

Studies of mesonic exotic states at LHCb

Ruiting Ma

University of Chinese Academy of Sciences, Beijing, China

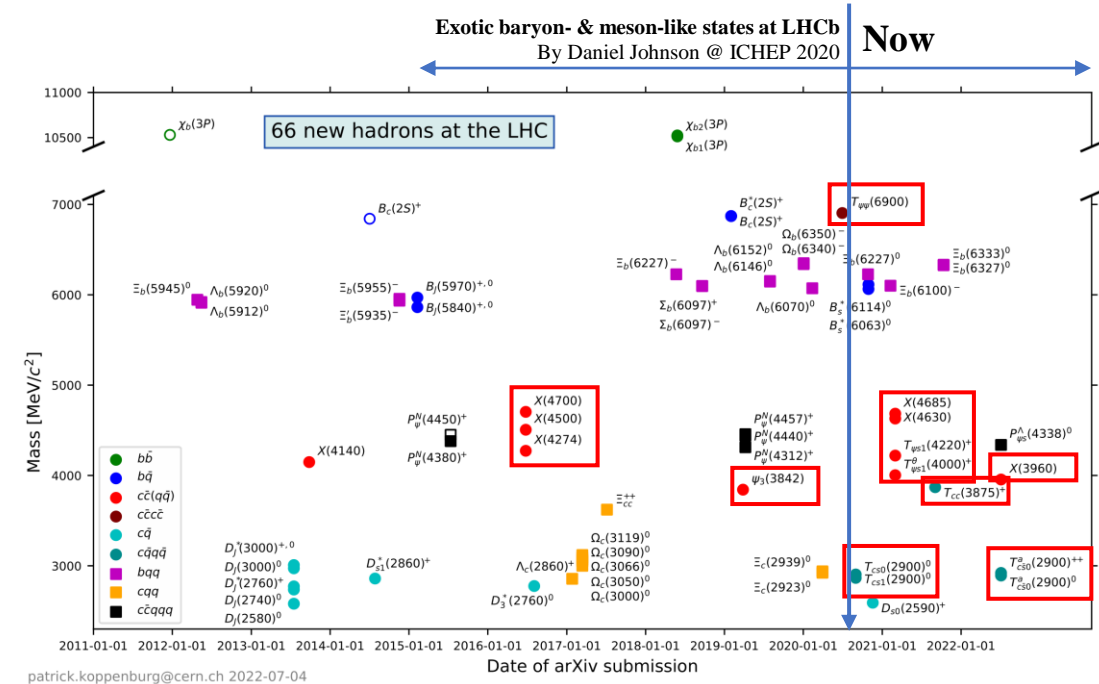
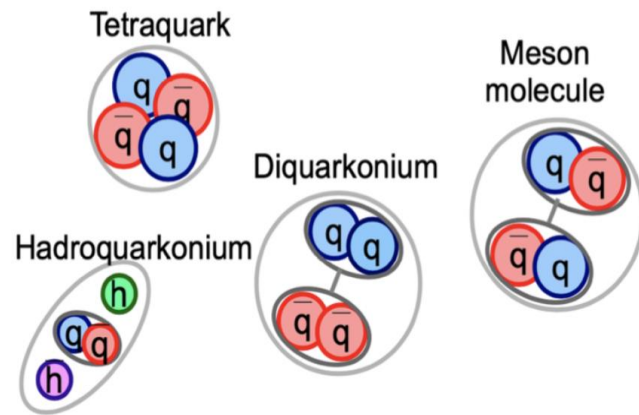
On behalf of the LHCb Collaboration

July. 9th, 2022



中国科学院大学
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- The existence of mesonic exotic state has been discussed since 1964¹.
- 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Hollow markers indicate superseded states.^{2,3}

● 66 new hadrons observed at LHCb!

- 15 mesonic exotic candidates.
- 5 baryonic exotic 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 $P_c(4457)^+$.

● Open-charm mesonic exotic states:

➤ $B^+ \rightarrow D^+ D^- K^+$

Phys. Rev. Lett. 125,242001

• $cs\bar{u}\bar{d}$: $X_0(2900)^0, X_1(2900)^0$

Phys. Rev. D102.112003

➤ Inclusive $D^0 D^0 \pi^+$

Nat. Phys. (2022)

• $cc\bar{u}\bar{d}$: T_{cc}^+

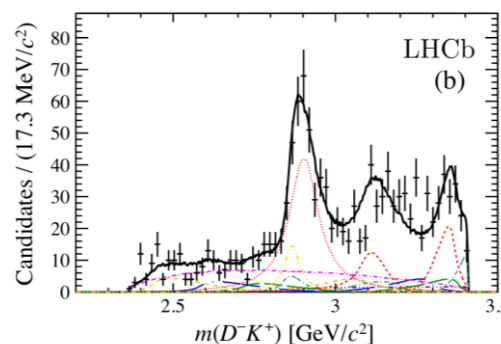
Nat. Commun. 13, 3351

➤ $B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$ & $B^+ \rightarrow D^- D_s^+ \pi^+$

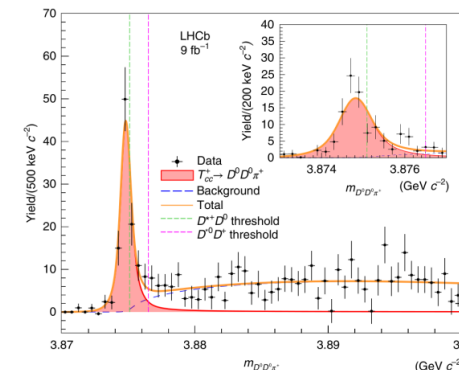
• $c\bar{s}u\bar{d}$: $T_{c\bar{s}0}^a(2900)^{++}$

LHCb Preliminary

• $c\bar{s}u\bar{d}$: $T_{c\bar{s}0}^a(2900)^0$



$X_{0,1}(2900)$



T_{cc}^+

● Hidden-charm mesonic exotic states:

➤ $B^+ \rightarrow J/\psi \phi K^+$

Phys. Rev. Lett. 127, 082001

• $c\bar{c}u\bar{s}$: $Z_{cs}(4000)^+, Z_{cs}(4220)^+$

• $c\bar{c}s\bar{s}$: $X(4630), X(4685)$

➤ $B^+ \rightarrow K^+ \pi^+ \pi^- J/\psi$

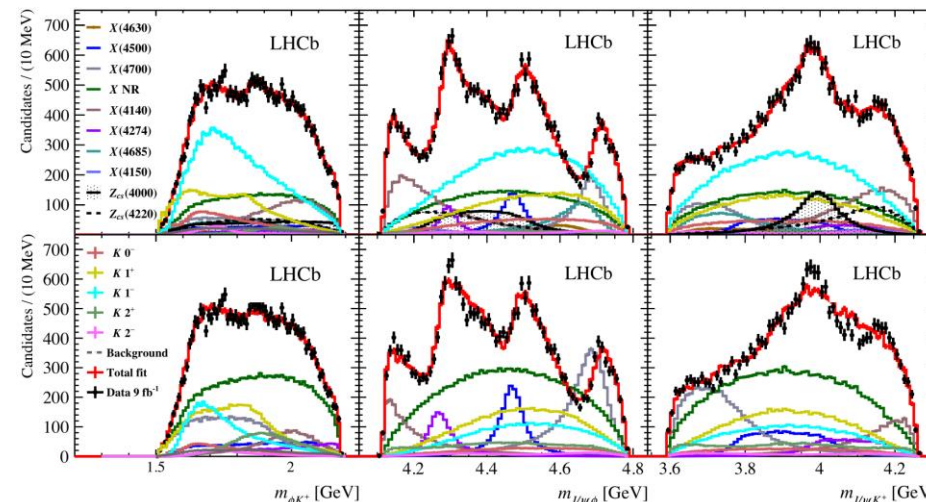
arXiv 2204.12597

• $\chi_{c1}(3872) \rightarrow \omega J/\psi$

➤ $B^+ \rightarrow D_s^+ D_s^- K^+$

LHCb Preliminary

• $c\bar{c}s\bar{s}$: $X(3960)$

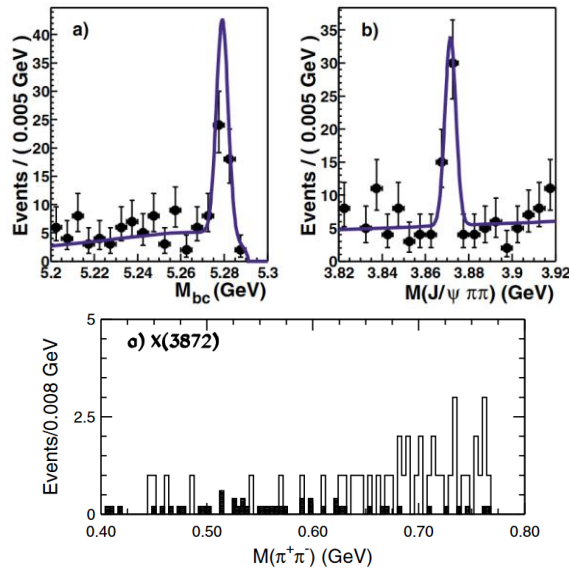


$Z_{cs}(4000)^+$

● Observation of **sizeable ω contribution** to $\chi_{c1}(3872) \rightarrow \pi^+ \pi^- J/\psi$ decay

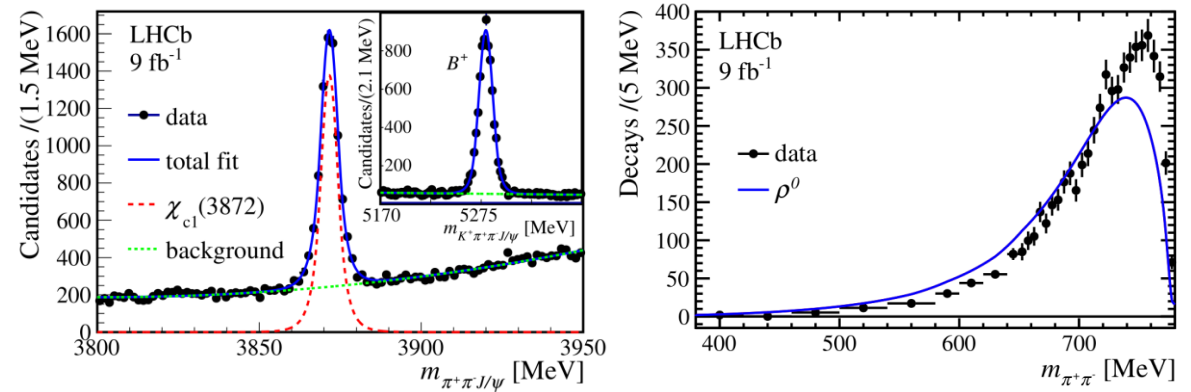
- The $\rho^0 J/\psi$ process is suggested to explain the $m_{\pi^+ \pi^-}$ distributions in $\chi_{c1}(3872) \rightarrow \pi^+ \pi^- J/\psi$ decay.
- $\chi_{c1}(3872) \rightarrow \rho^0 J/\psi$ is **isospin violating decay**. Should be **highly suppressed** in charmonium decays.
- Search for the isospin conserving $\chi_{c1}(3872) \rightarrow \omega J/\psi$ decay in $\chi_{c1}(3872) \rightarrow \pi^+ \pi^- J/\psi$ process.
- ◆ Study the $m_{\pi^+ \pi^-}$ distributions in $B^+ \rightarrow K^+ \chi_{c1}(3872), \chi_{c1}(3872) \rightarrow \pi^+ \pi^- J/\psi$ decays with **large statistic**.

Phys. Rev. Lett. 91.262001



$$N_{sig} = 35.7 \pm 6.8$$

19 years
× 190



$$N_{sig} = 6788 \pm 117$$

● Observation of **sizeable ω contribution** to $\chi_{c1}(3872) \rightarrow \pi^+ \pi^- J/\psi$ decay

- ◆ The $m_{\pi^+ \pi^-}$ distributions cannot be described by ρ^0 component.
- ◆ Well described by a two channel K -matrix model, including both ρ^0 and ω contribution!

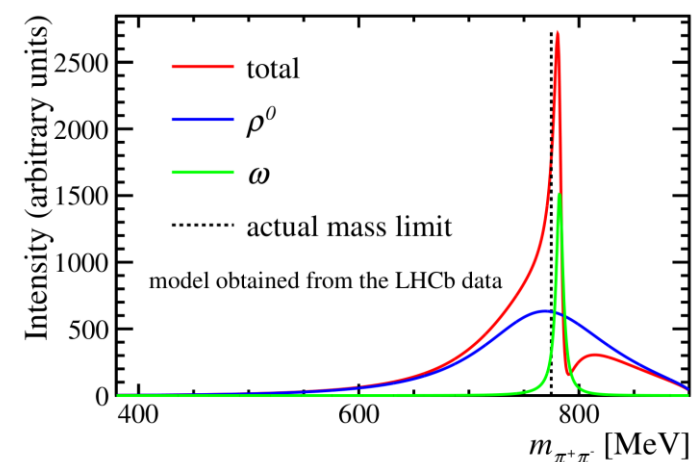
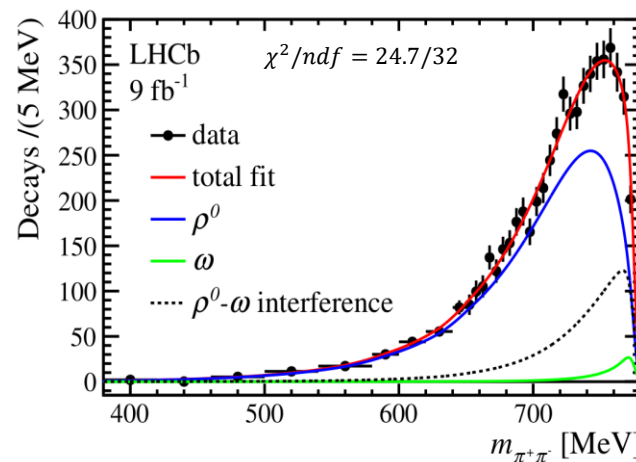
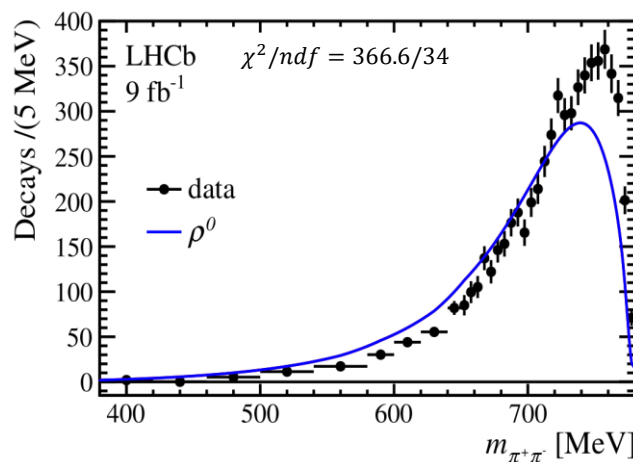
$$K = \frac{1}{m_\rho^2 - s} \begin{pmatrix} g_{\rho \rightarrow 2\pi}^2 & 0 \\ 0 & 0 \end{pmatrix} + \frac{1}{m_\omega^2 - s} \begin{pmatrix} g_{\omega \rightarrow 2\pi}^2 & g_{\omega \rightarrow 2\pi} g_{\omega \rightarrow 3\pi} \\ g_{\omega \rightarrow 2\pi} g_{\omega \rightarrow 3\pi} & g_{\omega \rightarrow 3\pi}^2 \end{pmatrix}$$

✓ The ω contribution:

- ✓ **(21.4 ± 2.3 ± 2.0)%** of the total rate.
- ✓ **(1.9 ± 0.4 ± 0.3)%** when excluding interference effects.

✓ The limit phase space impact the coupling constants.

- ✓ By setting $m_{\chi_{c1}(3872)} = 4000$ MeV: $\frac{g_{\chi_{c1}(3872) \rightarrow \rho^0 J/\psi}}{g_{\chi_{c1}(3872) \rightarrow \omega J/\psi}} = \sqrt{\frac{\mathcal{B}(\omega \rightarrow \pi^+ \pi^-)}{\mathcal{R}_{\omega/\rho}^0}} = 0.29 \pm 0.04.$
- ✓ **A factor of **six** larger** than expected for a pure charmonium state! (0.045 ± 0.001 for $\psi(2S)$)



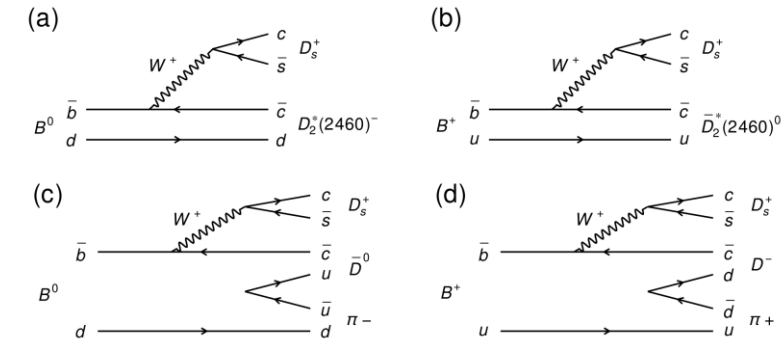
$$B^0 \rightarrow \bar{D}^0 D_s^+ \pi^- \text{ \& } B^+ \rightarrow D^- D_s^+ \pi^+$$

● First observation of a doubly charged tetraquark and its neutral partner.

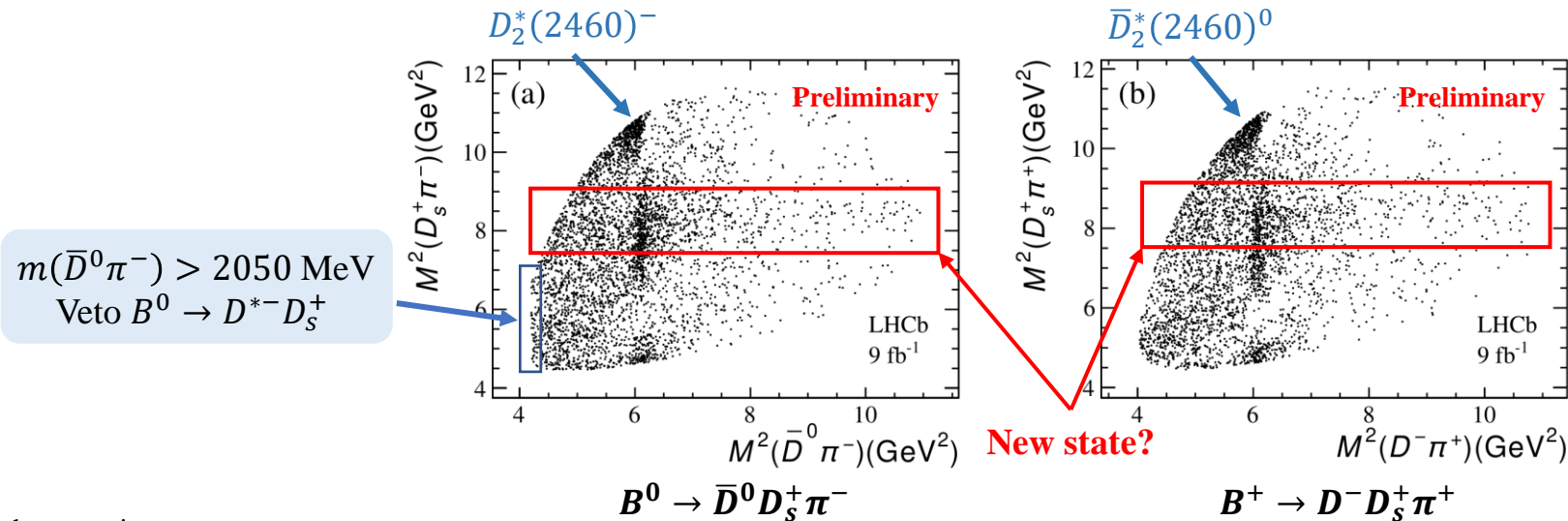
- The evidence of $X(5568)(B_s^0 \pi^+)^*$ and observation of $X_{0,1}(2900)(D^+ K^-)$ motivates the search for the $D_s^\pm \pi^\pm$ states.
- $D_{s0}^*(2317)^+(D_s^+ \pi^0)$ is thought to have some tetraquark component in several theoretical descriptions.

◆ $B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$ & $B^+ \rightarrow D^- D_s^+ \pi^+$ @ LHCb

- ✓ 4420 $B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$ candidates, purity **90.7%**.
- ✓ 3940 $B^+ \rightarrow D^- D_s^+ \pi^+$ candidates, purity **95.2%**.
- ✓ A faint horizontal band at the $D_s \pi$ mass square around 8.5 GeV^2
- ✓ Similar features in the Feynman diagrams and Dalitz plots
- ✓ **Simultaneous amplitude analysis!**

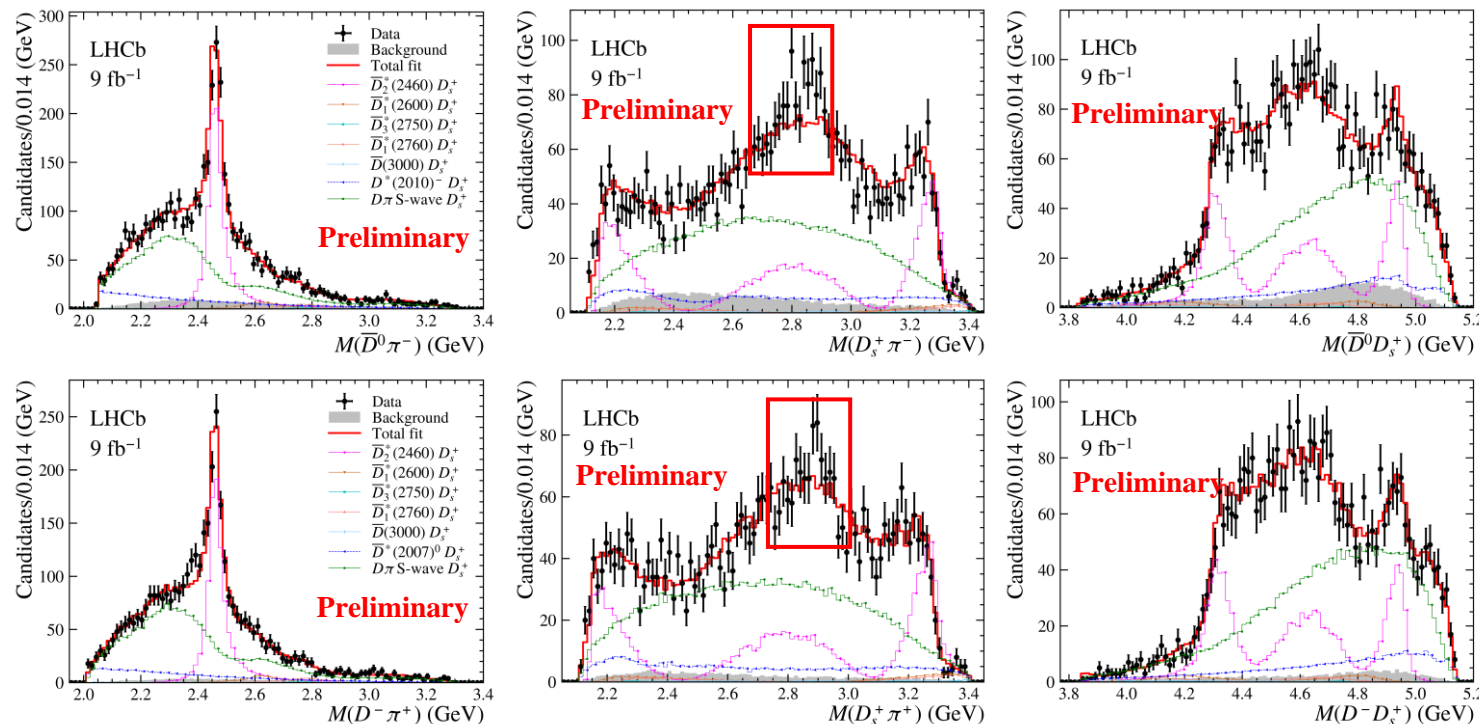


Feynman diagrams



*Has not been confirmed by other experiments.

- First observation of a doubly charged tetraquark and its neutral partner.



◆ Fit strategy – simultaneous fit

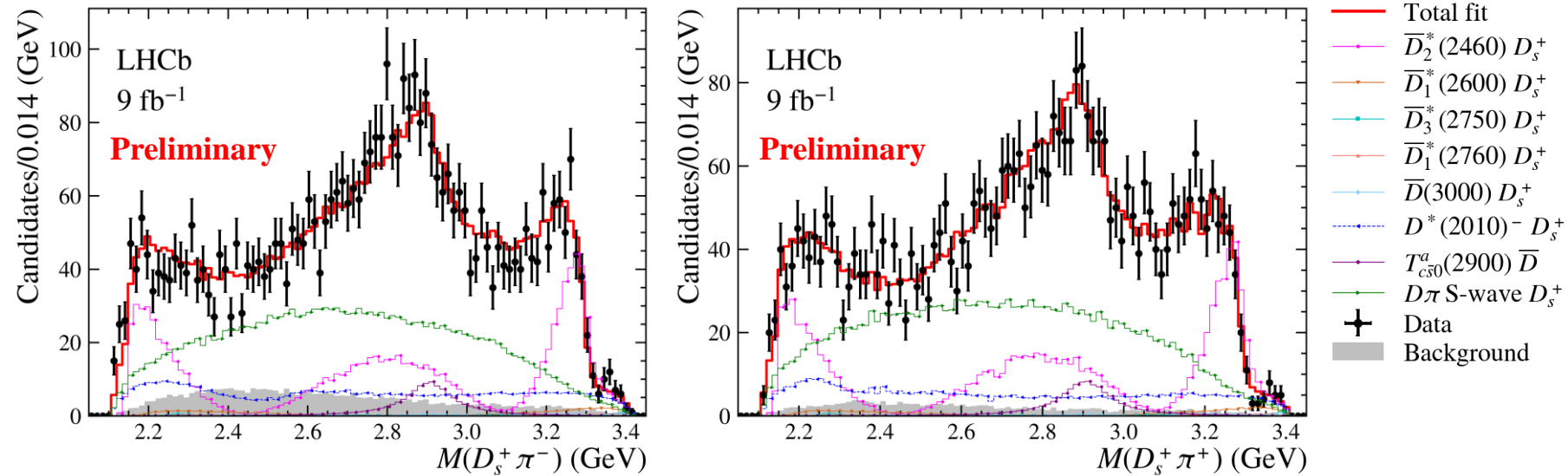
- ◆ Include all the D^* and D^{**} states with natural spin-parity.
- ◆ $\bar{D}\pi$ S-wave component: QMI spline points.*
- ◆ All parameters, except $\bar{D}^*(2007)^0$ and $D^*(2010)^-$ are shared.

✓ Fit result

- ✓ $m(\bar{D}\pi)$ and $m(\bar{D}D_s^+)$ well described.
- ✓ **Peaking structures near $m(D_s^+ \pi) = 2.9 \text{ GeV}$!**
- ✓ Further \bar{D}^{**} disfavored.

*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

- First observation of a doubly charged tetraquark and its neutral partner.



◆ 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 than 9σ .
- ✓ Mass and width are measured:

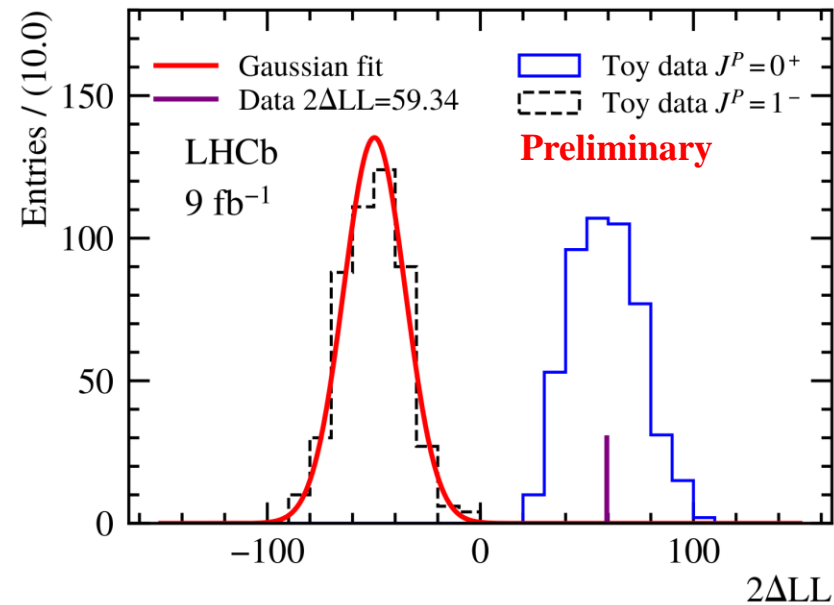
$$M = 2.908 \pm 0.011 \pm 0.020 \text{ GeV}$$

$$\Gamma = 0.136 \pm 0.023 \pm 0.011 \text{ GeV},$$

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

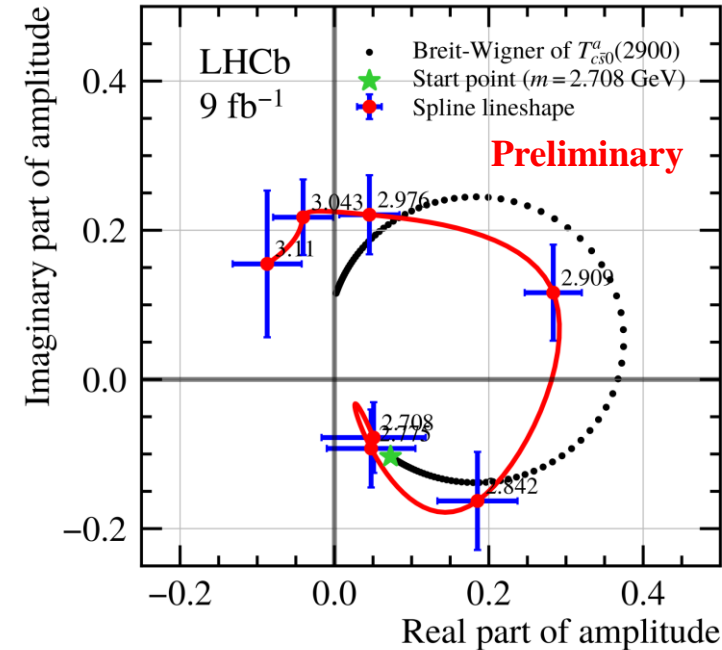
* Exotic hadron naming convention: <https://arxiv.org/abs/2206.15233>

- First observation of a doubly charged tetraquark and its neutral partner.



◆ Spin test

- ✓ Spin-parity favored 0^+ over 1^- with a significance about 7.6σ .



◆ Argand diagram

- ✓ Replace the BW of $T_{c\bar{s}0}^a$ with spline points.
- ✓ **Lineshape consistent.**

$$B^0 \rightarrow \bar{D}^0 D_s^+ \pi^- \text{ \& } B^+ \rightarrow D^- D_s^+ \pi^+$$

- First observation of a doubly charged tetraquark and its neutral partner.

◆ Separate $T_{c\bar{s}0}^a$ 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
$T_{c\bar{s}0}^a(2900)^0$	$2.892 \pm 0.014 \pm 0.015$	$0.119 \pm 0.026 \pm 0.012$	8.0σ
$T_{c\bar{s}0}^a(2900)^{++}$	$2.921 \pm 0.017 \pm 0.019$	$0.137 \pm 0.032 \pm 0.014$	6.5σ

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

● Observation of a resonant structure near the $D_s^+ D_s^-$ threshold

- Theoretical studies suggest that the $\chi_{c0}(3930)$ may be dominated by $c\bar{c}s\bar{s}$ constituents.
- Search for $D_s^+ D_s^-$ resonance near mass threshold.

◆ 360 signal yields, Clear band near $D_s^+ D_s^-$ mass threshold.

◆ All possible charmonium and D^{**} resonances are tested.

◆ No significant $D_s K$ state ($> 3\sigma$).

◆ Baseline model: $1^{--} \psi(4260), \psi(4660)$ states, a non-resonant component, and $0^{++} X(3960), X_0(4140)$ states.

◆ $X(3960)$ parameterised by a Flatté-like formula ($D_s^+ D_s^-$ channel):

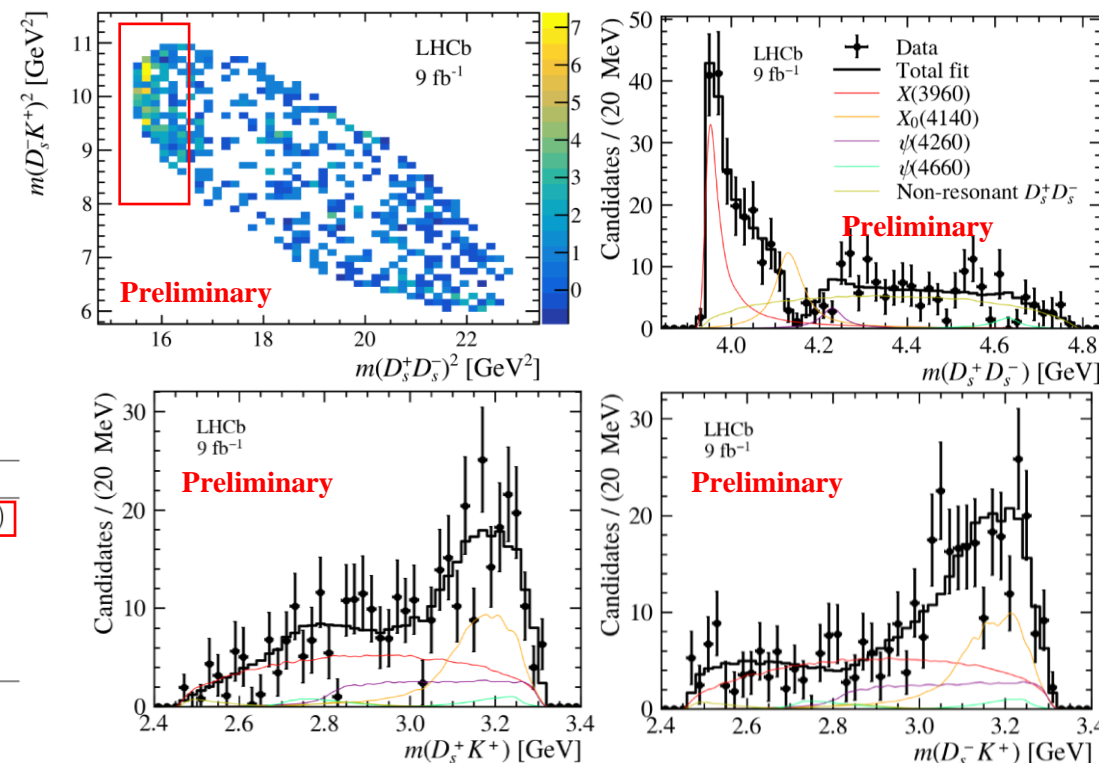
$$R(m | M_0, g_j) = \frac{1}{M_0^2 - m^2 - iM_0 \sum_j g_j \rho_j(m)},$$

✓ Fit result:

Component	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	\mathcal{F} (%)	\mathcal{S} (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 11$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 8.0$	12.6 (14.3)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 11$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 7.5$	3.7 (3.9)
$\psi(4260)$	1^{--}	4230 [59]	55 [59]	$3.6 \pm 0.4 \pm 3.0$	3.1 (3.3)
$\psi(4660)$	1^{--}	4633 [31]	64 [31]	$2.2 \pm 0.2 \pm 0.5$	2.9 (3.2)
NR	S -wave	-	-	$46.1 \pm 13.2 \pm 11.1$	3.1 (3.4)

	Mass (MeV)	Width (MeV)
$\chi_{c0}(3930)$	$3923.8 \pm 1.5 \pm 0.4$	$17.4 \pm 5.1 \pm 0.8$

Phys. Rev. D102, 112003



✓ $m(D_s^+ D_s^-)$ well described by fit model.

✓ The determined mass and width of $X(3960)$ are **consistent with the $\chi_{c0}(3930)$ observed in $B^+ \rightarrow D^+ D^- K^-$ analysis within 3σ .**

● Observation of a resonant structure near the $D_s^+ D_s^-$ threshold

➤ Whether $X(3960)$ and $\chi_{c0}(3930)$ states are the same resonance?

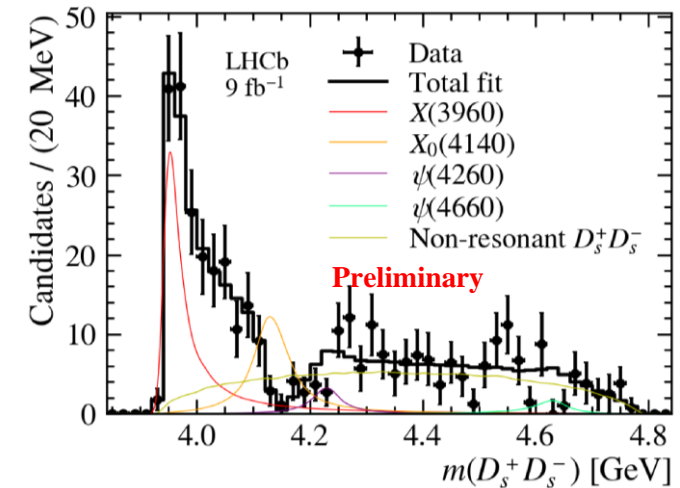
◆ Extended the Flatté-like formula, add $D^+ D^-$ channel.

- ✓ **Likelihood** is essentially **unchanged**.
- ✓ **Mass and width** are **consistent** with baseline model (0.5σ).

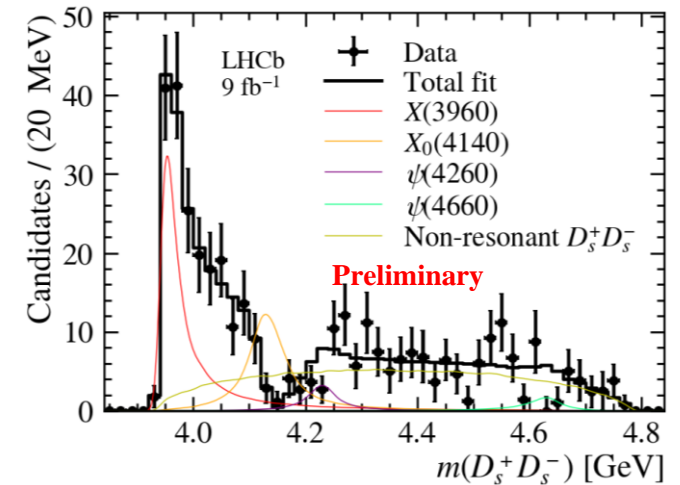
◆ Calculate the partial width ratio of X to $D^+ D^-$ and $D_s^+ D_s^-$:

$$\frac{\Gamma(X \rightarrow D^+ D^-)}{\Gamma(X \rightarrow D_s^+ D_s^-)} = \frac{\mathcal{B}^{(1)} \mathcal{F}_X^{(1)}}{\mathcal{B}^{(2)} \mathcal{F}_X^{(2)}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08,$$

- ✓ $\Gamma(X \rightarrow D^+ D^-)$ much smaller than $\Gamma(X \rightarrow D_s^+ D_s^-)$:
 - $X(3960)$ and $\chi_{c0}(3930)$ are **either not same state, or the same non-conventional charmonium-like state containing dominant $c\bar{c}s\bar{s}$ constituents**.



Baseline model



Extended Flatté

LHCb Preliminary

● Observation of a resonant structure near the $D_s^+ D_s^-$ threshold

- Whether the dip in $m(D_s^+ D_s^-)$ at 4.13 GeV relate to the nearby $J/\psi\phi$ threshold (4.12 GeV)?

◆ Employ a simple K -matrix model:

- ◆ Contains single $X(3960)$ state and two coupled channels, $D_s^+ D_s^-$ and $J/\psi\phi$.

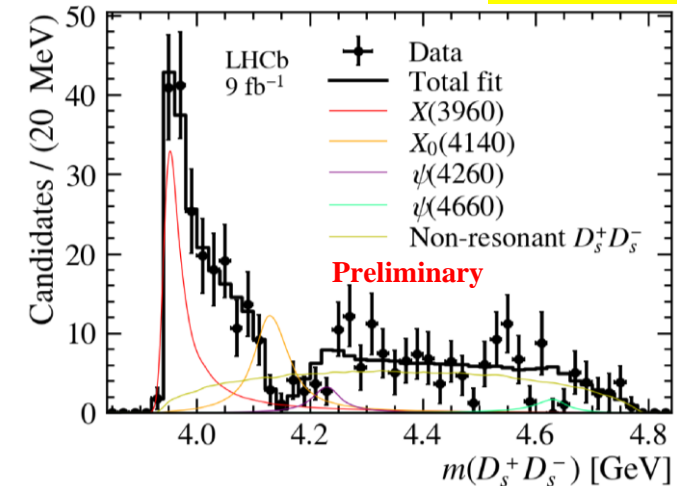
$$\begin{pmatrix} \mathcal{M}_{D_s^+ D_s^- \rightarrow D_s^+ D_s^-} & \mathcal{M}_{D_s^+ D_s^- \rightarrow J/\psi\phi} \\ \mathcal{M}_{J/\psi\phi \rightarrow D_s^+ D_s^-} & \mathcal{M}_{J/\psi\phi \rightarrow J/\psi\phi} \end{pmatrix} \equiv \begin{pmatrix} \mathcal{K}_{11} & \mathcal{K}_{12} \\ \mathcal{K}_{21} & \mathcal{K}_{22} \end{pmatrix}$$

✓ Fit quality consistent with baseline model:

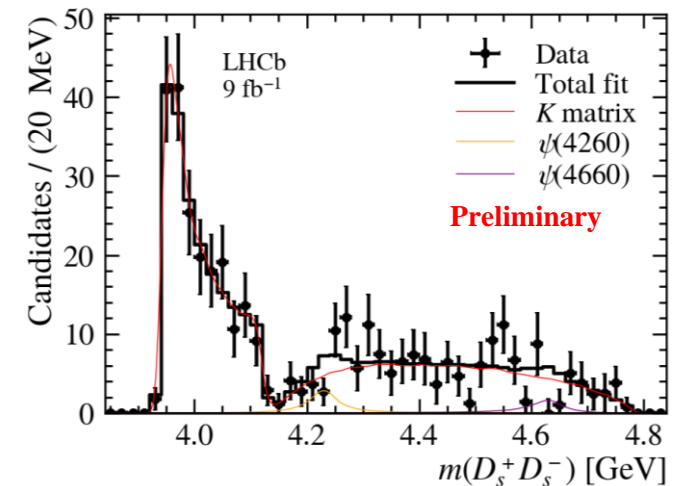
- ✓ $-2\ln\mathcal{L}$ is **worsen by 4.6**, while ndf is increased by 1.
- ✓ The dip is **well described** by the K -matrix model.

◆ The fit with two channels Flatté-like formular and K -matrix parameterizations are **unstable**.

- ✓ Neither of them is taken as baseline model.
- ✓ **More data samples are needed!**



Baseline model



K -matrix

- In the past two years, **great improvements on mesonic exotic states studies** have been performed in LHCb collaboration:

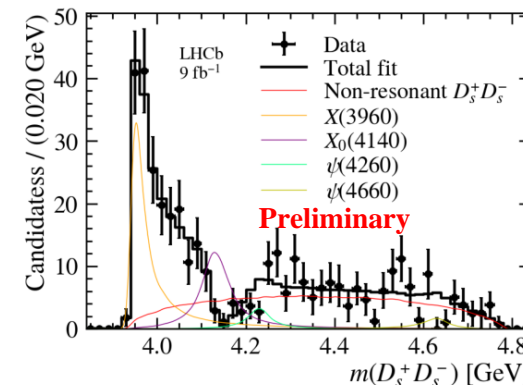
□ Open-charm:

- ✓ First open-charm tetraquark states: $X_{0,1}(2900)$,
- ✓ First doubly charm tetraquark state: T_{cc}^+
- ✓ First doubly charged tetraquark and its isospin partner: $T_{c\bar{s}}^a(2900)^{0,++}$

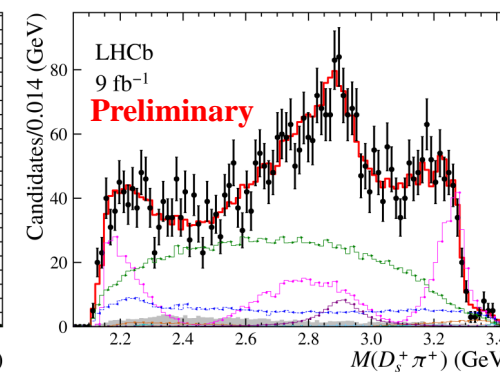
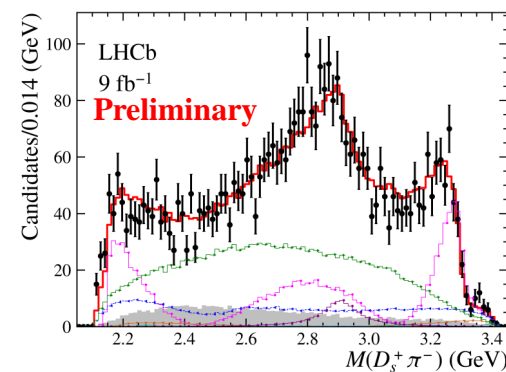
□ Hidden-charm:

- ✓ $D^+D^-: \chi_{c0}(3930)$
- ✓ $J/\psi K^+: Z_{cs}(4000)^+, Z_{cs}(4220)^+$
- ✓ $J/\psi \phi: X(4685), X(4630)$
- ✓ $\chi_{c1}(3872) \rightarrow \omega(\pi\pi)J/\psi$
- ✓ $D_s^+D_s^-: X(3960)$

- More analyses with LHCb Run 1 and Run 2 dataset are ongoing.
- LHC Run 3 data taking start recently.



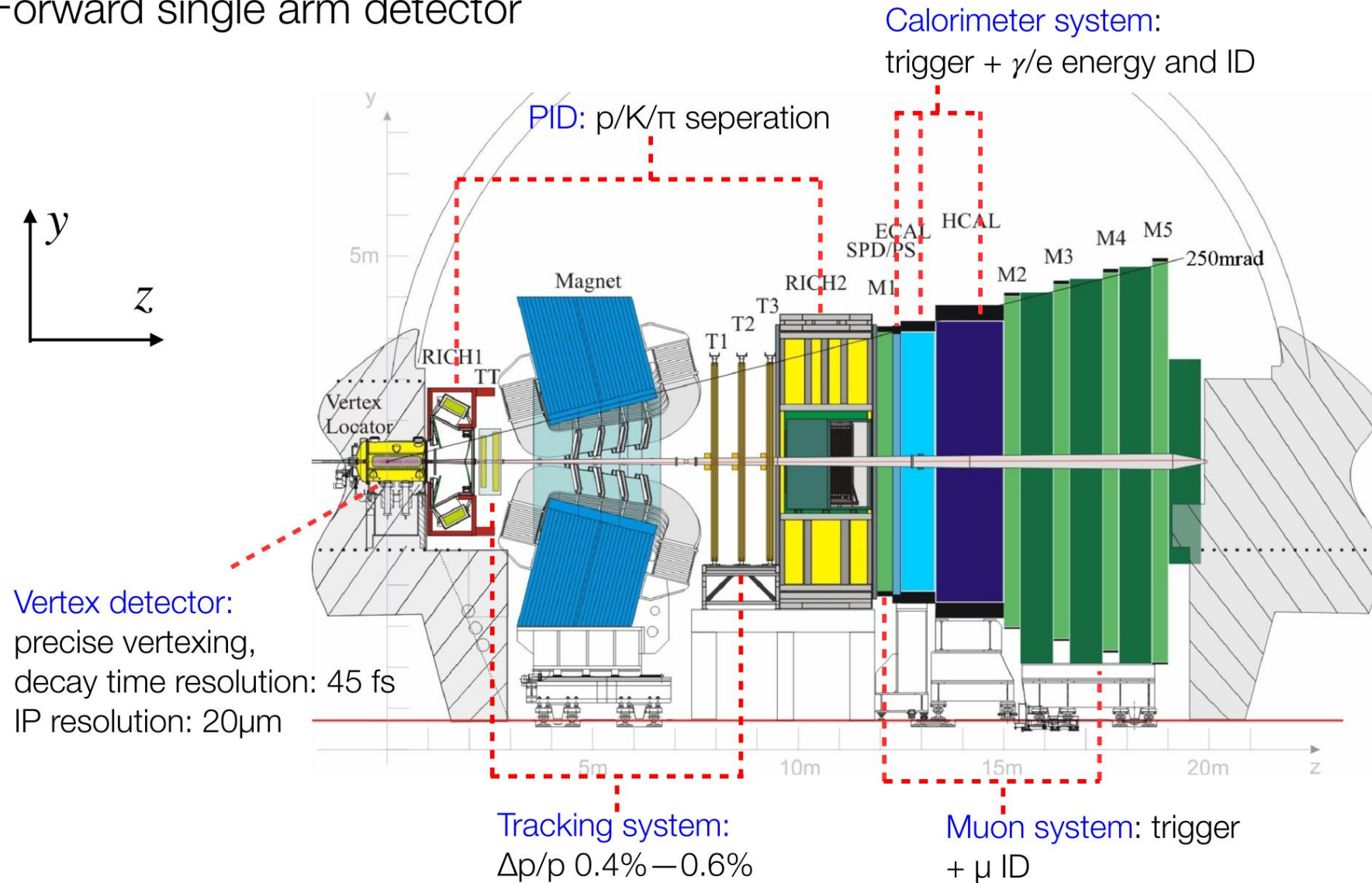
$X(3960)$



$T_{c\bar{s}}^a(2900)^{0,++}$

Back Up

Forward single arm detector



● Model-independent analysis of the $B^+ \rightarrow D^+ D^- K^+$ decay

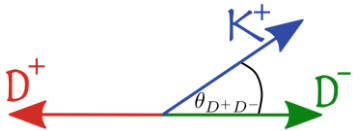
- Only charmonium states are expected to contribute to $B^+ \rightarrow D^+ D^- K^+$ decay.
- ✓ Clear $\psi(3770)$ and $\chi_{c2}(3930)$ peaks in $D^+ D^-$ spectrum.
- ✓ Obvious **peaking structures** in $D^- K^+$ spectrum at $8.5 \text{ GeV}^2/c^4$ ($2.9 \text{ GeV}/c^2$).

◆ Model-independent analysis :

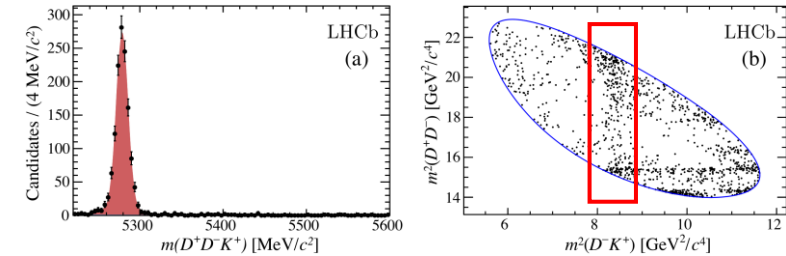
- ◆ Generate Phase space MC samples, and weighted by:

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

then project to $m(D^- K^+)$ and $m(D^+ K^+)$ spectra.



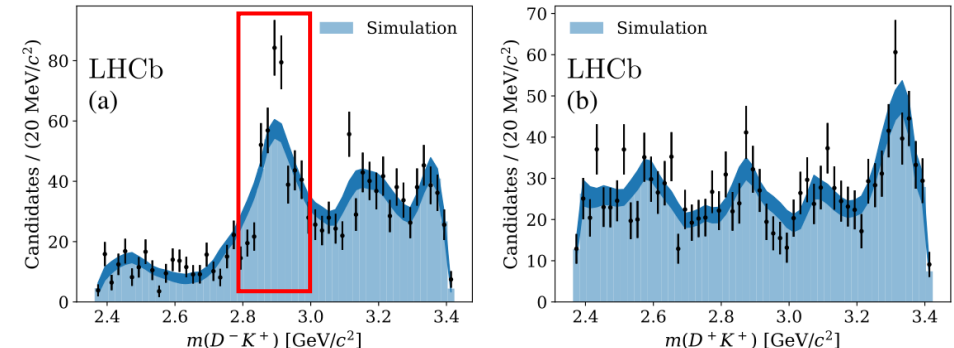
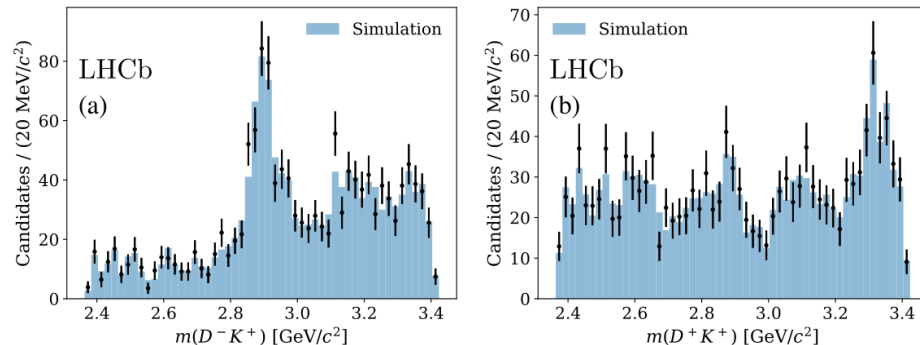
$$h(D^+ D^-) = \cos(\theta_{D^+ D^-})$$



$$P_k[h(D^+ D^-)] = \sqrt{\frac{2k+1}{2}} \times 2^k \sum_{r=0}^k [h(D^+ D^-)]^r \binom{k}{r} \left(\frac{k+r-1}{2} \right)$$

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

- ✓ $m(D^- K^+)$ could be well described with **high k_{max}** .
- ✓ **Clear deviation** on $m(D^- K^+)$ spectrum around $2.9 \text{ GeV}/c^2$ with $k_{max} = 4$ ($J_{max} = 2$).
- ✓ The **significance** of disagreement is estimated to be **3.9σ** with $k_{max} = 4$ and **3.7σ** with $k_{max} = 6$ by using test statistic.



● Amplitude analysis of the $B^+ \rightarrow D^+ D^- K^+$ decay

◆ Preform a model-dependent analysis to extract the parameter of the potential exotic state.

◆ Results with only $D^+ D^-$ resonances:

◆ Including $\psi(3770)$, $\chi_{c0}(3930)$, $\chi_{c2}(3930)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ resonances.

✓ $m(D^+ D^-)$ and $m(D^+ K^+)$ could be well described.

✓ Large deviation on $m(D^- K^+)$ spectrum around 2.9 GeV/c².

◆ Two $D^- K^+$ resonances are added:

□ $X_0(2900), J^P = 0^+$

- Mass: $2866 \pm 7 \pm 2 \text{ MeV}/c^2$
- Width: $57 \pm 12 \pm 4 \text{ MeV}$

□ $X_1(2900), J^P = 1^-$

- Mass: $2904 \pm 5 \pm 1 \text{ MeV}/c^2$
- Width: $110 \pm 11 \pm 4 \text{ MeV}$

◆ In $\chi_{cJ}(3930)$ region:

□ $\chi_{c0}(3930), J^P = 0^+$

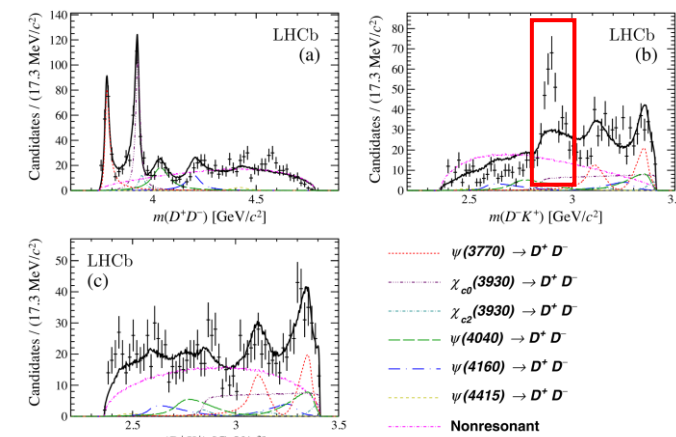
- Mass: $3923.8 \pm 1.5 \pm 0.4 \text{ MeV}/c^2$
- Width: $17.4 \pm 5.1 \pm 0.8 \text{ MeV}$

□ $\chi_{c2}(3930), J^P = 2^+$

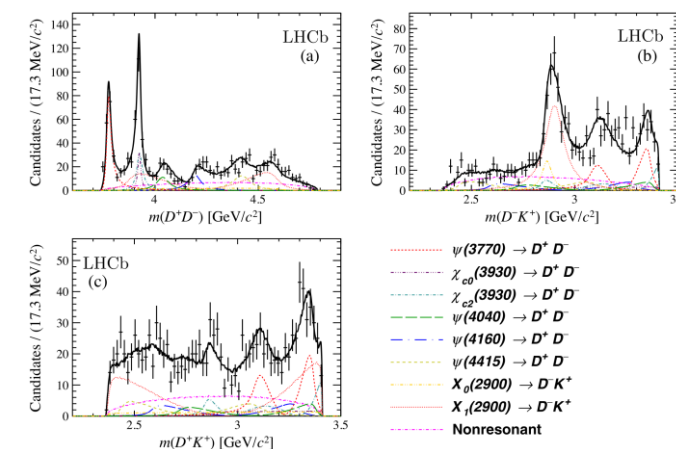
- Mass: $3926.8 \pm 2.4 \pm 0.8 \text{ MeV}/c^2$
- Width: $34.2 \pm 6.6 \pm 1.1 \text{ MeV}$

✓ With the **amplitude analysis**, two exotic $D^- K^+$ resonances with spin-0 and spin-1 are observed.

✓ Discovery of contributions from **spin-0 and spin-2 χ_{cJ} components** in the region of the existing $\chi_{c2}(3930)$.



Fitting result without $D^+ K^-$ resonances



Fitting result with $D^+ K^-$ resonances

● Observation of an exotic narrow doubly charmed tetraquark

- The existence of $QQ\bar{q}\bar{q}$ states have been widely discussed for a long time.
- Theoretical predictions for the mass of $cc\bar{u}\bar{d}$ state lie in the range $\delta m \in [-300, 300]$ MeV of $D^{*+}D^0$ mass threshold.

- ◆ Reconstruct the $D^0 D^0 \pi^+$ candidates by selecting two D^0 and a π^+ at same pp interaction point.
- ◆ Non- D^0 backgrounds are subtracted by a two-dimensional fit on D^0 versus D^0 mass spectra.
- ◆ Constrain D^0 mass to the known value.

✓ **Narrow peak near $D^{*+}D^0$ mass threshold!**

- ◆ Extract parameters of narrow peak by a fit:

- ◆ **Signal:** P-wave two-body ($D^0 D^0 + \pi^+$) Breit-Wigner function \otimes detector resolution.
- ◆ **Background:** two-body ($D^{*+} + D^0$) PHSP function + 2nd-order polynomial.

✓ Parameters are determined to be:

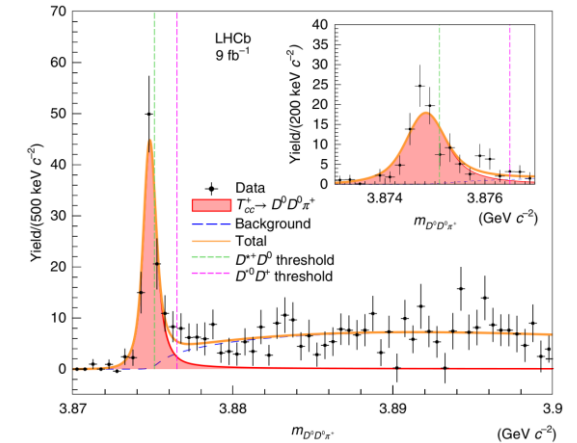
$$\delta m_{\text{BW}} = -273 \pm 61 \pm 5^{+11}_{-14} \text{ keV } c^{-2},$$

$$\Gamma_{\text{BW}} = 410 \pm 165 \pm 43^{+18}_{-38} \text{ keV},$$

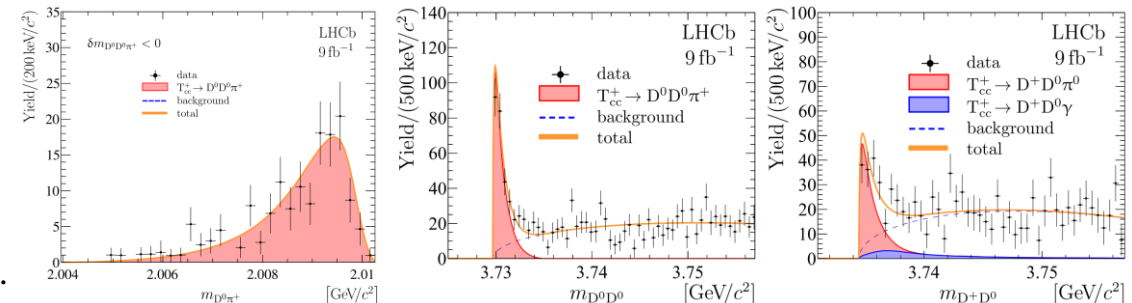
✓ First observation of a **doubly charmed tetraquark state:**

- ✓ The **narrowest** exotic state observed to date.
- ✓ Minimal quark content: **$cc\bar{u}\bar{d}$**
- ✓ Consistent with the expected **$1^+ T_{cc}^+$ isoscalar tetraquark ground state.**

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



◆ Further tests:



● Observation of New Resonances Decaying to $J/\psi K^+$ and $J/\psi \phi$

- The existence of the $Z_{cs} \rightarrow J/\psi K^+$ had been predicted.
- $Z_{cs}(3985)^+$ observed by BESIII in $(D_s^+ \bar{D}^{*0} + D_s^{*+} \bar{D}^0)$ final states.

◆ Run 1 result: Four $J/\psi \phi$ state observed, but no $J/\psi K^+$ resonance.

◆ Run 1 + 2:

- Distinct band near 16 GeV^2 of $J/\psi K^+$ mass squared.
- Run 1 model failed to describe the $m_{J/\psi K^+}$ distribution.

✓ The model requires improvements:

✓ Two new $J/\psi K^+$ states:

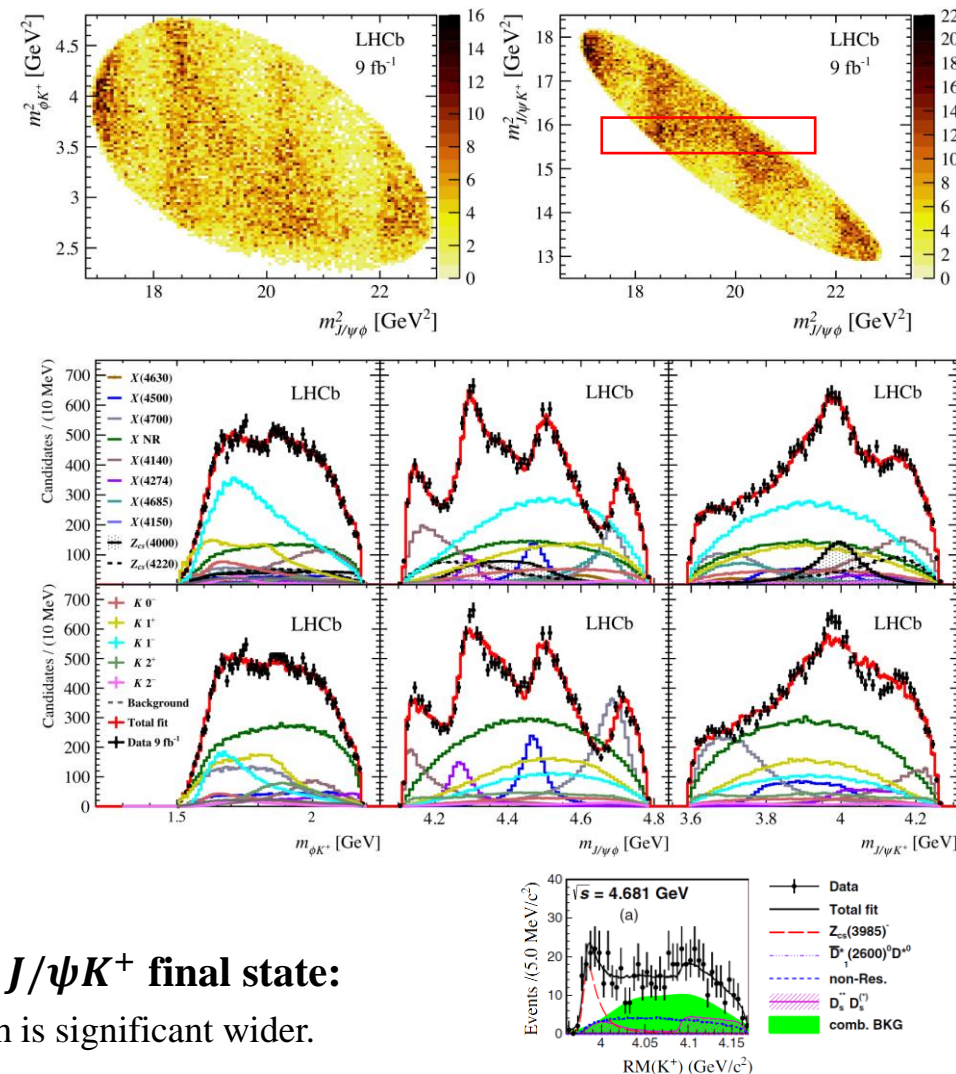
	Mass (MeV)	Width (MeV)	Spin-Parity
$Z_{cs}(4000)^+$	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	1^+
$Z_{cs}(4220)^+$	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$1^+ \text{ or } 1^-$

✓ Two new $J/\psi \phi$ states:

	Mass (MeV)	Width (MeV)	Spin-Parity
$X(4685)$	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	1^+
$X(4630)$	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	1^-

✓ First observation of a relatively narrow $Z_{cs}(4000)^+$ state decay to the $J/\psi K^+$ final state:

- ✓ Its mass consistent with $Z_{cs}(3985)^+$ observed by BESIII experiment, but width is significant wider.
- ✓ Further test support that they are different states.



BESIII result