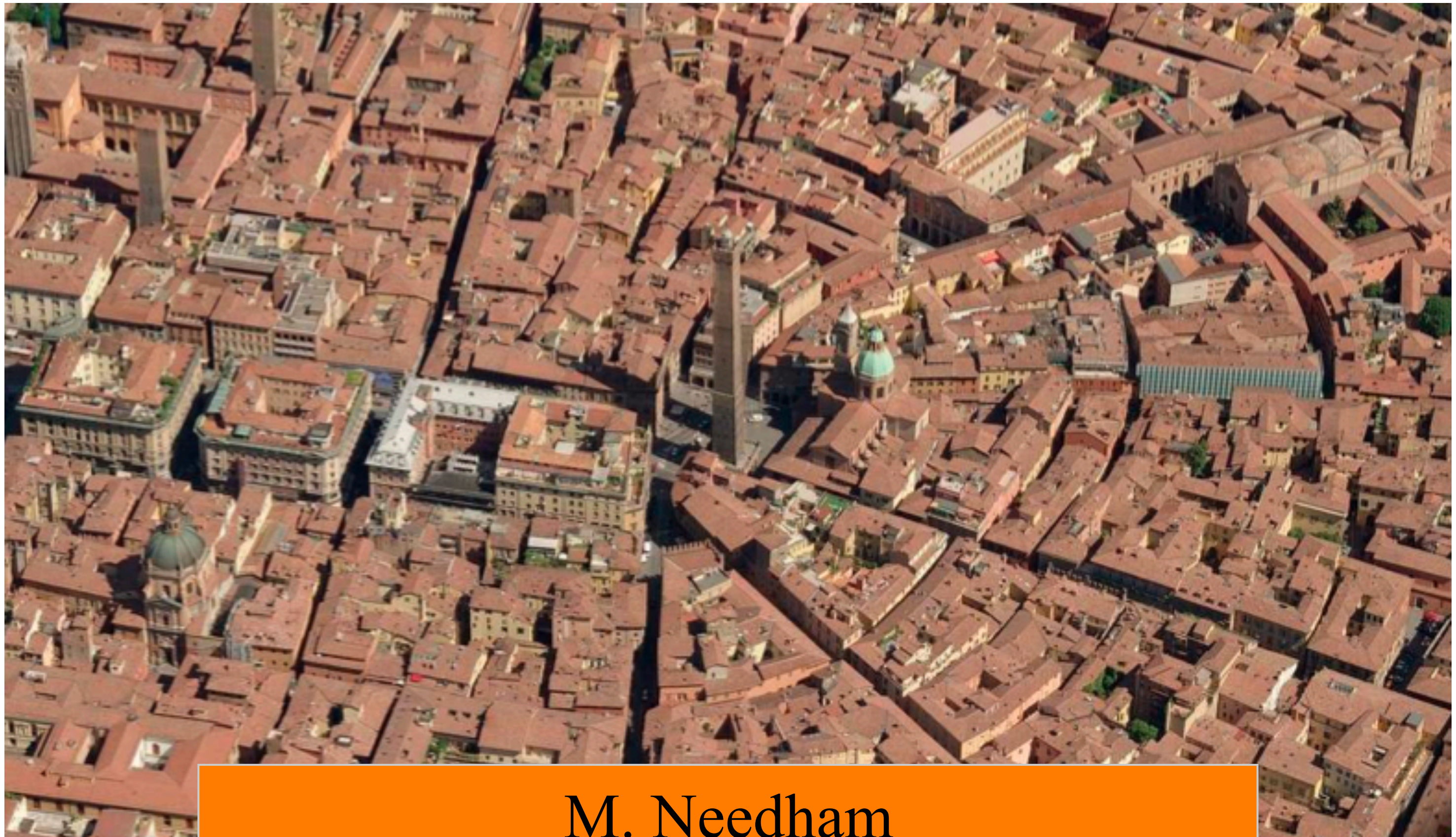
Spectroscopy at LHCb

Beauty 2013 Bologna



M. Needham
University of Edinburgh
On behalf of the LHCb collaboration

Outline

- Introduction
- Study of b baryons masses
- B_c physics
- Exotic spectroscopy: Determination of the X(3872) quantum numbers
- Summary + Outlook

+ open charm mass measurements

Selected highlights of a wide and fast moving program

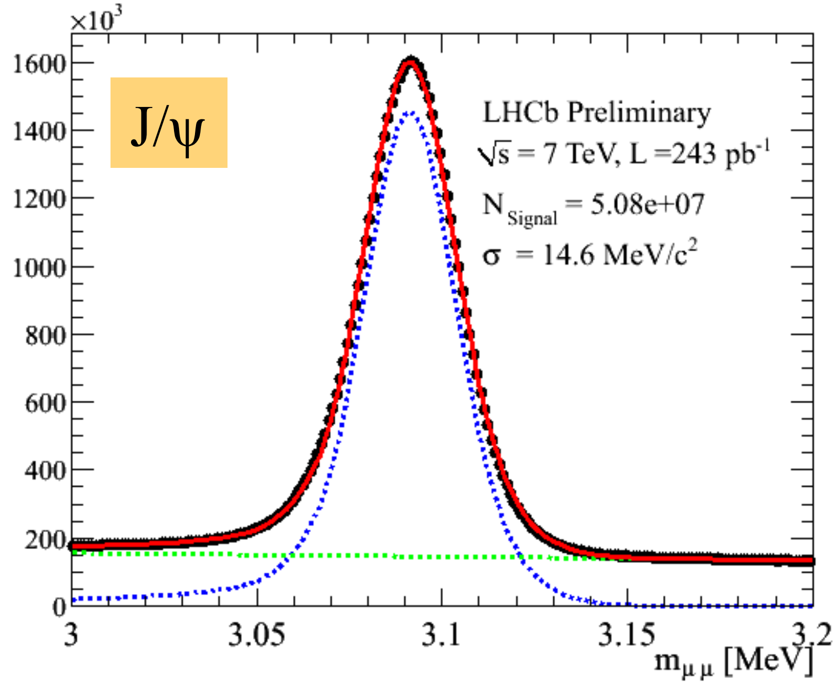
Introduction

Measurements of properties of heavy hadrons provide important tests of our understanding of QCD

- Comparision of properties such as lifetimes and masses
- Searches for new/exotic resonances

LHCb great place to do these studies !

- Huge samples of dimuon decays
- Excellent detector resolution
- Well understood performance

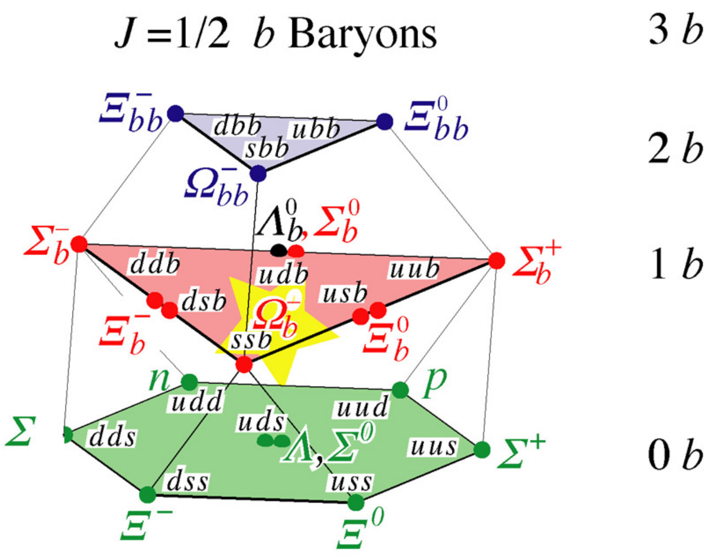


b baryons

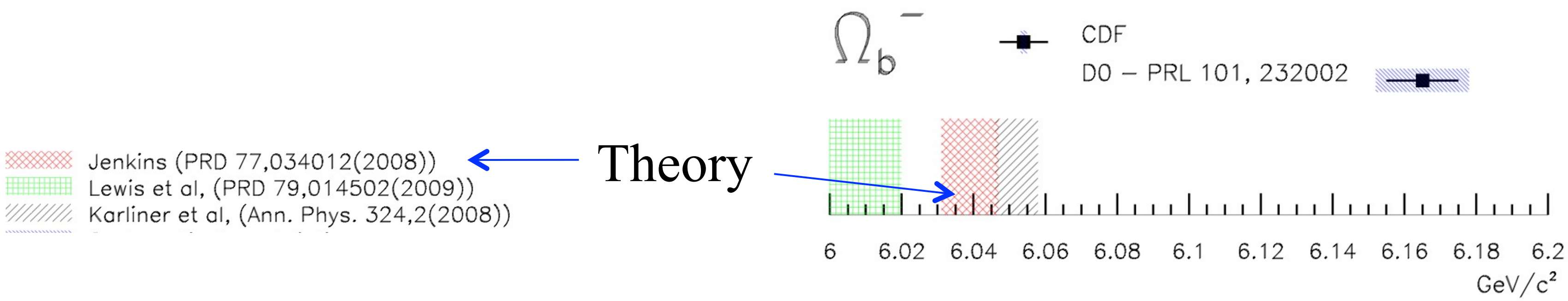
Until recently very poorly explored

Weakly decaying Λ_b, Ξ_b^-, Ω_b^- observed
+ strong decaying charged Σ_b

Excited states Λ_b^* states seen by LHCb
Phys. Rev. Lett. 109:172003 (2012)

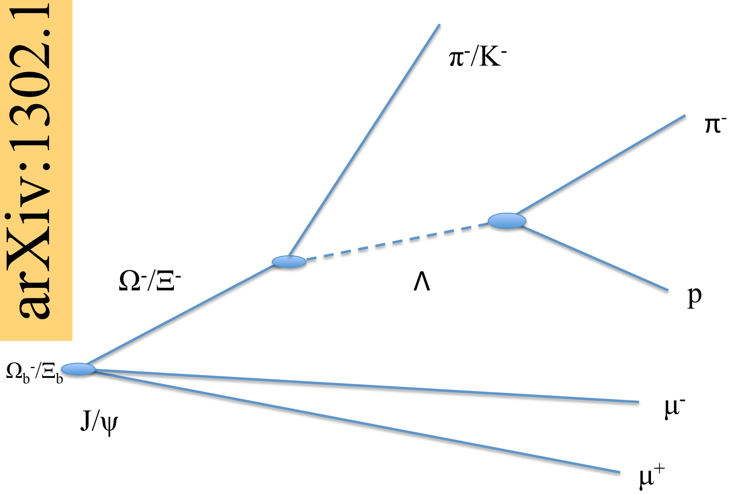


Puzzle from the Tevatron CDF/D0 agree on Ξ_b^- mass of but have widely different masses for Ω_b^-



b baryons: Ξ_b^-, Ω_b^-

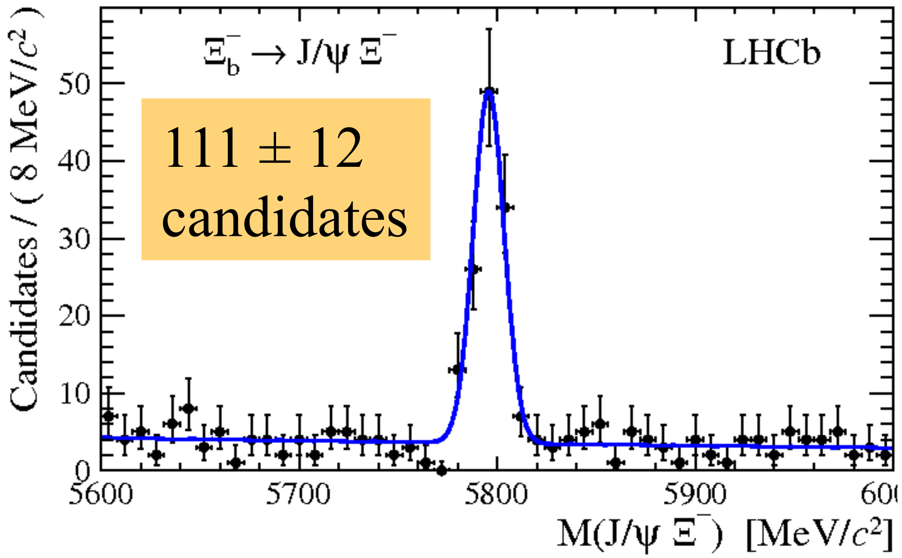
arXiv:1302.1072

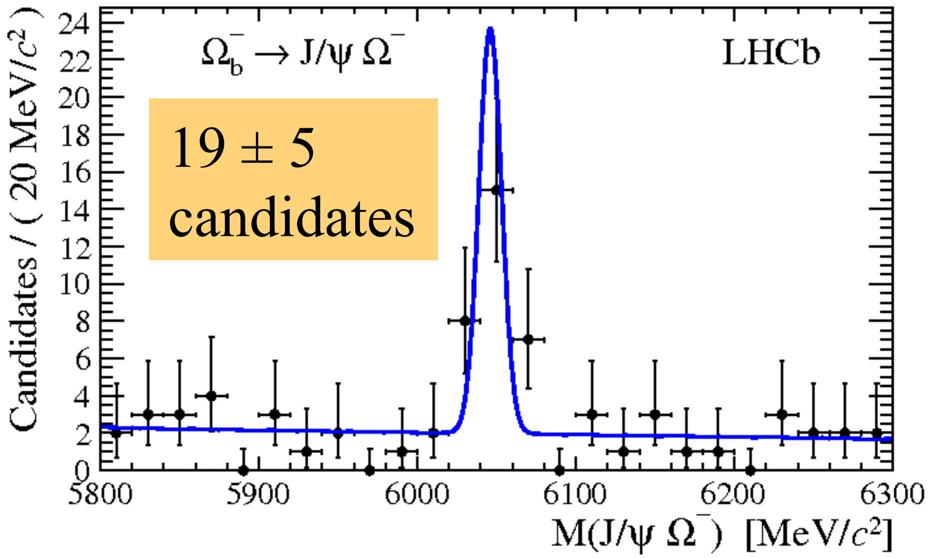


Study of Ξ_b^-, Ω_b^-, (+Λ_b) with 1 fb^{-1} of data collected in 2011

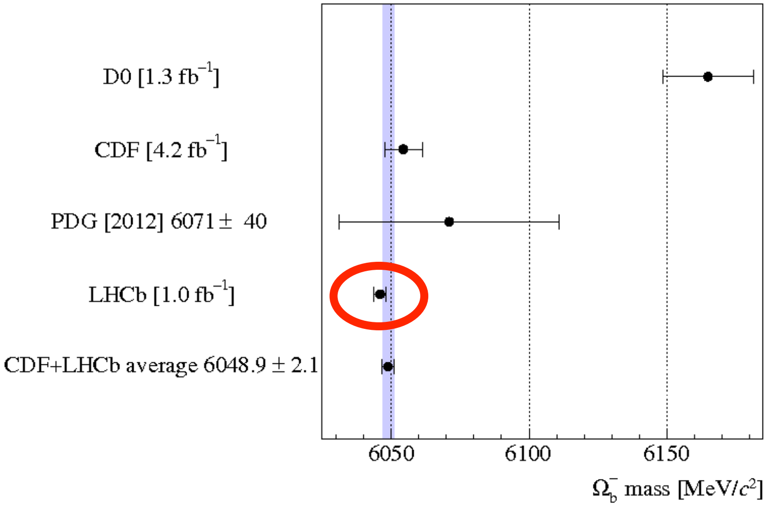
Use decays containing J/ψ in final state

Profit from good knowledge of momentum scale (3×10^{-4})





b baryons: Ξ_b^-, Ω_b^-

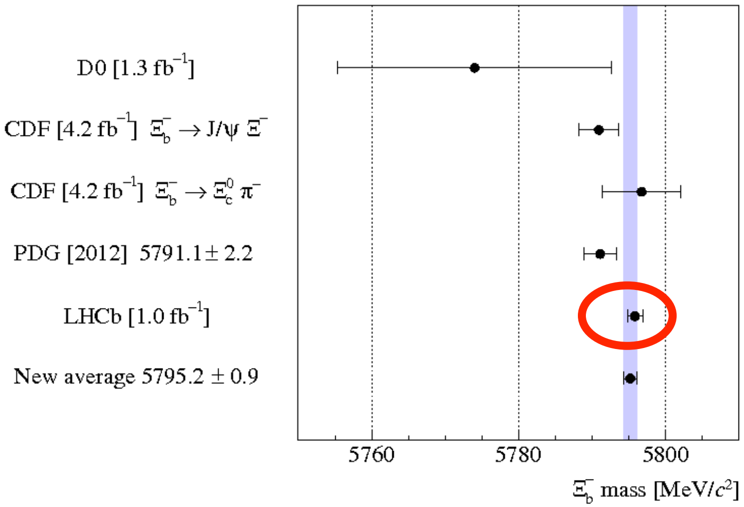


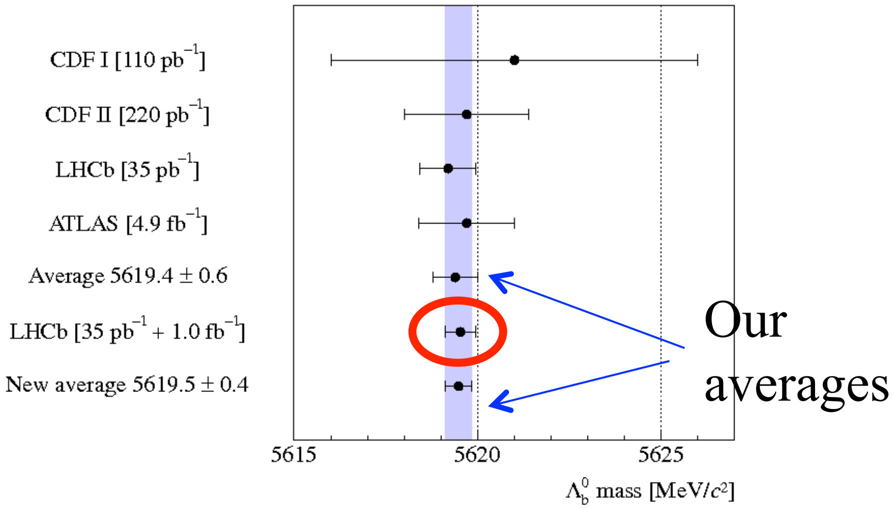
$$
\begin{aligned}
M(\Lambda_b^0) &= 5619.53 \pm 0.13\,(\text{stat}) \pm 0.45\,(\text{syst})\ \text{MeV}/c^2 \\
M(\Xi_b^-) &= 5795.8 \pm 0.9\,(\text{stat}) \pm 0.4\,(\text{syst})\ \text{MeV}/c^2 \\
M(\Omega_b^-) &= 6046.0 \pm 2.2\,(\text{stat}) \pm 0.5\,(\text{syst})\ \text{MeV}/c^2
\end{aligned}
$$

Main systematic: momentum scale

Result for Ω_b^- agrees with CDF/theory predictions

Most precise measurements for Λ_b, Ξ_b^-, Ω_b^-





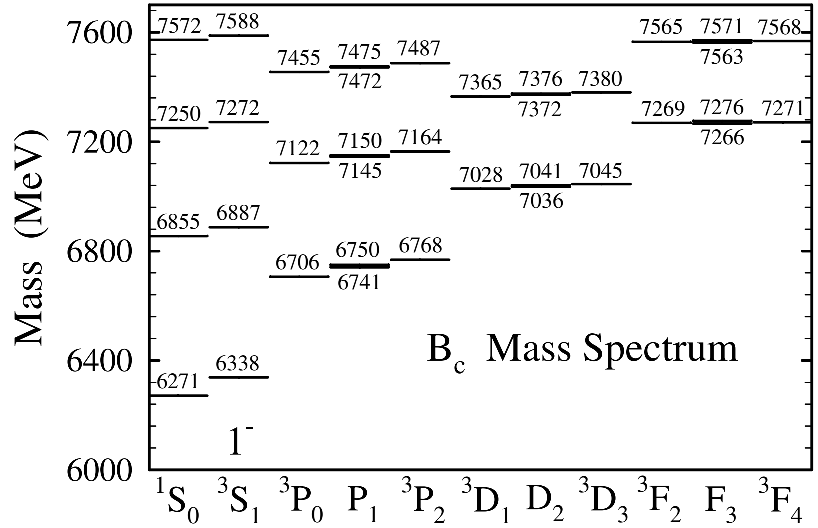
B_c physics

Ground state is unique meson containing two heavy quarks decaying weakly

Ideal testing ground for QCD models

Largely unexplored

From Godfrey, PRD 70, 054017



Winter 2013: Observation of three new modes by LHCb

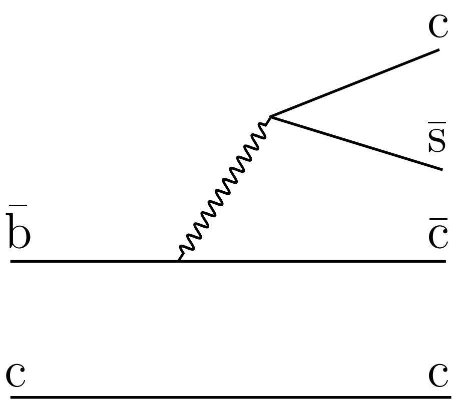
$$B_c^+ \to J/\psi D_s^{+(*)} \qquad\qquad B_c^+ \to \psi(2S)\pi^+$$

+ new measurement of the mass

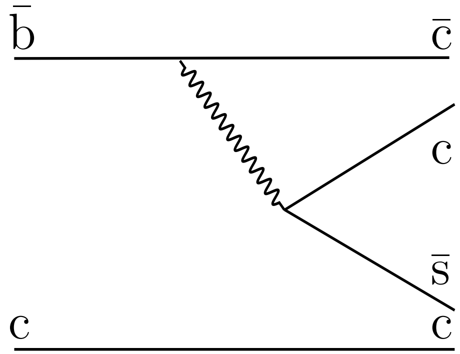
LHCb-Paper-2013-010

$B_c^+ \rightarrow J/\psi\, D_s^{(*)+}$

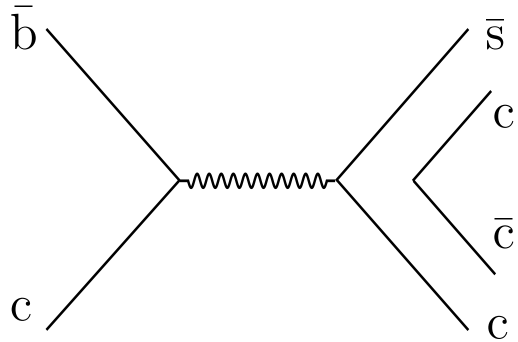
Spectator



Colour suppressed spectator



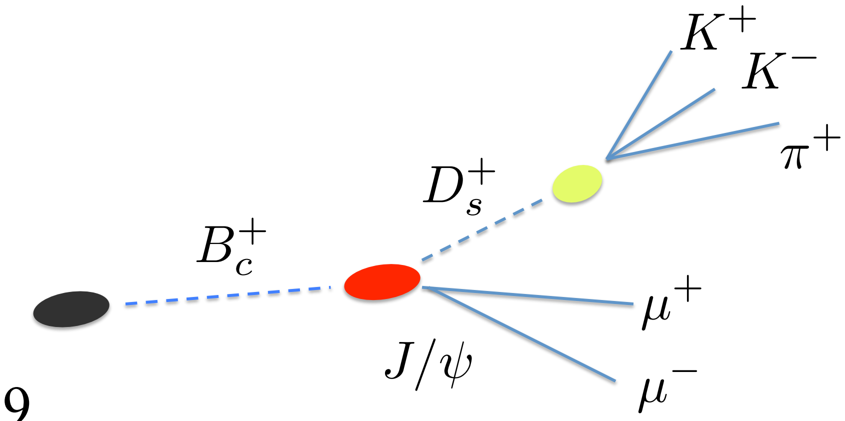
Annilhation



Spectator diagram expected to dominate

Measure:

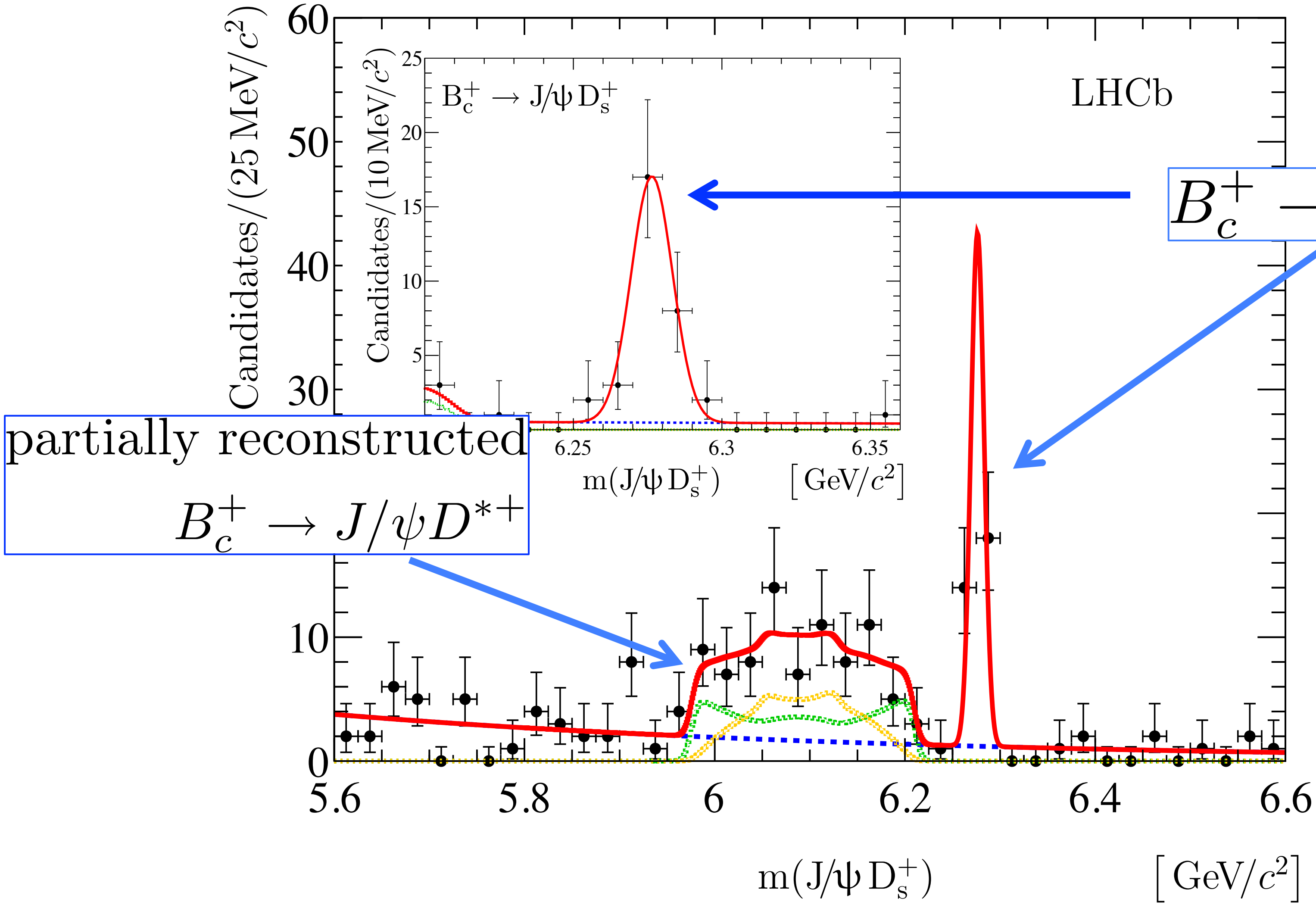
$$\mathcal{R}_{D_s^+/\pi^+} \equiv \frac{\Gamma\left(B_c^+ \rightarrow J/\psi\, D_s^+\right)}{\Gamma\left(B_c^+ \rightarrow J/\psi\, \pi^+\right)}$$



Theory predictions for R in range 1.2 – 2.9

$B_c^+ \rightarrow J/\psi\ D_s^{(*)+}$

First analysis to use full 2011+12 dataset (~ 3fb[-1]) !



Significance for both signals > 7σ

$B_c^+ \rightarrow J/\psi\, D_s^{(*)+}$

Results:

28.9 ± 5.6 candidates →

$$\frac{\mathcal{B}(B_c^+ \to J/\psi\, D_s^+)}{\mathcal{B}(B_c^+ \to J/\psi\, \pi^+)} = 2.96 \pm 0.67\,(\text{stat}) \pm 0.25\,(\text{syst})$$

[Dominant systematic $D_s^+ \rightarrow K^+K^-\pi^+$ branching ratio]

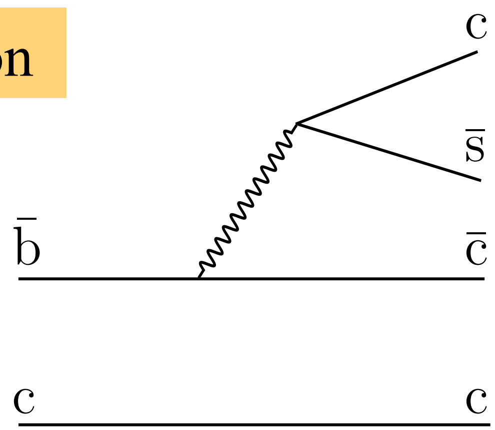
68.4 ± 9.6 candidates →

$$\frac{\mathcal{B}(B_c^+ \to J/\psi\, D_s^{*+})}{\mathcal{B}(B_c^+ \to J/\psi\, D_s^+)} = 2.36 \pm 0.56\,(\text{stat}) \pm 0.10\,(\text{syst})$$

Consistent with spectator dominance + naïve factorization

$$\mathcal{R}_{D_s^+/\pi^+} \equiv \frac{\Gamma(B_c^+ \to J/\psi\, D_s^+)}{\Gamma(B_c^+ \to J/\psi\, \pi^+)} \approx \frac{\Gamma(B \to \overline{D}^* D_s^+)}{\Gamma(B \to \overline{D}^* \pi^+)} \sim 1.6\text{ - }2.9$$

$$\mathcal{R}_{D_s^{*+}/D_s^+} \equiv \frac{\Gamma(B_c^+ \to J/\psi\, D_s^{*+})}{\Gamma(B_c^+ \to J/\psi\, D_s^+)} \approx \frac{\Gamma(B \to \overline{D}^* D_s^{*+})}{\Gamma(B \to \overline{D}^* D_s^+)} \sim 2.1 - 2.2$$



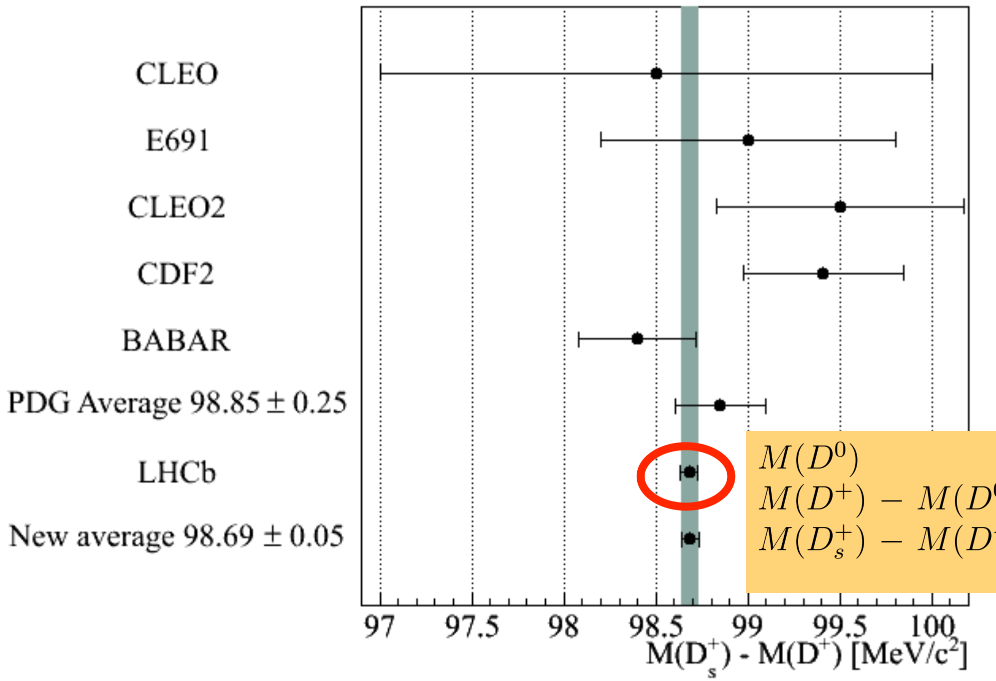
B_c^+ mass measurement

Low Q-value of the $B_c^+ \rightarrow J/\psi\, D_s^+$ decay allows precision measurement of the B_c mass

Intermezzo:

Other important systematic is D_s^+ mass. Profit from new LHCb measurements of D meson mass differences to minimize this.

LHCb-Paper-2013-011



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

B_c^+ mass measurement

D_s^+ mass

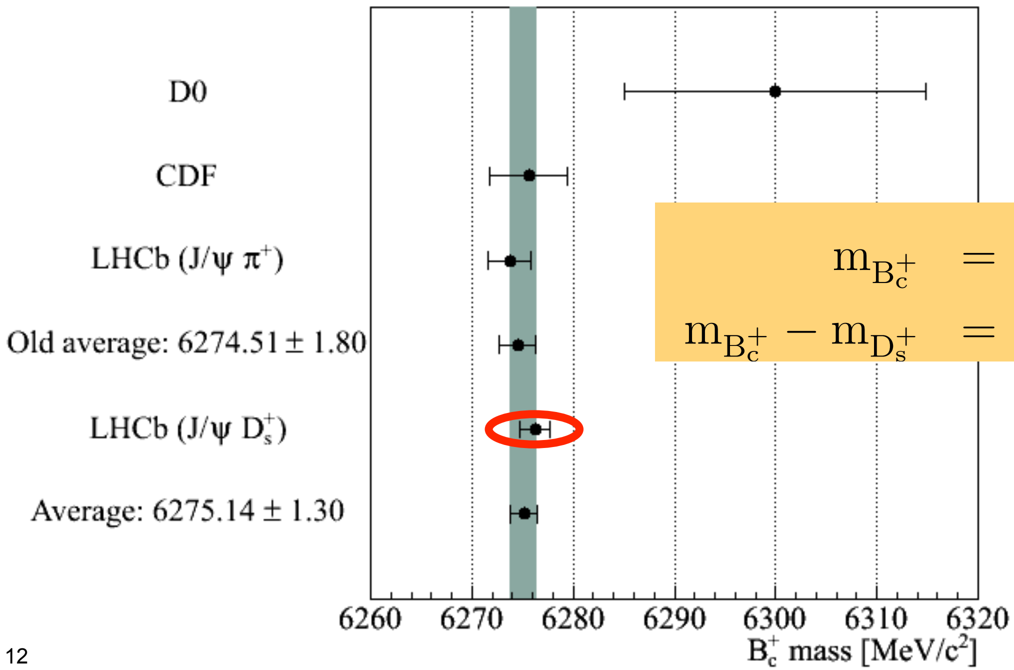
$$M(D_s^+) = M(D^0) + [M(D^+) - M(D^0)] + [M(D_s^+) - M(D^+)]$$

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

$$M(D_s^+) = 1968.47 \pm 0.33\ \mathrm{MeV}/c^2$$ PDG

Our Average

$$M(D_s^+) = 1968.31 \pm 0.20\ \mathrm{MeV}/c^2$$



$$m_{B_c^+} = 6276.28 \pm 1.44\,(\mathrm{stat}) \pm 0.36\,(\mathrm{syst})\ \mathrm{MeV}/c^2$$

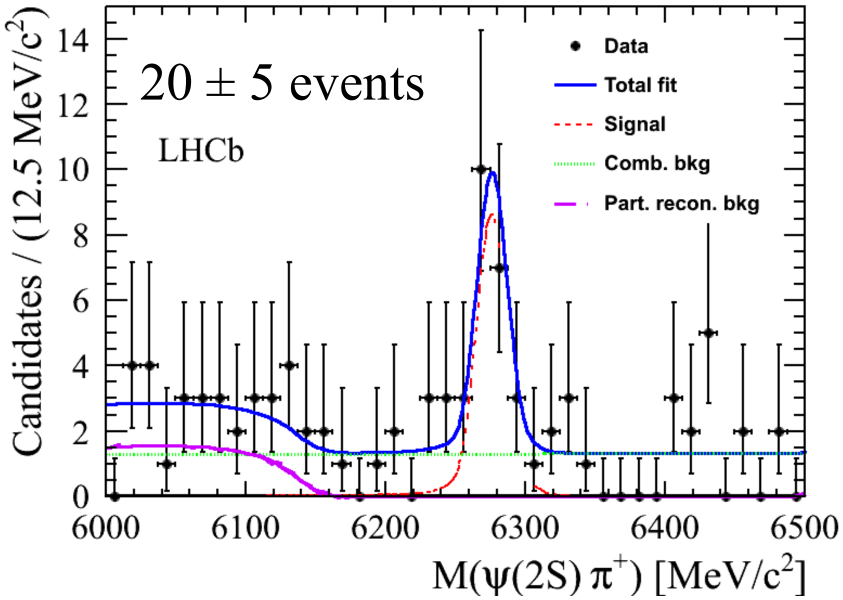
$$m_{B_c^+} - m_{D_s^+} = 4307.97 \pm 1.44\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst})\ \mathrm{MeV}/c^2$$

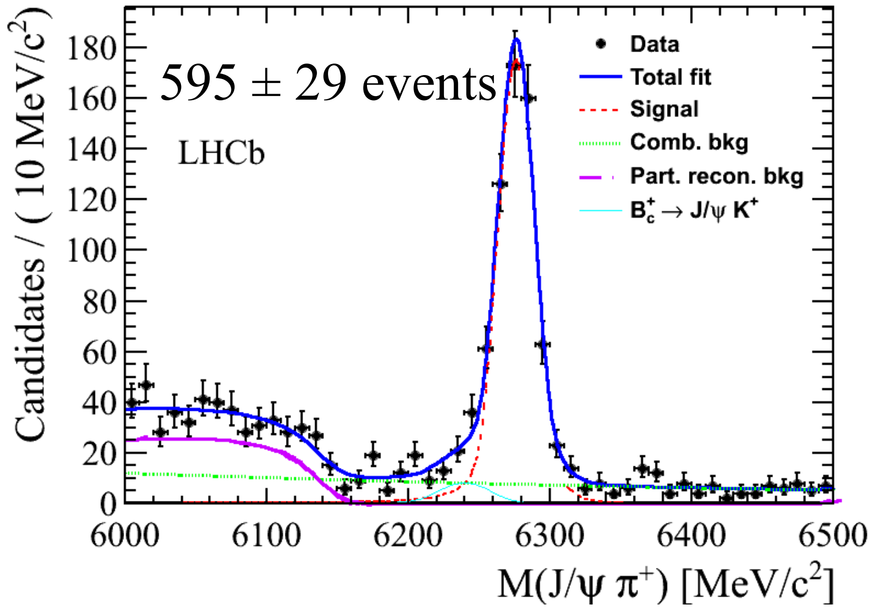
Most precise measurement of B_c mass to date !

$B_c^+ \rightarrow \psi(2S)\,\pi^+$

First observation of this mode using 1 fb^{-1} of data collected in 2011

arxiv:1303.1737





$$\frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 0.250 \pm 0.068\,(\mathrm{stat}) \pm 0.014\,(\mathrm{syst}) \pm 0.006\,(\mathcal{B})$$

Systematics

Component	Value (%)
BDT selection	4.5
Signal shape	1.7
Background shape	2.9
Simulation sample size	0.9
Total	5.7

Theory predictions $\displaystyle \frac{B(B_c^+ \to \psi(2S)\pi^+)}{B(B_c^+ \to J/\psi\pi^+)} \sim 0.13 - 0.42$

X(3872)

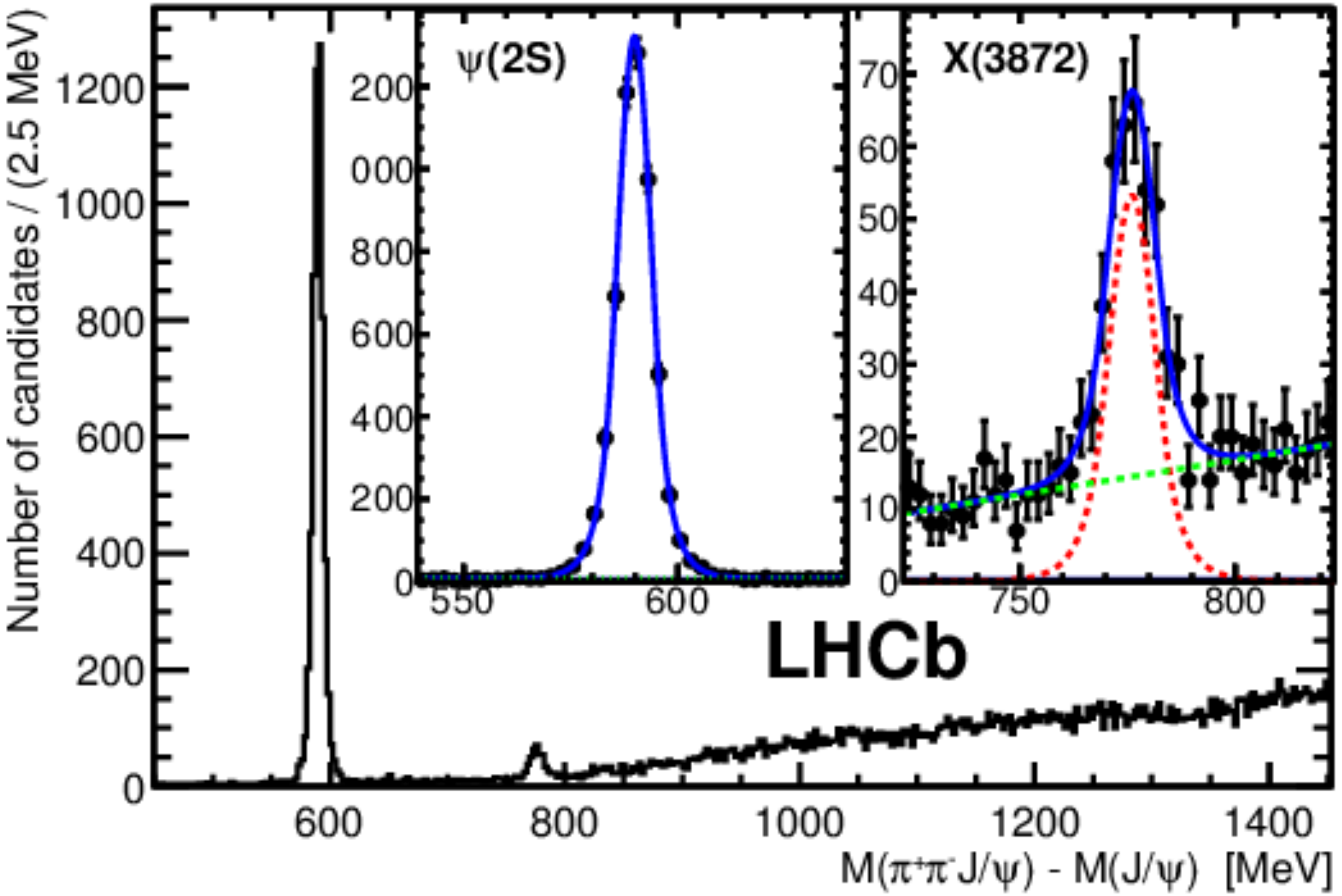
First of the exotic charmonium states discovered by Belle in 2003 in b meson decays (PRL. 91, 262001 2003)

- Properties well measured:
  - Mass known to <0.2 MeV and width, < 1 MeV
  - Quantum number restricted to 1^{++} or 2^{-+}
- But its nature is still uncertain: conventional charmonium, DD* molecule, η_{c2} (1^1D_2) if 2^{-+} , or tetraquark ?
  - If 1^{++} exotic interpretations favoured

X(3872) Quantum Numbers

X(3872) J^{PC} determined using 1 fb^{-1} of data collected in 2011

arXiv:1302.6269



$$313 \pm 26\ B^+ \rightarrow X(3872)K^+ \text{candidates}$$
$$X(3872) \rightarrow J/\psi\pi^+\pi^-$$

X(3872) Quantum Numbers

Full angular analysis in 5-D considering all angular correlations

Analysis performed in helicity basis

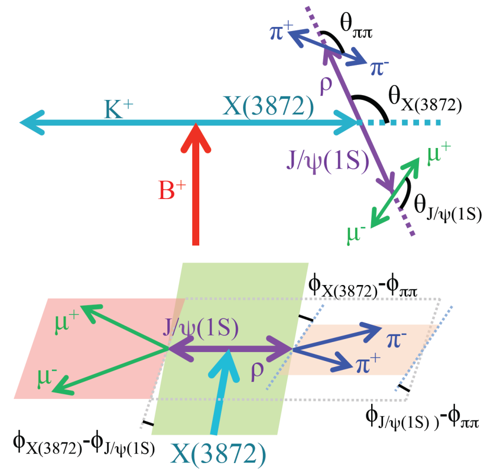
$J^{PC} = 1^{++}$ no free parameters

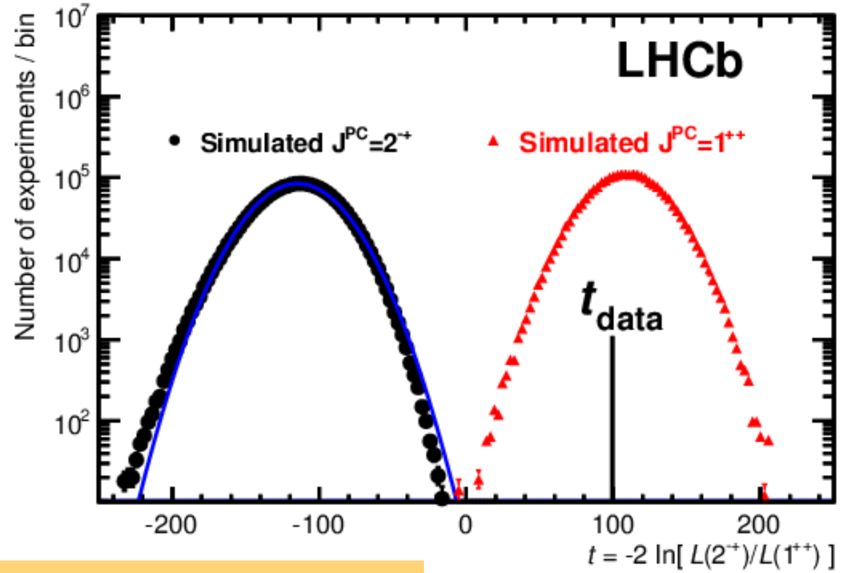
$J^{PC} = 2^{-+}$ one complex parameter α

Neymann-Pearson test [ratio of the likelihoods] to discriminate between two hypotheses

Data favour 1^{++} assignment

2^{-+} hypothesis rejected at $> 8\sigma$





$J^{PC} = 1^{++} \rightarrow$ X(3872) is exotic

X(3872): Next Steps

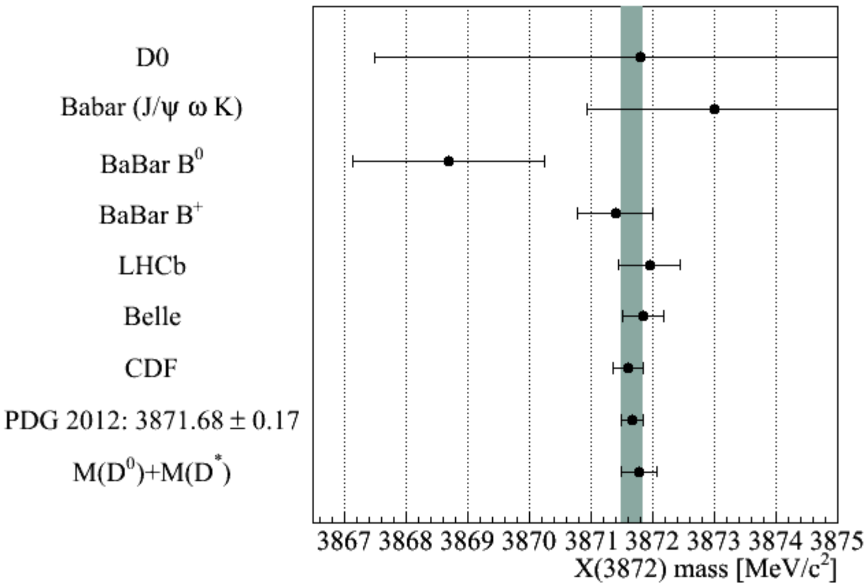
The X(3872) is not a conventional quarkonium state. But what is it ?

- Bound D-D* molecule [arXiv: hep-phy/0402237]
- Tetraquark state [arXiv:hep-ph/0412098]
- $\chi_{c1}(2^3P_1)$ charmonium-molecule mixture [arXiv:1106.1185]

More measurements are needed to elucidate nature of the X(3872)

- More precise measurements of the X(3872) [+ D masses]
- Natural width
- Production properties + decay modes
- Searches for other states

X(3872) mass



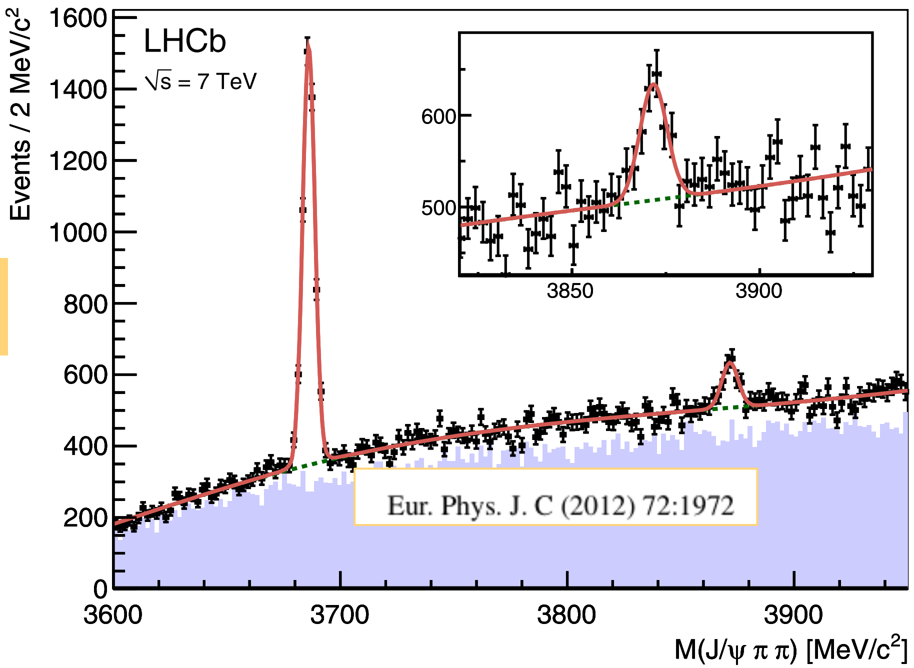
Early LHCb measurement

$$m_{X(3872)} = 3871.95 \pm 0.48\ (\text{stat}) \pm 0.12\ (\text{syst})\ \text{MeV}/c^2$$

Good prospects to improve !

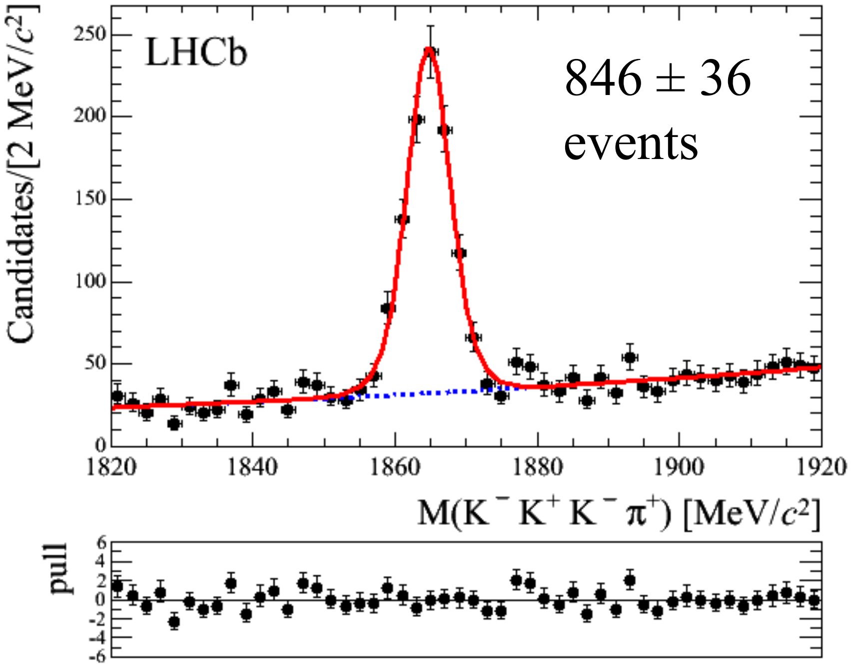
Binding energy of X(3872) is small

- $E_B = 0.16 \pm 0.26\ MeV/c^2$
- Remains open if really is bound molecule
- More precise measurements needed



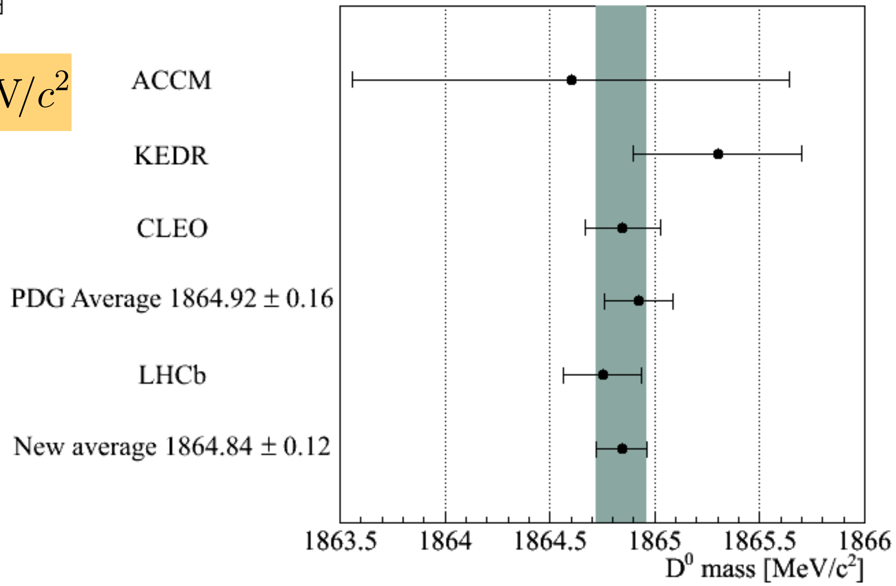
And also the D^0 mass

LHCb-Paper-2013-011



- D^0 mass crucial input to binding energy
- D^0 mass measurement using D produced in semileptonic b decays
- Use $D^0 \to K^- K^+ K^- \pi^+$
- Low Q-value, low systematics

$$M(D^0) \quad = 1864.75 \pm 0.15\,(\text{stat}) \pm 0.11\,(\text{syst})\ \text{MeV}/c^2$$



Reinforces conclusion X(3872) loosely bound
Consistent with Tomaradze et al
arxiv: 1212:4191

$$m_{D^0} = 1864.85 \pm 0.06\ \text{MeV}/c^2$$

Summary + Outlook

Several recent results on b baryons, B_c, exotic quarkonia presented

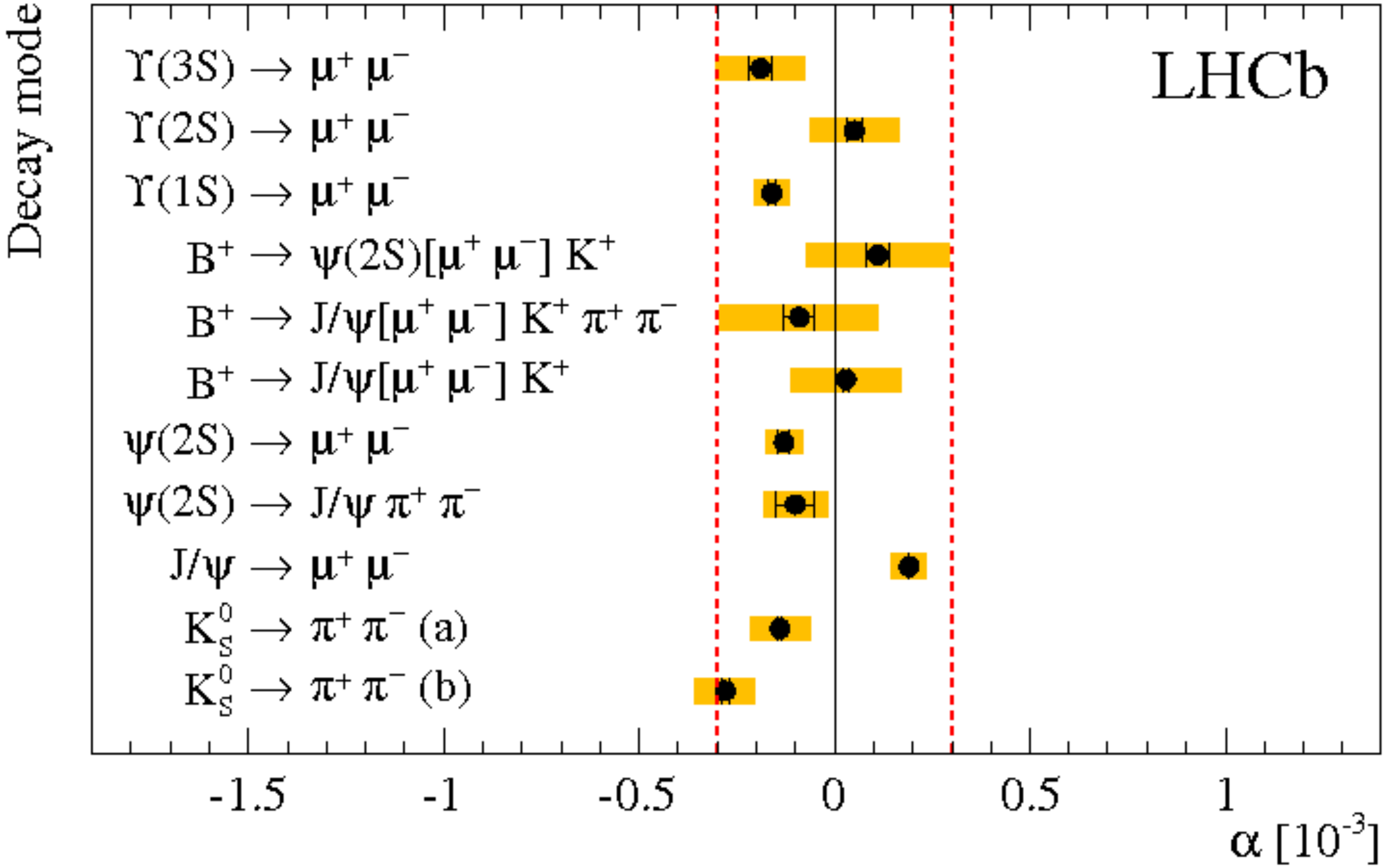
Exploits large clean sample of detached charmonia triggers + good understanding of spectrometer +much more to come from LHCb:

- Exploit 3 fb^{-1} of data collected in Run 1: O(50) million b ➔ J/ψ X triggers !
- Almost unlimited opportunities for data mining
- Possibility to use hadron triggered modes
- Spectroscopy of excited Beauty + charm states
- Precision supporting measurements: e.g D meson masses
- New avenues for exotic searches in B_c and b-baryon sectors

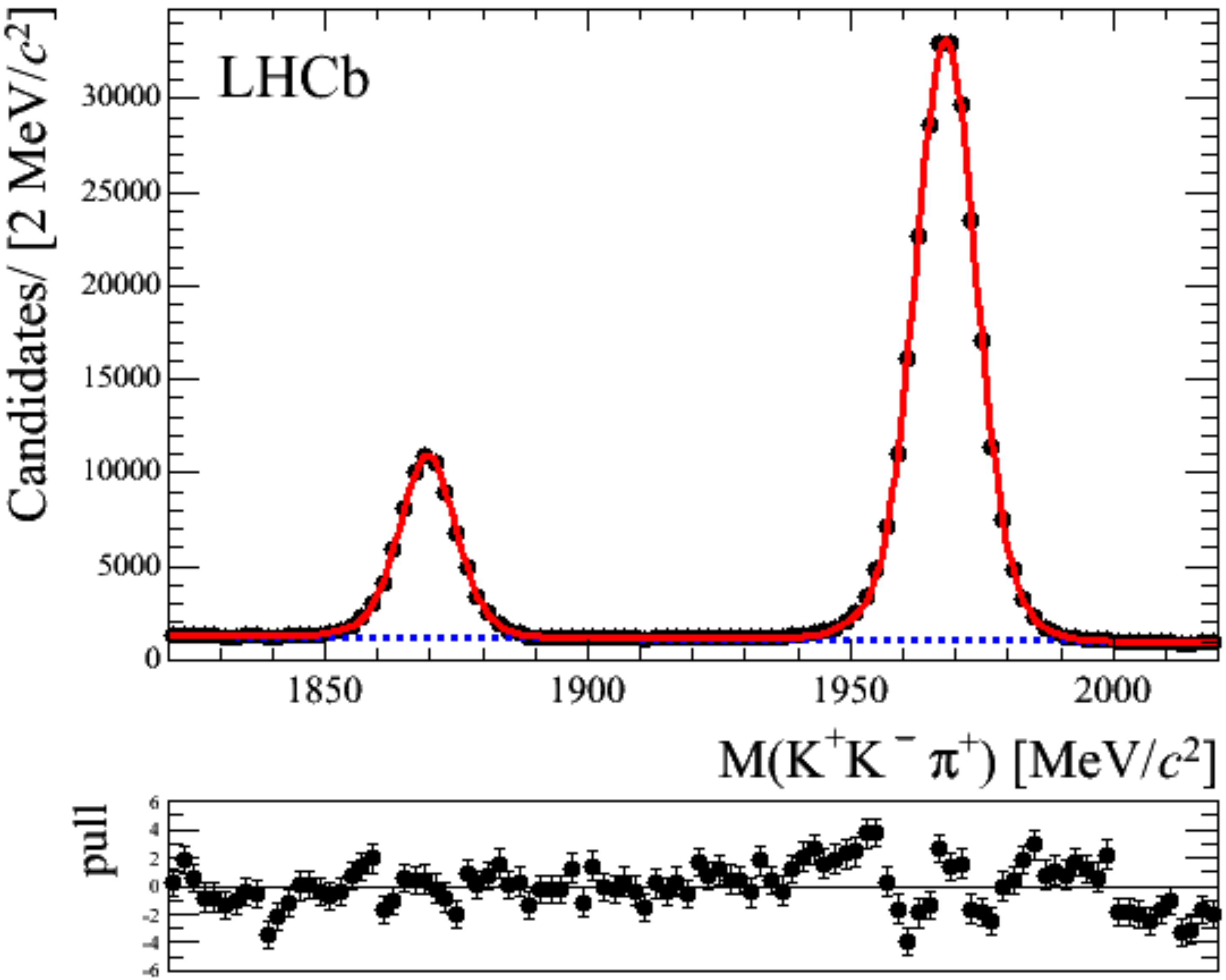
Backup

Momentum Scale

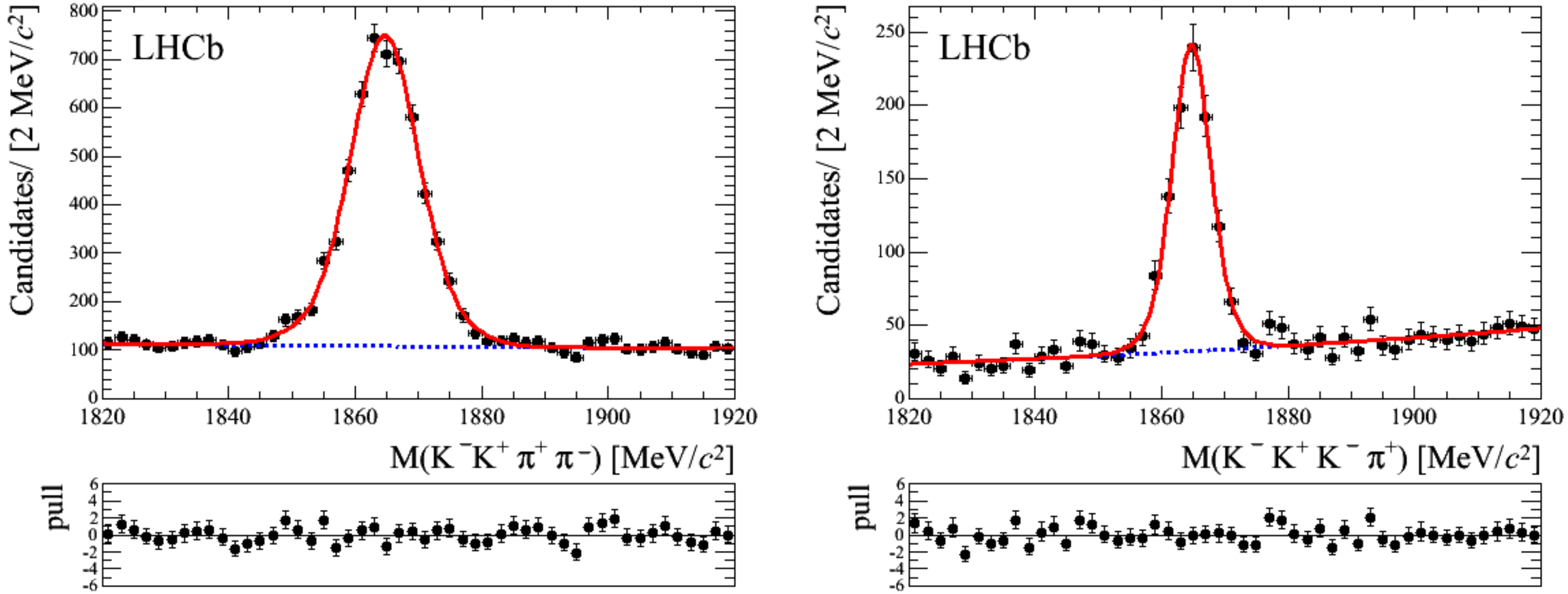
Momentum scale calibrated using various resonances



D masses

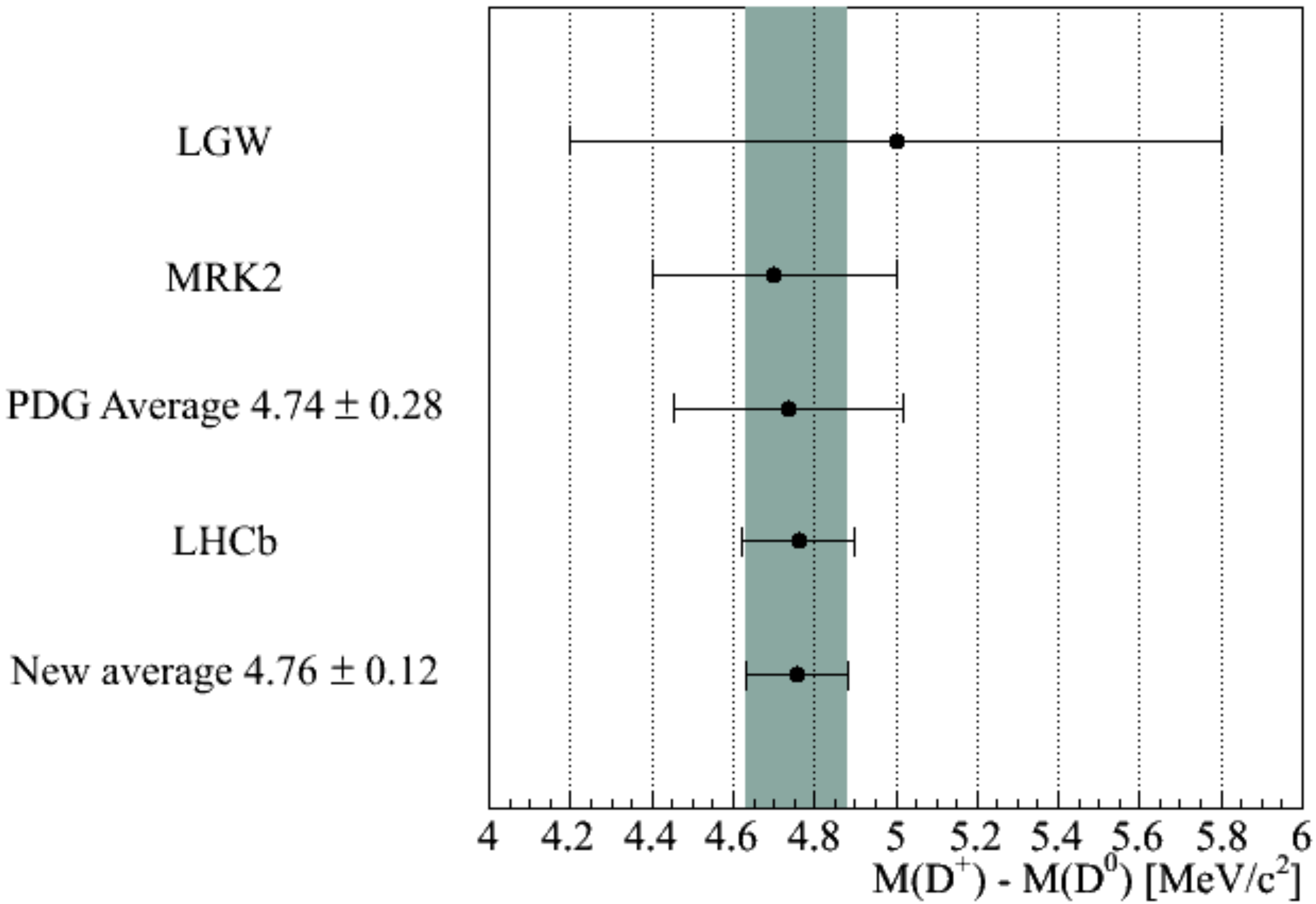

LHCb
Candidates/ [2 MeV/c^2]
30000
25000
20000
15000
10000
5000
0
1850
1900
1950
2000
M($K^+K^-\pi^+$) [MeV/c^2]
pull
6
4
2
0
-2
-4
-6

D masses



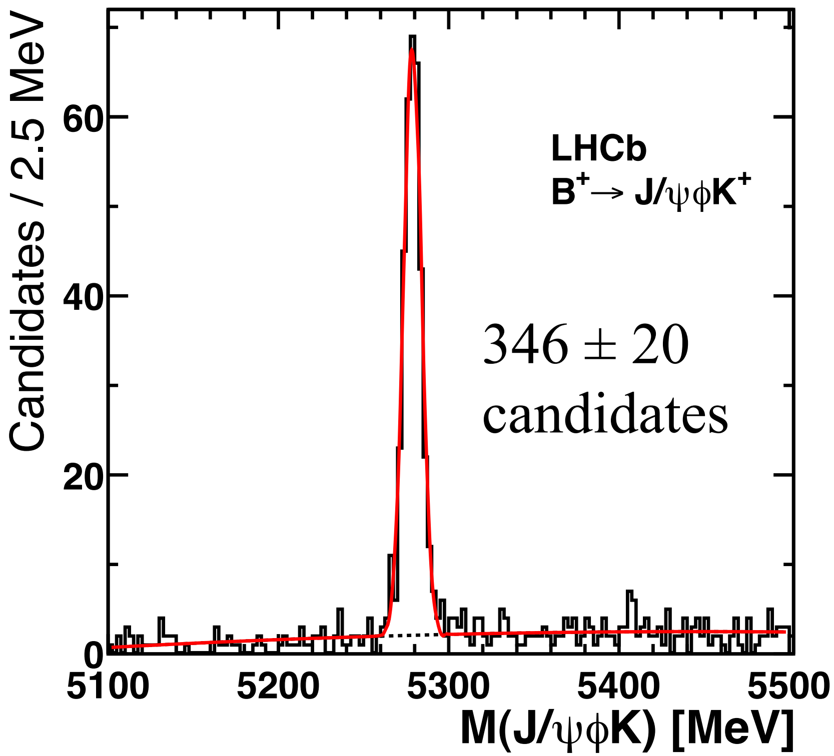
Decay mode	Yield	Fitted mass [MeV/c^2]	Corrected mass [MeV/c^2]	Resolution scale factor	χ^2/dof
$D^0 \to K^+K^-\pi^+\pi^-$	4608 ± 89	1864.68 ± 0.12	1864.74 ± 0.12	1.031 ± 0.021	0.83
$D^0 \to K^-K^+K^-\pi^+$	849 ± 36	1864.73 ± 0.15	1864.75 ± 0.15	0.981 ± 0.042	0.92
$D^+ \to K^+K^-\pi^+$	$68,787 \pm 321$	1869.44 ± 0.03	1869.50 ± 0.03	0.972 ± 0.003	2.5
$D_s^+ \to K^+K^-\pi^+$	$248,694 \pm 540$	1968.13 ± 0.03	1968.19 ± 0.03	0.971 ± 0.002	2.5

D^+ - D^0 mass difference



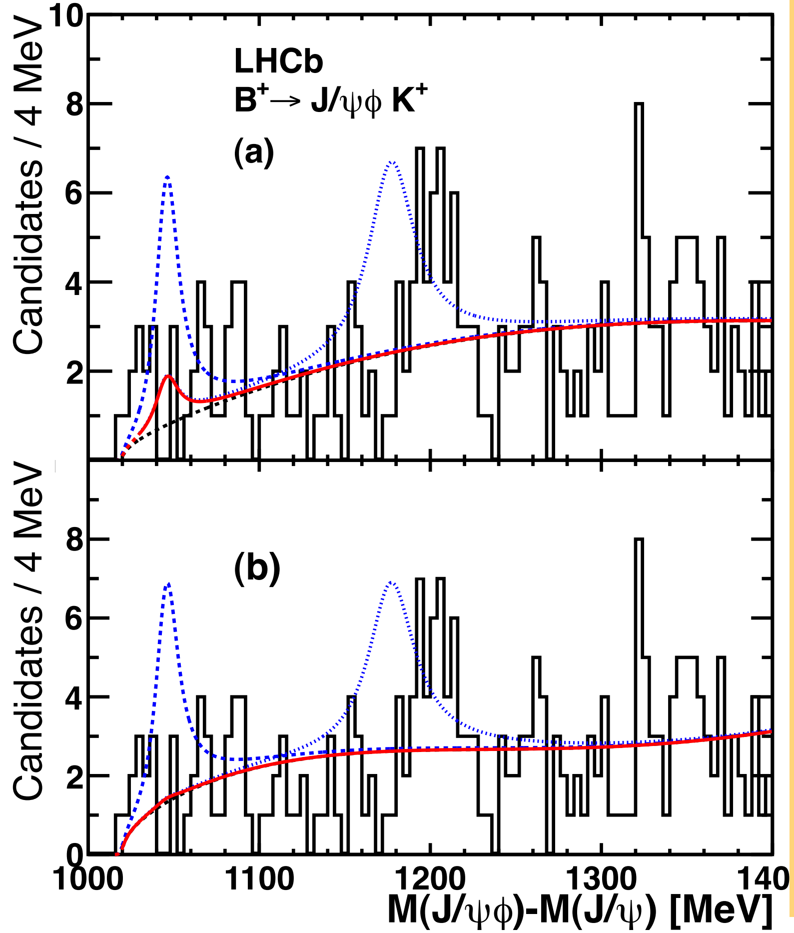
X(4140)

Result based on 370 pb^{-1} (early 2011 data)



$$\frac{\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\,\phi)}{\mathcal{B}(B^+ \to J/\psi\,\phi K^+)} < 0.07.$$

$$\frac{\mathcal{B}(B^+ \to X(4274)K^+) \times \mathcal{B}(X(4274) \to J/\psi\,\phi)}{\mathcal{B}(B^+ \to J/\psi\,\phi K^+)} < 0.08$$

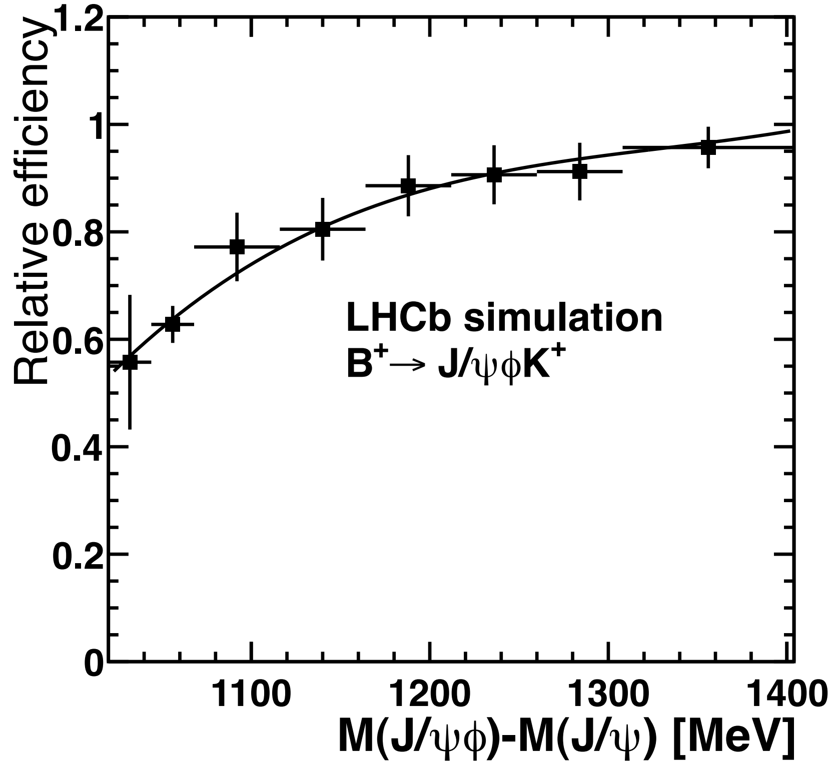


No signal observed, 90 % confidence levels given

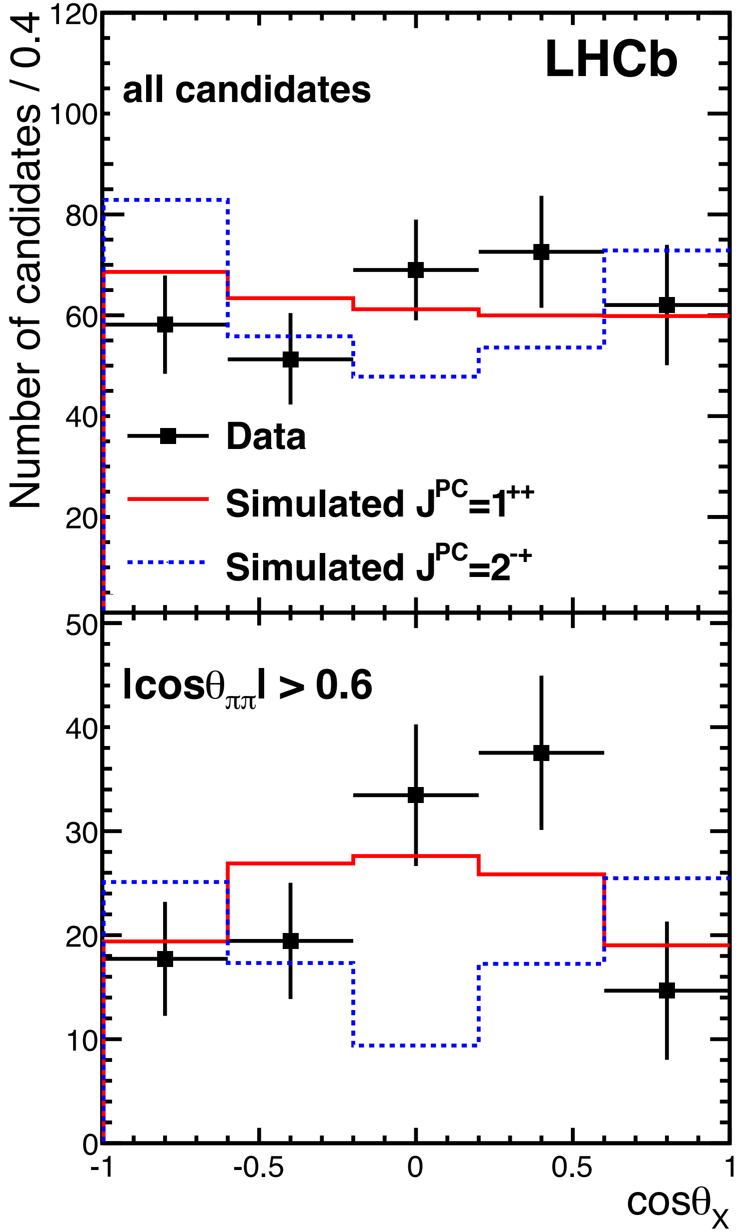
arXiv:1202.5087v1 [hep-ex] 23 Feb 2012

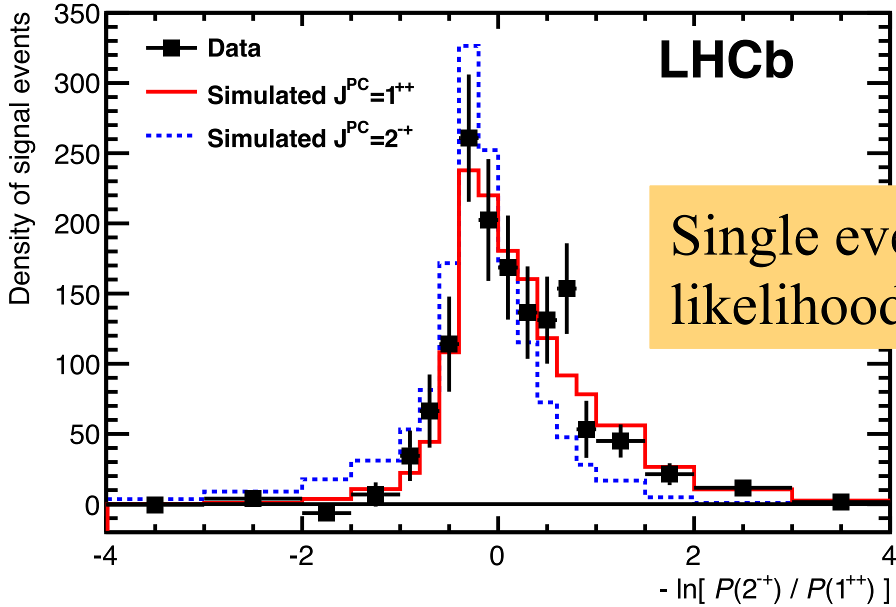
X(4140)

Result based on 370 pb-1 (early 2011 data)



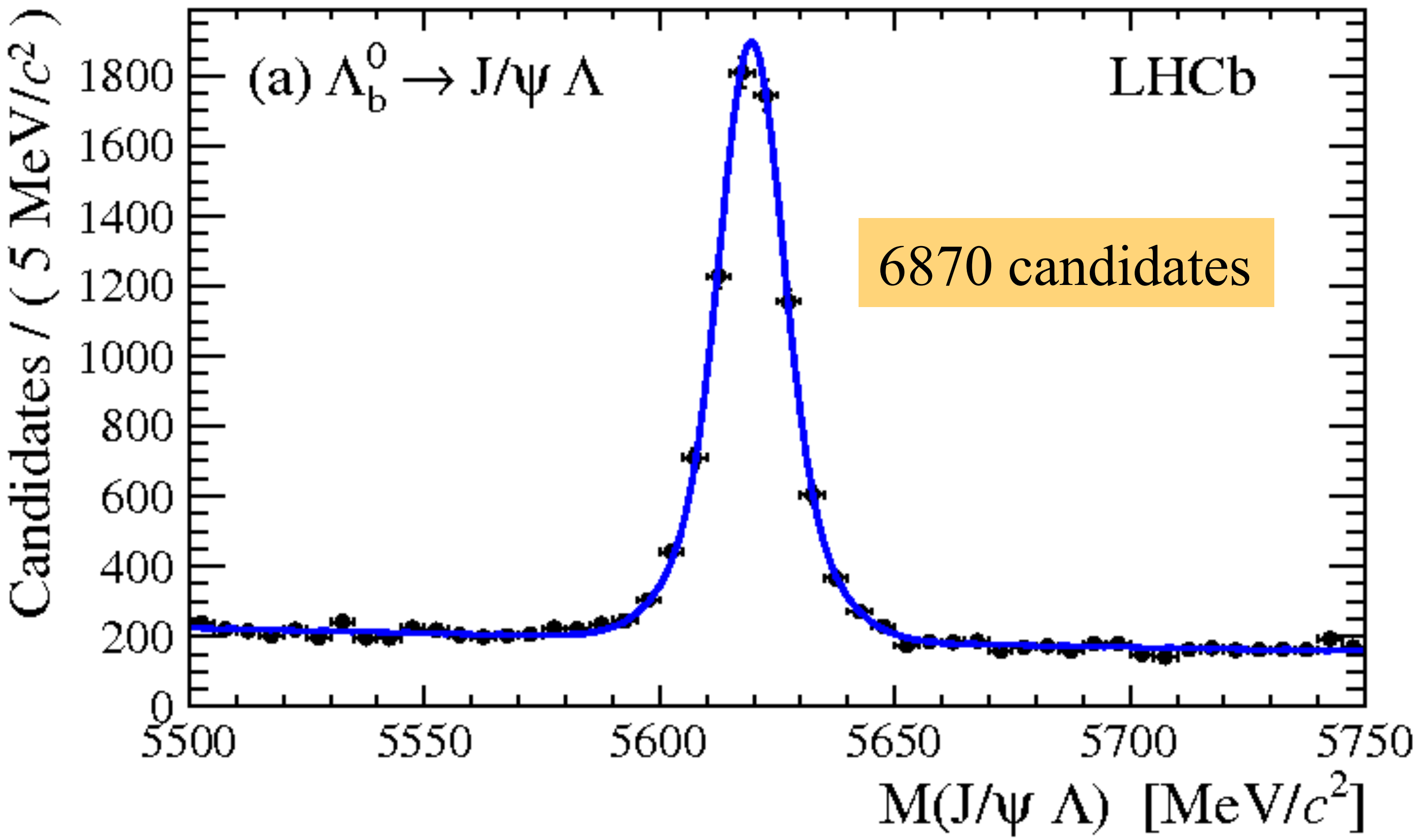
X(3872)





Single event likelihoods

$\Lambda_b{}^0$



(a) $\Lambda_b^0 \to J/\psi\ \Lambda$
LHCb
6870 candidates
Candidates / (5 MeV/c^2)
M(J/ψ Λ) [MeV/c^2]
0
200
400
600
800
1000
1200
1400
1600
1800
5500
5550
5600
5650
5700
5750

LHCb Detector