Meson spectroscopy at LHCb

Workshop on heavy hadron spectroscopy

July 17th/18th CERN

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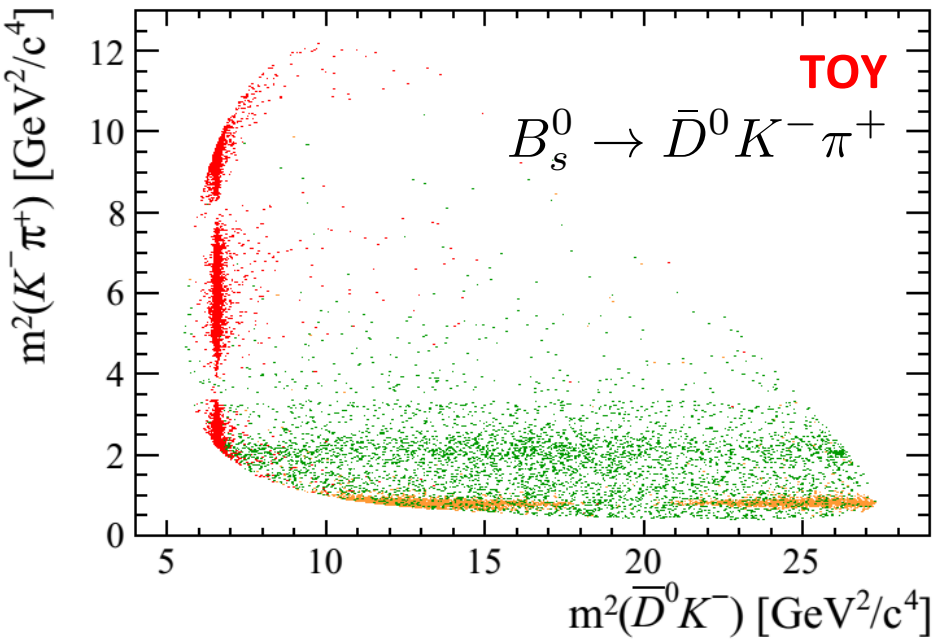
Introduction

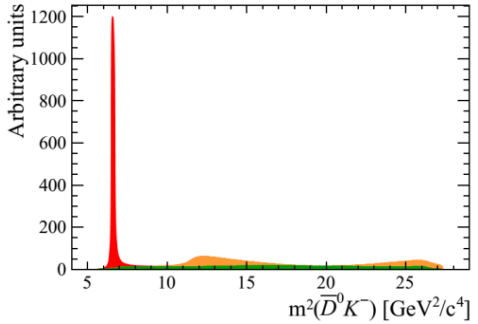
- Meson spectroscopy at LHCb
  - Two main methods, prompt studies and Dalitz plot analyses
  - Overview of results for beauty and charm mesons
  - (Some) personal bias towards DP analyses

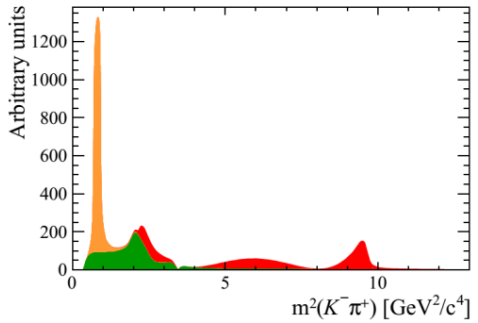
- Both methods have (dis)advantages
  - Prompt studies
    - High statistics, larger backgrounds, no* spin information
  - Dalitz plot analyses
    - High purity, spin/parity information, lower yields, need a parent

Dalitz plots

- One slide reminder…
  - Plot squares of invariant masses again each other
  - System is fully constrained -> access to spin information
  - Very power tool for spectroscopy (charm, light mesons)



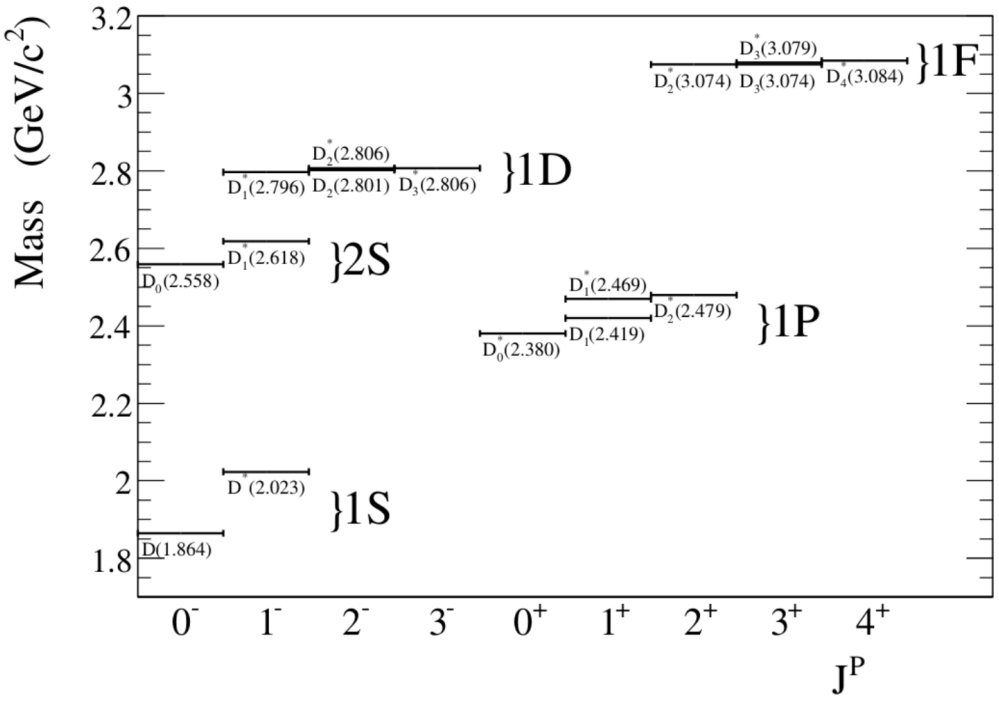




What are we looking for?

- Excited beauty/charm (strange) mesons
  - Spectra predicted by e.g. LQCD and HQET
  - Look for new states and compare

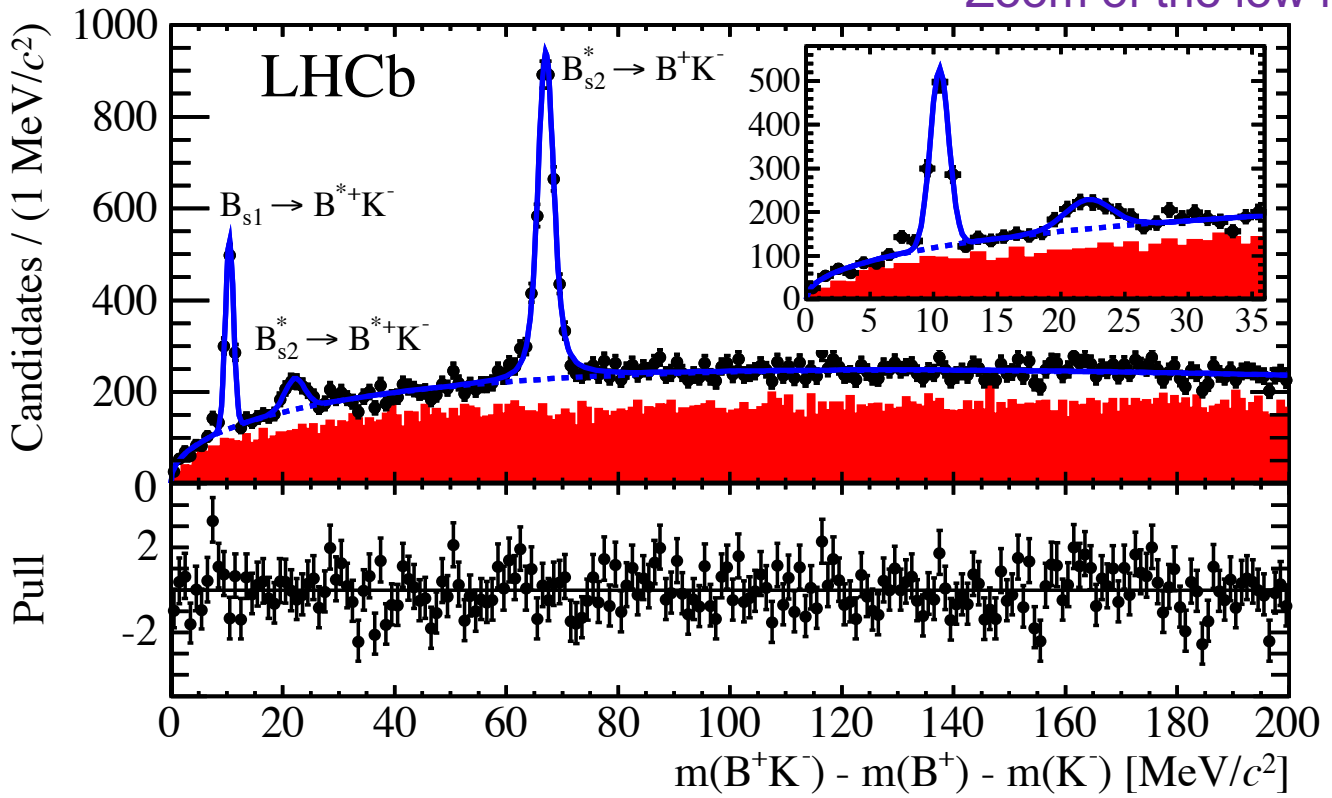
For example:
Predicted spectrum of
excited neutral charm states



Beauty

- Study of excited B_s^0 meson states with B^+K^-
  - Fit the mass distribution

Zoom of the low mass region



Beauty

- Study of excited B_s^0 meson states with B^+K^-
  - Measure the following parameters

$$m(B^{*+}) = 5324.26 \pm 0.30 \pm 0.23 \pm 0.17 \text{ MeV}/c^2,$$
$$m(B_{s1}) = 5828.40 \pm 0.04 \pm 0.04 \pm 0.41 \text{ MeV}/c^2,$$
$$m(B_{s2}^*) = 5839.99 \pm 0.05 \pm 0.11 \pm 0.17 \text{ MeV}/c^2,$$
$$\Gamma(B_{s2}^*) = 1.56 \pm 0.13 \pm 0.47 \text{MeV}/c^2$$

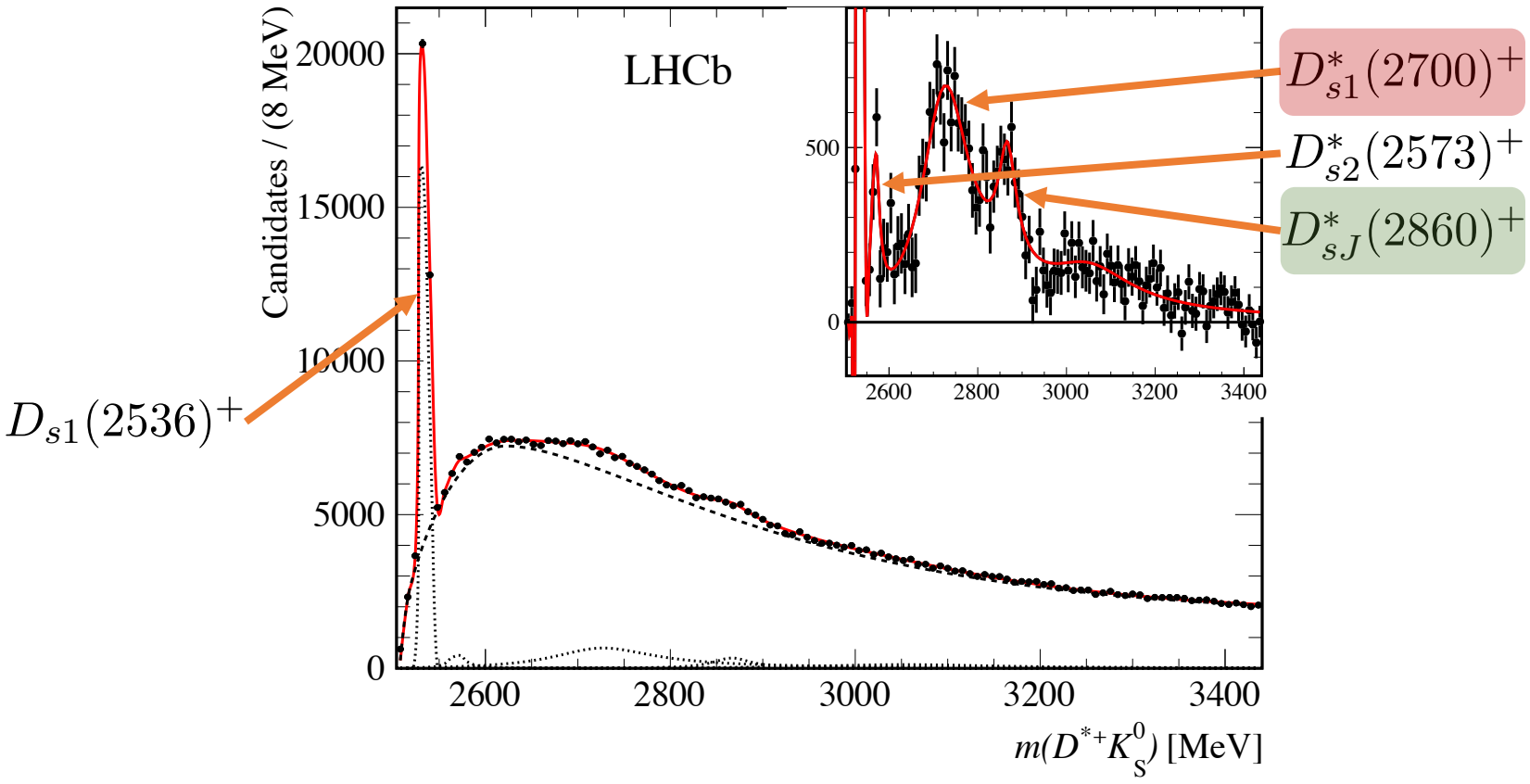
  - First measurement of the width for the B_{s2}^* state
  - Mass measurements significantly more precise than before

Charm spectroscopy

- Prompt production
  - $D^{*+}K^0_S\,, D^{*0}K^+$ LHCb-PAPER-2015-052
- Dalitz plot analyses
  - $B^+ \to D^-\pi^+\pi^+$ LHCb-PAPER-2016-026
  - $B^0 \to \bar{D}^0\pi^+\pi^-$ LHCb-PAPER-2014-070
  - $B^+ \to D^-K^+\pi^+$ LHCb-PAPER-2015-007
  - $B^0_s \to \bar{D}^0K^-\pi^+$ LHCb-PAPER-2014-035(6)

Charm spectroscopy (I)

- Study excited charm mesons with $D^{*+}K^0_S$, $D^{*0}K^+$
  - Perform a fit to the invariant mass distribution(s)



Charm spectroscopy (I)

- Study excited charm mesons with $D^{*+}K^0_S$, $D^{*0}K^+$
  - Measure the following parameters

$$m(D^*_{s1}(2700)^+) = 2732.3 \pm 4.3\,(\text{stat}) \pm 5.8\,(\text{syst})\ \text{MeV},$$
$$\Gamma(D^*_{s1}(2700)^+) = 136 \pm 19\,(\text{stat}) \pm 24\,(\text{syst})\ \text{MeV},$$

$$m(D^*_{sJ}(2860)^+) = 2867.1 \pm 4.3\,(\text{stat}) \pm 1.9\,(\text{syst})\ \text{MeV},$$
$$\Gamma(D^*_{sJ}(2860)^+) = 50 \pm 11\,(\text{stat}) \pm 13\,(\text{syst})\ \text{MeV}.$$

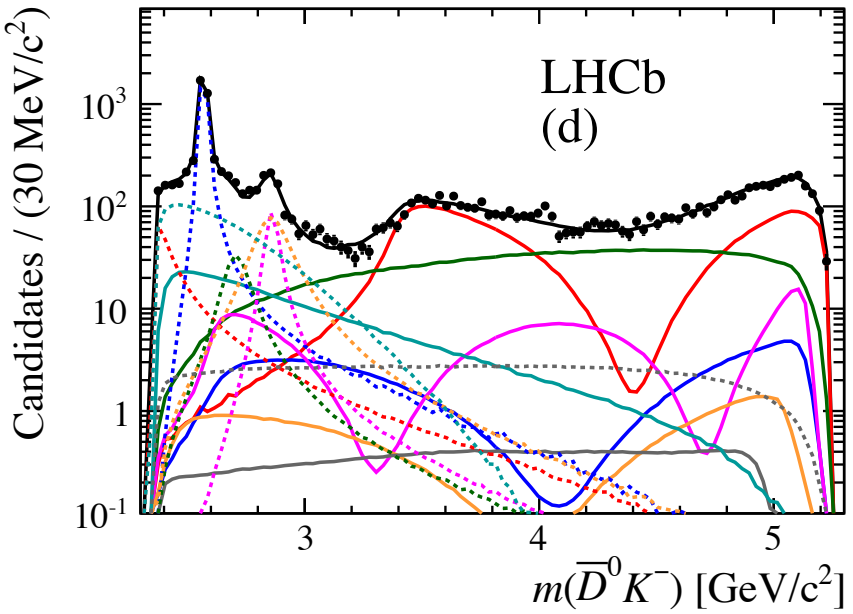
- Several other interesting results in the paper!

Charm spectroscopy (II)

- Dalitz plot analysis of $B_s^0 \to \bar{D}^0 K^- \pi^+$
  - Study excited charm-strange mesons
  - Amplitude fit using the isobar model

$$\mathcal{A}(s,t) = \sum_{j=1}^{N} c_j F_j(s,t)$$

Resonance	Spin	Dalitz plot axis	Model
$\overline{K}^*(892)^0$	1	$m^2(K^-\pi^+)$	RBW
$\overline{K}^*(1410)^0$	1	$m^2(K^-\pi^+)$	RBW
$\overline{K}_0^*(1430)^0$	0	$m^2(K^-\pi^+)$	LASS
$\overline{K}_2^*(1430)^0$	2	$m^2(K^-\pi^+)$	RBW
$\overline{K}^*(1680)^0$	1	$m^2(K^-\pi^+)$	RBW
$\overline{K}_0^*(1950)^0$	0	$m^2(K^-\pi^+)$	RBW
$D_{s2}^*(2573)^-$	2	$m^2(\overline{D}^0 K^-)$	RBW
$D_{s1}^*(2700)^-$	1	$m^2(\overline{D}^0 K^-)$	RBW
$D_{sJ}^*(2860)^-$	1	$m^2(\overline{D}^0 K^-)$	RBW
$D_{sJ}^*(2860)^-$	3	$m^2(\overline{D}^0 K^-)$	RBW
Nonresonant		$m^2(\overline{D}^0 K^-)$	EFF
$D_{s\,v}^{*-}$	1	$m^2(\overline{D}^0 K^-)$	RBW
$D_{s0\,v}^*(2317)^-$	0	$m^2(\overline{D}^0 K^-)$	RBW
B_v^{*+}	1	$m^2(\overline{D}^0 \pi^+)$	RBW



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Nonresonant		$m^2(D^0 K^-)$	EFF
$D_{s\,v}^{*-}$	1	$m^2(\overline{D}^0 K^-)$	RBW
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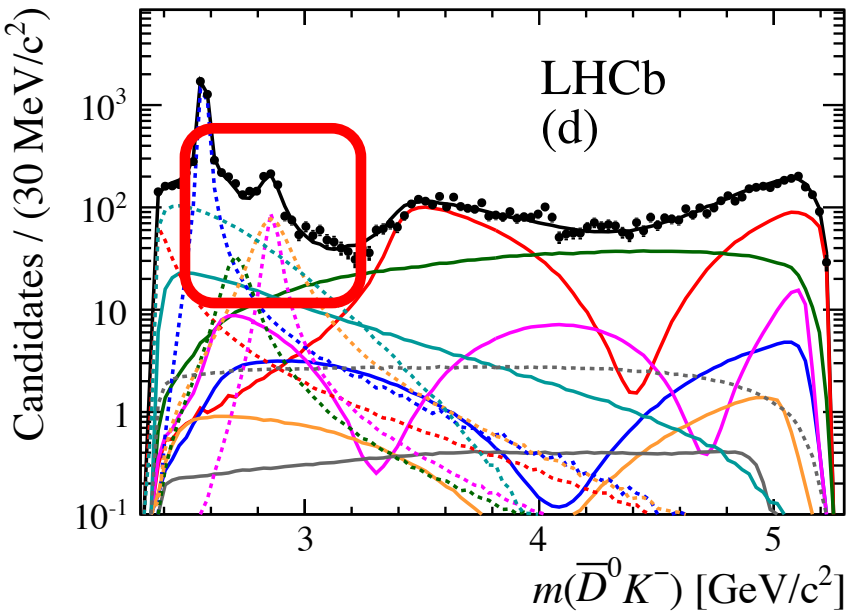
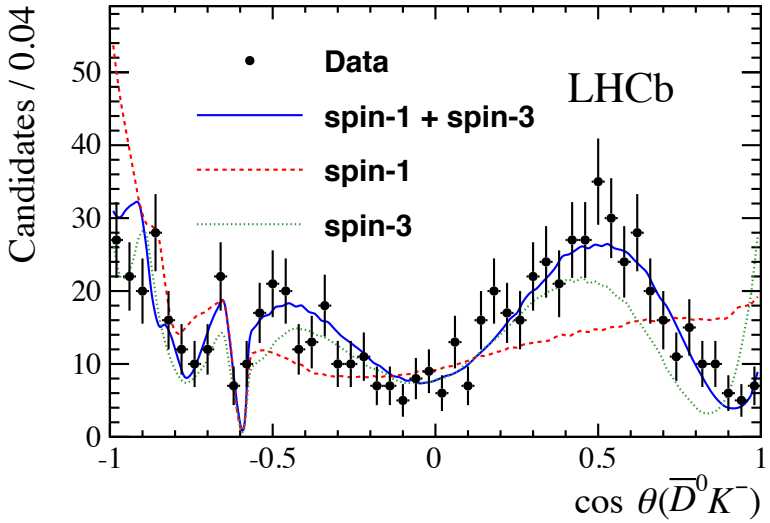
B_v^{*+}	1	$m^2(\overline{D}^0 \pi^+)$	RBW



Charm spectroscopy (II)

- Dalitz plot analysis of $B_s^0 \to \bar{D}^0 K^- \pi^+$
  - Resolved the $D_{sJ}^*(2860)$ bump into two states
    - First observations of the $D_{s1}^*(2860)^+$ and $D_{s3}^*(2860)^+$ mesons
    - With spins of 1 and 3, masses and widths below

$$
\begin{aligned}
m(D_{s2}^*(2573)^-) &= 2568.39 \pm 0.29 \pm 0.19 \pm 0.18\,\text{MeV}/c^2\,, \\
\Gamma(D_{s2}^*(2573)^-) &= 16.9 \pm 0.5 \pm 0.4 \pm 0.4\,\text{MeV}/c^2\,, \\
m(D_{s1}^*(2860)^-) &= 2859 \pm 12 \pm 6 \pm 23\,\text{MeV}/c^2\,, \\
\Gamma(D_{s1}^*(2860)^-) &= 159 \pm 23 \pm 27 \pm 72\,\text{MeV}/c^2\,, \\
m(D_{s3}^*(2860)^-) &= 2860.5 \pm 2.6 \pm 2.5 \pm 6.0\,\text{MeV}/c^2\,, \\
\Gamma(D_{s3}^*(2860)^-) &= 53 \pm 7 \pm 4 \pm 6\,\text{MeV}/c^2\,,
\end{aligned}
$$

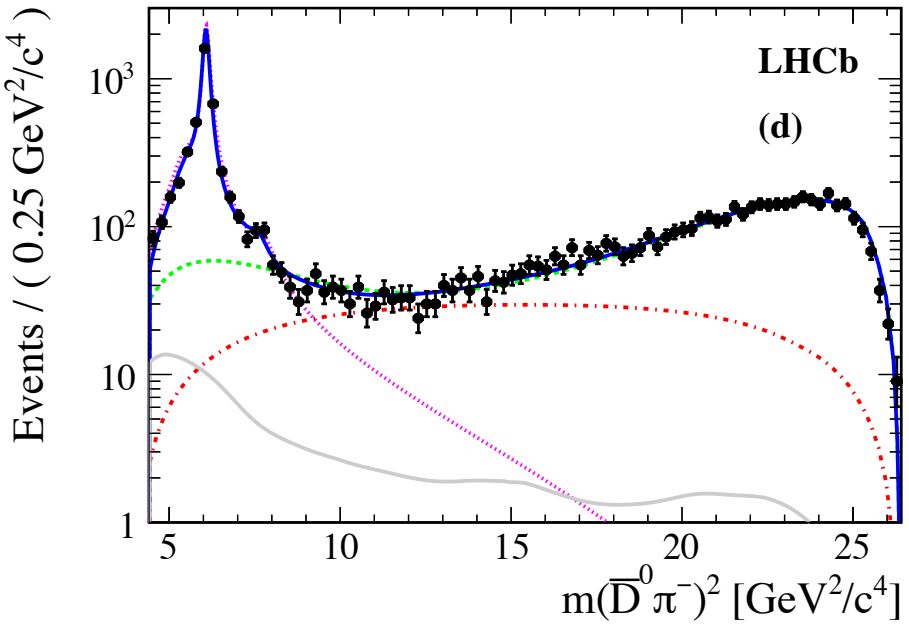


  - Many theory papers discussing these states
    - In generally favour idenfiying them as members of the 1D family

Charm spectroscopy (III)

- Dalitz plot analysis of $B^0 \to \bar{D}^0 \pi^+ \pi^-$
  - Study excited charm mesons

Resonance	Spin	Model
$\bar{D}^0\pi^-$ P-wave	1	Eq. 14
$D_0^*(2400)^-$	0	RBW
$D_2^*(2460)^-$	2	RBW
$D_J^*(2760)^-$	3	RBW
$\rho(770)$	1	GS
$\omega(782)$	1	Eq. 13
$\rho(1450)$	1	GS
$\rho(1700)$	1	GS
$f_2(1270)$	2	RBW
$\pi\pi$ S-wave	0	K-matrix
$f_0(500)$	0	Eq. 15
$f_0(980)$	0	Eq. 18
$f_0(2020)$	0	RBW
Nonresonant	0	Eq. 20



Two models used for the $\pi^+\pi^-$ S-wave

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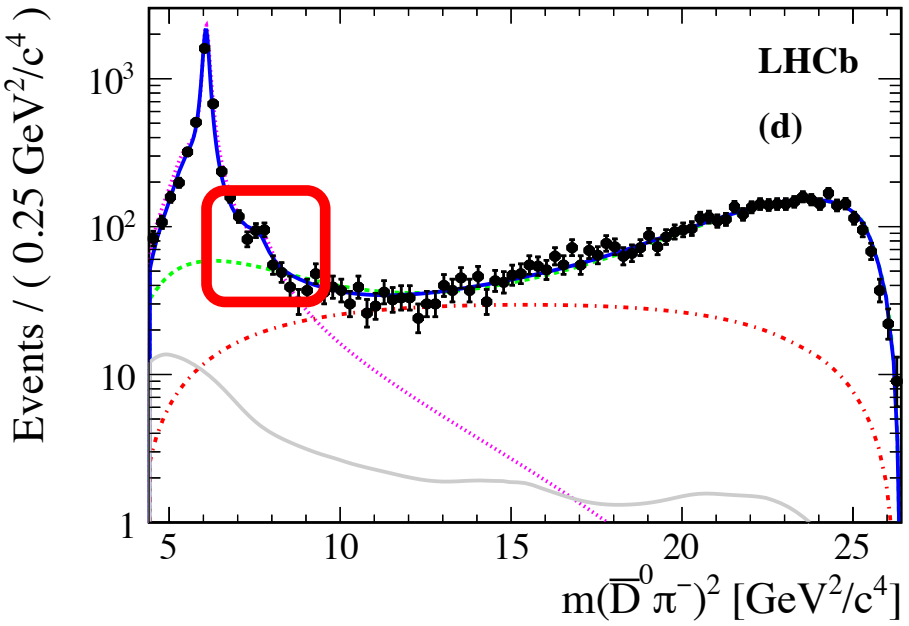
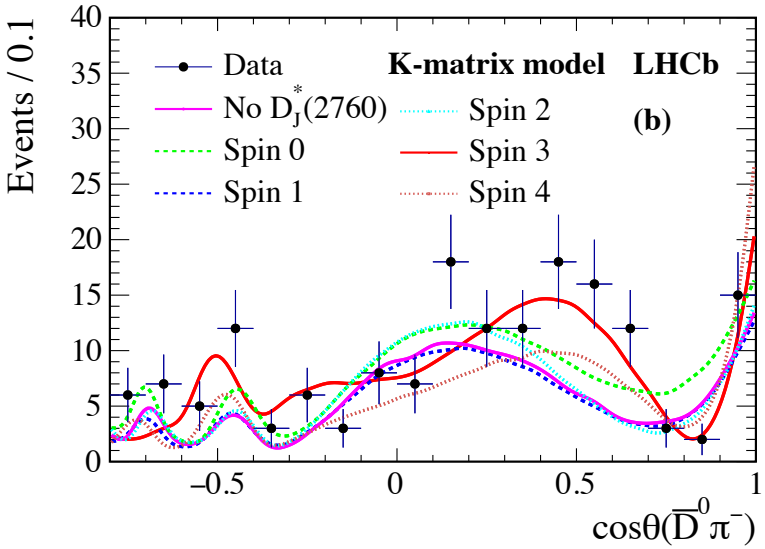


Two models used for the $\pi^+\pi^-$ S-wave

Charm spectroscopy (III)

- Dalitz plot analysis of $B^0 \to \bar{D}^0 \pi^+ \pi^-$
  - First observation of the $D_3^*(2760)^+$ meson
    - Determined to be spin 3, no sensitivity to a spin 1 partner

		Isobar	K-matrix
$D_0^*(2400)$	m	$2349 \pm 6 \pm 1 \pm 4$	$2354 \pm 7 \pm 11 \pm 2$
	Γ	$217 \pm 13 \pm 5 \pm 12$	$230 \pm 15 \pm 18 \pm 11$
$D_2^*(2460)$	m	$2468.6 \pm 0.6 \pm 0.0 \pm 0.3$	$2468.1 \pm 0.6 \pm 0.4 \pm 0.3$
	Γ	$47.3 \pm 1.5 \pm 0.3 \pm 0.6$	$46.0 \pm 1.4 \pm 1.7 \pm 0.4$
$D_3^*(2760)$	m	$2798 \pm 7 \pm 1 \pm 7$	$2802 \pm 11 \pm 10 \pm 3$
	Γ	$105 \pm 18 \pm 6 \pm 23$	$154 \pm 27 \pm 13 \pm 9$

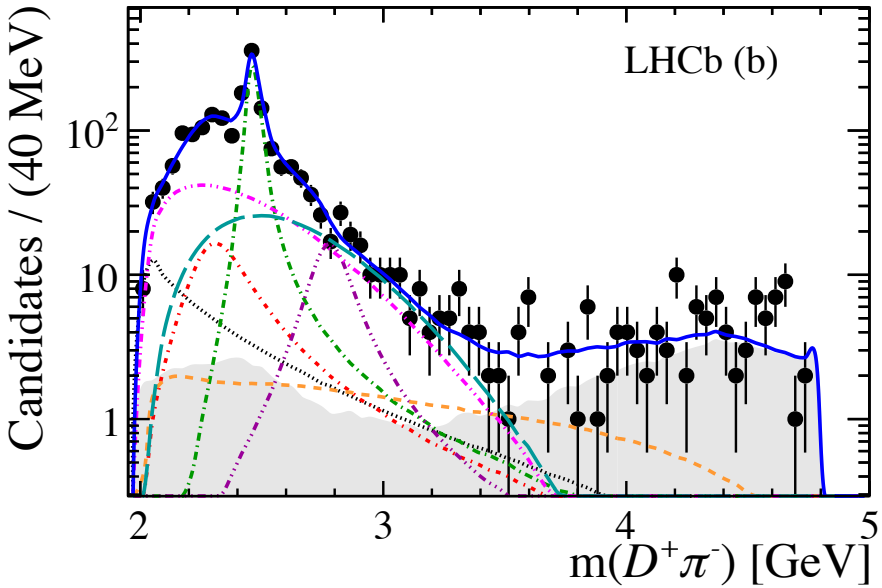


- Many more results in the paper from the amplitudes
  - Including studies of light mesons

Charm spectroscopy (IV)

- Dalitz plot analysis of $B^+ \to D^- K^+ \pi^+$
  - Study excited charm mesons
  - Simpler decay, expect structures only in $m(D\pi)$
    - Use Legendre moments to help with model building

Resonance	Spin	DP axis
$D_0^*(2400)^0$	0	$m^2(D\pi)$
$D_2^*(2460)^0$	2	$m^2(D\pi)$
$D_J^*(2760)^0$	1	$m^2(D\pi)$
Nonresonant	0	$m^2(D\pi)$
Nonresonant	1	$m^2(D\pi)$
$D_v^*(2007)^0$	1	$m^2(D\pi)$
B_v^{*0}	1	$m^2(DK)$



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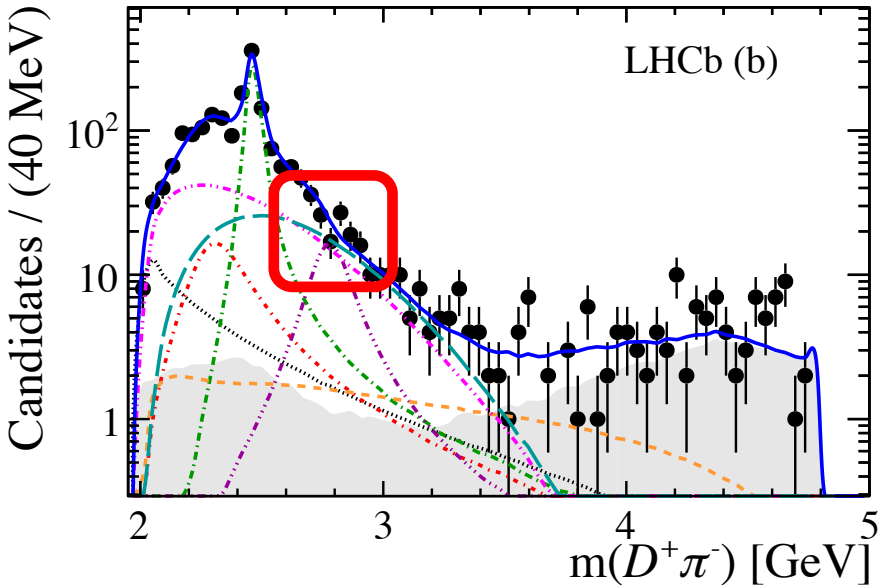
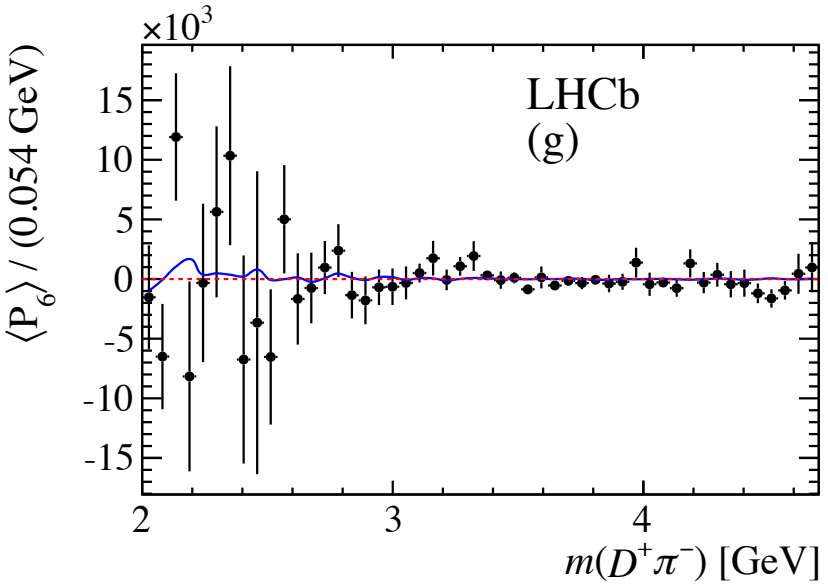
$D_J^*(2760)^0$	1	$m^2(D\pi)$
Nonresonant	0	$m^2(D\pi)$
Nonresonant	1	$m^2(D\pi)$
$D_v^*(2007)^0$	1	$m^2(D\pi)$
B_v^{*0}	1	$m^2(DK)$



Charm spectroscopy (IV)

- Dalitz plot analysis of $B^+ \to D^- K^+ \pi^+$
  - First observation of the $D_1^*(2760)^0$ meson
    - Determined to be spin 1
    - No sensitivity to a spin 3 partner

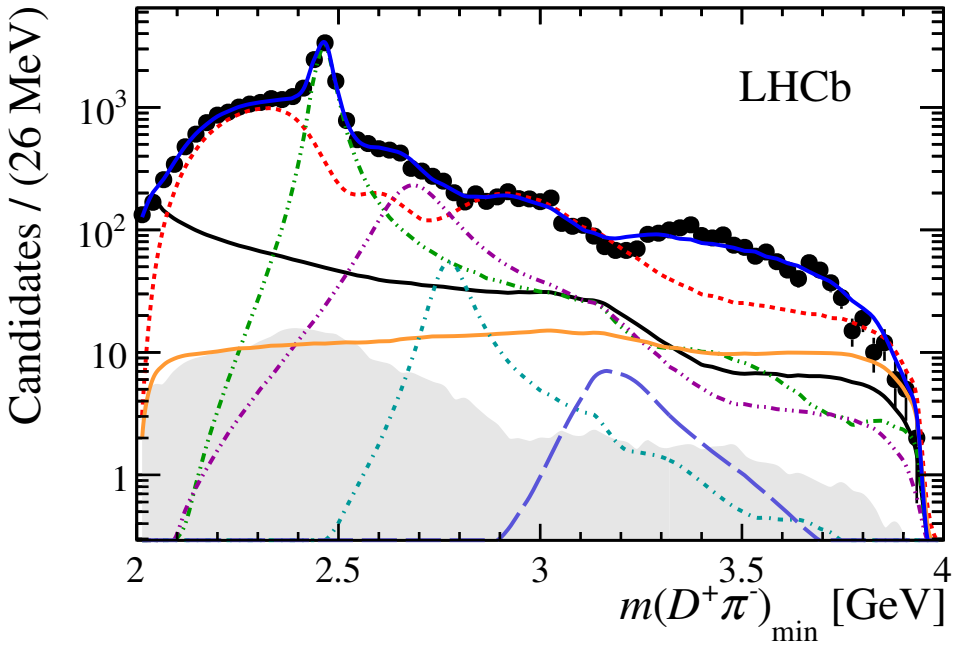
$$
\begin{aligned}
m(D_2^*(2460)^0) &= (2464.0 \pm 1.4 \pm 0.5 \pm 0.2)\,\text{MeV} \\
\Gamma(D_2^*(2460)^0) &= (43.8 \pm 2.9 \pm 1.7 \pm 0.6)\,\text{MeV} \\
m(D_1^*(2760)^0) &= (2781 \pm 18 \pm 11 \pm 6)\,\text{MeV} \\
\Gamma(D_1^*(2760)^0) &= (177 \pm 32 \pm 20 \pm 7)\,\text{MeV}
\end{aligned}
$$



Charm spectroscopy (V)

- Dalitz plot analysis of $B^+ \to D^- \pi^+ \pi^+$
  - Study excited charm mesons
  - Study the same resonances as the $B^+ \to D^- K^+ \pi^+$ analysis
    - Cabibbo favoured -> higher statistics

Resonance	Spin	Model
$D_2^*(2460)^0$	2	RBW
$D_1^*(2680)^0$	1	RBW
$D_3^*(2760)^0$	3	RBW
$D_2^*(3000)^0$	2	RBW
$D_v^*(2007)^0$	1	RBW
B_v^{*0}	1	RBW
Total S-wave	0	MIPW



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$D_v^*(2007)^0$	1	RBW
B_v^{*0}	1	RBW
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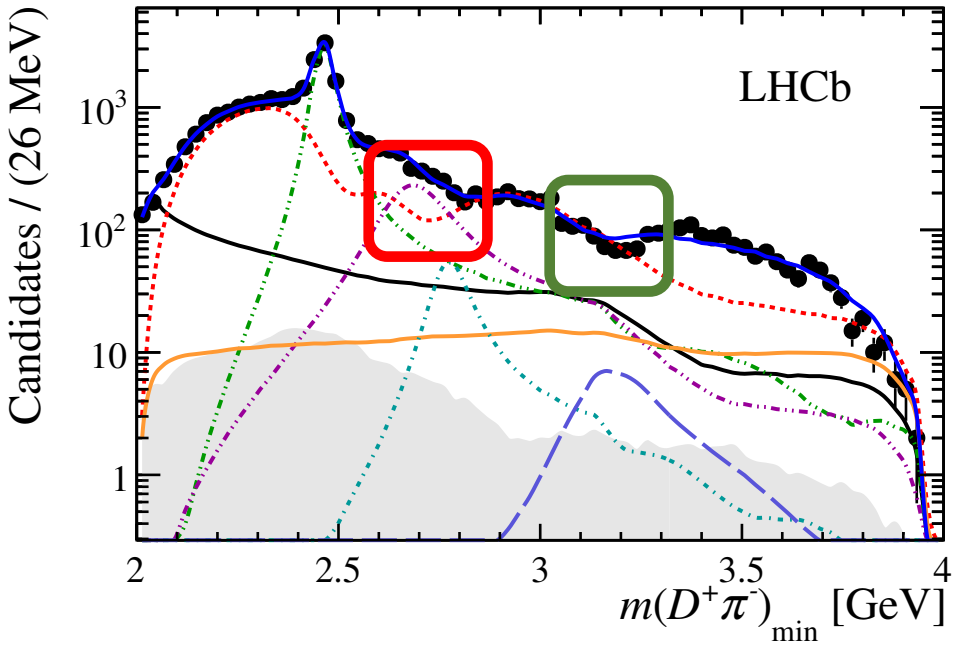


Charm spectroscopy (V)

- Dalitz plot analysis of $B^+ \to D^- \pi^+ \pi^+$
  - First observation of $D_1^*(2680)^0$, $D_3^*(2760)^0$, $D_2^*(3000)^0$ states
    - Spins determined significantly
    - No sign of the $D_1^*(2760)^0$ state in this decay?

$$
\begin{aligned}
m(D_2^*(2460)^0) &= 2463.7 \pm 0.4 \pm 0.4 \pm 0.6\,\text{MeV} \\
\Gamma(D_2^*(2460)^0) &= 47.0 \pm 0.8 \pm 0.9 \pm 0.3\,\text{MeV} \\
m(D_1^*(2680)^0) &= 2681.1 \pm 5.6 \pm 4.9 \pm 13.1\,\text{MeV} \\
\Gamma(D_1^*(2680)^0) &= 186.7 \pm 8.5 \pm 8.6 \pm 8.2\,\text{MeV} \\
m(D_3^*(2760)^0) &= 2775.5 \pm 4.5 \pm 4.5 \pm 4.7\,\text{MeV} \\
\Gamma(D_3^*(2760)^0) &= 95.3 \pm 9.6 \pm 7.9 \pm 33.1\,\text{MeV} \\
m(D_2^*(3000)^0) &= 3214 \pm 29 \pm 33 \pm 36\,\text{MeV} \\
\Gamma(D_2^*(3000)^0) &= 186 \pm 38 \pm 34 \pm 63\,\text{MeV}
\end{aligned}
$$

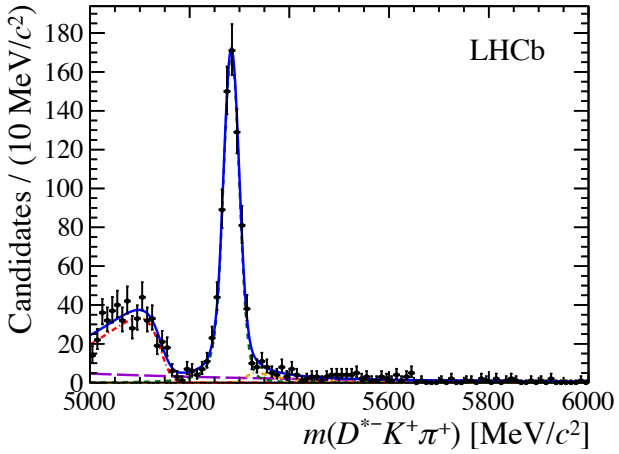
Summary

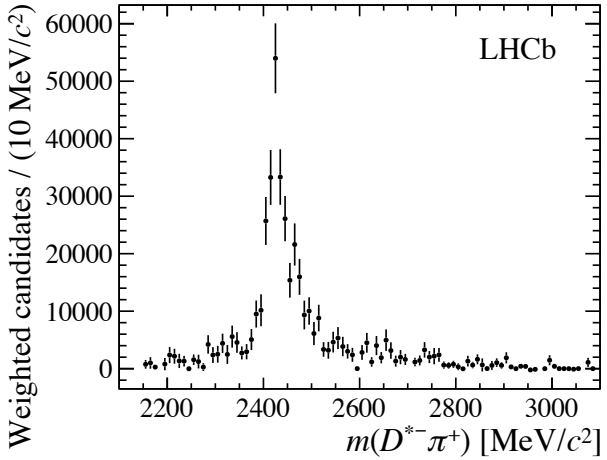
- LHCb very active in meson spectroscopy studies
  - 6 first observations of excited charm (strange) mesons
    - Only natural spin parity states though - need to do D*hh final states
  - Many worlds best measurements
    - Masses, widths, spins...
  - Active theory community interpretting out results
    - In total the papers shown have >>100 citations

Outlook

- Everything shown here is from Run 1
  - Already have more data in our pockets + 2017 + 2018
    - Should be able to explore higher mass states
    - Confirm and improve the measurements shown here
  - Expand the range of analyses
    - E.g. First step for $B^+ \to D^{*-}K^+\pi^+$ decays

$$\mathcal{B}(B^+ \to D^{*-}K^+\pi^+) = (8.2 \pm 0.3 \pm 0.6 \pm 1.3) \times 10^{-5}$$





Backups