Heavy Quark Spectroscopy at LHCb

Daniel Craik

University of Edinburgh

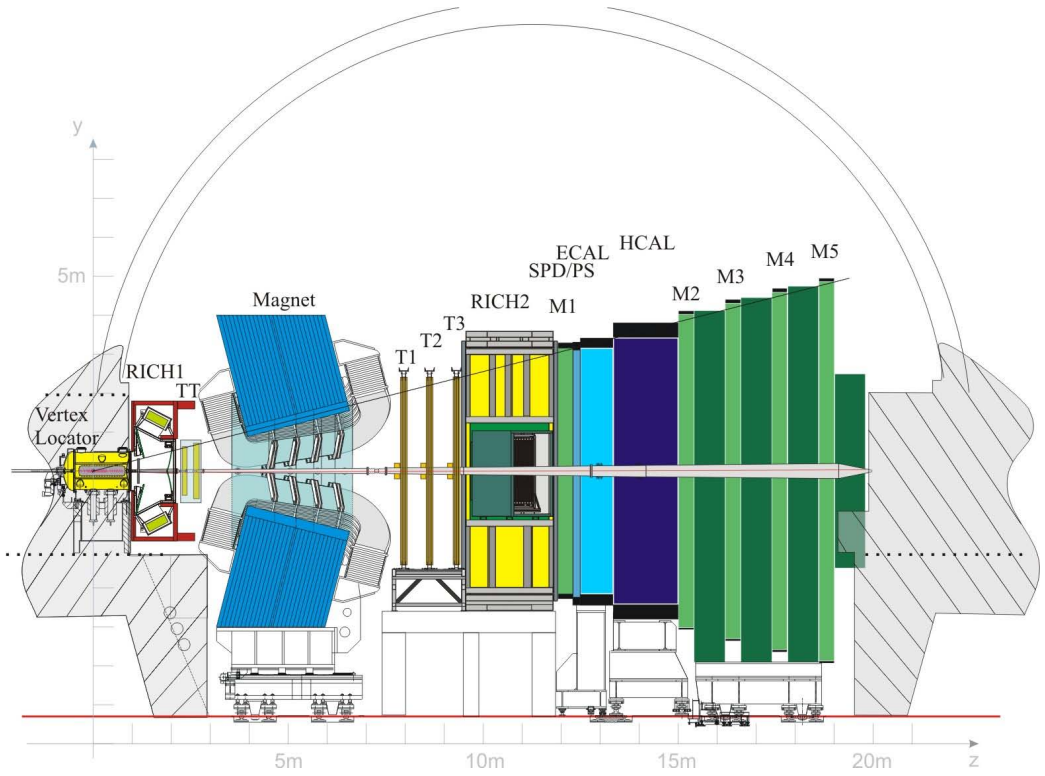
23rd August, 2016

on behalf of the LHCb Collaboration

Outline

- Wide range of heavy quark spectroscopy analyses performed at LHCb
- Talk will focus on most recent results
  - Search for Ξ_b^{**0} resonances
  - $p\bar{p}$ spectroscopy using $B^+ \to p\bar{p}K^+$ decays NEW!
  - D_s^+ spectroscopy in inclusive D^*K
  - D^0 spectroscopy from $B^- \to D^+\pi^-\pi^-$ decays NEW!
- All results based on analyses of full Run I dataset ($3\,\mathrm{fb}^{-1}$)
- Exotics covered in a separate talk (Giovanni — up next)

The LHCb Detector



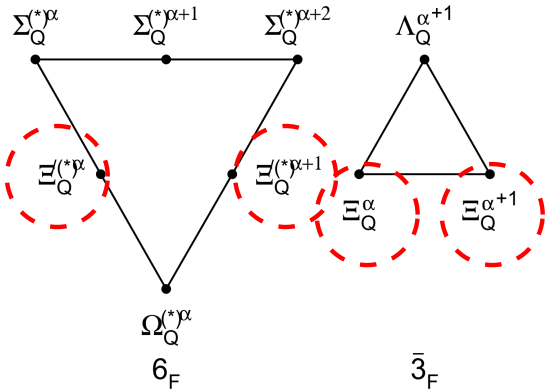
- Instrumentation in the forward region ($2 < \eta < 5$)
- Excellent vertex reconstruction
- Precise tracking before and after magnet
- Good PID separation up to $\sim 100\,\mathrm{GeV}/c$

Int. J. Mod. Phys. A 30 (2015) 1530022

Ξ_b^{**0} resonances

JHEP 05 (2016) 161

PRD 77 (2008) 014031



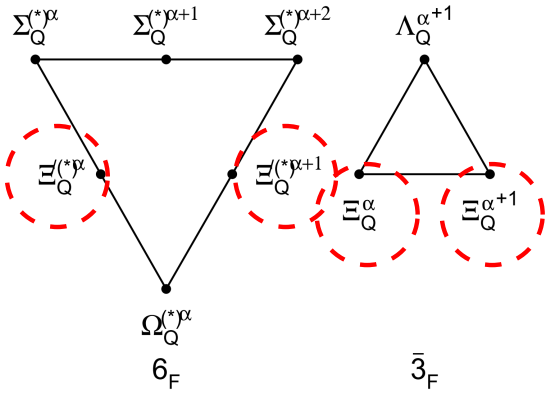
SU(3) flavour multiplets of singly-heavy baryons. Q denotes the heavy flavour, $\alpha + n$ denotes the baryon's charge.

- Ξ_Q baryons contain a heavy quark (b,c), a strange quark (s) and another light quark (u,d)

Ξ_b^{**0} resonances

JHEP 05 (2016) 161

PRD 77 (2008) 014031



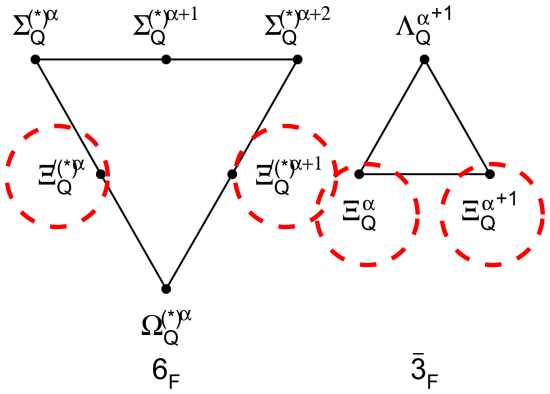
SU(3) flavour multiplets of singly-heavy baryons. Q denotes the heavy flavour, $\alpha + n$ denotes the baryon's charge.

- Ξ_Q baryons contain a heavy quark (b,c), a strange quark (s) and another light quark (u,d)
- Ξ_b^0 ground state has $J^P = \frac{1}{2}^+$, $b(su)$: $\uparrow$ ($\uparrow\downarrow$)

Ξ_b^{**0} resonances

JHEP 05 (2016) 161

PRD 77 (2008) 014031



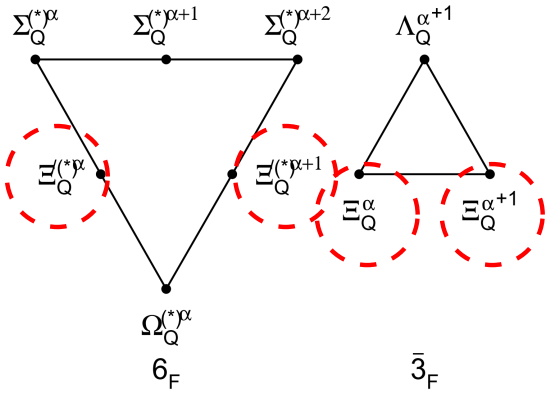
SU(3) flavour multiplets of singly-heavy baryons. Q denotes the heavy flavour, $\alpha + n$ denotes the baryon's charge.

- Ξ_Q baryons contain a heavy quark (b,c), a strange quark (s) and another light quark (u,d)
- Ξ_b^0 ground state has $J^P = \frac{1}{2}^+$, $b(su)$: $\uparrow$ ($\uparrow\downarrow$)
- $\Xi_b^{\prime 0}$ has $J^P = \frac{1}{2}^+$, $b(su)$: $\downarrow$ ($\uparrow\uparrow$)

Ξ_b^{**0} resonances

JHEP 05 (2016) 161

PRD 77 (2008) 014031



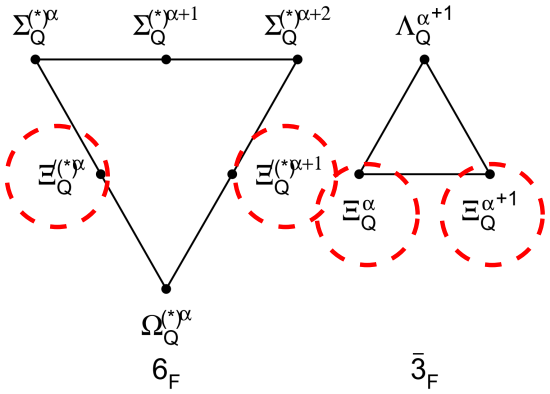
SU(3) flavour multiplets of singly-heavy baryons. Q denotes the heavy flavour, $\alpha + n$ denotes the baryon's charge.

- Ξ_Q baryons contain a heavy quark (b,c), a strange quark (s) and another light quark (u,d)
- Ξ_b^0 ground state has $J^P = \frac{1}{2}^+$, $b(su)$: $\uparrow$ ($\uparrow\downarrow$)
- $\Xi_b^{\prime 0}$ has $J^P = \frac{1}{2}^+$, $b(su)$: $\downarrow$ ($\uparrow\uparrow$)
- Ξ_b^{*0} has $J^P = \frac{3}{2}^+$, $b(su)$: $\uparrow$ ($\uparrow\uparrow$)

Ξ_b^{**0} resonances

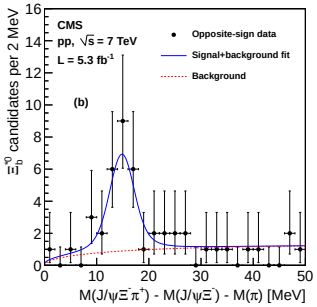
JHEP 05 (2016) 161

PRD 77 (2008) 014031



SU(3) flavour multiplets of singly-heavy baryons. Q denotes the heavy flavour, $\alpha + n$ denotes the baryon's charge.

PRL 109 (2012) 172003

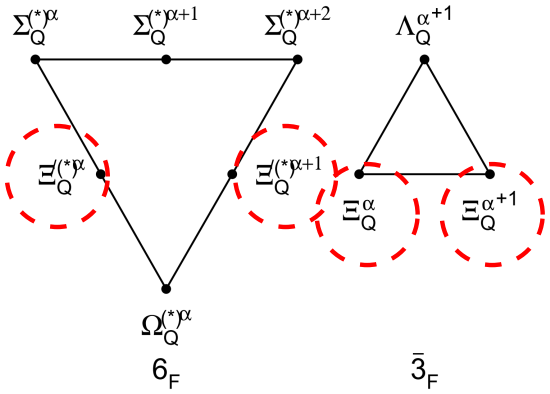


- Ξ_Q baryons contain a heavy quark (b,c), a strange quark (s) and another light quark (u,d)
- Ξ_b^0 ground state has $J^P = \frac{1}{2}^+$, $b(su)$: $\uparrow$ ($\uparrow\downarrow$)
- $\Xi_b^{\prime 0}$ has $J^P = \frac{1}{2}^+$, $b(su)$: $\downarrow$ ($\uparrow\uparrow$)
- Ξ_b^{*0} has $J^P = \frac{3}{2}^+$, $b(su)$: $\uparrow$ ($\uparrow\uparrow$)
- $\Xi_b^{*0} \to \Xi_b^- \pi^+$ seen by CMS (left)
- $\Xi_b^{\prime 0} \to \Xi_b^- \pi^+$ not seen
  - assumed below threshold

Ξ_b^{**0} resonances

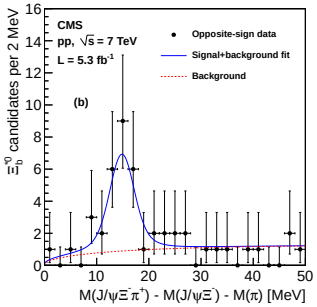
JHEP 05 (2016) 161

PRD 77 (2008) 014031

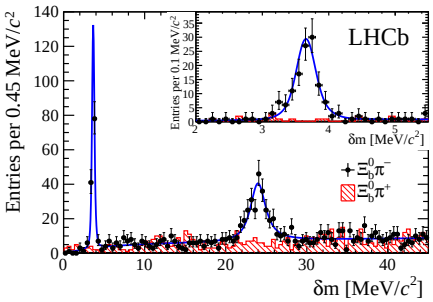


SU(3) flavour multiplets of singly-heavy baryons. Q denotes the heavy flavour, $\alpha + n$ denotes the baryon's charge.

PRL 109 (2012) 172003



PRL 114 (2015) 062004

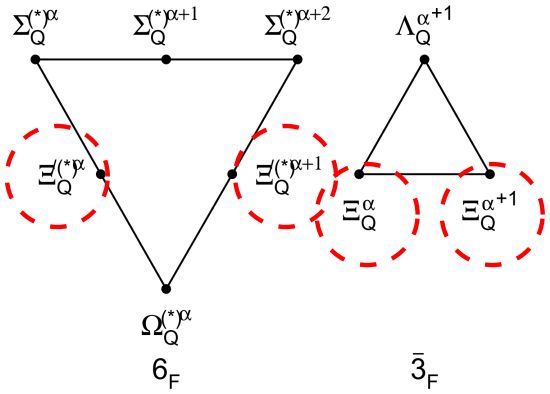


- Ξ_Q baryons contain a heavy quark (b,c), a strange quark (s) and another light quark (u,d)
- Ξ_b^0 ground state has $J^P = \frac{1}{2}^+$, $b(su)$: $\uparrow$ ($\uparrow\downarrow$)
- $\Xi_b^{\prime 0}$ has $J^P = \frac{1}{2}^+$, $b(su)$: $\downarrow$ ($\uparrow\uparrow$)
- Ξ_b^{*0} has $J^P = \frac{3}{2}^+$, $b(su)$: $\uparrow$ ($\uparrow\uparrow$)
- $\Xi_b^{*0} \to \Xi_b^- \pi^+$ seen by CMS (left)
- $\Xi_b^{\prime 0} \to \Xi_b^- \pi^+$ not seen
  - assumed below threshold
- Analogous states in Ξ_b^{**-} both seen to decay to $\Xi_b^0 \pi^-$ by LHCb (right)

Ξ_b^{**0} resonances

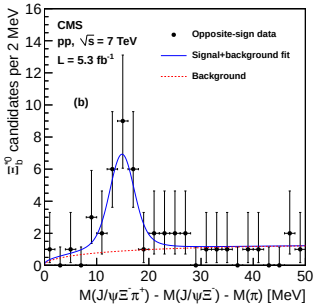
JHEP 05 (2016) 161

PRD 77 (2008) 014031

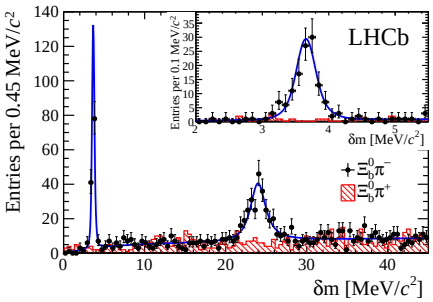


SU(3) flavour multiplets of singly-heavy baryons. Q denotes the heavy flavour, $\alpha + n$ denotes the baryon's charge.

PRL 109 (2012) 172003



PRL 114 (2015) 062004



- Ξ_Q baryons contain a heavy quark (b,c), a strange quark (s) and another light quark (u,d)
- Ξ_b^0 ground state has $J^P = \frac{1}{2}^+$, $b(su)$: $\uparrow$ ($\uparrow\downarrow$)
- $\Xi_b^{\prime 0}$ has $J^P = \frac{1}{2}^+$, $b(su)$: $\downarrow$ ($\uparrow\uparrow$)
- Ξ_b^{*0} has $J^P = \frac{3}{2}^+$, $b(su)$: $\uparrow$ ($\uparrow\uparrow$)
- $\Xi_b^{*0} \to \Xi_b^- \pi^+$ seen by CMS (left)
- $\Xi_b^{\prime 0} \to \Xi_b^- \pi^+$ not seen
  - assumed below threshold
- Analogous states in Ξ_b^{**-} both seen to decay to $\Xi_b^0 \pi^-$ by LHCb (right)
- Search for $\Xi_b^{**0} \to \Xi_b^- \pi^+$ performed at LHCb

Ξ_b^{**0} resonances

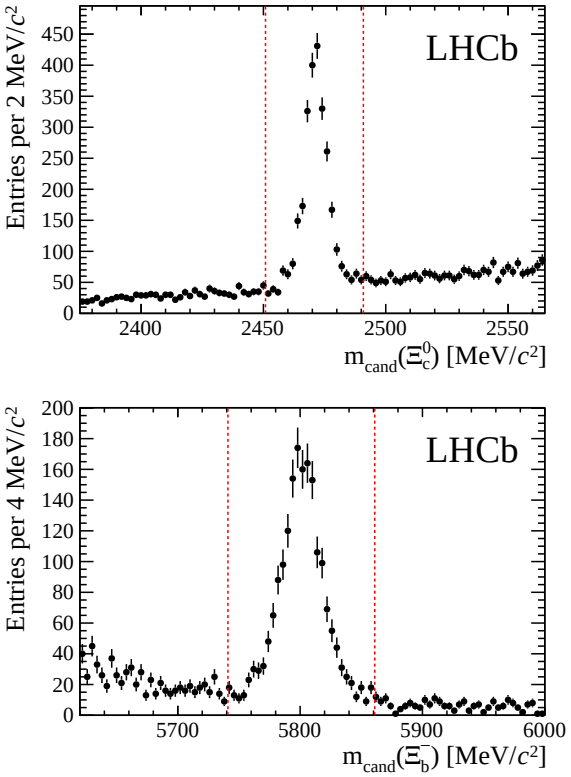
JHEP 05 (2016) 161

- Ξ_b^- candidates reconstructed from $\Xi_b^- \to \Xi_c^0 \pi^-$, $\Xi_c^0 \to pK^-K^-\pi^+$ decay chain

Ξ_b^{**0} resonances

JHEP 05 (2016) 161

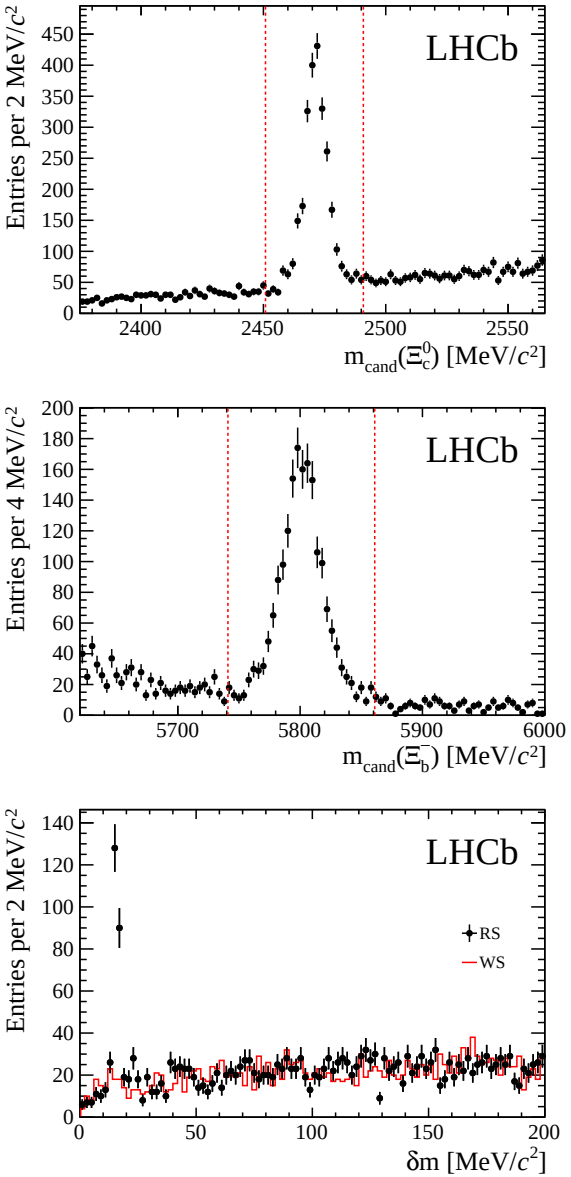
- Ξ_b^- candidates reconstructed from $\Xi_b^- \to \Xi_c^0 \pi^-$, $\Xi_c^0 \to pK^-K^-\pi^+$ decay chain
- Pure samples of Ξ_c^0 (top) and Ξ_b^- (middle) mesons obtained



Ξ_b^{**0} resonances

JHEP 05 (2016) 161

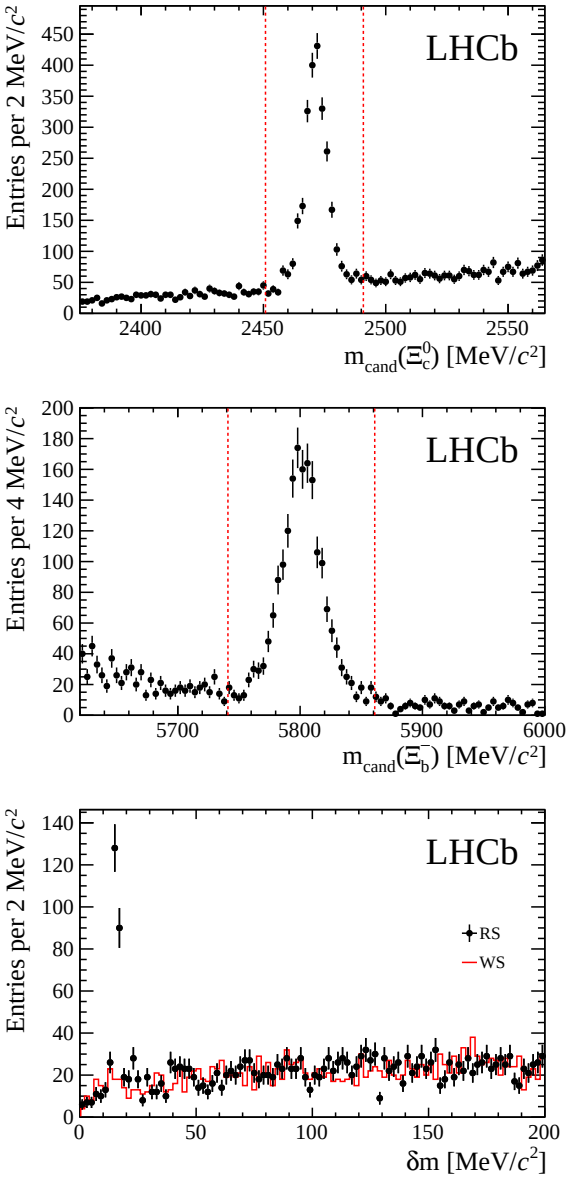
- Ξ_b^- candidates reconstructed from $\Xi_b^- \to \Xi_c^0 \pi^-$, $\Xi_c^0 \to pK^-K^-\pi^+$ decay chain
- Pure samples of Ξ_c^0 (top) and Ξ_b^- (middle) mesons obtained
- Ξ_b^- combined with π^+ to give Ξ_b^{*0} candidates (bottom)



Ξ_b^{**0} resonances

JHEP 05 (2016) 161

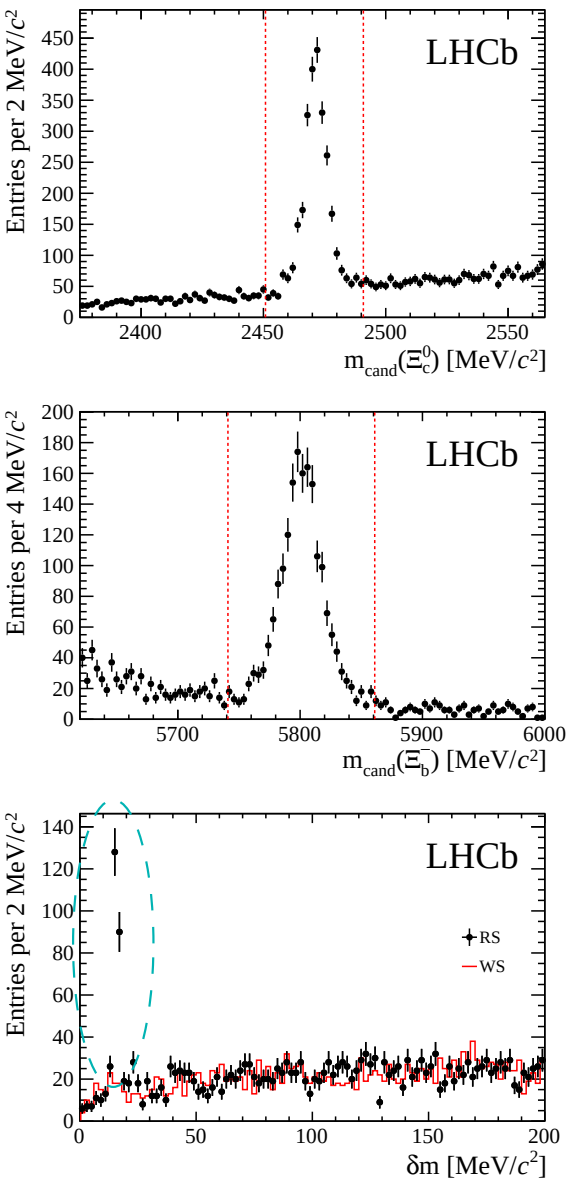
- Ξ_b^- candidates reconstructed from $\Xi_b^- \to \Xi_c^0 \pi^-$, $\Xi_c^0 \to pK^-K^-\pi^+$ decay chain
- Pure samples of Ξ_c^0 (top) and Ξ_b^- (middle) mesons obtained
- Ξ_b^- combined with π^+ to give Ξ_b^{*0} candidates (bottom)
- Estimate combinatorial background from **"wrong-sign" $\Xi_b^- \pi^-$** candidates



Ξ_b^{**0} resonances

JHEP 05 (2016) 161

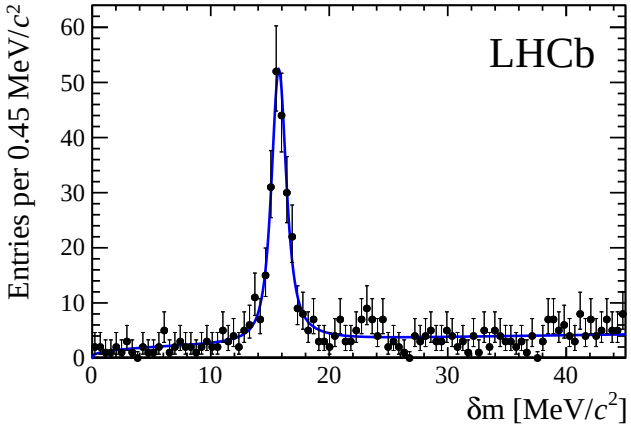
- Ξ_b^- candidates reconstructed from $\Xi_b^- \to \Xi_c^0 \pi^-$, $\Xi_c^0 \to pK^-K^-\pi^+$ decay chain
- Pure samples of Ξ_c^0 (top) and Ξ_b^- (middle) mesons obtained
- Ξ_b^- combined with π^+ to give Ξ_b^{*0} candidates (bottom)
- Estimate combinatorial background from **"wrong-sign" $\Xi_b^- \pi^-$** candidates
- Single **peak** seen in "right-sign" data



Ξ_b^{**0} resonances

JHEP 05 (2016) 161

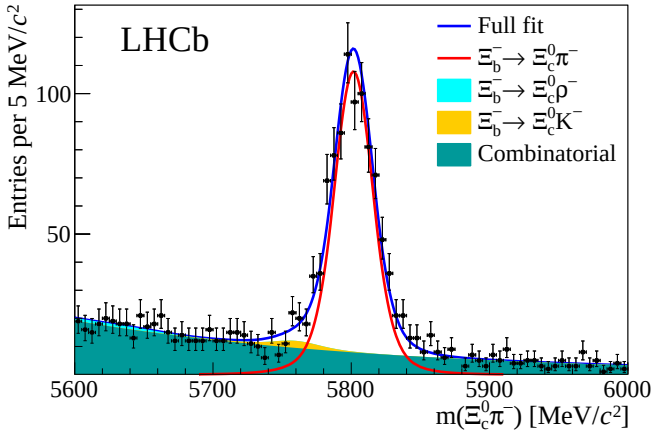
- Mass and width obtained from a fit to data
- Signal shape inconsistent with a natural width of zero
  - not well described by resolution effects alone
- Confirms observation by CMS
- Improved measurement of mass and first measurement of width

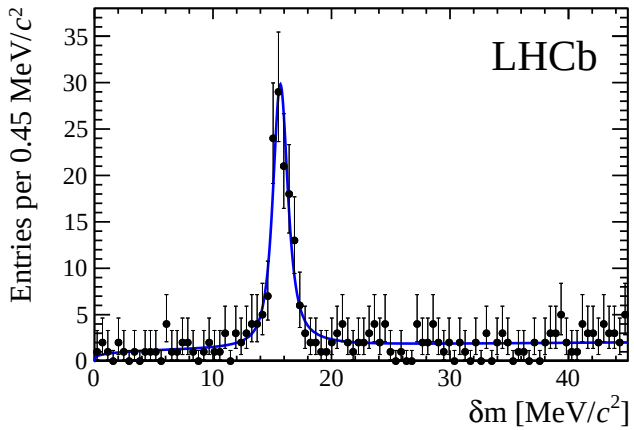


$$m(\Xi_b^{*0}) - m(\Xi_b^-) - m(\pi^+) = 15.727 \pm 0.068(\text{stat.}) \pm 0.023(\text{syst.})\,\text{MeV}/c^2\,,$$
$$\Gamma(\Xi_b^{*0}) = 0.90 \pm 0.16(\text{stat.}) \pm 0.08(\text{syst.})\,\text{MeV}\,.$$

Ξ_b^{**0} resonances

JHEP 05 (2016) 161





- Measure production rate relative to Ξ_b^-
- Common selection for inclusive and exclusive modes to reduce systematic uncertainties
- Ratio extracted from fits to both modes (left)

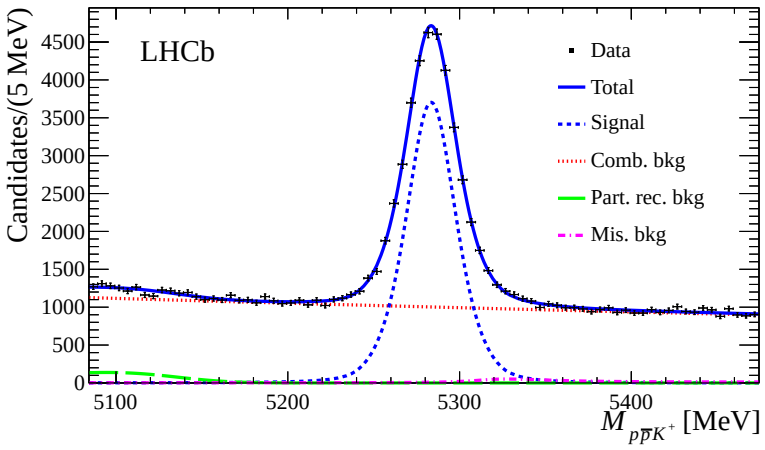
$$\frac{\sigma(pp \to \Xi_b^{*0} X) \times \mathcal{B}(\Xi_b^{*0} \to \Xi_b^- \pi^+)}{\sigma(pp \to \Xi_b^- X)} = 0.28 \pm 0.03(\text{stat.}) \pm 0.01(\text{syst.})$$

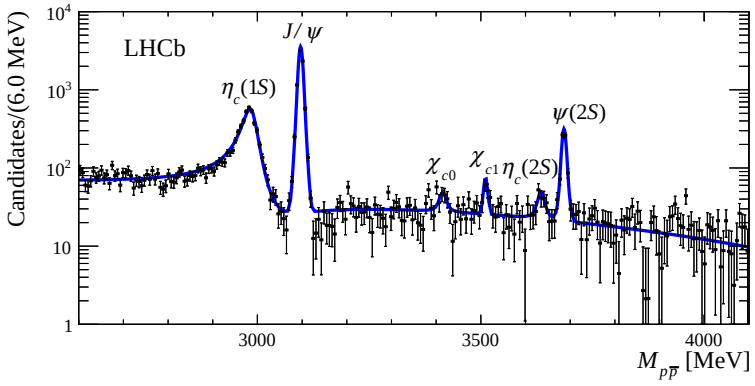
$\eta_c(2S) \to p\bar{p}$

NEW!

arXiv:1607.06446

- Onia an excellent environment to test QCD
- Study of charmonium decays to $p\bar{p}$ at LHCb
- Performed using large clean sample of $B^+ \to p\bar{p}K^+$ decays
- Exclusive study offers better control of background and resolution effects
- Fit performed to background-subtracted $p\bar{p}$ invariant mass (bottom)
  - weights obtained from fit to $m(p\bar{p}K^+)$ (top)



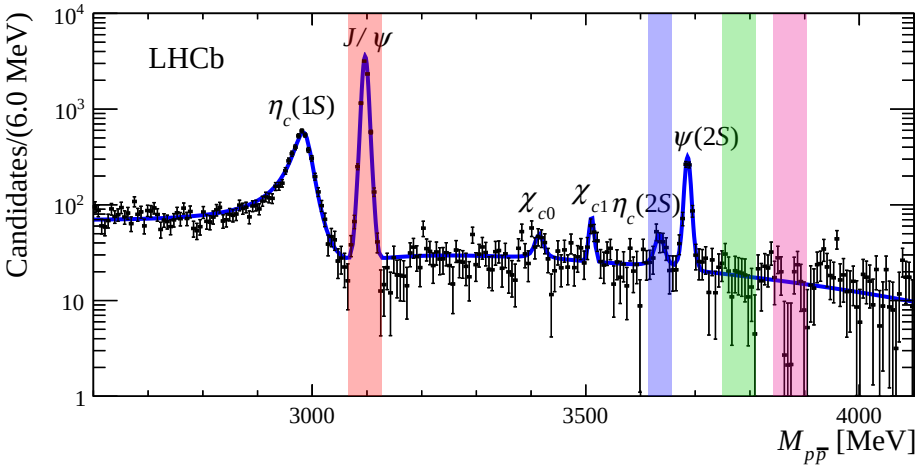


$\eta_c(2S) \to p\bar{p}$

NEW!

arXiv:1607.06446

- Known contributions from $\eta_c(1S)$, J/ψ, χ_{c0}, χ_{c1} and $\psi(2S)$
- Search for $\eta_c(2S)$, $\psi(3770)$ and $X(3872)$

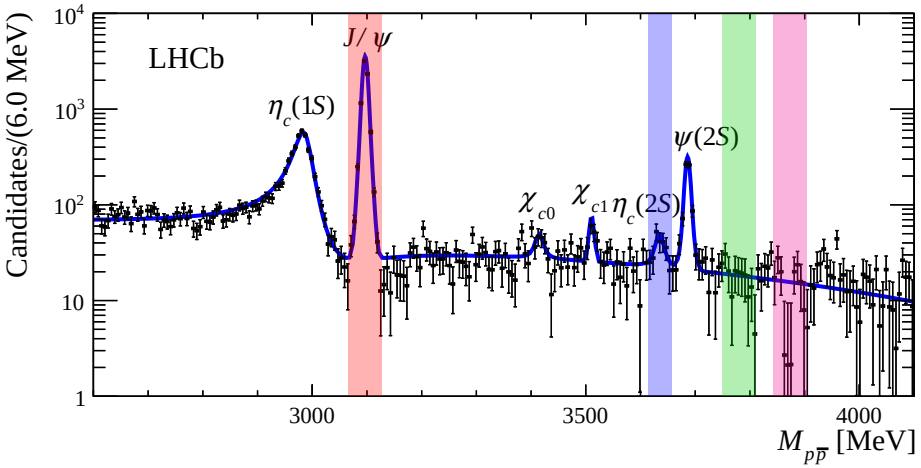


$\eta_c(2S) \to p\bar{p}$

NEW!

arXiv:1607.06446

- Known contributions from $\eta_c(1S)$, J/ψ, χ_{c0}, χ_{c1} and $\psi(2S)$
- Search for $\eta_c(2S)$, $\psi(3770)$ and $X(3872)$



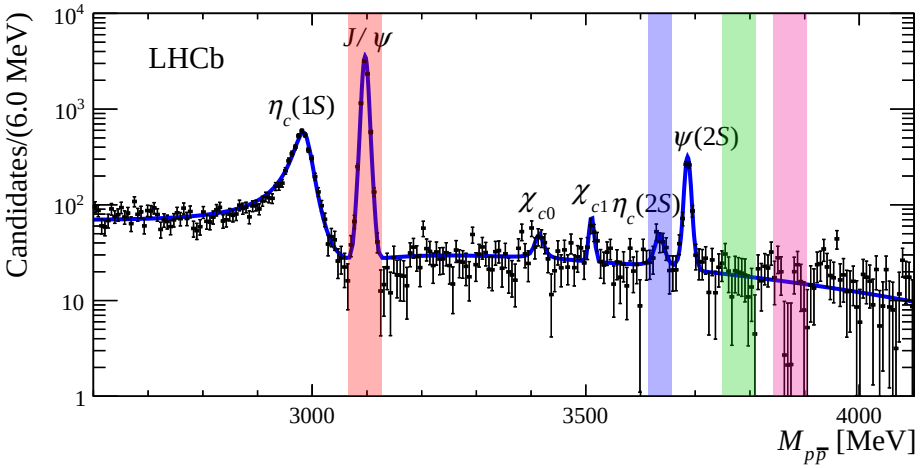
- First observation of $\eta_c(2S) \to p\bar{p}$

$\eta_c(2S) \to p\bar{p}$

NEW!

arXiv:1607.06446

- Known contributions from $\eta_c(1S)$, J/ψ, χ_{c0}, χ_{c1} and $\psi(2S)$
- Search for $\eta_c(2S)$, $\psi(3770)$ and $X(3872)$



- First observation of $\eta_c(2S) \to p\bar{p}$
- Limits set on $\psi(3770)$ and $X(3872)$

$\eta_c(2S) \to p\bar{p}$

NEW!

arXiv:1607.06446

- Product branching fractions measured relative to J/ψ
  - $\mathcal{R}_{[c\bar{c}]} = \frac{\mathcal{B}(B^+ \to [c\bar{c}]K^+) \times \mathcal{B}([c\bar{c}] \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi\, K^+) \times \mathcal{B}(J/\psi \to p\bar{p})}$
- Also measure masses of η_c resonances relative to corresponding ψ resonances and width of $\eta_c(1\mathrm{S})$

$$\begin{aligned}
\mathcal{R}_{\eta_c(2\mathrm{S})} &= (1.58 \pm 0.33(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})) \times 10^{-2}\,, \\
\mathcal{R}_{\psi(3770)} &< 9(10) \times 10^{-2}\,, \\
\mathcal{R}_{X(3872)} &< 0.20(0.25) \times 10^{-2}\,,
\end{aligned}$$

at the 90 % (95 %) confidence level

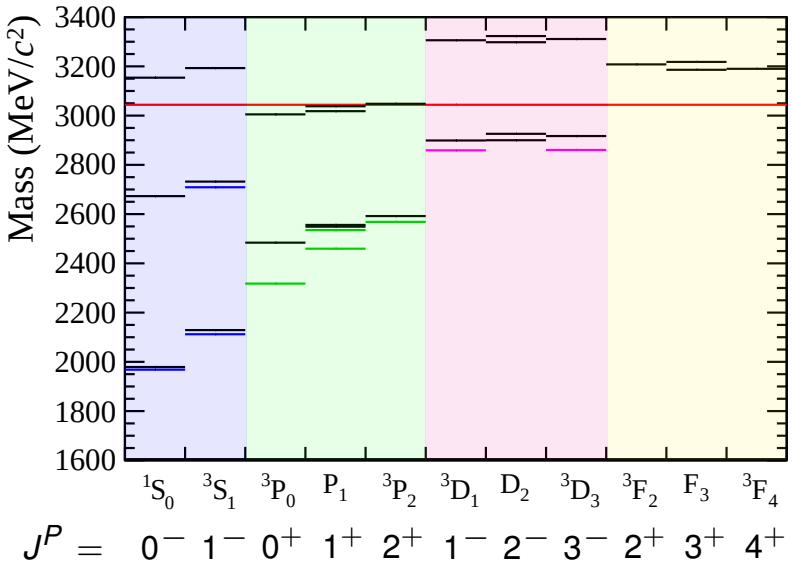
$$\begin{aligned}
m(J/\psi) - m(\eta_c(1\mathrm{S})) &= 110.2 \pm 0.5(\mathrm{stat.}) \pm 0.9(\mathrm{syst.})\,\mathrm{MeV}/c^2\,, \\
m(\psi(2\mathrm{S})) - m(\eta_c(2\mathrm{S})) &= 52.5 \pm 1.7(\mathrm{stat.}) \pm 0.6(\mathrm{syst.})\,\mathrm{MeV}/c^2\,, \\
\Gamma(\eta_c(1\mathrm{S})) &= 34.0 \pm 1.9(\mathrm{stat.}) \pm 1.3(\mathrm{syst.})\,\mathrm{MeV}
\end{aligned}$$

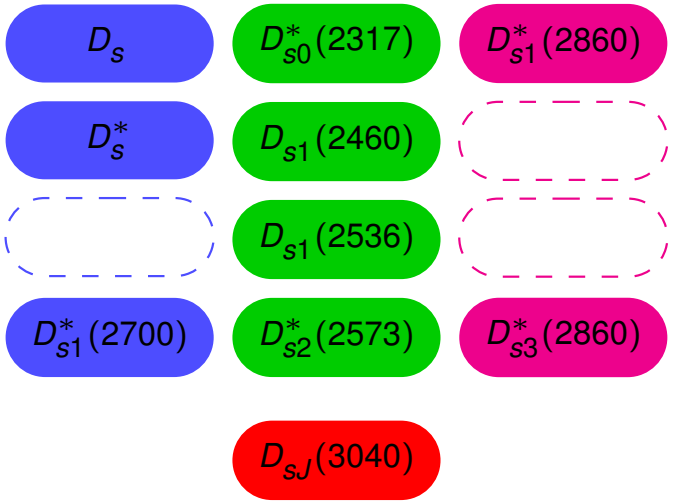
D_s^+ Spectroscopy

JHEP 02 (2016) 133

theory predictions from PRD 89 (2014) 074023

- Meson spectroscopy tests refine models of QCD



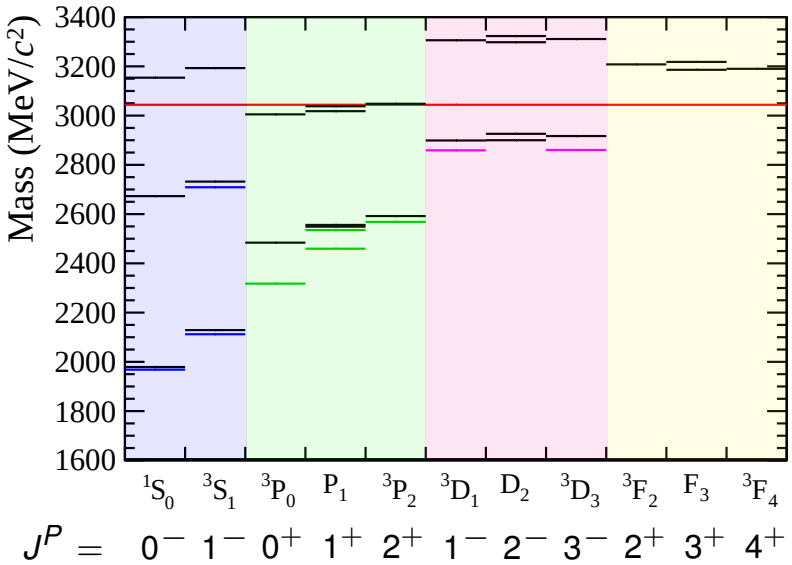


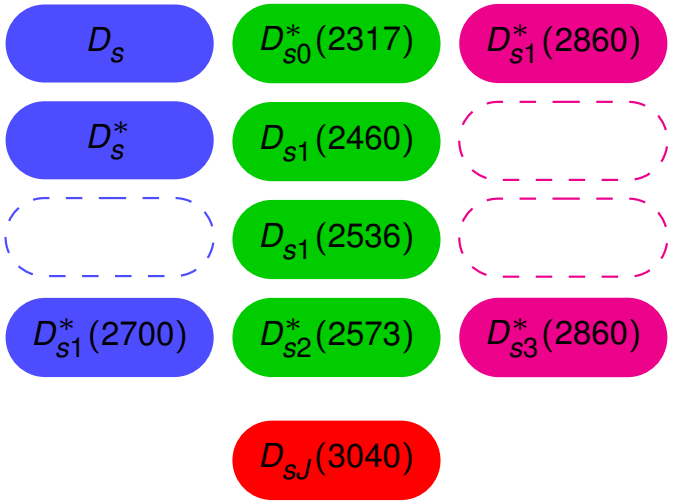
D_s^+ Spectroscopy

JHEP 02 (2016) 133

- Meson spectroscopy tests refine models of QCD
- D_s^+ mesons particularly interesting with one heavy and one light quark

theory predictions from PRD 89 (2014) 074023



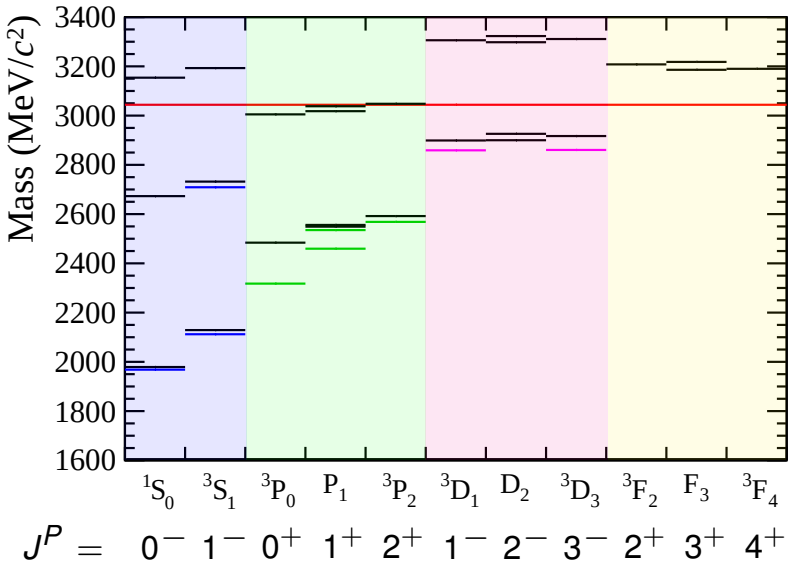


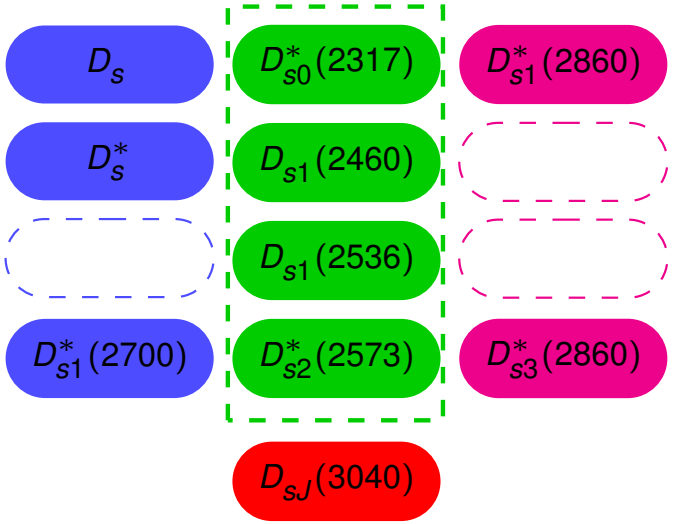
D_s^+ Spectroscopy

JHEP 02 (2016) 133

- Meson spectroscopy tests refine models of QCD
- D_s^+ mesons particularly interesting with one heavy and one light quark
- Unexpected large mass splitting seen between the 1P states PRL 90 (2003) 242001

theory predictions from PRD 89 (2014) 074023



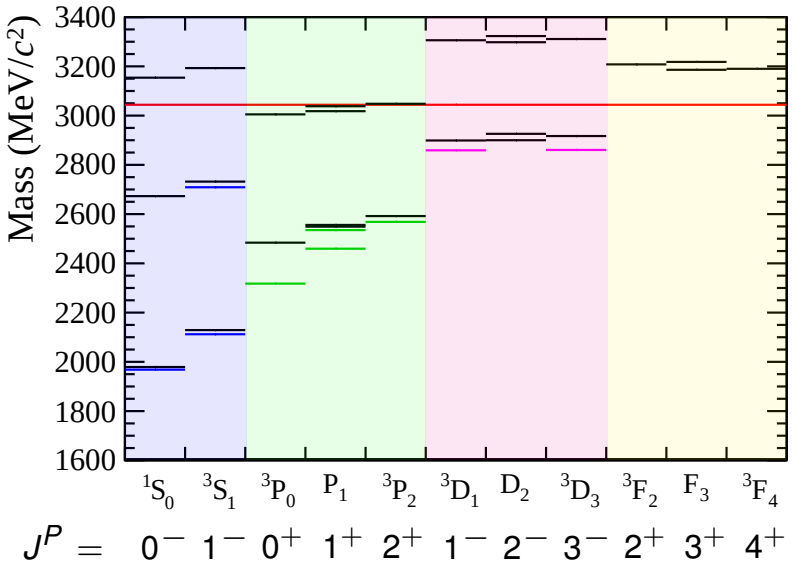


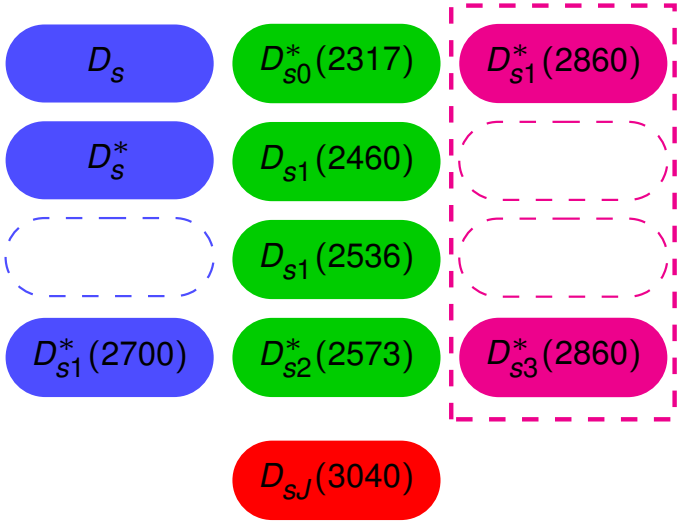
D_s^+ Spectroscopy

JHEP 02 (2016) 133

- Meson spectroscopy tests refine models of QCD
- D_s^+ mesons particularly interesting with one heavy and one light quark
- Unexpected large mass splitting seen between the 1P states PRL 90 (2003) 242001
- Two states recently observed by LHCb considered two of the four 1D states PRL 113 (2014) 162001

theory predictions from PRD 89 (2014) 074023



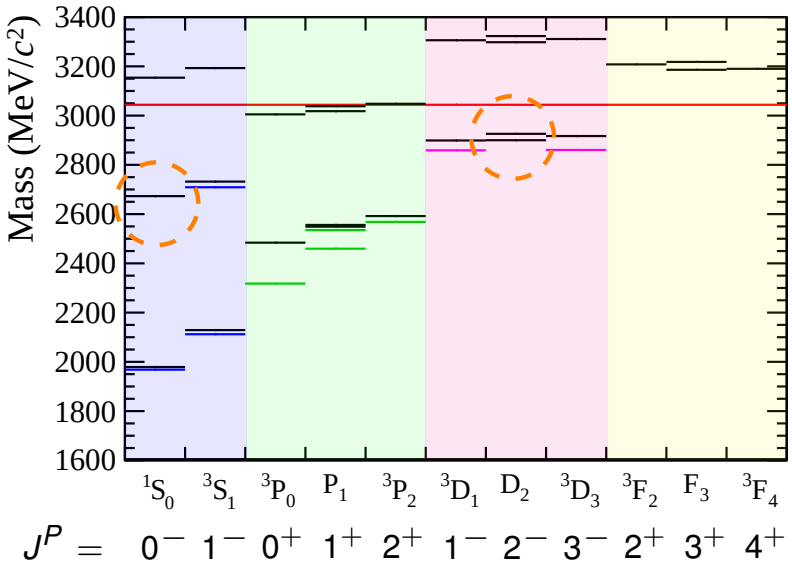


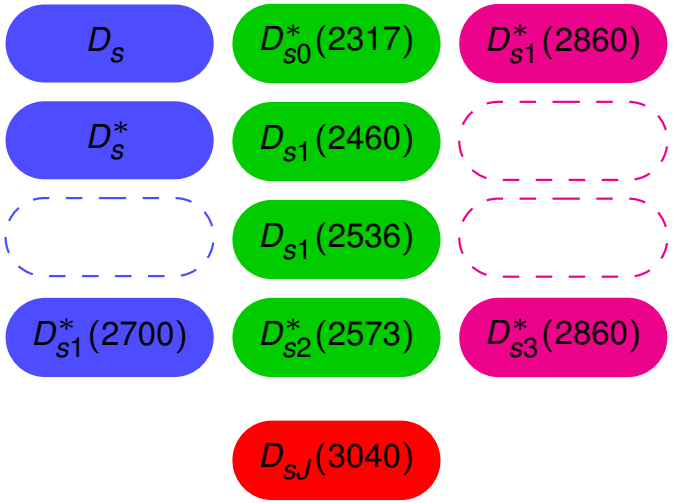
D_s^+ Spectroscopy

JHEP 02 (2016) 133

- Meson spectroscopy tests refine models of QCD
- D_s^+ mesons particularly interesting with one heavy and one light quark
- Unexpected large mass splitting seen between the 1P states PRL 90 (2003) 242001
- Two states recently observed by LHCb considered two of the four 1D states PRL 113 (2014) 162001
- At least **three more** states expected up to $3\,\mathrm{GeV}/c^2$
  - all with unnatural J^P

theory predictions from PRD 89 (2014) 074023





D_s^+ Spectroscopy

JHEP 02 (2016) 133

- Inclusive analysis of $pp \to D^{*+} K_S^0 X$ and $D^{*0} K^+ X$ decays

D_s^+ Spectroscopy

JHEP 02 (2016) 133

- Inclusive analysis of $pp \to D^{*+} K_S^0 X$ and $D^{*0} K^+ X$ decays
- Use $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ (shown) or $K^- \pi^+ \pi^+ \pi^-$ and $D^{*0} \to D^0 \pi^0$, $D^0 \to K^- \pi^+$ decay chains

D_s^+ Spectroscopy

JHEP 02 (2016) 133

- Inclusive analysis of $pp \to D^{*+} K_S^0 X$ and $D^{*0} K^+ X$ decays
- Use $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ (shown) or $K^- \pi^+ \pi^+ \pi^-$ and $D^{*0} \to D^0 \pi^0$, $D^0 \to K^- \pi^+$ decay chains
- Builds on previous analyses of $D^0 K^+$

D_s^+ Spectroscopy

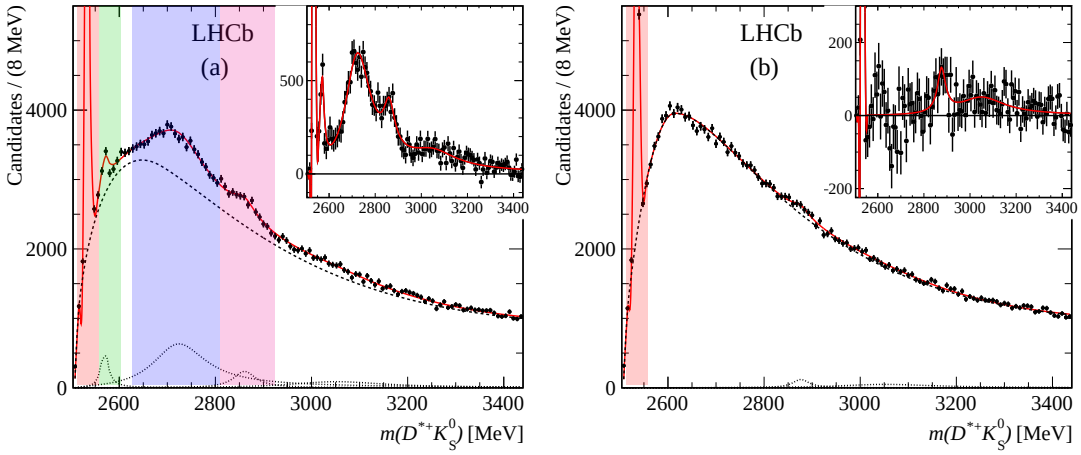
JHEP 02 (2016) 133

- Inclusive analysis of $pp \to D^{*+} K_S^0 X$ and $D^{*0} K^+ X$ decays
- Use $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ (shown) or $K^- \pi^+ \pi^+ \pi^-$ and $D^{*0} \to D^0 \pi^0$, $D^0 \to K^- \pi^+$ decay chains
- Builds on previous analyses of $D^0 K^+$
- Access to natural (NP) and unnatural (UP) spin-parities

D_s^+ Spectroscopy

JHEP 02 (2016) 133

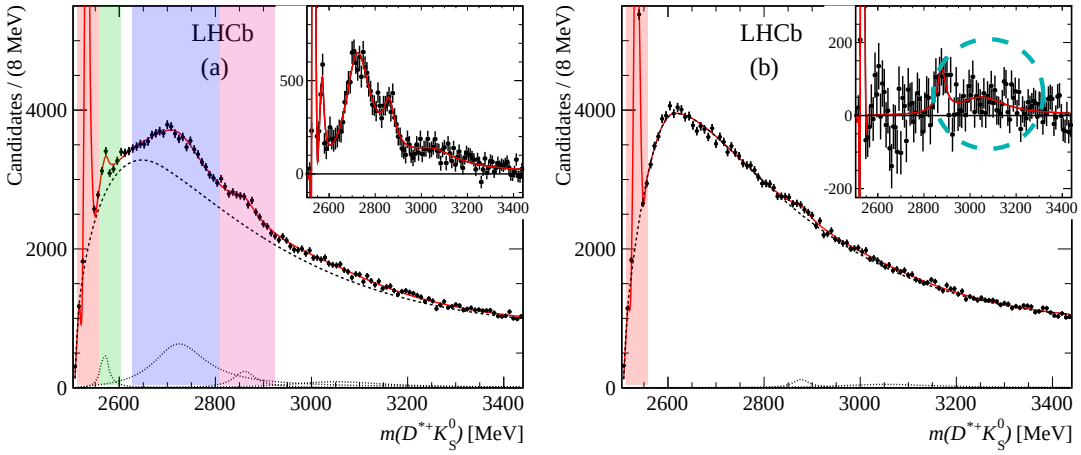
- Inclusive analysis of $pp \to D^{*+} K_S^0 X$ and $D^{*0} K^+ X$ decays
- Use $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ (shown) or $K^- \pi^+ \pi^+ \pi^-$ and $D^{*0} \to D^0 \pi^0$, $D^0 \to K^- \pi^+$ decay chains
- Builds on previous analyses of $D^0 K^+$
- Access to natural (NP) and unnatural (UP) spin-parities
- Plots show (a) $|\cos\theta_H| < 0.5$ and (b) > 0.5 to emphasise NP and UP components
  - Resonant contributions seen due to $D_{s1}(2536)^+$, $D_{s2}^*(2573)^+$, $D_{s1}^*(2700)^+$ and $D_{s3}^*(2860)^+$ resonances



D_s^+ Spectroscopy

JHEP 02 (2016) 133

- Inclusive analysis of $pp \to D^{*+} K_S^0 X$ and $D^{*0} K^+ X$ decays
- Use $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ (shown) or $K^- \pi^+ \pi^+ \pi^-$ and $D^{*0} \to D^0 \pi^0$, $D^0 \to K^- \pi^+$ decay chains
- Builds on previous analyses of $D^0 K^+$
- Access to natural (NP) and unnatural (UP) spin-parities
- Plots show (a) $|\cos\theta_H| < 0.5$ and (b) > 0.5 to emphasise NP and UP components
  - Resonant contributions seen due to $D_{s1}(2536)^+$, $D_{s2}^*(2573)^+$, $D_{s1}^*(2700)^+$ and $D_{s3}^*(2860)^+$ resonances
  - Weak evidence for structure around $3\ \mathrm{GeV}/c^2$



D_s^+ Spectroscopy

JHEP 02 (2016) 133

- NP and UP resonances identified by helicity angle distribution of D^* decay

D_s^+ Spectroscopy

JHEP 02 (2016) 133

- NP and UP resonances identified by helicity angle distribution of D^* decay
- NP resonances follow $\sin^2\theta_H$ distribution

D_s^+ Spectroscopy

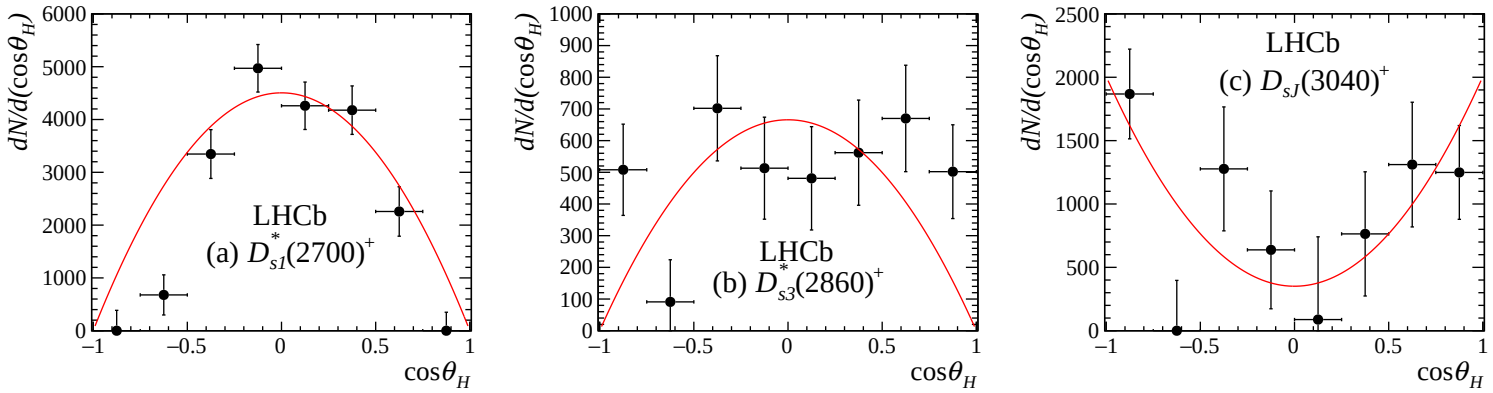
JHEP 02 (2016) 133

- NP and UP resonances identified by helicity angle distribution of D^* decay
- NP resonances follow $\sin^2\theta_H$ distribution
- UP resonances follow $1 + h\cos^2\theta_H$

D_s^+ Spectroscopy

JHEP 02 (2016) 133

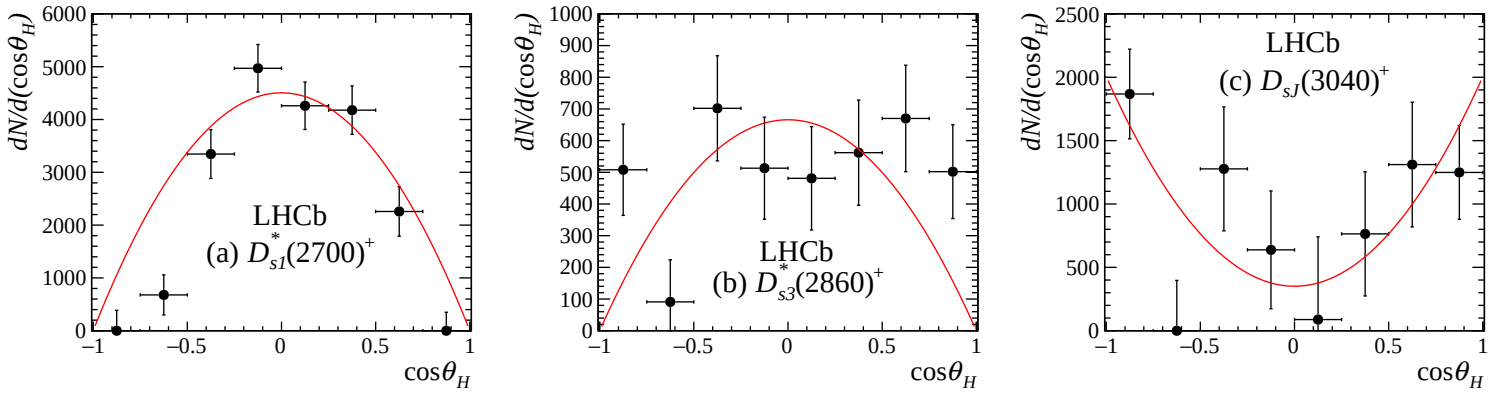
- NP and UP resonances identified by helicity angle distribution of D^* decay
- NP resonances follow $\sin^2\theta_H$ distribution
- UP resonances follow $1 + h\cos^2\theta_H$
- Expected background-subtracted distributions seen for (a–c) $D_{s1}^*(2700)^+$, $D_{s3}^*(2860)^+$ and $D_{sJ}(3040)^+$



D_s^+ Spectroscopy

JHEP 02 (2016) 133

- NP and UP resonances identified by helicity angle distribution of D^* decay
- NP resonances follow $\sin^2\theta_H$ distribution
- UP resonances follow $1 + h\cos^2\theta_H$
- Expected background-subtracted distributions seen for (a–c) $D_{s1}^*(2700)^+$, $D_{s3}^*(2860)^+$ and $D_{sJ}(3040)^+$
- Data consistent with additional UP contribution in $2.86\,\mathrm{GeV}/c^2$ region



D_s^+ Spectroscopy

JHEP 02 (2016) 133

- First observation of $D_{s2}^*(2573)^+ \to D^{*+}K_S^0$ decay
- Branching ratio relative to $D_{s2}^*(2573)^+ \to D^+K_S^0$ measured to be

$$\frac{\mathcal{B}(D_{s2}^*(2573)^+ \to D^{*+}K_S^0)}{\mathcal{B}(D_{s2}^*(2573)^+ \to D^+K_S^0)} = 0.044 \pm 0.005\,(\text{stat.}) \pm 0.011\,(\text{syst.})$$

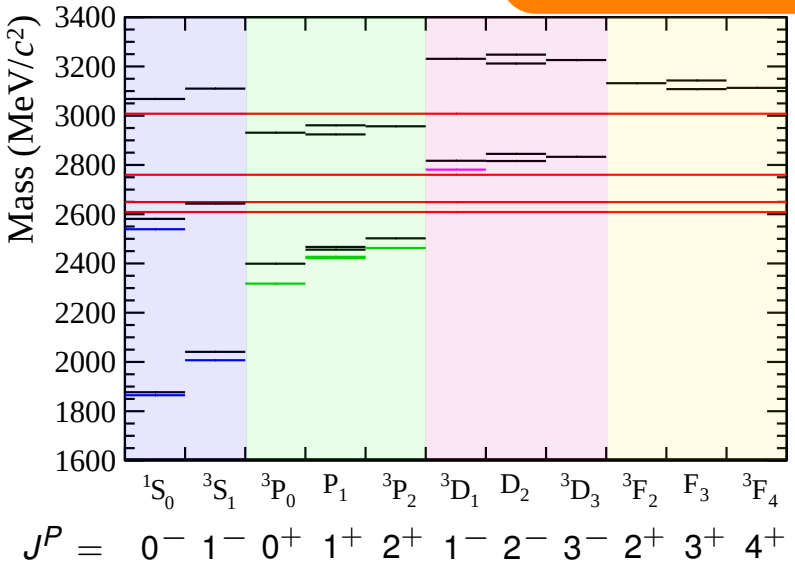
D^0 Spectroscopy

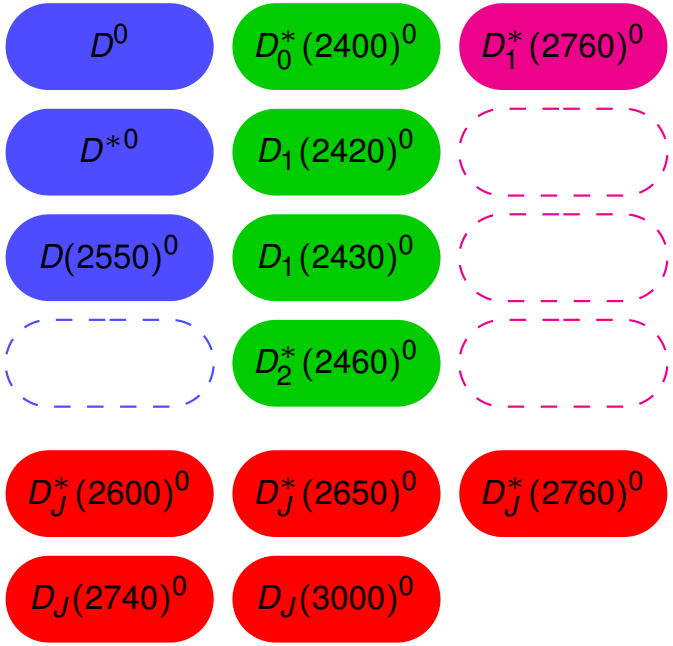
NEW!

arXiv:1608.01289

- D^0 spectrum similar to D_s^+

theory predictions from PRD 93 (2016) 034035





D^0 Spectroscopy

NEW!

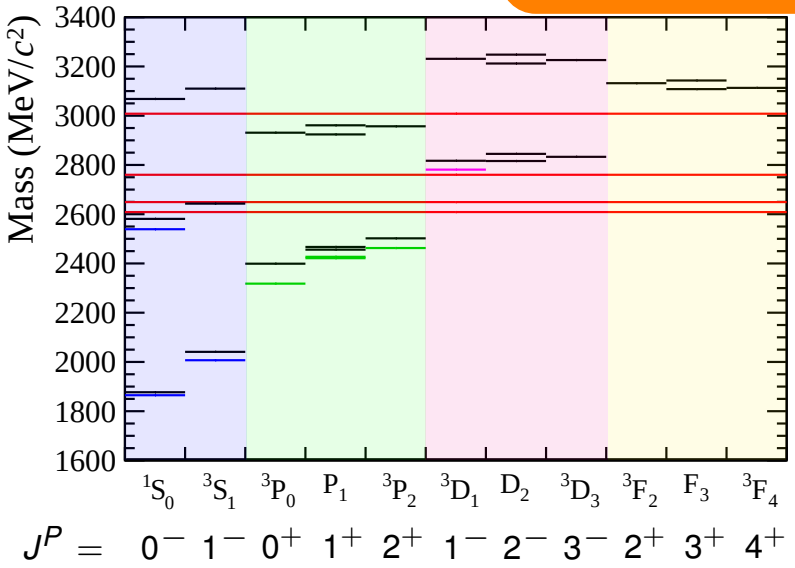
arXiv:1608.01289

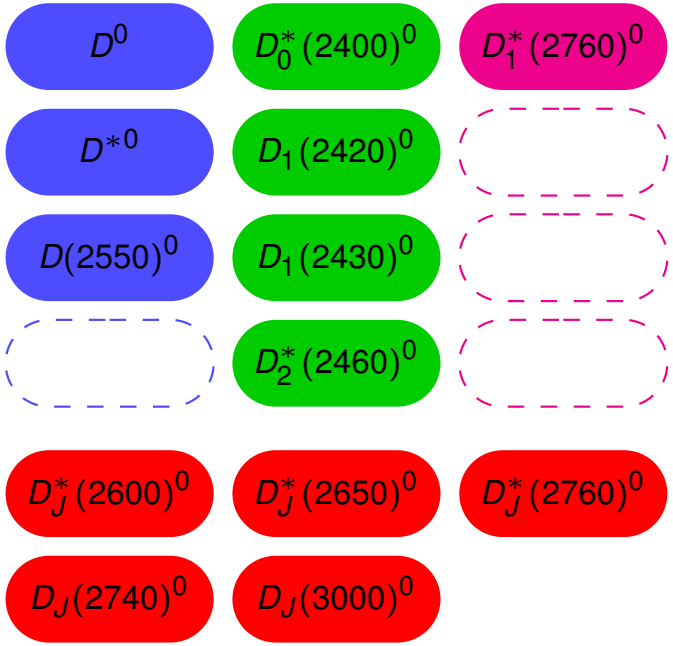
PRD 82 (2010) 111101

JHEP 09 (2013) 145

- D^0 spectrum similar to D_s^+
- Previously studied in $e^+e^- \to D^{(*)+}\pi^- X$ and $pp \to D^{(*)+}\pi^- X$ inclusive decays.

theory predictions from PRD 93 (2016) 034035





D^0 Spectroscopy

NEW!

arXiv:1608.01289

PRD 82 (2010) 111101

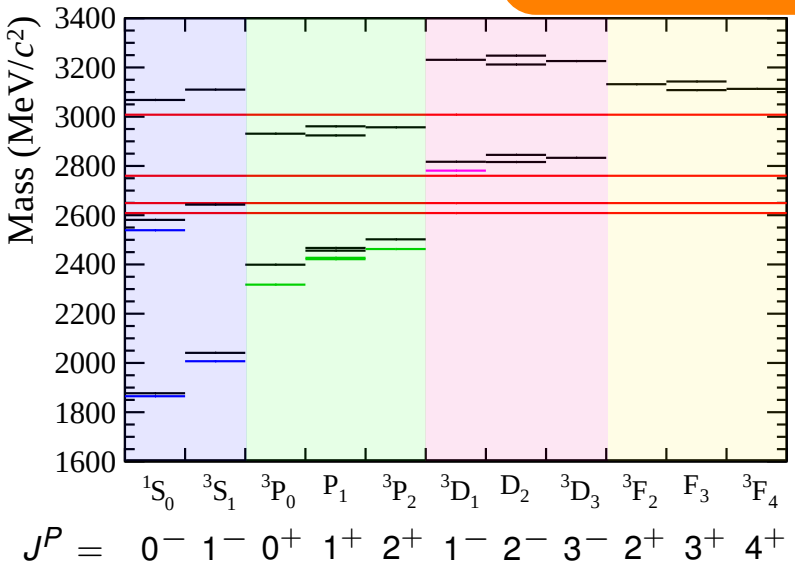
JHEP 09 (2013) 145

PRD 92 (2015) 032002

PRD 92 (2015) 012012

- D^0 spectrum similar to D_s^+
- Previously studied in $e^+e^- \to D^{(*)+}\pi^- X$ and $pp \to D^{(*)+}\pi^- X$ inclusive decays.
- May also be compared against D^+ spectroscopy results

theory predictions from PRD 93 (2016) 034035



D^0	$D_0^*(2400)^0$	$D_1^*(2760)^0$
D^{*0}	$D_1(2420)^0$	
$D(2550)^0$	$D_1(2430)^0$	
	$D_2^*(2460)^0$	
$D_J^*(2600)^0$	$D_J^*(2650)^0$	$D_J^*(2760)^0$
$D_J(2740)^0$	$D_J(3000)^0$	

D^0 Spectroscopy

NEW!

arXiv:1608.01289

PRD 82 (2010) 111101

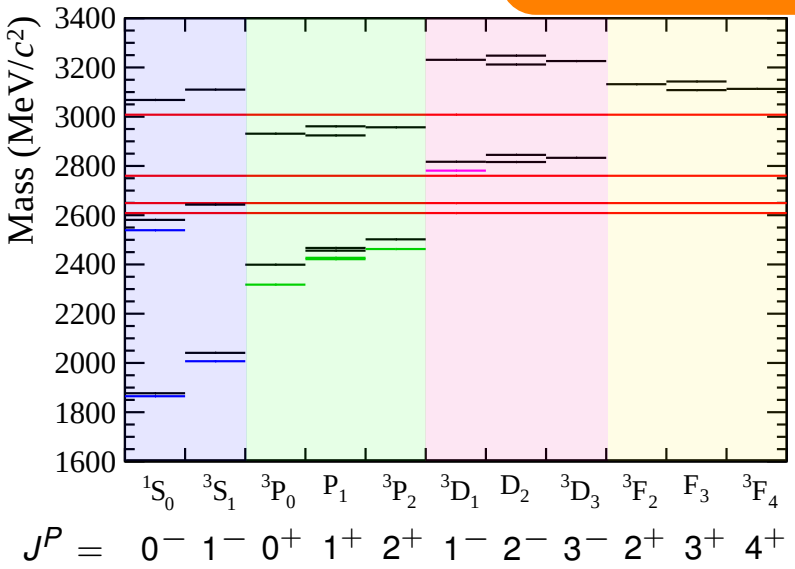
JHEP 09 (2013) 145

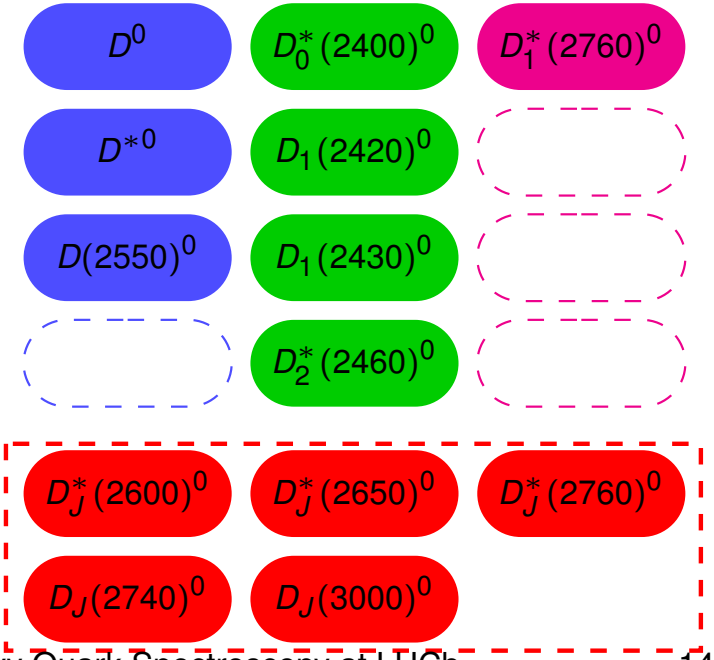
PRD 92 (2015) 032002

PRD 92 (2015) 012012

- D^0 spectrum similar to D_s^+
- Previously studied in $e^+e^- \to D^{(*)+}\pi^- X$ and $pp \to D^{(*)+}\pi^- X$ inclusive decays.
- May also be compared against D^+ spectroscopy results
- A number of claimed states have **unknown** J^P

theory predictions from PRD 93 (2016) 034035





D^0 Spectroscopy

NEW!

arXiv:1608.01289

PRD 82 (2010) 111101

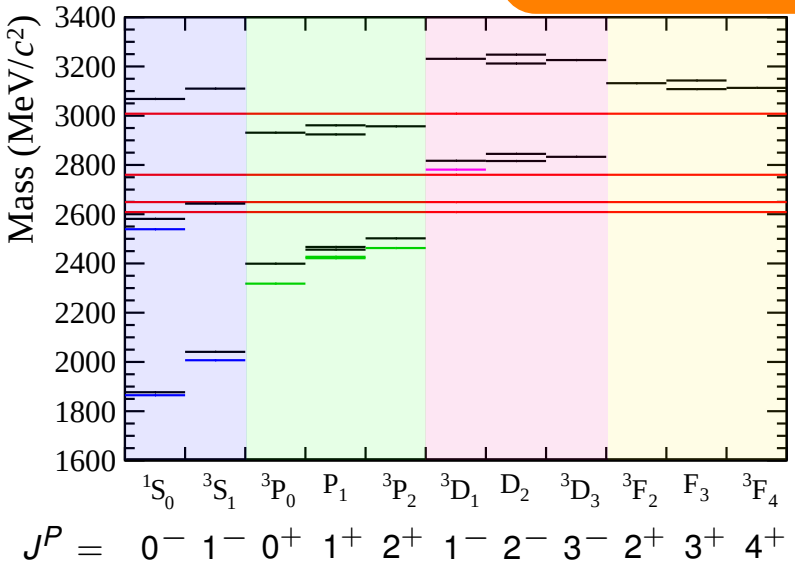
JHEP 09 (2013) 145

PRD 92 (2015) 032002

PRD 92 (2015) 012012

- D^0 spectrum similar to D_s^+
- Previously studied in $e^+e^- \to D^{(*)+}\pi^- X$ and $pp \to D^{(*)+}\pi^- X$ inclusive decays.
- May also be compared against D^+ spectroscopy results
- A number of claimed states have **unknown** J^P
- Dalitz plot analysis of $B^+ \to D^-\pi^+\pi^+$ decays allows J^P of natural states to be measured

theory predictions from PRD 93 (2016) 034035

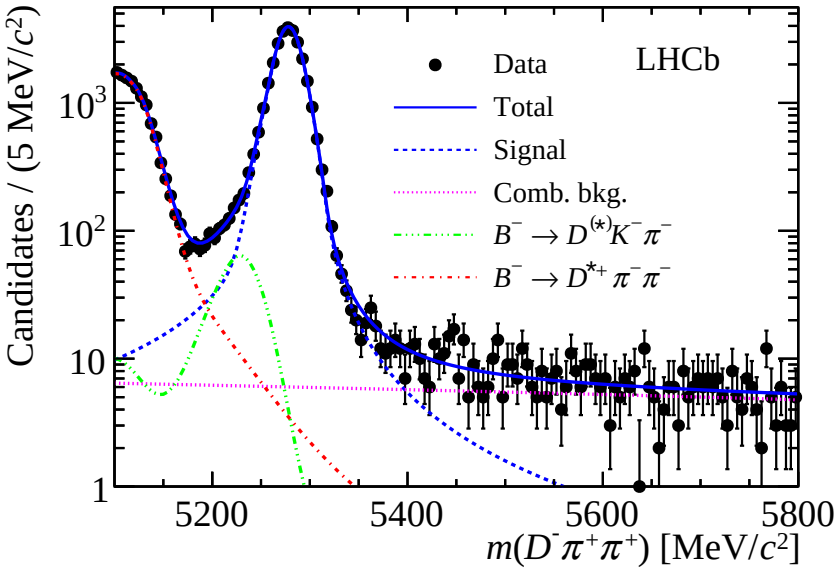


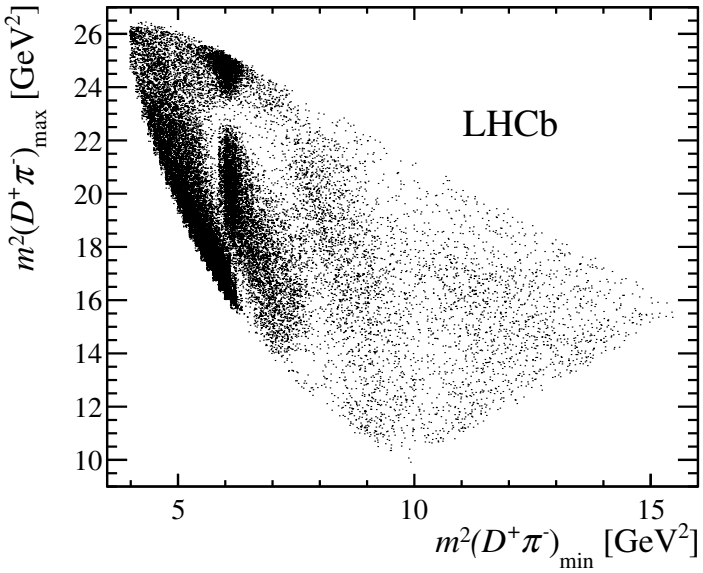
D^0	$D_0^*(2400)^0$	$D_1^*(2760)^0$
D^{*0}	$D_1(2420)^0$	
$D(2550)^0$	$D_1(2430)^0$	
	$D_2^*(2460)^0$	
$D_J^*(2600)^0$	$D_J^*(2650)^0$	$D_J^*(2760)^0$
$D_J(2740)^0$	$D_J(3000)^0$	

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

NEW!

arXiv:1608.01289



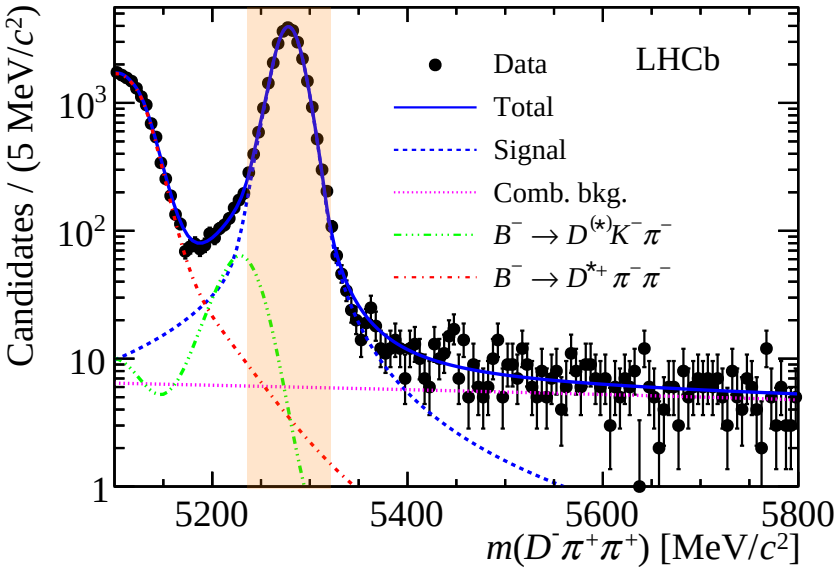


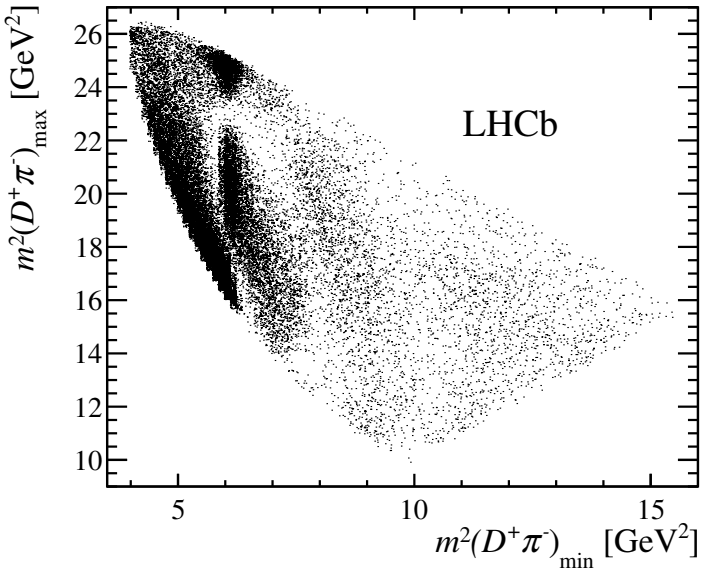
- Large pure sample of $B^- \to D^+\pi^-\pi^-$ decays

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

NEW!

arXiv:1608.01289



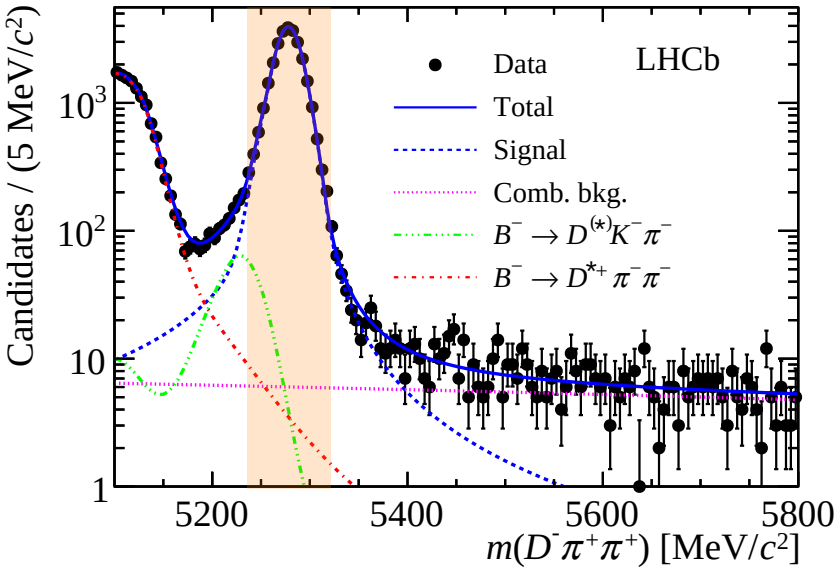


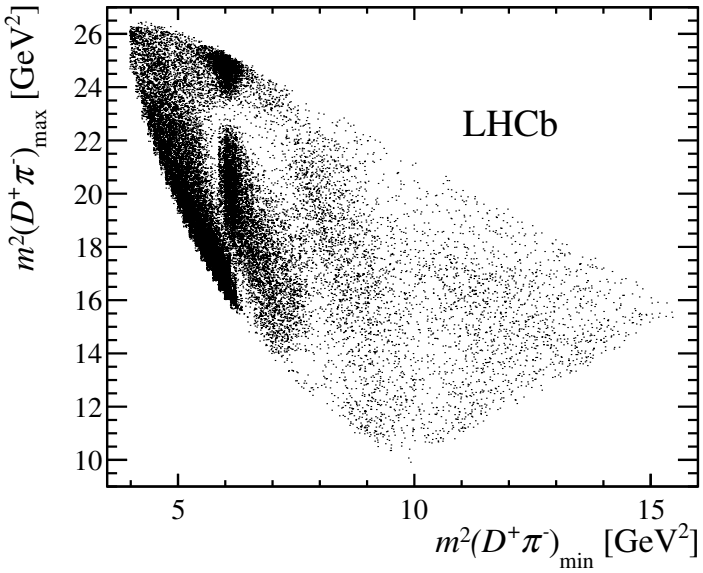
- Large pure sample of $B^- \to D^+\pi^-\pi^-$ decays
- **Signal window** contains 28 000 $B^- \to D^+\pi^-\pi^-$ decays with very small (1 %) background contribution

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

NEW!

arXiv:1608.01289

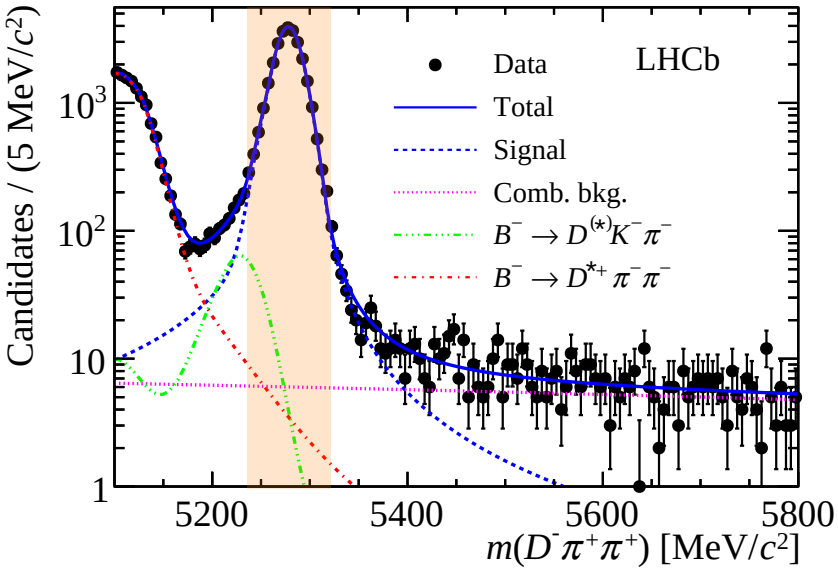


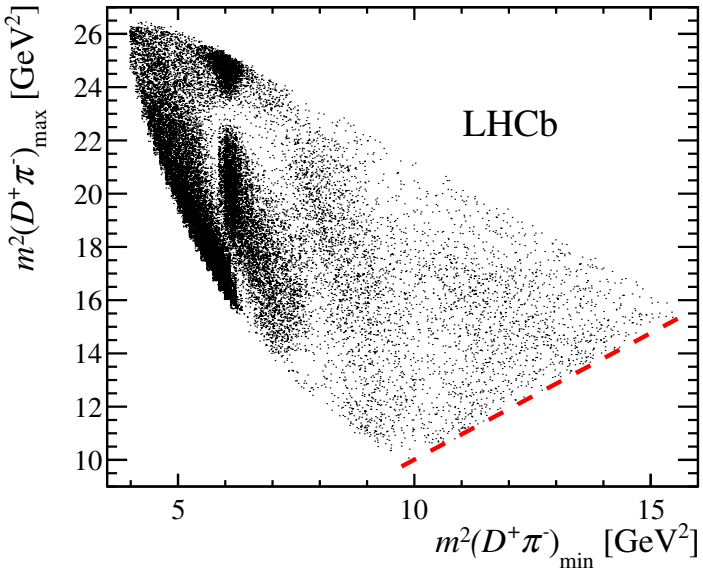


- Large pure sample of $B^- \to D^+\pi^-\pi^-$ decays
- **Signal window** contains 28 000 $B^- \to D^+\pi^-\pi^-$ decays with very small (1 %) background contribution
- Dalitz plot (right) gives details of the resonant structure of the three-body decay

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

NEW! arXiv:1608.01289

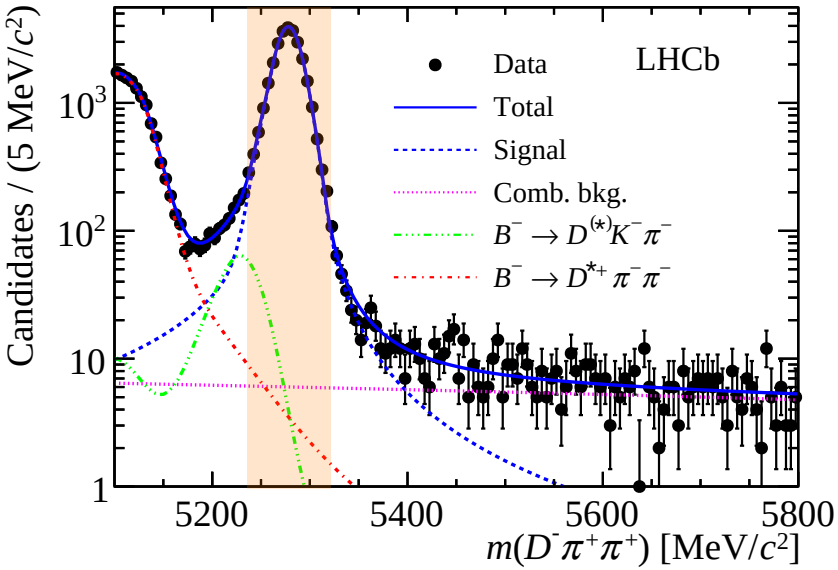


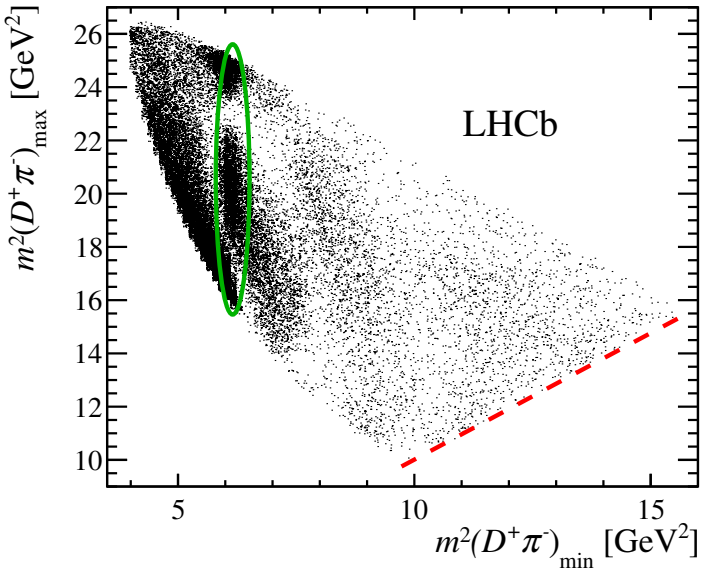


- Large pure sample of $B^- \to D^+\pi^-\pi^-$ decays
- **Signal window** contains 28 000 $B^- \to D^+\pi^-\pi^-$ decays with very small (1 %) background contribution
- Dalitz plot (right) gives details of the resonant structure of the three-body decay
  - DP **folded** at $m(D^+\pi_1^-) = m(D^+\pi_2^-)$ due to symmetry

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

NEW! arXiv:1608.01289





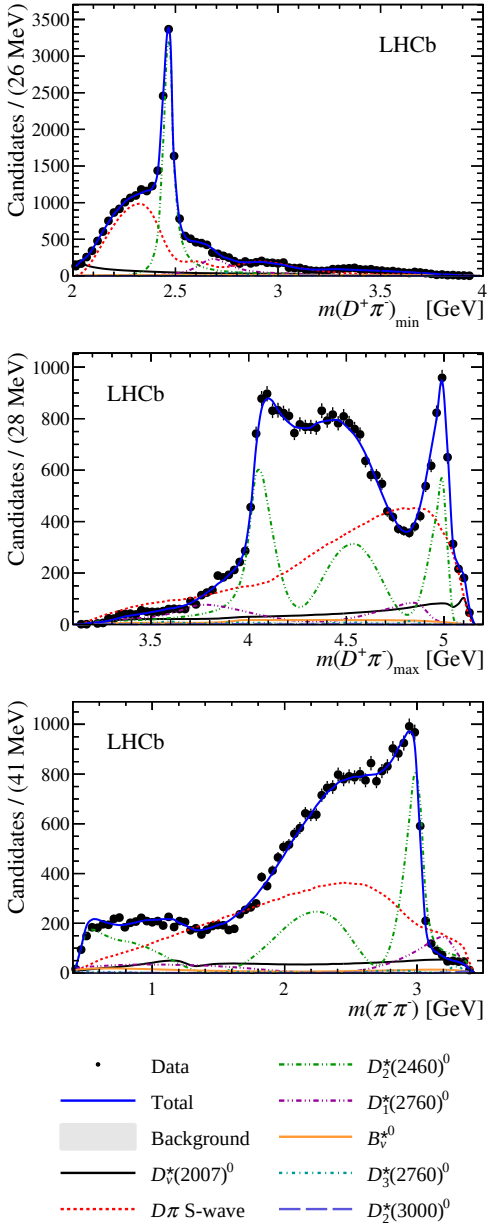
- Large pure sample of $B^- \to D^+\pi^-\pi^-$ decays
- **Signal window** contains 28 000 $B^- \to D^+\pi^-\pi^-$ decays with very small (1 %) background contribution
- Dalitz plot (right) gives details of the resonant structure of the three-body decay
  - DP **folded** at $m(D^+\pi_1^-) = m(D^+\pi_2^-)$ due to symmetry
  - Three-lobed structure at $m^2(D^+\pi^-)_{\rm min} \approx 6\,{\rm GeV}^2/c^4$ is due to spin-2 $D_2^*(2460)^0$ resonance

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

NEW!

arXiv:1608.01289

- Model-independent description used for $D^+\pi^-$ S-wave



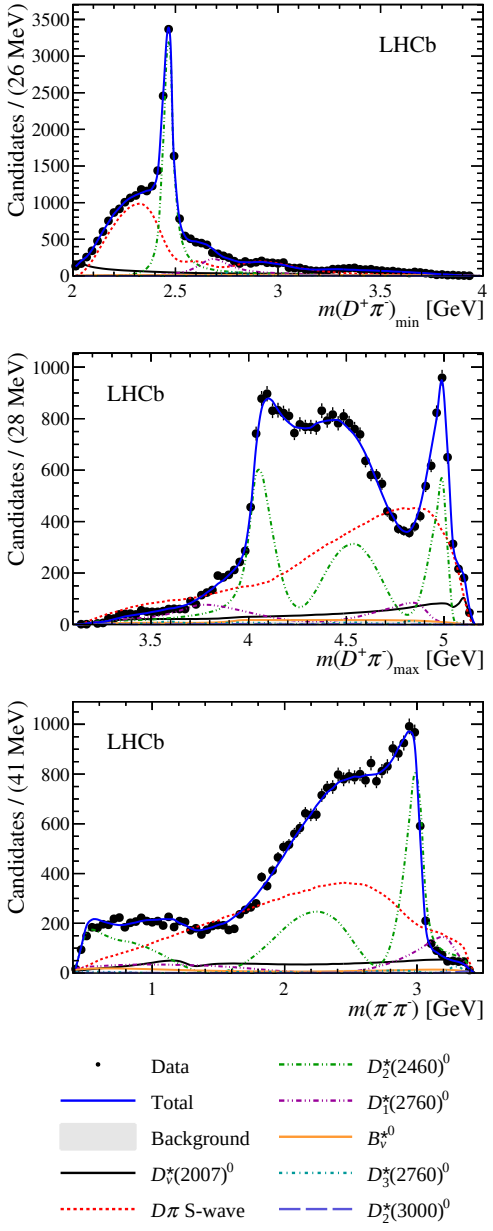
Resonance	Spin	Model	Parameters
$D_2^*(2460)^0$	2	RBW	Determined from data
$D_1^*(2680)^0$	1	RBW	
$D_3^*(2760)^0$	3	RBW	
$D_2^*(3000)^0$	2	RBW	
$D_v^*(2007)^0$	1	RBW	$m = 2006.98 \pm 0.15\,\text{MeV}$, $\Gamma = 2.1\,\text{MeV}$
B_v^{*0}	1	RBW	$m = 5325.2 \pm 0.4\,\text{MeV}$, $\Gamma = 0.0\,\text{MeV}$
Total S-wave	0	MIPW	See next slide

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

NEW!

arXiv:1608.01289

- Model-independent description used for $D^+\pi^-$ S-wave
- Non-resonant P-wave described by two virtual resonances



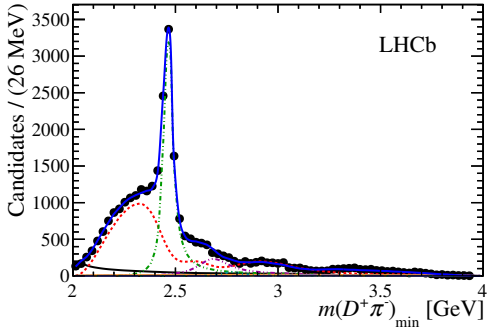
Resonance	Spin	Model	Parameters
$D_2^*(2460)^0$	2	RBW	Determined from data
$D_1^*(2680)^0$	1	RBW	
$D_3^*(2760)^0$	3	RBW	
$D_2^*(3000)^0$	2	RBW	
$D_v^*(2007)^0$	1	RBW	$m = 2006.98 \pm 0.15\,\text{MeV}$, $\Gamma = 2.1\,\text{MeV}$
B_v^{*0}	1	RBW	$m = 5325.2 \pm 0.4\,\text{MeV}$, $\Gamma = 0.0\,\text{MeV}$
Total S-wave	0	MIPW	See next slide

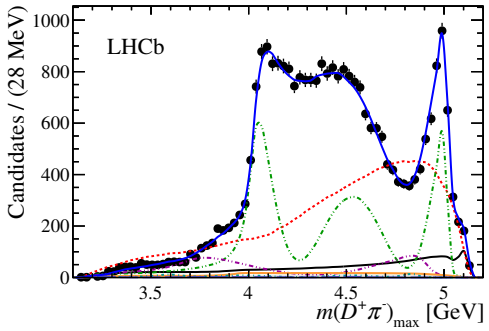
$B^- \to D^+\pi^-\pi^-$

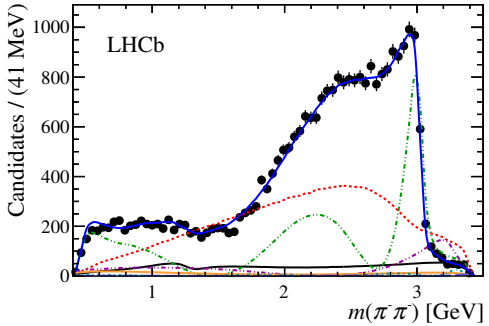
NEW!

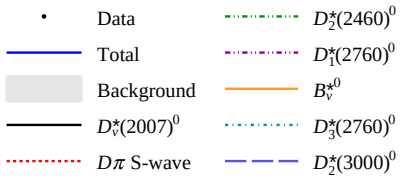
arXiv:1608.01289

- Model-independent description used for $D^+\pi^-$ S-wave
- Non-resonant P-wave described by two virtual resonances
- All other resonances described by relativistic Breit–Wigner functions









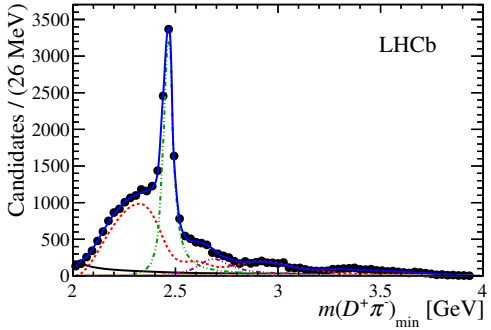
Resonance	Spin	Model	Parameters
$D_2^*(2460)^0$	2	RBW	Determined from data
$D_1^*(2680)^0$	1	RBW	
$D_3^*(2760)^0$	3	RBW	
$D_2^*(3000)^0$	2	RBW	
$D_v^*(2007)^0$	1	RBW	$m = 2006.98 \pm 0.15\,\text{MeV}$, $\Gamma = 2.1\,\text{MeV}$
B_v^{*0}	1	RBW	$m = 5325.2 \pm 0.4\,\text{MeV}$, $\Gamma = 0.0\,\text{MeV}$
Total S-wave	0	MIPW	See next slide

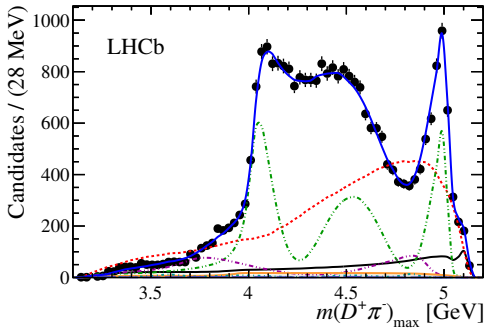
$B^- \to D^+\pi^-\pi^-$

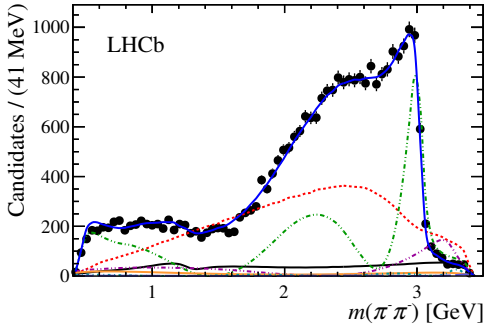
NEW!

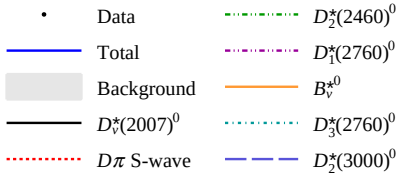
arXiv:1608.01289

- Model-independent description used for $D^+\pi^-$ S-wave
- Non-resonant P-wave described by two virtual resonances
- All other resonances described by relativistic Breit–Wigner functions
- Mass projections of the DP (left) show good agreement between data and fit function









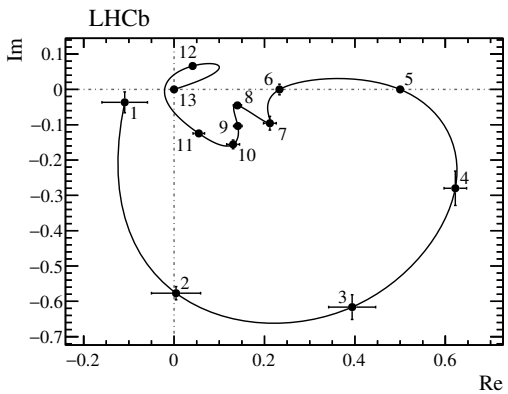
Resonance	Spin	Model	Parameters
$D_2^*(2460)^0$	2	RBW	Determined from data
$D_1^*(2680)^0$	1	RBW	
$D_3^*(2760)^0$	3	RBW	
$D_2^*(3000)^0$	2	RBW	
$D_v^*(2007)^0$	1	RBW	$m = 2006.98 \pm 0.15\,\text{MeV}$, $\Gamma = 2.1\,\text{MeV}$
B_v^{*0}	1	RBW	$m = 5325.2 \pm 0.4\,\text{MeV}$, $\Gamma = 0.0\,\text{MeV}$
Total S-wave	0	MIPW	See next slide

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

NEW!

arXiv:1608.01289

Resonance	Branching fraction (10^{-4})
$D_2^*(2460)^0$	$3.62 \pm 0.06 \pm 0.14 \pm 0.09 \pm 0.25$
$D_1^*(2680)^0$	$0.84 \pm 0.06 \pm 0.07 \pm 0.18 \pm 0.06$
$D_3^*(2760)^0$	$0.10 \pm 0.01 \pm 0.01 \pm 0.02 \pm 0.01$
$D_2^*(3000)^0$	$0.02 \pm 0.01 \pm 0.01 \pm 0.01 \pm 0.00$
$D_v^*(2007)^0$	$1.09 \pm 0.07 \pm 0.07 \pm 0.24 \pm 0.07$
B_v^*	$0.27 \pm 0.10 \pm 0.14 \pm 0.16 \pm 0.02$
Total S-wave	$5.78 \pm 0.08 \pm 0.06 \pm 0.09 \pm 0.39$



- Product branching fraction measured for each resonance ($\mathcal{B}(B^- \to R\pi^-) \times \mathcal{B}(R \to D^+\pi^-)$)
- Due to interference between broad overlapping states, total S-wave described in a model independent way
- Phase motion at low masses (points 1–6) consistent with presence of $D_0^*(2400)^0$ state

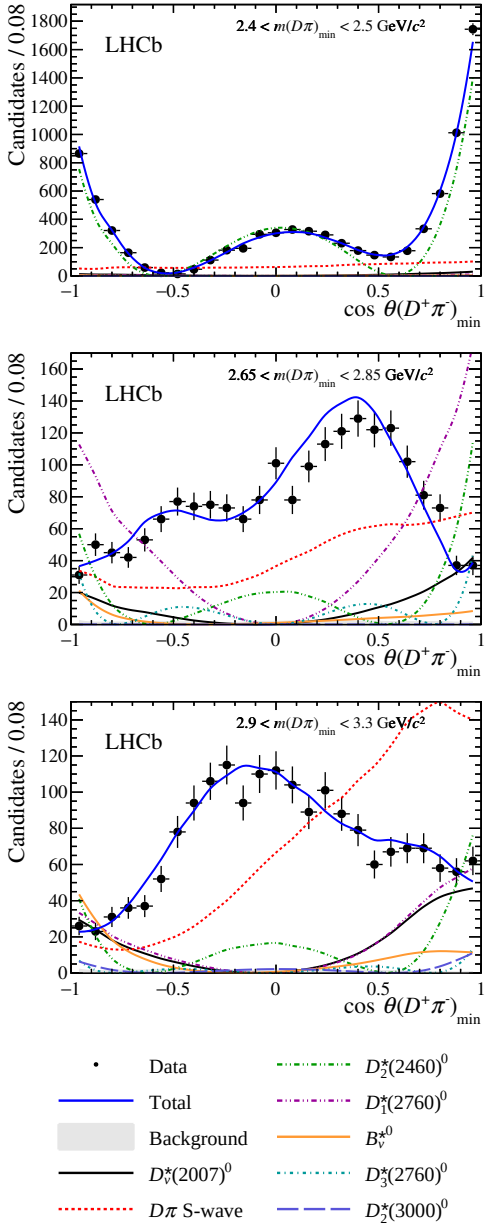
$B^- \to D^+\pi^-\pi^-$

NEW!

arXiv:1608.01289

Contribution	Mass (MeV)	Width (MeV)
$D_2^*(2460)^0$	2463.7 ± 0.8	47.0 ± 1.2
$D_1^*(2680)^0$	2681 ± 15	187 ± 15
$D_3^*(2760)^0$	2775.5 ± 7.9	95 ± 35
$D_2^*(3000)^0$	3214 ± 57	186 ± 81

- Masses and widths of resonances determined from fit
- Sensitivity to spins from angular distributions
- Angular projections of the DP around each resonance (left) show good agreement between data and fit function

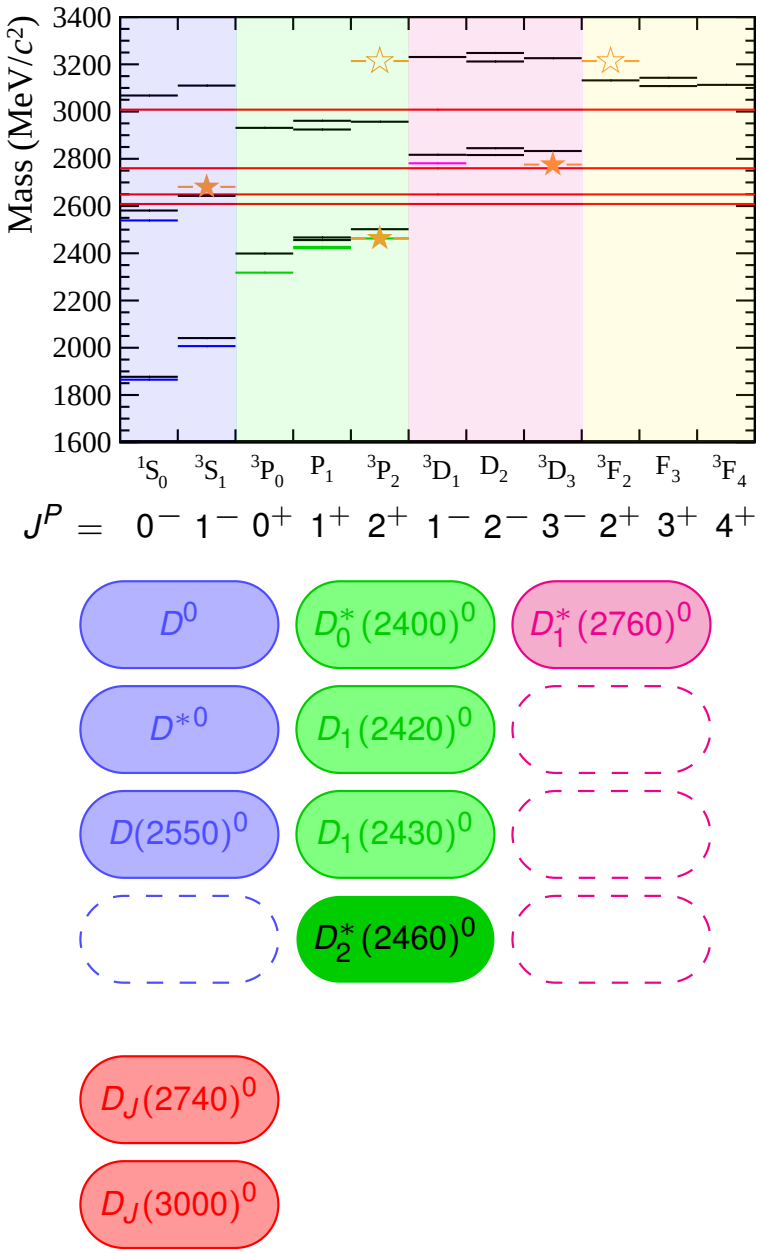


$B^- \to D^+\pi^-\pi^-$

NEW!

arXiv:1608.01289

- **$D_2^*(2460)^0$** in good agreement with world average

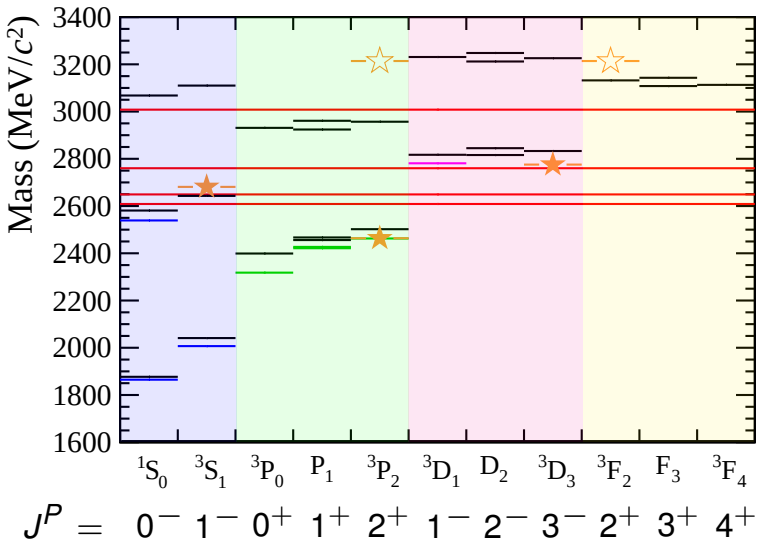


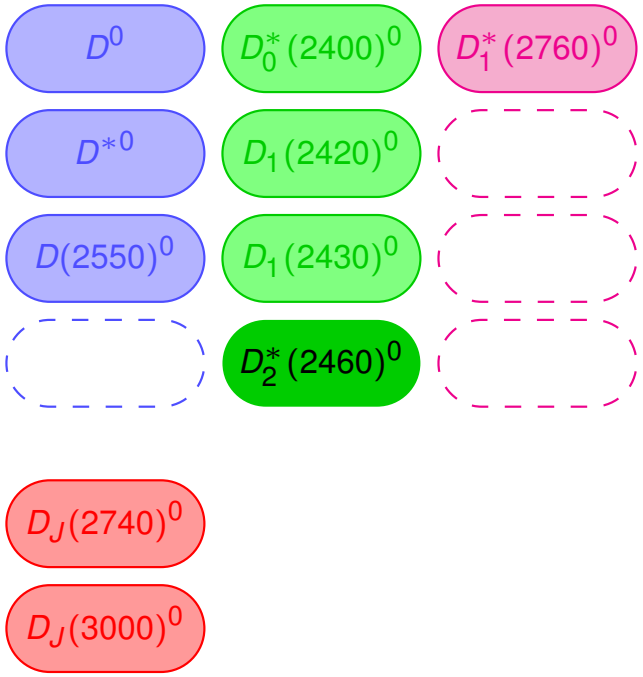
$B^- \to D^+\pi^-\pi^-$

NEW!

arXiv:1608.01289

- $D_2^*(2460)^0$ in good agreement with world average
- First observation of $D_3^*(2760)^0$ and $D_2^*(3000)^0$ resonances



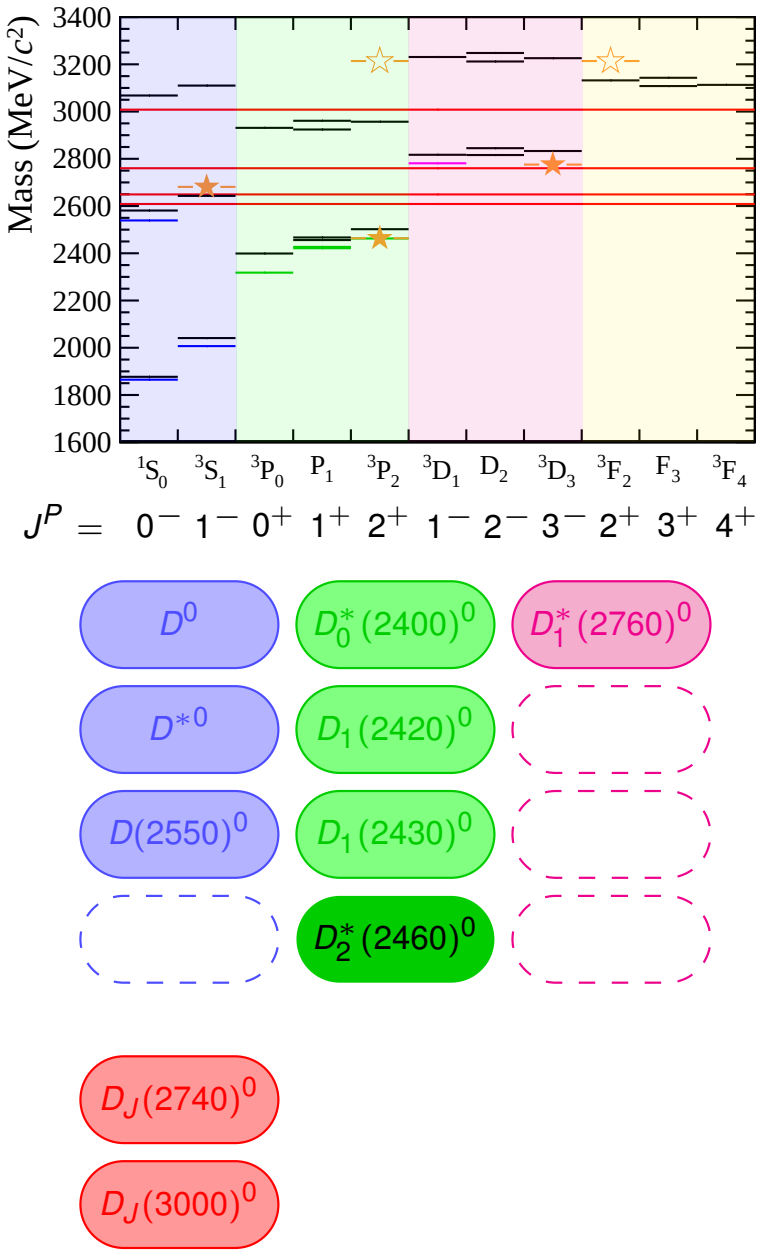


$B^- \to D^+\pi^-\pi^-$

NEW!

arXiv:1608.01289

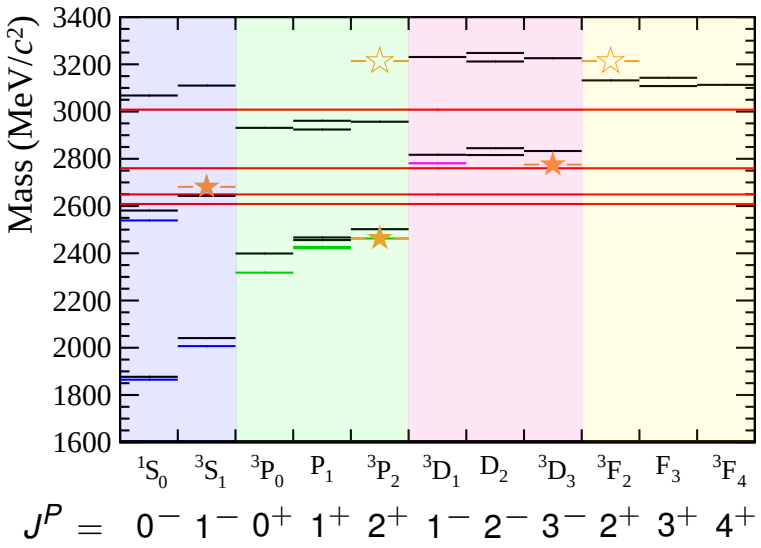
- $D_2^*(2460)^0$ in good agreement with world average
- First observation of $D_3^*(2760)^0$ and $D_2^*(3000)^0$ resonances
- $D_1^*(2680)^0$ and $D_3^*(2760)^0$ confirmed with significances in excess of 10σ

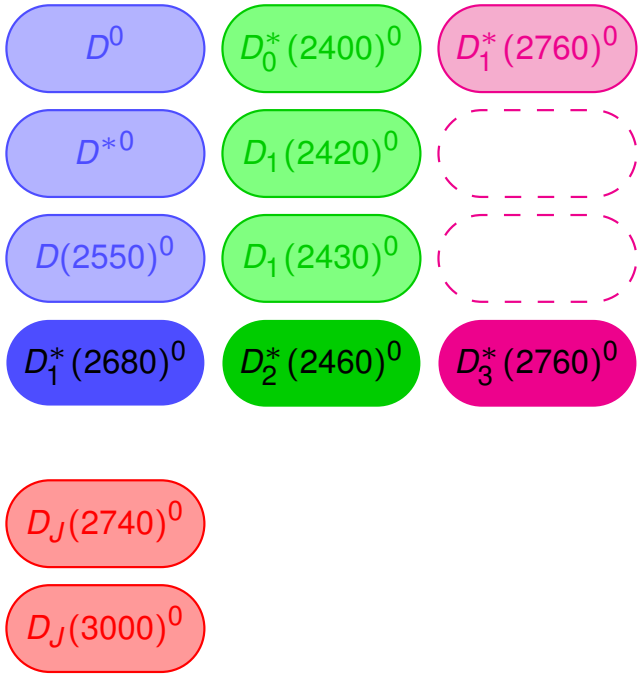


$B^- \to D^+\pi^-\pi^-$

NEW! arXiv:1608.01289

- $D_2^*(2460)^0$ in good agreement with world average
- First observation of $D_3^*(2760)^0$ and $D_2^*(3000)^0$ resonances
- $D_1^*(2680)^0$ and $D_3^*(2760)^0$ confirmed with significances in excess of 10σ
  - most likely correspond to **2S** and **1D** states, respectively

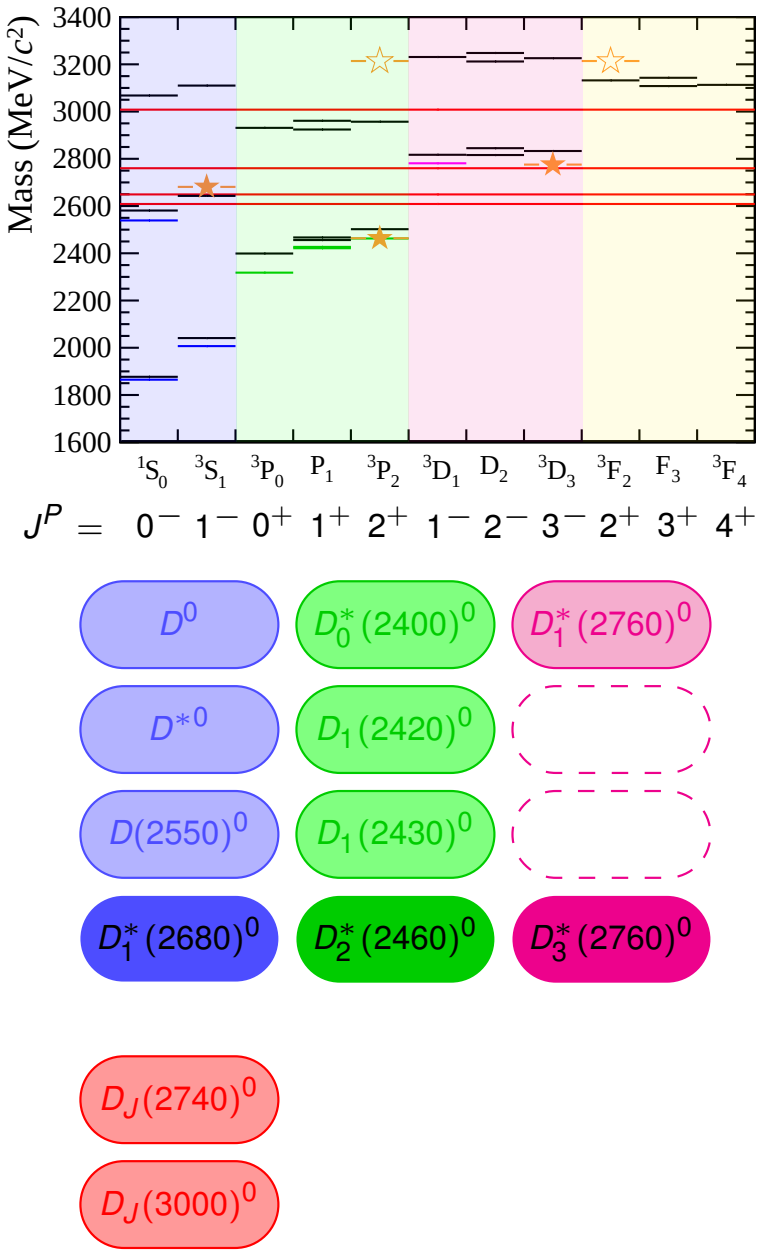




$B^- \to D^+\pi^-\pi^-$

NEW! arXiv:1608.01289

- $D_2^*(2460)^0$ in good agreement with world average
- First observation of $D_3^*(2760)^0$ and $D_2^*(3000)^0$ resonances
- $D_1^*(2680)^0$ and $D_3^*(2760)^0$ confirmed with significances in excess of 10σ
  - most likely correspond to **2S** and **1D** states, respectively
- $D_2^*(3000)^0$ confirmed with significance of 6.6σ

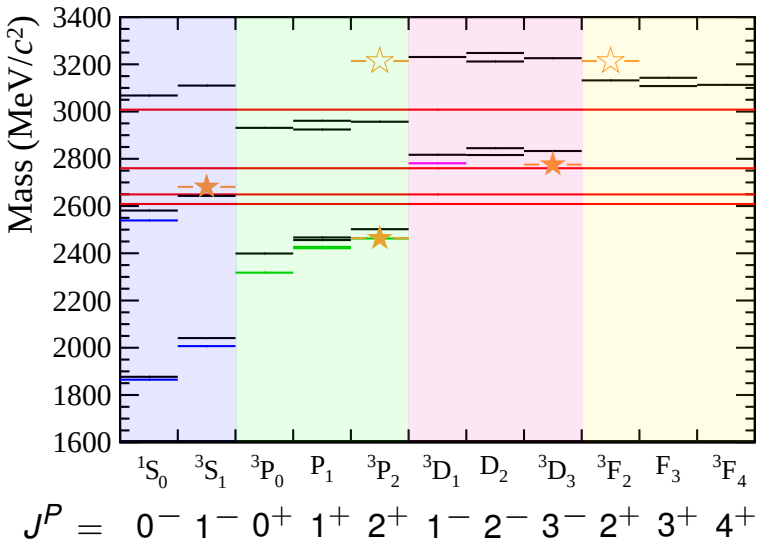


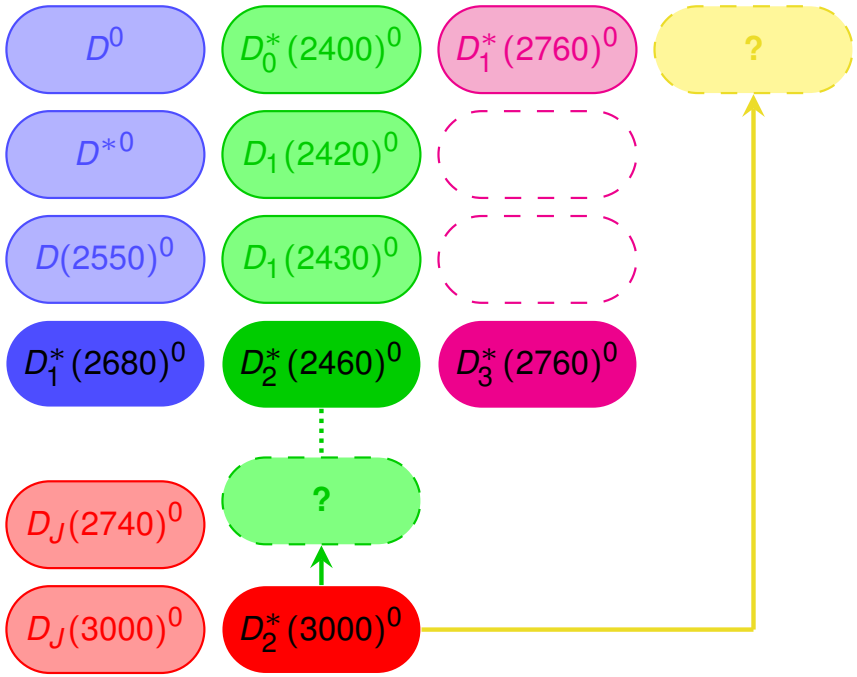
$B^- \to D^+\pi^-\pi^-$

NEW!

arXiv:1608.01289

- $D_2^*(2460)^0$ in good agreement with world average
- First observation of $D_3^*(2760)^0$ and $D_2^*(3000)^0$ resonances
- $D_1^*(2680)^0$ and $D_3^*(2760)^0$ confirmed with significances in excess of 10σ
  - most likely correspond to **2S** and **1D** states, respectively
- $D_2^*(3000)^0$ confirmed with significance of 6.6σ
  - may correspond to either **2P** or **1F** excitation



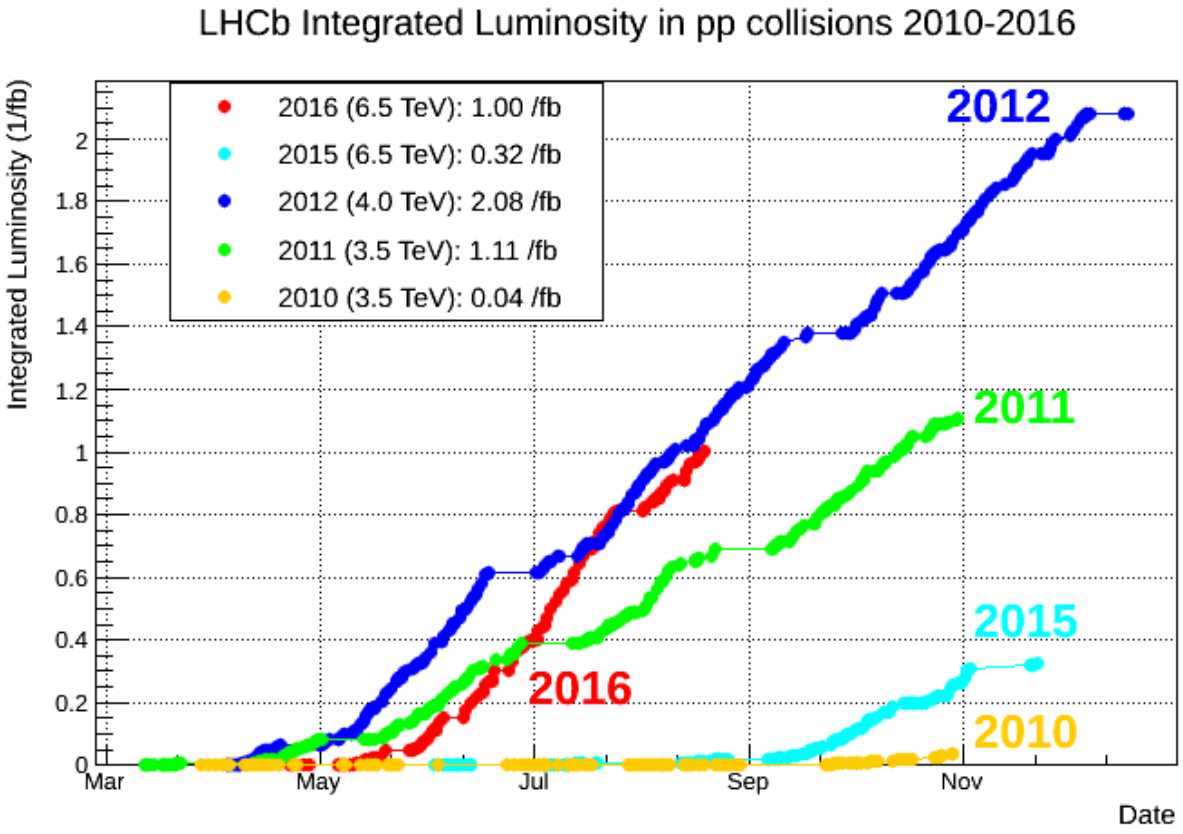


Summary

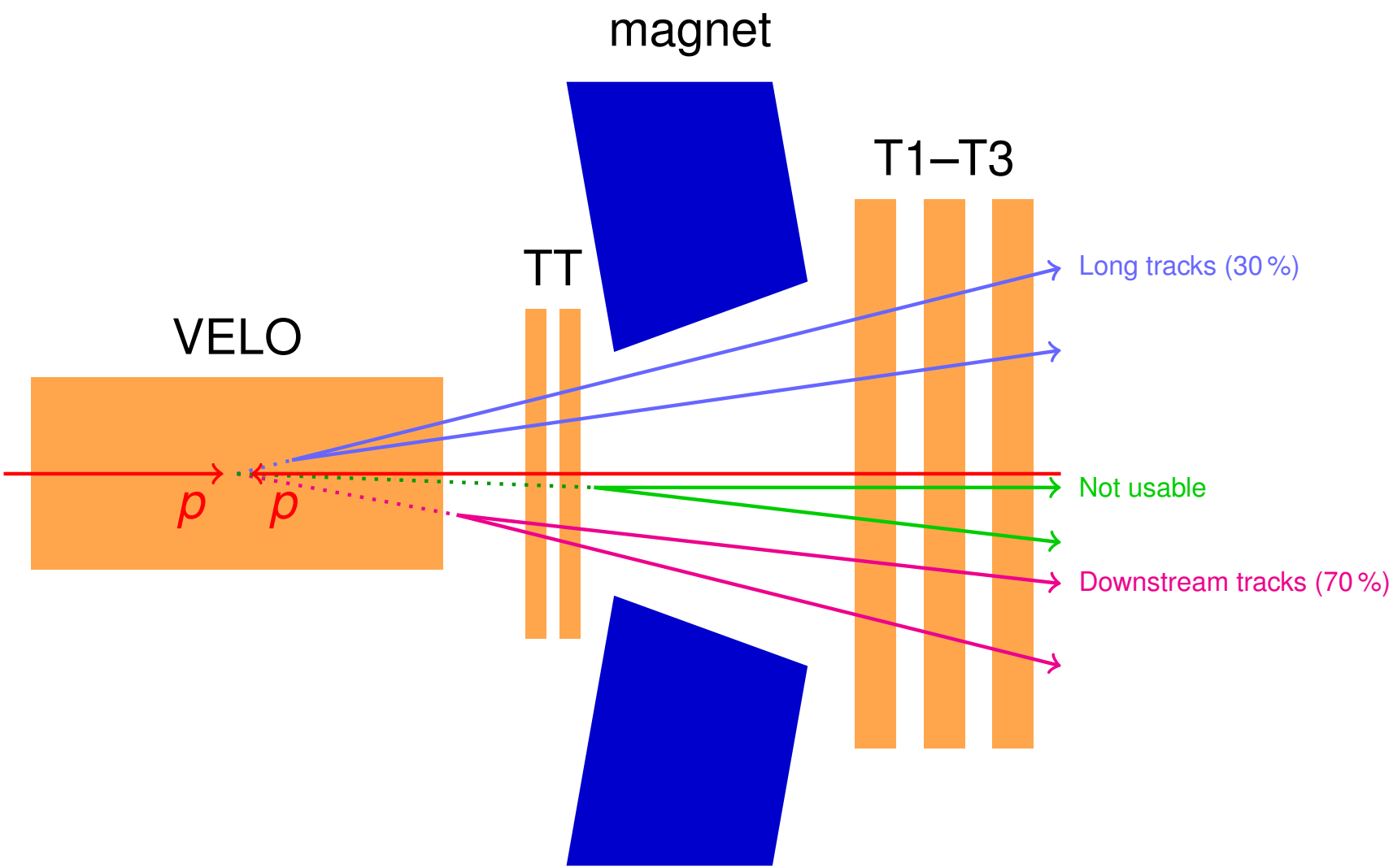
- LHCb confirms observation of $\Xi_b^{*0} \to \Xi_b^- \pi^+$
  - New **best** measurement of **mass**
  - **First** measurement of **width**
- **First observation** of $\eta_c(2S) \to p\bar{p}$ using $B^+ \to p\bar{p}K^+$ decays
- Inclusive $D^{*\pm}K_S^0$ spectroscopy gives **first observation** of $D_{s2}^*(2573)^\pm \to D^{*\pm}K_S^0$ decay
- Dalitz plot analysis of $B^- \to D^+\pi^-\pi^-$ decays gives **first observations** of $D_3^*(2760)^0$ and $D_2^*(3000)^0$
  - Spin of $D_1^*(2680)^0$ also determined for first time

Backup

Luminosity


LHCb Integrated Luminosity in pp collisions 2010-2016
2016 (6.5 TeV): 1.00 /fb
2015 (6.5 TeV): 0.32 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
Integrated Luminosity (1/fb)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Mar
May
Jul
Sep
Nov
Date
2012
2011
2015
2016
2010

K_S^0 Categories



Ξ_b^{**0} resonances

Effect	δm	Γ
Fit bias correction		0.016
Simulated sample size	0.007	0.034
Multiple candidates	0.009	0.007
Resolution model	0.001	0.072
Background description	0.002	0.001
Momentum scale	0.009	0.001
RBW shape	0.017	0.011
Sum in quadrature	0.023	0.082
Statistical uncertainty	0.068	0.162

Systematic uncertainties on the mass and width

JHEP 05 (2016) 161

Ξ_b^{**0} resonances

Effect	Uncertainty
Simulated sample size	2.4%
Tracking efficiency correction	3.0%
Fit quality efficiency correction	1.5%
Soft pion p_{T} cut	1.4%
Ξ_b^{*0} yield	1.0%
Ξ_b^{-} yield	2.0%
Sum in quadrature	4.9%

Systematic uncertainties on the production ratio

JHEP 05 (2016) 161

$\eta_c(2S) \to p\overline{p}$

State	Signal Yield
$\eta_c(1S)$+non res.	11246 ± 119
J/ψ	6721 ± 93
χ_{c0}	84 ± 22
χ_{c1}	95 ± 16
$\eta_c(2S)$	106 ± 22
$\psi(2S)$	588 ± 30
$\psi(3770)$	-6 ± 9
$X(3872)$	-14 ± 8

arXiv:1607.06446

$\eta_c(2S) \to p\overline{p}$

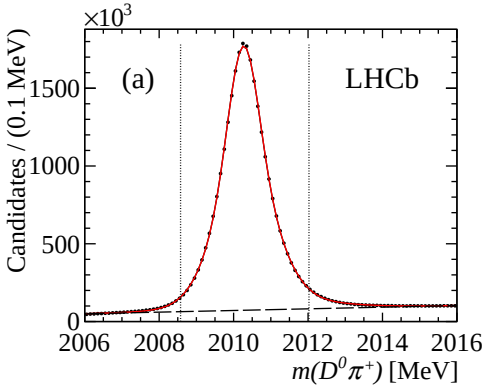
	$\eta_c(2S)$	$X(3872)$	$\psi(3770)$
Fit	5	3	5
BDT	8	2	11
Efficiency	2	1	1
Total	9	4	12

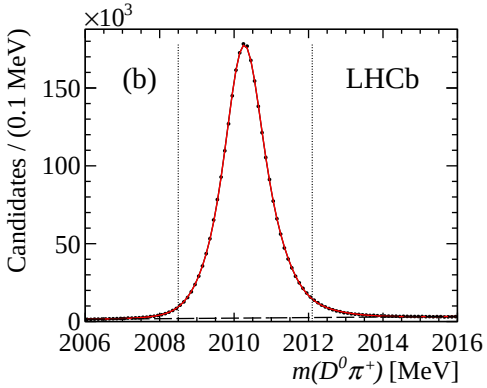
	$M_{J/\psi} - M_{\eta_c(1S)}$ [MeV]	$M_{\psi(2S)} - M_{\eta_c(2S)}$ [MeV]	$\Gamma_{\eta_c(1S)}$ [MeV]
Fit	0.90	0.10	1.20
BDT	0.21	0.55	0.40
Momentum scale	0.03	0.06	-
Total	0.92	0.56	1.27

Systematic uncertainties on (top) branching fractions (10^{-4}) and (bottom) mass and width measurements

arXiv:1607.06446

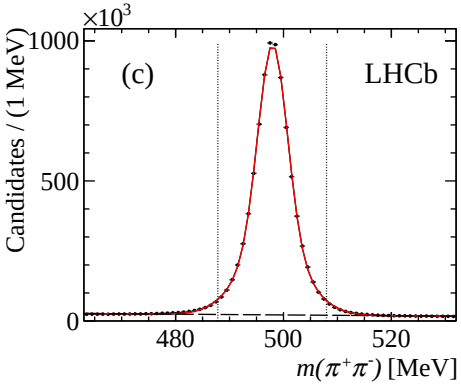
D_s^+ Spectroscopy

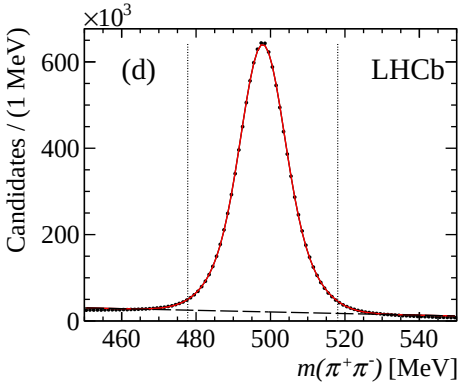


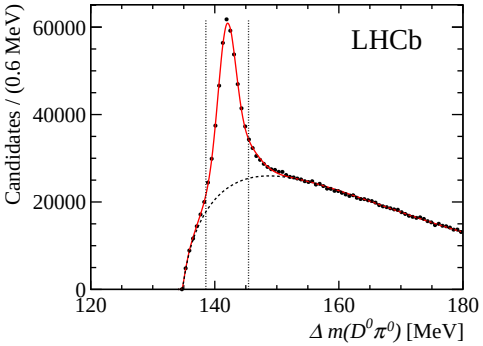


$D^{*+} \to D^0\pi^+$ candidates reconstructed from (a) $D^0 \to K^-\pi^+$ and (b) $D^0 \to K^-\pi^+\pi^+\pi^-$

$K_S^0 \to \pi^+\pi^-$ candidates reconstructed from (c) "long" tracks and (d) "downstream" tracks



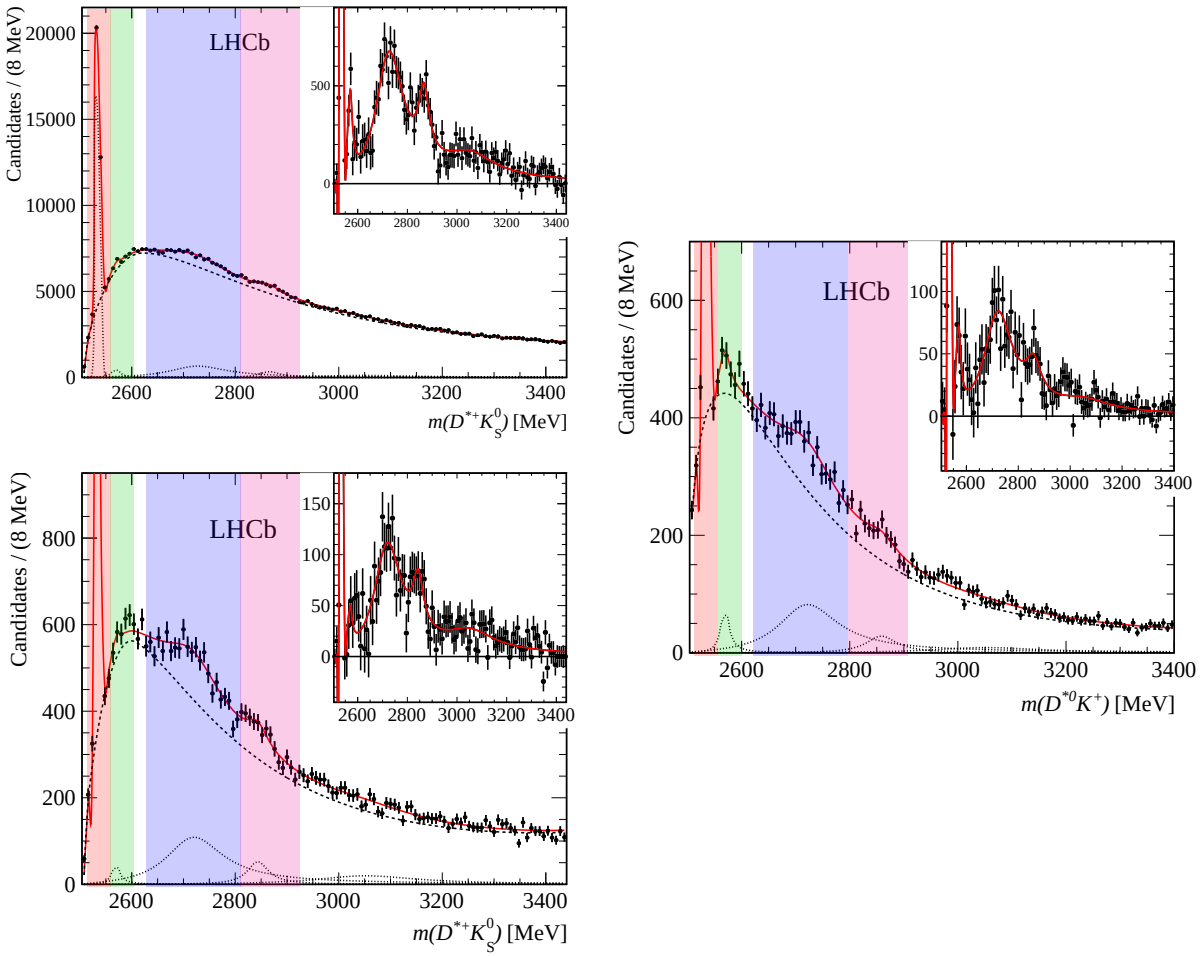




$m(D^0\pi^0) - m(D^0) - m(\pi^0)$ for $D^{*0} \to D^0\pi^0$ candidates

JHEP 02 (2016) 133

D_s^+ Spectroscopy



(Left) $m(D^{*+}K_s^0)$ for (top) $D^0 \to K^-\pi^+$ and (bottom) $K^-\pi^+\pi^+\pi^-$
(Right) $m(D^{*0}\pi^0)$ for $D^0 \to K^-\pi^+$

JHEP 02 (2016) 133

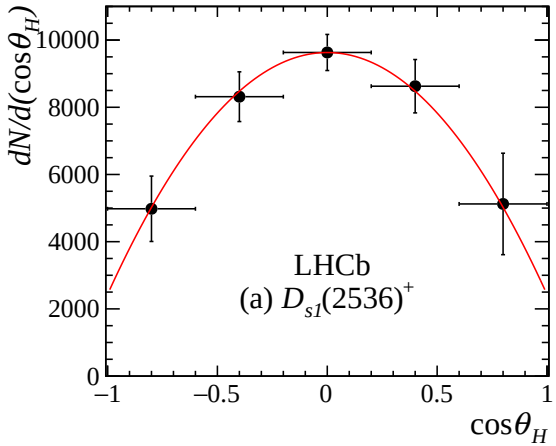
D_s^+ Spectroscopy

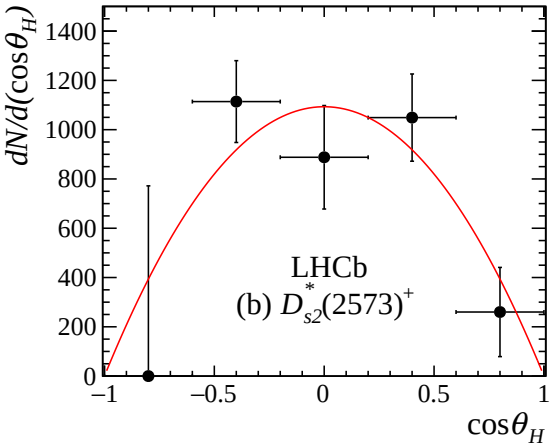
Data		$D_{s1}^*(2700)^+$	$D_{sJ}^*(2860)^+$	χ^2/ndf
(a) $D^{*+}K_S^0$	Mass	$2732.3 \pm 4.3 \pm 5.8$	$2867.1 \pm 4.3 \pm 1.9$	
$D^0 \to K^-\pi^+$	Width	$136 \pm 19 \pm 24$	$50 \pm 11 \pm 13$	
	Yield	$(1.57 \pm 0.28) \times 10^4$	$(3.1 \pm 0.8) \times 10^3$	94/103
	Significance	8.3	6.3	
(b) $D^{*+}K_S^0$	Mass	2729.3 ± 3.3	2861.2 ± 4.3	
$D^0 \to K^-\pi^+$	Width	136 (fixed)	57 ± 14	
NP sample	Yield	$(1.50 \pm 0.11) \times 10^4$	$(2.50 \pm 0.60) \times 10^3$	90/104
	Significance	7.6	7.1	
(c) $D^{*+}K_S^0$	Mass	2732.3 (fixed)	2876.7 ± 6.4	
$D^0 \to K^-\pi^+$	Width	136 (fixed)	50 ± 19	
UP sample	Yield	$(0 \pm 0.8) \times 10^3$	$(1.0 \pm 0.4) \times 10^3$	100/105
	Significance	0.0	3.6	
(d) $D^{*+}K_S^0$	Mass	2725.5 ± 6.0	2844.0 ± 6.5	
$D^0 \to K^-\pi^+\pi^+\pi^-$	Width	136 (fixed)	50 ± 15	
	Yield	$(2.6 \pm 0.4) \times 10^3$	490 ± 180	89/97
	Significance	4.7	3.8	
(e) $D^{*0}K^+$	Mass	2728.3 ± 6.5	2860.9 ± 6.0	
	Width	136 (fixed)	50 (fixed)	
	Yield	$(1.89 \pm 0.30) \times 10^3$	290 ± 90	79/99
	Significance	6.6	3.1	

JHEP 02 (2016) 133

D_s^+ Spectroscopy

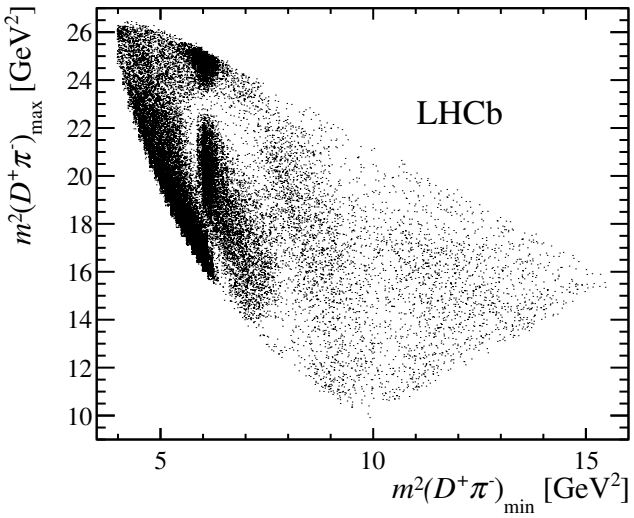
Resonance	J^P	Function	χ^2/ndf
$D_{s1}(2536)^+$	1^+	$1 + h\cos^2\theta_{\mathrm{H}}$	0.1/3
$D_{s2}^*(2573)^+$	2^+	$\sin^2\theta_{\mathrm{H}}$	2.2/4
$D_{s1}^*(2700)^+$	1^-	$\sin^2\theta_{\mathrm{H}}$	11.4/7
$D_{s3}^*(2860)^+$	3^-	$\sin^2\theta_{\mathrm{H}}$	13.4/7
$D_{sJ}(3040)^+$	UP	$1 + h\cos^2\theta_{\mathrm{H}}$	8.0/6

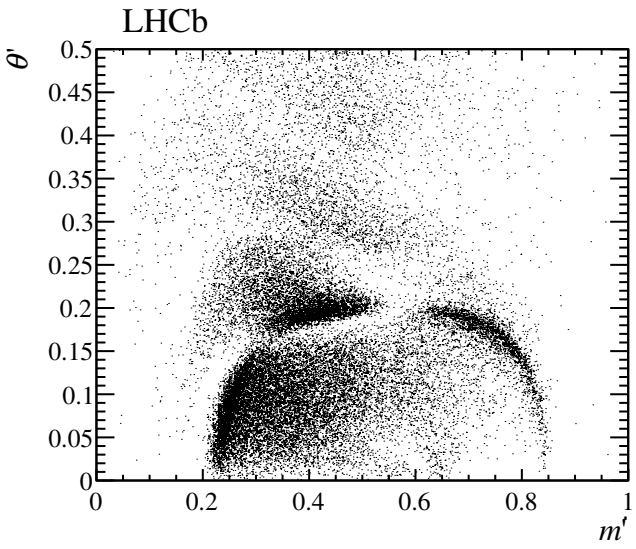




JHEP 02 (2016) 133

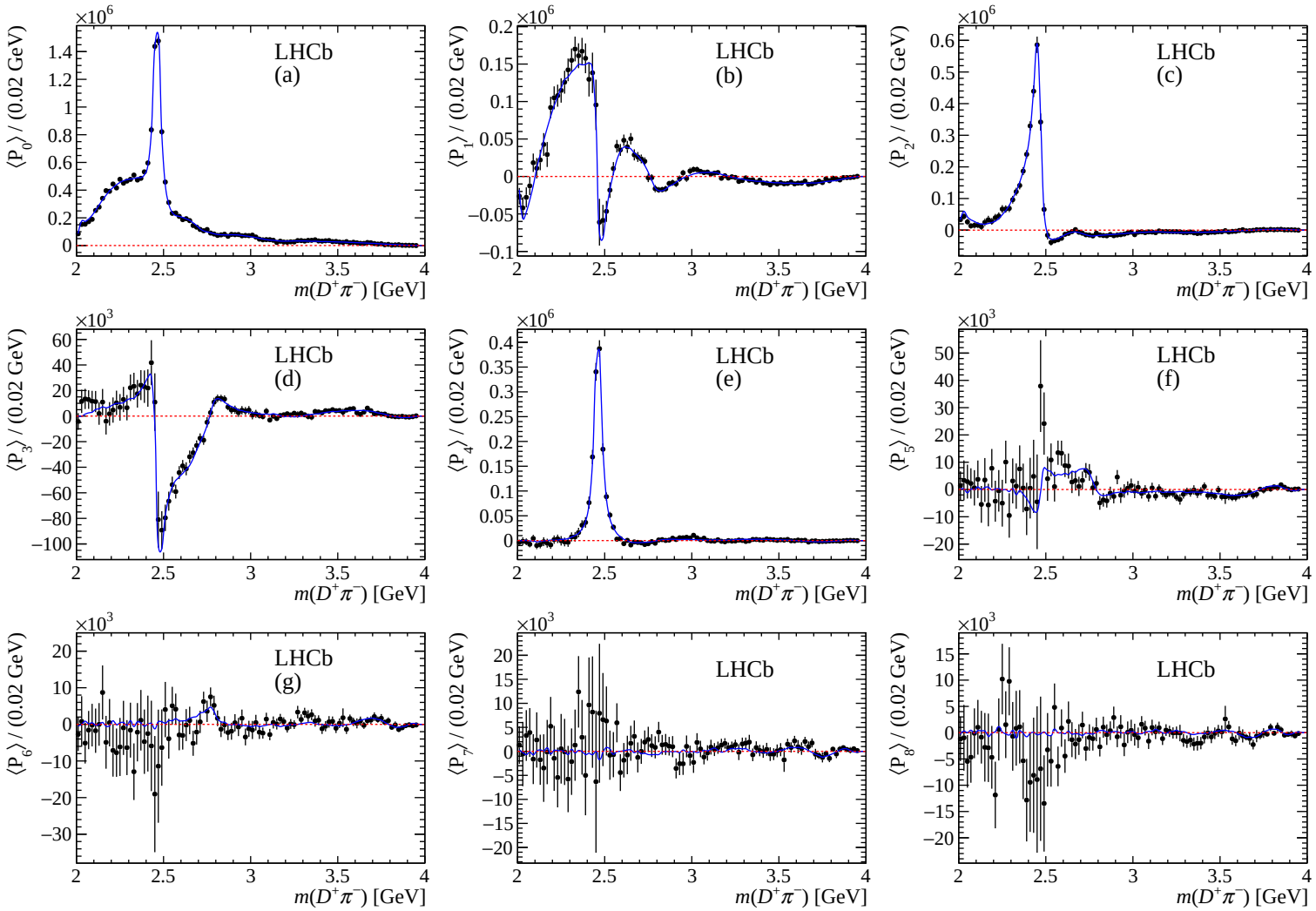
$B^- \to D^+\pi^-\pi^-$





arXiv:1608.01289

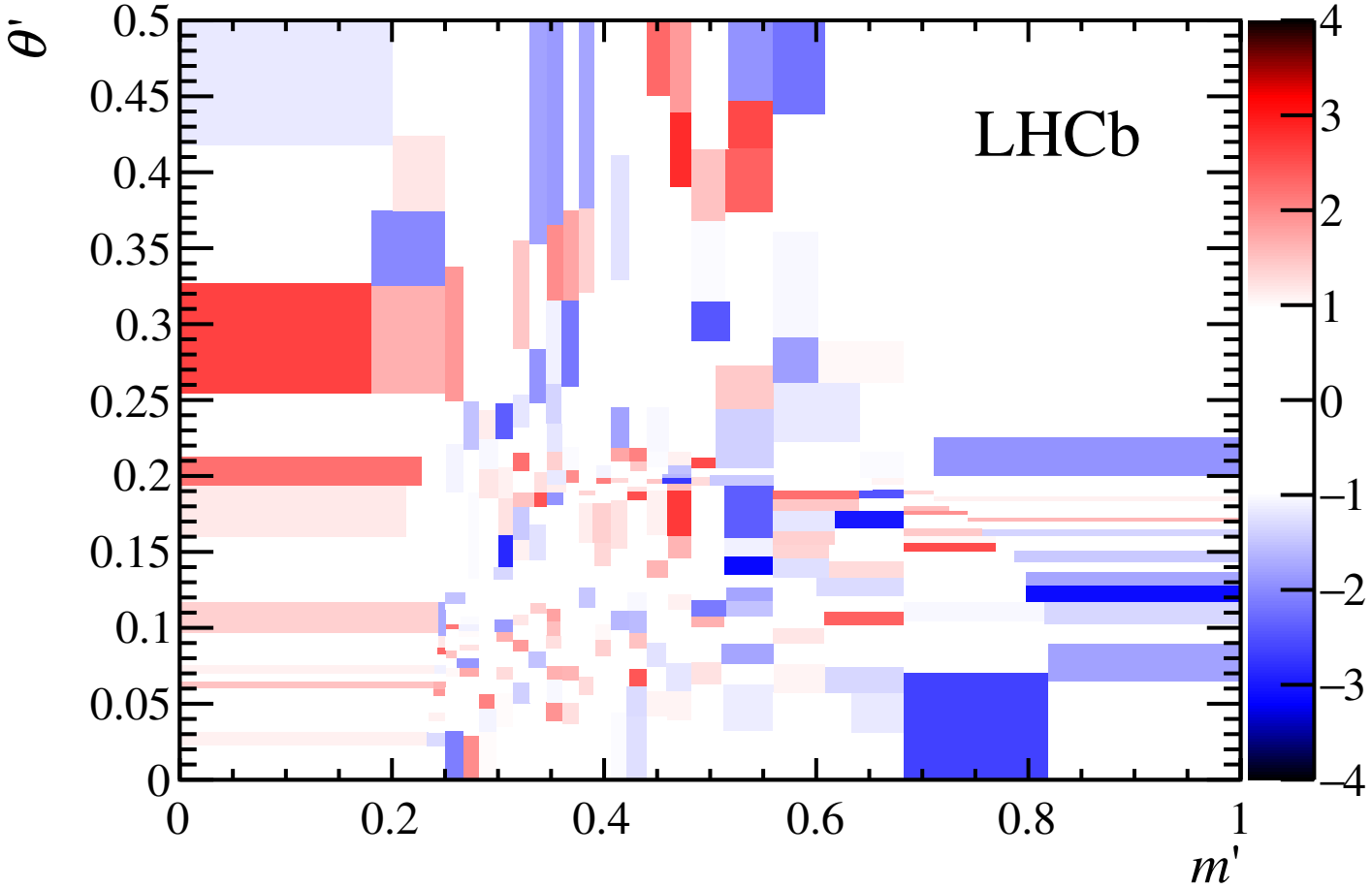
$B^- \to D^+\pi^-\pi^-$



The first nine unnormalised moments for background-subtracted efficiency-corrected data

arXiv:1608.01289

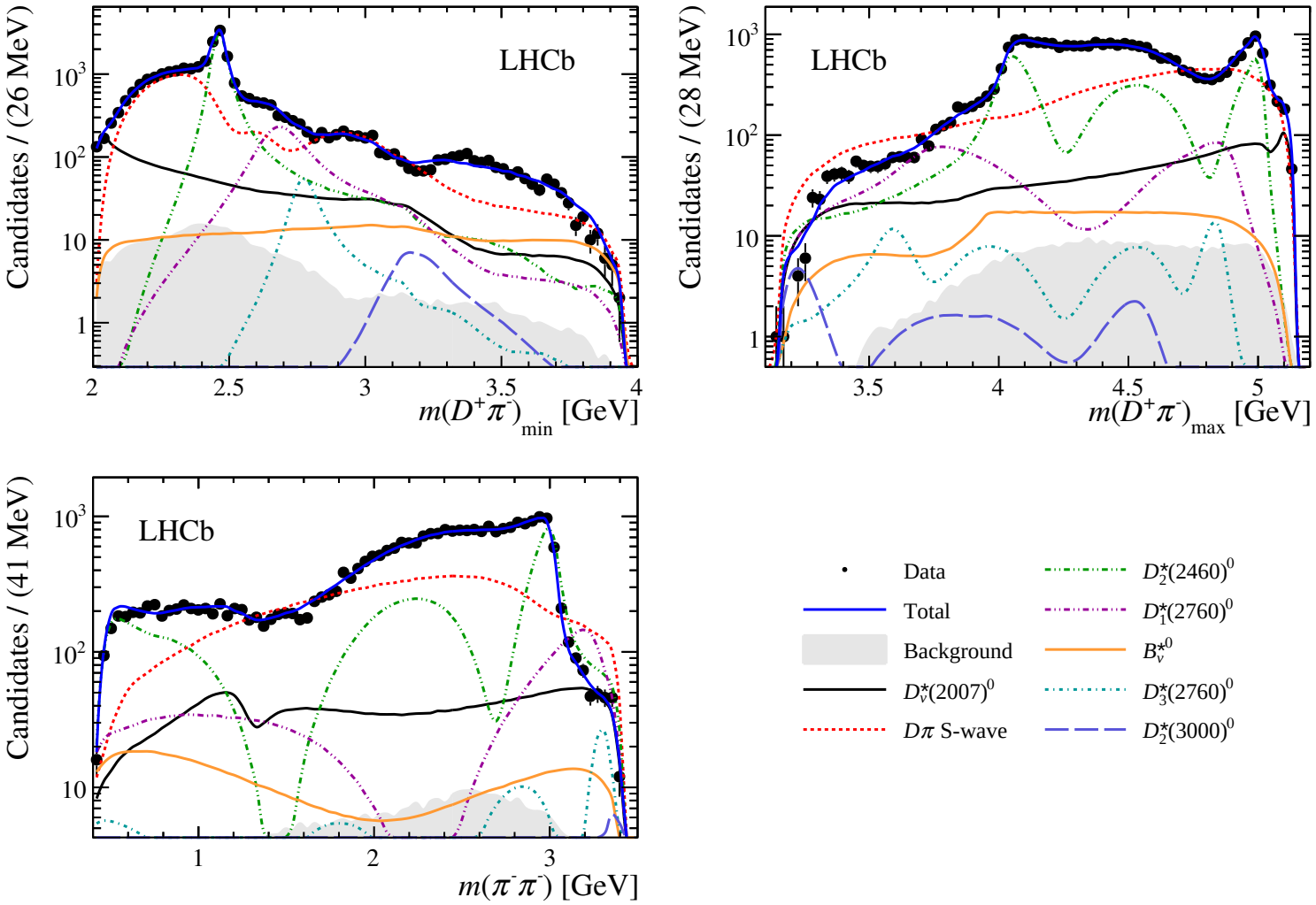
$B^- \to D^+\pi^-\pi^-$



Pulls between data and the fit model in equally populated bins across the square Dalitz plot

arXiv:1608.01289

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



Mass projections of the Dalitz plot on logarithmic scales

arXiv:1608.01289

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

	Nominal	S/B frac.	Eff.	Bkgd.	Fit bias	Total
$D_2^*(2460)^0$	35.7 ± 0.6	0.1	1.3	0.0	0.2	1.4
$D_1^*(2680)^0$	8.3 ± 0.6	0.0	0.7	0.1	0.1	0.7
$D_3^*(2760)^0$	1.0 ± 0.1	0.0	0.1	0.0	0.0	0.1
$D_2^*(3000)^0$	0.2 ± 0.1	0.0	0.1	0.0	0.0	0.1
$D_v^*(2007)^0$	10.8 ± 0.7	0.0	0.7	0.1	0.1	0.7
B_v^*	2.7 ± 1.0	0.0	1.4	0.1	0.2	1.4
Total S-wave	57.0 ± 0.8	0.1	0.6	0.1	0.1	0.6
$m\left(D_2^*(2460)^0\right)$	2463.7 ± 0.4	0.0	0.3	0.1	0.1	0.3
$\Gamma\left(D_2^*(2460)^0\right)$	47.0 ± 0.8	0.1	0.9	0.1	0.0	0.9
$m\left(D_1^*(2680)^0\right)$	2681.1 ± 5.6	0.1	4.8	0.9	0.2	4.9
$\Gamma\left(D_1^*(2680)^0\right)$	186.7 ± 8.5	0.5	8.4	1.0	1.2	8.6
$m\left(D_3^*(2760)^0\right)$	2775.5 ± 4.5	0.4	4.4	0.6	0.4	4.5
$\Gamma\left(D_3^*(2760)^0\right)$	95.3 ± 9.6	0.9	5.9	1.5	4.9	7.9
$m\left(D_2^*(3000)^0\right)$	3214 ± 29	3	29	13	9	33
$\Gamma\left(D_2^*(3000)^0\right)$	186 ± 38	2	31	8	12	34

	Nominal	Fixed params.	Add $D_1^*(2760)^0$	Alternative models	DP veto	Total
$D_2^*(2460)^0$	35.7 ± 0.6	0.9	0.0	0.0	0.1	0.9
$D_1^*(2680)^0$	8.3 ± 0.6	0.2	0.9	0.0	1.5	1.8
$D_3^*(2760)^0$	1.0 ± 0.1	0.0	0.0	0.0	0.2	0.2
$D_2^*(3000)^0$	0.2 ± 0.1	0.0	0.0	0.0	0.1	0.1
$D_v^*(2007)^0$	10.8 ± 0.7	2.3	0.1	0.0	0.2	2.3
B_v^*	2.7 ± 1.0	1.2	0.2	0.0	1.0	1.6
Total S-wave	57.0 ± 0.8	0.8	0.4	0.0	0.1	0.9
$m\left(D_2^*(2460)^0\right)$	2463.7 ± 0.4	0.4	0.1	0.0	0.4	0.6
$\Gamma\left(D_2^*(2460)^0\right)$	47.0 ± 0.8	0.2	0.0	0.0	0.1	0.3
$m\left(D_1^*(2680)^0\right)$	2681.1 ± 5.6	4.7	11.8	0.1	3.0	13.1
$\Gamma\left(D_1^*(2680)^0\right)$	186.7 ± 8.5	3.2	4.5	0.3	6.0	8.2
$m\left(D_3^*(2760)^0\right)$	2775.5 ± 4.5	3.4	0.4	0.0	3.3	4.7
$\Gamma\left(D_3^*(2760)^0\right)$	95.3 ± 9.6	2.8	3.2	0.0	32.9	33.1
$m\left(D_2^*(3000)^0\right)$	3214 ± 29	25	1	1	26	36
$\Gamma\left(D_2^*(3000)^0\right)$	186 ± 38	7	19	0	60	63

(Left) Experimental and (right) model systematic uncertainties on the parameters

arXiv:1608.01289

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

Resonance	Fit fraction (%)
$D_2^*(2460)^0$	$35.69 \pm 0.62 \pm 1.37 \pm 0.89$
$D_1^*(2680)^0$	$8.32 \pm 0.62 \pm 0.69 \pm 1.79$
$D_3^*(2760)^0$	$1.01 \pm 0.13 \pm 0.13 \pm 0.25$
$D_2^*(3000)^0$	$0.23 \pm 0.07 \pm 0.07 \pm 0.08$
$D_v^*(2007)^0$	$10.79 \pm 0.68 \pm 0.74 \pm 2.34$
B_v^*	$2.69 \pm 1.01 \pm 1.43 \pm 1.61$
Total S-wave	$56.96 \pm 0.78 \pm 0.62 \pm 0.87$

Fit fractions with statistical, experimental systematic, and model uncertainties

arXiv:1608.01289