Pentaquarks at LHCb

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for LHCb collaboration

QwG 2022, GSI Darmstadt,
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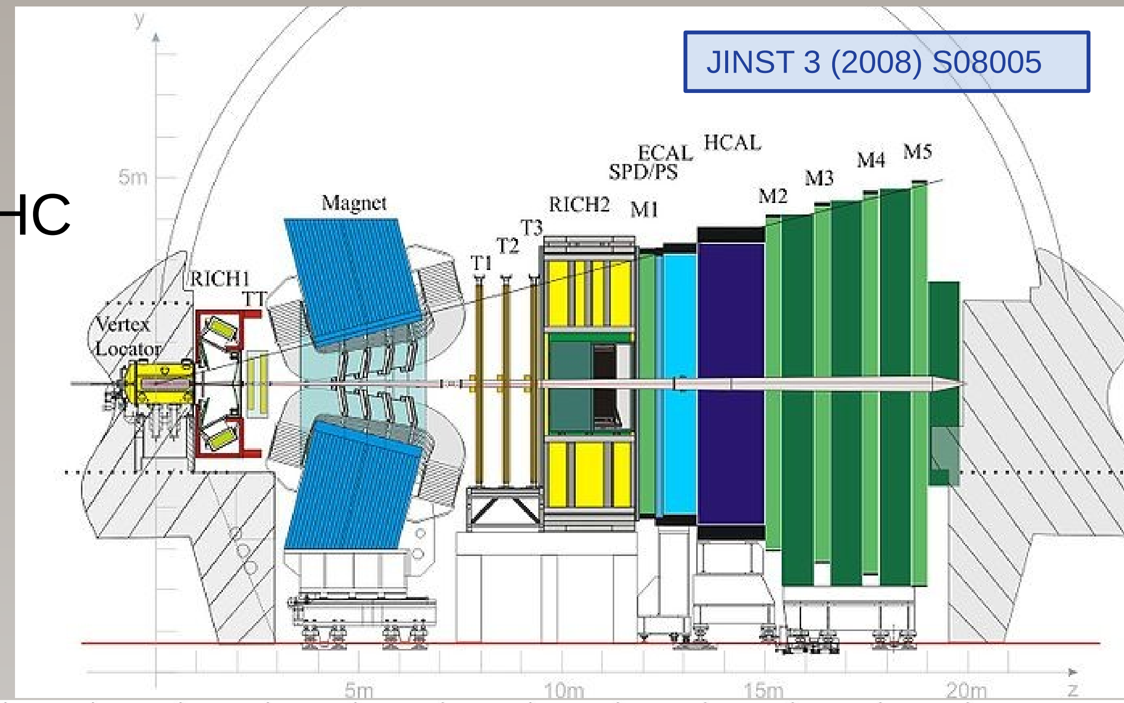
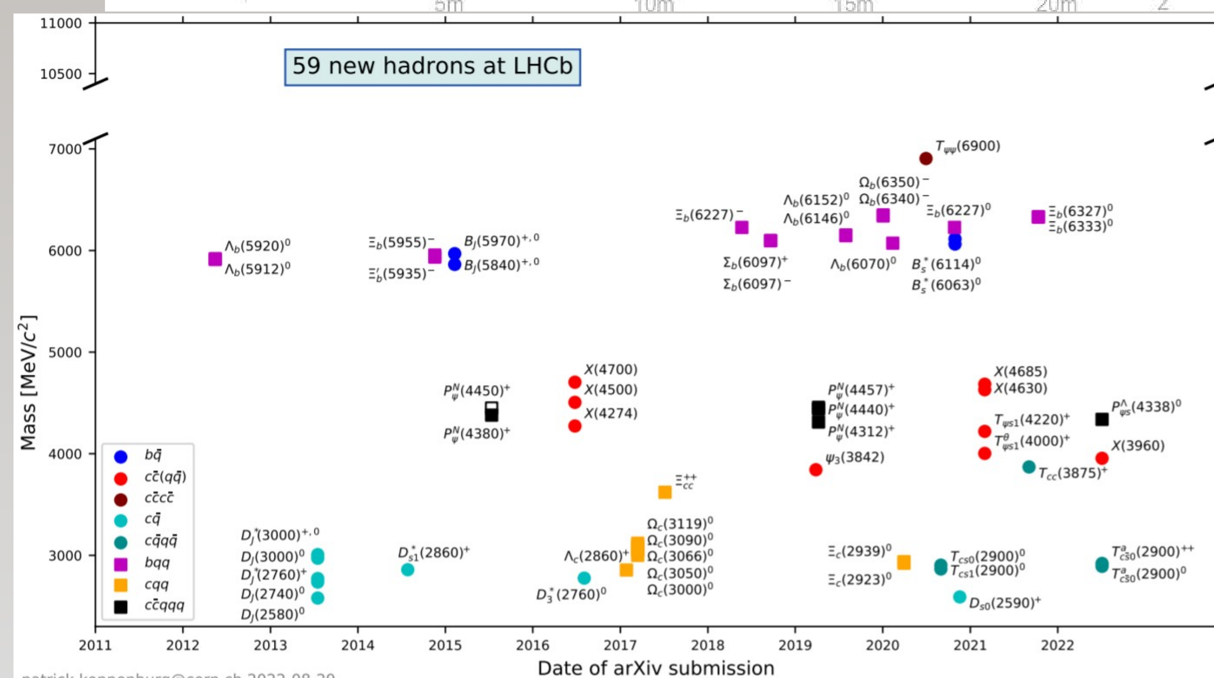
The LHCb detector

- LHCb - forward spectrometer at LHC with excellent
  - momenta/mass,
  - vertex/time resolution
  - particle identification (K/π/p/μ)

very powerful tool for
heavy hadron spectroscopy
→ contribute to major part
of hadrons discovered at LHC



JINST 3 (2008) S08005



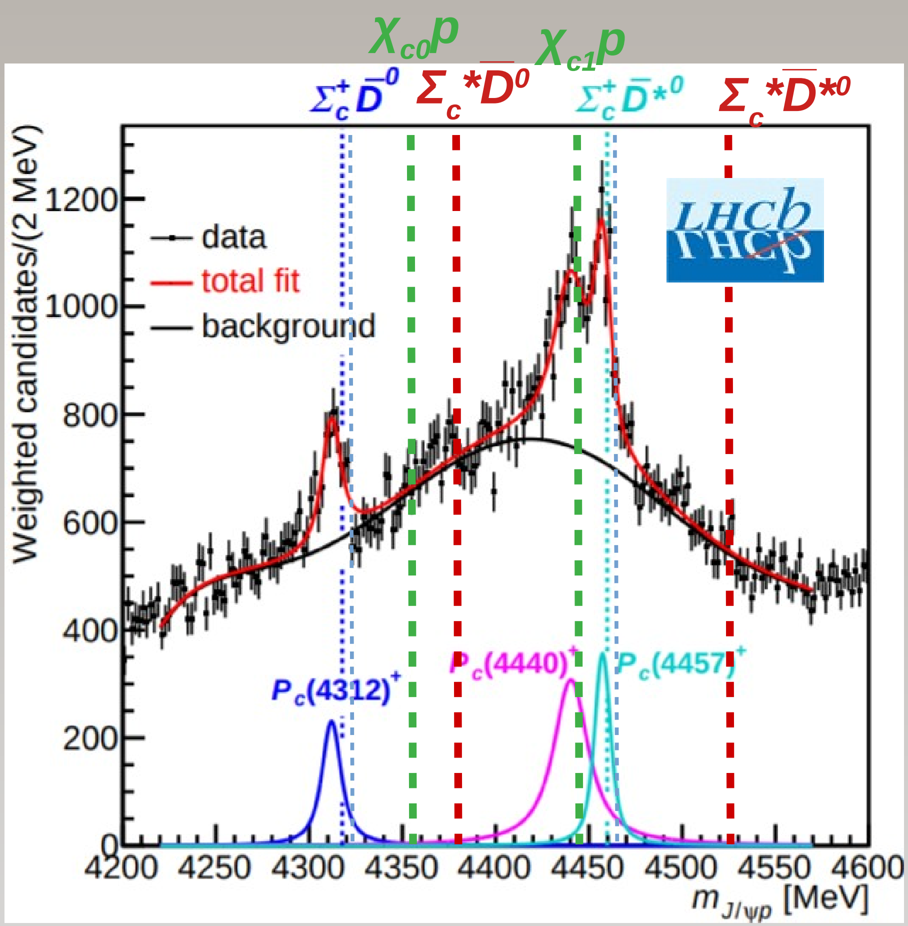
LHCb-FIGURE-2021-001

First pentaquarks in $\Lambda_b \rightarrow J/\psi pK$

PRL 115 (2015) 072001,
PRL 122 (2019) 222001

- In $\Lambda_b \rightarrow J/\psi pK$ now 3 narrow pentaquarks are seen

State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$



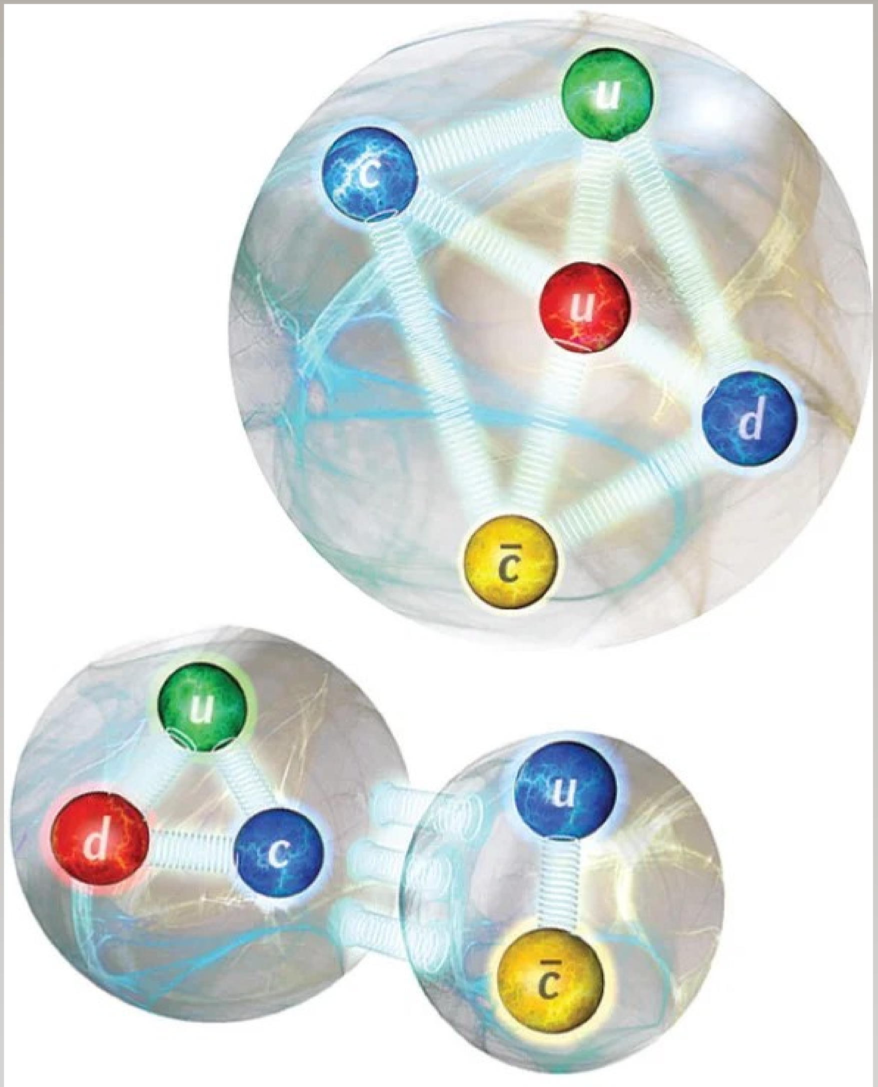
- Narrow (5-20 MeV)
- Note closeness to thresholds
- A wider state with
  M~4380 MeV and Γ~200 MeV
  to be confirmed with larger statistics

Interpretations

- Fit in both model frameworks:
  - **compact multiquark**
    - genuine QCD state
    - size ~1fm

    see Richard, arxiv:1606.08593;
    Esposito, Pilloni, Polosa, arXiv:1611.07920
  - **molecular state**
    - two hadrons bound by π/ρ/η
    (QCD analog of "van der Waals" force)
    - are well separated (1-10fm)
    - natural closeness to thresholds

    see Guo et al, arXiv:1705.00141
- Both suggest more of analogous states



Credit: Moonrunner Design

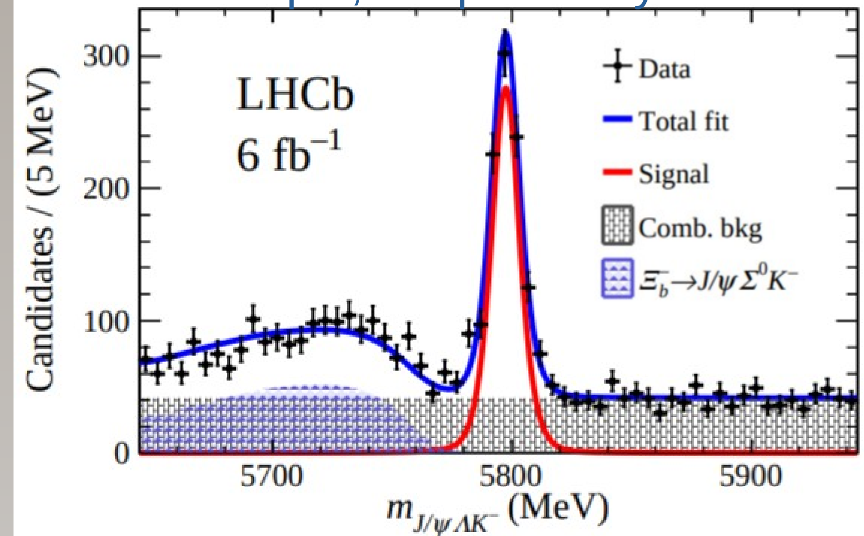
$\Xi_b \to J/\psi \Lambda K$

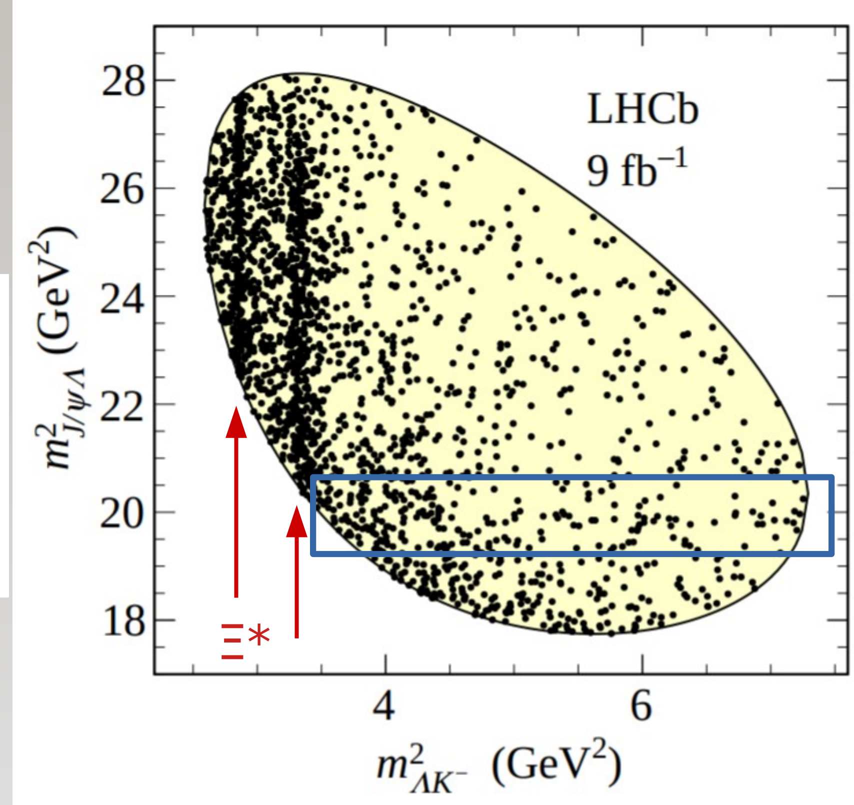
Science Bulletin 66 (2021) 1278

- Use full Run1+2 (3+6fb[-1]) dataset
- Reconstruct $\Lambda \to p\pi$ decayed both in and outside of the VELO
- In total 1750 signal events, purity ~80%
- $\Xi^* \to \Lambda K$ contributions are clearly seen
- Full amplitude analysis firstly contributions in ΛK are examined

State	M_0 (MeV)	Γ_0 (MeV)	LS couplings	J^P examined
$\Xi(1690)^-$	1690 ± 10	< 30	4 (6)	$(1/2, 3/2)^{\pm}$
$\Xi(1820)^-$	1823 ± 5	24^{+15}_{-10}	3 (6)	$3/2^-$
$\Xi(1950)^-$	1950 ± 15	60 ± 20	3 (6)	$(1/2, 3/2, 5/2)^{\pm}$
$\Xi(2030)^-$	2025 ± 5	20^{+15}_{-5}	3 (6)	$5/2^{\pm}$
NR ΛK^-	-	-	4 (4)	$1/2^-$

Run2 sample, $\Lambda \to p\pi$ decay in VELO

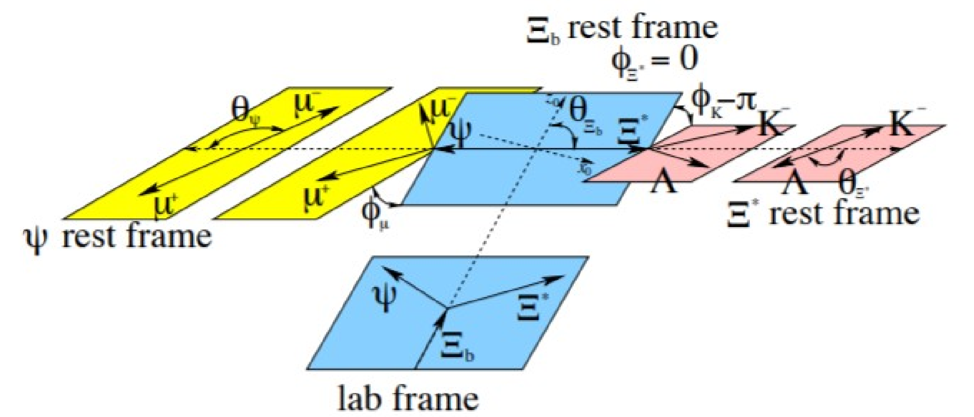




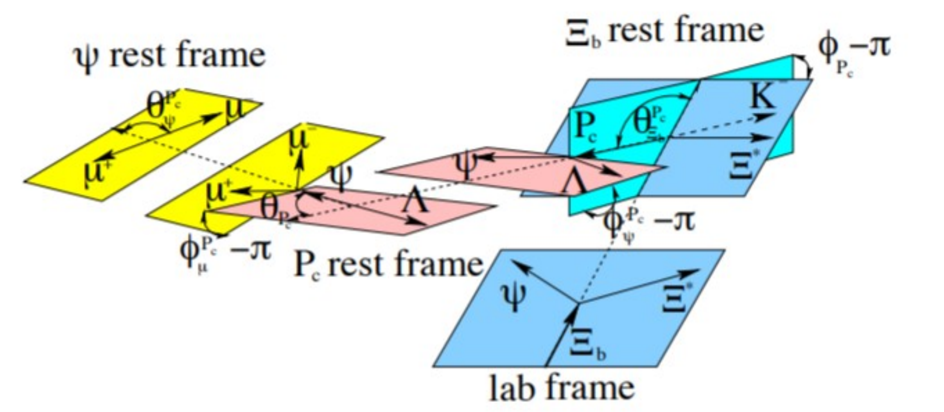
$\Xi_b \to J/\psi \Lambda K$, amplitude

Science Bulletin 66 (2021) 1278

- 6D amplitude, follow helicity formalism PRL 115 (2015) 072001 arXiv:1910.04566



(a) Ξ^{*-} chain



(b) P_{cs}^0 chain

$$\mathcal{M}^{\Xi^*}_{\lambda_{\Xi_b},\lambda_\Lambda,\Delta\lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Xi^*}} \sum_{\lambda_\psi} \mathcal{H}^{\Xi_b\to\Xi_n^*\psi}_{\lambda_{\Xi^*},\lambda_\psi} D^{\frac{1}{2}}_{\lambda_{\Xi_b},\lambda_{\Xi^*}-\lambda_\psi}(0,\theta_{\Xi_b},0)^* \mathcal{H}^{\Xi_n^*\to K\Lambda}_{\lambda_\Lambda,0} D^{J_{\Xi_n^*}}_{\lambda_{\Xi^*},\lambda_\Lambda}(\phi_\Lambda,\theta_{\Xi^*},0)^* R_{\Xi_n^*}(m_{\Lambda K})\, D^1_{\lambda_\psi,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*,$$

$$\mathcal{M}^{P_{cs}}_{\lambda_{\Xi_b},\lambda_\Lambda^{P_{cs}},\Delta\lambda_\mu^{P_{cs}}} \equiv \sum_j \sum_{\lambda_{P_{cs}}} \sum_{\lambda_\psi^{P_{cs}}} \mathcal{H}^{\Xi_b\to P_{cs\,j}K}_{\lambda_{P_{cs}},0} D^{\frac{1}{2}}_{\lambda_{\Xi_b},\lambda_{P_{cs}}}(\phi_{P_{cs}},\theta^{P_{cs}}_{\Xi_b},0)^* \mathcal{H}^{P_{cs\,j}\to\psi\Lambda}_{\lambda_\psi^{P_{cs}},\lambda_\Lambda^{P_{cs}}} D^{J_{P_{cs\,j}}}_{\lambda_{P_{cs}},\lambda_\psi^{P_{cs}}-\lambda_\Lambda^{P_{cs}}}(\phi_\psi,\theta_{P_{cs}},0)^* R_{P_{cs\,j}}(m_{\psi\Lambda})\ D^1_{\lambda_\psi^{P_{cs}},\Delta\lambda_\mu^{P_{cs}}}(\phi_\mu^{P_{cs}},\theta_\psi^{P_{cs}},0)^*$$

$$|\mathcal{M}|^2 = \sum_{\lambda_{\Xi_b}} \sum_{\lambda_\Lambda} \sum_{\Delta\lambda_\mu} \left| \mathcal{M}^{\Xi^*}_{\lambda_{\Xi_b},\lambda_\Lambda,\Delta\lambda_\mu} + e^{i\,\Delta\lambda_\mu\alpha_\mu} \sum_{\lambda_\Lambda^{P_{cs}}} d^{\frac{1}{2}}_{\lambda_\Lambda^{P_{cs}},\lambda_\Lambda}(\theta_\Lambda)\, \mathcal{M}^{P_{cs}}_{\lambda_{\Xi_b},\lambda_\Lambda^{P_{cs}},\Delta\lambda_\mu} \right|^2$$

- J^P determines allowed L,S values in $\Xi_b \to P_{\psi s} K$ and $P_{\psi s} \to J/\psi\Lambda$ decays and hence corresponding couplings:

$$H^{A\to BC}_{\lambda_B,\lambda_C} = \sum_L \sum_S \sqrt{\frac{2L+1}{2J_A+1}} B_{L,S} \left(\begin{array}{cc|c} J_B & J_C & S \\ \lambda_B & -\lambda_C & \lambda_B-\lambda_C \end{array} \right) \times \left(\begin{array}{cc|c} L & S & J_A \\ 0 & \lambda_B-\lambda_C & \lambda_B-\lambda_C \end{array} \right)$$

$\Xi_b \to J/\psi \Lambda K$

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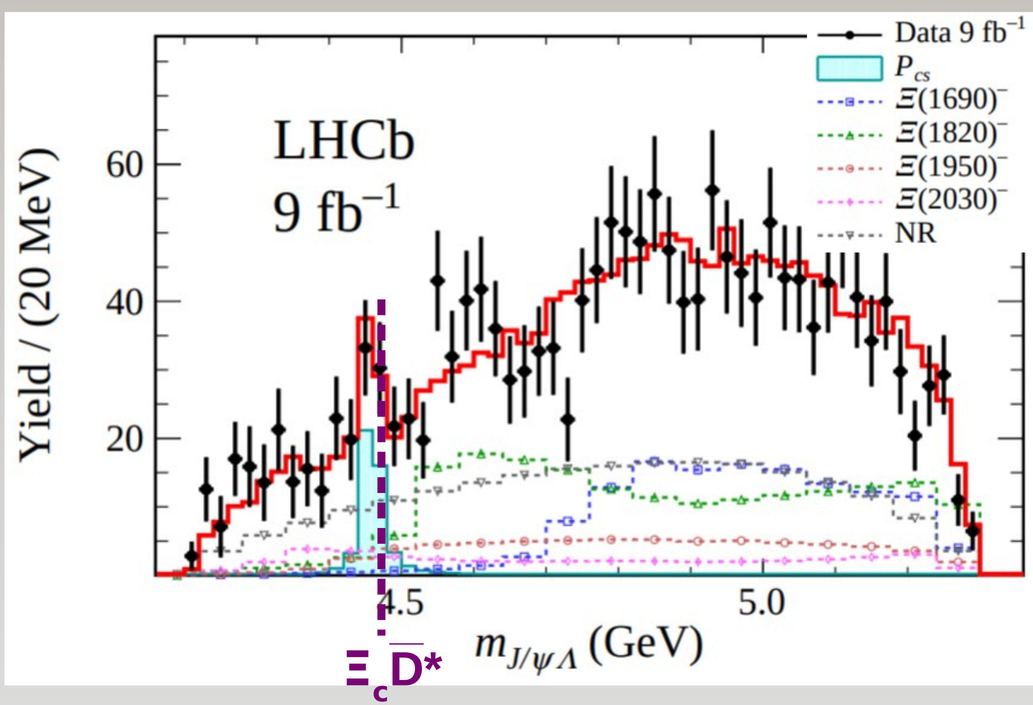
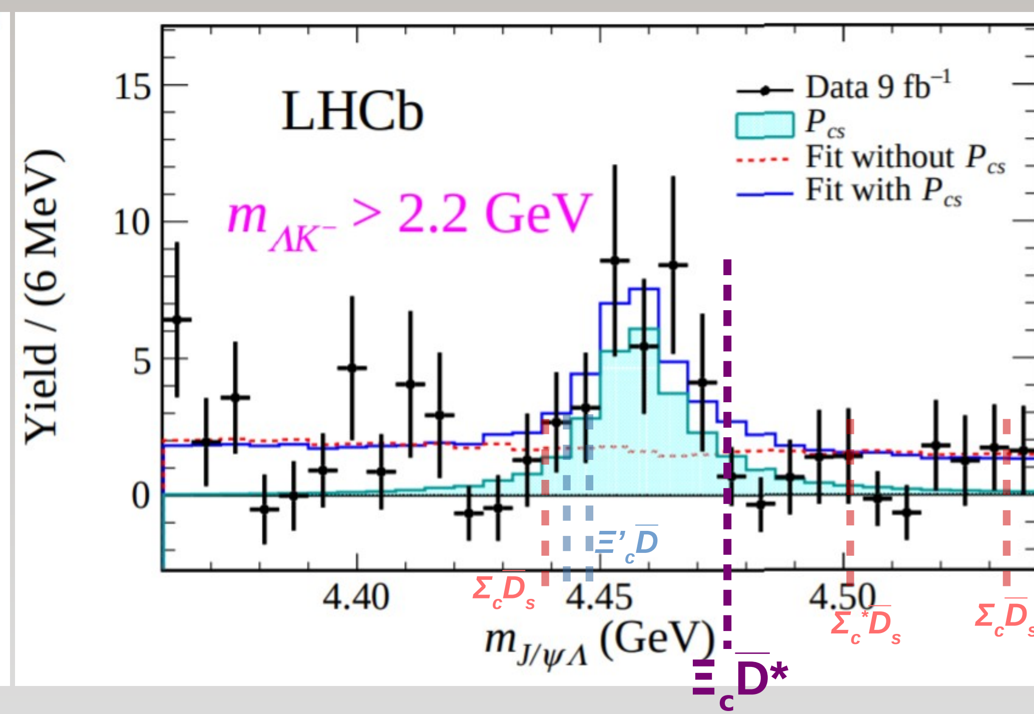
- A need for one $P_{\psi s} \to J/\psi\Lambda$ was found
- Significance 3.1σ
- Two resonances are possible *(analogous to P_ψ(4440) & P_ψ(4457))*
- J^P examined are $1/2^\pm$, $3/2^\pm$, $5/2^\pm$,
  none is excluded

State	M_0 (MeV)	Γ_0 (MeV)	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9}_{-0.6}\,^{+0.7}_{-1.3}$



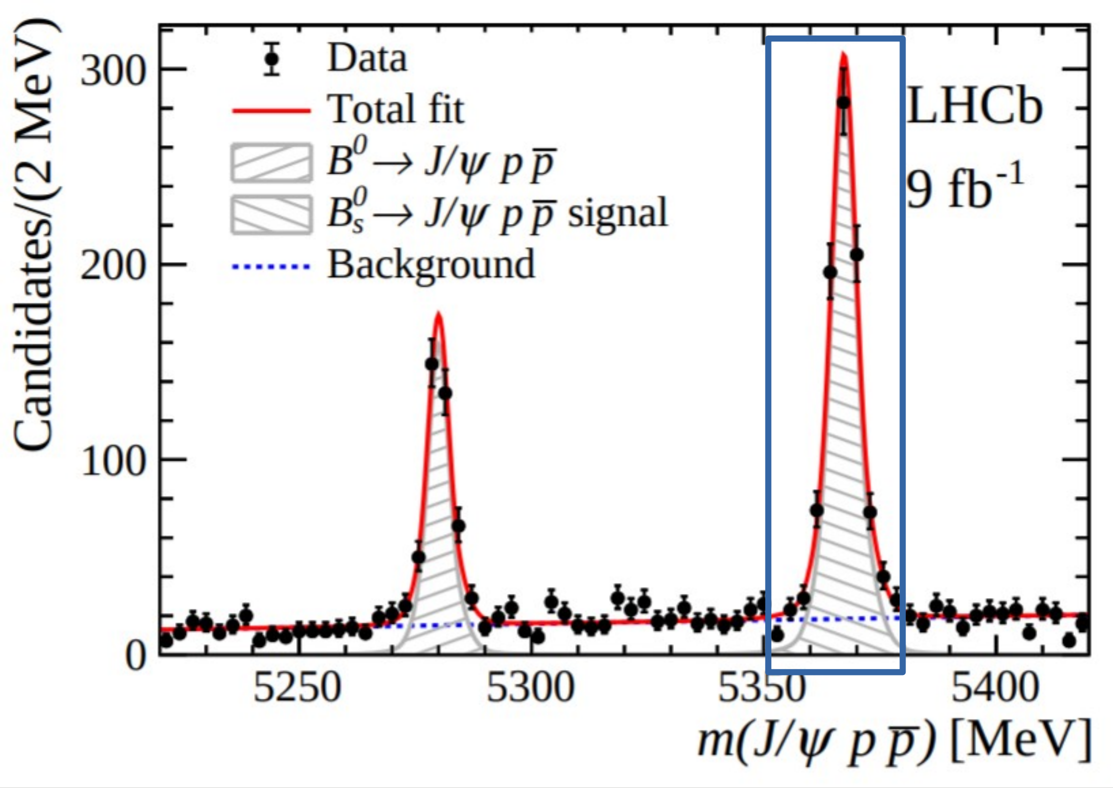


$B_s \to J/\psi p\bar{p}$

Phys. Rev. Lett. 128 (2022) 062001

- $B_{(s)}^0 \to J/\psi p\bar{p}$ decays were firstly observed in 2019
- Reanalyze the B_s decay with full Run1+2 data sample
- 800 signal events, ~85% purity
- Amplitude fit:
  - no conventional intermediate states! thus only
    - $X \to p\bar{p}$,
    - $P_\psi^+ \to J/\psi p$
    - $P_\psi^- \to J/\psi \bar{p}$

  are considered on top of NR
- No B-tagging → $P_\psi^+ \to J/\psi p$ and $P_\psi^- \to J/\psi \bar{p}$ are fully symmetric



$B_s \to J/\psi p\bar{p}$

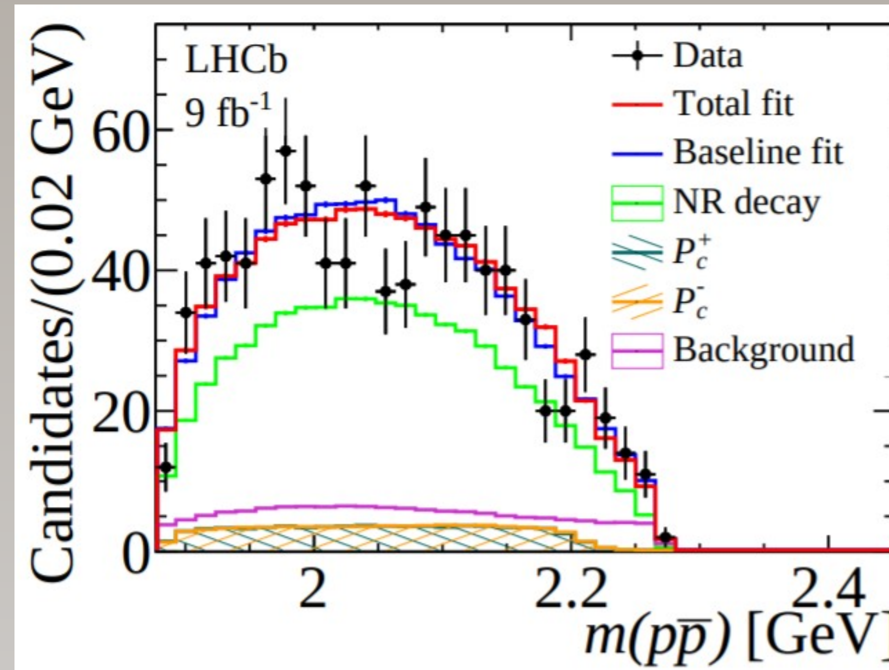
Phys. Rev. Lett. 128 (2022) 062001

- No structures in $p\bar{p}$ are seen
- Non-resonant proceeds with $p\bar{p}$ in 1^-
  (S-waves in production & decay)

- No evidence for $P_\psi(4312) \to J/\psi p$ seen in $\Lambda_b \to J/\psi pK$

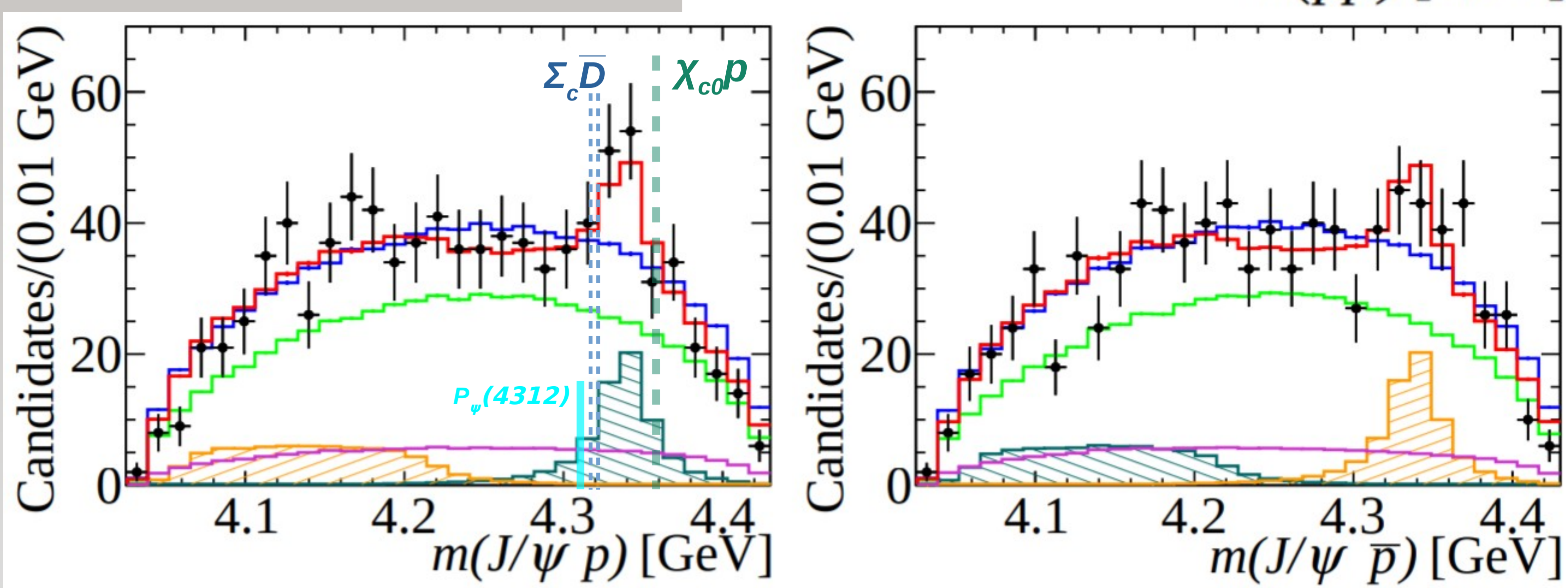
- Found $P_\psi \to J/\psi p$ with

$$M_{P_c} = 4337 \,^{+7}_{-4}\,^{+2}_{-2}\,\text{MeV},$$
$$\Gamma_{P_c} = 29 \,^{+26}_{-12}\,^{+14}_{-14}\,\text{MeV},$$

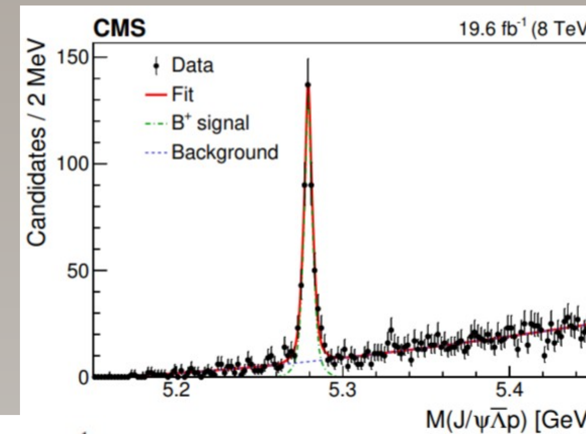


- Significances are 3.1 and 3.7σ

- J^P examined are $1/2^\pm$, $3/2^\pm$ none is excluded

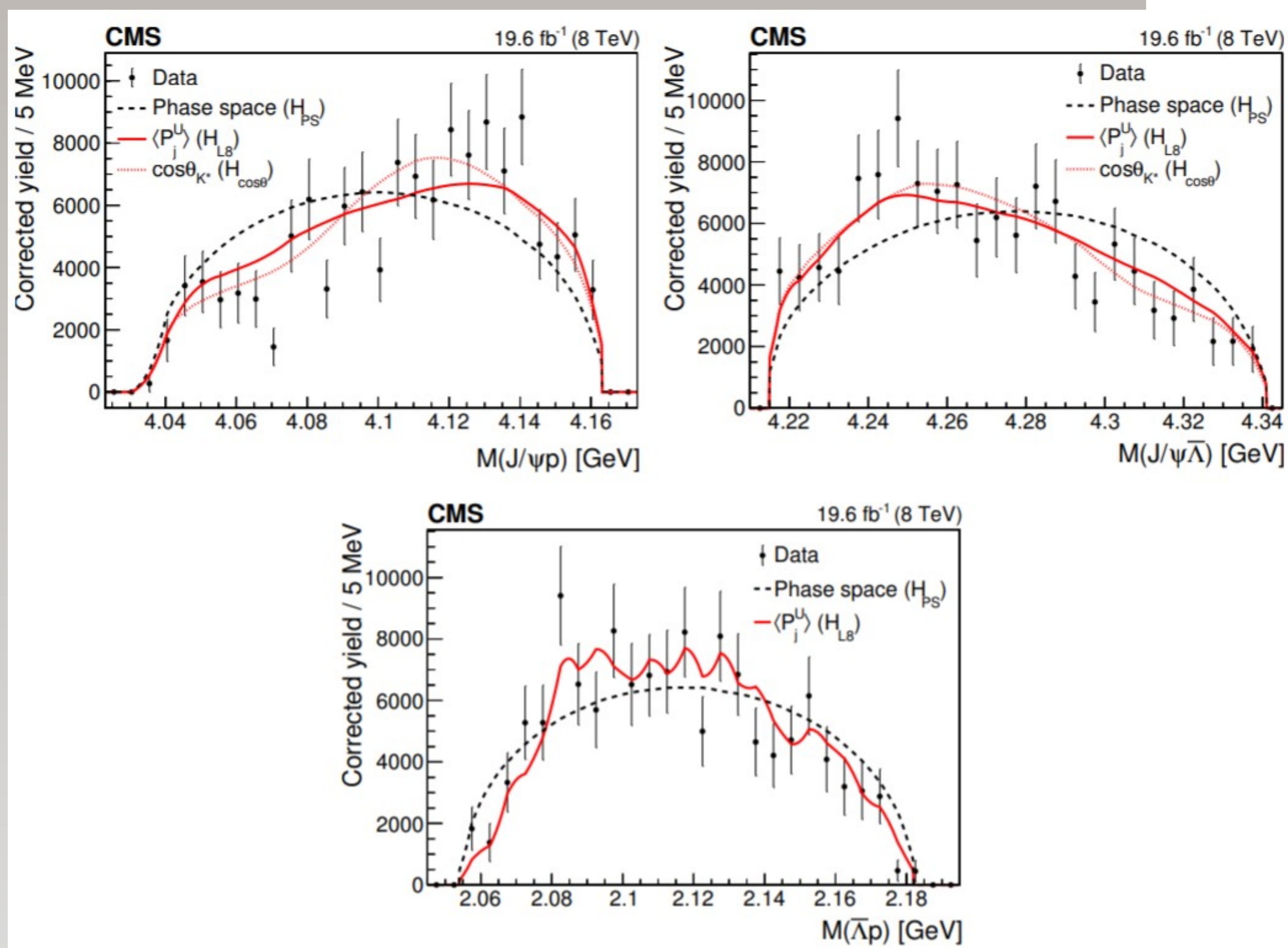


$B \to J/\psi \Lambda \bar{p}$



- Previous amplitude analysis by CMS:
  - $B \to J/\psi \Lambda \bar{p}$ inconsistent with phase-space
  - can be explained with $K^* \to \Lambda \bar{p}$ contributions

JHEP 12 (2019) 100



NEW!

$B \to J/\psi \Lambda \bar{p}$

LHCB-PAPER-2022-031, in prep.

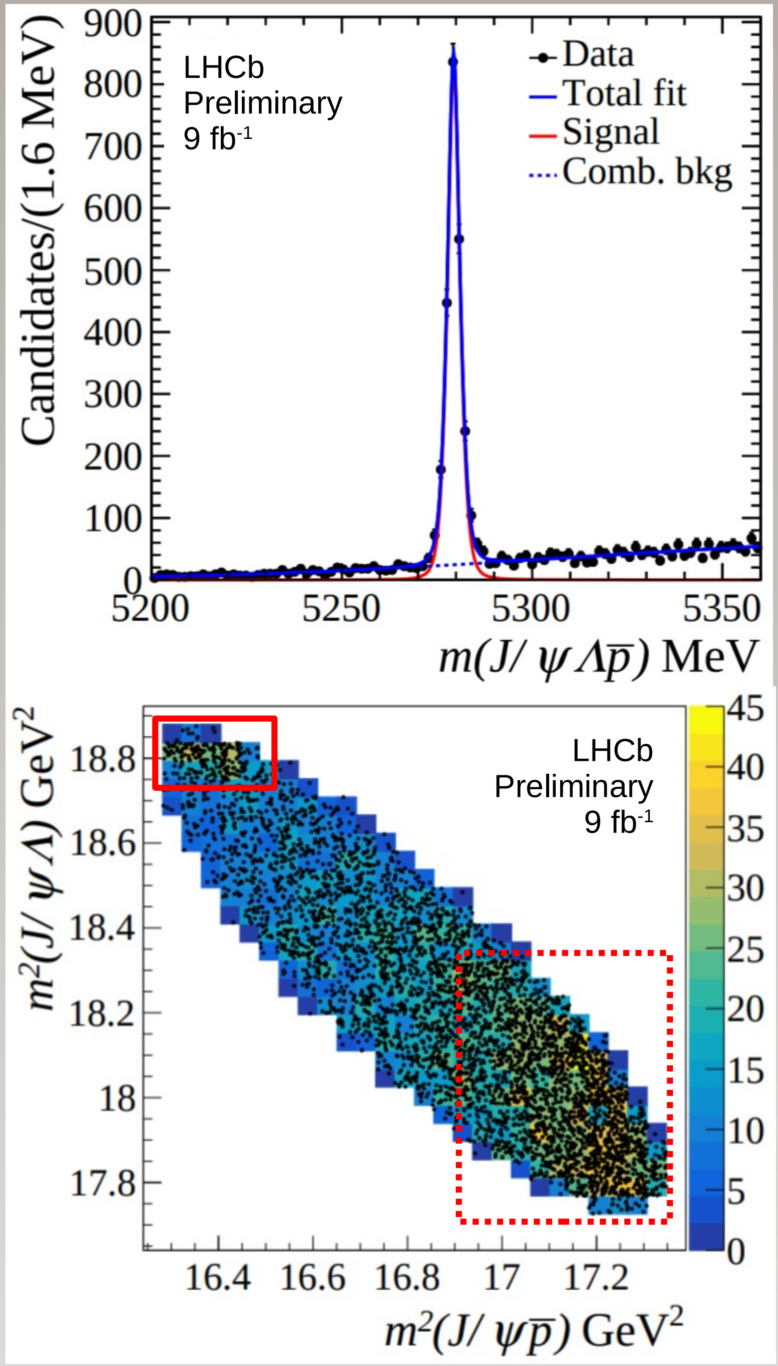
- Previous amplitude analysis by CMS:
  - $B \to J/\psi \Lambda \bar{p}$ inconsistent with phase-space
  - can be explained with $K^* \to \Lambda \bar{p}$ contributions

JHEP 12 (2019) 100

- 4.6k signal events (x10 more than CMS had), 93% purity

- Reconstruct $\Lambda \to p\pi$ decayed both in and outside of the VELO

- Amplitude analysis contributions:
  - non-resonant
  - $K^* \to \Lambda \bar{p}$
  - $P_\psi \to J/\psi \bar{p}$
  - $P_{\psi s} \to J/\psi \Lambda$

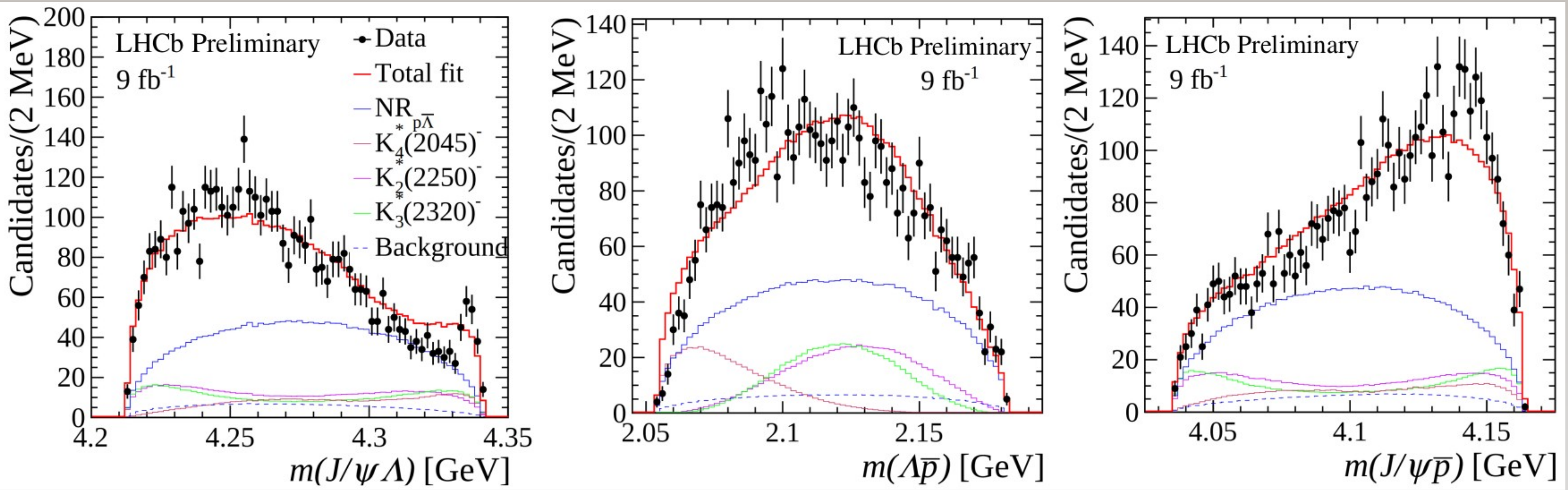


NEW!

$B \to J/\psi \Lambda \bar{p}$

LHCB-PAPER-2022-031, in prep.

- Model with only NR + $K_4^*(2045)$, $K_2^*(2250)$, $K_3^*(2320)$ fails to describe data



NEW!

$B \to J/\psi \Lambda \bar{p}$

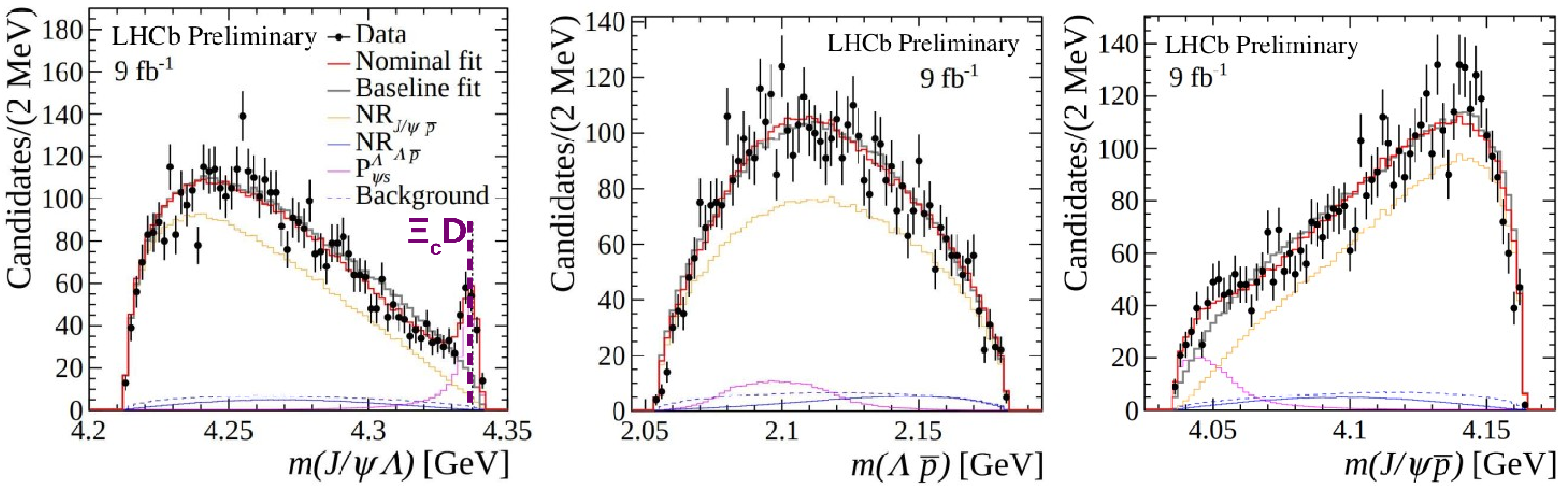
LHCB-PAPER-2022-031, in prep.

- Add narrow $P_{cs} \to J/\psi\Lambda$ state

$$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4\,\text{MeV} \text{ and } \Gamma_{P_{cs}} = 7.0 \pm 1.2 \pm 1.3\,\text{MeV}$$

- 15σ significance
- $1/2^-$ is preferred, $1/2^+$ rejected at 90% CL

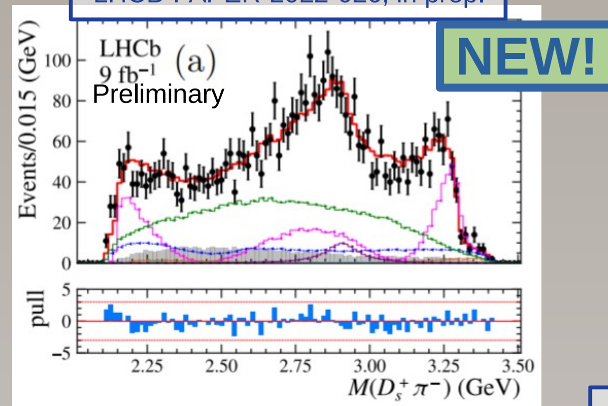
- Measured fit fractions:
  - $P_{\psi s}$: 12.5±0.7±1.9 %
  - NR($J/\psi\bar{p}$): 84.0±2.2±1.4 %
  - NR($\Lambda\bar{p}$): 11.3±1.3±1.7 %



Highlights on tetraquarks

- $T_{cs}^{++} \to D_s^+ \pi^+$ in $B^0 \to \overline{D}^0 D_s^+ \pi^+$

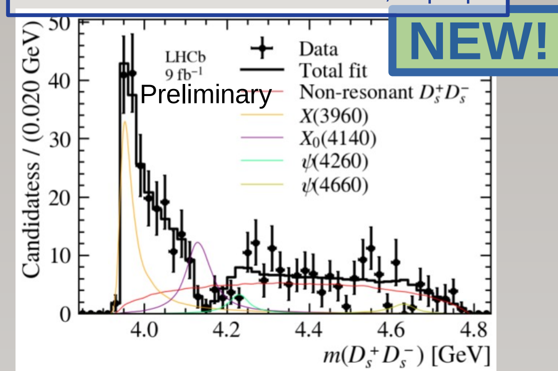
LHCB-PAPER-2022-026, in prep.



- $X \to D_s^+ D_s^-$ in $B^+ \to D_s^+ D_s^- K^+$
- $X \to J/\psi\eta$ resonance in $B \to J/\psi\eta K$
- $X(2900) \to DK$ in $B \to D^+ D^- K^+$

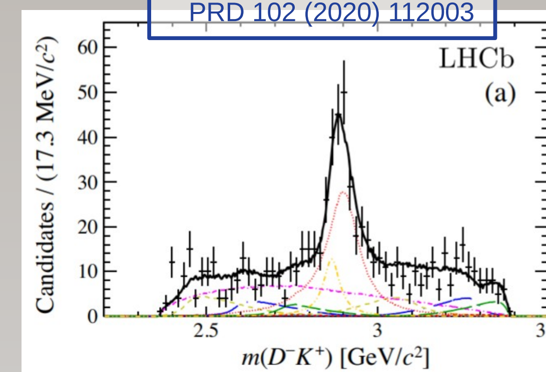
  → *see talk by Chen Chen*

LHCB-PAPER-2022-018/019, in prep.



JHEP 04 (2022) 046

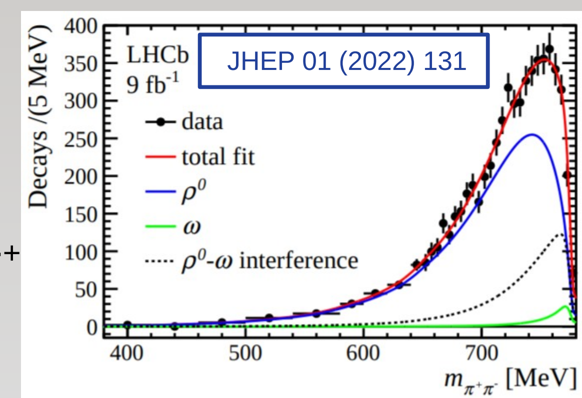
PRL 125 (2020) 242001, PRD 102 (2020) 112003



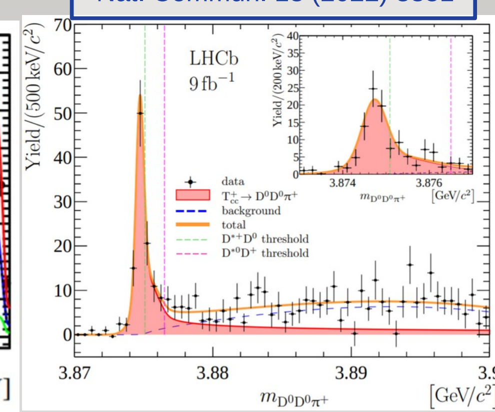
- Observation of ω contribution in $\chi_{c1}(3872) \to J/\psi\pi+\pi-$ decay
- Doubly charmed tetraquark $T_{cc}^+ \to D^0 D^0 \pi^+$

  → *see talk by Mikhail Mikhasenko*

JHEP 01 (2022) 131

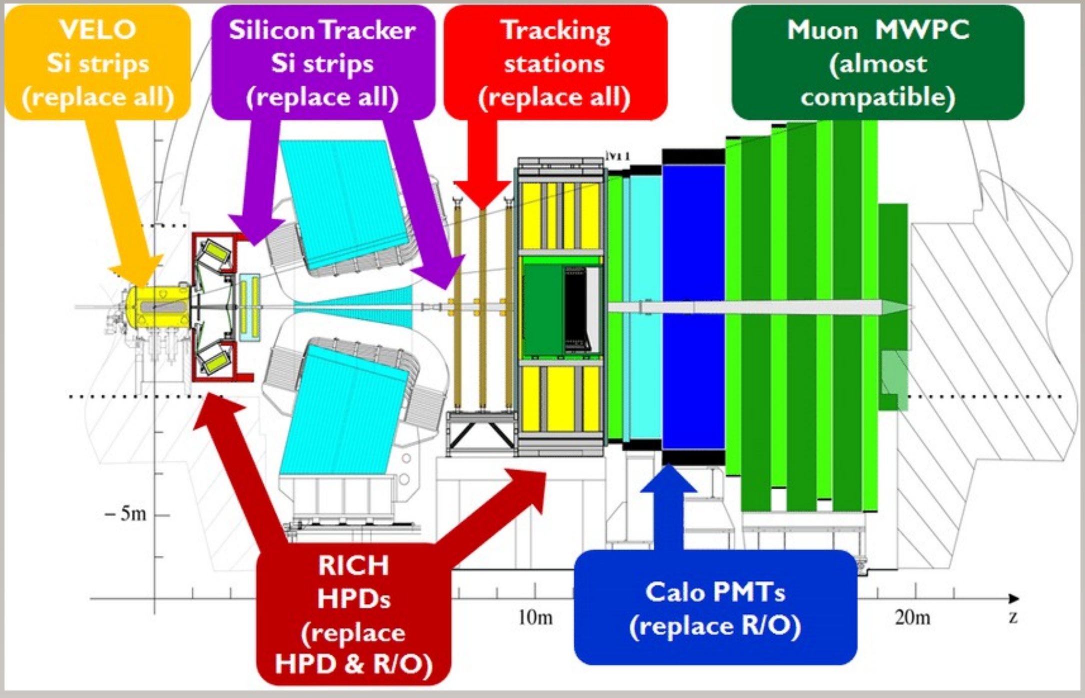


Nat. Phys. 18 (2022) 751, Nat. Commun. 13 (2022) 3351



Upgraded LHCb

- Major upgrades during last shutdown
  - Tracking&Vertexing
  - PID
  - Trigger



- Started to collect data in Run3 (2022-2025)
- Will give up to x5 (x10 for Run3&4) boost in statistics wrt current dataset
- More exciting results will follow

Summary

- Latest results on pentaquarks:
  - $P_{\psi s} \rightarrow J/\psi\Lambda$ in $\Xi_b \rightarrow J/\psi\Lambda K$ Science Bulletin 66 (2021) 1278
  - $P_{\psi} \rightarrow J/\psi p$ in $B_s \rightarrow J/\psi p\bar{p}$ Phys. Rev. Lett. 128 (2022) 062001
  - $P_{\psi s} \rightarrow J/\psi\Lambda$ in $B \rightarrow J/\psi\Lambda\bar{p}$ LHCB-PAPER-2022-031, in prep.
- A lot of results on tetraquarks as well
- New naming convention proposal arxiv:2206.15233
- Stay tuned

Appendix

$\Xi_b \to J/\psi\Lambda K$, systematics

Science Bulletin 66 (2021) 1278

- Systematic uncertainties:
  - J^P assignments for Ξ^* states
  - higher/all L, different d in Blatt-Weisskopf, different NR for ΛK, more Ξ*,
  - adding $\Lambda \to p\pi$ helicity angle to consideration in amplidure
  - splitting into bins of $\Xi^* \to \Lambda K$ helicity angle
  or/and removing $\Xi_b \to J/\psi\Sigma(\to\Lambda\gamma)K$ from sideband
  - limited statistics of simulation sample via efficiency

Source	$P_{cs}(4459)^0$			$\Xi(1690)^-$			$\Xi(1820)^-$			Ξ^{*-} (1950)	Ξ^{*-} (2030)	NR
	M_0	Γ_0	FF	M_0	Γ_0	FF	M_0	Γ_0	FF	FF	FF	FF
J^P	$^{+4.7}_{-0.3}$	$^{+0.0}_{-5.7}$	$^{+0.1}_{-1.3}$	$^{+1.2}_{-0.1}$	$^{+14.0}_{-0.9}$	$^{+6.7}_{-0.3}$	$^{+0.8}_{-0.2}$	$^{+1.4}_{-0.5}$	$^{+4.2}_{-0.3}$	$^{+0.2}_{-9.4}$	$^{+0.0}_{-4.1}$	$^{+0.9}_{-11.2}$
Model	$^{+0.7}_{-1.1}$	$^{+8.0}_{-2.0}$	$^{+0.7}_{-0.5}$	$^{+0.5}_{-0.4}$	$^{+1.8}_{-13.5}$	$^{+1.9}_{-8.9}$	$^{+1.0}_{-0.6}$	$^{+7.8}_{-8.2}$	$^{+6.9}_{-4.1}$	$^{+49.9}_{-5.4}$	$^{+3.8}_{-1.6}$	$^{+10.3}_{-6.4}$
Λ decay	$^{+0.0}_{-0.7}$	$^{+0.0}_{-4.7}$	$^{+0.0}_{-0.3}$	$^{+0.0}_{-0.4}$	$^{+0.2}_{-0.0}$	$^{+0.0}_{-0.8}$	$^{+0.0}_{-0.5}$	$^{+0.0}_{-7.2}$	$^{+0.0}_{-4.1}$	$^{+2.4}_{-0.0}$	$^{+0.0}_{-1.3}$	$^{+3.9}_{-0.0}$
sWeights	$^{+0.0}_{-0.2}$	$^{+0.3}_{-0.0}$	$^{+0.1}_{-0.0}$	$^{+0.1}_{-0.1}$	$^{+3.1}_{-0.2}$	$^{+1.4}_{-0.0}$	$^{+0.2}_{-0.2}$	$^{+2.2}_{-1.5}$	$^{+1.6}_{-0.5}$	$^{+0.7}_{-1.6}$	$^{+0.0}_{-0.2}$	$^{+0.0}_{-2.7}$
Efficiency	$^{+0.1}_{-0.1}$	$^{+0.0}_{-0.5}$	$^{+0.0}_{-0.1}$	$^{+0.1}_{-0.2}$	$^{+2.1}_{-1.5}$	$^{+0.8}_{-1.3}$	$^{+0.1}_{-0.2}$	$^{+1.1}_{-0.3}$	$^{+0.5}_{-0.7}$	$^{+2.3}_{-1.0}$	$^{+0.3}_{-0.2}$	$^{+1.1}_{-0.9}$
Final	$^{+4.7}_{-1.1}$	$^{+8.0}_{-5.7}$	$^{+0.7}_{-1.3}$	$^{+1.2}_{-0.4}$	$^{+14.0}_{-13.5}$	$^{+6.7}_{-8.9}$	$^{+1.0}_{-0.6}$	$^{+7.8}_{-8.2}$	$^{+6.9}_{-4.1}$	$^{+49.9}_{-9.4}$	$^{+3.8}_{-4.1}$	$^{+10.3}_{-11.2}$

Table 3: Summary of absolute systematic uncertainties for the fit parameters. The units for masses (M_0) and widths (Γ_0) are MeV. The fit fraction in percent is denoted FF.

$B_s \to J/\psi p\bar{p}$, systematics

Phys. Rev. Lett. 128 (2022) 062001

- Estimated with pseudo-experiments generated according to alternative model, fit with baseline model

Source	M_{P_c}	Γ_{P_c}	$A(P_c)$	$f(P_c)$	p (%)	σ
NR(X) model	0.1	1.4	0.013	6.4	0.003	4.2
$J^P(P_c)$ assignment	2	12	0.100	5.5	0.2	3.1
Efficiency	0.2	4	0.012	0.4	0.001	4.4
Background	0.1	2	0.001	0.7	0.001	4.3
Hadron radius	0.7	4	0.034	1.7	0.02	3.7
Fit bias	$^{+0.2}_{-0.1}$	$^{+5}_{-2}$	$^{+0.040}_{-0.040}$	–	–	–
Total	2	14	0.11	8.6	–	3.1

NEW!

$B \to J/\psi \Lambda \bar{p}$, systematics

LHCB-PAPER-2022-031, in prep.

Source	$M_{P^{\Lambda}_{\psi s}}$	$\Gamma_{P^{\Lambda}_{\psi s}}$	$f_{P^{\Lambda}_{\psi s}}$	$f_{\mathrm{NR}(J/\psi \bar{p})}$	$f_{\mathrm{NR}(\Lambda \bar{p})}$
Hadron radius	0.1	0.4	0.3	0.2	0.2
LS values	0.3	0.1	0.8	0.7	0.6
Breit–Wigner P_{ψ}^{N-}	0.1	0.9	0.8	...	...
$J^P(P^{\Lambda}_{\psi s})$ assignment	0.1	0.9	1.2	0.4	0.9
Fitting procedure	0.1	0.2	0.1	1.0	1.1
Efficiency	0.02	0.19	0.02	0.3	0.2
Λ decay parameters	0.02	0.04	0.01	0.3	0.2
Background	0.01	0.05	0.96	0.4	0.7
Mass resolution	0.01	0.03	0.01	0.1	0.1
Total	0.4	1.3	1.9	1.4	1.7

New naming convention proposed

arxiv:2206.15233

round table (29 sept)

- To bring more order in the fast-growing list of exotic hadrons
- Preserve minimal change to existing names
- Create framework for future discoveries

Table 5: Summary of the impact of the exotic hadron naming scheme on various states, based on current knowledge of their properties. Quantum numbers that are not specified or marked "?" are unknown and the corresponding super-/sub-scripts not given. The current name indicated is that used in the PDG listings [16].

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]