



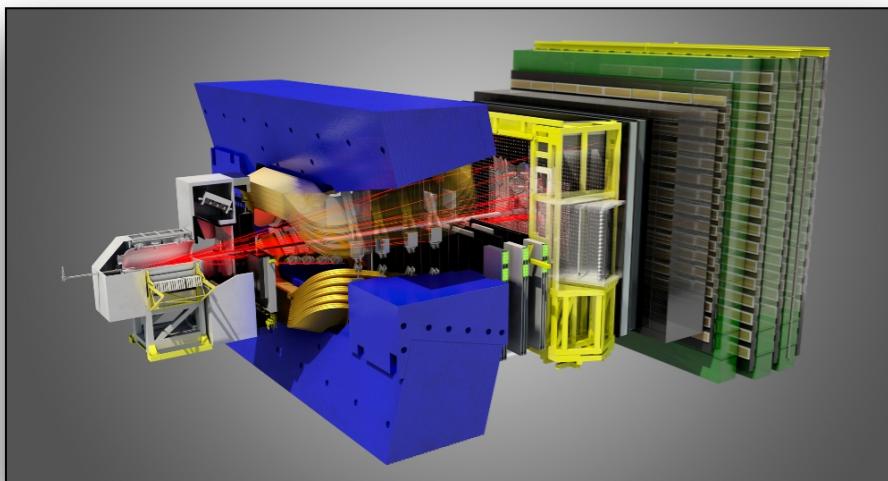
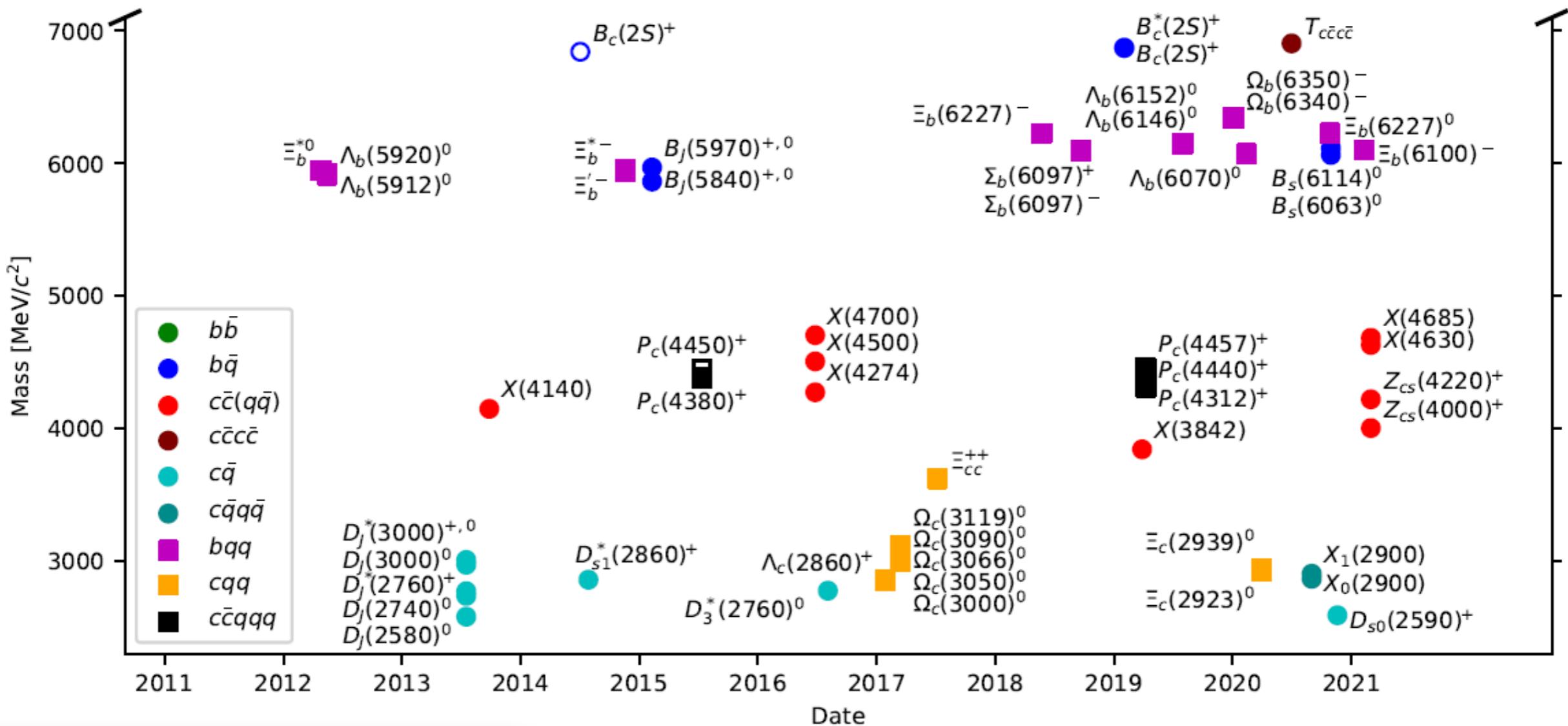
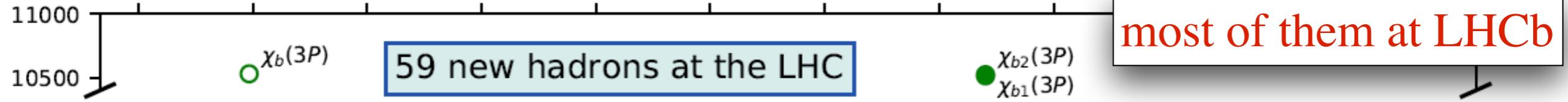
# New hadrons at LHCb

Alberto Reis

Centro Brasileiro de Pesquisas Físicas

Sixth Colombian Meeting on High Energy Physics  
Universidad del Magdalena, Santa Marta





LHCb is a flavour factory:

$$\sigma(pp \rightarrow b\bar{b}X) = 144 \pm 21 \mu b \quad (\sqrt{s} = 13 \text{ TeV})$$

$$\frac{\sigma_{b\bar{b}}}{\sigma_{\text{inel}}} \sim \frac{1}{400}$$

[PRL 118 \(2017\) 052002](#)

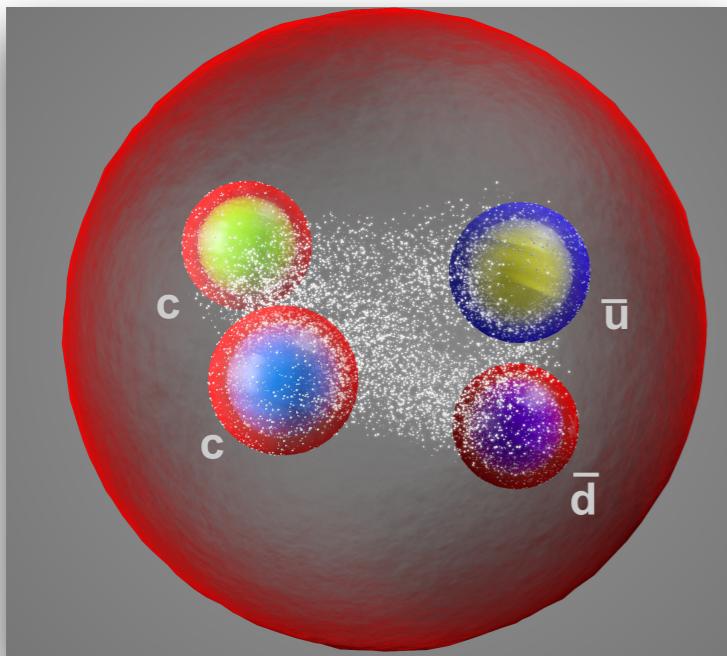
The existence of nonconventional hadrons, improperly named as "exotics", is conjectured since 1960's.

Murray Gell-Mann: "**in quantum mechanics, everything not forbidden is mandatory**"

Many of the new hadrons have masses close to a mass threshold,

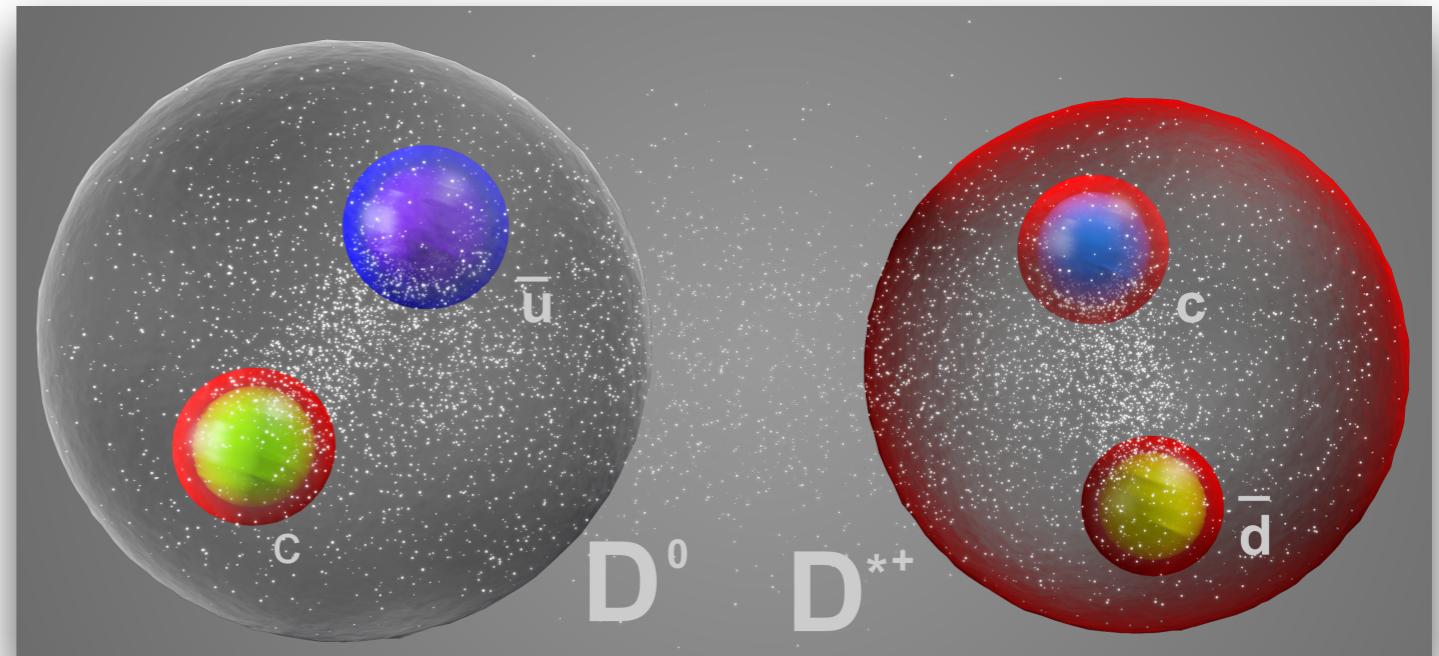
$$D^{(*)}\bar{D}^{(*)} / B^{(*)}\bar{B}^{(*)}$$

Tetraquarks?



compact object, each quark interacts with the other three via strong force

Hadronic molecules?



colour singlet states loosely bound by residual nuclear force, similar to van der Waals

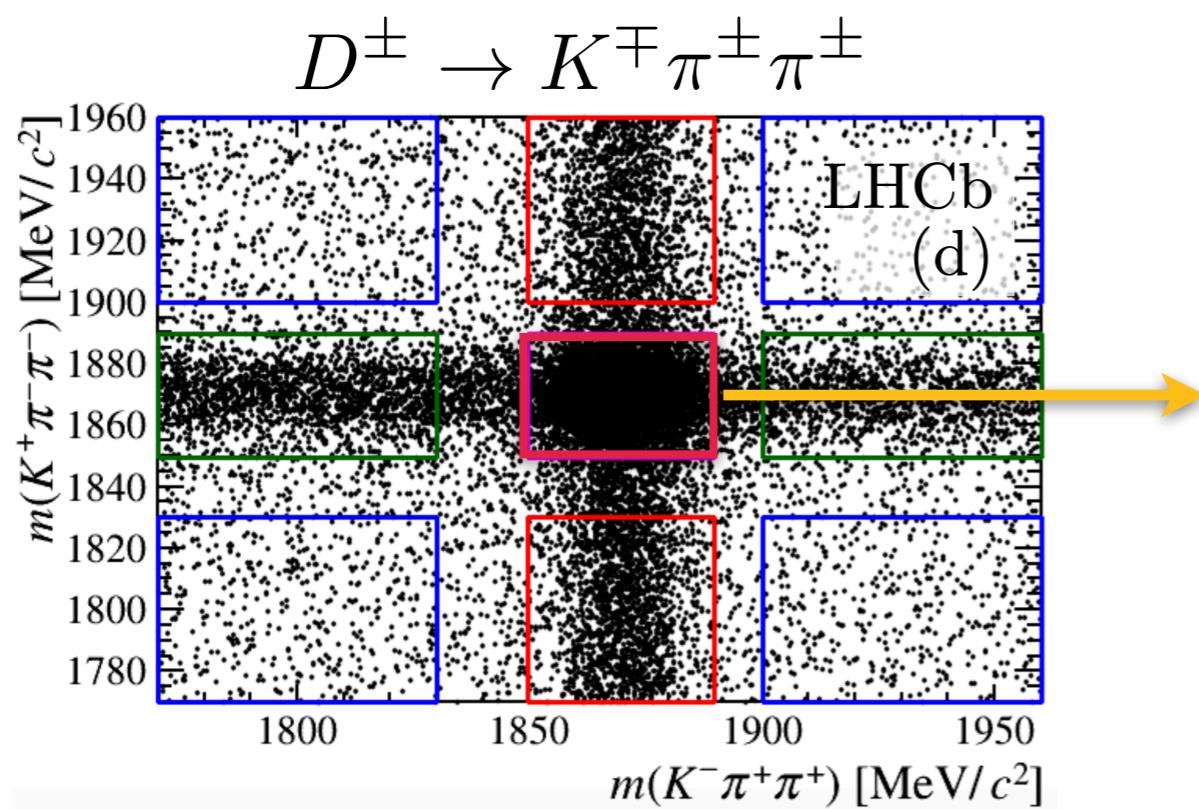
# Tetra- and pentaquark candidates and their plausible valence quark content

$X_0(2900)$ , $X_1(2900)$	$\bar{c}dus$	$\rightarrow$ only one heavy quark
$\chi_{c1}(3872)$	$c\bar{c}q\bar{q}$	
$Z_c(3900)$ , $Z_c(4020)$ , $Z_c(4050)$ , $X(4100)$ , $Z_c(4200)$ , $Z_c(4430)$	$c\bar{c}u\bar{d}$	often named charmonium-like
$Z_{cs}(3985)$ , $Z_{cs}(4000)$ , $Z_{cs}(4220)$	$c\bar{c}u\bar{s}$	close to a $D^{(*)}\bar{D}^{(*)}$ threshold
$\chi_{c1}(4140)$ , $\chi_{c1}(4274)$ , $\chi_{c0}(4500)$ , $\chi_{c0}(4700)$ , $X(4630)$ , $X(4685)$ , $X(4740)$	$c\bar{c}s\bar{s}$	
$X(6900)$	$c\bar{c}c\bar{c}$	$\rightarrow$ nothing prevents $Q_1 Q_2 \bar{Q}_3 \bar{Q}_4$ states
$Z_b(10610)$ , $Z_b(10650)$	$b\bar{b}u\bar{d}$	$\rightarrow$ bottomonium-like
$P_c(4312)$ , $P_c(4347)$ , $P_c(4380)$ , $P_c(4400)$ , $P_c(4457)$	$c\bar{c}uud$	
$P_{cs}(4459)$	$c\bar{c}uus$	pentaquarks

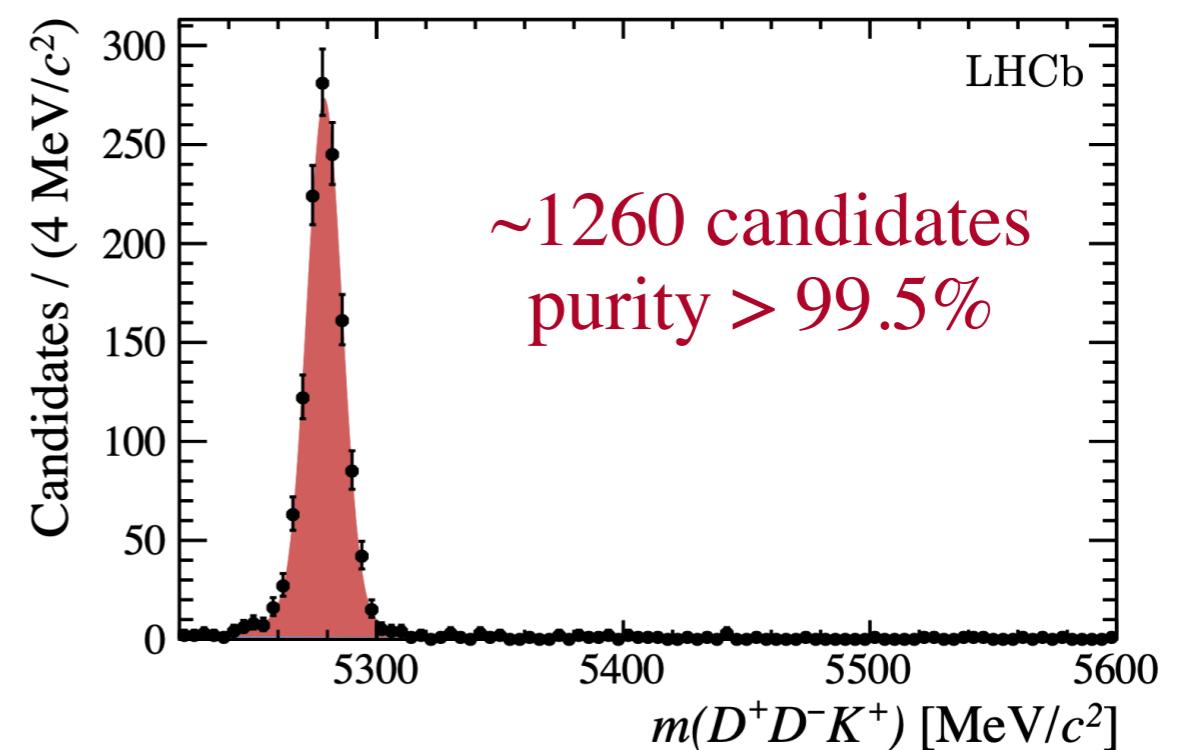
New hadrons: unique place to study strong interaction and confinement  
Decays of b-hadrons are a natural place to search for new hadrons

$$B^+ \rightarrow D^- D^+ K^+$$

- $B^+ \rightarrow D^{(*)+} D^{(*)-} K^+$  decays: unique opportunities to charmonium studies
- Resonances in the  $D^{(*)-} K^+$  channel are manifestly "exotic":  $c\bar{d}u\bar{s}$
- $B^+ \rightarrow D^+ D^- K^+$  with two different approaches :  $\begin{cases} \text{model independent} \\ \text{model dependent} \end{cases}$
- Full Run 1 + Run 2 data set: 9  $\text{fb}^{-1}$  @  $\sqrt{s} = 7, 8, 13 \text{ TeV}$



[PRL 125, \(2020\) 242001](#)



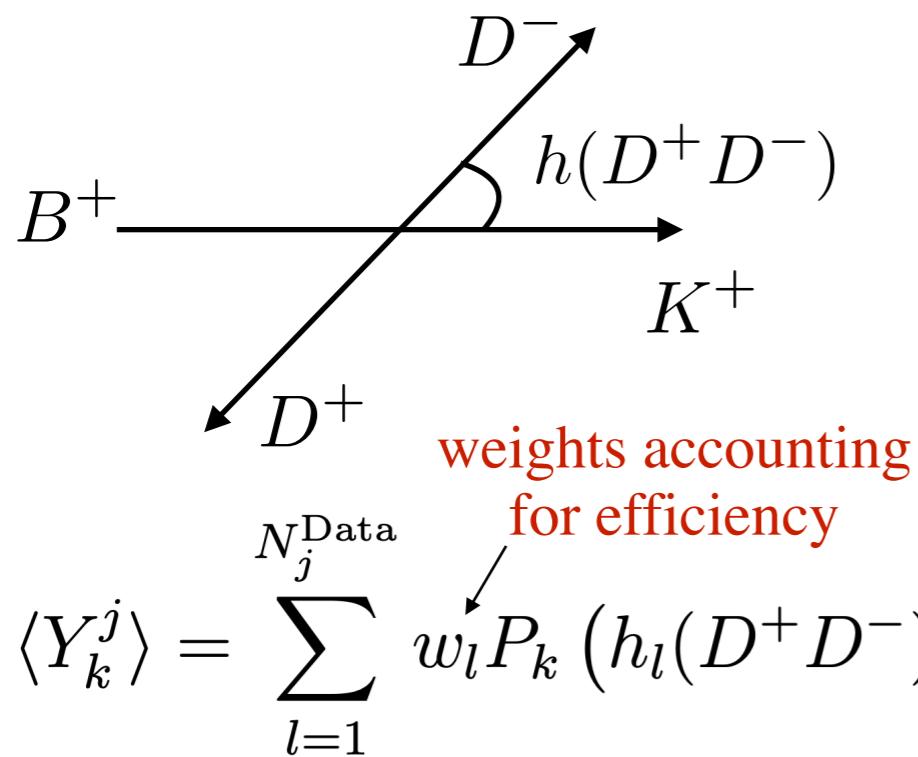
[PRD 102 \(2020\) 112003](#)

# MODEL – INDEPENDENT ANALYSIS

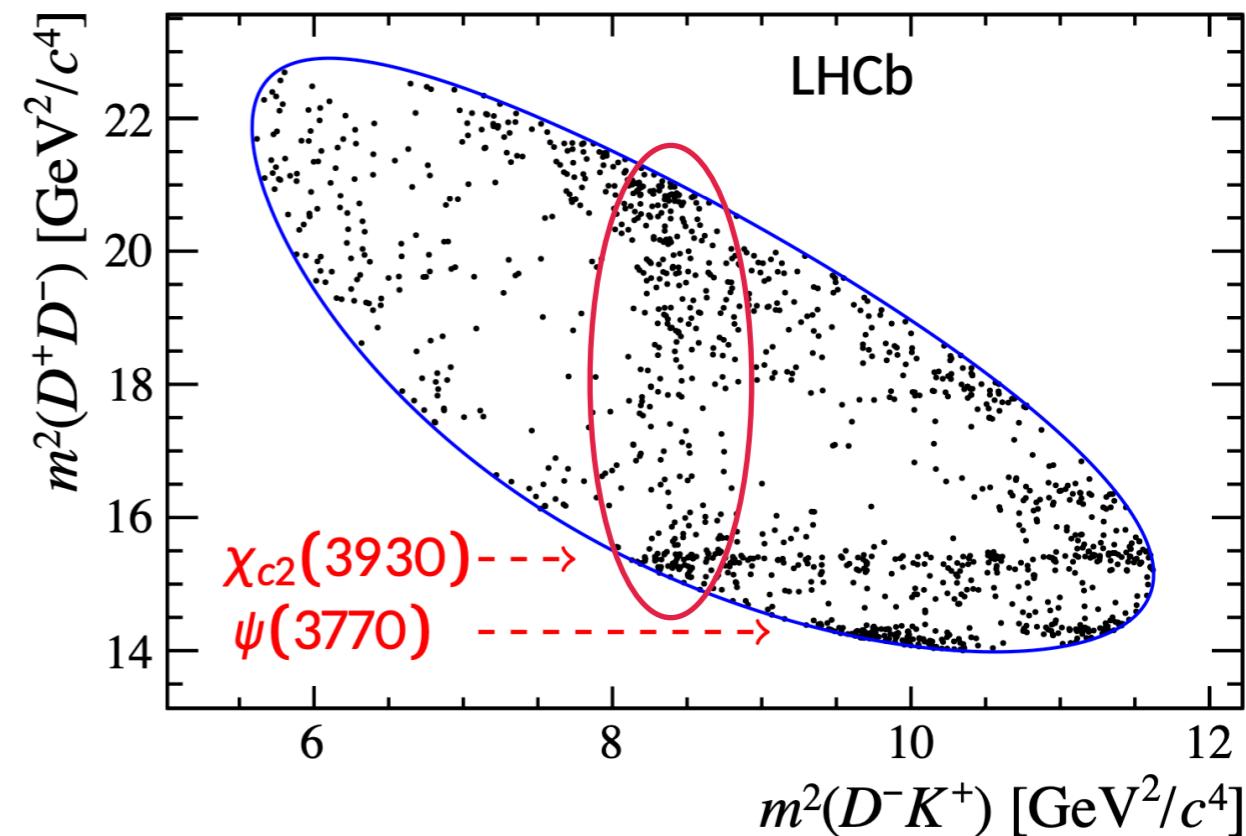
[PRD 102 \(2020\) 112003](#)

- A clear excess at  $m^2(D^-K^+) \sim 2.9$  GeV
- Could it be explained by  $c\bar{c}$  states?

Decompose the distribution of the helicity angle in Legendre polynomials, in slices of  $m(D^+D^-)$



If only  $D^+D^-$  resonances contribute, the Dalitz plot can be described by low-order moments ( $k_{\max} = 2J_{\max}$ )



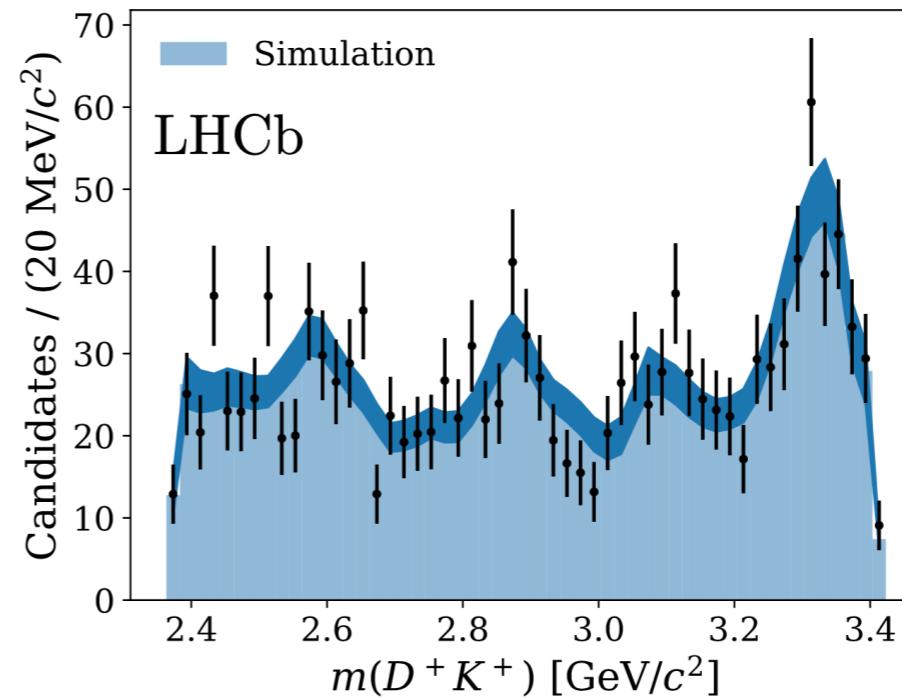
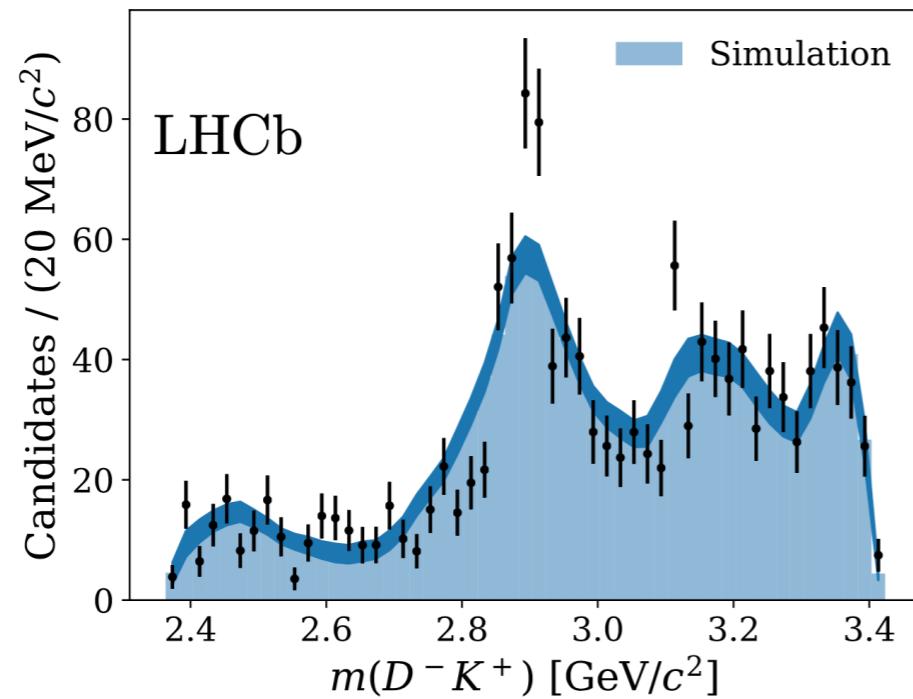
Simulate a sample uniformly in the Dalitz plot, weighted by the truncated moments

$$\eta_i = \frac{2}{N_j^{\text{Sim}}} \times \sum_{k=0}^{k_{\max}} \langle Y_k^j \rangle P_k(h_i(D^+D^-))$$

Then compare it to the  $m(D^-K^+)$  and  $m(D^+K^+)$  projections

# $B^+ \rightarrow D^- D^+ K^+$ : MODEL – INDEPENDENT ANALYSIS

Expansion up to spin-2 ( $k_{\max} = 4$ ): unable to describe the  $DK$  spectrum

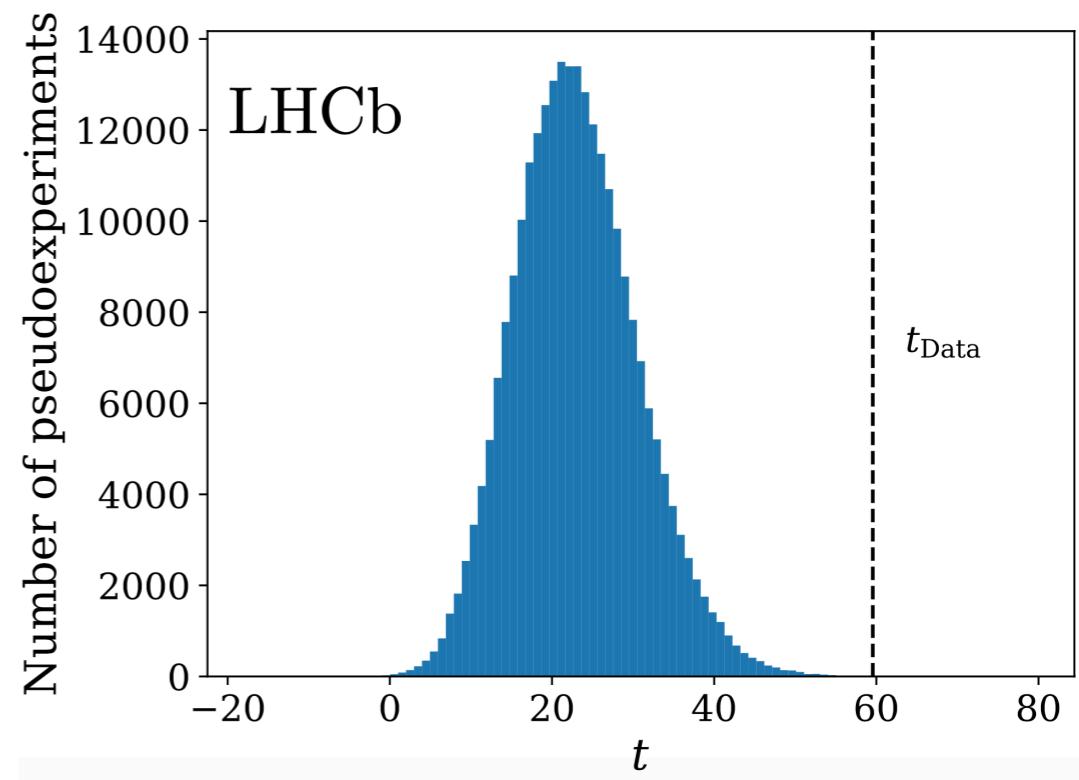


PRL 125, (2020) 242001

Significance of the discrepancy between truncated Legendre expansion and data assessed using pseudoexperiments and a test statistic

$$t = -2 \sum_{l=1}^{N^{\text{Data}}} s_l \log \left( \frac{\mathcal{P}(m_l(D^- K^+) | H_0) / I_{H_0}}{\mathcal{P}(m_l(D^- K^+) | H_1) / I_{H_1}} \right)$$

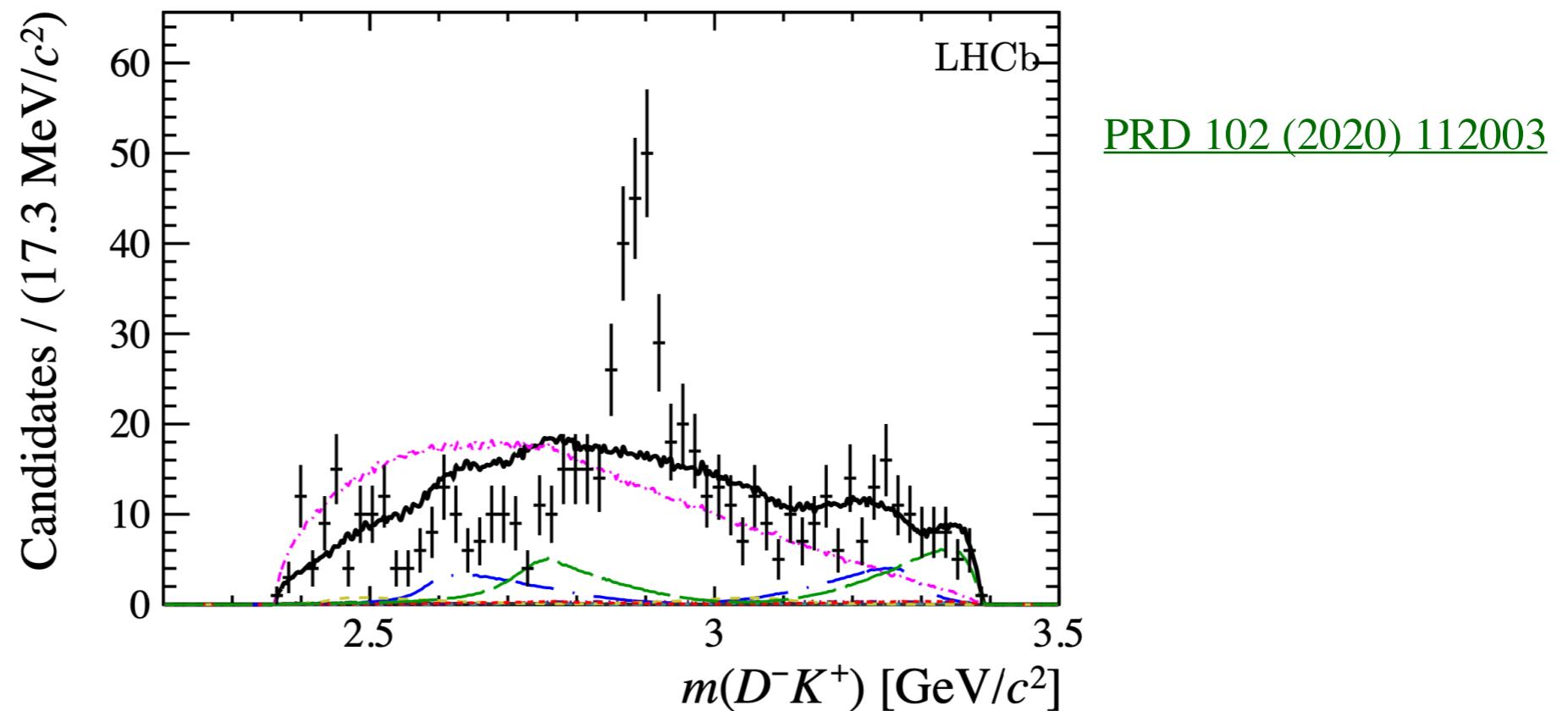
$t_{\text{data}}$  discrepant at level of  $4\sigma$



## MODEL – DEPENDENT ANALYSIS

Only charmonium resonances are anticipated, all with natural spin-parity  
 $\psi(3770)$ ,  $\chi_{c0}(3930)$ ,  $\chi_{c2}(3930)$ ,  $\psi(4040)$ ,  $\psi(4160)$ ,  $\psi(4415)$ ,  $D^+D^-$  NR

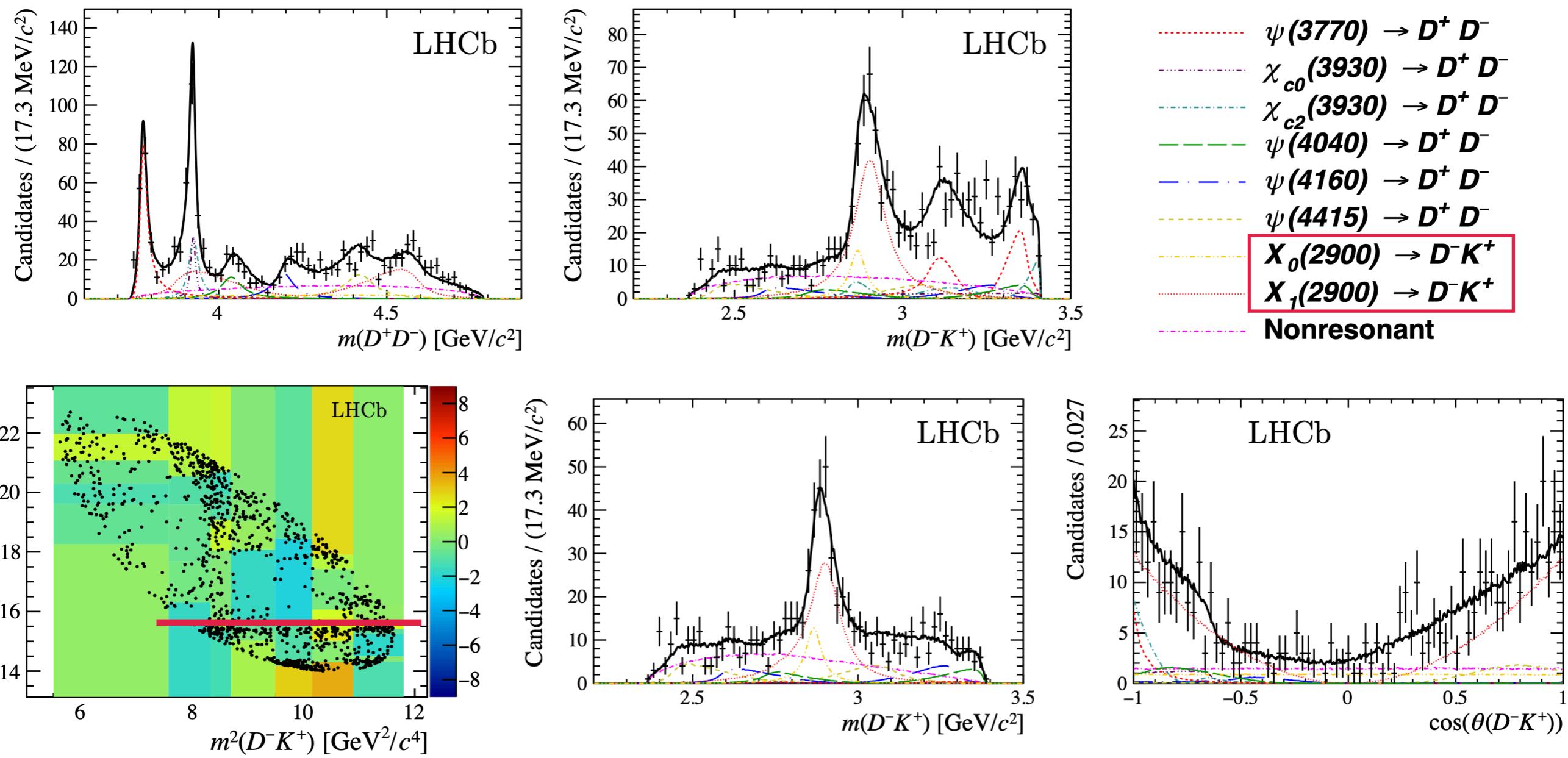
A model with only  $D^+D^-$  resonances cannot describe de data



Need to add resonances in the  $D^-K^+$  channel:

$$X_0(2900), X_1(2900)$$

# $B^+ \rightarrow D^- D^+ K^+$ : MODEL – DEPENDENT ANALYSIS

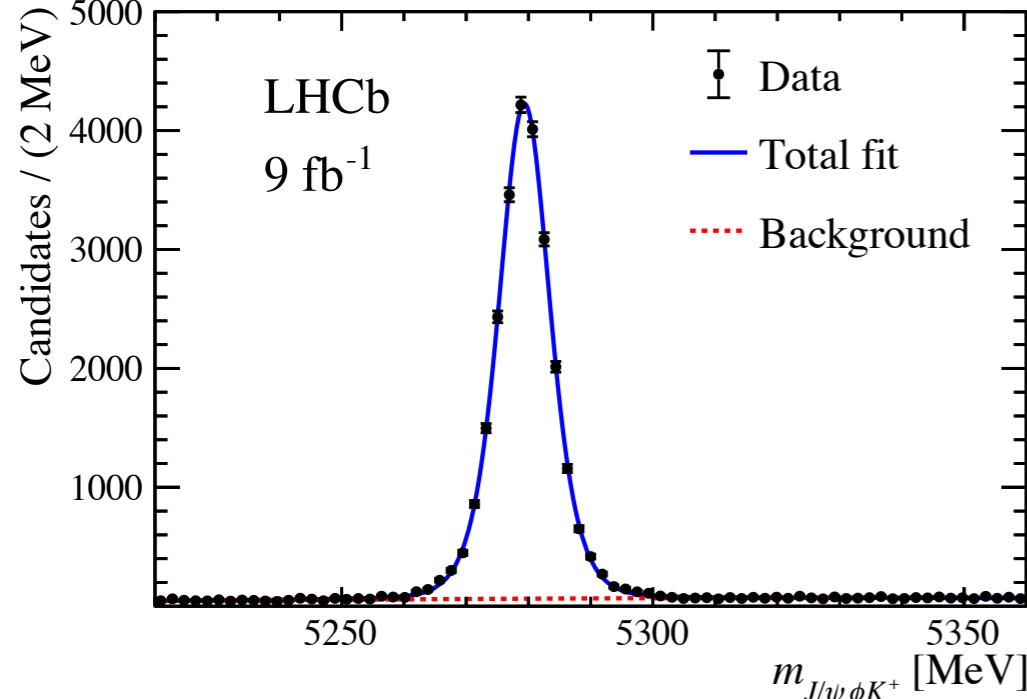


Resonance	Mass ( $\text{GeV}/c^2$ )	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$
$X_0(2900)$	$2.866 \pm 0.007 \pm 0.002$	$57 \pm 12 \pm 4$
$X_1(2900)$	$2.904 \pm 0.005 \pm 0.001$	$110 \pm 11 \pm 4$

Systematic uncertainties dominated by model composition (S- and P-wave)

New states overwhelmingly significant:  $\gg 5\sigma$

$$B^+ \rightarrow J/\psi \phi K^+$$



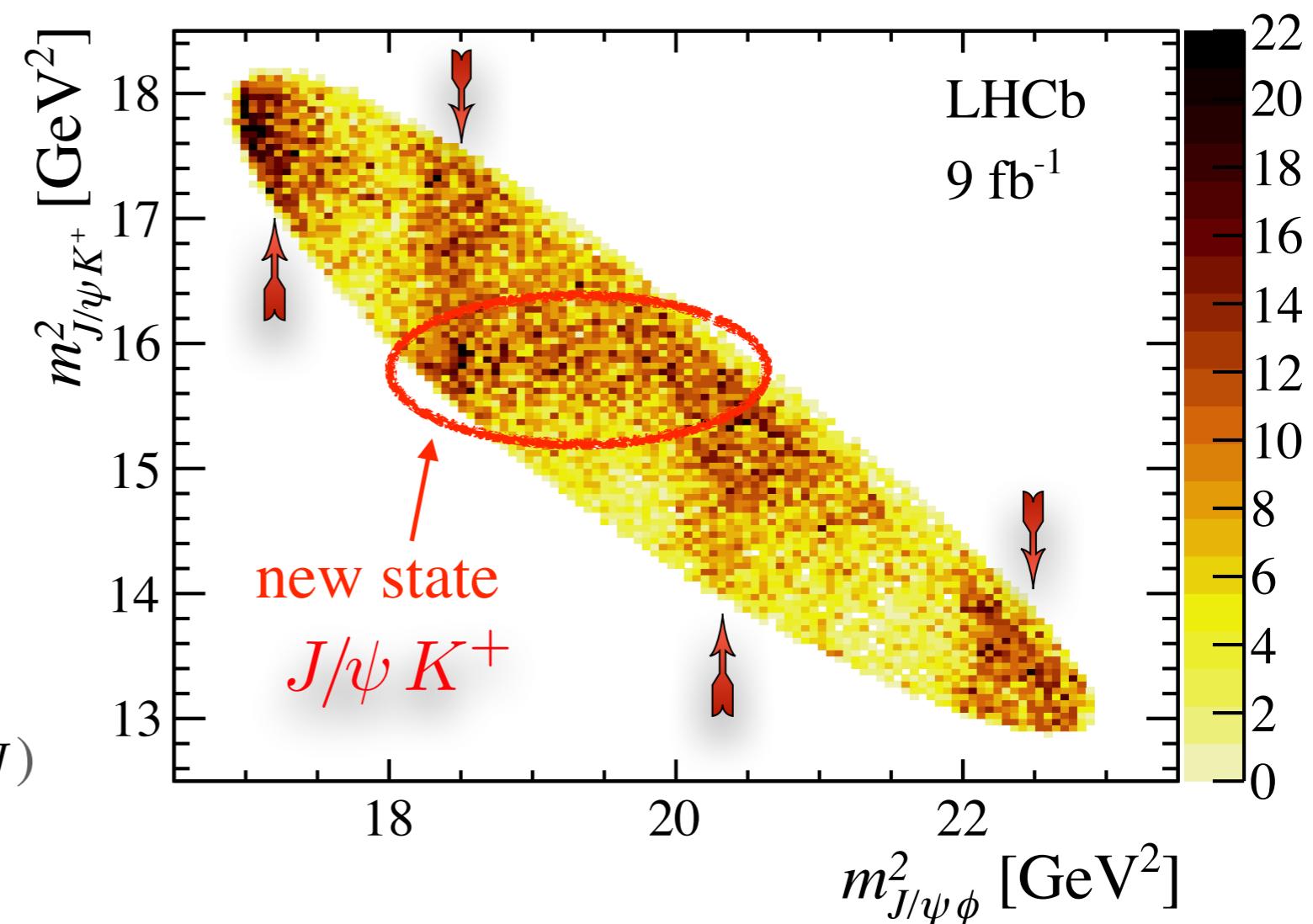
Four structures in  $J/\psi \phi$   
corresponding to  
known states:

$X(4140), X(4274),$   
 $X(4500), X(4700)$

(recent PDG convention:  $X \rightarrow \chi_{cJ}$ )

$B^+ \rightarrow J/\psi \phi K^+$  signal  
 $J/\psi \rightarrow \mu^+ \mu^-$ ,  $\phi \rightarrow K^+ K^-$

Run 1+2, 24k candidates, 96% purity



6D amplitude analysis, considering three decay chains (19 resonances):

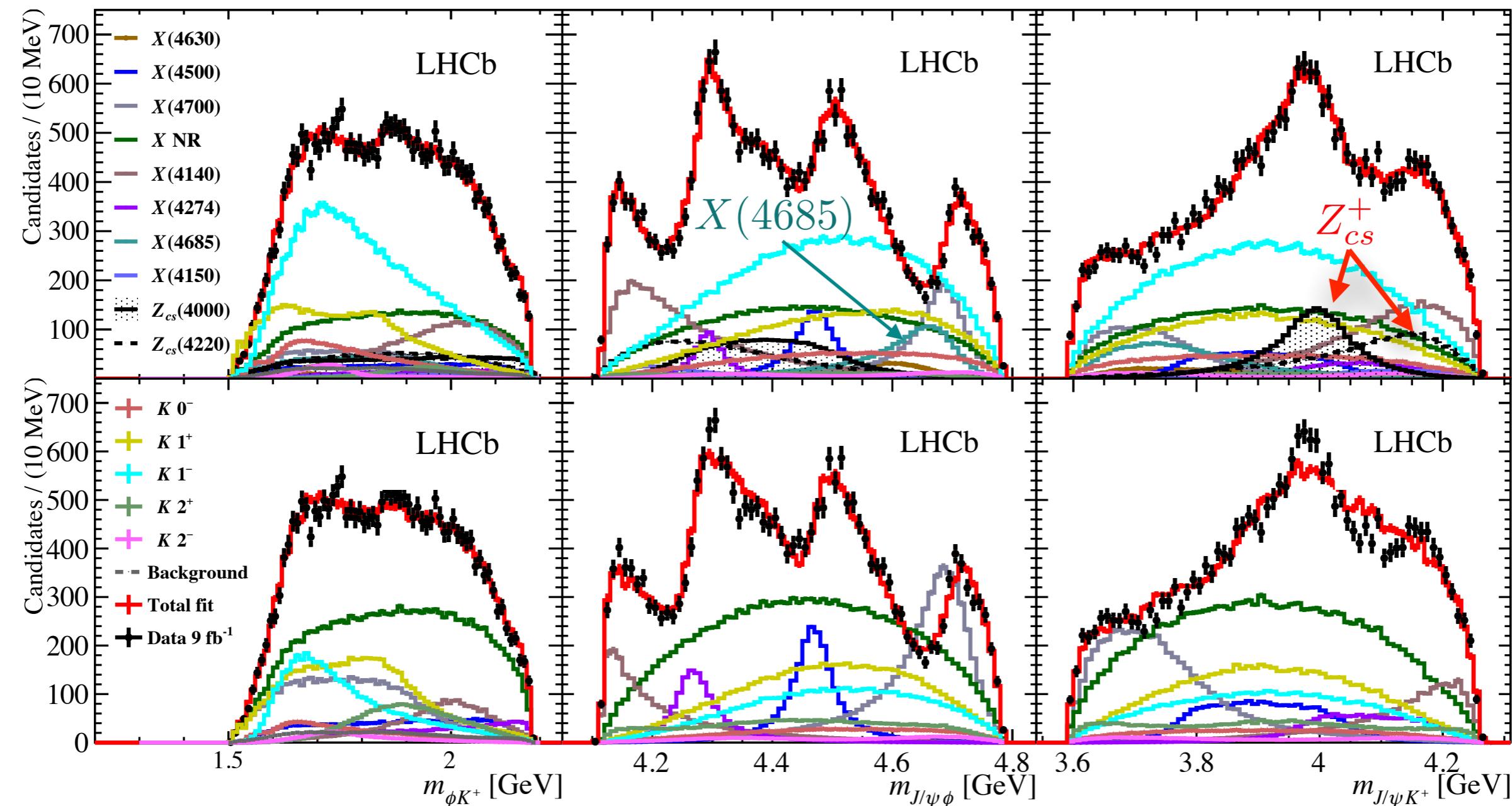
$K^{*+}(\phi K^+) J/\psi$ ,  $X(J/\psi \phi) K^+$ ,  $Z_{cs}^+(J/\psi K^+) \phi$

Helicity formalism for the decay amplitude:  $|\mathcal{M}|^2 = \sum_{\Delta\lambda_\mu=\pm 1} \left| \mathcal{M}_{\Delta\lambda_\mu}^{K^*} + \mathcal{M}_{\Delta\lambda_\mu}^Z + \mathcal{M}_{\Delta\lambda_\mu}^X \right|^2$

- $\mathcal{M}_{\Delta\lambda_\mu}^X(\theta_X, \theta_\psi^X, \theta_\phi^X, \phi_{K^+}^X, \phi_\mu^X, \alpha_\mu^X, m_{\psi\phi}) = e^{i\Delta\lambda_\mu\alpha_\mu^X} \sum_{\lambda_\psi^X} e^{i\lambda_\psi^X\phi_\mu^X} d_{\lambda_\psi^X, \Delta\lambda_\mu}^1(\theta_\psi^X)$   
 $\times \sum_{\lambda_\phi^X} e^{i\lambda_\phi^X\phi_{K^+}^X} d_{\lambda_\phi^X, 0}^1(\theta_\phi^X) \sum_i \mathcal{H}^{B^+ \rightarrow X_i K^+} \mathcal{H}_{\lambda_\psi^X, \lambda_\phi^X}^{X_i} d_{0, \lambda_\psi^X - \lambda_\phi^X}^{J_{X_i}}(\theta_X) R_{X_i}(m_{\psi\phi})$
- $\mathcal{M}_{\Delta\lambda_\mu}^{K^*}(\theta_{K^*}, \theta_\psi, \theta_\phi, \phi_{(\psi K^*)} \equiv \phi_\phi + \phi_\mu, \phi_{K^+}, m_{\phi K}) =$   
 $\sum_{\lambda_\psi} e^{i\lambda_\psi\phi_{(\psi K^*)}} d_{\lambda_\psi, \Delta\lambda_\mu}^1(\theta_\psi) \sum_{\lambda_\phi} e^{i\lambda_\phi\phi_{K^+}} d_{\lambda_\phi, 0}^1(\theta_\phi) \sum_n \mathcal{H}_{\lambda_\psi}^{B \rightarrow \psi K_n^*} \mathcal{H}_{\lambda_\phi}^{K_n^*} d_{\lambda_\psi, \lambda_\phi}^{J_{K_n^*}}(\theta_{K^*}) R_{K_n^*}(m_{\phi K})$
- $\mathcal{M}_{\Delta\lambda_\mu}^Z(\theta_Z, \theta_\psi^Z, \theta_\phi^Z, \phi_{(Z\phi)} \equiv \phi_{K^+}^Z + \phi_\psi^Z, \phi_\mu^Z, \alpha_\mu^Z, m_{\psi K^+}) = e^{i\Delta\lambda_\mu\alpha_\mu^Z} \sum_{\lambda_\psi^Z} e^{i\lambda_\psi^Z\phi_\mu^Z} d_{\lambda_\psi^Z, \Delta\lambda_\mu}^1(\theta_\psi^Z)$   
 $\times \sum_{\lambda_\phi^Z} e^{i\lambda_\phi^Z\phi_{(Z\phi)}} d_{\lambda_\phi^Z, 0}^1(\theta_\phi^Z) \sum_j \mathcal{H}_{\lambda_\phi^Z}^{B \rightarrow Z_j \phi} \mathcal{H}_{\lambda_\psi^Z}^{Z_j} d_{\lambda_\phi^Z, \lambda_\psi^Z}^{J_{Z_j}}(\theta_Z) R_{Z_j}(m_{\psi K})$

Parity conservation constrains  
helicity couplings and R(m) (RBW)  
allowing determination of  $J^P$

$$A \rightarrow 12 : \mathcal{H}_{\lambda_1, \lambda_2} \equiv \eta_A \eta_1 \eta_2 (-1)^{s_1 + s_2 - s_A} \mathcal{H}_{-\lambda_1, -\lambda_2}$$



new  
model

Run 1  
model

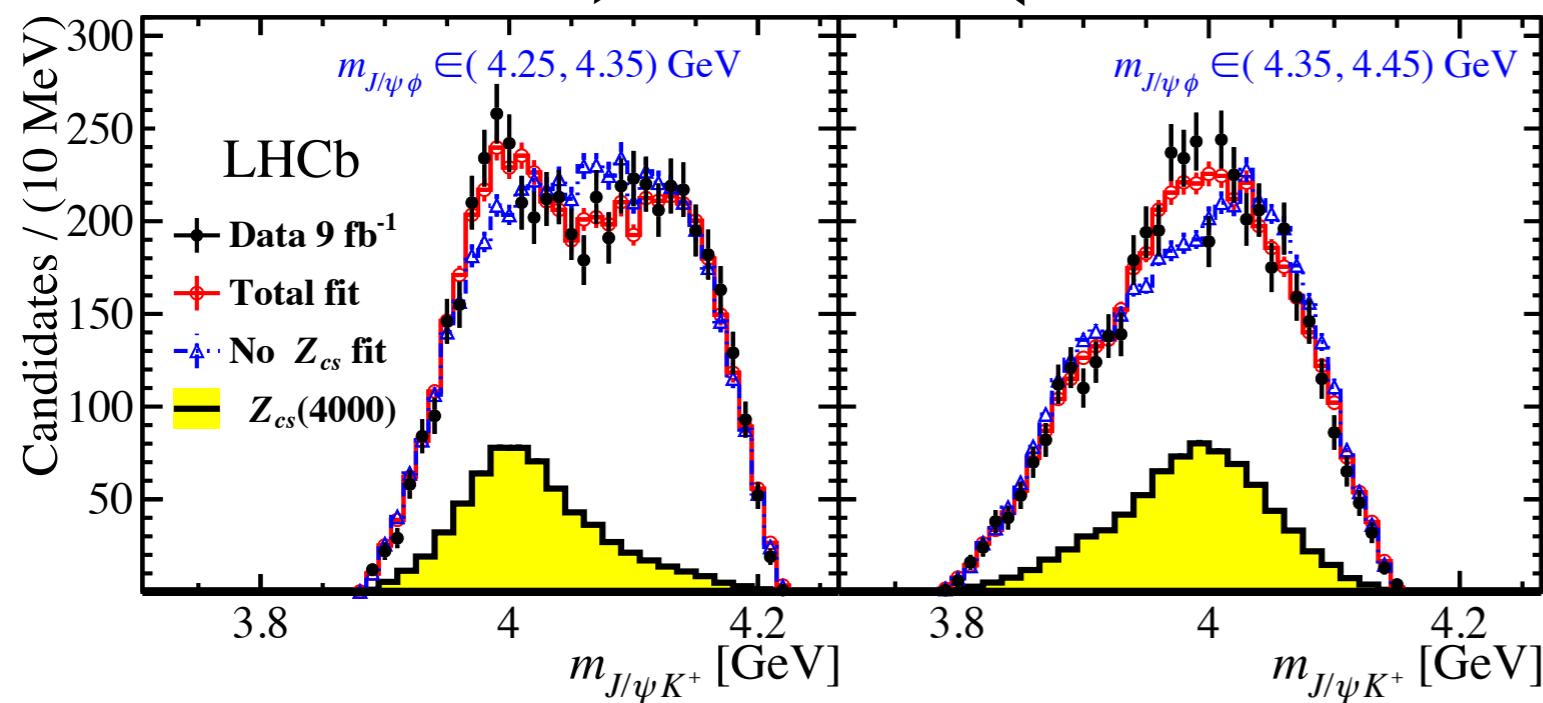
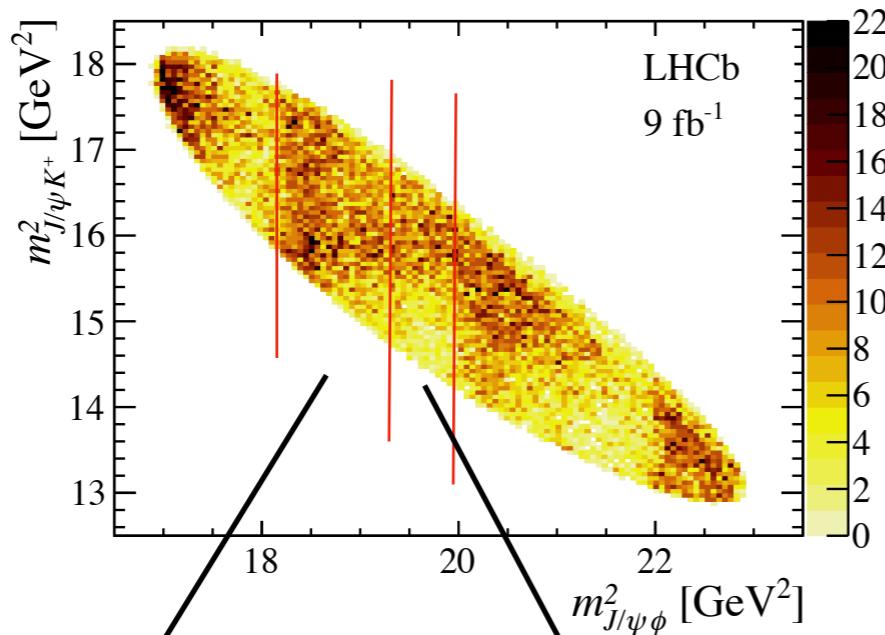
PRL 127 (2021) 082001

Best fit with three new states:

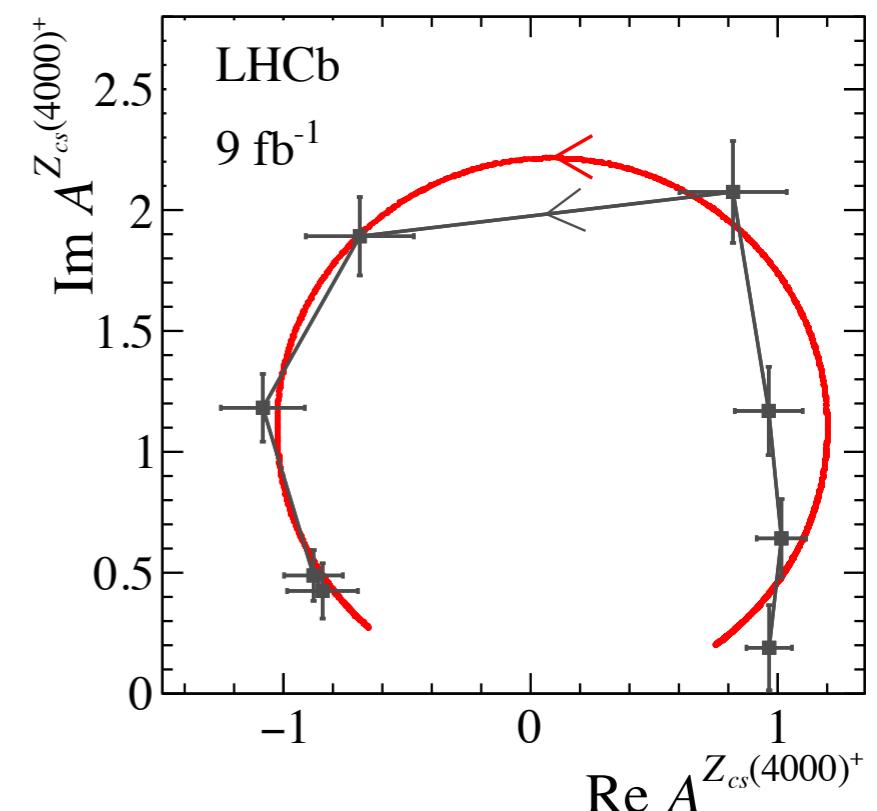
$$Z_{cs}^+(4000) \quad J^P = 1^+ (15\sigma)$$

$$Z_{cs}^+(4220) \quad J^P = 1^+ (6\sigma)$$

$$X(4685) \quad J^P = 1^+ (15\sigma)$$



Argand plot around  $Z_{cs}^+(4000)$ :  
counterclockwise evolution,  
typical resonant behaviour



PRL 127 (2021) 082001

	$m_0$ [MeV]	$\Gamma_0$ [MeV]
$Z_{cs}(4000)$	$4003 \pm 6 \pm 4$	$131 \pm 15 \pm 26$
$Z_{cs}(4220)$	$4216 \pm 24 \pm 43$	$233 \pm 52 \pm 97$

$$\Lambda_b^0 \rightarrow J/\psi p K^-$$

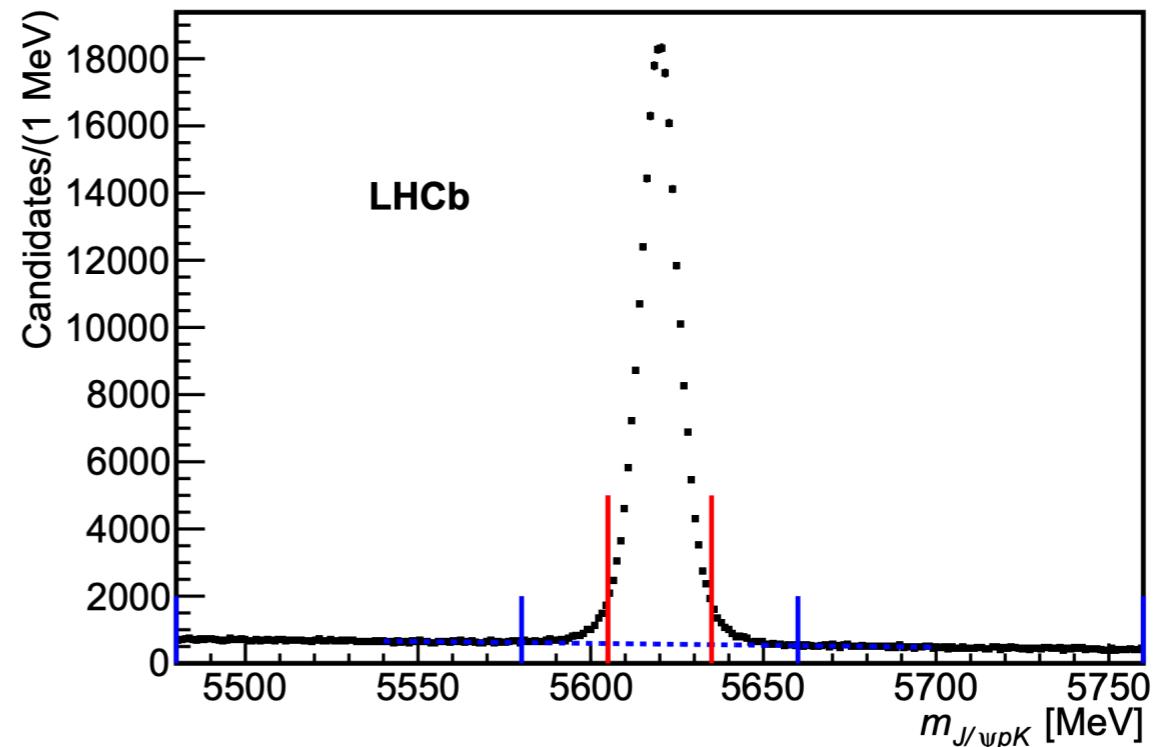
$$\Lambda_b^0 \rightarrow J/\psi p K^-$$

$\sim 245000$  candidates:

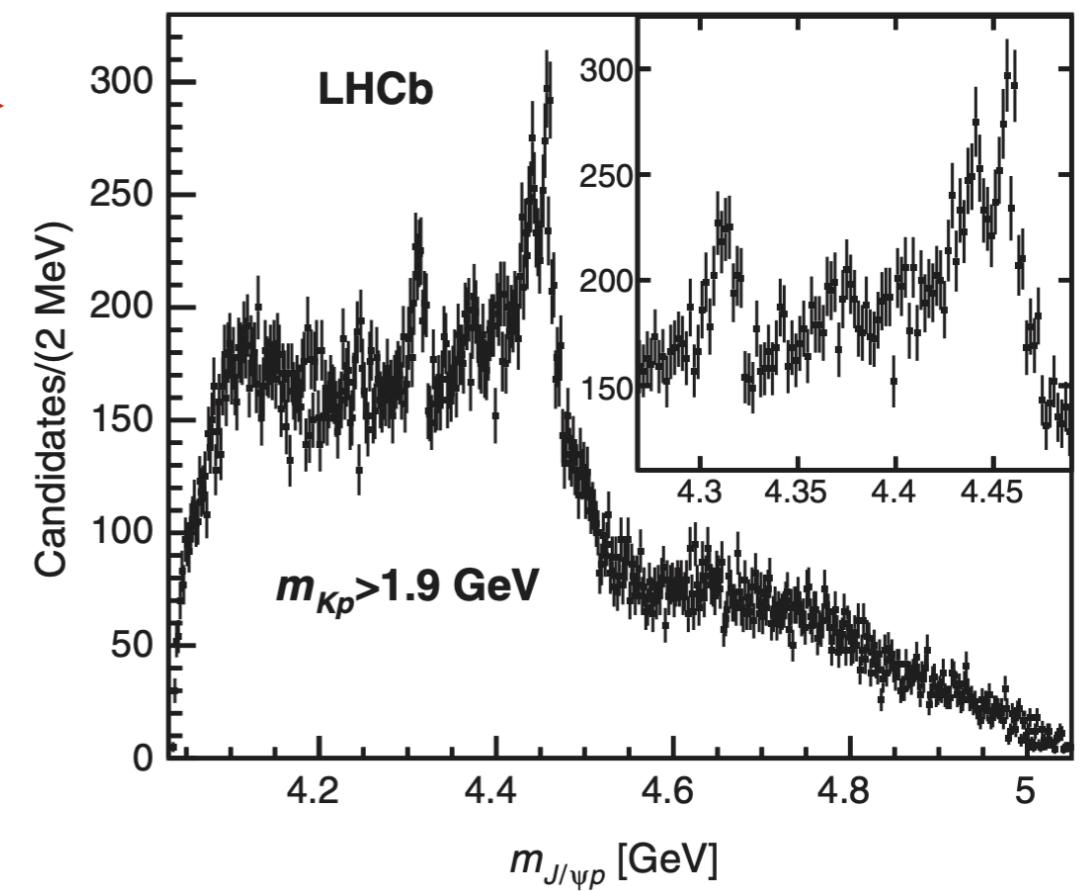
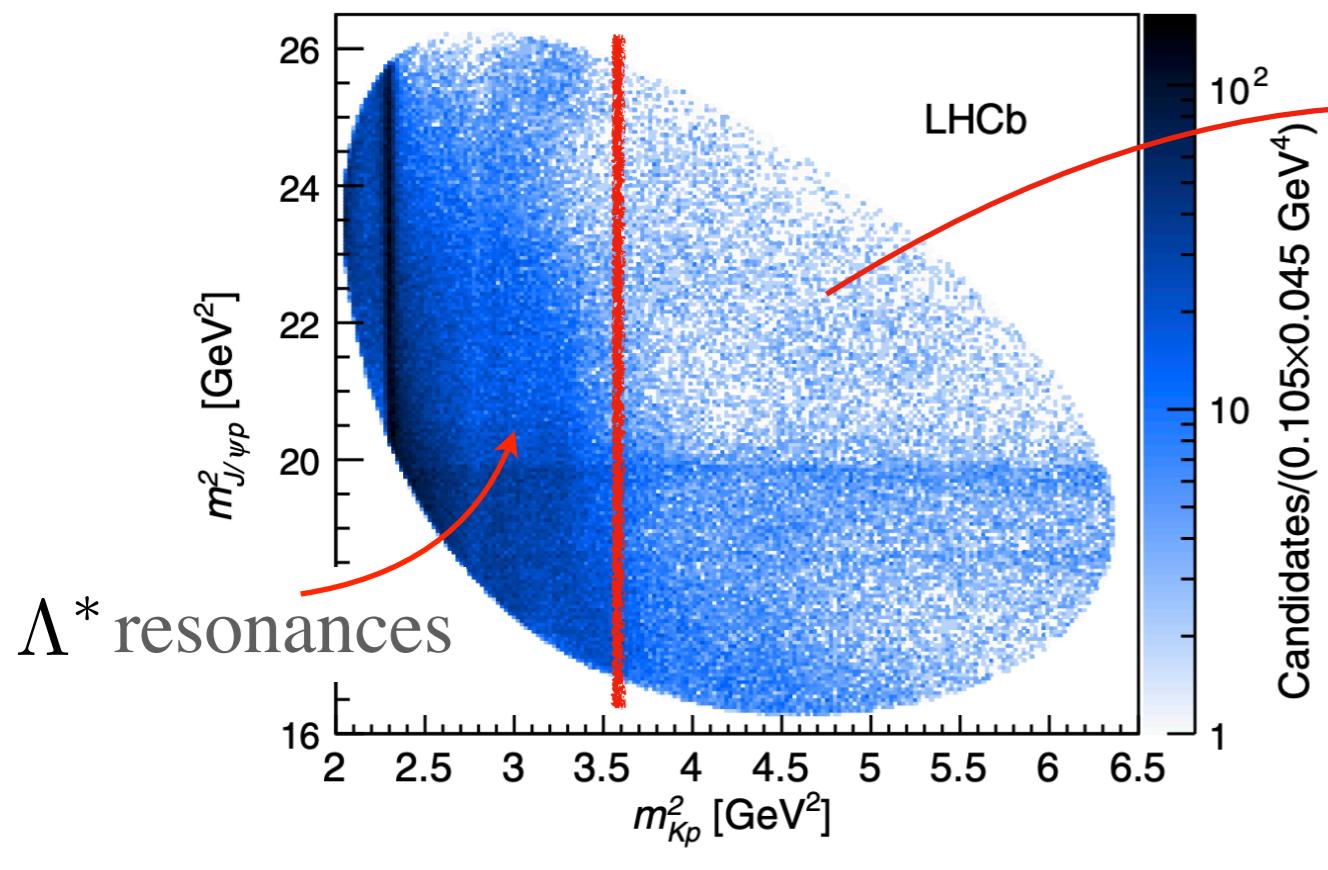
full (6D) amplitude analysis  
computationally challenging.

Ongoing effort

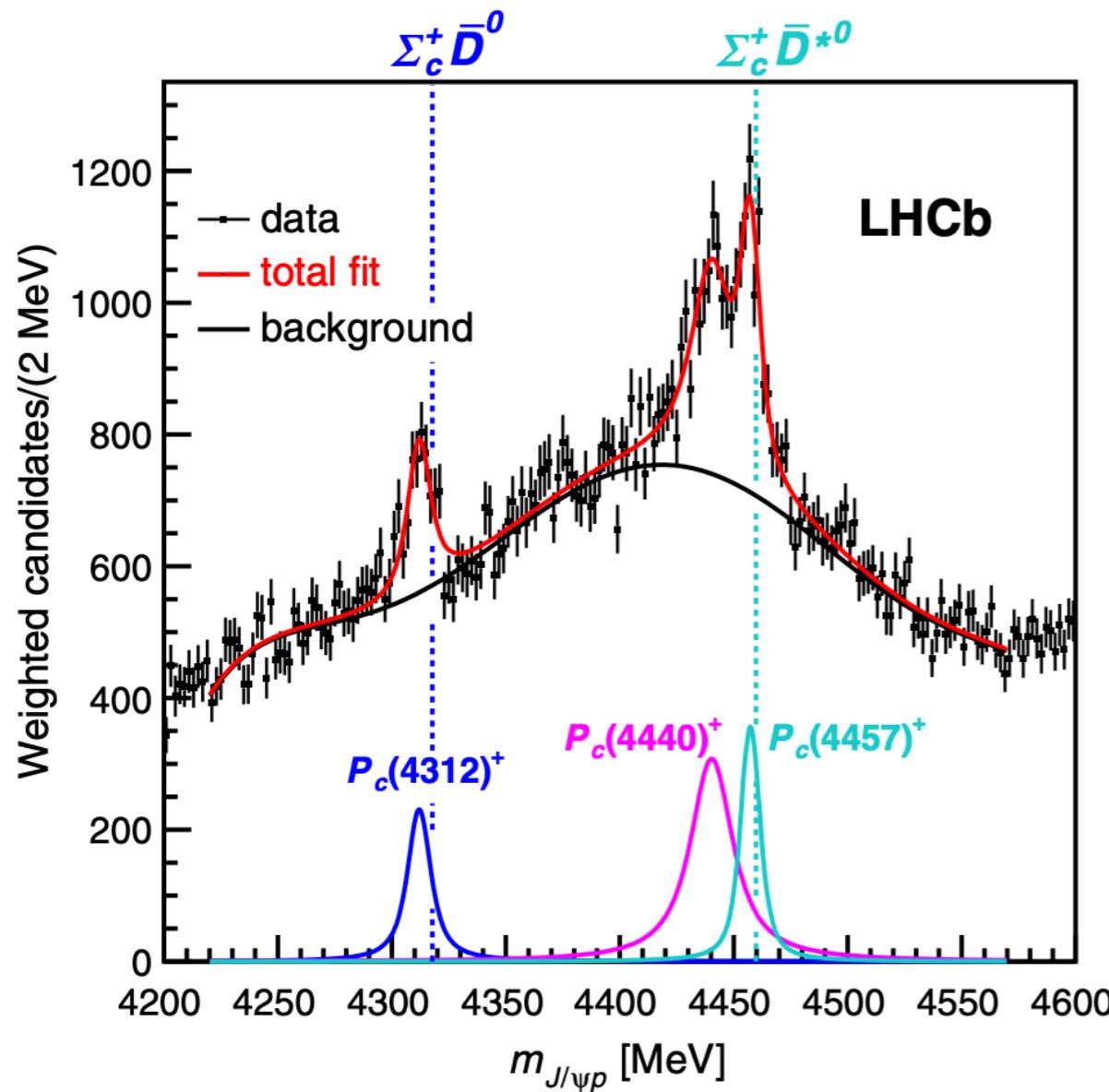
[PRL 122 \(2019\) 222001](#)



Narrow structures allow fits to  $m(J/\psi p)$  projection



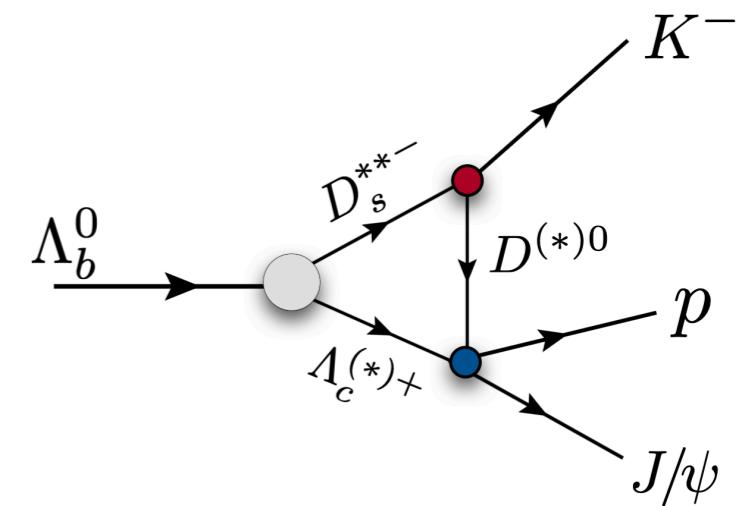
Three narrow structures found, two of them close to thresholds



Narrow widths: compelling case for bound states

Could it be something else?

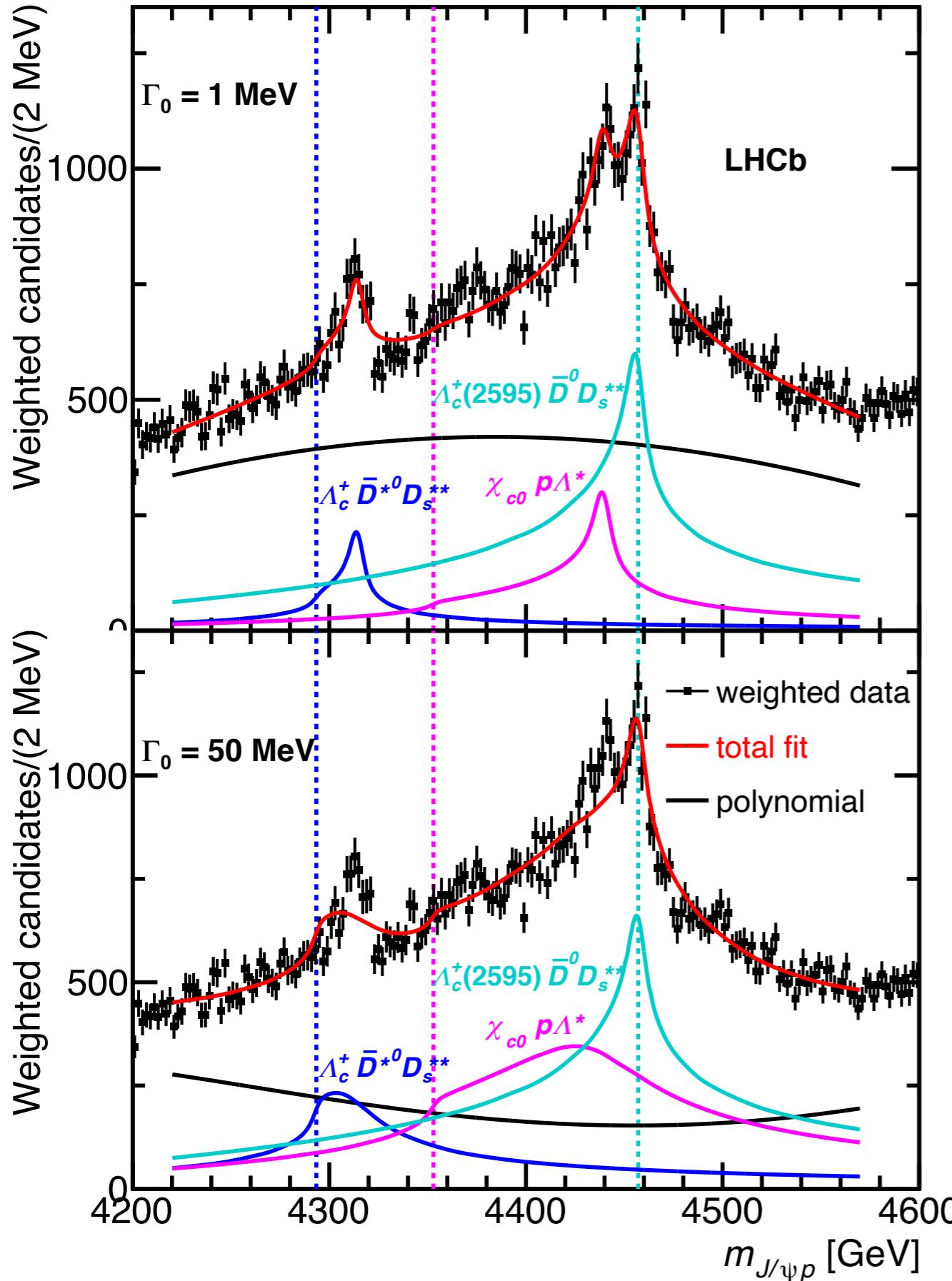
Triangle singularities



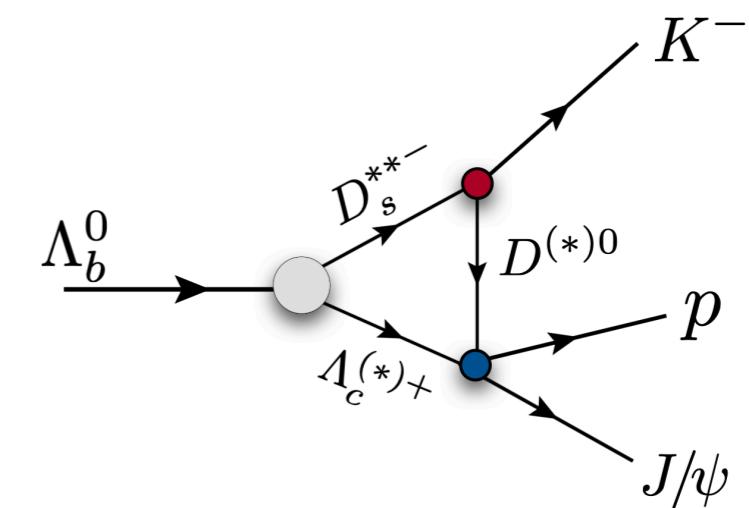
when particles in the loop are on-shell, a cusp above threshold is produced

[PRL 122 \(2019\) 222001](#)

State	$M$ [MeV]	$\Gamma$ [MeV]	(95% C.L.)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	( $<27$ )
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	( $<49$ )
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	( $<20$ )



$P_c^+(4557) :$   
close to  $\Lambda_c^+(2595)\bar{D}^0$  threshold



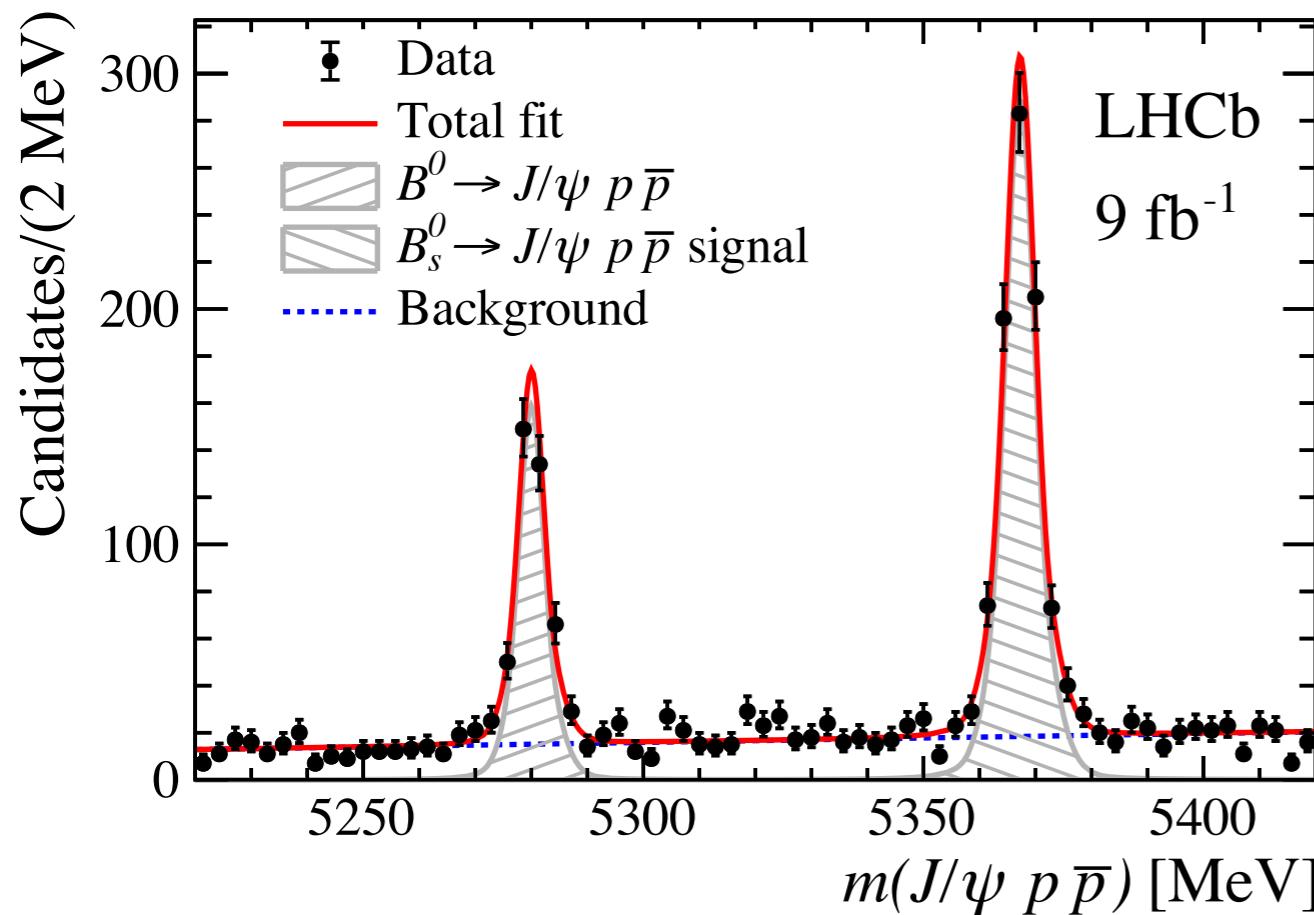
$$D_s^{*-} \rightarrow D_{s1}(2860)^- \\ (\Gamma_0 = 159 \pm 80 \text{ MeV})$$

reasonable fit obtained only  
assuming unrealistic  
widths for  $D_s^{*-}$

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

$B_s^0 \rightarrow J/\psi p\bar{p}$ : no conventional states are expected

Run1+2 data: 800  $B_s^0$  candidates



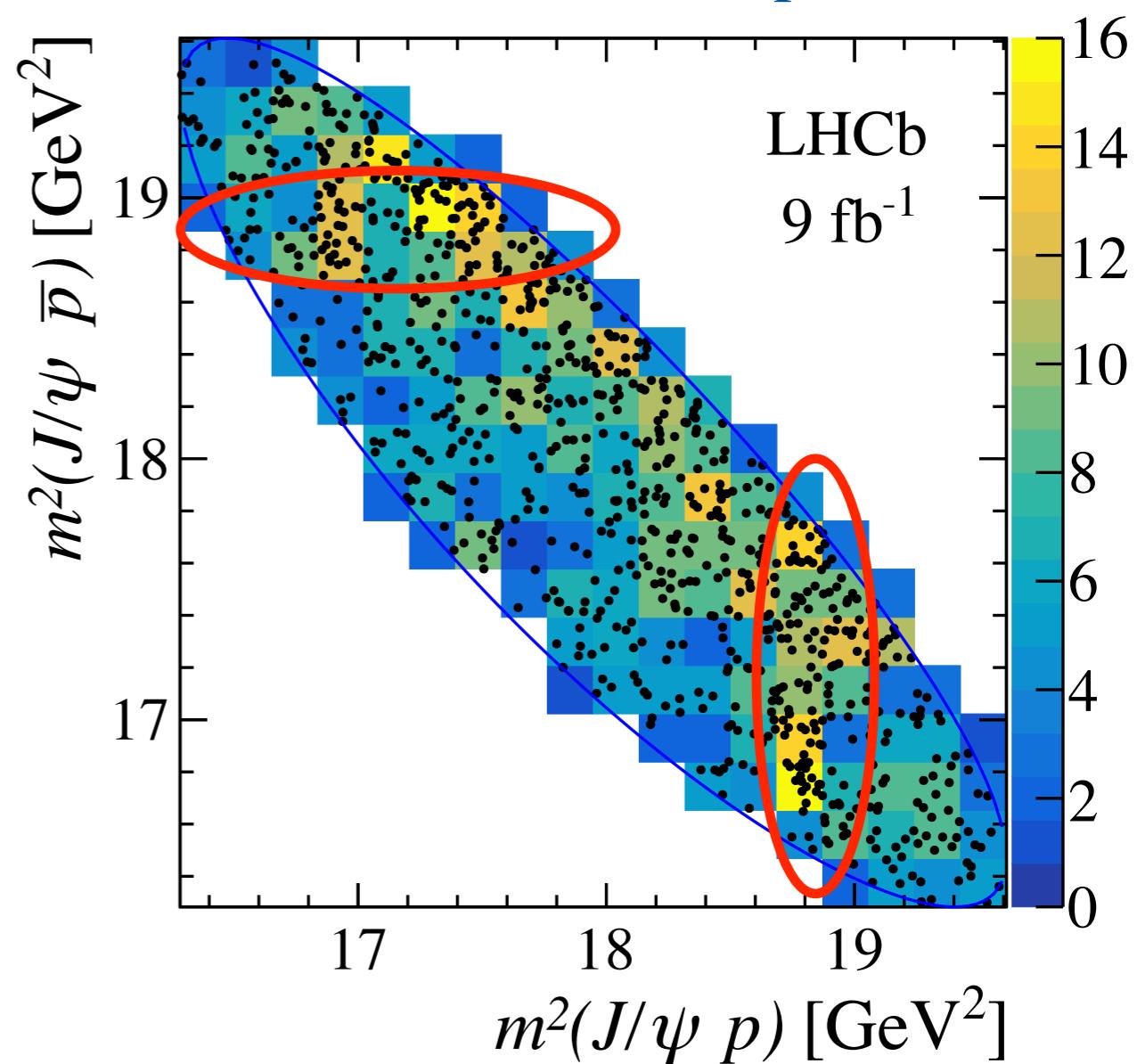
4D amplitude analysis, 3 decay chains:

$$B_s^0 \rightarrow J/\psi X (\rightarrow p\bar{p})$$

$$B_s^0 \rightarrow P_c^+ (\rightarrow J/\psi p)\bar{p}$$

$$B_s^0 \rightarrow P_c^- (\rightarrow J/\psi \bar{p})p$$

Structures observed at the same mass in both  $J/\psi p$  and  $J/\psi \bar{p}$  spectra



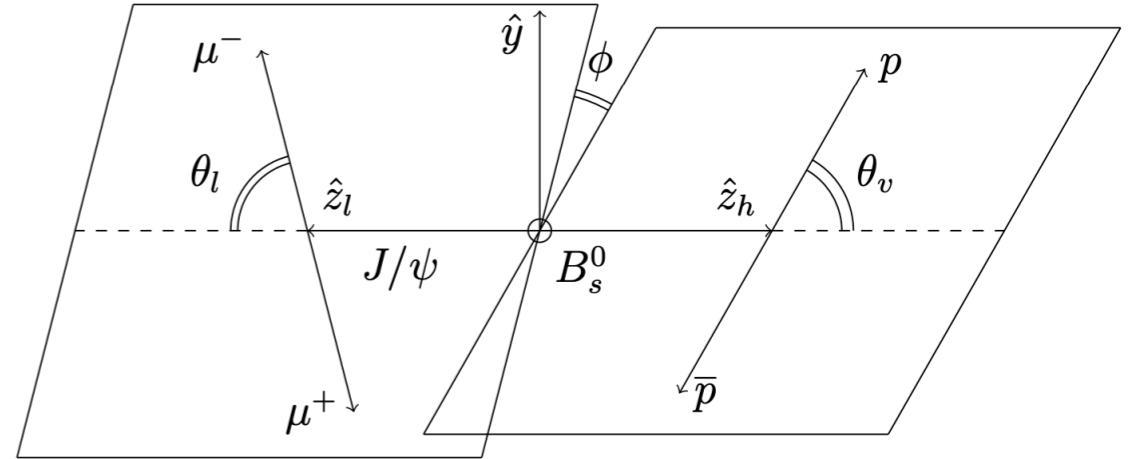
[LHCb-PAPER-2021-018](#)

Helicity formalism for the decay amplitude:

$$|\mathcal{M}|^2 = \sum_{\lambda_p} \sum_{\lambda_{\bar{p}}} \sum_{\eta} |\mathcal{M}^X +$$

$$+ e^{i\eta \cdot \alpha_\mu} \sum_{\lambda_p^{P_c}} \sum_{\lambda_{\bar{p}}^{P_c}} d_{\lambda_{\bar{p}}^{P_c}, \lambda_{\bar{p}}}^{1/2} (-\theta_{\bar{p}}^{P_c^+}) d_{\lambda_p^{P_c}, \lambda_p}^{1/2} (\theta_p^{P_c^+}) \mathcal{M}^{P_c^+} (\lambda_p^{P_c}, \lambda_{\bar{p}}^{P_c}, \eta) +$$

$$+ e^{i\eta \cdot \alpha_{\bar{\mu}}} \sum_{\lambda_p^{P_c}} \sum_{\lambda_{\bar{p}}^{P_c}} d_{\lambda_p^{P_c}, \lambda_p}^{1/2} (\theta_p^{P_c^-}) d_{\lambda_{\bar{p}}^{P_c}, \lambda_{\bar{p}}}^{1/2} (-\theta_{\bar{p}}^{P_c^-}) \mathcal{M}^{P_c^-} (\lambda_{\bar{p}}^{P_c}, \lambda_p^{P_c}, \eta) |^2$$



4D phase space:

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

$$\mathcal{M}_{\lambda_p, \lambda_{\bar{p}}, \eta}^X = \sum_{\lambda_\psi=0, \pm 1} \tilde{\mathcal{H}}_{\lambda_\psi, \lambda_X}^{B_s^0} R(m_{p\bar{p}}^2) D_{\lambda_X, \lambda_p - \lambda_{\bar{p}}}^{*J_X}(\phi_p, \theta_p, 0) \tilde{\mathcal{H}}_{\lambda_p, \lambda_{\bar{p}}}^X D_{\lambda_\psi, \eta}^{*1}(\phi_\mu, \theta_\mu, 0)$$

$$\mathcal{M}_{\lambda_p, \lambda_{\bar{p}}, \eta}^{P_c^+} = \sum_{\lambda_\psi=0, \pm 1} \tilde{\mathcal{H}}_{\lambda_{P_c}, \lambda_{\bar{p}}}^{B_s^0 \rightarrow P_c^+ \bar{p}} \mathcal{R}(m_{J/\psi p}^2) D_{\lambda_{P_c}, \lambda_\psi - \lambda_p}^{*J_{P_c}}(\phi_\psi^{\{P_c^+\}}, \theta_\psi^{\{P_c^+\}}, 0) \tilde{\mathcal{H}}_{\lambda_\psi, \lambda_p}^{P_c^+ \rightarrow \psi p} D_{\lambda_\psi, \eta}^{*1}(\phi_\mu^{P_c^+}, \theta_\psi^{P_c^+}, 0)$$

$$\mathcal{M}_{\lambda_p, \lambda_{\bar{p}}, \eta}^{P_c^-} = \sum_{\lambda_\psi=0, \pm 1} \tilde{\mathcal{H}}_{\lambda_{P_c}, \lambda_p}^{B_s^0 \rightarrow P_c^- p} \mathcal{R}(m_{J/\psi \bar{p}}^2) D_{\lambda_{P_c}, \lambda_{\bar{p}} - \lambda_\psi}^{*J_{P_c}}(\phi_{\bar{p}}^{\{P_c^-\}}, \theta_{\bar{p}}^{\{P_c^-\}}, 0) \tilde{\mathcal{H}}_{\lambda_{\bar{p}}, \lambda_\psi}^{P_c^- \rightarrow \bar{p}\psi} D_{\lambda_\psi, \eta}^{*1}(\phi_\mu^{P_c^-}, \theta_\psi^{P_c^-}, 0)$$

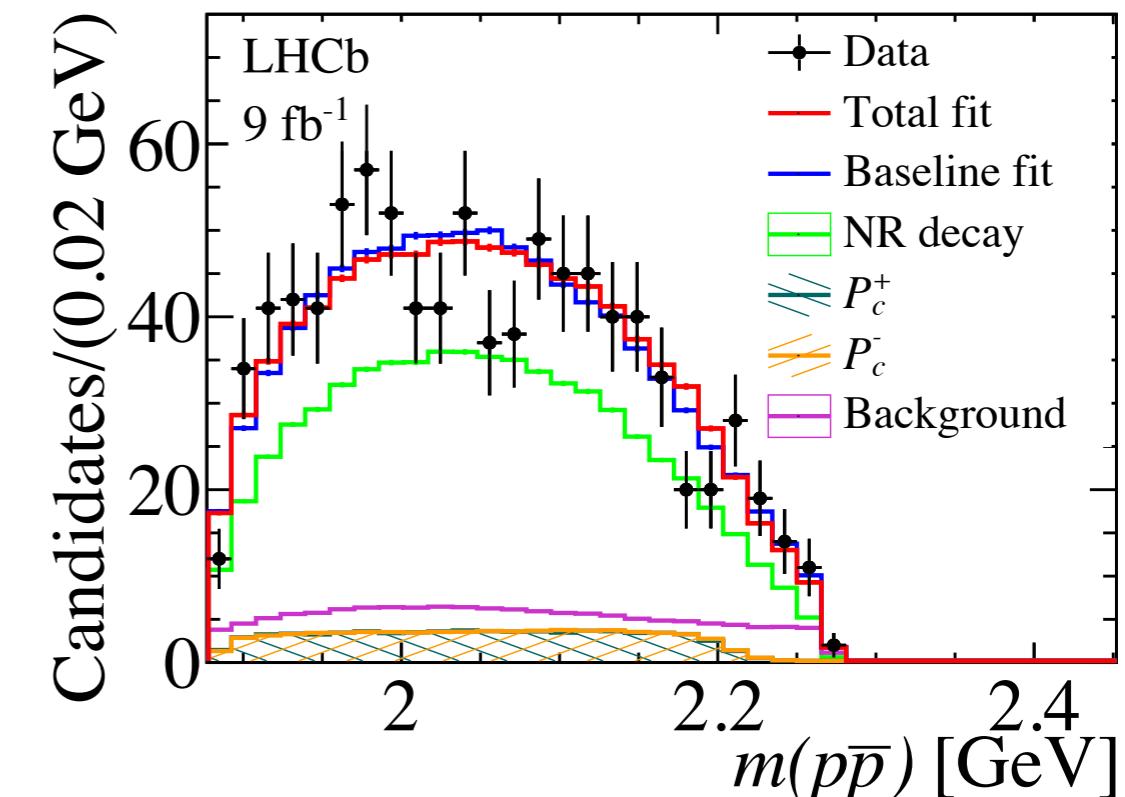
$$R_{P_{cj}}(m_{\psi p}) = B'_{L'_0}(p, p_0, d) \left( \frac{p}{M_{B_s^0}} \right)^{L_{B_s^0}^{P_{cj}}} \text{BW} \left( m_{\psi p} | M_0^{P_{cj}}, \Gamma_0^{P_{cj}} \right) B'_{L_{P_{cj}}}(q, q_0, d) \left( \frac{q}{M_0^{P_{cj}}} \right)^{L_{P_{cj}}}$$

- Fit with only  $B_s^0 \rightarrow J/\psi X (\rightarrow p\bar{p})$  chain (NR component) fails to describe the data
- The data is described by a model with a  $J^P = 1/2^+$  ( $3/2^+$  not excluded) resonance

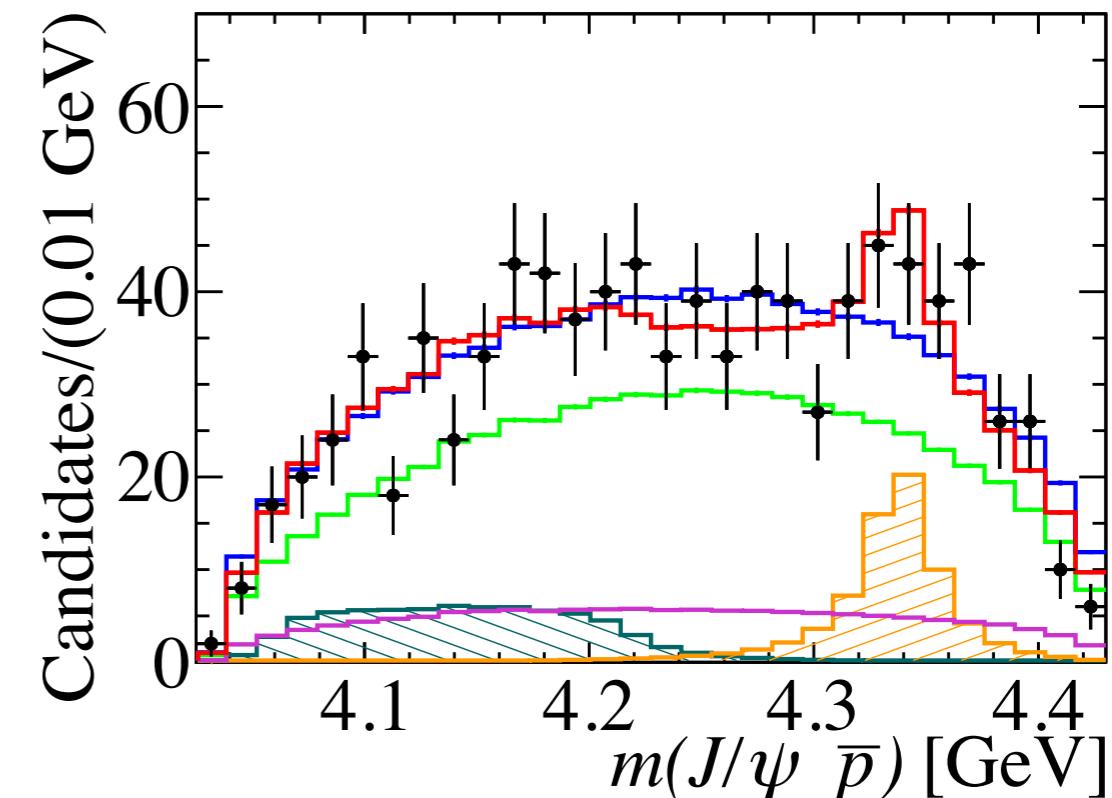
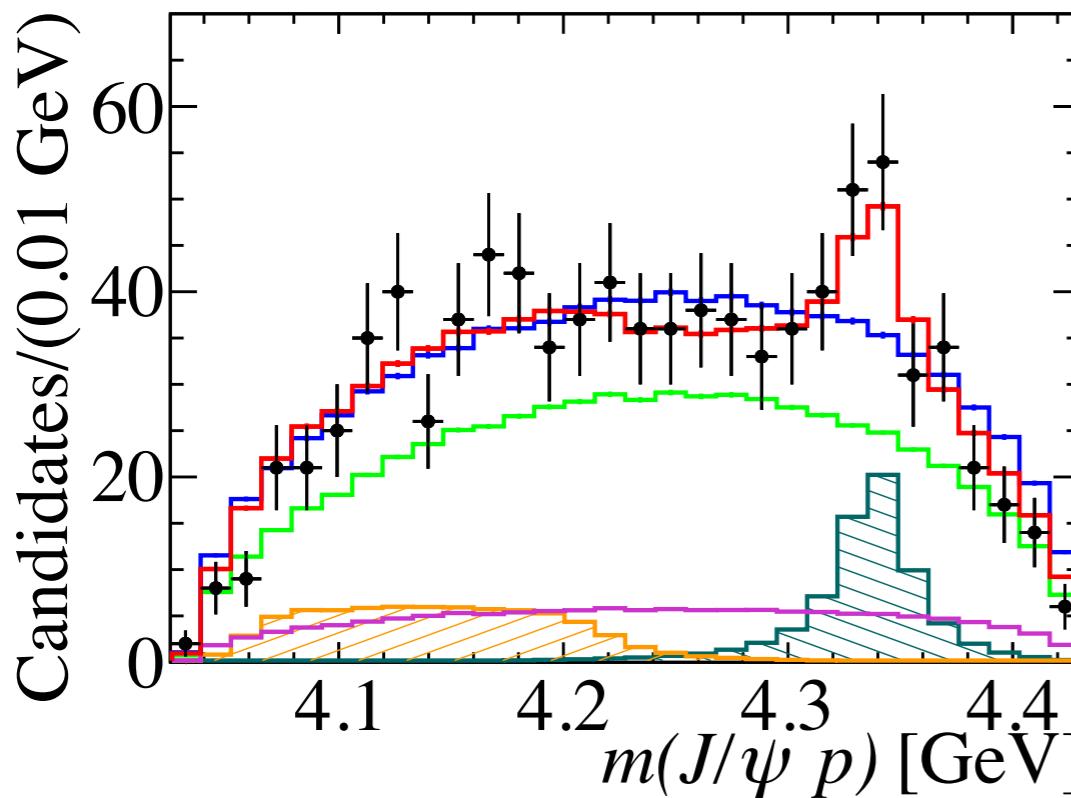
$$M_{P_c} = 4337^{+7}_{-4}{}^{+2}_{-2} \text{ MeV}$$

$$\Gamma_{P_c} = 29^{+26}_{-12}{}^{+14}_{-14} \text{ MeV}$$

*Not the same state found in  $\Lambda_b^0 \rightarrow J/\psi pK^-$*



[LHCb-PAPER-2021-018](#)



# Prompt $J/\psi\ J/\psi$ production

QCD-motivated models predict the existence of states with four heavy quarks

$$T_{Q_1 Q_2 \bar{Q}_3 \bar{Q}_4}, \quad Q_i = c, b$$

[Sci. Bull. 65 \(2020\) 1983](#)

Four-charm states could decay into a pair of  $J/\psi$  mesons

$$T_{cc\bar{c}\bar{c}} \rightarrow J/\psi J/\psi, m(T_{cc\bar{c}\bar{c}}) \approx [5.8 - 7.4] \text{ GeV}$$

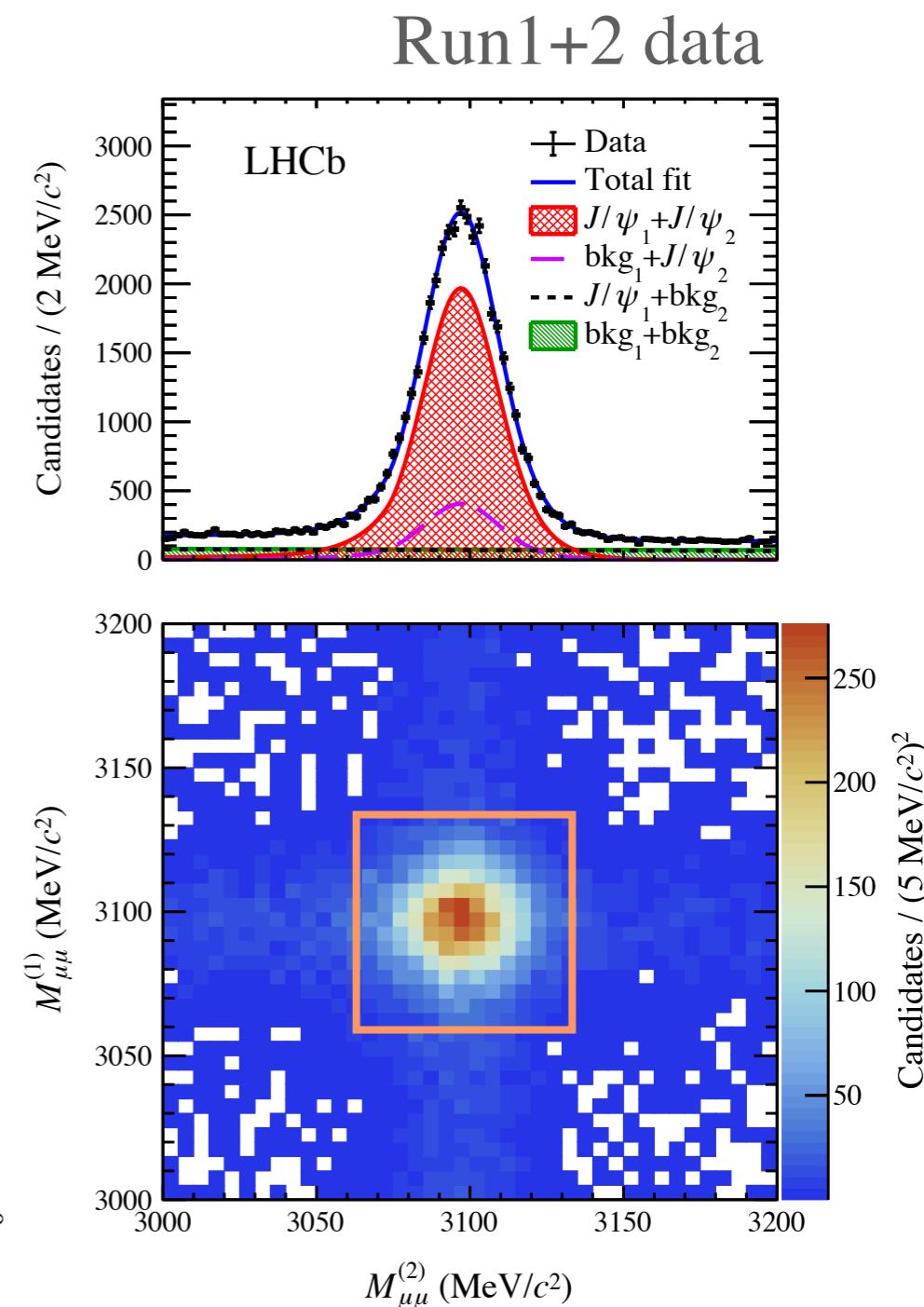
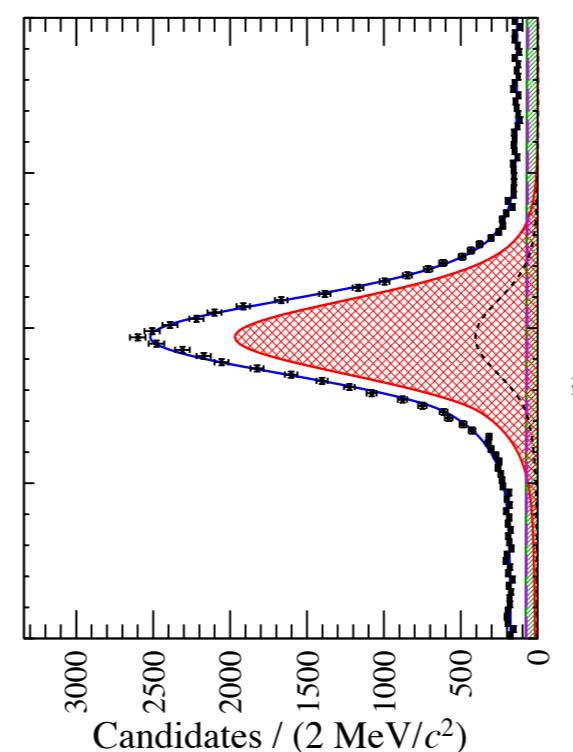
Two production mechanisms in  $pp$  collisions:

- ❖ single-parton scattering (SPS)
- ❖ double-parton scattering (DPS)

$T_{cc\bar{c}\bar{c}}$  : produced in SPS, over a DPS background

$$p_T^{\text{di-}J/\psi} > 5.2 \text{ GeV}$$

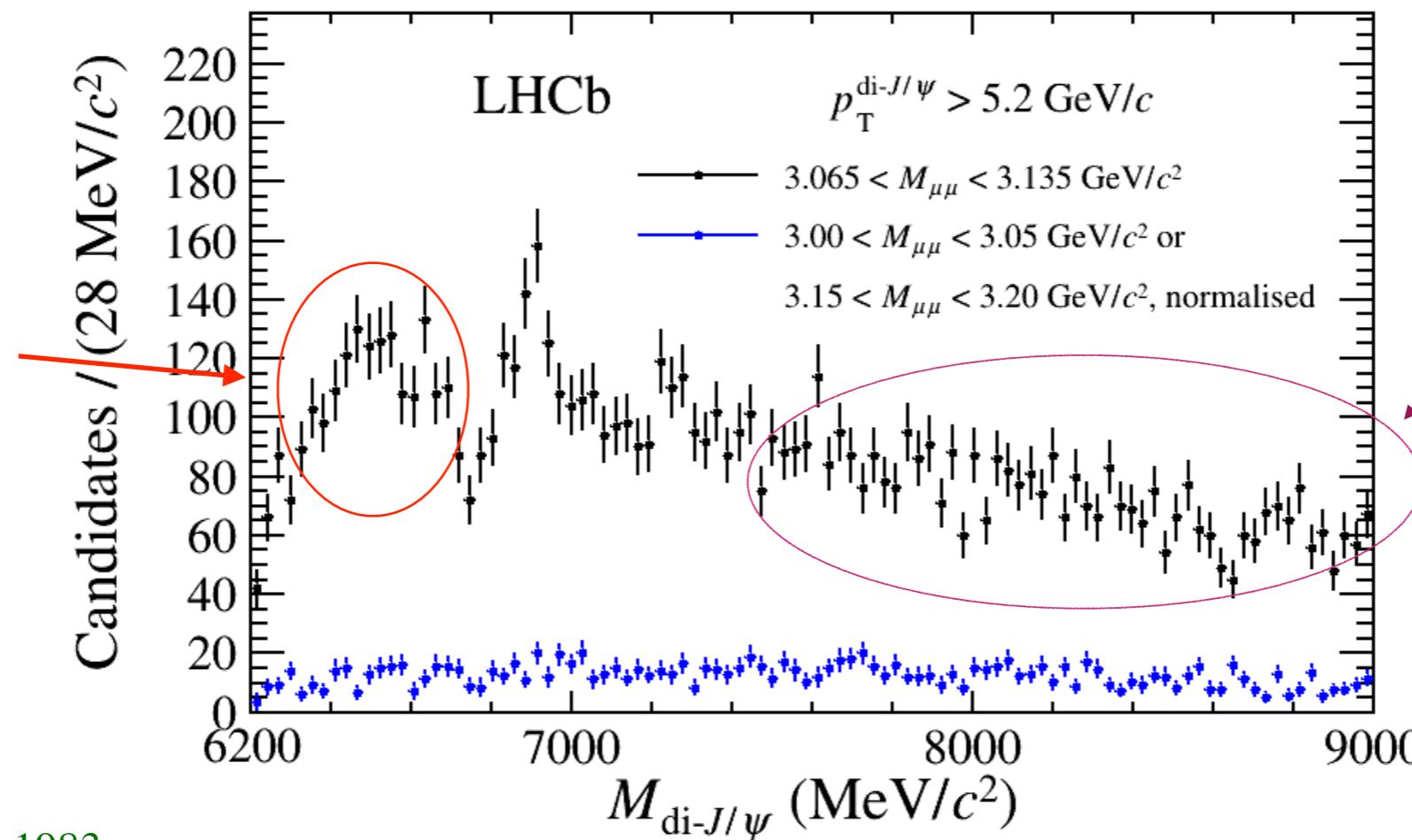
enriches the SPS component



First approach:  $p_T^{\text{di}-J/\psi} > 5.2 \text{ GeV}$

- uniform efficiency across  $M_{\text{di}-J/\psi}$  spectrum
- no structure found in the background

other states  
or  
feed-down  
from other  
tetraquarks,  
or  
rescattering



DPS dominates  
at high  $M_{\text{di}-J/\psi}$

[Sci. Bull. 65 \(2020\) 1983](#)

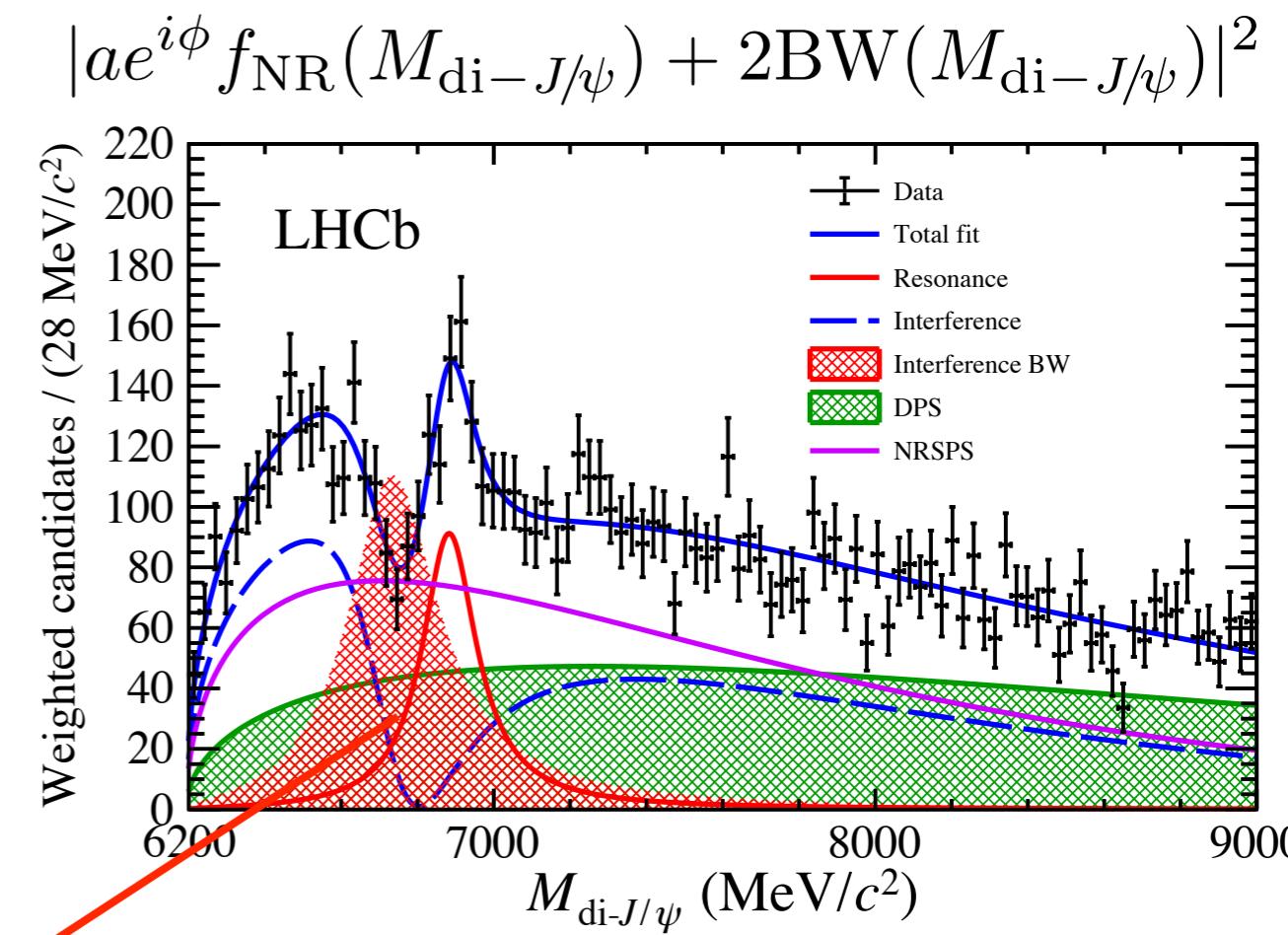
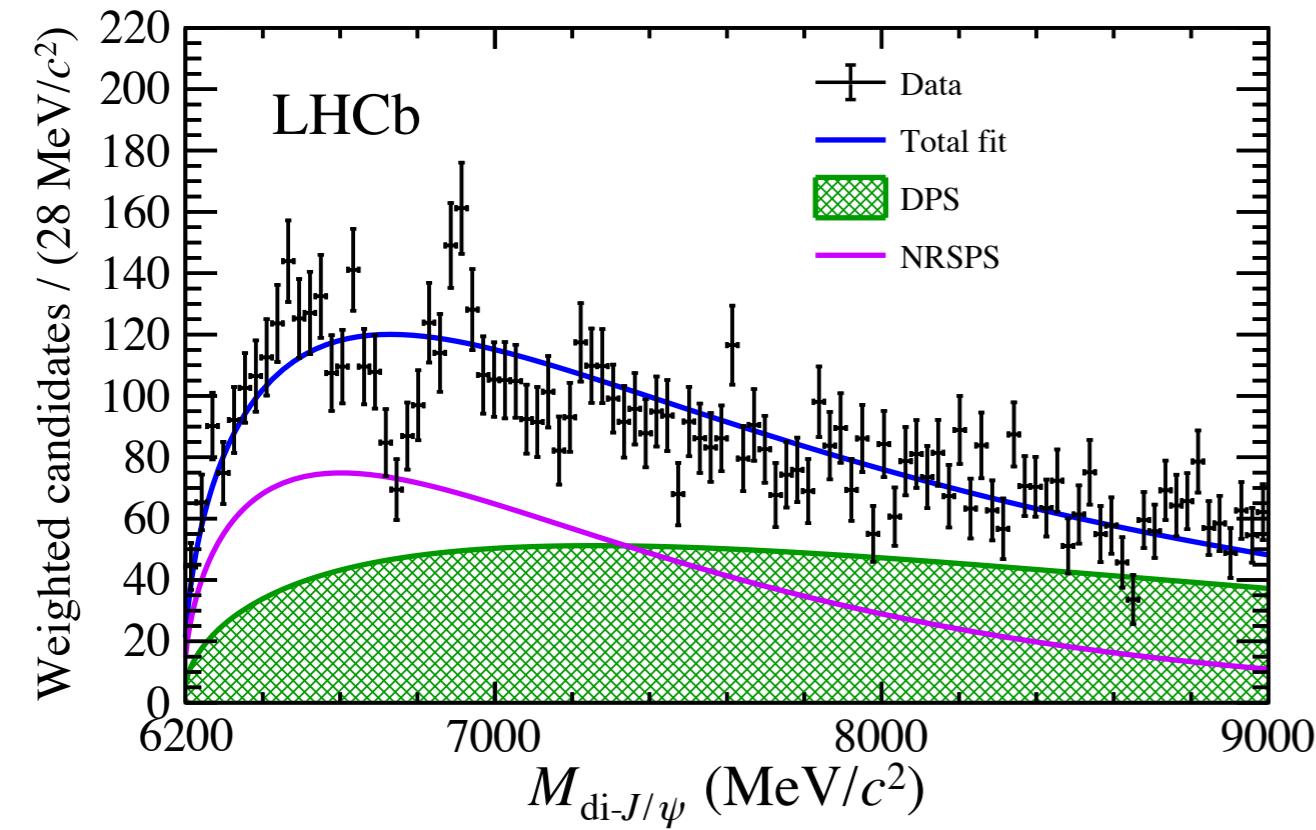
Non resonant SPS (NRSPS) plus DPS forms a continuum

Shapes parameterised by empirical functions based on predictions and simulations

First approach:  $p_T^{\text{di}-J/\psi} > 5.2 \text{ GeV}$

[Sci. Bull. 65 \(2020\) 1983](#)

A fit with only NRSPS and DPS fails to describe the data



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

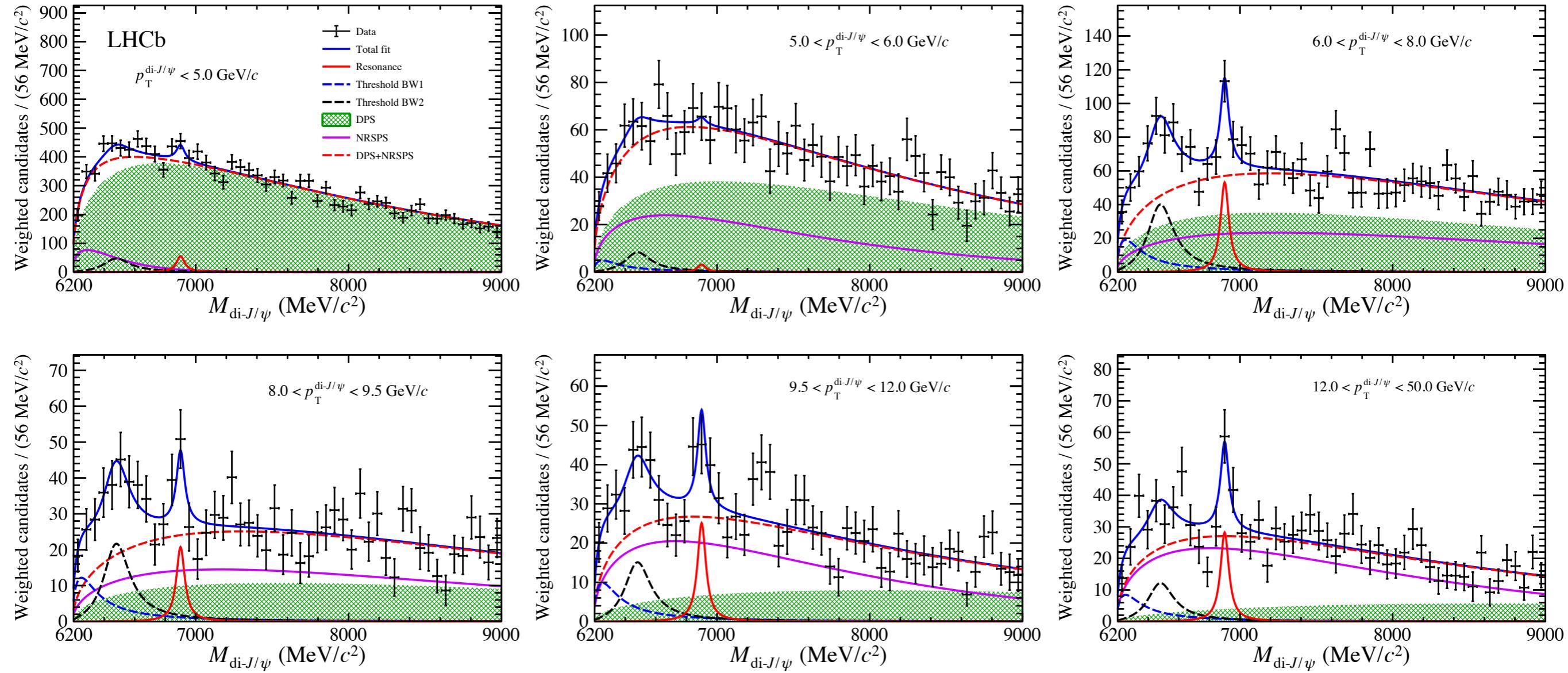
$T_{cc\bar{c}\bar{c}}$  ?

significance from a  $\chi^2$  test statistic  
using pseudoexperiments:

$6.9\sigma$

# Second approach: $M_{\text{di}-J/\psi}$ as a function of $p_T^{\text{di}-J/\psi}$

Same structures found in the same places in different  $p_T$  bins



The nature of the observed structures is uncertain.  $X(6900)$  could be one or more  $T_{cc\bar{c}\bar{c}}$  states

The enhancement near threshold may be due to a mixture of four charm quark states, or due to rescattering.

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

doubly charmed tetraquark

[LHCb-PAPER-2021-031](#)

[LHCb-PAPER-2021-032](#)

The existence of  $Q_1 Q_2 \bar{q}_1 \bar{q}_2$  is predicted since 1980's

In the limit  $M_{Q_i} \rightarrow \infty$ , the  $Q_1 Q_2 \bar{q}_1 \bar{q}_2$  system is deeply bound, as the  $\bar{\Lambda}_b^0$  or  $\Lambda_c^-$

Is the charm quark heavy enough to sustain a stable system with respect to the strong and EM interactions? If yes, the  $Q_1 Q_2 \bar{q}_1 \bar{q}_2$  state would be narrow.

Vast literature with theoretical predictions for the  $T_{cc}^+$  ( $cc\bar{u}\bar{d}$ ) ground state:

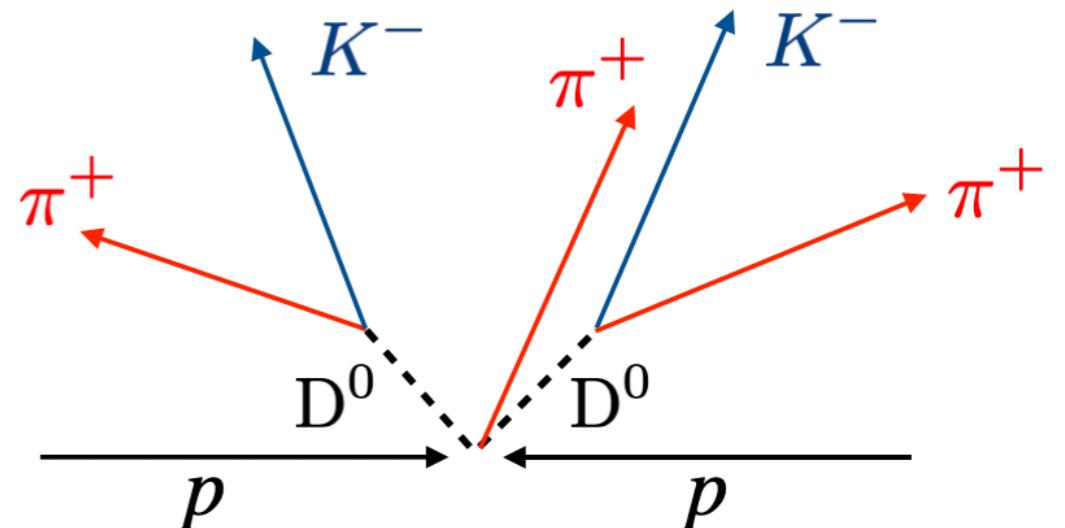
$J^P = 1^+$ ,  $I = 0$ , decaying to  $\underbrace{D^{*+} D^0}_{[c\bar{d}][c\bar{u}]}$ , yielding the final state  $D^0 D^0 \pi^+$

event topology

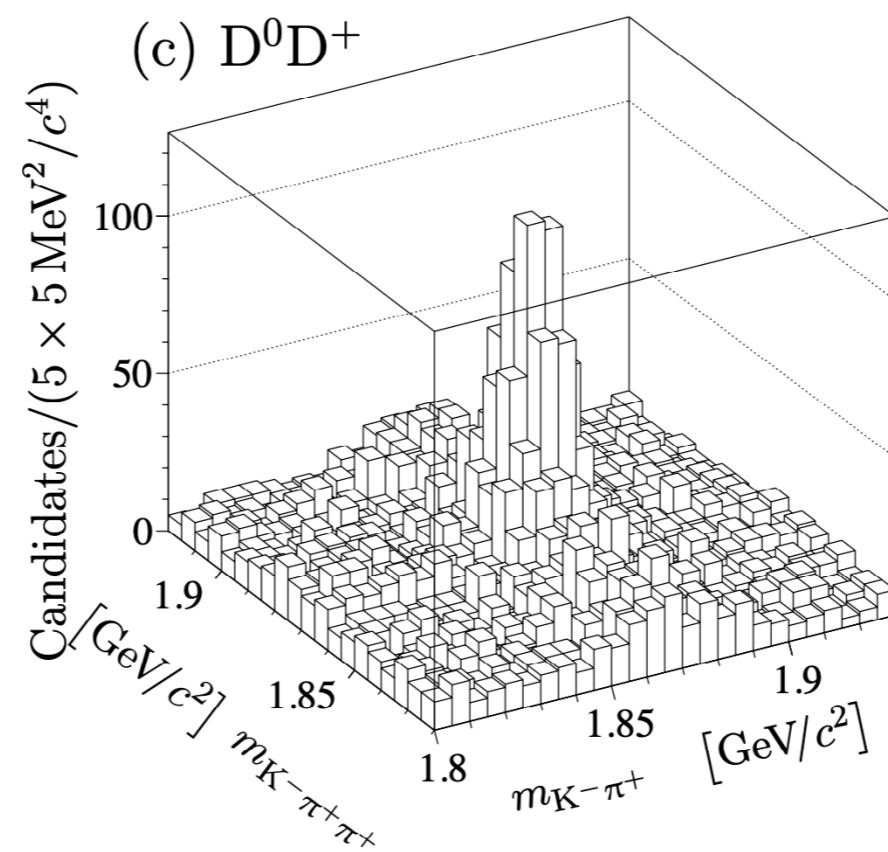
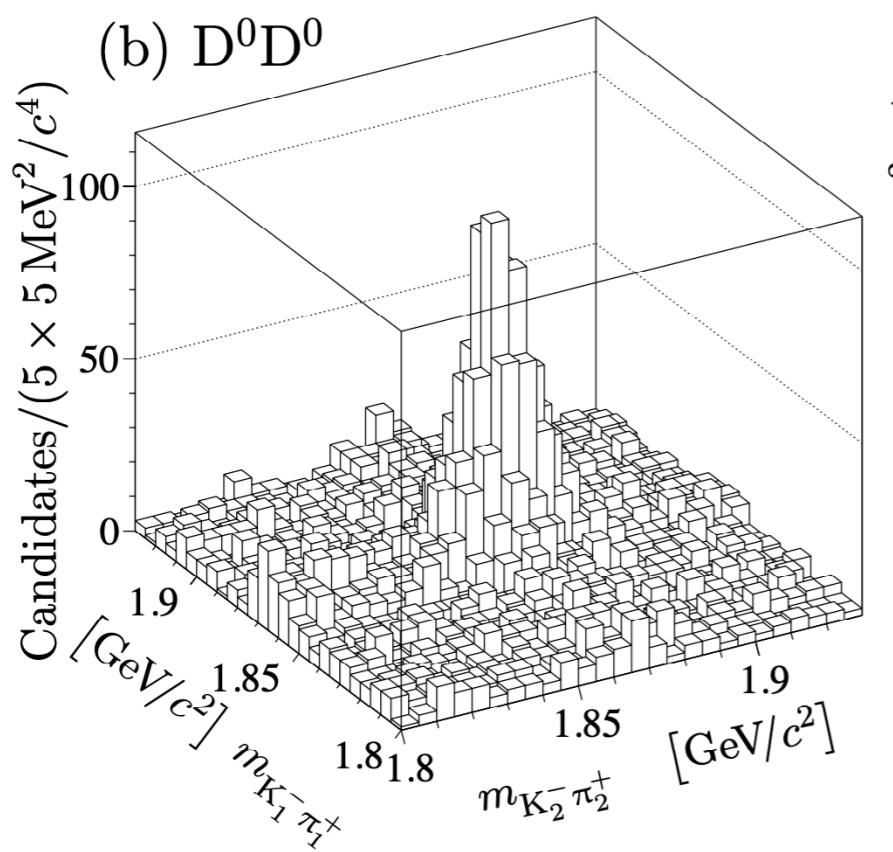
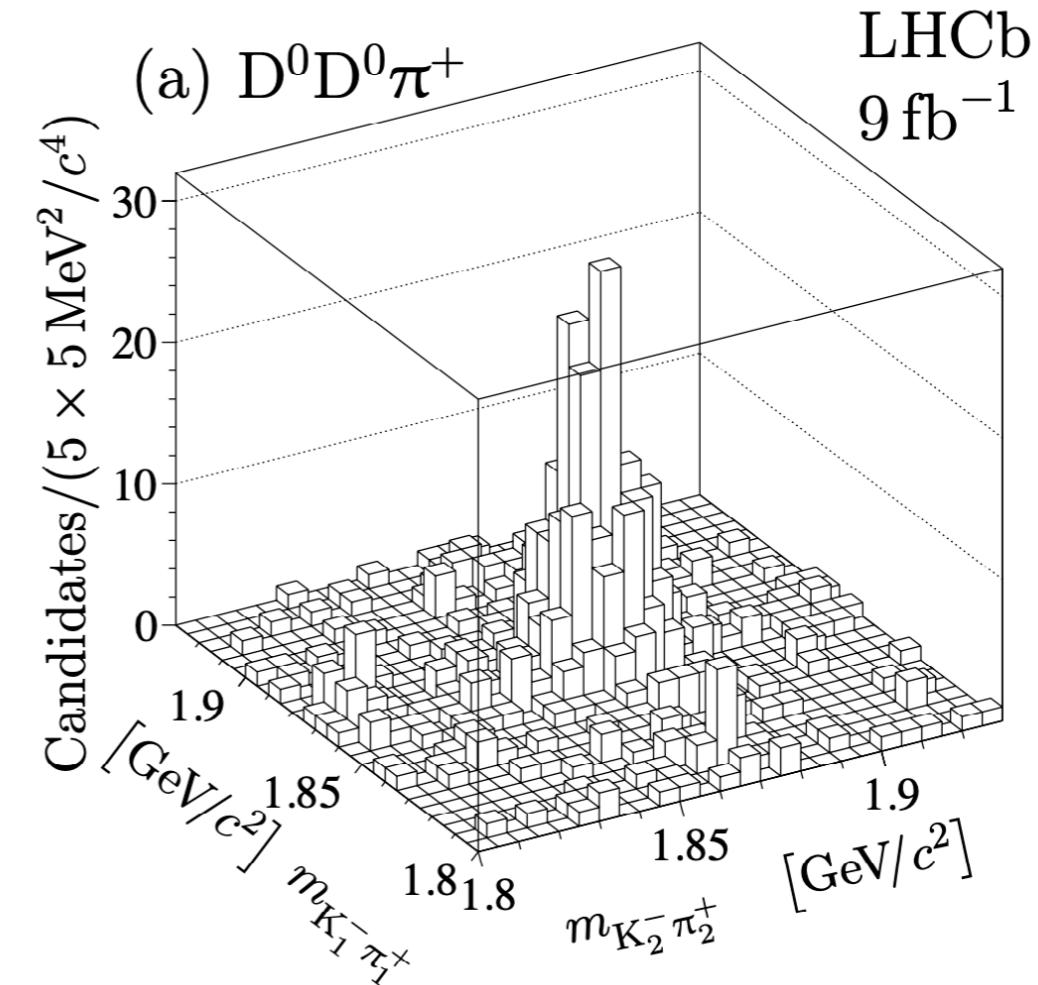
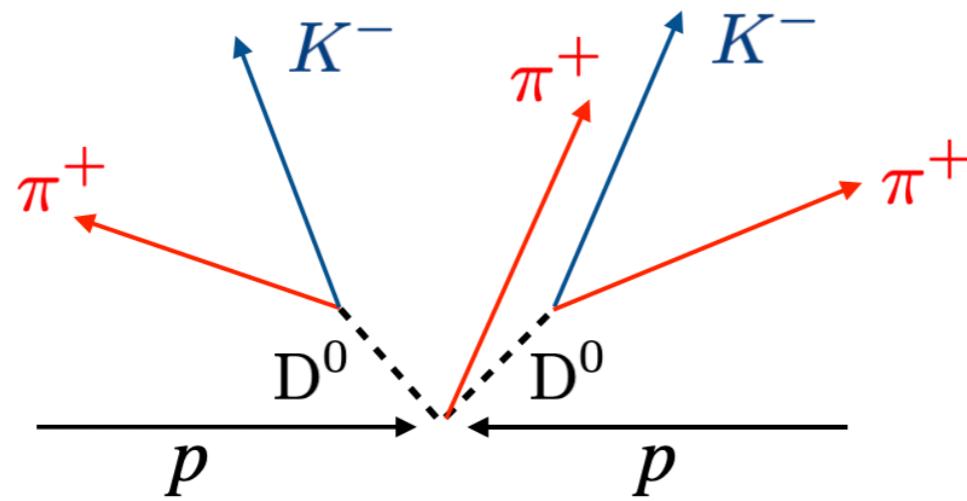
$T_{cc}^+$  should be a narrow state:

$$\delta m \equiv M_{T_{cc}^+} - (M_{D^{*+}} + M_{D^0})$$

$$-300 < \delta m < 300 \text{ MeV}$$



run 1+2 data



$D^0 D^+$  sample  
also selected

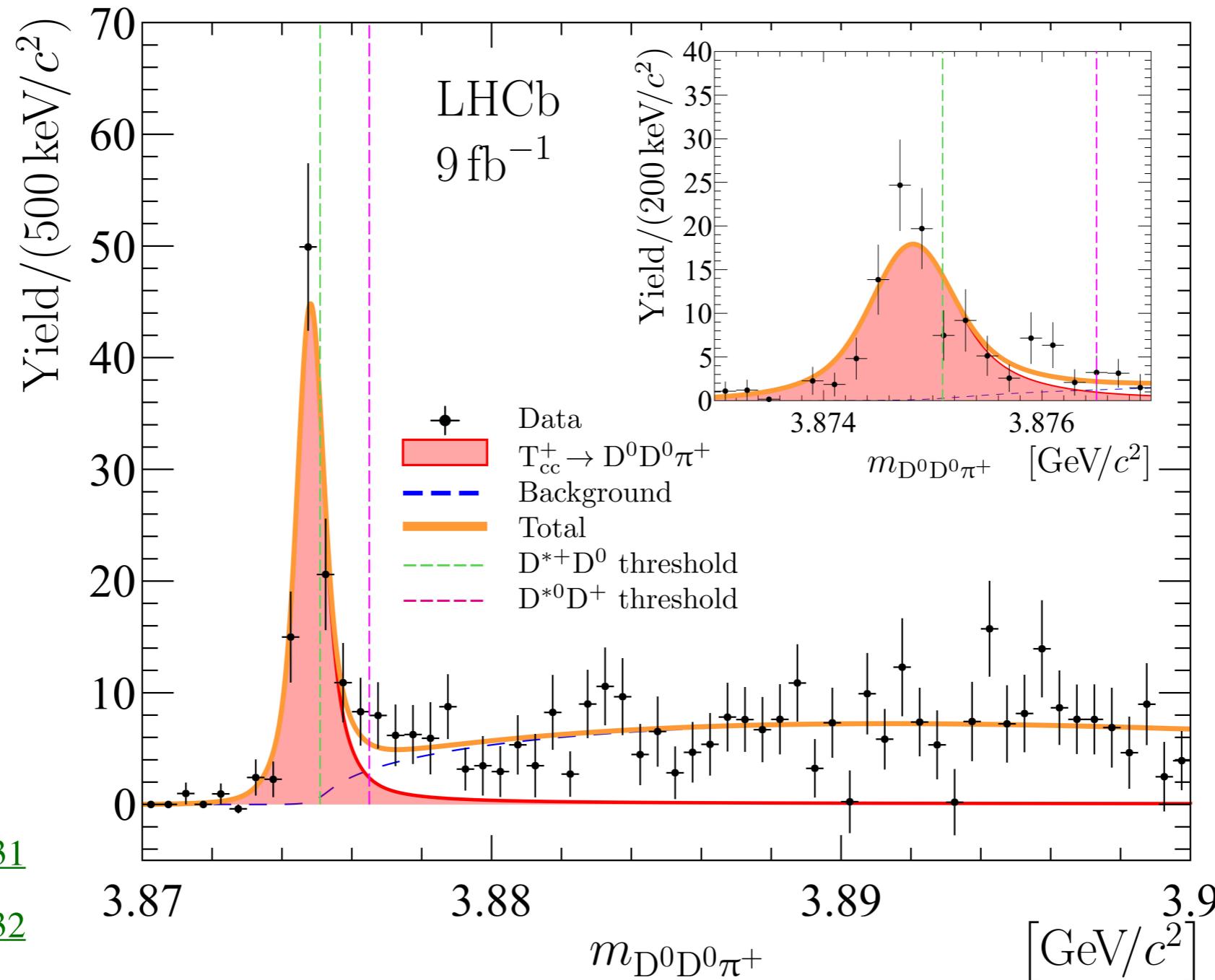
[LHCb-PAPER-2021-031](#)

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# Fit using unitarised Breit-Wigner to describe near-threshold resonances, convoluted with detector mass resolution

$T_{cc}^+ \rightarrow D^* D$ : natural width includes  $T_{cc}^+ \rightarrow D^0 D^+ \pi^0$ ,  $T_{cc}^+ \rightarrow D^0 D^+ \gamma$  and  $T_{cc}^+ \rightarrow D^0 D^0 \pi^+$

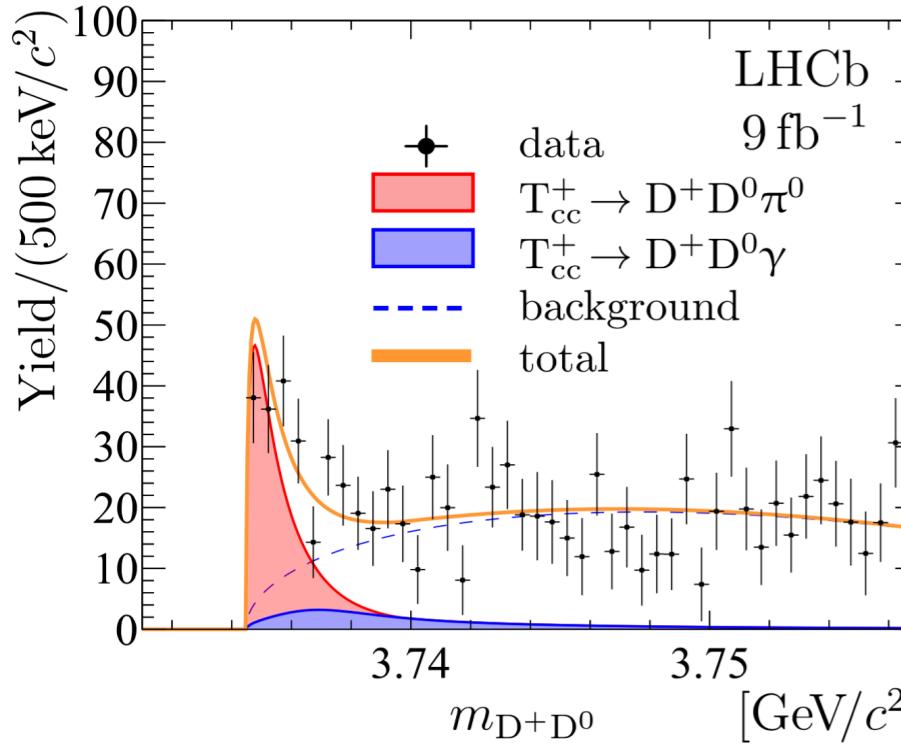
assuming  $L = 0$  for  $DD^*$ :  $T_{cc}^+ \rightarrow$  spin-1  $\rightarrow 186 \pm 24$  candidates ( $22\sigma$ )



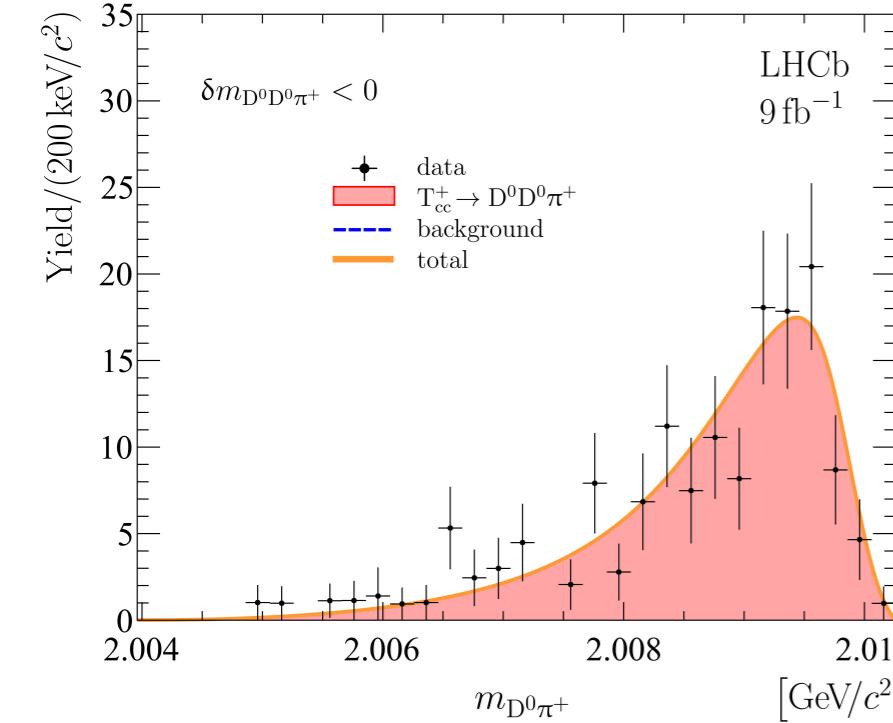
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$T_{cc}^+ \rightarrow D^{*0} D^+$   
 $171 \pm 26$  candidates



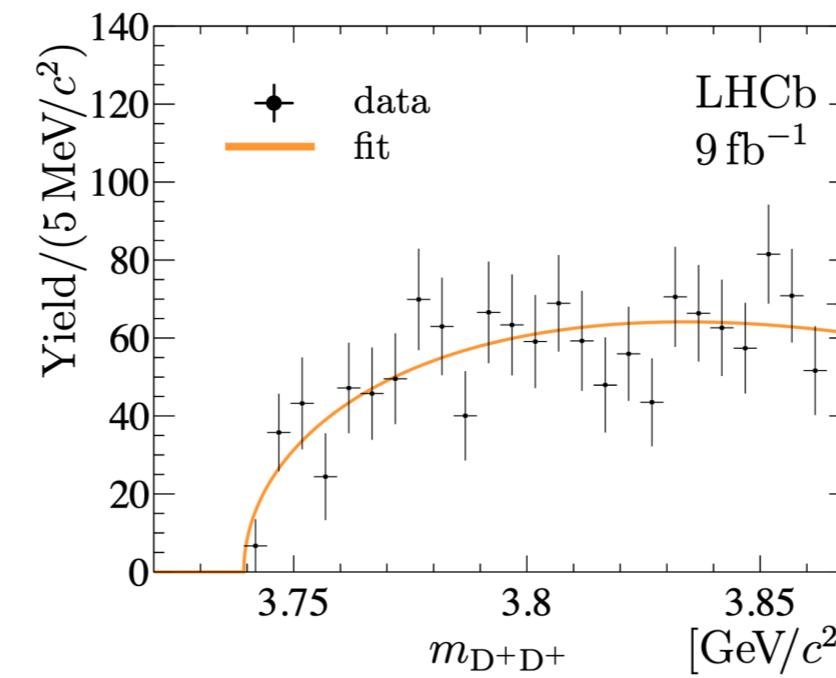
~90% of the  $T_{cc}^+$  signal  
from a true (off-shell)  $D^{*+}$



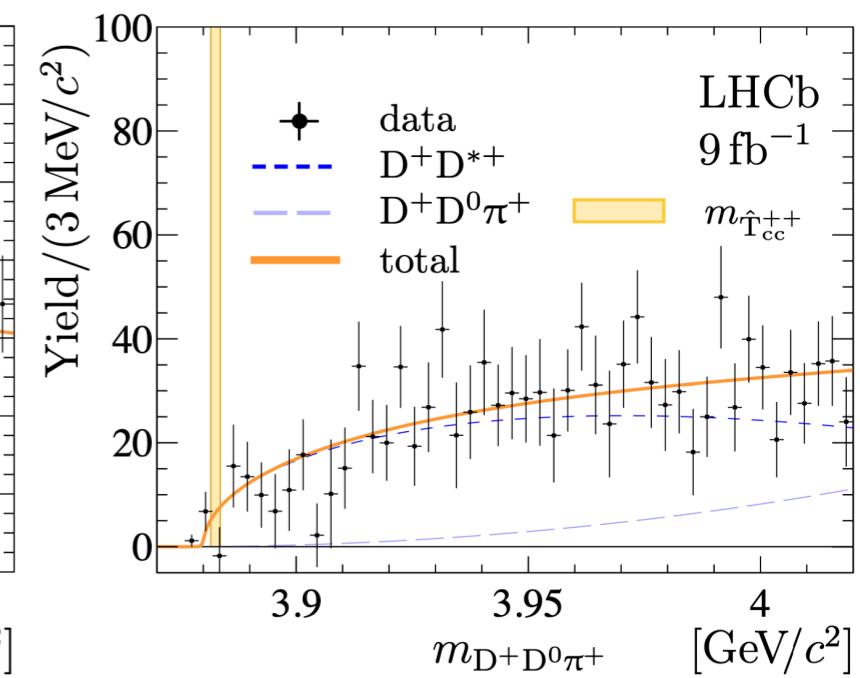
no  $T_{cc}^{++}$  signal found

Strong argument in favour of  $I = 0$

$D^+ D^+$



$D^+ D^{*+}$



$\delta m_U < 0 \rightarrow 9\sigma$

$$\delta m_U = -359 \pm 40^{+9}_{-6} \text{ keV}/c^2$$

$$\begin{aligned} \delta m_{\text{pole}} &= -360 \pm 40^{+4}_{-0} \text{ keV}/c^2 \\ \Gamma_{\text{pole}} &= 48 \pm 2^{+0}_{-14} \text{ keV}, \end{aligned}$$

[LHCb-PAPER-2021-031](#)

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# Summary

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VOLUME 32, NUMBER 1

1 JULY 1985

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Stephen Godfrey and Nathan Isgur

*Department of Physics, University of Toronto, Toronto, M5S 1A7 Canada*

(Received 12 December 1983; revised manuscript received 10 May 1985)

We show that mesons—from the  $\pi$  to the  $\Upsilon$ —can be described in a unified quark model with chromodynamics. The key ingredient of the model is a universal one-gluon-exchange-plus-linear-confinement potential motivated by QCD, but it is crucial to the success of the description to take into account relativistic effects. The spectroscopic results of the model are supported by an extensive analysis of strong, electromagnetic, and weak meson couplings.

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	2001	2021	2031
$D_{(s)J}$	10	27	?
$B_{(s)J}$	4	12	?
$c\bar{c}$ – like	13	40	?
$b\bar{b}$ – like	12	16	?
$c$ – baryons	8	27	?
$b$ – baryons	0	23	?

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**Hadron spectroscopy:  
a field with many opportunities for young talents**

- ❖ conventional and new states yet to be found;
- ❖ many unorthodox states are expected;
- ❖ what is the nature of the new states?
- ❖ LHCb, Belle II, BESIII: plenty of data, need new tools for analysis;