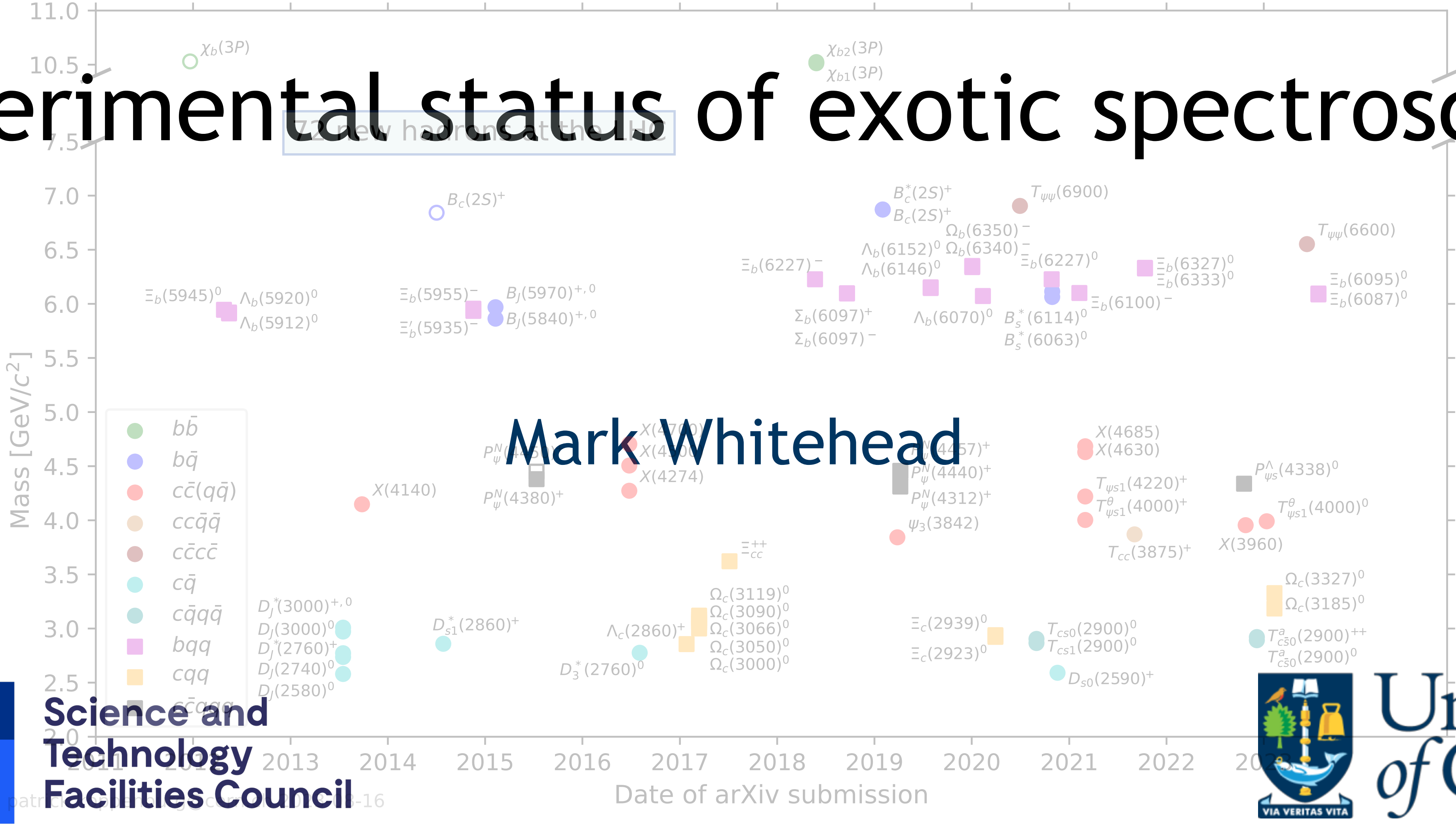
Experimental status of exotic spectroscopy



Mark Whitehead

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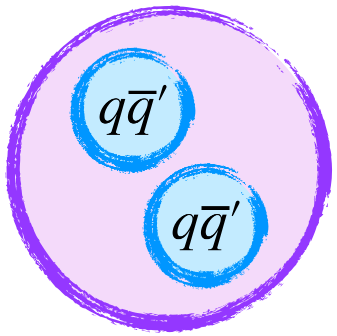
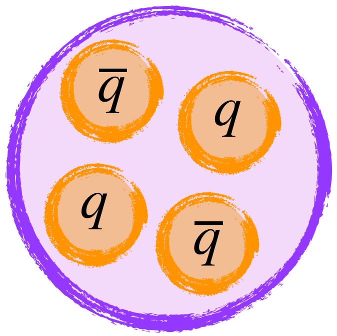
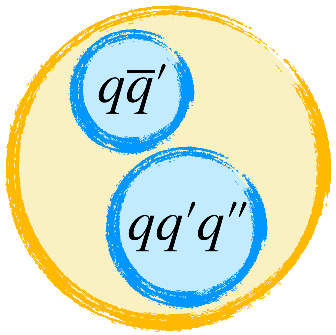
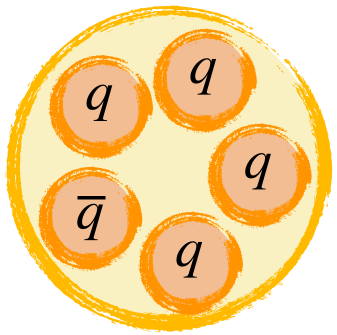
Disclaimer

- Strong personal bias
  - Focus on recent candidates with charm quarks
  - Focus on the latest results from the LHCb experiment
  - It goes without saying interesting work on going elsewhere e.g. BES III and Belle II
  - Exotic spectroscopy also a hot topic in light quark studies
    - Recent reviews see e.g. UK workshop: Exotic Hadron Spectroscopy 2023









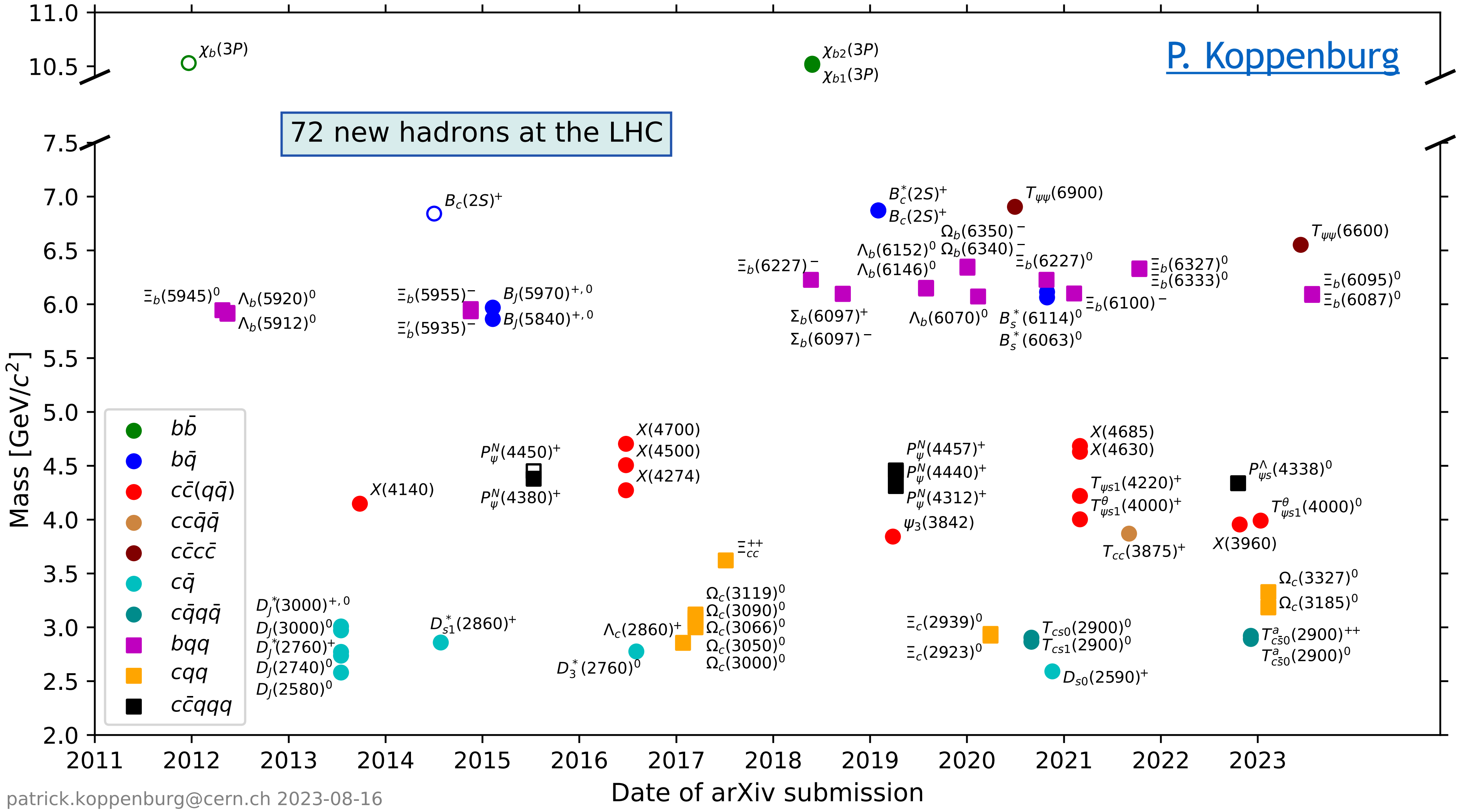
Contents

- Brief introduction
- Reminder of the LHCb experiment
- Recent results from LHCb
  - Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays
  - Study of the $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ decay
  - Study of $B^0 \to J/\psi \phi K_S^0$ decays
- Future prospects

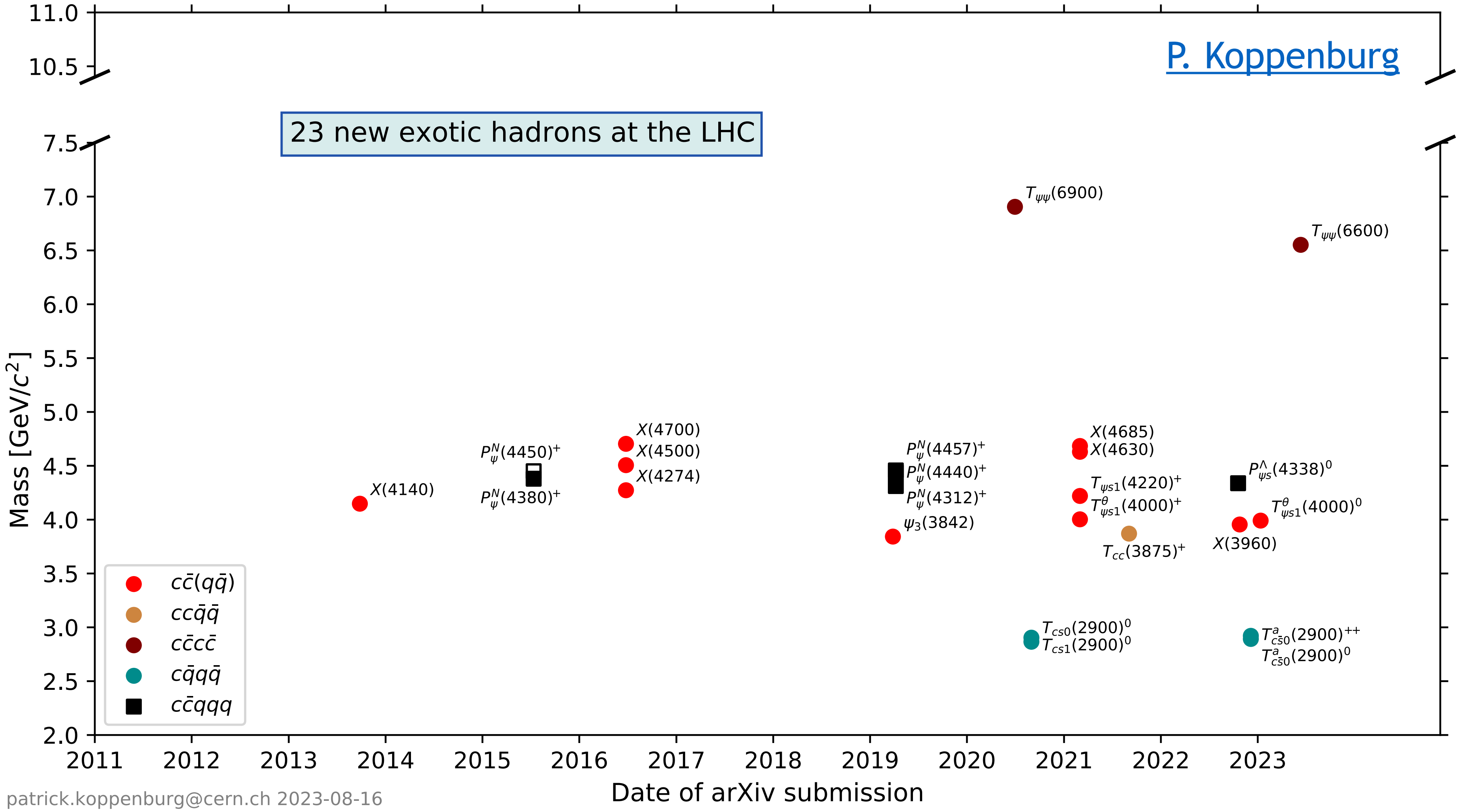
Introduction

- Spectroscopy remains a hot topic in particle physics
  - 72 new states discovered at the LHC (no, we didn't start/stop with the Higgs!)
  - 64 of those were discovered by LHCb, including 20+ exotic candidates
- For "standard" mesons and baryons
  - Do the spectra and particle properties agree with QCD calculations?
  - Are they really "standard"?
- For exotic candidates (non $q\bar{q}'$ nor $qq'q''$ states)
  - What are their internal quark structures?
  - Are they all similar or different?
  - Where are the hexaquark candidates?

Introduction

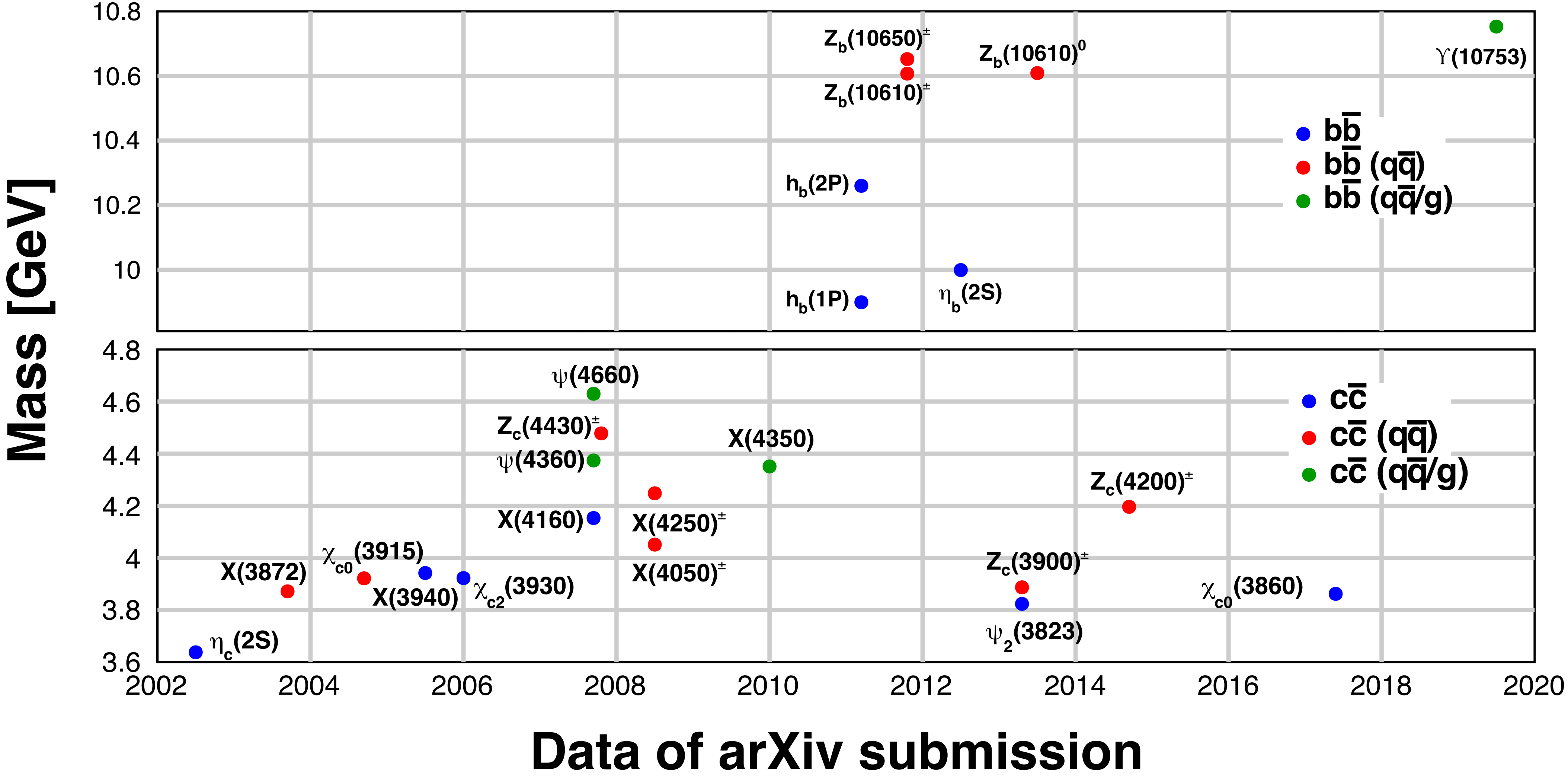


Introduction



Introduction

Belle



Sen Jia et al 2023 Chinese Phys. Lett. **40** 121301

How do we know if something is exotic?

- Can study the quarks in the final state particles
  - Strong interaction conserves quark flavour and all quantum numbers

- Lets look at an example
  - For a strong decay, expect to see a $q\bar{q}$ pair in the final state quarks e.g.

$$D^{*+} \rightarrow D^0 \pi^+$$
$$(c\bar{d}) \quad (c\bar{u})(u\bar{d})$$

  - What about $T_{cs0}(2900)^0$ first seen in the D^-K^+ final state

$$T_{cs0}(2900)^0 \rightarrow D^- K^+$$
$$(??) \quad (\bar{c}d)\ (\bar{s}u)$$

No associated strong decay of a meson of baryon

Isn’t it really just stamp collecting?

- Hopefully I don’t need to convince you that it isn’t!
  - Several puzzles in spectroscopy, clearly exotic states are just one them
  - Important to test our various models of QCD (lattice, HQET etc)

- There is nothing wrong with being excited about making discoveries!
  - Of course it is important to learn as much as possible from measurements
  - Let’s not loose the excitement and passion for finding something new though!

- Most cited LHCb paper?
  - CP violation?
  - Flavour anomalies?

Isn’t it really just stamp collecting?

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  - Several puzzles in spectroscopy, clearly exotic states are just one them
  - Important to test our various models of QCD (lattice, HQET etc)
- There i … ries!
  - Of co … nts
  - Let’s … hough!

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays #2

LHCb Collaboration • Roel Aaij (CERN) et al. (Jul 13, 2015)

Published in: *Phys.Rev.Lett.* 115 (2015) 072001 • e-Print: 1507.03414 [hep-ex]

pdf links DOI cite claim reference search 1,637 citations

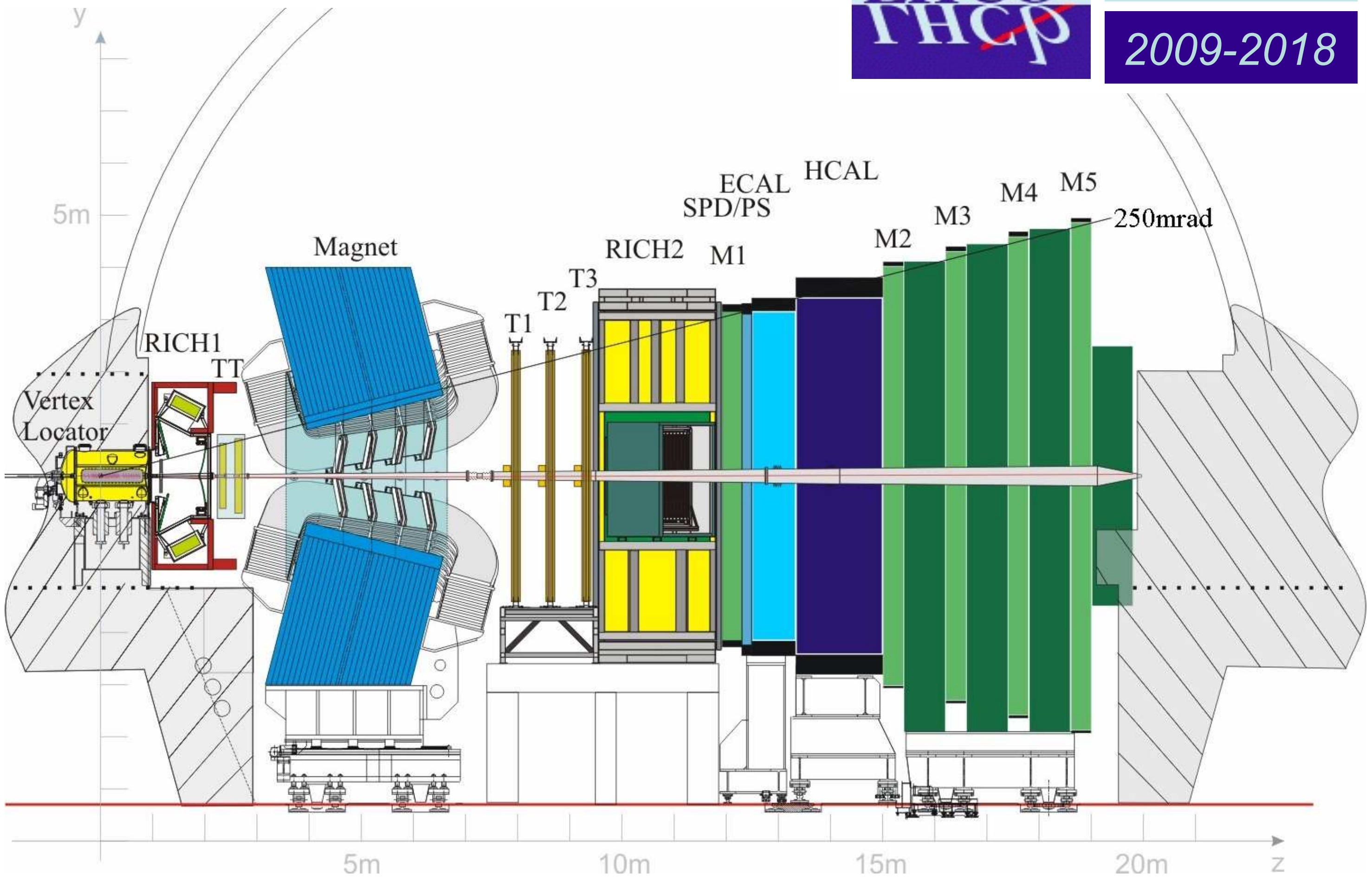
- Most cited LHCb paper?
  - CP violation?
  - Flavour anomalies?

Why the focus on LHCb?

- Designed to study weak decays of heavy hadrons
  - Excellent track and vertex resolution provides high purity samples (>90%) easily for fully reconstructed decays

- Heavy hadrons decay into almost infinite final states
  - Study those decay products in a quasi-background free environment

Original
2009-2018



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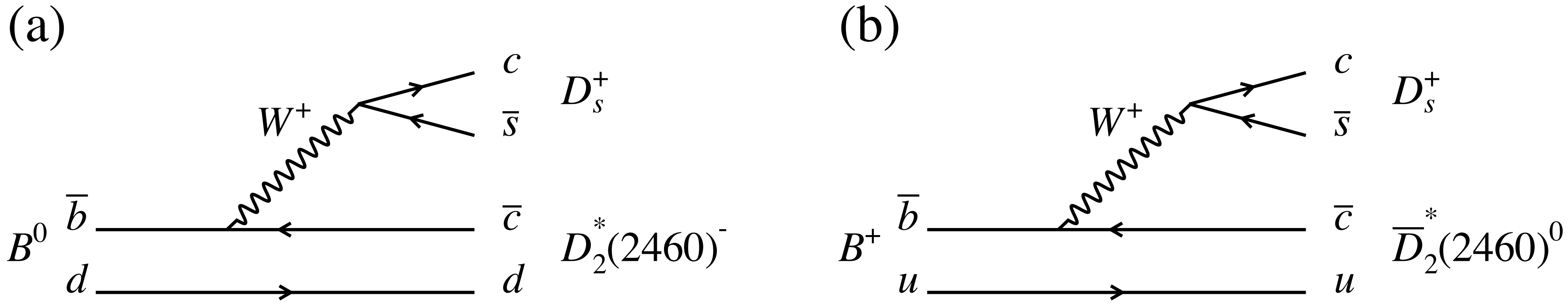
Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Decays of B mesons to double charm final states now very popular
  - Following the discovery of new particles in $B^+ \to D^+ D^- K^+$ decays

- Isospin partner decays analysed together
  - Expect standard excited charm mesons in the $\overline{D}^0 \pi^-$ and $D^- \pi^+$ channels
  - Anything else would likely be an exotic candidate



Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Decays of B mesons to double charm final states now very popular
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- Isospin partner decays analysed together
  - Expect standard excited charm mesons in the $\overline{D}^0 \pi^-$ and $D^- \pi^+$ channels
  - Anything else would likely be an exotic candidate
    - E.g. Z_{cs} tetraquark candidates seen to decay to $\overline{D}^* D_s^+, \overline{D} D_s^{*+}$ and $J/\psi K$
    - Motivation to search in the $D_s^+ \pi^-$ and $D_s^+ \pi^+$ from theory side in analogy to $T_{cs(0,1)}(2900)^0$ candidates in the $D^- K^+$ system

Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Three data samples initially
  - $B^0 \to \overline{D}^0 D_s^+ \pi^-$ with $\overline{D}^0 \to K^+ \pi^-$
  - $B^0 \to \overline{D}^0 D_s^+ \pi^-$ with $\overline{D}^0 \to K^+ \pi^- \pi^+ \pi^-$
  - $B^+ \to D^- D_s^+ \pi^+$ with $D^- \to K^+ \pi^- \pi^-$

  } $D_s^+ \to K^+ K^- \pi^+$

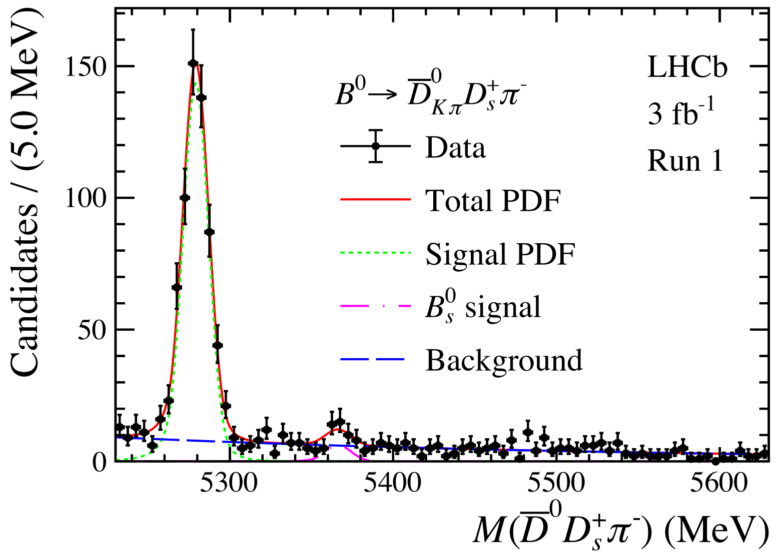
- Analysis uses the full Run 1 + Run 2 data sample of 9fb^{-1}

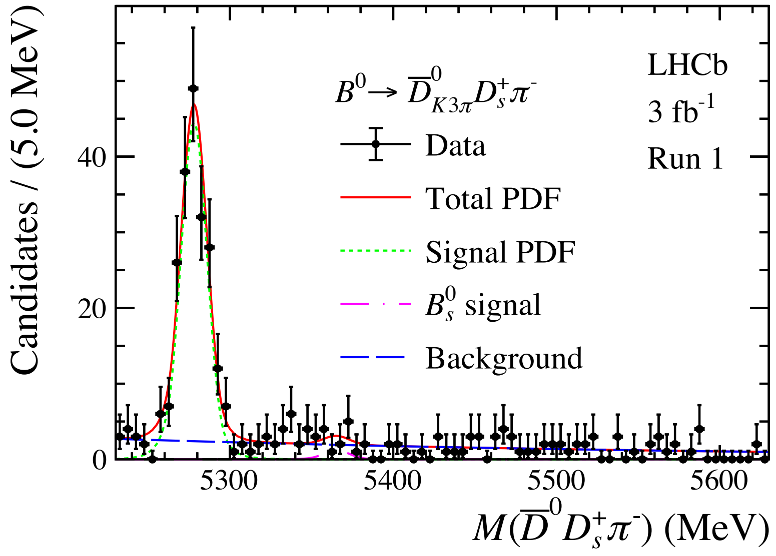
- Standard selections
  - Combinatorial background suppressed using a BDT (boosted decision tree)
  - Non-charm background surpassed with flight distance cuts

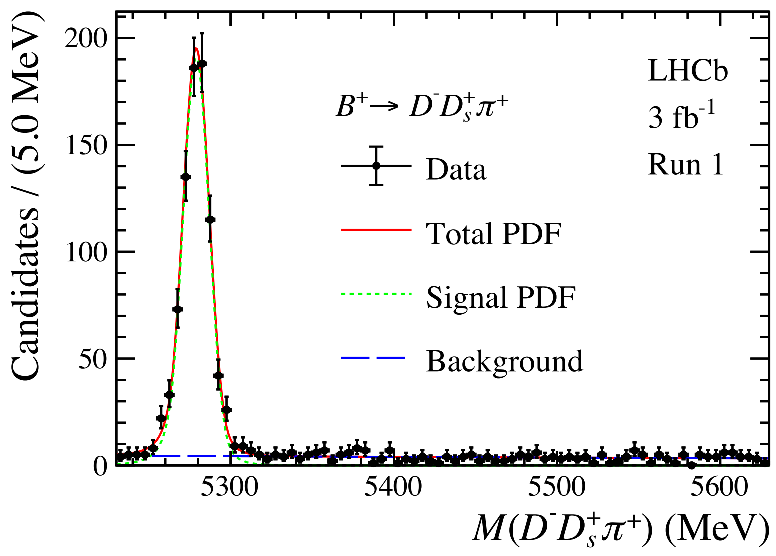
Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Firstly need to measure the yields before doing the amplitude fit
  - Separate fits for the three decay modes and split between Run 1 and Run 2
  - Double Crystal Ball functions for the signal (Gaussian core + tails)
  - Exponential function for the combinatorial background

Run 1 fits







Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Firstly need to measure the yields before doing the amplitude fit
  - Separate fits for the three decay modes and split between Run 1 and Run 2
  - Double Crystal Ball functions for the signal (Gaussian core + tails)
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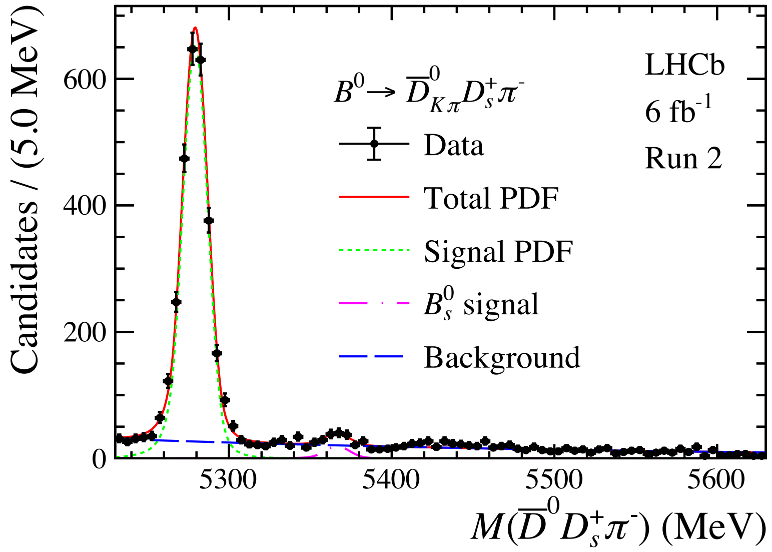
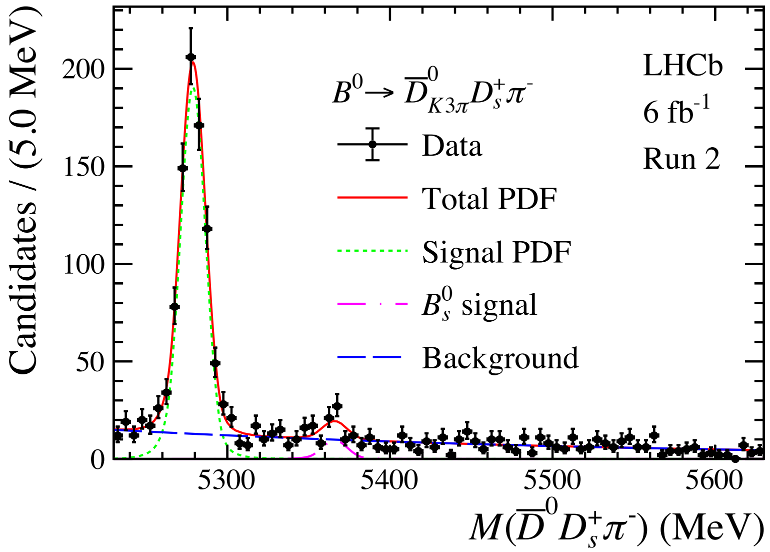
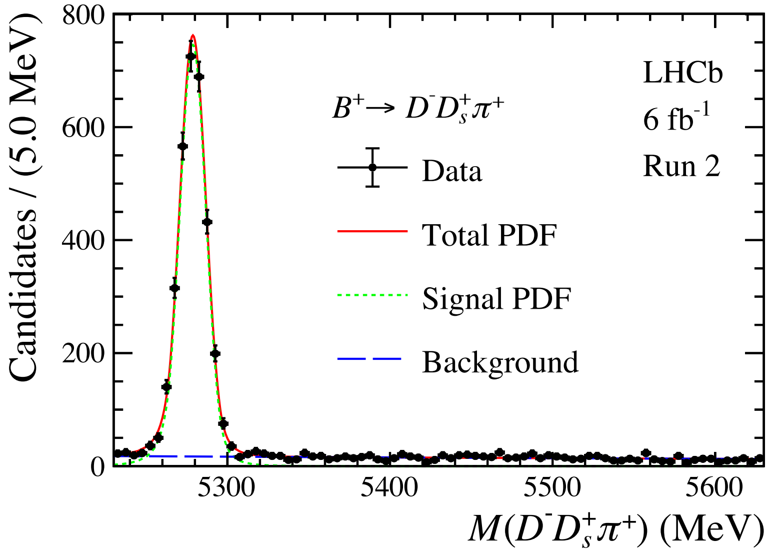
Run 2 fits







Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Fit results
  - Full results in the backup slides
  - Focus here on the yields in the signal region of $\pm 20\,\text{MeV}/c^2$ around the B mass
    - Corresponds to about 2.5-3 times the mass resolution

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 analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

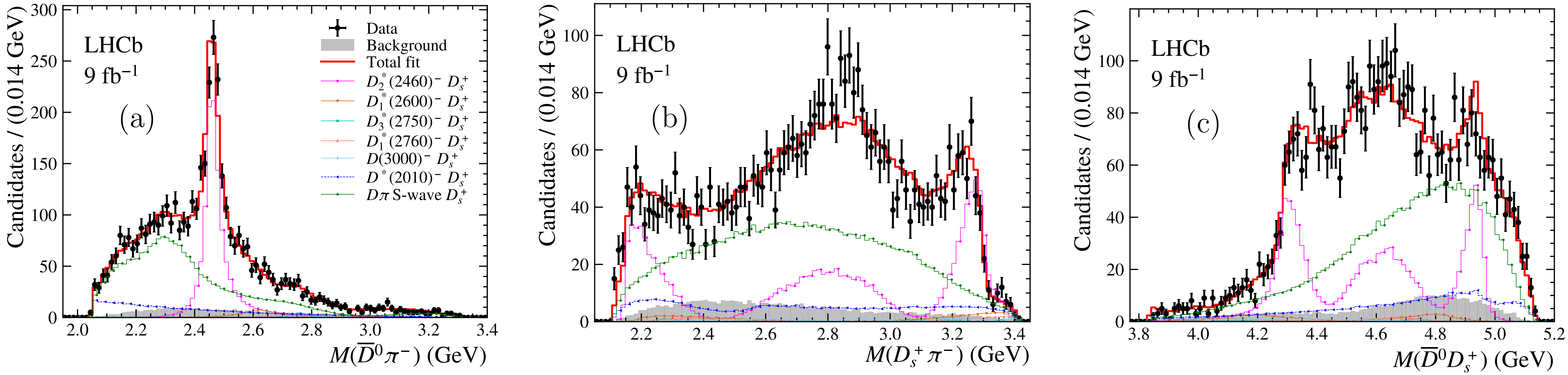
- Now need to perform an amplitude analysis
  - Take just the candidates from the signal regions and fix the yields
  - Include amplitudes for every sub-process that may contribute, starting with known/standard resonances

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

Phys. Rev. D108 (2023) 012017, Phys. Rev. Lett. 131 (2023) 041902

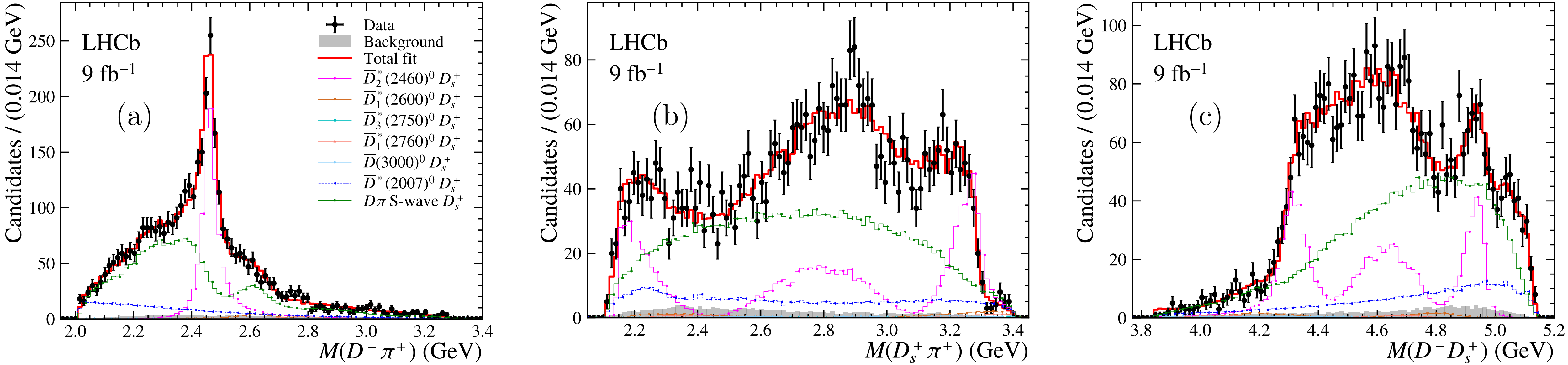
Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Projections from the fit with the list of known excited charm mesons
  - Full $B^0 \to \overline{D}^0 D_s^+ \pi^-$ dataset combining D decays and run periods
  - Good fit to data in the $\overline{D}^0 \pi^-$ projection (left)
  - Some possible deficiencies in the $D_s^+ \pi^-$ projection (centre)



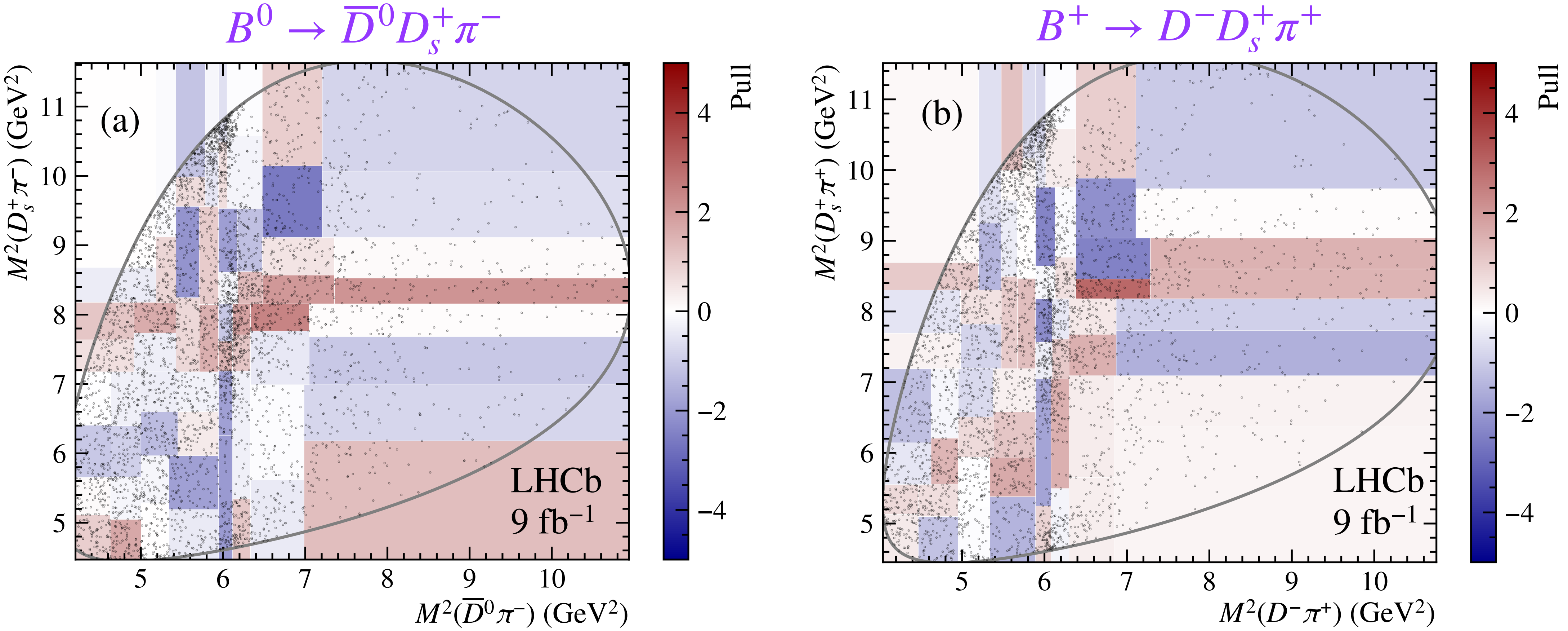
Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Projections from the fit with the list of known excited charm mesons
  - Full $B^+ \to D^- D_s^+ \pi^+$ dataset combining D decays and run periods
  - Good fit to data in the $D^-\pi^+$ projection (left)
  - Some possible deficiencies in the $D_s^+\pi^+$ projection (centre)



Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Have a look at the fit quality



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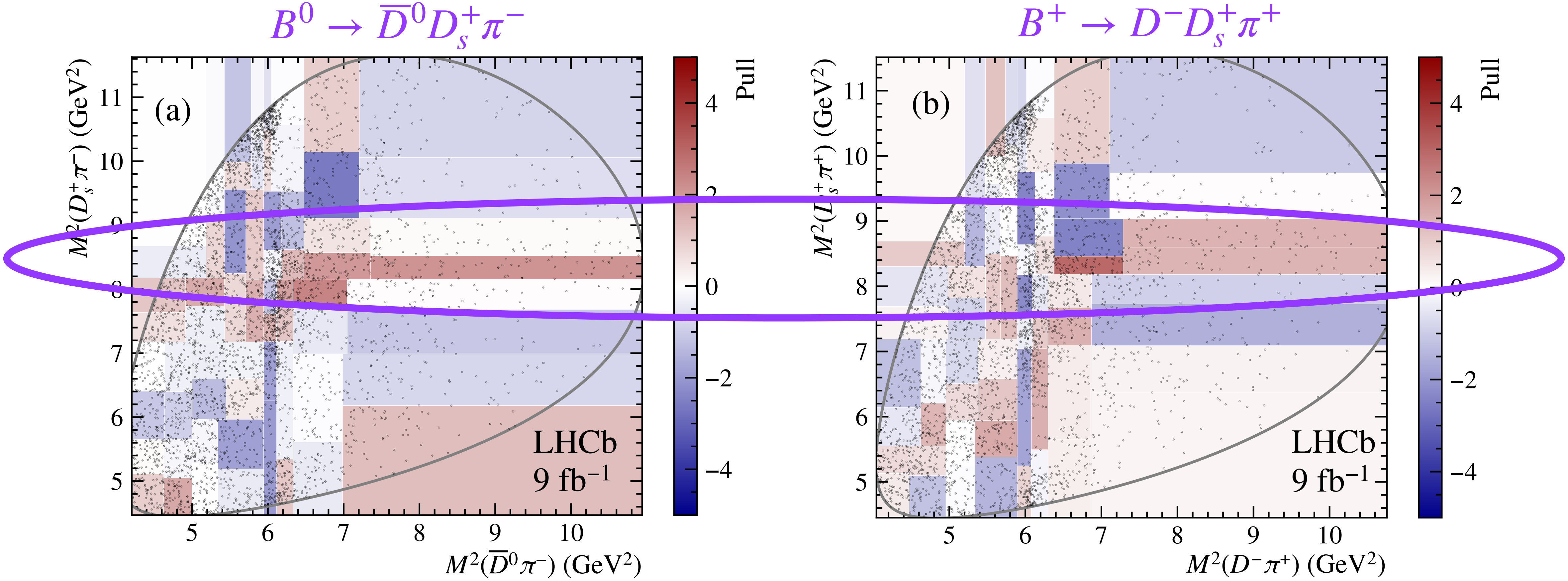
Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Have a look at the fit quality
  - Quite a bit of strong colour in the area flagged previously



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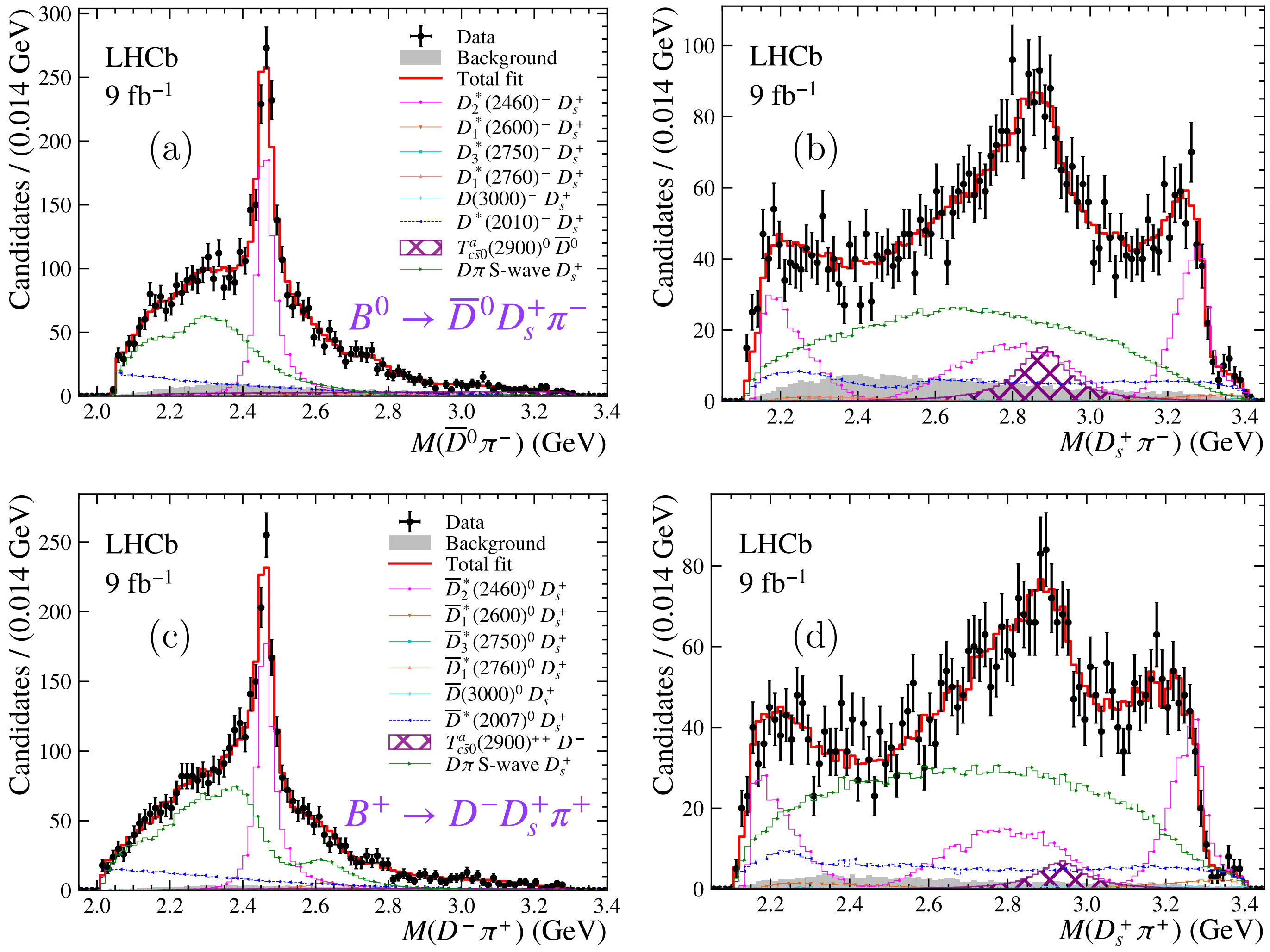
Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Since the problem seems to be in the $D_s^+\pi$ projections
  - Try adding one state per decay mode
  - No relation between them assumed
  - Float mass, width and spin

- Both data sets prefer a spin-0 resonance at $2900\,\mathrm{MeV}/c^2$



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Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

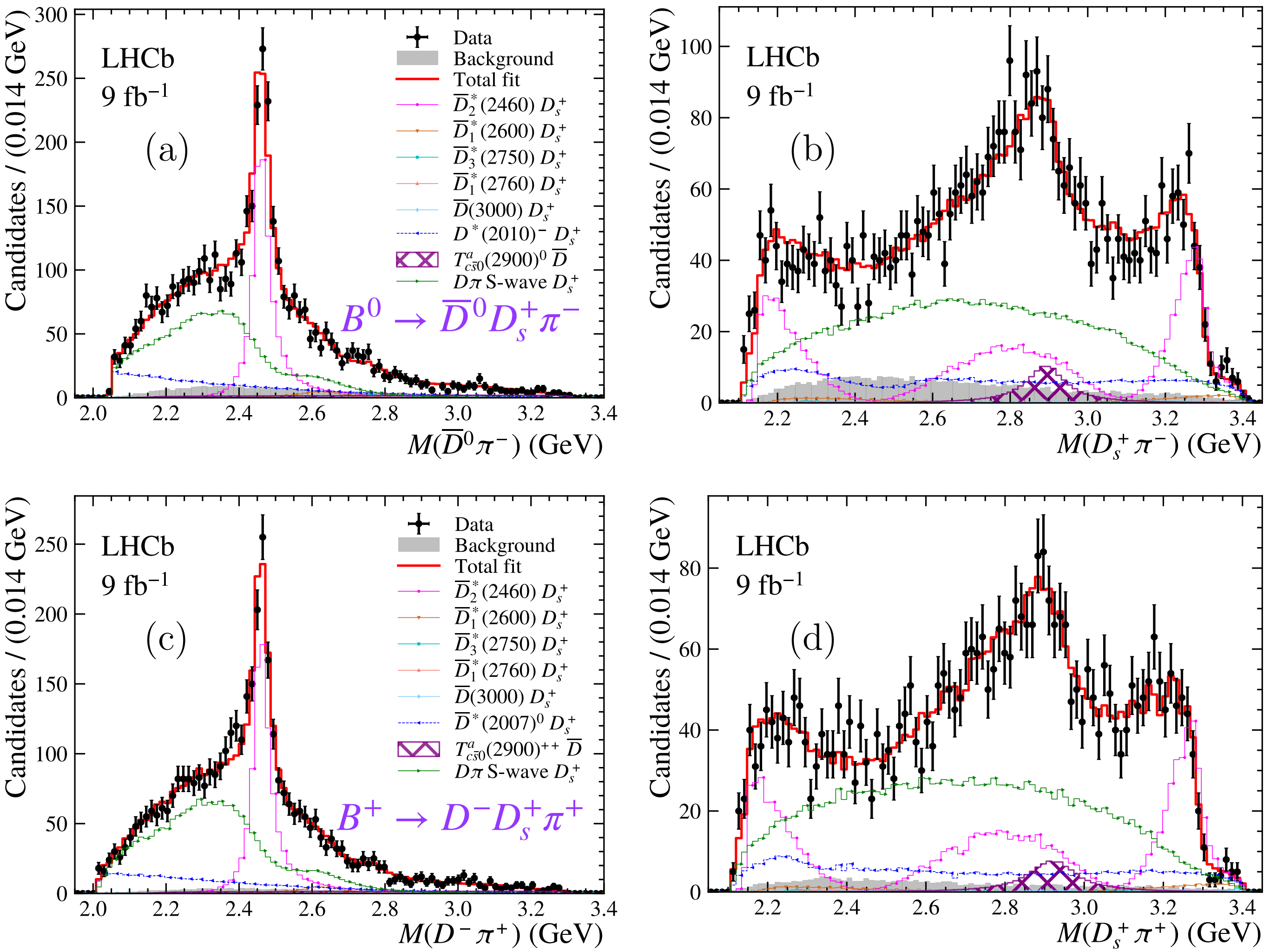
- Perform a simultaneous fit
  - Assuming isospin symmetry to relate the two states

$$T^a_{c\bar{s}0}(2900)^0: M = (2.892 \pm 0.014 \pm 0.015)\,\text{GeV}, \quad \Gamma = (0.119 \pm 0.026 \pm 0.013)\,\text{GeV},$$

Observed with 8σ significance

$$T^a_{c\bar{s}0}(2900)^{++}: M = (2.921 \pm 0.017 \pm 0.020)\,\text{GeV}, \quad \Gamma = (0.137 \pm 0.032 \pm 0.017)\,\text{GeV},$$

Observed with 6.5σ significance



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Study of the $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ decay

- This decay mode was first observed by BaBar and confirmed by Belle
  - BaBar saw evidence for a new charm baryon state - $\Xi_c(2930)^0$
  - Use LHCb's enormous Run 2 data sample to confirm the state and measure its properties

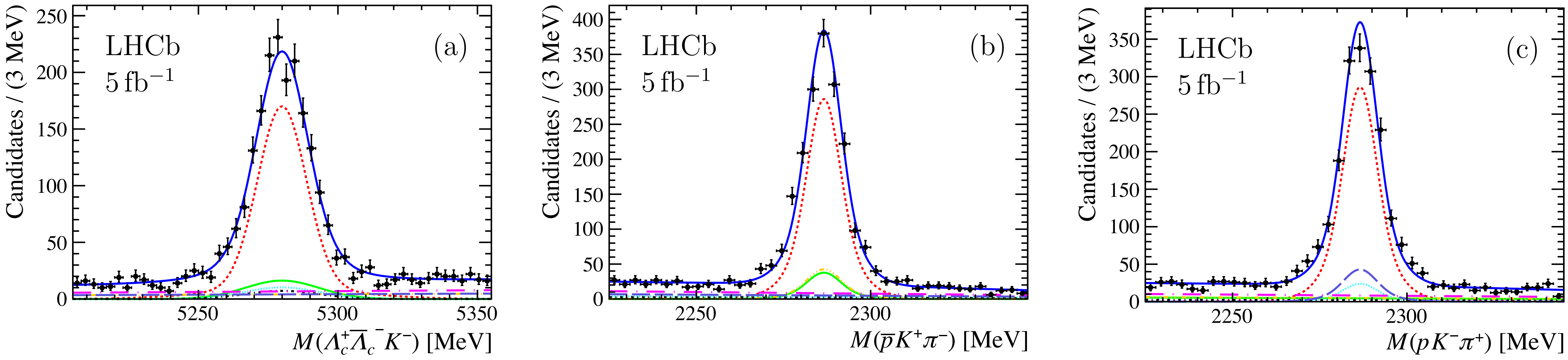
- Full decay mode to reconstruct

$$B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-, \Lambda_c^+ \to p K^- \pi^+, \overline{\Lambda}_c^- \to \overline{p} K^+ \pi^-$$

- In addition to the $\Xi_c(2930)^0$ state one can analyses
  - The $\Lambda_c^+ \overline{\Lambda}_c^-$ combination for exotic contributions (threshold enhancement: BESIII)
  - The $\overline{\Lambda}_c^- K^-$ channel which cannot result from a strong decay of a baryon

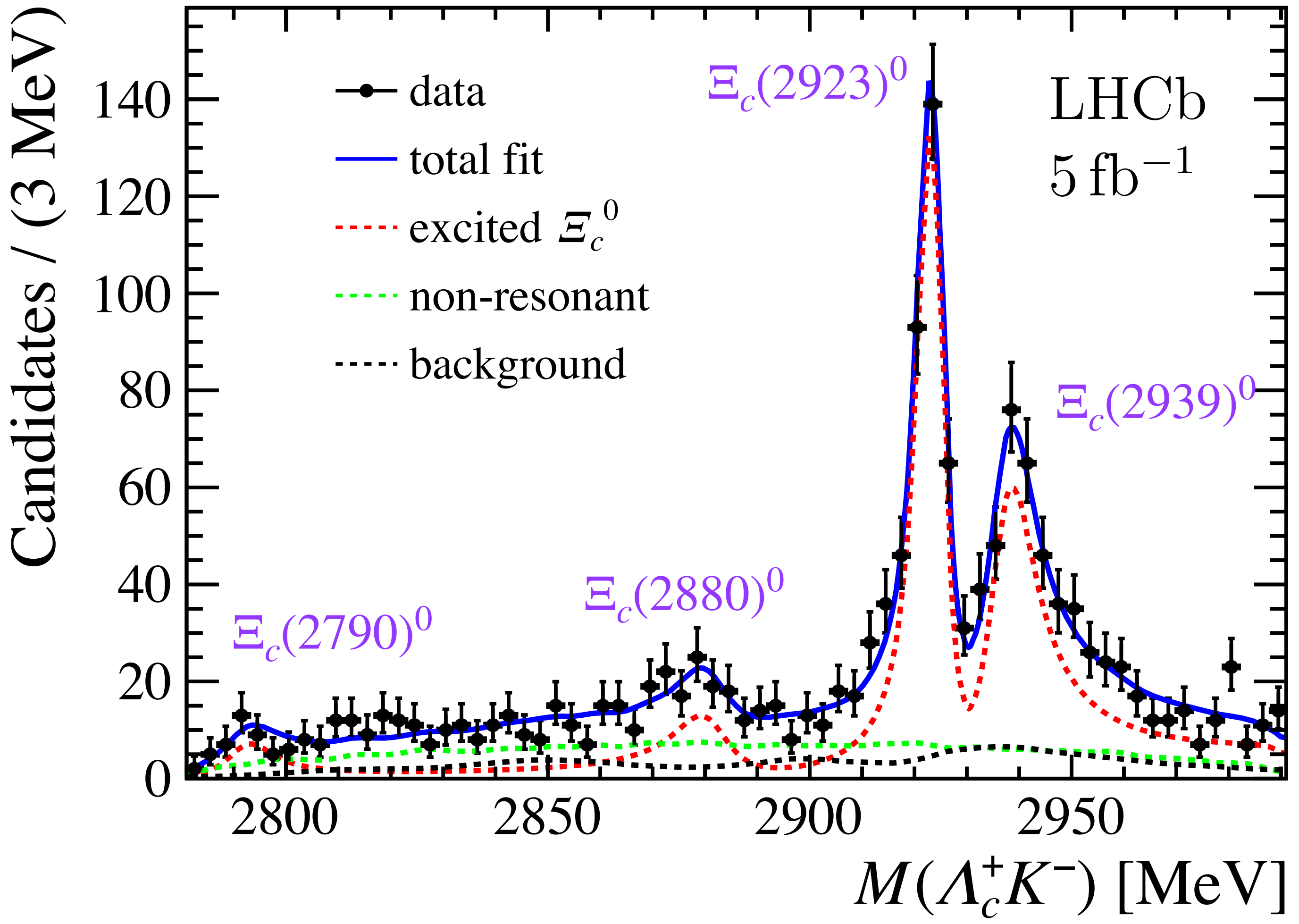
Study of the $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ decay

- Firstly need to select the signal candidates and count them
  - Combinatorial background suppressed using a BDT
  - Perform a 3D mass fit to the beauty and charm baryons mass distributions
  - In total the signal yield is determined to be 1365 ± 42



Study of the $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ decay

- Lets zoom into the $\Lambda_c^+ K^-$ invariant mass distribution
  - Clear double-peaked structure in the $\Xi_c(2930)^0$ region
  - Total Ξ_c fit model requires four states with interference effects allowed (and important)
  - Spin of the new states assumed to be 1/2



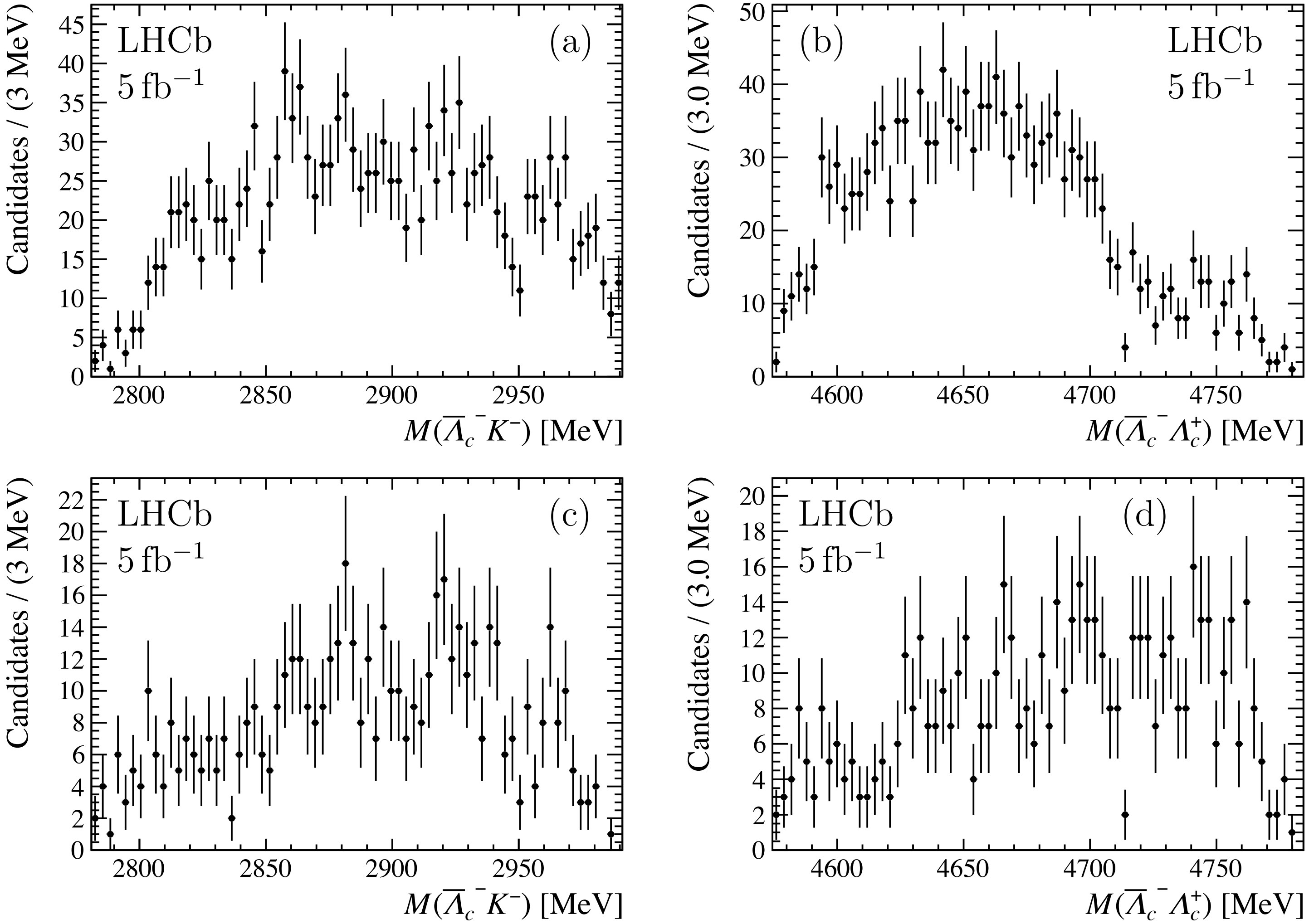
Study of the $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ decay

- Resolved the old $\Xi_c(2930)^0$ state into two resonances!
  - Both are overwhelmingly significant even with systematics included

State	Mass (MeV)	Width (MeV)	Significance
$\Xi_c(2880)^0$	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.2 \pm 5.8$	3.8σ
$\Xi_c(2923)^0$	$2924.5 \pm 0.4 \pm 1.1$	$4.8 \pm 0.9 \pm 1.5$	$> 10\sigma$
$\Xi_c(2939)^0$	$2938.5 \pm 0.9 \pm 2.3$	$11.0 \pm 1.9 \pm 7.5$	$> 10\sigma$

- What about the other mass distributions?

Study of the $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ decay



With Ξ_c contributions vetoed

Aside - non-observations also important!

- Why show a result with no exotic candidates?

- Whilst arguably less exciting, we must publish all null results too!
  - We are trying to understand the structure of exotic particles
  - Final states that they cannot decay to may give us further clues

- Some models can be proven wrong by non observations…

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Study of $B^0 \to J/\psi\phi K^0_S$ decays

- Motivated by other LHCb observations in related channels
  - Tetraquark candidates seen in $B^+ \to J/\psi\phi K^+$
  - These are known as $T^{\theta}_{\psi s1}(4000)^+$ and $T_{\psi s1}(4220)^+$
  - Search for possible isospin partners of these states to help understand their natures: hadronic molecules? Compact tetraquarks? Threshold effects?

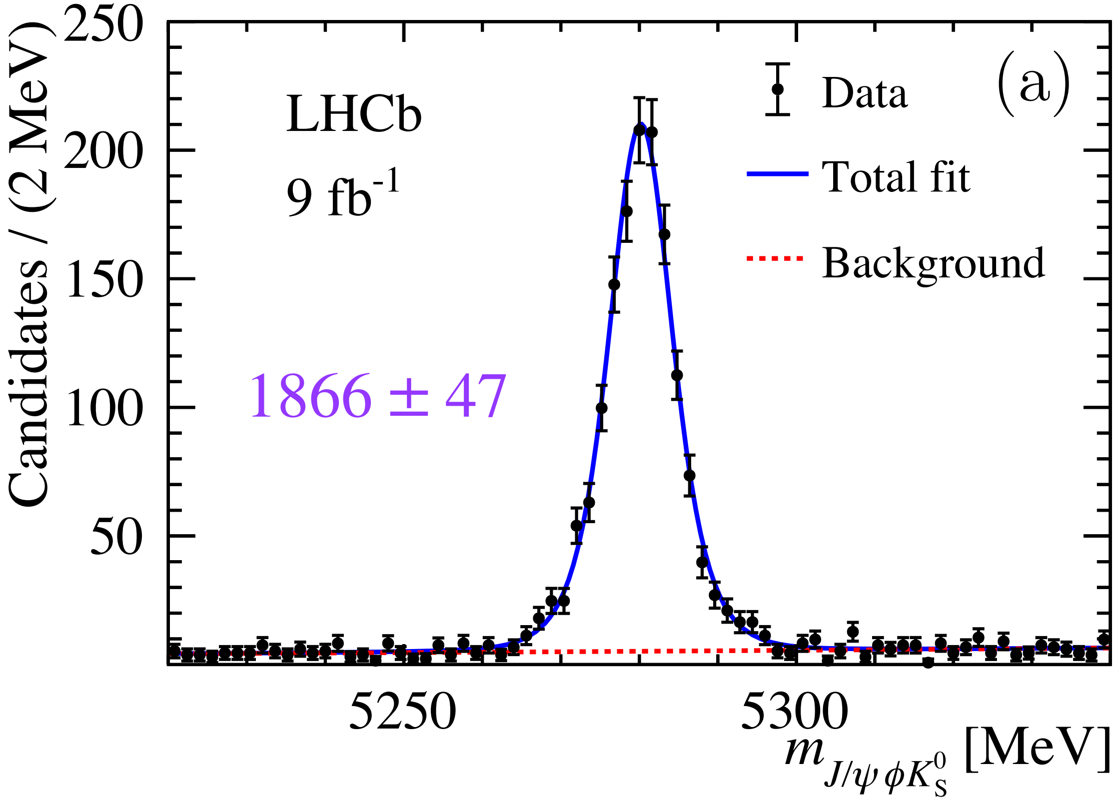
- Need to reconstruct the following decay chain
  - $B^0 \to J/\psi\phi K^0_S, J/\psi \to \mu^+\mu^-, \phi \to K^+K^-, K^0_S \to \pi^+\pi^-$

- Analysis used the full LHCb Run 1 and Run 2 data sample

Phys. Rev. Lett. 131 (2023) 131901

Study of $B^0 \to J/\psi \phi K_S^0$ decays

- By now, another similar data selection
  - Combinatorial background suppressed with a multivariate analyser
- Straightforward mass fit
  - Determine the signal yield
- Define mass window
  - $\pm 15\,\text{MeV}/c^2$ for amplitude analysis



Study of $B^0 \to J/\psi \phi K_S^0$ decays

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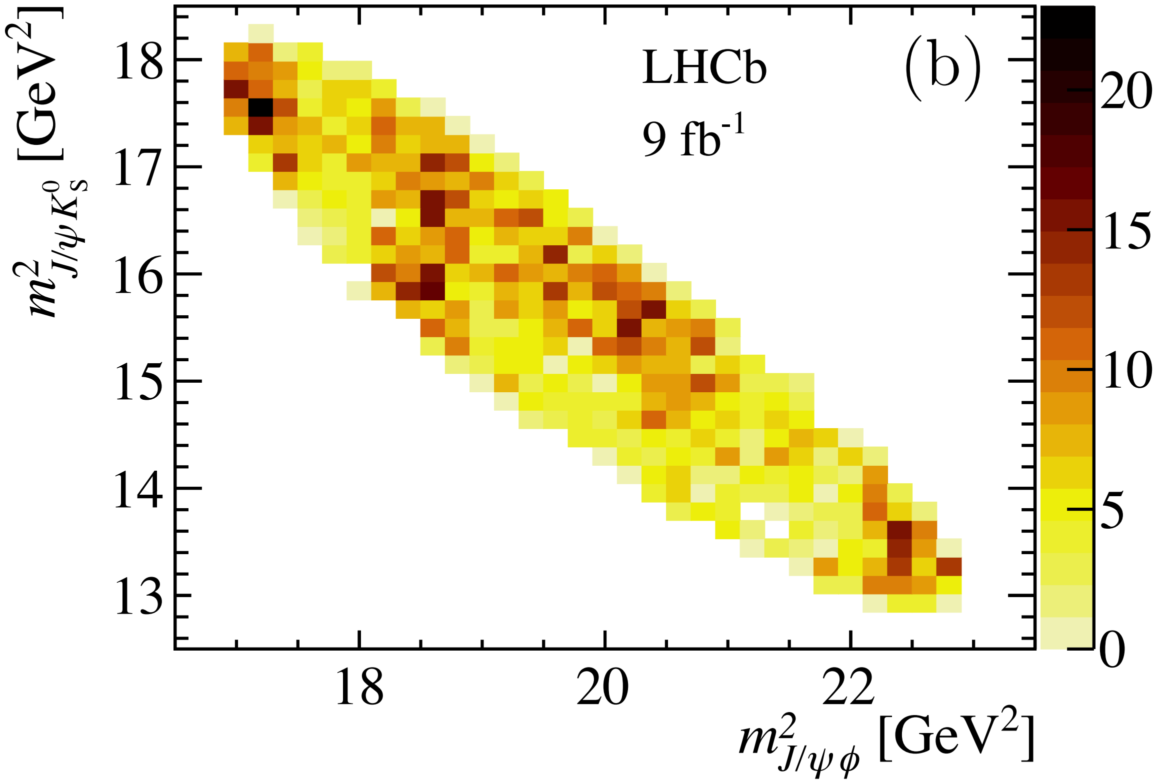
  - Combinatorial background suppressed with a multivariate analyser
- Straightforward mass fit
  - Determine the signal yield
- Define mass window
  - $\pm 15\,\mathrm{MeV}/c^2$ for amplitude analysis
  - Dalitz plot to show distribution of signal candidates
  - 94% purity in the signal window

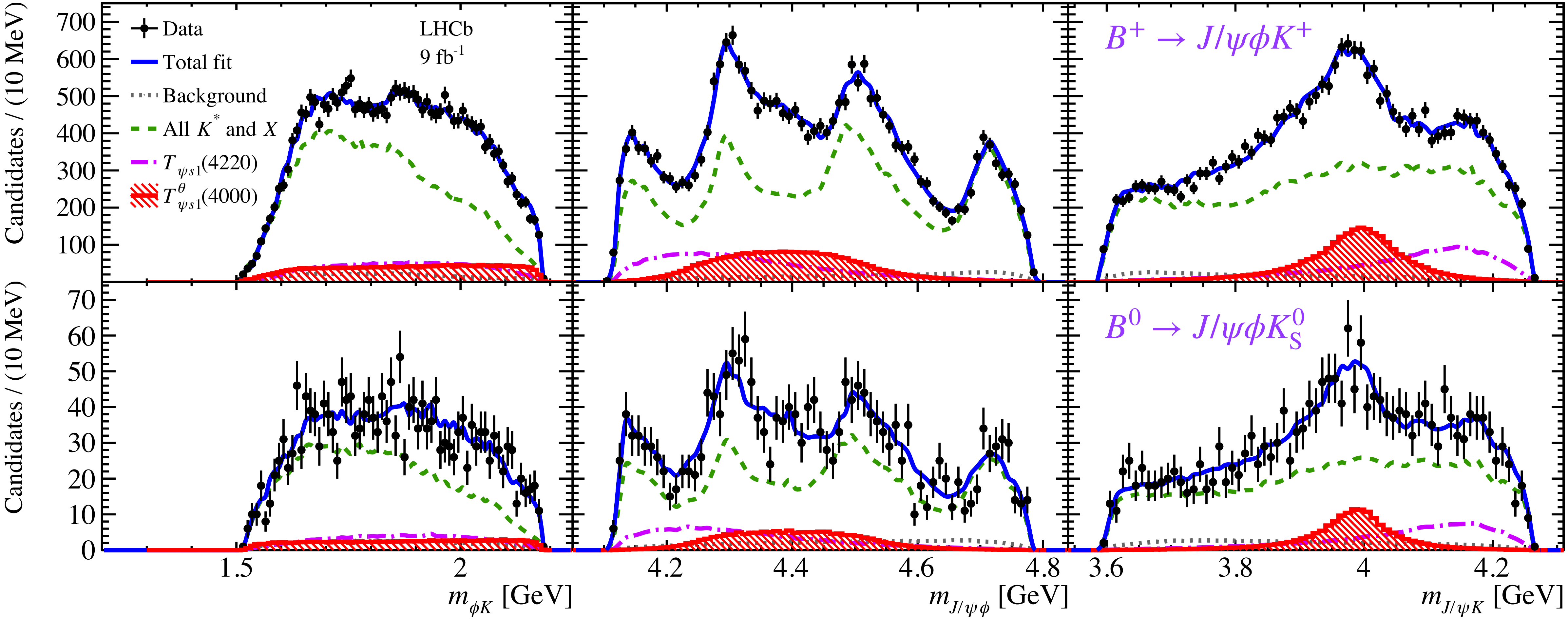


Study of $B^0 \to J/\psi\phi K^0_S$ decays

- Next step if to perform the amplitude analysis
  - Since the signal yield is relatively small and the number of amplitudes potentially rather large, perform a simultaneous fit with $B^+ \to J/\psi\phi K^+$ decays
  - Isospin symmetry to relate them together and guide the fit to the new channel

J^P	Contribution		Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
1^+	$2^1\mathrm{P}_1$	$K(1^+)$	4.5 (4.5)	$1861 \pm 10\,^{+16}_{-46}$	$149 \pm 41\,^{+231}_{-23}$	
	$2^3\mathrm{P}_1$	$K'(1^+)$	4.5 (4.5)	$1911 \pm 37\,^{+124}_{-48}$	$276 \pm 50\,^{+319}_{-159}$	
	$1^3\mathrm{P}_1$	$K_1(1400)$	9.2 (11)	1403	174	$15 \pm 3\,^{+3}_{-11}$
2^-	$1^1\mathrm{D}_2$	$K_2(1770)$	7.9 (8.0)	1773	186	
	$1^3\mathrm{D}_2$	$K_2(1820)$	5.8 (5.8)	1816	276	
1^-	$1^3\mathrm{D}_1$	$K^*(1680)$	4.7 (13)	1717	322	$14 \pm 2\,^{+35}_{-8}$
	$2^3\mathrm{S}_1$	$K^*(1410)$	7.7 (15)	1414	232	$38 \pm 5\,^{+11}_{-17}$
2^-	$2^3\mathrm{P}_2$	$K^*_2(1980)$	1.6 (7.4)	$1988 \pm 22\,^{+194}_{-31}$	$318 \pm 82\,^{+481}_{-101}$	$2.3 \pm 0.5 \pm 0.7$
0^-	$2^1\mathrm{S}_0$	$K(1460)$	12 (13)	1483	336	$10.2 \pm 1.2\,^{+1.0}_{-3.8}$
2^-		$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
1^-		$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+18}_{-110}$	$174 \pm 27\,^{+134}_{-73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
0^+		$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6\,^{+10}_{-8}$	$5.6 \pm 0.7\,^{+2.4}_{-0.6}$
		$X(4700)$	17 (18)	$4694 \pm 4\,^{+16}_{-3}$	$87 \pm 8\,^{+16}_{-6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
		$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+19}_{-11}$
1^+		$X(4140)$	13 (16)	$4118 \pm 11\,^{+19}_{-36}$	$162 \pm 21\,^{+24}_{-49}$	$17 \pm 3\,^{+19}_{-6}$
		$X(4274)$	18 (18)	$4294 \pm 4\,^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5\,^{+0.8}_{-0.4}$
		$X(4685)$	15 (15)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$	$7.2 \pm 1.0\,^{+4.0}_{-2.0}$
1^+		$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
		$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$

Study of $B^0 \rightarrow J/\psi \phi K^0_S$ decays



Study of $B^0 \to J/\psi\phi K^0_S$ decays

- Results for the new tetraquark candidate

$$M(T^{\theta}_{\psi s1}(4000)^0) = 3991\,^{+12}_{-10}\,^{+\ 9}_{-17}\,\text{MeV},$$
$$\Gamma(T^{\theta}_{\psi s1}(4000)^0) = \ \ 105\,^{+29}_{-25}\,^{+17}_{-23}\,\text{MeV},$$

  - Data sample too small to say more about the $T_{\psi s1}(4220)^+$ state as the parameters had to be kept fixed to those in the control channel

- The new candidate has significance of
  - Stand alone 4.0σ
  - With isospin symmetry imposed 5.4σ

Looking forwards - my two cents

- We need to understand the structure of exotic particles
  - With four and five quark states, how are the quarks arranged?
- Discovering them pseudo-randomly is a good start…
  - Perhaps it is time for a more focused, systematic, approach
  - Focus on related states and look for any more possible partners e.g.

$T_{cs0}(2900)^0$ $\quad$ $T^a_{c\bar{s}0}(2900)^0$ $\quad c\bar{s}\bar{u}d$

$T_{cs1}(2900)^0$ $\quad$ $T^a_{c\bar{s}0}(2900)^{++}$ $\quad c\bar{s}u\bar{d}$

$cs\bar{u}\bar{d}$

- Make sure we focus equally on final states they do not decay to

Looking forwards - my two cents

- We need to understand the structure of exotic particles
  - With four and five quark states, how are the quarks arranged?

- Discovering them pseudo-randomly is a good start…
  - Perh
  - Focu

The $T^{\theta}_{\psi s1}(4X00)$ family could be another starting point

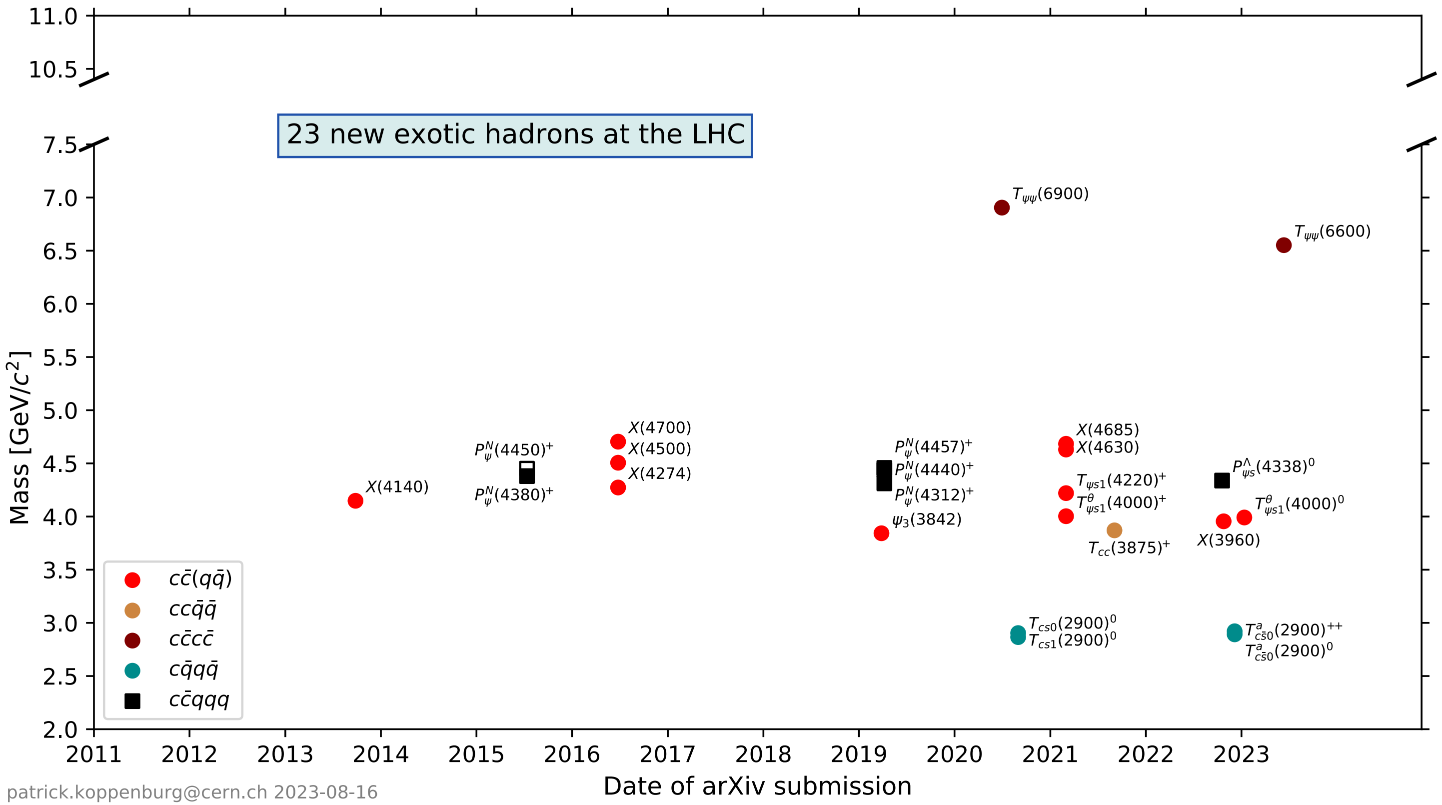
$T_{cs1}(2900)^0$ $cs\bar{u}\bar{d}$

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

- Make sure we focus equally on final states they do not decay to

Summary

- Exciting time in spectroscopy (again)
  - Huge number of recent observations
  - Challenge to understand them
- Where are the hexaquarks?



Back up

Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

Decay	Parameter	Run 1	Run 2
$B^0 \to \overline{D}^0_{K\pi} D_s^+ \pi^-$	Signal yield	587 ± 27	2641 ± 57
	B_s^0 signal	25.3 ± 8.3	77 ± 15
	Background yield	421 ± 26	1440 ± 49
	Mean (MeV)	5279.12 ± 0.38	5279.16 ± 0.18
	Width (MeV)	7.89 ± 0.35	7.73 ± 0.17
	Exponential slope	$-(3.08 \pm 0.52) \times 10^{-3}$	$-(2.98 \pm 0.29) \times 10^{-3}$
$B^0 \to \overline{D}^0_{K3\pi} D_s^+ \pi^-$	Signal yield	185 ± 15	759 ± 32
	B_s^0 signal	4.9 ± 4.6	38 ± 11
	Background yield	136 ± 14	692 ± 33
	Mean (MeV)	5277.98 ± 0.70	5278.79 ± 0.34
	Width (MeV)	8.01 ± 0.59	7.72 ± 0.33
	Exponential slope	$-(2.56 \pm 0.90) \times 10^{-3}$	$-(3.03 \pm 0.41) \times 10^{-3}$
$B^+ \to D^- D_s^+ \pi^+$	Signal yield	798 ± 30	3123 ± 59
	Background yield	311 ± 21	1201 ± 40
	Mean (MeV)	5278.88 ± 0.33	5278.74 ± 0.16
	Width (MeV)	8.08 ± 0.30	8.05 ± 0.14
	Exponential slope	$-(0.82 \pm 0.61) \times 10^{-3}$	$-(0.90 \pm 0.31) \times 10^{-3}$