Tetraquark studies in LHCb

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on behalf of the LHCb collaboration

@Implications of LHCb measurements and future prospects

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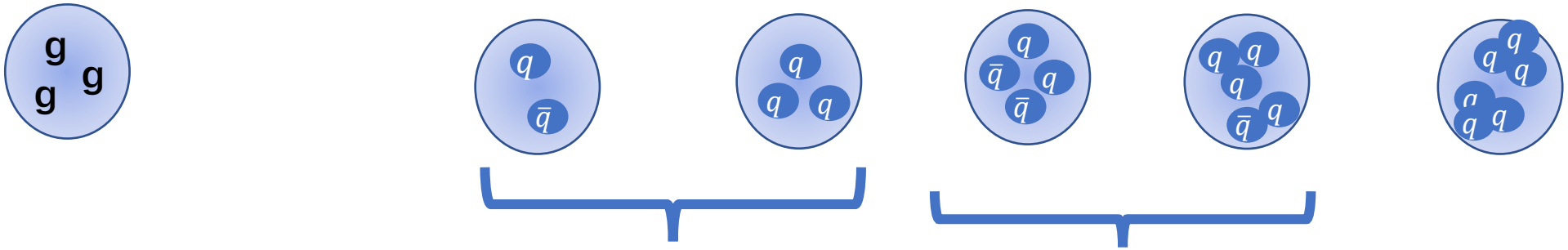
Outline

- Introduction
- $T^{a}_{c\bar{s}0}(2900)$ in $B \to DD_s\pi$ LHCb−PAPER−2022−026 in preparation LHCb−PAPER−2022−027 in preparation
- $X(3960)$ in $B^+ \to D_s^+ D_s^- K^+$ LHCb-PAPER-2022-018 in preparation
- $T^{\theta}_{\phi s1}(3960)$ in $B^0 \to J/\psi\phi K_S$ LHCb−PAPER−2022−040 in preparation
- $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$ **LHCB-PAPER-2021-045** arXiv:2204.12597
- Summary

Introduction

- Tetraquark: exotic meson composed of 4 valence quarks

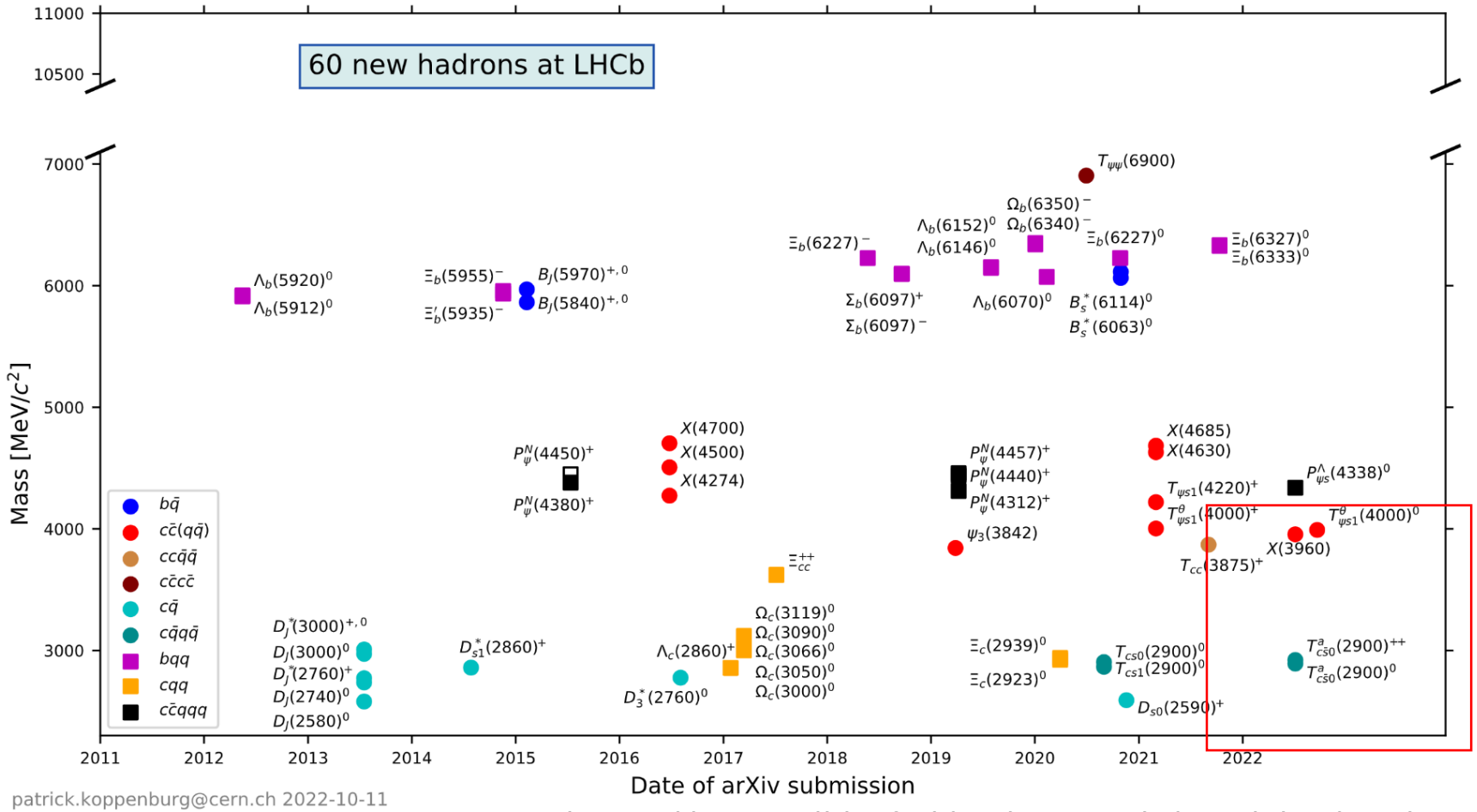
	glueball	quark	meson	baryon	tetraquark	pentaquark	others
Number of quarks	0	1	2	3	4	5	6 and more
candidates	-	-	π, K	p, n	$Z_c(3900)^+$	$P_c(4380)^+$	${}^{2}_{1}H^+$



Exotic states | classical quark model | Exotic states | Normal nucleon

Introduction

- 4 new tetraquark candidates in LHCb

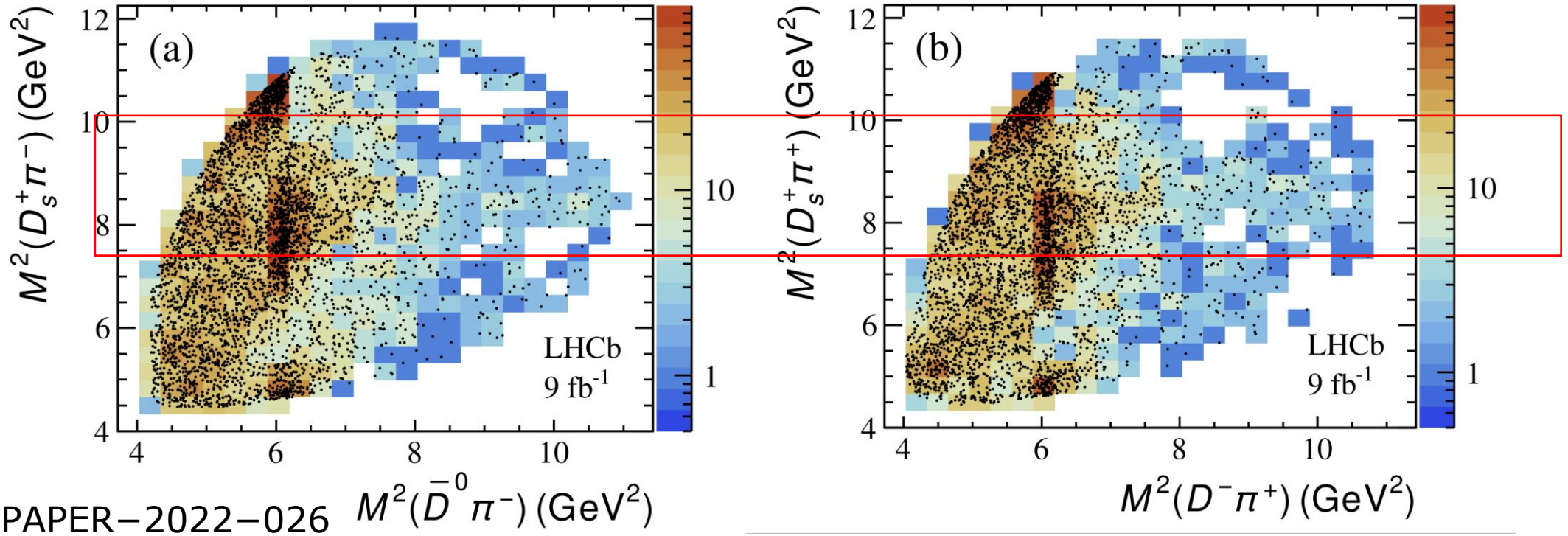


New states this year

https://www.nikhef.nl/~pkoppenb/particles.html

$B \to D D_s \pi$

- Isospin related decays: $B^0 \to \bar{D}^0 D_s^+ \pi^-$, $B^+ \to D^- D_s^+ \pi^+$
- Dominated by D^* states: $D_2^*(2460)$ et al.
- sign of $D_s \pi$ contribution



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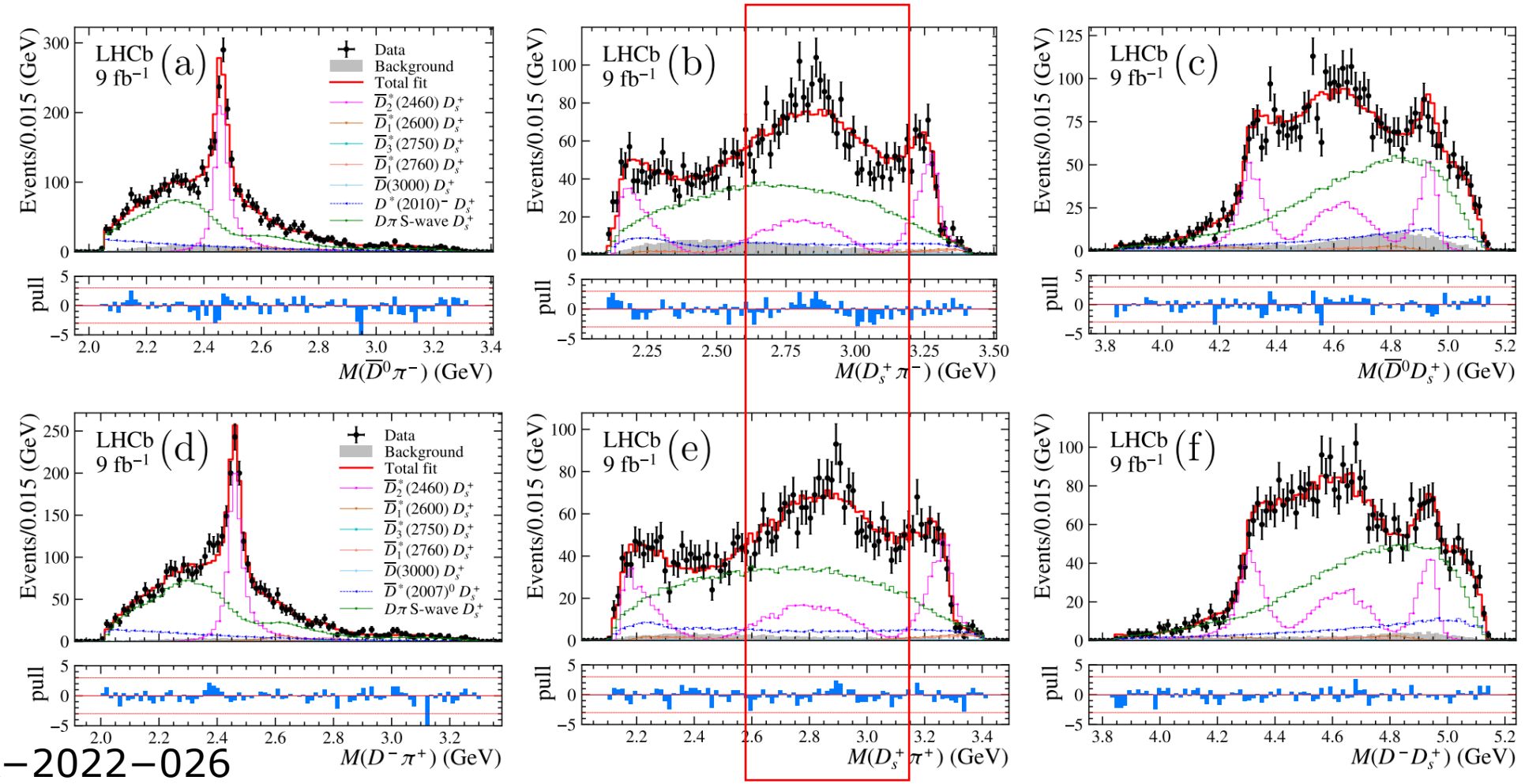
Amplitude analysis without new states

- Only D^* states and $D\pi$ S-wave, can not describe it well



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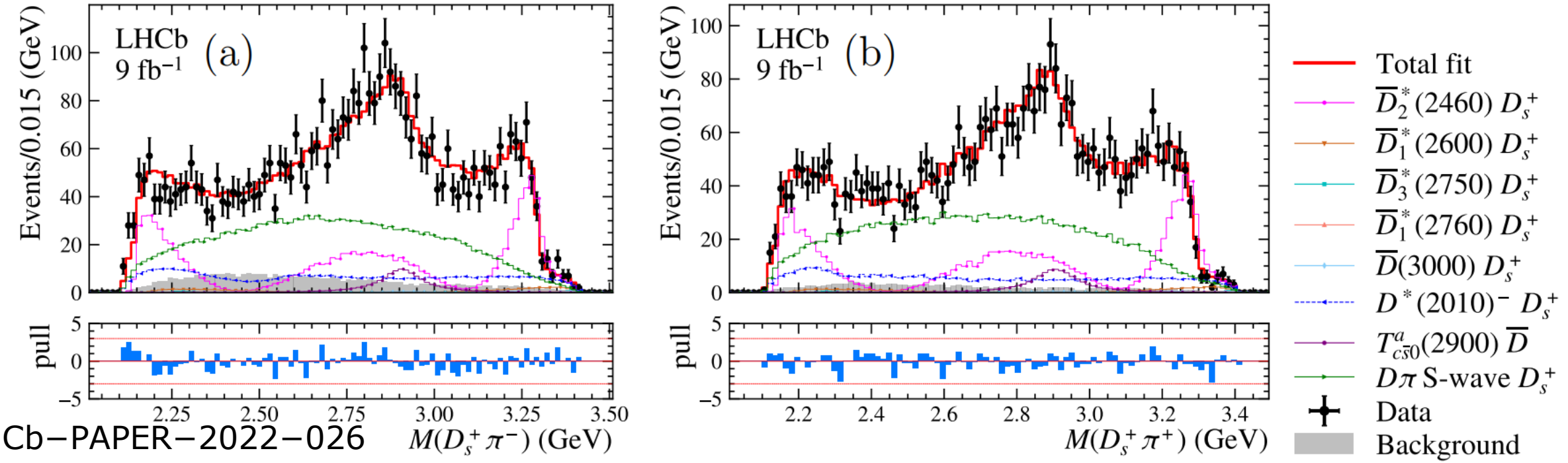
With $T_{c\bar{s}0}(2900)^{0,++}$

- New states $T_{c\bar{s}0}(2900)^{0,++}$
  - Mass: $2908 \pm 11 \pm 20$ MeV
  - Width: $136 \pm 23 \pm 11$ MeV
  - $> 9\,\sigma$ significant



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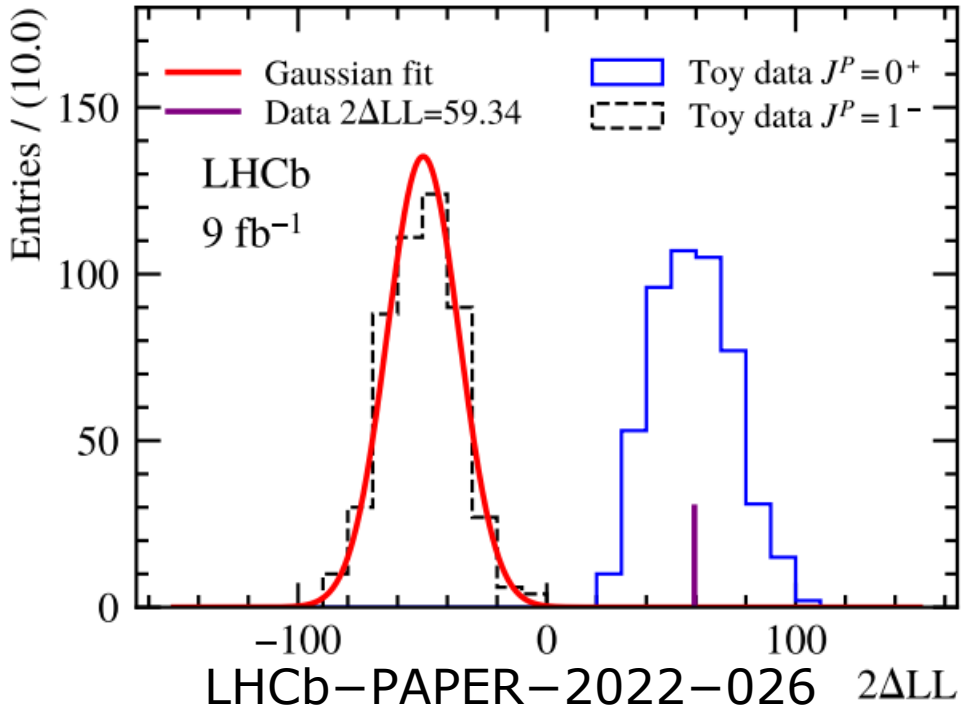
Properties of $T_{c\bar{s}0}(2900)^{0,++}$

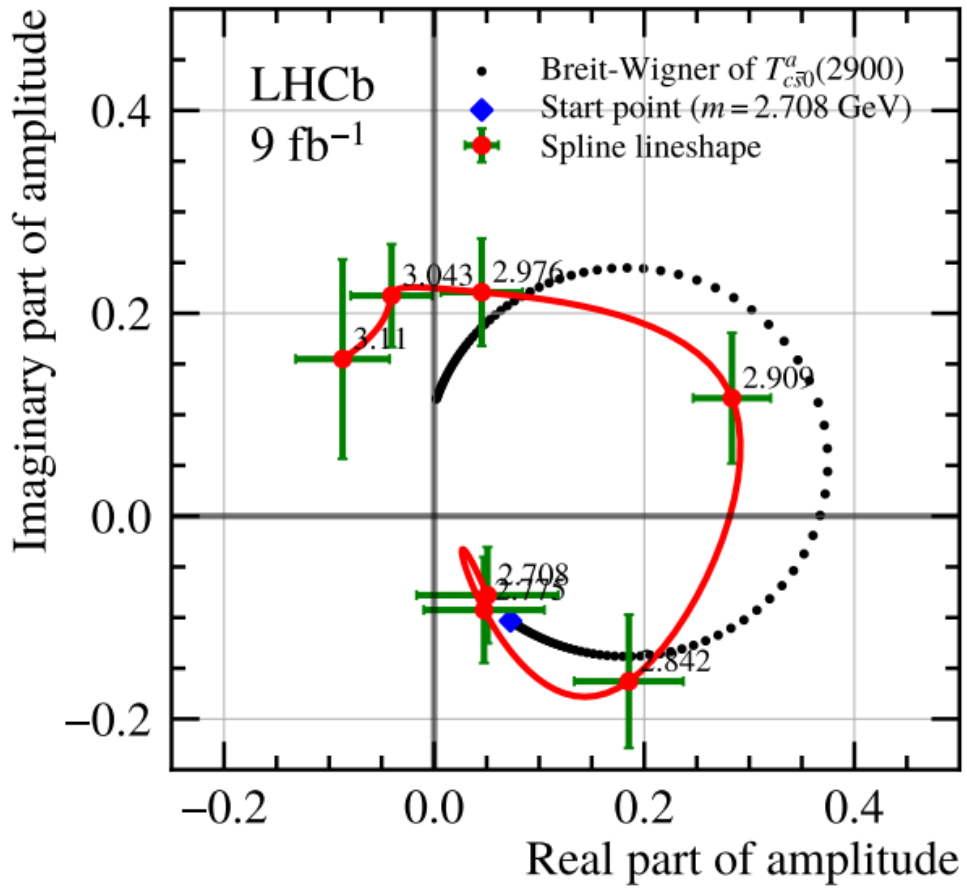
	Mass (MeV/c^2)	Width (MeV)	significances
$T^a_{c\bar{s}0}(2900)^0$	$2892 \pm 14 \pm 15$	$119 \pm 26 \pm 12$	8.0σ
$T^a_{c\bar{s}0}(2900)^{++}$	$2921 \pm 17 \pm 19$	$137 \pm 32 \pm 14$	6.5σ
Constraint as same	$2908 \pm 11 \pm 20$	$136 \pm 23 \pm 11$	$> 9\sigma$

- Remove constrains of mass and width
  - Consists with the same mass and width
  - Single states are also significant
- Spin Parity: prefer 0^+ states
  - Only 1^- states is 6.3σ significant
  - 7.5σ significant for 0^+ states over 1^-
  - 1.3σ for additional 1^- when including 0^+



Model independent results

- Validation of lineshape
  - Normal states have Breit-Wigner like shape
- Breit-Wigner Model
  - Circle in Argand diagram
- Model independent
  - Spline function
  - 7 interpolation points
  - Mostly consist with Breit-Wigner
- Agree with new states in $D_s\pi$



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Relation to $X_0(2900)$ in $D^+D^-K^+$

$$T^a_{c\bar{s}0}(2900) \to D_s^+\pi^\pm$$

- Spin parity: 0^+
- Charge: 0, +2
- Quark combination
  - $c\bar{s}u\bar{d},\ c\bar{s}d\bar{u}$
- Mass: $2908 \pm 11 \pm 20$ MeV
- Width: $136 \pm 23 \pm 11$ MeV

$$X_0(2900)/T_{cs0}(2900) \to D^+K^-$$

- Spin parity : $0^+, 1^-$
- Charge: 0
- Quark combination
  - $cs\bar{u}\bar{d}$

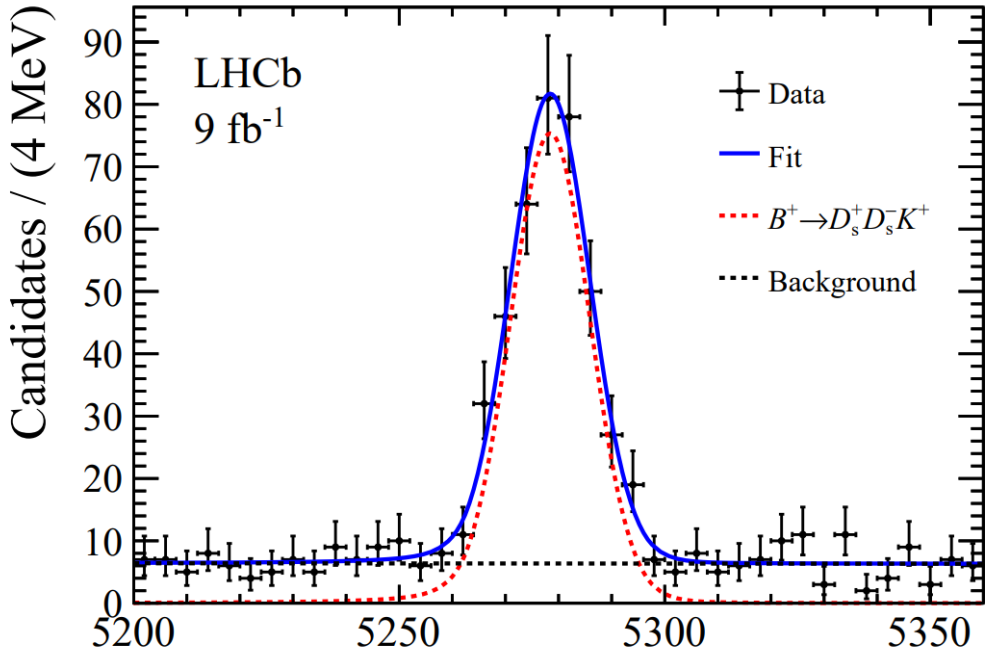
How about $D^+K^+(c\bar{s}d\bar{u})$?

- Mass: $2866 \pm 7 \pm 2$ MeV
- Width: $57 \pm 12 \pm 4$ MeV

Similar quark combination, but $s \Leftrightarrow \bar{s}$
$T^a_{c\bar{s}0}(2900)$ mass and width larger than $T_{cs0}(2900)$

$B^+ \to D_s^+ D_s^- K^+$

- $\frac{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)}{\mathcal{B}(B^+ \to D^+ D^- K^+)} = 0.525 \pm 0.033 \pm 0.027 \pm 0.034$
- Relative pure data in LHCb



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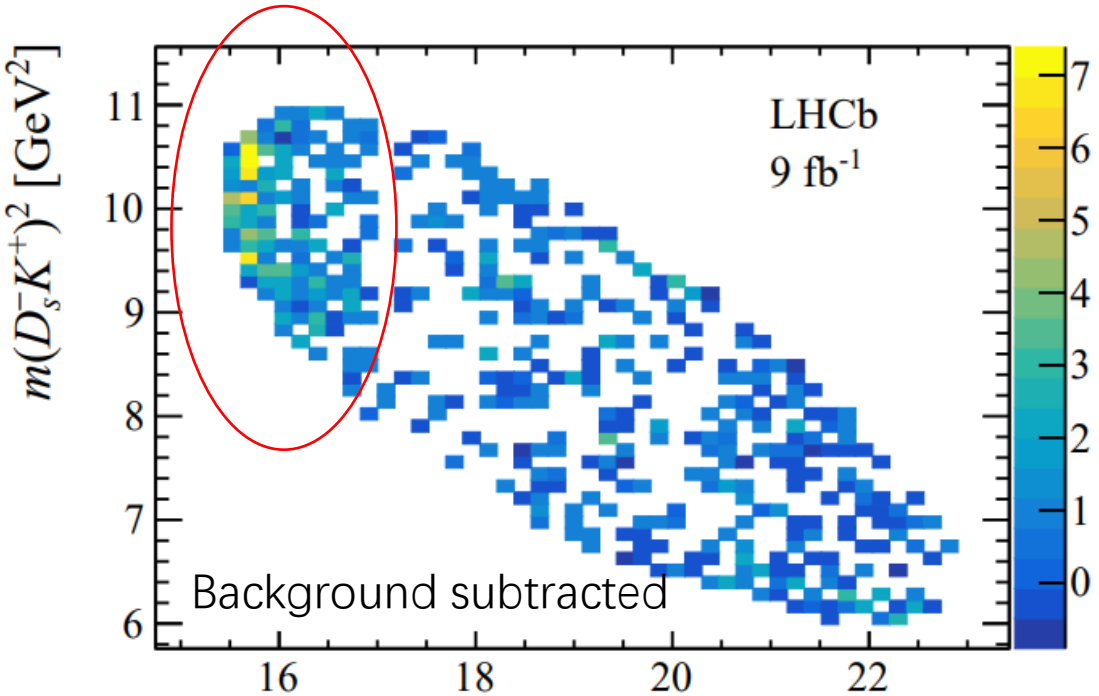
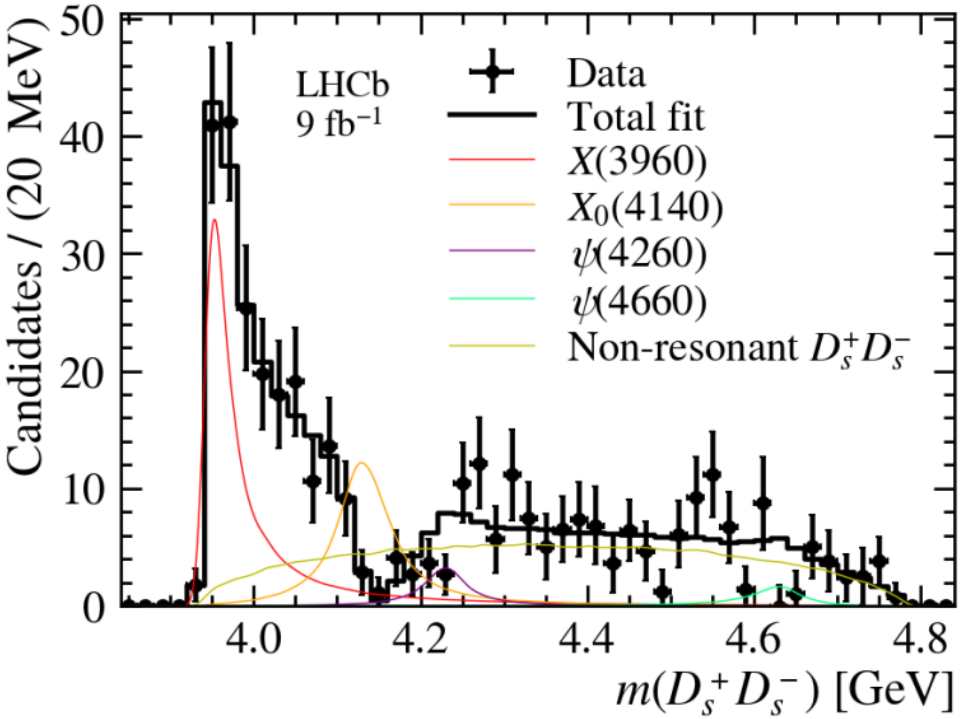
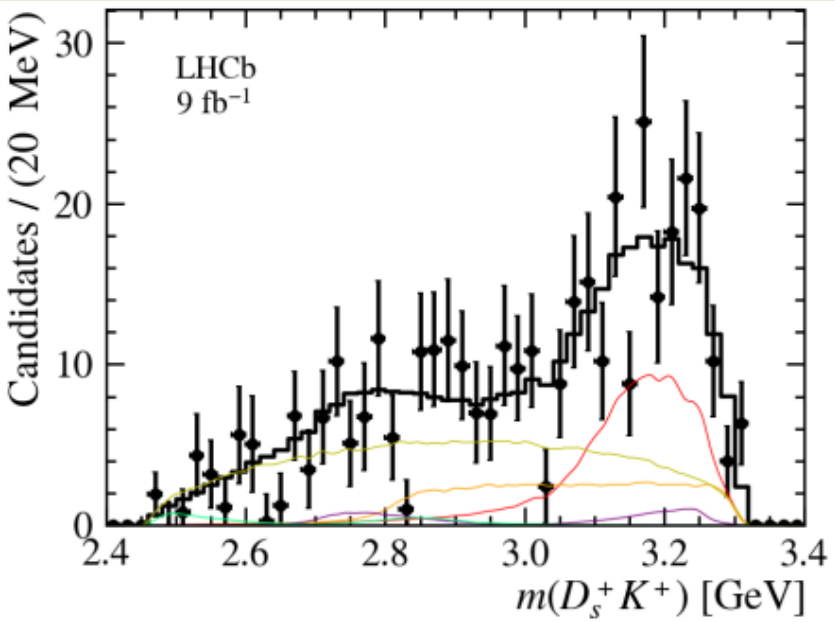


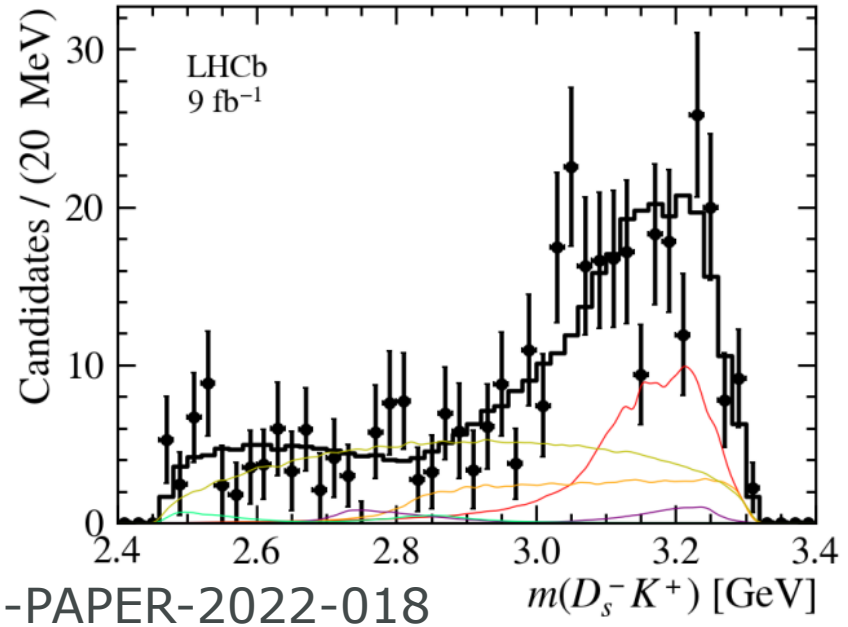
LHCb-PAPER-2022-018

Amplitude analysis

- New state X(3960): 0^{++} , 12.6σ
  - Mass: $3956 \pm 5 \pm 10$ MeV
  - Width: $43 \pm 13 \pm 8$ MeV
  - Close to $D_s^+ D_s^-$ threshold







LHCb-PAPER-2022-018

Relation to $\chi_{c0}(3930)$ in DDK

$X(3960) \to D_s^+ D_s^-$

- Spin parity: 0^{++}
- Mass and width
  - Mass: $3956 \pm 5 \pm 10$ MeV
  - Width: $43 \pm 13 \pm 8$ MeV

$\chi_{c0}(3930) \to D^+ D^-$

- Spin parity: 0^{++}
- Mass and width
  - Mass: $3923.8 \pm 1.5 \pm 0.4$ MeV
  - Width: $17.4 \pm 5.1 \pm 0.8$ MeV

If $X(3960)$ is $\chi_{c0}(3930)$

$$\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^-)} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08 < 1$$

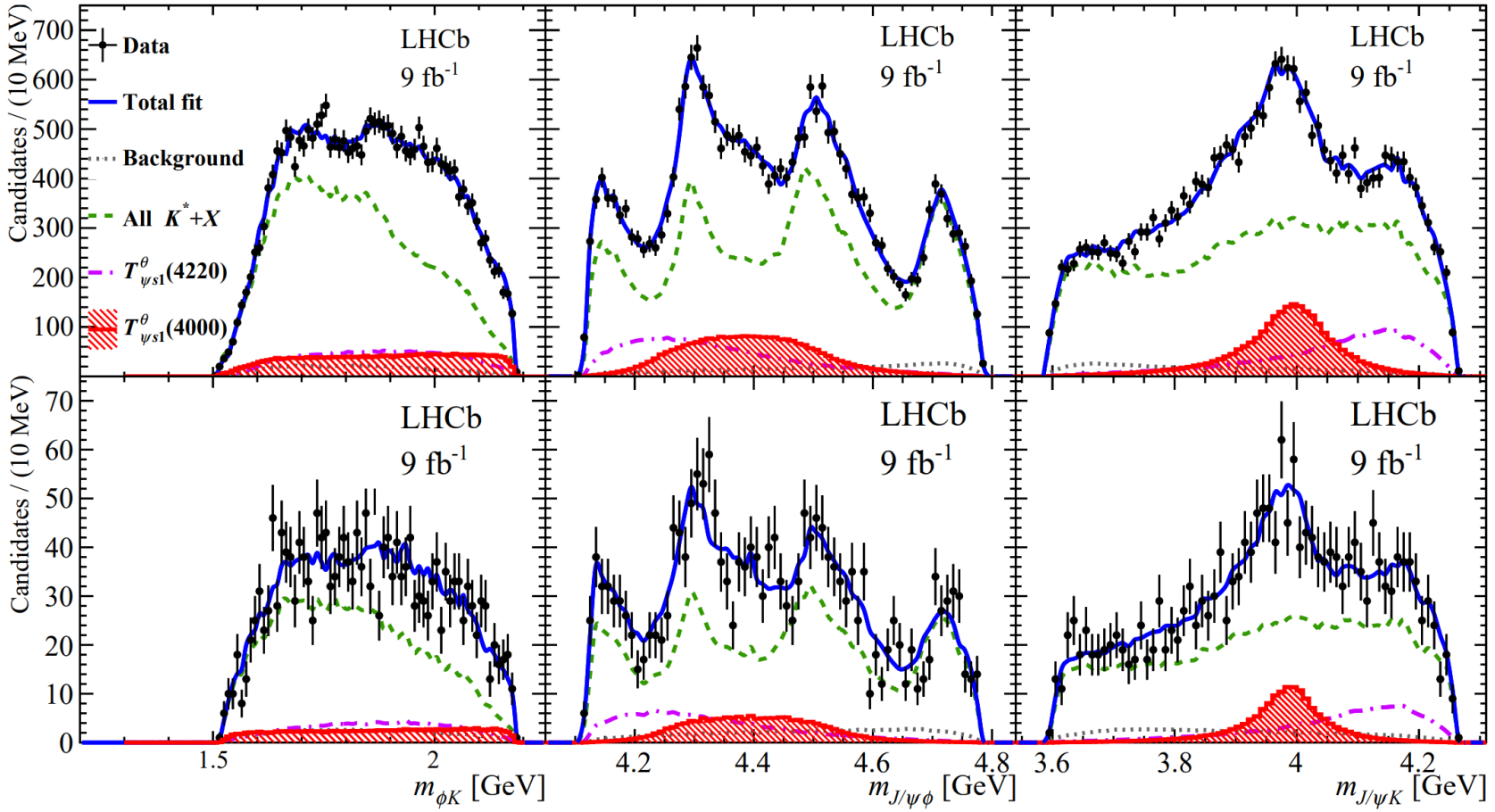
$X(3960)$ should have $s\bar{s}$ components for large fraction for $D_s^+ D_s^-$

$T^{\theta}_{\psi s1}(4000)^0$ in $B^0 \to J/\psi\phi K^0_S$

- Similar as $B^+ \to J/\psi\phi K^+$ (PRL.127.082001)

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

$B^0 \to J/\psi\phi K_S$



LHCb−PAPER−2022−040

$T^{\theta}_{\psi s1}(4000)^0$ vs $Z_{cs}(4000)^+/T^{\theta}_{\psi s1}(4000)^+$

- Properties

	J^P	Mass (MeV/c^2)	Width (MeV)	Fit fraction
$T^{\theta}_{\psi s1}(4000)^0 \to J/\psi K^0_S$	1^+	$3991.3^{+11.7+8.5}_{-10.4-16.7}$	$104.8^{+29.3+17.1}_{-25.3-23.3}$	$7.9 \pm 2.5^{+3.0}_{-2.8}$
$Z^+_{cs}/T^{\theta}_{\psi s1}(4000)^+ \to J/\psi K^+$	1^+	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$

- Consistent with being isospin partners
  - $\Delta m = -12.1^{+11.1+6.0}_{-10.2-4.2}$
- Significance from simultaneous fits
  - $B^0 \to J/\psi\phi K_S$ and $B^+ \to J/\psi\phi K^+$ together
  - 4.0σ without isospin symmetry for $T^{\theta}_{\psi s1}$
  - 5.4σ with isospin symmetry constrains

$\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$

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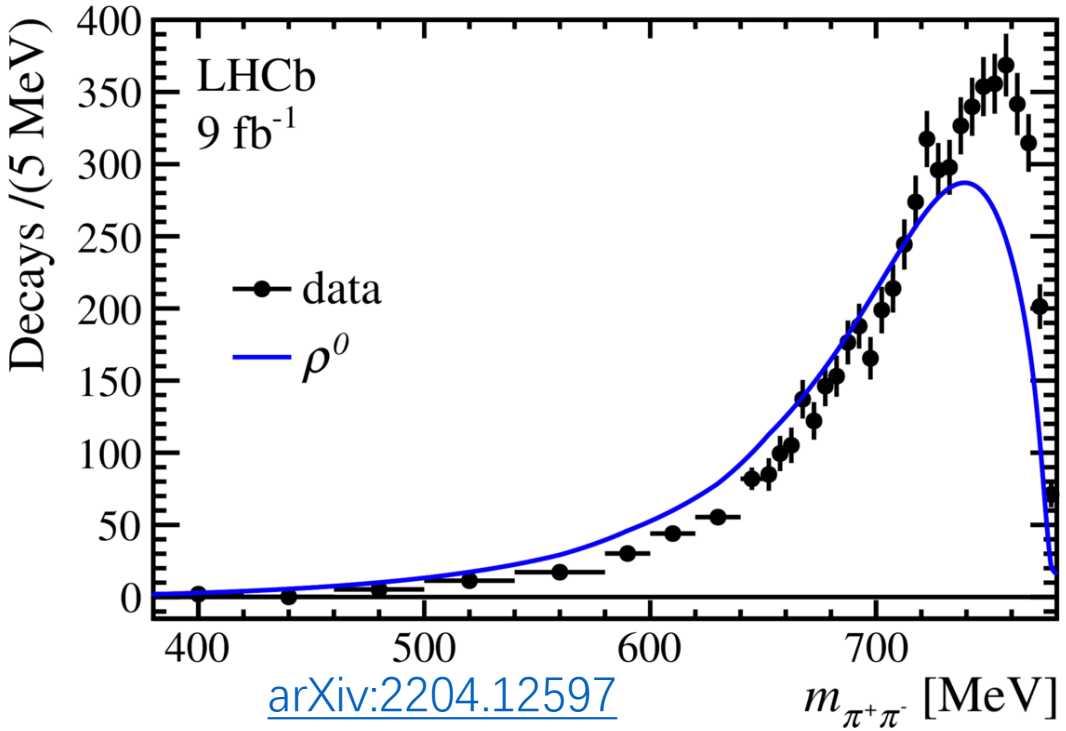
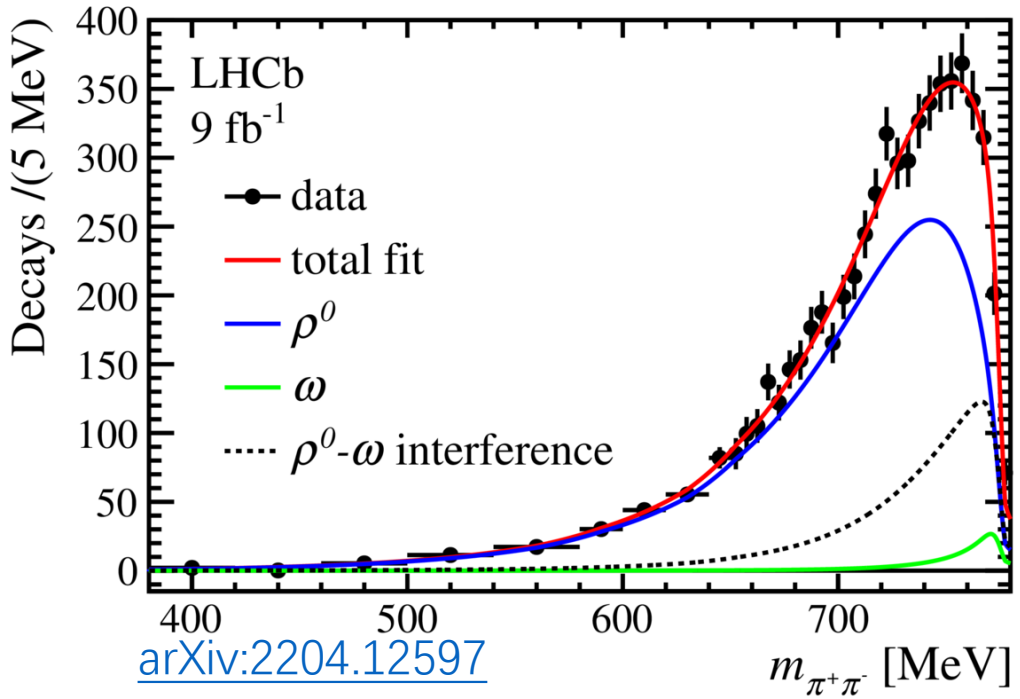
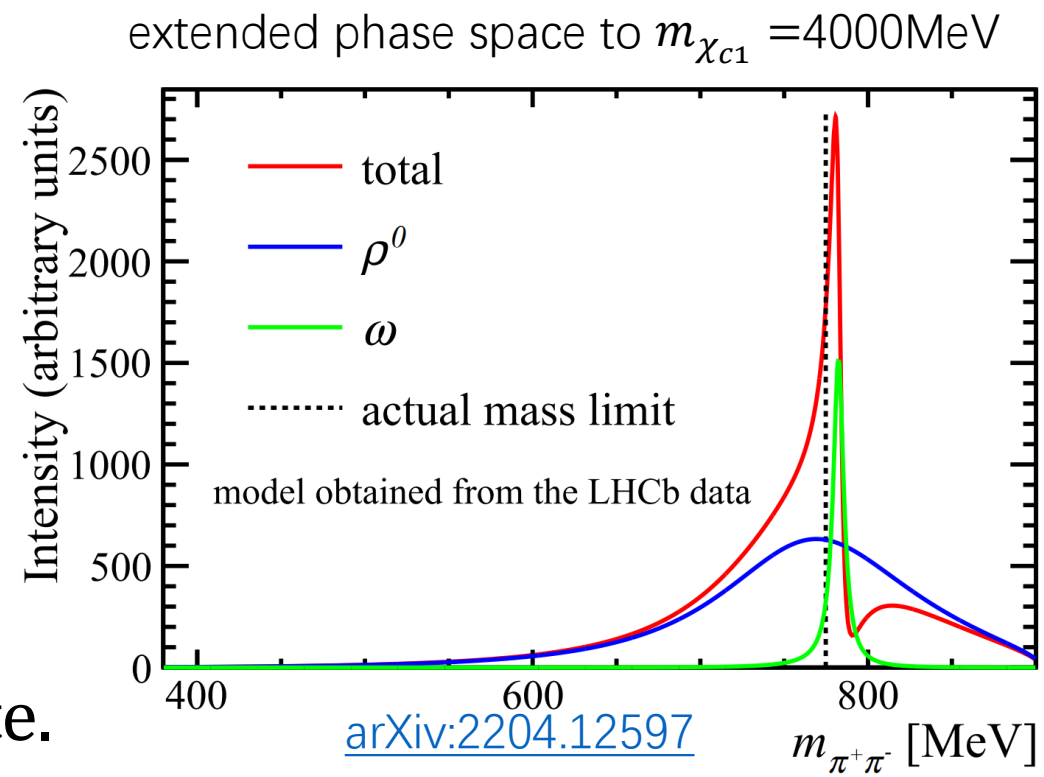
- Using $\chi_{c1}(3872) \to \rho^0 J/\psi$ only do not fit well
- sizeable $\chi_{c1}(3872) \to \omega J/\psi$ contribution:
  - Including interference: $(21.4 \pm 2.3 \pm 2.0)\%$
  - Pure: $(1.9 \pm 0.4 \pm 0.3)\%$





Isospin violation

- $\chi_{c1}(3872)$
  - $\chi_{c1} \to \omega J/\psi$ conserves isospin
  - $\chi_{c1} \to \rho J/\psi$ violates isospin
- Violation estimated for couplings
  - $\frac{g_{\chi_{c1}\to\rho J/\psi}}{g_{\chi_{c1}\to\omega J/\psi}} = \sqrt{\frac{\mathcal{B}(\omega\to 2\pi)}{R'_{\omega/\rho}}} = 0.29 \pm 0.04$
  - Compare to $\frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = 0.045 \pm 0.001$
- Too large isospin violation for $\chi_{c1}(3872)$ to be a pure charmonium state.



Summary

- 3 new tetraquark candidates found in LHCb.
- $T^{a}_{c\bar{s}0}(2900)^{0,++}$ in $B \to DD_s\,\pi$
  - 0^+, mass=2908 $\pm$ 11 $\pm$ 20 MeV, width= 136 $\pm$ 23 $\pm$ 11 MeV
  - First doubly charged tetraquark candidate
  - Similar quark components with $X(2900) \to DK$
- $X(3960)$ in $B^+ \to D_s^+ D_s^- K^+$
  - 0^{++}, mass= 3956 $\pm$ 5 $\pm$ 10 MeV, width= 43 $\pm$ 13 $\pm$ 8 MeV
  - If same as $X(3930)$, $X(3960)$ should have $s\bar{s}$ component
- $T^{\theta}_{\psi s1}(4000)^0$ in $B^0 \to J/\psi\phi K_S^0$
  - isospin partner of $Z_{cs}(4000)$
- Observed $\chi_{c1}(3872) \to \omega J/\psi$ in $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$

Thank you for your attention!

backup

Search for new states in $B^+ \to (J/\psi\eta)K^+$

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- Scan the $J/\psi\eta$ mass with new states, check the fraction