Observation of a doubly charged tetraquark state and its neutral partner at LHCb

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On behalf of the LHCb Collaboration

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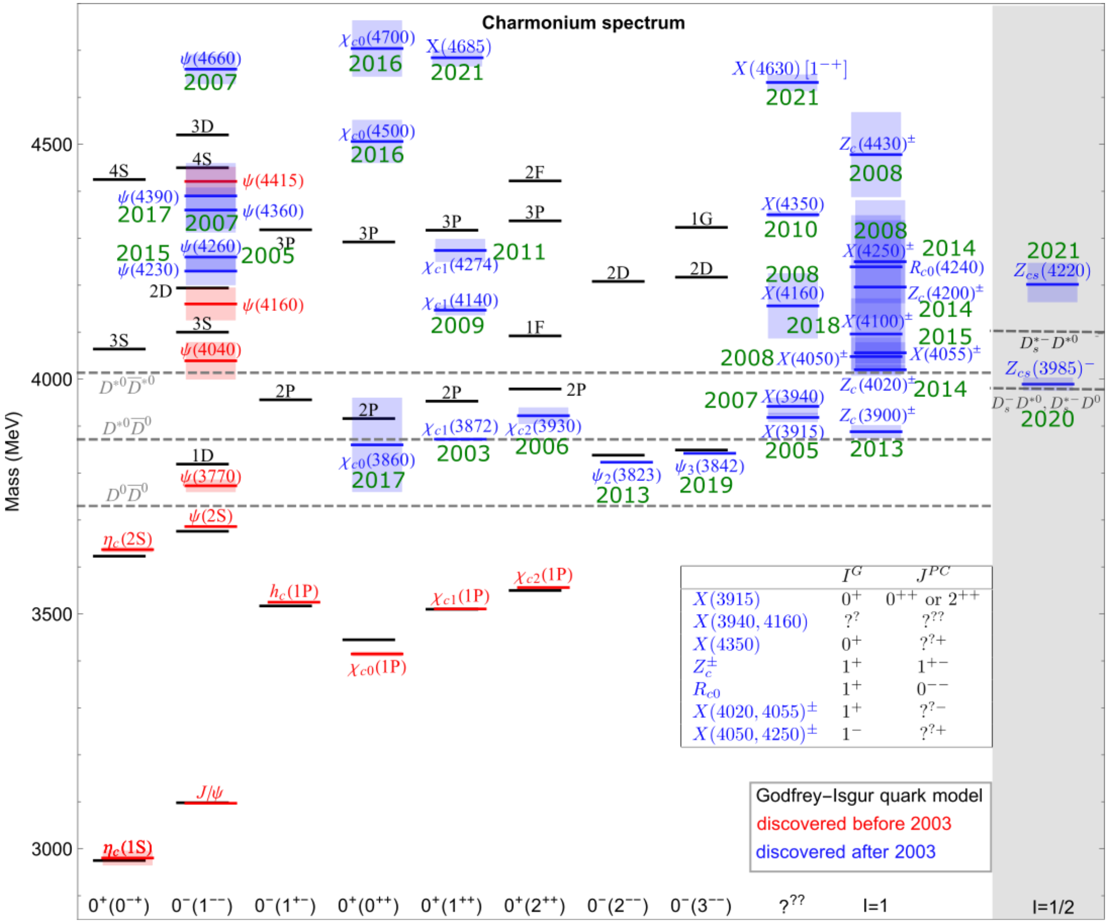
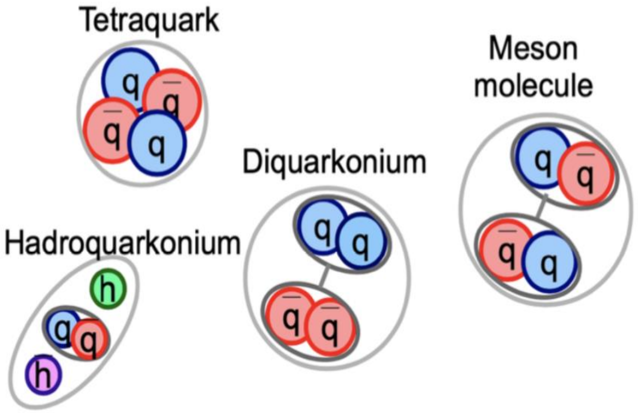


	I^G	J^{PC}
X(3915)	0+	0++ or 2++
X(3940, 4160)	??	???
X(4350)	0+	??+
$Z_c^{\pm}$	1+	1+-
R_{c0}	1+	0--
X(4020, 4055)±	1+	??-
X(4050, 4250)±	1-	??+

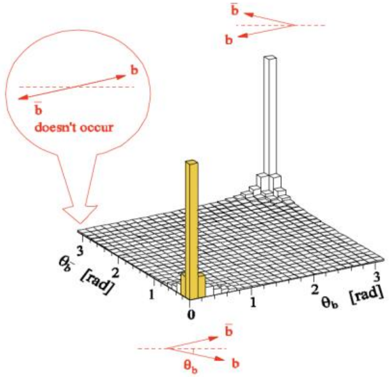
Charmonium(-like) structures[1]

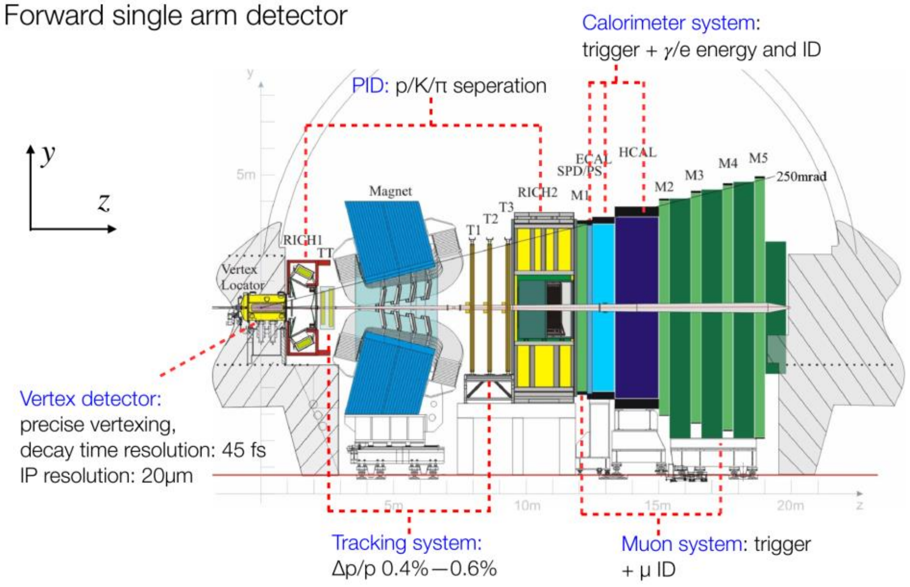


- **The existence of mesonic exotic state** has been discussed since **1964[2]**.
- In 2003, Belle Collaboration reported the first observation of $\chi_{c1}(3872)$.
- Many exotic states are observed in the past two decades.
- A series of **theoretical models** are established to describe these states.

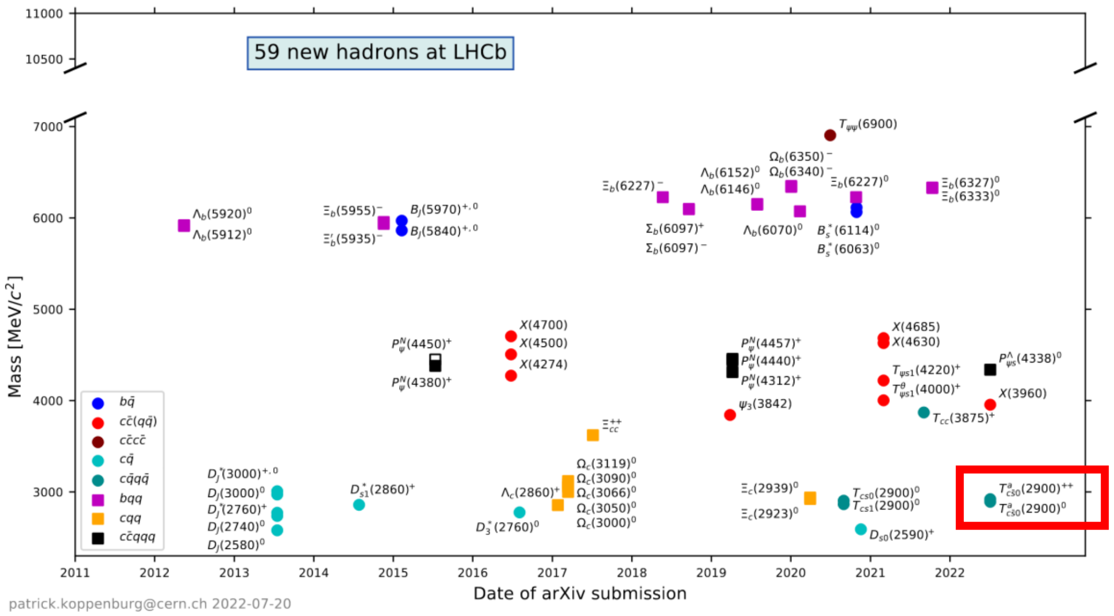
[1] From Fengkun's talk on the *XYZ* Workshop in China
[2] M. Gell-Mann, A schematic model of baryons and mesons, Phys. Lett. 8 (1964) 214.

Introduction





The LHCb detector



Masses and discovery date for states observed at LHCb. Hollow markers indicate superseded states.[1], [2]

- **59 new hadrons observed at LHCb!**
  - 15 tetraquark candidates.
  - 5 pentaquark candidates.[3]

[1] https://www.nikhef.nl/~pkoppenb/particles.html
[2] Exotic hadron naming convention: https://arxiv.org/abs/2206.15233
[3] $P_c(4450)^+$ resolved into $P_c(4440)^+$ and $P_c(4457)^+$.

- **Why $D_s^+\pi^\pm$ states?**
  - **The $D_{s0}^*(2317)^+$ ($D_s^+\pi^0$) state was observed in 2003.**
  - It is thought to have some **tetraquark component** in several theoretical descriptions, whose $I=1$ partners can exist in the **$D_s^+\pi^\pm$ final states.**
  - **Prof. Hai-Yang:** It would be astonishing if a doubly charged resonance is found.

PLB 566 (2003) 193–200

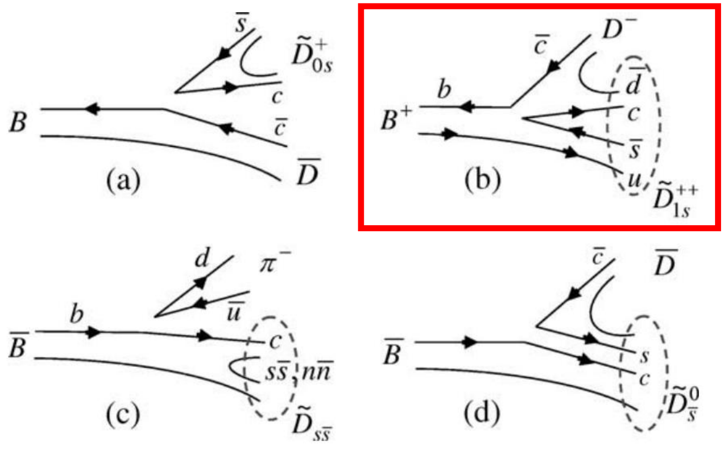
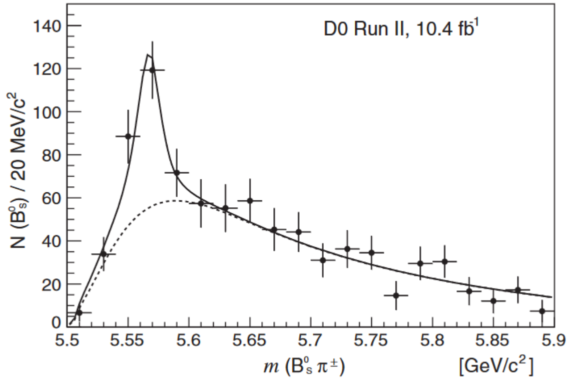


Fig. 2. Diagrams for (a) $B \to \bar{D}\tilde{D}_{0s}^+$, (b) $B^+ \to D^-\tilde{D}_{1s}^{++}$ ($B \to \bar{D}\tilde{D}_{Is}$), (c) $\bar{B} \to \pi^-\tilde{D}_{s\bar{s}}, \pi^-\tilde{D}$, (d) $B \to D\tilde{D}_{\bar{s}}^0$.

  - **Evidence of $X(5568)^+$ ($B_s^0\pi^\pm$) claimed by D0 Collaboration in 2016.**
  - **Not been confirmed by the other experiments.**
  - Natural to search for $D_s^+\pi^\pm$ resonances as predicted in the diquark-antidiquark model.

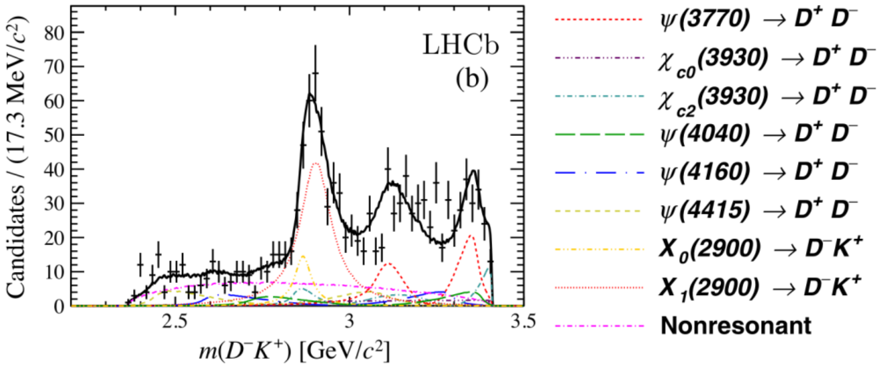
PRL 117, 022003 (2016)



$X(5568)^+$

● Why $D_s^{+}\pi^{\pm}$ states?

- In 2020, the $X_0(2900)^0$ and $X_1(2900)^0$ $(cs\bar{u}\bar{d})$, have been observed at LHCb in D^+K^- final states.
- They are candidates to be the first observed tetraquarks consisting of four different flavors.



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

➢ Would there be exotic states decaying into $D_s^{+}\pi^{-}$ $(c\bar{s}\bar{u}d)$ or $D_s^{+}\pi^{+}$ $(c\bar{s}u\bar{d})$ final states?

● Amplitude analyses of $B^0 \to \bar{D}^0 D_s^{+}\pi^{-}$ and $B^+ \to D^- D_s^{+}\pi^{+}$ decays.

➢ Only **excited** $\bar{D}^*$ states with natural spin-parity expected to contribute.

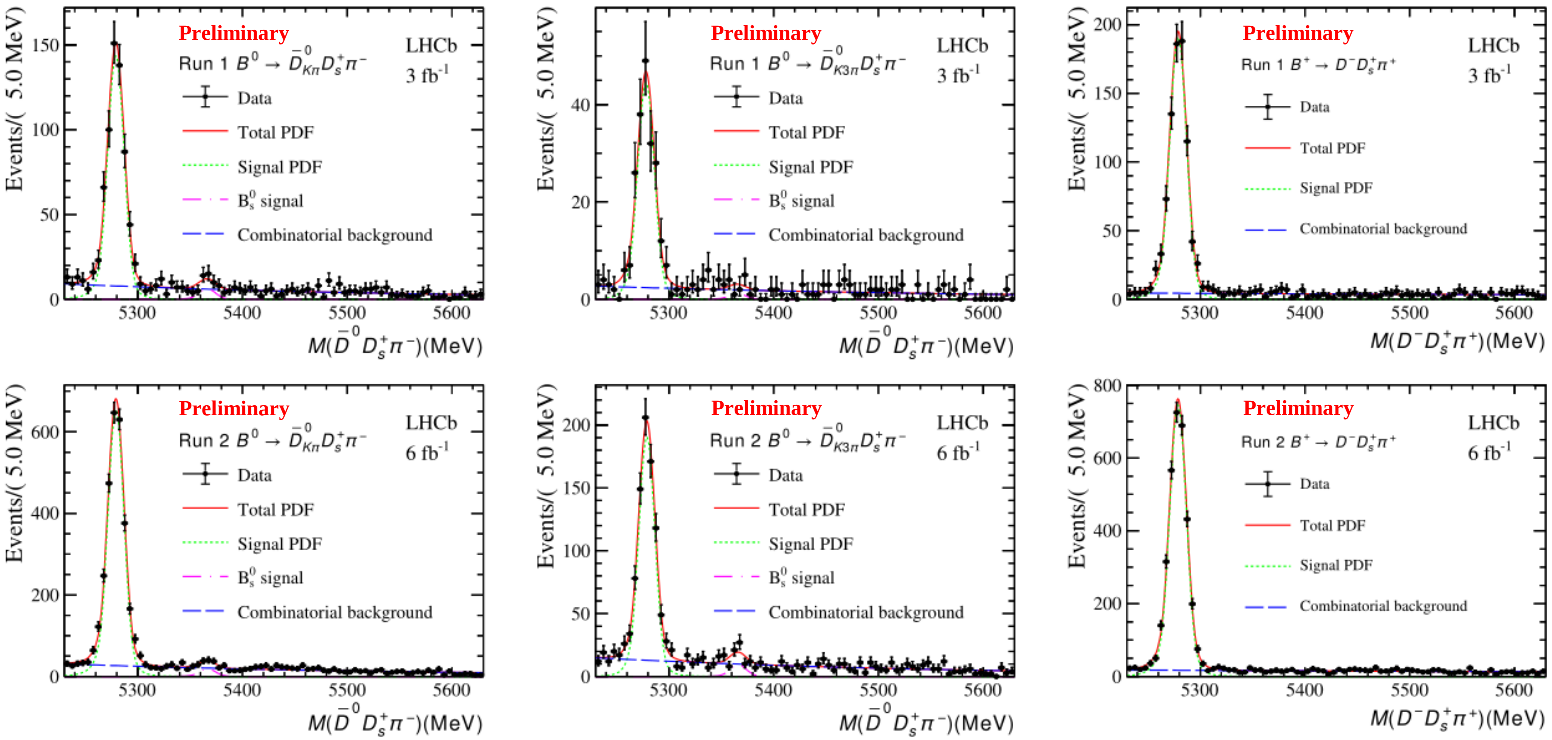
➢ Ideal channels to search for **possible exotic states** decaying to $D_s^{+}\pi^{\pm}$ final states.

- **Can be explored by LHCb datasets with large statistic!**

Datasets

LHCb Preliminary

- $B^0 \to \bar{D}^0 D_s^+ \pi^-$ & $B^+ \to D^- D_s^+ \pi^+$
  - Using all the Run 1 and Run 2 datasets.



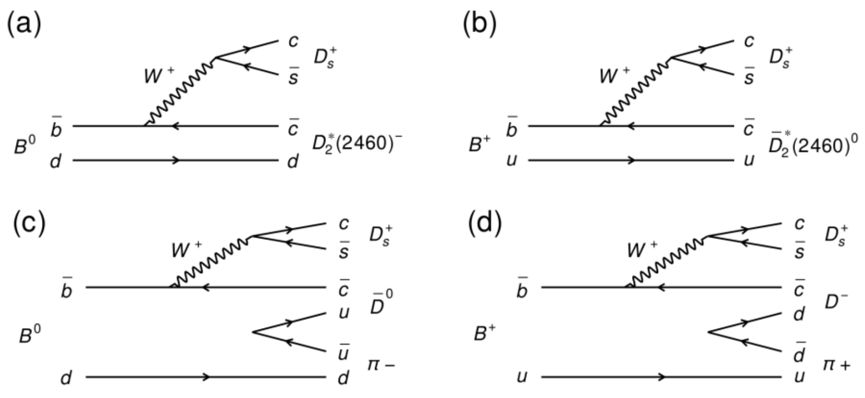
- $\bar{D}^0 \to K^+\pi^-, K^+\pi^-\pi^-\pi^+$
- $D^- \to K^+\pi^-\pi^-$
- $D_s^+ \to K^+K^-\pi^+$

✓ **In B signal region:**

- ✓ **4009 $B^0 \to \bar{D}^0 D_s^+ \pi^-$ signals, purity 90.7%.**
- ✓ **3750 $B^+ \to D^- D_s^+ \pi^+$ signals, purity 95.2%.**

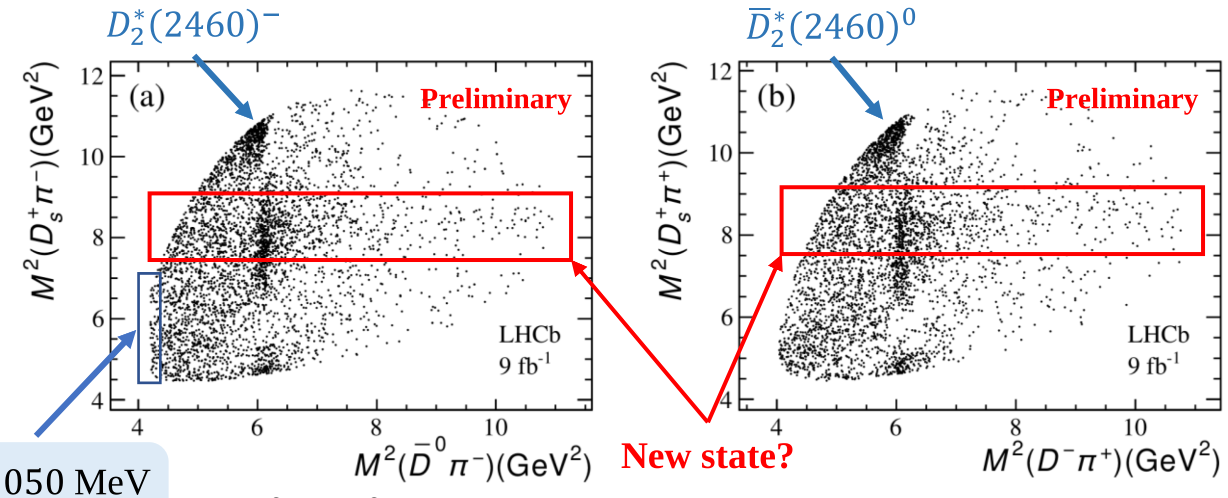
Dalitz plots

LHCb Preliminary



Feynman diagrams

$m(\bar{D}^0\pi^-) > 2050$ MeV
Veto $B^0 \to D^{*-}D_s^+$



$B^0 \to \bar{D}^0 D_s^+ \pi^-$ $B^+ \to D^- D_s^+ \pi^+$

- ✓ Clear spin-2 vertical band at the $\bar{D}\pi$ **mass squared** around $\mathbf{6\ GeV^2}$.
- ✓ **A faint horizontal band** at the $D_s\pi$ **mass squared** around $\mathbf{8.5\ GeV^2}$.

- **Very similar features** in the Dalitz plots of two channels, which are **isospin-related**.
- It suggests the feasibility to perform **simultaneous fit** of the two channels.
  - The amplitude parameters of all components are set to be the same of the two channels.

Amplitude formalism

- **Unbinned maximum likelihood fits performed with TF-PWA**

$$P(x;\Theta) = f_{\rm sig} \cdot P_{\rm sig}^{\rm norm}(x;\Theta) + f_{\rm bkg} \cdot P_{\rm bkg}^{\rm norm}(x),$$

Fractions determined from mass fits

- **Background modelled from upper sideband with extrapolating into signal regions**

- **Signal PDF:** $$P_{\rm sig}^{\rm norm}(x;\Theta) = \frac{\epsilon(x)|\mathcal{A}(x;\Theta)|^2}{I_{\rm sig}(\Theta)}.$$

Normalization factor

- **Efficiencies obtained from full simulation with corrections for data-simulation difference**

- **Amplitude model:** $\mathcal{A}(x;\Theta) = \sum c_i \cdot \mathcal{A}_i(x;\Theta_i),$

Angular distribution + line shape (RBW etc.)

● **The $\bar{D}\pi$ candidates with natural spin-parity on PDG:**

Resonance	J^P	Mass (GeV)	Width (GeV)	Comments
$\bar{D}^*(2007)^0$	1^-	2.00685 ± 0.00005	$< 2.1 \times 10^{-3}$	Width set to be 0.1 MeV
$D^*(2010)^-$	1^-	2.01026 ± 0.00005	$(8.34 \pm 0.18) \times 10^{-5}$	
$\bar{D}_0^*(2300)$	0^+	2.343 ± 0.010	0.229 ± 0.016	#
$\bar{D}_2^*(2460)$	2^+	2.4611 ± 0.0007	0.0473 ± 0.0008	#
$\bar{D}_1^*(2600)^0$	1^-	2.627 ± 0.010	0.141 ± 0.023	#
$\bar{D}_3^*(2750)$	3^-	2.7631 ± 0.0032	0.066 ± 0.005	#
$\bar{D}_1^*(2760)^0$	1^-	2.781 ± 0.022	0.177 ± 0.040	#
$\bar{D}_J^*(3000)^0$	??	3.214 ± 0.060	0.186 ± 0.080	# $J^P = 4^+$ is assumed

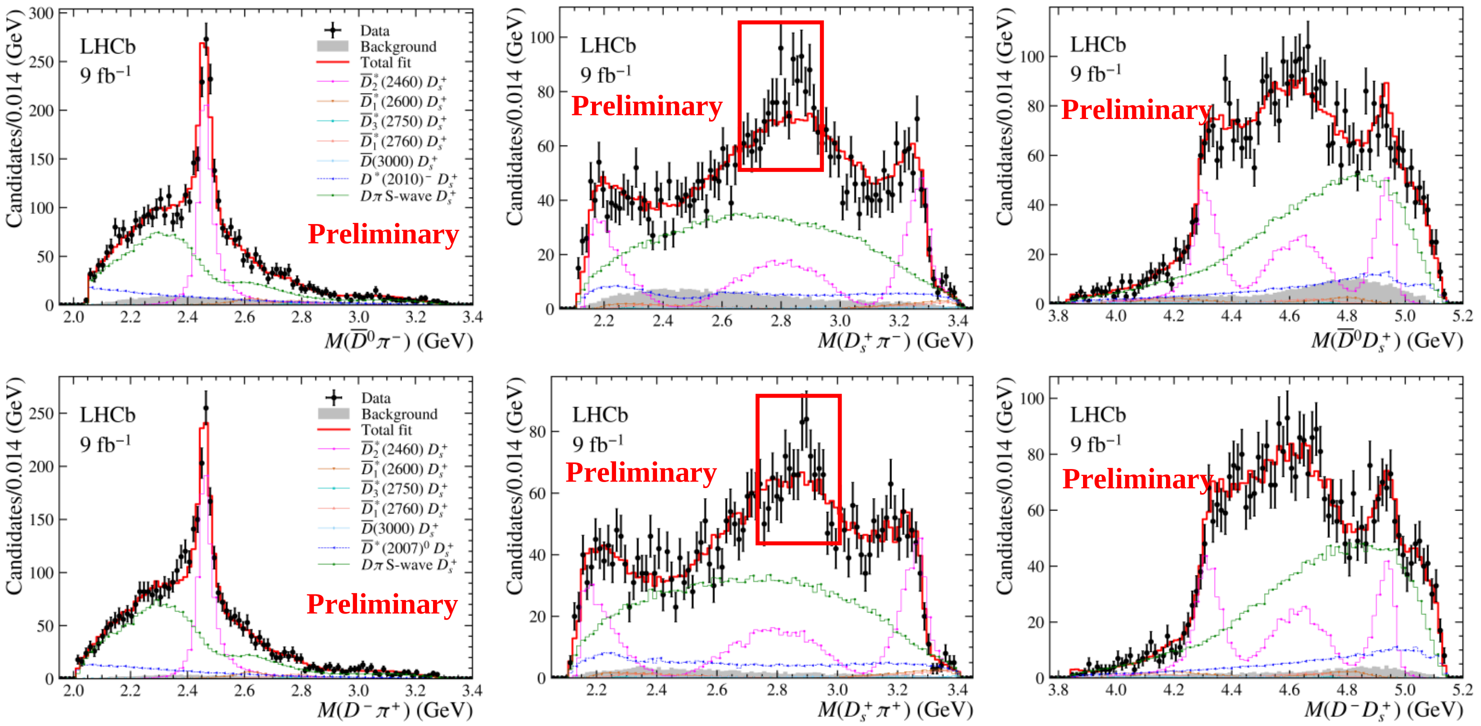
◆ **Fit strategy – simultaneous fit**

- Include all the D^* and D^{**} states with natural spin-parity.
- $\bar{D}\pi$ S-wave component: quasi-model-independent description (QMI) spline points.*
- All parameters, except $\bar{D}^*(2007)^0$ and $D^*(2010)^-$ are shared.
- Spin-parity of $D(3000)$ not established yet.

*11 spline points at [1.9, 2.0, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, 2.9, 3.4] GeV

Amplitude analysis

LHCb Preliminary

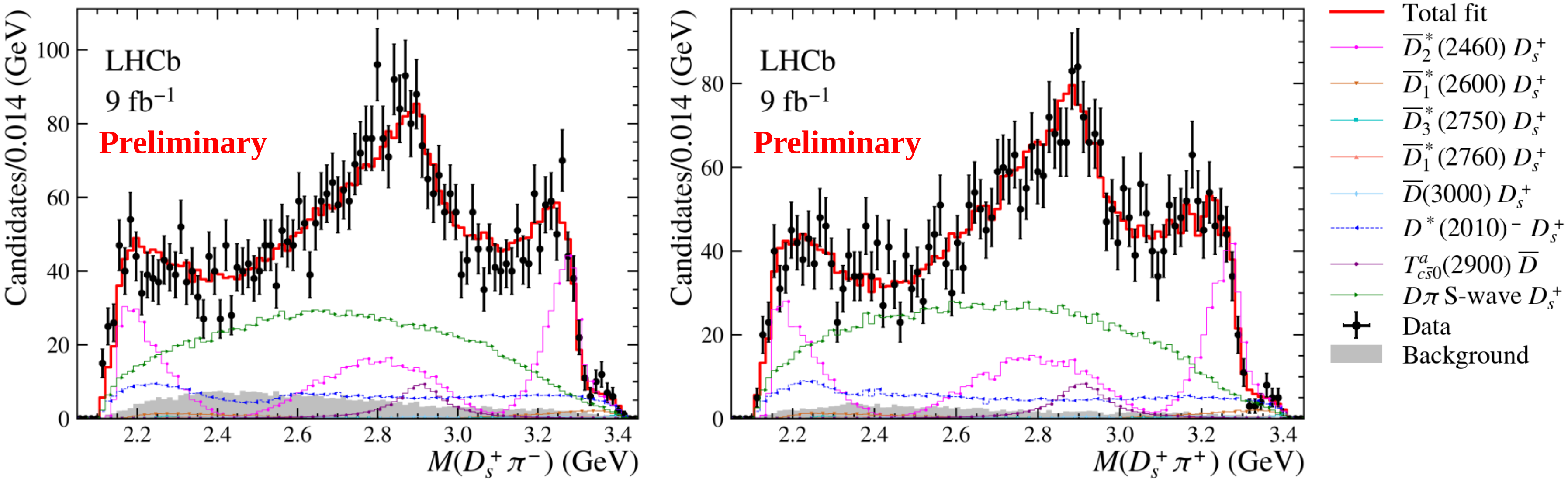


- ✓ **Fit result**
  - ✓ $M(\bar{D}\pi)$ and $M(\bar{D}D_s^+)$ **well described.**
  - ✓ $D_1^*(2600), D_1^*(2760), D(3000)$ **not significant**, however, **still included** conservatively.
  - ✓ Spin-parity of $\boldsymbol{D(3000)}$ favors $\mathbf{4^+}$.
  - ✓ **Further new $\bar{D}^{**}$ state** with spin-parity up to 4^+ tested to be **disfavored**.

Peaking structures not well desceibed near $M(D_s^+\pi) = 2.9$ GeV !

Amplitude analysis

LHCb Preliminary



◆ **Two $D_s^+\pi$ exotic states with shared parameters are added.**

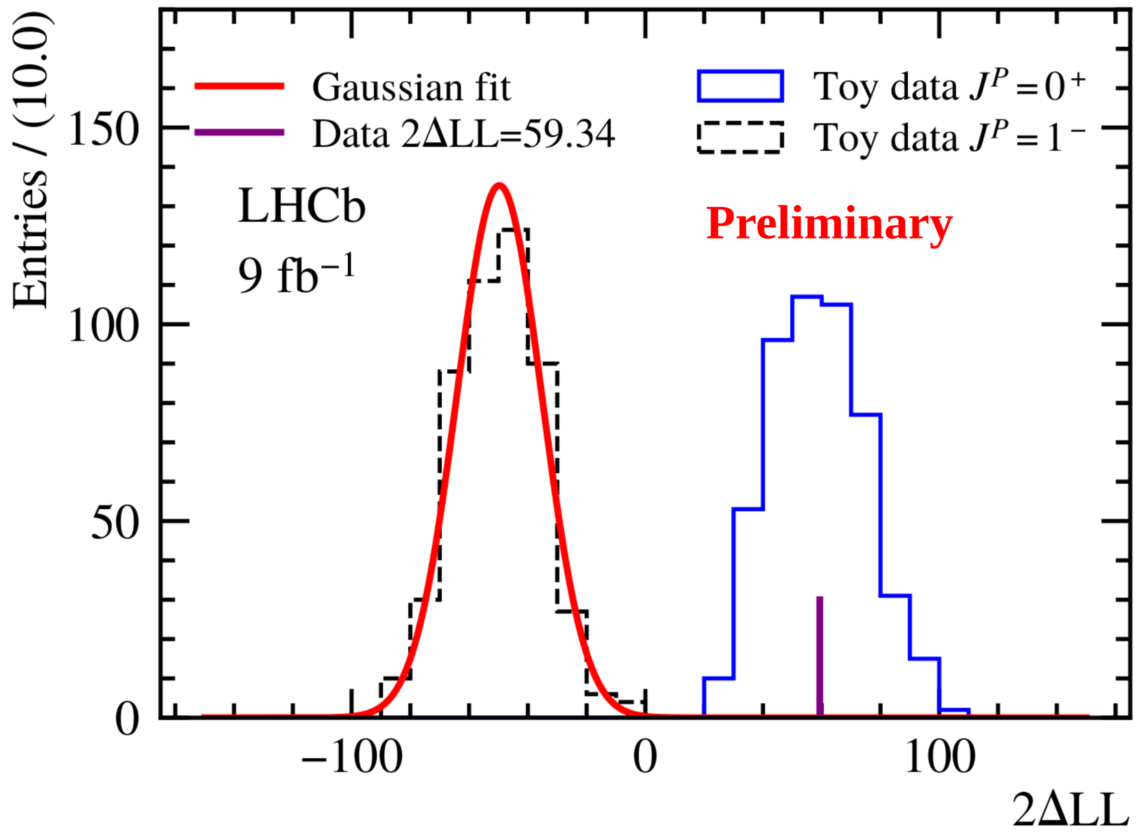
- ✓ J^P up to 3^+ are tested, **0^+** produces the best likelihood.
- ✓ Significance greater that **9σ**.
- ✓ Mass and width are measured:

$$M = 2.908 \pm 0.011 \pm 0.020\,\mathrm{GeV}$$
$$\Gamma = 0.136 \pm 0.023 \pm 0.013\,\mathrm{GeV}$$

✓ **Named* as $T^{a}_{c\bar{s}0}(2900)^0$ ($D_s^+\pi^-$) and $T^{a}_{c\bar{s}0}(2900)^{++}$ ($D_s^+\pi^+$)**

* Exotic hadron naming convention: https://arxiv.org/abs/2206.15233

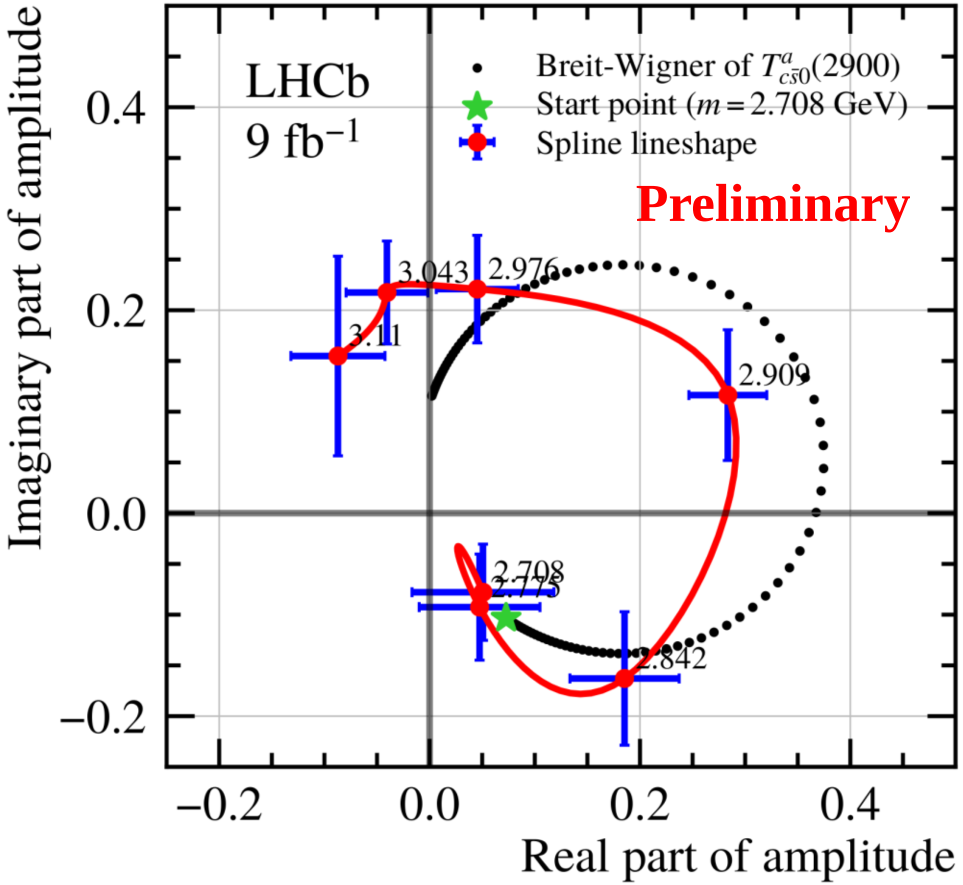
LHCb Preliminary



◆Spin test

- ✓ Generate pseudoexperiments.
- ✓ Spin-parity favored $\mathbf{0^+}$ **over** $\mathbf{1^-}$ with a significance about $\mathbf{7.6\sigma}$**.**
- ✓ 0^+ is also significantly preferred when exotics not constrained by isospin.

LHCb Preliminary



◆Argand diagram

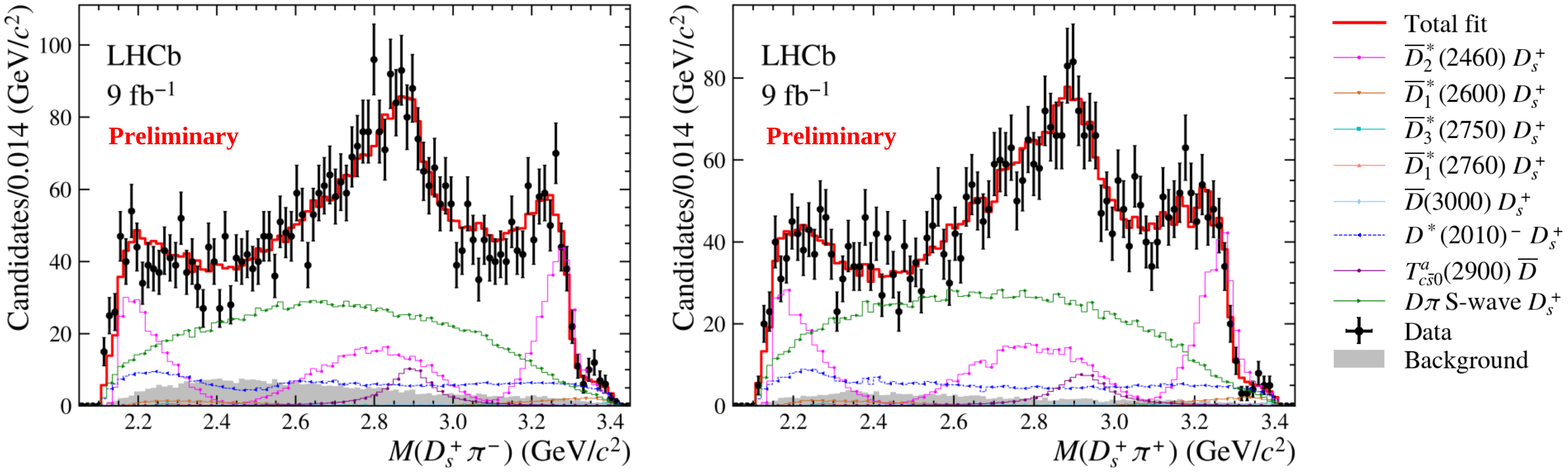
- ✓ Replace the BW of $T^{a}_{c\bar{s}0}$ with spline points.
- ✓ The 7 points from $m - \frac{3}{2}\Gamma$ to $m + \frac{3}{2}\Gamma$, where m and Γ is the fitted values of $T^{a}_{c\bar{s}0}$ mass and width.
- ✓ **Lineshape consistent with RBW.**

Separate $T^{a}_{c\bar{s}0}(2900)^{0}$ and $T^{a}_{c\bar{s}0}(2900)^{++}$

LHCb Preliminary

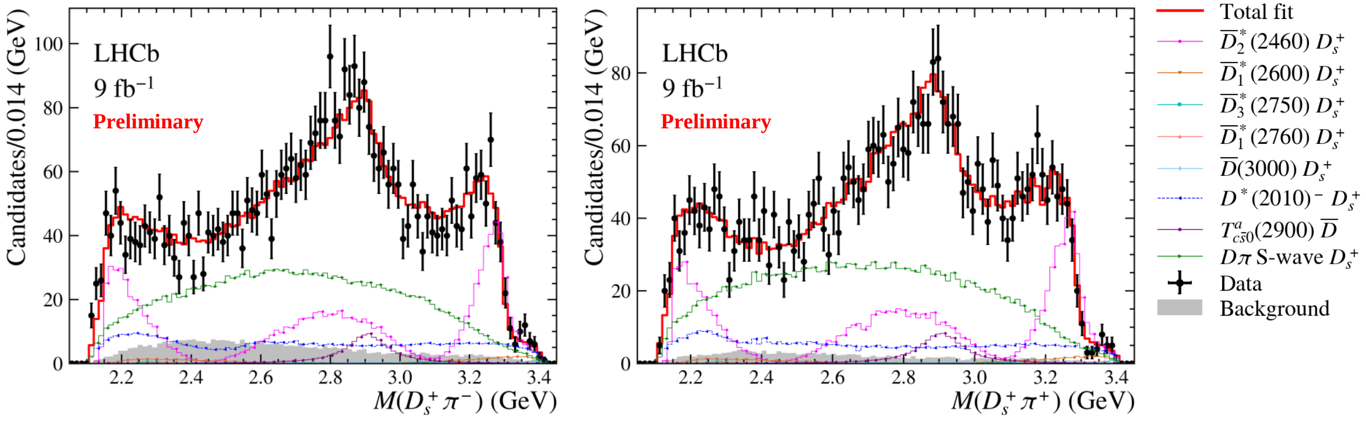
◆ Separate $T^{a}_{c\bar{s}0}$ parameters

- ✓ $-\ln\mathcal{L}$ improved by **2.8**, with **4** free parameters added.
- ✓ Masses and widths are **consistent** with each other.
- ✓ **Isospin triplet!**



	Mass (GeV)	Width (GeV)	Significance
$T^{a}_{c\bar{s}0}(2900)^{0}$	$2.892 \pm 0.014 \pm 0.015$	$0.119 \pm 0.026 \pm 0.013$	8.0σ
$T^{a}_{c\bar{s}0}(2900)^{++}$	$2.921 \pm 0.017 \pm 0.020$	$0.137 \pm 0.032 \pm 0.017$	6.5σ

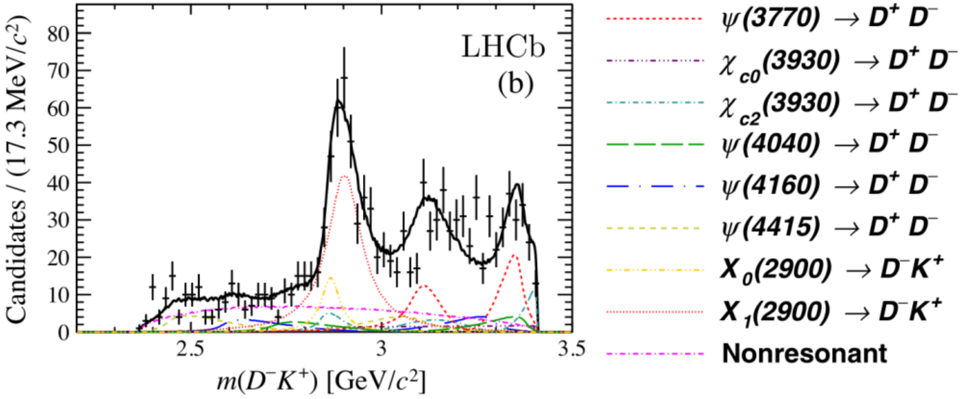
LHCb Preliminary



$T^a_{c\bar{s}0}(2900)^0[c\bar{s}\bar{u}d]$ $\quad$ $T^a_{c\bar{s}0}(2900)^{++}[c\bar{s}u\bar{d}]$

- **$T^a_{c\bar{s}0}(2900)$ & $X_0(2900)$**
  - ✓ Similar mass, but width and flavor contents are different.
  - ✓ $T^a_{c\bar{s}1}(2900)$?
  - ✓ $T^a_{c\bar{s}0}(2900)^{++} \to D^+K^+$?
  - ✓ $T^a_{c\bar{s}0}(2900)^+ \to D_s^+\pi^0,\ D_s^+\pi^+\pi^-$?

More statistic needed!



$X_0(2900), X_1(2900)[cs\bar{u}\bar{d}]$ PRD 102, 112003 (2020)

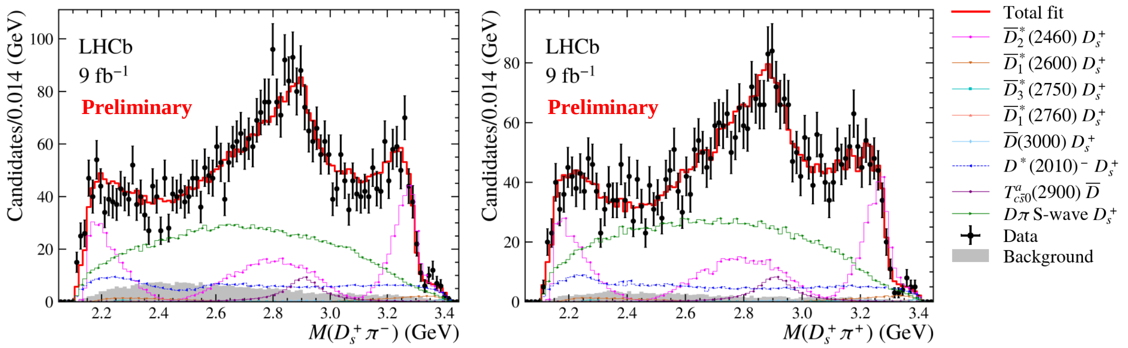
	Mass (GeV)	Width (GeV)
$T^a_{c\bar{s}0}(2900)$	$2.908 \pm 0.011 \pm 0.020$	$0.136 \pm 0.023 \pm 0.020$
$X_0(2900)$	$2.866 \pm 0.007 \pm 0.002$	$0.057 \pm 0.012 \pm 0.004$
$X_1(2900)$	$2.904 \pm 0.005 \pm 0.001$	$0.110 \pm 0.011 \pm 0.004$

Summary

LHCb Preliminary

- **First observation** of a **doubly charged mesonic** exotic state, together with its **neutral partner**.
  - ✓ Belong to the **same isospin triplet**.
  - ✓ **Spin-parity: 0^+.**
  - ✓ Minimum quark content: $\boldsymbol{T^{a}_{c\bar{s}0}(2900)^{++}}$**: [$c\bar{s}u\bar{d}$]; $\boldsymbol{T^{a}_{c\bar{s}0}(2900)^{0}}$: [$c\bar{s}\bar{u}d$]**
  - ✓ **Similar mass** with $X_0(2900)$ ($cs\bar{u}\bar{d}$), but **width and flavor contents are different**.

- **Next step**
  - ➢ Several **ongoing $\boldsymbol{B \to DDh}$ analyses** with LHCb Run 1 and Run 2 datasets.
    - $\boldsymbol{B}$: $B^{0,+}, B_s^0, \Lambda_b^0 \ldots$; $\boldsymbol{D}$: $D^{0,+}, D^{*+}, D_s^+, \Lambda_c^+ \ldots$; $\boldsymbol{h}$: $K^+, \pi^+, p, \Lambda \ldots$
  - ➢ LHC Run 3 data taking started recently.
    - ✓ More statistic, detailed analysis on $B \to \bar{D}D_s\pi$
    - ✓ $B \to \bar{D}D_s\pi^0, B \to \bar{D}D_s\pi\pi, B_s \to \bar{D}D_sK\pi \ldots$



Thank you!

Back Up

Amplitude formalism

Amplitude formula

- **For decay $B \to D(1)D_s^+(2)\pi(3)$, the amplitude is**

$$\mathcal{A} = \sum_a C_a \cdot f_a(m_{12}^2) \cdot T_a(\theta_{12}) + \sum_b C_b \cdot f_b(m_{23}^2) \cdot T_b(\theta_{23}) + \sum_c C_c \cdot f_c(m_{13}^2) \cdot T_c(\theta_{13}),$$

- C is complex coefficient
- $f(m^2)$ is lineshape function
- $T(\theta)$ is the angular term

- **For resonance, we use the relativistic Breit-Wigner lineshape**

$$f_{BW} = q(m)^{L_1} p(m)^{L_2} \frac{F_1(m, L_1) F_2(m, L_2)}{m_0^2 - m^2 - i m_0 \Gamma(m)}$$

with running width

$$\Gamma(m) = \Gamma_0 \left(\frac{q(m)}{q_0}\right)^{2L_2+1} \frac{m_0}{m} F_2^2(m, L_2)$$

- **The Blatt-Weisskopf form factors**

$$F(m, L) = \begin{cases} 1 & L = 0 \\ \sqrt{\frac{1+z^2(m)}{1+z_0^2}} & L = 1 \\ \sqrt{\frac{9+3z^2(m)+z^4(m)}{9+3z_0^2+z_0^4}} & L = 2 \\ \sqrt{\frac{225+45z^2(m)+6z^4(m)+z^6}{225+45z_0^2+6z_0^4+z_0^6}} & L = 3 \end{cases}$$

Maximum likelihood fit (cFit*)

- $\mathrm{PDF}(x;\Theta) = |A(x;\Theta)|^2$, where x is the data point, Θ is the parameter set.
- $-2\ln L = -2\sum_i^N \ln \mathrm{PDF}(x;\Theta)$

*Detailed implementations in back-up slide