Exotic and excited open charm spectroscopy in B decays at LHCb

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on behalf of the LHCb collaboration

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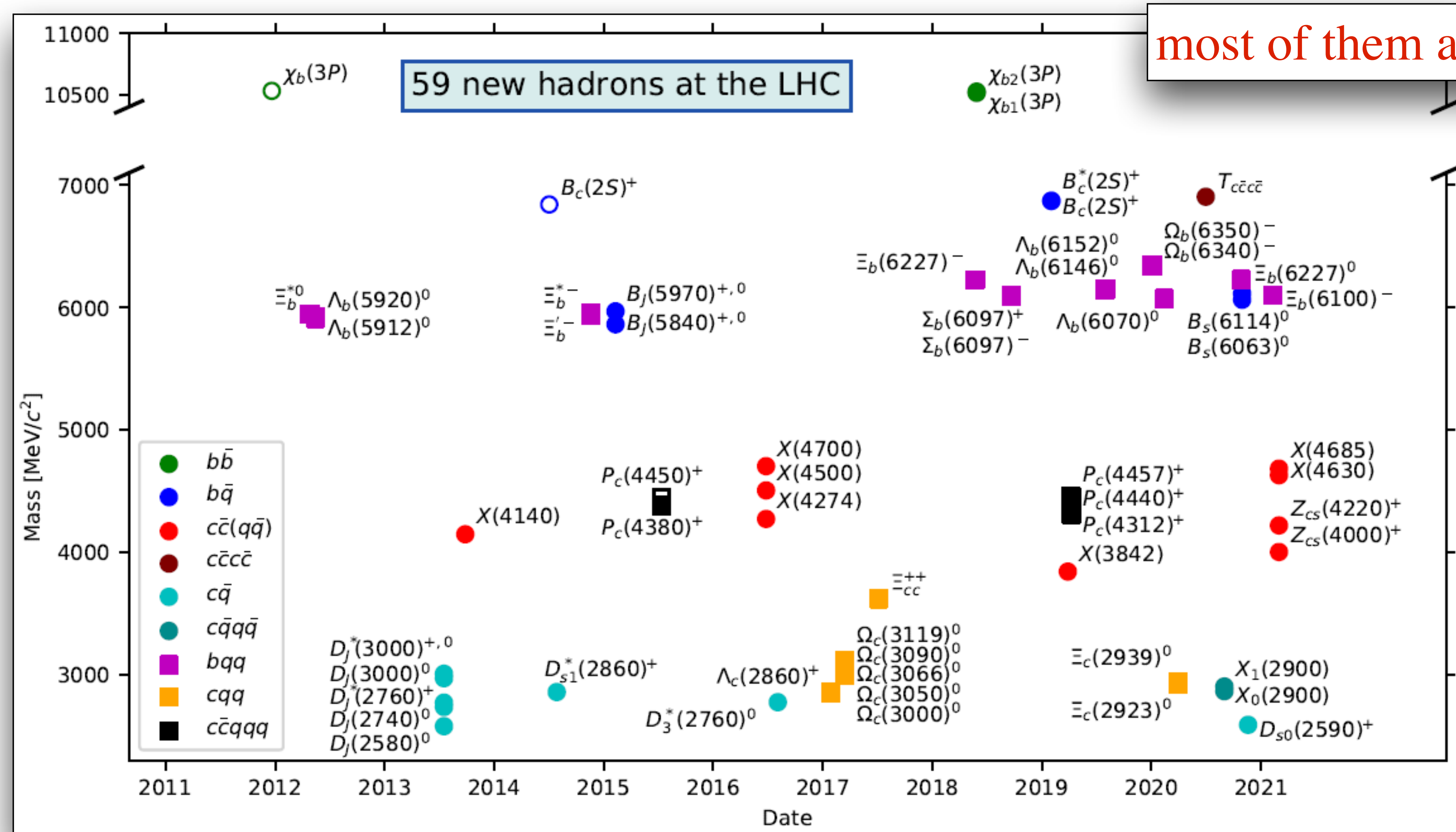
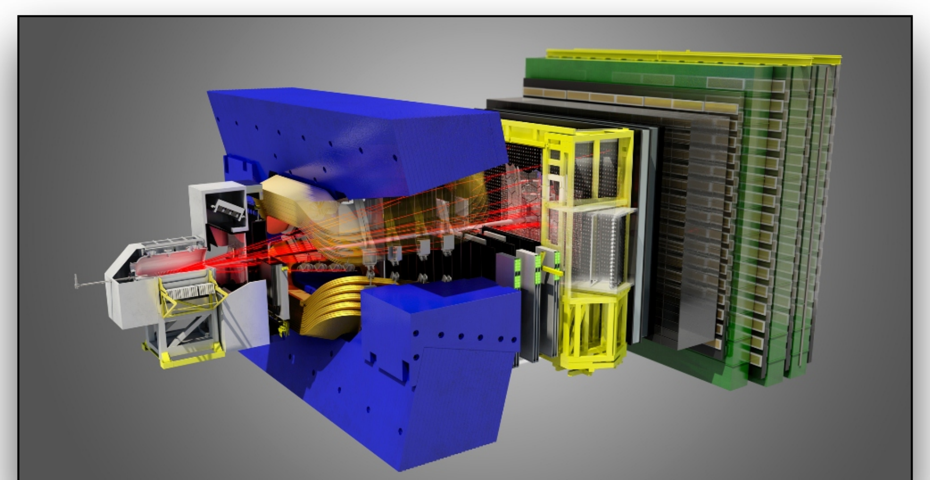


most of them at LHCb



LHCb is a flavour factory:

$$\sigma(pp \to b\bar{b}X) = 144 \pm 21\mu b \quad (\sqrt{s} = 13 \text{ TeV})$$

$$\frac{\sigma_{b\bar{b}}}{\sigma_{\text{inel}}} \sim \frac{1}{400}$$

PRL 118 (2017) 052002

Methods

Two different approaches for excited charmed mesons studies:

inclusive production $pp \to D_J X$

- large yields
- large background
- unable to determine J^P

exclusive decays $B \to \overline{D}Dh,\ B \to D^{(*)}hh$

- smaller samples
- low background
- angular analysis allows J^P determination

Dalitz plot analysis formalism:

decay amplitude:

$$\mathcal{M} = \sum_k c_k A_k \qquad A_k \to \text{form factors } x \ \overset{J^P}{\boxed{\text{angular function}}} \ x \text{ line shape}$$

output: $c_k, m_0^k, \Gamma_0^k, J^P, f_k \qquad f_k = \frac{|c_k|^2 \int A_k(\Phi) d\Phi}{\sum_{i,j} c_i c_j^* A_i(\Phi) A_j(\Phi) d\Phi} \qquad \Phi = \text{phase space}$

As sample sizes increase, better models are needed

Outline

- Excited charmed mesons in $B^- \to D^{*+}\pi^-\pi^-$

  PRD 101 (2019) 032005

- Excited charmed-strange meson in $B^0 \to D^- D^+ K^+ \pi^-$

  PRL 126 (2021) 122002

- New charm-strange resonances in $B^+ \to D^- D^+ K^+$

  PRL 125, (2020) 242001

  PRD 102 (2020) 112003

Excited charmed mesons in

$B^- \to D^{*+}\pi^-\pi^-$

PRD 101 (2019) 032005

$B^- \to D^{*+}\pi^-\pi^-$

Well-established states, with spin-parity assignment: $D_1(2420)$, $D_2^*(2460)$

BaBar and LHCb observed $\underline{D_0(2550),\ D_J^*(2600),\ D(2740),\ D_3^*(2750)}$

no spin-parity assignments

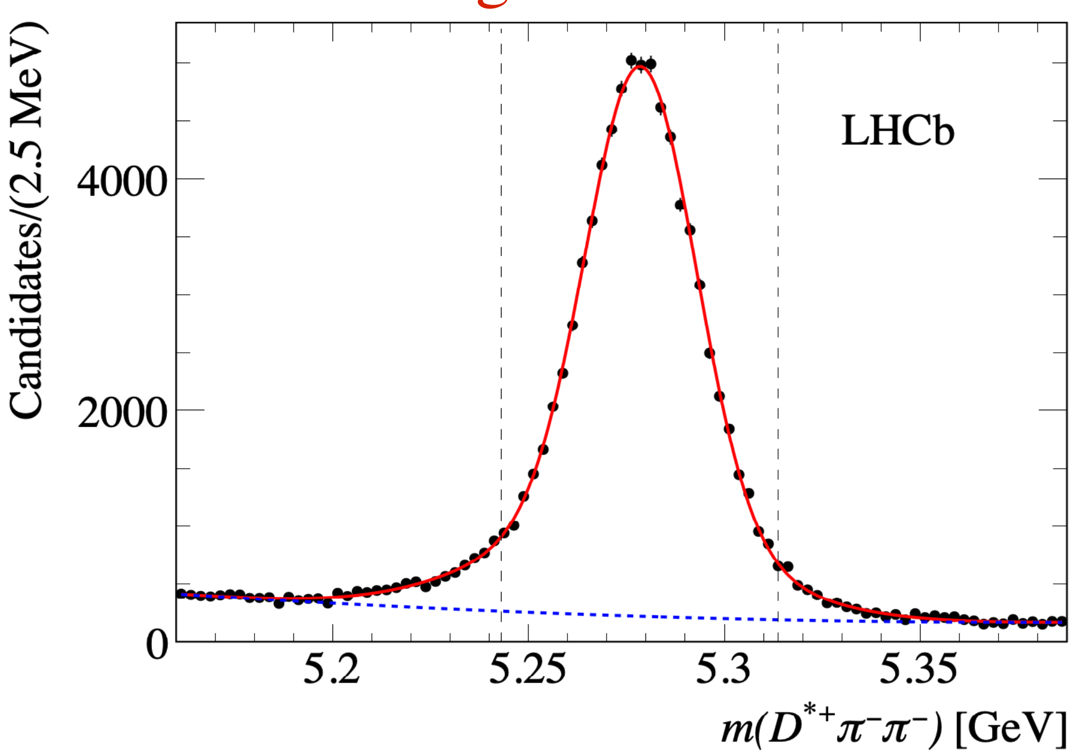
PRD **82** (2010) 111101,
JHEP **09** (2013) 145

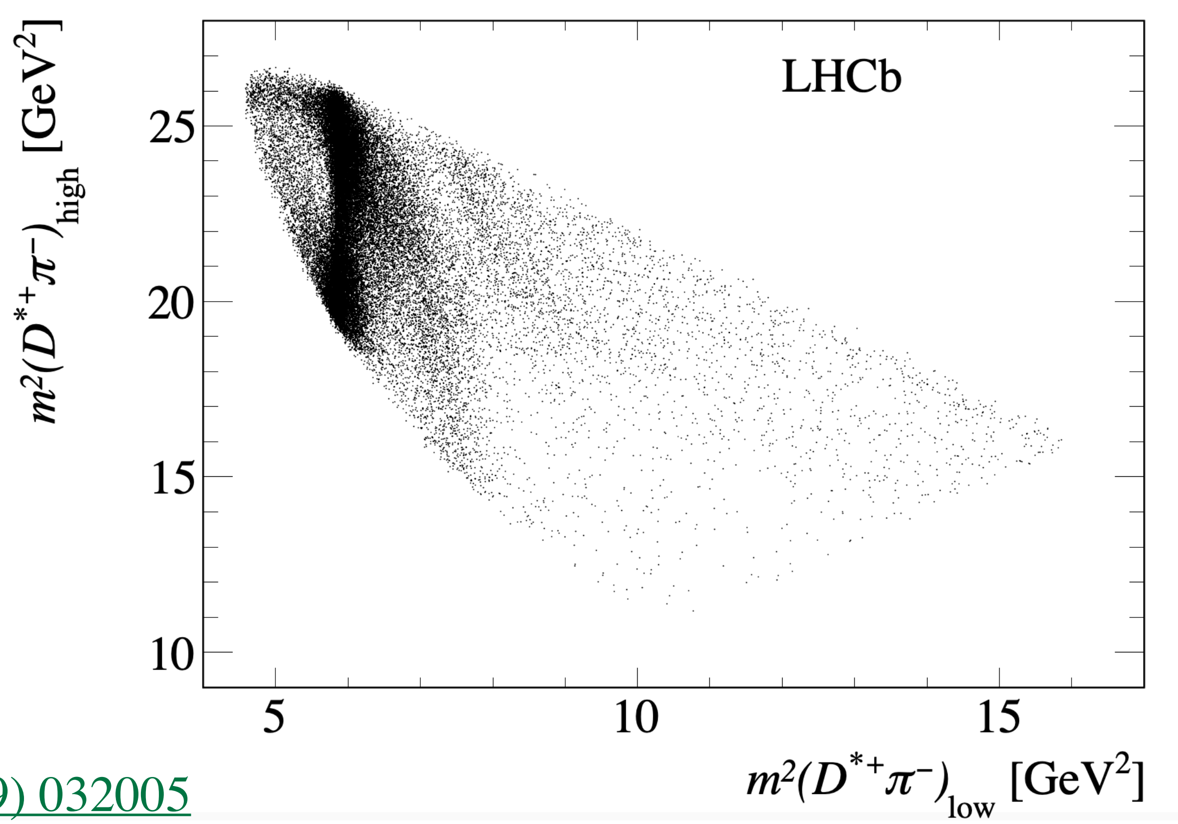
This analysis: $D_J \to D^*\pi$ spectroscopy from Dalitz plot analysis of B^- decays,

$$pp \to B^- X,\ B^- \to D^{*+}\pi^-\pi^-,\ D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+$$

(4.7 fb^{-1} @ 7, 8 and 13 TeV)

80K signal candidates





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$B^- \to D^{*+}\pi^-\pi^-$

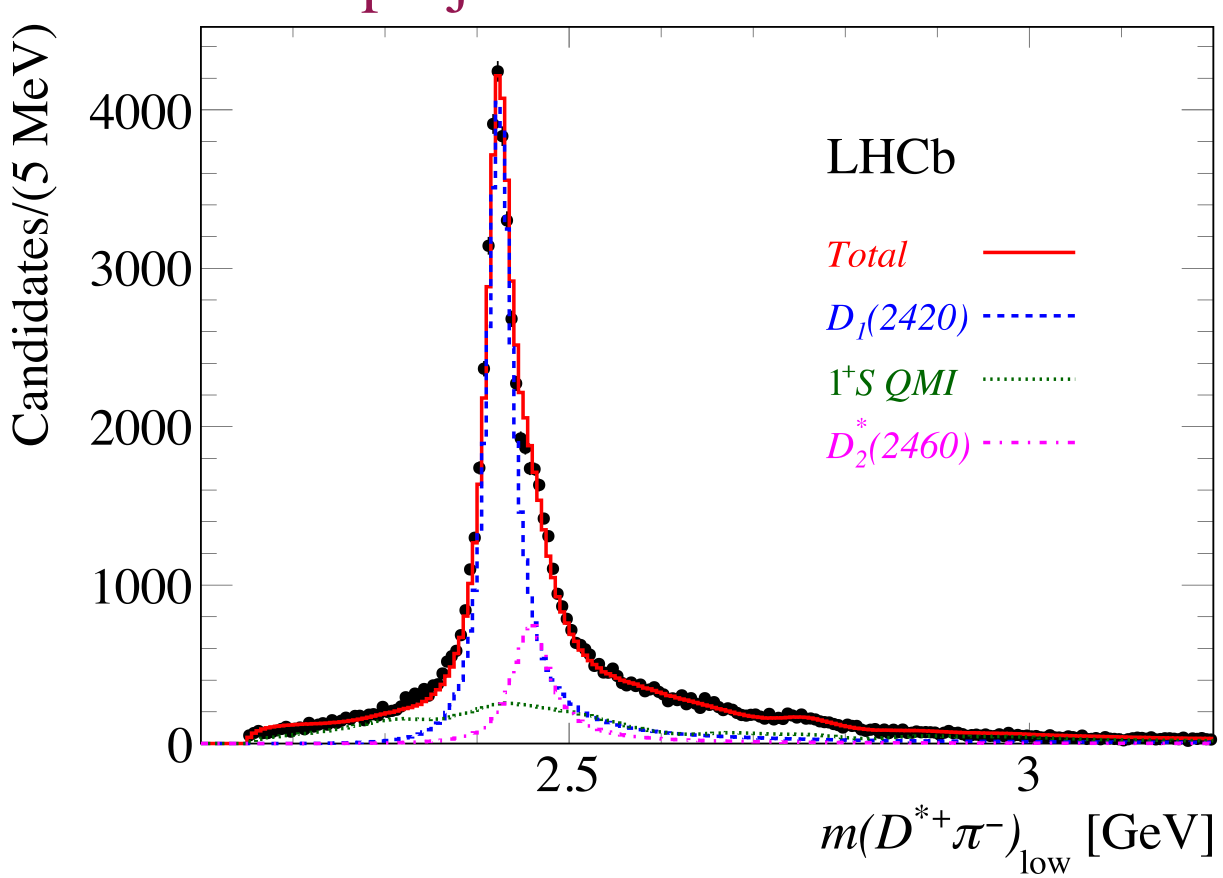
Amplitude analysis performed within the isobar model framework

$$\mathcal{M} = \sum_k c_k A_k \qquad A_k \to \text{ form factors } x \text{ angular function } x \text{ line shape}$$

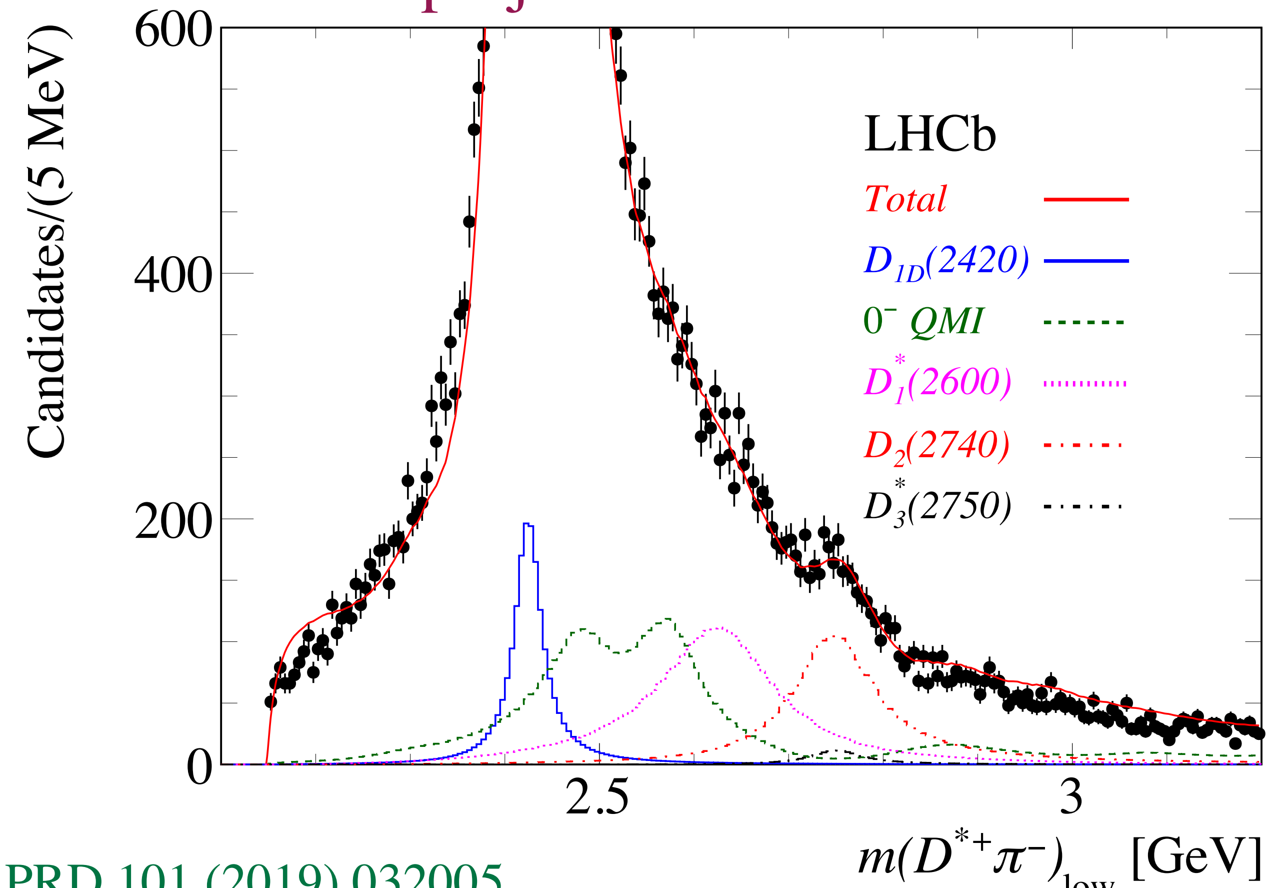
Blatt-Weisskopf — Zemach tensors — BW, QMI

- Two approaches for the line shapes: relativistic BW and binned amplitude (QMI)
- Same spin-parity assignments with both approaches

projection of the fit result



projection of the fit result



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Results:

spin-parity and fit fractions

Resonance	J^P	fraction (%)	phase (rad)
• $D_1(2420)$	$1^+ D$	$56.5 \pm 0.3 \pm 1.1$	0
• $D_1(2430)$	$1^+ S$	$26.0 \pm 0.4 \pm 1.7$	$-1.57 \pm 0.02 \pm 0.08$
$D_2^*(2460)$	2^+	$15.4 \pm 0.2 \pm 0.1$	$-0.77 \pm 0.01 \pm 0.01$
$D_1(2420)$	$1^+ S$	$5.9 \pm 0.5 \pm 2.9$	$1.69 \pm 0.02 \pm 0.06$
• $D_0(2550)$	0^-	$5.3 \pm 0.1 \pm 0.5$	$1.50 \pm 0.02 \pm 0.06$
• $D_1^*(2600)$	1^-	$5.0 \pm 0.1 \pm 0.5$	$0.76 \pm 0.02 \pm 0.03$
• $D_2(2740)$	$2^- P$	$0.57 \pm 0.07 \pm 0.23$	$-2.14 \pm 0.07 \pm 0.16$
• $D_2(2740)$	$2^- F$	$1.9 \pm 0.1 \pm 1.0$	$0.49 \pm 0.04 \pm 0.40$
• $D_3^*(2750)$	3^-	$0.78 \pm 0.06 \pm 0.13$	$-1.54 \pm 0.05 \pm 0.04$
Sum		$117.3 \pm 0.8 \pm 3.8$	

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Breit-Wigner parameters

Resonance	J^P	Mass [MeV]	Width [MeV]
$D_1(2420)$	1^+	$2424.8 \pm 0.1 \pm 0.7$	$33.6 \pm 0.3 \pm 2.7$
$D_1(2430)$	1^+	$2411 \pm 3 \pm 9$	$309 \pm 9 \pm 28$
$D_2^*(2460)$	2^+	2460.56 ± 0.35	47.5 ± 1.1
$D_0(2550)$	0^-	$2518 \pm 2 \pm 7$	$199 \pm 5 \pm 17$
$D_1^*(2600)$	1^-	$2641.9 \pm 1.8 \pm 4.5$	$149 \pm 4 \pm 20$
$D_2(2740)$	2^-	$2751 \pm 3 \pm 7$	$102 \pm 6 \pm 26$
$D_3^*(2750)$	3^-	$2753 \pm 4 \pm 6$	$66 \pm 10 \pm 14$

Systematic uncertainties dominated by BW parametrisation of the resonances

Excited charmed-strange meson in

$$B^0 \to D^- D^+ K^+ \pi^-$$

PRL 126 (2021) 122002

Heavy quark limit $(m_Q \to \infty)$

- meson properties determined by those of the light quark

$$\vec{j}_q = \vec{s}_q + \vec{L}$$
$$\vec{S} = \vec{s}_q + \vec{s}_Q$$

- j_q, s_Q : separately conserved

Numerous missing states

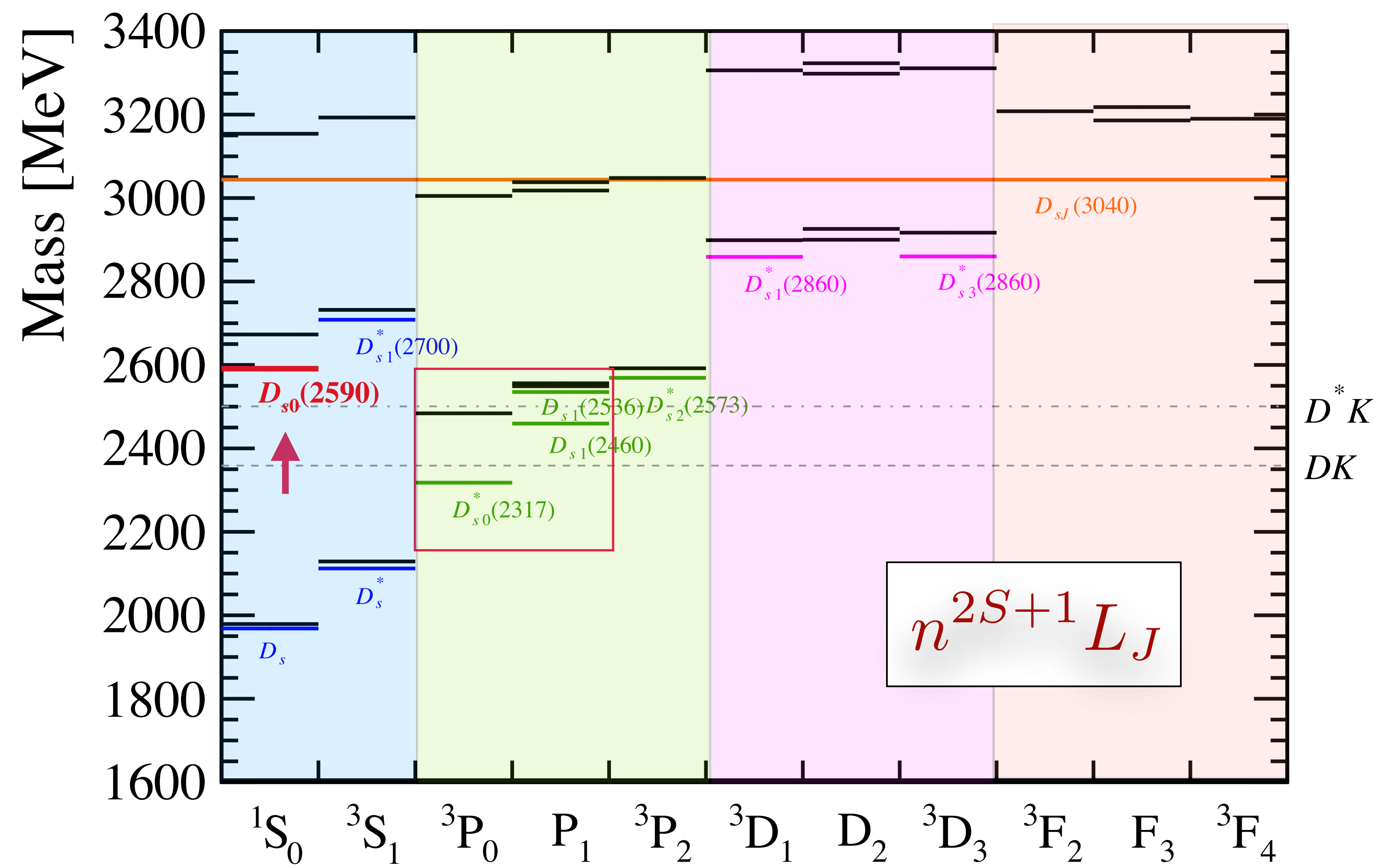
Masses systematically below HQL predictions

Phys. Rev. **D93** 034035

This study:

$$B^0 \to D^- D_{sJ}^+,\ D_{sJ}^+ \to D^+ K^+ \pi^-$$

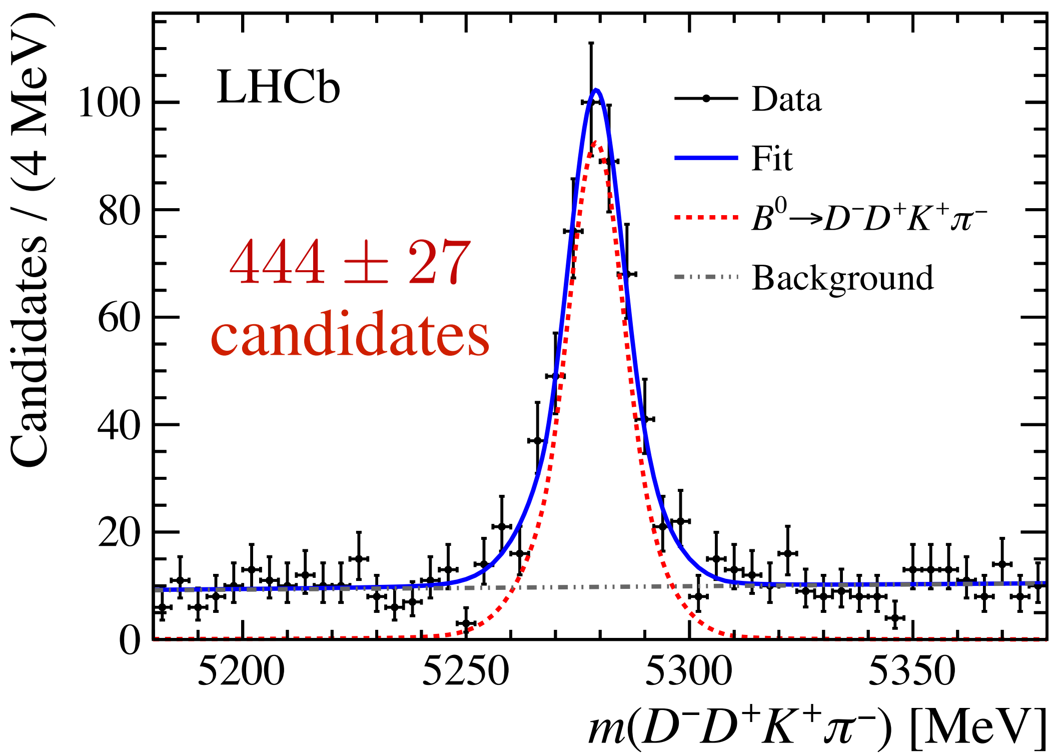
With $m(K^+\pi^-) < 0.75$ GeV only unnatural spin-parity states are allowed



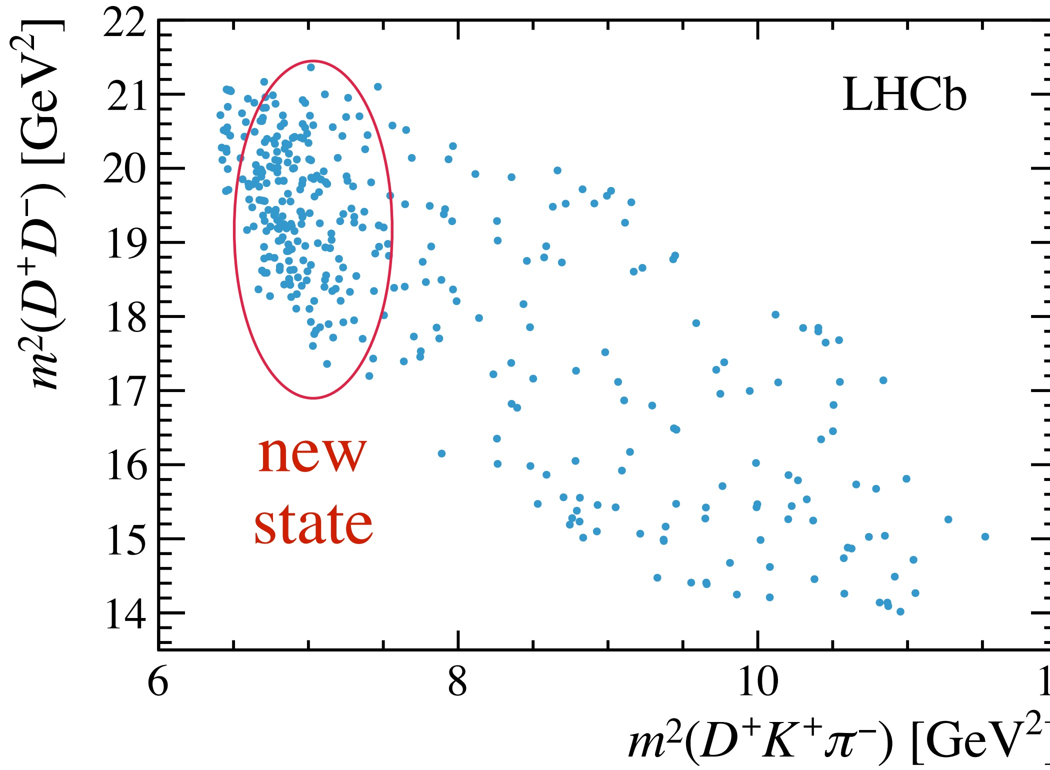
PDG

State	J^P	Mass(MeV)	Width(MeV)	Dominant decays
$D_{s0}^*(2317)^+$	0^+	2317.7 ± 0.6	< 3.8	$D_s^+\pi^0$
$D_{s1}(2460)^+$	1^+	2459.5 ± 0.6	< 3.5	$D_s^{*+}\pi^0$
$D_{s1}(2536)^+$	1^+	2535.10 ± 0.06	0.92 ± 0.05	$D^{*+}K^0$
$D_{s2}^*(2573)^+$	2^+	2569.1 ± 0.8	16.9 ± 0.8	D^0K^+
$D_{s1}^*(2700)^+$	1^-	$2708.3^{+4.0}_{-3.4}$	120 ± 11	$D^{(*)}K$
$D_{s1}^*(2860)^+$	1^-	2859 ± 27	159 ± 80	D^0K^+
$D_{s3}^*(2860)^+$	3^-	2860 ± 7	53 ± 10	$D^{(*)}K$
$D_{sJ}(3040)^+$	$??$	3044^{+31}_{-9}	239 ± 60	D^*K

$m(K^+\pi^-) < 0.75$ GeV



$K^+\pi^-$ in S-wave $(K_0^*(700)^0)$



$$(K\pi)_S(0^+) + D^+(0^-) \to \text{ spin } J = L \text{ and parity } P = (-1)^{L+1} \; (0^-, 1^+, 2^-, \ldots)$$

- Resonance parameters and spin-parity determined by amplitude analysis

$$\mathcal{M} = \sum_k \mathcal{H}^{D_{sk}} \, d_{0,0}^{J_{D_{sk}}}(\theta_{D_s}) \, p^{L_{B^0}} \, F_{L_{B^0}}(pa) \, q^{L_{D_{sk}}} \, F_{L_{D_{sk}}}(qa) \, \mathrm{BW}(m_{K^+\pi^-}) \, \mathrm{BW}_{D_{sk}}(m_{D^+K^+\pi^-})$$

- Three components: $D_{sJ}^+(X)$, $D_{s1}(2536)^+$ $(J^P = 1^+)$, nonresonant $(J^P = 0^-)$
- Background (with no peaking structures) subtraction with *sPlot* technique

$B^0 \to D^- D^+ K^+ \pi^-$

- Width of the D_{sJ}^+ : sum of two open channels, $\Gamma^{D_{sJ}^+} = \Gamma^{D_{sJ}^+ \to D^* K} + \Gamma^{D_{sJ}^+ \to DK\pi}$
- Cannot determine the ratio of partial widths, $r = \Gamma^{D_{sJ}^+ \to DK\pi}(m_0)/\Gamma^{D_{sJ}^+}(m_0)$
- Pole position is stable. Assuming $\Gamma^{D_{sJ}^+} = \Gamma_0, \quad \Gamma_0 \ll M_0$

$$M_R - i\frac{\Gamma_R}{2} = \sqrt{M_0^2 - iM_0\Gamma_0} = M_0\sqrt{1 - i\frac{\Gamma_0}{M_0}} \approx M_0(1 - \frac{i}{2}\frac{\Gamma_0}{M_0}) = M_0 - i\frac{\Gamma_0}{2}$$

Systematic uncertainties

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Source	m_R [MeV]	Γ_R [MeV]	Fit fraction ($\times 10^{-2}$) D_{s0}^+	D_{s1}^+	NR	D_{s0}^+–NR	D_{s1}^+/D_{s0}^+
$D_{s0}(2590)^+$ width model	6.1	8.0	4.7	0.0	15.0	19.6	0.5
$D_{s1}(2536)^+$ mass shape	0.3	4.3	2.3	0.6	3.5	5.3	1.1
$K^+\pi^-$ mass shape	2.7	2.6	3.0	0.2	1.2	4.4	0.1
Blatt-Weisskopf factor	0.7	3.4	2.8	0.3	1.3	3.0	0.2
Including $c\bar{c}$ resonances	1.1	5.4	2.7	0.1	6.3	10.0	0.4
$D^+\pi^-$ resonance veto	2.4	2.1	4.6	0.3	9.4	4.6	0.2
Simulation correction	0.2	1.1	0.3	0.1	0.7	0.8	0.2
Momentum calibration	0.5	0.4	1.3	0.0	1.4	2.5	0.2
Total	7.2	11.7	8.6	0.8	19.3	23.9	1.4

RESULTS

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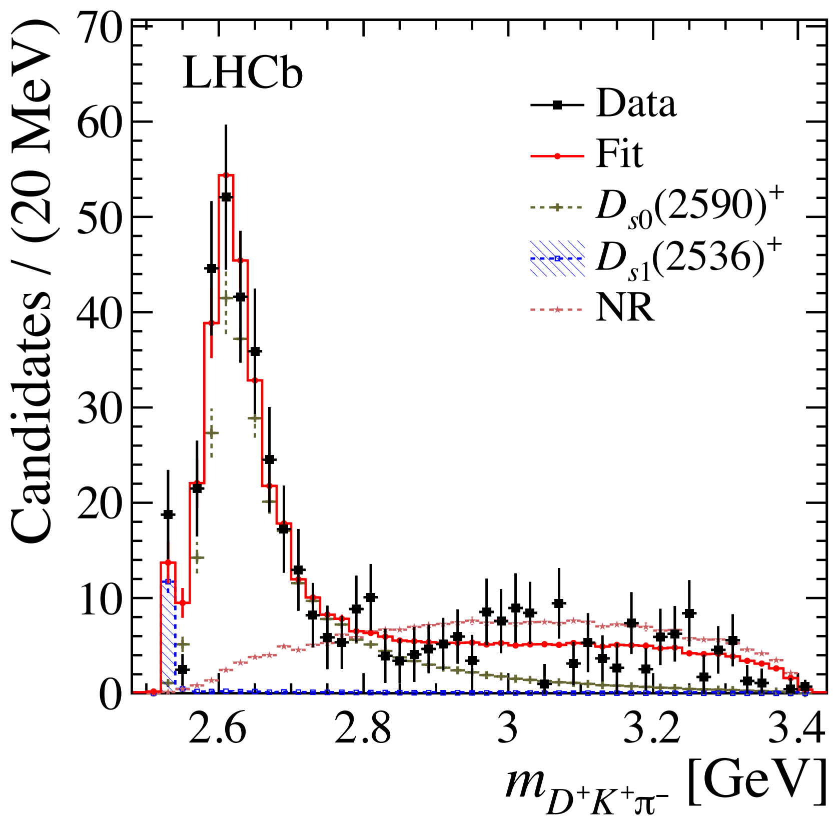
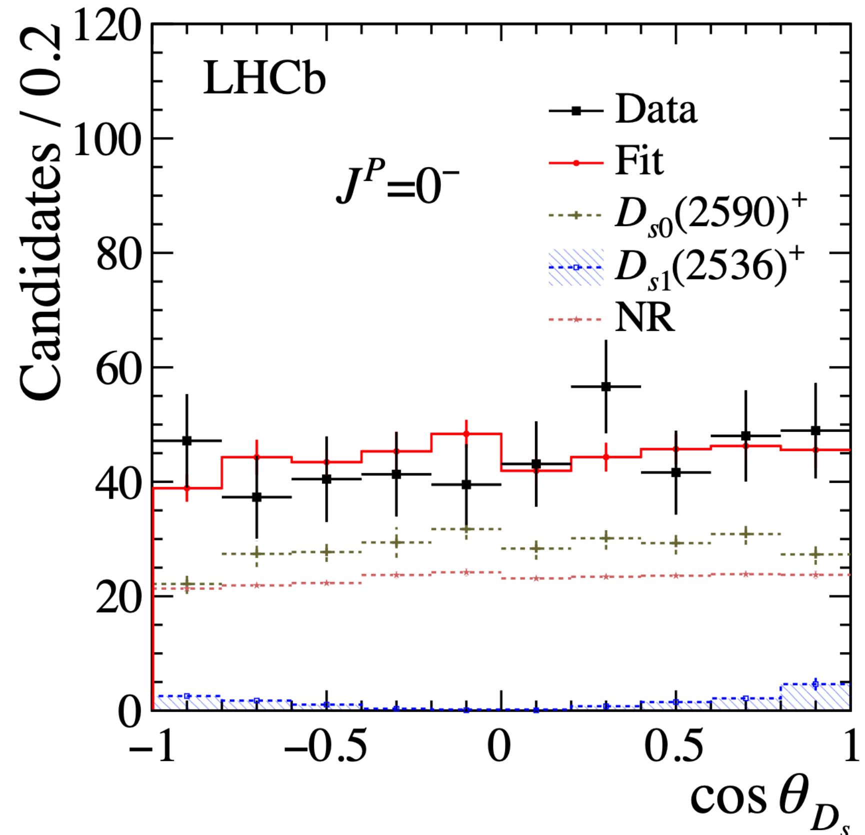
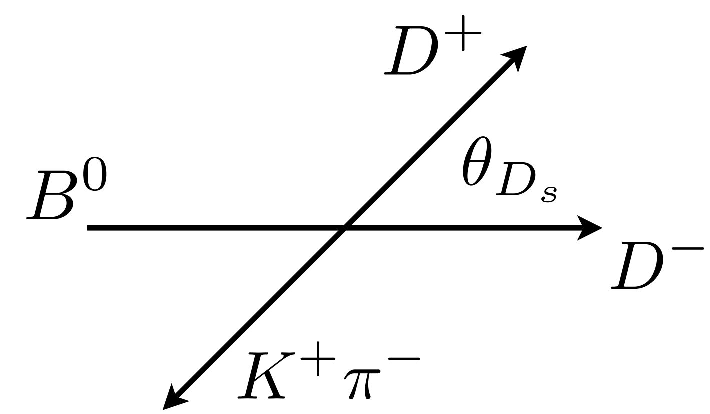




best fit: $J^P = 0^-$

$J^P = 1^+$ and $J^P = 2^-$ rejected with significance over 10 std deviations



	Fit fraction $(\times 10^{-2})$
$D_{s0}(2590)^+$	63 ± 9 (stat) $\pm$ 9 (syst)
$D_{s1}(2536)^+$	3.9 ± 1.4 (stat) $\pm$ 0.8 (syst)
NR	51 ± 11 (stat) $\pm$ 19 (syst)
D_{s0}^+–NR	-18 ± 18 (stat) $\pm$ 24 (syst)
D_{s1}^+/D_{s0}^+	6.1 ± 2.4 (stat) $\pm$ 1.4 (syst)

Pole mass and width:

$m_R = 2591 \pm 6 \pm 7$ MeV

$\Gamma_R = 89 \pm 16 \pm 12$ MeV

A new D_s^+ excited state: $D_{s0}(2590)^+$, with $J^P = 0^-$. The $D_s(2^1S_0)^+$?

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

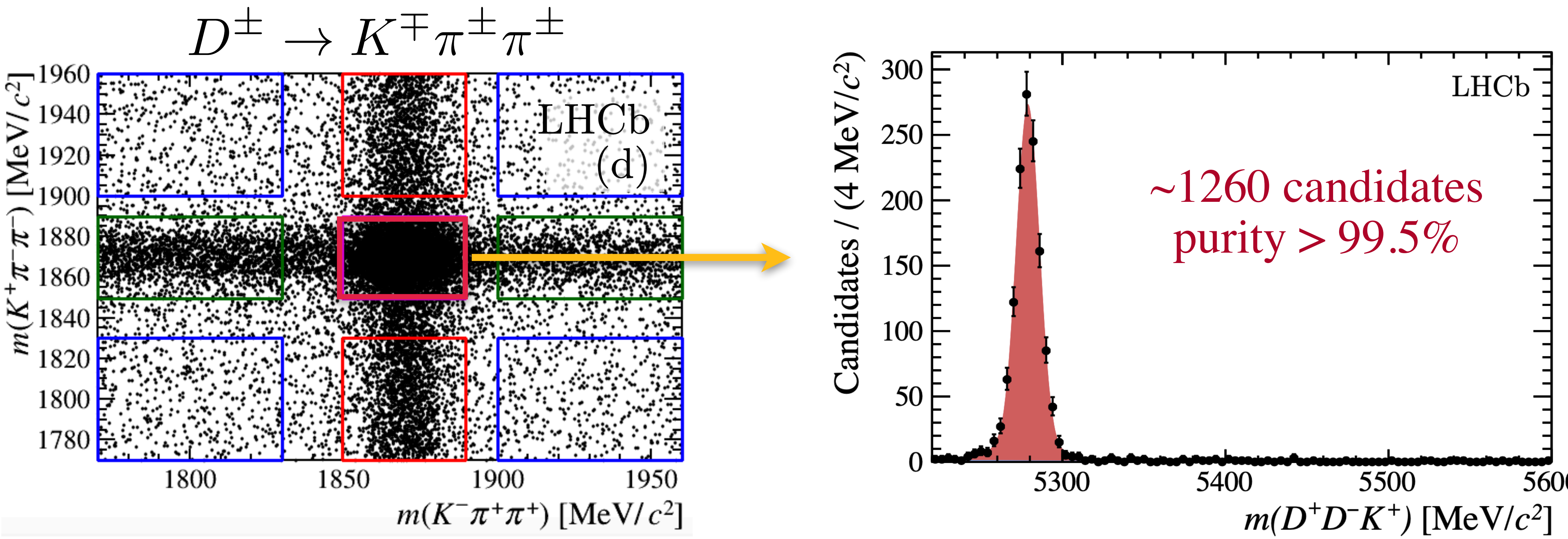
New charm-strange resonances in the DK channels

PRL 125, (2020) 242001

PRD 102 (2020) 112003

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

- $B^+ \to D^{(*)+} D^{(*)-} K^+$ decays: unique opportunities to charmonium studies
- Resonances in the $D^{(*)-} K^+$ channel are manifestly "exotic": $c\bar{d}u\bar{s}$
- $B^+ \to D^+ D^- K^+$ with two different approaches : $\begin{cases} \text{model independent} \\ \text{model dependent} \end{cases}$
- Full Run 1 + Run 2 data set: 9 fb^{-1} @ $\sqrt{s} = 7,\ 8,\ 13$ TeV



PRL 125, (2020) 242001 PRD 102 (2020) 112003

Model – independent analysis

- A clear excess at $m^2(D^-K^+) \sim 2.9$ GeV
- Could it be explained by $c\bar{c}$ states?

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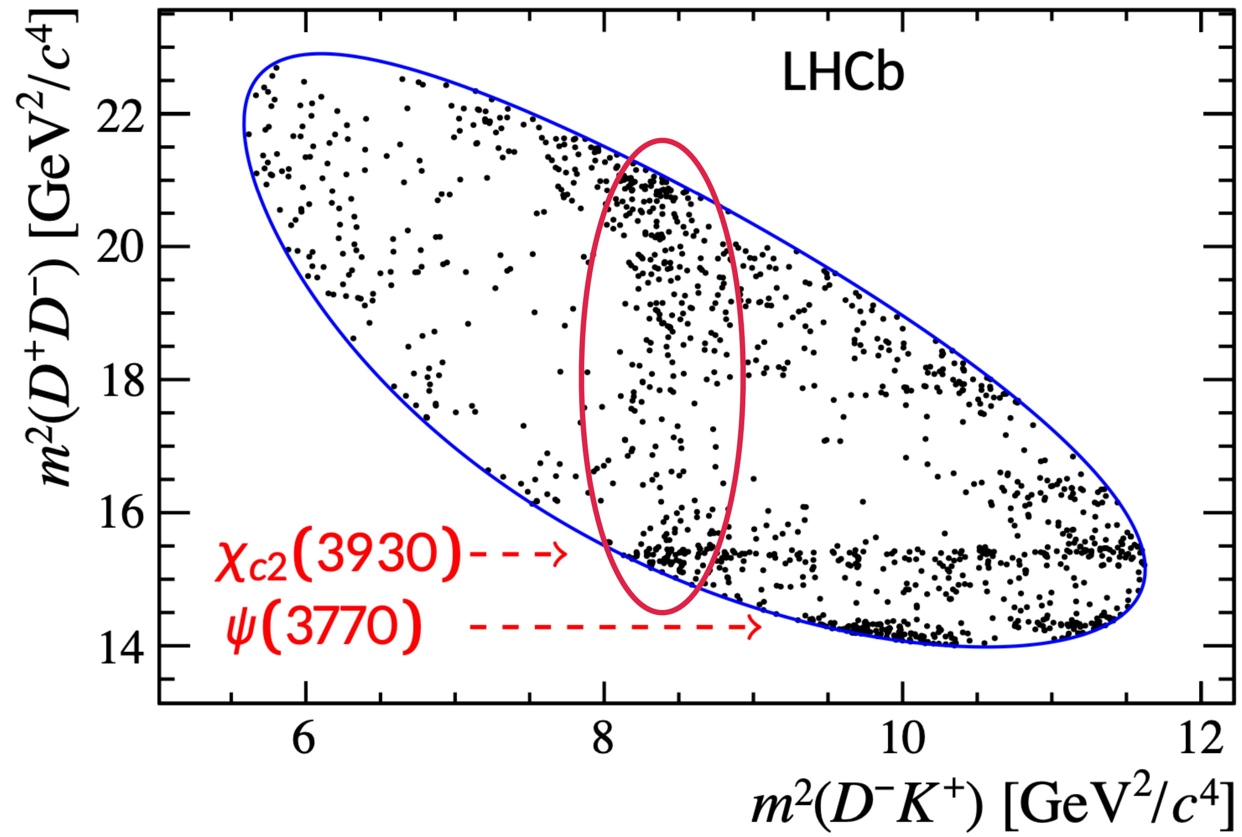
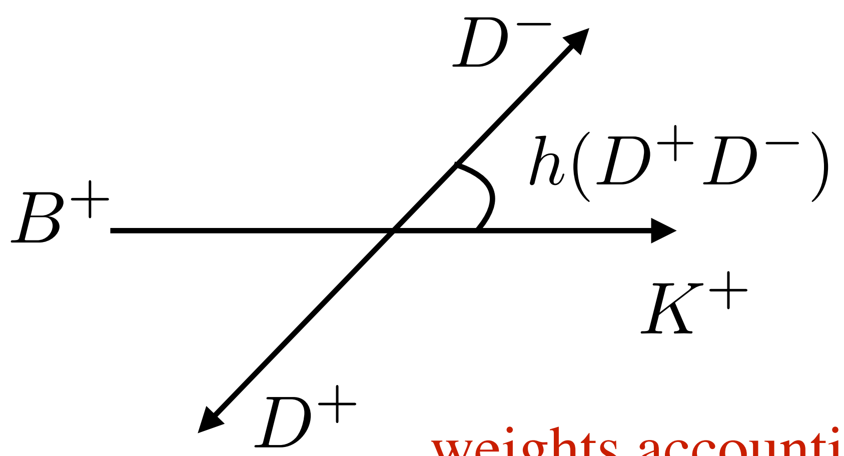


Decompose the distribution of the helicity angle in Legendre polynomials, in slices of $m(D^+D^-)$



weights accounting for efficiency

$$\langle Y_k^j \rangle = \sum_{l=1}^{N_j^{\mathrm{Data}}} w_l P_k\left(h_l(D^+D^-)\right)$$

If only D^+D^- resonances contribute, the Dalitz plot can be described by low-order moments $(k_{\max} = 2J_{\max})$

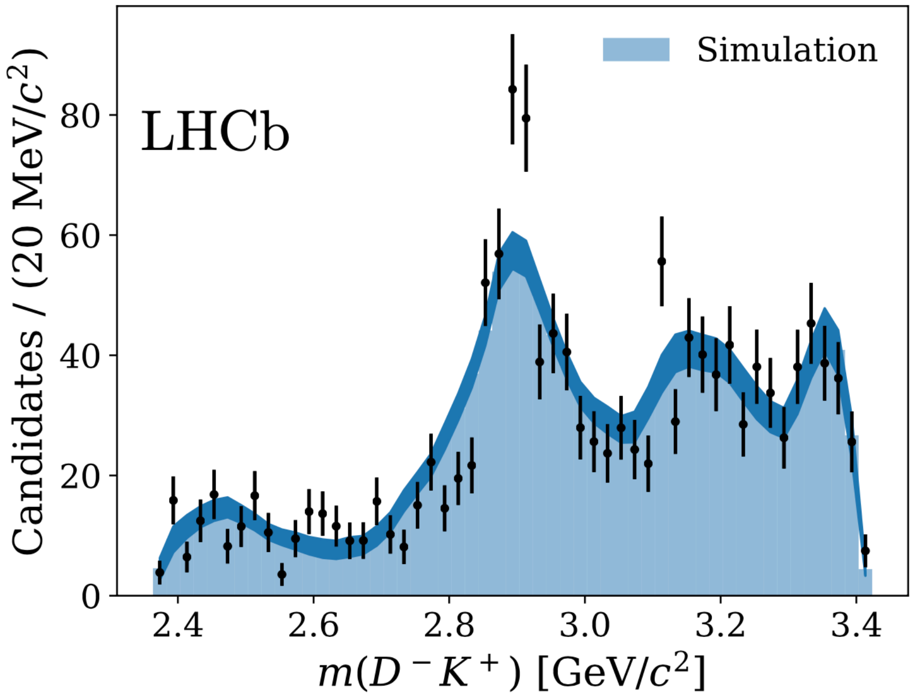
Simulate a sample uniformly in the Dalitz plot, weighted by the truncated moments

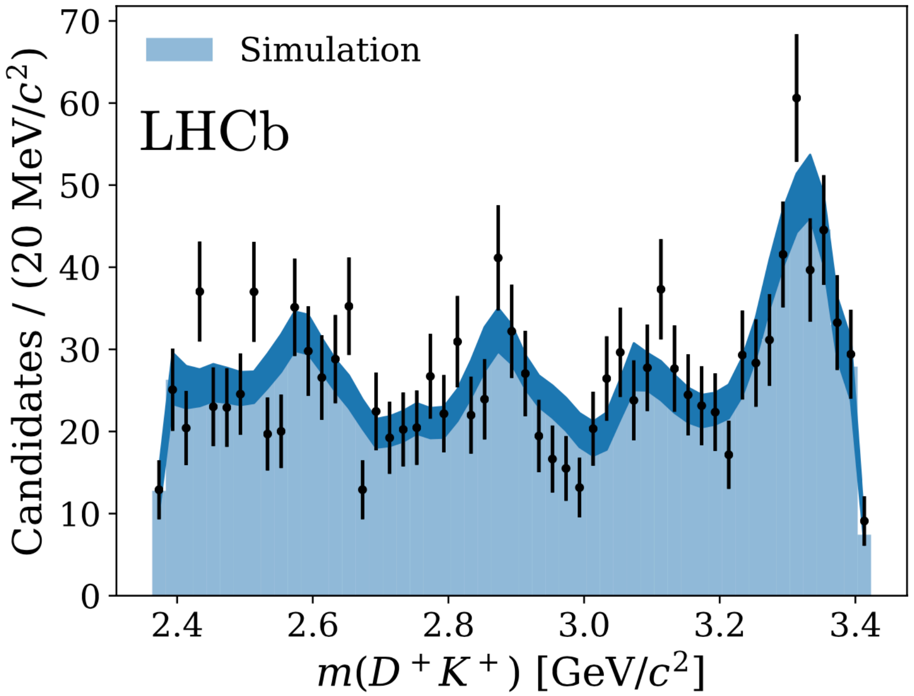
$$\eta_i = \frac{2}{N_j^{\mathrm{Sim}}} \times \sum_{k=0}^{k_{\max}} \langle Y_k^j \rangle P_k\left(h_i(D^+D^-)\right)$$

Then compare it to the $m(D^-K^+)$ and $m(D^+K^+)$ projections

$B^+ \to D^- D^+ K^+$: Model – independent analysis

Expansion up to spin-2 ($k_{\max} = 4$): unable to describe the DK spectrum





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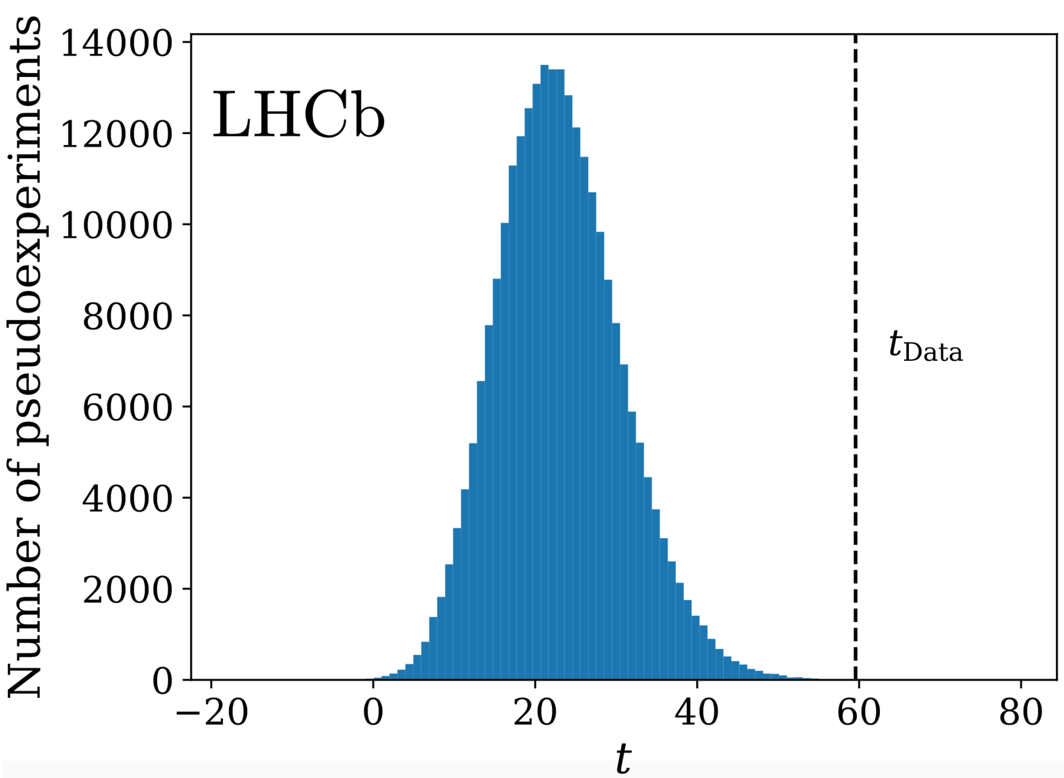
Significance of the discrepancy between truncated Legendre expansion and data assessed using pseudoexperiments and a test statistic

$$t = -2 \sum_{l=1}^{N^{\mathrm{Data}}} s_l \log \left(\frac{\mathcal{P}\left(m_l(D^-K^+)|H_0\right)/I_{H_0}}{\mathcal{P}\left(m_l(D^-K^+)|H_1\right)/I_{H_1}} \right)$$

t_{data} discrepant at level of 4σ

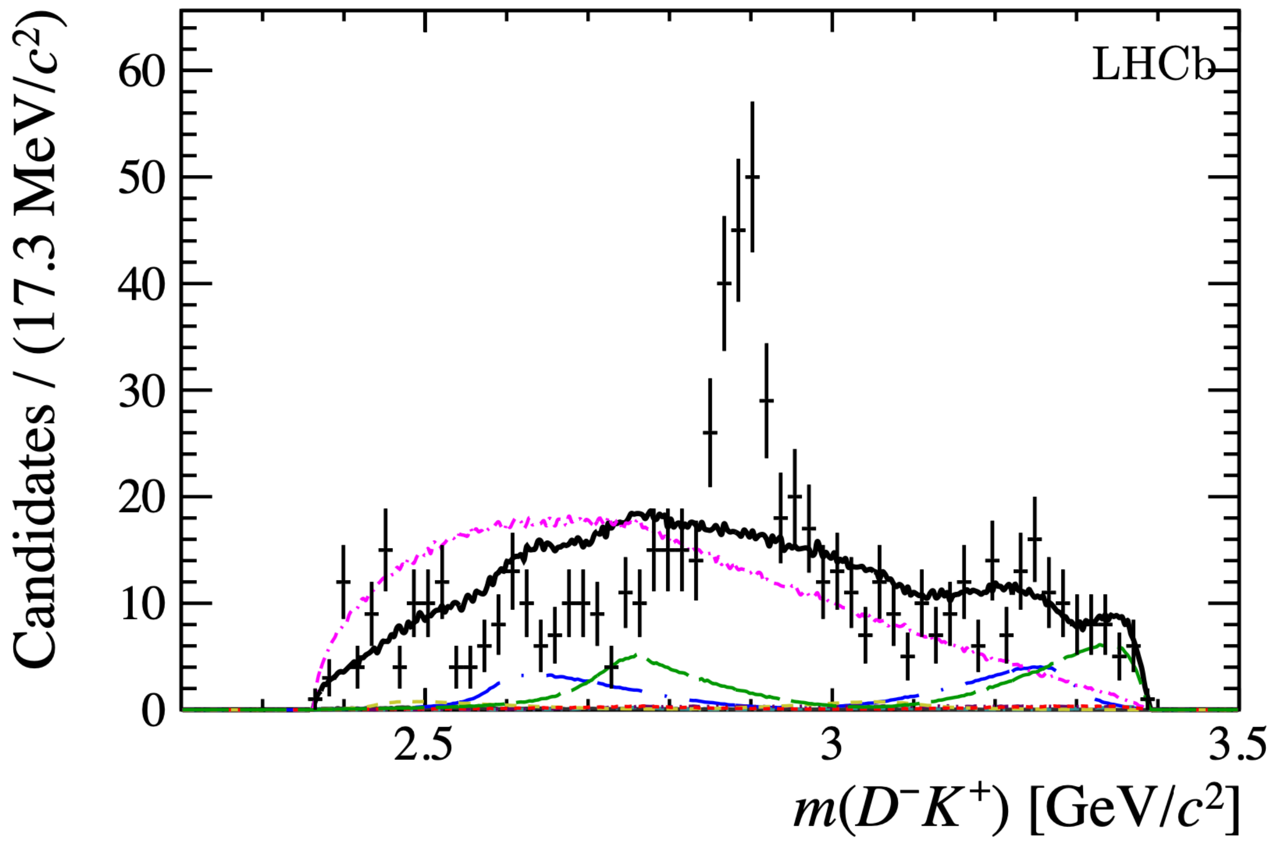


Model – dependent analysis

Only charmonium resonances are anticipated, all with natural spin-parity

$\psi(3770),\ \chi_{c0}(3930),\ \chi_{c2}(3930),\ \psi(4040),\ \psi(4160),\ \psi(4415),\ D^+D^-$ NR

A model with only D^+D^- resonances cannot describe de data



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Need to add resonances in the D^-K^+ channel:

$X_0(2900),\ X_1(2900)$

$B^+ \to D^- D^+ K^+$: Model – dependent analysis

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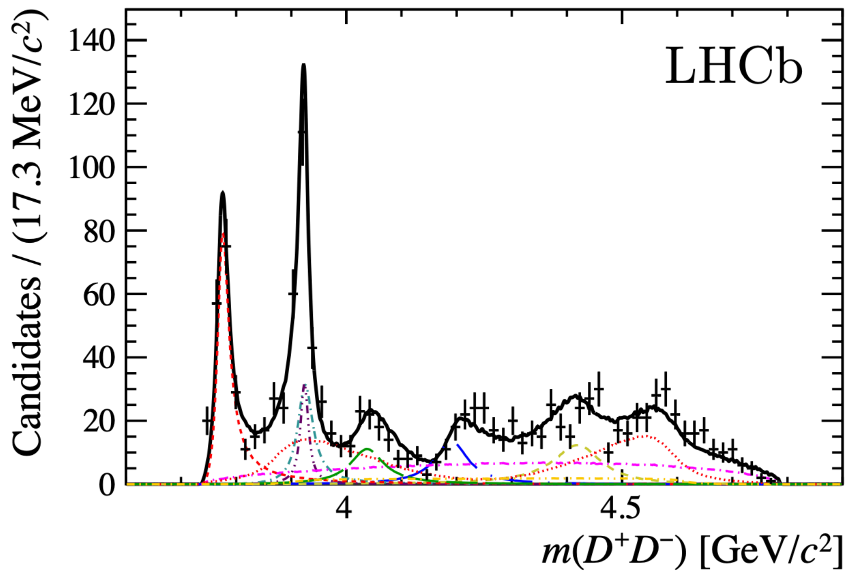

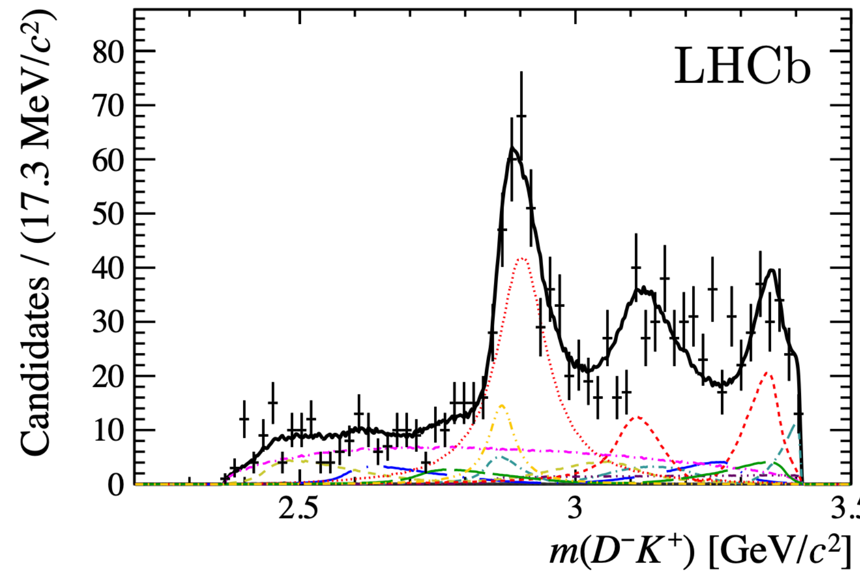

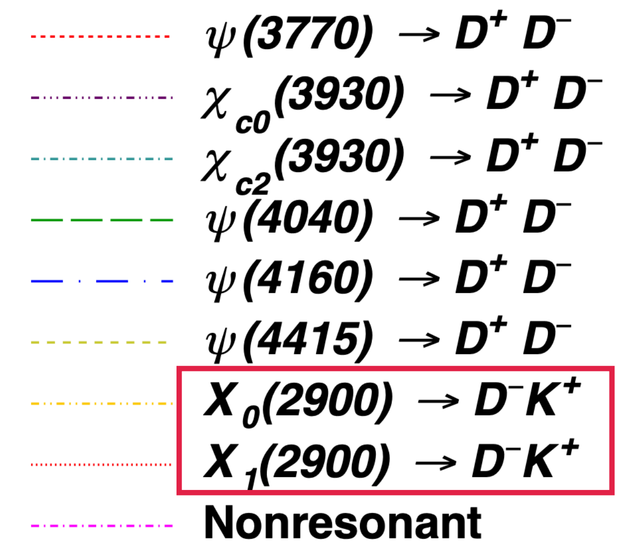

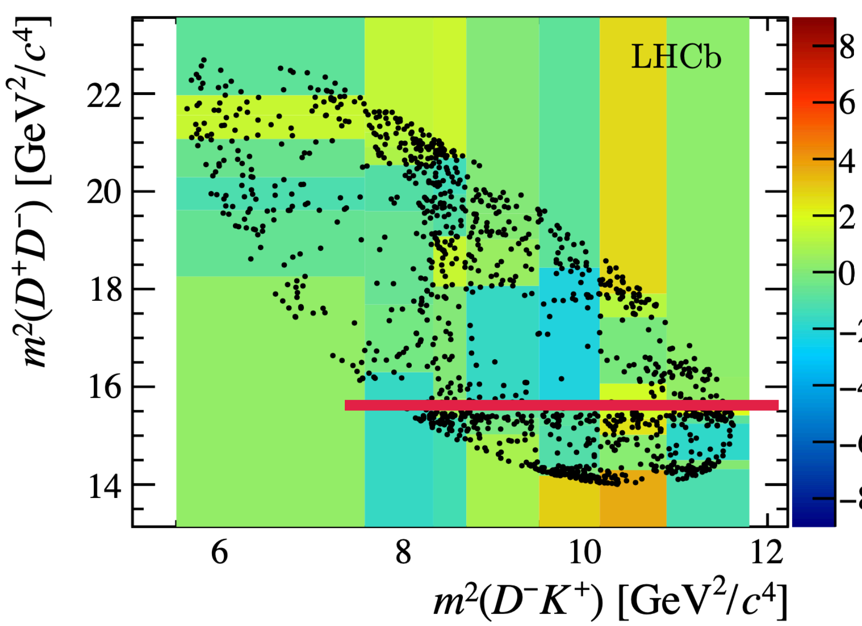

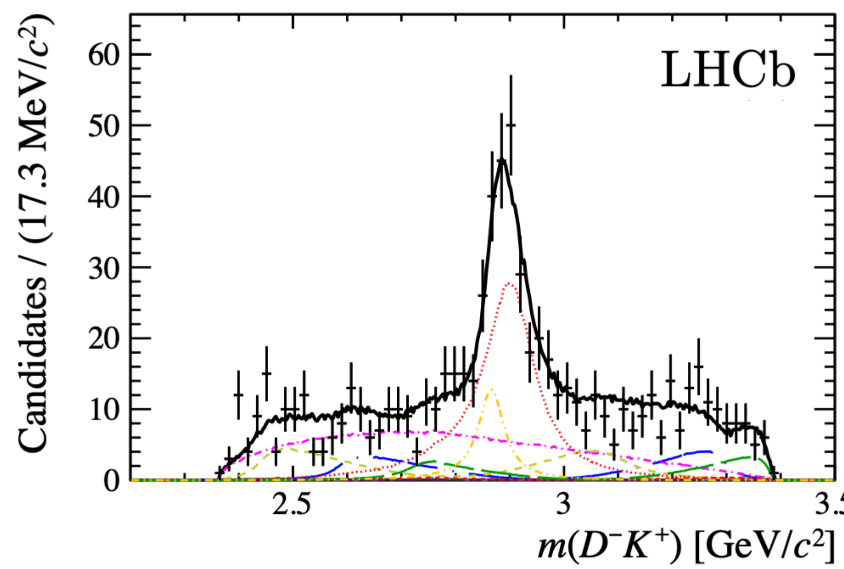

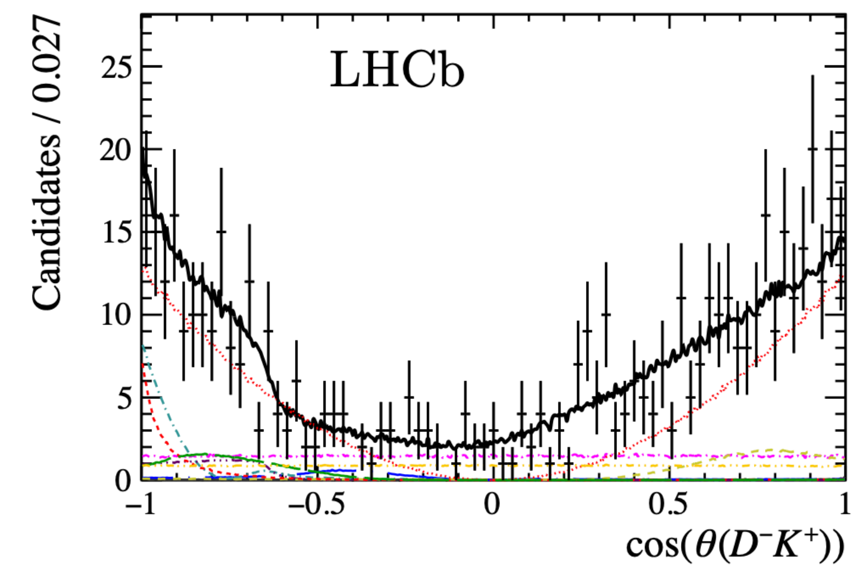

Resonance	Mass (GeV/c^2)	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$
$X_0(2900)$	$2.866 \pm 0.007 \pm 0.002$	$57 \pm 12 \pm 4$
$X_1(2900)$	$2.904 \pm 0.005 \pm 0.001$	$110 \pm 11 \pm 4$

Systematic uncertainties dominated by model composition (S- and P-wave)

New states overwhelmingly significant: $\gg 5\sigma$

Summary and conclusions

- Spectroscopy of excited D mesons is a lively field:
  many predicted states yet to be discovered

- Decays of B mesons are an excellent tool for investigation:
  allow the determination of quantum numbers

$B^- \to D^{*+}\pi^-\pi^-$ ➯ spin-parity assignment for various excited D states

$D_1(2430),\ D_0(2550),\ D_1^*(2600),\ D_2(2740),\ D_3^*(2750)$

$B^0 \to D^- D^+ K^+ \pi^-$ ➯ A new D_s^+ excited state ($J^P = 0^-$): $D_{s0}(2590)^+$

$M = 2591 \pm 9\ \mathrm{MeV}, \qquad \Gamma = 89 \pm 20\ \mathrm{MeV}$

$B^+ \to D^+ D^- K^+$ ➯ Two new states decaying to $D^- K^+$
(minimal quark content $\bar{c}du\bar{s}$)

$X_0(2900):\ M = 2.866 \pm 0.007\ \mathrm{GeV}/c^2, \qquad \Gamma = 57 \pm 13\ \mathrm{MeV}$

$X_1(2900):\ M = 2.904 \pm 0.005\ \mathrm{GeV}/c^2, \qquad \Gamma = 110 \pm 12\ \mathrm{MeV}$