Observation of doubly-charged tetraquark candidate at LHCb (CLHCP 2022)

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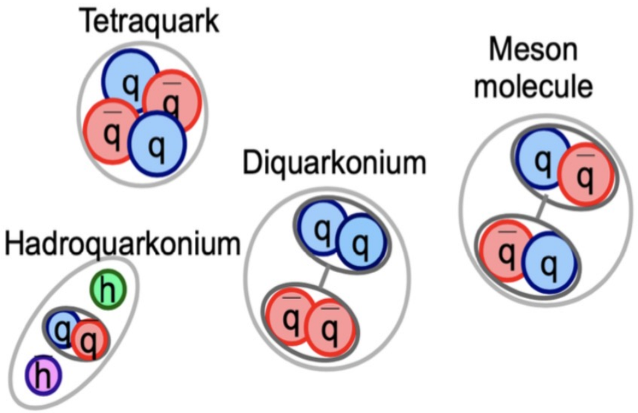
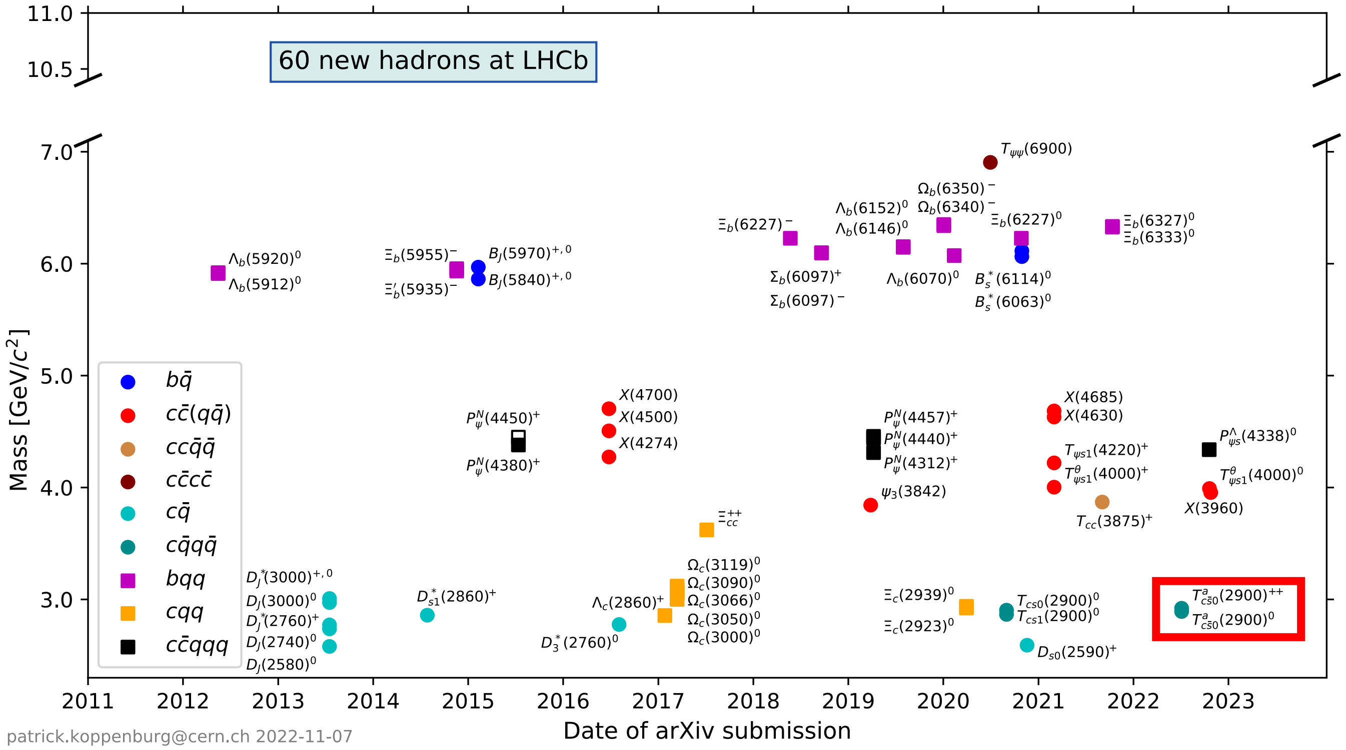
On behalf of the LHCb Collaboration

Nov. 25th, 2022

- **The existence of mesonic exotic state** has been discussed since **1964**[1]**.**
- In 2003, Belle Collaboration reported the first observation of $\chi_{c1}(3872)$.
- Many mesonic exotic states are observed in the past two decades.
- A series of **theoretical models** are established to describe these states.





Masses and discovery date for states observed at LHCb. Hollow markers indicate superseded states.[2, 3]

- **60 new hadrons observed at LHCb!**
  - 15 tetraquark candidates.
  - 5 pentaquark candidates.[4]

[1] M. Gell-Mann, A schematic model of baryons and mesons, Phys. Lett. 8 (1964) 214.
[2] https://www.nikhef.nl/~pkoppenb/particles.html
[3] Exotic hadron naming convention: https://arxiv.org/abs/2206.15233
[4] $P_c(4450)^+$ resolved into $P_c(4440)^+$ and $P_c(4457)^+$.

- $T^{a}_{cs0}(2900)^{++}$: $[c\bar{s}u\bar{d}]$; $T^{a}_{cs0}(2900)^{0}$: $[c\bar{s}\bar{u}d]$

● 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.

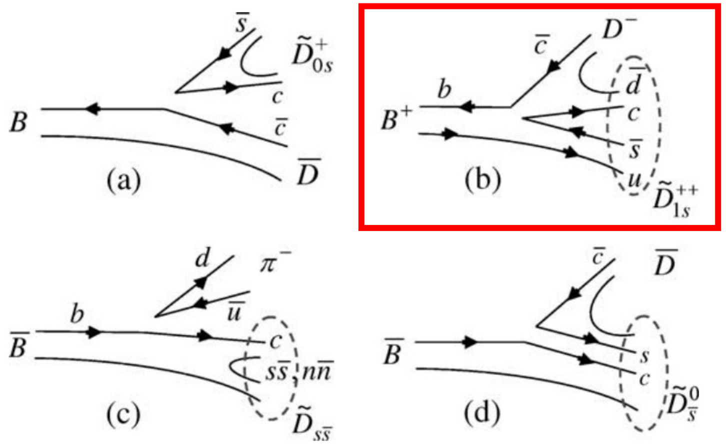
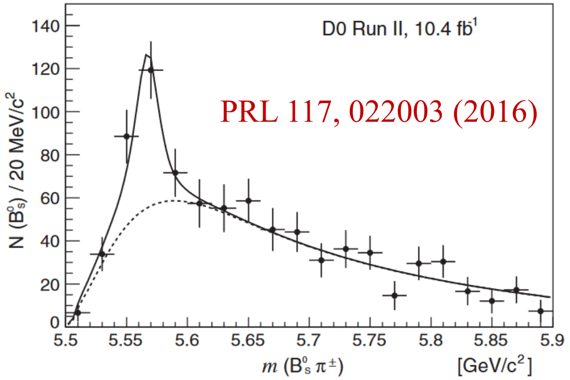


Fig. 2. Diagrams for (a) $B \to \bar{D}\tilde{D}_{0s}^{+}$, (b) $B^{+} \to D^{-}\tilde{D}_{1s}^{++}$ ($B \to \bar{D}\tilde{D}_{Is}$), (c) $\bar{B} \to \pi^{-}\tilde{D}_{s\bar{s}}, \pi^{-}\tilde{D}$, (d) $B \to \bar{D}\tilde{D}_{\bar{s}}^{0}$.

PLB 566 (2003) 193–200

- **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.

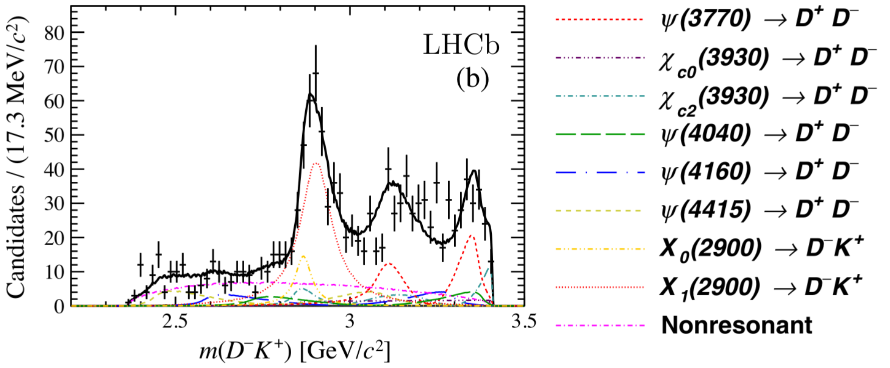


PRL 117, 022003 (2016)

$X(5568)^{+}$

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!**

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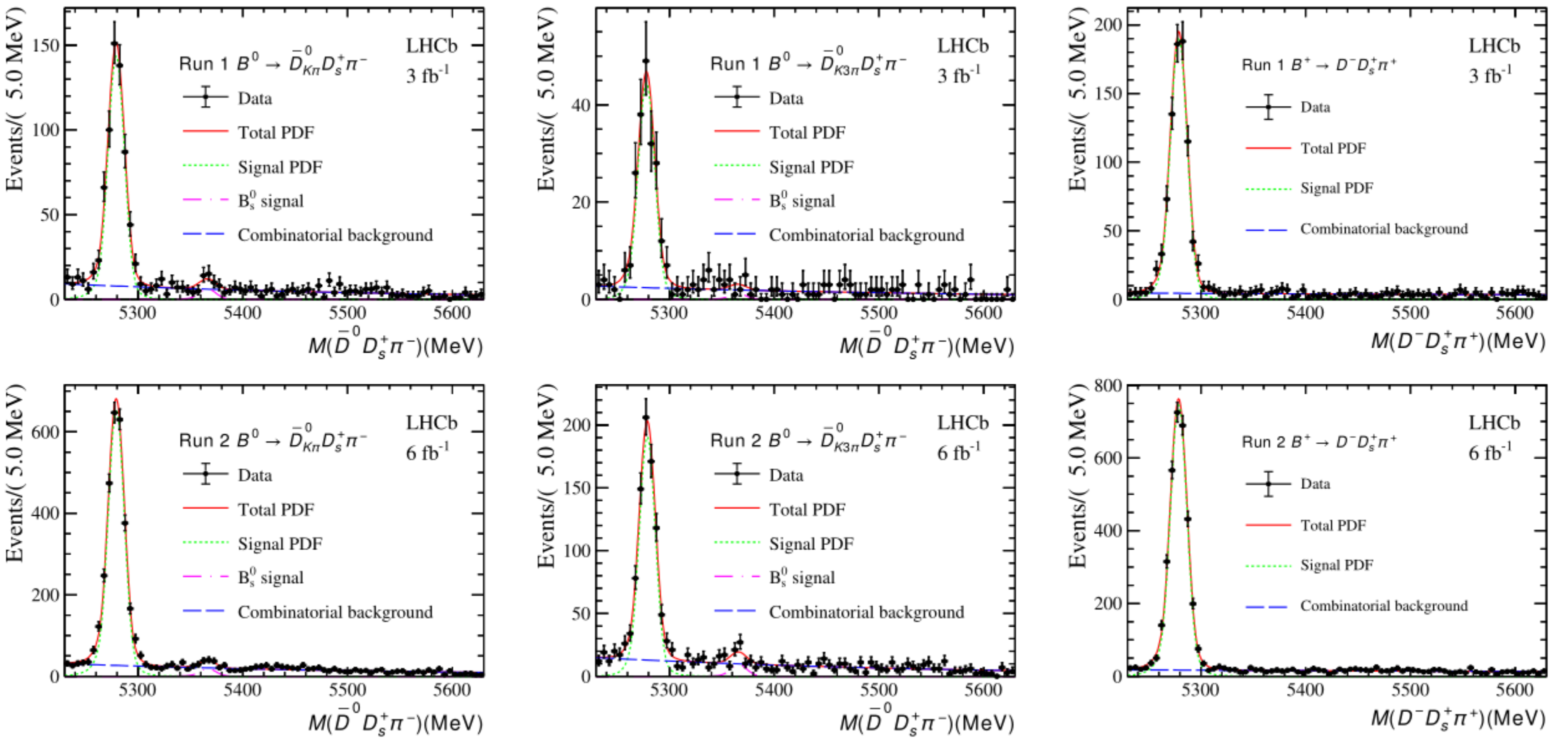
- $\boldsymbol{B^0 \to \bar{D}^0 D_s^+ \pi^- \ \& \ B^+ \to D^- D_s^+ \pi^+}$
  - Using all the Run 1 and Run 2 datasets.



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

✓ **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%.**

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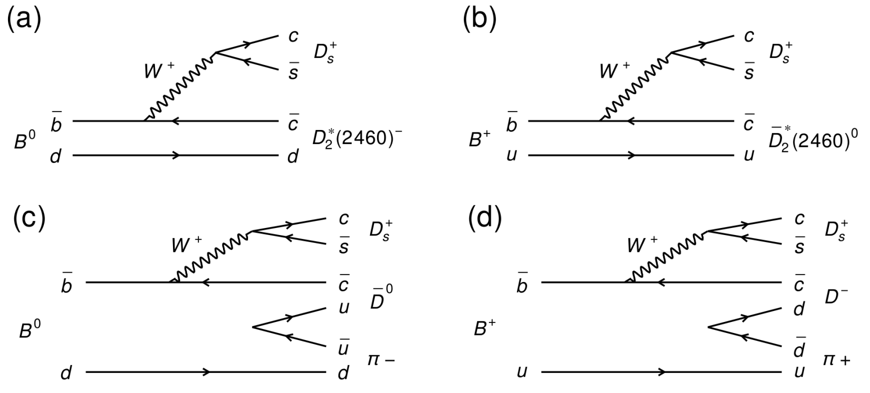
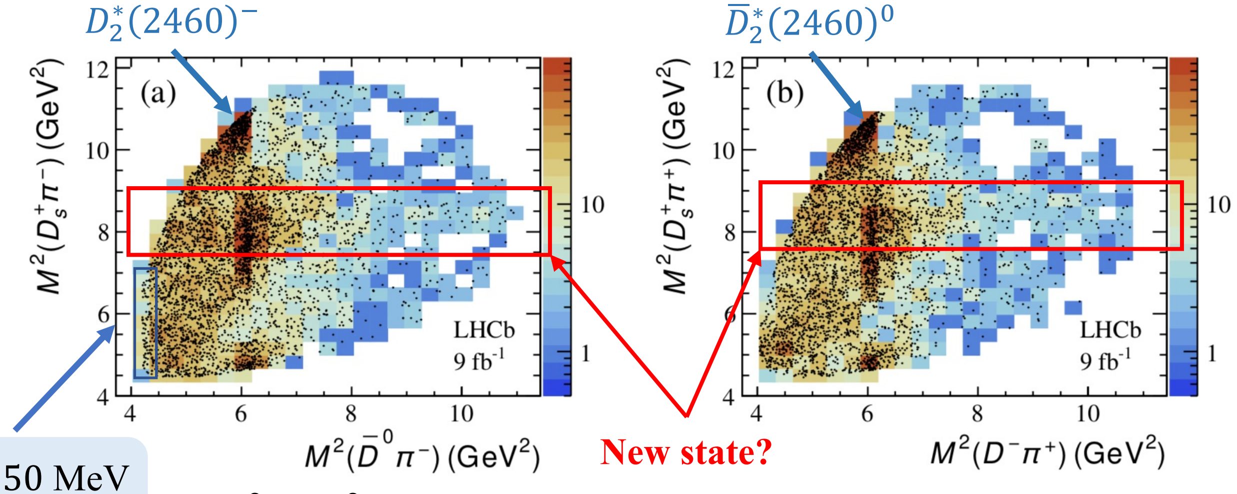


Feynman diagrams

$m(\bar{D}^0\pi^-) > 2050$ 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 **6 GeV^2.**

✓ **A faint horizontal band** at the $D_s\pi$ **mass squared** around **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

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

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

Fractions determined from mass fits

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

- **Signal PDF:**

$$P^{\mathrm{norm}}_{\mathrm{sig}}(x;\Theta) = \frac{\epsilon(x)|\mathcal{A}(x;\Theta)|^2}{I_{\mathrm{sig}}(\Theta)}.$$

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.)

Fitting model

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- **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.

*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

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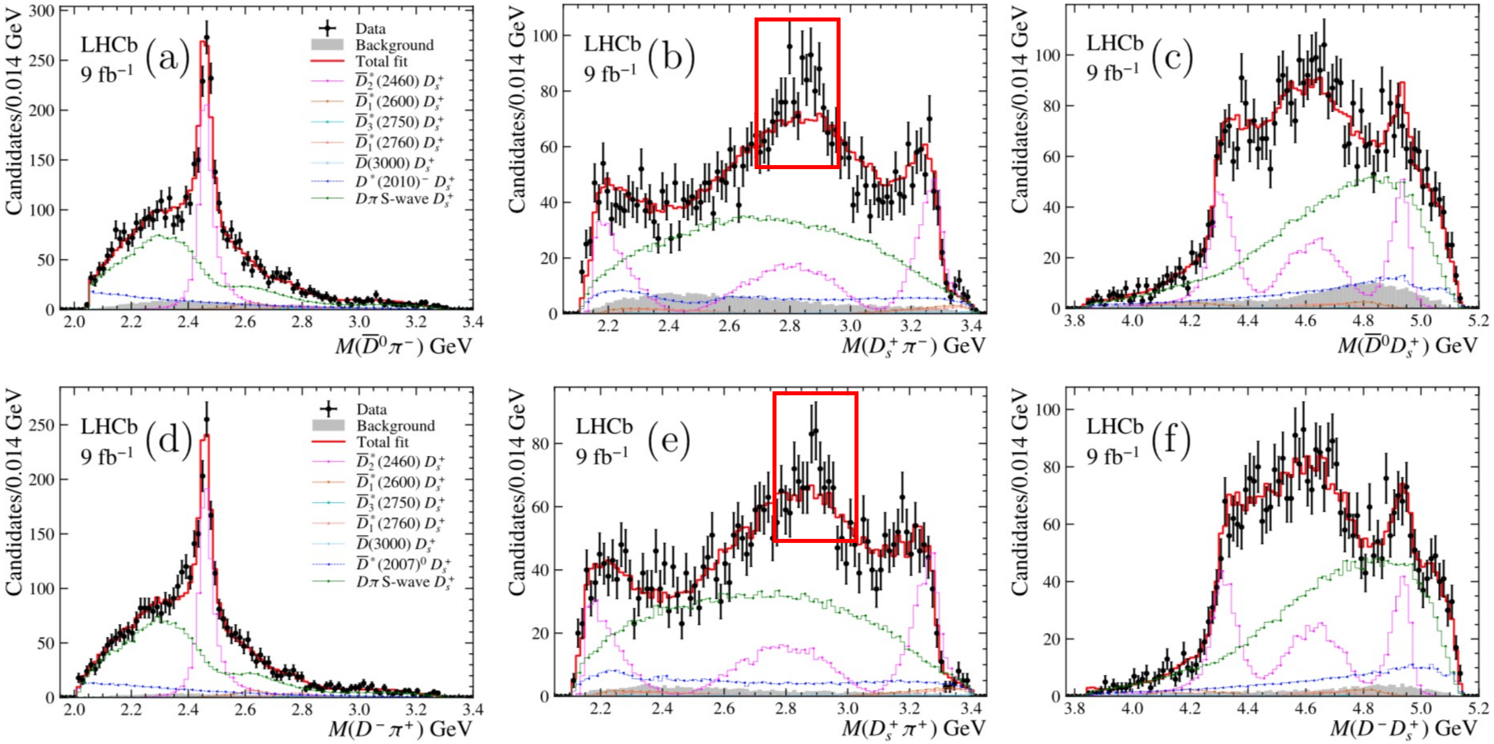

- ✓ **Fit result**
  - ✓ $M(\bar{D}\pi)$ and $M(\bar{D}D_s^+)$ **well described.**
  - ✓ $D_1^*(2600), D_1^*(2760), D(3000)$ **not significant**, however, **still included** conservatively.
  - ✓ Spin-parity of $\boldsymbol{D(3000)}$ favors $\mathbf{4^+}$.
  - ✓ **Further new $\bar{D}^{**}$ state** with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

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

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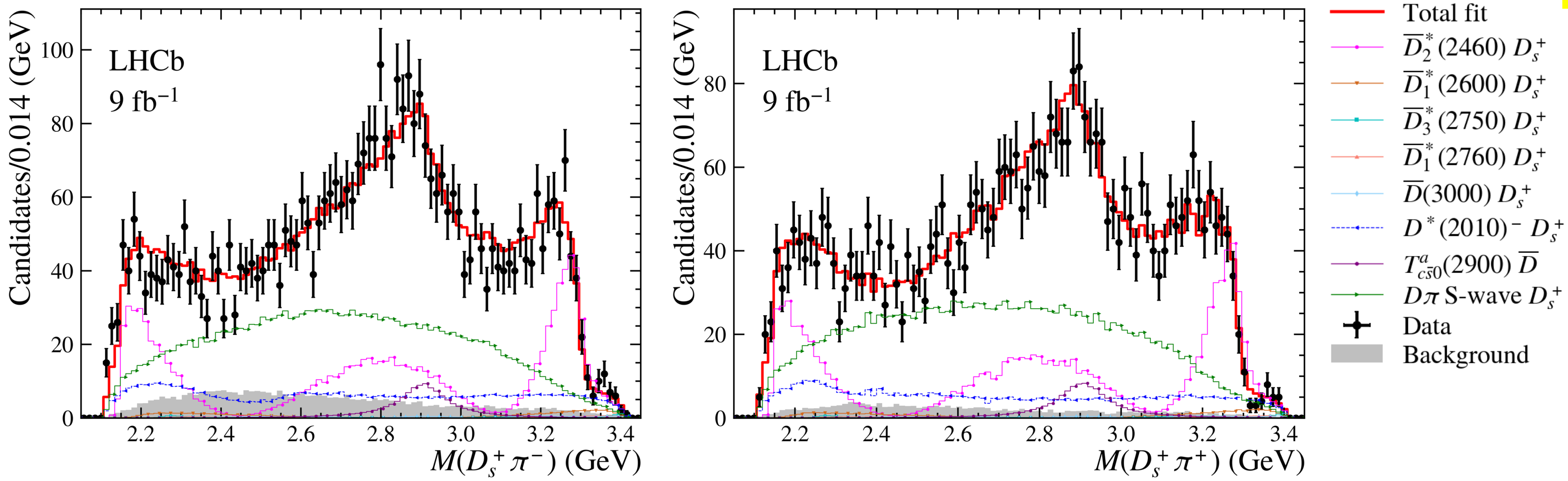

◆ **Two** **$D_s^+\pi$ exotic states** **with shared parameters are added**.

- ✓ 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

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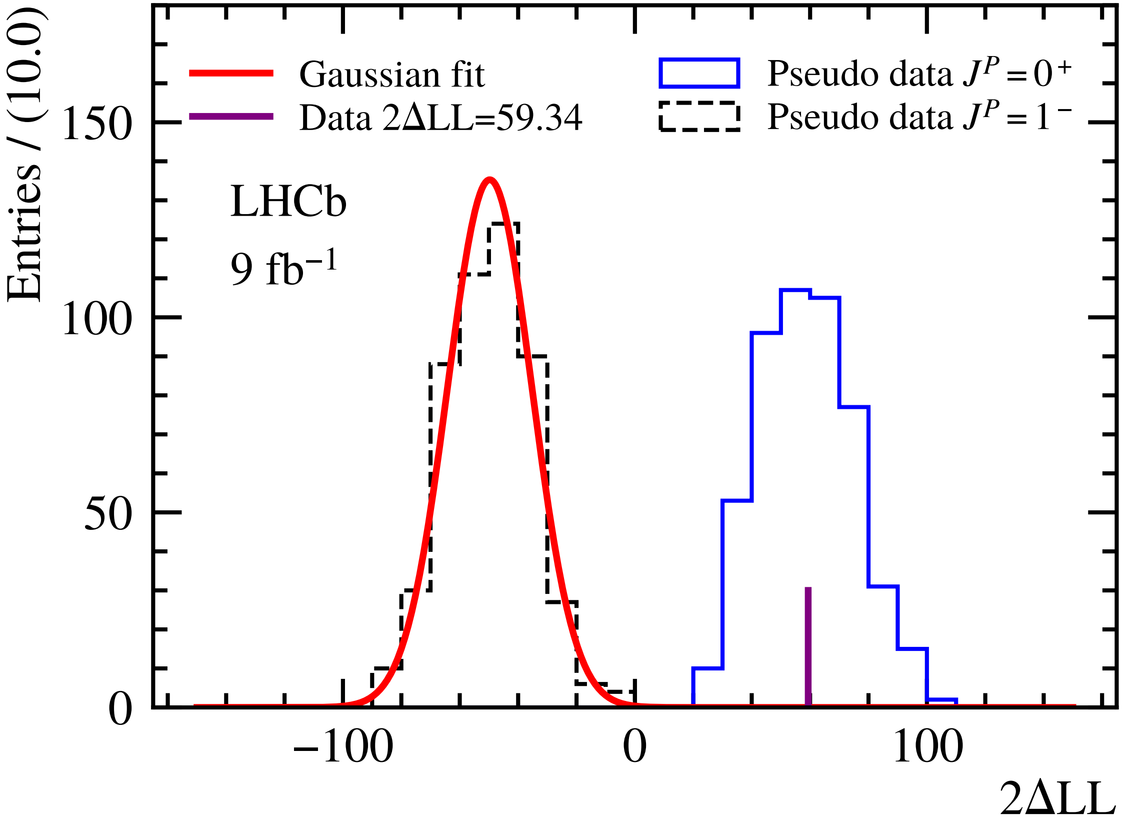

◆Spin test

- ✓ Generate pseudoexperiments.
- ✓ Spin-parity favored **0^+ over 1^-** with a significance about **7.5σ.**
- ✓ 0^+ is also significantly preferred when exotics not constrained by isospin.

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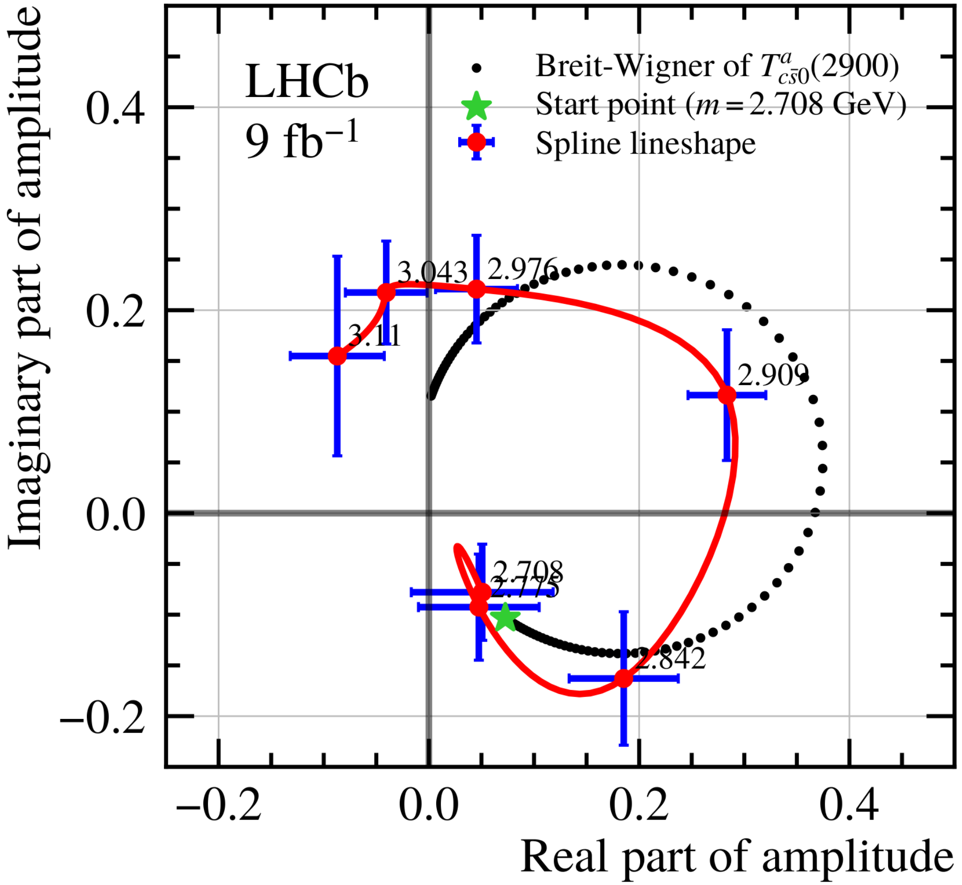

◆Argand diagram

✓ Replace the RBW of $T_{c\bar{s}0}^{a}$ 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 $T_{c\bar{s}0}^{a}$ mass and width.

✓ **Lineshape consistent with RBW.**

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

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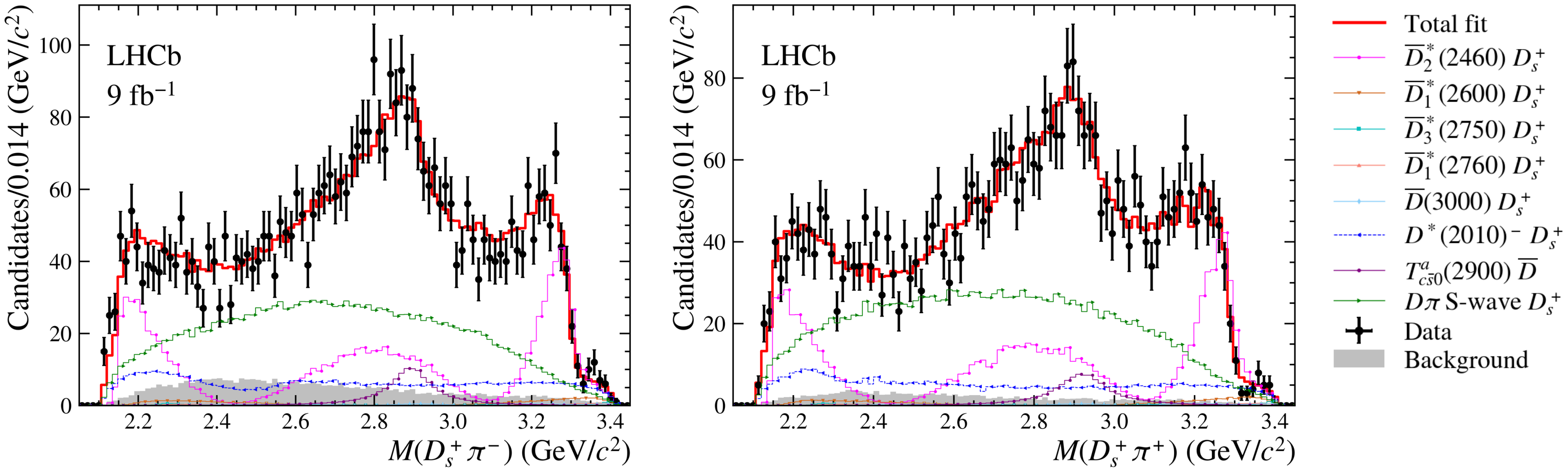
- **Separate $T^a_{c\bar{s}0}$ parameters**
  - ✓ $-\ln\mathcal{L}$ improved by **2.8**, with **4** free parameters added.
  - ✓ Masses and widths are **consistent** with each other.
  - ✓ **Isospin triplet!**

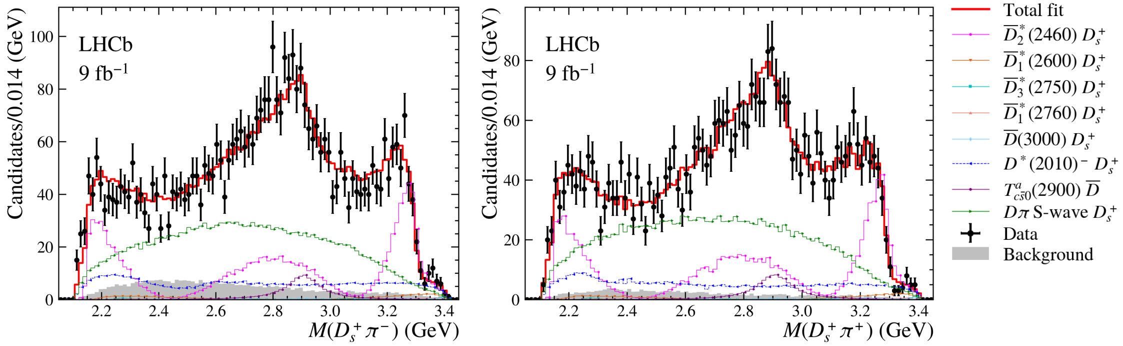


	Mass (GeV)	Width (GeV)	Significance
$T^a_{c\bar{s}0}(2900)^0$	$2.892 \pm 0.014 \pm 0.015$	$0.119 \pm 0.026 \pm 0.013$	8.0σ
$T^a_{c\bar{s}0}(2900)^{++}$	$2.921 \pm 0.017 \pm 0.020$	$0.137 \pm 0.032 \pm 0.017$	6.5σ

Summary

- **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: $T^{a}_{c\bar{s}0}(2900)^{++}$: $[c\bar{s}u\bar{d}]$; $T^{a}_{c\bar{s}0}(2900)^{0}$: $[c\bar{s}\bar{u}d]$
  - ✓ **Similar mass** with $X_0(2900)$ $(cs\bar{u}\bar{d})$, but **width and flavor contents are different**.

- **Next step**
  - ➢ Several **ongoing $B \to DDh$ 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 $B \to \bar{D}D_s\pi$
    - ✓ $B \to \bar{D}D_s\pi^0, B \to \bar{D}D_s\pi\pi, B_s \to \bar{D}D_sK\pi$ …

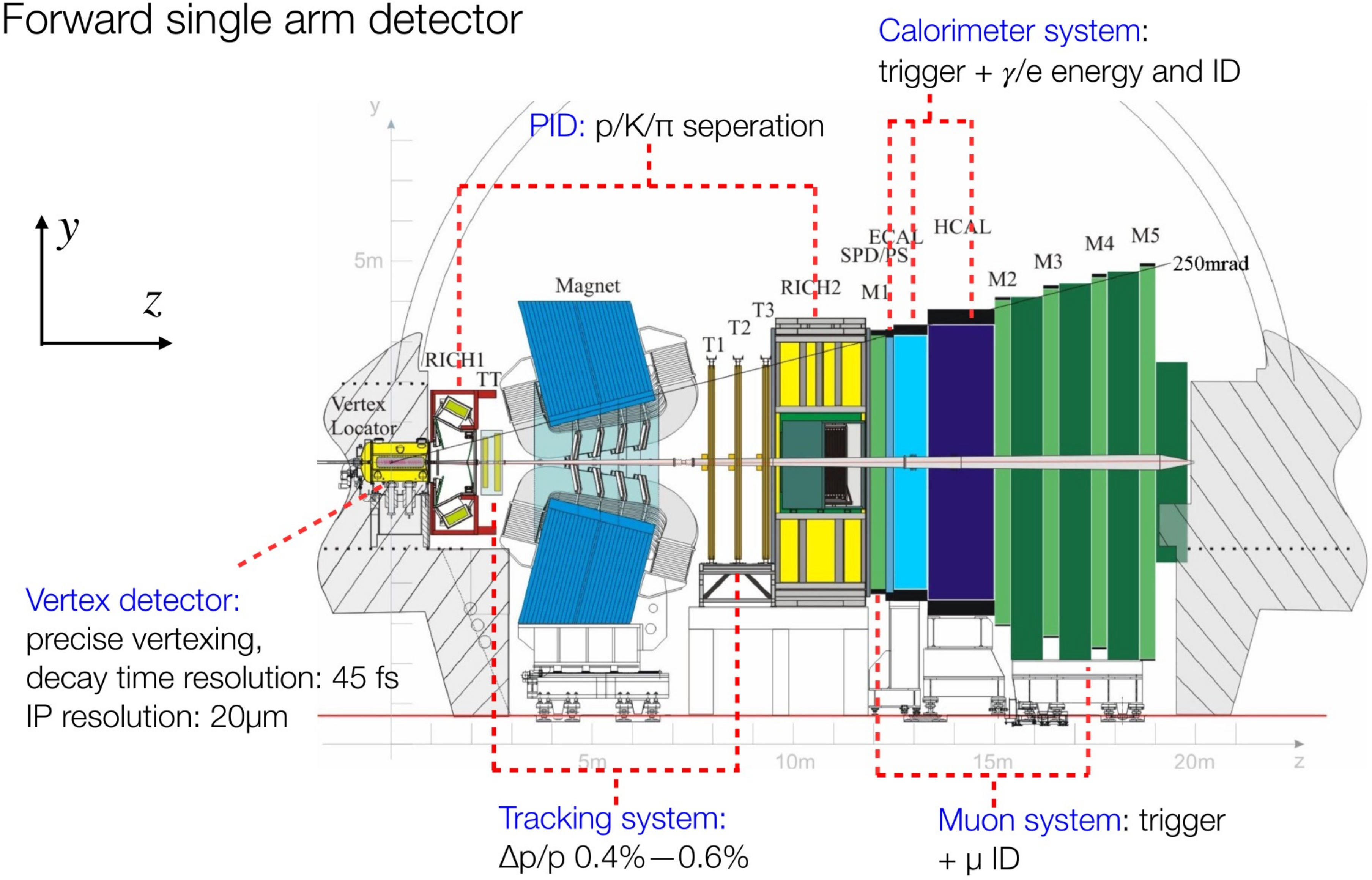


Thank you!

Back Up

The LHCb detector

Forward single arm detector



Datasets

Table 2: Signal and background yields inside the B mass signal window, together with the signal purity, split by run period and decay mode. The uncertainties shown are statistical.

Decay	Parameter	Run 1	Run 2
$B^0 \to \overline{D}^0_{K\pi} D_s^+ \pi^-$	Signal yield	564 ± 26	2534 ± 55
	Total candidates	633	2753
	Purity	89.1%	92.1%
$B^0 \to \overline{D}^0_{K3\pi} D_s^+ \pi^-$	Signal yields	177 ± 14	734 ± 31
	Total candidates	199	835
	Purity	88.9%	87.9%
$B^+ \to D^- D_s^+ \pi^+$	Signal yield	766 ± 29	2984 ± 57
	Total candidates	797	3143
	Purity	96.1%	94.9%

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

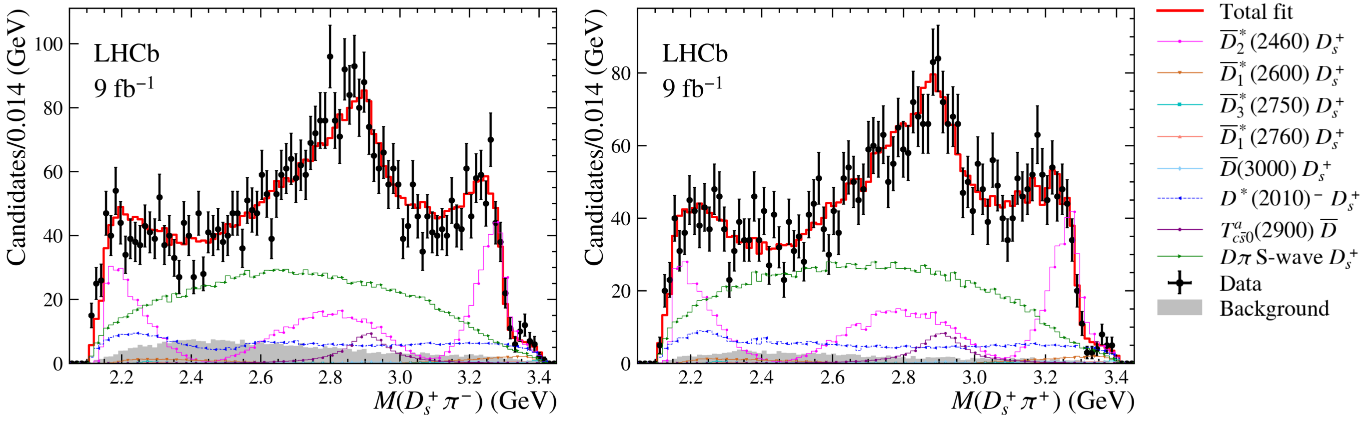
$$F(m, L) = \begin{cases} 1 & L = 0 \\ \sqrt{\frac{1+z^2(m)}{1+z_0^2}} & L = 1 \\ \sqrt{\frac{9+3z^2(m)+z^4(m)}{9+3z_0^2+z_0^4}} & L = 2 \\ \sqrt{\frac{225+45z^2(m)+6z^4(m)+z^6}{225+45z_0^2+6z_0^4+z_0^6}} & L = 3 \end{cases}$$

Maximum likelihood fit (cFit*)

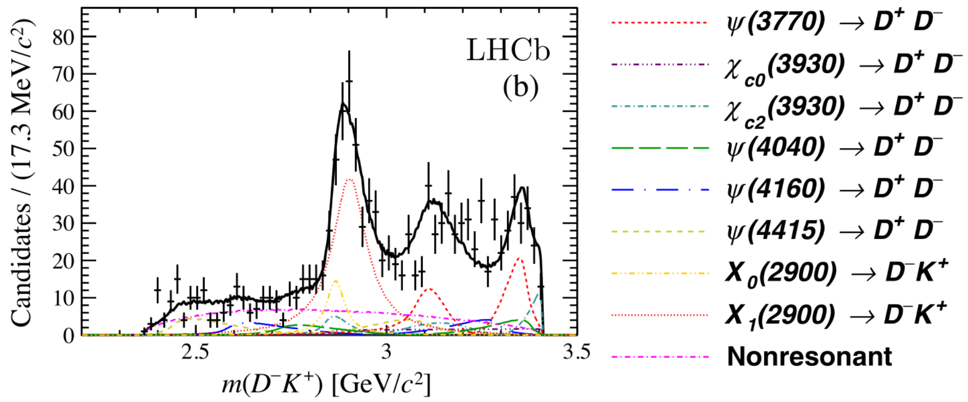
- $\mathrm{PDF}(x;\Theta) = |A(x;\Theta)|^2$, where x is the data point, Θ is the parameter set.
- $-2\ln L = -2\sum_i^N \ln \mathrm{PDF}(x;\Theta)$

*Detailed implementations in back-up slide

LHCb Preliminary



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



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

- $T^{a}_{c\bar{s}0}(2900)$ & $X_0(2900)$
  - ✓ 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!

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