Tetra- and pentaquark 'spectroscopy'

LHCP, 7-12 June '21

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on behalf of the LHCb collaboration

June 10th, 2021

Outline

Introduction to exotic spectroscopy

Recent results by LHCb

- Evidence for a new structure in $J/\psi p$ and $J/\psi \bar{p}$ systems in $B_s \to J/\psi p \bar{p}$ decays

New

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

Exotics in the quark model

SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

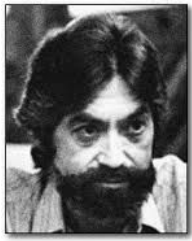
Received 4 January 1964

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowes

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)

CERN - Geneva



general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

Multiquark hadrons are called **exotics**:

- ‘tetraquarks’ with 4 quarks
- ‘pentaquarks’ with 5 quarks

Exotics in the quark model

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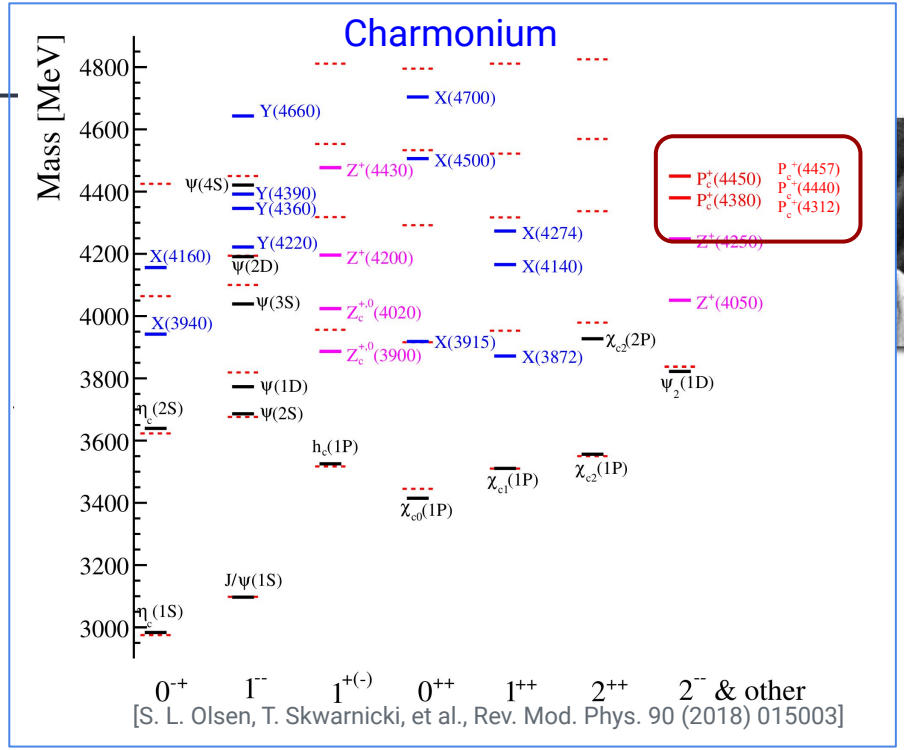


[S. L. Olsen, T. Skwarnicki, et al., Rev. Mod. Phys. 90 (2018) 015003]

Multiquark hadrons are called **exotics**:

- 'tetraquarks' with 4 quarks
- 'pentaquarks' with 5 quarks

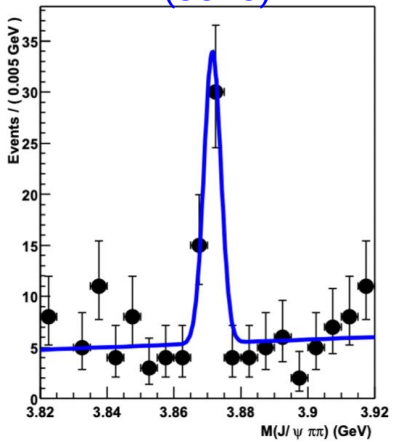
X, Y: neutral,
Z charged

~30 exotics states seen in heavy-quark sector

First exotic candidates

Tetraquark
by Belle in 2003 in
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays

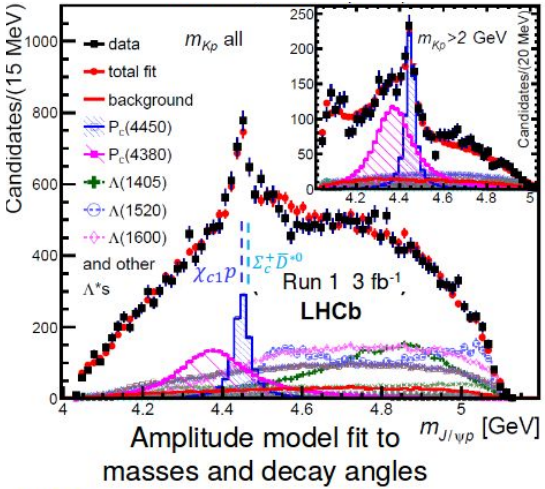
X(3870)



[Phys. Rev. Lett. **91**, 262001]

Pentaquark
by LHCb in 2015 in $\Lambda_b \to J/\psi pK$

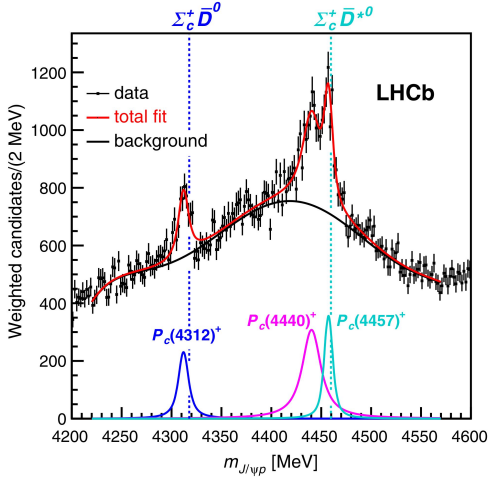
Run1 [PRL 115, 072001 (2015)]



Amplitude model fit to masses and decay angles

$P_c(4380)$ and $P_c(4450)$

Run1 + Run2 [PRL 122, 222001 (2019)]

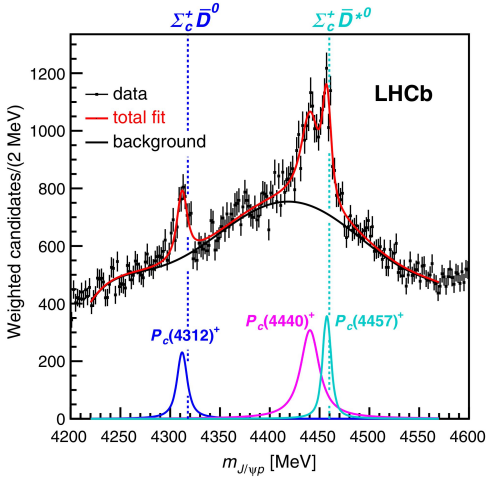


new state: $P_c(4312)^+$ + 2 peaks at 4450 MeV

The unresolved nature

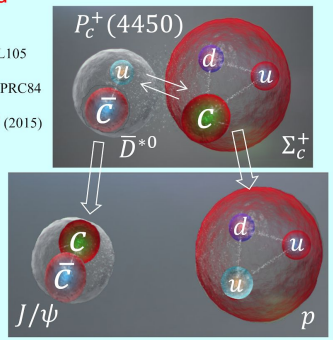
Theoretical interpretations

- Molecules
- Compact states
- Kinematic effects



Loosely-bound pentaquark

Wu,Molina,Oset,Zou, PRL105 (2010) 232001
Wang,Huang,Zhang,Zou, PRC84 (2011) 015203
Karliner,Rosner, PRL 115 (2015) 122001
and others

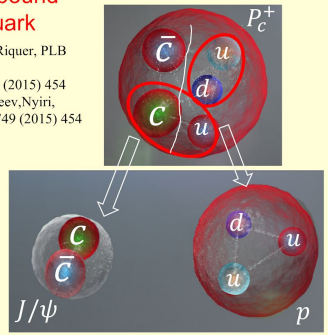


$M_{P_c^+} = M_{\bar{D}^{*0}} + M_{\Sigma_c^+} - \sim$few MeV

Low binding energy,
narrow states,
S-wave only

Tightly-bound pentaquark

Maiani,Polosa, Riquer, PLB 749 (2015) 289
Lebed, PLB 749 (2015) 454
Anisovich,Matveev,Nyiri, Sarantsev PLB 749 (2015) 454
and others

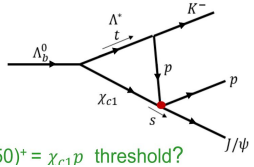


$M_{P_c^+} = M_{J/\psi} + M_p + \sim$400MeV

Tightly bound states,
Large widths,
isospin multiplets

Triangle diagram

Guo,Meissner,Wang,Yang, PRD 92 (2015) 071502
Liu, Wang, Zhao, PLB 757 (2016) 231
Mikhasenko, arXiv:1507.06552
Szczepaniak, PLB 757 (2016) 61
and others



$P_c(4450)^+ = \chi_{c1}p$ threshold?

Favor molecular hypothesis:

- Close to threshold of molecules and narrow widths

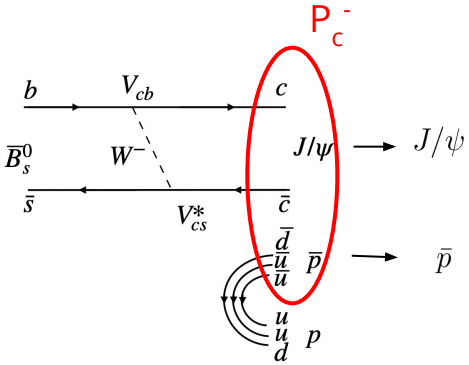
⇒ **We need independent evidence**

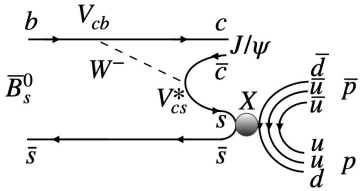
Evidence of new structure in $J/\psi p$ and $J/\psi \bar{p}$ systems in $B^0_{(s)} \to J/\psi p\bar{p}$ decays

Preliminary RESULTS

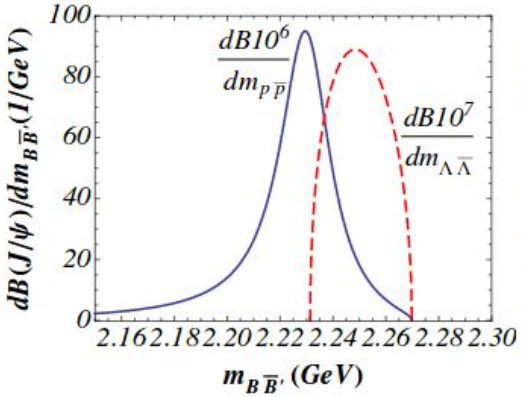
Searching for pentaquarks in $B^0_{(s)} \to J/\psi p\bar{p}$

Candidate for pentaquark searches in $J/\psi p$ and $J/\psi \bar{p}$ and for glueball[2] in $p\bar{p}$ system





Resonant state $f_J(2230) \to p\bar{p}$, peak at 2.2 GeV and $J^P = 2^{++}$ or 4^{++} [2]



→ Same final state as $\Lambda_b \to J/\psi pK$ [1] but mesonic decay

Clean channel: not known resonances w.r.t. $\Lambda_b \to J/\psi pK$, where several Λ^* resonances are present

[1] PRL 122, 222001 (2019)
[2] Eur. Phys. J. C75 (2015), no. 3 101

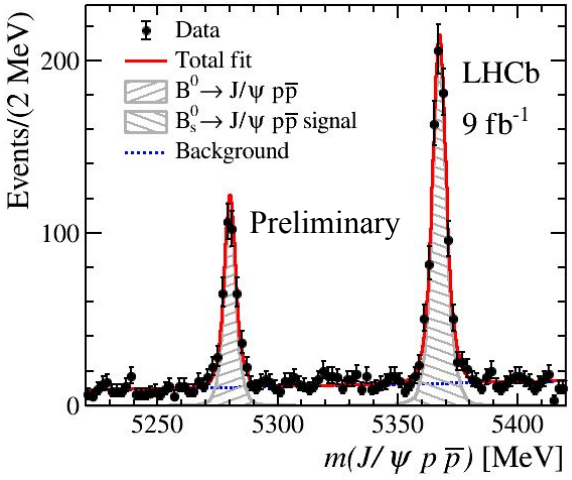
Selection

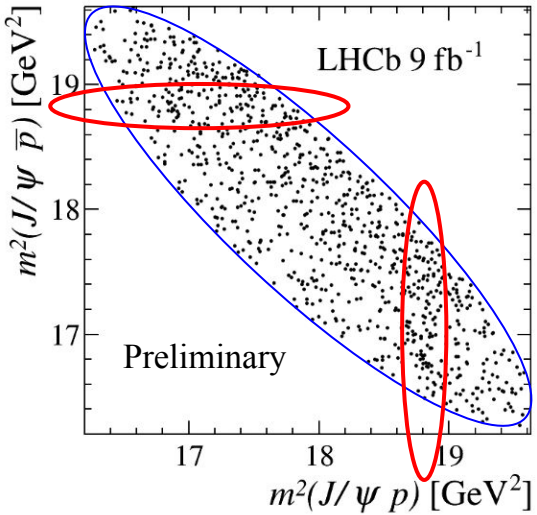
Dataset: 9 fb^{-1}
~800 B_s events in 3σ window
with 15% of background

$N_{sig}(B_s)$ = 776 +/- 30

f_{bkg} = 14.9 +/- 0.6 %

Purity: 85.1%





Structure in J/ψp,
but to rule out possible pp
reflections

Amplitude analysis
in 4D

[LHCb-PAPER-2021-018]

The amplitude analysis

4D phsp

$\Phi=(m_{pp}, \cos\theta_l, \cos\theta_v, \varphi)$

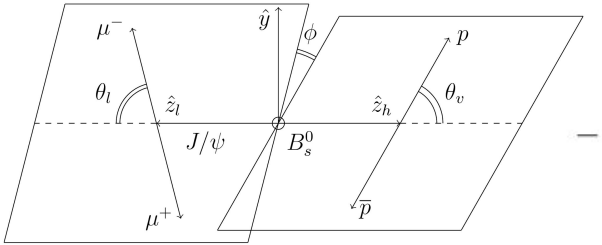
DATA

MODEL

FIT

Helicity formalism

- flavour untagged B_s decays
- assuming CP symmetry



$$-2\ln\mathcal{L}(\vec{\omega}) = -2\sum_i \ln\mathcal{P}\left(m_{p\bar{p}i}, \Omega_i|\vec{\omega}\right)$$

Fit models:

- Baseline model: only non resonant (NR) in pp chain
- Baseline + old P_c states: $P_c(4312)$
- Baseline + new P_c state ⇒ Nominal model

Building a first model

Non resonant contribution ($J^{PC}=1^{--}$) + bkg

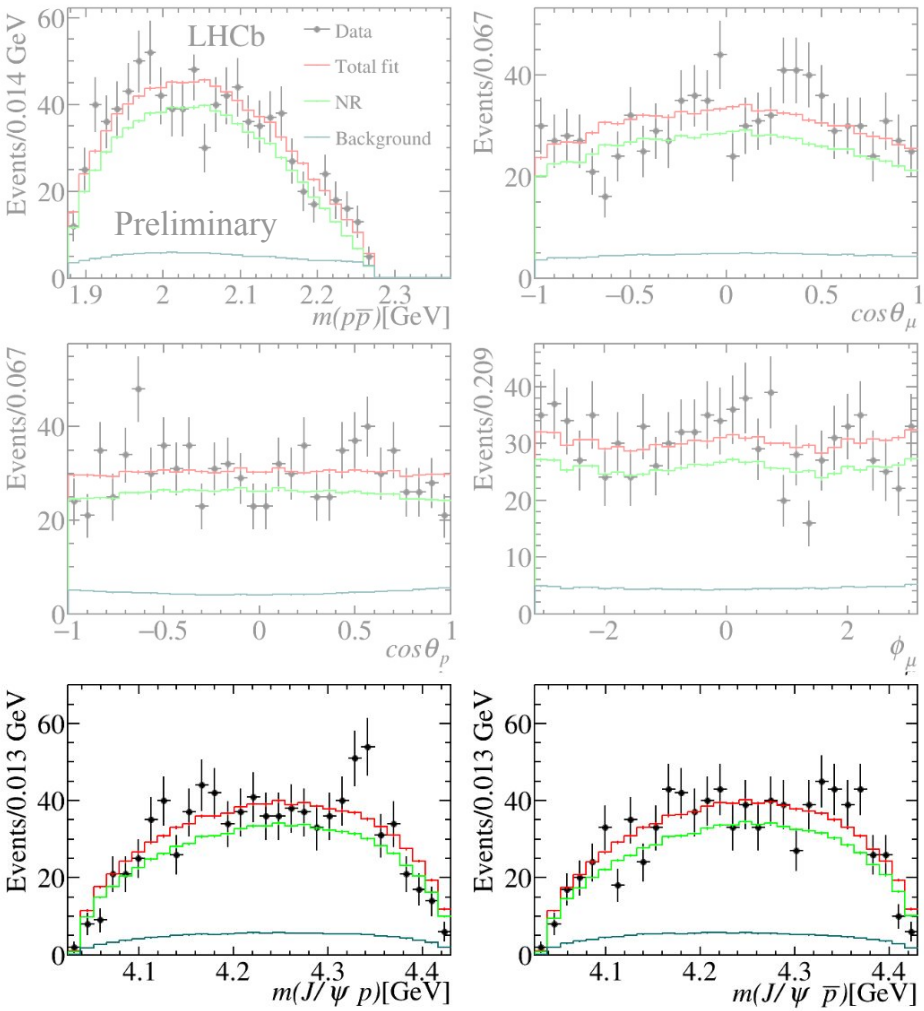
→ $J^{PC}=1^{--}$ is the only term in S-wave

→ Different J^P can be excluded
(2ΔlogL worse by 140 units)

⇨ $m(J/\psi p(\bar{p}))$ still not well described

Goodness-of-fit test:
$$\chi^2/ndf = 1.7 \rightarrow p = 4 \cdot 10^{-3}$$

Can we improve upon this model?



Improve with P_c states

Add P_c^+ and P_c^- with same M, Γ and coupling

→ Improvement in $cos\theta_p$ (helicity angle of p)

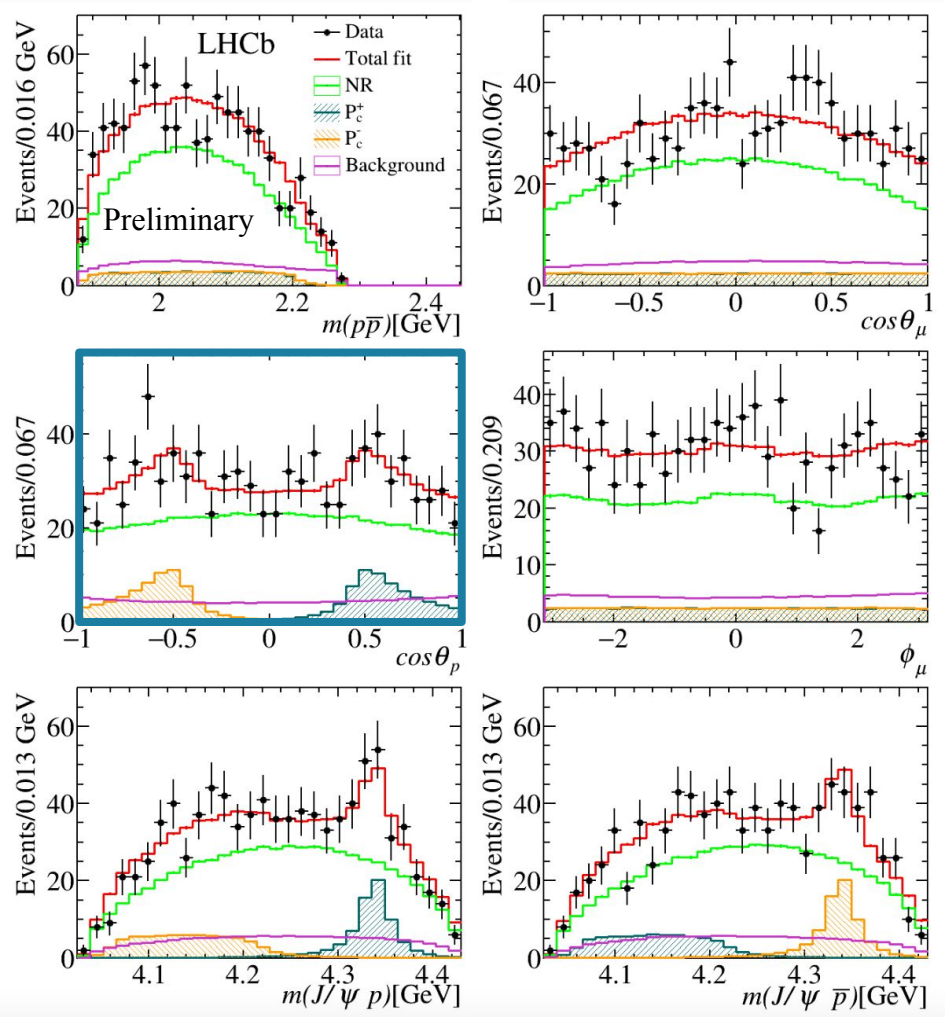
Goodness of fit test:

$$\chi^2/ndf = 0.998 \pm 0.008$$

Other models tested:

- **Old P_c states** observed by LHCb in 2019
- **Glueball** at M~2.2GeV and Γ=20 MeV

⇒ No evidence



LHCb-PAPER-2021-018

Testing different J^P

LHCb-PAPER-2021-018

Models with different J^P of P_c^+ have been tested

J^P	M_0	Γ_0	$f(P_c)(\%)$	$A(P_c)$	$\phi(P_c)$
$1/2^-$	4335^{+3}_{-3}	23^{+11}_{-8}	$17.4^{+7.0}_{-3.8}$	$0.15^{+0.07}_{-0.05}$	$2.8^{+1.3}_{-1.4}$
$1/2^+$	4337^{+7}_{-4}	29^{+26}_{-12}	$22.0^{+8.5}_{-4.4}$	$0.19^{+0.19}_{-0.08}$	$-0.6^{+2.4}_{-3.0}$
$3/2^-$	4337^{+5}_{-3}	23^{+16}_{-9}	$18.6^{+6.9}_{-3.0}$	$0.14^{+0.08}_{-0.05}$	$-1.3^{+1.9}_{-2.0}$
$3/2^+$	4336^{+3}_{-2}	15^{+9}_{-6}	$11.7^{+4.2}_{-2.7}$	$0.10^{+0.05}_{-0.03}$	$-3.1^{+0.6}_{-0.6}$

Significance

Likelihood-ratio based frequentistic tests with 'look-elsewhere' effect considered

Values in the range: 3.1-3.7 σ

$$J^P = 1/2^+ \quad \sigma = 3.73 \pm 0.05$$
$$J^P = 3/2^+ \quad \sigma = 3.09 \pm 0.04$$

None of the J^P can be discarded with CL_s method @95% of CL

→ dominant systematic uncertainty

Evidence of a new exotic state

LHCb-PAPER-2021-018

New pentaquark-like state (uud cc-bar) with significance between 3.1 - 3.7σ

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

Fit fraction of the sum of $P_c^+ + P_c^-$

$$f(P_c) = 22.0^{+8.5}_{-4.0}(\text{stat}) \pm 8.6(\text{sys})\%$$

Preliminary

⇨ $P_c(4337)$ not consistent with previously observed P_c states

We can exclude:

- **Old P_c states**, in particular $P_c(4312)$
- **Glueball** $f_J(2230)$

Theoretical interpretation:

- no near threshold except for $\chi_{c0}(1P)p$
- Tight pentaquark?

⇒ need predictions from theorists

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

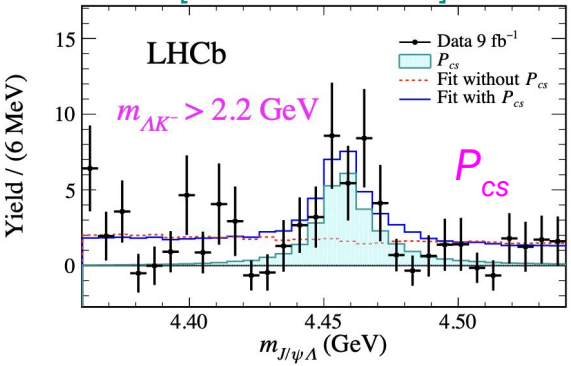
The $B^+ \to J/\psi \phi K^+$ decay

LHCb analysis Run1 data:

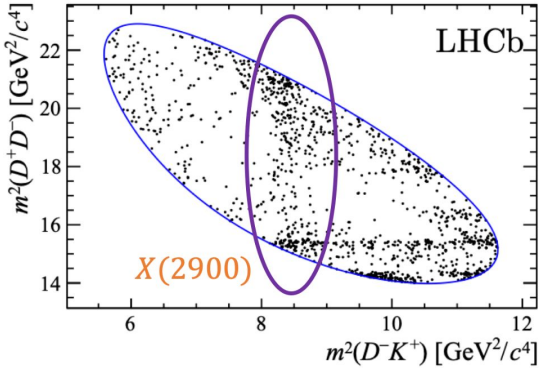
- $J/\psi\phi$ structures:
  - observation of $X(4274)$, $X(4500)$ and $X(4700)$
- $J/\psi K^+$ structure: evidence

⇒ search for Z_{cs}^+ after evidence of P_{cs} and observation of $X(2900)$

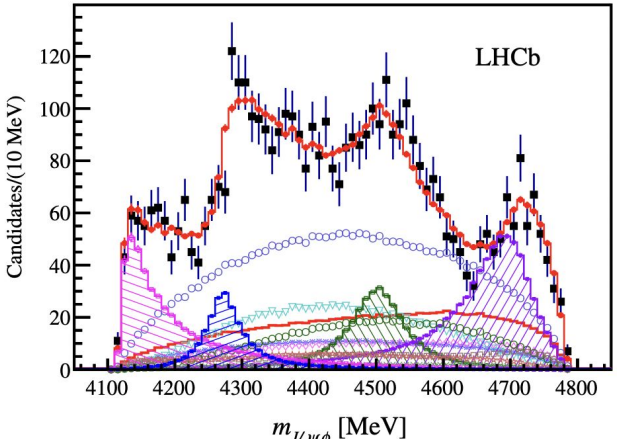
[arXiv:2012.10380]

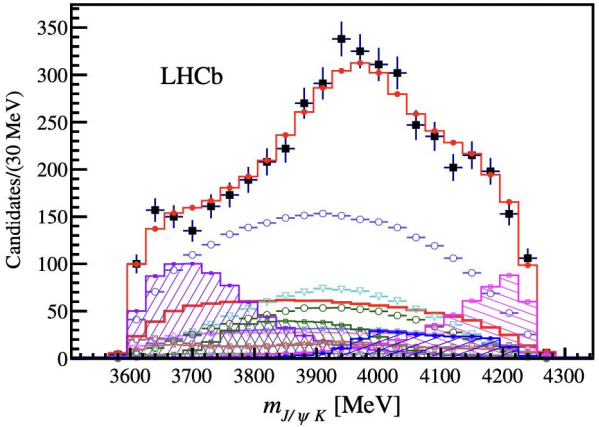


PRL 125 (2020) 242001



LHCb Run 1: Phys. Rev. Lett. 118, 022003



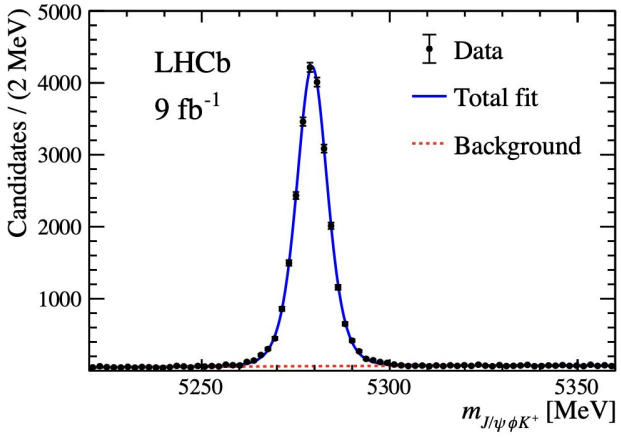


A zoo exotic channel

[arXiv:2103.01803]

Optimised selection: 9 fb^{-1}

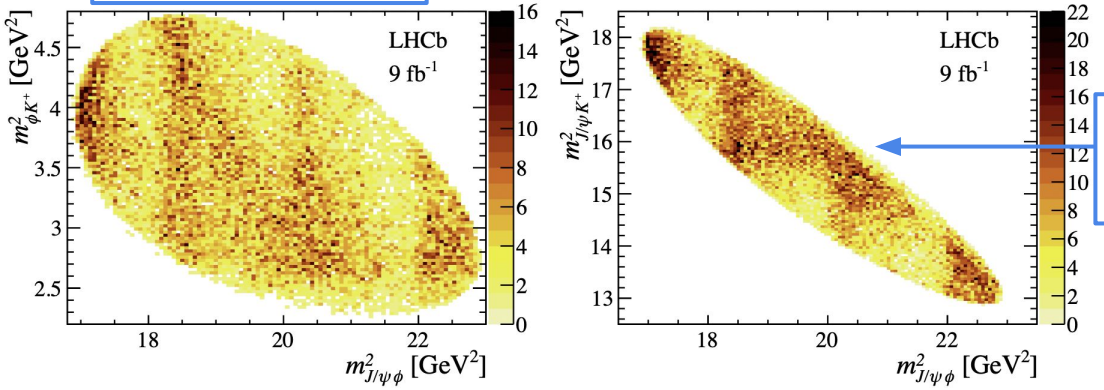
- N_{sig} ~24k, 6 times Run 1 data,
- background fraction of 4% in +/-15MeV
  → 15% higher signal efficiency



Clear structures in the Dalitz plot:

- four X states in $J/\psi\phi$
- clear band at 16 MeV^2 in $J/\psi K$

several X states



Z_{cs}^{+} state?

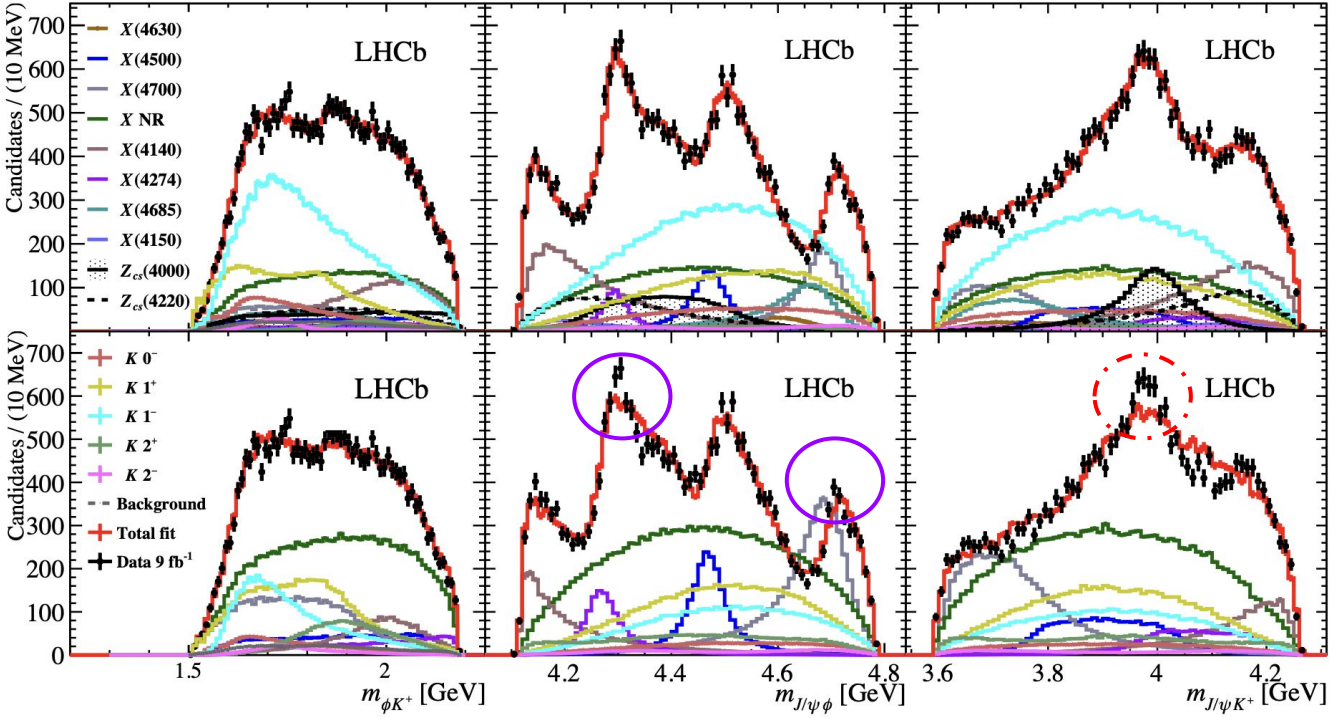
New X and Z_{cs} states

[arXiv:2103.01803]

Amplitude fit based on Run 1 model

but extended with:

Run1 model



New X and Z_{cs} states

[arXiv:2103.01803]

Amplitude fit based on Run 1 model

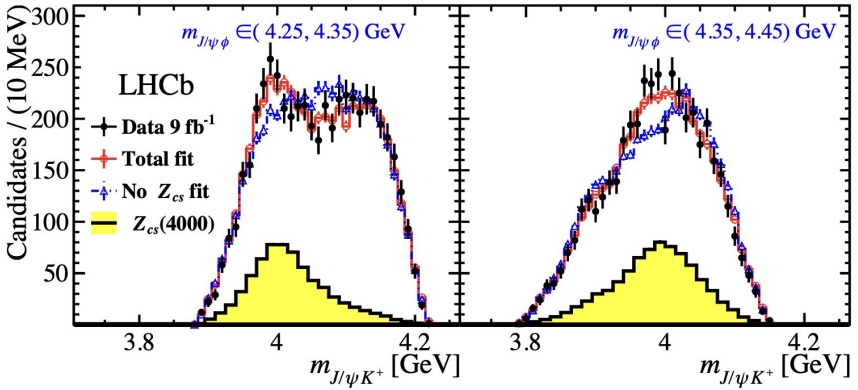
but extended with:

+ 2 X states:
  $X(4630)$ and $X(4685)$
+ 2 $Z_{cs}^{+} \to J/\psi K^{+}$
  $\to$ tetraquark with strangeness

Observation of all >5σ

Contribution	Significance [×σ]	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(4630)$	5.5 (5.7)	$4626 \pm 16 {}^{+18}_{-110}$	$174 \pm 27 {}^{+134}_{-73}$	$2.6 \pm 0.5 {}^{+2.9}_{-1.5}$
$X(4685)$	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)	$4216 \pm 24 {}^{+43}_{-30}$	$233 \pm 52 {}^{+97}_{-73}$	$10 \pm 4 {}^{+10}_{-7}$

Fit projection for $Z_{cs}(4000)$ onto $J/\psi K^{+}$ in two slices of $J/\psi\phi$



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[arXiv:2103.01803]

Amplitude fit based on Run 1 model

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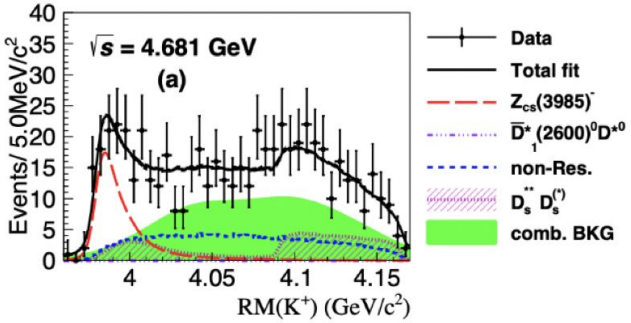
New state observed by BESIII $Z(3985)$ in $D_s^- D^{*0} + D^0 D_s^{*-}$ [PRL 126 (2021) 102201]

No evidence that is the same as $Z_{cs}(4000)$ state:

- Fixing $Z_{cs}(4000)$ to BESIII's result
  ⇒ -2 ΔlogL worse by 160 units



Conclusion and prospects

A lot of interesting results from LHCb

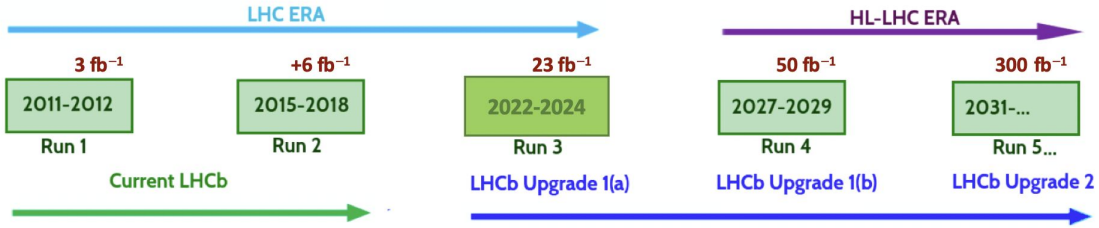
- New evidence of pentaquark $P_c(4337)$ in $B_s \to J/\psi p\bar{p}$
- Observation of 4 new exotics in $B^+ \to J/\psi \phi K^+$:
  2 Z_{cs} with strangeness
- First P_{cs} evidence in $\Xi_b^- \to J/\psi \Lambda K$ [arXiv:2012.10380]
- Observation of X(2900) in $B^+ \to D^+ D^- K^+$ [PRD 102 (2020) 112003]

Need larger dataset:

- to confirm the evidences
- to help understand the nature of these states

LHCb is boosting data to a new level:

- ~7x more data by 2029, half by 2024
- expected 6x increase with Upgrade II

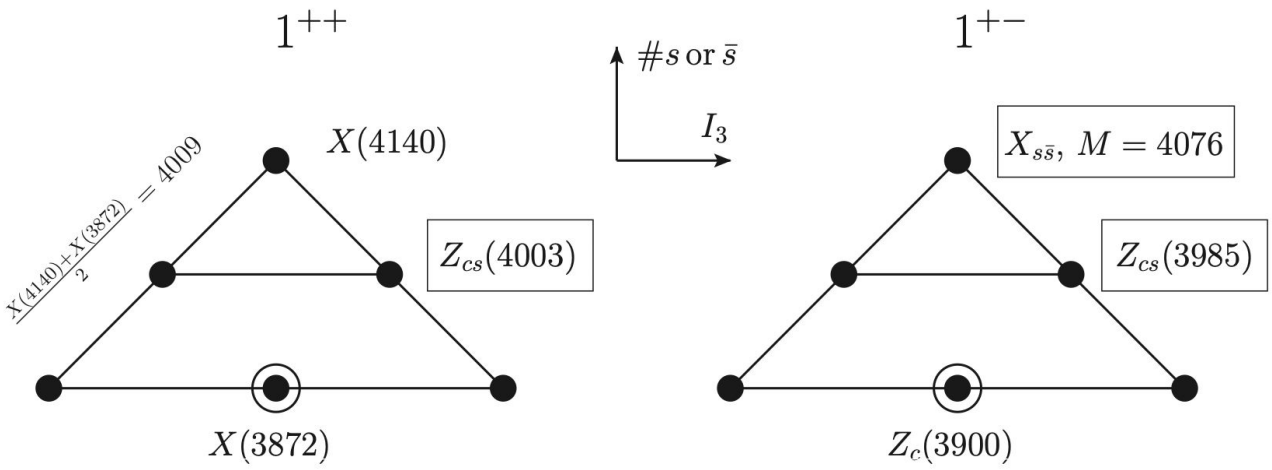


Thank you for listening!

BACKUP SLIDES

Tetraquark multiplets

For $SU(3)_f$ symmetry, $Z_{cs}(4003)$ and $Z_{cs}(3985)$ belongs to 1^{++} and 1^{+-} nonets [arXiv:2103.08331v2]



Z_{cs} mass prediction = 4009 MeV

Prediction for a new state X_{ss} with mass equal to 4076 MeV,

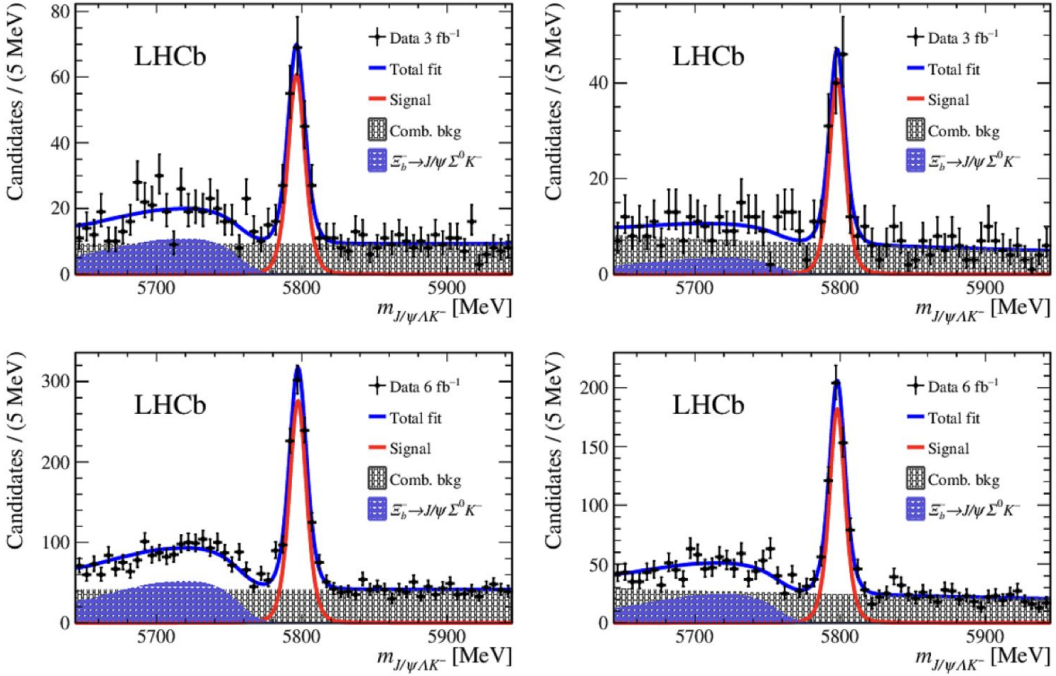
- Decaying to: $\eta_c\,\varphi$, $\eta J/\Psi$, $D_s^{-*}D_s$

Evidence of $P_{\text{cs}} \to J/\psi\Lambda$

Evidence of $P_{cs} \rightarrow J/\psi\Lambda$

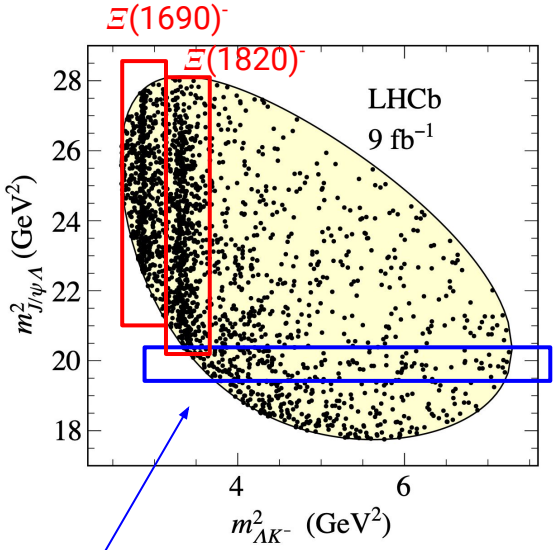
[arXiv:2012.10380]

~1750 Ξ_b^- signals in $\Xi_b^- \rightarrow J/\psi\Lambda K$ decays, with purity ~ 80%



Λ decay in VELO

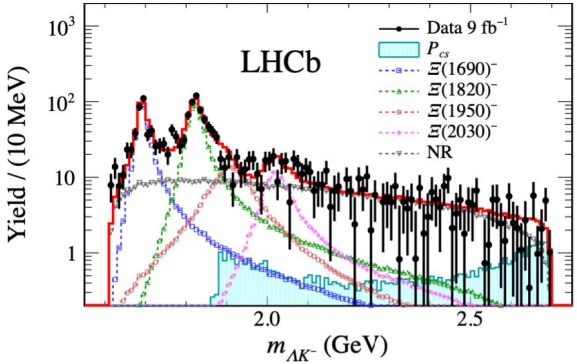
Λ decay after VELO

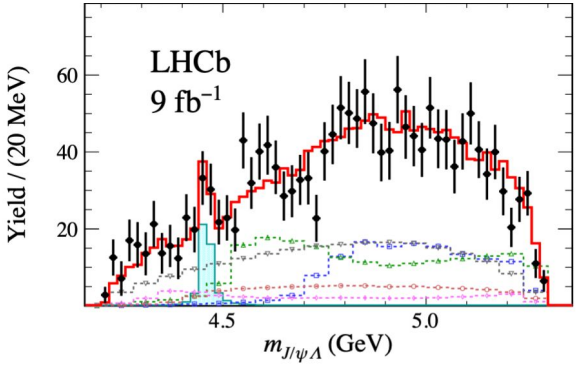


Potential $P_{cs} \rightarrow$ need an amplitude analysis to answer

Evidence of $P_{cs} \to J/\psi\Lambda$

[arXiv:2012.10380]

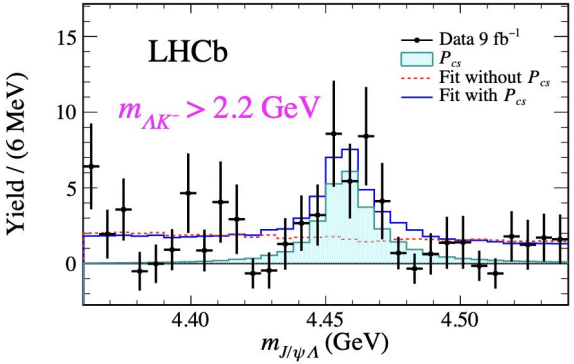


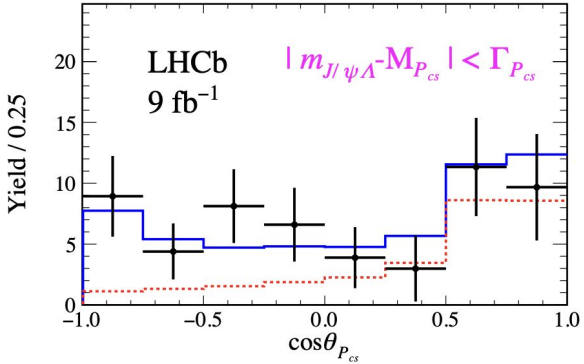


⇒ $P_{cs}(4459)$ at 3.1σ including systematics

M = 4458.8 ± 2.9 (stat) MeV
Γ = 17.3 ± 6.5 (stat) MeV

- More prominent when Ξ^{*-} resonances are suppressed
- Improvement in $cos\theta_{Pcs}$

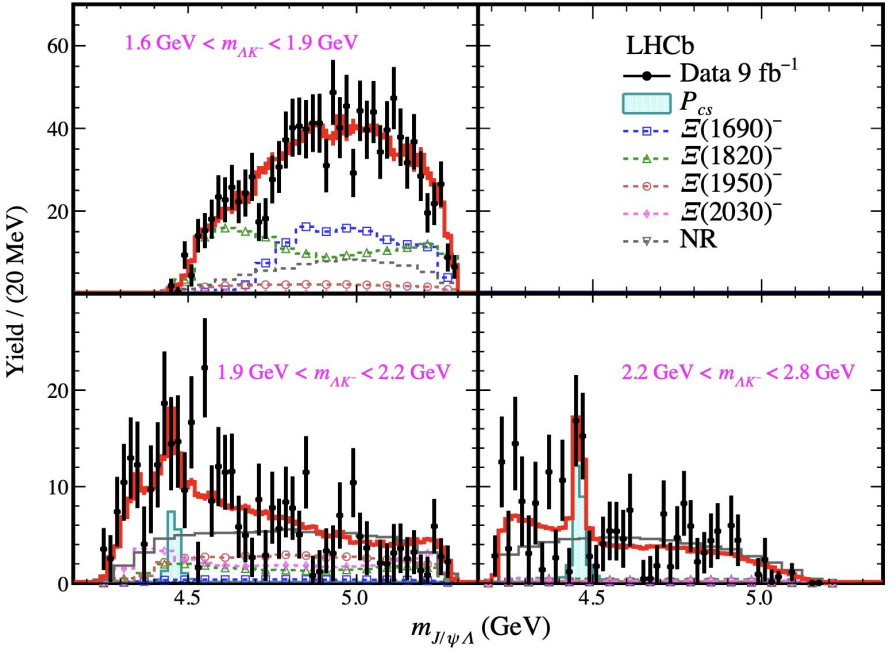




Evidence of $P_{cs} \rightarrow J/\psi\Lambda$

[arXiv:2012.10380]

No other P_{cs} states observed



State	M_0 (MeV)	Γ_0 (MeV)	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9+0.7}_{-0.6-1.3}$
$\Xi(1690)^-$	$1692.0 \pm 1.3\,^{+1.2}_{-0.4}$	$25.9 \pm 9.5\,^{+14.0}_{-13.5}$	$22.1\,^{+6.2+6.7}_{-2.6-8.9}$
$\Xi(1820)^-$	$1822.7 \pm 1.5\,^{+1.0}_{-0.6}$	$36.0 \pm 4.4\,^{+7.8}_{-8.2}$	$32.9\,^{+3.2+6.9}_{-6.2-4.1}$
$\Xi(1950)^-$	1910.6 ± 18.4	105.7 ± 23.2	$11.5\,^{+5.8+49.9}_{-3.5-\ 9.4}$
$\Xi(2030)^-$	2022.8 ± 4.7	68.2 ± 8.5	$7.3\,^{+1.8+3.8}_{-1.8-4.1}$
NR	–	–	$35.8\,^{+4.6+10.3}_{-6.4-11.2}$

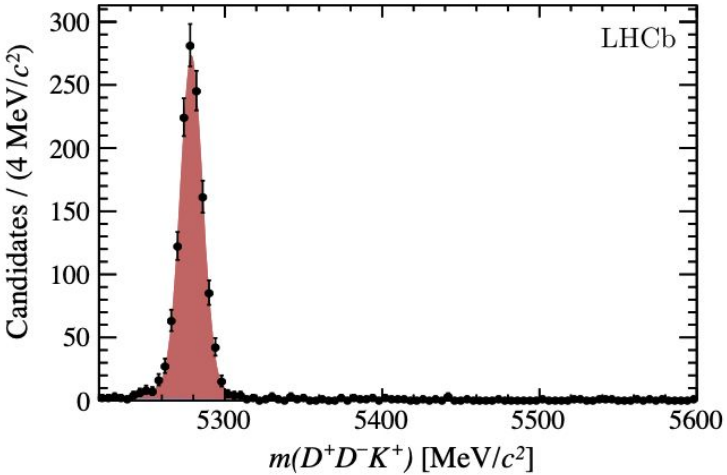
- New pentaquark with strangeness:
  - test of SU(3) flavour symmetry
  - 19 MeV below the $\Xi_c^{\,0} D^{*0}$ threshold
    ⇒ molecular interpretation?
- 2 new Ξ^{*-} states

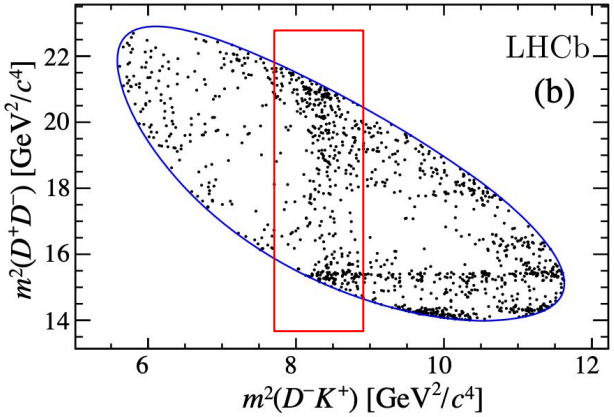
Observation of *X(2900)*

$B^+ \to D^+D^-K^+$ decays

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

~ 1260 signal events in +/-20 MeV
Purity > 99.5%



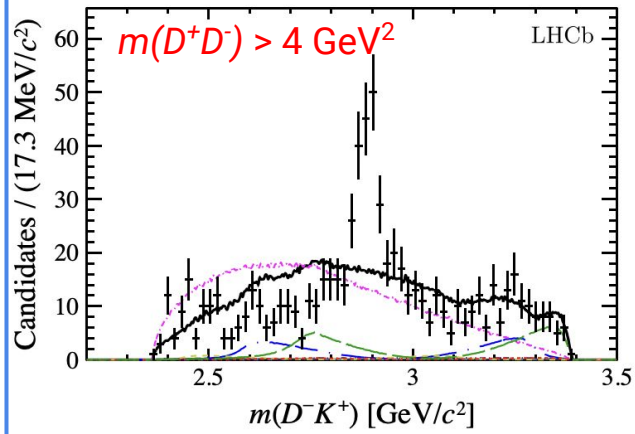


Both amplitude analysis & model-independent analysis to investigate D^-K^+ structure

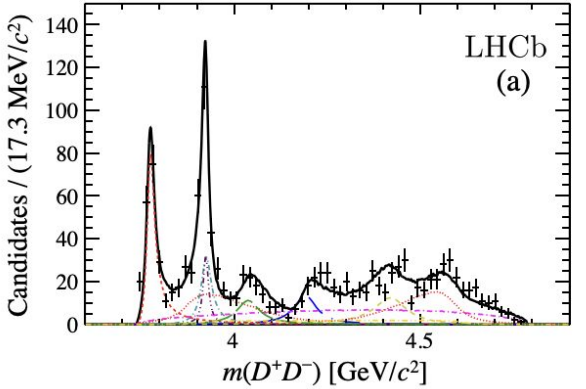
Amplitude analysis

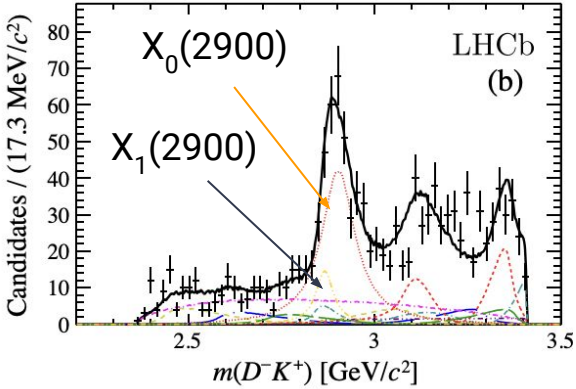
[PRD 102 (2020) 112003]

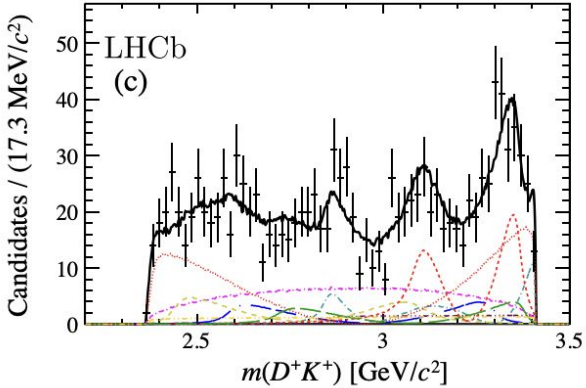
Resonances in D^+D^- do not describe the data well



+ two X(2900) with overwhelming significances







- $\psi(3770) \to D^+ D^-$
- $\chi_{c0}(3930) \to D^+ D^-$
- $\chi_{c2}(3930) \to D^+ D^-$
- $\psi(4040) \to D^+ D^-$
- $\psi(4160) \to D^+ D^-$
- $\psi(4415) \to D^+ D^-$
- $X_0(2900) \to D^- K^+$
- $X_1(2900) \to D^- K^+$
- Nonresonant

Model-independent analysis

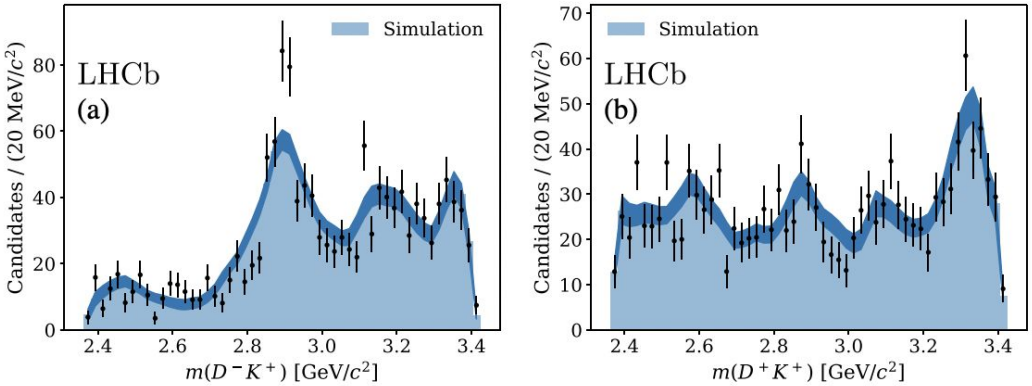
PRL 125 (2020) 242001

Expansion in Legendre polynomials in $m(D^+D^-)$ up to order $\mathbf{k_{max}=2J_{max}}$

Coefficients:

$$\langle Y_k^j \rangle = \sum_{l=1}^{N_j^{\mathrm{Data}}} w_l P_k[h_l(D^+D^-)],$$

Up to order 4: $\mathbf{J_{max}=2}$ for resonances in D^+D^-



Deviations in $m(D^-K^+)$ can be observed at 3.9σ
⇒ compatible with new exotic structures

⇒ Support results of amplitude analysis