Recent LHCb Results on heavy hadron spectroscopy

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24th High-Energy Physics international conference in Quantum Chromodynamics
5-9 July 2021, Montpellier - FR

Outline

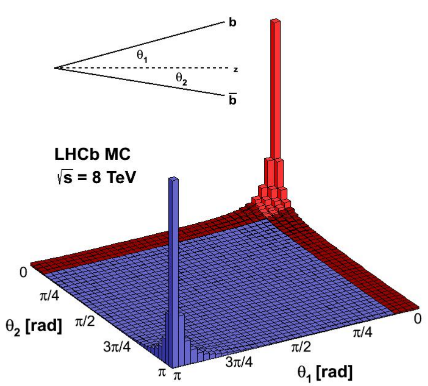
- The LHCb detector and overview of recent LHCb results about heavy hadron spectroscopy
- Highlights
  - Observation of a new D_s^+ meson in $B^0 \rightarrow D^- D^+ K^+ \pi^-$ decays[PRL 126 (2021) 122002]
  - Evidence of a new pentaquark candidate with strangeness [arXiv:2012.10380]
  - Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$ [arXiv:2103.01803]
- Summary and prospects

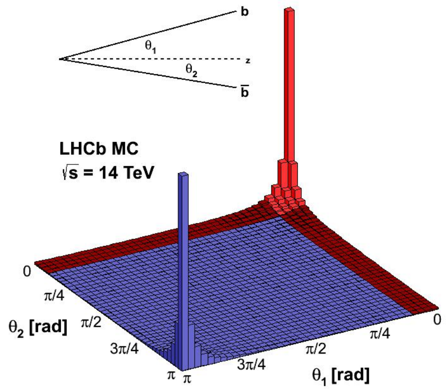
The LHCb detector

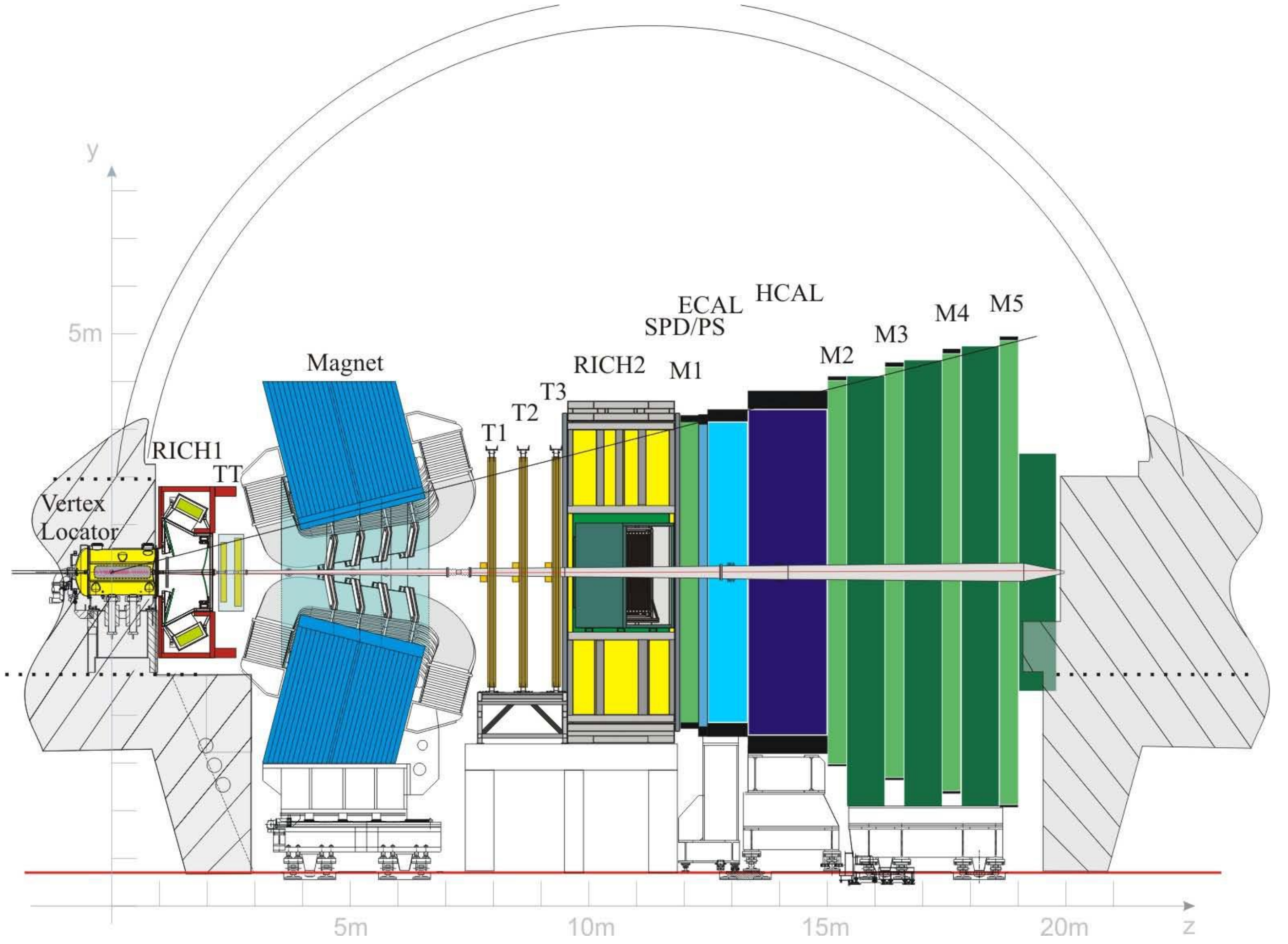
Int. J. Mod. Phys. A 30, 1530022 (2015)
JINST 3 (2008) S08005

A single-arm forward spectrometer, designed for the study of heavy flavor physics

- Excellent vertex, IP and decay-time resolution
  σ(IP) ≈ 20μm for high-p_T tracks
  σ(τ) ≈ 45fs for $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^- \pi^+$ decays
- Very good momentum resolution
  δp/p ≈ 0.5%-1% for p ∈(0,200) GeV
  σ(m_B) ≈ 24 MeV for two-body decays
- Hadron and muon identification
  $\varepsilon_{K\to K}$≈ 95% for $\varepsilon_{\pi\to K}$≈ 5% up to 100 GeV
  $\varepsilon_{\mu\to\mu}$≈ 97% for $\varepsilon_{\pi\to\mu}$≈ 1%-3%





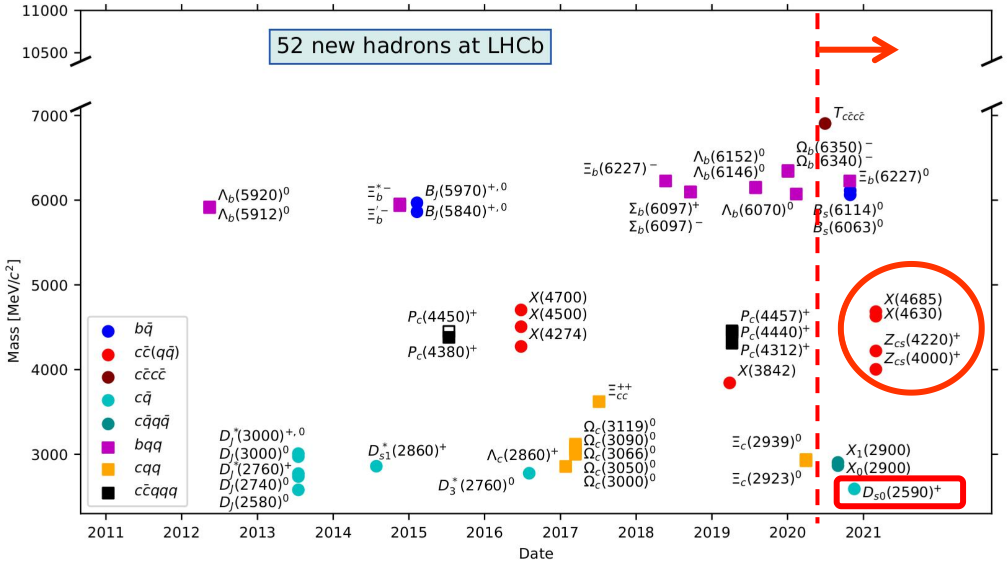


2<η<5 range: ~25% $b\bar{b}$ pairs
in LHCb acceptance

Overview of recent LHCb results about heavy hadron spectroscopy

Some searches:

- Ω_{cc}^{+} via $\Xi_c^+ K^- \pi^+$[arXiv:2105.06841]
- Ω_{bc}^{+} and Ξ_{bc}^{0} via $\Lambda_c^+ \pi^-$ and $\Xi_c^+ \pi^-$[arXiv:2104.04759]
- Ξ_{bc}^{0} via $D^0 p K^-$[JHEP 2011 (2020) 095]



[LHCb-FIGURE-2021-001]
(also cited from Jingyi's talk at QCD21)

Observation of some new states:

- A new Ξ_b^0 state decaying to $\Xi_b^- \pi^+$[PRD 103 (2021) 012004]
- Two new excited B_s^0 states decaying to $B^+ K^-$ [arXiv:2010.15931]
- New spin-0 and spin-1 $D^+ K^-$ resonances and $\chi_{c0}(3930)$, $\chi_{c2}(3930)$ states [PRL 125 (2020) 242001, PRD 102 (2020) 112003]
- X(4740) state in $B_s^0 \to J/\psi \pi^- \pi^+ K^- K^+$ decay[JHEP 2102 (2021) 024]
- X(6900) in di-J/ψ system[Sci. Bull. 65 (2020) 1983]

PRL 126 (2021) 122002

Observation of a new D_s^+ meson in $B^0 \to D^- D^+ K^+ \pi^-$ decays

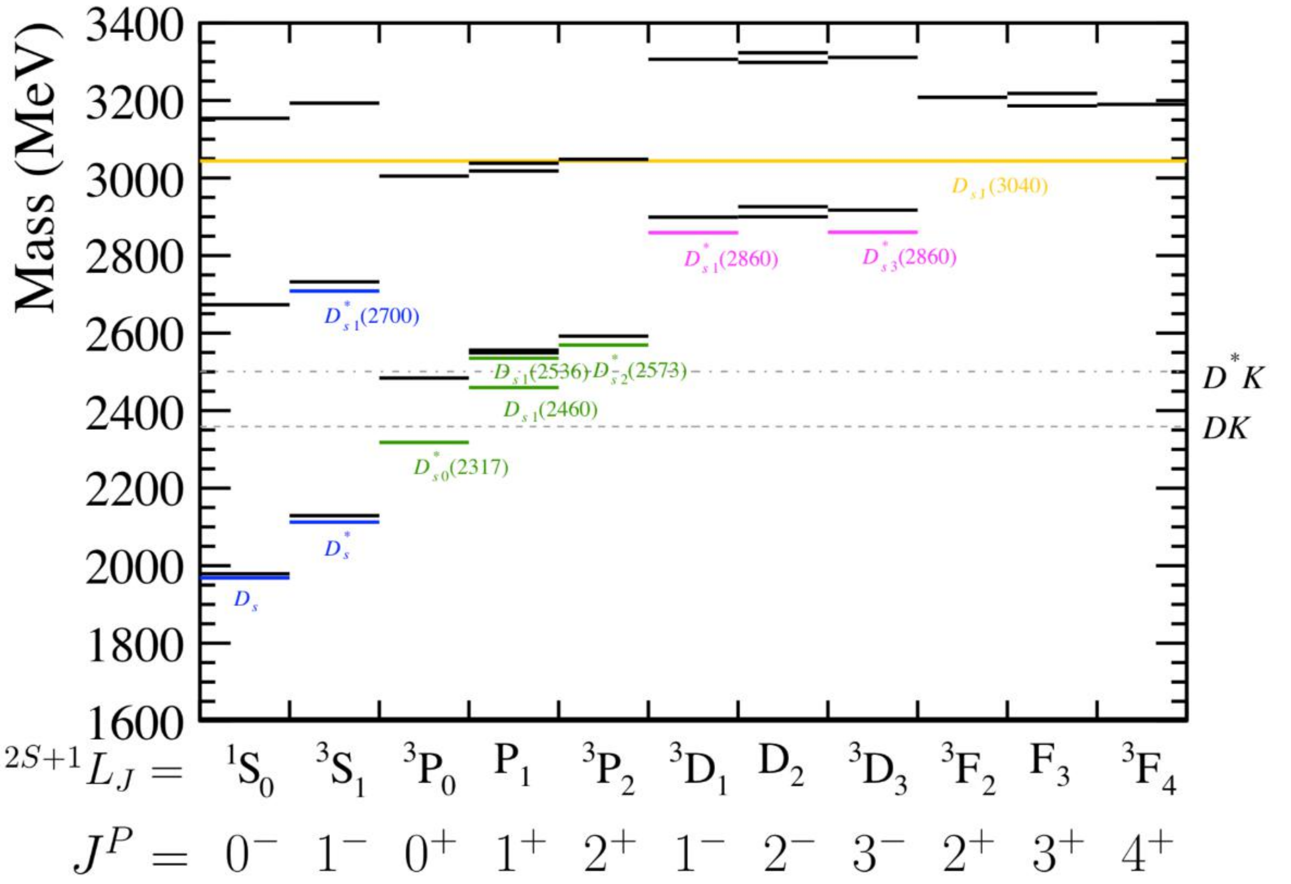
Overview of D_s^+ spectroscopy and motivation

PRL 126 (2021) 122002

D_s spectroscopy overview

- 10 states experimentally established
- Below 3.1 GeV, still 6 states missing
  - 2^1S_0 state expected to be the lightest one

(cited from Chen Chen's talk at CLHCP2020)



- Theoretical predictions[PRD 93 (2016) 034035]
- Experimental values from PDG

Why $B^0 \to D^- D^+ K^+ \pi^-$?

- DK pair → states with natural $J^P(0^+, 1^-, 2^+$, etc)
- $D^{*0}K^+$ or $D^{*+}K^0$ →low efficiency at LHCb
- $D^+K^+\pi^-$ → ideal final state for new D_s state

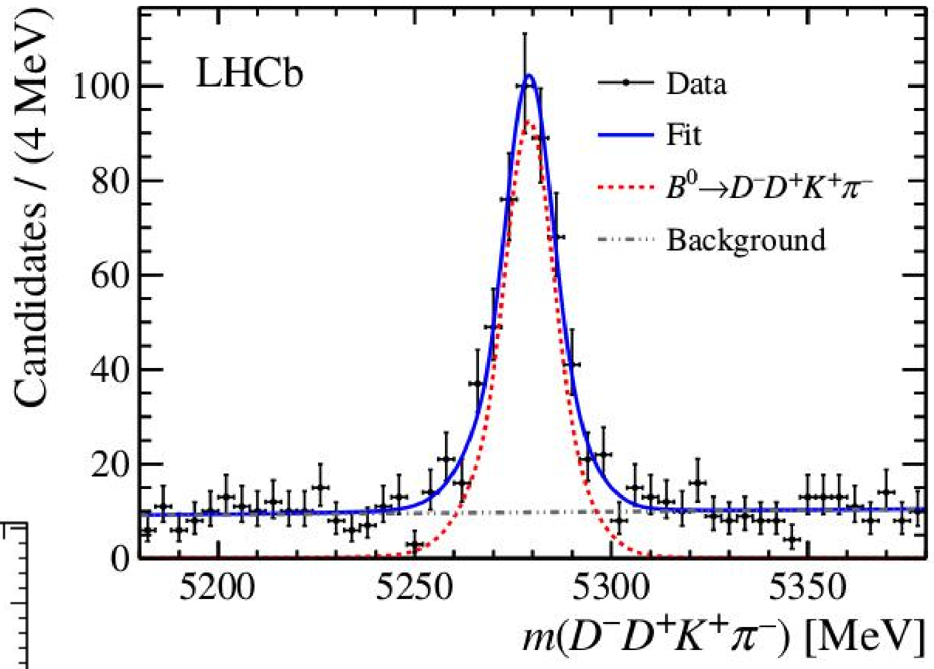
Especially, require $M(K^+\pi^-)<M(K(890)^*)$, sensitive to states with unnatural $J^P(0^-, 1^+, 2^-$, etc) and mass>2.5 GeV

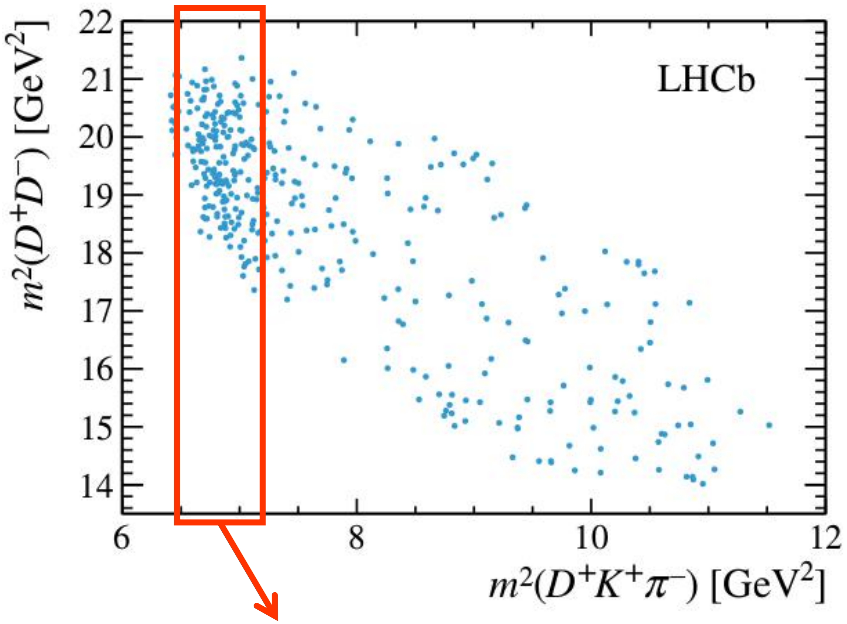
Data sample and amplitude analysis of $B^0 \rightarrow D^- D^+ K^+ \pi^-$ PRL 126 (2021) 122002

2016-2018 data collected by the LHCb detector, ~5.4fb^{-1}

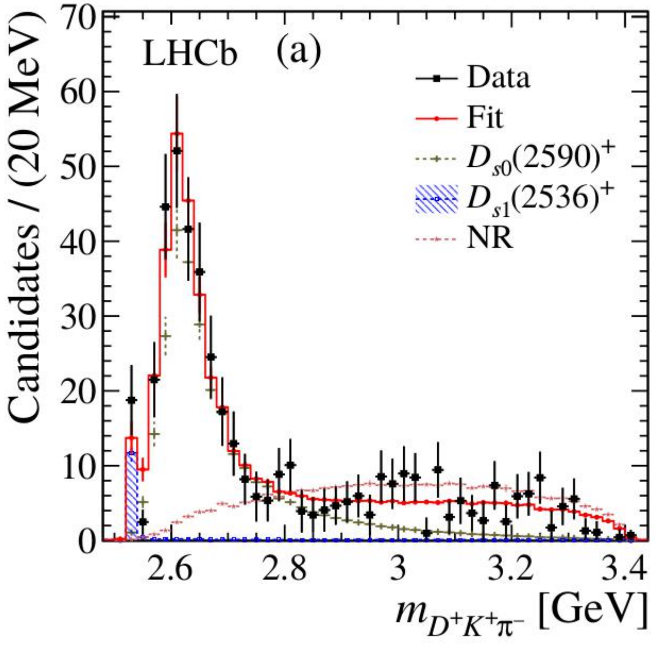
- Require m($K^+\pi^-$)<0.75 GeV
- Only combinatorial background

→Signal yield: ~450





Clear band in Dalitz plot



A new D_s^+ state with significance > 20σ

Pole mass: 2591 ± 6(stat) ± 7(syst) MeV

Pole width: 89 ± 16(stat) ± 12(syst) MeV

J^P=0$^-$ prefered with significance > 15σ

Evidence of a $J/\psi\Lambda$ structure and observation of two excited Ξ^- states in $\Xi_b^- \to J/\psi\Lambda K^-$ decay

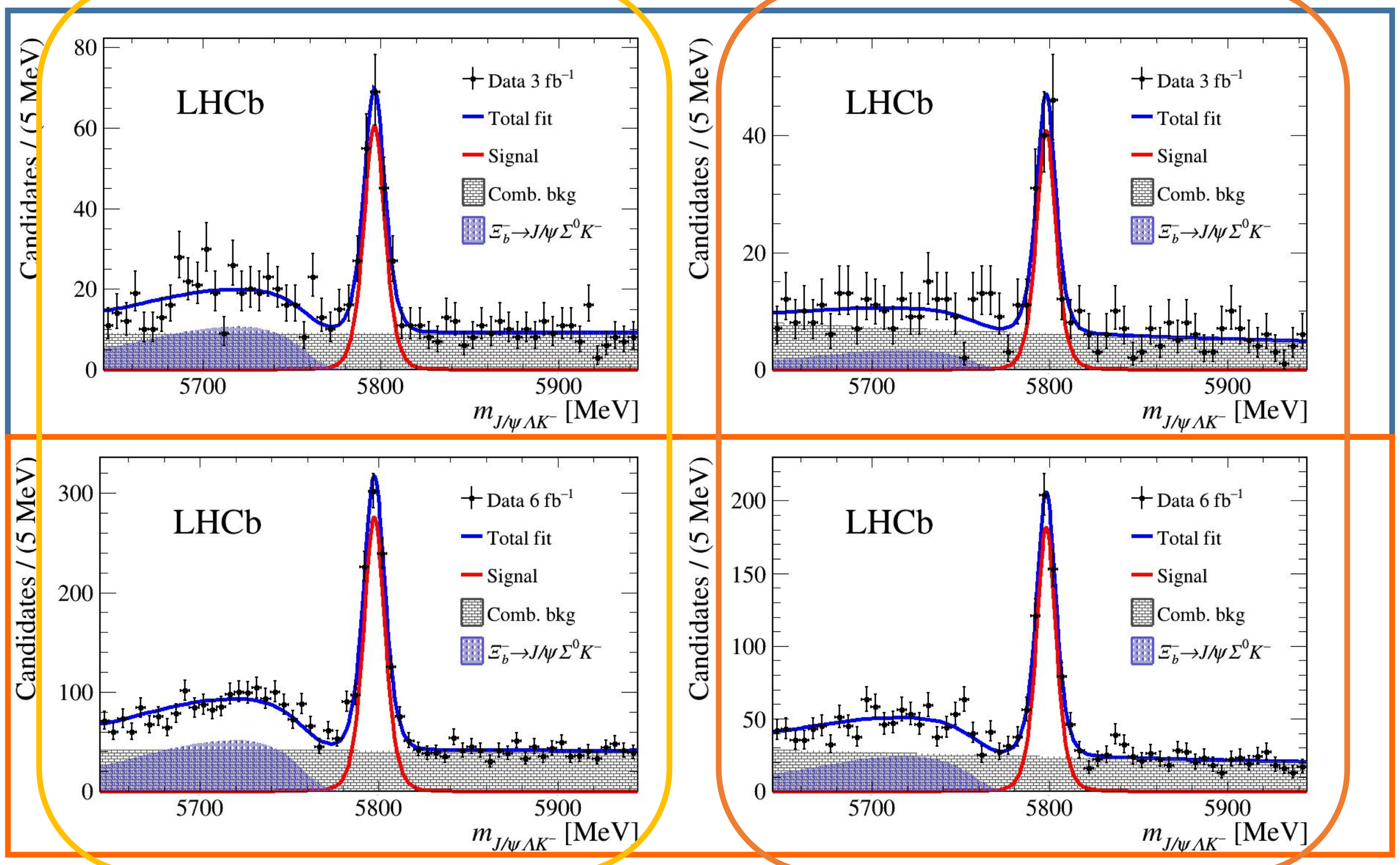
$\Xi_b^- \to J/\psi \Lambda K^-$, $J/\psi \to \mu^+\mu^-$, $\Lambda \to p\pi$:

Sci.Bull. 66 (2021) 1278

suggested as a channel for pentaquark P_{cs} [PRC 93 (2016) 065203]

first observed by LHCb in 2017[PLB 772 (2017) 265]

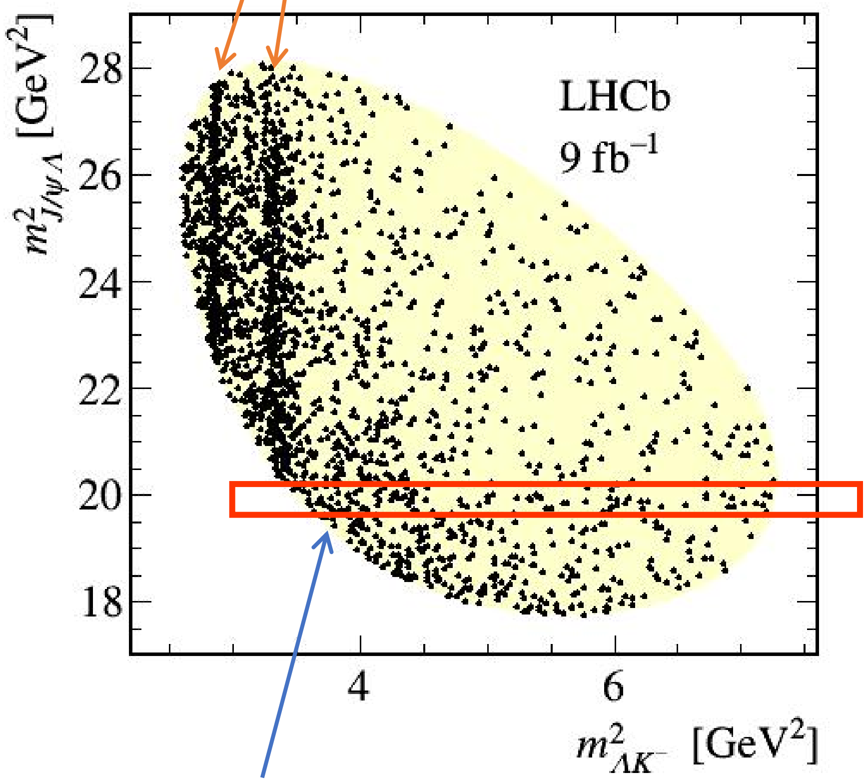
With Run I and Run II data, ~1750 signals, purity ~80%



Λ decay in vertex detector

Λ decay outside vertex detector

Clear Ξ^* contribution



Potential P_{cs} contribution?

Amplitude analysis performed…

Full 6D amplitude analysis performed:

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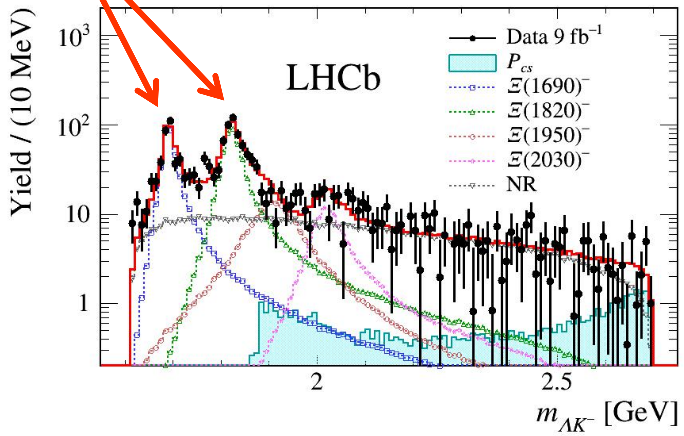
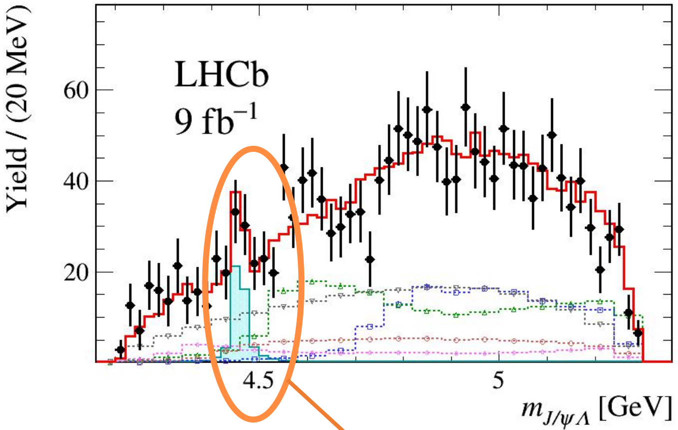
Adding a P_{cs} improves -2lnL by 43 units, ~4.3σ significance

After considering syst. uncertainty and look-elsewhere effect, **3.1σ significance**

Two Ξ^* states





Statistics not enough to determine J^P of $\Xi(1690)^-$ and P_{cs}

Possible two-peak structure of P_{cs} can't be refuted

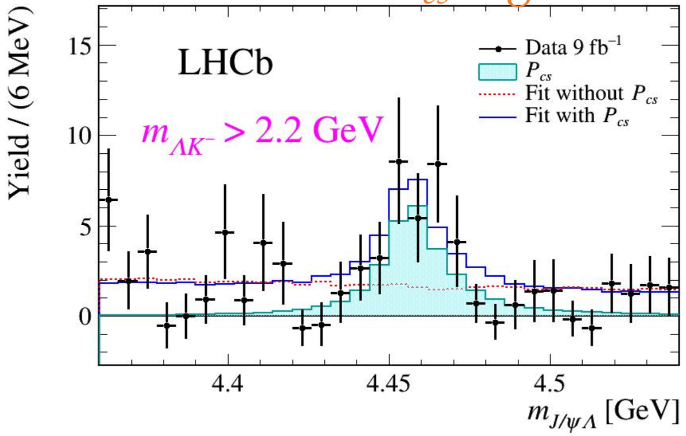
Two-peak structure apears in P_c state in $\Lambda_b^- \to J/\psi p K^-$[PRL 122 (2019) 222001]

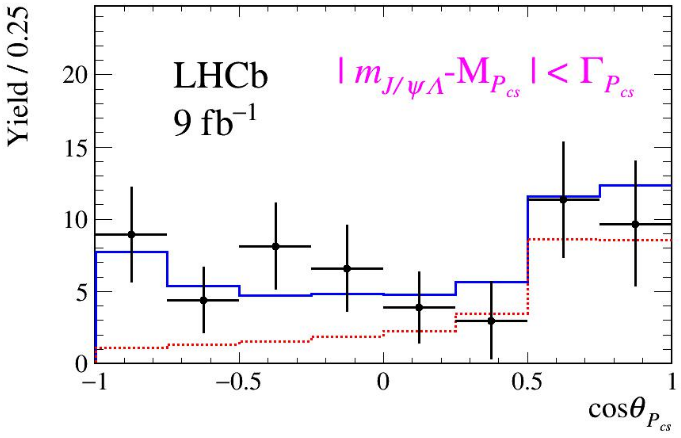
P_{cs} mass 19MeV below the $\Xi_c^0 \overline{D}^{*0}$ threshold

State	M_0 [MeV]	Γ_0 [MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9+0.7}_{-0.6-1.3}$
$\Xi(1690)^-$	$1692.0 \pm 1.3\,^{+1.2}_{-0.4}$	$25.9 \pm 9.5\,^{+14.0}_{-13.5}$	$22.1\,^{+6.2+6.7}_{-2.6-8.9}$
$\Xi(1820)^-$	$1822.7 \pm 1.5\,^{+1.0}_{-0.6}$	$36.0 \pm 4.4\,^{+7.8}_{-8.2}$	$32.9\,^{+3.2+6.9}_{-6.2-4.1}$

Consistent with PDG, precision improved

Zoom into P_{cs} region





Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi \phi$

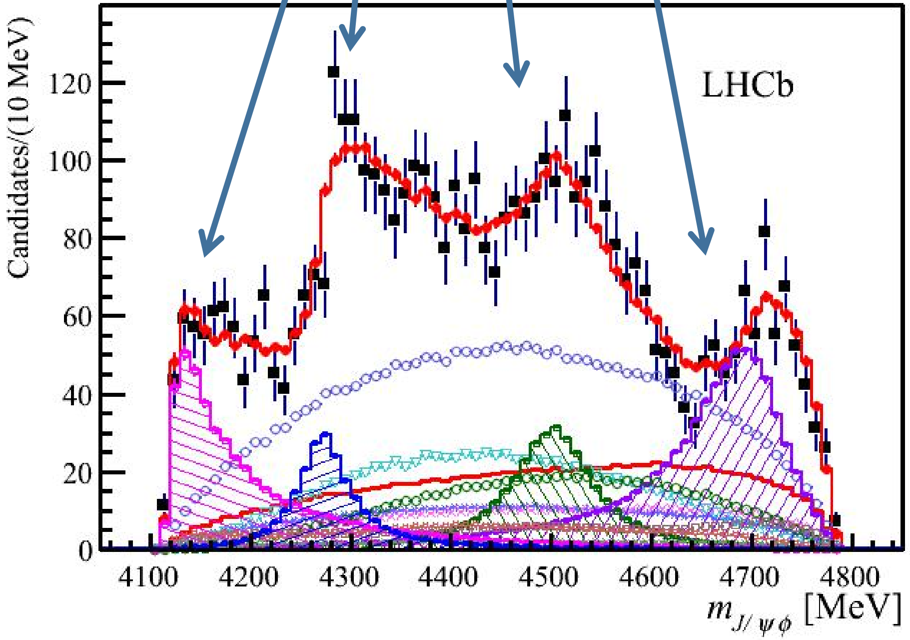
Previous analysis of $B^+ \to J/\psi\phi K^+$

arXiv:2103.01803

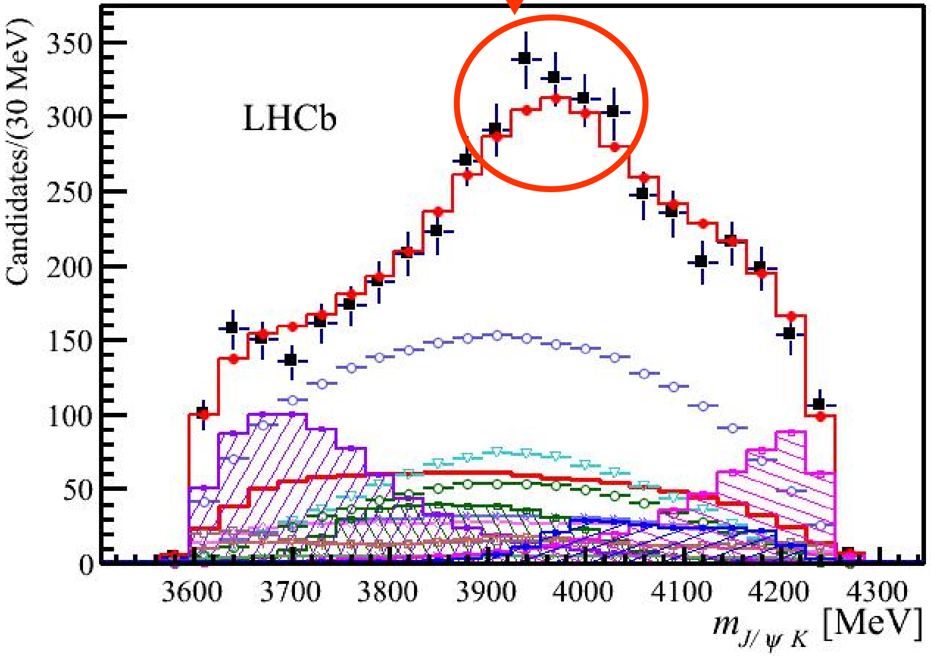
Amplitude analysis is performed with Run I data(3fb^{-1})

[PRL 118 (2017) 022003, PRD 95 (2017) 012002]

Four significant $J/\psi\phi$ structures are observed



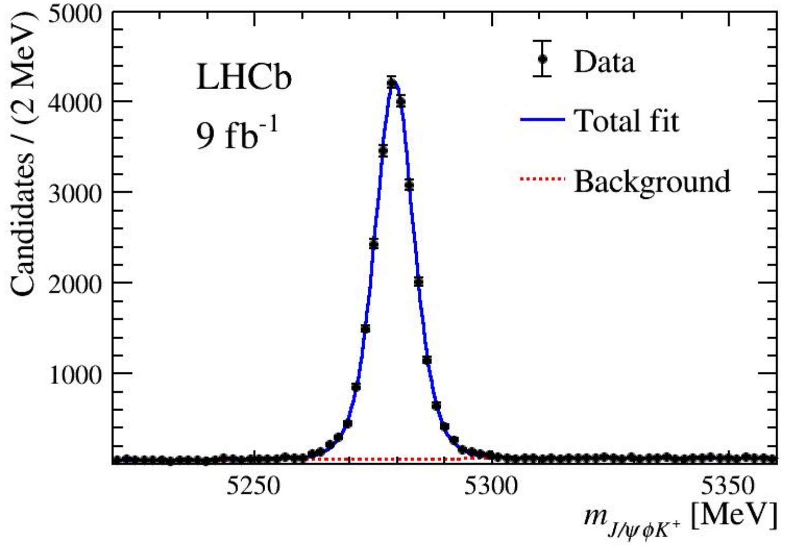
A hint of $J/\psi K^+$ structure

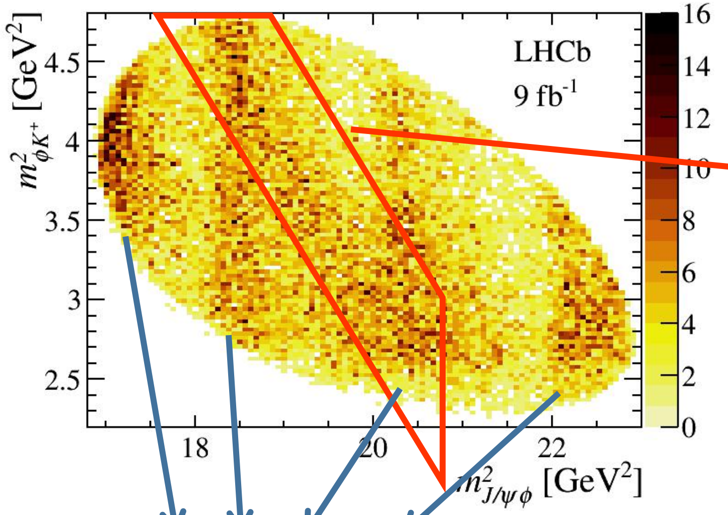


Larger data sample leads to further exploration in $B^+ \to J/\psi\phi K^+$

Updated $B^+ \to J/\psi\phi K^+$ samples

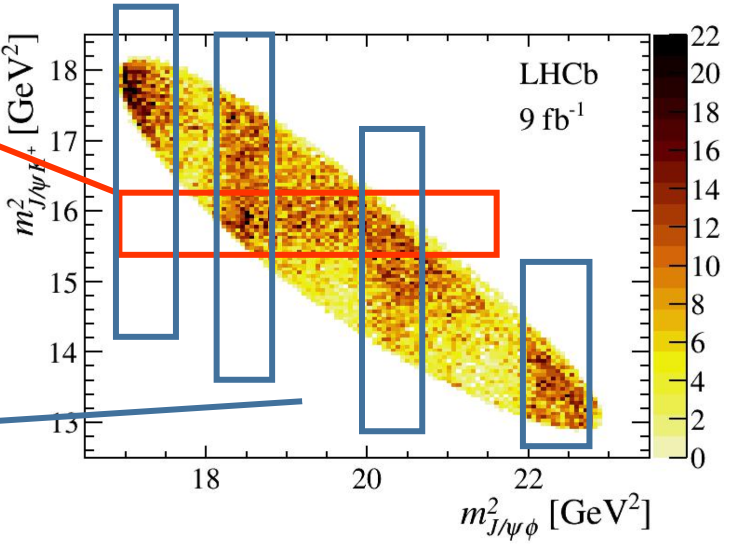
larger dataset(Run I+Run II) and
improved selection(15% higher signal efficiency)
$\to$
~6x signal yield(~24k)
much smaller comb. BKG fraction(~4%)





Significant $J/\psi K^+$ bands: Z_{cs} candidates$\to$

Explored by performing amplitude analysis



Clear contribution from $J/\psi\phi$ resonances, same as Run I

Full 6D amplitude model

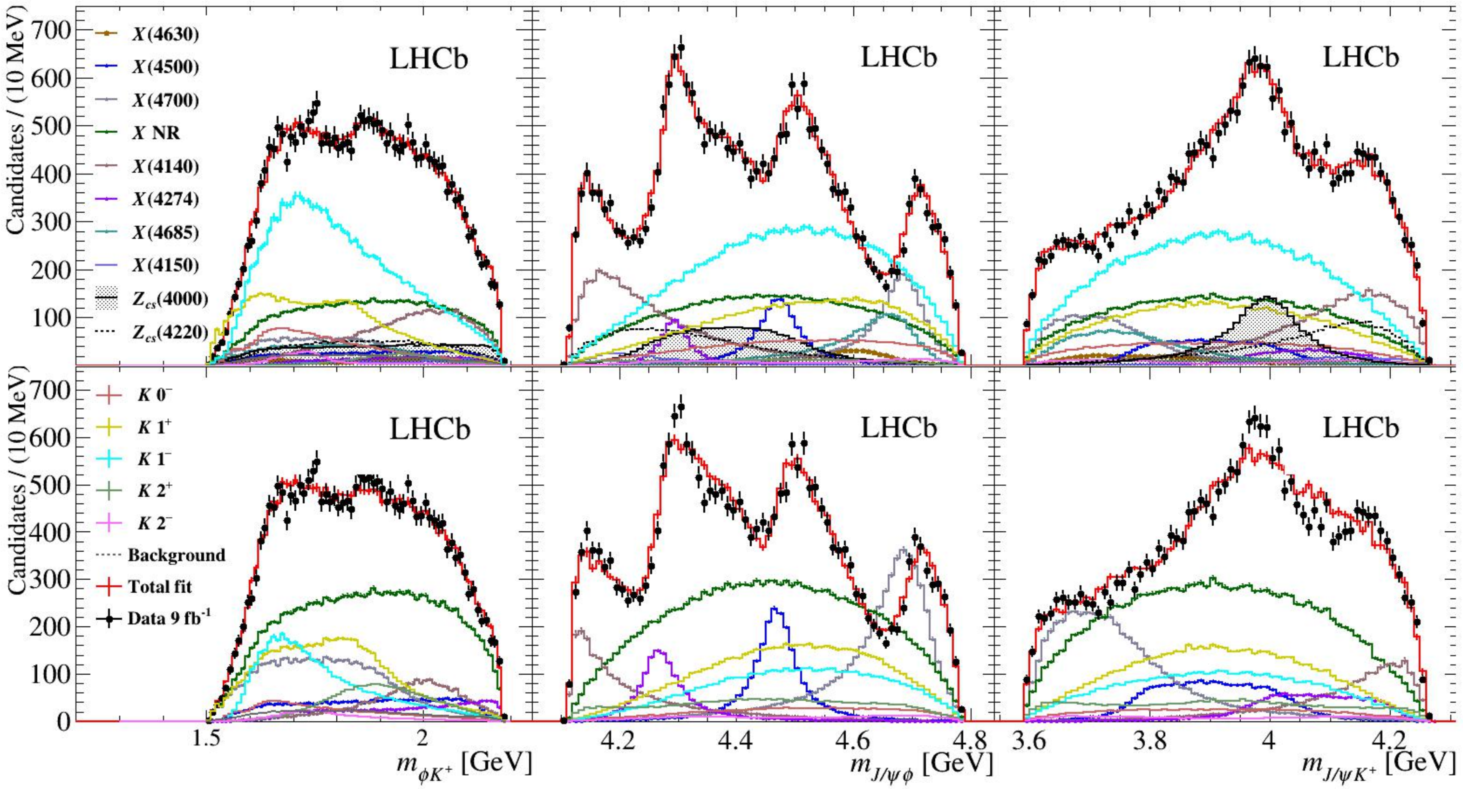
arXiv:2103.01803

Due to increased sample size, Run I model can't fit data well

→ K^* improved model + new exotic states

1^+ Z_{cs} and 1^+ X produce largest improvement, each~15σ(stat.)

$1^{+/-}$ Z_{cs}, 1^- X, 2^- X improve fit quality significantly, are also included, each>5σ(stat.)



← default model

← Run I model

Amplitude fit results

Breit-Wigner mass, width

arXiv:2103.01803

Fit Fraction

Contribution	Significance [$\times\sigma$]	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+18}_{-110}$	$174 \pm 27\,^{+134}_{-73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5\,^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6\,^{+10}_{-8}$	$5.6 \pm 0.7\,^{+2.4}_{-0.6}$
$X(4700)$	17 (18)	$4694 \pm 4\,^{+16}_{-3}$	$87 \pm 8\,^{+16}_{-6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3\,^{+8}_{-10}$
$X(4140)$	13 (16)	$4118 \pm 11\,^{+19}_{-36}$	$162 \pm 21\,^{+24}_{-49}$	$17 \pm 3\,^{+19}_{-6}$
$X(4274)$	18 (18)	$4294 \pm 4\,^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5\,^{+0.8}_{-0.4}$
$X(4685)$	15 (15)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$	$7.2 \pm 1.0\,^{+4.0}_{-2.0}$
All $Z_{cs}(1^+)$				$25 \pm 5\,^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$

$J^P = 1^{+/-}$ prefered,

need more data

- Four X states observed in Run I are confirmed.
- Observation of two Z_{cs} states, both significance >5σ.
- Observation of two new X states, both significance >5σ.

Summary and prospects

The LHCb detector produces many nice results, fruitful on heavy hadron spectroscopy!

Some highlights:

- New $D_{s0}(2590)^+$ state is first observed with high significance(>20σ) in $B^0 \rightarrow D^- D^+ K^+ \pi^-$

  J^P=0^- prefered with significance > 15σ
  Strong candidate to be the missing $D_s(2^1S_0)^+$ state
- Evidence of $P_{cs}(4459)^0$ in $\Xi_b^- \rightarrow J/\psi \Lambda K^-$

  P_{cs} mass 19MeV below the $\Xi_c^0 \overline{D}^{*0}$ threshold
  More data is needed to explore J^P and possible two-peak structure
- Observation of two $c\bar{c}u\bar{s}$ tetraquarks and two $c\bar{c}s\bar{s}$ tetraquarks in $B^+ \rightarrow J/\psi \phi K^+$

  1^+ $Z_{cs}(4000)^+$ with significance > 15σ, $1^{+/-}$ $Z_{cs}(4220)^+$ with larger width

  Two new X states observed, four X states observed in Run I analysis confirmed

The upgrade of the LHCb detector is going on wheels : arXiv:1808.08865

- 7x data by 2029 than current(14x for hadronic decays), half of these by 2024

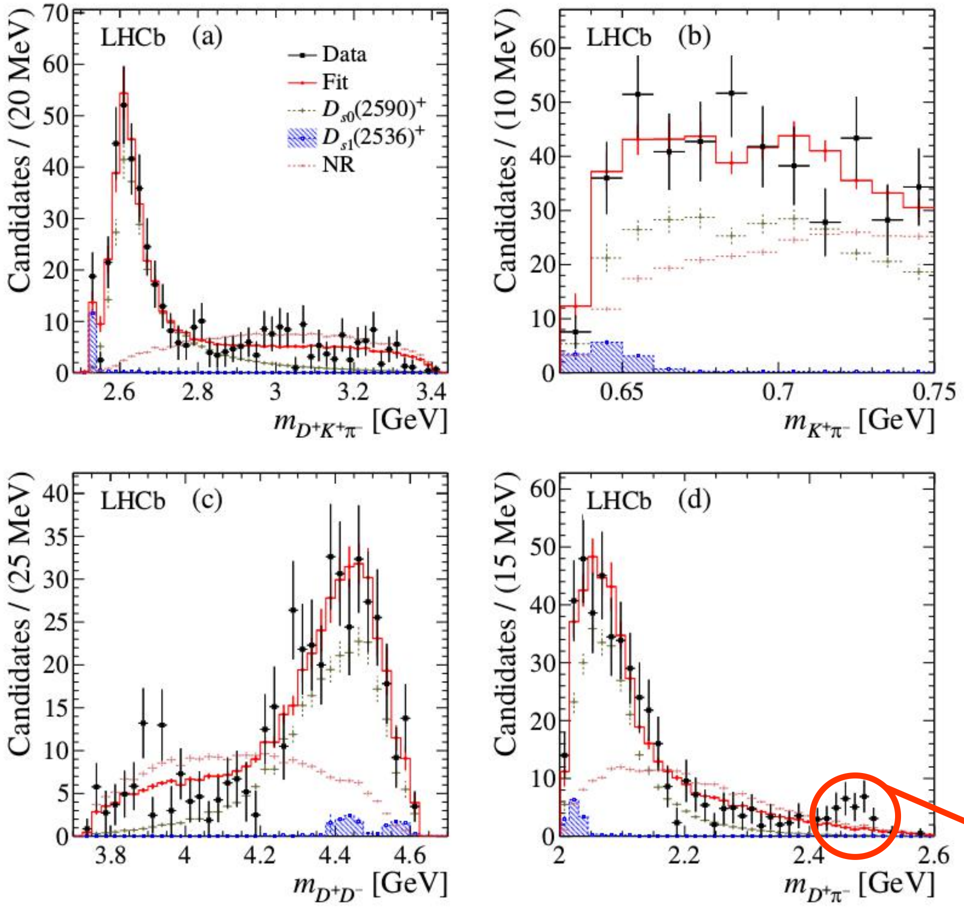
Thank you for your attention!
Any question or comment?

Backup

Amplitude analysis of $B^0 \to D^- D^+ K^+ \pi^-$

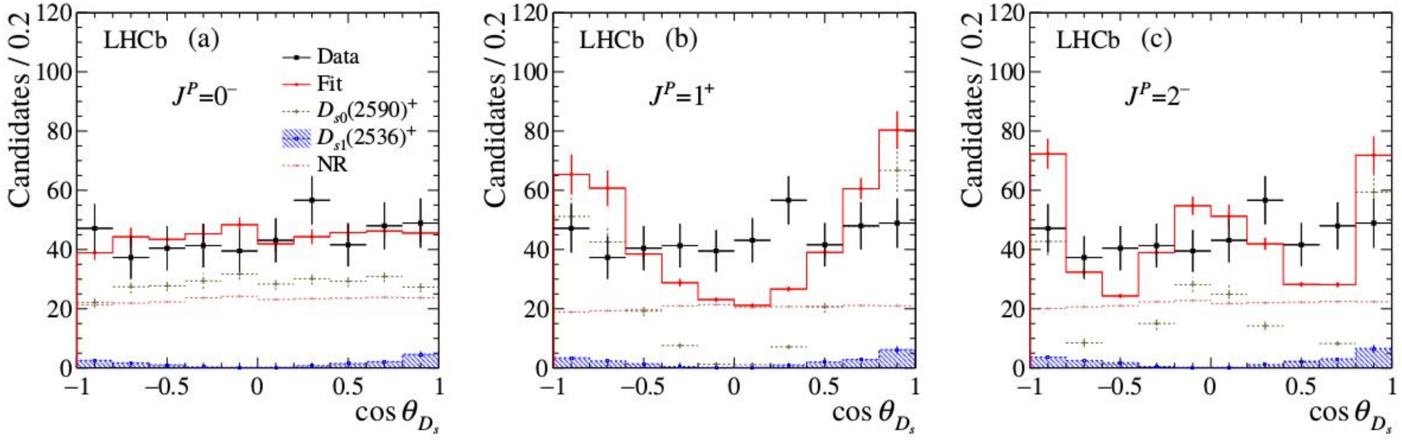
PRL 126 (2021) 122002

Mass projections of different systems:



	Fit fraction $(\times 10^{-2})$
$D_{s0}(2590)^+$	63 ± 9 (stat) ± 9 (syst)
$D_{s1}(2536)^+$	3.9 ± 1.4 (stat) ± 0.8 (syst)
NR	51 ± 11 (stat) ± 19 (syst)
D_{s0}^+–NR	−18 ± 18 (stat) ± 24 (syst)
D_{s1}^+/D_{s0}^+	6.1 ± 2.4 (stat) ± 1.4 (syst)

Spin-parity test: $J^P = 0^-$ is the most consistent with data.



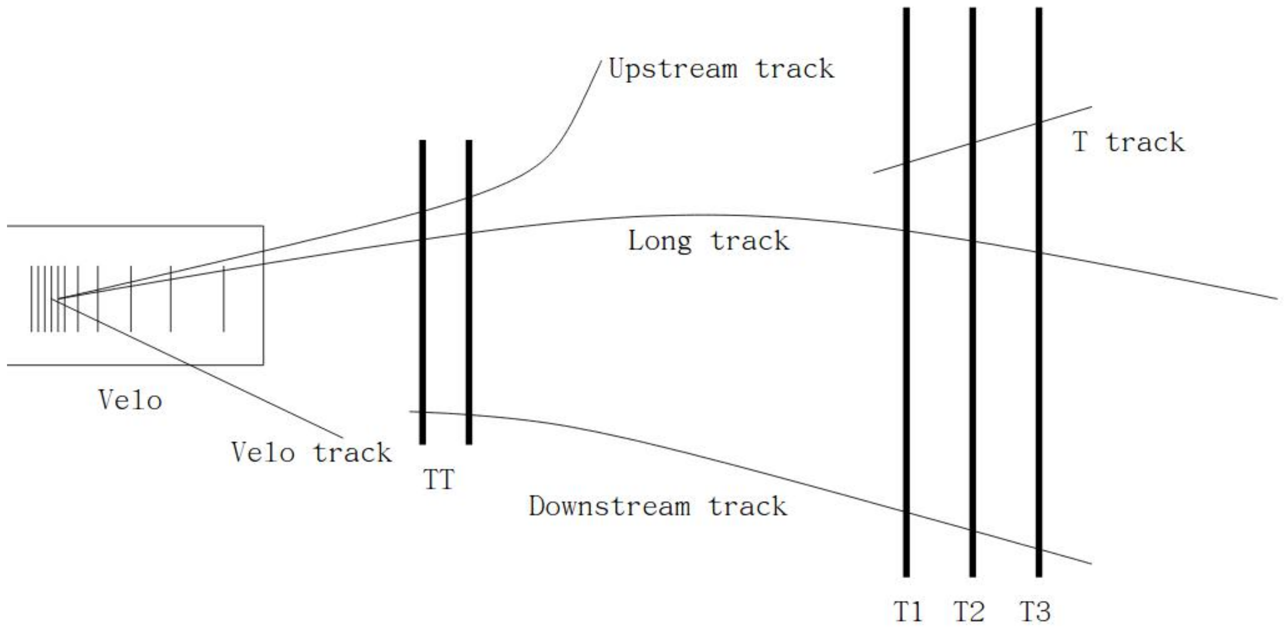
Could be from the $D_s^*(2460)^+$ contribution, handled in syst. study

Λ reconstruction at LHCb

Int. J. Mod. Phys. A 30, 1530022 (2015)
JINST 3 (2008) S08005

Due to large mean life time of Λ baryon, most Λ particles decay after Velo.

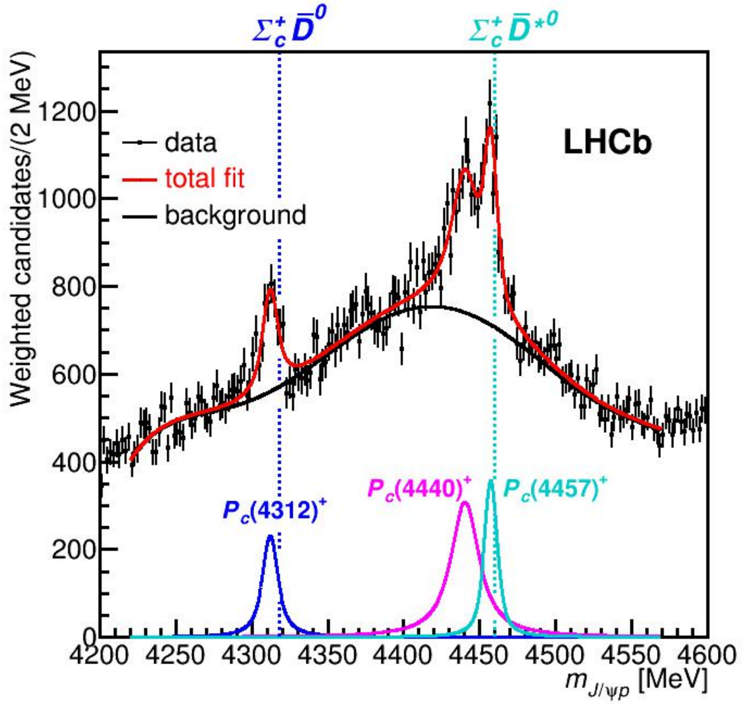
- For Λ decays in Velo, reconstructed by two Long tracks;
- For Λ decays outside Velo, reconstructed by two Downstream tracks;



Two-peak structures in P_c and P_{cs} spectra

PRL 122 (2019) 222001
Sci.Bull. 66 (2021) 1278

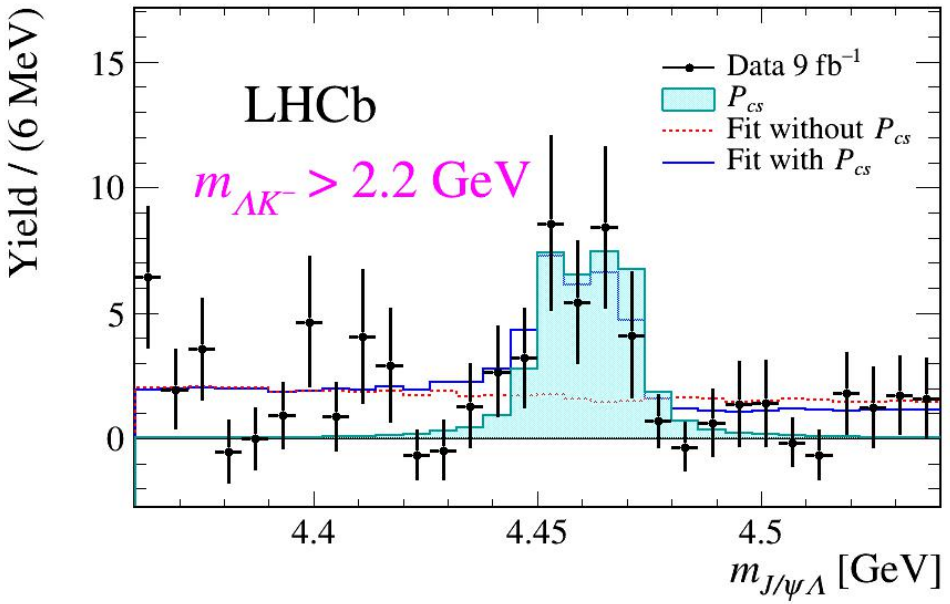
Two-peak interpretation with a statistical significance of 5.4σ



relative contributions

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Improves 2lnL by 4.8 units for 4 additional free parameters



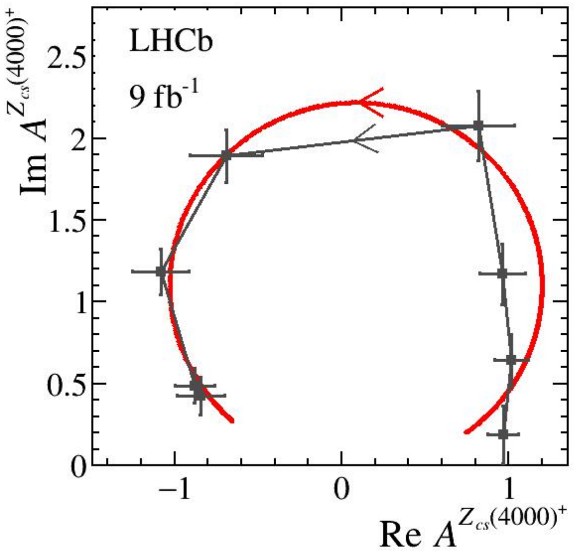
$M_1 = 4454.9 \pm 2.7$(stat) MeV, $\Gamma_1 = 7.5 \pm 9.7$(stat) MeV;

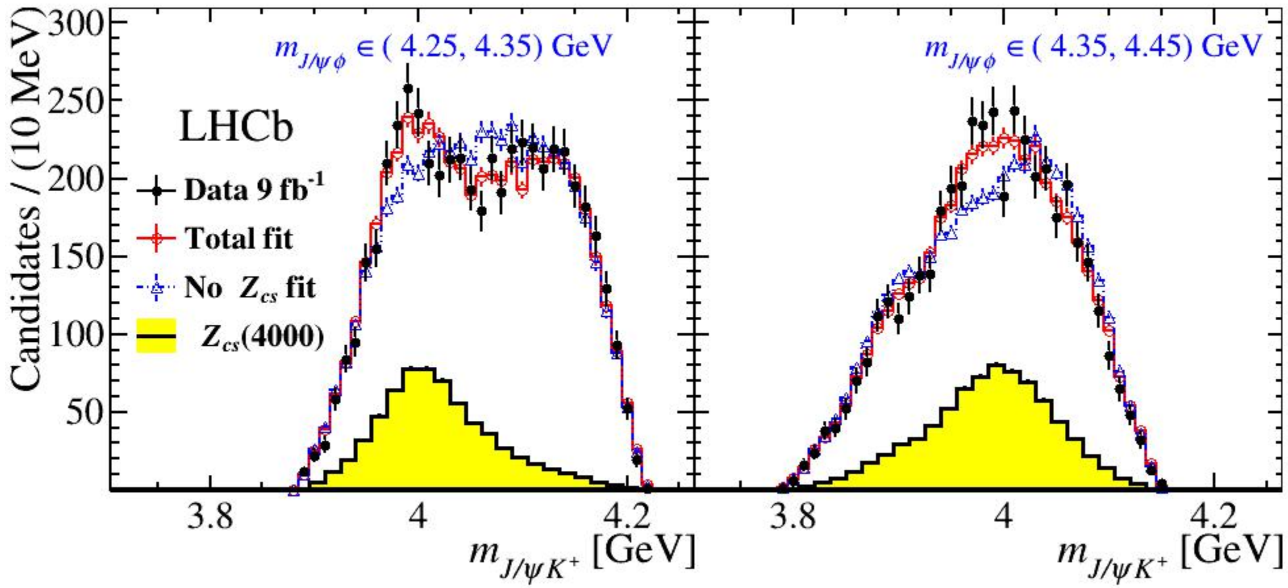
$M_2 = 4467.8 \pm 3.7$(stat) MeV, $\Gamma_1 = 5.2 \pm 5.3$(stat) MeV.

Test of the 1^+ $Z_{cs}(4000)^+$ state

arXiv:2103.01803

Argand diagram shows the magnitude and phase obtained from data fit is consistent with expected BW hehaviour.





Fit projections onto $m_{J/\psi K^+}$ in two slices of $m_{J/\psi\varphi}$ for the default model with and without the 1^+ $Z_{cs}(4000)^+$ state.