Heavy flavour spectroscopy at LHCb

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On behalf of the LHCb Collaboration

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Stockholm 2013

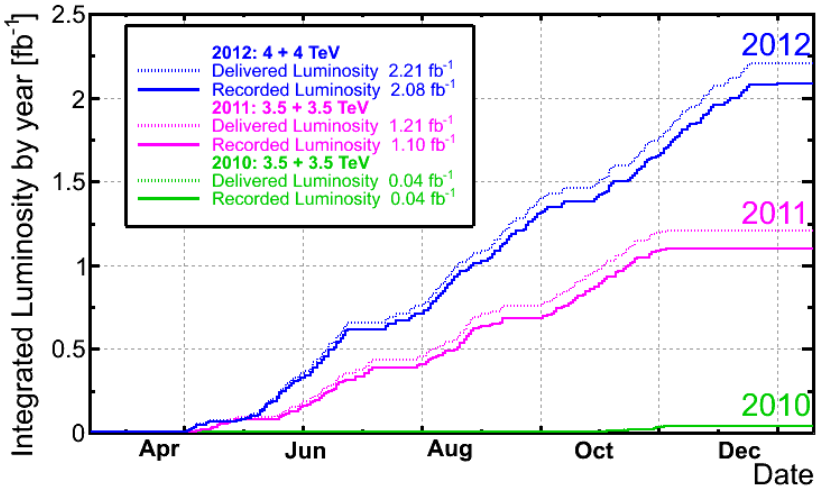
Overview of this talk

- Analysis of inclusively promptly produced $D^{(*)}\pi$ pairs
  Data sample 1 fb^{-1} @ 7 TeV (2011)
  - $D^0[K\pi]\pi^+, D^+[K\pi\pi]\pi^-, D^{*+}[D^0\pi]\pi^-$ + c.c.
  - Arxiv:1307.4556

New

- Analysis of $B^+ \to K^+\mu^+\mu^-$ decays at low recoil
  Data sample 3 fb^{-1} @ 7+8 TeV (2011 + 2012)
  - Charmonium resonance observed
  - Preliminary results, LHCb-Paper-2013-039

New



LHCb well equipped for spectroscopy studies

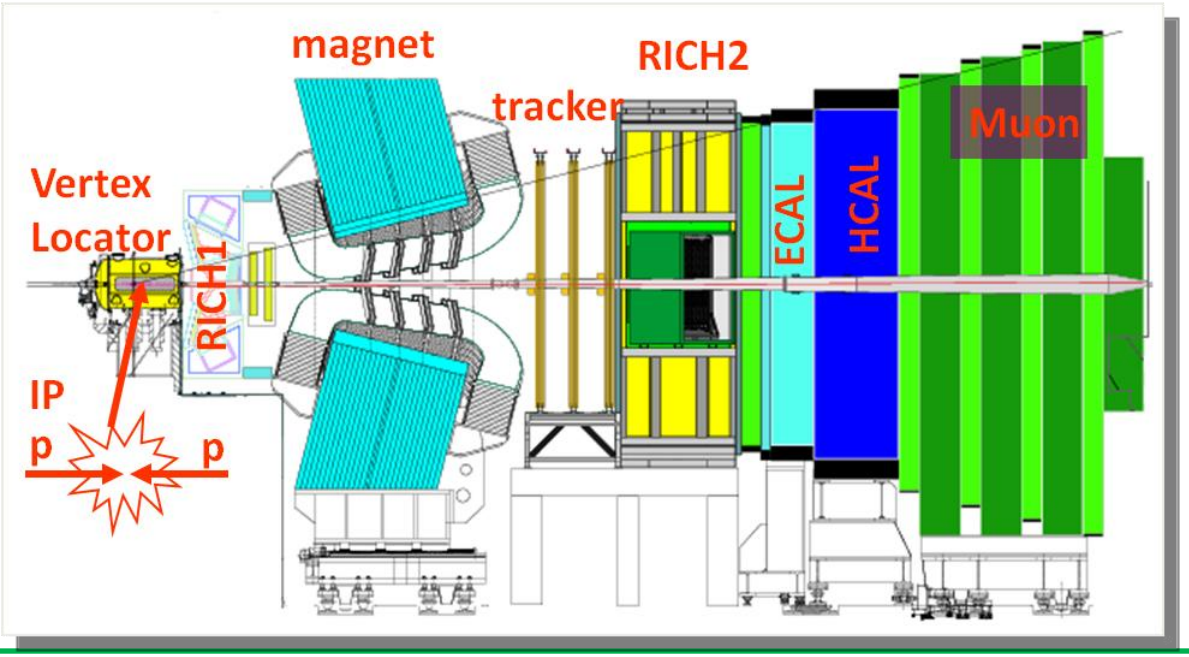
large visible cross-section → charm/total ~ 1/10, beauty/charm ~ 1/20

excellent momentum and mass resolution

vertex resolution σ_τ ~ 40 fs

- *prompt vs. detached*

excellent particle ID thanks to the RICHes



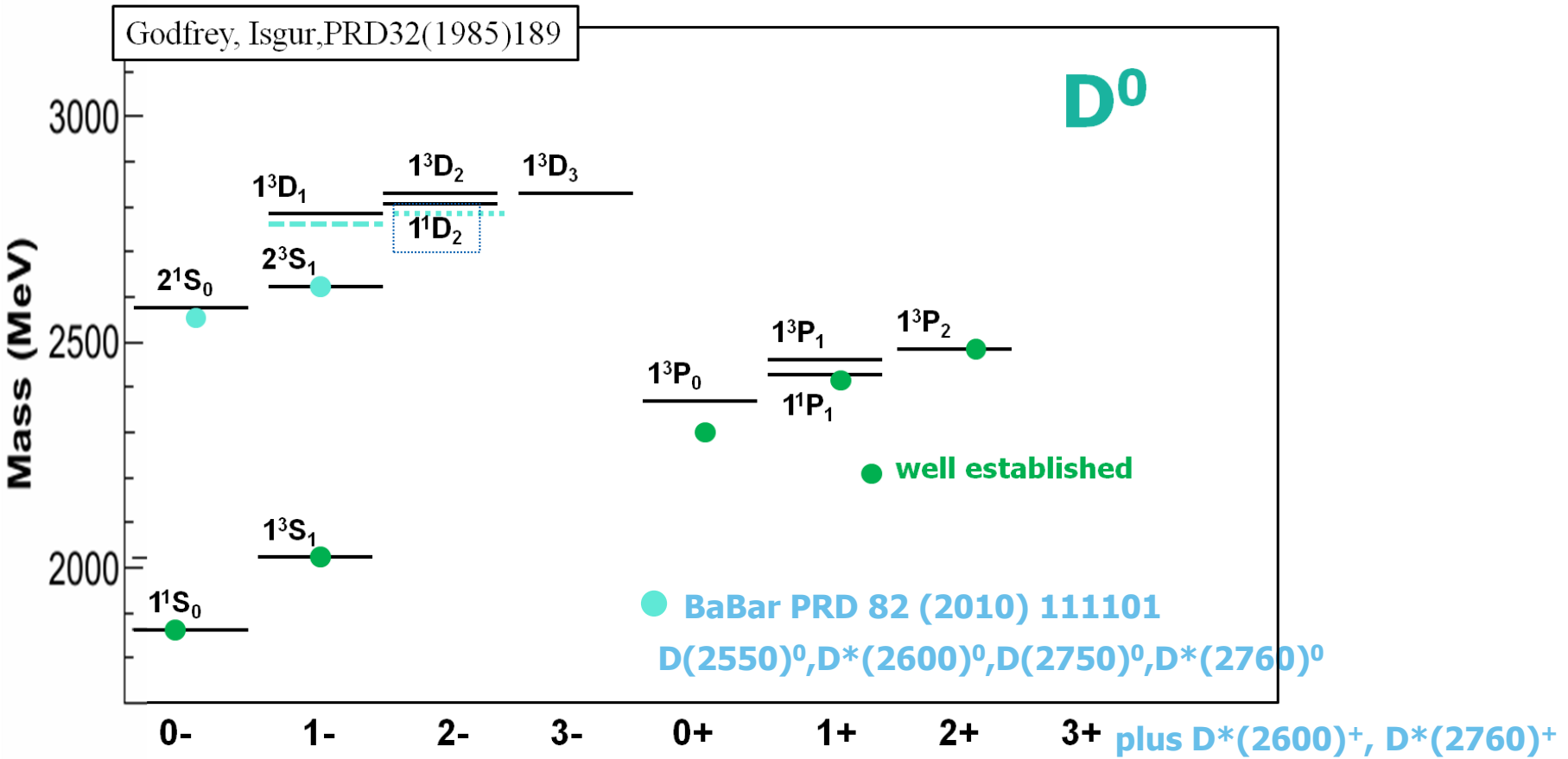
powerful and flexible trigger

3 kHz to storage

automatic luminosity leveling➔ $\mathcal{L} = 4 \cdot 10^{32}$ cm^{-2} s^{-1}

Stable data taking conditions

Rich variety of charmed mesons predicted since the '80s but many still undiscovered



- most J^P need confirmation
- mass shifts up to 50 MeV

→

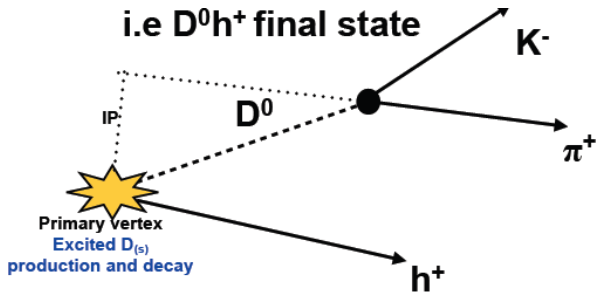
- natural $J^P = 0^+, 1^-, 2^+, \ldots$
- unnatural $J^P = 0^-, 1^+, 2^-, \ldots$

Data sample and selection

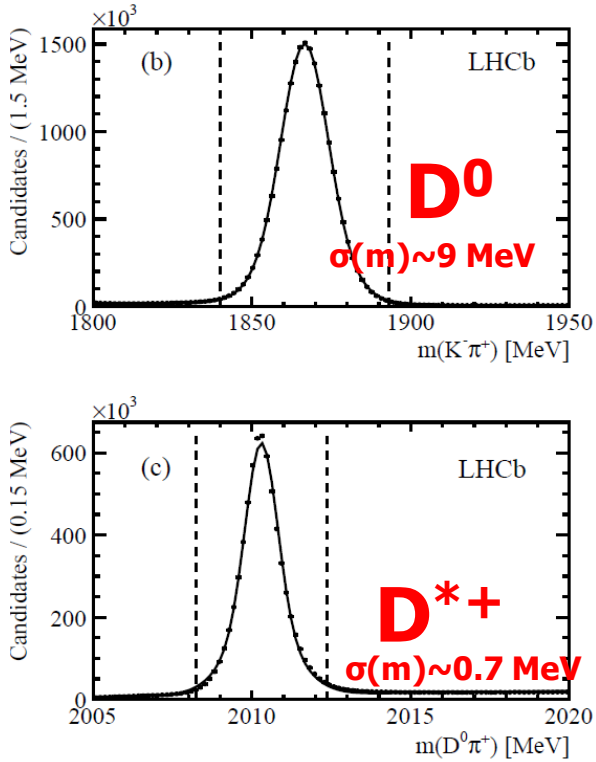
$pp \to D^+\pi^- X$ ~ 7.9 M

$pp \to D^0\pi^+ X$ ~ 7.5 M

$pp \to D^{*+}\pi^- X$ ~ 2.1 M

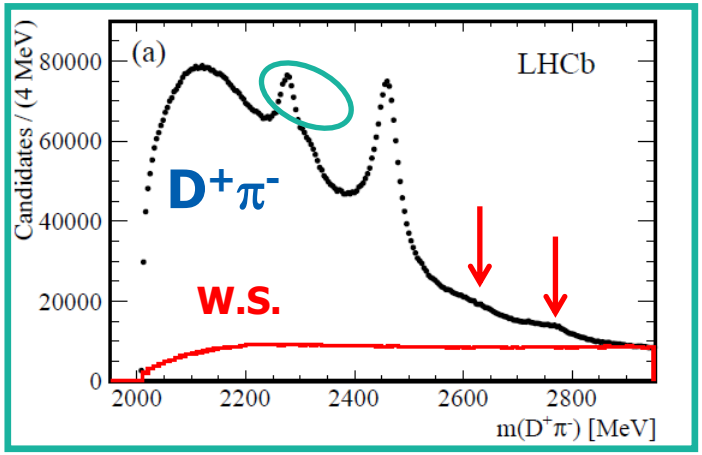


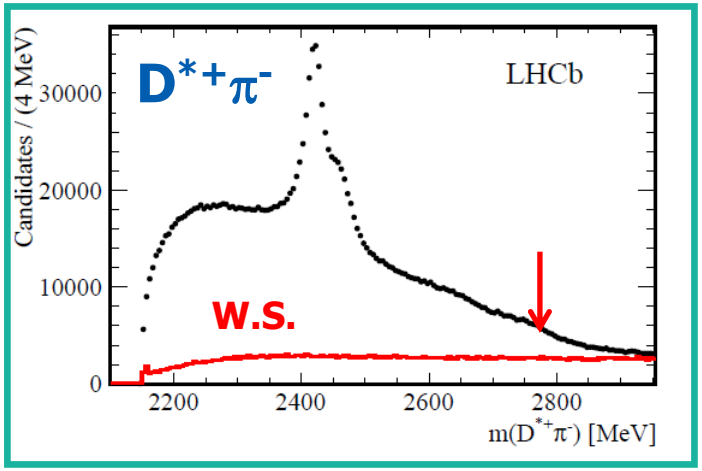
Charm pointing to primary vertex



Invariant mass spectra

$D_2^*(2460)^0$ $D_1(2420)^0$ $D_2^*(2460)^0$





arXiv:1307.4556

$D^0\pi^+$ too

arXiv:1307.4556

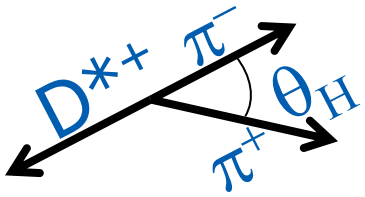
Clear contributions from well-known $D_1(2420)^0$ and $D_2^*(2460)^0$

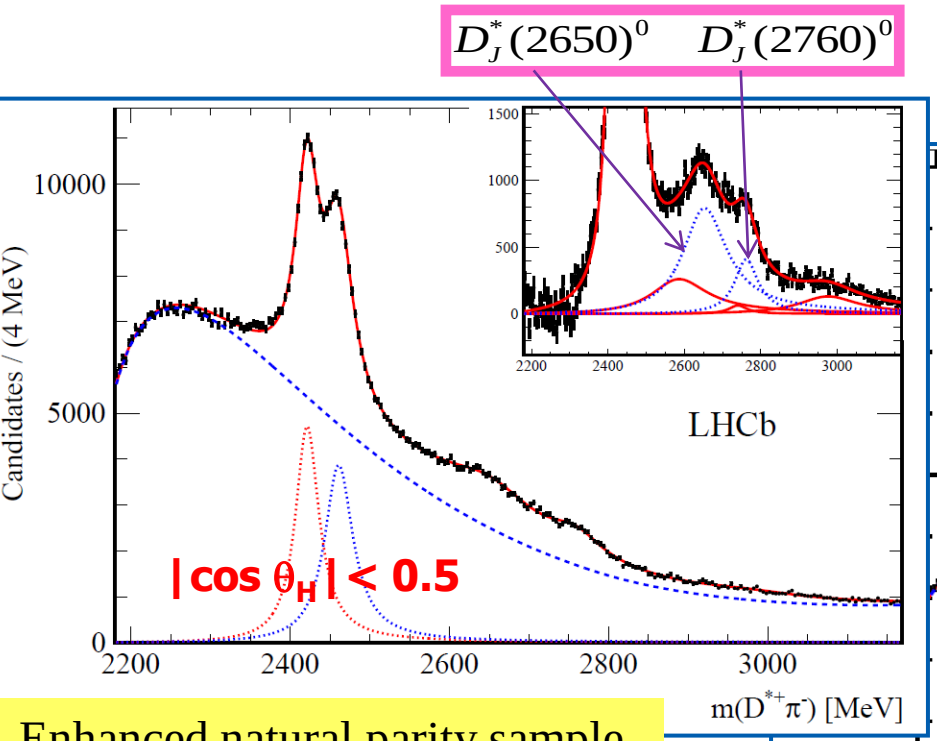
plus reflections from partially reconstructed decays ➔ 

↓ ↓ *arrows indicate other possible structures* ➔

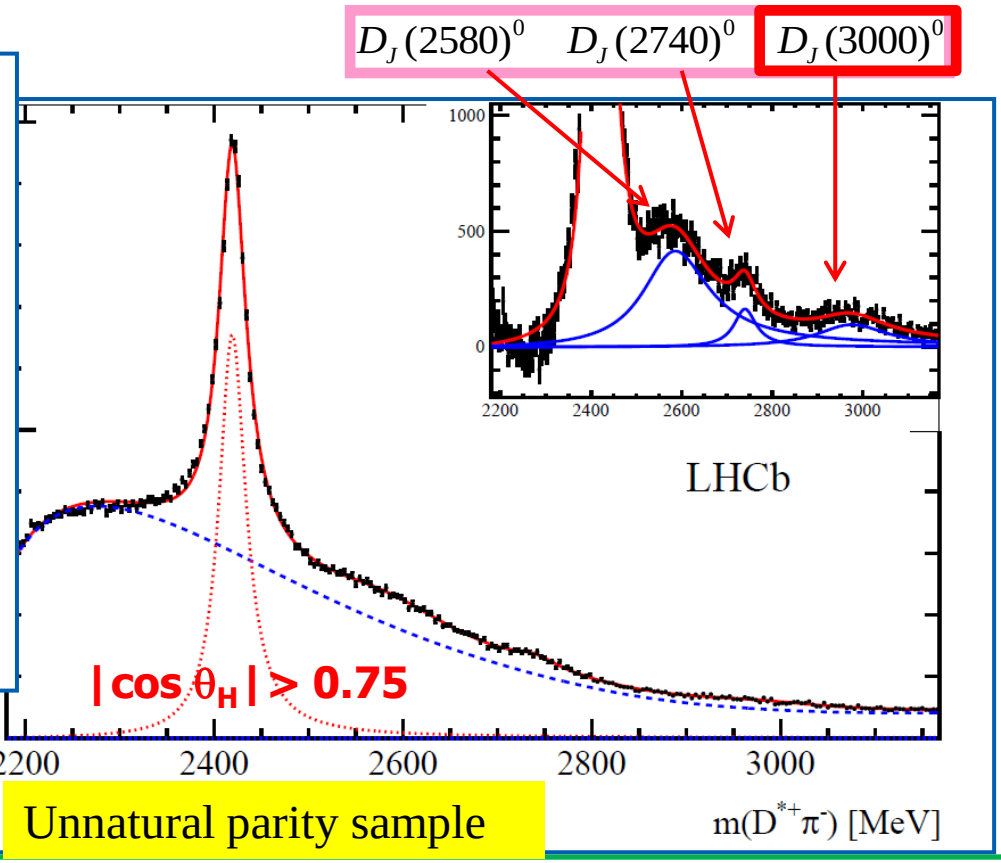
Background subtraction

- empirical background shape: $B(m) = \Phi(m)\exp(P_2(m))$
- for $D^*\pi$ decays use $\cos\theta_H$ to enhance natural/unnatural J^P
- Breit-Wigner signal fit





Enhanced natural parity sample



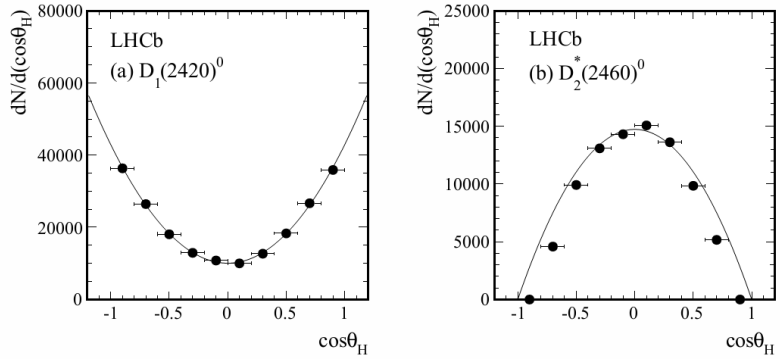
Unnatural parity sample

arXiv:1307.4556

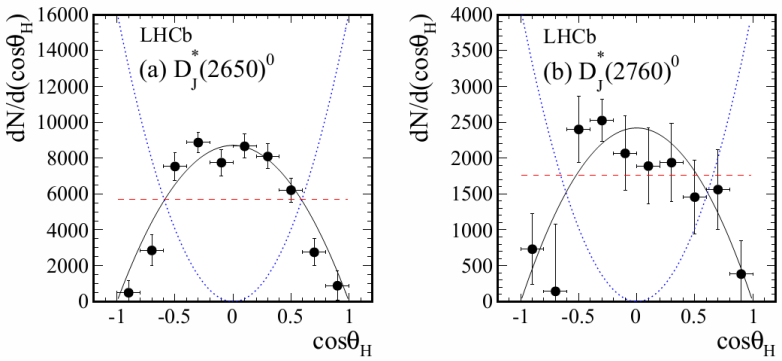
Spin-parity analysis

θ_H = helicity angle

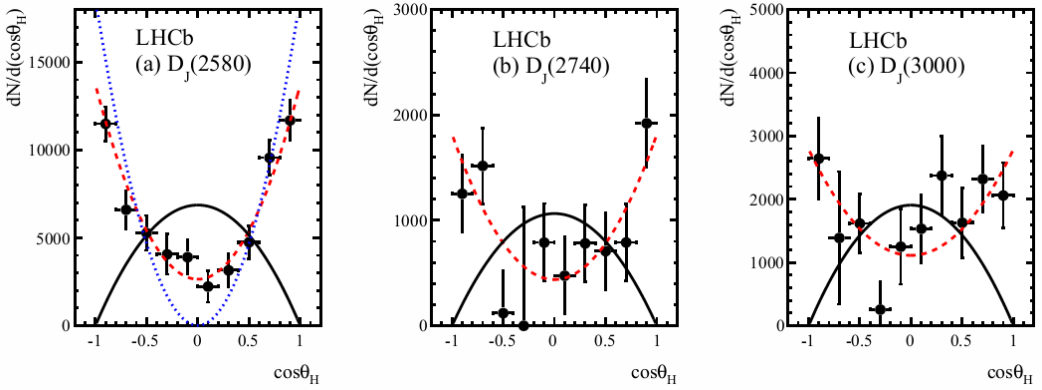
Confirm assignments
for well-established states
- $D_1(2420)^0$ $J^P = 1^+$
- $D^*_2(2460)^0$ $J^P = 2^+$



Natural parity assignment
for $D^*_J(2650)^0$ and
$D^*_J(2760)$



Unnatural parity assignment
for $D_J(2580)^0$ and $D_J(2740)$
Suggested for $D_J(3000)$



arXiv:1307.4556

LHCb

arXiv:1307.4556

Unnatural J^P

Natural J^P

Seen only in $D^*\pi$ 1^- Natural J^P

Natural J^P

Unnatural J^P

Unnatural J^P, 2^-

NEW, compatible with unnatural J^P

Natural J^P

Natural J^P, 1^-

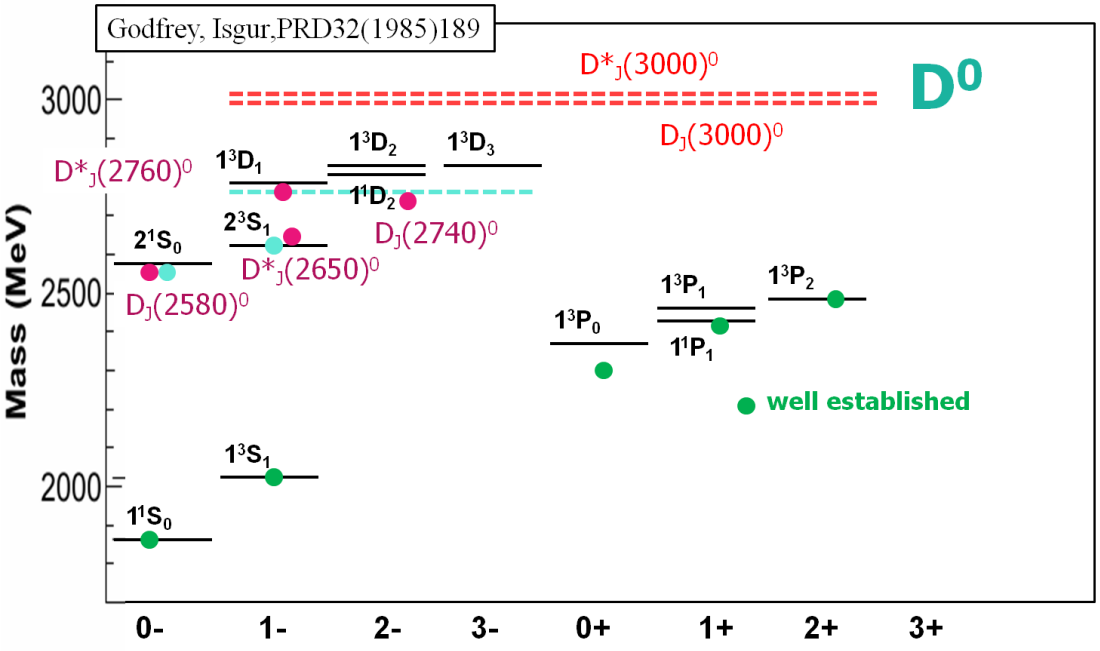
NEW

Natural J^P

Natural J^P, 1^-

NEW

Resonance	Final state	Mass (MeV)	Width (MeV)	Nσ
$D_1(2420)^0$	$D^{*+}\pi^-$	$2419.6 \pm 0.1 \pm 0.7$	$35.2 \pm 0.4 \pm 0.9$	
$D_2^*(2460)^0$	$D^{*+}\pi^-$	$2460.4 \pm 0.4 \pm 1.2$	$43.2 \pm 1.2 \pm 3.0$	
$D_J^*(2650)^0$	$D^{*+}\pi^-$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$	24.5
$D_J^*(2760)^0$	$D^{*+}\pi^-$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 3.4 \pm 37.0$	10.2
$D_J(2580)^0$	$D^{*+}\pi^-$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.8 \pm 46.0$	18.8
$D_J(2740)^0$	$D^{*+}\pi^-$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$	7.2
$D_J(3000)^0$	$D^{*+}\pi^-$	2971.8 ± 8.7	188.1 ± 44.8	9.0
$D_2^*(2460)^0$	$D^+\pi^-$	$2460.4 \pm 0.1 \pm 0.1$	$45.6 \pm 0.4 \pm 1.1$	
$D_J^*(2760)^0$	$D^+\pi^-$	$2760.1 \pm 1.1 \pm 3.7$	$74.4 \pm 3.4 \pm 19.1$	17.3
$D_J^*(3000)^0$	$D^+\pi^-$	3008.1 ± 4.0	110.5 ± 11.5	21.2
$D_2^*(2460)^+$	$D^0\pi^+$	$2463.1 \pm 0.2 \pm 0.6$	$48.6 \pm 1.3 \pm 1.9$	
$D_J^*(2760)^+$	$D^0\pi^+$	$2771.7 \pm 1.7 \pm 3.8$	$66.7 \pm 6.6 \pm 10.5$	18.8
$D_J^*(3000)^+$	$D^0\pi^+$	3008.1 (fixed)	110.5 (fixed)	6.6



- Confirmation of $D_1(2420)$ and $D_2^*(2460)$
- Partial agreement with Babar results
- Three new candidates seen around 3000 MeV

LHCb

arXiv:1307.4556

	Resonance	Final state	Mass (MeV)	Width (MeV)	Nσ
Unnatural J^P	$D_1(2420)^0$	$D^{*+}\pi^-$	$2419.6 \pm 0.1 \pm 0.7$	$35.2 \pm 0.4 \pm 0.9$	
Natural J^P	$D_2^*(2460)^0$	$D^{*+}\pi^-$	$2460.4 \pm 0.4 \pm 1.2$	$43.2 \pm 1.2 \pm 3.0$	
Seen only in $D^*\pi$ 1^- Natural J^P	$D_J^*(2650)^0$	$D^{*+}\pi^-$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$	24.5
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Unnatural J^P	$D_J(2580)^0$	$D^{*+}\pi^-$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.8 \pm 46.0$	18.8
Unnatural J^P, 2^-	$D_J(2740)^0$	$D^{*+}\pi^-$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$	7.2
NEW, compatible with unnatural J^P	$D_J(3000)^0$	$D^{*+}\pi^-$	2971.8 ± 8.7	188.1 ± 44.8	9.0
Natural J^P	$D_2^*(2460)^0$	$D^+\pi^-$	$2460.4 \pm 0.1 \pm 0.1$	$45.6 \pm 0.4 \pm 1.1$	
Natural J^P, 1^-	$D_J^*(2760)^0$	$D^+\pi^-$	$2760.1 \pm 1.1 \pm 3.7$	$74.4 \pm 3.4 \pm 19.1$	17.3
NEW	$D_J^*(3000)^0$	$D^+\pi^-$	3008.1 ± 4.0	110.5 ± 11.5	21.2
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NEW	$D_J^*(3000)^+$	$D^0\pi^+$	3008.1 (fixed)	110.5 (fixed)	6.6

Final states $D^+\pi^-$ and $D^0\pi^+$ more tricky because of feeddown from D^*

Largest contribution to systematics from bkgd. model

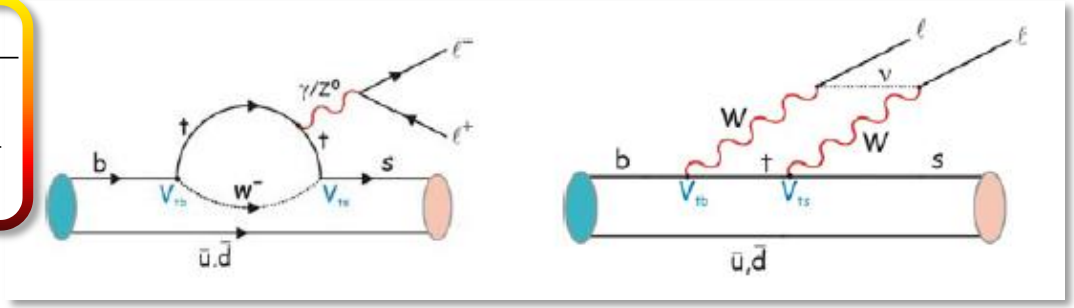
➔ $D_J(3000)$ parameters strongly correlated with bkgd.

Several cross-checks of fit stability performed.

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

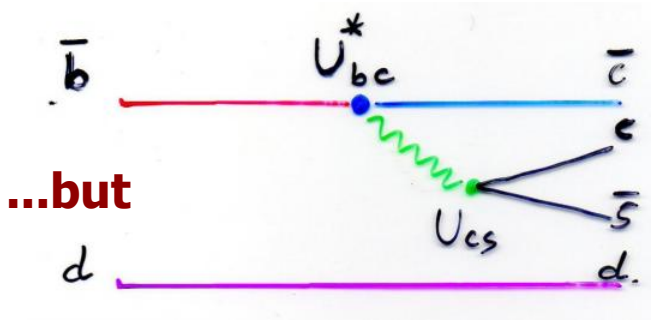
$B^{\pm} \to K^{\pm} \ell^+ \ell^-$

$B^0 \to K^0 \ell^+ \ell^-$



FCNC transitions

Good place to look for physics beyond the SM



...but

J/ψ, ψ' ➔ μ⁺ μ⁻

bkgd ☞ resonances region
$8 < q^2 < 14$ GeV²
normally excluded from analysis

LHCb previous results (1 fb-1) on charged B decay $B^+ \to K^+ \mu^+ \mu^-$
doi:10.1007/JHEP02(2013)105 $\mathcal{B} = (4.36 \pm 0.23)\ 10^{-7}$

For LHCb latest results on neutral B decay $B^0 \to K^{0*} \mu^+ \mu^-$ arXiv:1304.6325

Low recoil region of $d\Gamma/dm_{\mu\mu}$

Contribution from resonances above open charm threshold can be described by Operator Product Expansion (OPE). Correction to BF(low recoil) was estimated < 2%

See Beylich, Buchalla & Feldmann
Eur. Phys. J. **C71** (2011) 1635

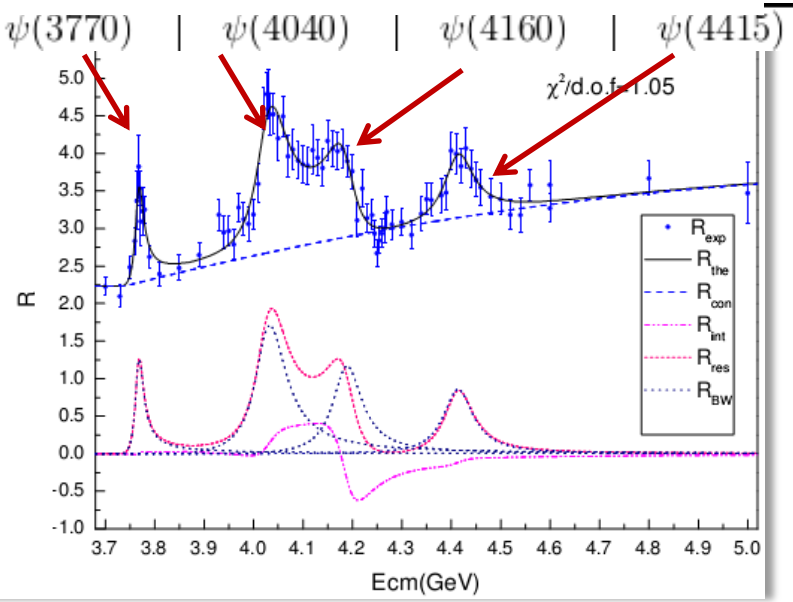
$$R(q^2) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

BES analysis includes interference and strong phases in the fit

BES

Ablikim et al., PLB 660 (2008) 315

Resonance	Mass [MeV/c^2]	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



Data sample and selection

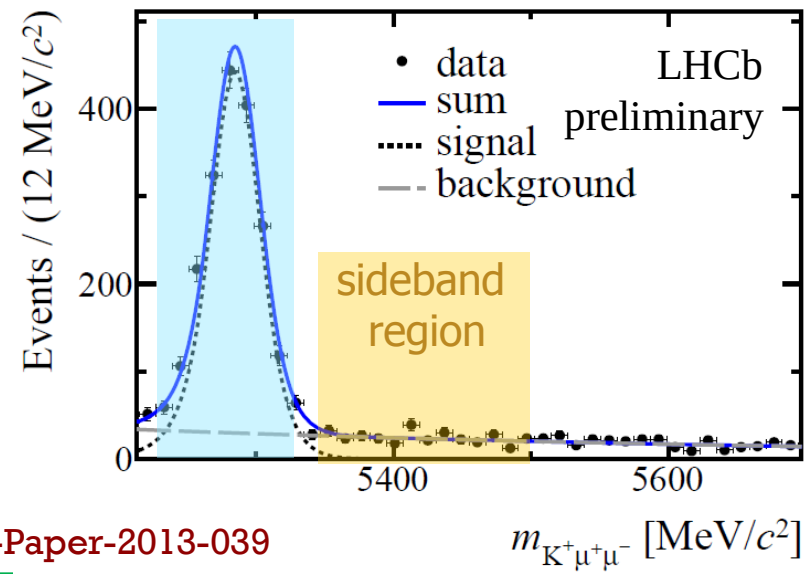
- Muon L0 Trigger + Software trigger
- Offline Selection cuts (most important bkgd is combinatorial)
  - large IP of tracks wrt PV
  - positive muon identification
  - good vertex quality
  - B^+ candidate pointing to PV
- **μ–K** vetos to reject peaking bkgds

  e.g. $B^+ \rightarrow$ "μ^+ $J/\psi(\rightarrow K^+\mu^-)$"

- Multivariate analysis (BDT)
  - geometric and kinematic variables
    - IP of decay products
    - B^+ vertex quality
  - Signal training: MC
  - Bkgd training: 10% events in sideband
  - Very good selection power
    - 90% signal efficiency
    - 6% bkgd efficiency

$m_{\mu\mu} > 3.77$ MeV

←1830 candidates, S/B = 8

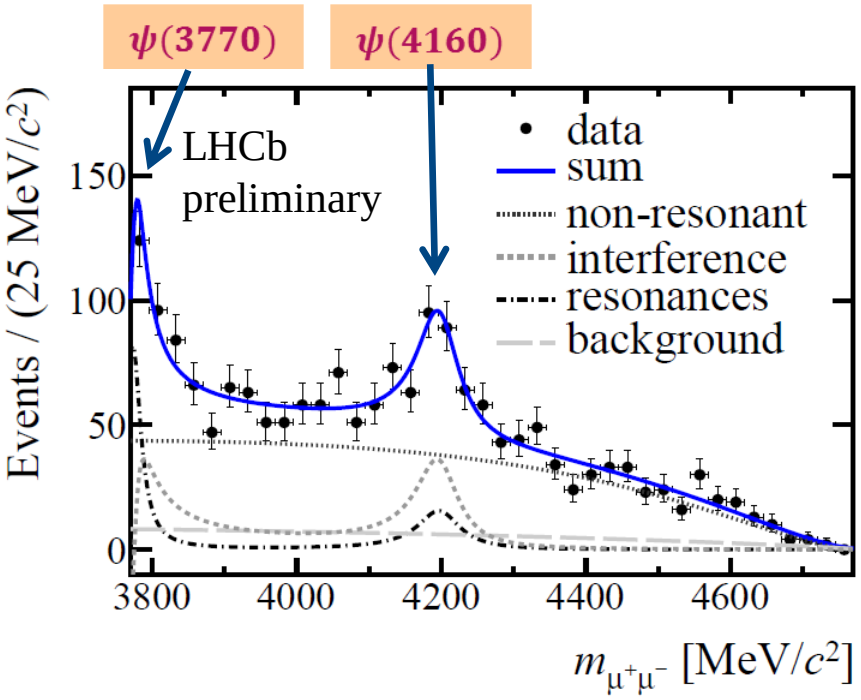


LHCb-Paper-2013-039

Mass fit I

1^{--} interference taken into account ➔ PDF built with amplitudes and relative phases

$m_{\mu\mu}$ spectrum fitted with Argus function + Breit Wigners



	Unconstrained	$\psi(4160)$
$\mathcal{B}[\times 10^{-9}]$	$3.9\,^{+0.7}_{-0.6}$	$3.5\,^{+0.9}_{-0.8}$
Mass [MeV/c^2]	$4191\,^{+9}_{-8}$	4190 ± 5
Width [MeV/c^2]	$65\,^{+22}_{-16}$	66 ± 12
Phase [rad]	-1.7 ± 0.3	-1.8 ± 0.3

> 6σ significance

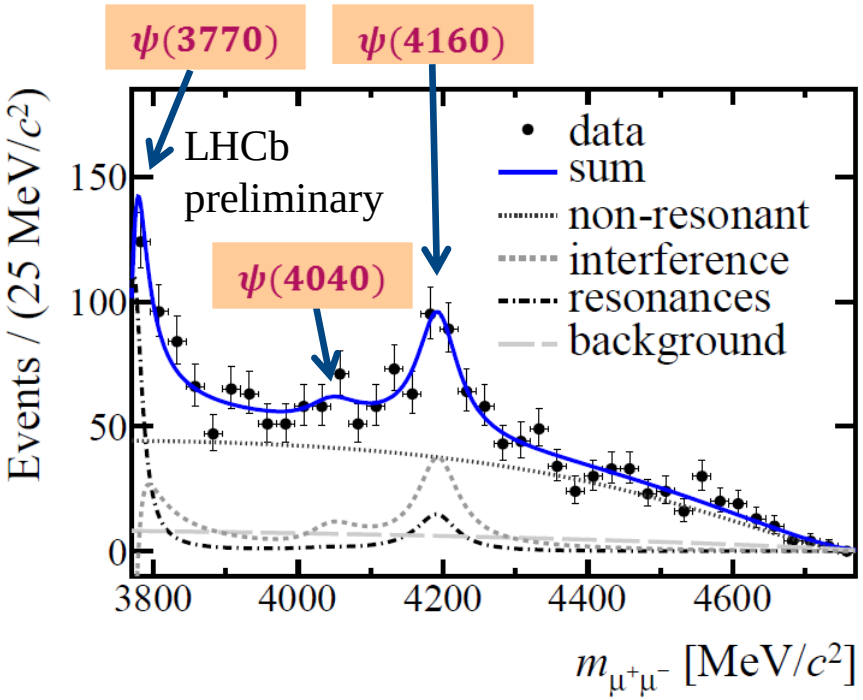
Very good agreement with BES

LHCb-Paper-2013-039

Mass fit II

1^{--} interference taken into account ➔ PDF built with amplitudes and relative phases

$m_{\mu\mu}$ spectrum fitted with Argus function + Breit Wigners



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Phase [rad]	-1.7 ± 0.3	-1.8 ± 0.3

Constrained to BES

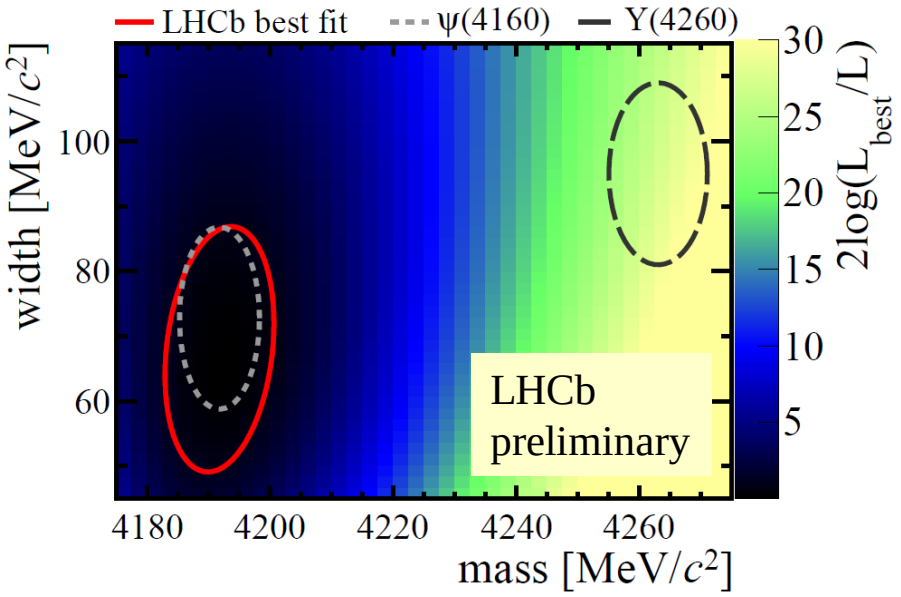
LHCb-Paper-2013-039

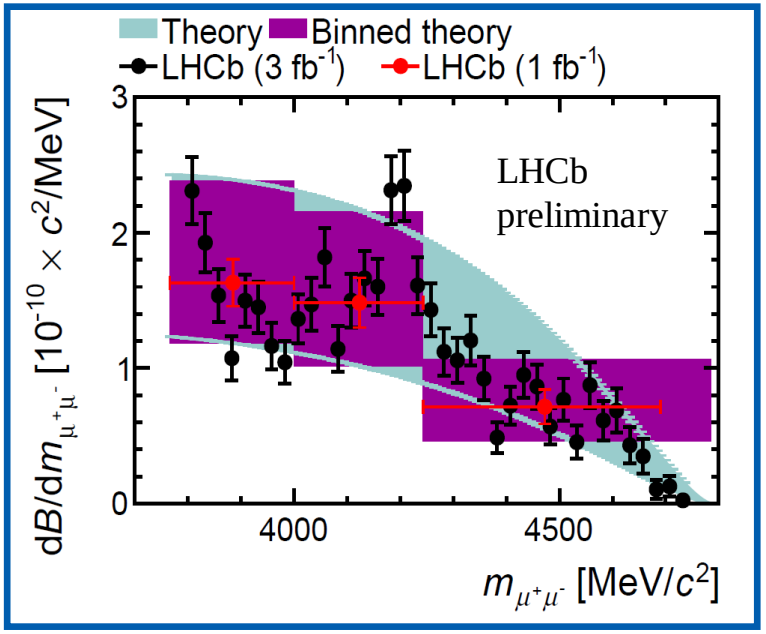
No need for ψ(4040)
Set 95% limit

$$\mathcal{B}(B^+ \to \psi(4040)K^+)\mathcal{B}(\psi(4040) \to \mu^+\mu^-) < 1.5 \cdot 10^{-9}$$

Mass fit III

Alternative $\Upsilon(4260)$ hypothesis rejected by > 4 sigma





20% effect on BF
>> than OPE estimates

LHCb-Paper-2013-039

CONCLUSIONS

We presented two of the most recent preliminary LHCb results in b and c spectroscopy

c spectroscopy

- Two natural parity and two unnatural parity mesons observed
- Possible new candidates with unnatural/natural parity $D_J(3000)^0$, $D_{J*}(3000)^{0,+}$

b spectroscopy

- We observed an important resonant contribution in $B^+ \to K^+\mu^+\mu^-$ decays at low recoil (about 20% of non-resonant signal)
- Consistent with the $\psi(4160)$. Confirm BES mass and width
- No $\psi(4040)$ contribution. Upper limit set. $Y(4260)$ rejected.

Stay tuned for more results!

Spares

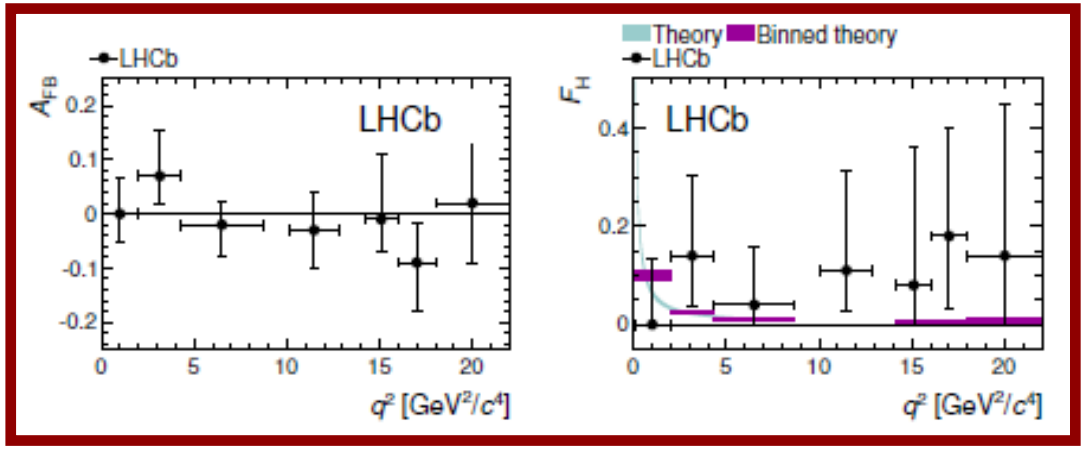
$B^+ \to K^+ \mu^+ \mu^-$

$\mathcal{B}$ = (4.36 ± 0.23) 10^{-7} *LHCb doi:10.1007/JHEP02(2013)105* LHCb 1 fb^{-1}

$$\frac{1}{\Gamma_l}\frac{d\Gamma_l}{d\cos\theta} = \frac{3}{4}(1 - F_H^l)(1 - \cos^2\theta) + \frac{1}{2}F_H^l + A_{\rm FB}^l \cos\theta$$

SM predictions

- $F_H = \mathcal{O}(0.02)$
- $A_{FB} = 0$

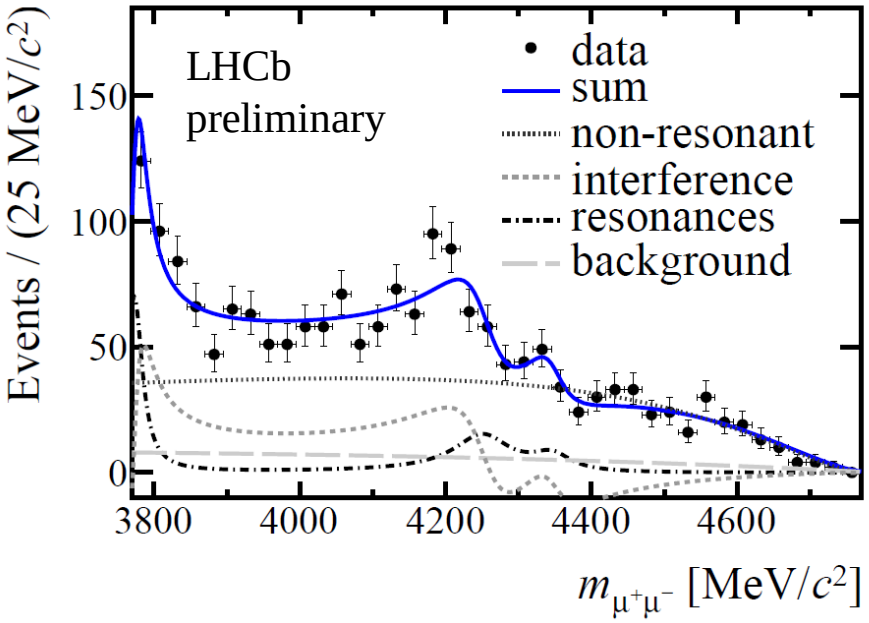


New analysis based on full 2011 + 2012
7 + 8 TeV sample: **3.0 fb^{-1}** ➔

Mass fit III

Alternative fit with Y contributions rejected by > 4 sd

$Y(4260)$
$Y(4350)$



LHCb-Paper-2013-039

LHCb Preliminary
LHCb-Paper-2013-026

Unnatural J^P
Natural J^P
Seen only in $D^*\pi$ 1^- Natural J^P
Natural J^P
Unnatural J^P
Unnatural J^P, 2^-
NEW, compatible with unnatural J^P
Natural J^P
Natural J^P, 1^-
NEW
Natural J^P
Natural J^P, 1^-
NEW

Resonance	Final state	Mass (MeV)	Width (MeV)	Nσ
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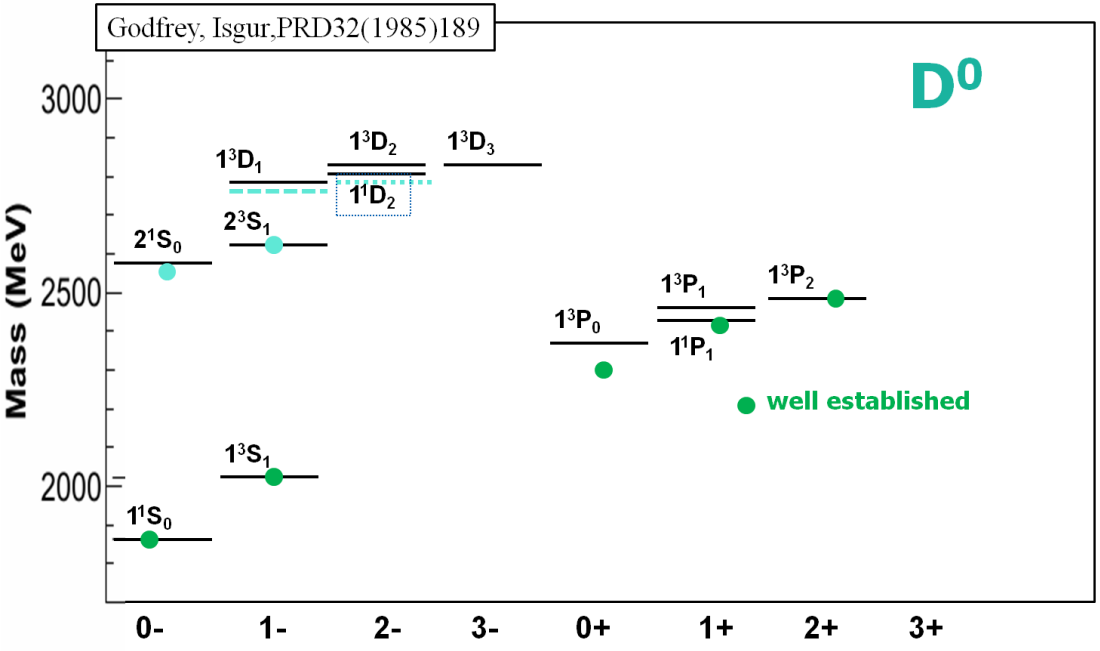
$D_J^*(2760)^+$	$D^0\pi^+$	$2771.7 \pm 1.7 \pm 3.8$	$66.7 \pm 6.6 \pm 10.5$	18.8
$D_J^*(3000)^+$	$D^0\pi^+$	3008.1 (fixed)	110.5 (fixed)	6.6



Largest contribution to systematics from bkgd. model
➔ $D_J(3000)$ parameters strongly correlated with bkgd.
Several cross-checks of fit stability performed.