Hadronic B decays

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On behalf of the LHCb collaboration, with results from BaBar & Belle

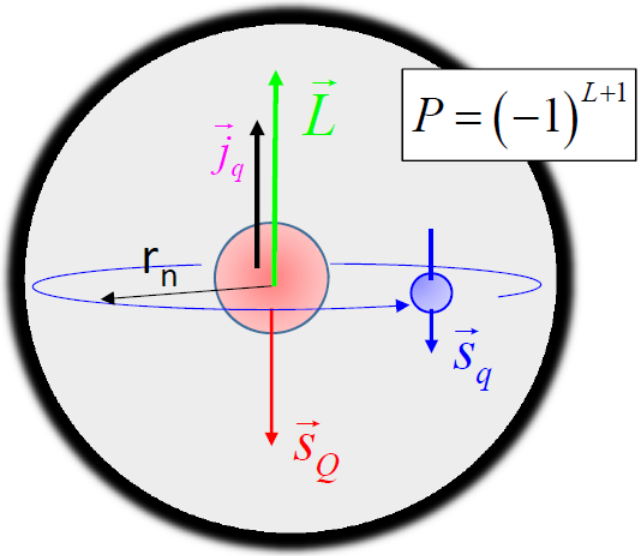
Excited D meson spectroscopy

- Many D and D_s resonances discovered in recent decade
- But nature of such resonances unclear/unknown in many cases
- Amplitude analyses of B decays can help !
  - Provide access to natural-spin resonances only

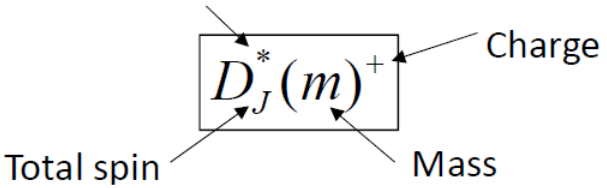
J^P $Q\bar{q}$ meson

$\vec{J} = \vec{j}_q + \vec{s}_Q$

$= \vec{L} + \vec{s}_q$



* Indicates "natural" parity (0^+, 1^-, 2^+ ...)



Outlook to a review of recent results

Excited D meson spectroscopy from B → D X decays

- ❑ B → D h h(')
- ❑ B → $\bar{D}^{(*)}$ $D^{(*)}$ K

22 modes possible !

Neutral B mode	Charged B mode
$B^0 \to D^- D^0 K^+$	$B^+ \to \bar{D}^0 D^+ K^0$
$B^0 \to D^- D^{*0} K^+$	$B^+ \to \bar{D}^0 D^{*+} K^0$
$B^0 \to D^{*-} D^0 K^+$	$B^+ \to \bar{D}^{*0} D^+ K^0$
$B^0 \to D^{*-} D^{*0} K^+$	$B^+ \to \bar{D}^{*0} D^{*+} K^0$
$B^0 \to D^- D^+ K^0$	$B^+ \to \bar{D}^0 D^0 K^+$
$B^0 \to D^- D^{*+} K^0 + D^{*-} D^+ K^0$	$B^+ \to \bar{D}^0 D^{*0} K^+$
	$B^+ \to \bar{D}^{*0} D^0 K^+$
$B^0 \to D^{*-} D^{*+} K^0$	$B^+ \to \bar{D}^{*0} D^{*0} K^+$
$B^0 \to \bar{D}^0 D^0 K^0$	$B^+ \to D^- D^+ K^+$
$B^0 \to \bar{D}^0 D^{*0} K^0 + \bar{D}^{*0} D^0 K^0$	$B^+ \to D^- D^{*+} K^+$
	$B^+ \to D^{*-} D^+ K^+$
$B^0 \to \bar{D}^{*0} D^{*0} K^0$	$B^+ \to D^{*-} D^{*+} K^+$

- ❑ Study of resonant structures
  - $c\bar{c}$, $c\bar{s}$, $c\bar{d}$
- ❑ Determination of basic properties such as mass, width *and* spin
- ❑ Determination of branching fractions of B → (D) X "resonance decays"

A (very brief) selection of hadronic b-hadron decays

- ❑ New b-hadron decays from LHCb

D meson spectroscopy from $B \to D X$ decays

See Markus Roehrken's talk that includes γ from $B \to D h$

$B^0 \to D_s^- K_S^0 \pi^+$ and $B^+ \to D_s^- K^+ K^+$

PRD 91, 032008 (2015)

Motivation

- Check validity of theoretical descriptions of 3-body hadronic decays
- Spectroscopy studies in D_s K subsystem

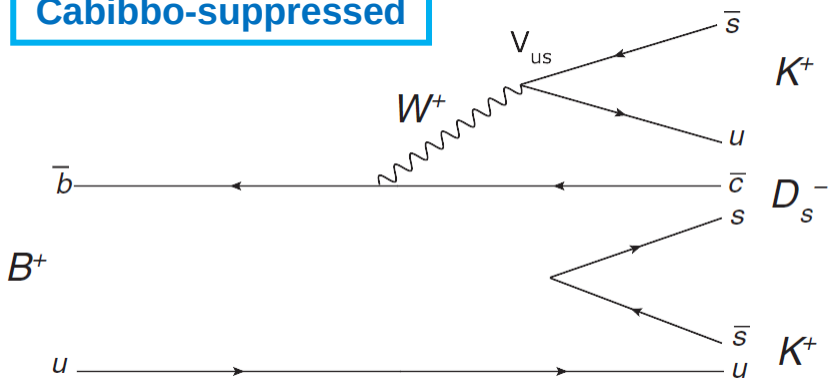
Analysis

- 657M B $\bar{B}$ pairs @ Υ(4S) resonance
- D_s reconstructed in final states $\phi\,\pi$, $K^*\,K^+$ and $K_S\,K^+$

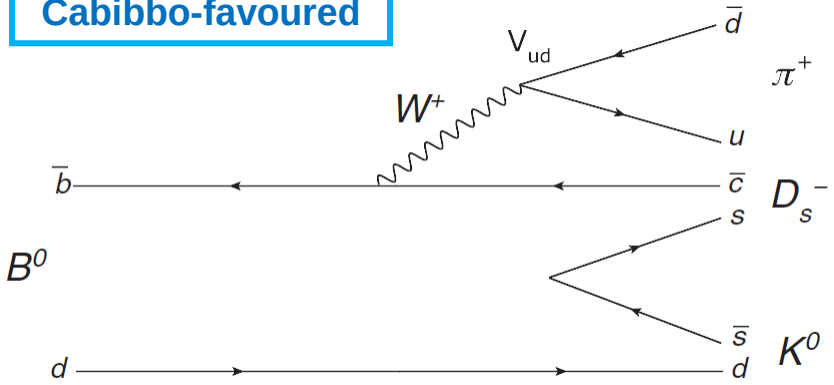
$$\mathcal{B}(B^0 \to D_s^- K_S^0 \pi^+) = [0.47 \pm 0.06(\text{stat}) \pm 0.05(\text{syst})] \times 10^{-4}$$

$$\mathcal{B}(B^+ \to D_s^- K^+ K^+) = [0.93 \pm 0.22(\text{stat}) \pm 0.10(\text{syst})] \times 10^{-5}$$

Cabibbo-suppressed



Cabibbo-favoured



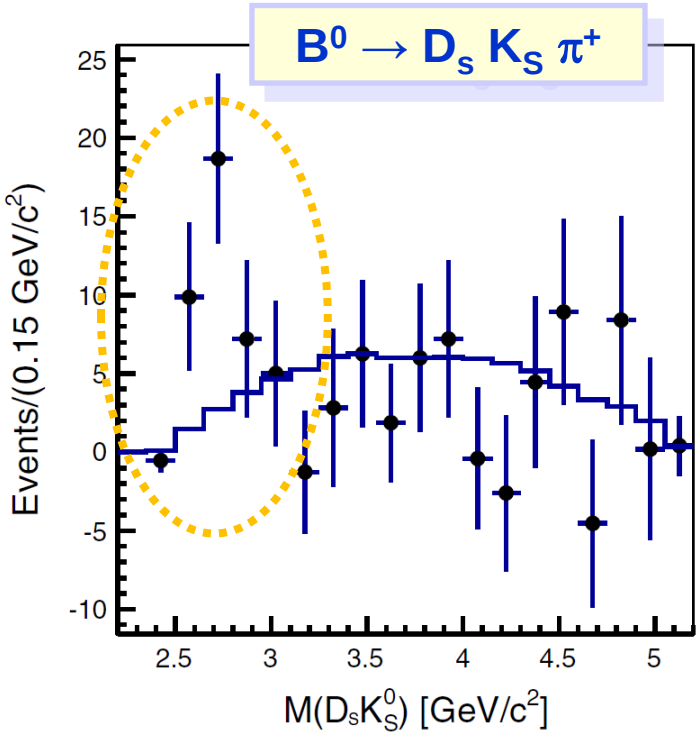
$B^0 \to D_s^- K_S^0 \pi^+$ and $B^+ \to D_s^- K^+ K^+$

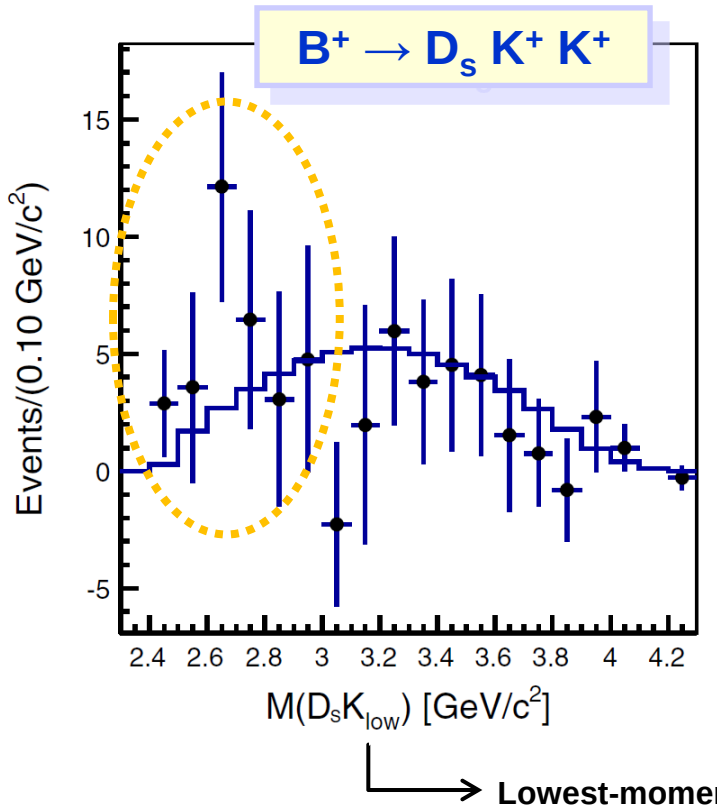
PRD 91, 032008 (2015)

- Study of 2-body D_s K invariant mass distributions
  ⇒ surplus of events in low mass region

Histogram: phase-space dist.

Points: background-subtracted data in signal region





- Similar patterns observed in other hadronic and semileptonic modes
- Could be explained by production of resonances below the $D_s^{(*)}$ K threshold

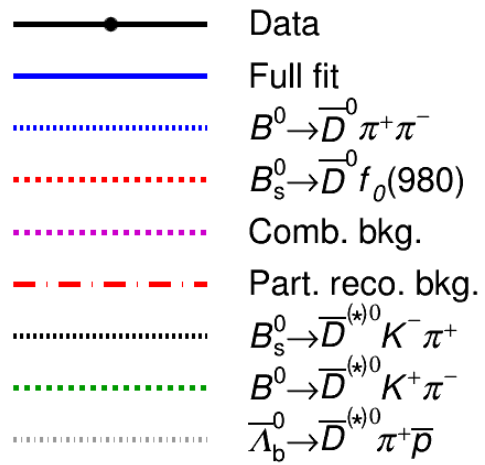
$B_s \to \overline{D}^0 f_0(980)$ - search

arXiv:1505.01654 [hep-ex]

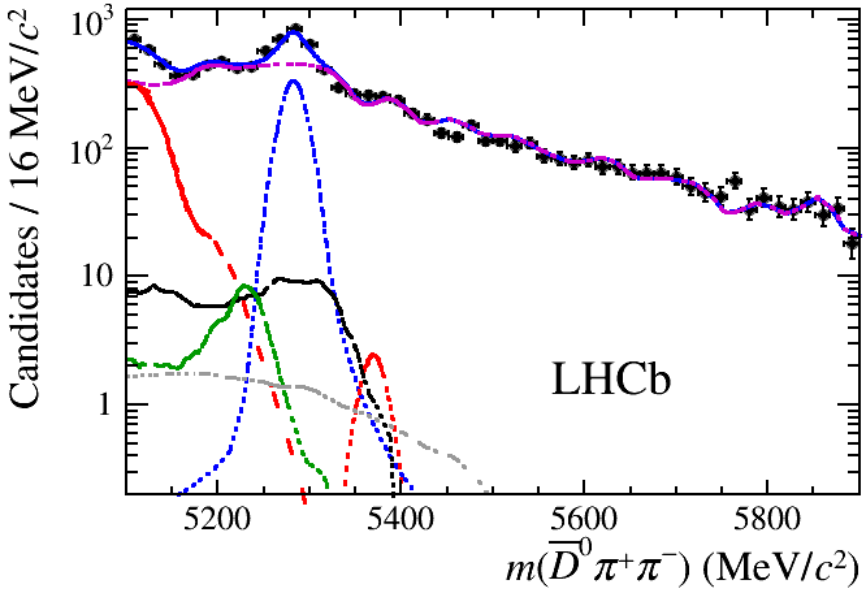
- Full run-I data sample (3 fb^{-1})
- $f_0(980)$ reconstructed in $\pi^+ \pi^-$ mass range [900, 1080] MeV/c^2
- Data in bins of selection neural network output
- 1st 90% (95%) C.L. upper limits set on decay mode :

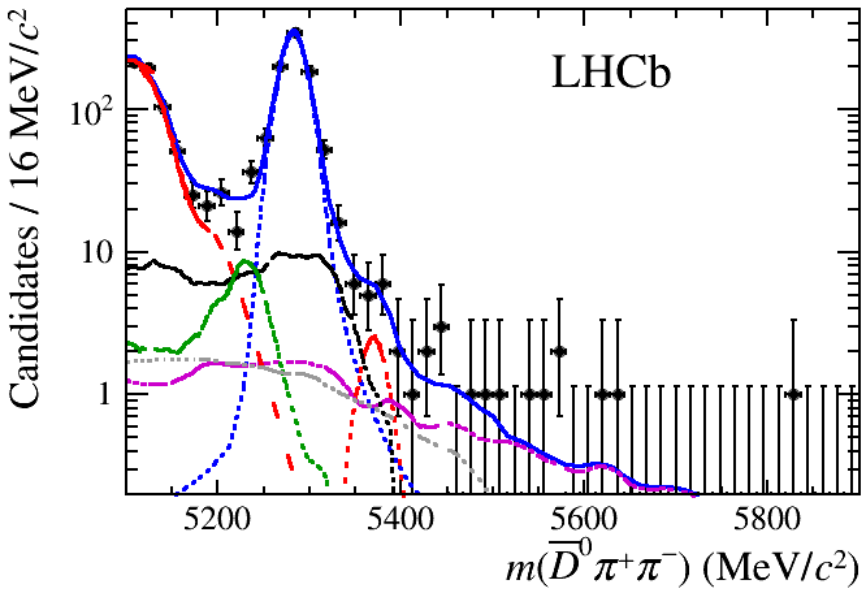
$$\mathcal{B}(B_s^0 \to \overline{D}^0 f_0(980)) < 3.1\,(3.4) \times 10^{-6}$$

⇒ Total yield of 29 ± 17 signal events



Increasing purity

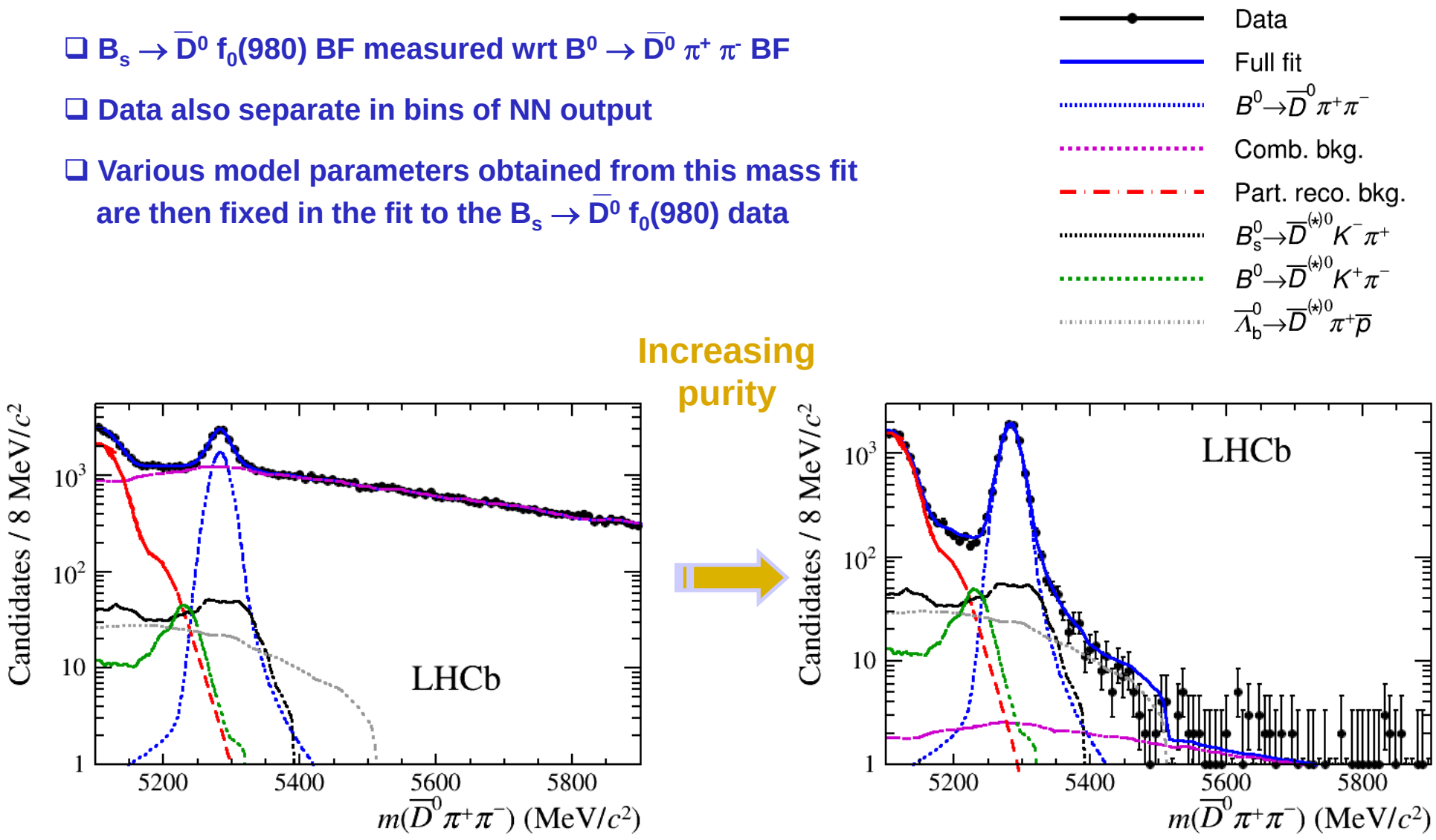




$B_s \to \overline{D}^0 f_0(980)$ – normalisation mode

arXiv:1505.01654 [hep-ex]

- $B_s \to \overline{D}^0 f_0(980)$ BF measured wrt $B^0 \to \overline{D}^0 \pi^+ \pi^-$ BF
- Data also separate in bins of NN output
- Various model parameters obtained from this mass fit are then fixed in the fit to the $B_s \to \overline{D}^0 f_0(980)$ data



$B^- \to D^+ K^- \pi^-$ – 1st observation

PRD 91, 092002 (2015)

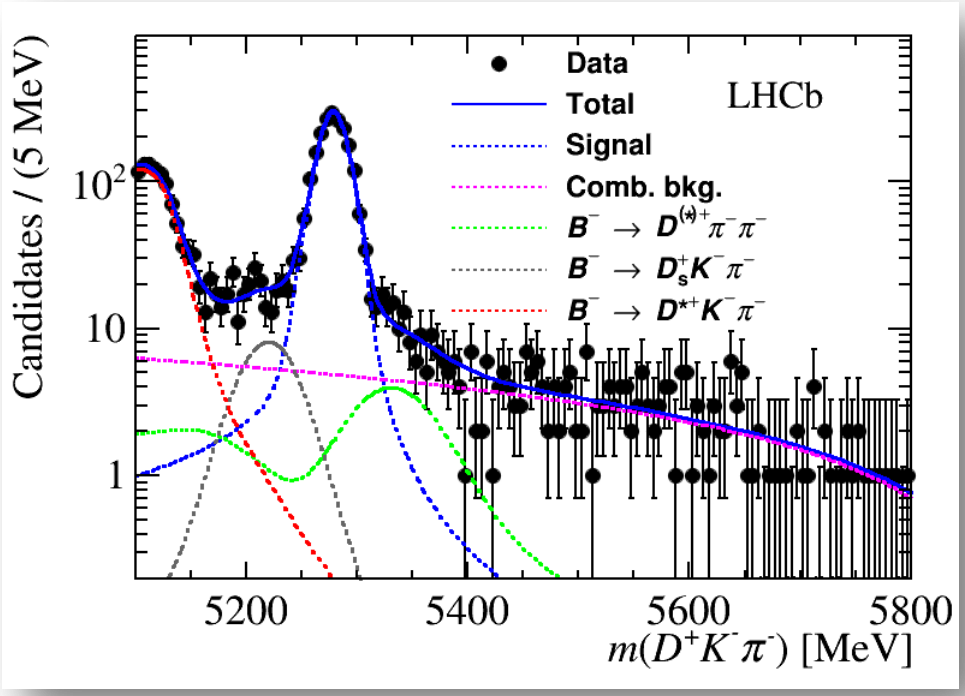
Motivation

- Study of properties of D^{**0} states
- Potentially a measurement of γ with $B^- \to D_2^*(2460)^0 K^-$

1st observation

$$\mathcal{B}(B^- \to D^+ K^- \pi^-) = (7.31 \pm 0.19 \pm 0.22 \pm 0.39) \times 10^{-5}$$

From uncertainty on $B^- \to D^+ \pi^- \pi^-$ BF



Analysis

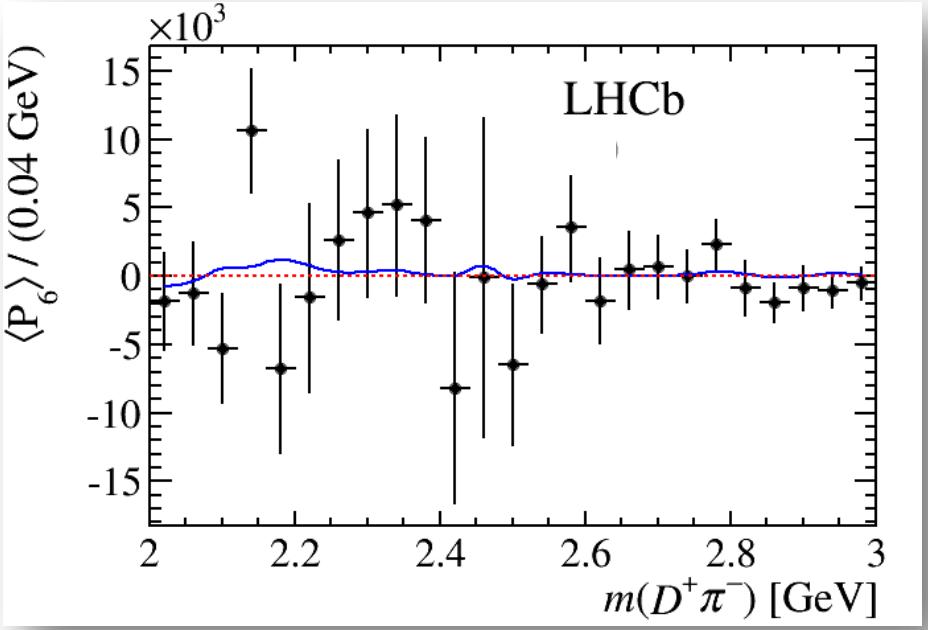
- Full data sample ($3fb^{-1}$)
- Close to 2000 signal candidates
  - With high purity ~ 93% in signal region
- D^+ reconstructed in $K^- \pi^+ \pi^+$ mode
- BF normalised to $B^- \to D^+ \pi^- \pi^-$

$B^- \to D^+ K^- \pi^-$ – Dalitz plot analysis

PRD 91, 092002 (2015)

Angular moments

- Resonances expected in m(D π) only
- Legendre-polynomial weighted angular moments for background-subtracted and efficiency-corrected D K π data
  $\Rightarrow$ no evidence for resonances > spin-2



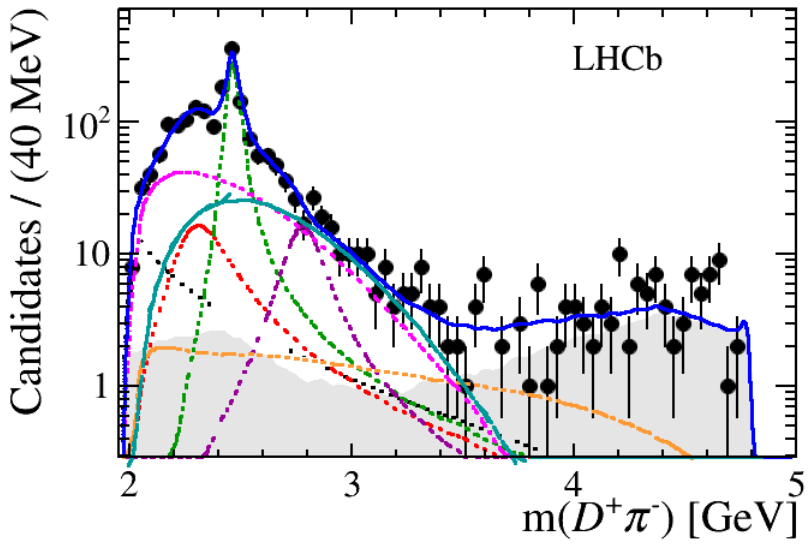
Model

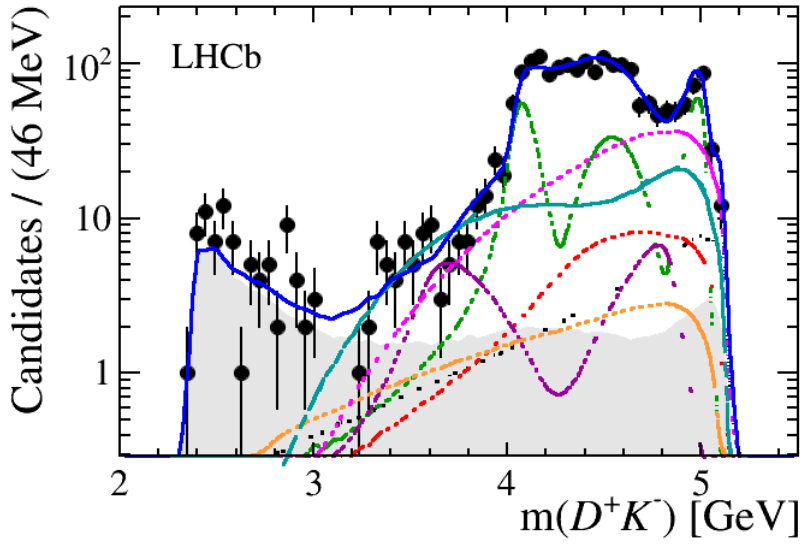
- Isobar approach
- Coherent sum of the $D_0^*(2400)^0$, $D_2^*(2460)^0$ and $D_J^*(2760)^0$ resonances and S- and P-wave non-resonant contributions from virtual $D_v^*(2007)^0$, and B_v^{*0} resonances

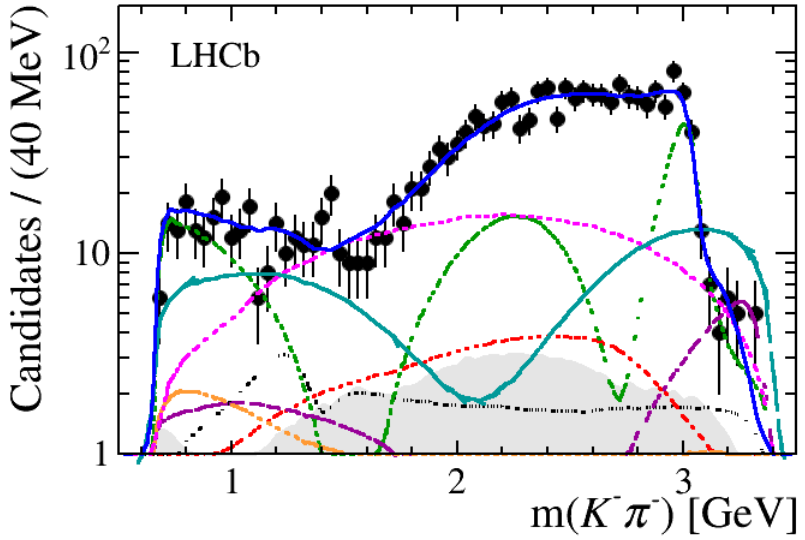
$B^- \to D^+ K^- \pi^-$ – Dalitz plot analysis

PRD 91, 092002 (2015)

- Fit projections onto the D π, D K and K π invariant mass distributions







Data
Total
Background
$D^*_{0v}(2007)^0$
$D^*_0(2400)^0$
$D^*_2(2460)^0$
$D^*_1(2760)^0$
B^{*0}_v
Nonresonant S-wave
Nonresonant P-wave

$B^- \to D^+ K^- \pi^-$ – Dalitz plot analysis results

PRD 91, 092002 (2015)

❑ **Masses and widths of D**⁰ resonances**

$$
\begin{aligned}
m(D_2^*(2460)^0) &= (2464.0 \pm 1.4 \pm 0.5 \pm 0.3)\ \text{MeV} \\
\Gamma(D_2^*(2460)^0) &= (43.8 \pm 2.9 \pm 1.7 \pm 0.6)\ \text{MeV} \\
m(D_1^*(2760)^0) &= (2781 \pm 18 \pm 11 \pm 6)\ \text{MeV} \\
\Gamma(D_1^*(2760)^0) &= (177 \pm 32 \pm 20 \pm 7)\ \text{MeV}
\end{aligned}
$$

→ From model uncertainties

❑ **$D_2^*(2460)^0$:**
Properties in agreement with world average values

❑ **$D_1^*(2760)^0$:**
- **Mass consistent with previous measurements**
- **Width in tension**
- **Spin determined to be 1 (other hypotheses rejected with high significance)**

1st determination of spin-1 nature of $D_J^*(2760)^0$!

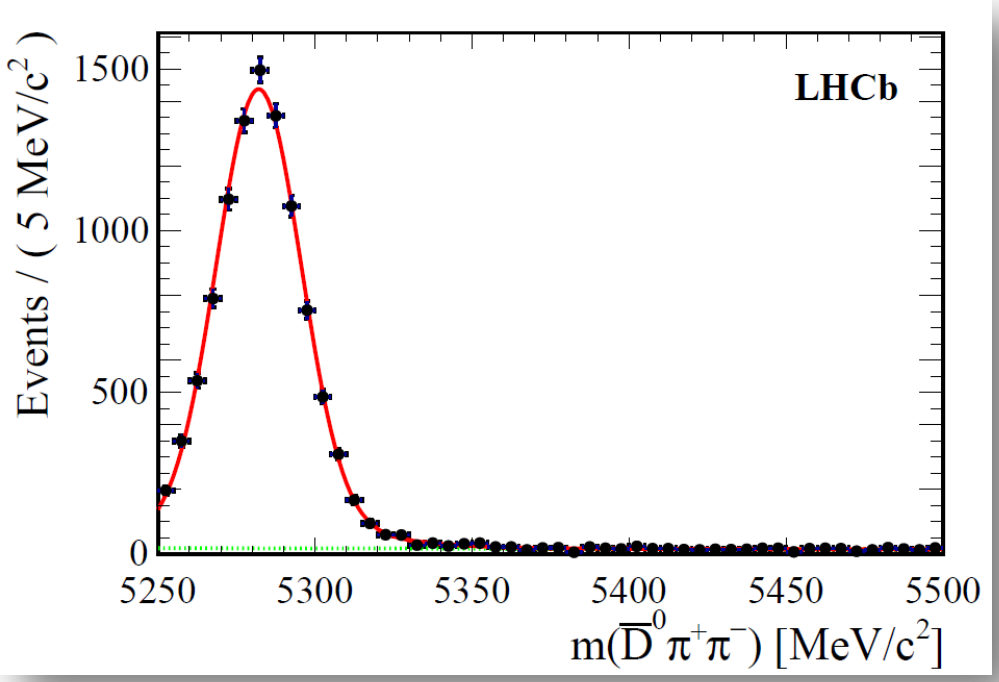
❑ **Full details of DP fits in the paper …**

$B^0 \to \bar{D}^0 \pi^+ \pi^-$ – BFs & Dalitz plot analysis

arXiv:1505.01710 [hep-ex]

Motivation

- Study of properties of D^{**+} states in $m(D^0 \pi^+)$ and light resonances in $m(\pi \pi)$
- Sensitivity to the β angle



Analysis

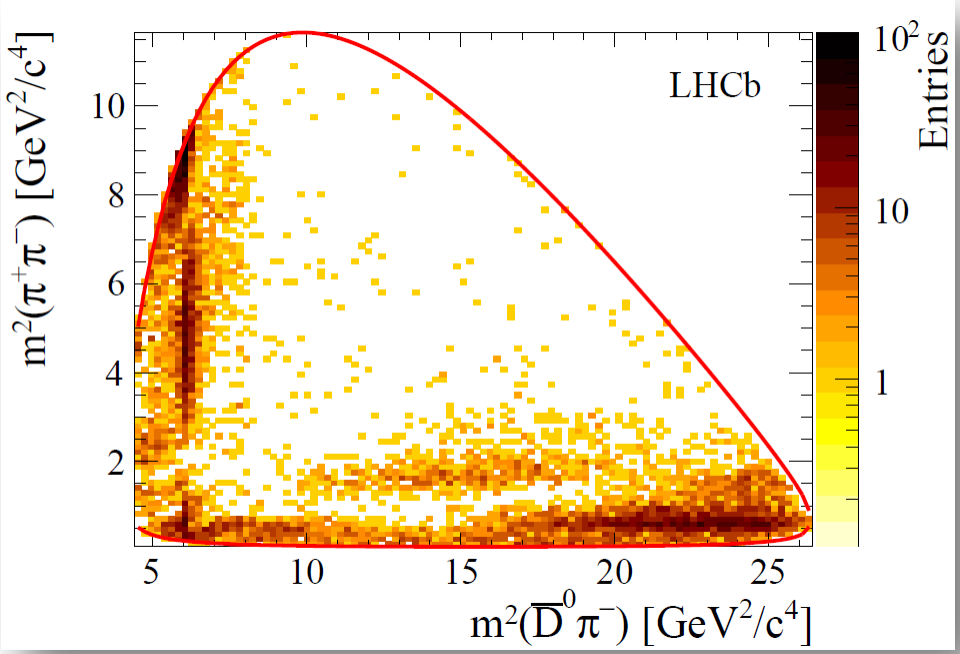
- Full data sample ($3fb^{-1}$)
- ~ 10000 signal candidates
  - With high purity ~ 98% in signal region
    ⇒ larger and more pure sample than B factories
- D^0 reconstructed in $K^- \pi^+$ mode
- BFs normalised to $B^0 \to D^*(2010)^- \pi^+$

$B^0 \to \bar{D}^0 \pi^+ \pi^-$ – Dalitz plot analysis

arXiv:1505.01710 [hep-ex]

2 models investigated for $\pi\pi$ S-wave

- **Isobar model**
  - Separate amplitudes for the 3 f_0 resonances + a non-resonant term
- **K-matrix formalism**
  - All 4 components above globally parameterised by a single amplitude

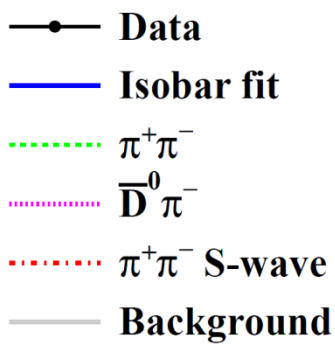


Resonance	Spin	Model	m_r (MeV/c^2)	Γ_0 (MeV)
$\bar{D}^0\pi^-$ P-wave	1	Eq. 14	Floated	
$D_0^*(2400)^-$	0	RBW	Floated	
$D_2^*(2460)^-$	2	RBW	Floated	
$D_J^*(2760)^-$	3	RBW	Floated	
$\rho(770)$	1	GS	775.02 ± 0.35	149.59 ± 0.67
$\omega(782)$	1	Eq. 13	781.91 ± 0.24	8.13 ± 0.45
$\rho(1450)$	1	GS	1493 ± 15	427 ± 31
$\rho(1700)$	1	GS	1861 ± 17	316 ± 26
$f_2(1270)$	2	RBW	1275.1 ± 1.2	$185.1 \,^{+\,2.9}_{-\,2.4}$
$\pi\pi$ S-wave	0	K-matrix		
$f_0(500)$	0	Eq. 15		
$f_0(980)$	0	Eq. 18		
$f_0(2020)$	0	RBW	1992 ± 16	442 ± 60
Nonresonant	0	Eq. 20		

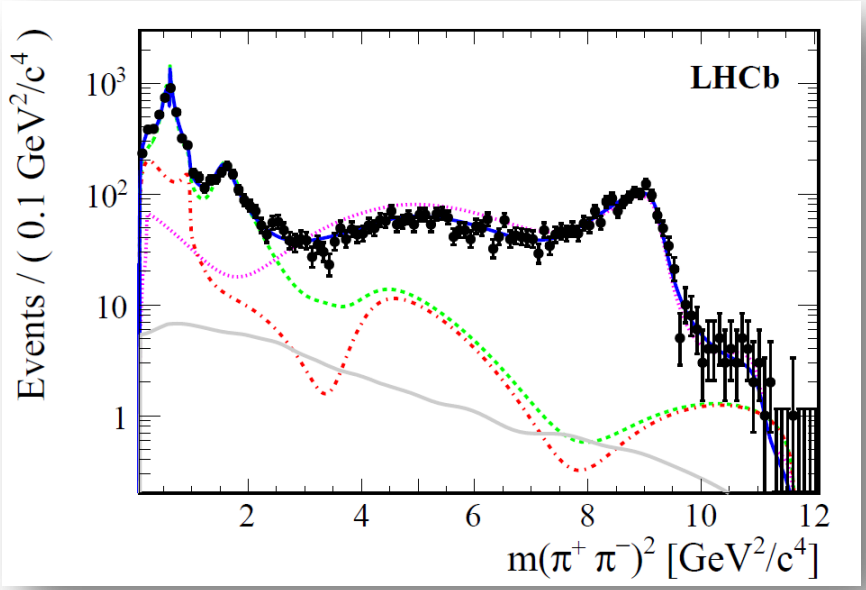
$B^0 \to \bar{D}^0 \pi^+ \pi^-$ – Dalitz plot analysis

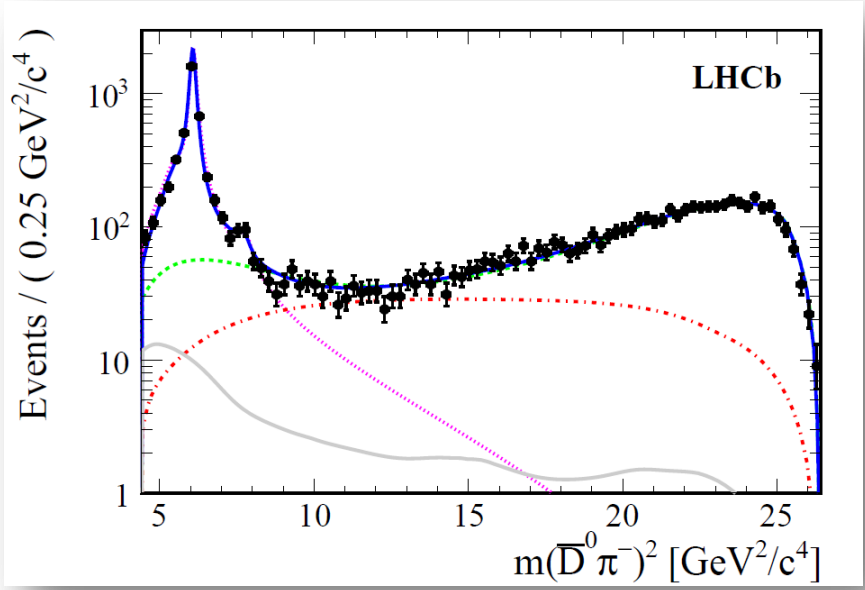
arXiv:1505.01710 [hep-ex]

- Rich structure in m($\pi\,\pi$), as expected
- Resonance @ 2760 MeV in m(D π)



- Example results from the fit with the Isobar model
  - Good agreement with fit with the K-matrix model





$B^0 \to \bar{D}^0 \pi^+ \pi^-$ – DP analysis results

arXiv:1505.01710 [hep-ex]

- Masses and widths of D^{**+} resonances

		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	$105 \pm 18 \pm 6 \pm 23$	$154 \pm 27 \pm 13 \pm 9$

Experimental syst. uncer.

Model-dependent syst. uncer.

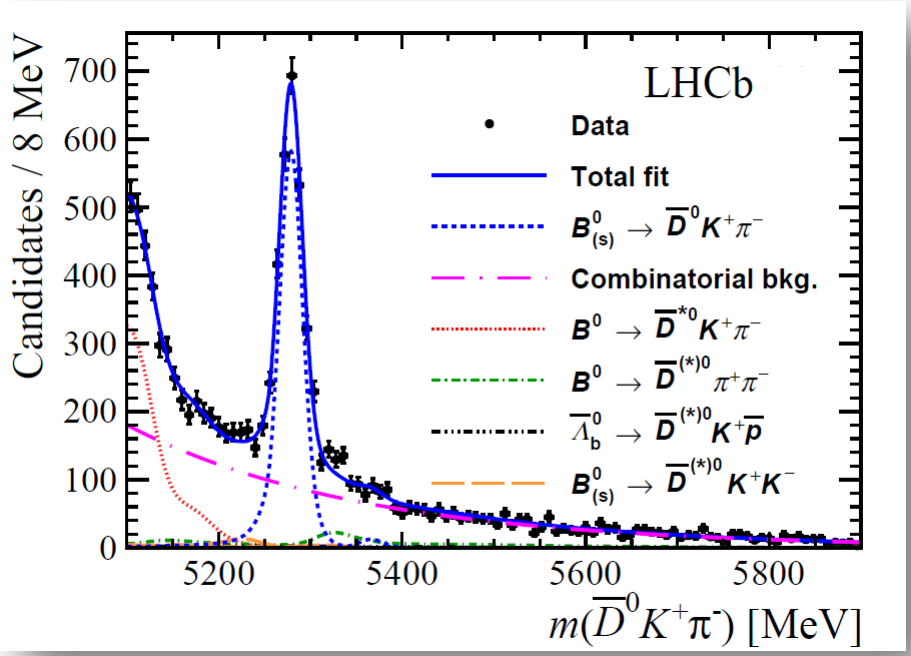
- $D_J^*(2760)^+$:
  - Spin determined to be 3 (other hypotheses rejected with high significance)
- No evidence for an additional spin-1 state
- Full details of DP fits and BF measurements in the paper …

$B^0 \to \bar{D}^0 K^+ \pi^-$ – Dalitz plot analysis

arXiv:1505.01505 [hep-ex]

Motivation

- Study of properties of D^{**+} states in $m(D^0 \pi^+)$ and light resonances in $m(K \pi)$
- Decay has access to same D^{**} resonances as $B^0 \to \bar{D}^0 \pi \pi$ analysis, but with lower stats
- Sensitivity to γ from analysis of $B^0 \to D K^+ \pi^-$ decays



Analysis

- Full data sample ($3fb^{-1}$)
- ~ 2500 signal candidates
  - With high purity ~ 75% in signal region
- D^0 reconstructed in $K^- \pi^+$ mode

$$
\begin{aligned}
m(D_0^*(2400)^-) &= (2360 \pm 15 \pm 12 \pm 28)\,\text{MeV} \\
\Gamma(D_0^*(2400)^-) &= (255 \pm 26 \pm 20 \pm 47)\,\text{MeV} \\
m(D_2^*(2460)^-) &= (2465.6 \pm 1.8 \pm 0.5 \pm 1.2)\,\text{MeV} \\
\Gamma(D_2^*(2460)^-) &= (46.0 \pm 3.4 \pm 1.4 \pm 2.9)\,\text{MeV}\,,
\end{aligned}
$$

- No evidence for the $D_J(2760)^+$

$B^0 \to D^- D^0 K^+$ and $B^+ \to \bar{D}^0 D^0 K^+$

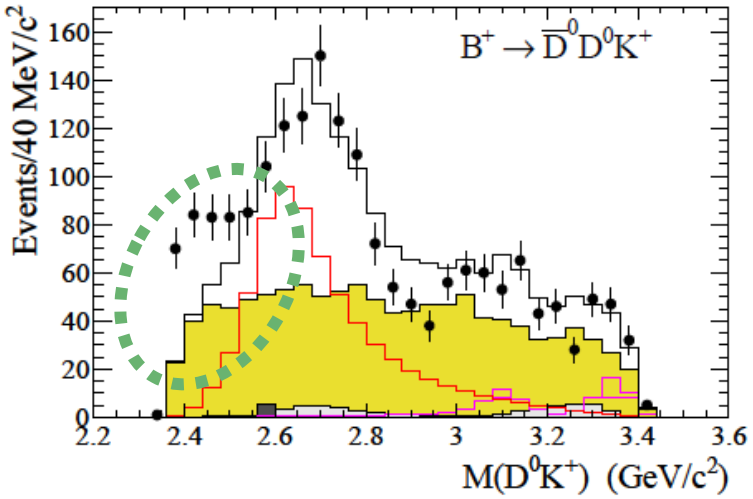
PRD 91, 052002 (2015)

Motivation

- Study in detail the $D_{s1}(2700)$ with a full Dalitz plot analysis

Analysis

- Full data sample (429 fb^{-1})
- ~ 1500 or 1900 signal candidates in B^0 and B^+ modes
  - But purity only ~ 42%
- Look at 2-body mass distributions $D^0 \bar{D}^0$, $D^0 K^+$, $\bar{D}^0 K^+$



Dalitz plot model

- Isobar model containing $D_{s1}^*(2700)^+$, $D_{s2}^*(2573)^+$, $\psi(3770)$, $\psi(4160)$ and a dominant component (fit fraction ~ 45%) that remains unidentified !
- $D_{s1}(2700)$ observed in both decay modes, spin determined to be 1
- Enhancement between 2350 and 2500 MeV remains to be interpreted …

⇒ LHCb can/will certainly contribute to such studies ...
… expect a sample of size similar to that of BaBar *but* with a rather high purity … stay tuned …

Hadronic b-hadron decays

See Youngmoon Goh's talk on charmless hadronic B decays

See Marcello Rotondo's talk on baryonic B decays

See Nicola Neri's talk on production and decay of heavy flavour baryons

$B_s \to \eta' \eta'$ – 1st observation

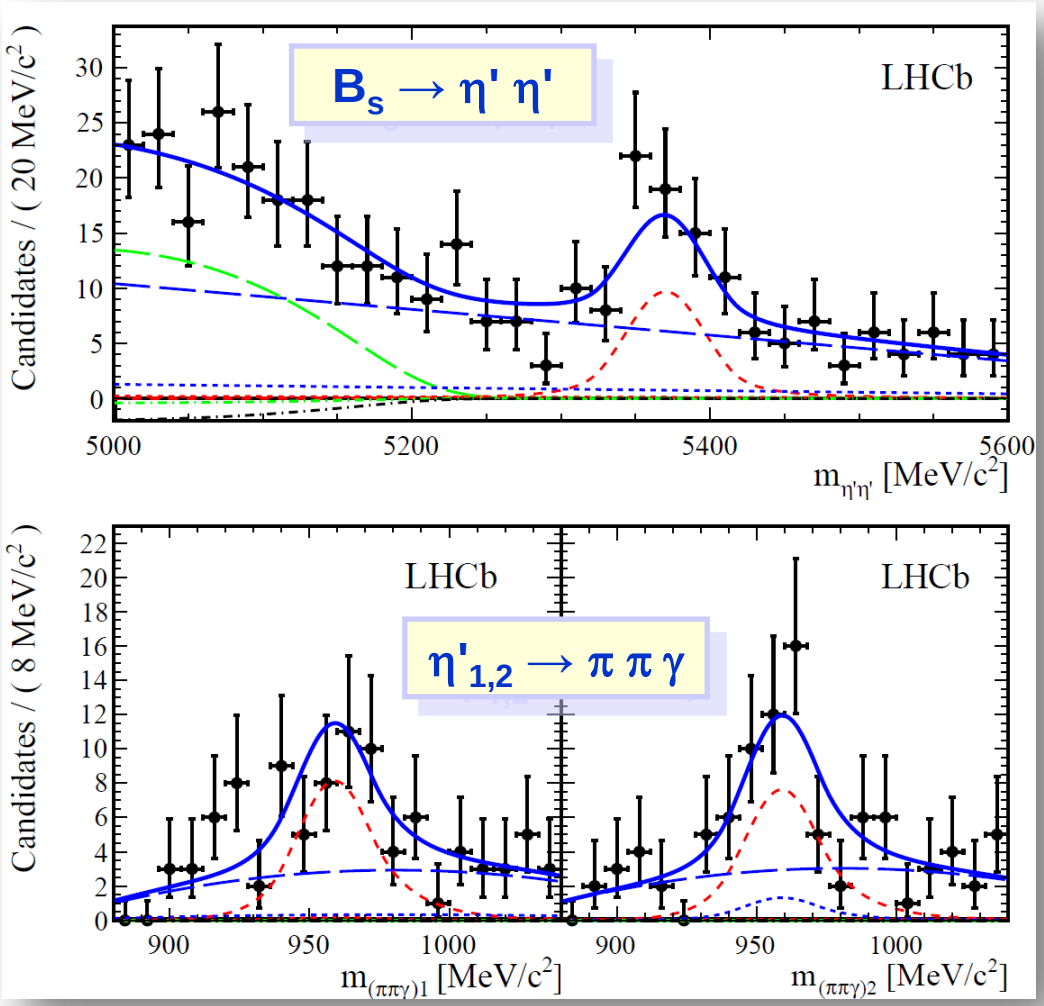
arXiv:1503.07483 [hep-ex]

Motivation

- Few B decays with $\eta^{(\prime)}$ in final state experimentally known
  - Though the BFs are large
  - Only LHCb can look at the B_s modes
- Time-dependent CP analysis possible without angular analysis

Analysis

- Full run-I data sample (3 fb^{-1})
- Observed yield N = 36.4 ± 7.8 ± 1.6
  - Significance: 6.4σ
- Measurement of $B_s \to \eta' \eta'$ BF
  - And CP asymmetries of control channels $B^+ \to \eta' K^+$ and $B^+ \to \phi K^+$



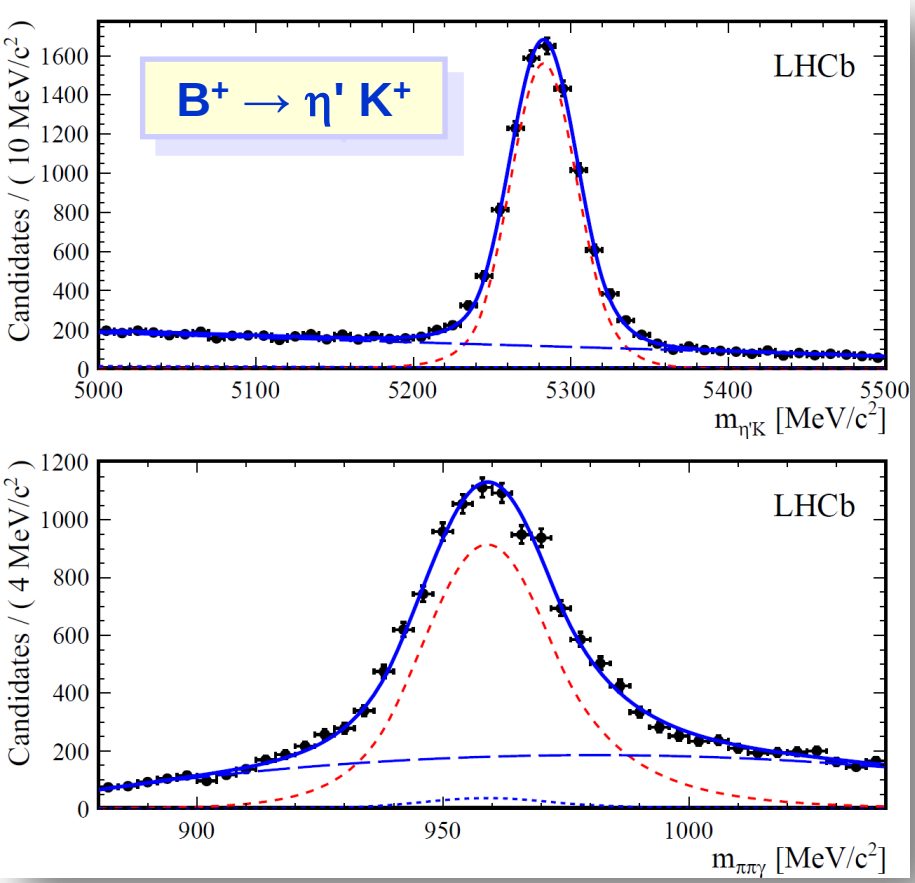
$$\mathcal{B}(B_s^0 \to \eta'\eta') = [3.31 \pm 0.64\,(\text{stat}) \pm 0.28\,(\text{syst}) \pm 0.12\,(\text{norm})] \times 10^{-5}$$

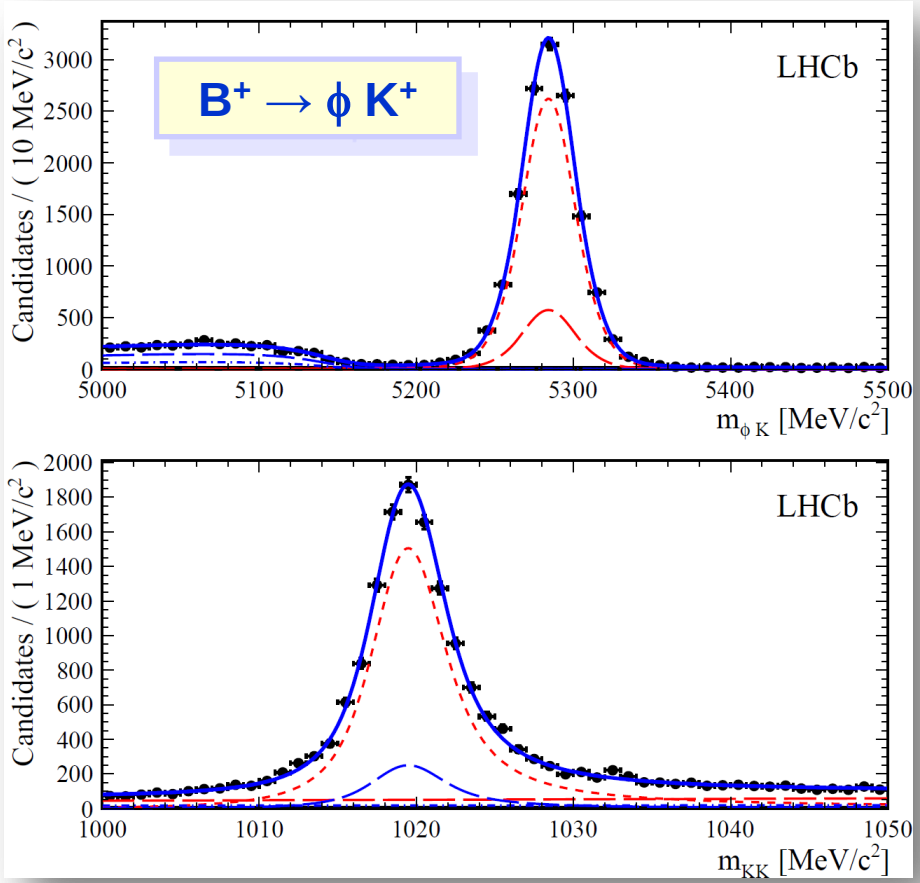
$B_s \to \eta' \eta'$ – A_{CP} of normalisation modes

arXiv:1503.07483 [hep-ex]

- Asymmetries compatible with Standard Model predictions

$$\mathcal{A}^{CP}(B^{\pm} \to \eta' K^{\pm}) = [-0.2 \pm 1.2\,(\text{stat}) \pm 0.1\,(\text{syst}) \pm 0.6\,(\text{norm})] \times 10^{-2}$$
$$\mathcal{A}^{CP}(B^{\pm} \to \phi K^{\pm}) = [+1.7 \pm 1.1\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.6\,(\text{norm})] \times 10^{-2}$$





Conclusions

- Open charm spectroscopy studies rather popular and diverse
  - B decays offer a great environment for such studies

- Plenty of first observations and determination of resonance properties ! Notably
  - 1st observation of $B^- \to D^+ K^- \pi^-$
  - $D_J^*(2760)^0$ spin determined to be 1
  - $D_J^*(2760)^+$ spin determined to be 3
  - $D_{sJ}^*(2700)^+$ spin determined to be 1
- A plethora of branching fraction measurements for contributing resonant decays

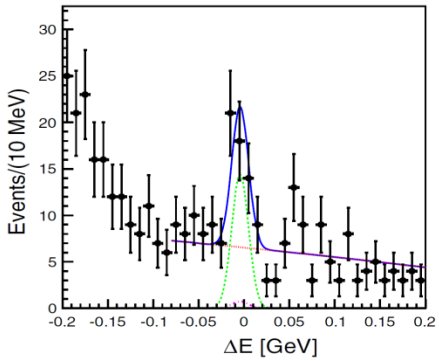
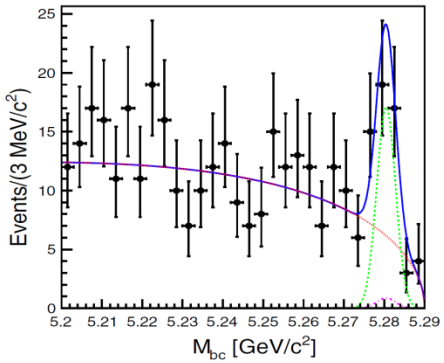
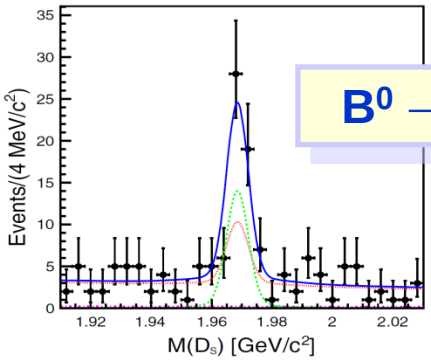
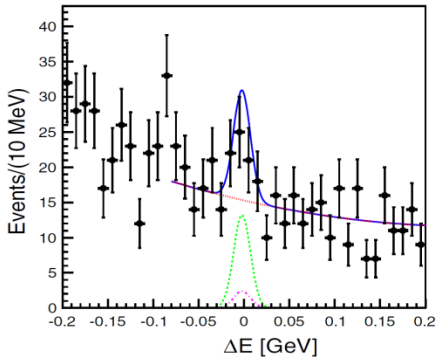
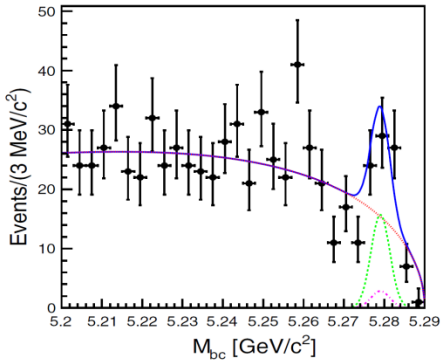
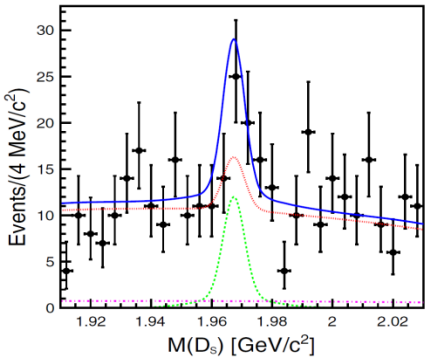
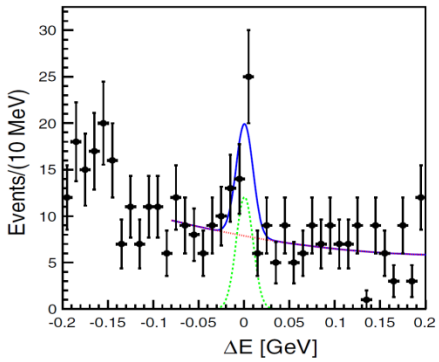
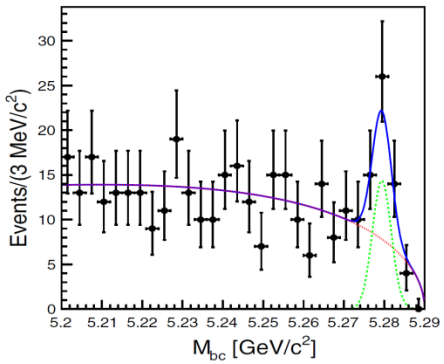
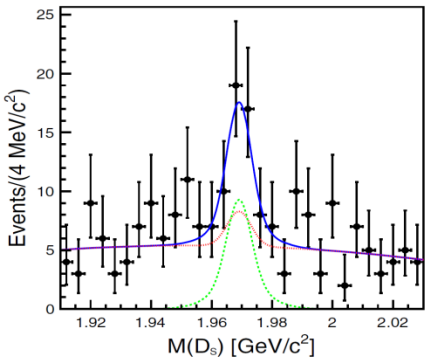
- Future prospects for D** spectroscopy are very promising !

Thank you

$B^0 \to D_s^- K_S^0 \pi^+$ and $B^+ \to D_s^- K^+ K^+$

PRD 91, 032008 (2015)

$B^0 \to D_s K_S \pi^+$

	ΔE	M_{bc}	D_s mass
$D_s \to \phi \pi$			
$D_s \to K^{*0} K$			
$D_s \to K_S K$			

$\Lambda_b \to \Lambda\, \eta^{(\prime)}$

Long (Downstream) Λ :
Decay products leave hits
inside (outside) vertex detector

arXiv:1505.03295 [hep-ex]

Motivation

- No known b-baryon decays to final states with a $\eta^{(\prime)}$
  - BFs predicted relatively large, of order 10^{-6}
  - Only LHCb can look at the b-baryon modes
- Study of η-η' mixing

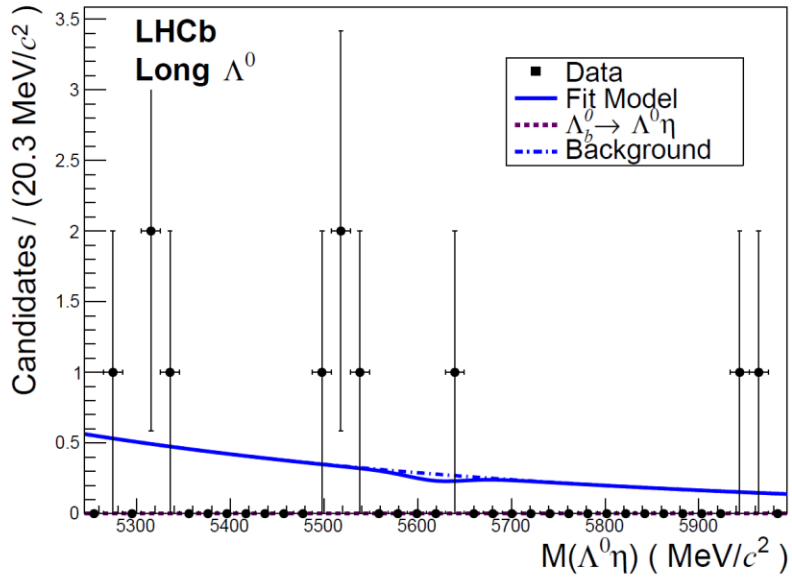
Analysis

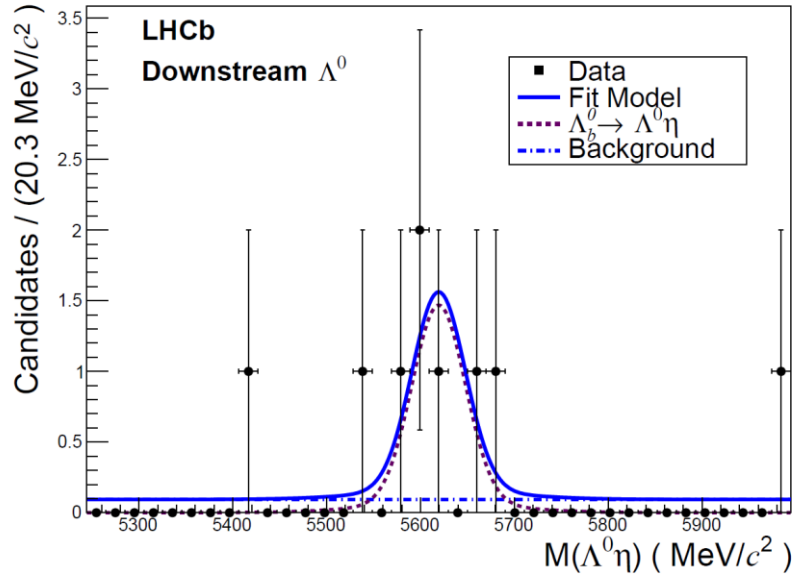
- Full run-I data sample (3 fb^{-1})
- Evidence for the $\Lambda_b \to \Lambda\, \eta$ decay
  - Yield of 5.3 ± 3.8 events & significance of 3.0σ

$$\mathcal{B}(\Lambda_b^0 \to \Lambda\eta) = (9.3^{+7.3}_{-5.3}) \times 10^{-6}$$

- 90% C.L. upper limit on $\Lambda_b \to \Lambda\, \eta'$

$$\mathcal{B}(\Lambda_b^0 \to \Lambda\eta') < 3.1 \times 10^{-6}$$

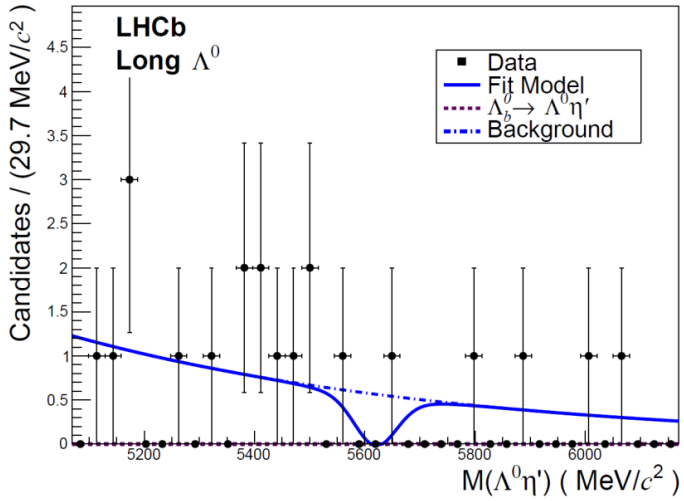


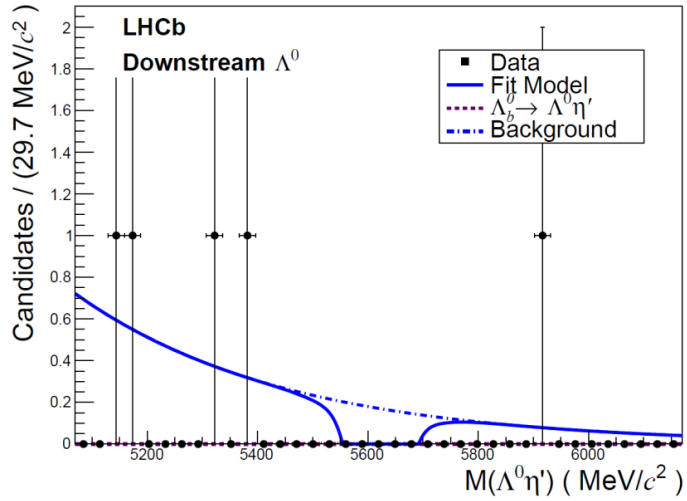


$\Lambda_b \to \Lambda\, \eta^{(\prime)}$ – details

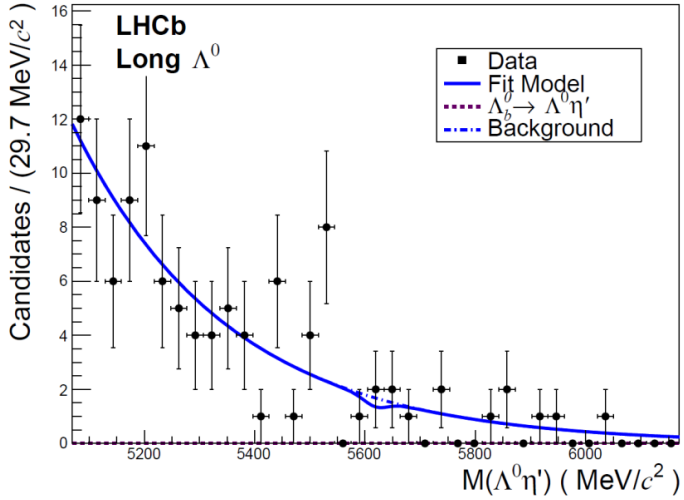
arXiv:1505.03295 [hep-ex]

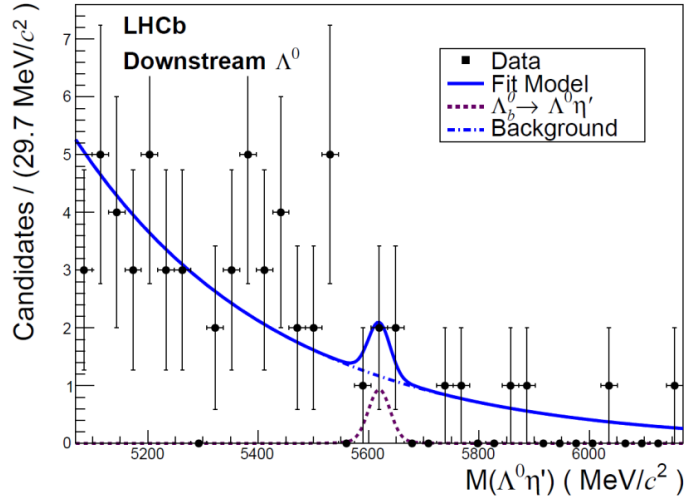
- η' daughter reconstructed in decay mode $\eta' \to \pi\,\pi\,\eta$, $\eta \to \gamma\,\gamma$





- η' daughter reconstructed in decay mode $\eta' \to \pi\,\pi\,\gamma$





- η daughter reconstructed in decay mode $\eta \to \pi\,\pi\,\pi^0$