^-)}{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)} = (1.68 \pm 0.32 \pm 0.05) \times 10^{-3}}$$

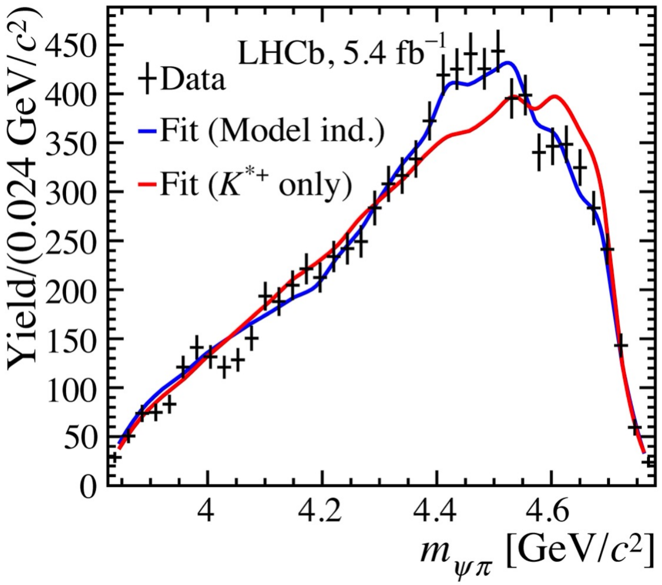
[PRD 113 (2026) 072019]

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

[PRD 113 (2026) L071101]

- First four-dimensional amplitude analysis of $B^+ \to \psi(2S)K_S^0\pi^+$ performed using 5.4 fb^{-1} data at $\sqrt{s} = 13$ TeV
  - ✓ related via isospin symmetry to $\bar{B}^0 \to \psi(2S)K^-\pi^+$ where the first charged charmonium-like state $T_{c\bar{c}1}(4430)^+(Z_c(4430)^+, J^P = 1^+)$ was seen [PRL 100 (2008) 142001] [PRL 112 (2014) 222002]
- Fits with different parametrisations of $\psi(2S)\pi^+$ amplitudes are performed

Model independent



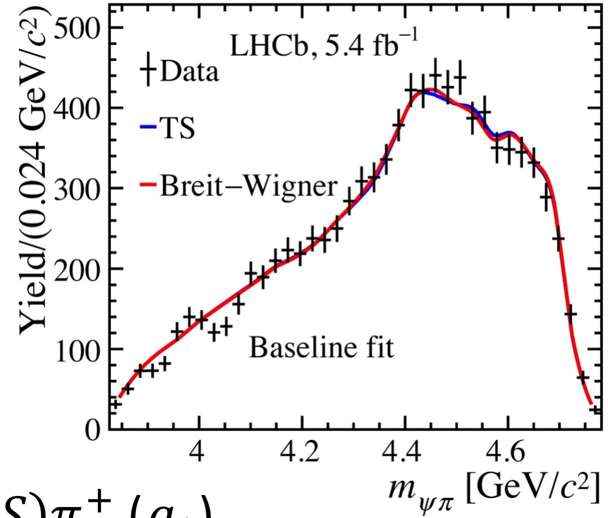
✓ discrepancy resolved by adding $\psi(2S)\pi^+$ component which shows resonant behavior

Model dependent

✓ **Breit Wigner:**

$$M = 4.452 \pm 0.016^{+0.055}_{0.033}\ \text{GeV}$$
$$\Gamma = 0.174 \pm 0.019^{+0.083}_{-0.020}\ \text{GeV}$$
$$f = (3.7 \pm 0.6^{+4.0}_{-0.7})\%$$
$$J^P = 1^+$$

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



- **Molecular scenario:** Flatté model with coupling to $\bar{D}_1^*(2600)^0 D^+$ (g_2) and $\psi(2S)\pi^+$ (g_1)

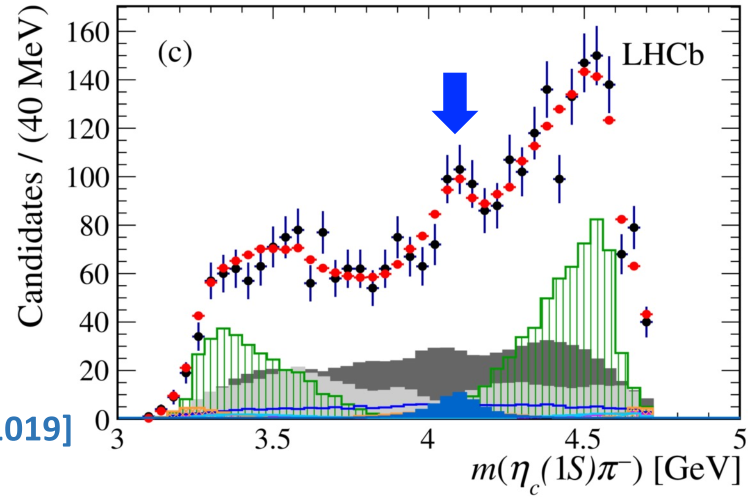
$$g_2 = 0.00 \pm 1.78 \pm 2.81\ \text{GeV}/c^2, \left|\frac{g_2}{g_1}\right| < 6.8 \text{ @ } 95\%\ \text{CL}$$

- **Triangle singularity mechanism:** model incorporating singularity in $\psi(4230)K^{*+}\pi^+$ triangle diagram gives reasonable description

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

[EPJC 86 (2026) 537]

- LHCb saw evidence for an $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)K^+\pi^-$ with 4.7 fb^{-1} data at 13 TeV

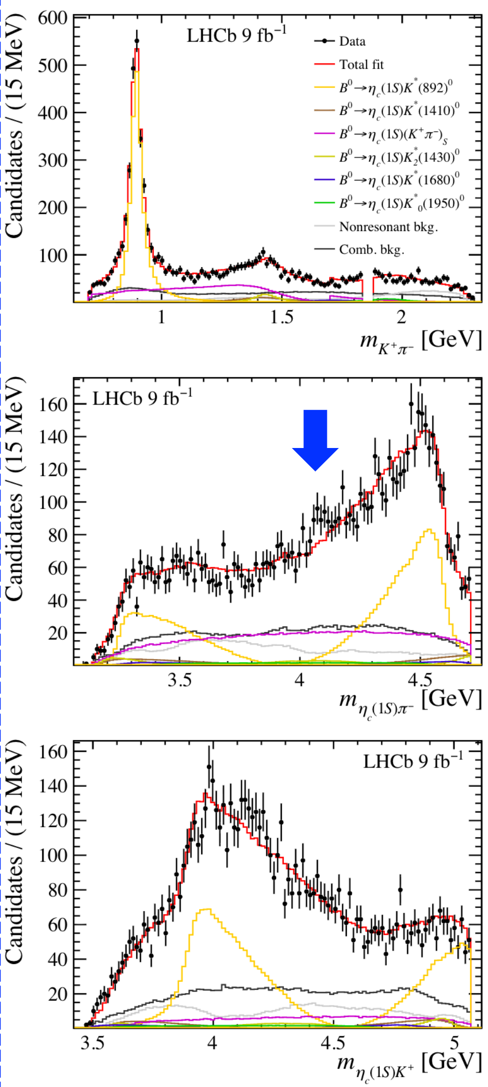


[EPJC 78 (2018) 1019]

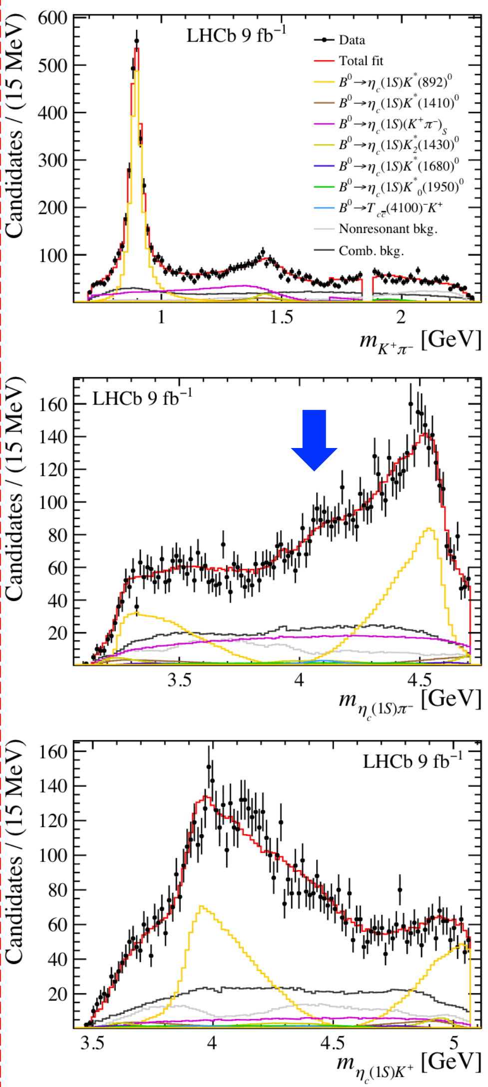
- Update with full 9 fb^{-1} Run1+2 data
  - ✓ inclusion of $T_{c\bar{c}}(4100)^- \to \eta_c(1S)\pi^-$ improves the description, but significance is only **$2.5\,\sigma$** after considering systematic uncertainties
  - ✓ the result supersedes the old one above

$$\boxed{\mathcal{B}(B^0 \to \eta_c(1S)K^+\pi^-) = (5.82 \pm 0.20 \pm 0.23 \pm 0.55) \times 10^{-4}}$$

$K^{*0} \to K^+\pi^-$ only



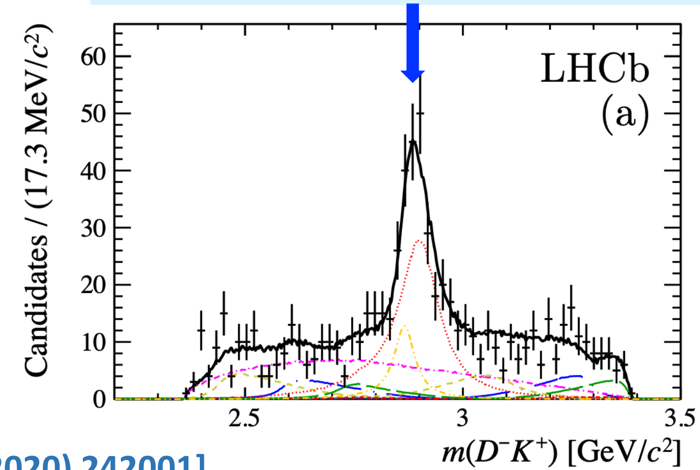
adding $T_{c\bar{c}} \to \eta_c(1S)\pi^-$



More single-charm tetraquarks

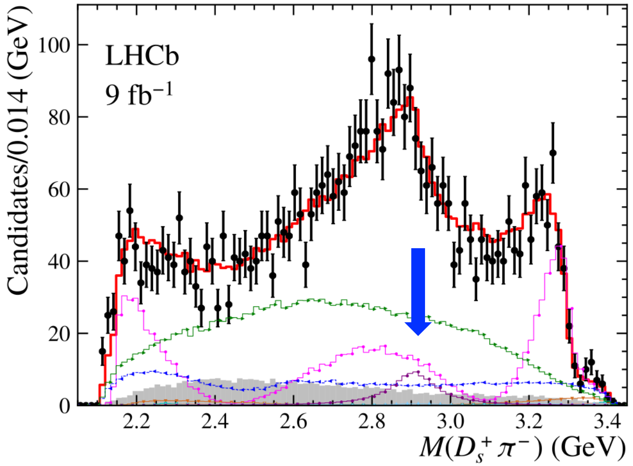
At prod.	Charm		Beauty		Charm + Beauty	
$Q\bar{Q}$	$cq\bar{q}\bar{q}$	$c\bar{q}qqq/\bar{c}qqqq$	$bq\bar{q}\bar{q}$	$b\bar{q}qqq/\bar{b}qqqq$		
	$c\bar{c}q\bar{q}$	$c\bar{c}qqq$	$b\bar{b}q\bar{q}$	$b\bar{b}qqq$		
$Q\bar{Q}+Q\bar{Q}$	$cc\bar{q}\bar{q}$	$c\bar{q}cqq$	$bb\bar{q}\bar{q}$	$b\bar{q}bqq$	$bc\bar{q}\bar{q}$	$b\bar{c}qqq/\bar{b}cqqq$
	$cc\bar{c}\bar{q}$	$c\bar{c}cqq$	$bb\bar{b}\bar{q}$	$b\bar{b}bqq$	$bq\bar{c}\bar{q}$	$b\bar{q}cqq$
	$cc\bar{c}\bar{c}$		$bb\bar{b}\bar{b}$		......	

$T^*_{cs0}(2870)^0, T^*_{cs1}(2900)^0$

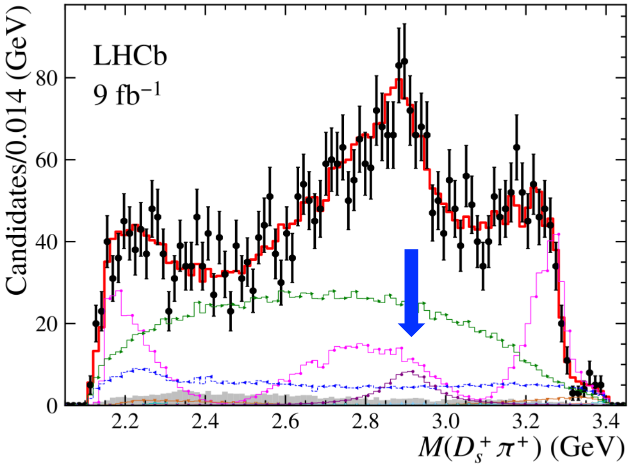


[PRL 125 (2020) 242001]
[PR D102 (2020) 112003] $B^+ \to D^+[D^-K^+]$

$T^*_{c\bar{s}0}(2900)^0$



$T^*_{c\bar{s}0}(2900)^{++}$

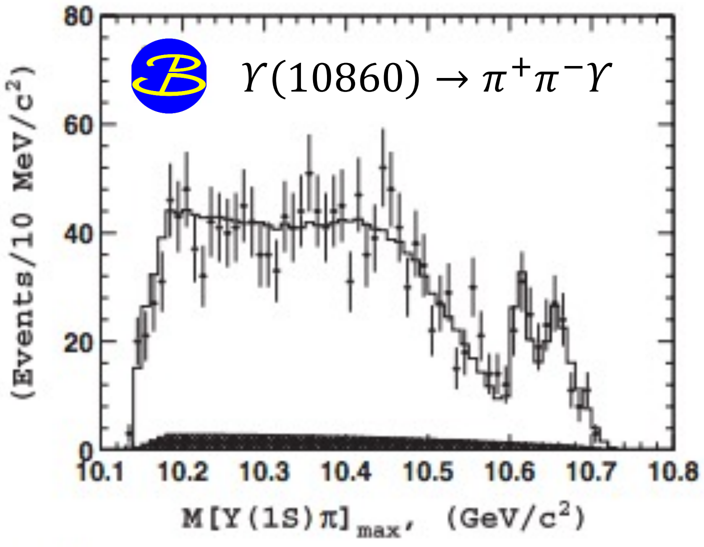


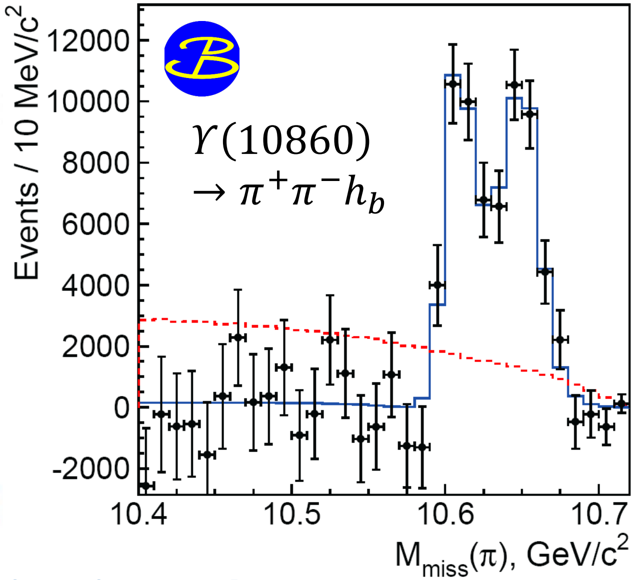
[PRL 131 (2023) 041902] $B^+ \to D^-[D_s^+\pi^+] \& B^0 \to \bar{D}^0[D_s^+\pi^-]$

Bottomonium-like states

At prod.	Charm		Beauty		Charm + Beauty	
$Q\bar{Q}$	$cq\bar{q}\bar{q}$	$c\bar{q}qqq/\bar{c}qqqq$	$bq\bar{q}\bar{q}$	$b\bar{q}qqq/\bar{b}qqqq$		
	$c\bar{c}q\bar{q}$	$c\bar{c}qqq$	$b\bar{b}q\bar{q}$	$b\bar{b}qqq$		
$Q\bar{Q}+Q\bar{Q}$	$cc\bar{q}\bar{q}$	$c\bar{q}cqq$	$bb\bar{q}\bar{q}$	$b\bar{q}bqq$	$bc\bar{q}\bar{q}$	$b\bar{c}qqq/\bar{b}cqqq$
	$cc\bar{c}\bar{q}$	$c\bar{c}cqq$	$bb\bar{b}\bar{q}$	$b\bar{b}bqq$	$bq\bar{c}\bar{q}$	$b\bar{q}cqq$
	$cc\bar{c}\bar{c}$		$bb\bar{b}\bar{b}$		……	

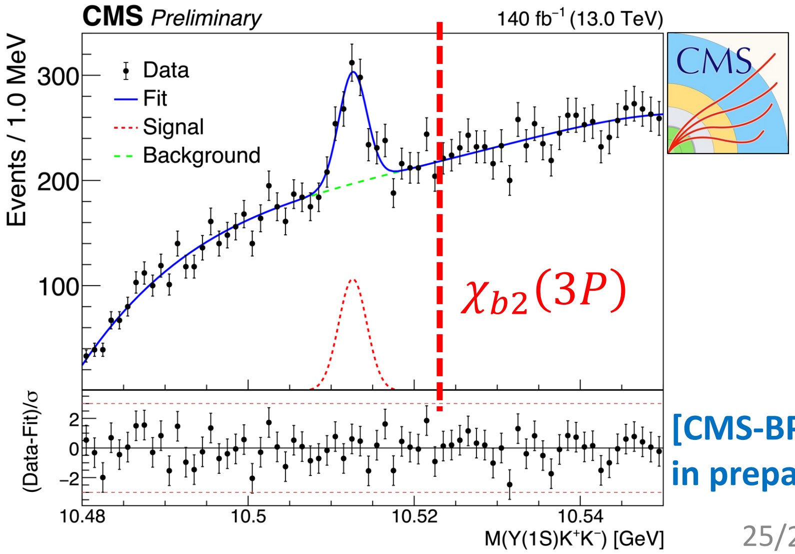
$Z_b(10610)\&Z_b(10650)$





[PRL 108 (2012) 122001]

✓ Peak in $\Upsilon(1S)\phi$: $\chi_{b1}(3P)$ or exotic?

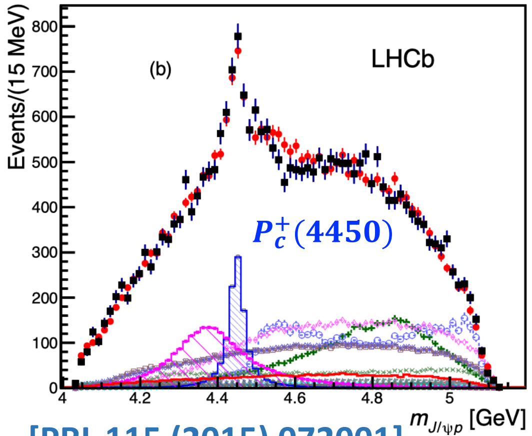


[CMS-BPH-25-009] in preparation

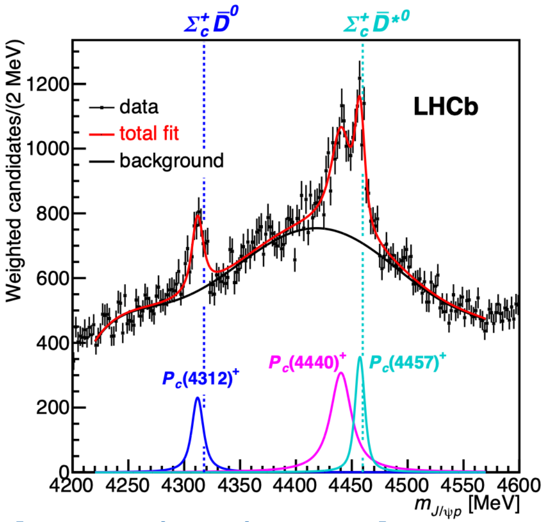
Pentaquarks

At prod.	Charm		Beauty		Charm + Beauty	
$Q\bar{Q}$	$cq\bar{q}\bar{q}$	$c\bar{q}qqq/\bar{c}qqqq$	$bq\bar{q}\bar{q}$	$b\bar{q}qqq/\bar{b}qqqq$		
	$c\bar{c}q\bar{q}$	$c\bar{c}qqq$	$b\bar{b}q\bar{q}$	$b\bar{b}qqq$		
$Q\bar{Q}+Q\bar{Q}$	$cc\bar{q}\bar{q}$	$c\bar{q}cqq$	$bb\bar{q}\bar{q}$	$b\bar{q}bqq$	$bc\bar{q}\bar{q}$	$b\bar{c}qqq/\bar{b}cqqq$
	$cc\bar{c}\bar{q}$	$c\bar{c}cqq$	$bb\bar{b}\bar{q}$	$b\bar{b}bqq$	$bq\bar{c}\bar{q}$	$b\bar{q}cqq$
	$cc\bar{c}\bar{c}$		$bb\bar{b}\bar{b}$		......	

$\Lambda_b^0 \to [J/\psi\, p]K^-$

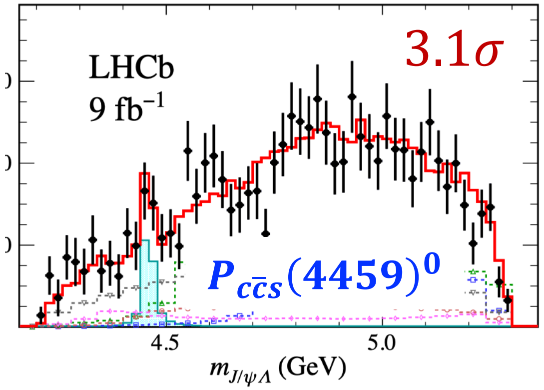


[PRL 115 (2015) 072001]



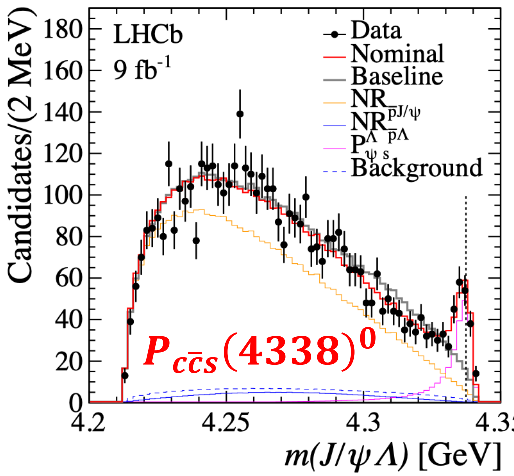
[PRL 122 (2019) 222001]

$\Xi_b^- \to [J/\psi\Lambda]K^-$



[Science Bulletin 66 (2021) 1278]

$B^- \to [J/\psi\Lambda]\bar{p}$



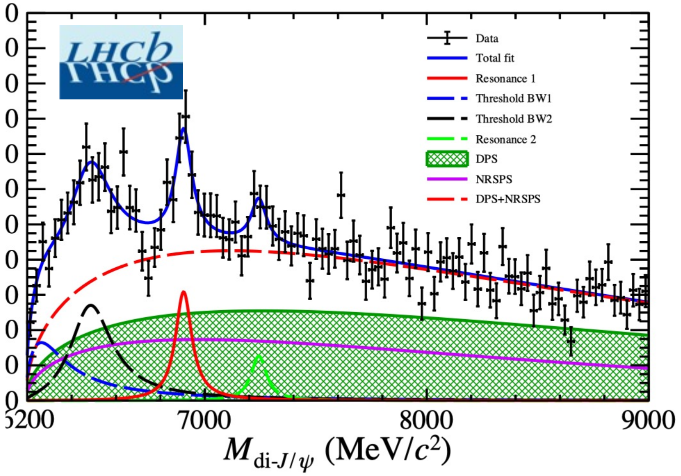
[PRL 131 (2023) 031901]

$T_{cc\bar{c}\bar{c}}$ and T_{cc}^{+}

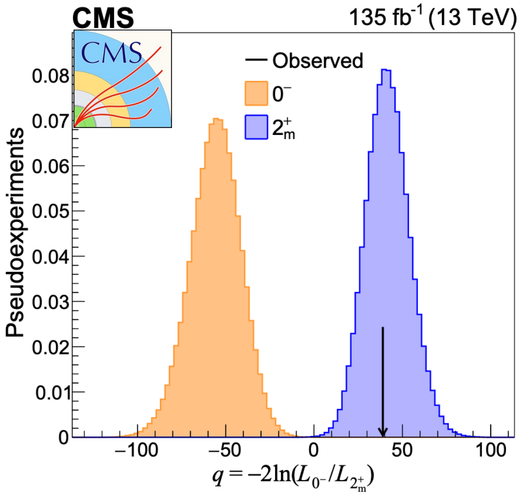
At prod.	Charm		Beauty		Charm + Beauty	
$Q\bar{Q}$	$cq\bar{q}\bar{q}$	$c\bar{q}qq/\bar{c}qqqq$	$bq\bar{q}\bar{q}$	$b\bar{q}qq/\bar{b}qqqq$		
	$c\bar{c}q\bar{q}$	$c\bar{c}qqq$	$b\bar{b}q\bar{q}$	$b\bar{b}qqq$		
$Q\bar{Q}+Q\bar{Q}$	$cc\bar{q}\bar{q}$	$c\bar{q}cqq$	$bb\bar{q}\bar{q}$	$b\bar{q}bqq$	$bc\bar{q}\bar{q}$	$b\bar{c}qqq/\bar{b}cqqq$
	$cc\bar{c}\bar{q}$	$c\bar{c}cqq$	$bb\bar{b}\bar{q}$	$b\bar{b}bqq$	$bq\bar{c}\bar{q}$	$b\bar{q}cqq$
	$cc\bar{c}\bar{c}$		$bb\bar{b}\bar{b}$		......	

$J/\psi + J/\psi$

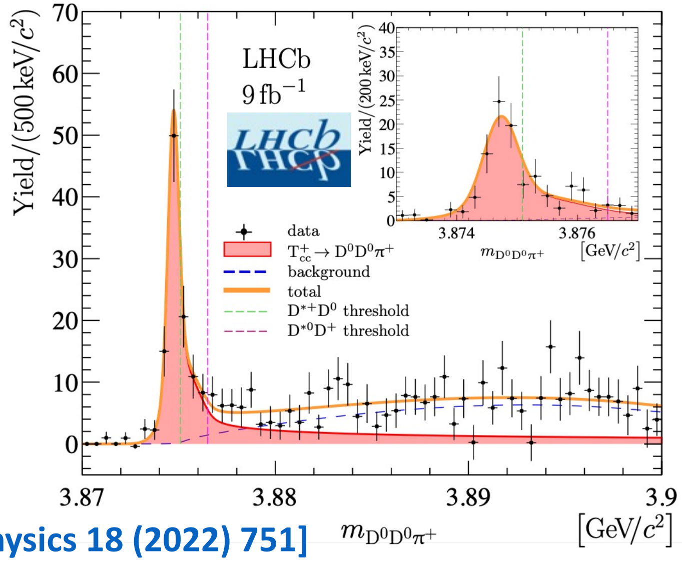
[Science Bulletin 65 (2020) 1983]



[Nature 648 (2025) 58]



$D^0D^0\pi^+$



[Nature Physics 18 (2022) 751]
[Nature Comm. 13 (2022) 3351]

Looking beyond

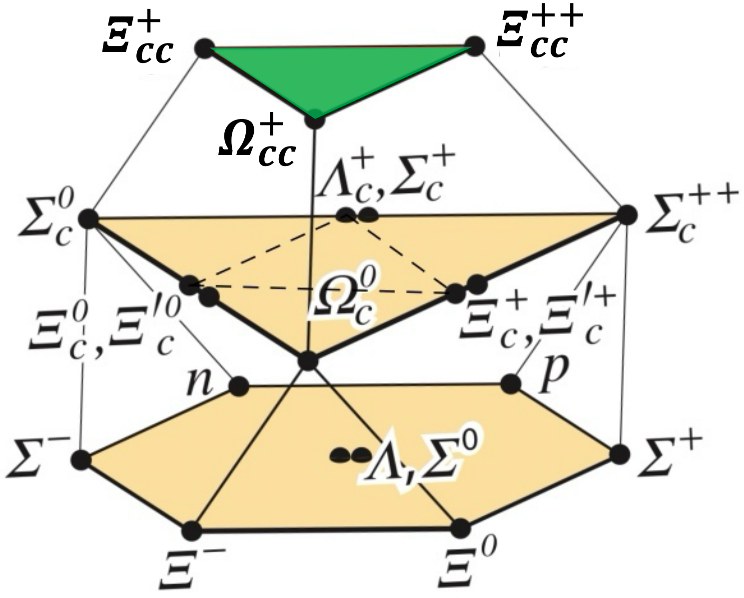
At prod.	Charm		Beauty		Charm + Beauty	
$Q\bar{Q}$	$cq\bar{q}\bar{q}$	$c\bar{q}qqq/\bar{c}qqqq$	$bq\bar{q}\bar{q}$	$b\bar{q}qqq/\bar{b}qqqq$		
	$c\bar{c}q\bar{q}$	$c\bar{c}qqq$	$b\bar{b}q\bar{q}$	$b\bar{b}qqq$		
$Q\bar{Q}+Q\bar{Q}$	$cc\bar{q}\bar{q}$	$c\bar{q}cqq$	$bb\bar{q}\bar{q}$	$b\bar{q}bqq$	$bc\bar{q}\bar{q}$	$b\bar{c}qqq/\bar{b}cqqq$
	$cc\bar{c}\bar{q}$	$c\bar{c}cqq$	$bb\bar{b}\bar{q}$	$b\bar{b}bqq$	$bq\bar{c}\bar{q}$	$b\bar{q}cqq$
	$cc\bar{c}\bar{c}$		$bb\bar{b}\bar{b}$		……	

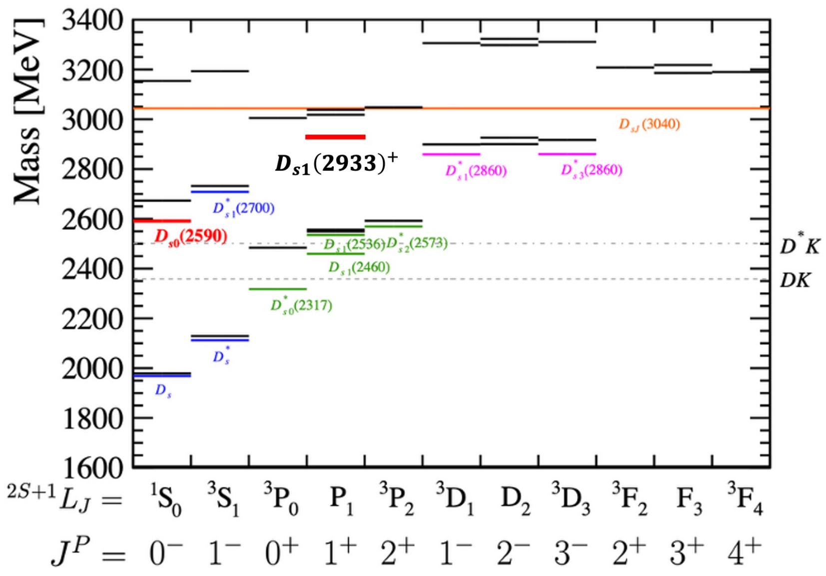
- $\boldsymbol{cc\bar{c}\bar{q}}$**?**
- **Single-$\boldsymbol{b}$ multiquark states**: within reach?
- $\boldsymbol{\bar{b}c}$**-like exotic states**: decay modes for some of them are experimentally more friendly than higher excited states, e.g. $B_c^+ + p/K^\pm/\pi^\pm$
- **Pentaquarks other than $\boldsymbol{c\bar{c}qqq}$**: single-c/b may be accessible if exist
- **Hexaquark states?**
- **Weakly decaying exotic hadrons:** T_{bb} widely recognized, but far from reach; T_{bc}?

Summary

➢ Hadron spectroscopy is currently experiencing a golden age, to which LHCb continues making relevant contributions

- **Expanding the boundaries**
  - ✓ Observation of Ξ_{cc}^{+} and Ω_{cc}^{+}
- **Enriching the spectra**
  - ✓ Observation of new excited Σ_c^0
  - ✓ Observation of $D_{s1}(2933)^+$
- **Decoding the nature**
  - ✓ Observation of $\chi_{c1}(3872) \to J/\psi\mu^+\mu^-$
  - ✓ Study of $T_{c\bar{c}1}(4430)^+$ in $B^+ \to \psi(2S)K_S^0\pi^+$





Stay tuned!

Thank you!