Brookhaven Forum 2021
Opening New Windows to the Universe (BF2021)

This conference will be held as a virtual event.
November 3–5, 2021

Exotic searches at LHCb

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on behalf of the LHCb Collaboration

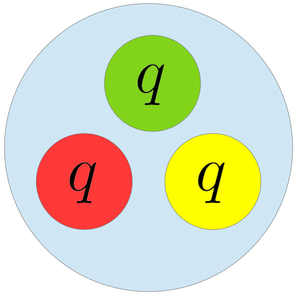
Outline

- Introduction to exotic spectroscopy
- The LHCb detector
- Pentaquark studies
  - Evidence of a $J/\psi\ \Lambda$ structure in $\Xi_b^- \rightarrow J/\psi\ \Lambda\ K^-$ decays
  - Evidence of $J/\psi\ p\ (\bar{p})$ structures in $B^0_s \rightarrow J/\psi\ p\ \bar{p}$
- Selected tetraquark studies
  - Tetraquarks observation in $B^+ \rightarrow J/\psi\ \Phi\ K^+$
  - Observation of doubly charmed tetraquark in prompt $D^0\ D^0\ \pi^+$ decay
- Conclusions and outlooks

Introduction

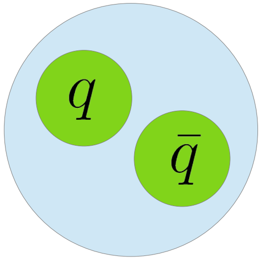
Hadron spectroscopy very important to probe low-energy non-perturbative QCD dynamics

Quarks are confined in baryons and mesons
(**conventional hadrons**)



baryons

mesons



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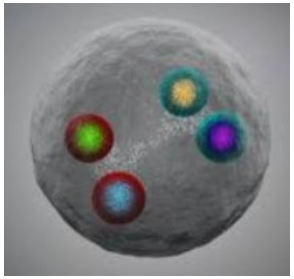
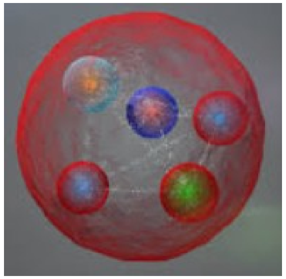
different multi-quarks compounds
are also allowed
(**exotic hadrons**)

$(q\bar{q}q\bar{q})$
tetraquarks





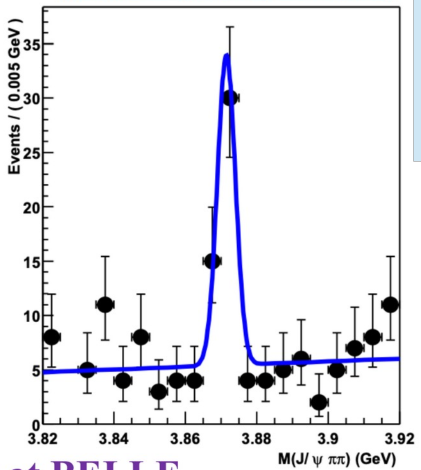
$(qqqq\bar{q})$
pentaquarks

Multiquarks states are first predicted in 1964 in quark model original paper, by **M. Gell-Mann** and **G. Zweig**.

First exotic candidates

Tetraquarks and pentaquarks have been observed !

[PRL 91 (2003) 262001]



2003 at BELLE

First tetraquark observation from Belle in 2003

$$B^{\pm} \to J/\psi\, K^{\pm}\, \pi^{+}\, \pi^{-}$$

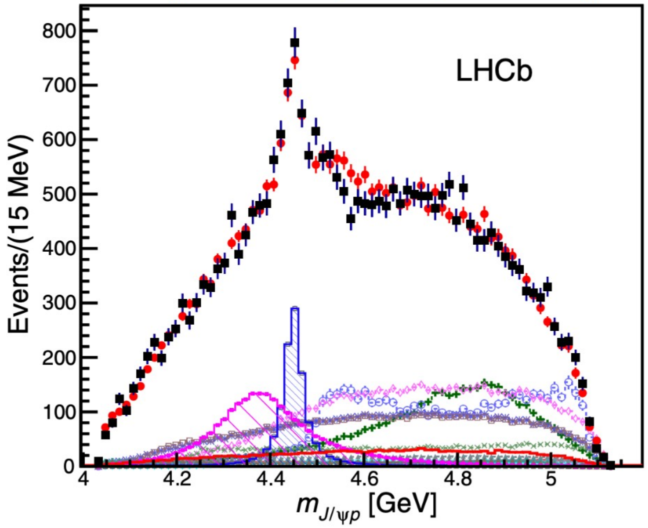
X(3872) in J/ψ π π

First pentaquark evidence from LHCb in 2015

$$\Lambda_b \to J/\psi\, p\, K$$

P(4450) in J/ψ p mass

[PRL 115 (2015) 072001]

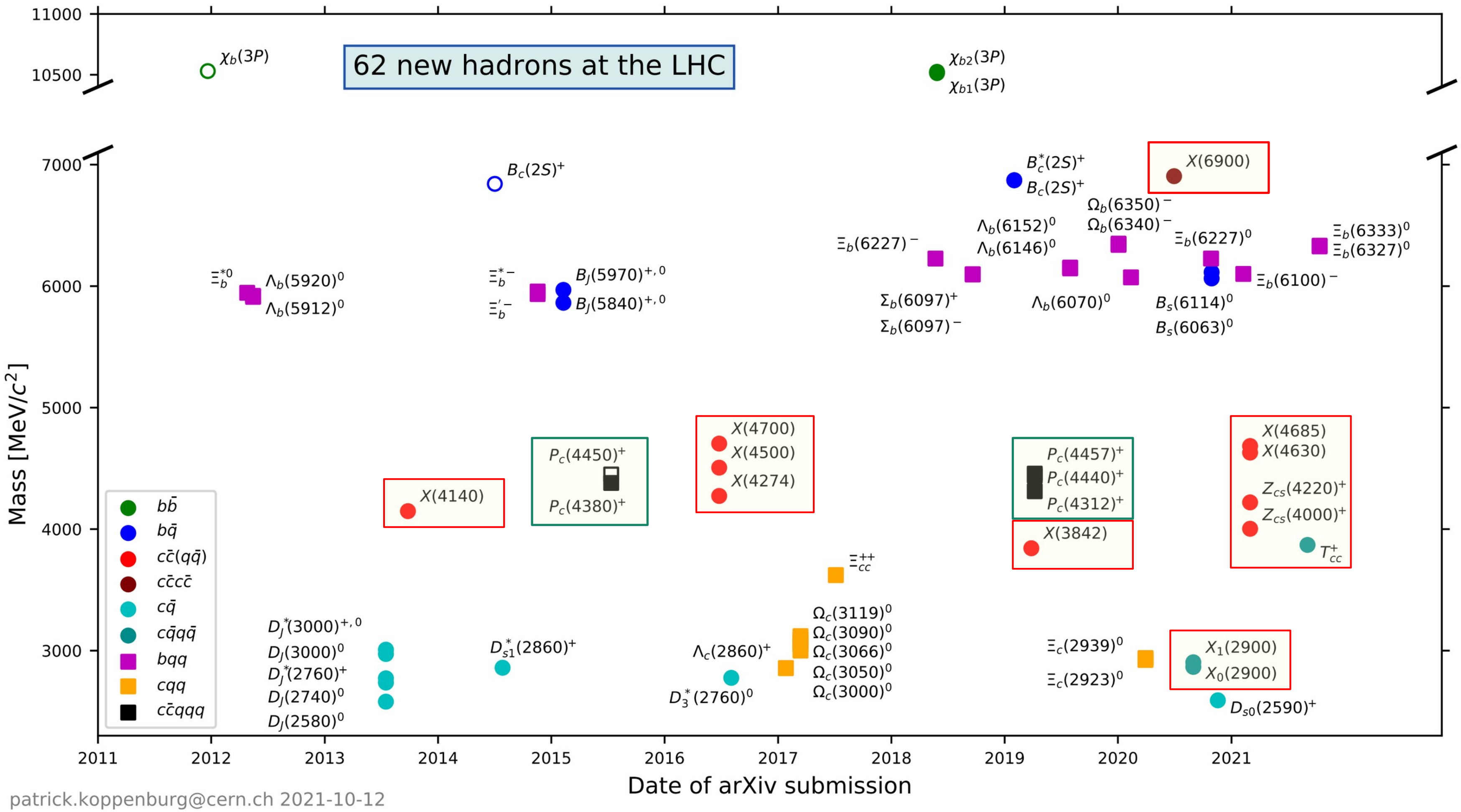


2015 at LHCb

Not yet clear the nature of these compounds

A forest of new states

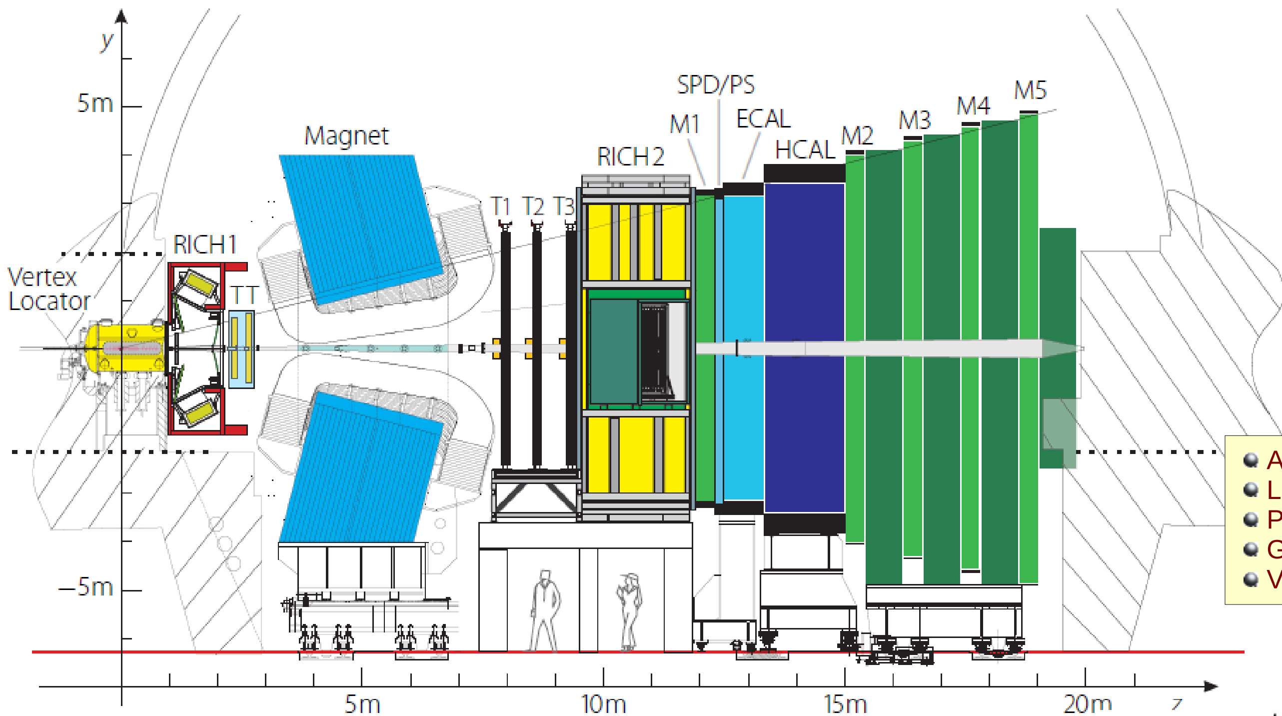
62 new hadrons discovered at LHC and 18 of them are “exotic”

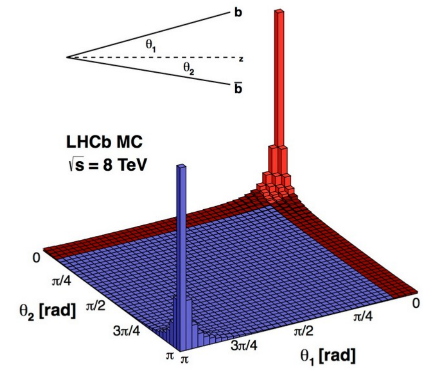


Though quantum chromodynamics naturally allows the existence of states beyond conventional mesons and baryons, the detailed mechanisms responsible for binding multi-quark states are still largely **mysterious**.

JINST **3** S08005

The LHCb experiment





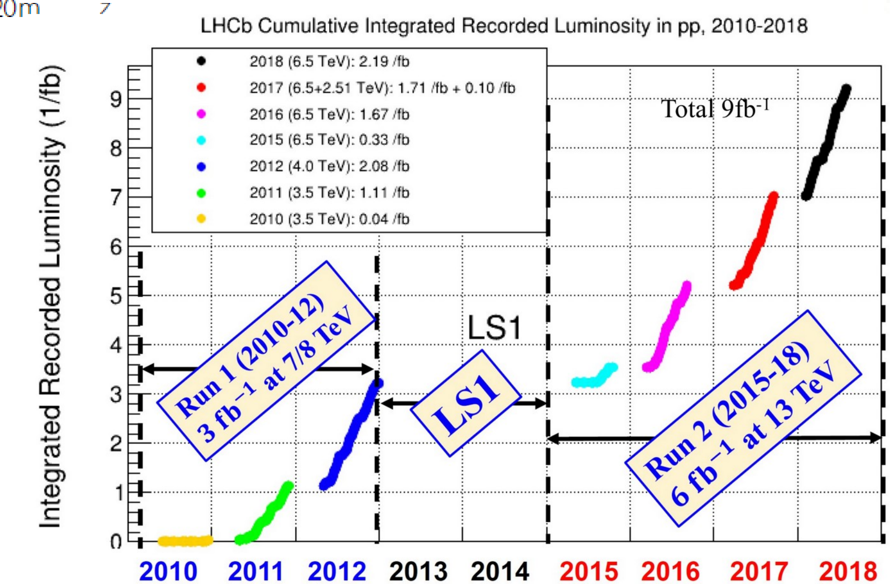
bb production angles

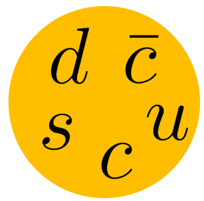
- All kinds of hadrons can be produced
- Large statistics: 6×10^4 b b-bar /sec @ 13 TeV
- Powerful particle identification
- Good momentum resolution
- Very high vertex resolution: σ_{IP} = 20 μm on B and D

Single arm spectrometer, 25% of $b\bar{b}$ pairs produced in the acceptance

Designed for heavy flavor physics measurements

Unique kinematic region: high rapidity (2.0 < y < 5) and low pT





Evidence of J/ψ Λ structure in the $\Xi_b^- \to J/\psi\, \Lambda\, K^-$

Science Bulletin
Volume 66, Issue 13, 15 July 2021, Pages 1278-1287

Sci.Bull. 66, 13, 1278-1287 (2021)

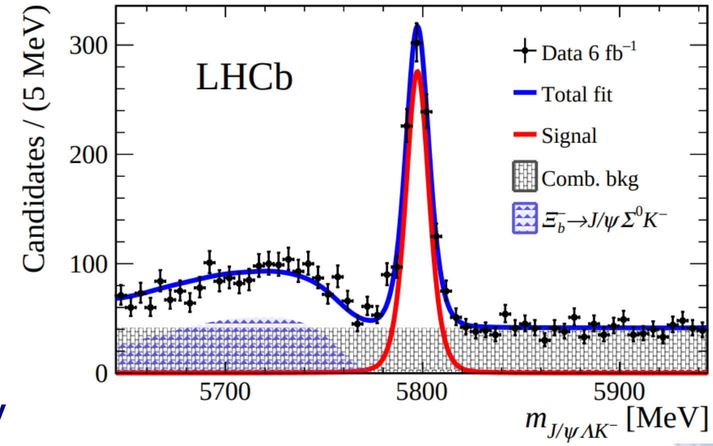
Study $\Xi_b^- \to J/\psi\, \Lambda\, K^-$

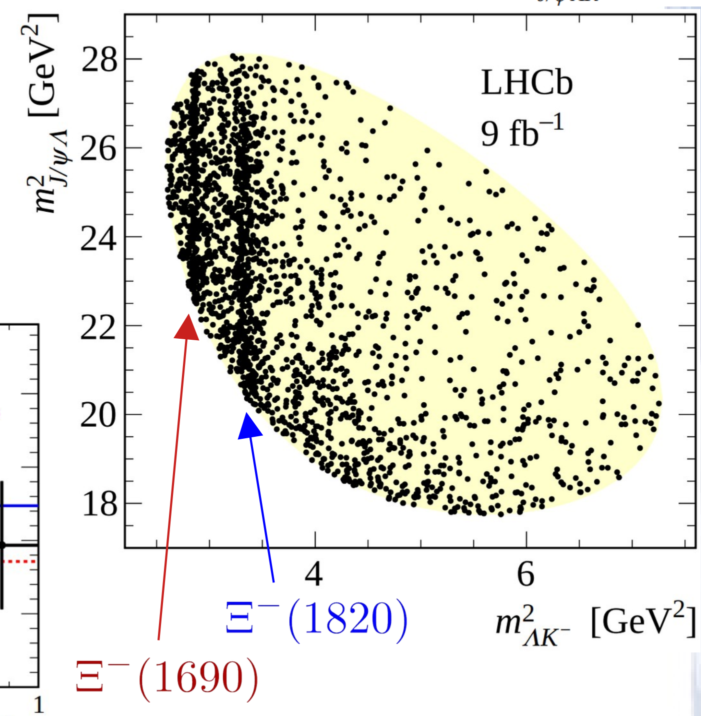
1800 $\Xi_b^- \to J/\psi\, \Lambda\, K^-$ decays selected

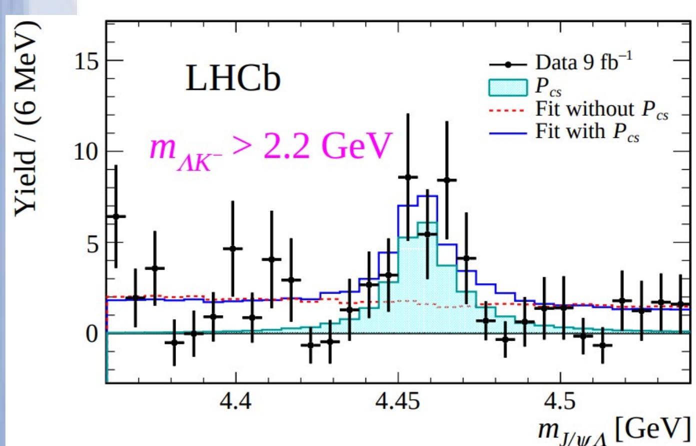
ΛK^- spectrum dominated by $\Xi(1690)$ and $\Xi(1820)$ excited states

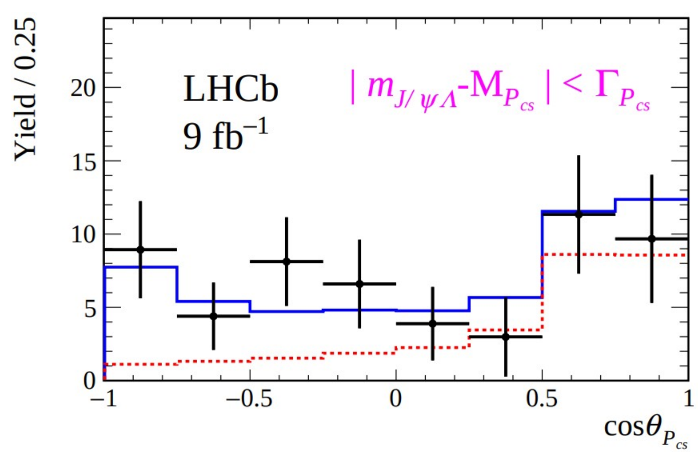
Amplitude analysis performed: statistics quite limited and only few components needed in the fit

Clear structure seen in the $J/\psi\, \Lambda$, particularly in the non resonant ΛK^- region, with 3.1σ significance









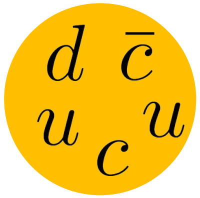
$$P_{cs}(4459)^0$$

$$m = 4458.8 \pm 2.9^{+4.7}_{-1.1}\ \text{MeV} \quad \Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}\ \text{MeV}$$

Mass close to the $\Xi_c D^*$ mass th.

Searching for pentaquarks in $B^0_{(s)} \to J/\psi\, p\, \bar{p}$

Science Bulletin
Volume 66, Issue 13, 15 July 2021, Pages 1278-1287



Sci.Bull. 66, 13, 1278-1287 (2021)

$B^0_{(s)} \to J/\psi\, p\, \bar{p}$: selection

Decay very clean, good candidate for **pentaquarks** searches in **J/ψ p** and **J/ψ p̄** and for **glueball** in **pp̄** system

~ **800 $B^0_s \to J/\psi\, p\, \bar{p}$** decays selected in 3σ region with 15% background and 85% purity

Dalitz plot shows hints of structures in J/ψ p and J/ψ p̄ invariant masses

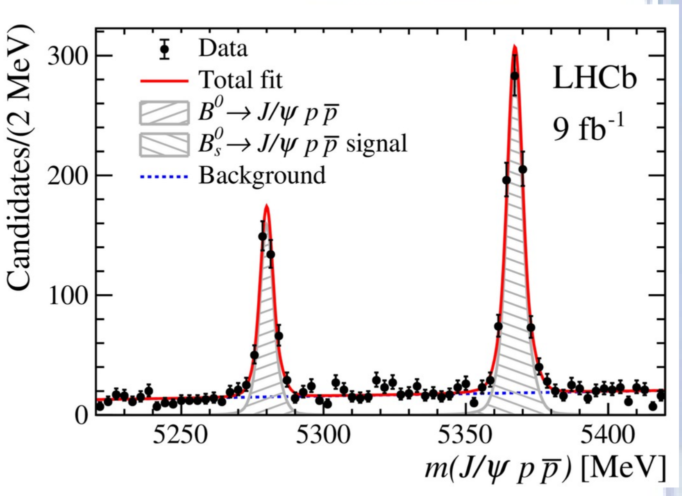
Amplitude analysis of the B^0_s candidates performed.

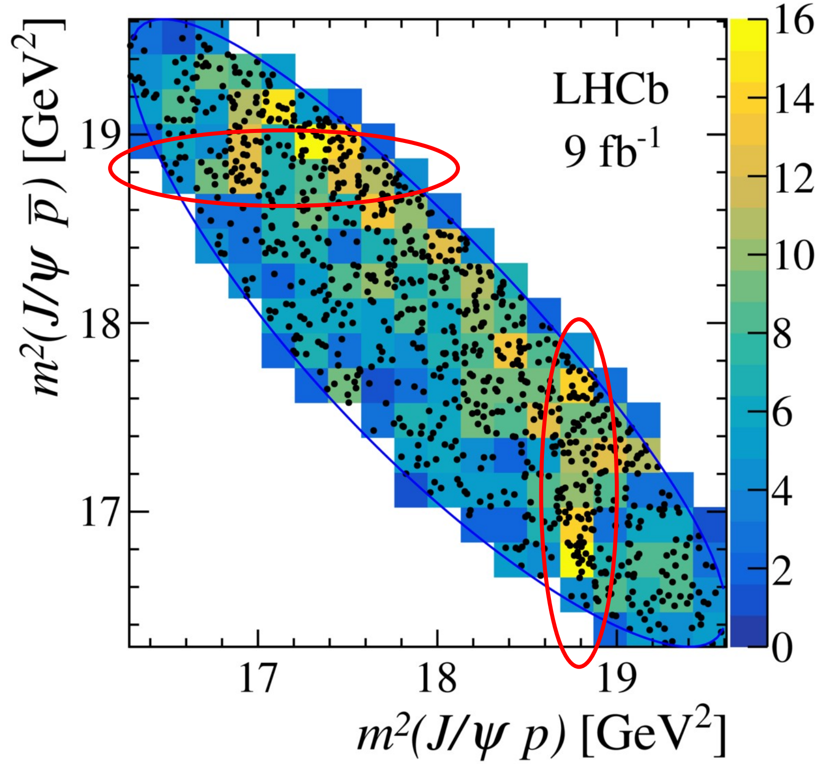
Three interfering decay chains are considered in the amplitude model

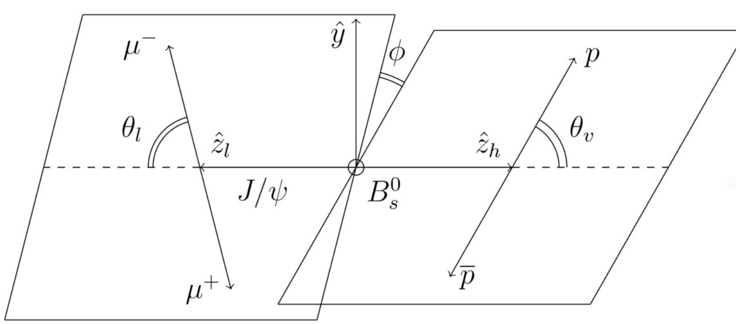
$$B_s^0 \to J/\psi\, X(\to p\,\bar{p})$$
$$B_s^0 \to P_c^+(\to J/\psi\, p)\,\bar{p}$$
$$B_s^0 \to P_c^-(\to J/\psi\, \bar{p})\,p$$

4D phase space

$$\{m_{p\bar{p}}, \cos\theta_l, \cos\theta_v, \phi\}$$







Sci.Bull. 66, 13, 1278-1287 (2021)

$B^0_{(s)} \rightarrow J/\psi\, p\, \bar{p}$ amplitude analysis

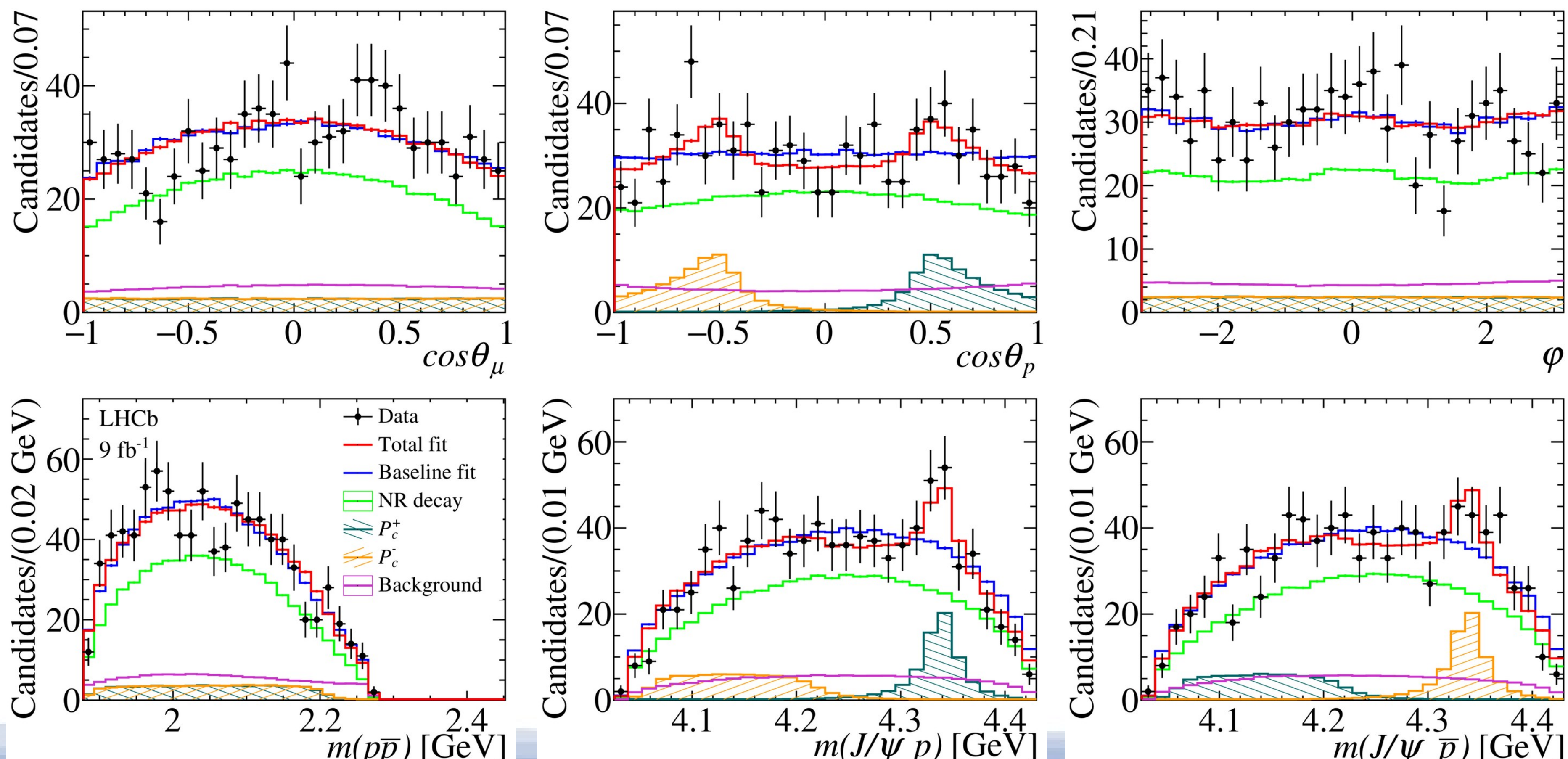
First Fit performed with a non resonant decay + background (**baseline**) $\chi^2 = 64/38 \quad p - \text{value} = 4 \times 10^{-5}$

In the second model two resonant contributions from P^+_c and P^-_c are added, with identical masses, widths and couplings (**baseline + Resonant contribution**). $\chi^2/\text{n.d.f.} = 0.998 \pm 0.008$

New pentaquark-like states P^+_c and P^-_c ($uudc\bar{c}$) with significance between **3.1 - 3.7σ**

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

P_c(4337) not consistent with previously observed P_c states
None of the J^P can be discarded



$\bar{s}\ \bar{c}\ s\ c$

Observation of new $X \rightarrow J/\psi\ \Phi$ and $Z_{cs} \rightarrow J/\psi\ K^+$ states in $B^+ \rightarrow J/\psi\ \Phi\ K^+$

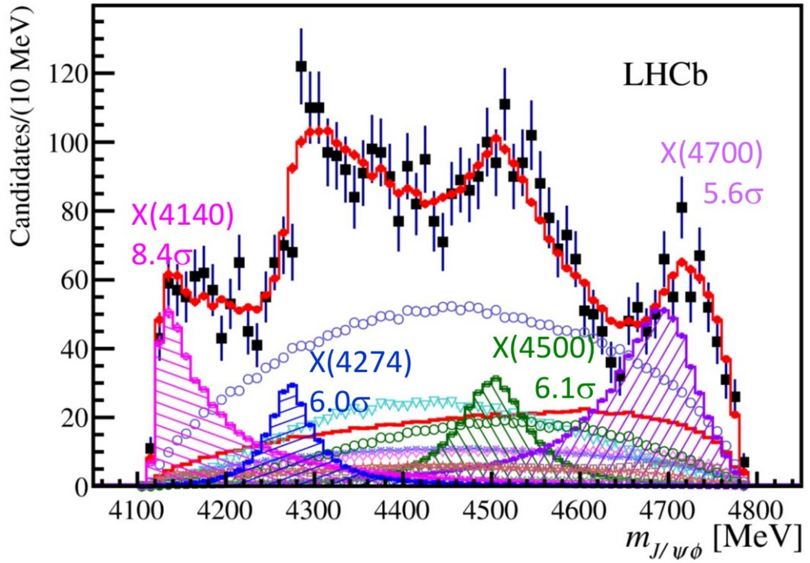
$\bar{s}\ \bar{c}\ u\ c$

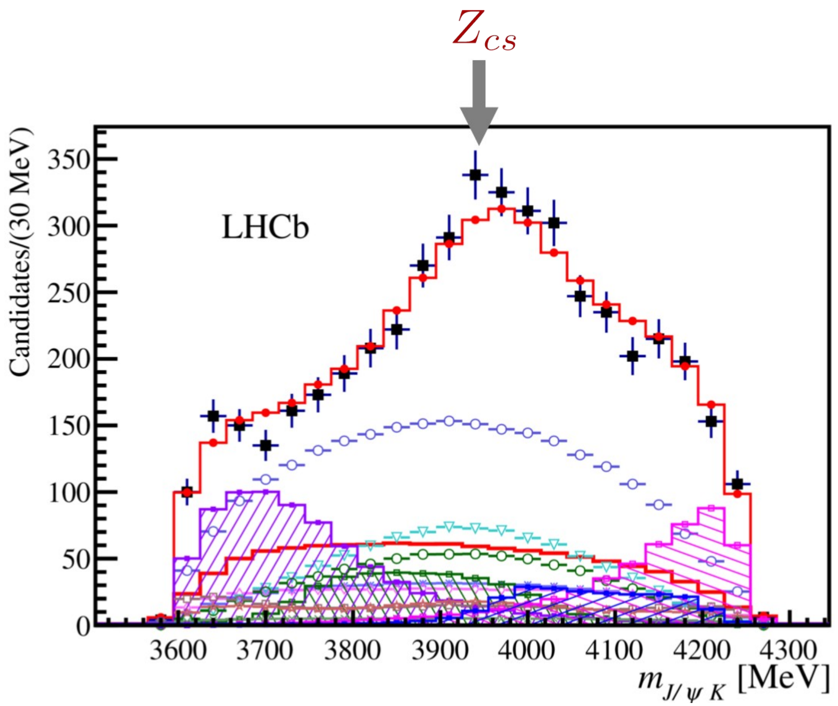
PHYSICAL REVIEW LETTERS **127**, 082001 (2021)

PRL 118, 022003 (2017)

$B^+ \to J/\psi\ \Phi\ K^+$ analysis with Run1 data

- The decay $\mathbf{B^+ \to J/\psi\ \Phi\ K^+}$ was first studied with Run1 data
- An amplitude analysis was performed using ~4000 signal events in order to see possible resonances $\mathbf{X \to J/\psi\ \Phi}$ or $\mathbf{Z^+ \to J/\psi\ K^+}$
- Four different $X \to J/\psi\ \Phi$ resonances observed: X(4140), X(4274), X(4500) and X(4700)
- Hint for a possible structure in $J/\psi\ K^+$ spectrum (Z_{cs} ?)

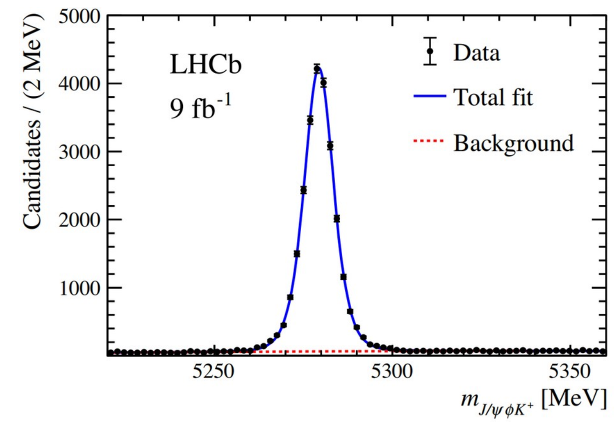


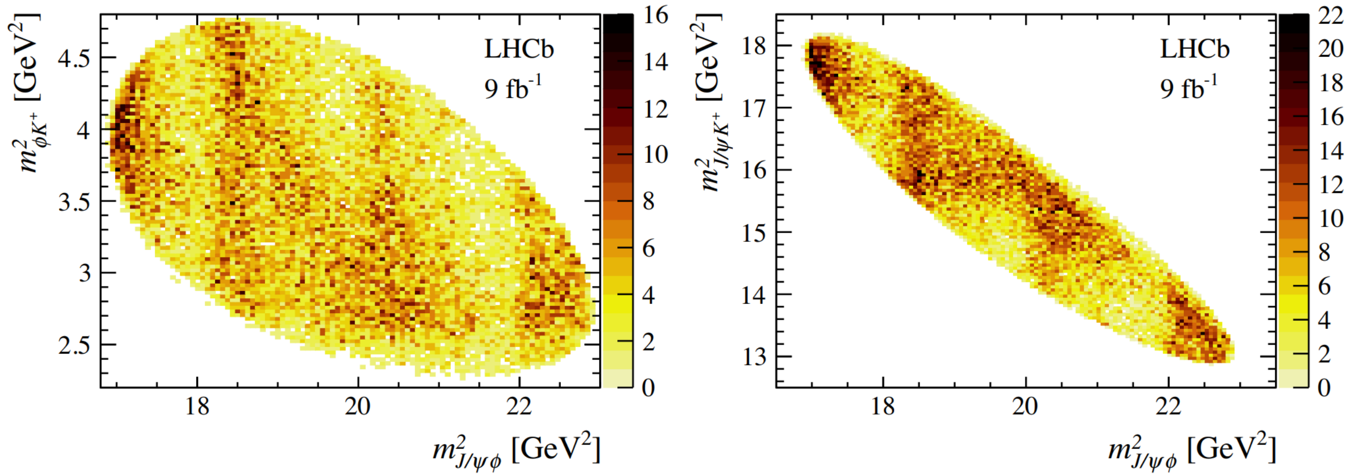


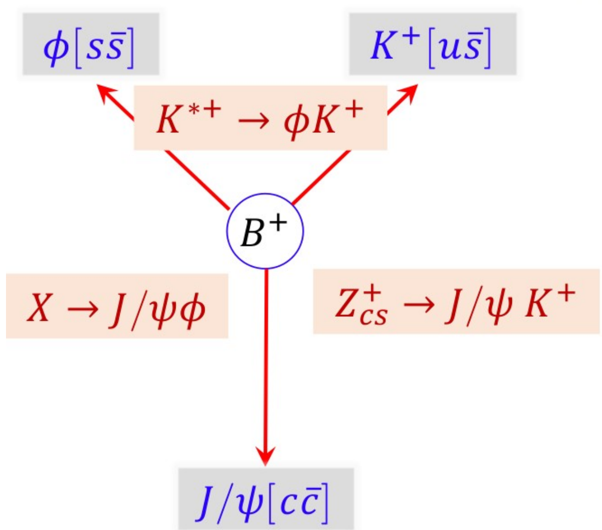
Distribution of $m(J/\psi\ \Phi)$ and $m(J/\psi\ K^+)$ together with the amplitude analysis fit

$B^+ \rightarrow J/\psi\, \Phi\, K^+$ analysis with full LHCb dataset

- Analysis repeated on full dataset and improved selection **~24K signal events** (×6)
- Efficiency improved by 15% and the background reduced by factor 6
- Clear structures in the Dalitz plots, both in the $J/\psi\, \Phi$ and $J/\psi\, K^+$ masses



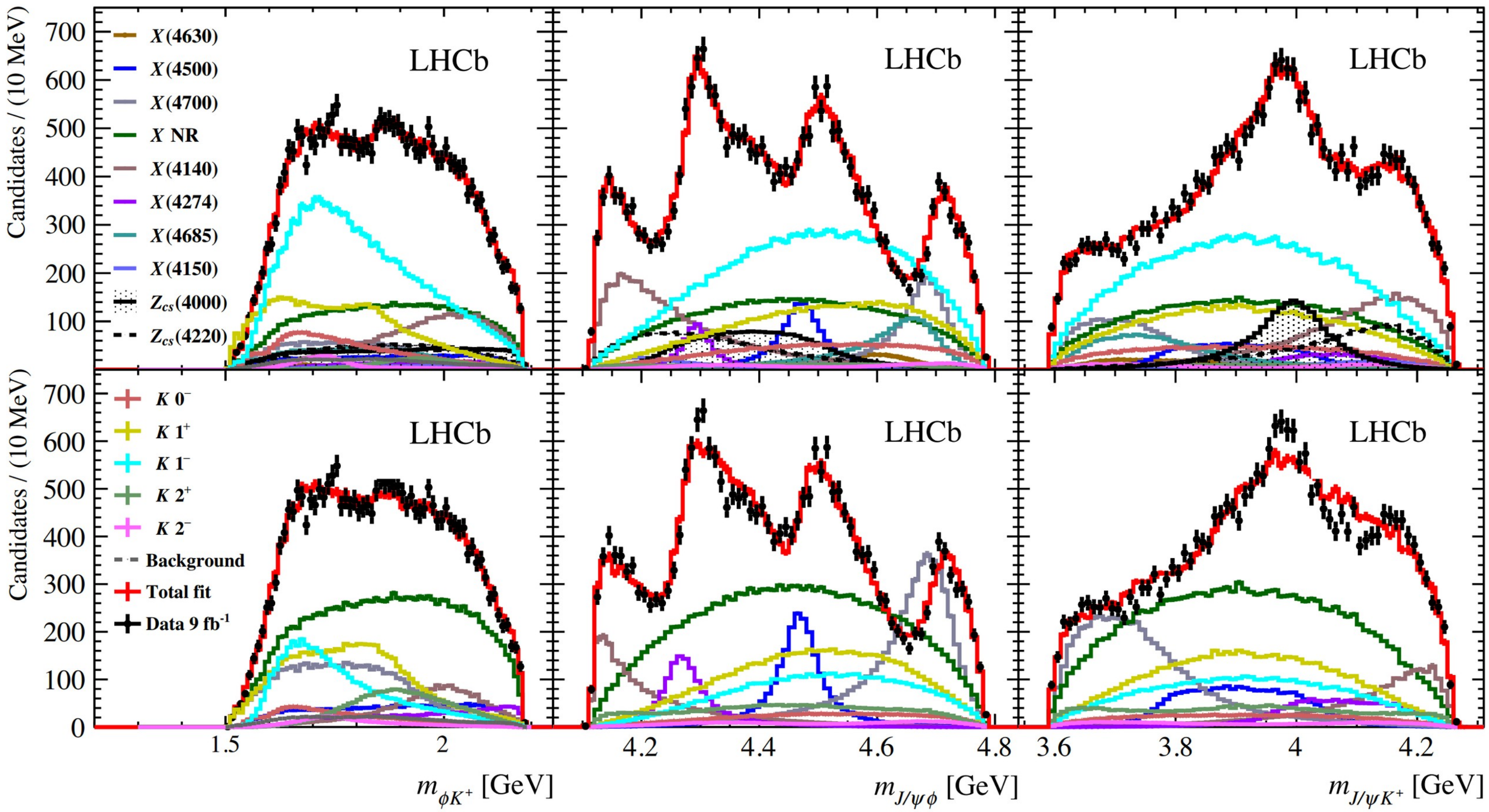




- 6D amplitude analysis to decouple all resonant contributions (K^{*+}, X, Z^+_{cs})
- For each decay chain (K^{*+}, X, Z^+_{cs}) six variables in the fit (mass and five angles)

PRL 127, 082001 (2021)

$B^+ \rightarrow J/\psi\ \Phi\ K^+$ analysis with all data



updated model

Run1 model

Model used in the Run1 analysis not completely satisfactory to reproduce data.

Need to add other exotic states (X, Z^+_{cs}).

$B^+ \rightarrow J/\psi\ \Phi\ K^+$ analysis with full LHCb dataset

Contribution	Significance	Fit results		
		M_0 [MeV]	Γ_0 [MeV]	FF%
$X(2^-)$				
$X(4150)$	8.7σ	4146 ± 18	135 ± 28	2.0 ± 0.5
$X(1^-)$				
$X(4630)$	5.7σ	4626 ± 16	174 ± 27	2.6 ± 0.5
All $X(0^+)$				19.5 ± 4.8
$X(4500)$	20σ	4474 ± 3	77 ± 6	5.6 ± 0.7
$X(4700)$	18σ	4694 ± 4	87 ± 8	8.9 ± 1.2
$NR_{J/\psi\phi}$	5.7σ			28.0 ± 7.5
All $X(1^+)$				26.0 ± 3.4
$X(4140)$	16σ	4118 ± 11	162 ± 21	17.2 ± 2.9
$X(4274)$	18σ	4294 ± 4	53 ± 5	2.8 ± 0.49
$X(4685)$	15σ	4684 ± 7	126 ± 15	7.2 ± 1.0
All $Z(1^+)$				25.0 ± 4.9
$Z_{cs}(4000)$	16σ	4003 ± 6	131 ± 15	9.4 ± 2.1
$Z_{cs}(4220)$	8.4σ	4216 ± 24	233 ± 52	10.3 ± 3.8

Resonances observed in the **Run1** analysis confirmed

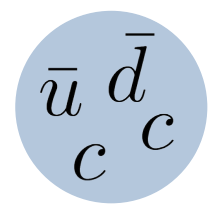
Two other **$X \rightarrow J/\psi\ \Phi$** states, **X(4630)** and **X(4685)**, were observed.

Two **$Z_{cs}^+ \rightarrow J/\psi\ K^+$** states were observed, both with > 5σ

The J^P of $Z_{cs}(4000)$ and X(4685) are firmly determined to be 1^+

Doubly-charmed tetraquark T^{+}_{cc}

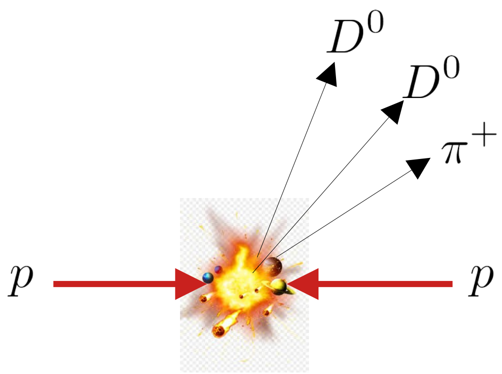
arXiv:2109.01056v2 [hep-ex] 3 Sep 2021



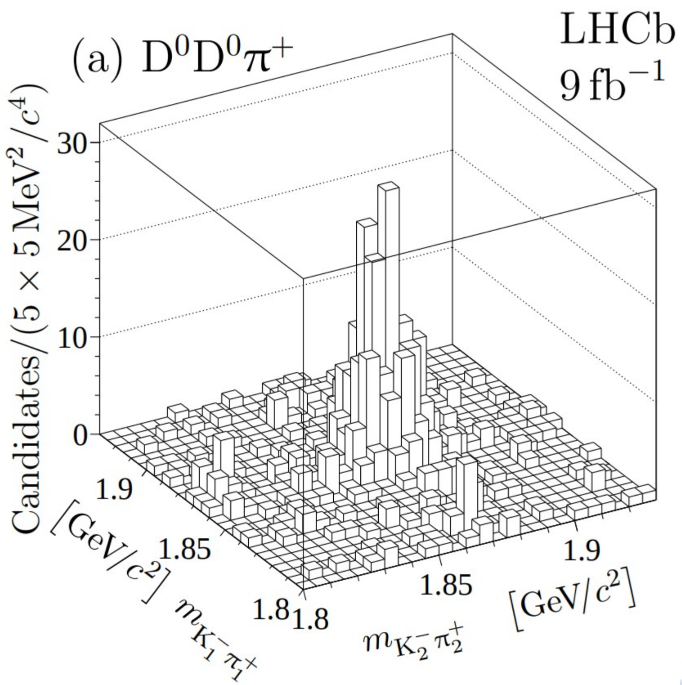
arXiv:2109.01056v2

Search for exotic state in prompt $D^0 D^0 \pi^+$

- D^0 reconstructed via the $D^0 \to K^+ \pi^-$ decay
- All the three particles are required to come from the same p-p interaction
- To subtract background not originating from two D^0 candidates an extended fit to the two-dimensional distribution of the masses of the two D^0 candidates is performed



- Two-dimensional distributions of the mass of one D candidate versus the mass of the other D candidate from selected **$D^0D^0\pi^+$** combination is shown.
- This distribution illustrate the relatively small combinatorial background



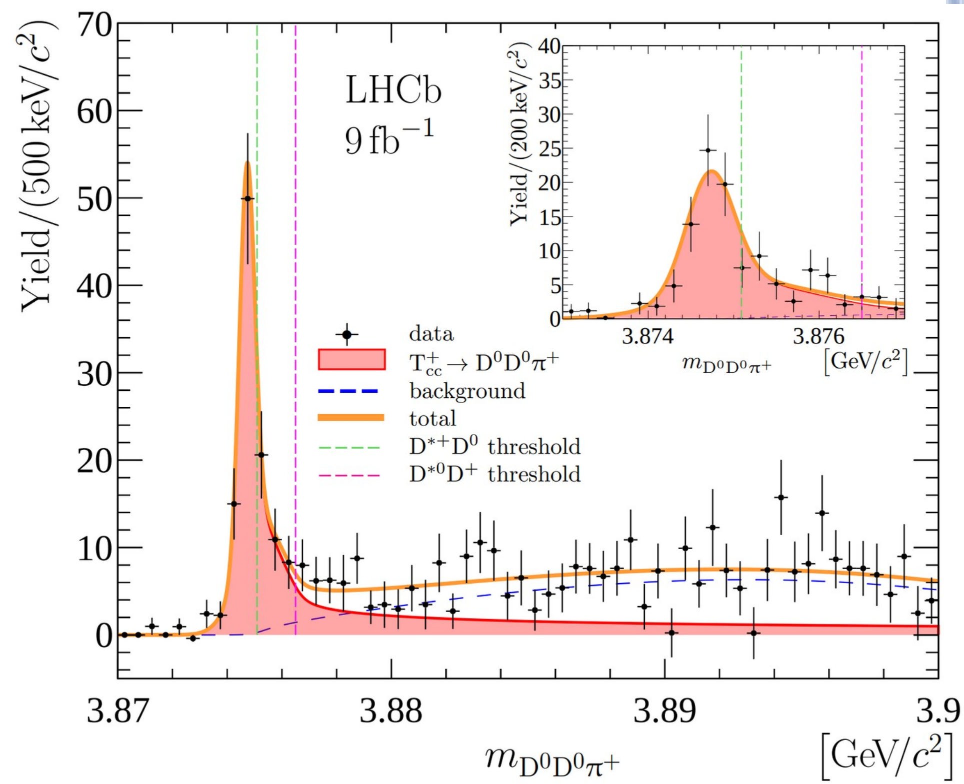
arXiv:2109.01056v2

Observation of $T^{+}_{cc} \rightarrow D^0 D^0 \pi^+$

- A narrow peak near the D^{*+}+D^0 mass threshold is clearly visible
- Signal model: detector resolution ⊗ unitarised three-body BW function (U)
  - The typical mass resolution ~400 keV is reached by constraining the D0 mass to the known value in the fit

$$\delta m_U = m_U - m_{D^{*+}} - m_{D^0}$$

Parameter	Value
N	186 ± 24
δm_{U}	$-359 \pm 40\,\mathrm{keV}/c^2$



- The narrowest exotic state observed to date
- Consistent with expectation for ground isoscalar T^{+}_{cc} ($cc\bar{u}\bar{d}$) with $J^P = 1^+$
- The existence of T^{+}_{cc} suggests the existence of T^{-}_{bb} ($bb\bar{u}\bar{d}$) that should be stable for strong and electromagnetic interaction

Conclusions

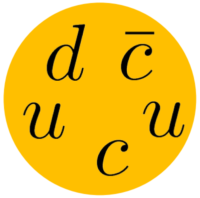
Presented only some of the results on exotic states at LHCb

- Evidence of a $J/\psi\ \Lambda$ structure in $\Xi_b^- \rightarrow J/\psi\ \Lambda\ K^-$ decays
- Evidence of $J/\psi\ p\ (\bar{p})$ structures in $B^0_s \rightarrow J/\psi\ p\ \bar{p}$
- Tetraquarks observation in $B^+ \rightarrow J/\psi\ \Phi\ K^+$
- Observation of doubly-charmed tetraquark $T^+_{cc} \rightarrow D^0\ D^0\ \pi^+$

In order to confirm and better investigate these results more data is needed

Thank you for listening !

Spares



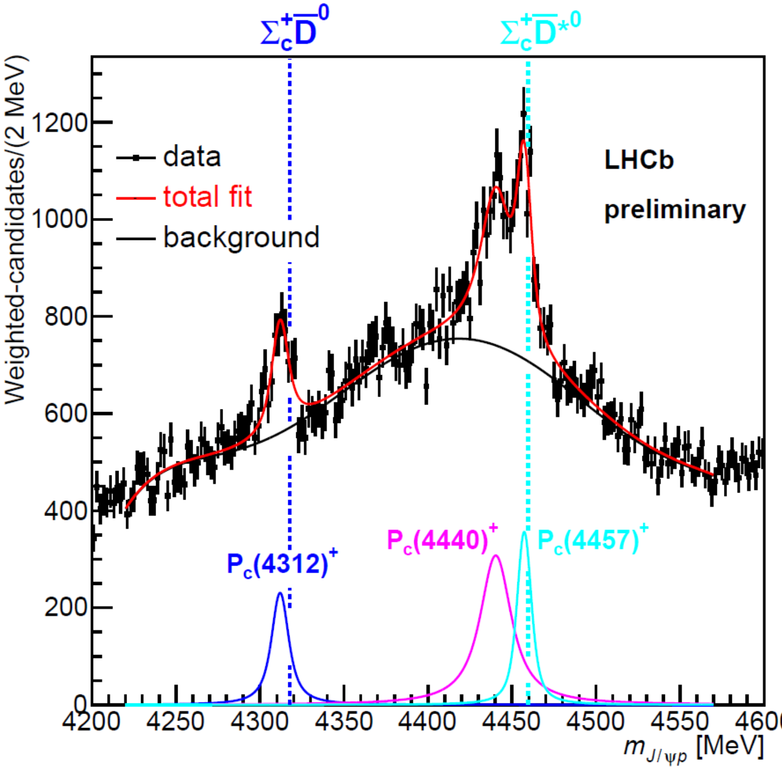
Observation of new pentaquarks states P_c^+ in $\Lambda_b \rightarrow J/\psi\ p\ K^-$

PHYSICAL REVIEW LETTERS **122**, 222001 (2019)

PRL 122, 222001 (2019)

Study $\Lambda_b \to J/\psi\, p\, K^-$

- Decay very clean to select, with BF ~ 3×10^{-4}
- 2.5×10^5 $\Lambda_b \to J/\psi\, p\, K^-$ decays selected (Run1+Run2)
- Study of the **invariant mass of the J/ψ p** system
- Confirmed the preliminary results of the Run1 analysis, $P_c(4440)$ and $P_c(4457)$, plus a new narrow resonance $P_c(4312)$
- Many variations of the m(J/ψ p) fits are performed to study the robustness of the measured P_c^+ properties
  - With or without m(p K) > 1900 MeV/c to avoid Λ* contamination



State	M [MeV]	Γ [MeV]	(95% C.L.)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(<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)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

- Since all three states are narrow and lie just below the $\Sigma_c^+ D^0$ and $\Sigma_c^+ D^{*0}$, they provide a possible experimental evidence for the existence of bound states of a baryon and a meson

Observation of a four-charm-quark tetraquark

Science Bulletin
Volume 65, Issue 23, 15 December 2020, Pages 1983-1993

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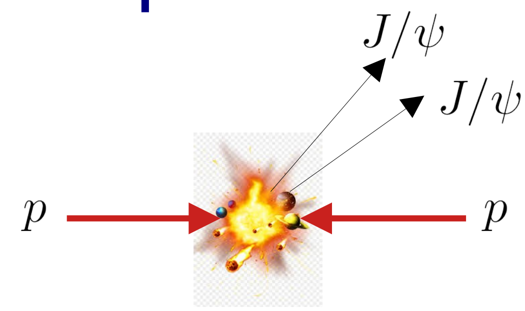
Sci.Bull. 65, 23, 1983-1993 (2020)

Observation of a four-charm-quark tetraquark

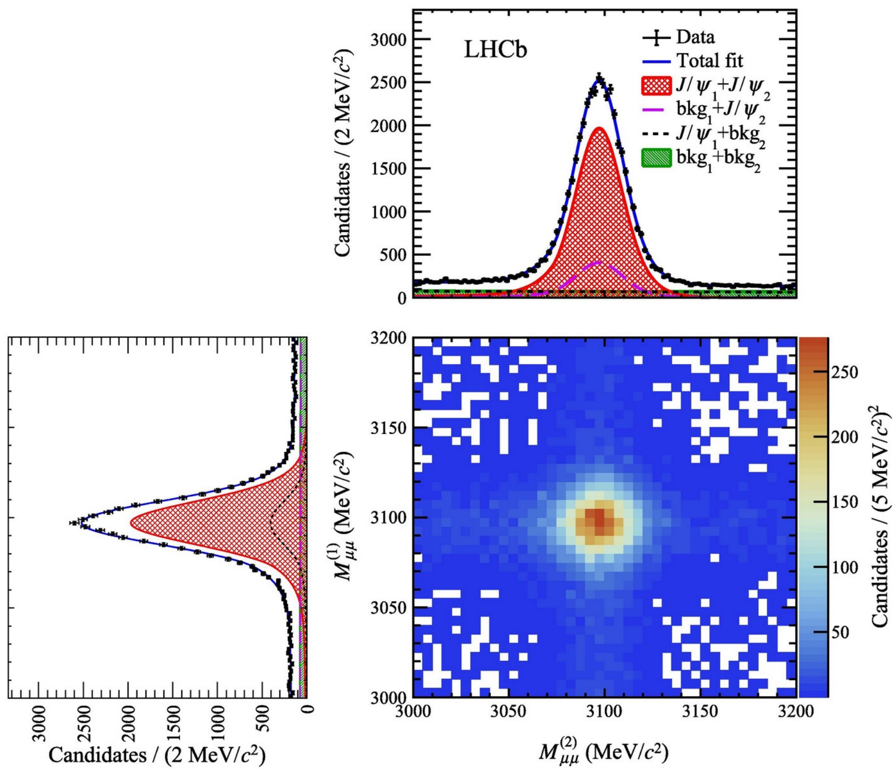
Selection of events with **two prompt J/ψ** directly from the same IP

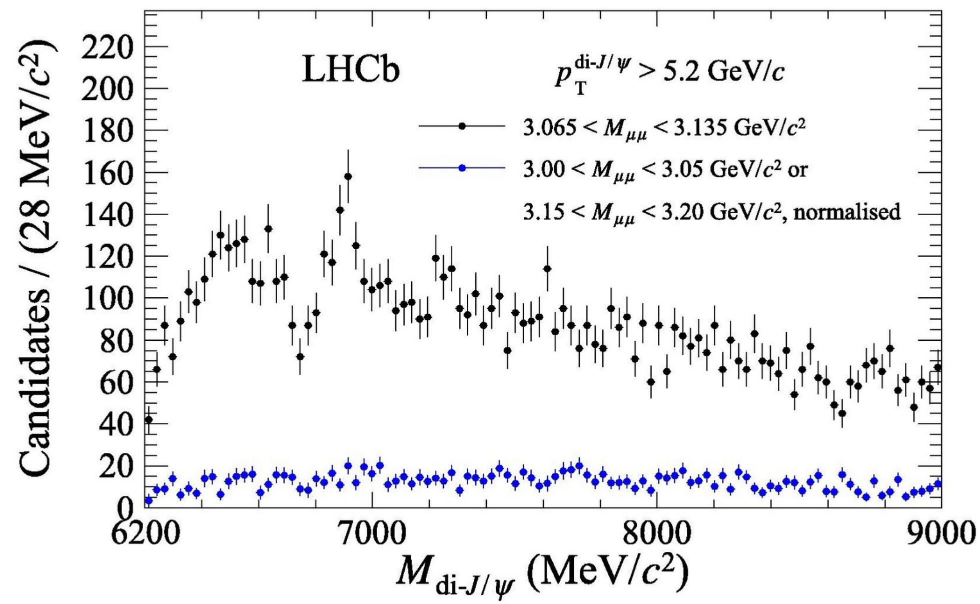


J/ψ reconstructed via J/ψ →μ⁺μ⁻ decay

J/ψ from b and pile-up background suppressed using vertexing information

About 34k di-J/ψ signals collected





- Clear structures for m(J/ψ J/ψ)<7.4 GeV/c²
- No structures in the J/ψ side-bands sample
- Broad structure in 6.2-6.8 GeV, just above the mass threshold
- Narrow structure at 6.9 GeV and hint for structure at 7.2 GeV

Fit of the J/ψ-pair invariant mass spectrum

<u>Model 0</u>: **No structures**, sum of the non resonant SPS (NRSPS) and DPS production.

in 6.2-7.4 GeV range rejected by 6σ

<u>Model 1</u>: A resonance at 6.9 GeV and two S-wave relativistic BW at the threshold

- Significance of the resonances at the threshold > 6σ
- Significance of the T(6900) > 5σ
- Difficult to model the dip at 6.8 GeV

$$m[X(6900)] = 6905 \pm 11 \pm 7\ \mathrm{MeV/c^2}$$
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\ \mathrm{MeV/c^2}$$

<u>Model 2</u>: A wide BW interfering with SPS, a second BW for 6.9 GeV peak

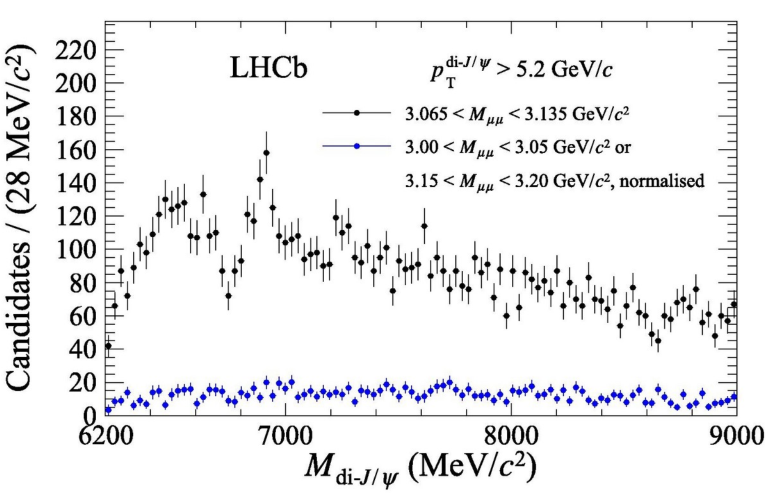
- Fit quality improve from P(χ^2)= 4.6% to 15.5%
- Significance of the T(6900) > 5σ

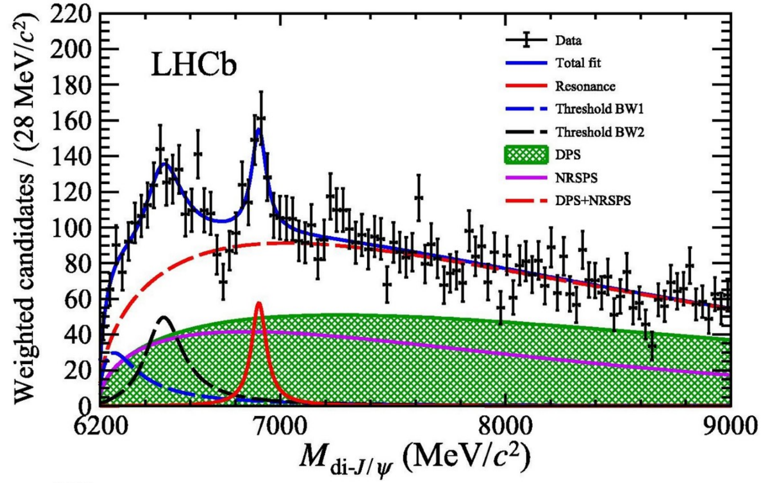
$$m[X(6900)] = 6886 \pm 11 \pm 11\ \mathrm{MeV/c^2}$$
$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\ \mathrm{MeV/c^2}$$

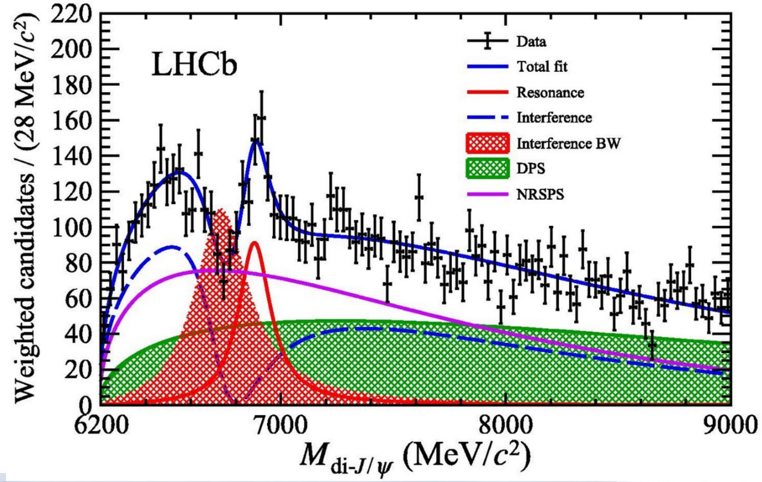
Non trivial structures in the spectrum

First evidence of a four charm-quarks tetraquark T(6900)

$$cc\bar{c}\bar{c}$$







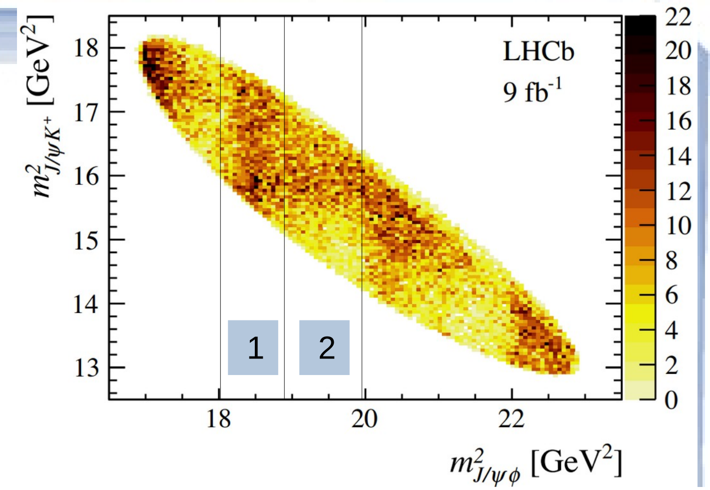
Z_{cs} results

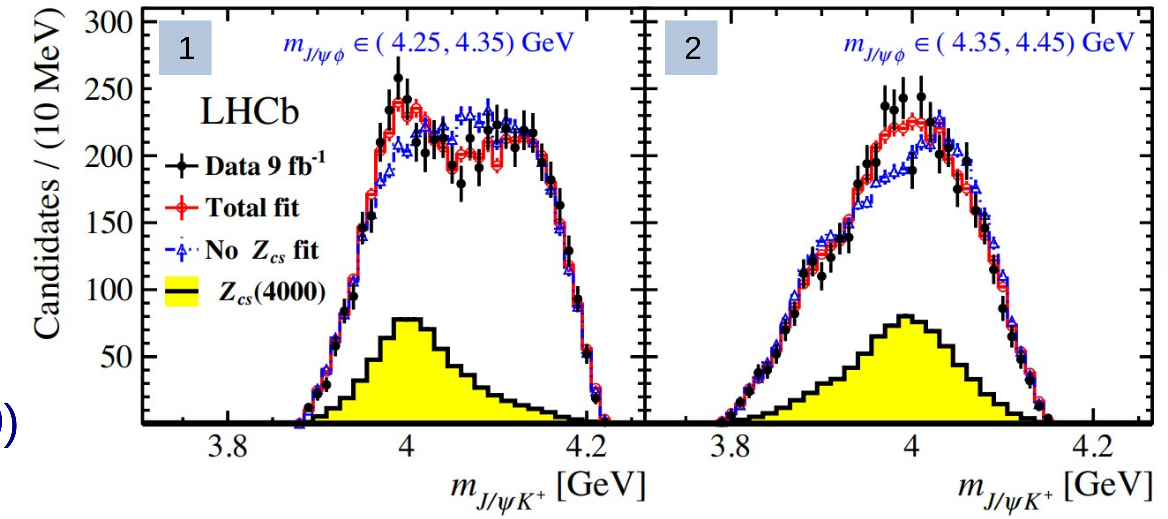
The Z_{cs}(4000) peak is particularly clear in two J/ψ Φ mass regions

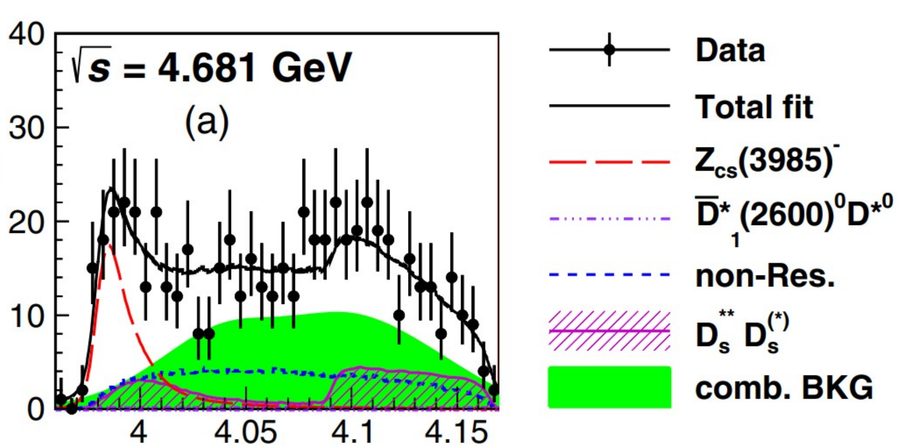
Resonance character of Z(4000) confirmed by the Argand diagram, obtained by independent line shape fit

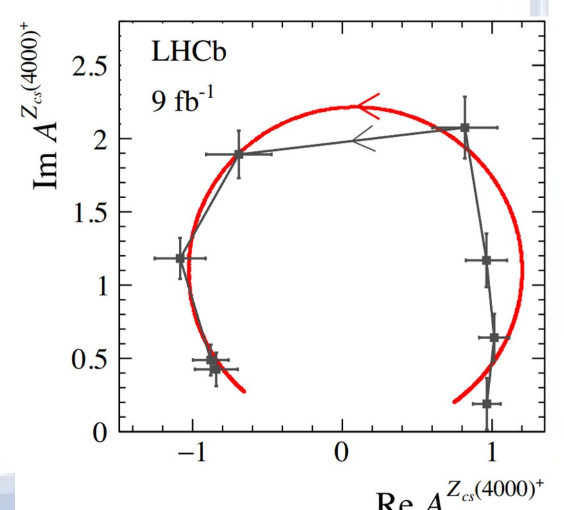
BESIII recently reported the observation of Z^{-}_{cs}(3985) in the D_sD^*+DD_s^* mass

The states have similar masses, but different widths: no evidence that Z(4000) is the same as Z(3985) seen by BESIII









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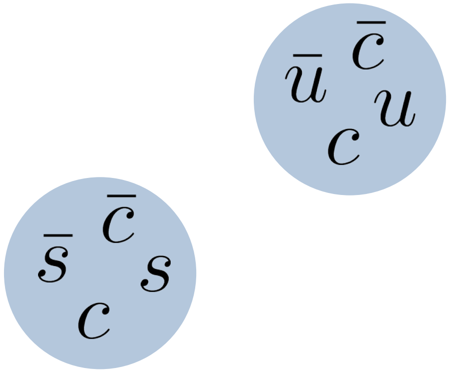
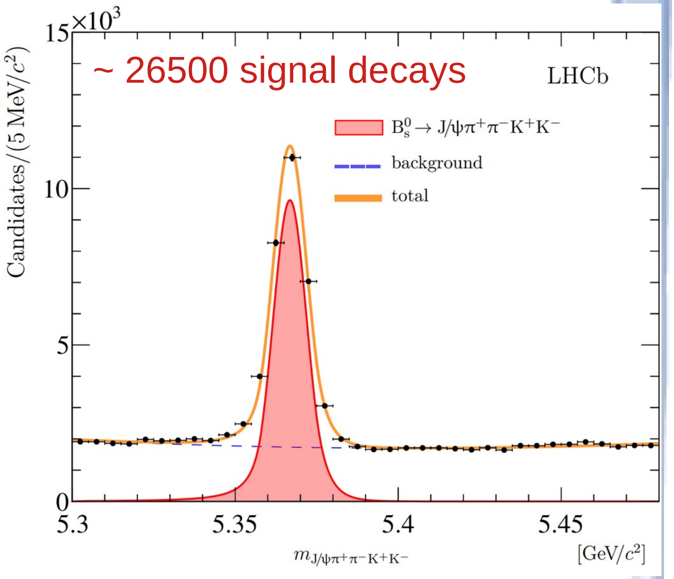
Study of the decay $B_s \to J/\psi\ \pi^+\ \pi^-\ K^+\ K^-$

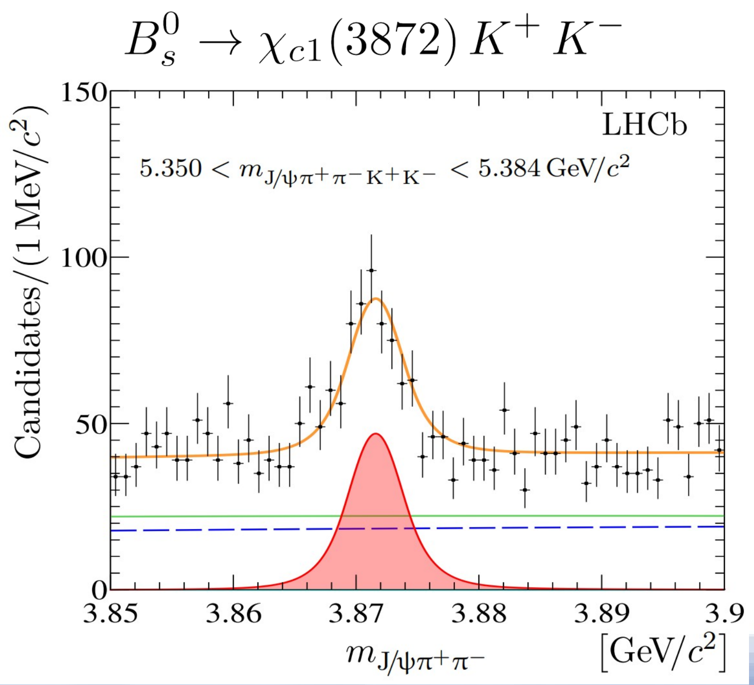
JHEP02(2021)024

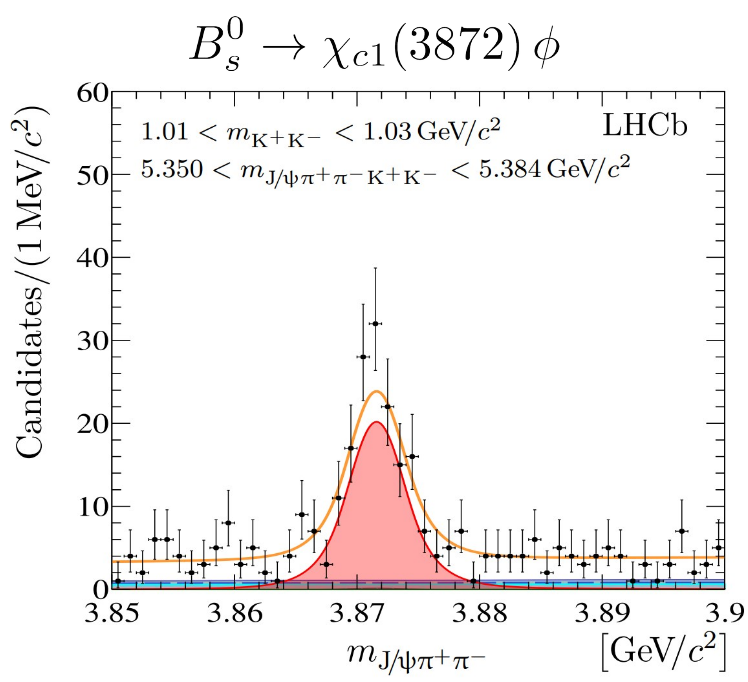


Study of the decay $B_s \to J/\psi\, \pi^+ \pi^- K^+ K^-$

- Study of possible **structures** in $J/\psi\, \pi^+ \pi^-$ and $J/\psi\, K^+ K^-$ masses
- Search for exotic $\chi_{c1}(3872)$ meson, first observed in the mass spectrum of $J/\psi\, \pi^+ \pi^-$ at Belle, and confirmed by other experiments.
- $\chi_{c1}(3872)$ state **confirmed** in $\chi_{c1}(3872) \to J/\psi\, \pi^+ \pi^-$
- $B_s \to J/\psi\, K^* K^*$ and $B_s \to \chi_{c1}(3872) K^+ K^-$ observed for the first time
- Precise measurements of the ratios of BF between intermediate $\chi_{c1}(3872)\, \Phi$, $\chi_{c1}(3872) K^+ K^-$, $J/\psi\, K^* K^*$, $\psi(2S)\, \Phi$ states
- Confirmed the **quantum numbers $J^{PC} = 1^{++}$**, which disfavours an assignment as a conventional charmonium

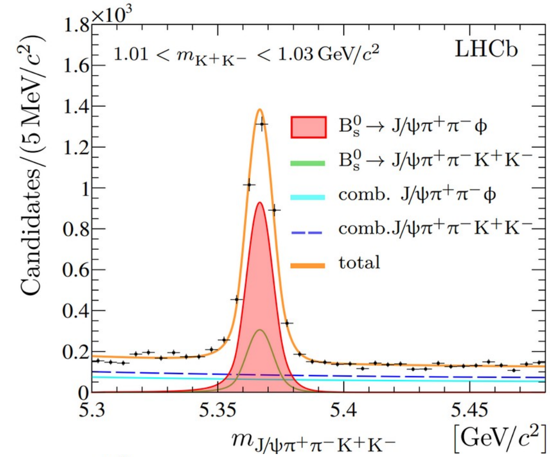


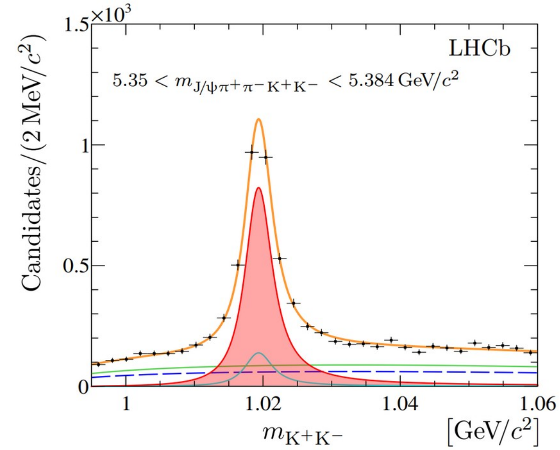




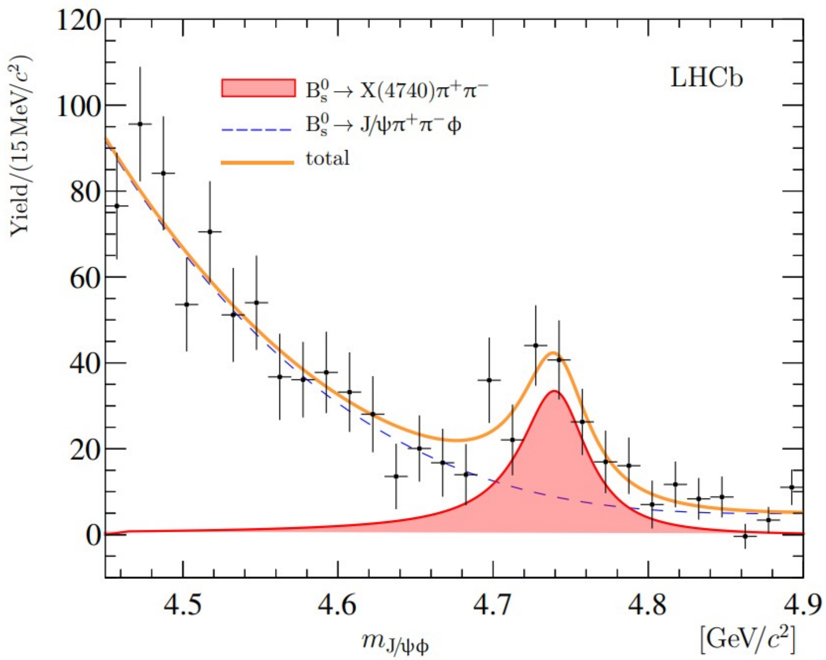
Study of the decay $B_s \to J/\psi\, \pi^+ \pi^- K^+ K^-$

- A selection of J/ψ Φ events is performed requiring
  - $m(K^+ K^-) < 1.06$ GeV/c^2
  - Excluding the J/ψ $\pi^+ \pi^-$ mass region around Φ(2S) and $\chi_{2c}(3872)$
- A combined **two dimensional fit** is performed to the m(K+K-) and m(J/ψ K+K-π+π-) selecting the Bs and the Φ signals and then a sPlot is used to obtain a background subtracted m(J/ψ Φ) distribution.
- A clear **peak** is observed around 4740 MeV in the J/ψ Φ invariant mass, with a significance of 5.5σ





X(4740) structure		
$N_{X(4740)}$		175 ± 39
$m_{X(4740)}$	[MeV/c^2]	4740.6 ± 6.0
$\Gamma_{X(4740)}$	[MeV]	52.8 ± 15.1



- To exclude the possibility of an interference case, an amplitude analysis is needed
- Is this X(4700) the same resonance $\chi_{c0}(4700)$ observed in the $B^+ \to J/\psi\, \Phi\, K^+$?
- The measured mass is close to the value expected for a tetraquark with quantum numbers $J^{PC} = 2^{++}$

Further study on exotic $\chi_{c1}(3872)$

JHEP08(2020)123

PHYS. REV. D 102, 092005 (2020)

- A recent study has been done to make precise measurements of the properties of a mysterious particle $\chi_{c1}(3872)$.

  Two different, minimally overlapping, data sets used, with $\chi_{c1}(3872)$ reconstructed via $J/\psi\ \pi^+ \pi^-$ decay
  - Run 1 (3 fb^{-1}) 15500 events of inclusive $b \rightarrow \chi_{c1}(3872)$ X
  - Run 1 and Run 2 (9 fb^{-1}) 4230 events of exclusive $B^+ \rightarrow \chi_{c1}(3872)\ K^+$ decays

- Precise measurements of the mass and the width
- The comparison with the decays involving $\psi_2(3823)$ and $\psi(2S)$ together with the tiny (~70 KeV) mass difference with the $D^0\ D^{0*}$ mass favors interpretation of the state as a quasi-bound D^0-D^{0*} molecule
- Further investigation needed to draw conclusions