HADRON 2021

19TH INTERNATIONAL CONFERENCE ON HADRON SPECTROSCOPY AND STRUCTURE

Experimental review of hidden-charm states

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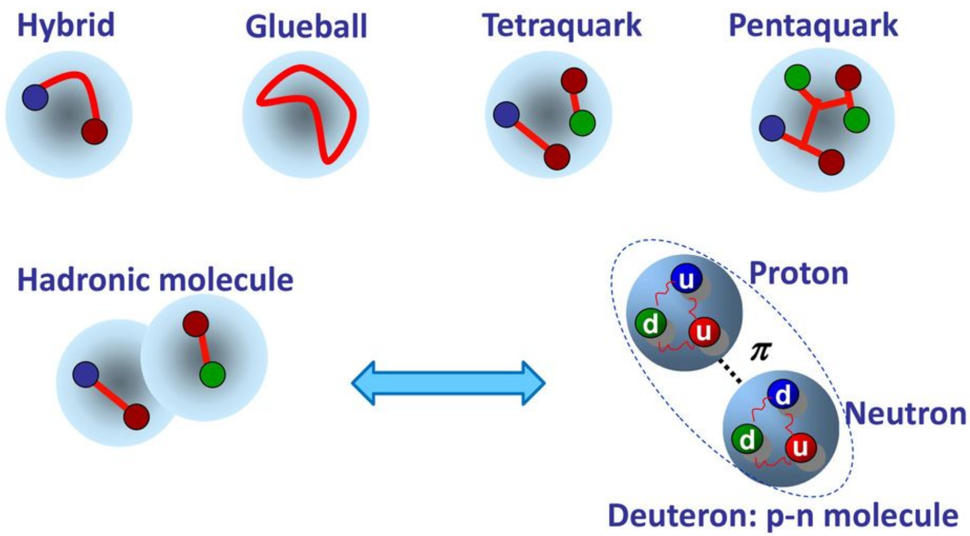
On behalf of the LHCb collaboration

CERN

Exotic hadrons

- The existence of exotic hadrons was already predicted since the establishment of quark model by M. Gell-Mann and G. Zweig in 1964
- Different compositions and binding schemes: $q\bar{q}g$ hybrid, glueball, compact multiquark state, molecular state …

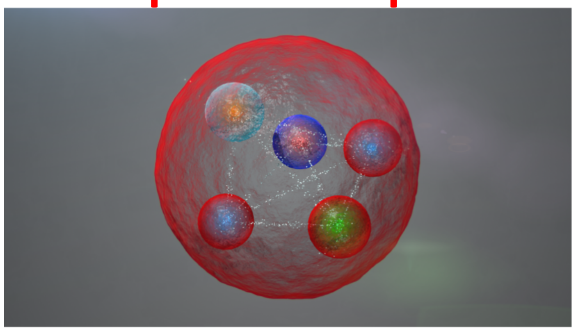


- Study of exotic hadrons can
  - ✓ provide new insights into internal structure and dynamics of hadrons
  - ✓ act as a unique probe to non-perturbative behavior of QCD

Multiquark states

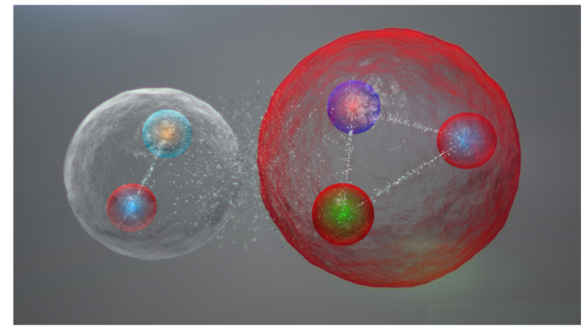
- Since the ***discovery of*** $\boldsymbol{\chi_{c1}(3872)}$ by BELLE in 2003, there is an explosion of discoveries of candidates for tetra- and penta-quark states
- Two main players for multiquark state modelling:

Compact multiquark



(Di-)quarks bound via color forces
- Typical size $\boldsymbol{\mathcal{O}(1\ \mathrm{fm})}$
- Mass proximity to threshold **accidental**
- J^{PC} and flavor **multiplets** expected
- Width can be **large**
- No (strong) hierarchy of couplings

Hadron molecule



Hadrons bound via mesonic exchange
- Typical size $\boldsymbol{\mathcal{O}(10\ \mathrm{fm})}$
- Mass proximity to threshold **natural**
- J^{PC} combinations highly **restricted**
- Width is **narrow** if below threshold
- Fall-apart decay **dominant**

- Other possible scenarios: hadro-quarkonium, hybrid …
- ***Experimental discoveries*** help guide the development of theoretical models

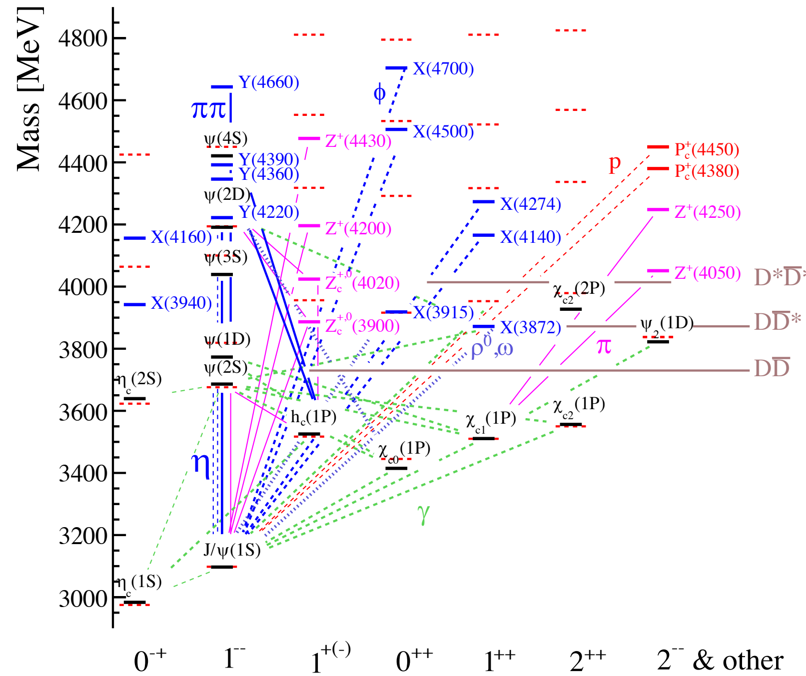
Hidden-charm states

- Experimentally, the key step is to identify exotic hadron states
- Hidden-charm states is an ideal place for exotic study
  - ✓Theoretical models well-established for conventional states
    - Heavy quark mass ⇒ application of QCD factorization
    - Non-relativistic ⇒ construction of potential models
  - ✓Experimentally easy to measure
    - Narrow and non-overlapping
    - Charmonia below $D\overline{D}$ threshold are all observed with properties agree with theoretical predictions

  ⇒ Exotic states easier to be identified compared to light and heavy-light systems

  ✓Tens of non-standard hidden-charm states observed in the past decade
- ***The LHCb experiment*** is at the forefront of such endeavor

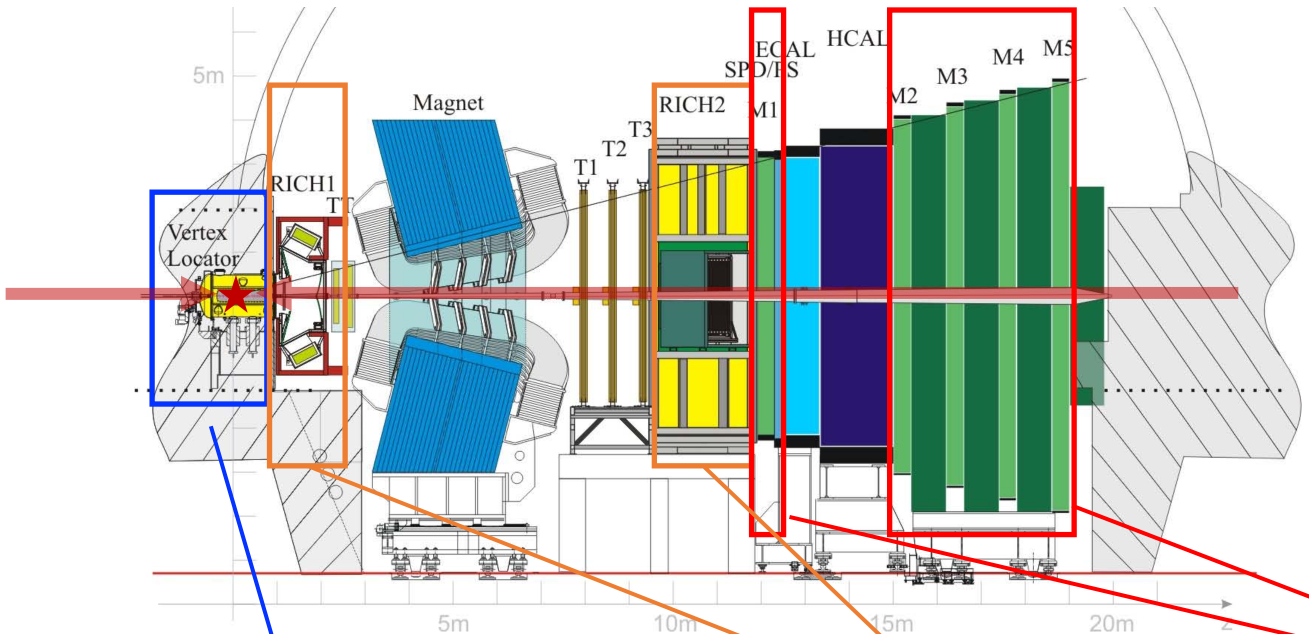
[Rev. Mod. Phys. 90, 15003 (2018)]



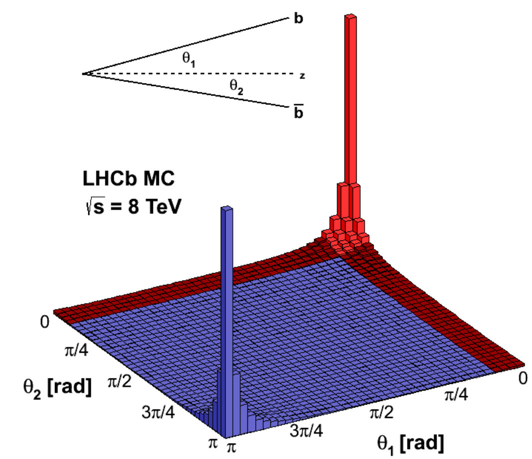
The LHCb detector

- LHCb is a single-arm forward region spectrometer covering $2 < \eta < 5$, dedicated to heavy flavor physics at the Large Hadron Collider

[JINST 3 (2008) S08005]



2.4% 4π angle
=> 25% $b\bar{b}$



Vertex Locator: high precision; capable of separating b/c hadron production and decay vertices

$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$

RICHs: efficient identification of pions, kaons and protons

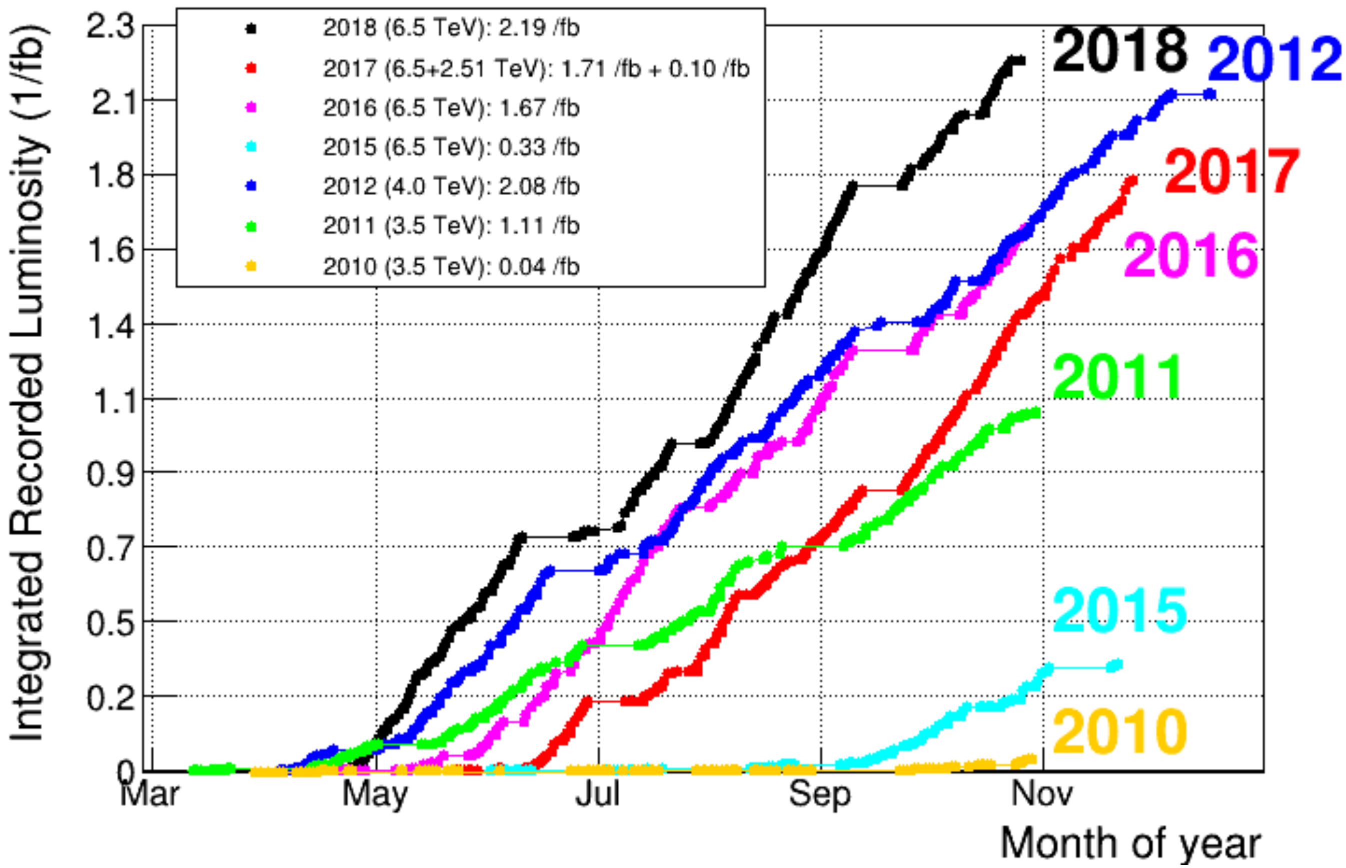
$\varepsilon(K \to K) \sim 95\%$
@ misID rate $(\pi \to K) \sim 5\%$

Muon system (M1-M5): efficient muon identification and trigger

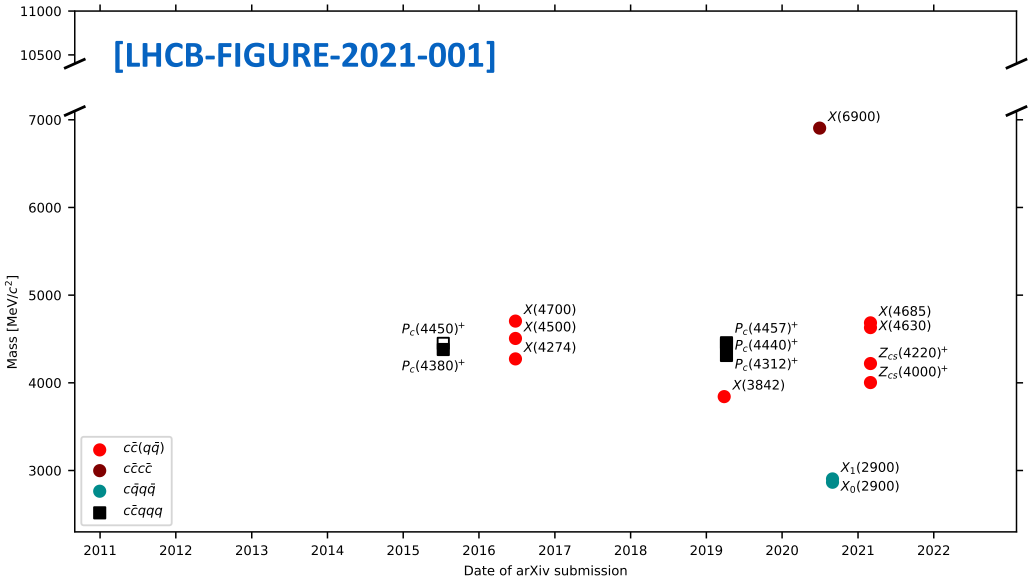
$\varepsilon(\mu \to \mu) \sim 97\%$
@ misID rate $(\pi \to \mu) \sim 1-3\%$

LHCb data taking

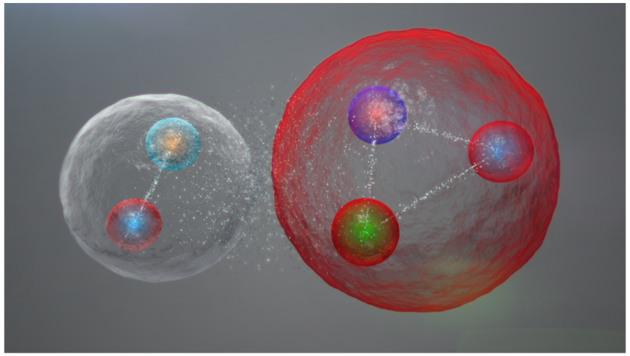
- Run 1 (2011-2012): $\mathcal{L}_{\text{int}} = 1\ \text{fb}^{-1}$ @ 7 TeV & $2\ \text{fb}^{-1}$ @ 8 TeV
- Run 2 (2015-2018): $\mathcal{L}_{\text{int}} = 6\ \text{fb}^{-1}$ @ 13 TeV

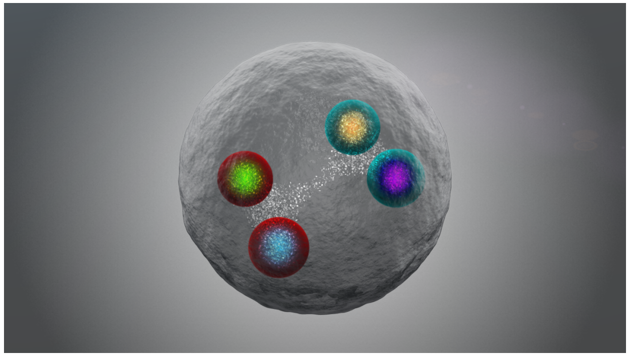


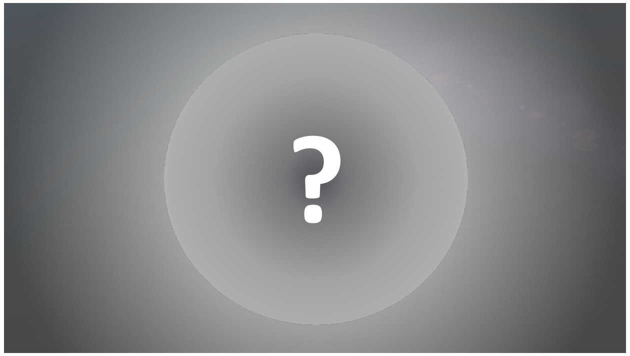
Exotic hadrons @ LHCb



*This talk focuses more on recent results

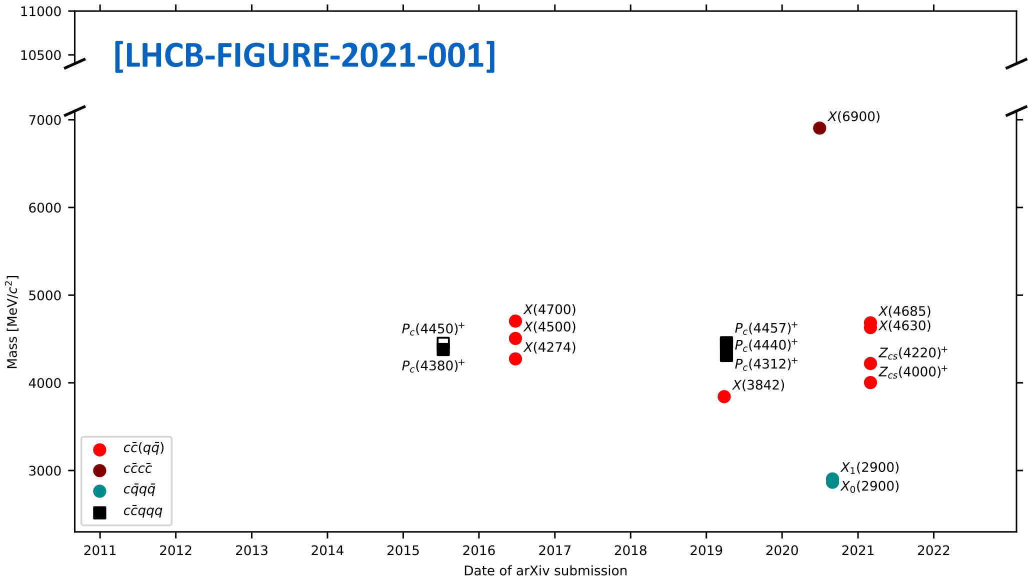






- ❑ Hidden-charm pentaquark
- ❑ Hidden-charm tetraquark
- ❑ Beyond hidden-charm

Exotic hadrons @ LHCb



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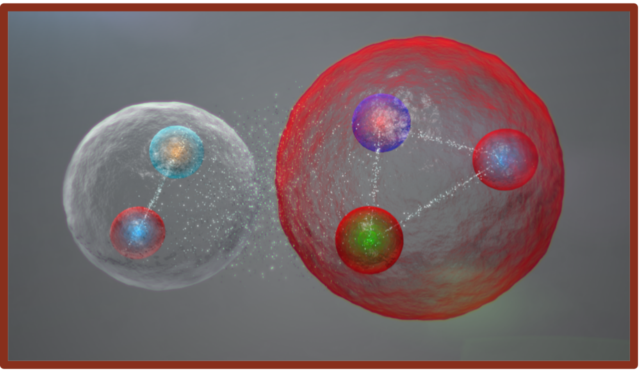
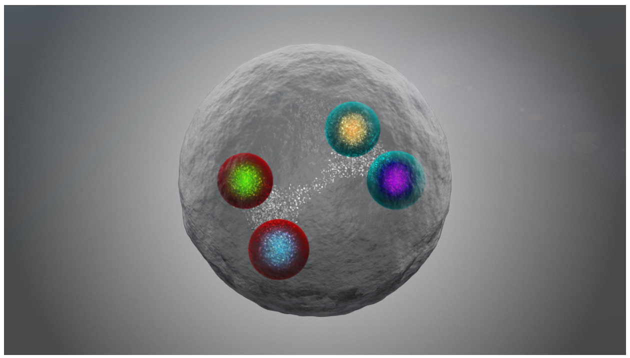
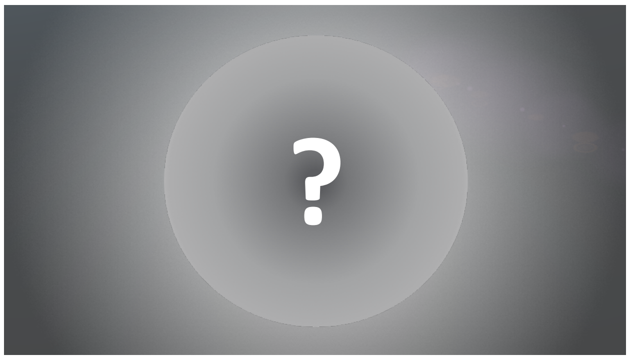






❑ **Hidden-charm pentaquark**

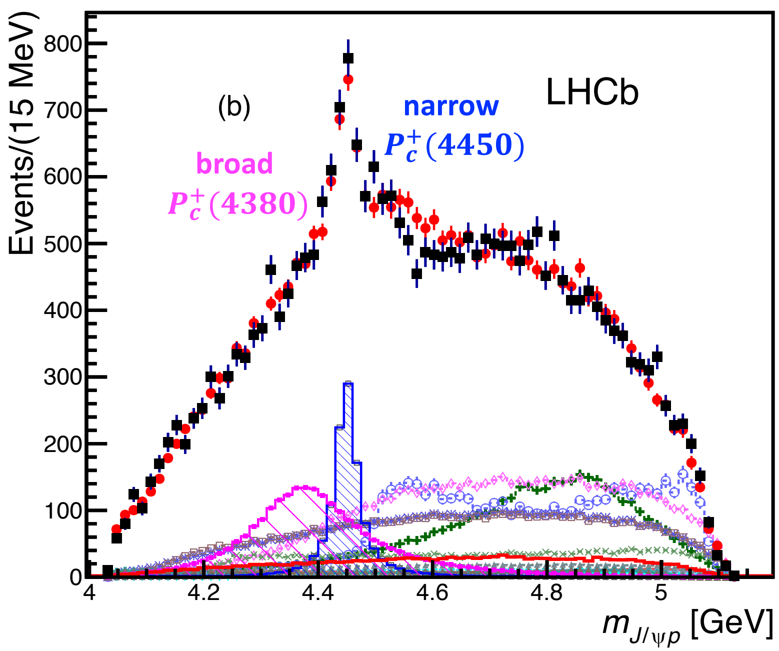
❑ Hidden-charm tetraquark

❑ Beyond hidden-charm

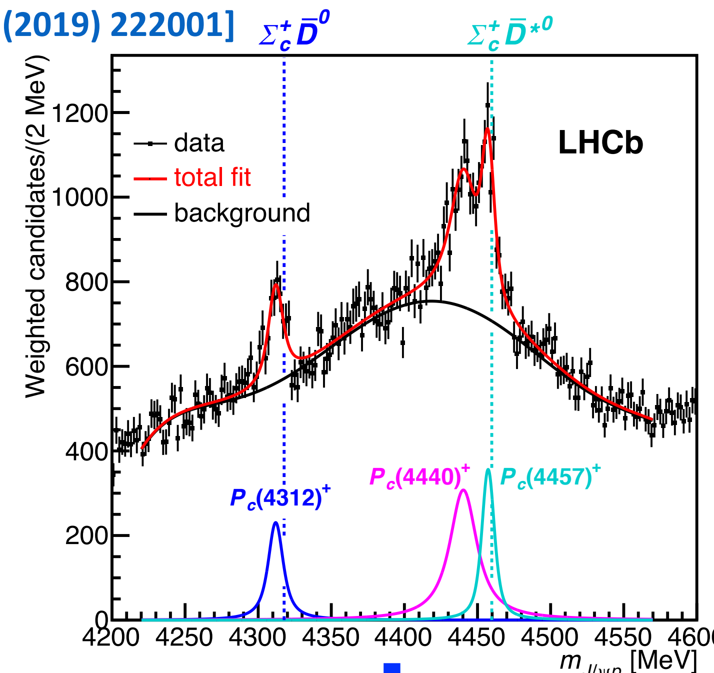
Observation of P_c^+ in $\Lambda_b^0 \to J/\psi K^- p$

- $P_c^+(c\bar{c}uud)$ states were first observed in $\Lambda_b^0 \to J/\psi K^- p$ using LHCb Run1 data
- Later, the $\Lambda_b^0 \to J/\psi K^- p$ study was updated using Run 1 + Run 2 data
  - ✓A new narrow $P_c^+(4312)$ observed with significance of 7.3 σ
  - ✓The $P_c^+(4450)$ structure is resolved into two peaks, $P_c^+(4440)$ and $P_c^+(4457)$

[PRL 115 (2015) 072001]

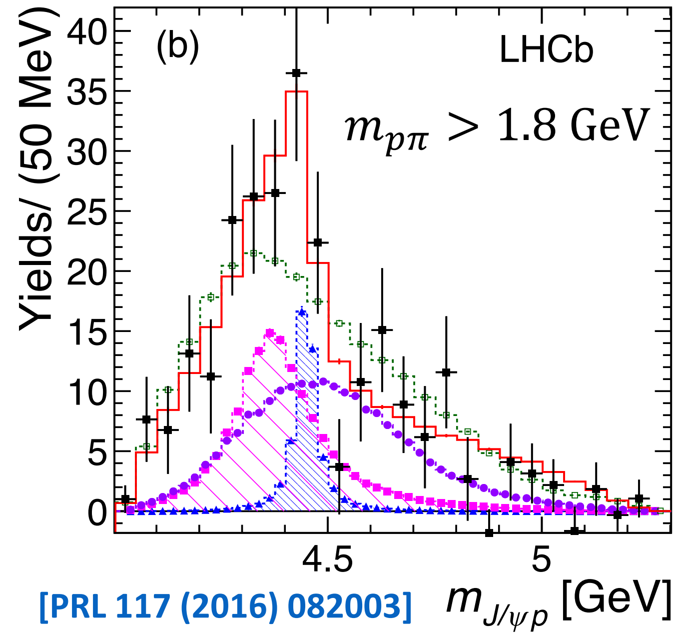


[PRL 122 (2019) 222001]



Proximity of $\Sigma_c^+\bar{D}^0$ and $\Sigma_c^+\bar{D}^{*0}$ thresholds to the peaks suggests they play an important role in the dynamics

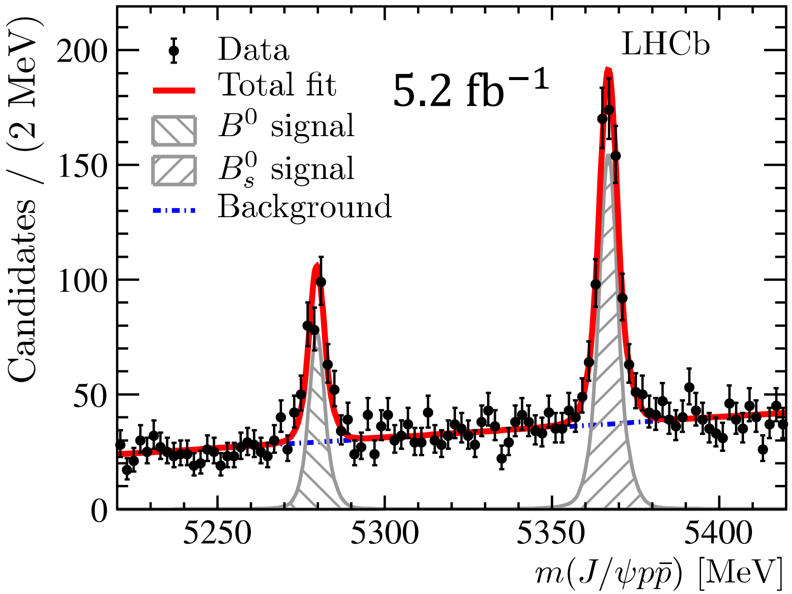
P_c^+ search in other decay modes



[PRL 117 (2016) 082003]

$\Lambda_b^0 \to J/\psi p \pi^-$

- Cabibbo-suppressed decay
- Consistent with existence of same P_c^+ states
- Large statistics is needed for firm confirmation



[PRL 122 (2019) 191804]

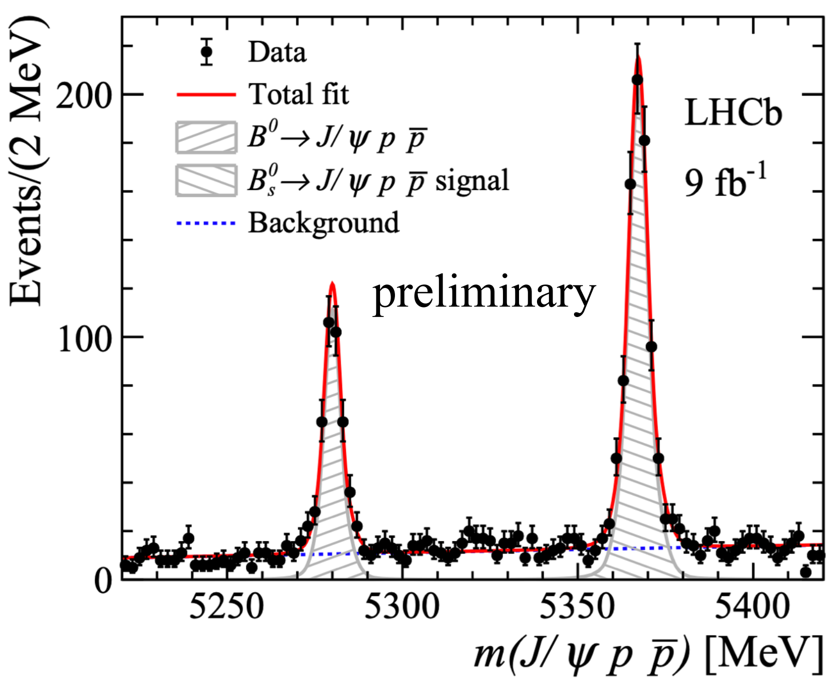
$B_s^0 \to J/\psi p \bar{p}$

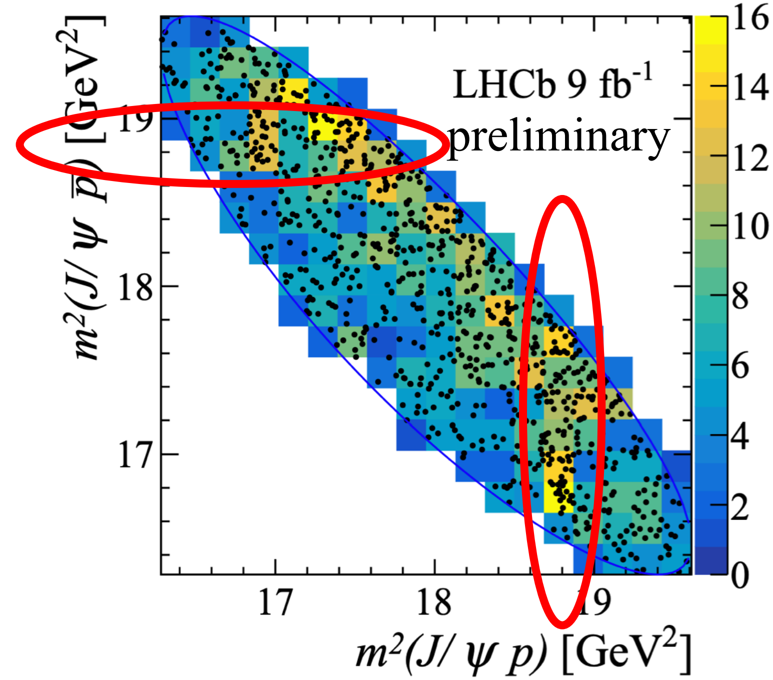
- $m(J/\psi p) \in [4034,4429]$ MeV$/c^2$
- Clean mode: no well-established $p\bar{p}$ resonance
- Inverted $\mathcal{B}(B^0 \to J/\psi p\bar{p}) < \mathcal{B}(B_s^0 \to J/\psi p\bar{p})$ suggests there may exist P_c^+ contribution

⇒ amplitude analysis

$B_s^0 \to J/\psi p\bar{p}$ - dataset and selection

- ➢Dataset: Full Run1+Run2 LHCb data corresponding to 9 fb^{-1}
- ➢Selection: based on boosted decision tree (BDT) and optimized





$N(B_s^0) = 797 \pm 31$

Purity in 3σ: $\sim 85\%$

Hints of horizontal and vertical bands in $(18.8 - 19.0)\ \text{GeV}^2$

$\Rightarrow$4D $(m_{p\bar{p}}, \theta_p, \theta_\mu, \phi)$ amplitude analysis

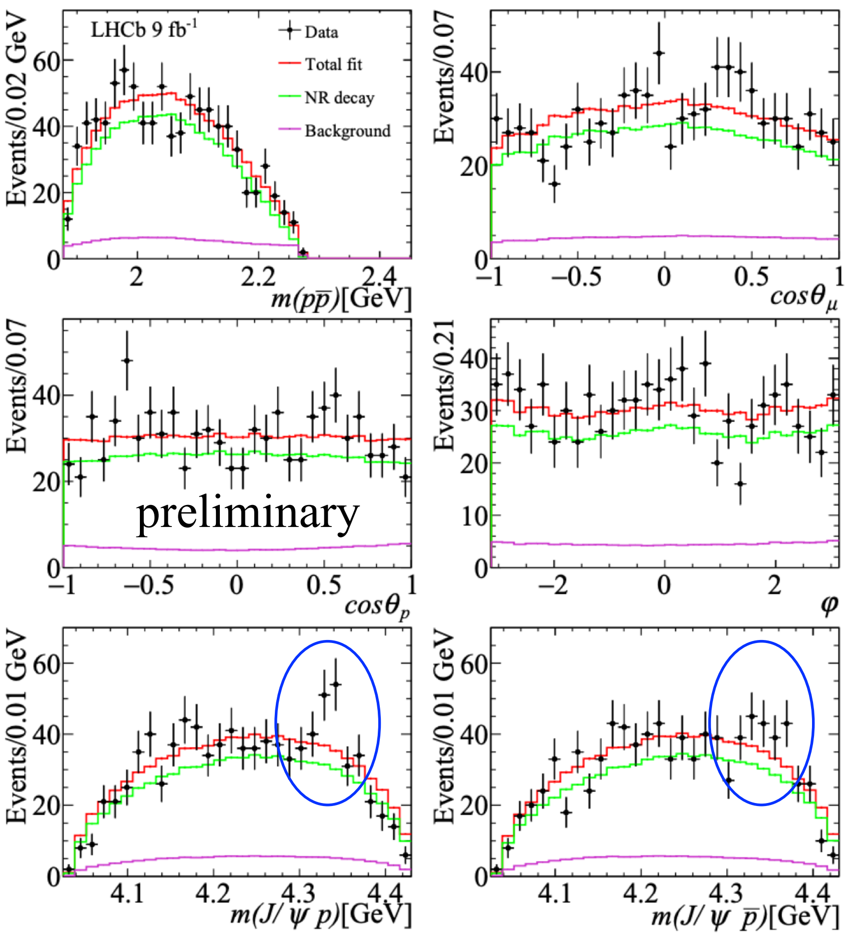
[LHCb-PAPER-2021-018] in preparation

$B_s^0 \to J/\psi p\bar{p}$ - amplitude analysis

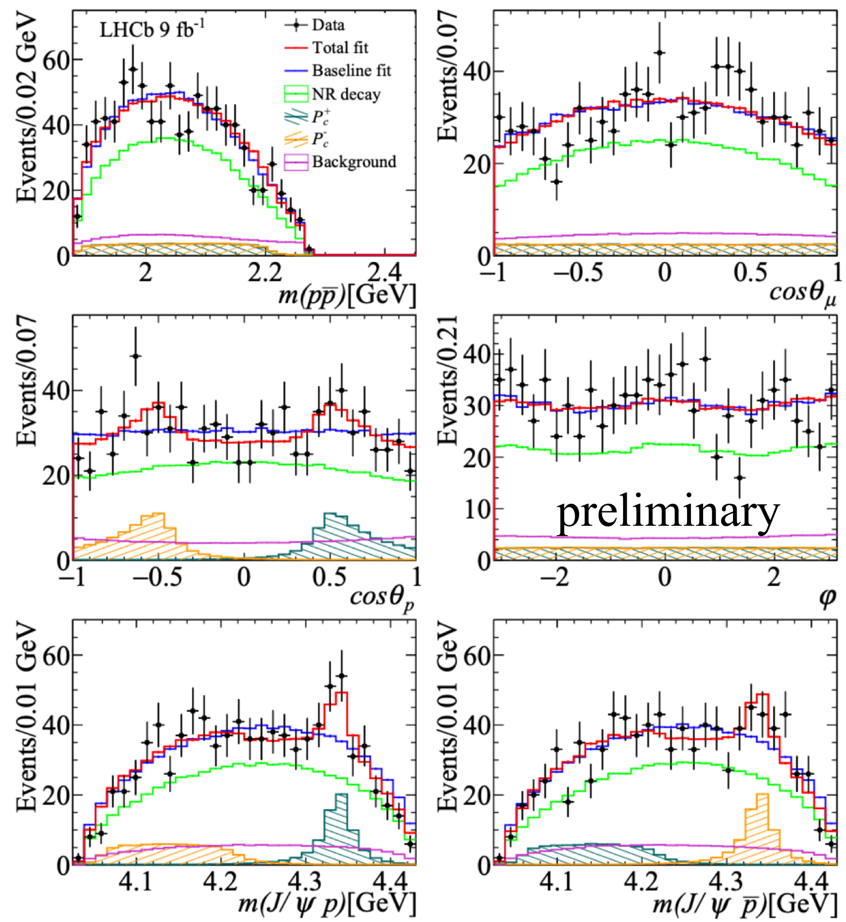
[LHCb-PAPER-2021-018] in preparation

- The B_s^0 sample is flavor untagged, assuming CP symmetry

✓ Null hypothesis model: only NR $p\bar{p}$ contribution with $J^P = 1^-$



✓ Add Breit-Wigner shaped P_c^+ and P_c^- with floating and identical M, Γ and couplings



$B_s^0 \to J/\psi p\bar{p}$ - evidence of new P_c

- Significance of the P_c estimated with look-elsewhere effect considered
  - ✓The best J^P hypothesis is $1/2^+$ for $P_c^+ \Rightarrow 3.7\sigma$
  - ✓For different J^P hypotheses in $1/2^\pm, 3/2^\pm \Rightarrow 3.1-3.7\sigma$
  - ✓None of the J^P hypotheses can be excluded at 95%

- The P_c state is measured to have

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

  - ✓Its mass and width are distinct from previous P_c states
  - ✓It peaks ~ 10 MeV below the $\chi_{c0}(1\text{P})p$ threshold

- No evidence of
  - ✓$P_c(4312)$ and $P_c(4440)$ observed in $\Lambda_b^0 \to J/\psi K^- p$
  - ✓Glueball candidate $f_\text{J}(2230)$

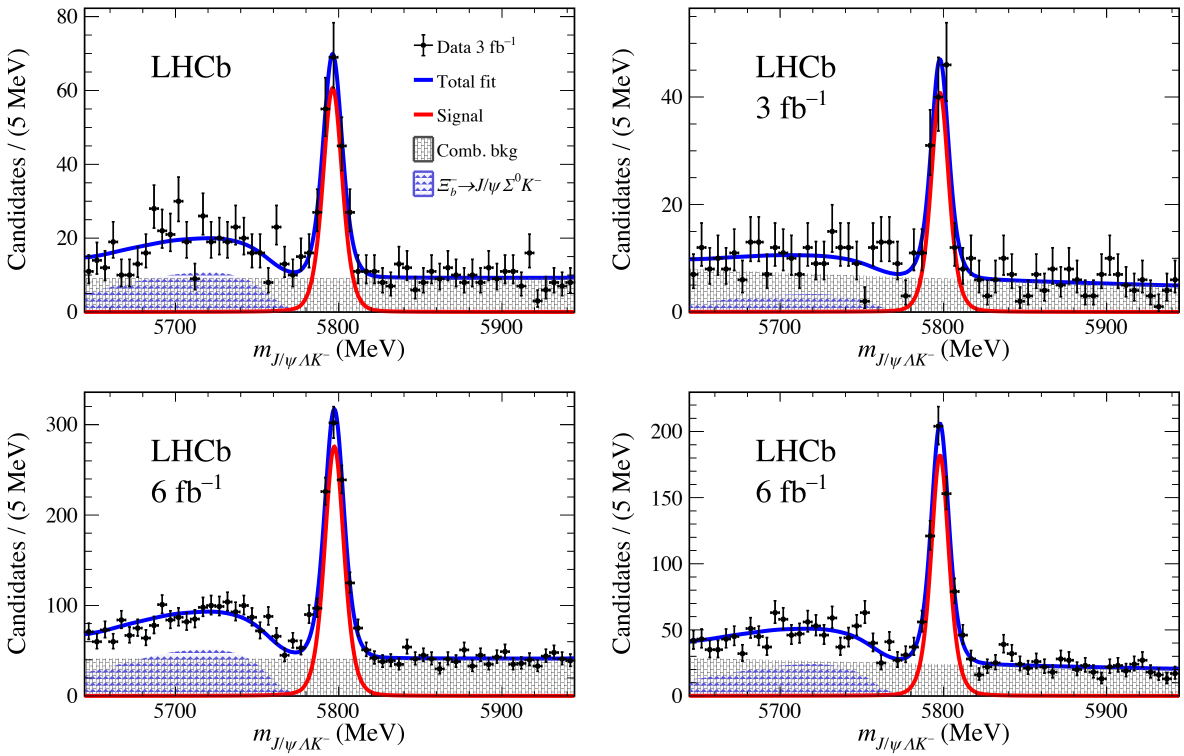
[LHCb-PAPER-2021-018] in preparation

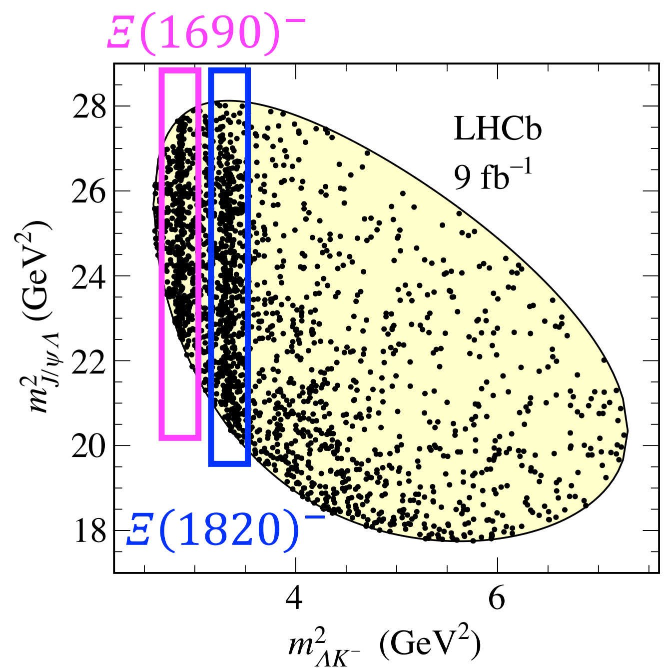
P_{cs}^0 search in $\Xi_b^- \to J/\psi \Lambda K^-$

- P_{cs}^0 $(c\bar{c}sud)$, strange partner of P_c^+, is searched for in $\Xi_b^- \to J/\psi \Lambda K^-$
- Dataset: Full Run1+Run2 LHCb data corresponding to 9 fb^{-1}

[Science Bulletin 66 (2021) 1278]

Λ decay inside VELO | Λ decay outside VELO





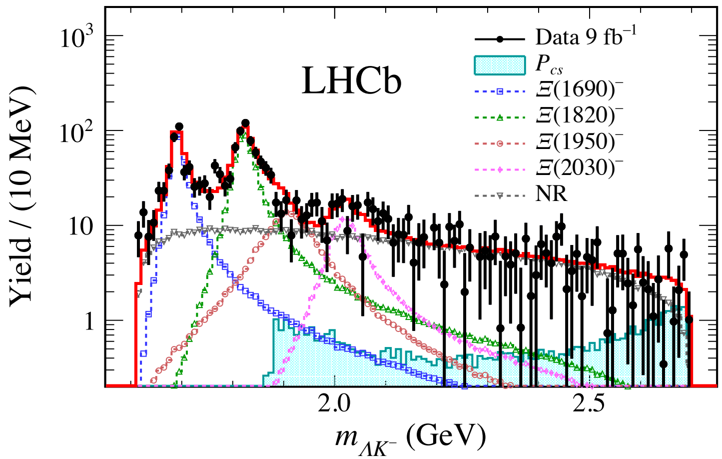
$N(\Xi_b^-) = 1750 \pm 50$

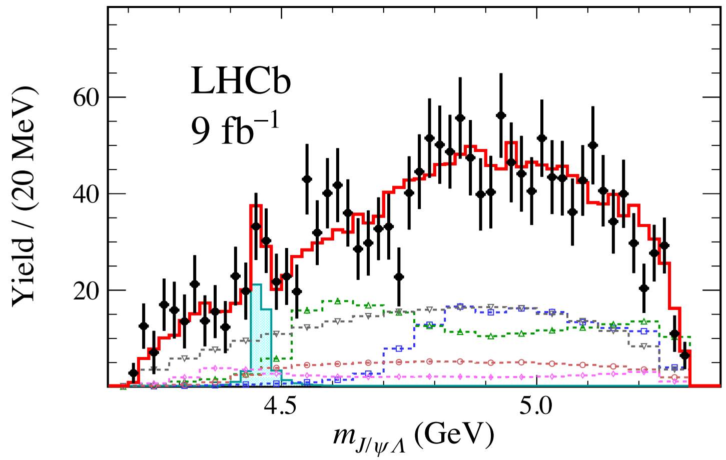
Purity in 3σ: ~80%

✓ $J/\psi\Lambda$ spectrum to be further explored in amplitude analysis

Evidence of P_{cs}^0

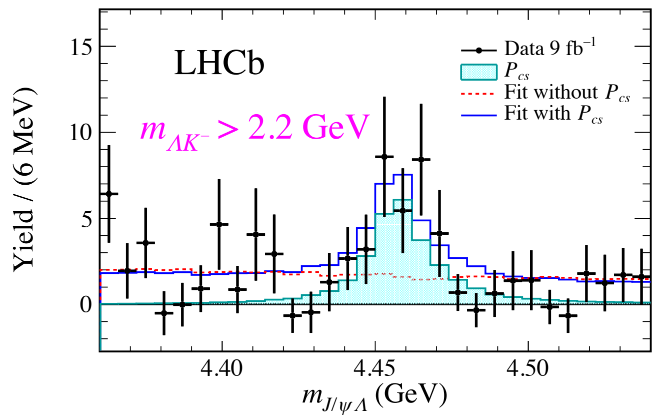
[Science Bulletin 66 (2021) 1278]

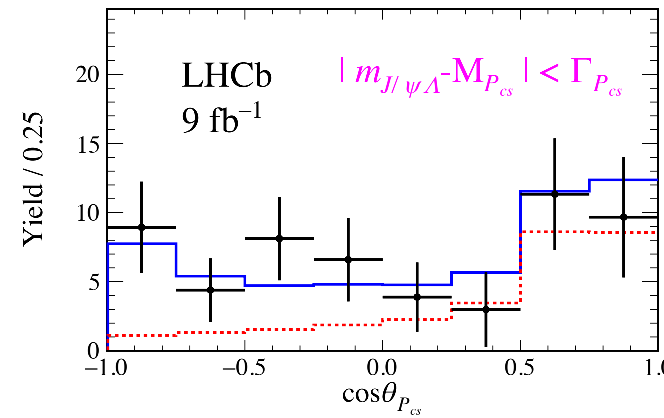




P_{cs}^0 significance:
3.1σ

P_{cs}^0 more visible after excluding low-mass Ξ^{*-} contribution:

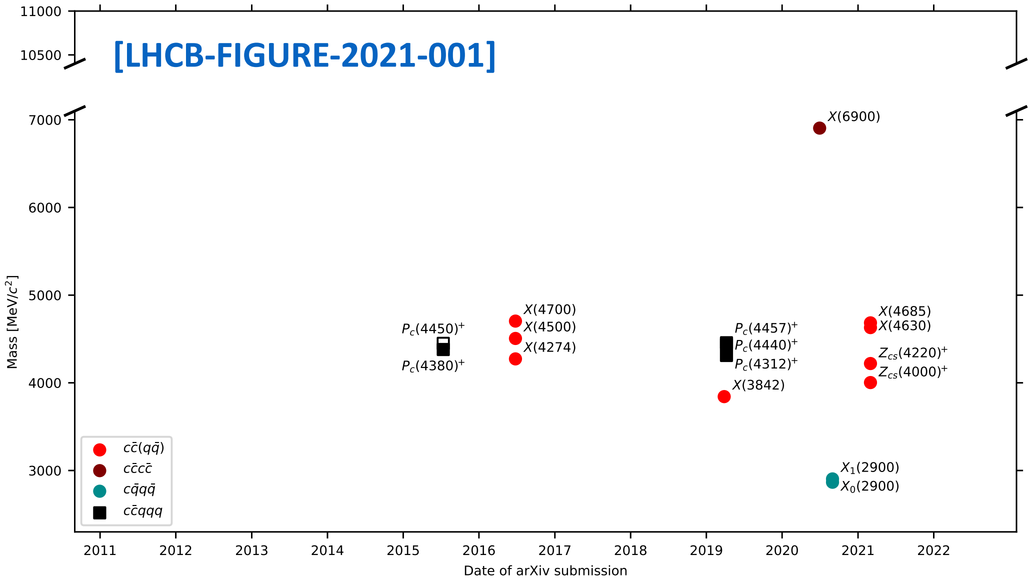




$$m(P_{cs}^0) = 4458.8 \pm 2.9^{+4.7}_{-1.1}\ \mathrm{MeV}, \Gamma(P_{cs}^0) = 17.3 \pm 6.5^{+8.0}_{-5.7}\ \mathrm{MeV}$$

- Mass ~19 MeV below of $\Xi_c^0 \bar{D}^{*0}$ threshold
- The data cannot confirm or refute the two-peak hypothesis
- J^P determination needs more data

Exotic hadrons @ LHCb



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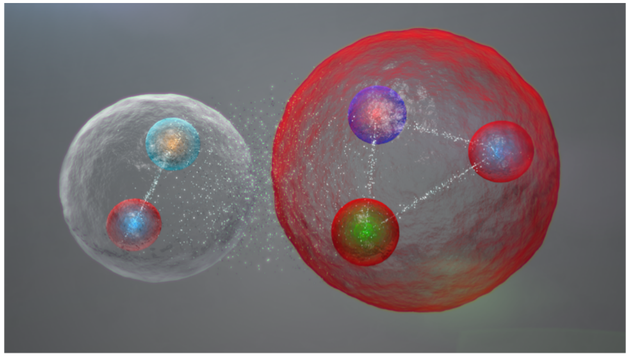
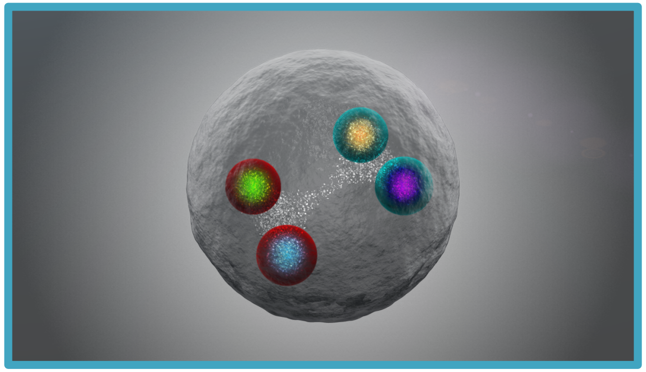
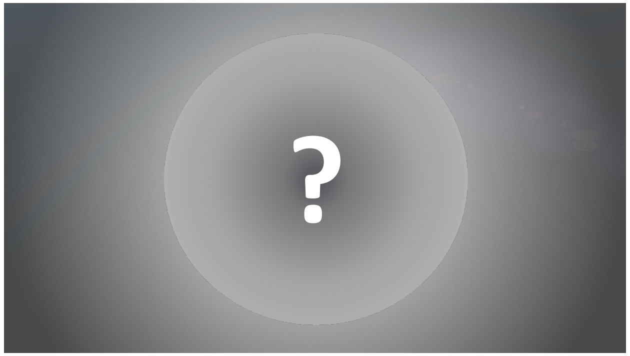






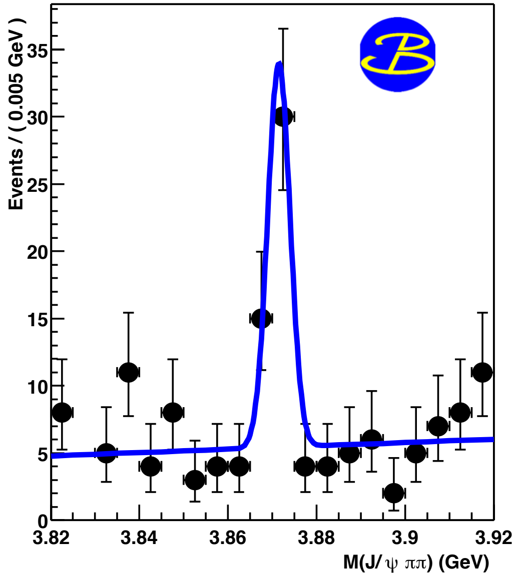
❑ Hidden-charm pentaquark

❑ **Hidden-charm tetraquark**

❑ Beyond hidden-charm

$\chi_{c1}(3872)$ (or $X(3872)$)

- $\chi_{c1}(3872)$ is the first observed hidden-charm exotic hadron with most abundant experimental information
  - ✓ First observed in $B^{\pm} \rightarrow K^{\pm}\chi_{c1}(3872)$ with $\chi_{c1}(3872) \rightarrow J/\psi\pi^{+}\pi^{-}$ by Belle



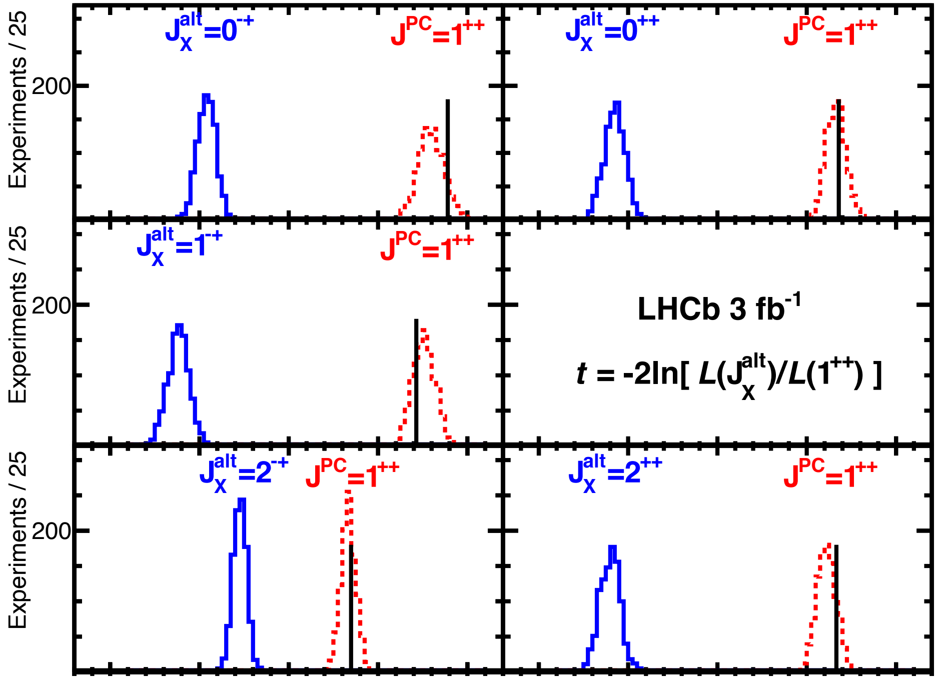
[PRL 91 (2003) 262001]

  - ✓ Confirmed by other experiments in several decay modes: $J/\psi\pi^{+}\pi^{-}\pi^{0}$ ($J/\psi\omega$), $D^{0}\overline{D}^{0}\pi^{0}$, $D^{0}\overline{D}^{*0}$, $J/\psi\gamma$, $\psi(2S)\gamma$, $\chi_{c1}(1P)\pi^{0}$

$\chi_{c1}(3872)$ (or $X(3872)$)

- $\chi_{c1}(3872)$ is the first observed charmonium-like exotic hadron with most abundant experimental information
  - ✓First observed in $B^{\pm} \to K^{\pm}\chi_{c1}(3872)$ with $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$ by Belle
  - ✓Confirmed by other experiments in several decay modes: $J/\psi\pi^+\pi^-\pi^0$ $(J/\psi\omega)$, $D^0\overline{D}^0\pi^0$, $D^0\overline{D}^{*0}$, $J/\psi\gamma$, $\psi(2S)\gamma$, $\chi_{c1}(1P)\pi^0$
  - ✓$\boldsymbol{J^{PC} = 1^{++}}$

- J^{PC} other than 1^{++} and 2^{-+} excluded by CDF [PRL 98 (2007) 132002]
- $\boldsymbol{J^{PC} = 1^{++}}$ **determined by LHCb**



[PR D92 (2015) 011102(R)]

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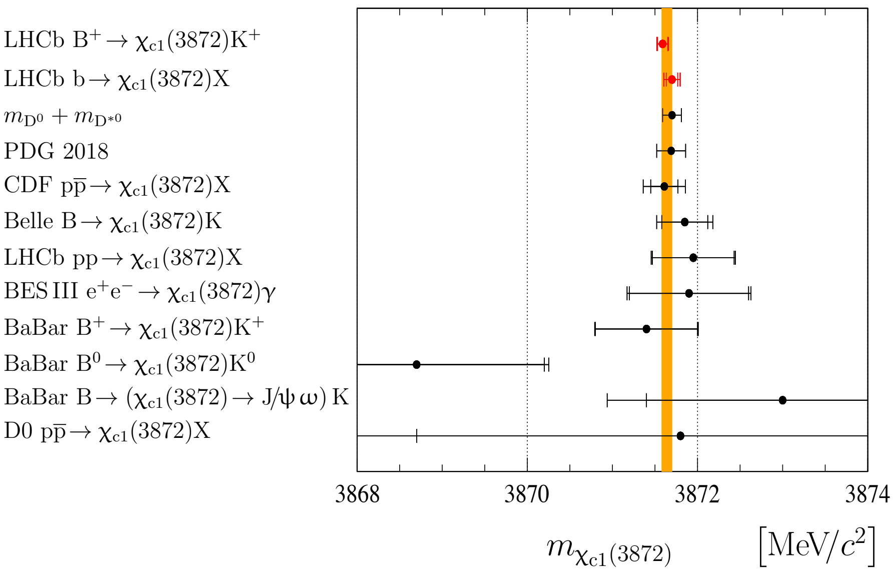
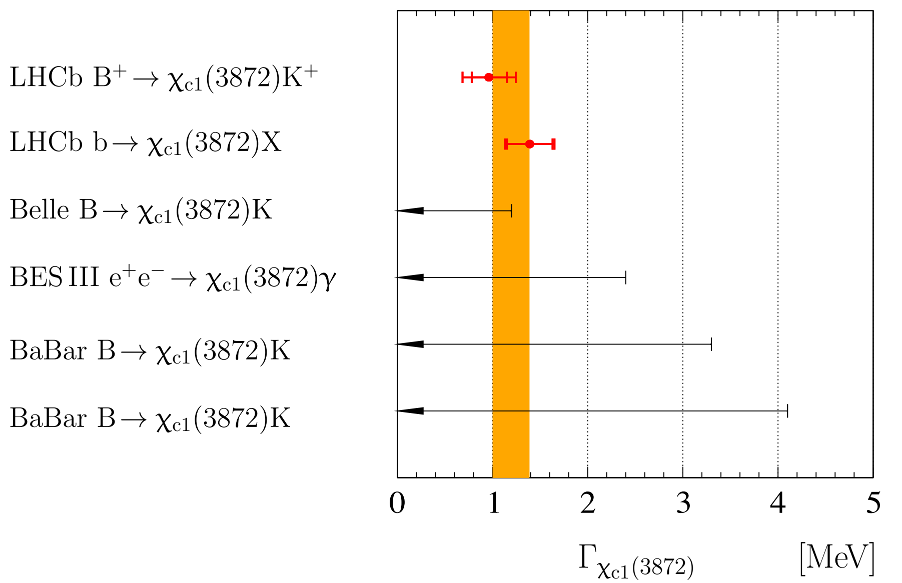
  - ✓ Confirmed by other experiments in several decay modes: $J/\psi\pi^{+}\pi^{-}\pi^{0}$ $(J/\psi\omega)$, $D^{0}\overline{D}^{0}\pi^{0}$, $D^{0}\overline{D}^{*0}$, $J/\psi\gamma$, $\psi(2S)\gamma$, $\chi_{c1}(1P)\pi^{0}$
  - ✓ $J^{PC} = 1^{++}$
  - ✓ Breit-Wigner $\mathbf{M = 3871.64 \pm 0.06\ MeV/c^2; \Gamma = 1.19 \pm 0.19\ MeV}$

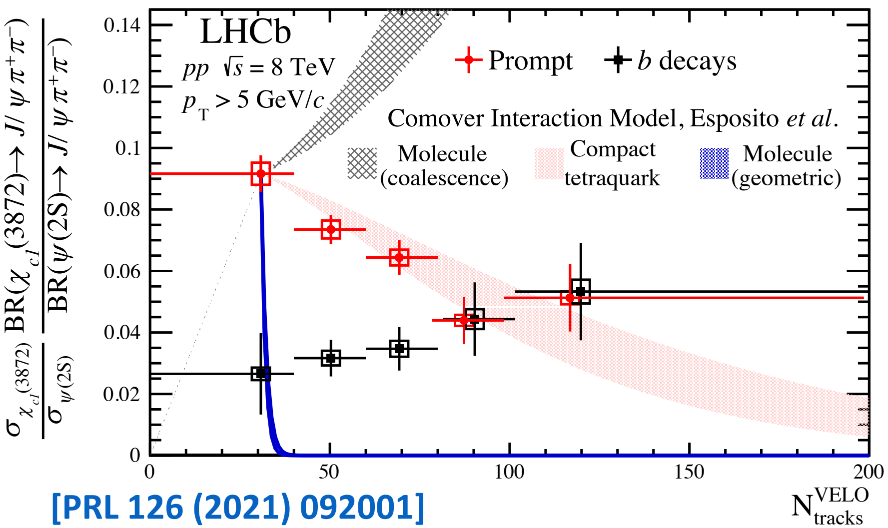
[PRD 102 (2020) 092005] [JHEP 08 (2020) 123]





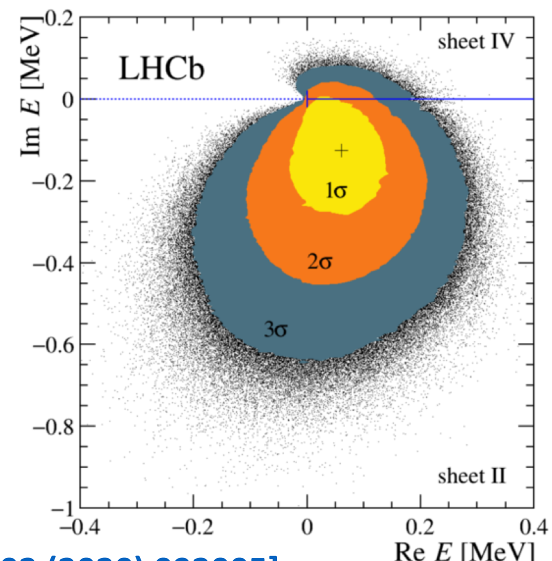
Nature of $\chi_{c1}(3872)$

- Intriguing properties of $\chi_{c1}(3872)$:
  - ✓ Measured mass below prediction for $\chi_{c1}(2^3P_1)$ at present
  - ✓ $\chi_{c1}(3872) \rightarrow J/\psi\rho$ is isospin violating
  - ✓ **Mass extremely close to $D^0\bar{D}^{*0}$ threshold $3871.70 \pm 0.11\ \mathrm{MeV}/c^2$**
- No consensus on its nature: conventional $\chi_{c1}(2^3P_1)$, $D^0\bar{D}^{*0}$ molecular state, tetraquark, $c\bar{c}g$ hybrid, vector glueball, or mixed?



[PRL 126 (2021) 092001]

- ✓ Stronger suppression of $\chi_{c1}(3872)$ than $\psi(2S)$
- ✓ Comover model favors the compact tetraquark scenario



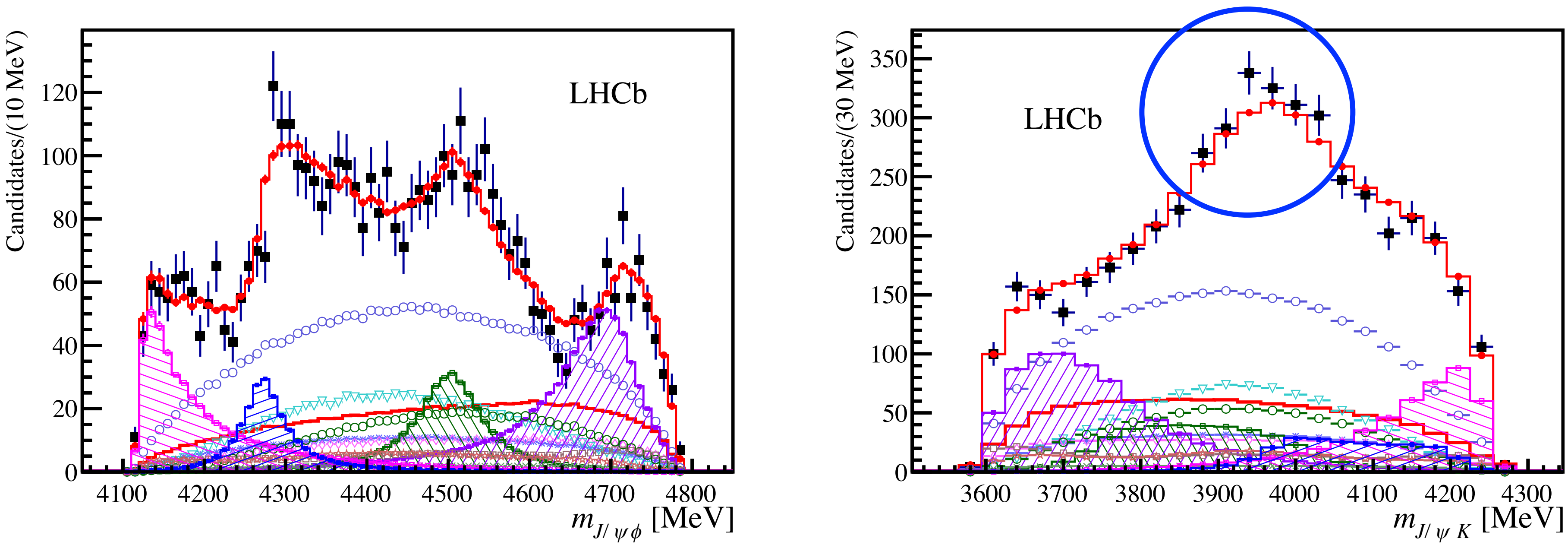
[PRD 102 (2020) 092005]

- ✓ Study of analytical structure of Flatté amplitude in the vicinity of $D^0\bar{D}^{*0}$ prefer quasi-bound state of $D^0\bar{D}^{*0}$ scenario

Four X states in $J/\psi\phi$

[PRL 118 (2017) 022003]

- LHCb performed first full amplitude analysis of $B^+ \to J/\psi\phi K^+$ using Run 1 data
- The data cannot be described by a model containing only $K^{*+} \to \phi K^+$
- Four $X \to J/\psi\phi$ structures observed, each with significance $> 5\ \sigma$
- Their quantum numbers determined with significance of at least $4\ \sigma$

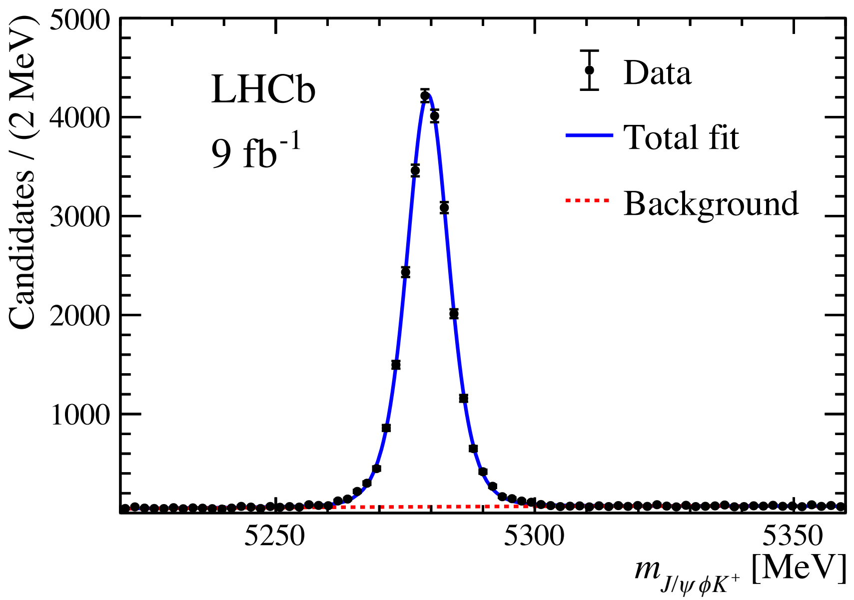


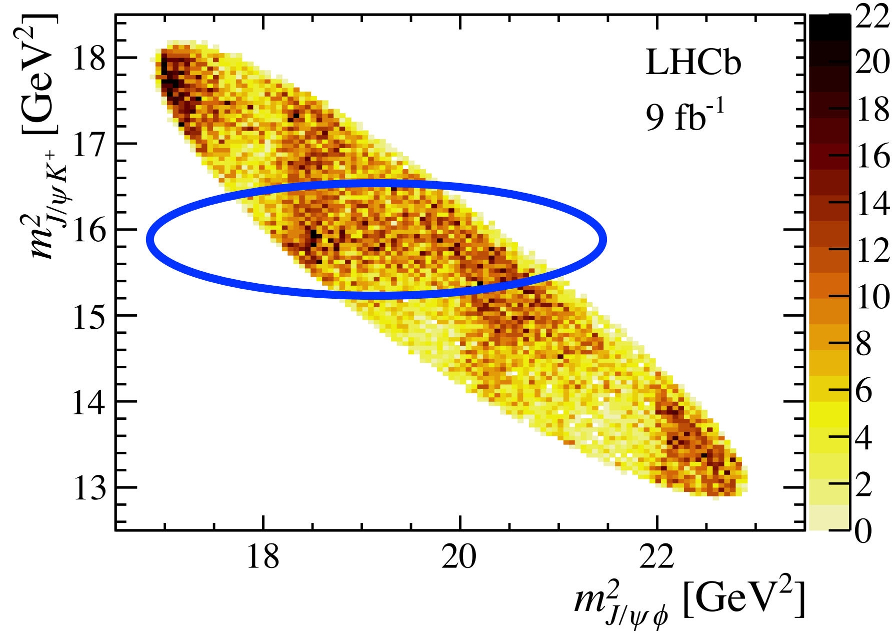
✓ Hint for $Z_{cs}^+ \to J/\psi K^+$?

$B^+ \to J/\psi\phi K^+$ update

- Dataset: Full Run1+Run2 LHCb data corresponding to 9 fb^{-1}
- Selection criterion is improved

[arXiv: 2103.01803]
accepted by PRL





Signal yield ~6 times larger:

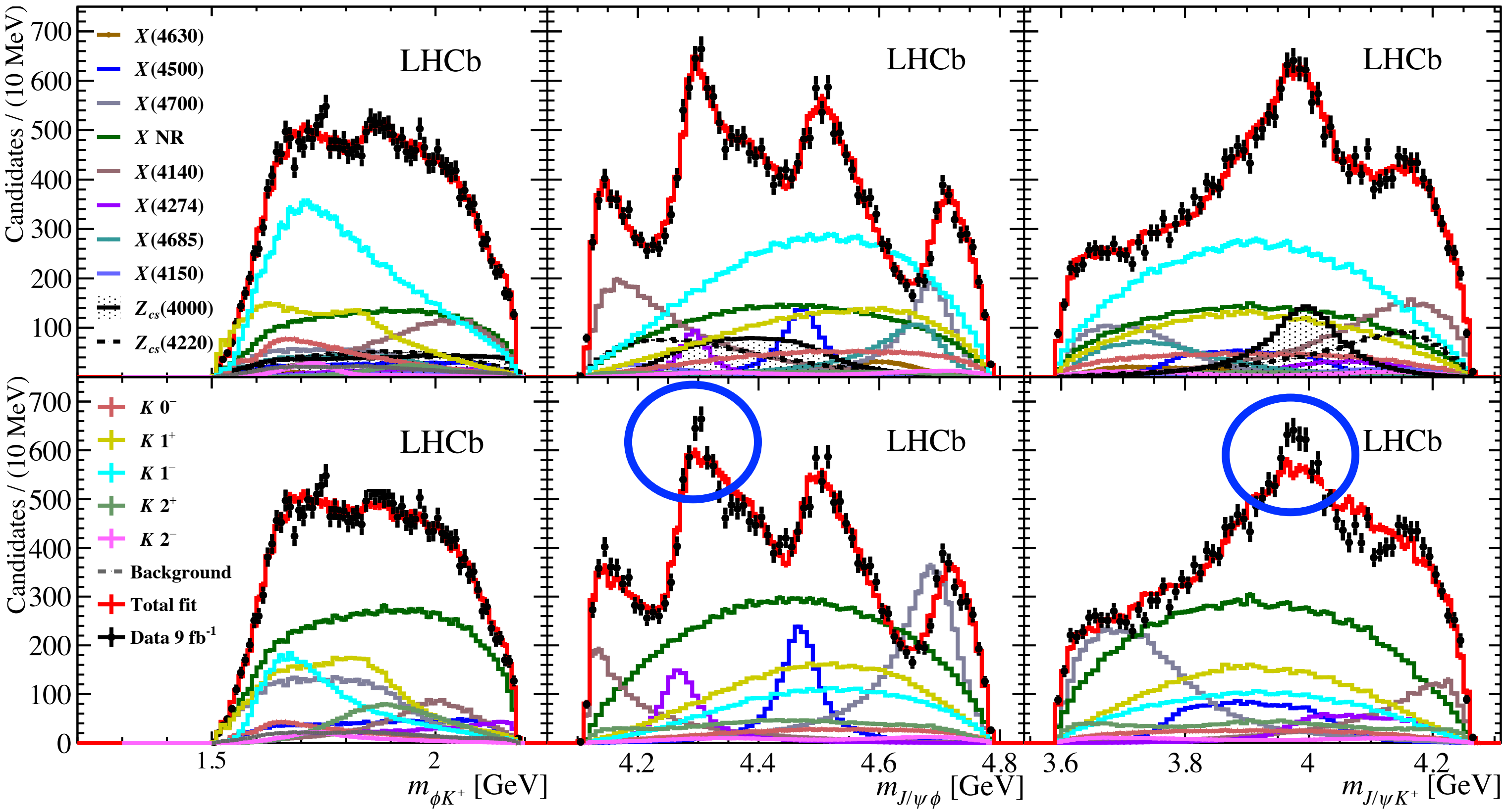
$$N(B^+) = 24220 \pm 170$$

Largely reduced background fraction:
$\sim$4% in $\pm$15 MeV signal region

A distinct band near
$M(J/\psi K^+)^2 \sim 16\ \mathrm{GeV}^2$
$\Rightarrow$ amplitude analysis

Amplitude fit of $B^+ \to J/\psi\phi K^+$

[arXiv: 2103.01803] accepted by PRL



Updated model

Run 1 model

- New states included in updated model:
  - ✓1^+ Z_{cs}^+ and 1^+ X produce the largest improvements
  - ✓Additional Z_{cs}^+ (either 1^+ or 1^-)
  - ✓Two X with 1^- and 2^-

Amplitude fit result

[arXiv: 2103.01803]
accepted by PRL

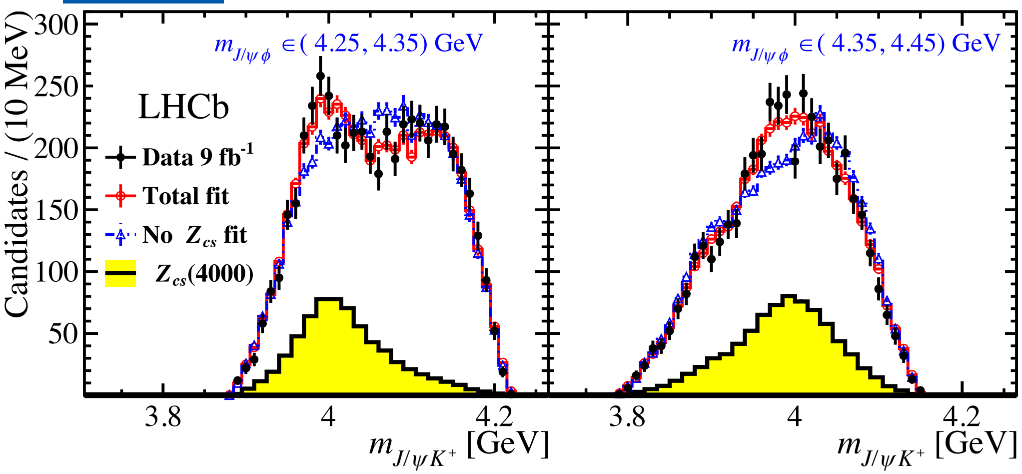
Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+18}_{-110}$	$174 \pm 27\,^{+134}_{-73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
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)	$4694 \pm 4\,^{+16}_{-3}$	$87 \pm 8\,^{+16}_{-6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
$NR_{J/\psi\phi}$	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 assignments:
  - ✓ J^P for previously reported four X states confirmed
  - ✓ $Z_{cs}(4000)$ $J^P = 1^+$ and $X(4685)$ $J^P = 1^+$ firmly determined
  - ✓ $X(4150)$: 2^- preferred by 4σ; $X(4630)$: 1^- over 2^- at 3σ
  - ✓ $Z_{cs}(4220)$ could be 1^+ or 1^-

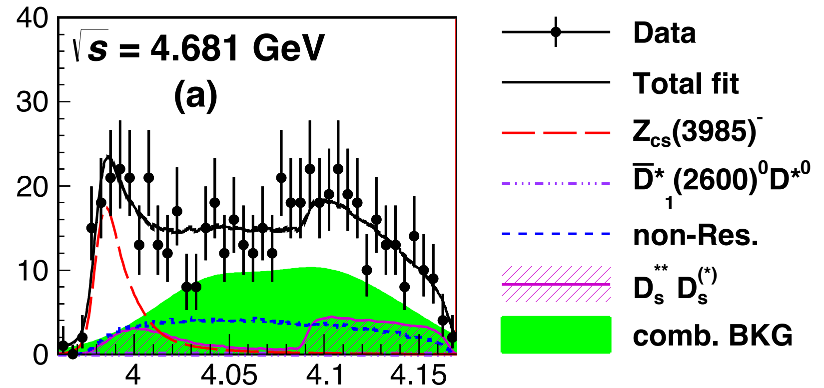
Z_{cs}^{+} at LHCb vs BESIII

- BESIII observed a Z_{cs}^{-} structure in K^{+} recoil-mass spectra in $e^{+}e^{-} \rightarrow K^{+}(D_s^{-}D^{*0} + D_s^{*-}D^{0})$

[arXiv: 2103.01803] accepted by PRL



[PRL 126 (2021) 102001]



$M(Z_{cs}(4000)^{+}) = 4003 \pm 6^{+4}_{-14}$ MeV

$\Gamma(Z_{cs}(4000)^{+}) = 131 \pm 15 \pm 26$ MeV

$M(Z_{cs}(3985)^{-}) = 3985.2^{+2.1}_{-2.0} \pm 1.7$ MeV

$\Gamma(Z_{cs}(3985)^{-}) = 13.8^{+8.1}_{-5.2} \pm 4.9$ MeV

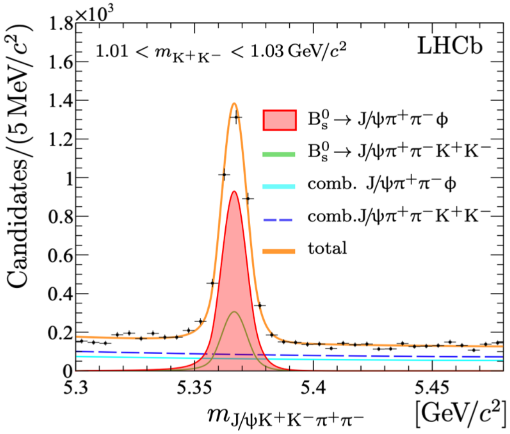
✓ Significantly different widths

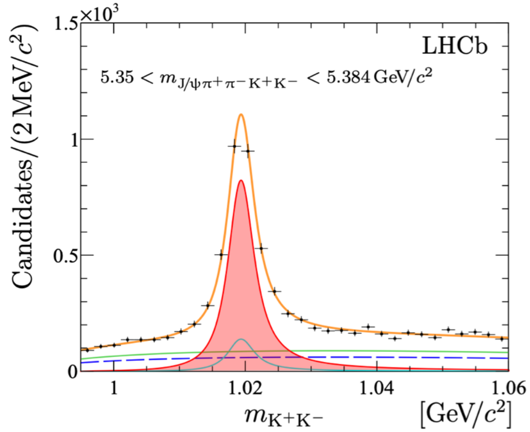
- No evidence that $Z_{cs}(4000)^{+}$ is the same as $Z_{cs}(3985)^{-}$

X in $B_s^0 \to [J/\psi\phi(\to K^+K^-)]\pi^+\pi^-$

[JHEP 02 (2021) 024]

- Dataset: Full Run1+Run2 LHCb data corresponding to 9 fb^{-1}

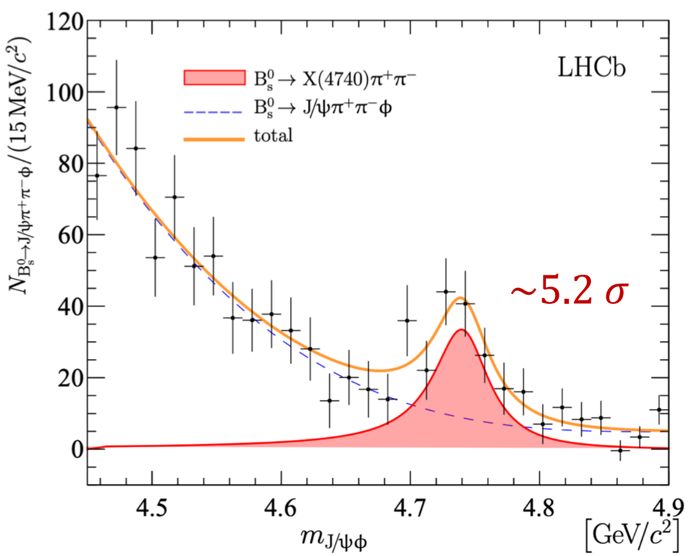


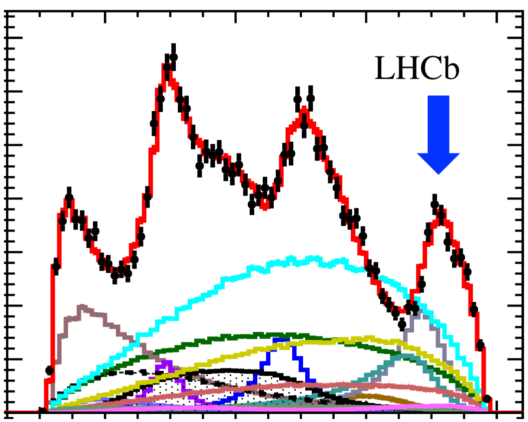


✓ $\psi(2S)$ and $\chi_{c1}(3872)$ vetoed by cutting on $M(J/\psi\pi^+\pi^-)$

- One-dimensional fit to $M(J/\psi\phi)$:

$$m_{X(4740)} = 4741 \pm 6 \pm 6\ \text{MeV}/c^2,$$
$$\Gamma_{X(4740)} = 53 \pm 15 \pm 11\ \text{MeV},$$





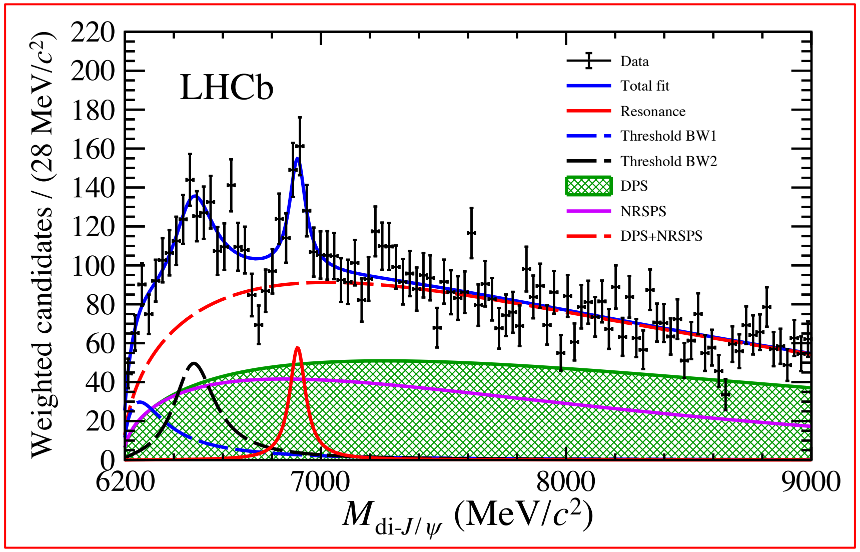
✓Same peak?
Stay tuned

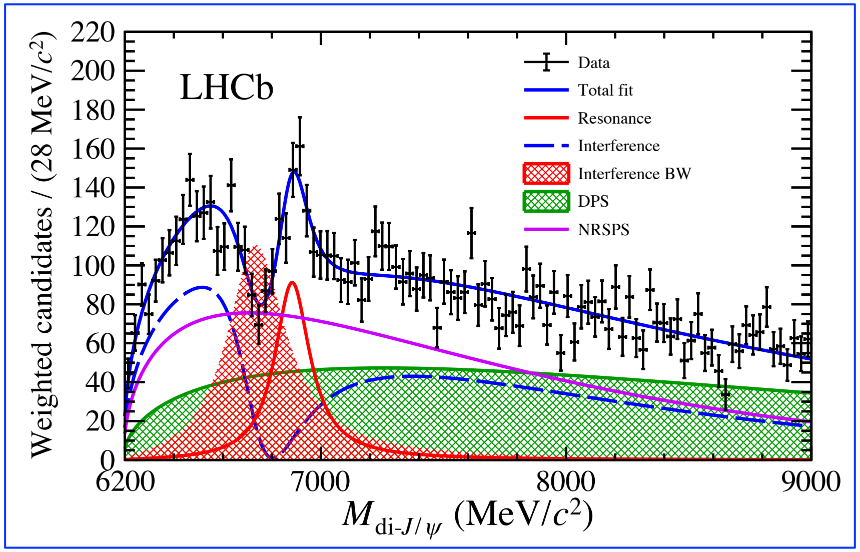
[arXiv: 2103.01803]
accepted by PRL

Structure in J/ψ-pair spectrum

[Science Bulletin 65 (2020) 1983]

- The J/ψ-pair invariant mass spectrum is inconsistent with non-resonant production only hypothesis by more than 5 σ in the $[6.2,7.4]\ \mathrm{GeV}/c^2$ mass region
- A narrow peaking structure matching the lineshape of a $T_{cc\bar{c}\bar{c}}$ resonance and a broader structure close to the threshold are found
- Two possible interpretations:





$M(X(6900)) = 6905 \pm 11 \pm 7\ \mathrm{MeV}/c^2$

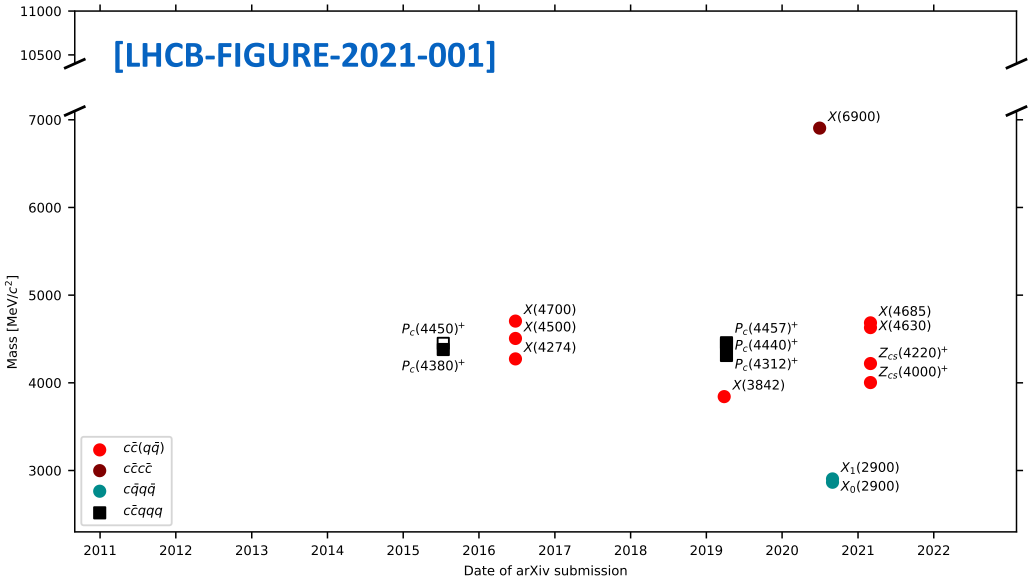
$\Gamma(X(6900)) = 80 \pm 19 \pm 33\ \mathrm{MeV}/c^2$

$M(X(6900)) = 6886 \pm 11 \pm 11\ \mathrm{MeV}/c^2$

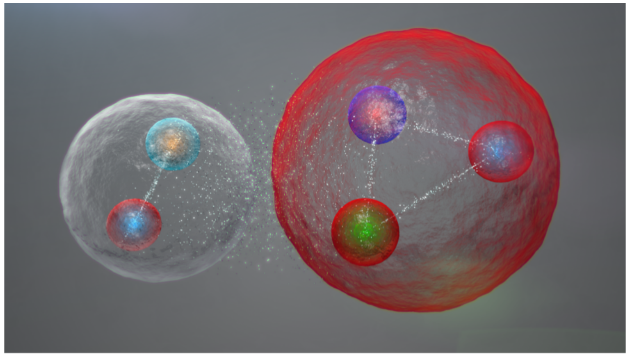
$\Gamma(X(6900)) = 168 \pm 33 \pm 69\ \mathrm{MeV}/c^2$

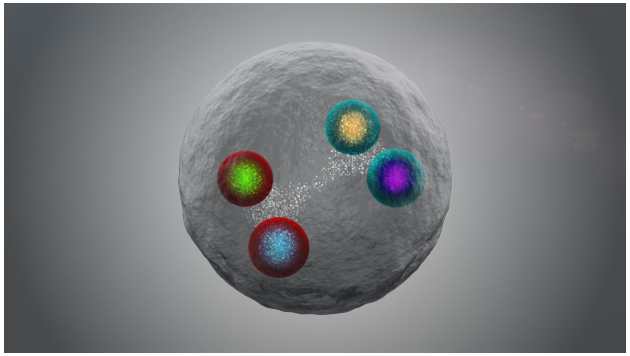
- Other possibilities: feeddown contribution, e.g. $T_{cc\bar{c}\bar{c}} \to \chi_c(\to J/\psi\gamma) + J/\psi$; near-threshold kinematic rescattering effects

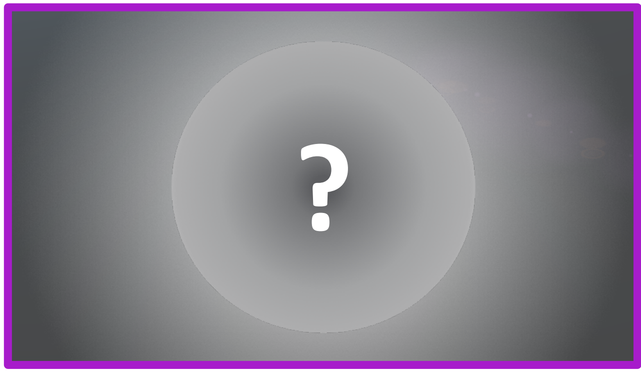
Exotic hadrons @ LHCb



*This talk focuses more on recent results







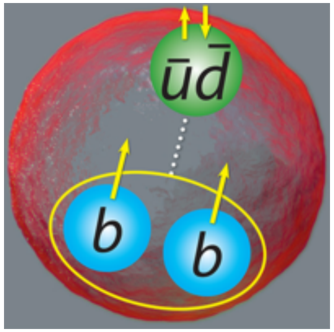
❑ Hidden-charm pentaquark

❑ Hidden-charm tetraquark

❑ **Beyond hidden-charm**

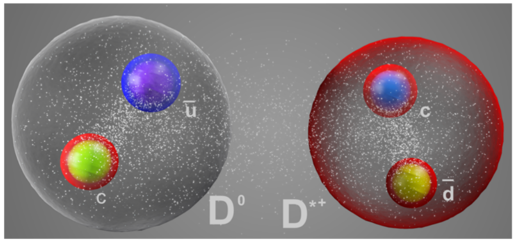
$Q_1 Q_2 \bar{q}_1 \bar{q}_2$ state

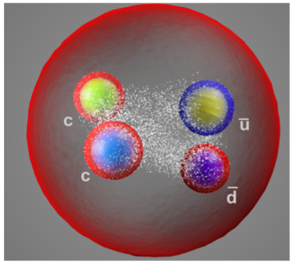
- All exotic hadrons observed so far decay via strong interaction
- $Q_1 Q_2 \bar{q}_1 \bar{q}_2$ is prime candidate for **long-lived exotic state** stable against strong interaction, which would be highly intriguing



- The $bb\bar{u}\bar{d}$ state is widely predicted to be stable with binding energy about 215 MeV with respect to BB^* threshold [PRL 119 (2017) 202001]
- For $bc\bar{u}\bar{d}$ and $cc\bar{u}\bar{d}$ systems, there is currently no consensus
- There are various predictions for ground $cc\bar{u}\bar{d}$ state with $J^P = 1^+$ (T_{cc}^+):

$$\delta m \equiv m_{T_{cc}^+} - (m_{D^{*+}} + m_{D^0})$$
$$-250 < \delta m < 260 \text{ MeV}/c^2$$

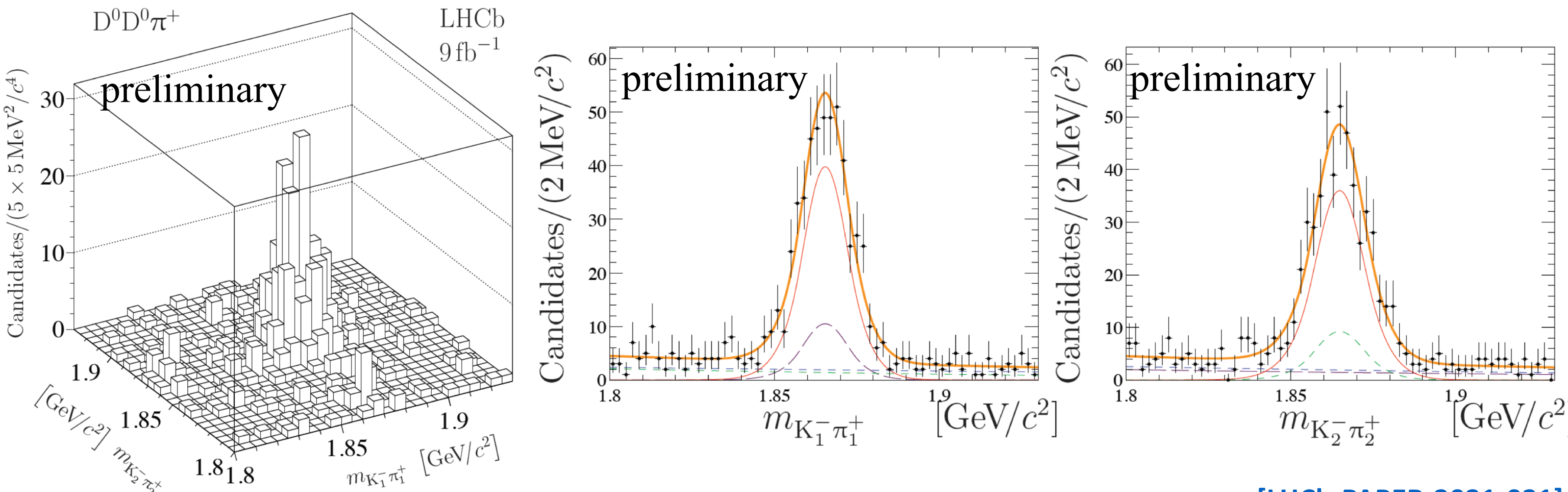




- The $D^0 D^0 \pi^+$ spectrum is studied at LHCb

$D^0 D^0 \pi^+$ sample

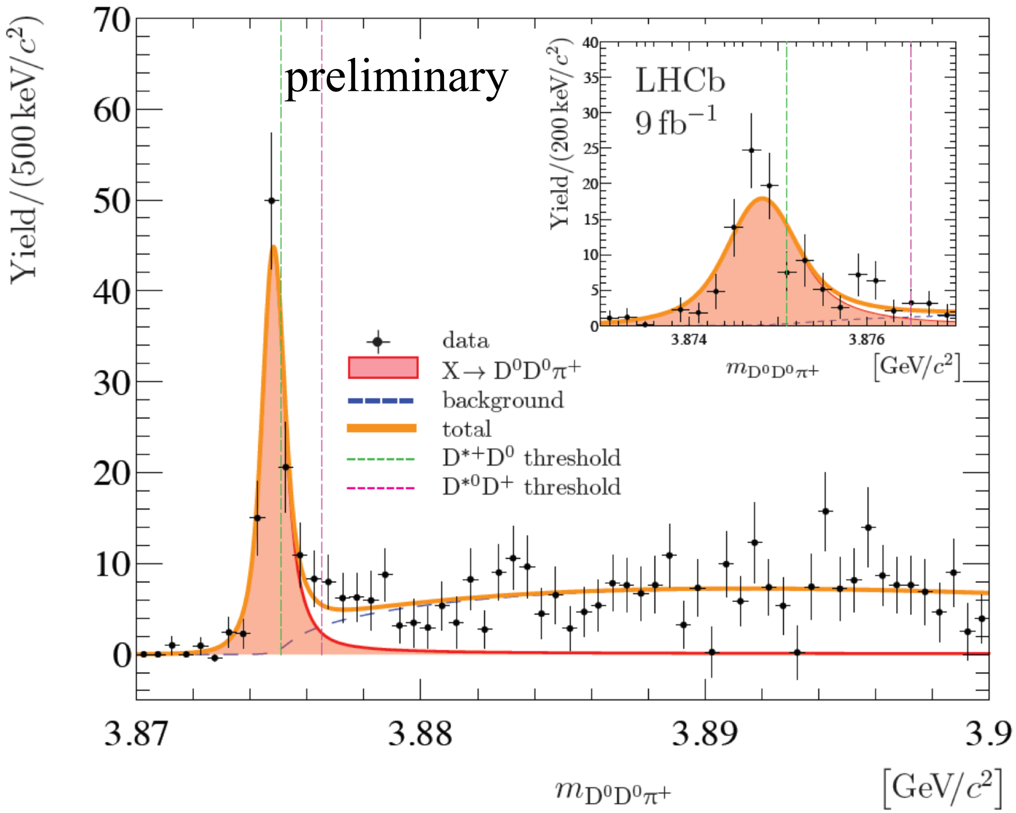
- Dataset: Full Run1+Run2 LHCb data corresponding to 9 fb^{-1}
- $D^0 \to K^-\pi^+$ & two D^0 mesons pointing to a common primary vertex
- Cut-based selection on kinematics, particle identification, track and vertex quality, decay time, and mass range



[LHCb-PAPER-2021-031]
In preparation

- Non-D^0 background subtracted according to $(m_{K_1^-\pi_1^+}, m_{K_2^-\pi_2^+})$ fit

$D^0D^0\pi^+$ spectrum



[LHCb-PAPER-2021-031]
In preparation

Parameter	value
N	117 ± 16
$\delta m_{\rm BW}$	-273 ± 61 keV/c^2
$\Gamma_{\rm BW}$	410 ± 165 keV
$\mathcal{S}$	21.7 σ
$\mathcal{S}_{\delta m_{\rm BW}<0}$	4.3 σ

- Signal model: detector **resolution ⊗** relativistic P-wave two-body **Breit-Wigner** function modified by a Blatt-Weisskopf form factor, where $T_{cc}^+ \to AB$ is assumed with $m_A = 2m_{D^0}$ and $m_B = m_{\pi^+}$
- Background model: product of two-body phase-space function and a positive 2nd-order polynomial

T_{cc}^{+} result

Source	$\sigma_{\delta m_{\rm BW}}$ [keV/c^2]	$\sigma_{\Gamma_{\rm BW}}$ [keV]
Fit model		
Resolution model	2	7
Resolution correction factor	1	30
Background model	3	30
Model parameters	< 1	< 1
Momentum scale	3	—
Energy loss corrections	1	—
$D^{*+} - D^0$ mass difference	2	—
Total	5	43
J^P *quantum numbers*	$^{+11}_{-14}$	$^{+18}_{-38}$

preliminary

[LHCb-PAPER-2021-031]
In preparation

$$\delta m_{BW} = -273 \pm 61 \pm 5^{+11}_{-14}\ \text{keV}/c^2, \Gamma_{BW} = 410 \pm 165 \pm 43^{+18}_{-38}\ \text{keV}$$

- consistent with expectation for ground isoscalar $T_{cc}^{+}(cc\bar{u}\bar{d})$ state with $J^P = 1^+$
- The observation supports existence of a stable $bb\bar{u}\bar{d}$ state, and gives argument in favor of a stable $bc\bar{u}\bar{d}$ state
- A dedicated study of the reaction amplitudes for $T_{cc}^{+} \to D^0 D^0 \pi^+$ and $T_{cc}^{+} \to D^0 D^+ \pi^0(\gamma)$ yielding insights on the **fundamental resonance properties**, like pole position, scattering length and effective range will come soon!

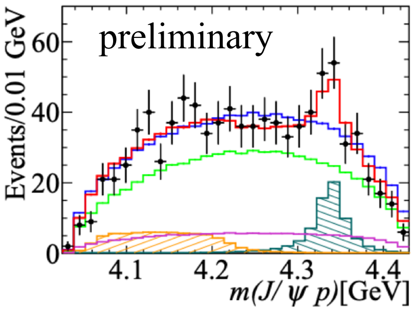
Summary and prospect

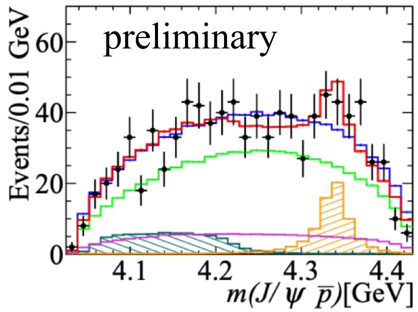
- LHCb keeps making important contributions to study of exotic states
  - ✓**Hidden-charm pentaquark:** discovery of P_c^+s; evidence of P_{cs}^0
  - ✓**Hidden-charm tetraquark:** $\chi_{c1}(3872)$ study; observation of X states and Z_{cs}^+; discovery of $T_{cc\bar{c}\bar{c}}$
  - ✓**Doubly charmed tetraquark:** discovery of T_{cc}^+, ….
- There is yet no coherent theoretical picture that can describe all observed exotic hadron candidates, which calls for more experimental studies
- In the upcoming Run 3, the upgraded LHCb detector and a new software-only trigger system will be implemented.

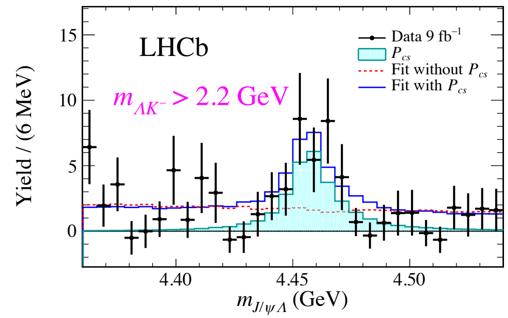
An ~ 3 times larger statistics will open possibilities for

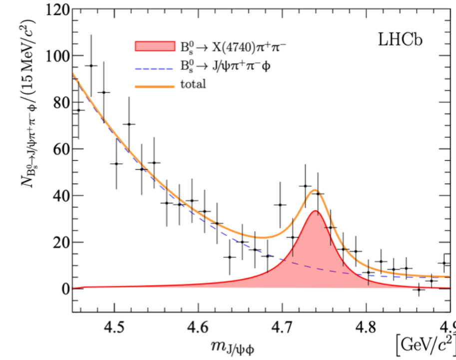
- ✓Better understanding of observed exotic states: exploration in more decay modes, (firmer) J^{PC} assignments, nature study…
- ✓Evidence $\rightarrow$ observation for $P_c(4340)^{\pm}$ and $P_{cs}(4459)^0$?
- ✓Discovery of yet unseen exotics

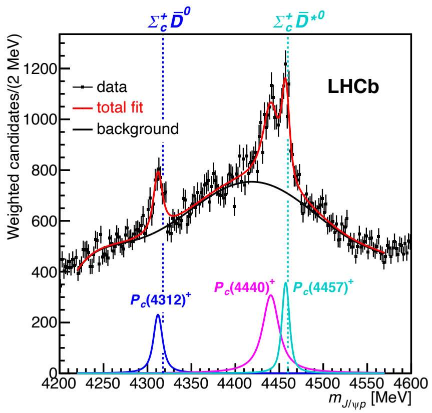
The understanding of exotic hadron states will be further promoted.

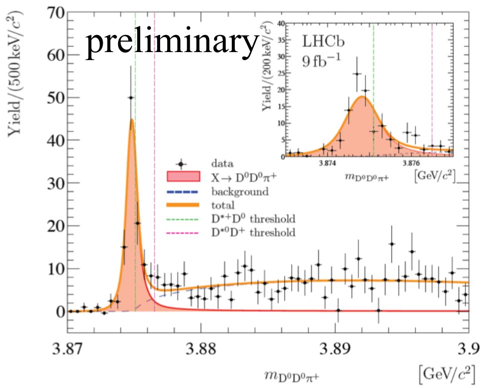


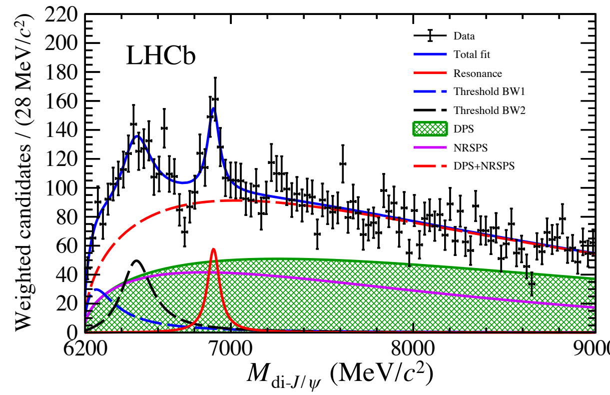


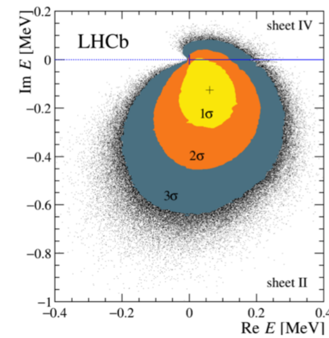


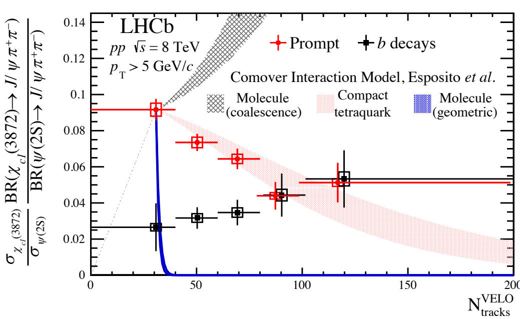


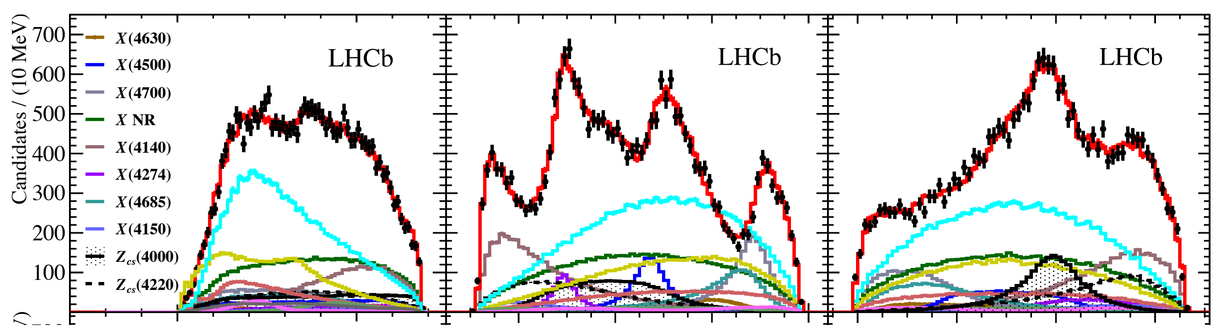












… and more exciting results are to come!

Simon Eidelman 1948-2021

Our distinguished LHCb Collaborator Simon Eidelman recently passed away.

He will be greatly missed by his many friends and colleagues.

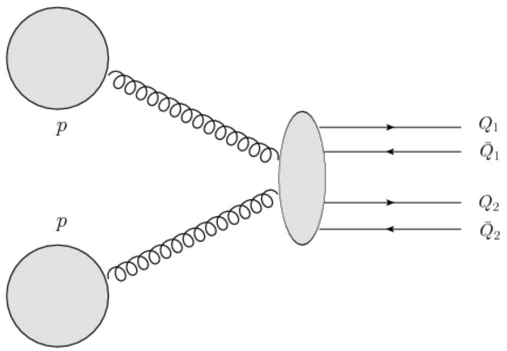
The LHCb Collaboration sends its condolences and has dedicated the papers on the observation of the T_{cc}^{+} state to his memory

LHCb-PAPER-2021-031

Back up

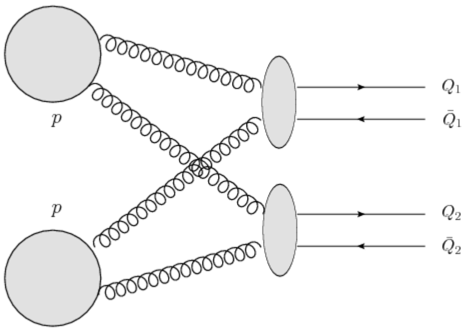
Prompt J/ψ pair production

Single parton scattering (SPS)



- ➢$T_{cc\bar{c}\bar{c}}$ state is a special case of SPS
- ➢Theories have large uncertainties, but a smooth continuum spectrum is expected assuming no resonance
- ➢Non-resonant SPS contribution may interfere with resonance

Double parton scatterings (DPS)

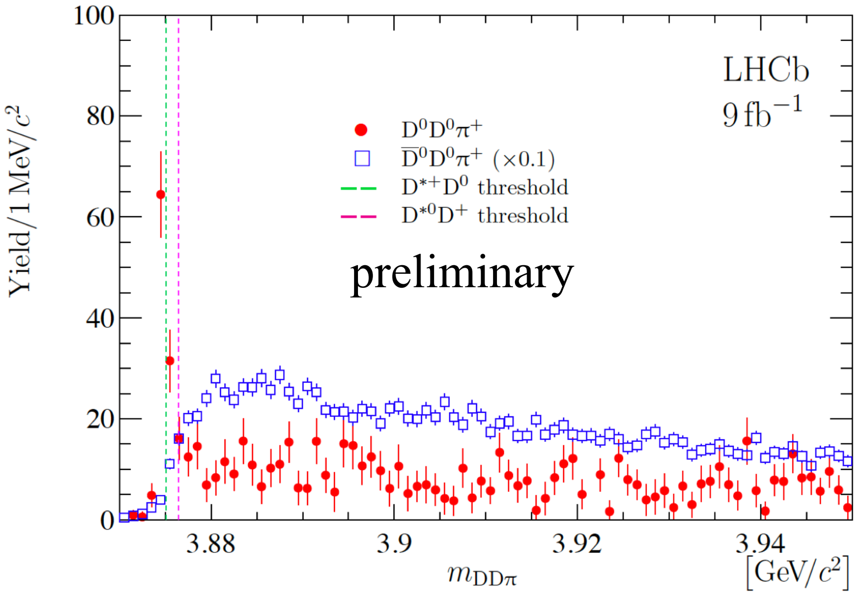


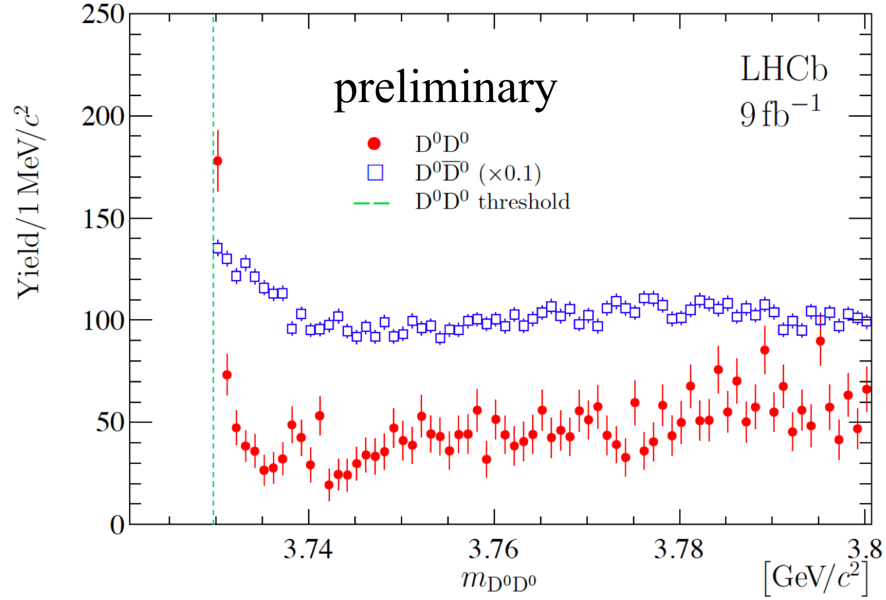
- ➢Two J/ψ mesons produced independent of each other

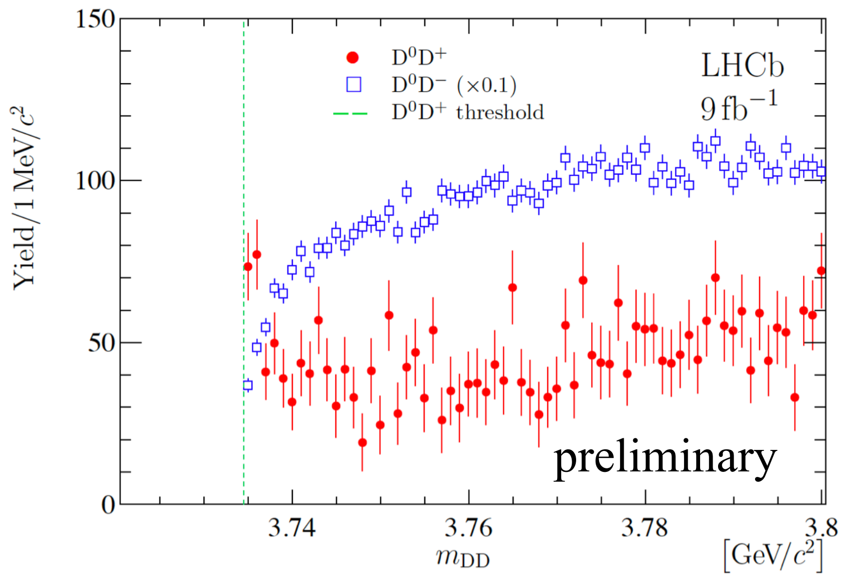
$$\sigma^{DPS}_{J/\psi J/\psi} = \frac{1}{1+\delta_{J/\psi J/\psi}} \frac{\sigma_{J/\psi}\sigma_{J/\psi}}{\sigma_{\text{eff}}}$$

- ➢Dominates high J/ψ pair mass region

Opposite-sign mass distributions







[LHCb-PAPER-2021-031]
In preparation