Amplitude analysis of $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

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LHCb-PAPER-2023-047

PhysRevLett.133.131902

@CLHCP 2024

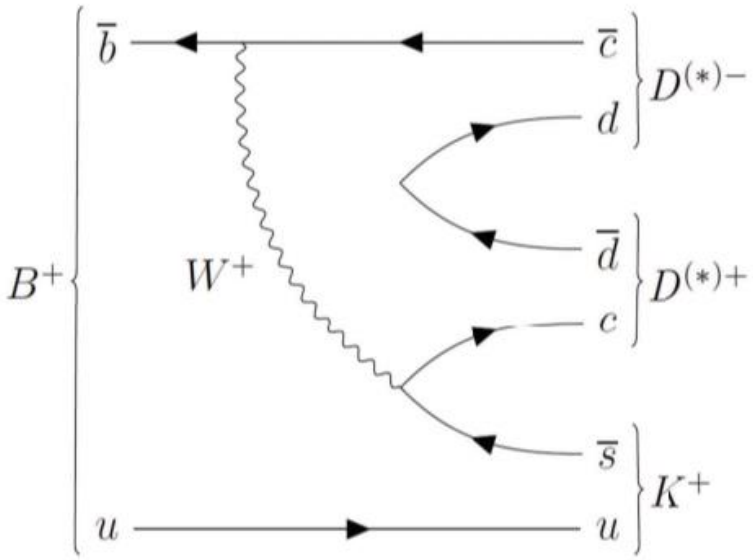
2024 Nov

Outline

- Introduction
- Fit results
  - charmonium(-like) states
  - exotic states
- Summary

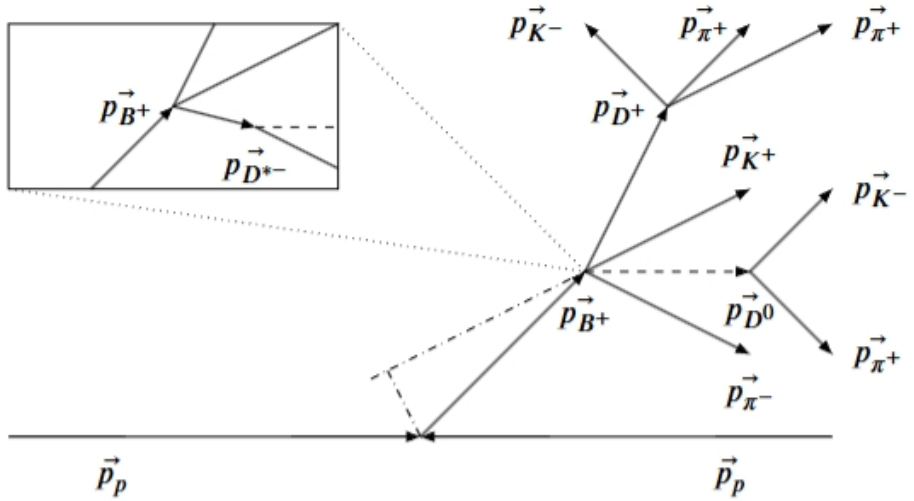
Introduction

- $B^+ \to D^{*\pm}D^{\mp}K^+$: two channels
  - $B^+ \to D^{*-}D^{+}K^+$
  - $B^+ \to D^{*+}D^{-}K^+$
- Possible resonances:
  - $D^{*\pm}D^{\mp}[c\bar{c}d\bar{d}]$: charmonium(-like)
    - 3.9 ~ 4. 8 GeV
    - Normal charmonium
      - $\psi(4040), \psi(4160), \chi_{c2}(3930), \chi_{c1}(4274)\cdots$
    - Charmonium(-like) states
      - $\chi_{c1}(3872)\ (\text{aka}\ X(3872)), Z_c(3900), X(4020), Z_c(4430), \cdots$
  - $D^{(*)-}K^+[\bar{c}\bar{s}ud]$: $T^*_{cs0}(2870)^0$ (aka $\mathrm{X}_0(2900)$), $T^*_{cs1}(2900)$(aka $\mathrm{X}_1(2900)$)
    - Found in $B^+ \to D^+T^*_{cs0,1}\ (\to D^-K^+)$ **PRL 125 (2020) 242001, PRD 102 (2020) 112003**
  - $D^{(*)+}K^+[c\bar{s}u\bar{d}]$: $T^*_{c\bar{s}0}(2900)^{++}$
    - Found in $B^+ \to D^-T^*_{c\bar{s}0}(2900)^{++}(\to D_s^+\pi^+)$ **PRL 131 (2023) 041902, PRD 108 (2023) 012017**

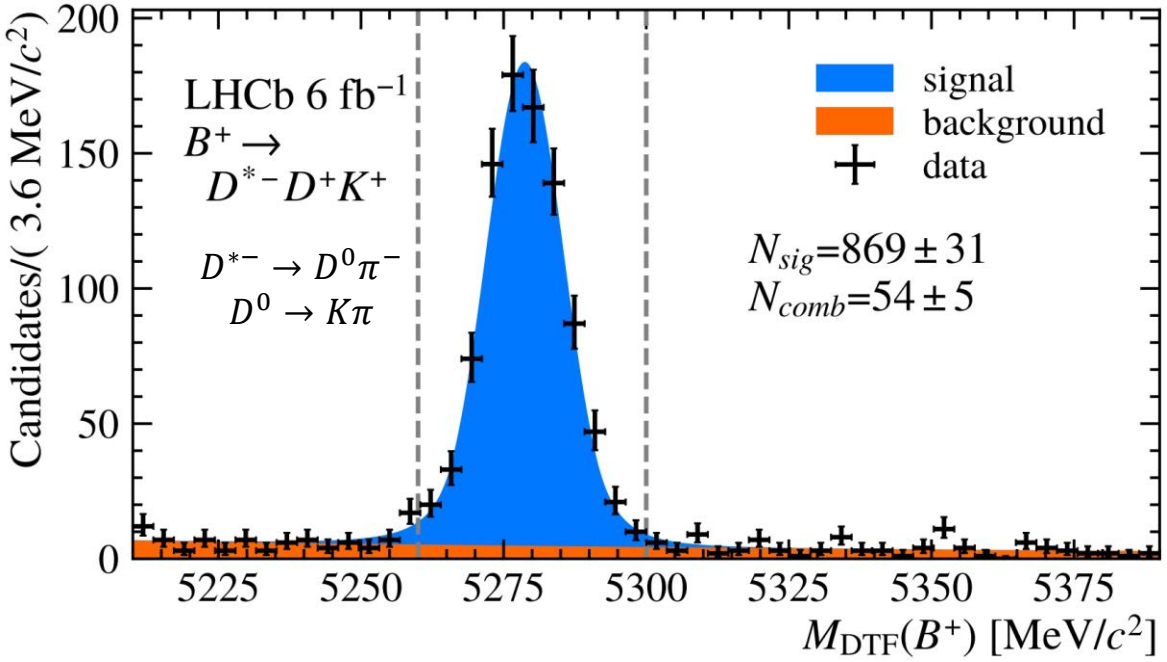


Data samples

- Reconstruction:
  - $B^+ \to D^{*\pm} D^{\mp} K^+, D^{*-} \to \bar{D}^0 \pi^-,$
  - With
    - $\bar{D}^0 \to K^- \pi^+$
    - $\bar{D}^0 \to K^- \pi^+ \pi^+ \pi^-$



- LHCb Run 1 (3 fb^{-1}) + Run 2 (6 fb^{-1})
  - Total 3.6k events
  - Purity ~ 95%



Charmuinon(-like) states

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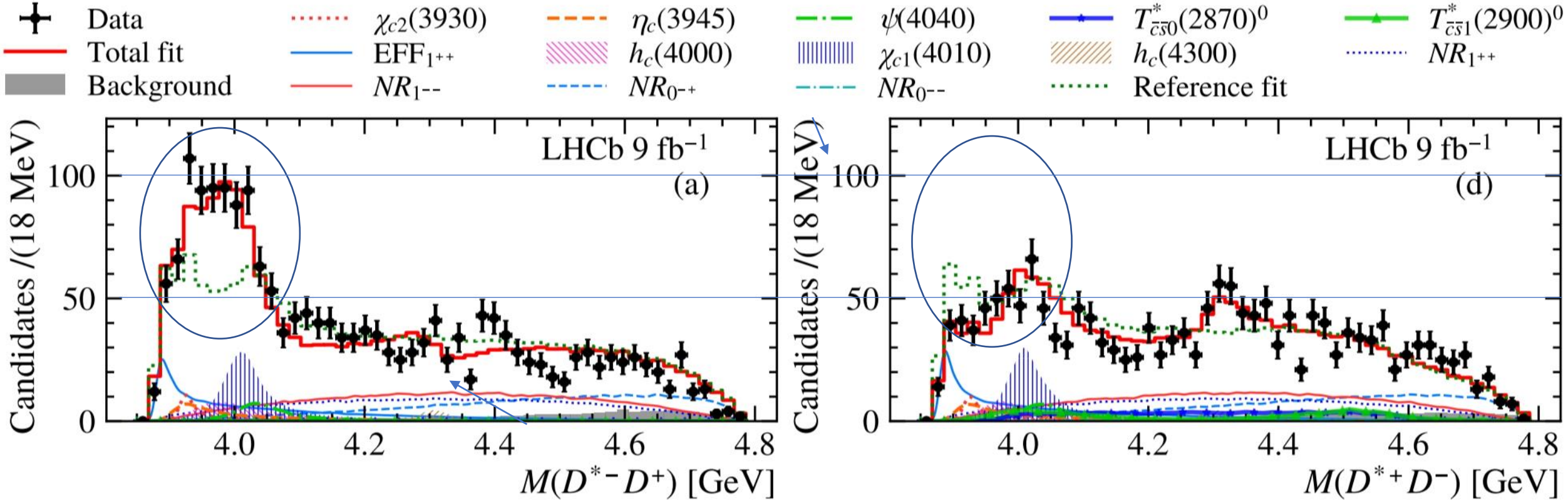
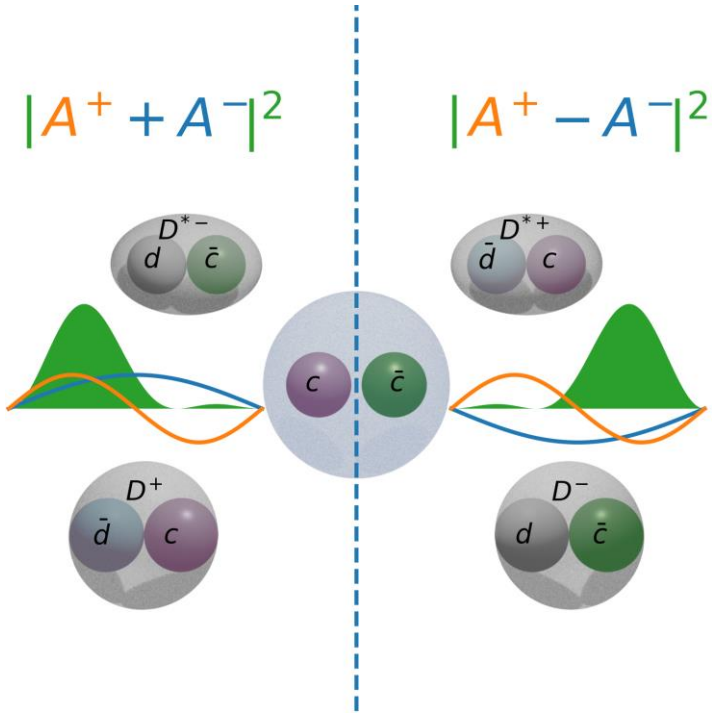
- Large difference in 3.9 – 4.0 GeV
  - $T^*_{cs0,1}$ is small in that range, do not expect large effect
  - Large difference due to C-parity



C-parity relation

- Used to constrains $R^0 \to D^{*-}D^{+}$ and $R^0 \to D^{*+}D^{-}$
  - $A^{R^0 \to D^{*-}D^{+}} = C_R A^{R^0 \to D^{*+}D^{-}}$
  - C_R is the C parity of R
- Effect of this relation
  - Two contribution with the same J^P
    - $\mathrm{R}_1(C = +1)$ and $\mathrm{R}_2(\mathrm{C} = -1)$
  - For $B^+ \to R(\to D^{*+}D^{-})K^+$
    - $|A|^2 = |A_1 + A_2|^2 = |A_1|^2 + |A_2|^2 + 2Re\,(A_1 A_2^*)$
  - For $B^+ \to R(\to D^{*-}D^{+})K^+$
    - $|A'|^2 = |A_1 - A_2|^2 = |A_1|^2 + |A_2|^2 - 2Re\,(A_1 A_2^*)$
  - $|A|^2 - |A'|^2 = 4Re(A_1 A_2^*)$
    - Only the interference can contribute to the difference of two channel



Distribution of difference

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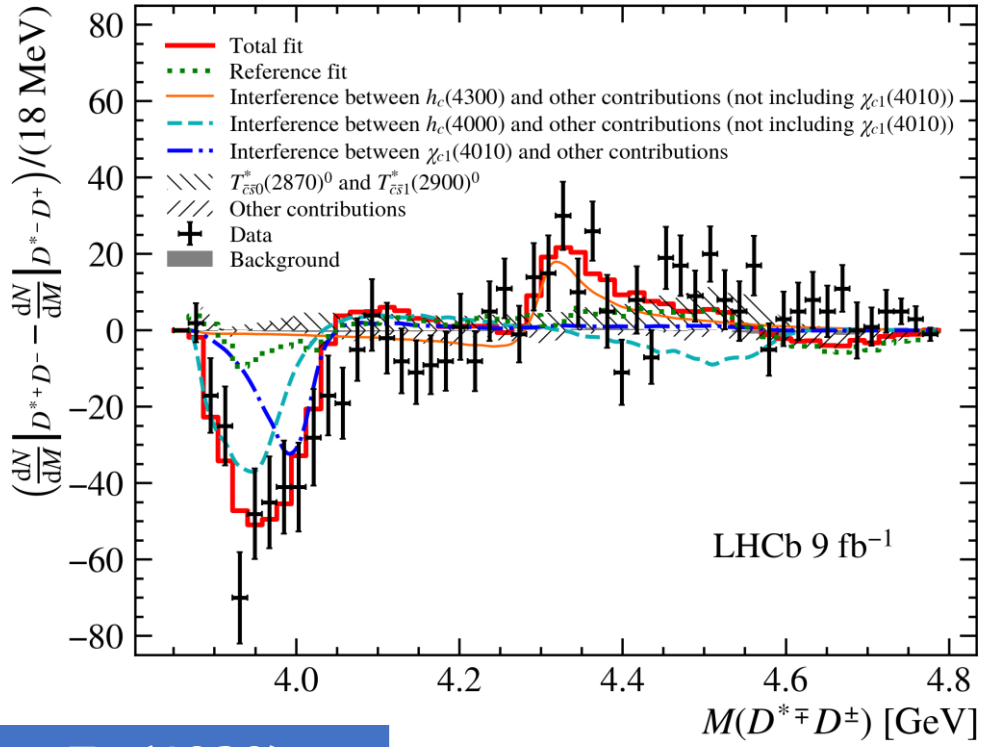
- Difference
  - Require two new states with different C-parities
  - Prefer 1^+ contribution in angular distribution.
- Reference fit w/o new states (green dotted)
  - Bad Fit quality
  - Required new states
- Add two states around 4.0 GeV
  - Similar mass as $T_{c\bar{c}}(4020)[1^{+-}]$ (aka $X(4020), Z_c(4020)$)
  - $h_c(4000)[1^{+-}]$: much larger width than $T_{c\bar{c}}(4020)$
  - $\chi_{c1}(4010)[1^{++}]$: different C-parity than $T_{c\bar{c}}(4020)$



	$h_c(4000)$	$\chi_{c1}(4010)$	$T_{c\bar{c}}(4020)$
J^{PC}	1^{+-}	1^{++}	1^{+-}
$mass$/MeV	4000^{+17+29}_{-14-22}	$4012.5^{+3.6+4.1}_{-3.9-3.7}$	$4025^{+2.0}_{-4.7} \pm 3.1$
$width$/MeV	184^{+71+97}_{-45-61}	$62.7^{+7.0+6.4}_{-6.4-6.6}$	$23.0 \pm 6.0 \pm 1.0$

PRL 115 (2015) 182002

$h_c(4300)$ contribution

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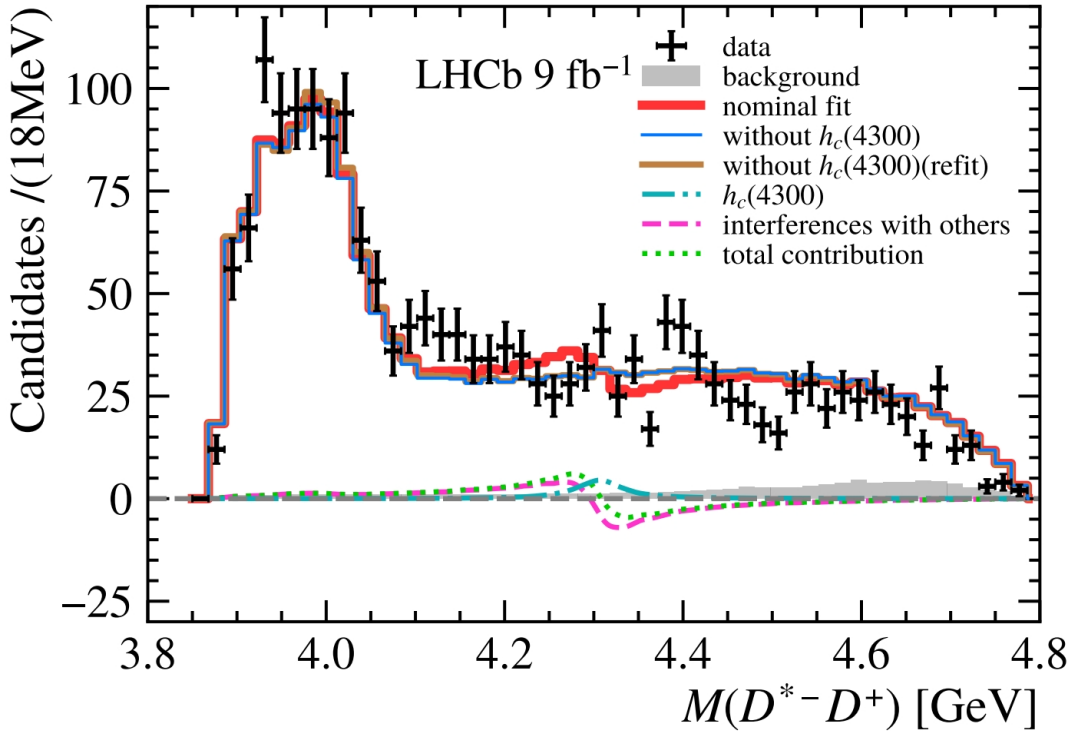
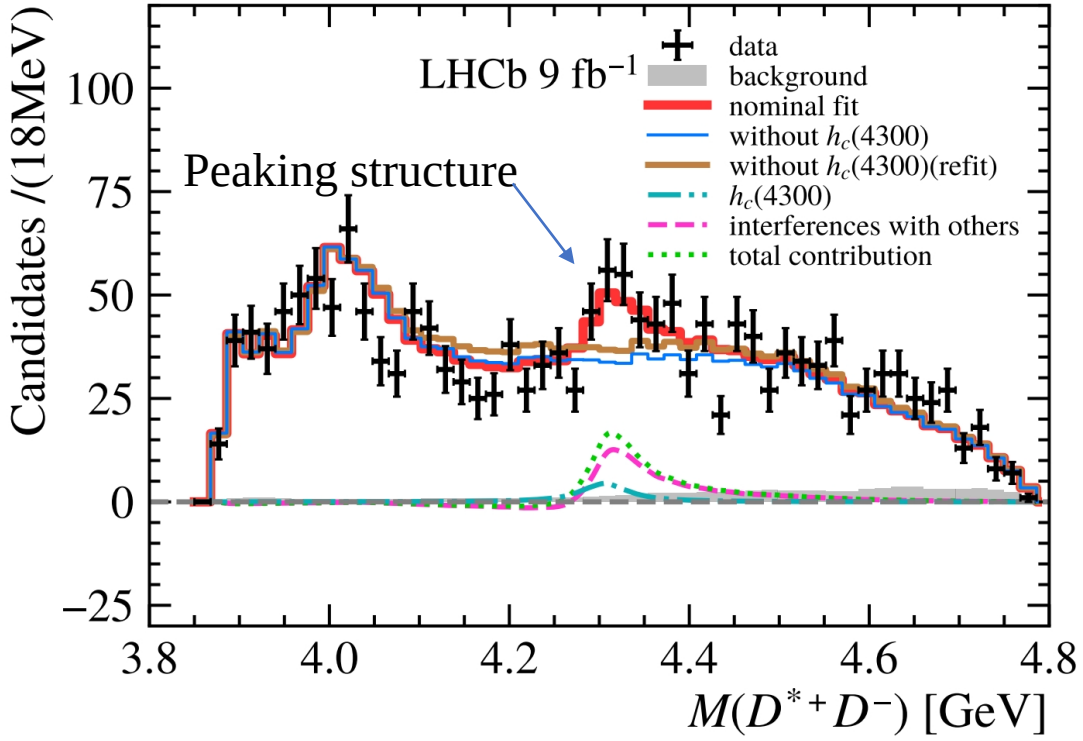
- Peaking structure in 4.3 GeV
  - Significance 6.1 σ
  - Similar mass and width as $\chi_{c1}(4274)$, but different C-parity
  - Consistent with $h_c(3P)$ prediction

$h_c(4300)$	$J^{PC} = 1^{+-}$	$h_c(3P)$	$J^{PC} = 1^{+-}$
$m_0 = 4307.3^{+6.4+3.3}_{-6.6-4.1}$	$\Gamma_0 = 58^{+28+28}_{-16-25}$	$m_0 = 4318$	$\Gamma_0 = 75$
$\chi_{c1}(4274)$	$J^{PC} = 1^{++}$	$\chi_{c1}(3P)$	$J^{PC} = 1^{++}$
$m_0 = 4294 \pm 4^{+6}_{-3}$	$\Gamma_0 = 53 \pm 5 \pm 5$	$m_0 = 4317$	39
PRL 118 (2017) 2, 022003		PRD 72, (2005) 054026	





C-parity determination

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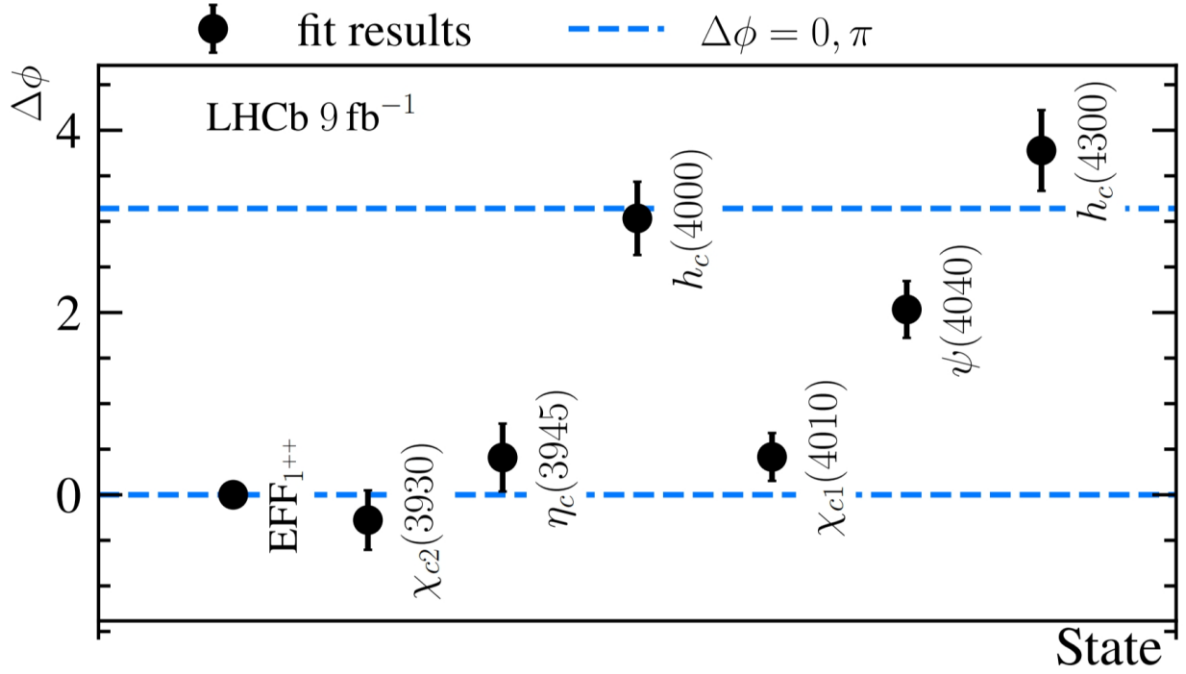
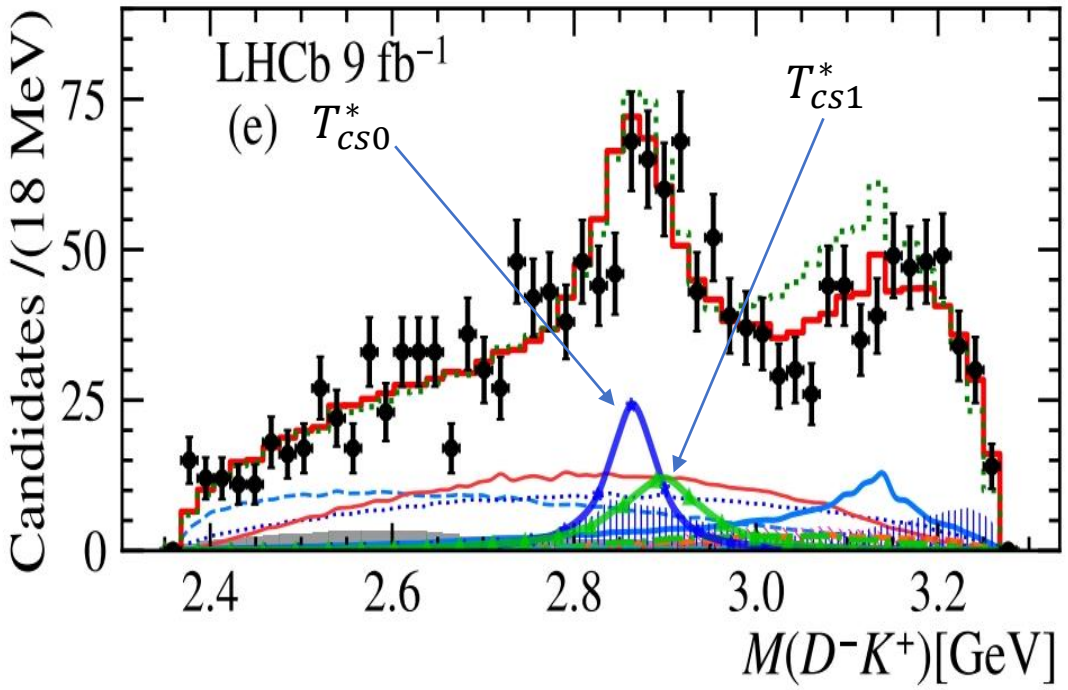
- Validation of C-parity determination
  - Replace C-parity with phase parameters.
  - $C = \exp(i\Delta\phi) \Rightarrow \begin{cases} \Delta\phi = 0, \ C = +1 \\ \Delta\phi = \pi, \ C = -1 \end{cases}$
- $\Delta\phi$ consistent with 0 or π
  - except $\psi(4040)$: 2.7σ difference
- Keep the C-parity of $\chi_{c2}(3930)$ and $\psi(4040)$ and flip all others ($C \to -C$), the $-\ln L$ become worse about 50.



$T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$

- Previous work PRL 125 (2020) 242001, PRD 102 (2020) 112003
  - $B^+ \to X D^+, X \to D^- K^+$
    - $B^+ \to T^*_{cs0}(2870)^0 D^+$: S wave
    - $B^+ \to T^*_{cs1}(2900)^0 D^+$: only P wave
- New production mode
  - $B^+ \to X D^{*+}, X \to D^- K^+$
    - $B^+ \to T^*_{cs0}(2870)^0 D^{*+}$: P wave
    - $B^+ \to T^*_{cs1}(2900)^0 D^{*+}$: S, P, D waves
- Different ratios of branching factions

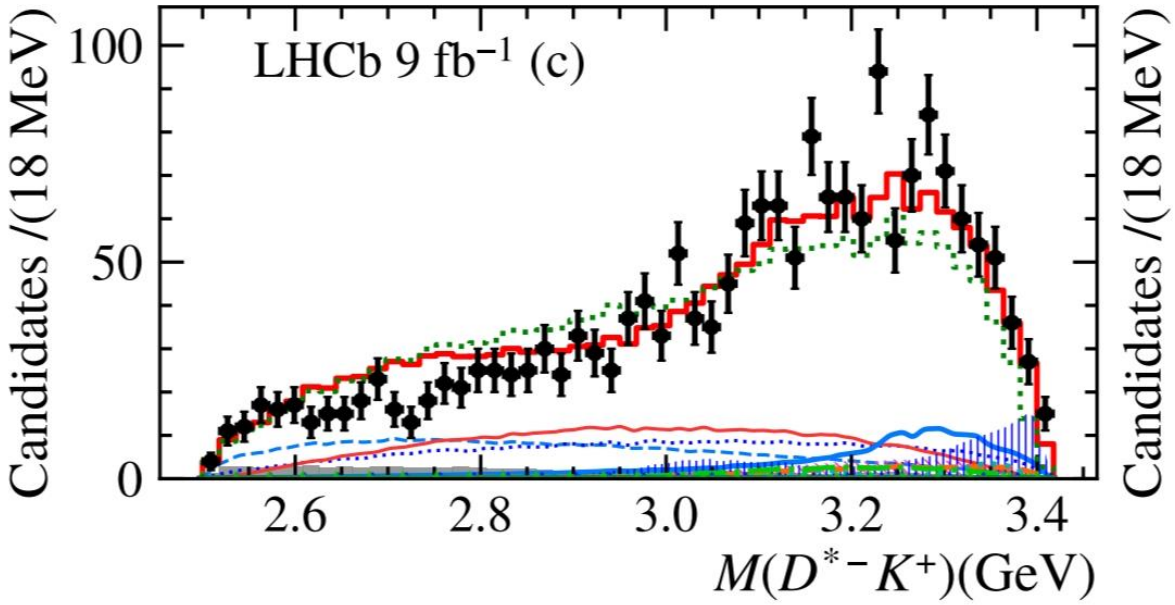
	$B^+ \to D^{*+} D^- K^+$	$B^+ \to D^+ D^- K^+$
$\frac{B(B^+ \to T^*_{cs0}(2870)^0 D^{(*)+})}{B(B^+ \to T^*_{cs1}(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

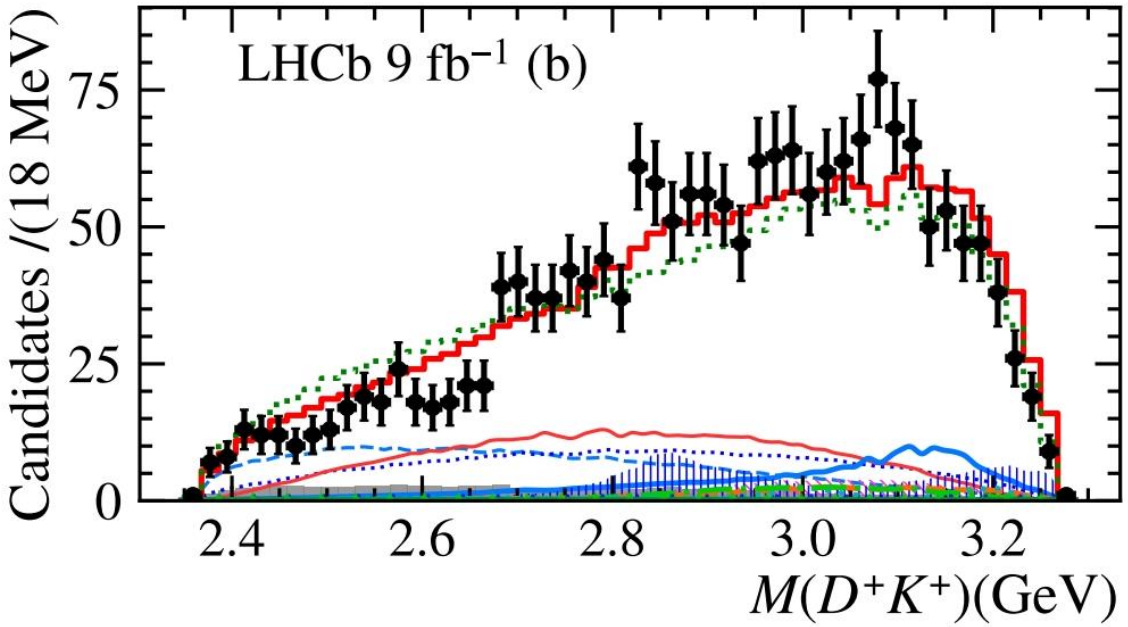


- Mass and width consistent within uncertainties

$T^*_{cs1}(2900)^0$ and $T^*_{c\bar{s}0}(2900)^{++}$

- $T^*_{cs1}(2900) \to D^{*-}K^+$
  - No peak around 2.9 GeV
  - Fit fraction < 1.5% @ 95CL (stat.)
  - Related to $\frac{B(T_{cs1}\to D^*K)}{B(T_{cs1}\to DK)}$ <21% @ 95CL
- $T^*_{c\bar{s}0}(2900)^{++} \to D^+K^+$
  - Also no peak around 2.9 GeV
  - Fit fraction < 3.3 % @ 95CL (stat.)





Summary

- Simultaneous fit for $B^+ \to D^{*\pm} D^{\mp} K^+$
- Constrains of C-parity
  - $B^+ \to R(\to D^{*-} D^{+}) K^+$
  - $B^+ \to R(\to D^{*+} D^{-}) K^+$
- New production mode:
  - $B^+ \to D^{*+} T^*_{cs0}(2870)^0 / B^+ \to D^{*+} T^*_{cs1}(2900)^0$
- New charmonium(-like) states
  - $\boldsymbol{\chi_{c1}(4010)}$
  - $\boldsymbol{h_c(4000)}$

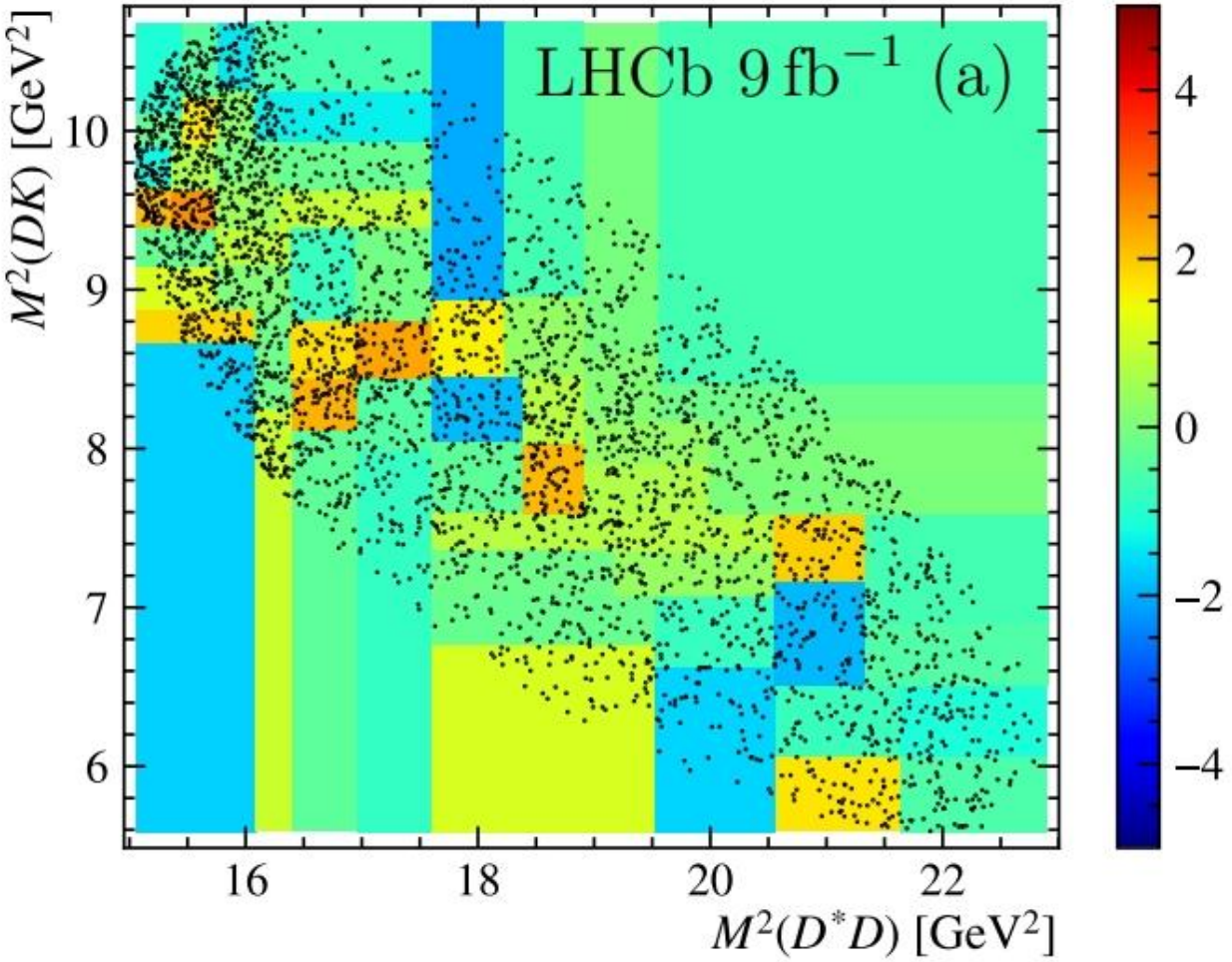
  } Different C-parity, describe the difference of two channels

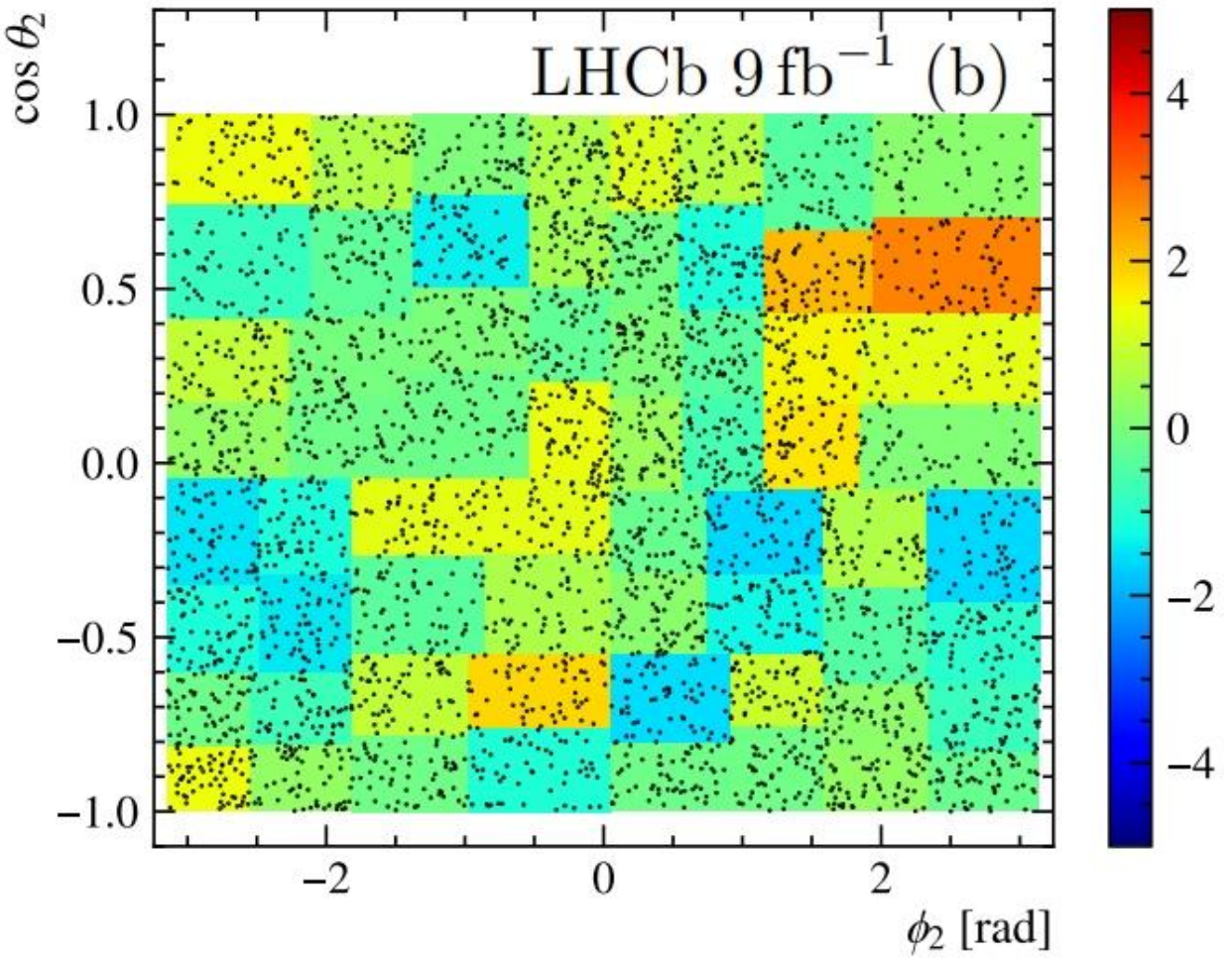
  - $h_c(4300)$ a peak in 4.3GeV

Thank you for your attention!

backup

2D distribution

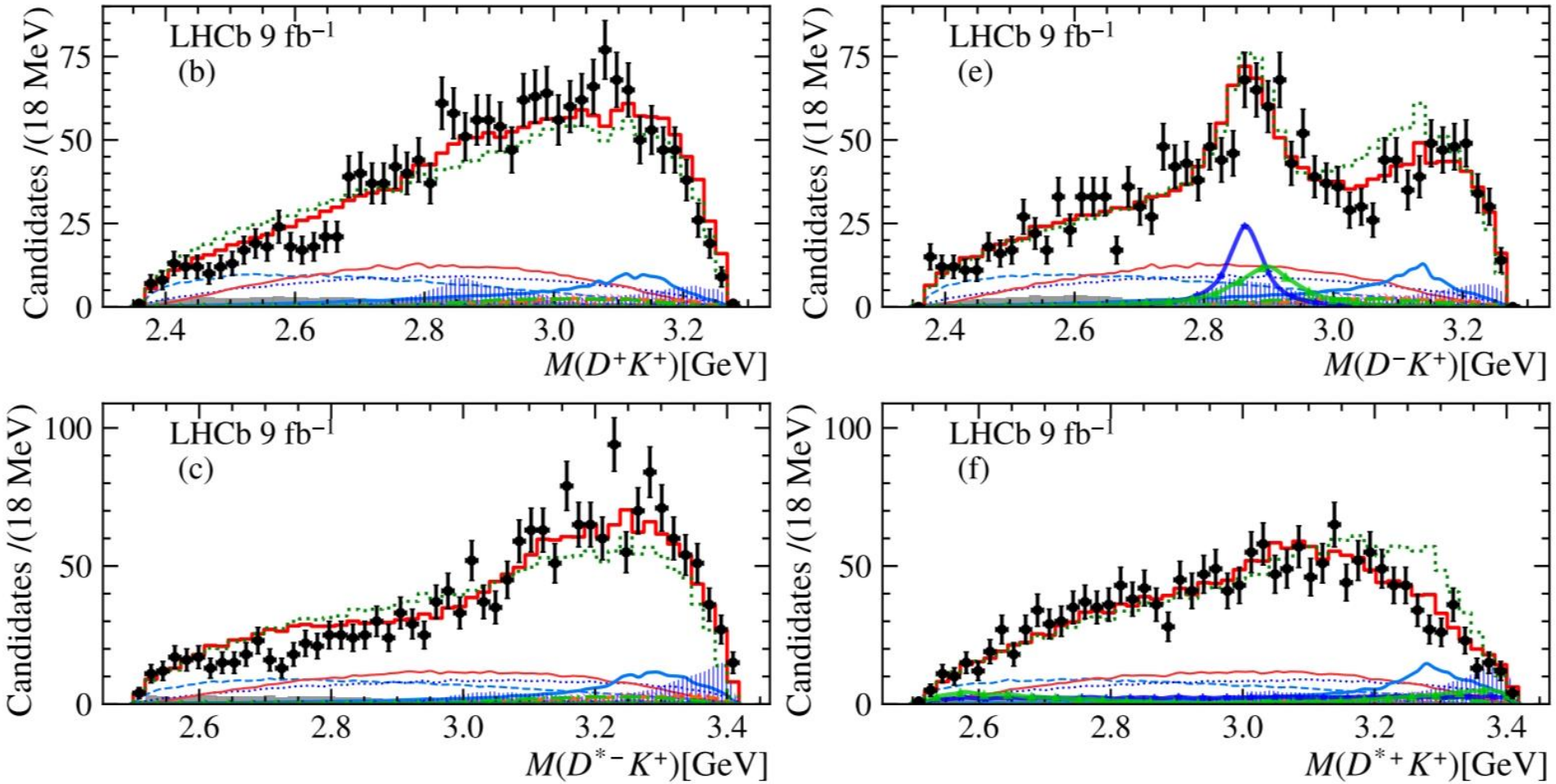




Fit fraction and ratio

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

Other projection of $B^+ \to D^{*\pm}D^{\mp}K^+$



Log scale projection