Charmed Spectroscopy at LHCb

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Outline

- The LHCb detector
- Charmed meson D_J spectroscopy
- Search for the doubly charmed baryon Ξ_{cc}^{+}
- Summary

The LHCb detector

Single arm forward detector, optimized for heavy flavour physics

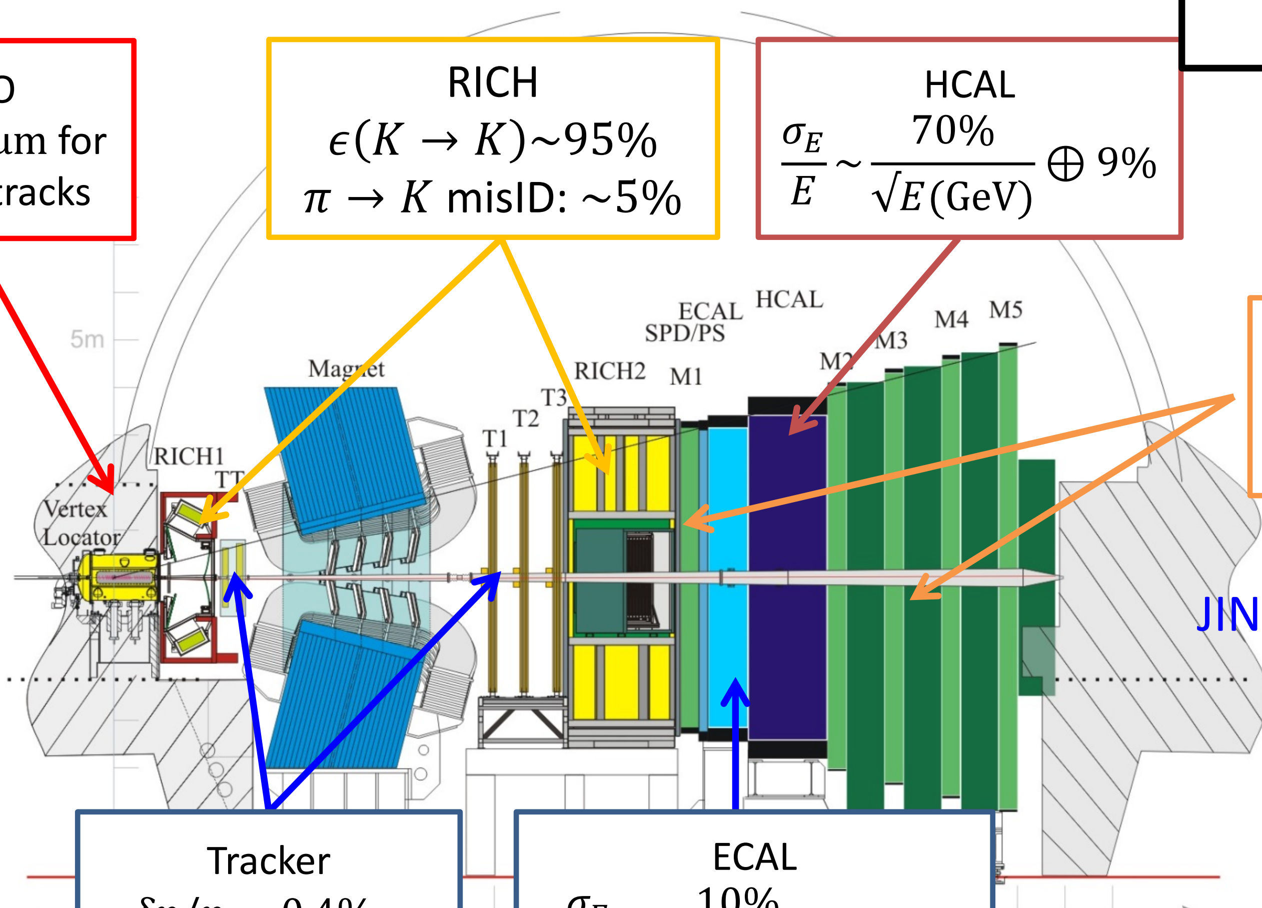
Pseudorapidity coverage
$2 < \eta < 5$

VELO
$\sigma_{IP} \sim 20\mu m$ for high p_T tracks

RICH
$\epsilon(K \to K) \sim 95\%$
$\pi \to K$ misID: $\sim 5\%$

HCAL
$\frac{\sigma_E}{E} \sim \frac{70\%}{\sqrt{E(\mathrm{GeV})}} \oplus 9\%$

Muon System
$\epsilon(\mu \to \mu) \sim 97\%$
$\pi \to \mu$ misID: $1-3\%$



JINST 3 S08005 (2008)

Tracker
$\delta p/p = 0.4\% \sim 0.6\%$

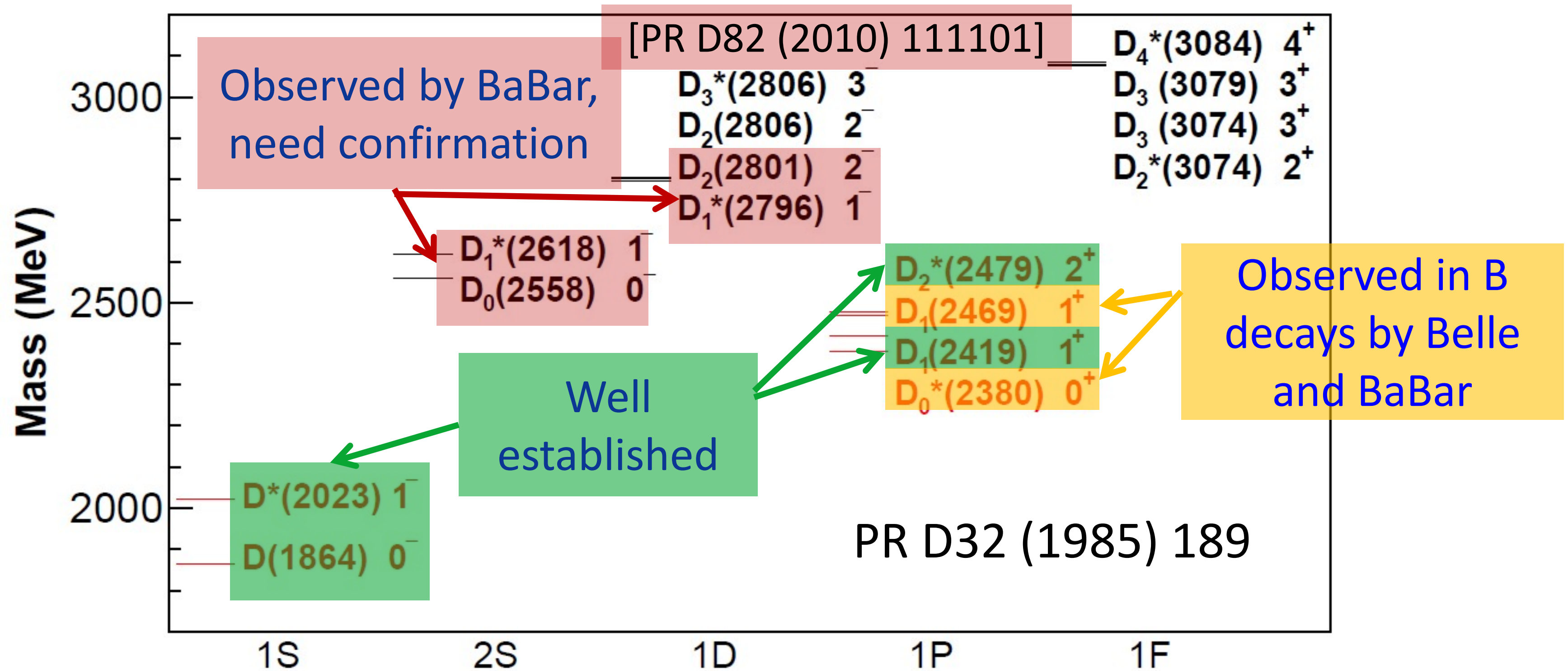
ECAL
$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E(\mathrm{GeV})}} \oplus 1\%$

- Charmed meson D_J spectroscopy

  [JHEP 09 (2013) 145, LHCb-PAPER-2013-026]

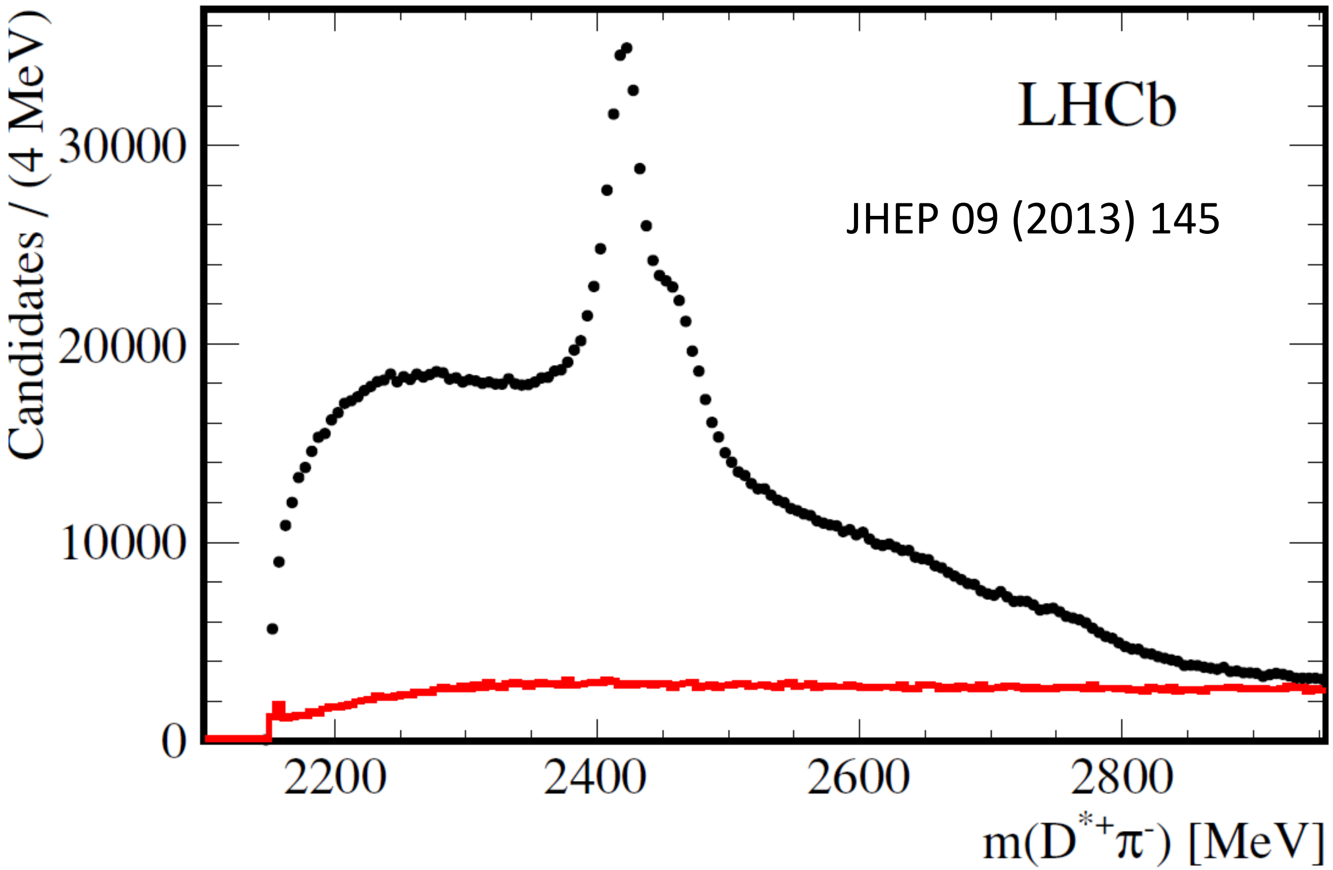
Introduction

- D_J meson spectroscopy provides tests of the quark model
  - Only few states observed
- BaBar experiment found four new states which need to be confirmed



- LHCb study the D_J mesons in $D^+\pi^-$, $D^0\pi^+$ and $D^{*+}\pi^-$ final states using 1fb^{-1} pp collision data

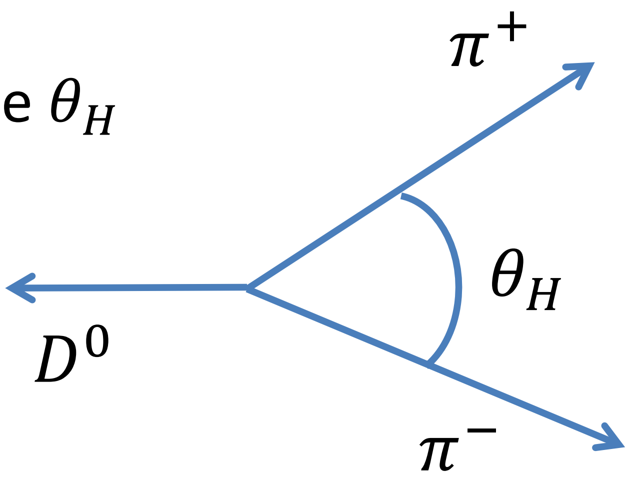
$D^{*+}\pi^-$ mass spectra



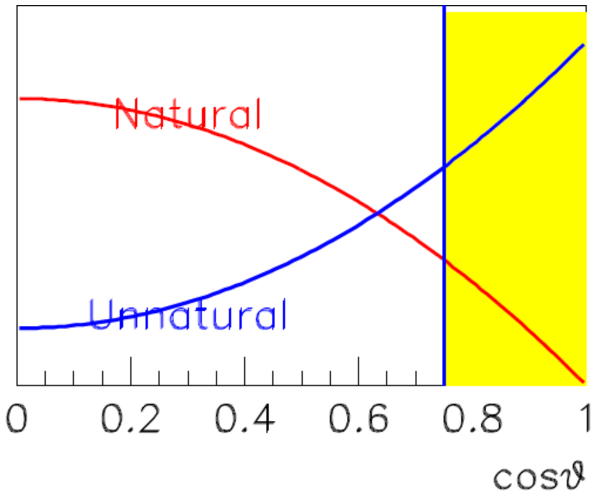
- Clear signal of $D_1(2420)^0$ and $D_2^*(2460)^0$
- Complex structures in the mass range 2600 – 2800 MeV
- No significant structure in the wrong sign ($D^{*+}\pi^+$) sample

$D^{*+}\pi^-$ angular distributions

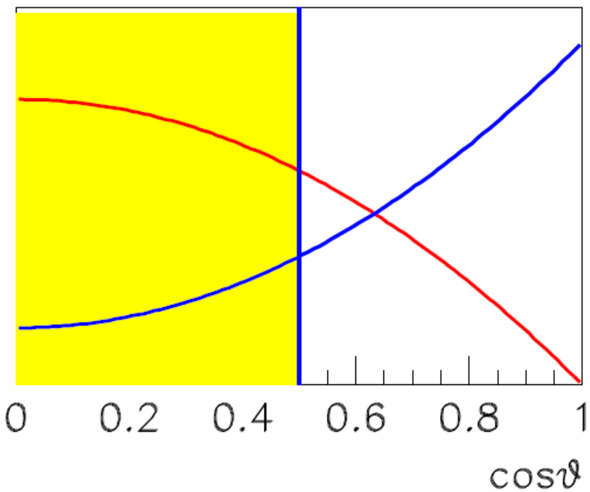
- Extract spin-parity of D_J in the angular distribution of $D^{*+}\pi^-$ using the helicity angle θ_H
  - Natural Parity: $J^P = 0^+, 1^-, 2^+ ..$
    - Angular distribution: $\propto \sin^2\theta_H$
  - Unnatural Parity: $J^P = 0^-, 1^+, 2^- ..$
    - Angular distribution: $\propto 1 + h\cos^2\theta_H$



Enhanced Unnatural Parity Sample: $|\cos\theta_H| > 0.75$



Natural Parity Sample: $|\cos\theta_H| < 0.5$



- Contributions from Natural Parity states highly suppressed
  - $D_2^*(2460)^0$ contribution consistent with zero
  - Clear $D_1(2420)^0$ signal

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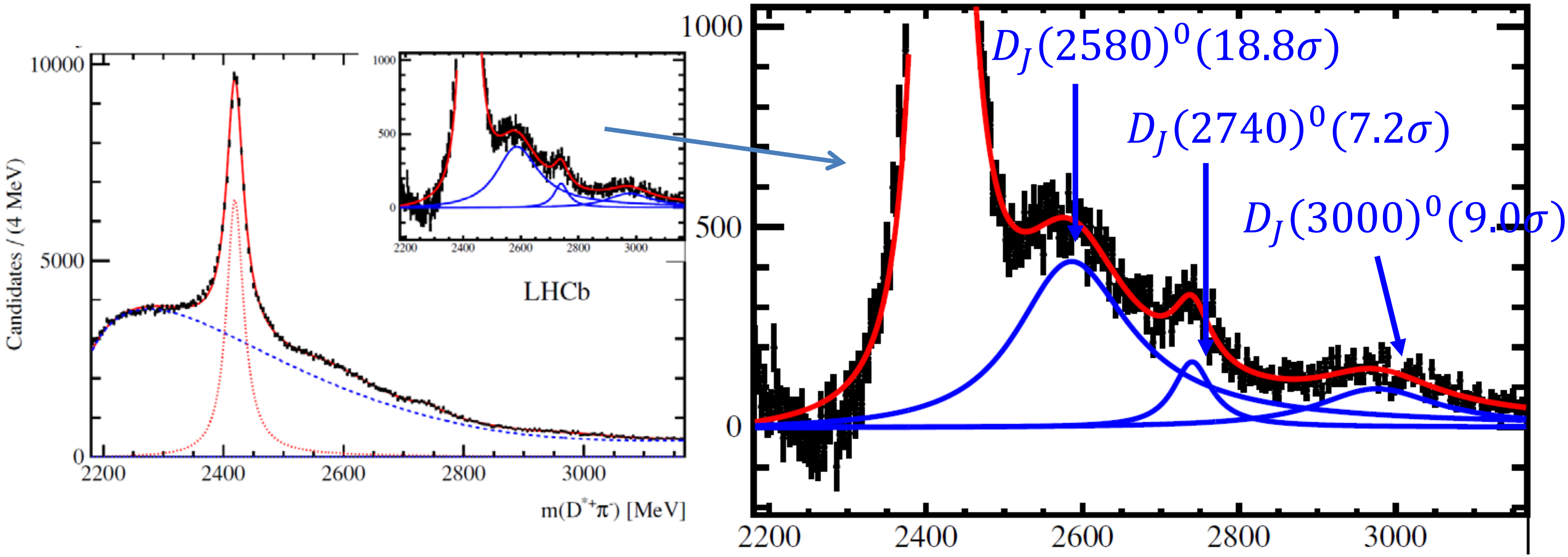
- Three new structures observed: $D_J(2580)^0$, $D_J(2740)^0$ and $D_J(3000)^0$



Background subtracted distribution

- Expect contribution from Natural Parity states and Unnatural Parity states
  - Clear $D_1(2420)^0$ and $D_2^*(2460)^0$ signal

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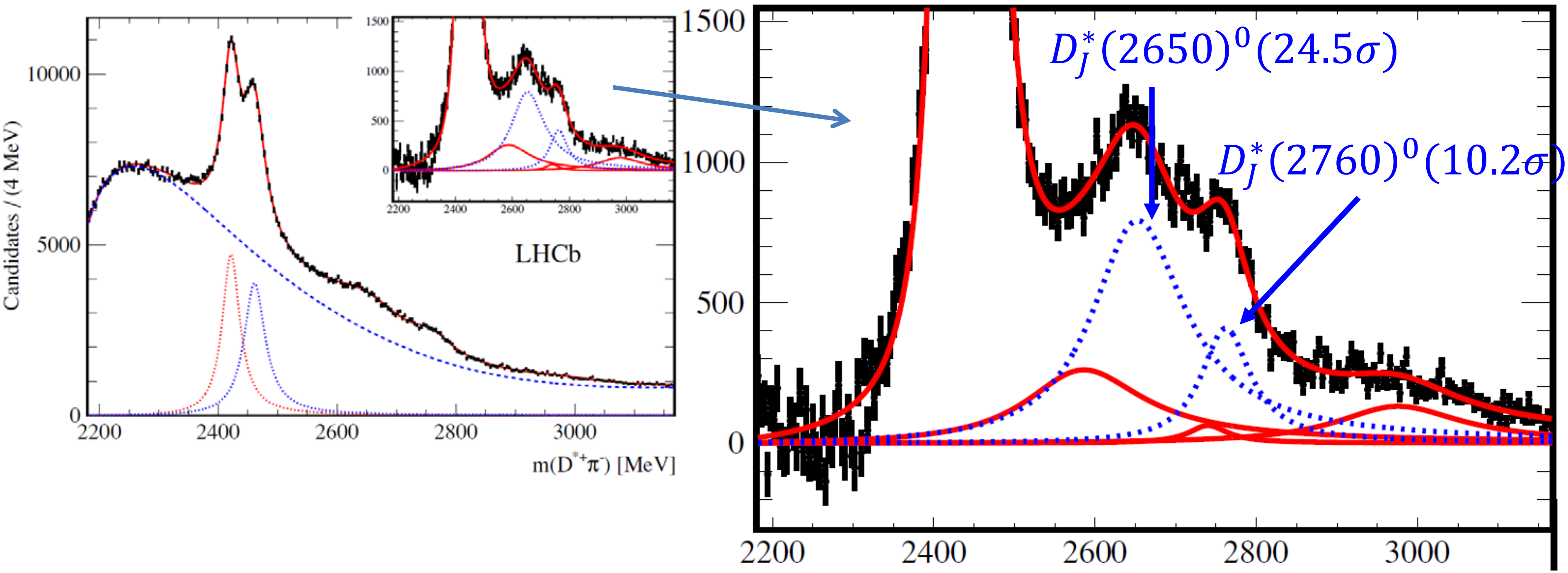
- Two new structures observed: $D_J^*(2650)^0$ and $D_J^*(2760)^0$



Background subtracted distribution

Angular distribution(I)

Unnatural Parity hypothesis

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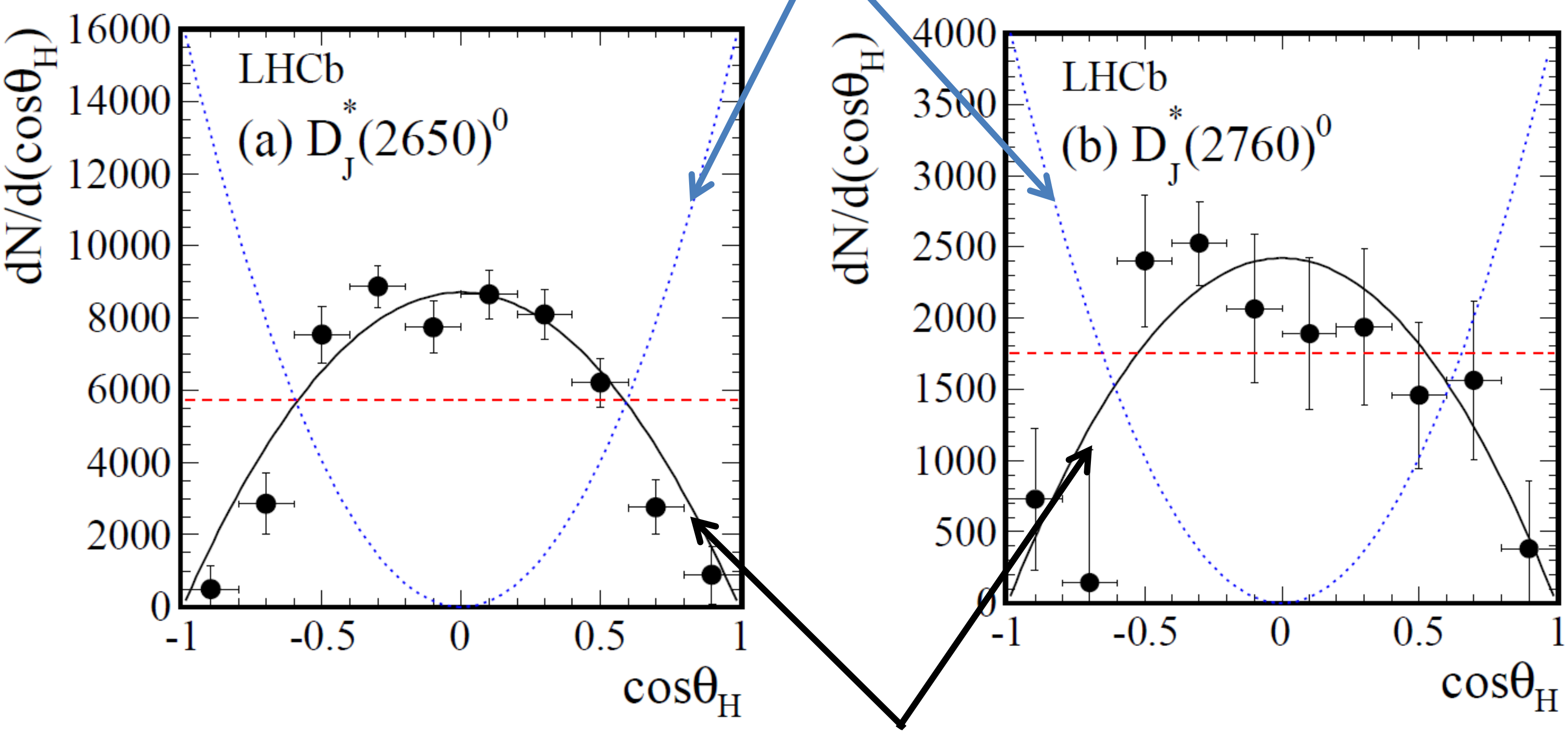

Natural Parity hypothesis

- $D_J^*(2650)^0$ and $D_J^*(2760)^0$ found to have natural parity

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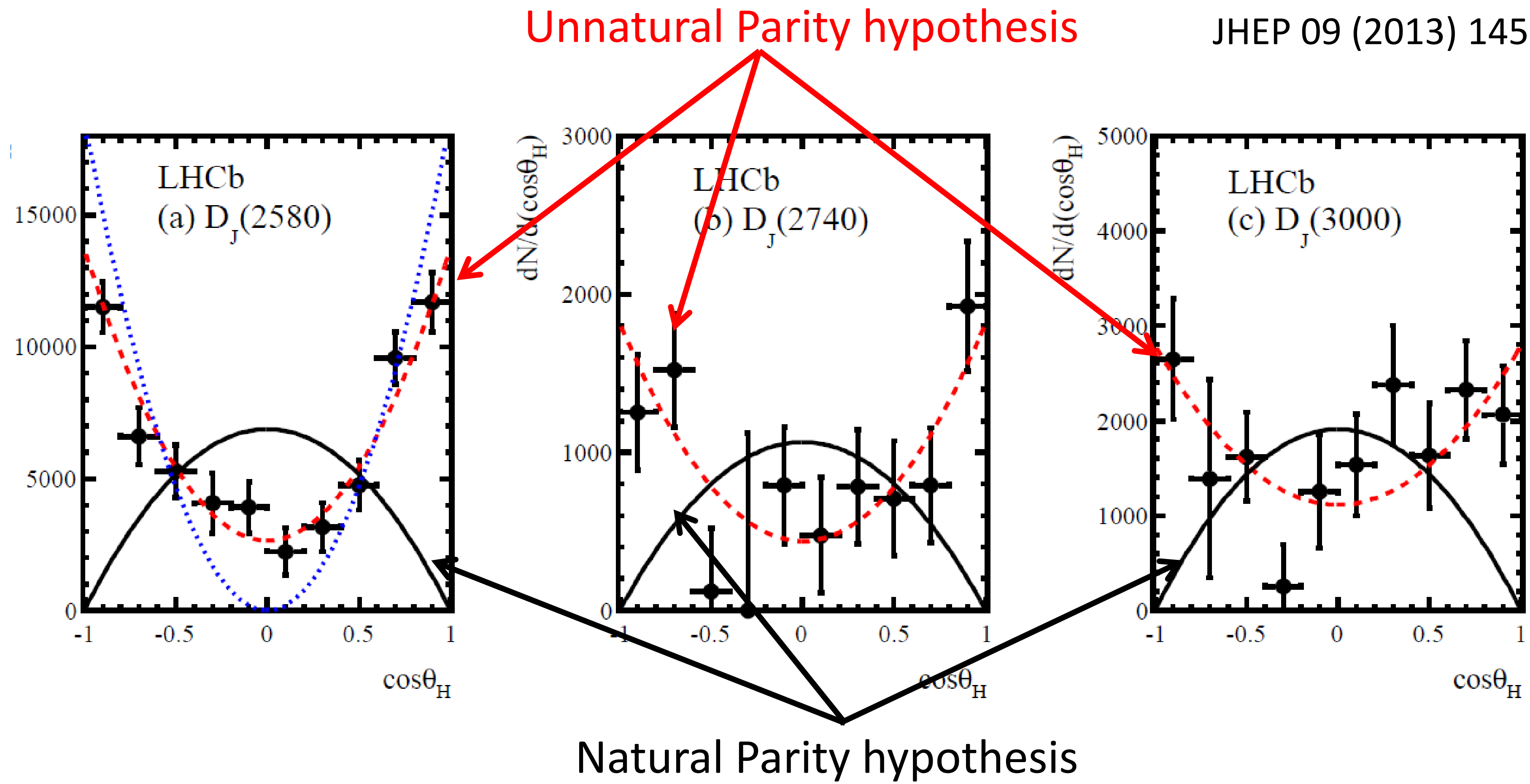
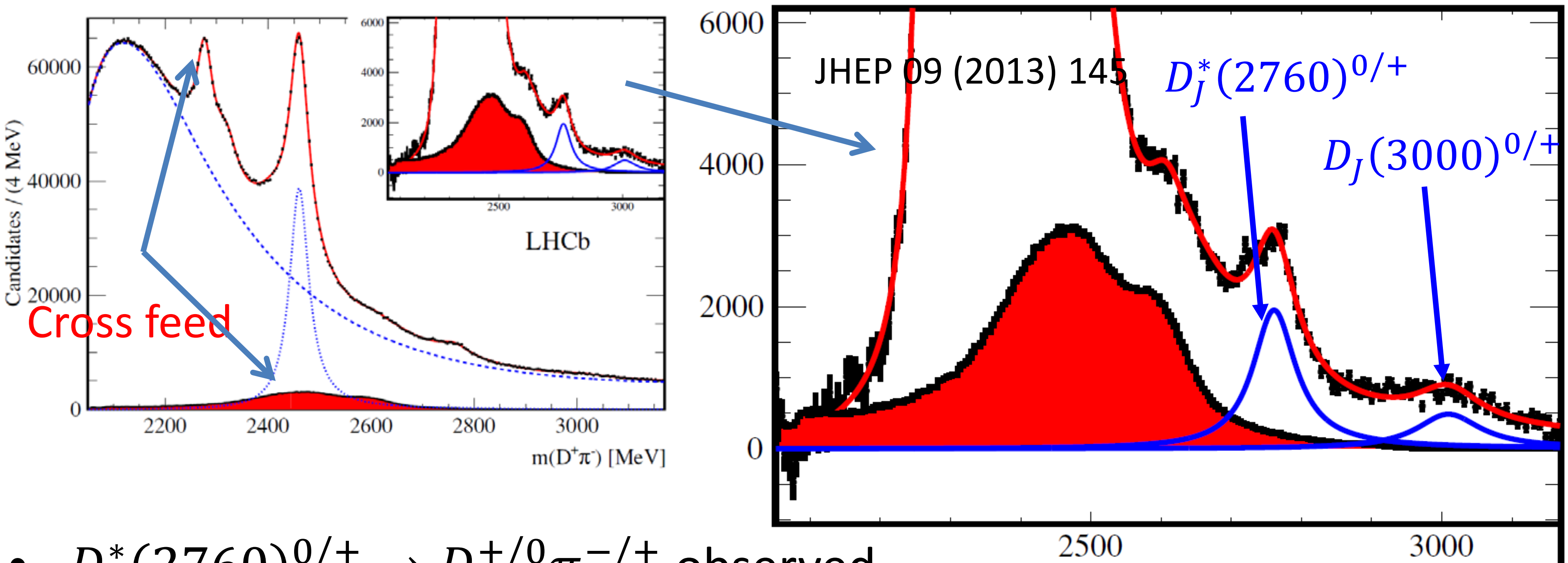


- $D_J(2580)^0$,$D_J(2740)^0$ and $D_J(3000)^0$ found to have unnatural parity

$D^{+/0}\pi^{-/+}$ mass spectra

- Only natural parity resonances could contribute due to parity conservation: $D_2^*(2460)^{0/+}, D_J^*(2650)^{0/+}, D_J^*(2760)^{0/+}$
- Cross-feed from higher excited states $D_J \to \pi^+ D^{*+/0}(\to D^{+/0}\pi^0/\gamma)$



- $D_J^*(2760)^{0/+} \to D^{+/0}\pi^{-/+}$ observed
- Require a broad structure around 3000 MeV to fit the spectra

- We observe four new states: $D_J^*(2650)^0$, $D_J^*(2760)^{0/+}$, $D_J(2580)^0$ and $D_J(2740)^0$

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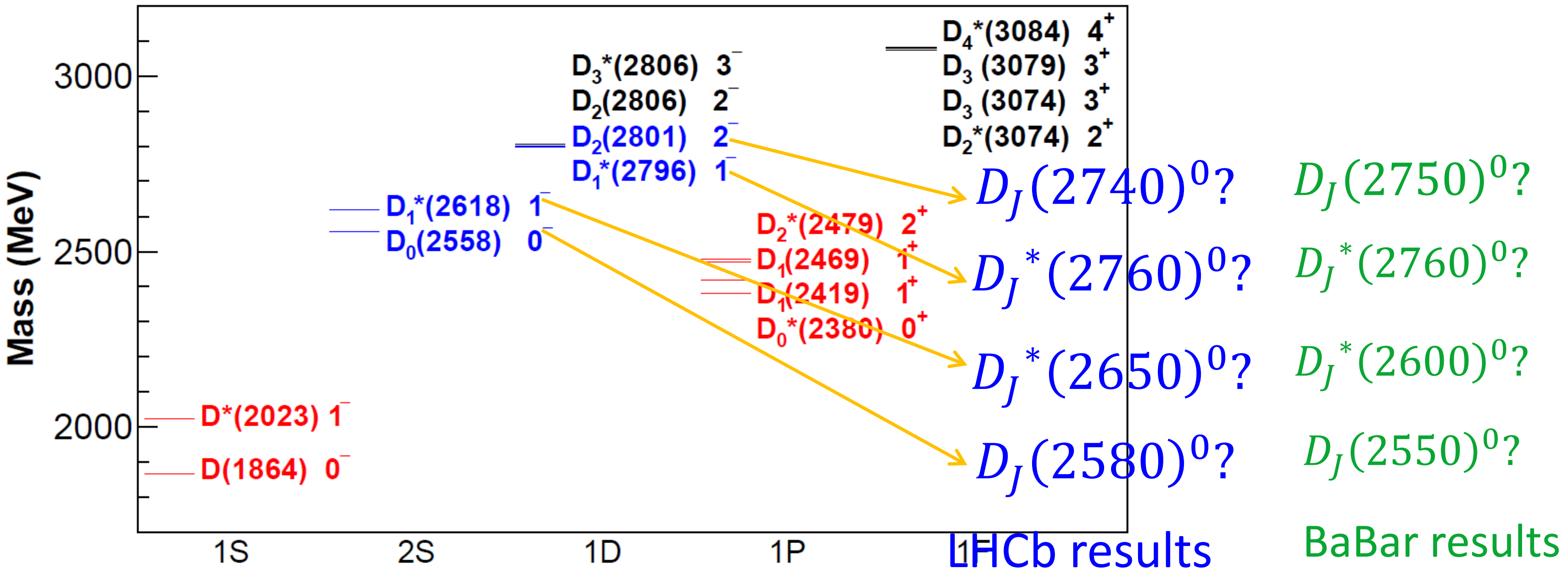
  - Partially agree with BaBar results [PR D82 (2010) 111101]



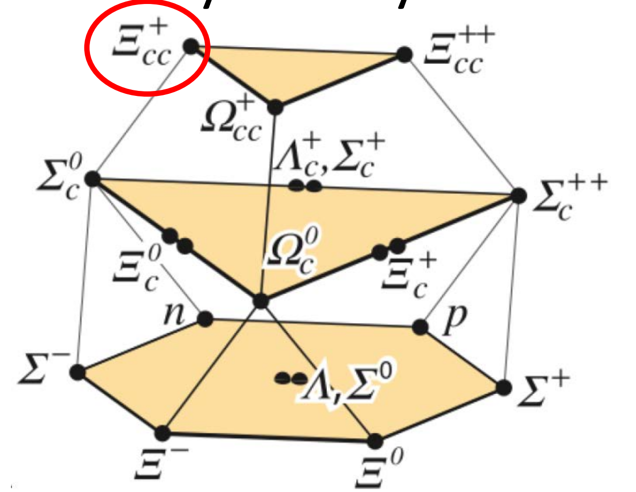
- Broad structure around 3000 MeV in the $D^{*+}\pi^-$ and $D\pi$ mass spectra could be superposition of several states

Search for the doubly charmed baryon Ξ_{cc}^{+}

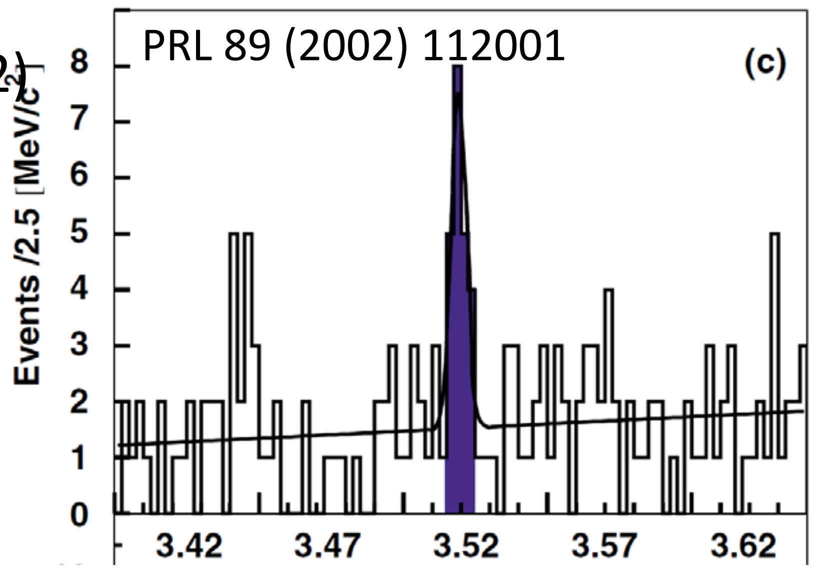
[JHEP 1312 (2013) 090, LHCb-PAPER-2013-049]

Doubly charmed baryon Ξ_{cc}^{+}

- Ξ_{cc}^{+} predicted by quark model and expected to decay weakly.
- Various theoretical predictions
  - $m(\Xi_{cc}^{+}) \sim [3500, 3700] \mathrm{MeV}/c^2$
  - $\tau(\Xi_{cc}^{+}) \sim [100, 250]$ fs
  - Cross section at LHC : $\mathcal{O}(10^2)$ nb



- SELEX claimed the observation of Ξ_{cc}^{+} in $\Lambda_c^+ K^- \pi^+$ and $p D^+ K^-$ [PRL 89 (2002) 112001, PLB 628 (2005) 18]
  - $m(\Xi_{cc}^{+}) = 3519 \mathrm{~MeV}/c^2$
  - $\tau(\Xi_{cc}^{+}) < 33$ fs @ $90\% C.L.$
- Not confirmed by FOCUS, BaBar or Belle



Ξ_{cc}^{+} search at LHCb (I)

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- Search for Ξ_{cc}^{+} through $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+, \Lambda_c^+ \to p K^- \pi^+$
  - Dataset: 0.65 fb^{-1} of 2011 data at $\sqrt{s} = 7$ TeV
  - Relevant triggers only online for half the year
- Measure the cross section ratio relative to the control Λ_c^+

$$R = \frac{\sigma(\Xi_{cc}^{+})\, \mathcal{B}(\Xi_{\mathrm{cc}}^{+} \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}$$

- Assuming $\mathcal{B}(\Xi_{\mathrm{cc}}^{+} \to \Lambda_c^+ K^- \pi^+) \approx \mathcal{B}(\Lambda_c^+ \to p K^- \pi^+) \approx 5\%$, the expected value of R at LHCb is of order $10^{-5} - 10^{-4}$.
- Analysis performed in a blind approach

- Construct δm quantity for better resolution
  - $\delta m = m(\Lambda_c^+ K^- \pi^+) - m(\Lambda_c^+) - m(K^-) - m(\pi^+)$

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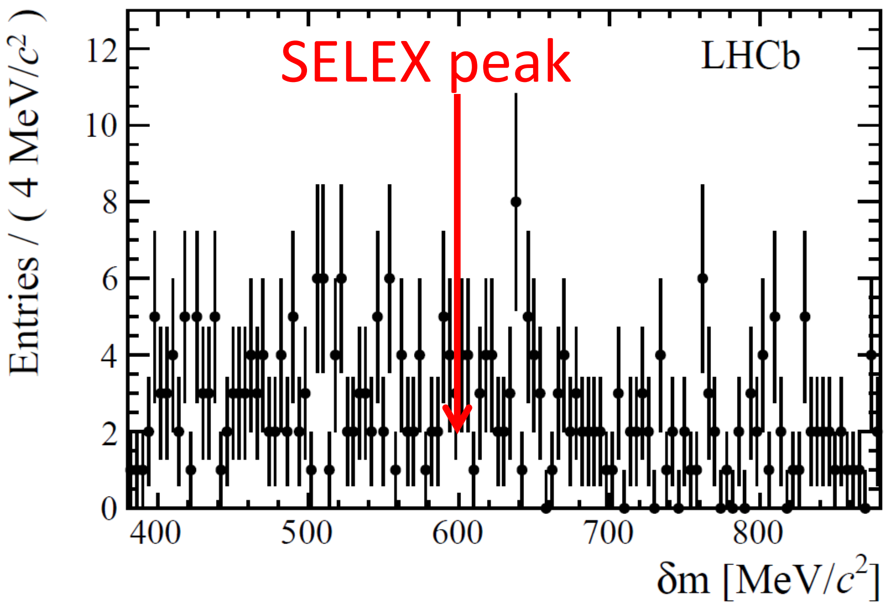
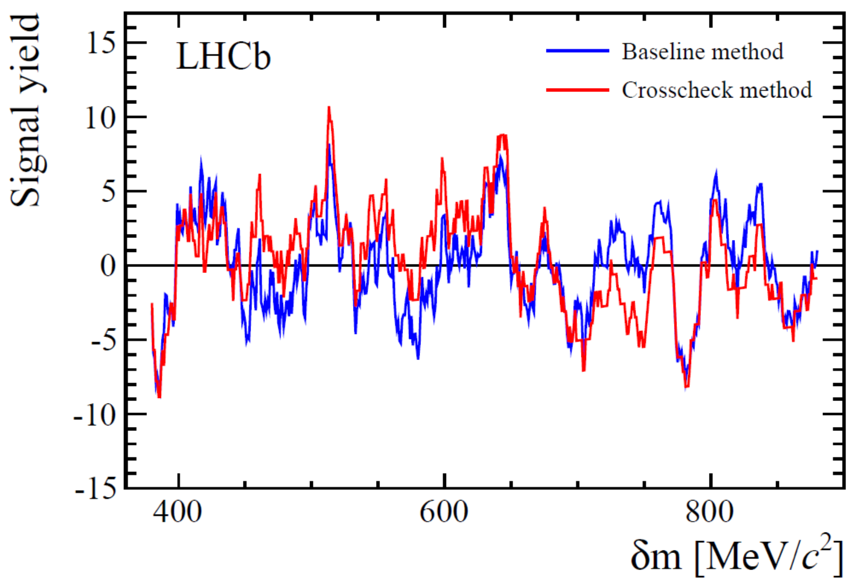
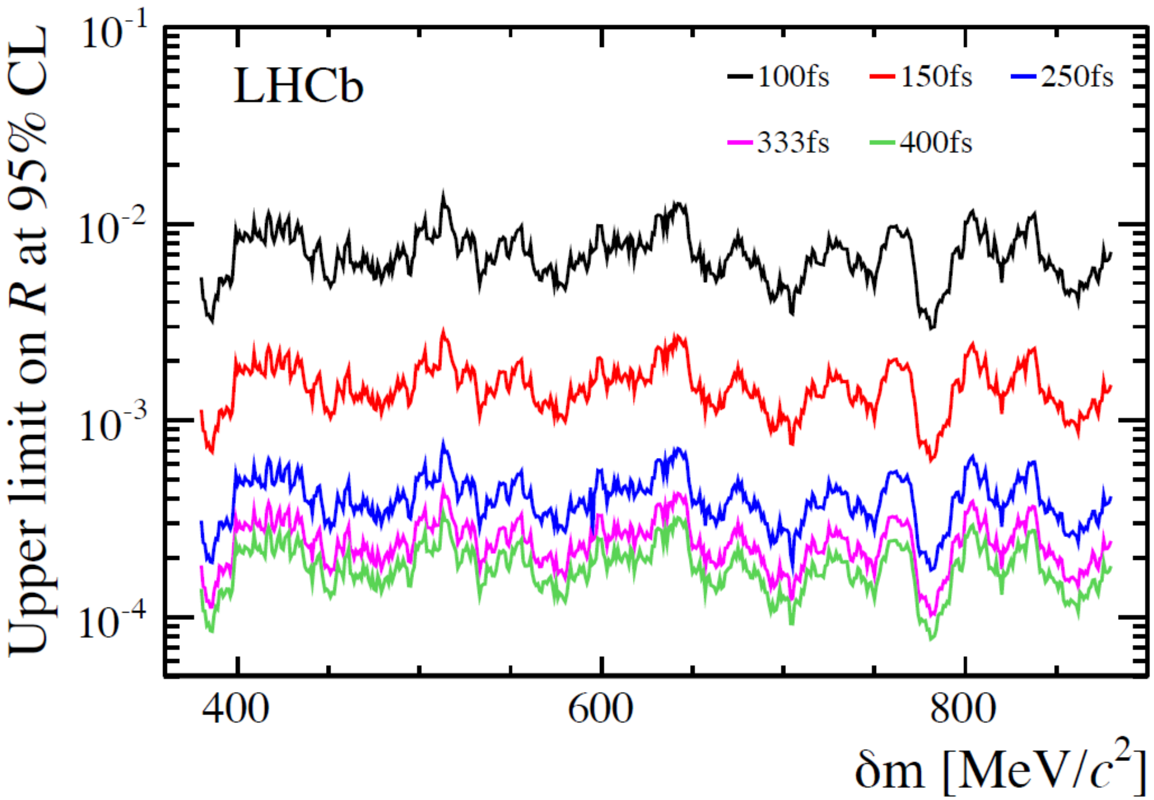
- Signal yield fit using two methods
- No significant signal observed





Upper limits for R

- Upper limits depends on efficiency, which varies with Ξ_{cc}^{+} mass and lifetime
  - The efficiency given as a function of δm, for 5 different lifetime hypotheses



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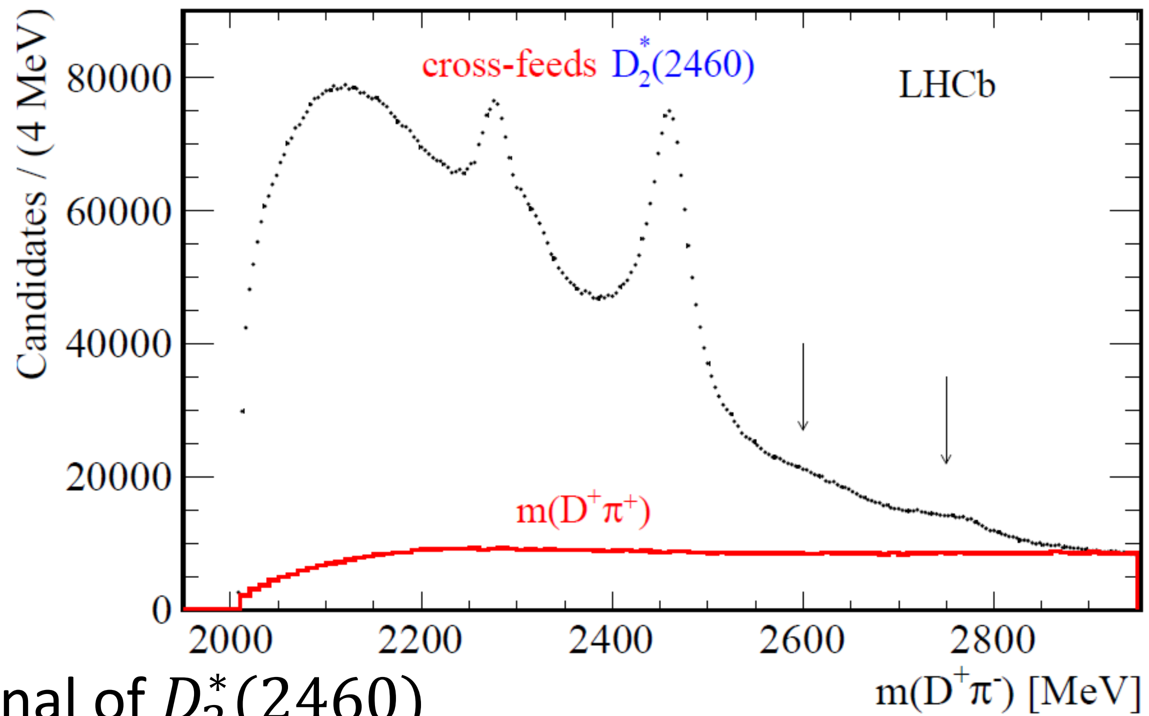
Summary

- LHCb has made important progress on charm spectroscopy
- In the sector of the D_J spectroscopy four new states observed.
- No significant signal observed in Ξ_{cc}^{+} search
- Results will be updated with larger dataset

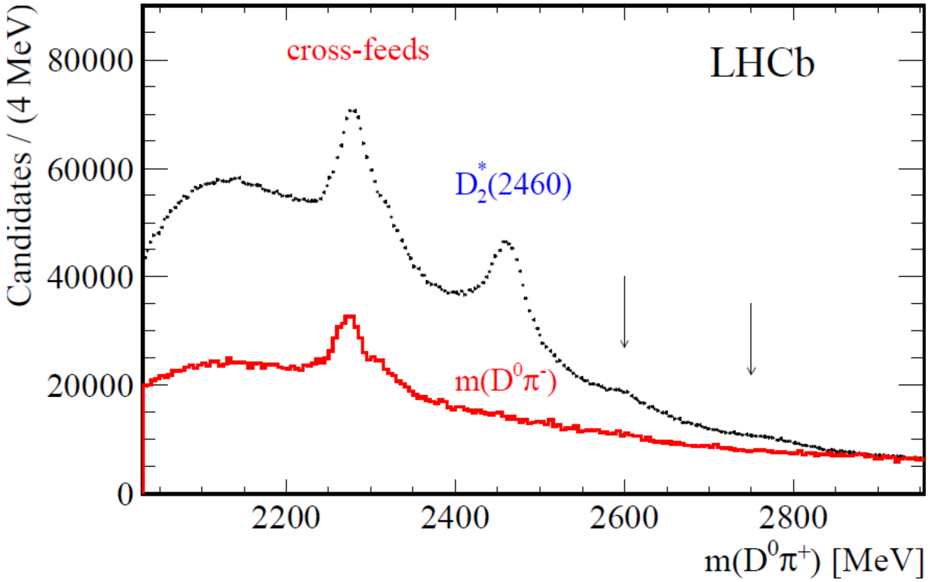
backup

$D^+\pi^-$ mass spectra



- Clear signal of $D_2^*(2460)$
- Cross-feed from $D_1(2420)^0$ or $D_2^*(2460) \to \pi^- D^{*+}(\to D^+\pi^0/\gamma)$
  - Could also cross-fed by higher unknown resonances
- Weak structures around 2600 and 2750 MeV
- No significant structure in wrong sign $D^+\pi^+$ mass spectra

$D^0\pi^+$ mass spectra

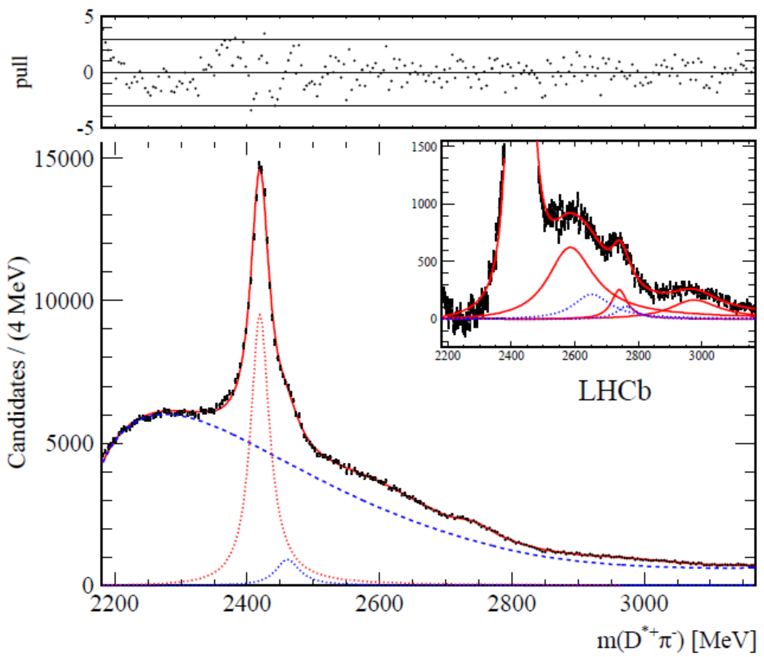


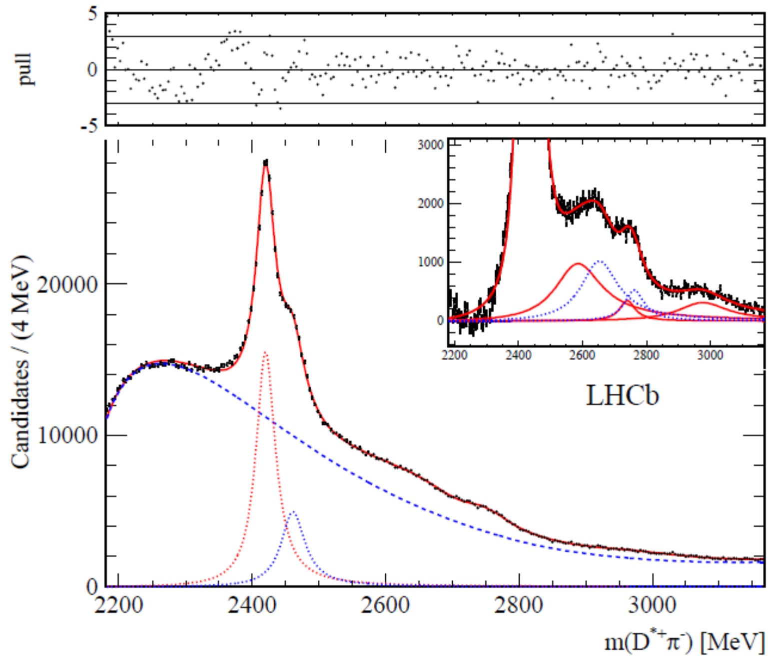
- Clear signal of $D_2^*(2460)$
- Cross-feed from

$$D_1(2420)^+ \text{ or } D_2^*(2460)^+ \to \pi^+ D^{*0}(\to D^0\pi^0/\gamma)$$

  - Could also cross-fed by higher unknown resonances Weak structures around 2600 and 2750 MeV
- The wrong sign $D^0\pi^-$ mass spectra shows cross-feeds from:

$$D_1(2420)^0 \text{ or } D_2^*(2460)^0 \to \pi^- D^{*+}(\to D^0\pi^+)$$





- Unnatural Parity Sample: fix all resonances parameters except for $D_1(2420)^0$
- Total Sample: all resonances parameters fixed

Fit result

Resonance	Final state	Mass (MeV)	Width (MeV)	Yields $\times 10^3$	Sign.
$D_1(2420)^0$	$D^{*+}\pi^-$	$2419.6 \pm 0.1 \pm 0.7$	$35.2 \pm 0.4 \pm 0.9$	$210.2 \pm 1.9 \pm 0.7$	
$D_2^*(2460)^0$	$D^{*+}\pi^-$	$2460.4 \pm 0.4 \pm 1.2$	$43.2 \pm 1.2 \pm 3.0$	$81.9 \pm 1.2 \pm 0.9$	
$D_J^*(2650)^0$	$D^{*+}\pi^-$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$	$50.7 \pm 2.2 \pm 2.3$	24.5
$D_J^*(2760)^0$	$D^{*+}\pi^-$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 3.4 \pm 37.0$	$14.4 \pm 1.7 \pm 1.7$	10.2
$D_J(2580)^0$	$D^{*+}\pi^-$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.8 \pm 46.0$	$60.3 \pm 3.1 \pm 3.4$	18.8
$D_J(2740)^0$	$D^{*+}\pi^-$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$	$7.7 \pm 1.1 \pm 1.2$	7.2
$D_J(3000)^0$	$D^{*+}\pi^-$	2971.8 ± 8.7	188.1 ± 44.8	9.5 ± 1.1	9.0
$D_2^*(2460)^0$	$D^+\pi^-$	$2460.4 \pm 0.1 \pm 0.1$	$45.6 \pm 0.4 \pm 1.1$	$675.0 \pm 9.0 \pm 1.3$	
$D_J^*(2760)^0$	$D^+\pi^-$	$2760.1 \pm 1.1 \pm 3.7$	$74.4 \pm 3.4 \pm 19.1$	$55.8 \pm 1.3 \pm 10.0$	17.3
$D_J^*(3000)^0$	$D^+\pi^-$	3008.1 ± 4.0	110.5 ± 11.5	17.6 ± 1.1	21.2
$D_2^*(2460)^+$	$D^0\pi^+$	$2463.1 \pm 0.2 \pm 0.6$	$48.6 \pm 1.3 \pm 1.9$	$341.6 \pm 22.0 \pm 2.0$	
$D_J^*(2760)^+$	$D^0\pi^+$	$2771.7 \pm 1.7 \pm 3.8$	$66.7 \pm 6.6 \pm 10.5$	$20.1 \pm 2.2 \pm 1.0$	18.8
$D_J^*(3000)^+$	$D^0\pi^+$	3008.1 (fixed)	110.5 (fixed)	7.6 ± 1.2	6.6

Fitting model.

☐ Background model:

$$B(m) = P(m)e^{a_1 m + a_2 m^2} \; for \; m < m_0$$

$$B(m) = P(m)e^{b_0 + b_1 m + b_2 m^2} \; for \; m > m_0$$

where $P(m)$ is the two-body phase space.

b_0 and b_1 are obtained by imposing continuity on the function and its first derivative.

☐ Use relativistic Breit-Wigner for $D_2^*(2460)$ and $D_0^*(2400)$ decaying to $D\pi$.

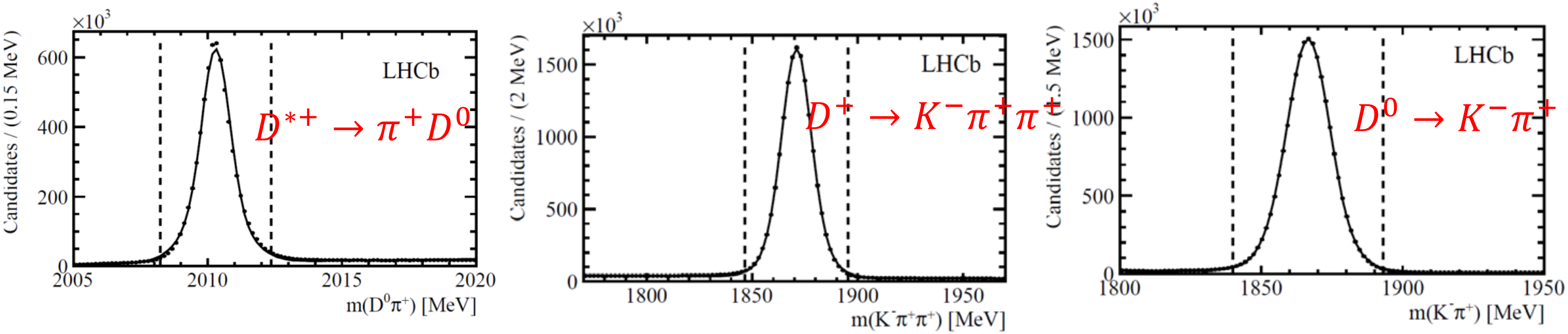
☐ Simple Breit-Wigner are used for the other structures.

☐ Each Breit-Wigner is multiplied by the phase-space factor.

☐ The cross-feed lineshapes from $D_1(2420)$ and $D_2^*(2460)$ appearing in the $D^+\pi^-$ and $D^0\pi^+$ mass spectra are described by a Breit-Wigner function fitted to the data.

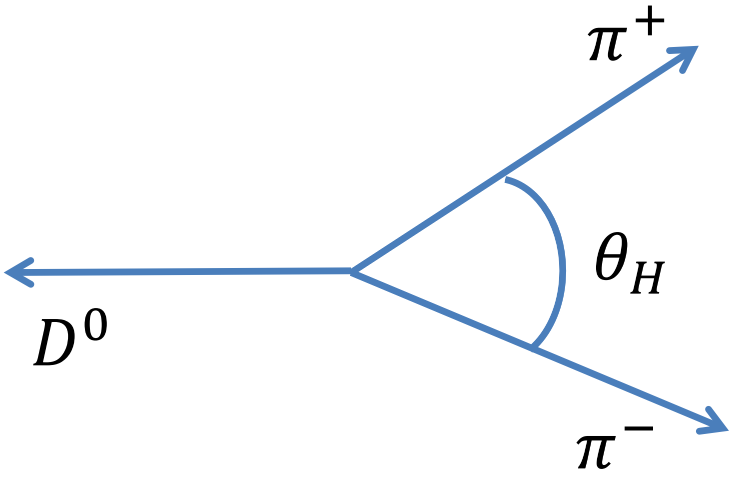
D_J spectroscopy at LHCb

- Search for D_J in $D^{(*)}\pi$ mass spectrum based on 1fb^{-1} data at $\sqrt{s} = 7$ TeV
  - $pp \to X + \pi^- D^{*+}, D^{*+} \to \pi^+ D^0, D^0 \to K^- \pi^+$
  - $pp \to X + \pi^- D^+, D^+ \to K^- \pi^+ \pi^+$
  - $pp \to X + \pi^+ D^0, D^0 \to K^- \pi^+$
- Very clean signals of D^{*+}, D^+ and D^0



$D^{*+}\pi^-$ angular distributions

- D^{*+} is a vector meson
  - $\Rightarrow$ Angular distribution of $D^{*+}\pi^-$ contains information about spin-parity of D_J
  - – θ_H: the angle between the primary pion π^- and the slow pion π^+ from D^{*+} in the rest frame of $D^{*+}\pi^-$
- Angular distribution: $\propto \sin^2\theta_H$
  - – Natural parity: $J^P = 0^+, 1^-, 2^+, \ldots$
- Angular distribution:$\propto 1 + h\cos^2\theta_H$
  - – Unnatural parity: $J^P = 0^-, 1^+, 2^-, \ldots$



Angular distribution(I)

Divide the $\cos\theta_H$ into 10 bins and fit the yield of each resonance in each bin

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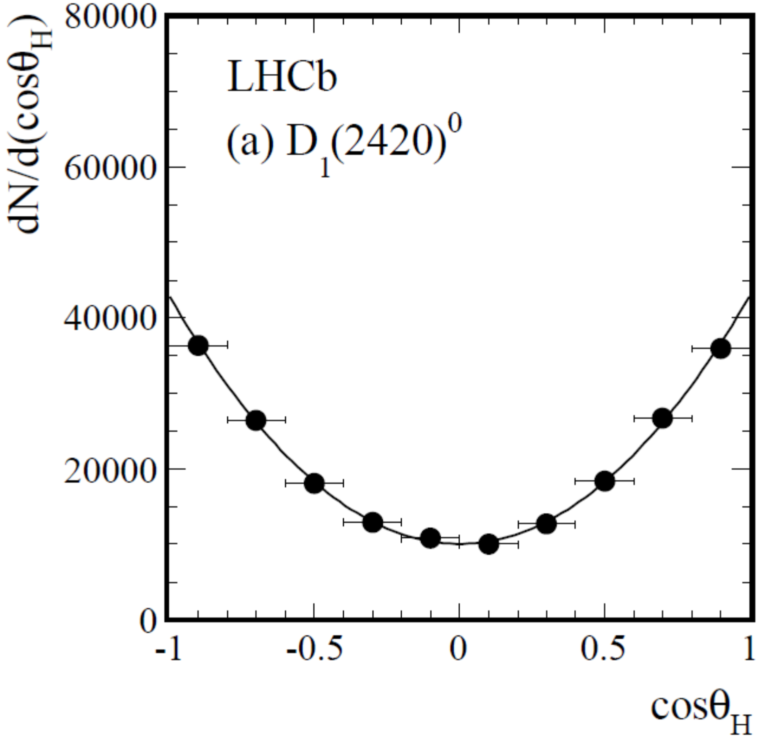
$D_1(2420)^0 : J^P = 1^+$, expect $\theta_H \propto 1 + h\cos^2\theta_H$



$D_2^*(2460)^0 : J^P = 2^+$, expect $\theta_H \propto \sin^2\theta_H$