Hadron Spectroscopy at LHCb

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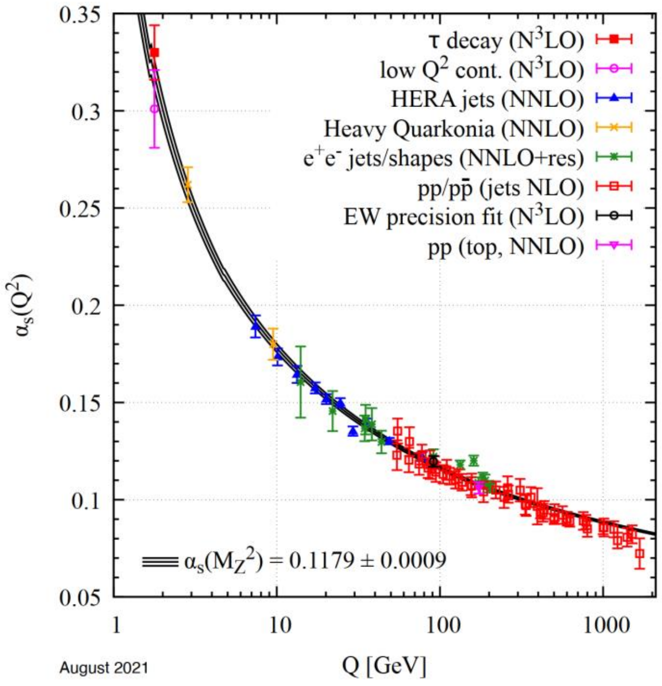
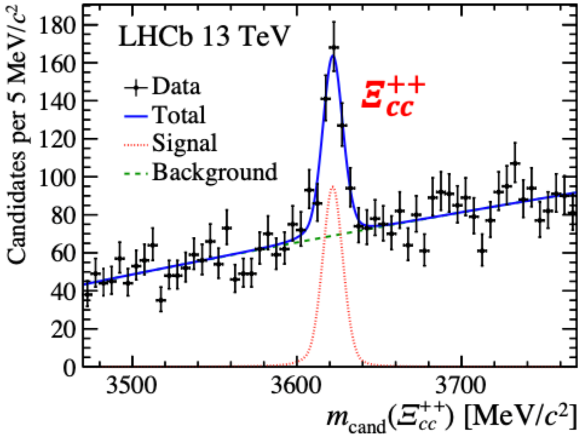
Background review

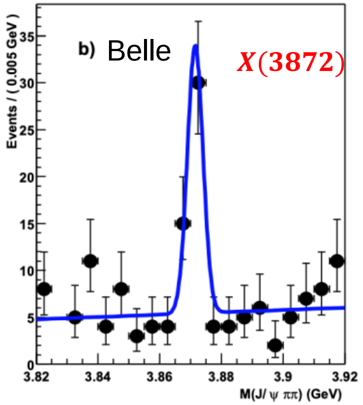
- QCD shows non-perturbative behavior at the energy scale of nuclei and hadrons.
  - *Spectroscopy* is the powerful tool to understand QCD at this energy scale. Experimental results will be important to test the relevant theories.
- Spectroscopy of conventional hadrons (mesons and baryons) enriched in 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.



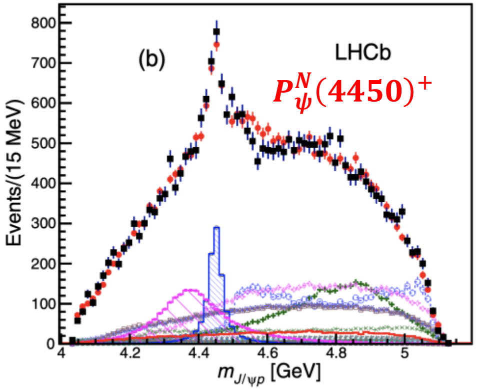
PDG Appendix



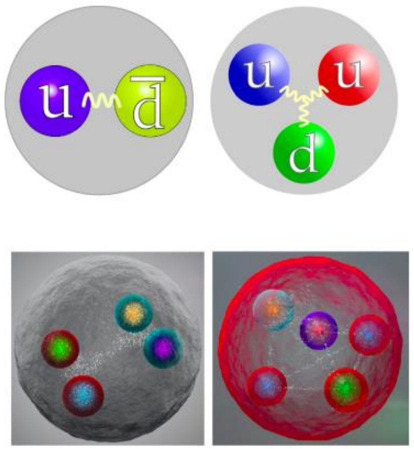
PRL117(2017) 112001



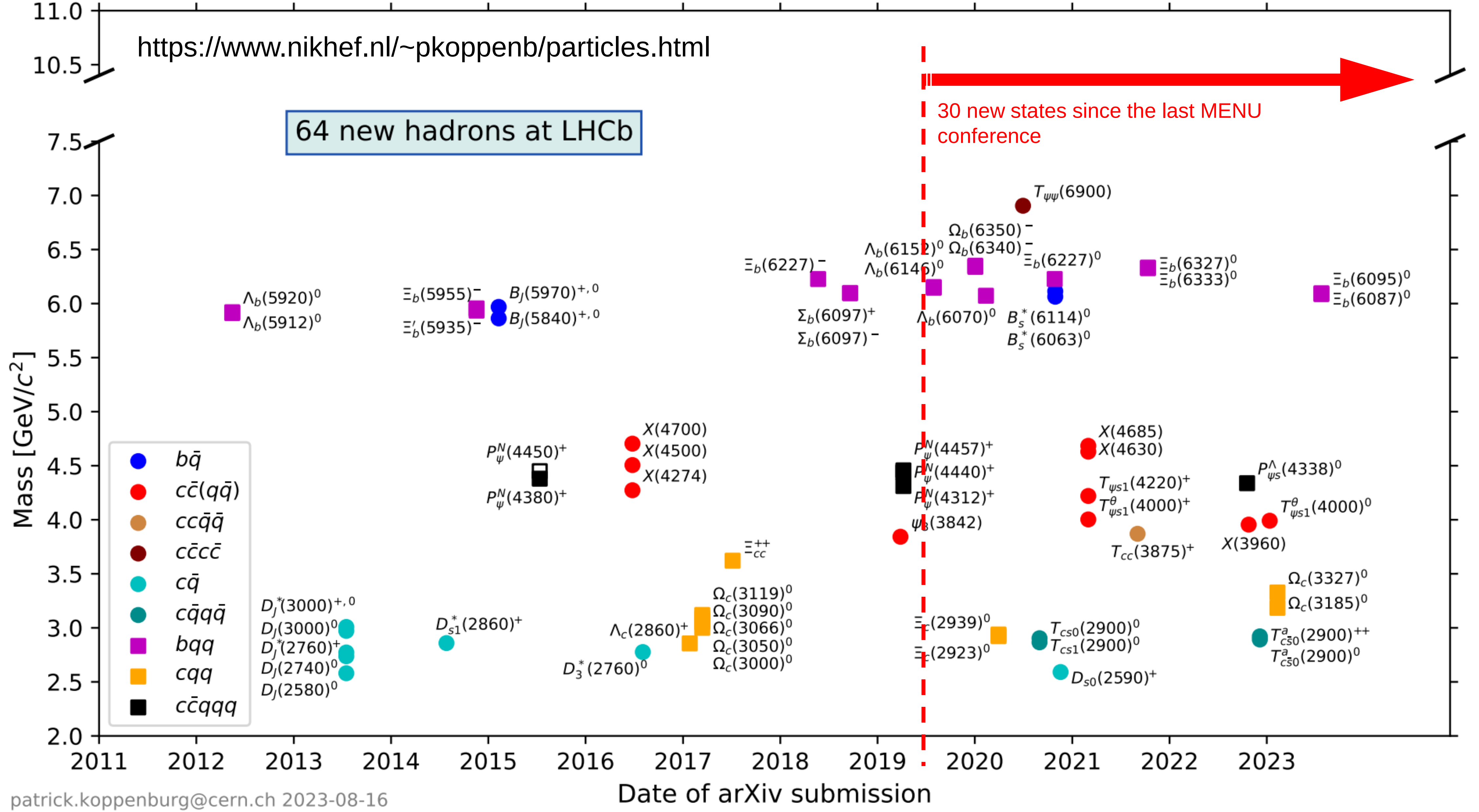
PRL 91 (2003) 262001



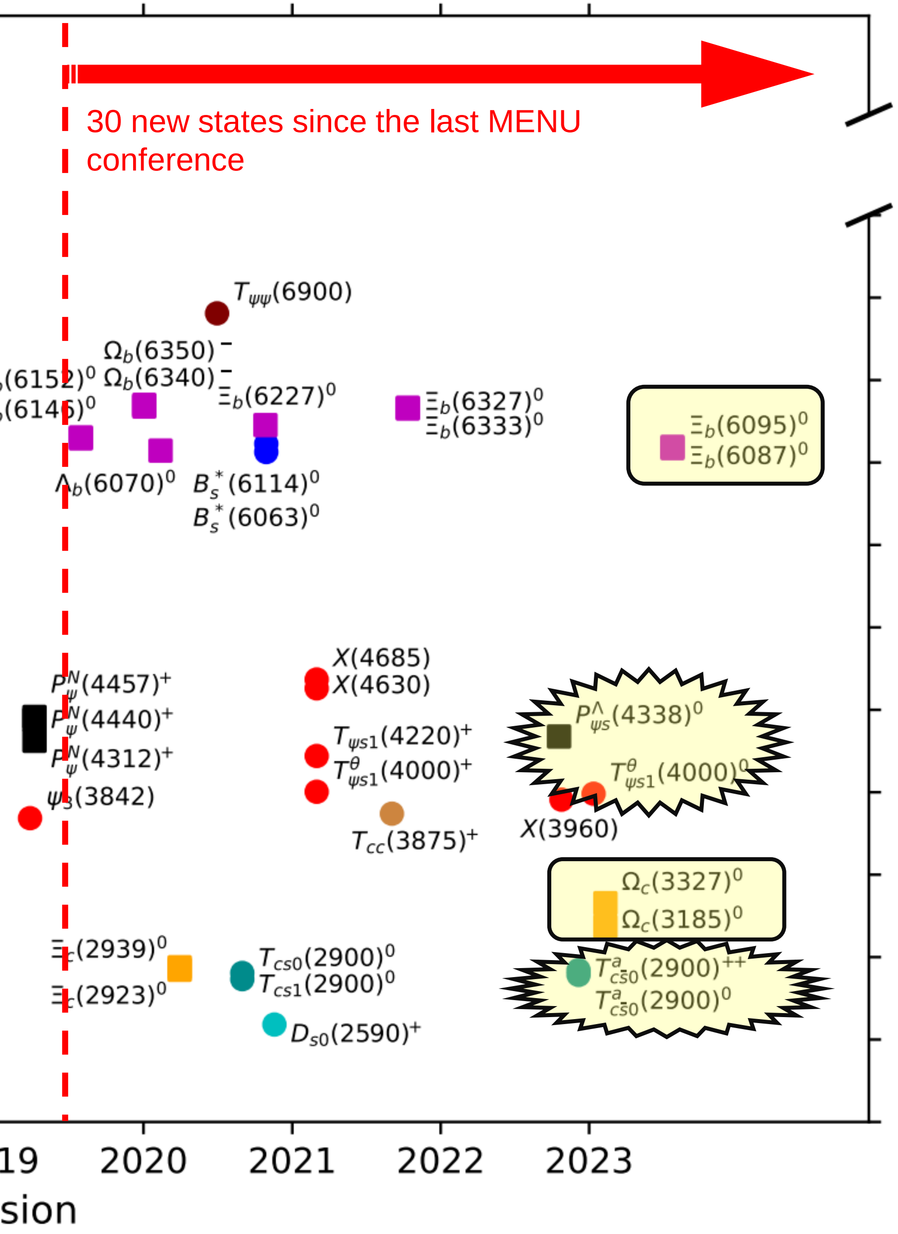
PRL115(2015)072001



Hadrons discovered by LHCb



Results shown in this talk



- Only limited (more recent) published analyses are covered by this talk.
- **Conventional hadrons**
  - New excited Ω_c^0 states:
    - $\Omega_c(3327)^0, \Omega_c(3185)^0$ — PRL131 (2023)131902
  - New excited Ξ_b^0 states:
    - $\Xi_b(6095)^0, \Xi_b(6087)^0$ — arXiv:2307.13399, Accepted by PRL
  - New b-baryon decay mode
    - Observation & BF measurement of $\Xi_b^- \to \Lambda_b^0 \pi^-$ — PRD108 (2023) 072002
- **Exotics**
  - New pentaquark candidate:
    - $P_{\psi s}^\Lambda(4338)^0$ — PRL131 (2023) 031901
  - New tetraquark candidates:
    - $T_{\psi s1}^\theta(4000)^0$ — PRL131 (2023) 131901
    - $T_{c\bar{s}0}^a(2900)^{++/0}$ — PRL131 (2023) 041902

Results not specially included in this talk
…… but worth mentioning

- About new measurements of the decay properties of established hardon states, or products of the corresponding exotic states research.
    - Observation of $\Omega_c^0 \to \Omega^- K^+ / \Xi^- \pi^+$ and precision Ω_c^0 mass measurement arXiv:2308.08512
    - Obs. & BF of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$
    - Obs. & BF of $\Xi_b^0 \to \Xi_c^+ D_s^{*-}$ and $\Xi_b^- \to \Xi_c^0 D_s^-$

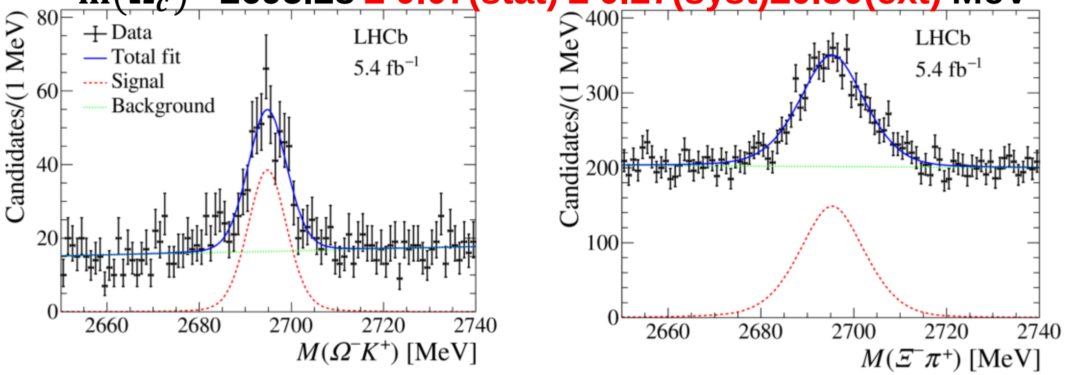
See Marian Stahl's talk in the parallel session

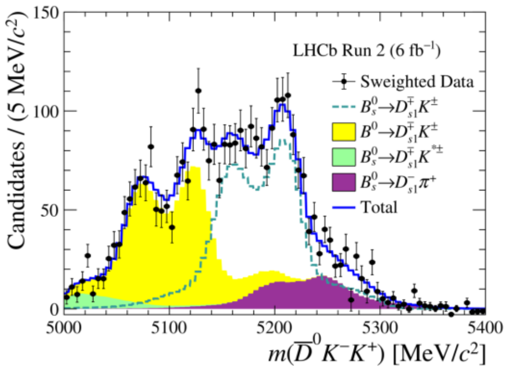
- Observation of $B_{(s)}^0 \to D_{s1}(2536)^{\mp} K^{\pm}$ arXiv:2308.00587
- Obs. & BF of $B^+ \to J/\psi \eta' K^+$ JHEP08(2023)174
- Observation of $B_s^0 \to \chi_{c1}(3872)\pi^+\pi^-$ JHEP07(2023)084
- PWA of $D_{(s)}^+ \to \pi^+\pi^-\pi^+$ ($\omega(782)$ contribution is found) JHEP07(2023)204
- Observation of $B^0 \to p\bar{p}p\bar{p}$ decays PRL131 (2023) 091901

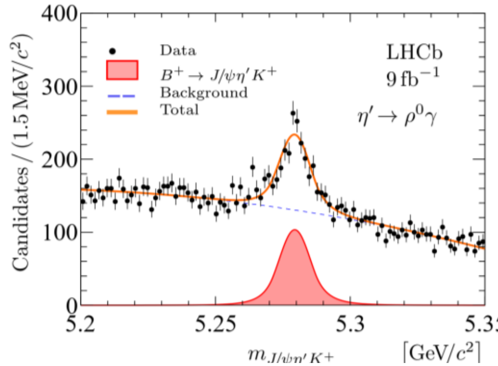
- **New naming convention for exotics** is submitted by LHCb (LHCb-PUB-2022-013).

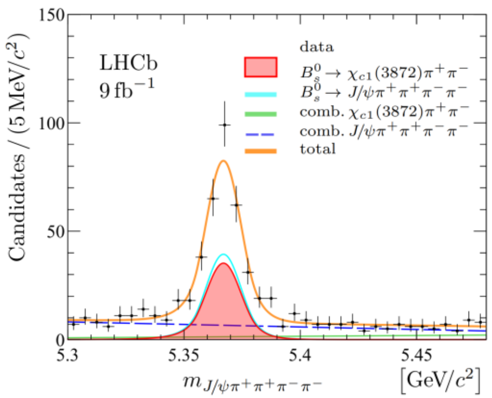
arXiv:2206.15233

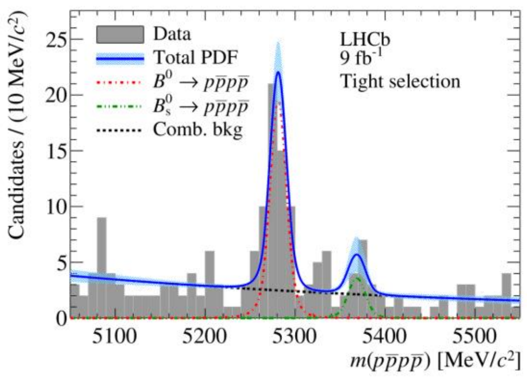
$\mathbf{m(\Omega_c^0)}$ =2695.28 ± 0.07(stat) ± 0.27(syst)±0.30(ext) MeV







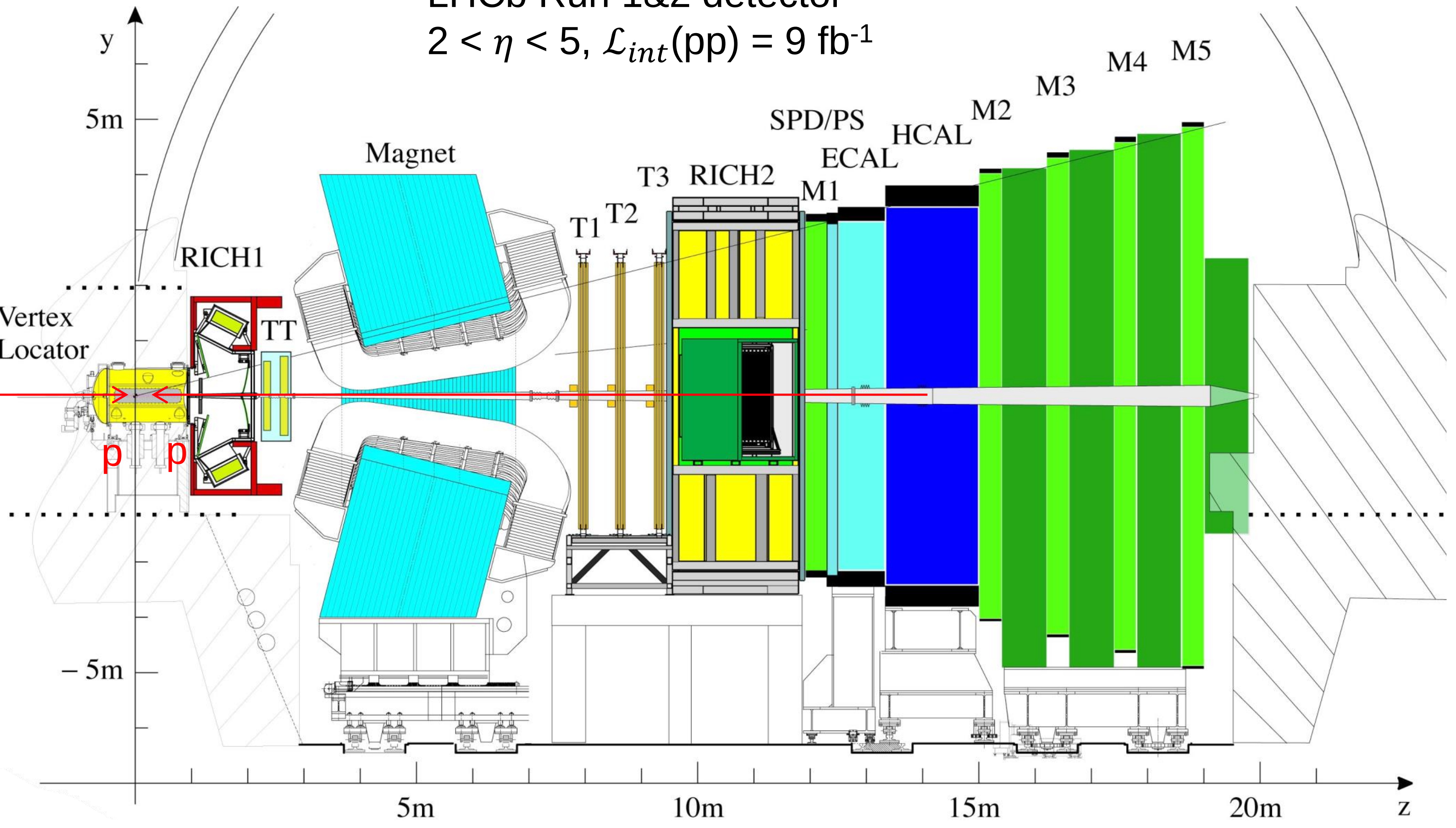




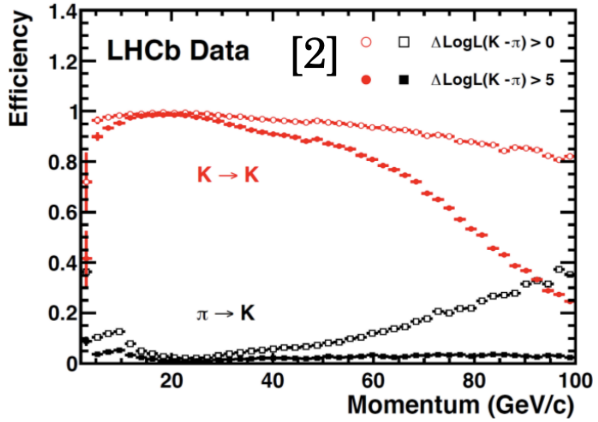
LHCb detector

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

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



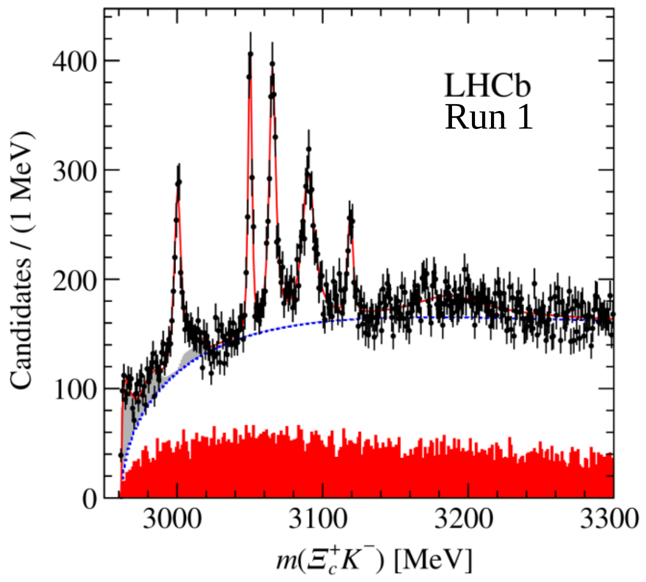
- Excellent tracking and vertexing
  - $\sigma(p)/p < 1\%$ @ $\epsilon_{\text{track}} > 96\%$
  - $\sigma(\text{IP}) = (15 + 29/p_T)\ \mu m$
- Excellent PID
  - $\epsilon_{\text{PID}}(K) \approx 95\%$ @ MisID$(\pi \to K) \approx 5\%$
  - $\epsilon_{\text{PID}}(\mu) \approx 97\%$ @ MisID$(\pi \to \mu)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



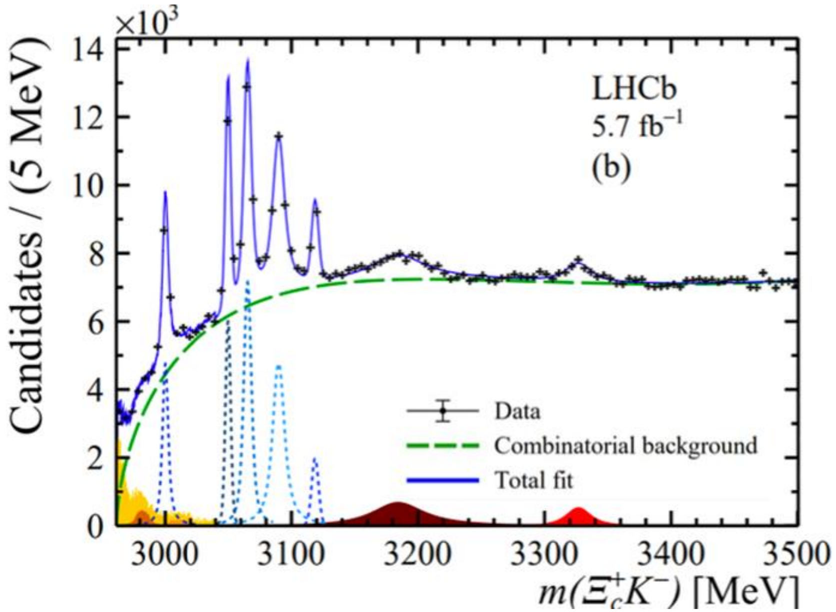
JINST3 (2008) S08005
IJMPA 30 (2015) 1530022

New excited Ω_c^0 states

- Five narrow Ω_c^{0*} states observed in Run1. ⇒ updated with Run1&2 data



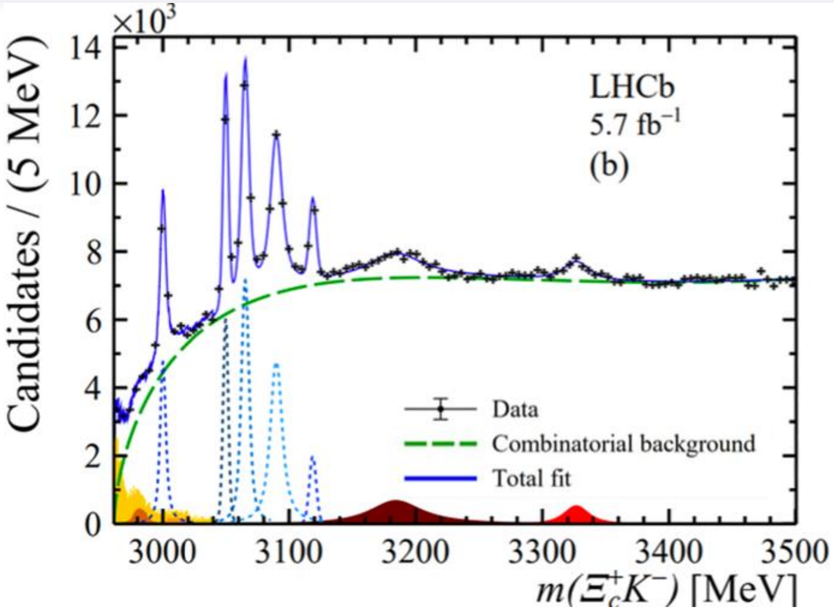
PRL118(2017) 182001



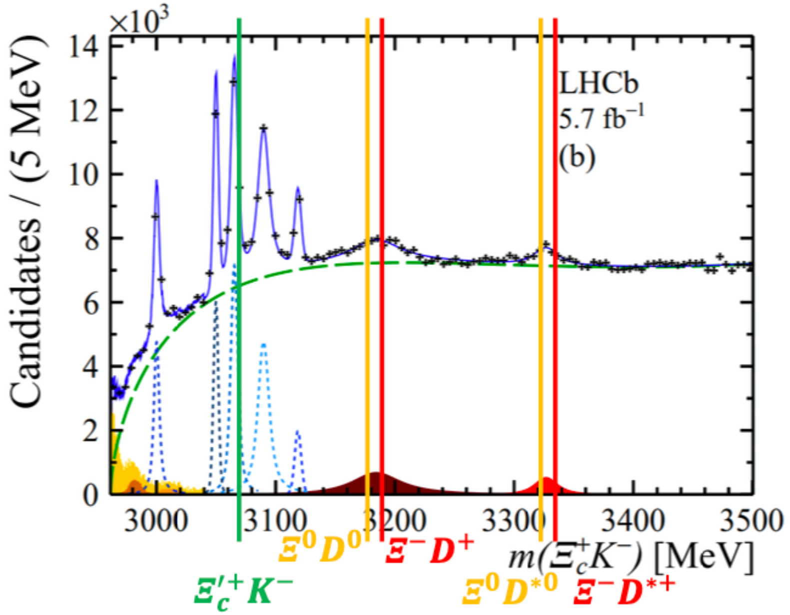
PRL131(2023)131902

- Confirmed the Run 1 results.
- Two broader states, namely $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$, are observed for the first time.

New excited Ω_c^0 states



PRL131(2023)131902



Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.44 \pm 0.07\,^{+0.07}_{-0.13} \pm 0.23$	$3.83 \pm 0.23\,^{+1.59}_{-0.29}$
$\Omega_c(3050)^0$	$3050.18 \pm 0.04\,^{+0.06}_{-0.07} \pm 0.23$	$0.67 \pm 0.17\,^{+0.64}_{-0.72}$
		< 1.8 MeV, 95% C.L.
$\Omega_c(3065)^0$	$3065.63 \pm 0.06\,^{+0.06}_{-0.06} \pm 0.23$	$3.79 \pm 0.20\,^{+0.38}_{-0.47}$
$\Omega_c(3090)^0$	$3090.16 \pm 0.11\,^{+0.06}_{-0.10} \pm 0.23$	$8.48 \pm 0.44\,^{+0.61}_{-1.62}$
$\Omega_c(3119)^0$	$3118.98 \pm 0.12\,^{+0.09}_{-0.23} \pm 0.23$	$0.60 \pm 0.63\,^{+0.90}_{-1.05}$
		< 2.5 MeV, 95% C.L.
$\Omega_c(3185)^0$	$3185.1 \pm 1.7\,^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7\,^{+10}_{-20}$
$\Omega_c(3327)^0$	$3327.1 \pm 1.2\,^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5\,^{+13}_{-1}$

confirmed

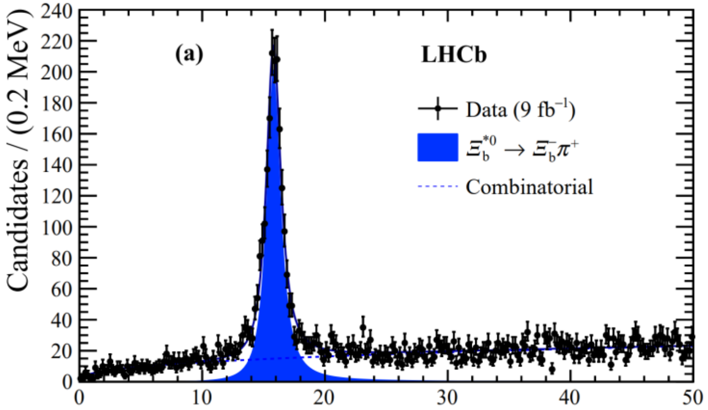
new

- Two broader states, namely $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$, are observed for the first time.
  - Mass and width are measured
  - Near Ξ^0D^{*0} and $\Xi_c^+K^-$ thresholds

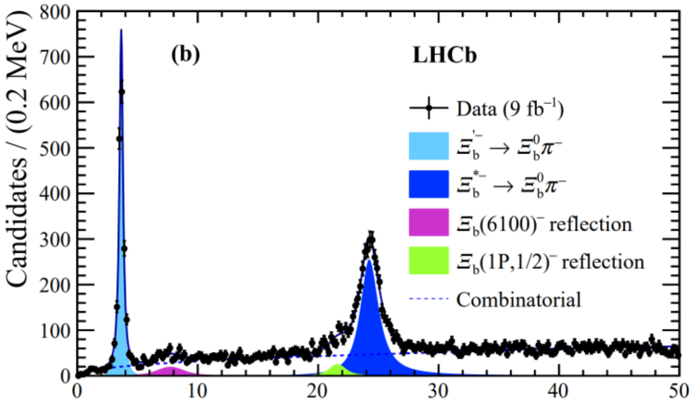
New excited Ξ_b^0 states

arXiv:2307.13399,
Accepted by PRL

- The ground state $\Xi_b^{0/-}$ was reconstructed by combining $\Xi_c^{+/0}$ with π^- or $\pi^-\pi^+\pi^-$.
- Then combined with another pion $\Rightarrow$ Ξ_b^{*0} or $\Xi_b'^-$/ Ξ_b^{*-}

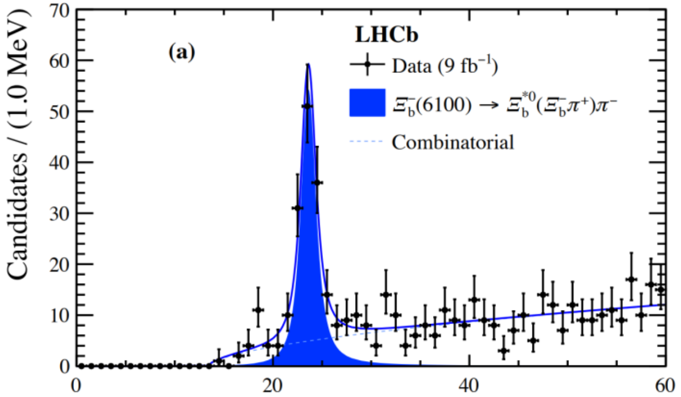


$Q = m(\Xi_b^-\pi^+) - m(\Xi_b^-) - m(\pi^+)$

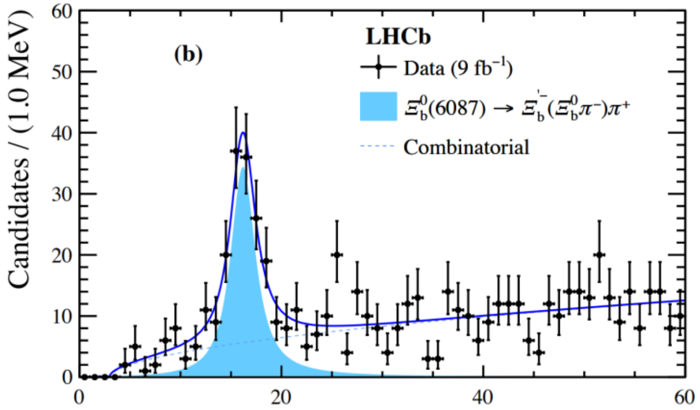


$Q = m(\Xi_b^0\pi^-) - m(\Xi_b^0) - m(\pi^-)$

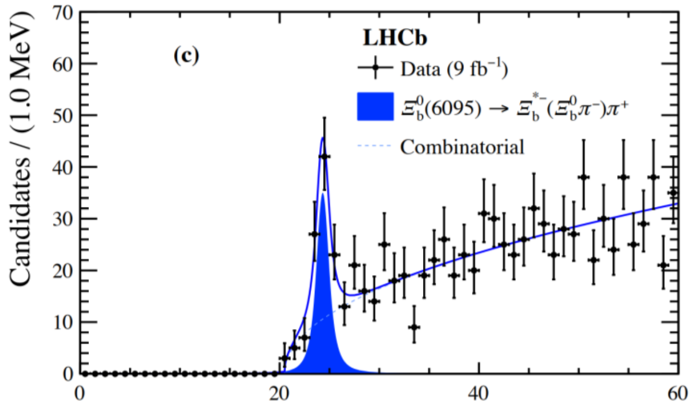
- Finally combined it with the second opposite-charged pion



$Q = m(\Xi_b^-\pi^+\pi^-) - m(\Xi_b^-) - 2m(\pi^\pm)$



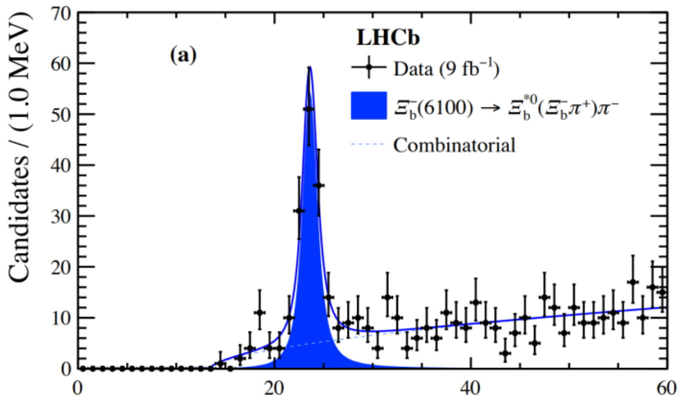
$Q = m(\Xi_b^0\pi^-\pi^+) - m(\Xi_b^0) - 2m(\pi^\pm)$



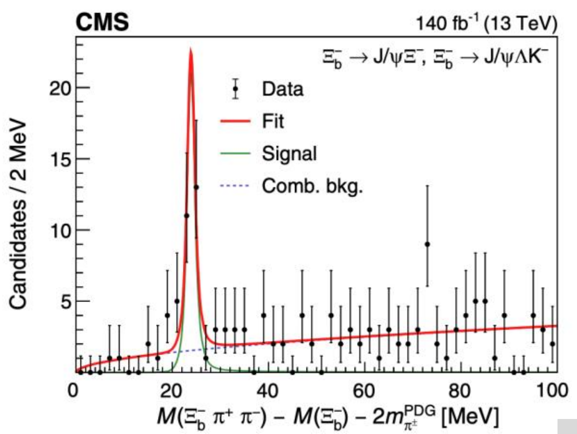
$Q = m(\Xi_b^0\pi^-\pi^+) - m(\Xi_b^0) - 2m(\pi^\pm)$

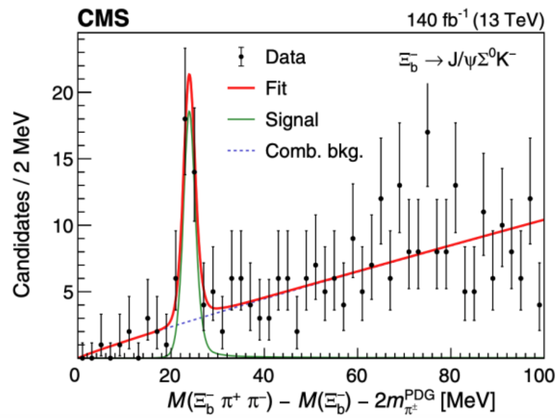
New excited Ξ_b^0 states

arXiv:2307.13399,
Accepted by PRL



$Q = m(\Xi_b^-\pi^+\pi^-) - m(\Xi_b^-) - 2m(\pi^\pm)$





PRL126 (2021)252003

- $\Xi_b(6100)^-$ (observed by CMS) is confirmed by LHCb with significance >12σ.
- First observation of $\Xi_b(6087)^0$ and $\Xi_b(6095)^0$:
  - Significance >10σ (and 8σ).
  - Decay properties are measured.
  - Maybe P-wave states coupling to the b quark to give a pair of states with $J^P = \frac{1}{2}^-$ and $J^P = \frac{3}{2}^-$

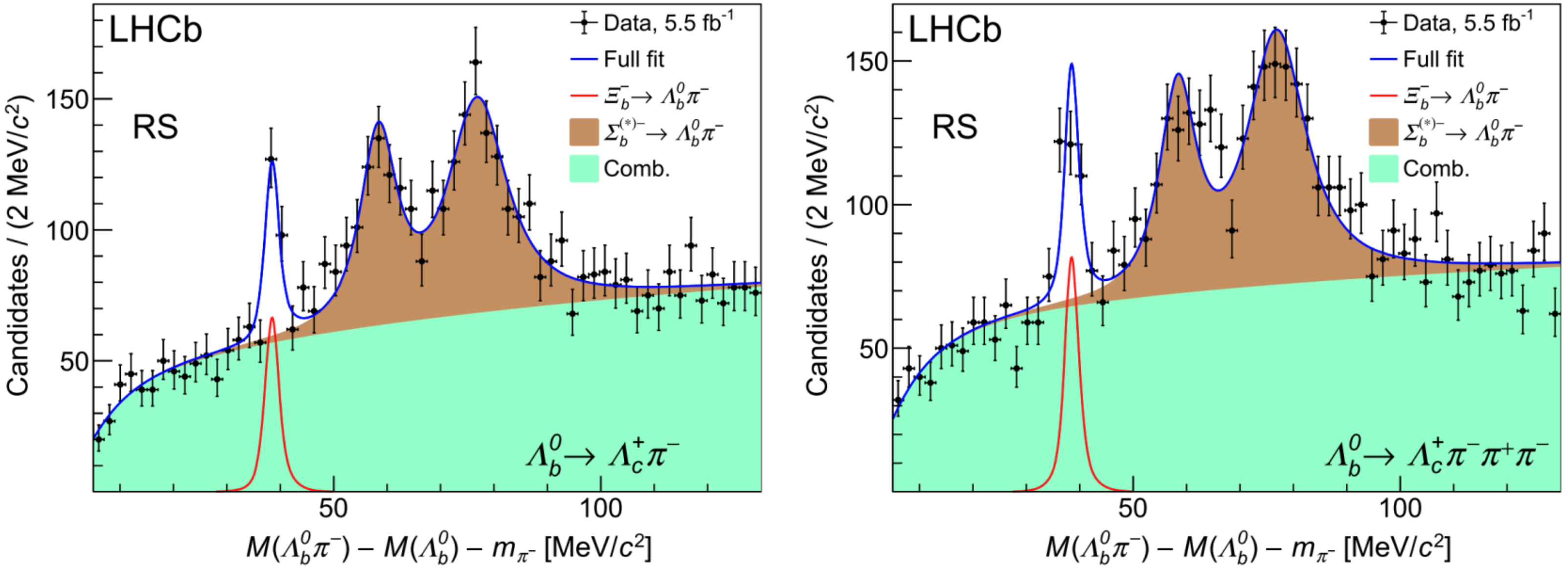
State	Observ.	Value (MeV)	
$\Xi_b(6100)^-$	Q_0	$23.6 \pm 0.11 \pm 0.02$	confirmed
	Γ	$0.94 \pm 0.30 \pm 0.08$	
	m_0	$6099.74 \pm 0.11 \pm 0.02 \pm 0.6\ (\Xi_b^-)$	
$\Xi_b(6087)^0$	Q_0	$16.20 \pm 0.20 \pm 0.06$	new
	Γ	$2.43 \pm 0.51 \pm 0.10$	
	m_0	$6087.24 \pm 0.20 \pm 0.06 \pm 0.5\ (\Xi_b^0)$	
$\Xi_b(6095)^0$	Q_0	$24.32 \pm 0.15 \pm 0.03$	new
	Γ	$0.50 \pm 0.33 \pm 0.11$	
	m_0	$6095.36 \pm 0.15 \pm 0.03 \pm 0.5\ (\Xi_b^0)$	

Observation & BF measurement of $\Xi_b^- \to \Lambda_b^0 \pi^-$

1^{st} show

PRD108 (2023) 072002

- A previous LHCb study using Run 1 dataset shows an evidence for the strangeness-changing weak decay $\Xi_b^- \to \Lambda_b^0 \pi^-$. ⇒ Updated with Run 2 dataset. PRL115 (2015) 241801



$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \mathcal{B}(\Xi_b^- \to \Lambda_b^0 \pi^-) = (7.3 \pm 0.8 \pm 0.6) \times 10^{-4}$$

- Using the independent $f_{\Xi_b^-}/f_{\Lambda_b^0}$ measurement from PRD 99 (2019) 052006, the BF is determined as:

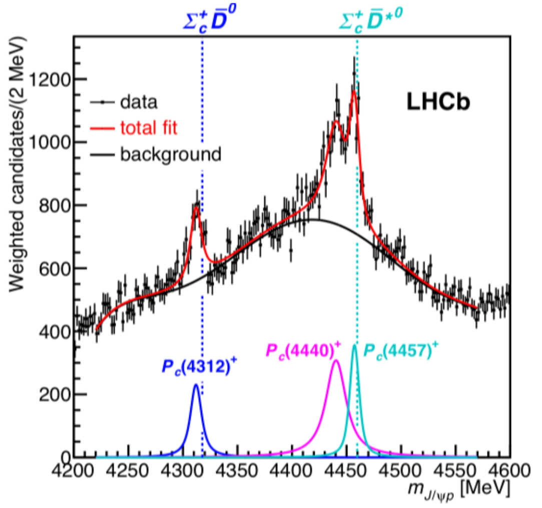
$$\mathcal{B}(\Xi_b^- \to \Lambda_b^0 \pi^-) = (0.89 \pm 0.10 \pm 0.07 \pm 0.29)\%$$

- Consistent with predictions from
  - some diquark model : H.Y. Cheng et.al. JHEP03(2016)028
  - current algebra approaches: e.g., PLB 750. (2015) 653
  - duality: e.g., PRD 93 (2016) 034020

Observation of $P_{\psi s}^{\Lambda}(4338)^0$

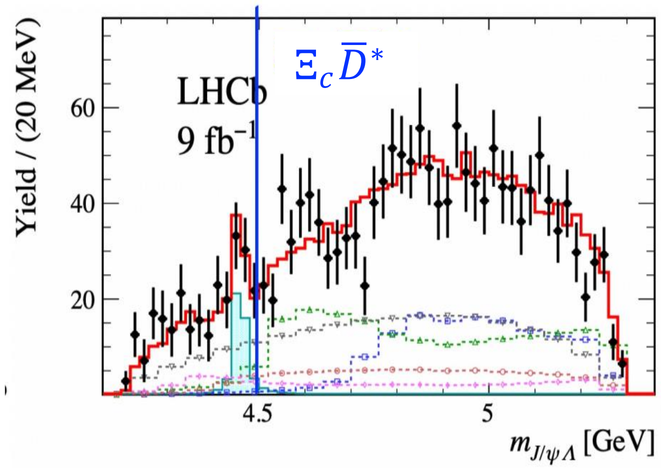
PRL131 (2023) 031901

- The mass of pentaquarks is found to be close to charm-baryon and charm-meson threshold.
  - The interpretation as hadronic *molecular-state* is one of the popular theories.



P_{ψ}^{N} **in** $\Lambda_b^0 \to J/\psi pK$ PRL 122 (2019) 222001

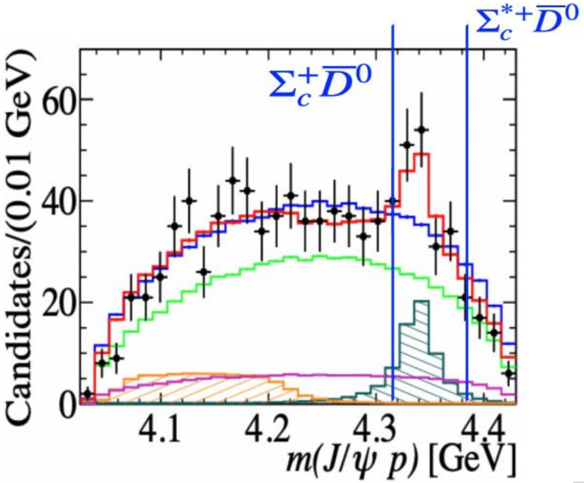
$(c\bar{c}uud)$



Evidence of $P_{\psi s}^{\Lambda}$ **in** $\Xi_b^- \to J/\psi\Lambda K^-$

Sci.Bull.66 (2021) 1278

$(c\bar{c}uds)$



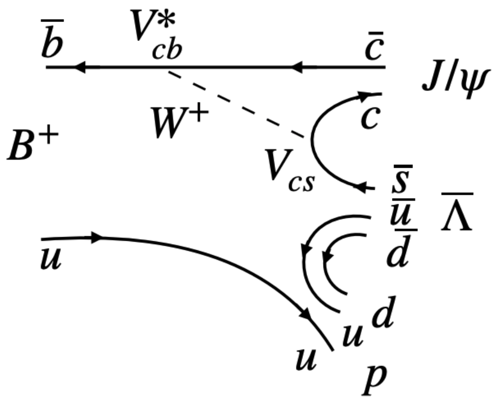
Evidence of P_{ψ}^{N} **in** $B_s^0 \to J/\psi p\bar{p}$ PRL 128(2022) 062001

$(c\bar{c}uud)$

- $B^+ \to J/\psi\bar{\Lambda}p$ is an ideal decay to search for pentaquark candidates related to the thresholds of $\Xi_c^+ D^-$, $\Lambda_c^+ D_s^-$, and $\Lambda_c^+ \overline{D}^0, \Sigma_c\bar{D}^{(*)}$ at the same time.
- 93% purity of 4617 *B* candidates.
- 6D amplitude fit is performed.

$J/\psi\Lambda$

$J/\psi p$

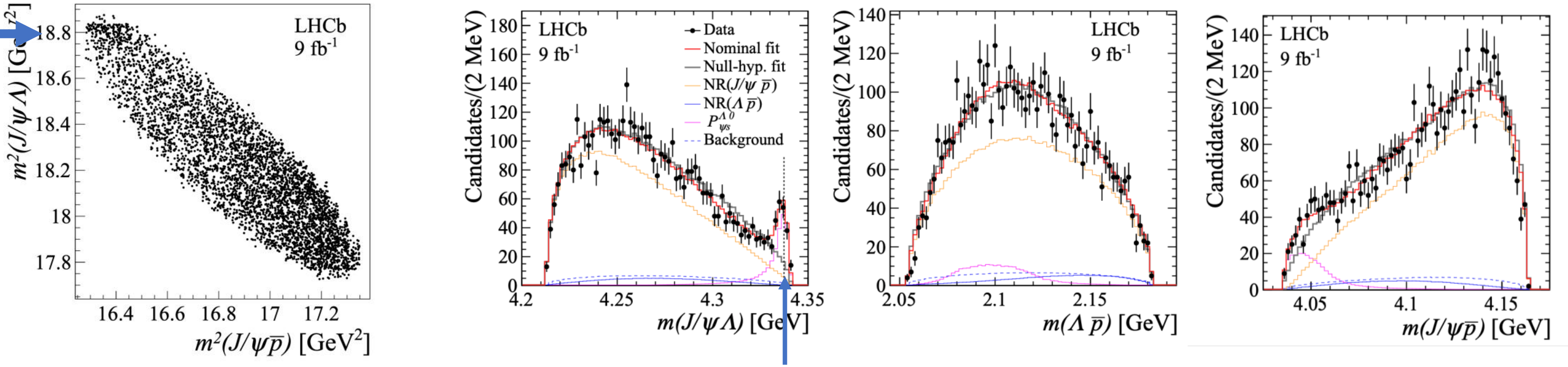


Tree-level Feynman diagram for $B^+ \to J/\psi\bar{\Lambda}p$ decay

Observation of $P_{\psi s}^{\Lambda}(4338)^0$

PRL131 (2023) 031901

- Start from the K^* model: $K_{2,3,4}^*$ and NR($\Lambda\bar{p}$) - can't describe the data well.
- Nominal model: NR($\Lambda\bar{p}$), NR($J/\psi\bar{p}$) and $P_{\psi s}^{\Lambda}$ - significantly improve the likelihood.



- $\boldsymbol{P_{\psi s}^{\Lambda}(4338)^0}$ **is observed for the first time** with significance >10σ (w.r.t. to the non-$P_{\psi s}^{\Lambda}{}^0$ hypo).
  - Minimal quark component: $c\bar{c}uds$
  - The first observation of a **hidden-charm pentaquark candidate with strangeness**.
  - $J^P = \frac{1}{2}^-$ preferred. BW mass and width are reported.
  - Close to $\Xi_c^+ D^-$ threshold and J^P consistent with S-wave $\Xi_c \bar{D}$ molecular state.

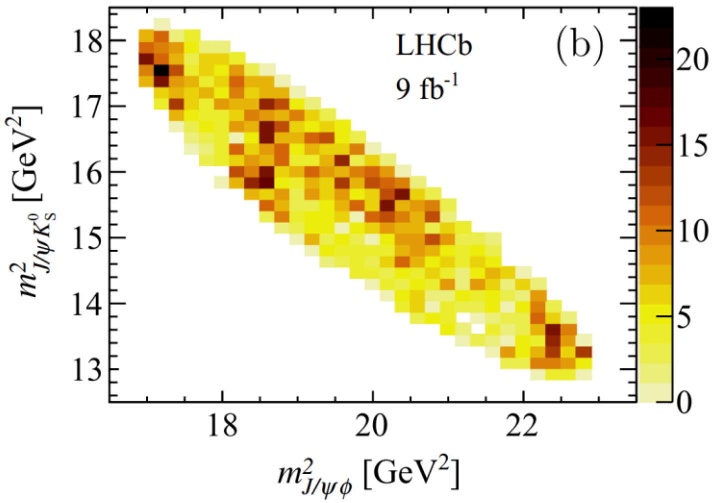
$$M(P_{\psi s}^{\Lambda}) = 4338.2 \pm 0.7 \pm 0.4\text{MeV}$$
$$\Gamma(P_{\psi s}^{\Lambda}) = 7.0 \pm 1.2 \pm 1.3\text{MeV}$$

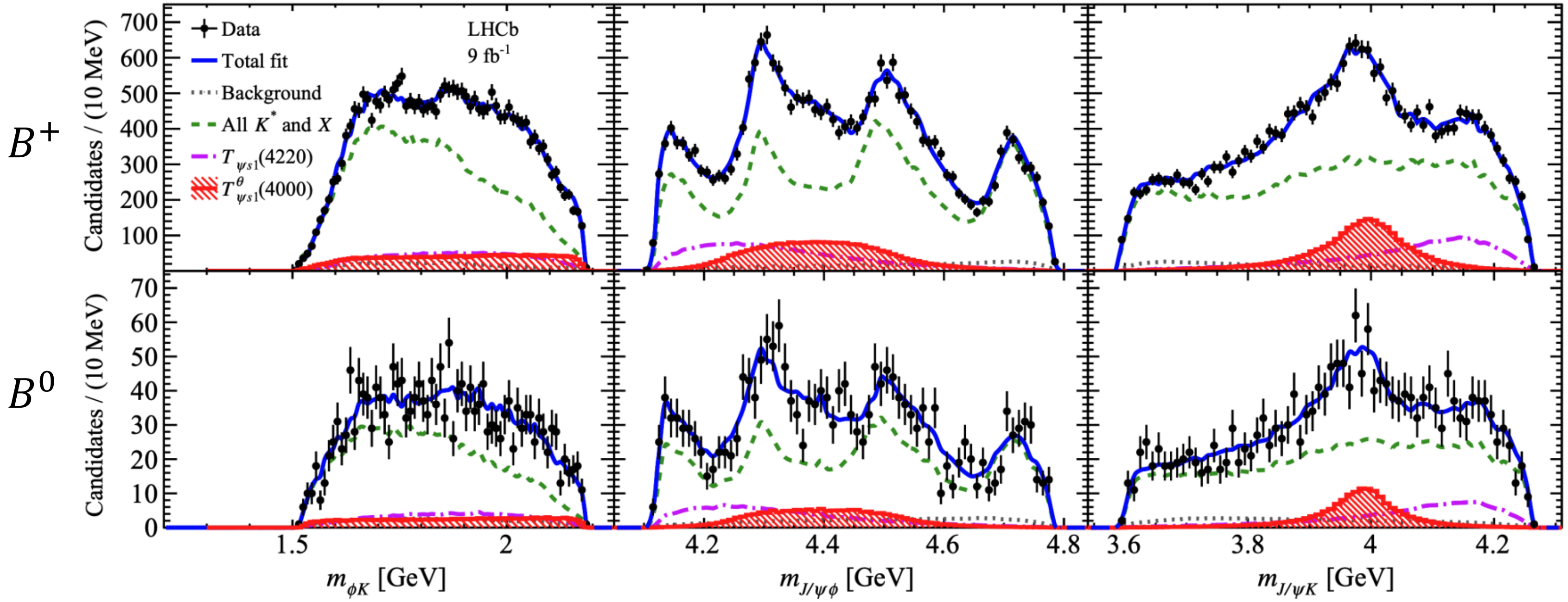
Evidence of $T^{\theta}_{\psi s1}(4000)^0$

PRL131 (2023) 131901

PRL127 (2021) 082001

- $T^{\theta}_{\psi s1}(4000)^+$ and $T_{\psi s1}(4220)^+$ are observed in $B^+ \to J/\psi\phi K^+$ decays.
  - Searching for their isospin partners to identify the full SU(3) nonet that involves these states.
  - The $B^0 \to J/\psi\phi K^0_S$ decay is an ideal process to search for that states due to the isospin symmetry.
  - Simultaneous fit is performed to $B^0 \to J/\psi\phi K^0_S$ and the $B^+ \to J/\psi\phi K^+$ samples.





- Evidence of a $J/\psi K^0_S$ structure with a significance of 4σ is seen.
- Denoted as $T^{\theta}_{\psi s1}(4000)^0$ $(c\bar{c}d\bar{s})$, which likely to be the isospin partner of $T^{\theta}_{\psi s1}(4000)^+$ $(c\bar{c}u\bar{s})$.

$$M\left(T^{\theta}_{\psi s1}(4000)^0\right) = 3991^{+12+9}_{-10-17}\ \text{MeV}$$
$$\Gamma\left(T^{\theta}_{\psi s1}(4000)^0\right) = 105^{+29+17}_{-25-23}\ \text{MeV}$$
$$\Delta M = -12^{+11}_{-10}{}^{+6}_{-4}\ \text{MeV}$$

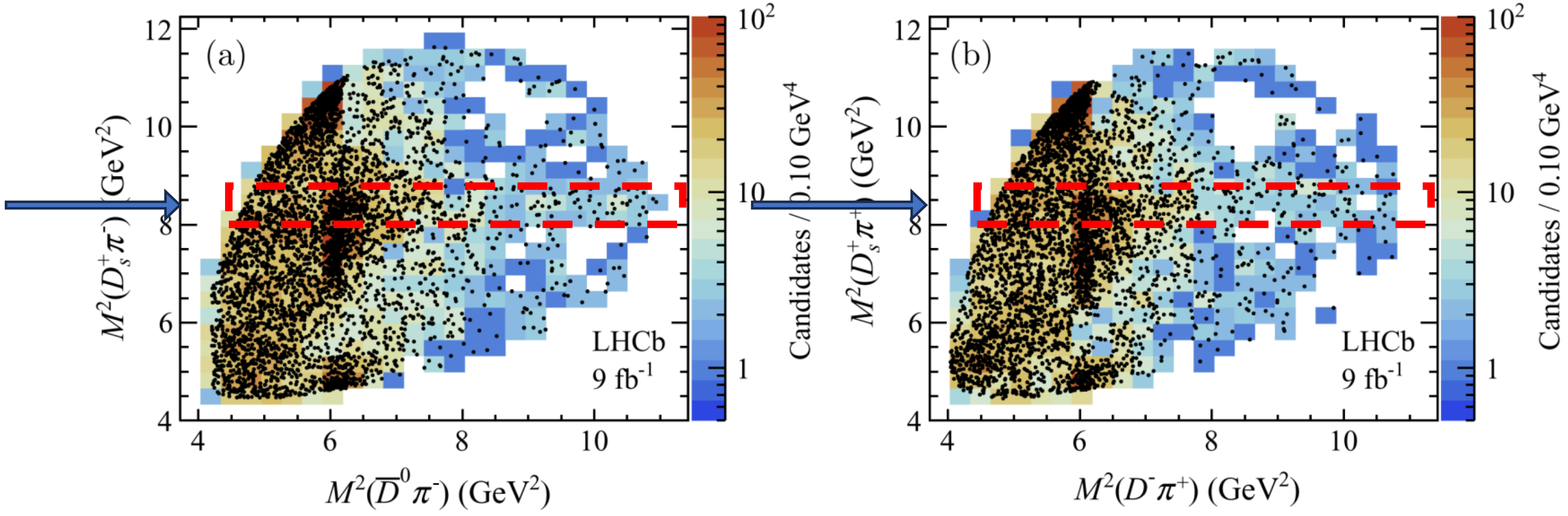
Observation of $T^a_{c\bar{s}0}(2900)^{++}$ and $T^a_{c\bar{s}0}(2900)^0$

PRD108 (2023) 012017 PRL131 (2023) 041902

- Exotics composed of **four different quark types** attracts great interest in studies of hadron spectroscopy.

PRL125 (2020) 242001 PRD102 (2020) 112003

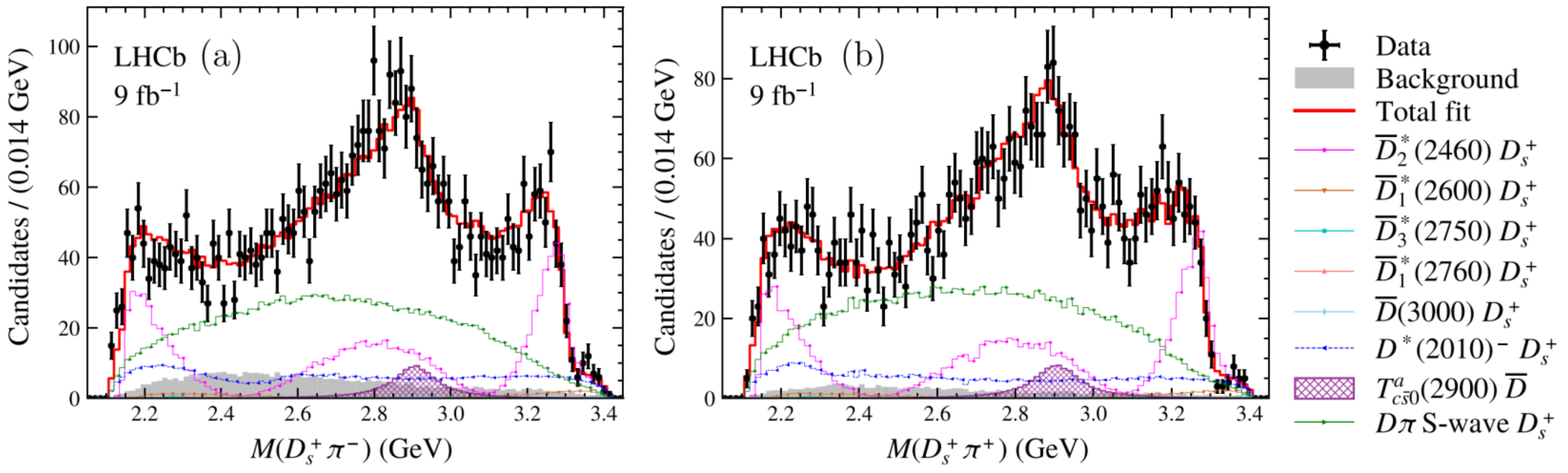
  - $X_0(2900)$ and $X_1(2900)$, with quark component $cs\bar{u}\bar{d}$, are observed in $B^+ \to D^+D^-K^+$ decay.
  - Search for tetraquark candidates, with quark component $c\bar{s}u\bar{d}$ or $c\bar{s}\bar{u}d$, can be performed in $B^+ \to D^-D_s^+\pi^+$ and $B^0 \to \bar{D}^0D_s^+\pi^-$ decays.
  - A combined amplitude analysis of the $B^+ \to D^-D_s^+\pi^+$ and $B^0 \to \bar{D}^0D_s^+\pi^-$ decays is performed.
  - Structure at 2.9 GeV in $D_s^+\pi^{+/-}$ spectra can not be well described by any known or new $D^{*+/0} \to \bar{D}^{0/-}\pi^+$ resonances.

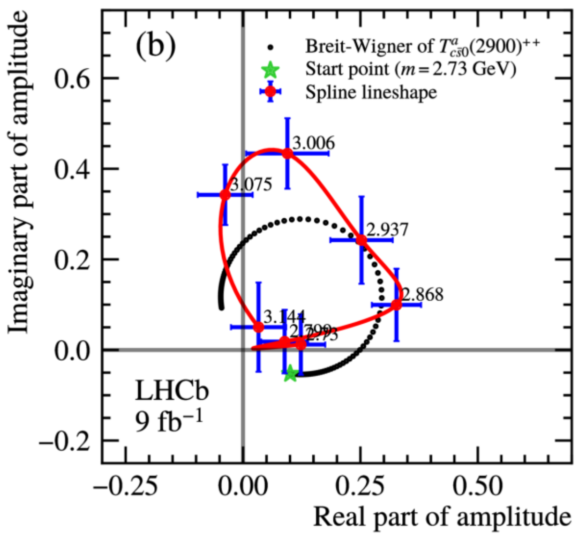


Observation of $T^a_{c\bar{s}0}(2900)^{++}$ and $T^a_{c\bar{s}0}(2900)^0$

PRL131 (2023) 041902

- With two additional $D_s^+\pi^\pm$ components, the data is better described.





- Both states prefer $J^P = 0^+$ (1^- is rejected by >7σ).
- Separated fit reports: (both M and Γ in great agreement)

$$T^a_{c\bar{s}0}(2900)^0: \; M = 2.892 \pm 0.014 \pm 0.015 \text{ GeV}$$
$$\Gamma = 0.119 \pm 0.026 \pm 0.013 \text{ GeV}$$

8.0σ

$$T^a_{c\bar{s}0}(2900)^{++}: \; M = 2.921 \pm 0.017 \pm 0.020 \text{ GeV}$$
$$\Gamma = 0.137 \pm 0.032 \pm 0.017 \text{ GeV}$$

6.5σ

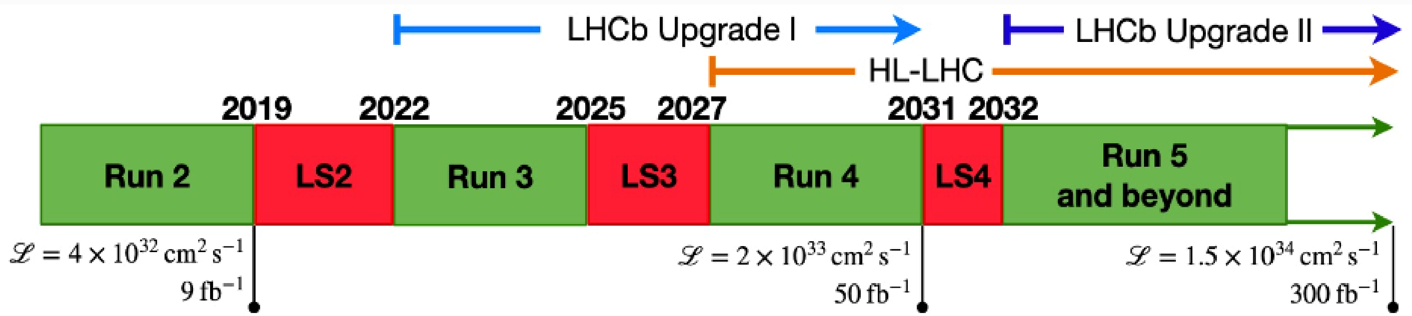
- Shared fit reports: (assume they belong to isospin triplet)

$$M = 2.908 \pm 0.011 \pm 0.020 \text{ GeV}$$
$$\Gamma = 0.136 \pm 0.023 \pm 0.013 \text{ GeV}$$

Combined significance >9.0σ

$T^a_{c\bar{s}0}(2900)^{++}$ is the first observed **doubly-charged** tetraquark candidate.

Summary and prospects



arXiv:2305.10515

- Some recent interesting results presented:
  - New conventional hadrons
    - New excited Ω_c^0 states: $\Omega_c(3327)^0, \Omega_c(3185)^0$
    - New excited Ξ_b^0 states: $\Xi_b(6095)^0, \Xi_b(6087)^0$
  - New exotics
    - New pentaquark candidates: $P_{\psi s}^{\Lambda}(4338)^0$
    - New tetraquark candidates: $X(3960), T_{\psi s1}^{\theta}(4000)^0, T_{c\bar{s}0}^{a}(2900)^{++/0}$
- Higher statistics in upgrade boosts hadron spectroscopy studies at LHCb:
  - Search for more conventional excited states
  - *Evidence* of some hadrons/decay modes ⇒ *Observation*
  - Search for new decay modes of observed exotic hadrons, e.g., $P_{\psi}^{N^+}$
  - Determine J^P and other properties of multiquark states
  - ……

Thanks for listening

Questions and comments are welcomed.

Backup

Impact on recently discovered hadrons

Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name	Reference
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+$, $J^{PC} = 1^{++}$	$\chi_{c1}(3872)$	[24, 25]
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\psi 1}(3900)^+$	[26–28]
$c\bar{c}u\bar{d}$	$X(4100)^+$	$I^G = 1^-$	$T_\psi(4100)^+$	[29]
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\psi 1}(4430)^+$	[30, 31]
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G = 0^+$, $J^{PC} = 1^{++}$	$\chi_{c1}(4140)$	[32–35]
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2}$, $J^P = 1^+$	$T^\theta_{\psi s1}(4000)^+$	[7]
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2}$, $J^P = 1^?$	$T_{\psi s1}(4220)^+$	[7]
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+$, $J^{PC} = ?^{?+}$	$T_{\psi\psi}(6900)$	[4]
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$	[5, 6]
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$	[5, 6]
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$	[8, 9]
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$	[36]
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_\psi(4312)^+$	[3]
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P^\Lambda_{\psi s}(4459)^0$	[20]