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Meson spectroscopy at LHCb

M. Kreps on behalf of the LHCb Collaboration

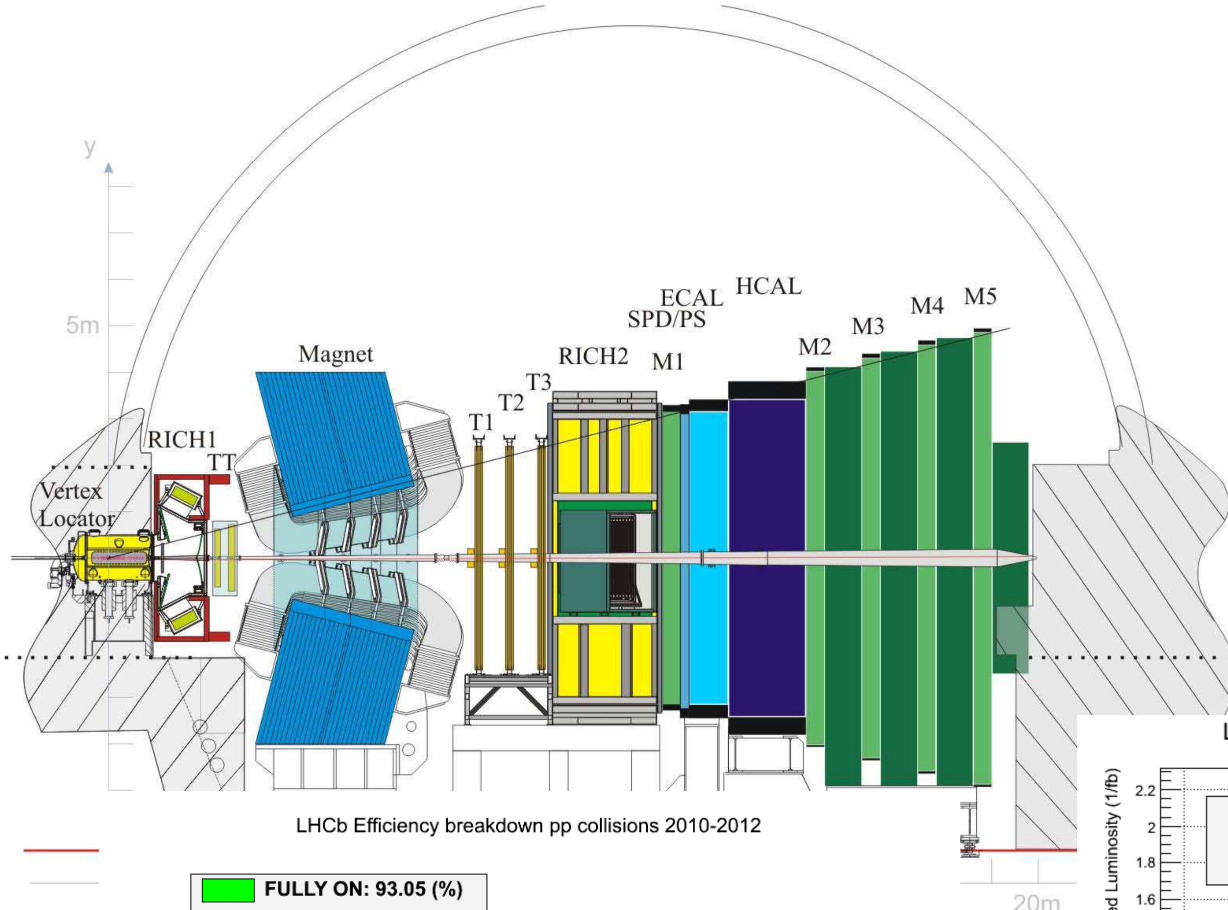
Physics Department

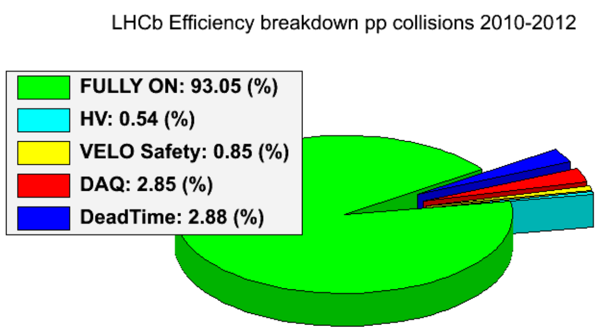
Outline:

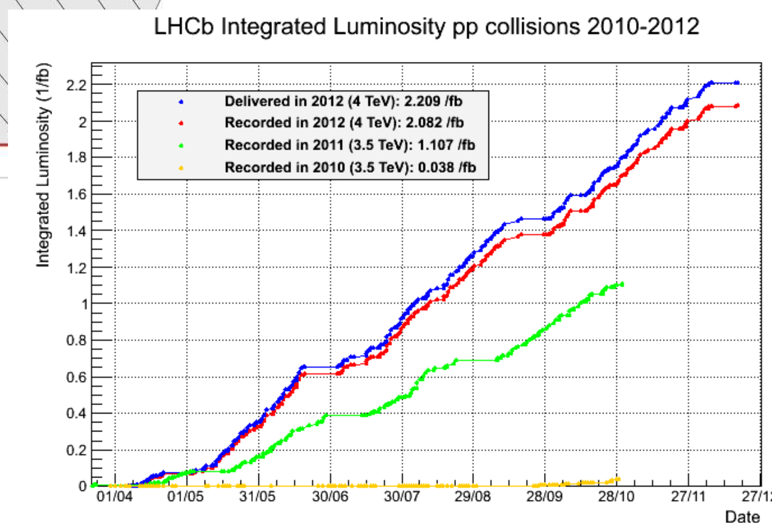
- Study of D_J mesons
- $D_{(s)}$ meson masses
- B_c^+ mass and $B_c^+ \to B_s \pi^+$ observation
- $\psi(4160)$ in $B^+ \to K^+\mu^+\mu^-$
- $X(3872)$ quantum numbers

LHCb detector

- Good mass resolution
- Good time resolution
- High trigger rate on c and b
- Uniform running conditions







Open charm mesons

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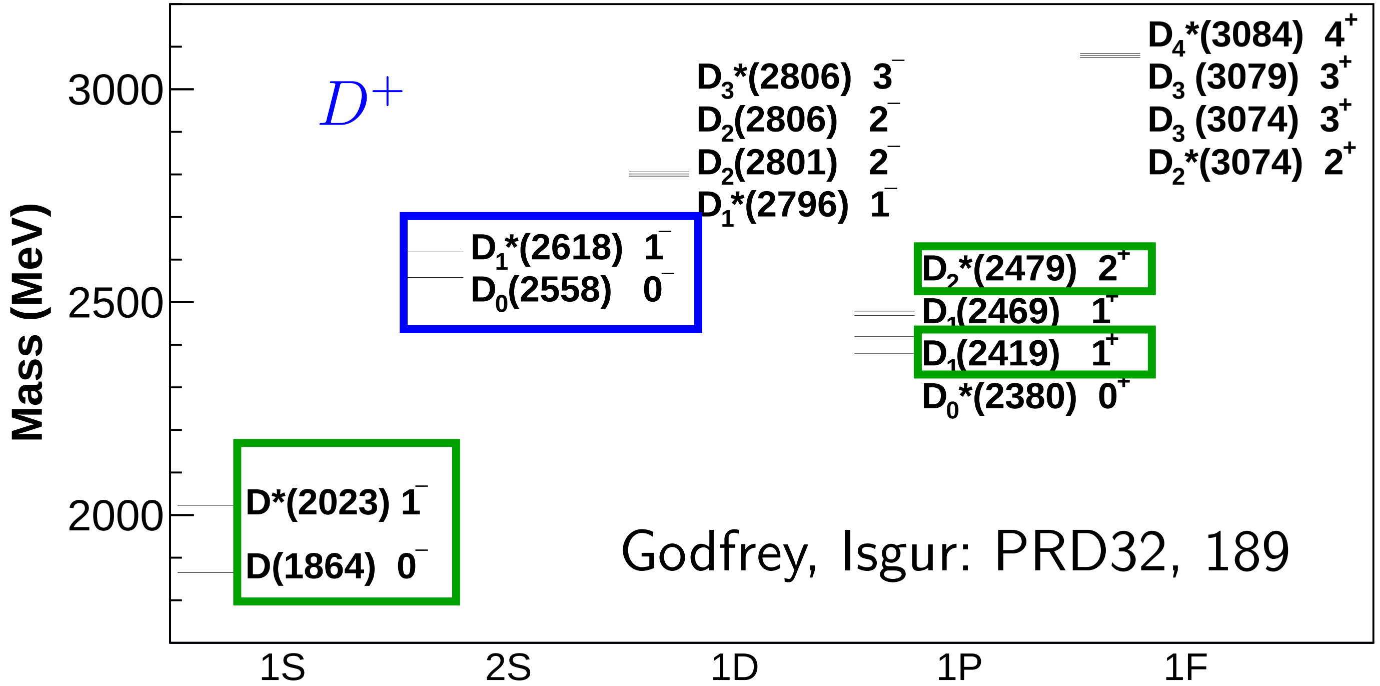
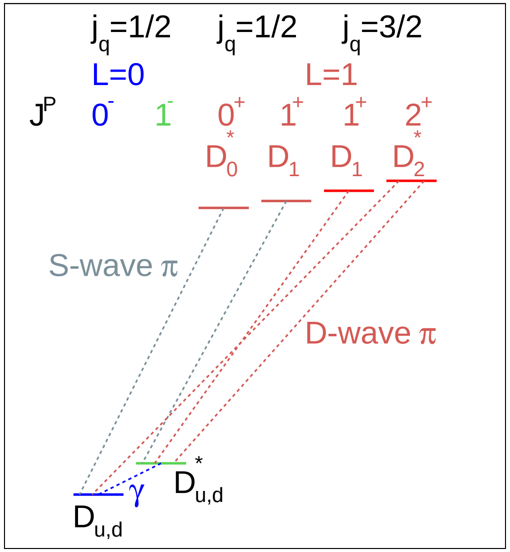
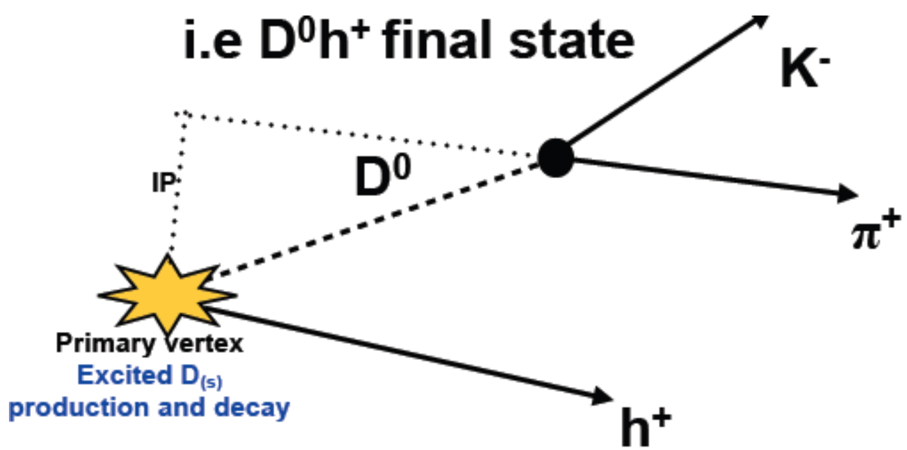


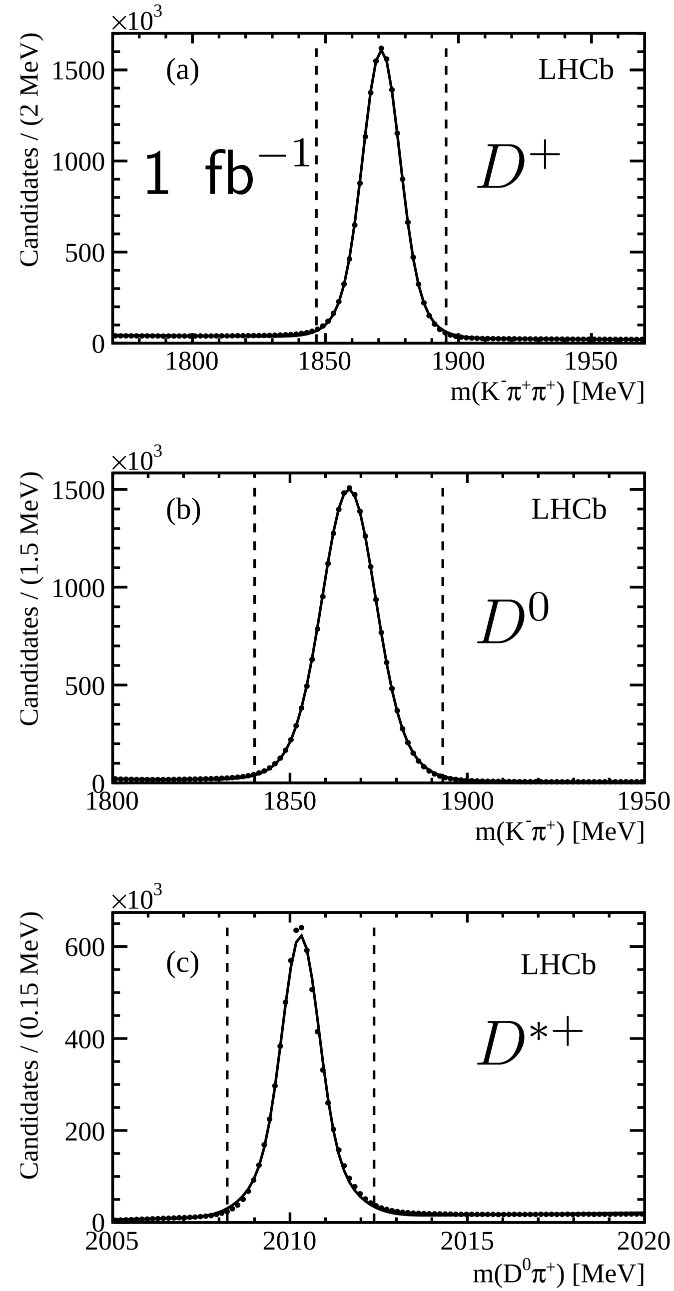


- Spectrum for D^0 mesons basically same
- 1S and narrow 1P states well established
- Broad 1P states recently observed at B-factories
- BABAR observed in $e^+e^- \to c\bar{c} \to D^*\pi X$ four additional states
- Some could be possibly assigned, but not all are clear
- Further studies are needed

D_J mesons

- We study processes:
  $pp \to D^+\pi^- X$
  $pp \to D^0\pi^+ X$
  $pp \to D^{*+}\pi^- X$
- D meson reconstructed as
  - $D^+ \to K^-\pi^+\pi^+$; $N = 15.1M$
  - $D^0 \to K^-\pi^+$; $N = 20.4M$
  - $D^{*+} \to D^0\pi^+$; $N = 6.4M$
- Purity in all cases very high
- Resolutions 8.1, 8.8 and 0.69 MeV/c^2



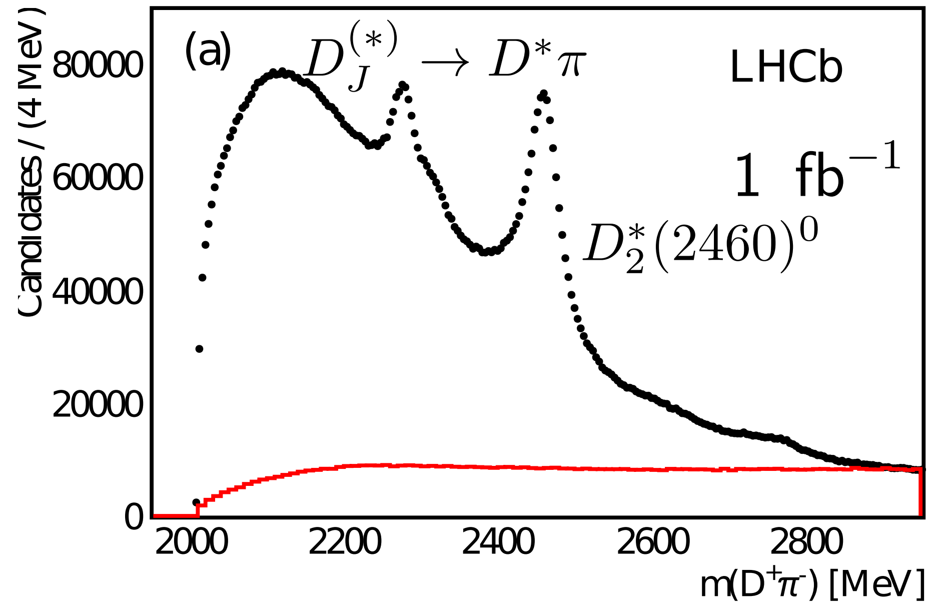


D_J mass spectra

arXiv:1307.4556

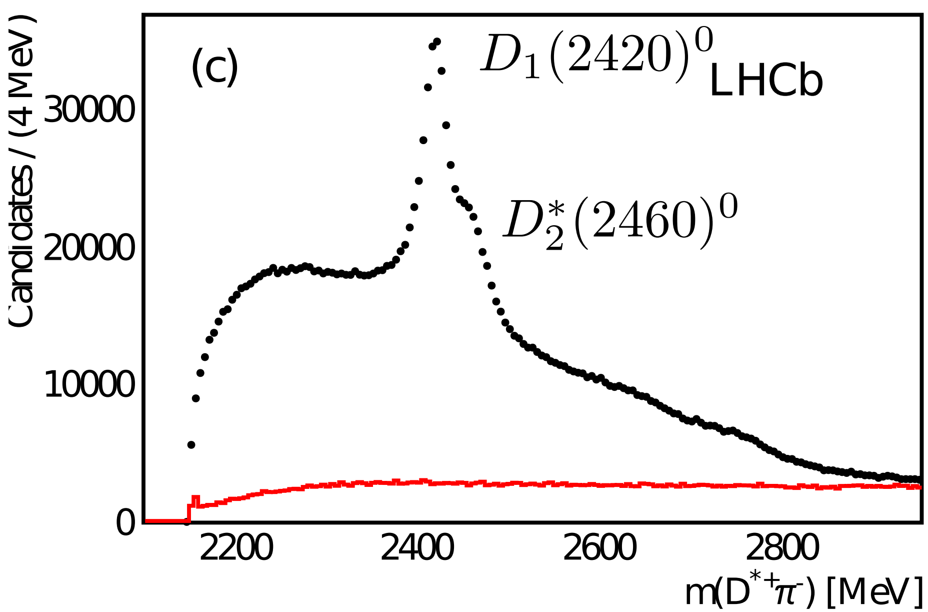
NEW

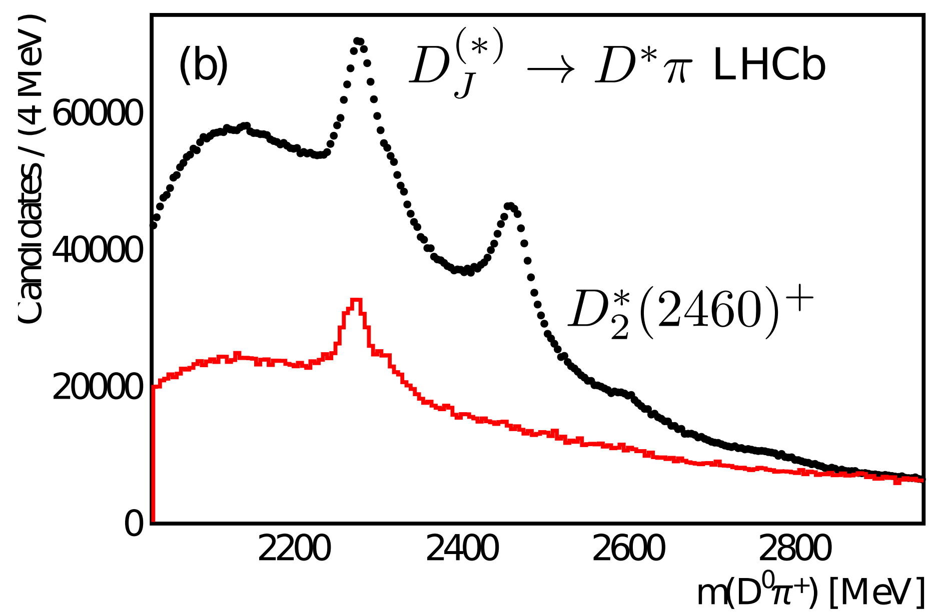
- Strong signals for $D_2^*(2460)$ and $D_1(2420)$
- Activity in 2.6–2.8 GeV
- Feedthrough in $D\pi$ from decays to $D^*\pi$



Right sign data

Wrong sign data





$D^{*+}\pi^-$ fit

arXiv:1307.4556

NEW

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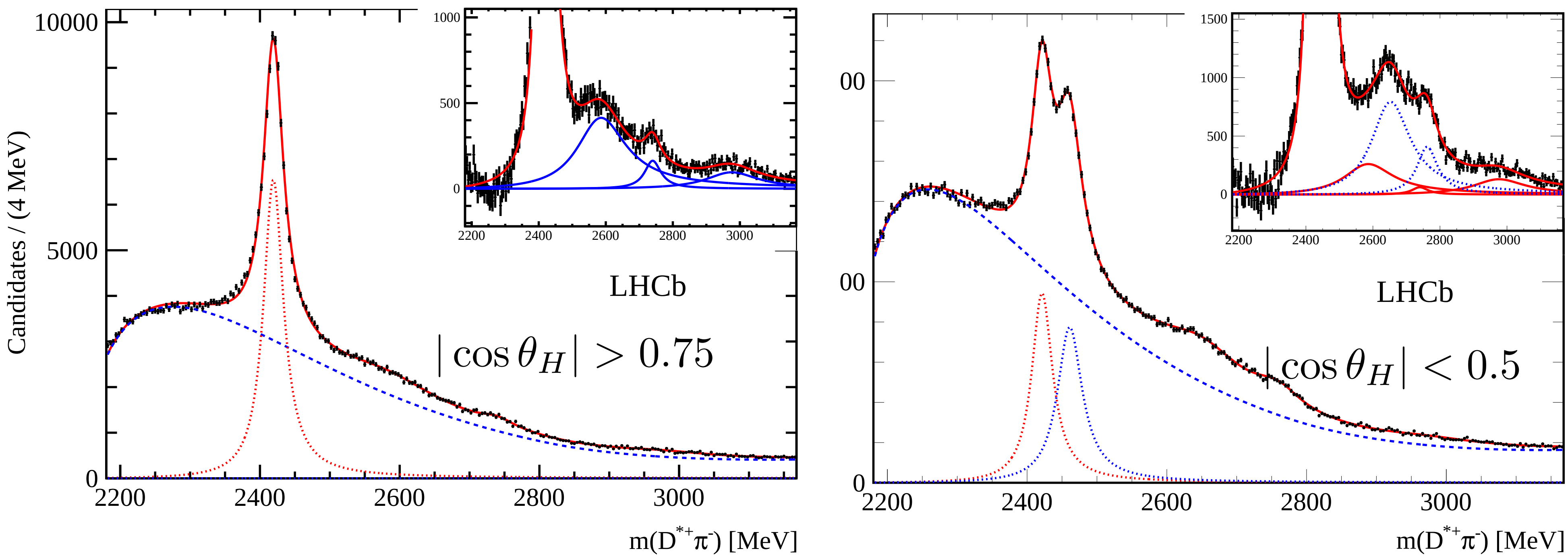
- Split sample by D^* helicity angle
  - Unnatural parity $(0^-, 1^+, 2^-, ...)$ $1 + h\cos^2\theta_H$
  - Natural parity $(0^+, 1^-, 2^+, ...)$ $\sin^2\theta_H$
- First fit sample enhanced in unnatural parity
- Then sample enhanced in natural parity with unnatural parity contributions fixed

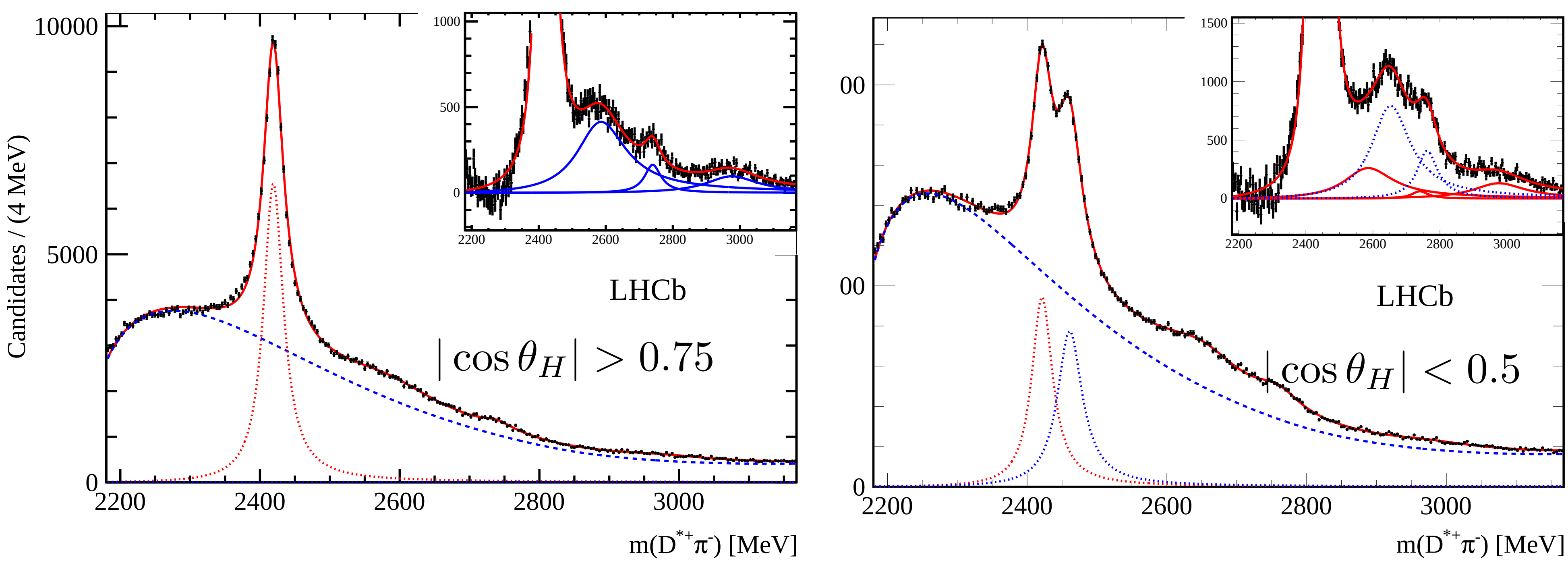


$D^{*+}\pi^-$ fit

arXiv:1307.4556

NEW

Resonance	Mass (MeV)	Width (MeV)	Significance (σ)
$D_1(2420)^0$	$2419.6 \pm 0.1 \pm 0.7$	$35.2 \pm 0.4 \pm 0.9$	
$D_2^*(2460)^0$	$2460.4 \pm 0.4 \pm 1.2$	$43.2 \pm 1.2 \pm 3.0$	
$D_J^*(2650)^0$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$	24.5
$D_J^*(2760)^0$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 3.4 \pm 37.0$	10.2
$D_J(2580)^0$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.8 \pm 46.0$	18.8
$D_J(2740)^0$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$	7.2
$D_J(3000)^0$	2971.8 ± 8.7	188.1 ± 44.8	9.0



Spin-parity analysis

arXiv:1307.4556

NEW

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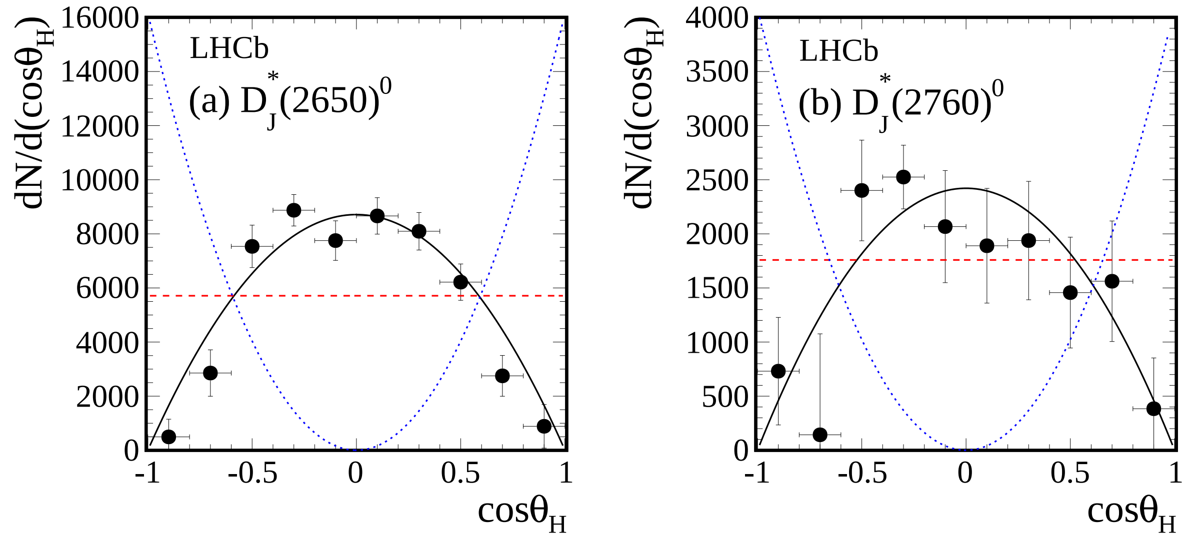
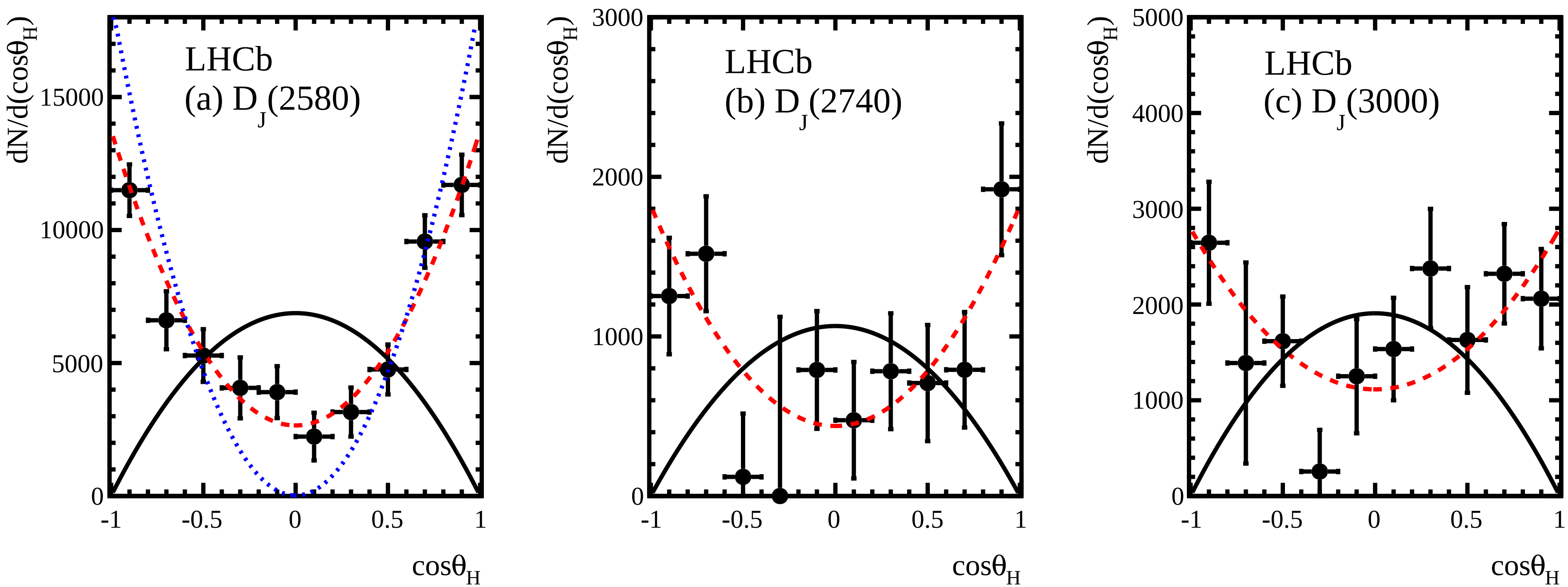
- $D^*\pi$ allows spin-parity analysis
- Fit mass in bins of $\cos\theta_H$
- Test natural vs. unnatural parity vs. 0^-





Spin-parity results

arXiv:1307.4556

NEW

Resonance	J^P Function	χ^2/ndf	J^P Function	χ^2/ndf	J^P Function	χ^2/ndf	h Parameter
$D_1(2420)^0$	1^+ $1+h\cos^2\theta_H$	0.67/8					3.30 ± 0.48
$D_2^*(2460)^0$	2^+ $\sin^2\theta_H$	8.5/9					
$D_J^*(2650)^0$	Natural $\sin^2\theta_H$	6.8/9	Unnatural Const.	200/9	0^- $\cos^2\theta_H$	342/9	
$D_J^*(2760)^0$	Natural $\sin^2\theta_H$	5.8/9	Unnatural Const.	26/9	0^- $\cos^2\theta_H$	94/9	
$D_J(2580)^0$	Natural $\sin^2\theta_H$	151/9	Unnatural $1+h\cos^2\theta_H$	3.4/8	0^- $\cos^2\theta_H$	23/9	4.2 ± 1.3
$D_J(2740)^0$	Natural $\sin^2\theta_H$	34/9	Unnatural $1+h\cos^2\theta_H$	6.6/8			3.1 ± 2.2
$D_J(3000)^0$	Natural $\sin^2\theta_H$	36.6/9	Unnatural $1+h\cos^2\theta_H$	10/8			1.5 ± 0.9

$D^0\pi^+$ and $D^+\pi^-$ Fits

arXiv:1307.4556

NEW

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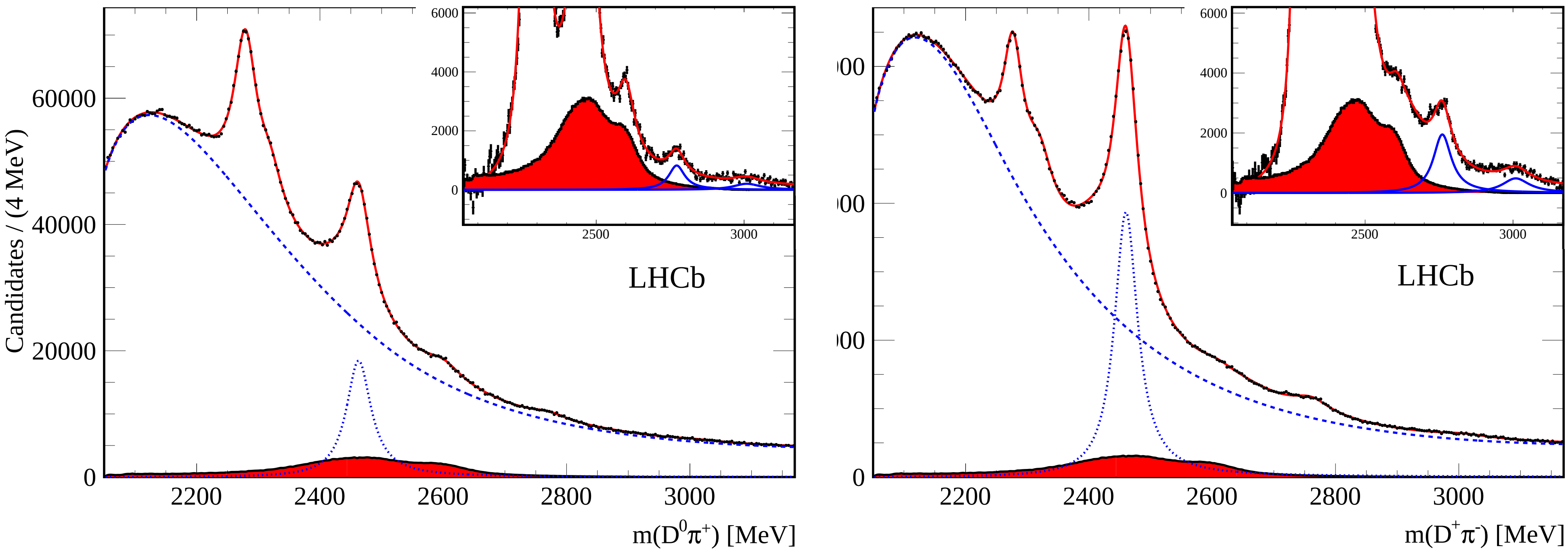
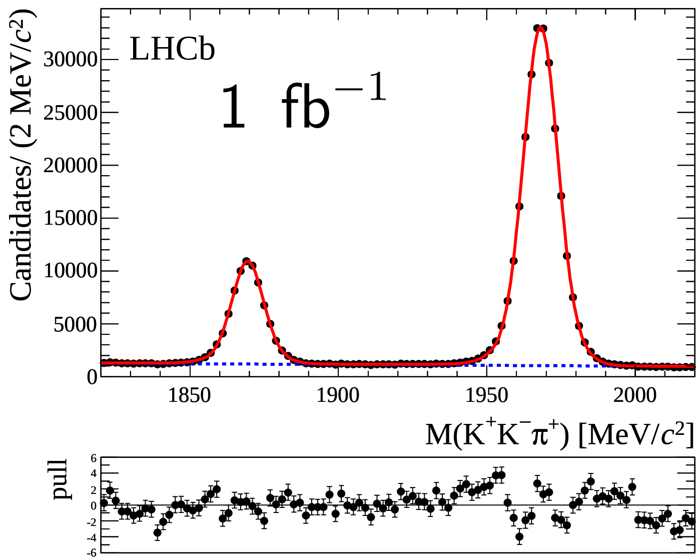
- Fits more involved due to reflections from $D^*\pi$ final states
- Reflections fixed based on $D^{*+}\pi^-$ results
- See clear $D_2^*(2460)$, $D_J^*(2760)$ and $D_J^*(3000)$
- Resonance parameters consistent with $D^{*+}\pi^-$
- For $D_J^*(2760)$ only fit to $D^{*+}\pi^-$ reliable for resonance parameters

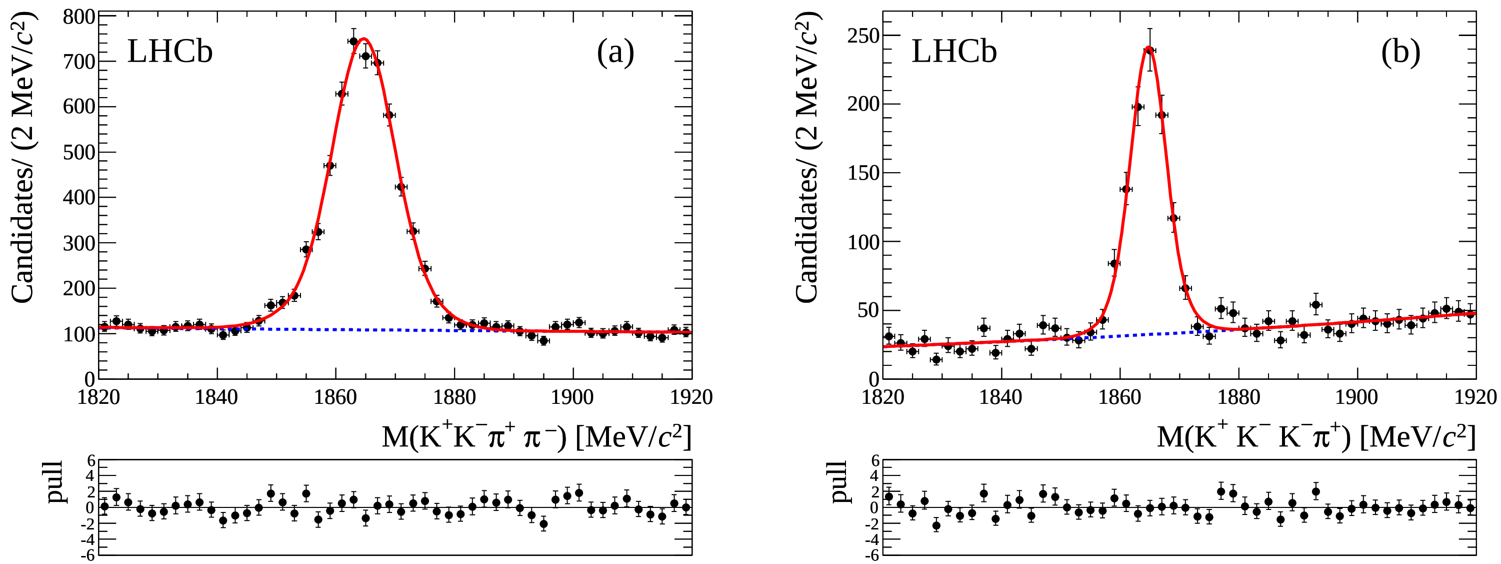


Ground state $D_{(s)}$ mesons

- Huge samples available at LHCb
- Dominant systematic uncertainty from momentum and energy loss calibration
- Smaller Q value of the decay $\Rightarrow$ smaller sensitivity to momentum calibration
- Have large samples of other particles to calibrate momentum

JHEP 06 (2013), 065





Ground state $D_{(s)}$ mesons

JHEP 06 (2013), 065

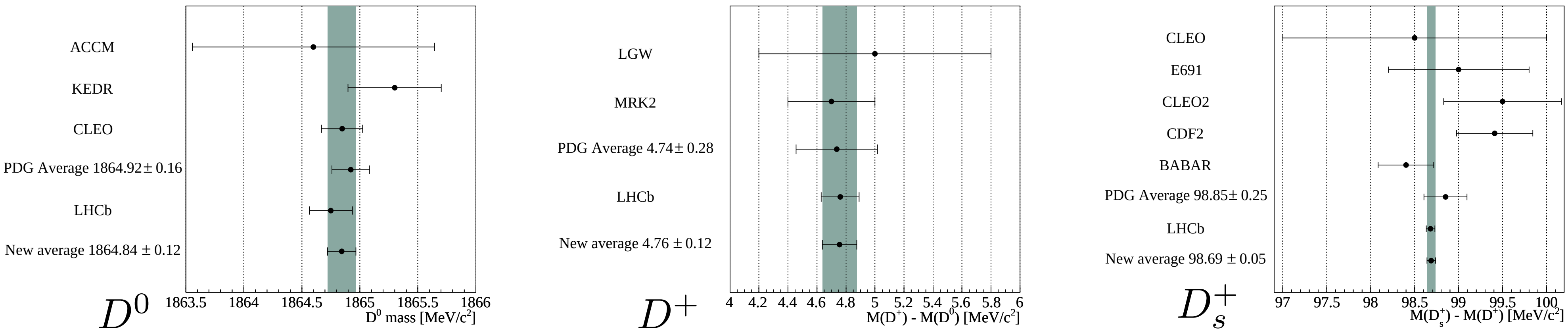
- Direct results

$$
\begin{aligned}
M(D^0) &= 1864.75 \pm 0.15\,(\text{stat}) \pm 0.11\,(\text{syst})\ \text{MeV}/c^2, \\
M(D^+) - M(D^0) &= 4.76 \pm 0.12\,(\text{stat}) \pm 0.07\,(\text{syst})\ \text{MeV}/c^2 \\
M(D_s^+) - M(D^+) &= 98.68 \pm 0.03\,(\text{stat}) \pm 0.04\,(\text{syst})\ \text{MeV}/c^2
\end{aligned}
$$

- Adding PDG information, we derive

$$M(D_s^+) = 1968.19 \pm 0.20 \pm 0.14 \pm 0.08\,\text{MeV}/c^2$$

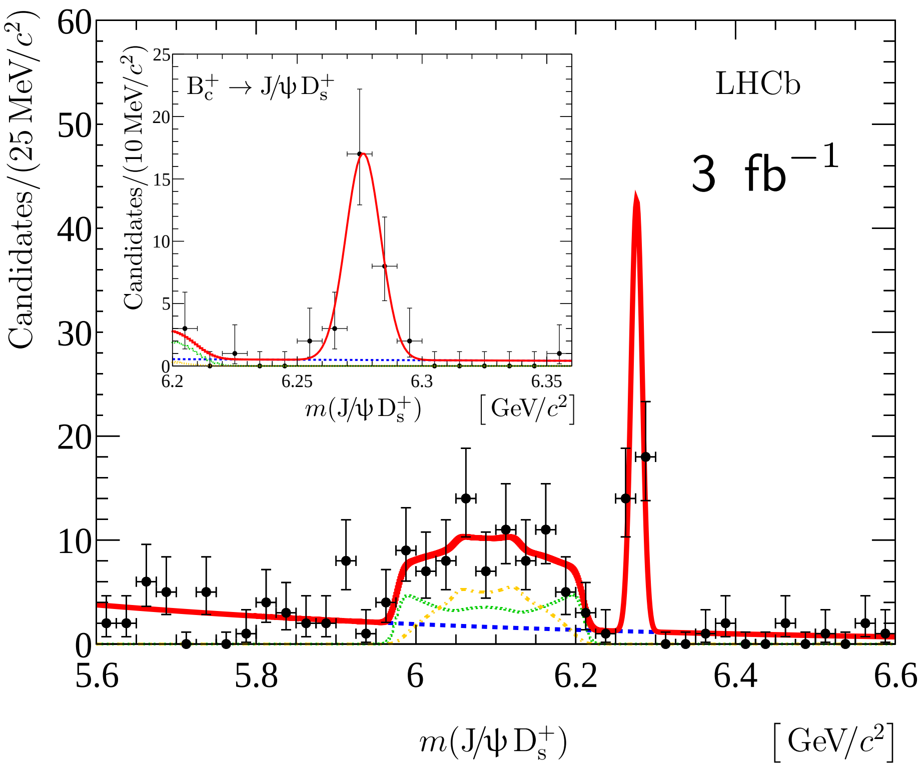
- Mass difference best in world
- D^0 mass matches in precision existing best measurement
- For D^0 knowledge of kaon mass becomes important



B_c mass

PR D87, 112012

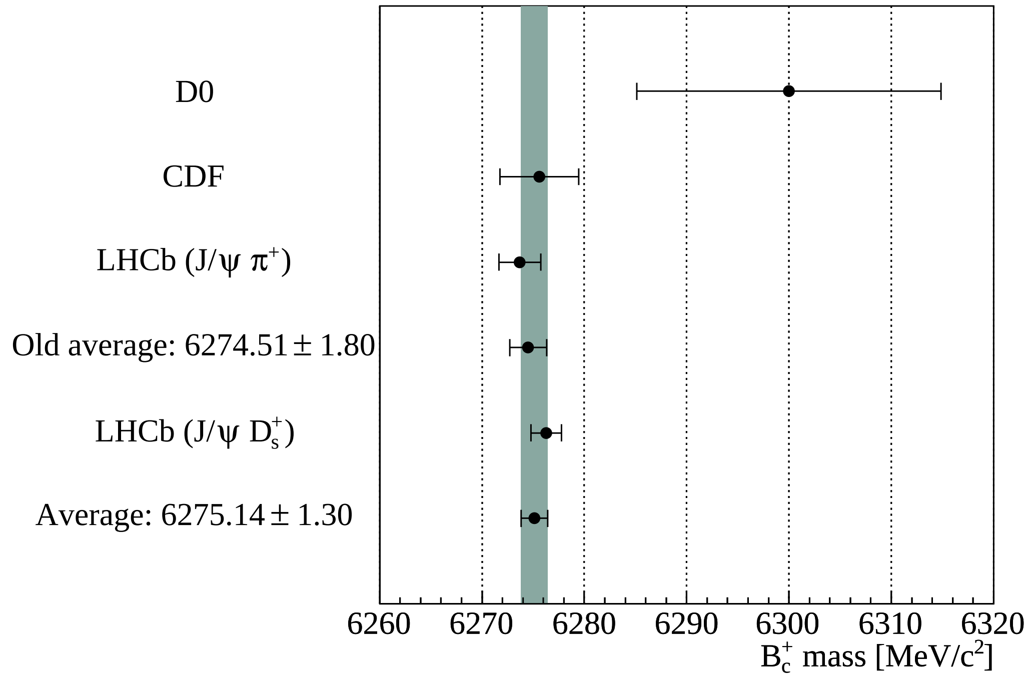
- Mass of the B_c currently determined from $J/\psi\,\pi^+$ decays
- They have rather large Q value $\Rightarrow$ large systematic uncertainty from momentum scale
- Benefits from precise masses of daughters
- Recently we observed new decay $B_c \to J/\psi\, D_s^+$
- Q value here is about same as $B^0 \to J/\psi\, K^*$



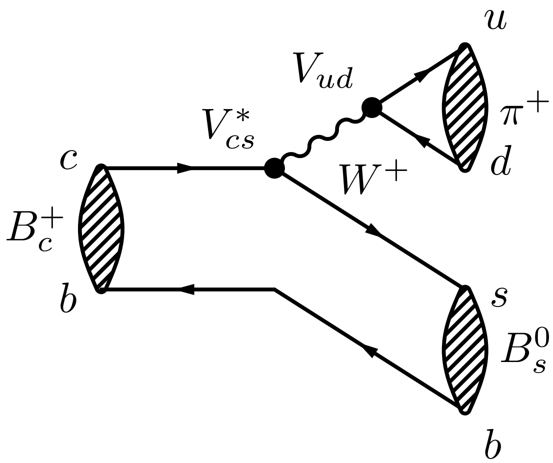
B_c mass

PR D87, 112012

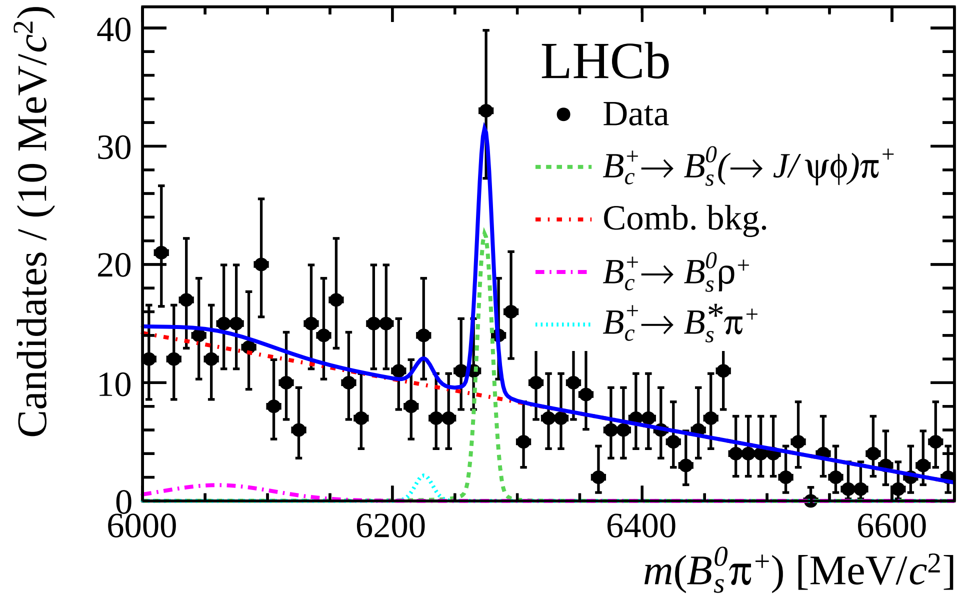
- $m(B_c) - m(D_s) = 4307.97 \pm 1.44 \pm 0.20\ \text{MeV}/c^2$
- Using our determination of $m(D_s)$ including correlations
  $m(B_c) = 6276.28 \pm 1.44 \pm 0.36\ \text{MeV}/c^2$
- Consistent with PDG
- Uncertainty about same as PDG
- Potential for improvement as statistically dominated

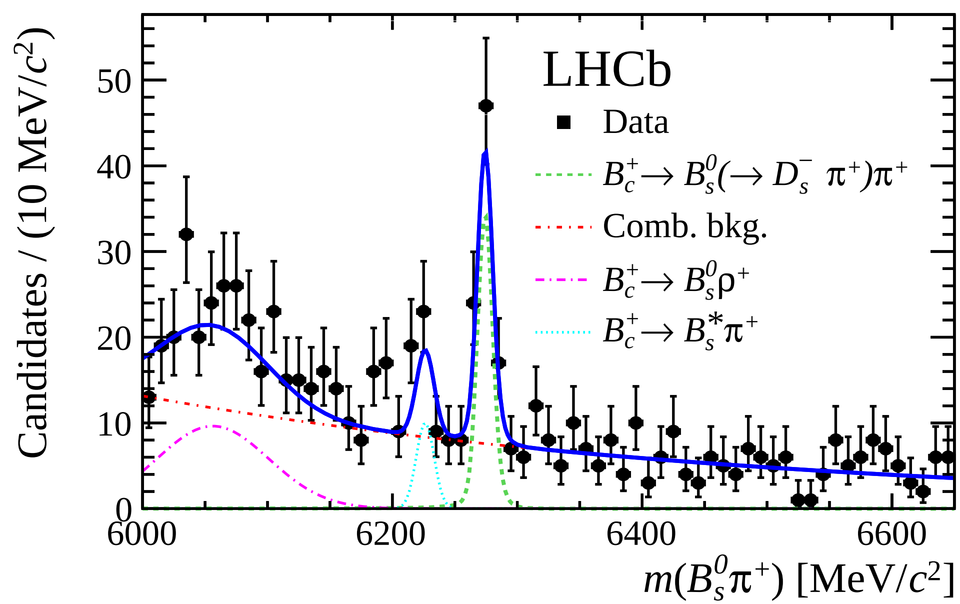


Observation of $B_c^+ \to B_s\pi^+$



NEW LHCb-PAPER-2013-044





- B_c can decay via b-, c-quark decay or weak annihilation
- Up to now all decays through c-quark decay
- b-quark decay should give larger rate
- $B_c \to B_s\pi$ decay first of this kind
- Statistical significance 7.7σ
  $\frac{f_c}{f_s} \times \mathcal{B}(B_c^+ \to B_s\pi^+) =$
  $\left(2.38 \pm 0.35 \pm 0.11\,^{+0.17}_{-0.12}\right) \times 10^{-3}$

$c\bar{c}$ above $D\bar{D}$ threshold

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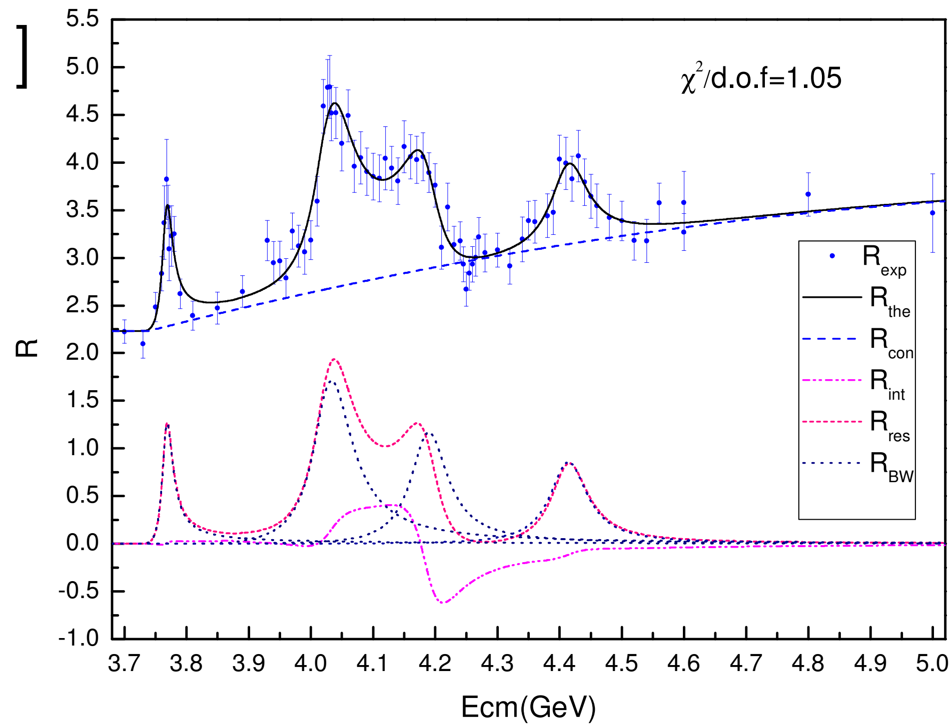
- Practically all information on 1^{--} $c\bar{c}$ states from

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

- Interferences rarely taken into account
- Best knowledge from BES (PLB 660, 315) which takes interferences into account

State	Mass [MeV]	Width [MeV]
$\psi(3770)$	3773.2 ± 0.3	27.2 ± 1.0
$\psi(4040)$	4039.6 ± 4.3	84.5 ± 12.3
$\psi(4160)$	4191.7 ± 6.5	71.8 ± 12.3
$\psi(4415)$	4415.1 ± 7.9	71.5 ± 19.0



$B^+ \to K^+\mu^+\mu^-$ decays

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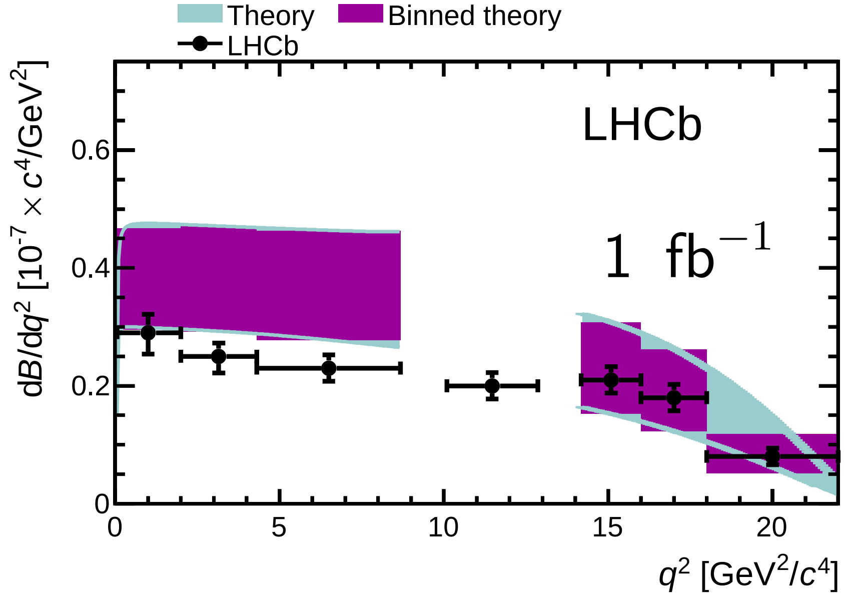
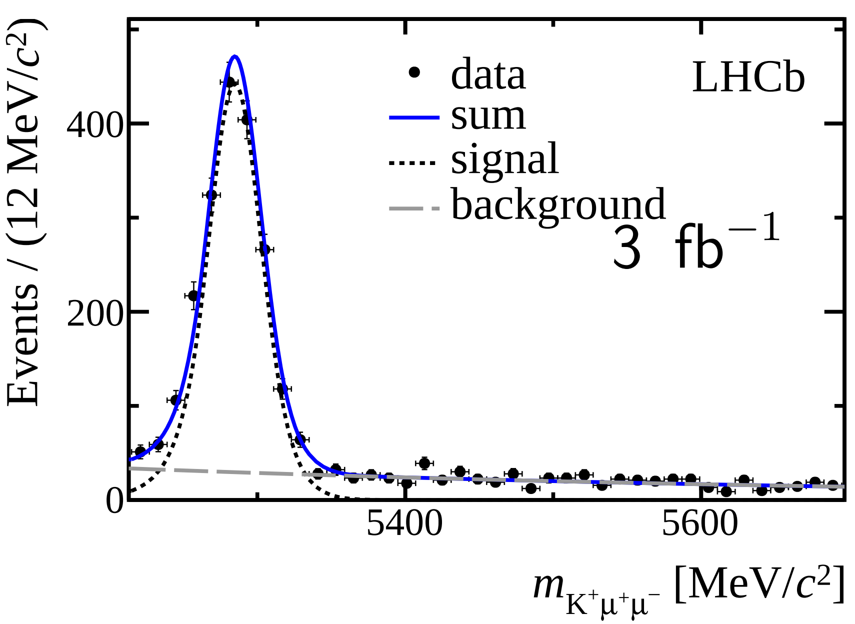
LHCb-PAPER-2013-039

- Significant effort goes into study of $b \to sl^+l^-$ FCNCs
- In measurements, J/ψ and $\psi(2S)$ is removed
- $c\bar{c}$ states above $\psi(2S)$ kept, expected to contribute about 2% of non-resonant (Beylich, Buchalla, Feldmann: EPJ C71, 1635)
- We are getting to point when B^+ data can test such contributions
- Have 1830 B^+ decays with $m(\mu^+\mu^-) > 3770\ \mathrm{MeV}/c^2$
- Very low background



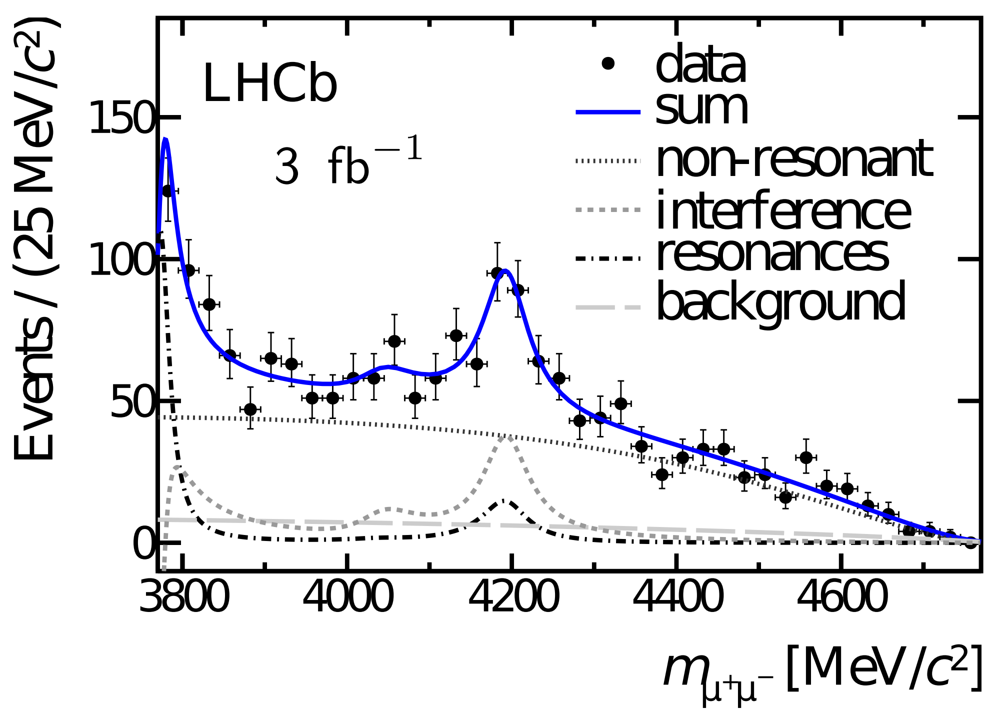


Dimuon spectrum

LHCb-PAPER-2013-039

- See signal at $\approx 4.2\ \mathrm{GeV}/c^2$
- Fit Breit-Wigner for observed peak
- Non-resonant contribution according to latest theory (Khodjamirian et al., JHEP 09, 089; Bouchard et al., arXiv:1306.2384; Bobeth et al., JHEP 01, 107)
- Non-B background
- Fit takes into account interference between BW and non-resonant contribution
- Parameters

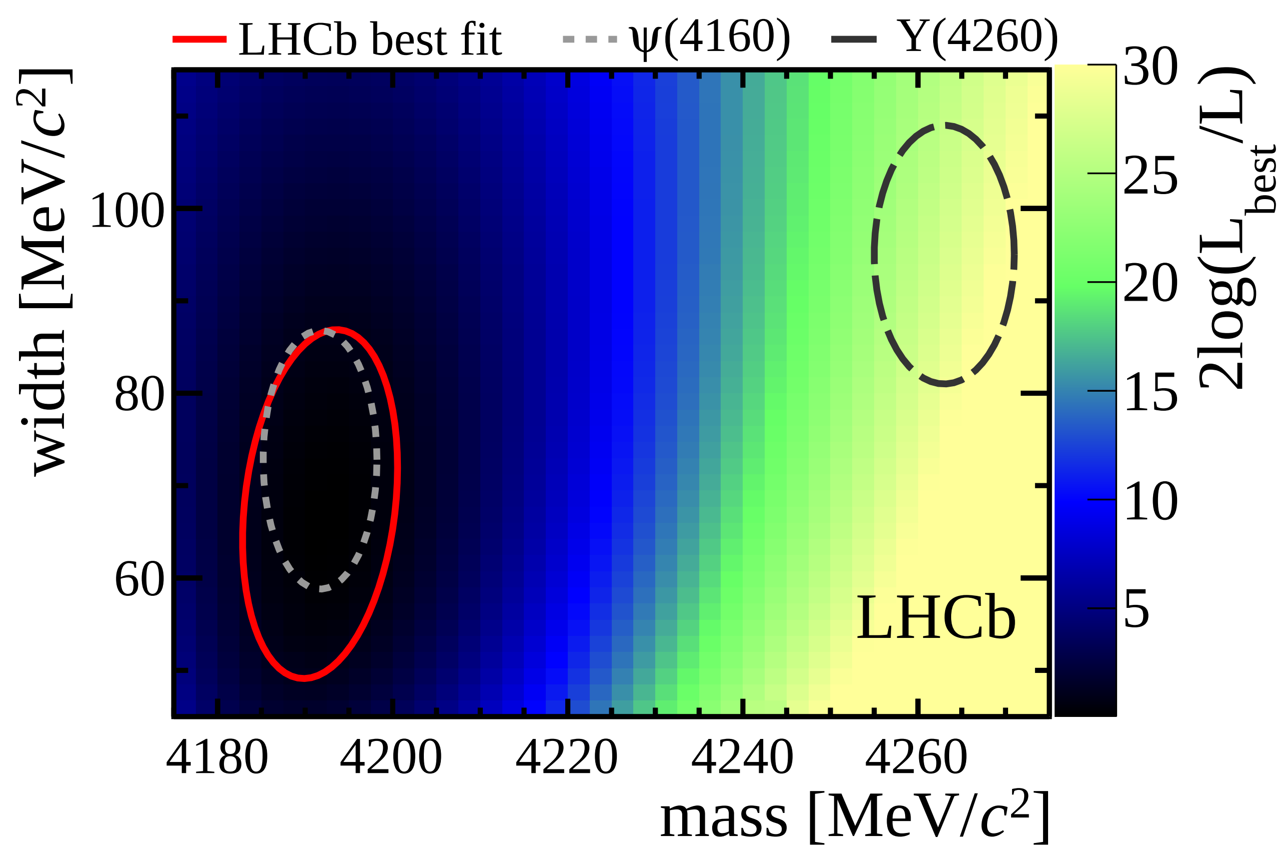
$\mathcal{B}[\times 10^{-9}]$	$3.5\,^{+0.9}_{-0.8}$
Mass $[\,\mathrm{MeV}/c^2]$	4190 ± 5
Width $[\,\mathrm{MeV}/c^2]$	66 ± 12



Interpretation

LHCb-PAPER-2013-039

- Consistent with $\psi(4160)$
- Interpretation as $Y(4260)$ excluded at 4σ
- Contributes about 20% above $\psi(2S)$ mass



$X(3872)$ quantum numbers

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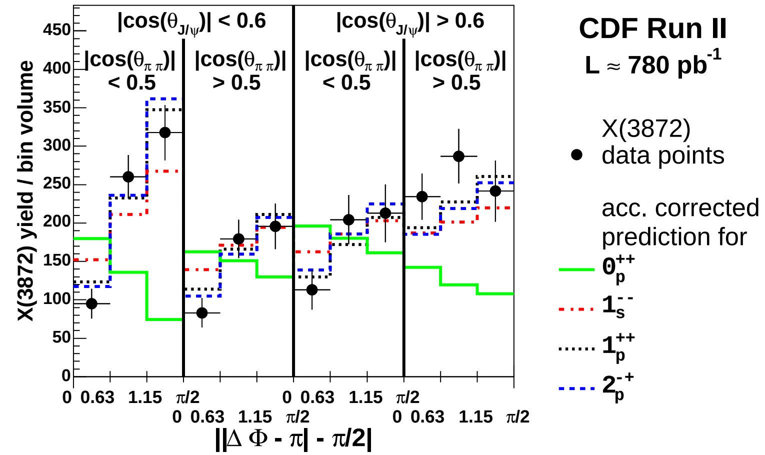
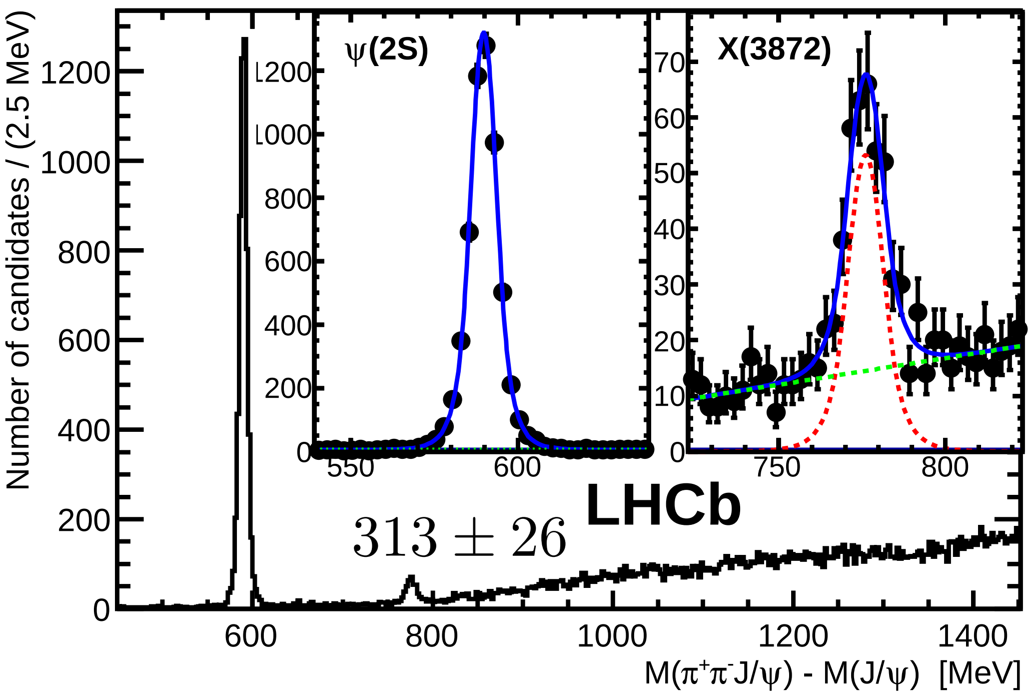
- Its 10 years since observation of $X(3872)$
- Triggered renewed interest to $c\bar{c}$ states
- Lot of speculations what $X(3872)$ is
- Determination of quantum numbers important
  - Not all hypotheses work with any J^{PC}
  - Restricts its position in spectrum
- In 2006 CDF restricted J^{PC} to 1^{++} or 2^{-+}
- BABAR favours 2^{-+} from observation of $X(3872) \to J/\psi\,\omega$





PRL 110, 222001

$X(3872)$ quantum numbers

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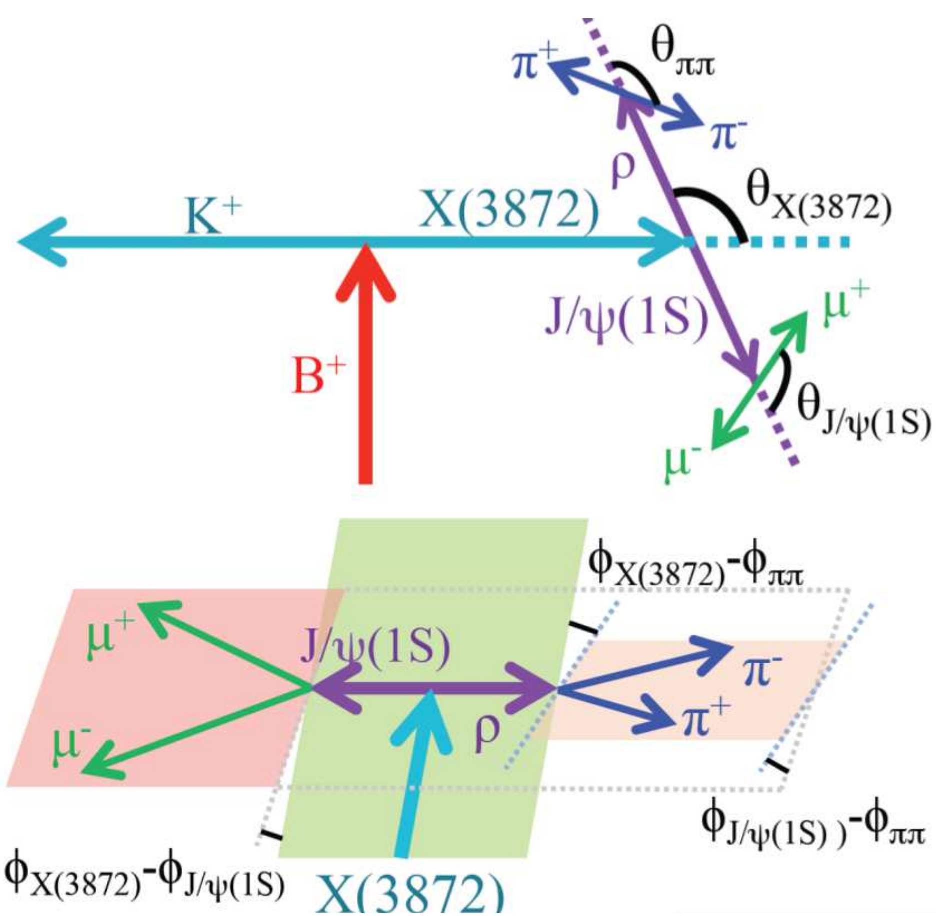
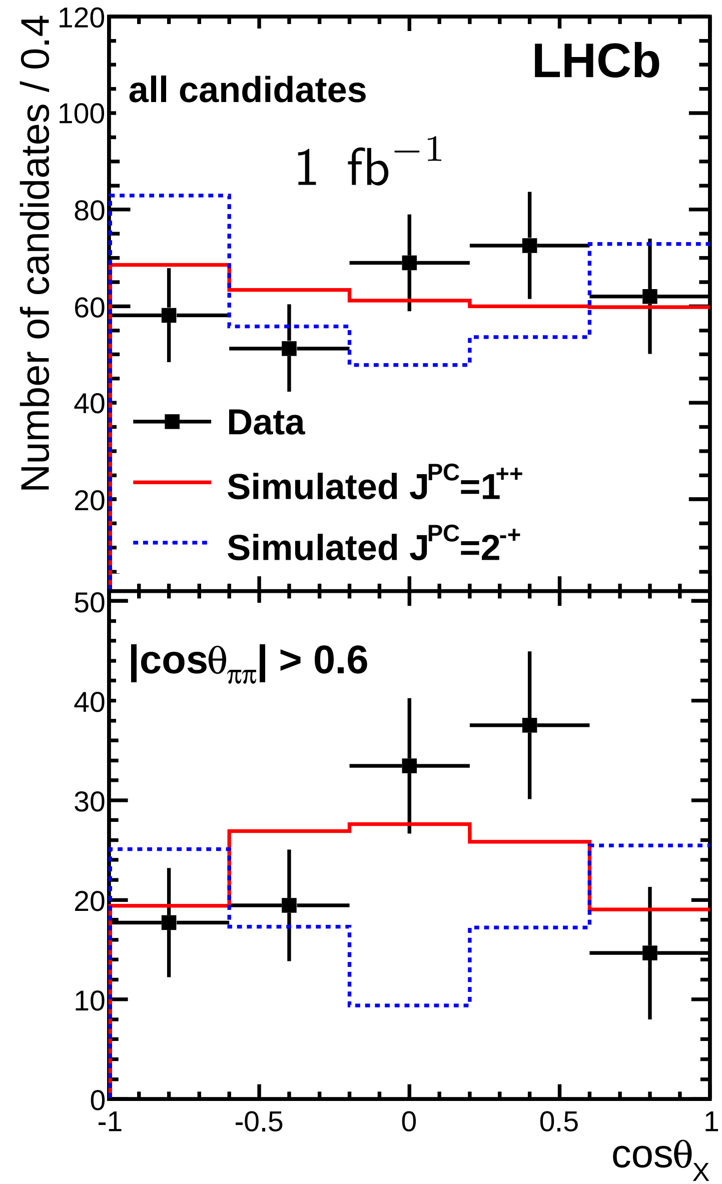
PRL 110, 222001

- LHCb uses $B^+ \to J/\psi\, K^+$ decays
- Full angular analysis performed
- Introduces “production” polarization

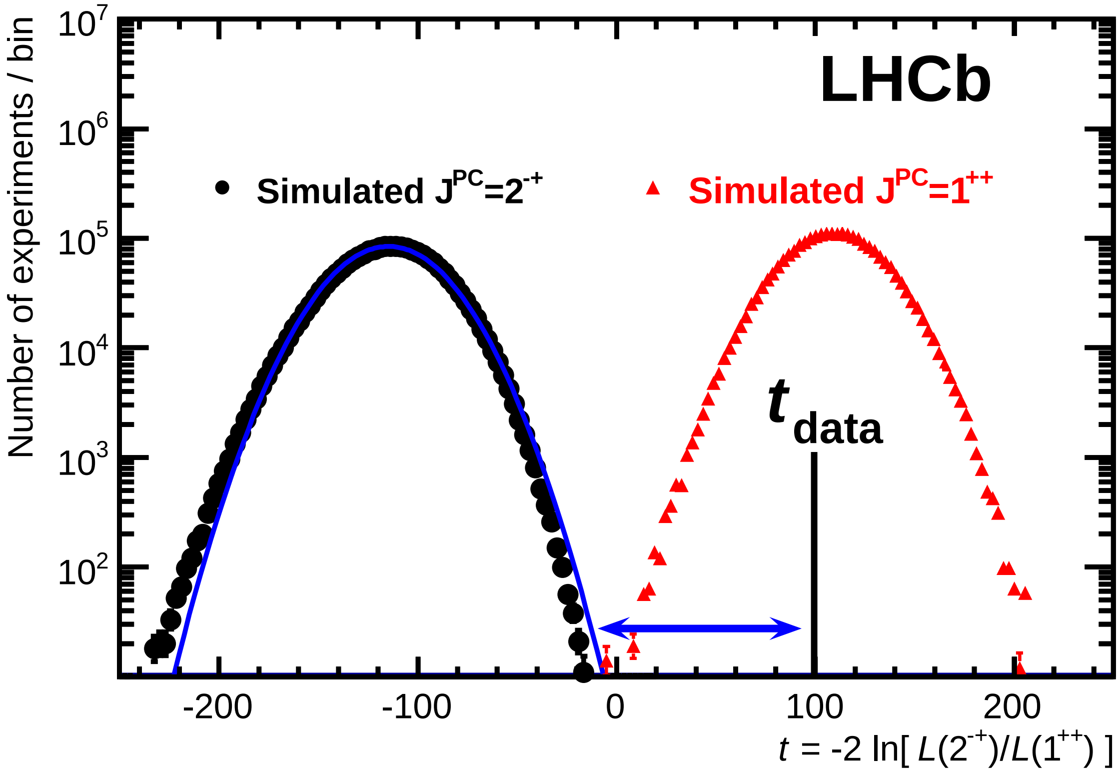




$X(3872)$ quantum numbers

PRL 110, 222001

- Use likelihood ratio $-2\ln[L(2^{-+})/L(1^{++})]$
- Allows to distinguish between 1^{++} and 2^{-+} hypotheses
- Excludes 2^{-+} at 8.2σ
- Only $c\bar{c}$ possibility is $\chi_{c1}(2^3P_1)$, but mass is off
- New D^0 mass weakens pure molecule interpretation



Conclusions

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- Significant improvement to experimental knowledge of D_J mesons
- We find additional states
- Some information on parity available
- We improve on ground state $D_{(s)}$ masses
  - Implication for $X(3872)$
- Observed $B_c \to J/\psi\, D_s$ and improved B_c mass measurement
- Observe $\psi(4160)$ in $B^+ \to K^+\mu^+\mu^-$ at unexpectedly high rate
- Finally after almost 10 years pinpointed $X(3872)$ J^{PC}
- List of available results at http://lhcbproject.web.cern.ch/lhcbproject/CDS/cgi-bin/index.php
- Many other topics in progress and in some cases not all data analysed

$\Rightarrow$ More news to expect