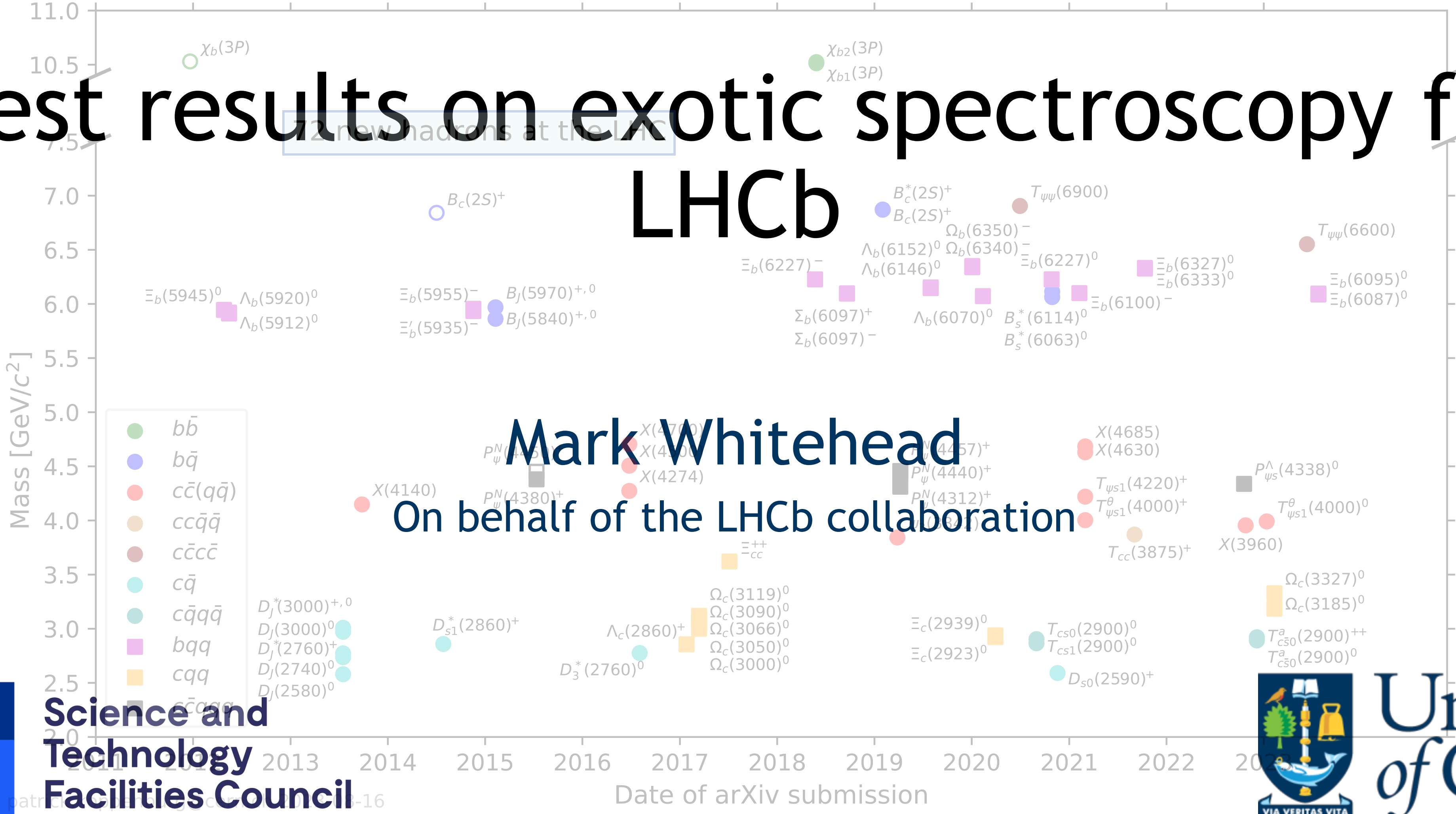
Latest results on exotic spectroscopy from LHCb



Mark Whitehead

On behalf of the LHCb collaboration

Science and Technology Facilities Council

University of Glasgow

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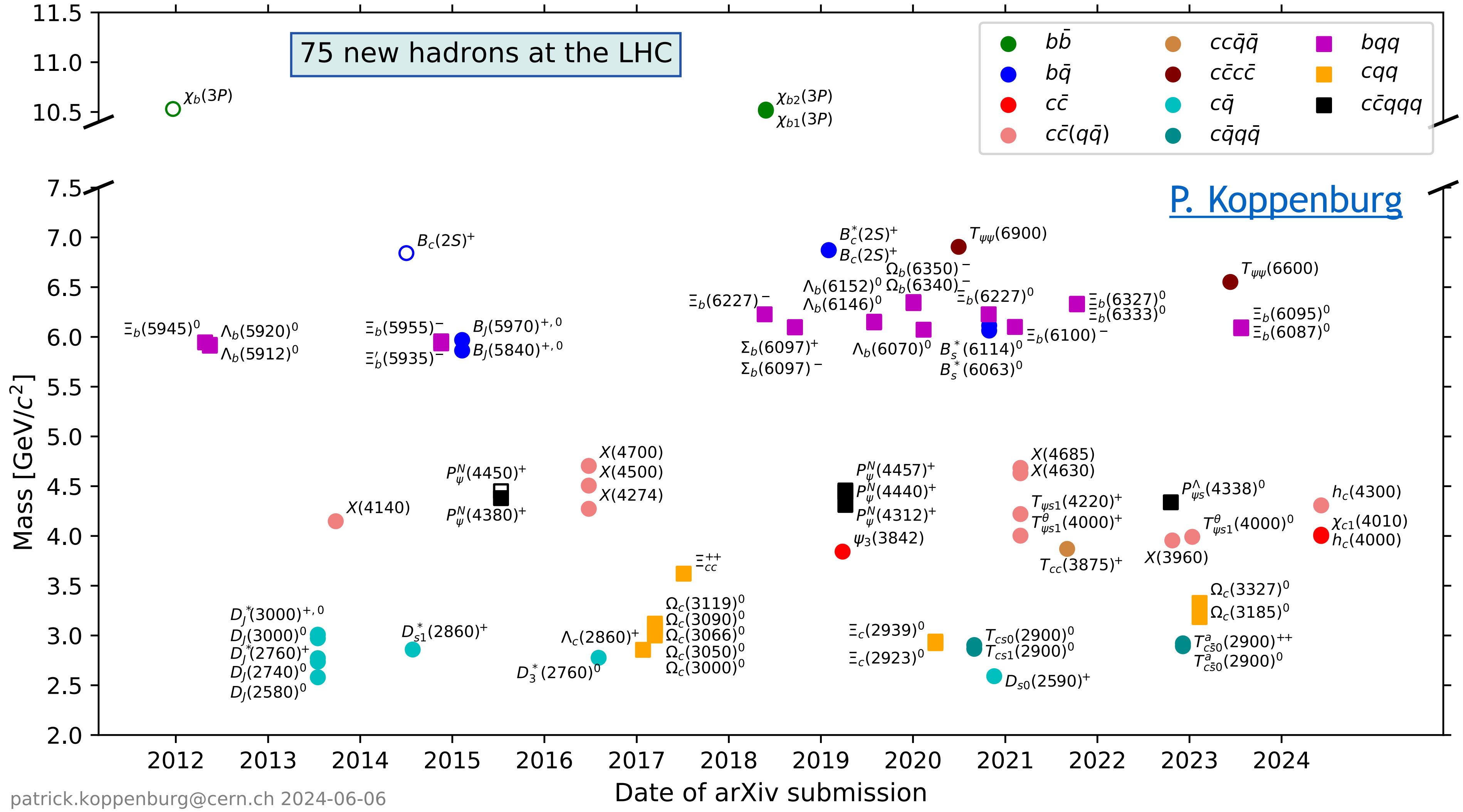
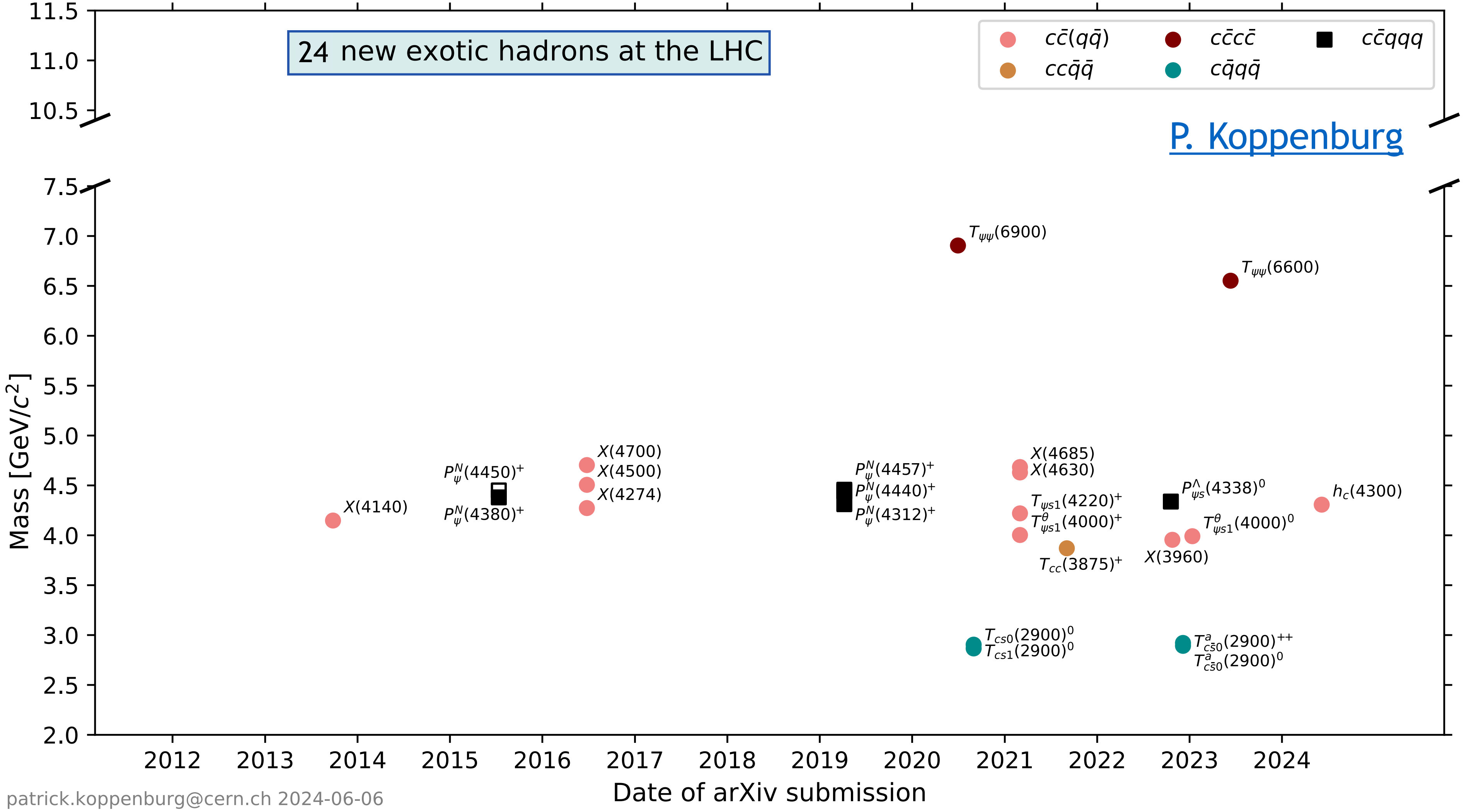
- Reminder of the LHCb experiment
- Recent results from LHCb
  - Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays
    - Quick look at a new result from $B^+ \to D^{*-} D_s^+ \pi^+$
  - Study of $B^+ \to D^{*\pm} D^{\mp} K^+$ decays
  - Radiative decays of $\chi_{c1}(3872)$
- Future prospects

Introduction



Introduction

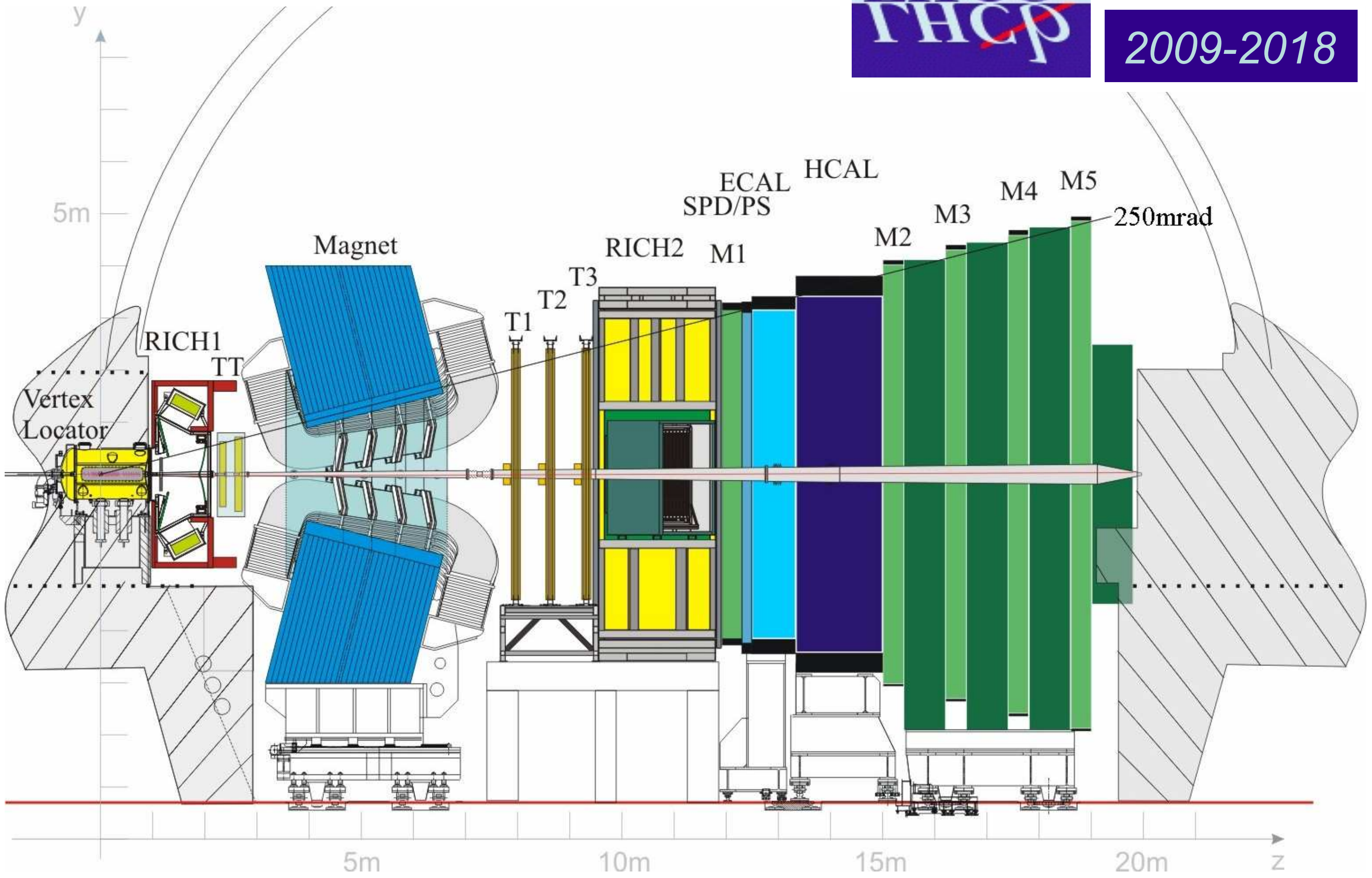


The LHCb experiment

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

Original

2009-2018



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

- 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
    - Quick look at a new result from $B^+ \to D^{*-} D_s^+ \pi^+$
  - Study of $B^+ \to D^{*\pm} D^{\mp} K^+$ decays
  - Radiative decays of $\chi_{c1}(3872)$
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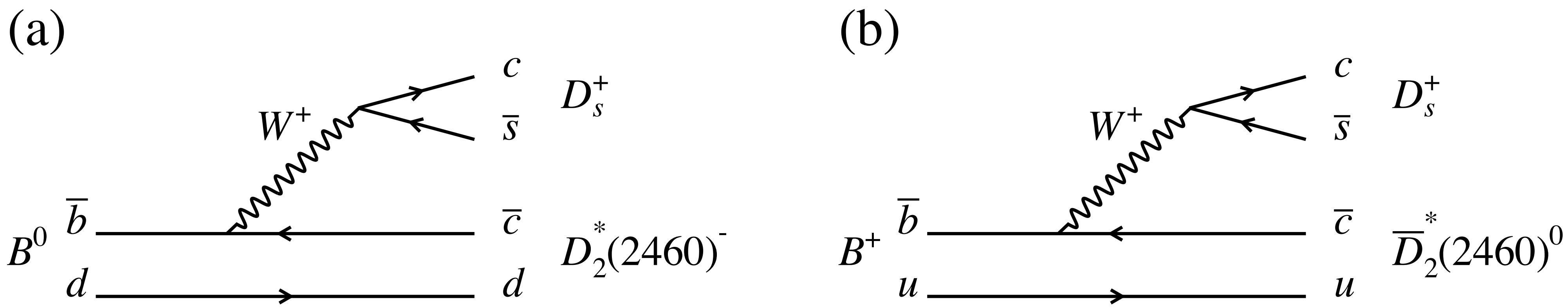
Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- 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
  - 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
    - 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

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

- 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 $D^- \to K^+ \pi^- \pi^-$

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

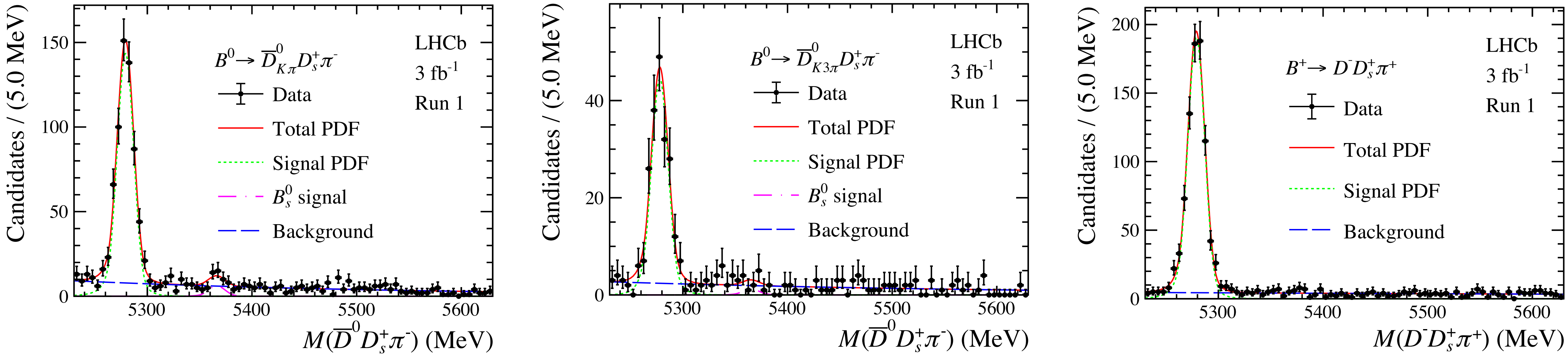
- Analysis uses the full Run 1 + Run 2 data sample of $9\mathrm{fb}^{-1}$

- 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
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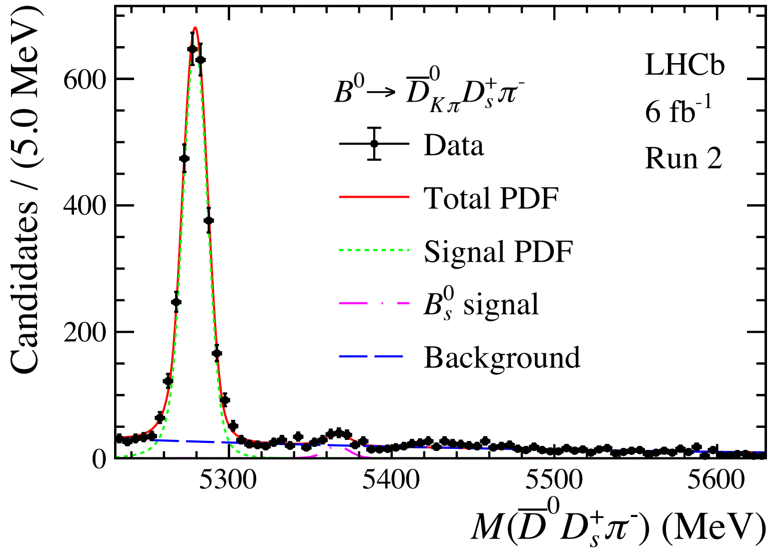
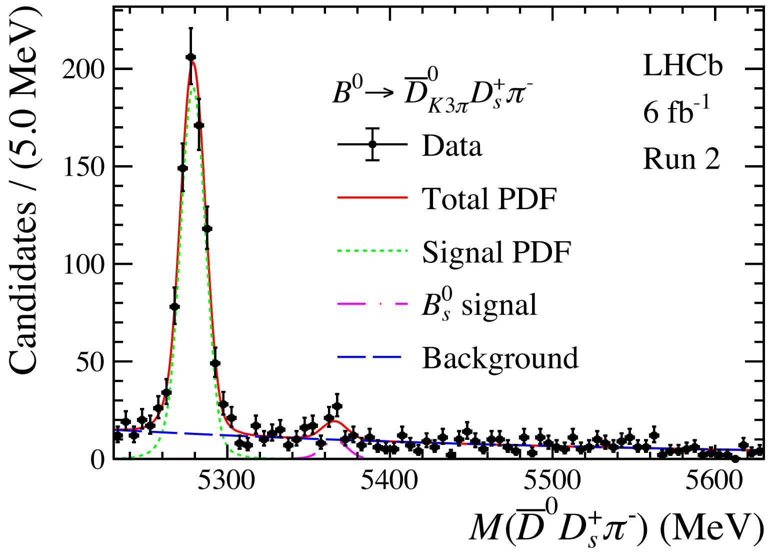
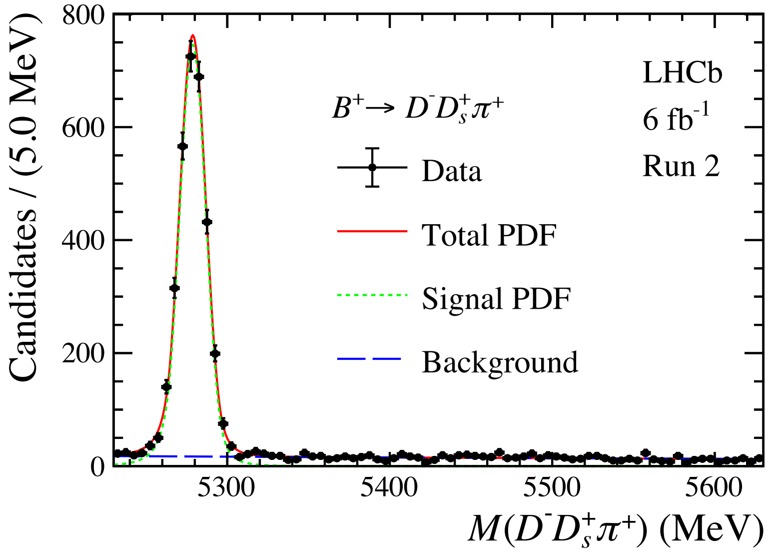
Run 2 fits







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 $\pm 20\,\mathrm{MeV}/c^2$ 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%

~4k signal candidates per channel

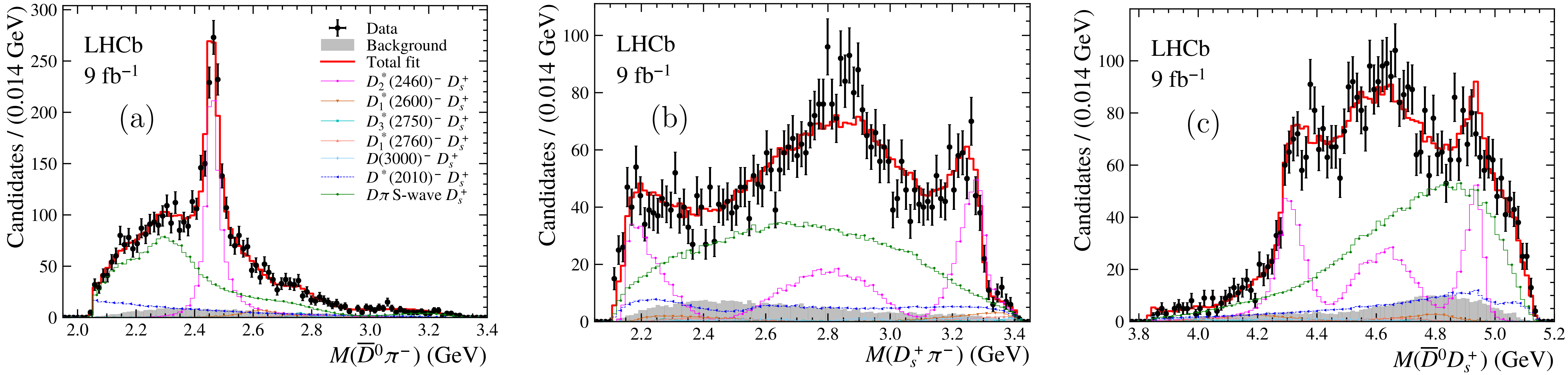
Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- 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

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)



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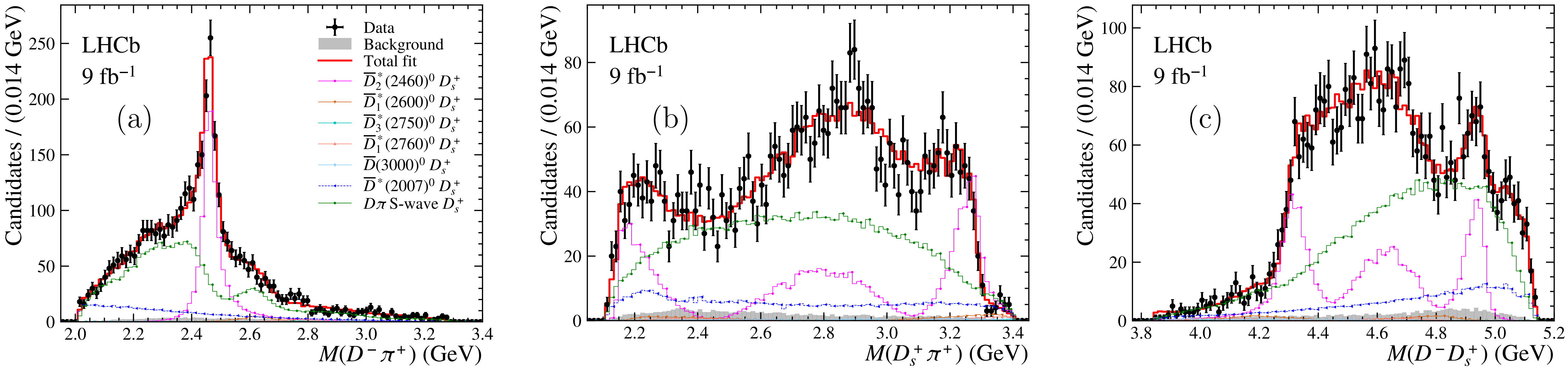
Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- 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)



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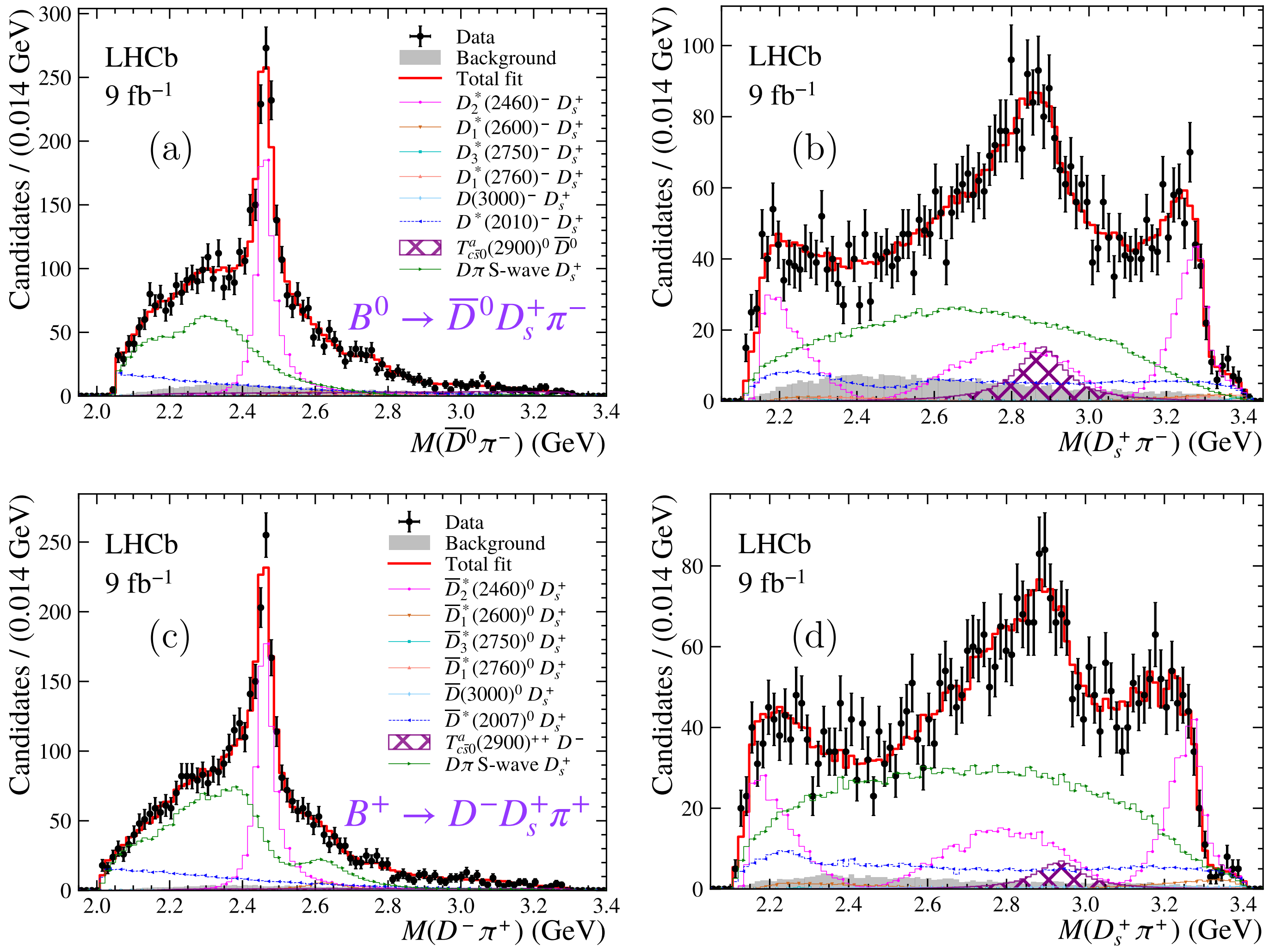
Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- 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

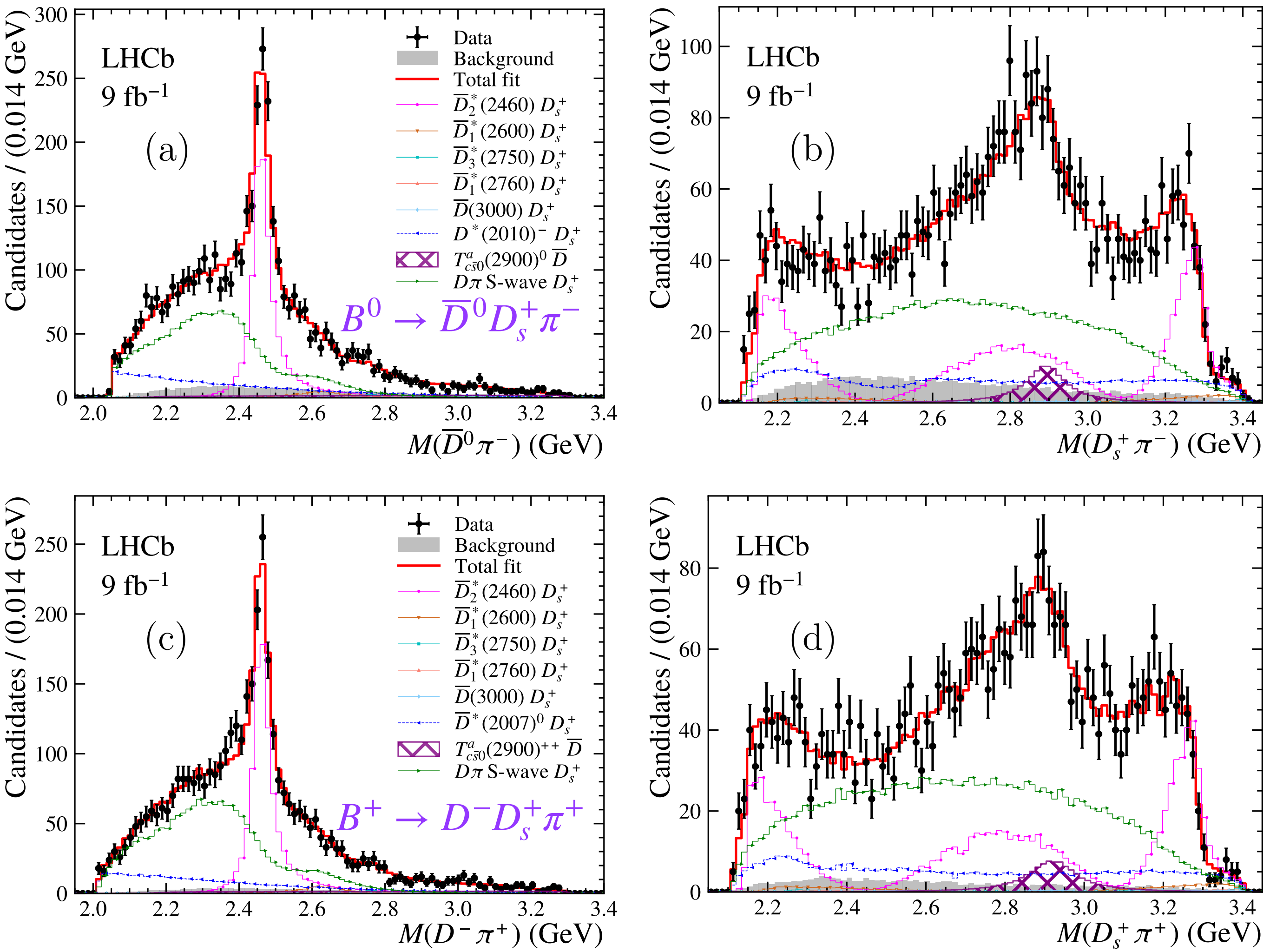
- Perform a simultaneous fit
  - Assuming isospin symmetry to relate the two states

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

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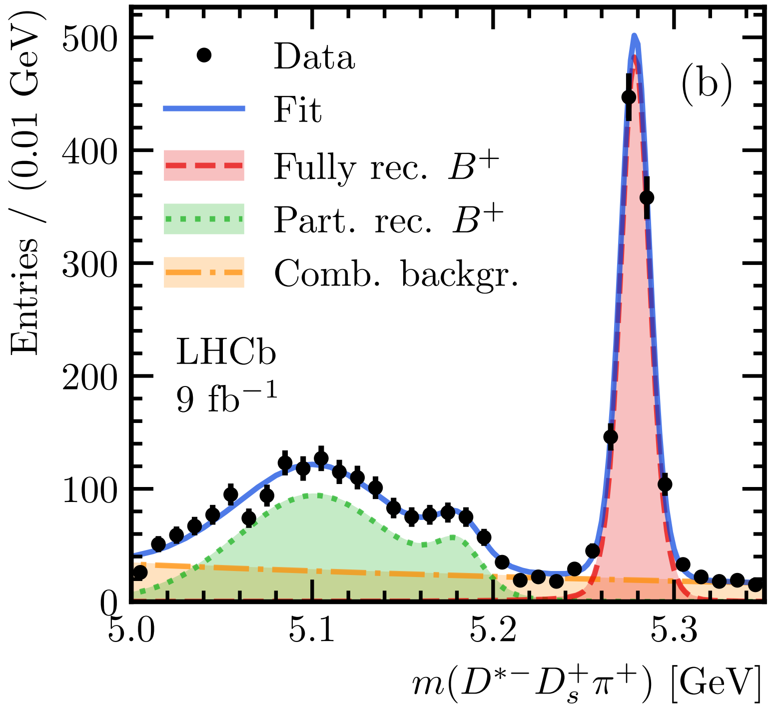
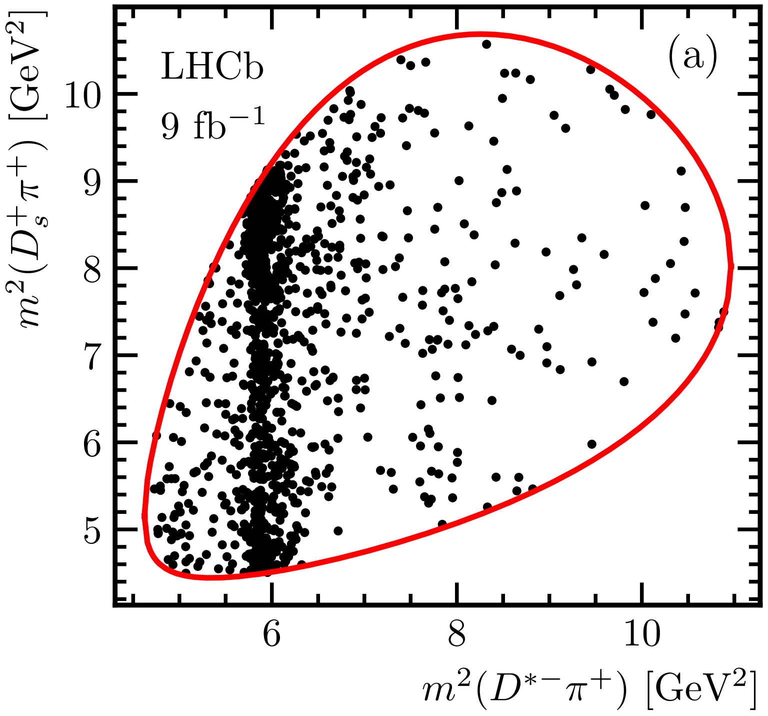
Amplitude analysis of $B^+ \to D^{*-} D_s^+ \pi^+$ decays

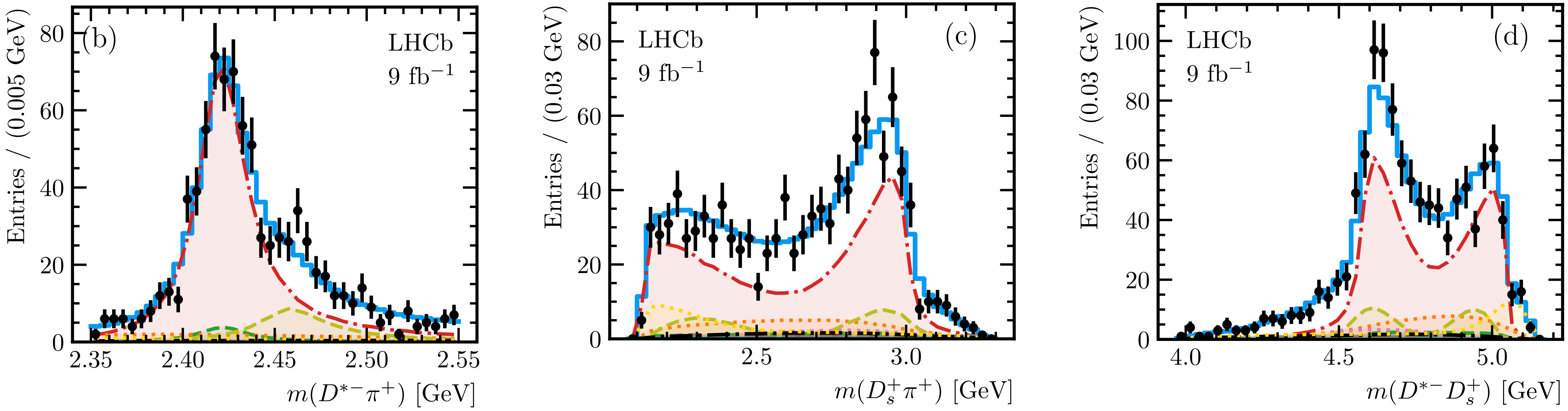
- Very recent paper from LHCb
  - Do we see the $T_{c\bar{s}0}(2900)^{++}$ state?
  - About 850 events in the signal region, analysis strategy ~as before





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

- Very recent paper from LHCb
  - Do we see the $T_{c\bar{s}0}(2900)^{++}$ state?
  - Region of interest dominated by reflections from $D_1(2420), D_1(2430)$ states
  - No evidence for the tetraquark with this limited data set
  - Fit fraction for $T_{c\bar{s}0}(2900)^{++} < 2.3\,\%\ (90\,\%\ \mathrm{CL})$



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  - **Study of $B^+ \to D^{*\pm} D^{\mp} K^+$ decays**
  - Radiative decays of $\chi_{c1}(3872)$
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Study of the $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

- Study resonant structures in $B^+ \to D^{*+} D^- K^+, B^+ \to D^{*-} D^+ K^+$ decays
  - Again motivated by tetraquark observations in $B^+ \to D^+ D^- K^+$ decays
  - Interest to study this family of tetraquarks further!

- Simultaneous analysis of the two final states
  - Expect charmonium(-like) contributions to be equal in both (C conservation)

- Use the full Run 1 + Run 2 data sample from LHCb
  - Find 1636 ± 43 decays in $B^+ \to D^{*+} D^- K^+$ sample
  - Find 1772 ± 44 decays in $B^+ \to D^{*-} D^+ K^+$ sample
  - Purity in both modes around 95%

Study of the $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

- Study resonant structures in $B^+ \to D^{*+} D^- K^+, B^+ \to D^{*-} D^+ K^+$ decays
  - Baseline model
  - Lots to discuss!

Component	$J^{P(C)}$	Fit fraction [%] $B^+ \to D^{*+} D^- K^+$	Fit fraction [%] $B^+ \to D^{*-} D^+ K^+$	Branching fraction $[10^{-4}]$
$\text{EFF}_{1^{++}}$	1^{++}	$10.9\,^{+2.3}_{-1.2}\,^{+1.6}_{-2.1}$	$9.9\,^{+2.1}_{-1.0}\,^{+1.4}_{-1.9}$	$0.74\,^{+0.16}_{-0.08}\,^{+0.11}_{-0.14} \pm 0.07$
$\eta_c(3945)$	0^{-+}	$3.4\,^{+0.5}_{-1.0}\,^{+1.9}_{-0.7}$	$3.1\,^{+0.5}_{-0.9}\,^{+1.7}_{-0.6}$	$0.23\,^{+0.04}_{-0.07}\,^{+0.13}_{-0.05} \pm 0.02$
$\chi_{c2}(3930)^{\dagger}$	2^{++}	$1.8\,^{+0.5}_{-0.4}\,^{+0.6}_{-1.2}$	$1.7\,^{+0.5}_{-0.4}\,^{+0.6}_{-1.1}$	$0.12\,^{+0.03}_{-0.03}\,^{+0.04}_{-0.08} \pm 0.01$
$h_c(4000)$	1^{+-}	$5.1\,^{+1.0}_{-0.8}\,^{+1.5}_{-0.8}$	$4.6\,^{+0.9}_{-0.7}\,^{+1.4}_{-0.7}$	$0.35\,^{+0.07}_{-0.05}\,^{+0.10}_{-0.05} \pm 0.03$
$\chi_{c1}(4010)$	1^{++}	$10.1\,^{+1.6}_{-0.9}\,^{+1.3}_{-1.6}$	$9.1\,^{+1.4}_{-0.8}\,^{+1.2}_{-1.4}$	$0.69\,^{+0.11}_{-0.06}\,^{+0.09}_{-0.11} \pm 0.06$
$\psi(4040)^{\dagger}$	1^{--}	$2.8\,^{+0.5}_{-0.4}\,^{+0.5}_{-0.5}$	$2.6\,^{+0.5}_{-0.4}\,^{+0.4}_{-0.5}$	$0.19\,^{+0.04}_{-0.03}\,^{+0.03}_{-0.03} \pm 0.02$
$h_c(4300)$	1^{+-}	$1.2\,^{+0.2}_{-0.5}\,^{+0.2}_{-0.2}$	$1.1\,^{+0.2}_{-0.5}\,^{+0.2}_{-0.2}$	$0.08\,^{+0.01}_{-0.03}\,^{+0.02}_{-0.01} \pm 0.01$
$T^*_{\bar{c}\bar{s}0}(2870)^{0\,\dagger}$	0^+	$6.5\,^{+0.9}_{-1.2}\,^{+1.3}_{-1.6}$	–	$0.45\,^{+0.06}_{-0.08}\,^{+0.09}_{-0.10} \pm 0.04$
$T^*_{\bar{c}\bar{s}1}(2900)^{0\,\dagger}$	1^-	$5.5\,^{+1.1}_{-1.5}\,^{+2.4}_{-1.6}$	–	$0.38\,^{+0.07}_{-0.10}\,^{+0.16}_{-0.11} \pm 0.03$
$\text{NR}_{1^{--}}(D^{*\mp}D^{\pm})$	1^{--}	$20.4\,^{+2.3}_{-0.6}\,^{+2.1}_{-2.6}$	$18.5\,^{+2.1}_{-0.5}\,^{+1.9}_{-2.3}$	$1.39\,^{+0.16}_{-0.04}\,^{+0.14}_{-0.17} \pm 0.12$
$\text{NR}_{0^{--}}(D^{*\mp}D^{\pm})$	0^{--}	$1.2\,^{+0.6}_{-0.1}\,^{+0.7}_{-0.6}$	$1.1\,^{+0.6}_{-0.1}\,^{+0.6}_{-0.5}$	$0.08\,^{+0.04}_{-0.01}\,^{+0.05}_{-0.04} \pm 0.01$
$\text{NR}_{1^{++}}(D^{*\mp}D^{\pm})$	1^{++}	$17.8\,^{+1.9}_{-1.4}\,^{+3.6}_{-2.6}$	$16.1\,^{+1.7}_{-1.3}\,^{+3.3}_{-2.3}$	$1.21\,^{+0.13}_{-0.10}\,^{+0.24}_{-0.17} \pm 0.11$
$\text{NR}_{0^{-+}}(D^{*\mp}D^{\pm})$	0^{-+}	$15.9\,^{+3.3}_{-1.2}\,^{+3.3}_{-3.3}$	$14.5\,^{+3.0}_{-1.1}\,^{+3.0}_{-3.0}$	$1.09\,^{+0.23}_{-0.08}\,^{+0.22}_{-0.23} \pm 0.09$

Study of the $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

- Study resonant structures in $B^+ \to D^{*+} D^- K^+, B^+ \to D^{*-} D^+ K^+$ decays
  - Baseline model
  - Lots to discuss!
  - New charmonium(-like) states

Component	$J^{P(C)}$	Fit fraction [%] $B^+ \to D^{*+} D^- K^+$	Fit fraction [%] $B^+ \to D^{*-} D^+ K^+$	Branching fraction $[10^{-4}]$
$\text{EFF}_{1^{++}}$	1^{++}	$10.9\,^{+2.3}_{-1.2}\,^{+1.6}_{-2.1}$	$9.9\,^{+2.1}_{-1.0}\,^{+1.4}_{-1.9}$	$0.74\,^{+0.16}_{-0.08}\,^{+0.11}_{-0.14} \pm 0.07$
$\eta_c(3945)$	0^{-+}	$3.4\,^{+0.5}_{-1.0}\,^{+1.9}_{-0.7}$	$3.1\,^{+0.5}_{-0.9}\,^{+1.7}_{-0.6}$	$0.23\,^{+0.04}_{-0.07}\,^{+0.13}_{-0.05} \pm 0.02$
$\chi_{c2}(3930)^{\dagger}$	2^{++}	$1.8\,^{+0.5}_{-0.4}\,^{+0.6}_{-1.2}$	$1.7\,^{+0.5}_{-0.4}\,^{+0.6}_{-1.1}$	$0.12\,^{+0.03}_{-0.03}\,^{+0.04}_{-0.08} \pm 0.01$
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$T^*_{\bar{c}\bar{s}0}(2870)^{0\,\dagger}$	0^{+}	$6.5\,^{+0.9}_{-1.2}\,^{+1.3}_{-1.6}$	–	$0.45\,^{+0.06}_{-0.08}\,^{+0.09}_{-0.10} \pm 0.04$
$T^*_{\bar{c}\bar{s}1}(2900)^{0\,\dagger}$	1^{-}	$5.5\,^{+1.1}_{-1.5}\,^{+2.4}_{-1.6}$	–	$0.38\,^{+0.07}_{-0.10}\,^{+0.16}_{-0.11} \pm 0.03$
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$\text{NR}_{0^{--}}(D^{*\mp}D^{\pm})$	0^{--}	$1.2\,^{+0.6}_{-0.1}\,^{+0.7}_{-0.6}$	$1.1\,^{+0.6}_{-0.1}\,^{+0.6}_{-0.5}$	$0.08\,^{+0.04}_{-0.01}\,^{+0.05}_{-0.04} \pm 0.01$
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$\text{NR}_{0^{-+}}(D^{*\mp}D^{\pm})$	0^{-+}	$15.9\,^{+3.3}_{-1.2}\,^{+3.3}_{-3.3}$	$14.5\,^{+3.0}_{-1.1}\,^{+3.0}_{-3.0}$	$1.09\,^{+0.23}_{-0.08}\,^{+0.22}_{-0.23} \pm 0.09$

Study of the $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

- Study resonant structures in $B^+ \to D^{*+} D^- K^+, B^+ \to D^{*-} D^+ K^+$ decays
  - Baseline model
  - Lots to discuss!
  - New charmonium(-like) states
  - Tetraquarks seen in one channel
  - $T_{c\bar{s}0}(2870)^0$ forbidden in $B^+ \to D^{*-} D^+ K^+$ and the spin-1 state not seen

Component	$J^{P(C)}$	Fit fraction [%] $B^+ \to D^{*+} D^- K^+$	Fit fraction [%] $B^+ \to D^{*-} D^+ K^+$	Branching fraction $[10^{-4}]$
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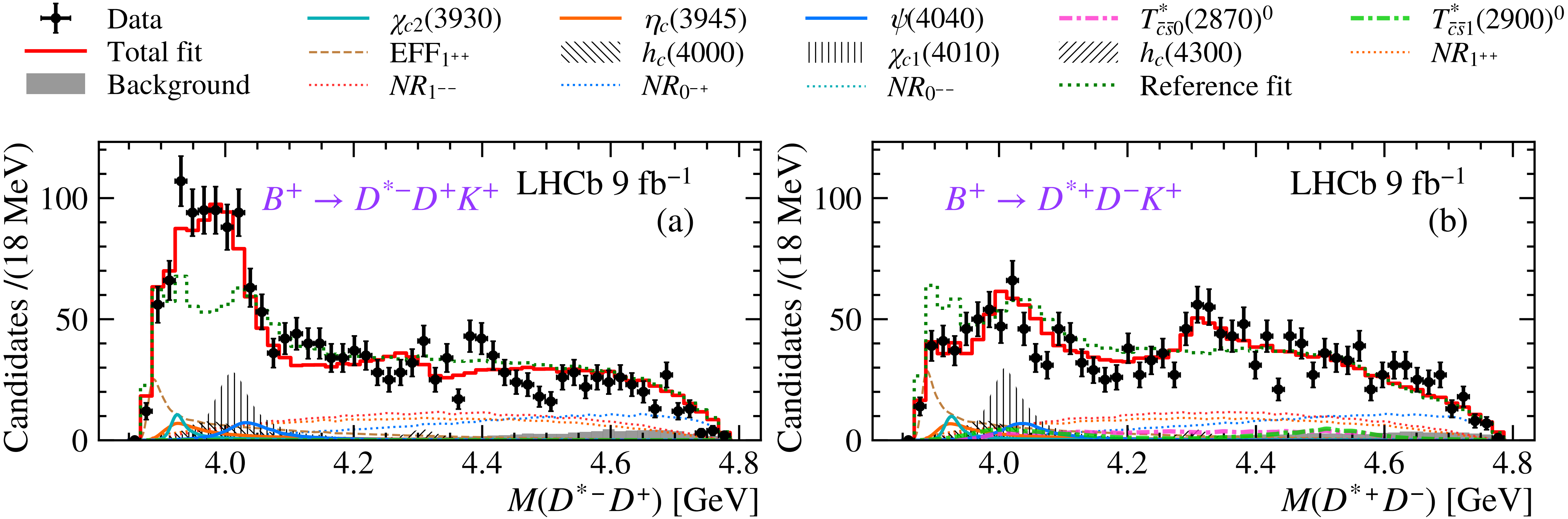
$\eta_c(3945)$	0^{-+}	$3.4\,^{+0.5}_{-1.0}\,^{+1.9}_{-0.7}$	$3.1\,^{+0.5}_{-0.9}\,^{+1.7}_{-0.6}$	$0.23\,^{+0.04}_{-0.07}\,^{+0.13}_{-0.05} \pm 0.02$
$\chi_{c2}(3930)^{\dagger}$	2^{++}	$1.8\,^{+0.5}_{-0.4}\,^{+0.6}_{-1.2}$	$1.7\,^{+0.5}_{-0.4}\,^{+0.6}_{-1.1}$	$0.12\,^{+0.03}_{-0.03}\,^{+0.04}_{-0.08} \pm 0.01$
$h_c(4000)$	1^{+-}	$5.1\,^{+1.0}_{-0.8}\,^{+1.5}_{-0.8}$	$4.6\,^{+0.9}_{-0.7}\,^{+1.4}_{-0.7}$	$0.35\,^{+0.07}_{-0.05}\,^{+0.10}_{-0.05} \pm 0.03$
$\chi_{c1}(4010)$	1^{++}	$10.1\,^{+1.6}_{-0.9}\,^{+1.3}_{-1.6}$	$9.1\,^{+1.4}_{-0.8}\,^{+1.2}_{-1.4}$	$0.69\,^{+0.11}_{-0.06}\,^{+0.09}_{-0.11} \pm 0.06$
$\psi(4040)^{\dagger}$	1^{--}	$2.8\,^{+0.5}_{-0.4}\,^{+0.5}_{-0.5}$	$2.6\,^{+0.5}_{-0.4}\,^{+0.4}_{-0.5}$	$0.19\,^{+0.04}_{-0.03}\,^{+0.03}_{-0.03} \pm 0.02$
$h_c(4300)$	1^{+-}	$1.2\,^{+0.2}_{-0.5}\,^{+0.2}_{-0.2}$	$1.1\,^{+0.2}_{-0.5}\,^{+0.2}_{-0.2}$	$0.08\,^{+0.01}_{-0.03}\,^{+0.02}_{-0.01} \pm 0.01$
$T^*_{c\bar{s}0}(2870)^{0\,\dagger}$	0^+	$6.5\,^{+0.9}_{-1.2}\,^{+1.3}_{-1.6}$	–	$0.45\,^{+0.06}_{-0.08}\,^{+0.09}_{-0.10} \pm 0.04$
$T^*_{c\bar{s}1}(2900)^{0\,\dagger}$	1^-	$5.5\,^{+1.1}_{-1.5}\,^{+2.4}_{-1.6}$	–	$0.38\,^{+0.07}_{-0.10}\,^{+0.16}_{-0.11} \pm 0.03$
$\mathrm{NR}_{1^{--}}(D^{*\mp}D^{\pm})$	1^{--}	$20.4\,^{+2.3}_{-0.6}\,^{+2.1}_{-2.6}$	$18.5\,^{+2.1}_{-0.5}\,^{+1.9}_{-2.3}$	$1.39\,^{+0.16}_{-0.04}\,^{+0.14}_{-0.17} \pm 0.12$
$\mathrm{NR}_{0^{--}}(D^{*\mp}D^{\pm})$	0^{--}	$1.2\,^{+0.6}_{-0.1}\,^{+0.7}_{-0.6}$	$1.1\,^{+0.6}_{-0.1}\,^{+0.6}_{-0.5}$	$0.08\,^{+0.04}_{-0.01}\,^{+0.05}_{-0.04} \pm 0.01$
$\mathrm{NR}_{1^{++}}(D^{*\mp}D^{\pm})$	1^{++}	$17.8\,^{+1.9}_{-1.4}\,^{+3.6}_{-2.6}$	$16.1\,^{+1.7}_{-1.3}\,^{+3.3}_{-2.3}$	$1.21\,^{+0.13}_{-0.10}\,^{+0.24}_{-0.17} \pm 0.11$
$\mathrm{NR}_{0^{-+}}(D^{*\mp}D^{\pm})$	0^{-+}	$15.9\,^{+3.3}_{-1.2}\,^{+3.3}_{-3.3}$	$14.5\,^{+3.0}_{-1.1}\,^{+3.0}_{-3.0}$	$1.09\,^{+0.23}_{-0.08}\,^{+0.22}_{-0.23} \pm 0.09$

Study of the $B^+ \to D^{*\pm}D^{\mp}K^+$ decays

- Study resonant structures in $B^+ \to D^{*+}D^-K^+, B^+ \to D^{*-}D^+K^+$ decays



Discrepancies covered by model systematics

Study of the $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

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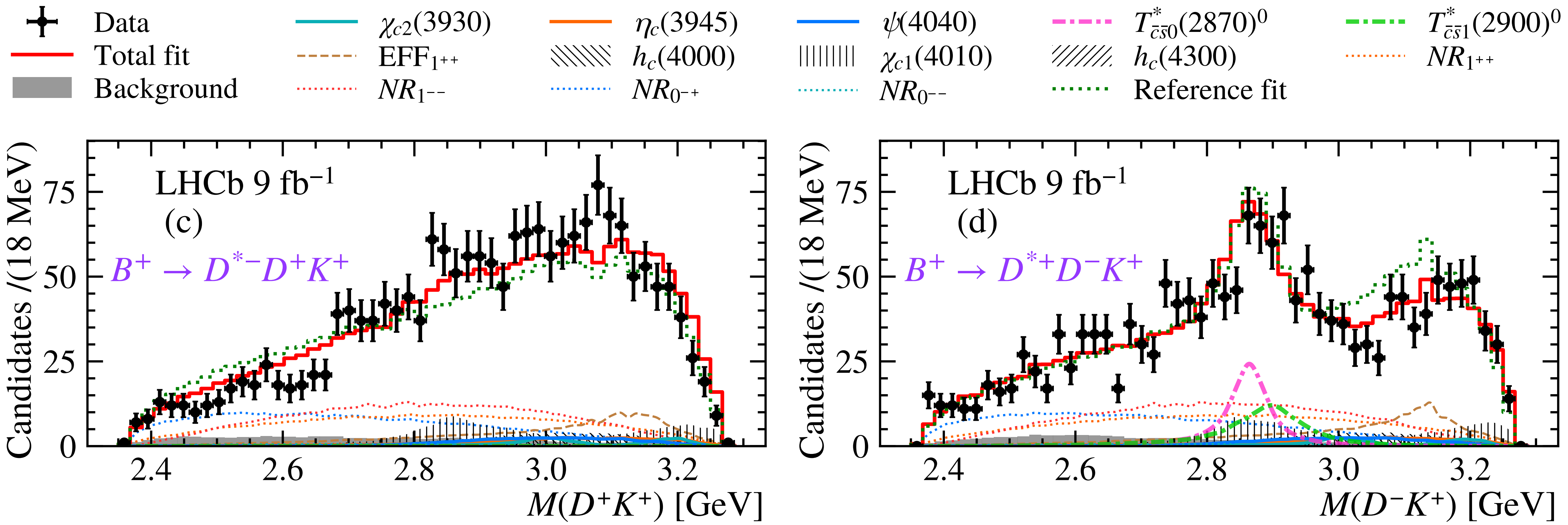

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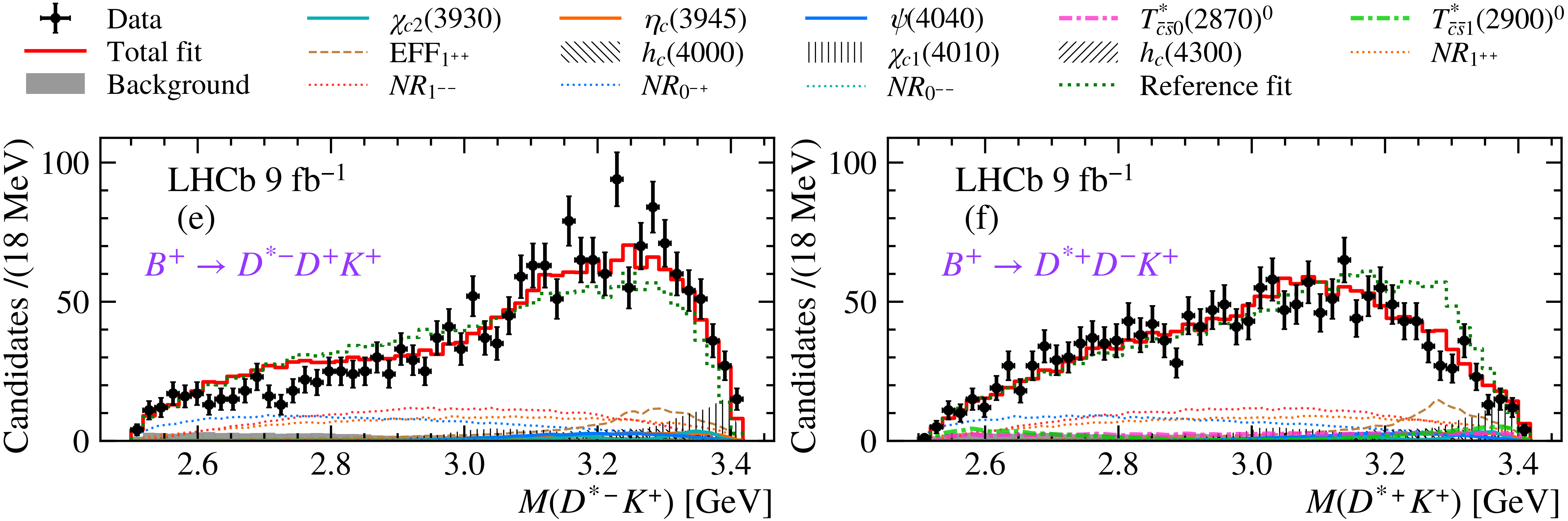


Discrepancies covered by model systematics

Study of the $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

- Study resonant structures in $B^+ \to D^{*+} D^- K^+, B^+ \to D^{*-} D^+ K^+$ decays
  - Tetraquark candidates in fair agreement with previous results
  - Seems to be a difference in the ratio of the two states in this final state

Property	This work	Previous work
$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{\bar{c}\bar{s}0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{\bar{c}\bar{s}1}(2900)^0$ width [MeV]	$92 \pm 16 \pm 16$	110 ± 12
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})$	$(4.5\,^{+0.6}_{-0.8}\,^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})$	$(3.8\,^{+0.7}_{-1.0}\,^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
$\frac{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})}{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

11σ

9.1σ

Consistent with X(3940) seen by Belle	$\eta_c(3945)$	$h_c(4000)$	$\chi_{c1}(4010)$	and $h_c(4300)$
	10σ	9.1σ	16σ	6.4σ
	0^{-+}	1^{+-}	1^{++}	1^{+-}

- 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
    - Quick look at a new result from $B^+ \to D^{*-} D_s^+ \pi^+$
  - Study of $B^+ \to D^{*\pm} D^{\mp} K^+$ decays
  - Radiative decays of $\chi_{c1}(3872)$
- Future prospects

Radiative decays of the $\chi_{c1}(3872)$ state

- Try to learn more about this famous state by studying these decay modes
  - Aim to measure the ratio of branching fractions

$$\mathcal{R}_{\psi\gamma} = \frac{\Gamma(\chi_{c1}(3872) \to \psi(2S)\gamma)}{\Gamma(\chi_{c1}(3872) \to J/\psi\gamma)}$$

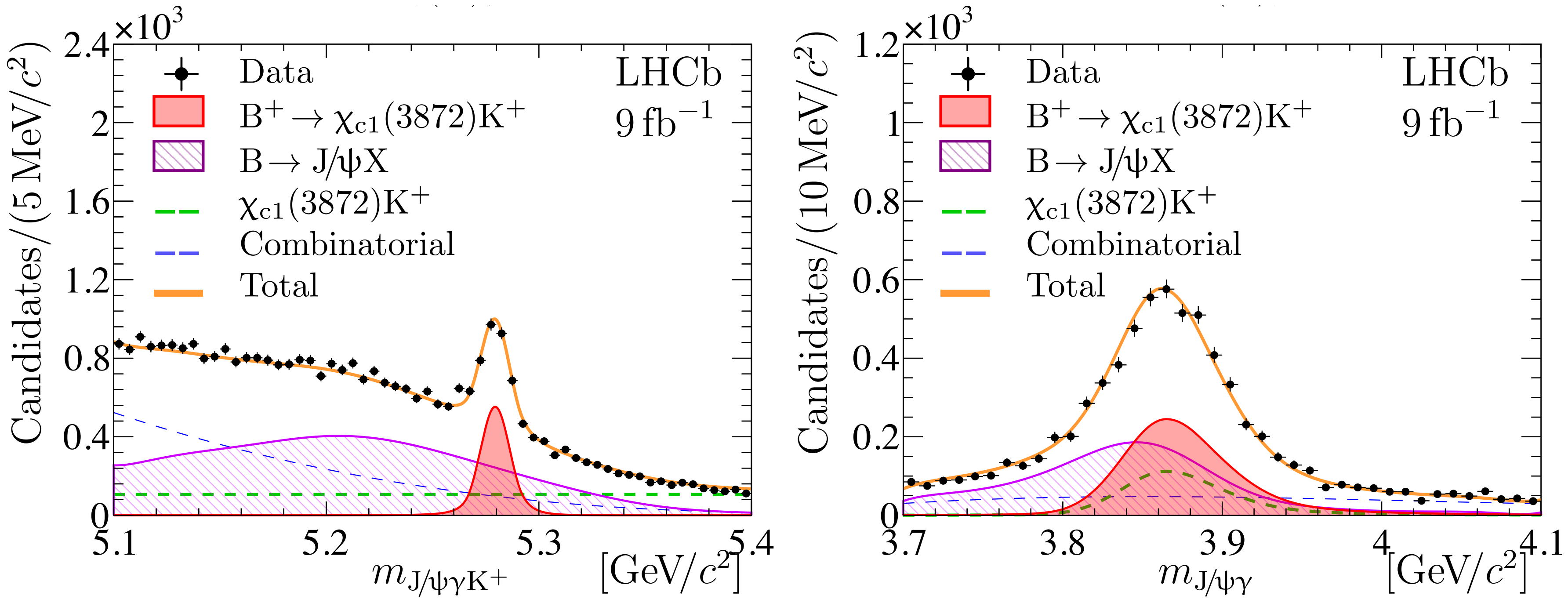
  - Predictions vary strongly depending on the nature of the $\chi_{c1}(3872)$ state

- Experimental history
  - BaBar measured $\mathcal{R}_{\psi\gamma} = 3.4 \pm 1.4$
  - LHCb measured $\mathcal{R}_{\psi\gamma} = 2.46 \pm 0.64 \pm 0.29$
  - Belle and BESIII found no significant signal for $\chi_{c1}(3872) \to \psi(2S)\gamma$

Radiative decays of the $\chi_{c1}(3872)$ state

- In the latest LHCb measurement we determine

$$\mathcal{R}_{\psi\gamma} = \frac{\Gamma(B^+ \to [\chi_{c1}(3872) \to \psi(2S)\gamma]K^+)}{\Gamma(B^+ \to [\chi_{c1}(3872) \to J/\psi\gamma]K^+)}$$



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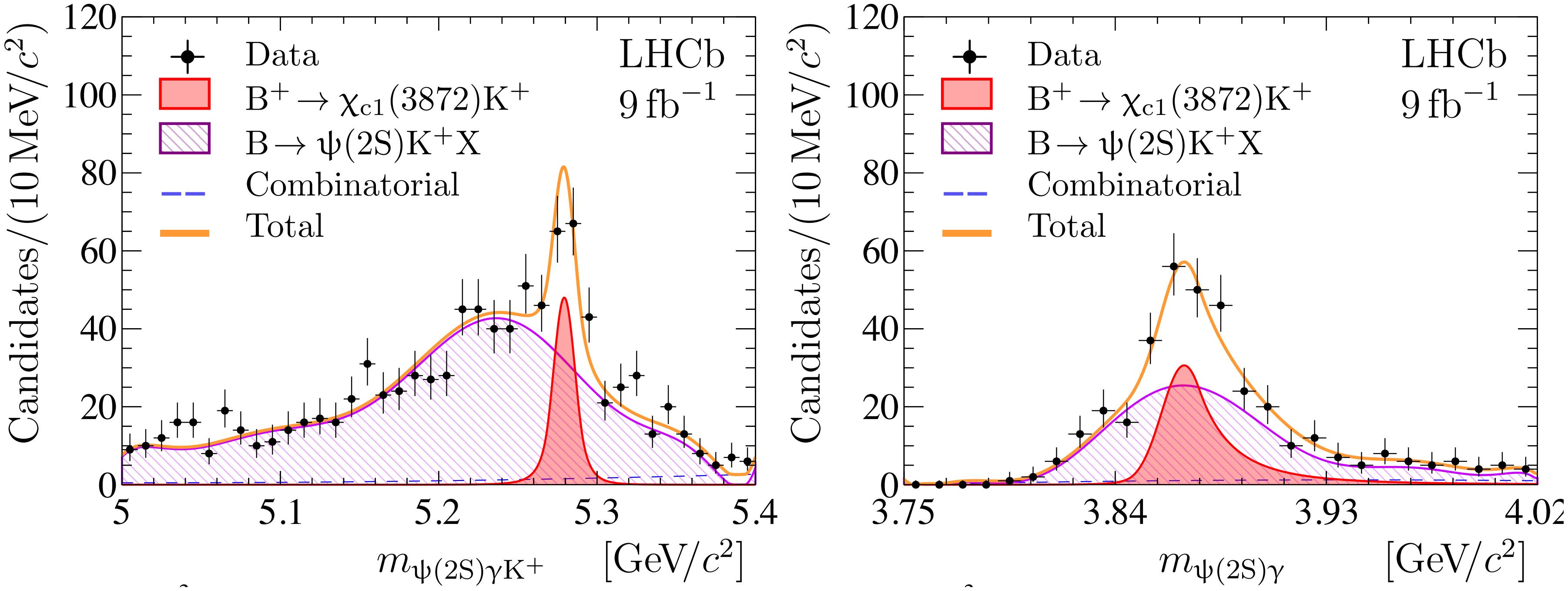


Radiative decays of the $\chi_{c1}(3872)$ state

- Summary of yield from the mass fits

Parameter		Data-taking period Run 1	Run 2
$\psi(2S)\gamma K^+$		5.3σ	6.7σ
$N_{B^+\to(\chi_{c1}(3872)\to\psi(2S)\gamma)K^+}$		40 ± 8	63 ± 10
$N_{B\to\psi(2S)K^+X}$		567 ± 24	885 ± 29
N_{comb}		55 ± 17	132 ± 19
$J/\psi\gamma K^+$			
$N_{B^+\to(\chi_{c1}(3872)\to J/\psi\gamma)K^+}$	$[10^3]$	0.43 ± 0.03	1.69 ± 0.05
$N_{B\to J/\psi X}$	$[10^3]$	3.61 ± 0.11	18.72 ± 0.26
$N_{\chi_{c1}(3872)K^+}$	$[10^3]$	1.18 ± 0.06	5.53 ± 0.23
N_{comb}	$[10^3]$	4.05 ± 0.11	17.46 ± 0.21

Stat only

Radiative decays of the $\chi_{c1}(3872)$ state

- Summary of results by year

$$\mathcal{R}_{\psi\gamma}^{\mathrm{Run\,1}} = 2.50 \pm 0.52\,^{+0.20}_{-0.23} \pm 0.06$$
$$\mathcal{R}_{\psi\gamma}^{\mathrm{Run\,2}} = 1.49 \pm 0.23\,^{+0.13}_{-0.12} \pm 0.03$$

  - Averaged (BLUE method) to give

$$\mathcal{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$

  - Inconsistent with an upper limit from BESIII
  - Inconsistent with many predictions using DD* molecular models

Summary

- Exciting time in spectroscopy (again)
  - Huge number of recent observations
  - Challenge remains to understand them

- Looking forward to cracking open the Run 3 data sample!
  - Expecting to collect roughly the Run 1 + Run 2 sample per year
  - Early indications show the factor of two gain in hadronic final states from the new software only trigger seems realistic

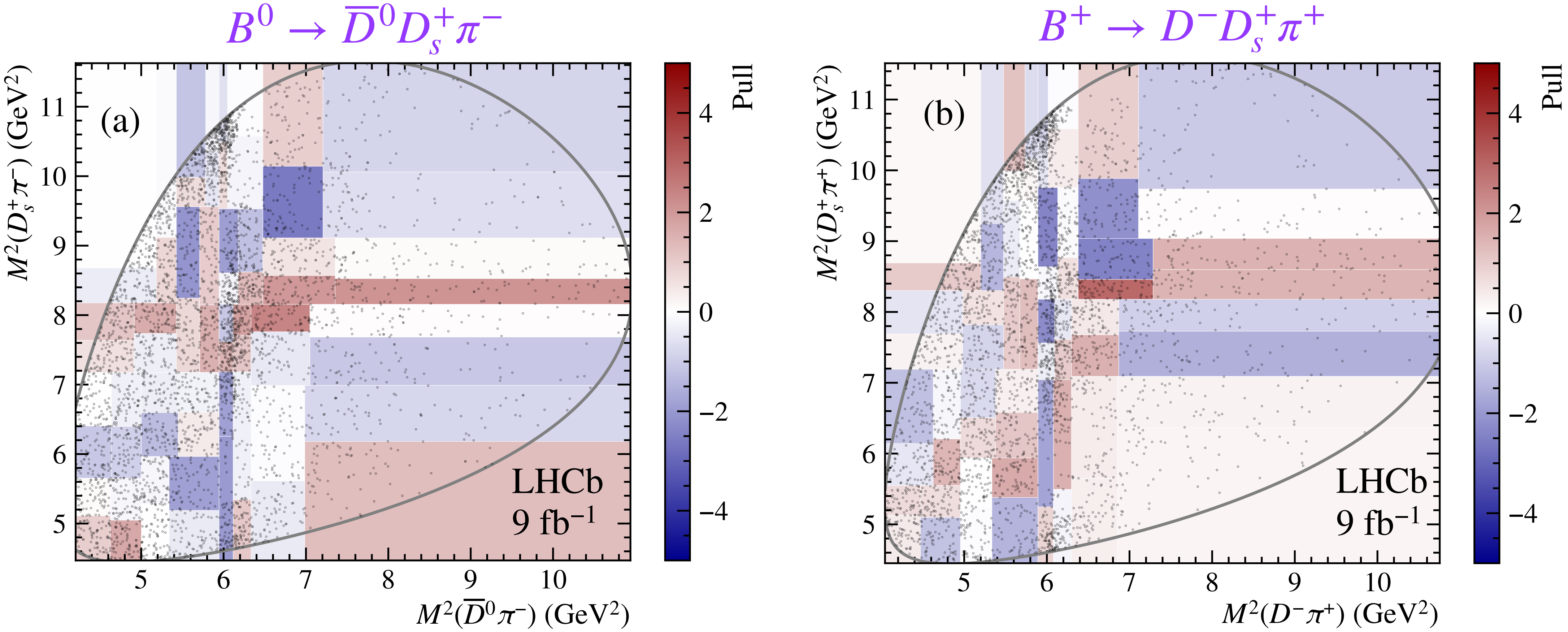
Back up

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	$-(0.82 \pm 0.61) \times 10^{-3}$	$-(0.90 \pm 0.31) \times 10^{-3}$

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

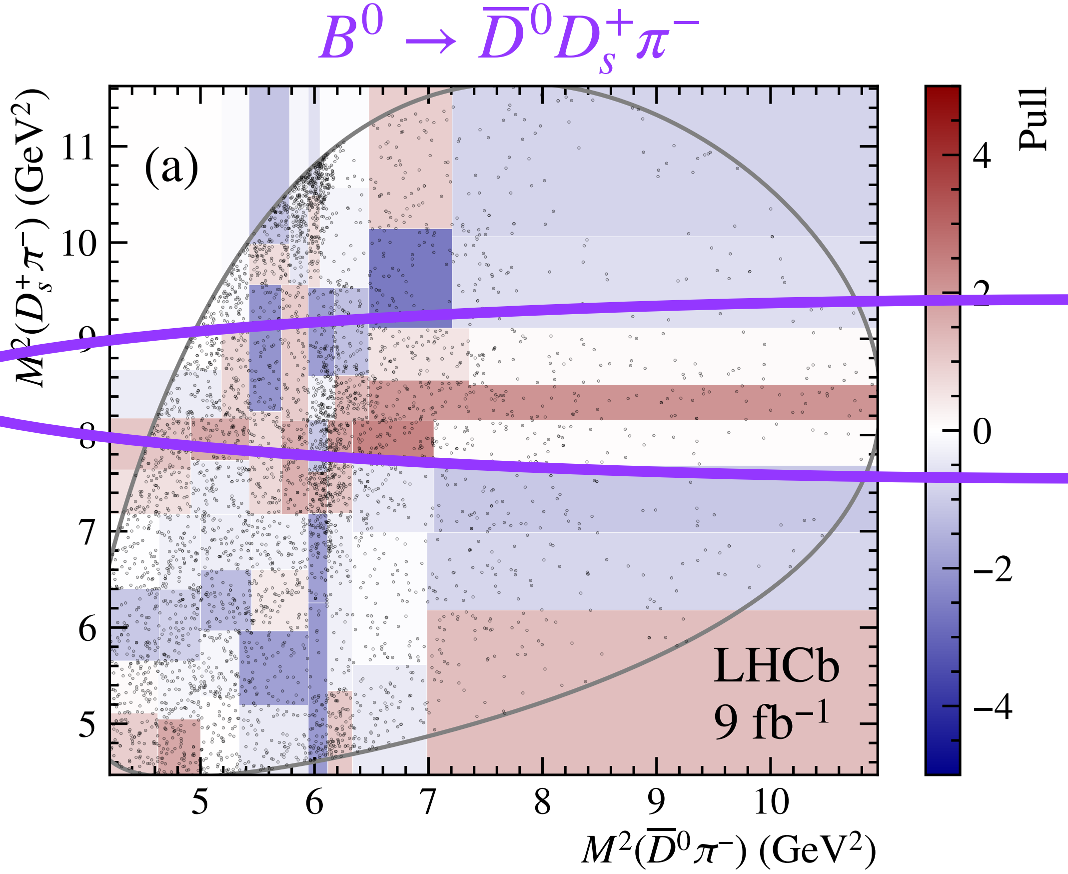
- Have a look at the fit quality

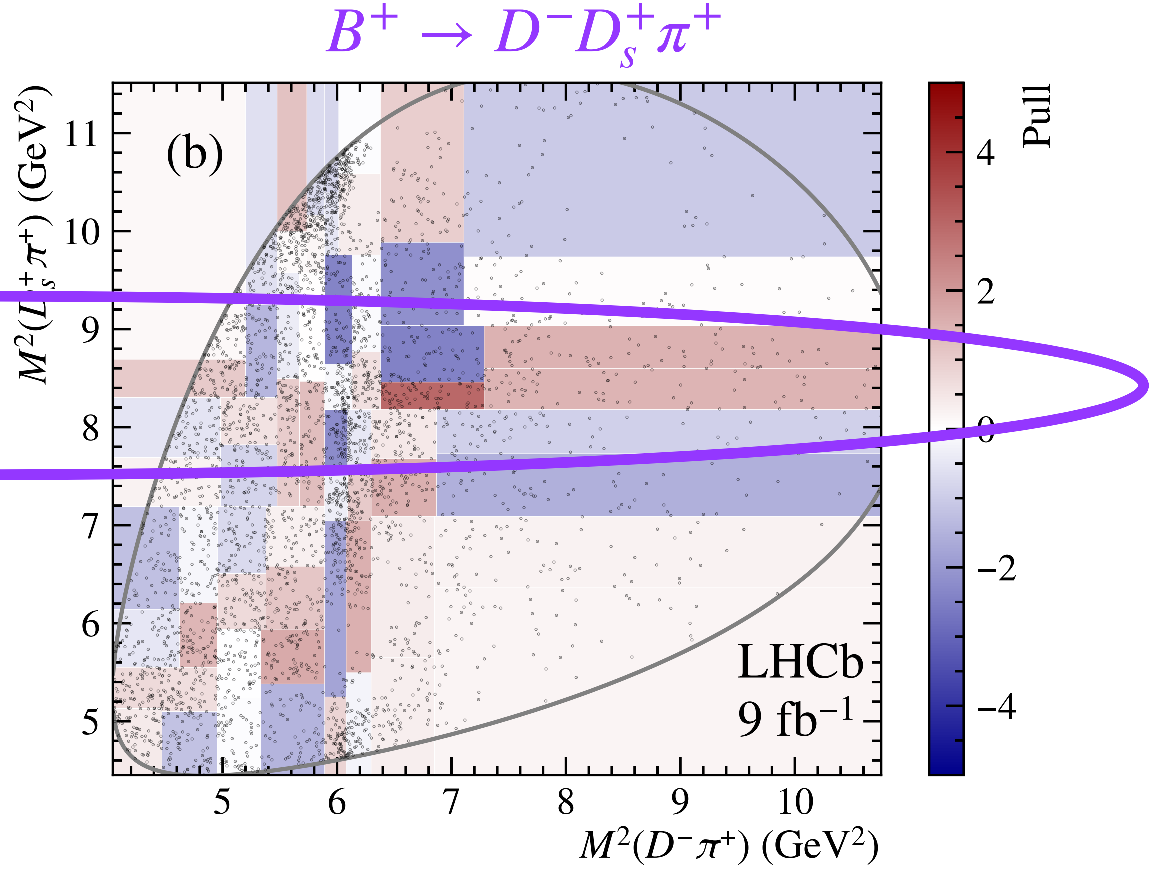


Phys. Rev. D108 (2023) 012017, Phys. Rev. Lett. 131 (2023) 041902

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

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





Study of the $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

- Study resonant structures in $B^+ \to D^{*+} D^- K^+, B^+ \to D^{*-} D^+ K^+$ decays

This work		Known states [6]		$c\bar{c}$ prediction [34]	
$\eta_c(3945)$	$J^{PC} = 0^{-+}$	$X(3940)$ [9, 10]	$J^{PC} = ?^{??}$	$\eta_c(3S)$	$J^{PC} = 0^{-+}$
$m_0 = 3945\,^{+28}_{-17}\,^{+37}_{-28}$	$\Gamma_0 = 130\,^{+92}_{-49}\,^{+101}_{-70}$	$m_0 = 3942 \pm 9$	$\Gamma_0 = 37\,^{+27}_{-17}$	$m_0 = 4064$	$\Gamma_0 = 80$
$h_c(4000)$	$J^{PC} = 1^{+-}$	$T_{c\bar{c}}(4020)^0$ [35]	$J^{PC} = ?^{?-}$	$h_c(2P)$	$J^{PC} = 1^{+-}$
$m_0 = 4000\,^{+17}_{-14}\,^{+29}_{-22}$	$\Gamma_0 = 184\,^{+71}_{-45}\,^{+97}_{-61}$	$m_0 = 4025.5\,^{+2.0}_{-4.7} \pm 3.1$	$\Gamma_0 = 23.0 \pm 6.0 \pm 1.0$	$m_0 = 3956$	$\Gamma_0 = 87$
$\chi_{c1}(4010)$	$J^{PC} = 1^{++}$			$\chi_{c1}(2P)$	$J^{PC} = 1^{++}$
$m_0 = 4012.5\,^{+3.6}_{-3.9}\,^{+4.1}_{-3.7}$	$\Gamma_0 = 62.7\,^{+7.0}_{-6.4}\,^{+6.4}_{-6.6}$			$m_0 = 3953$	$\Gamma_0 = 165$
$h_c(4300)$	$J^{PC} = 1^{+-}$			$h_c(3P)$	$J^{PC} = 1^{+-}$
$m_0 = 4307.3\,^{+6.4}_{-6.6}\,^{+3.3}_{-4.1}$	$\Gamma_0 = 58\,^{+28}_{-16}\,^{+28}_{-25}$			$m_0 = 4318$	$\Gamma_0 = 75$
		$\chi_c(4274)$ [36]	$J^{PC} = 1^{++}$	$\chi_{c1}(3P)$	$J^{PC} = 1^{++}$
		$m_0 = 4294 \pm 4\,^{+6}_{-3}$	$\Gamma_0 = 53 \pm 5 \pm 5$	$m_0 = 4317$	$\Gamma_0 = 39$

$$\eta_c(3945),\ h_c(4000),\ \chi_{c1}(4010)\ \text{and}\ h_c(4300)$$

$\eta_c(3945)$	$h_c(4000)$	$\chi_{c1}(4010)$	$h_c(4300)$
10σ	9.1σ	16σ	6.4σ
0^{-+}	1^{+-}	1^{++}	1^{+-}

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.

$T_{cs0}(2900)^0$

$T_{cs1}(2900)^0$

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

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

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

- 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