Heavy Flavour Spectroscopy (X, Y, Z, B_c, B^{**})

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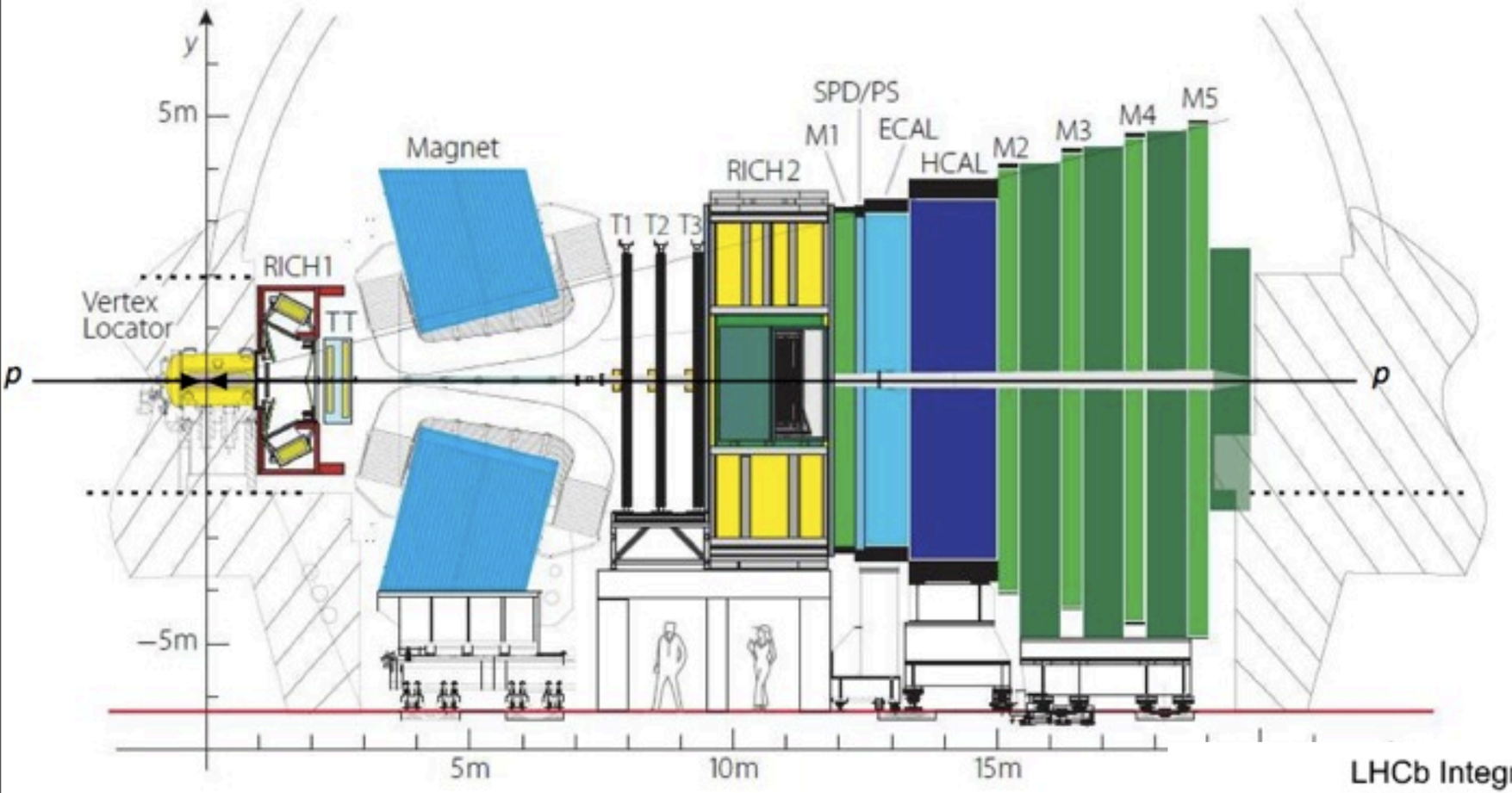
Outline

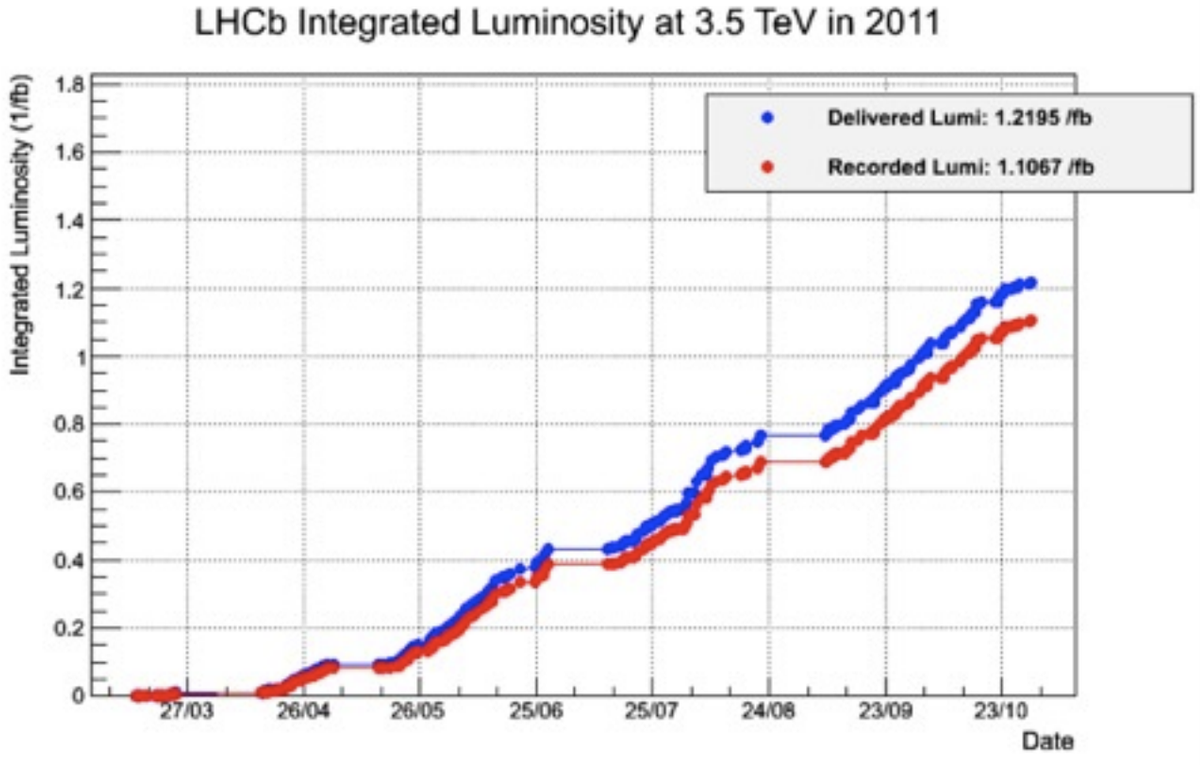
- ➢ **Brief view of the LHCb experiment**
- ➢ **Charmonium-like exotic states (*X, Y, Z*)**
- ➢ **Excited B^{**} states**
- ➢ **B_c^+ measurements**
- ➢ **Conclusion and prospects**

The LHCb Experiment



pp Collisions at 7 TeV

- **Designed for heavy quark physics**
- **~0.04 fb^{-1} data collected in 2010**
- **~1 fb^{-1} data collected in 2011**
- **With around 1.5×10^{11} *b* events in the acceptance, LHCb is shedding light on the nature of heavy flavour spectroscopy**



X,Y,Z States

Recently, discoveries or evidences have been made in the well understood charmonium system and new resonance structures found are noted as *X, Y, Z* to indicate their unknown nature

☛ **Many models exist:**

- ➢ **Tetra-quark: Tightly bound four quarks**
- ➢ **Molecular state: Loosely bound mesons**
- ➢ **Charmonium hybrids: charmonium states with an excited gluonic degree of freedom**
- ➢ **Threshold effects**

☛ **Focus on current LHCb results of *X(3872)* and *X(4140)***

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment ($\#\sigma$)	Year	Status
X(3872)	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B\to K(\pi^+\pi^- J/\psi)$	Belle , *BABAR*	2003	OK
		(<2.2)		$p\bar{p}\to(\pi^+\pi^- J/\psi)+\ldots$	CDF, DØ		
				$B\to K(\omega J/\psi)$	Belle *BABAR*		
				$B\to K(D^{*0}\bar{D}^0)$	Belle, *BABAR*		
				$B\to K(\gamma J/\psi)$	Belle, *BABAR*		
				$B\to K(\gamma\psi(2S))$	*BABAR*, Belle		
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B\to K(\omega J/\psi)$	Belle, *BABAR*	2004	OK
				$e^+e^-\to e^+e^-(\omega J/\psi)$	Belle		
X(3940)	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^-\to J/\psi(D\bar{D}^*)$	Belle	2007	NC!
				$e^+e^-\to J/\psi\,(\ldots)$	Belle		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^-\to\gamma(D\bar{D})$	*BABAR*, Belle	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^- J/\psi)$	Belle	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B\to K(\pi^+\chi_{c1}(1P))$	Belle	2008	NC!
X(4140)	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B\to K(\phi J/\psi)$	CDF	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^-\to J/\psi(D\bar{D}^*)$	Belle	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B\to K(\pi^+\chi_{c1}(1P))$	Belle	2008	NC!
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^- J/\psi)$	*BABAR*	2005	OK
					CLEO		
					Belle		
				$e^+e^-\to(\pi^+\pi^- J/\psi)$	CLEO		
				$e^+e^-\to(\pi^0\pi^0 J/\psi)$	CLEO		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B\to K(\phi J/\psi)$	CDF	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^-\to e^+e^-(\phi J/\psi)$	Belle	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-\psi(2S))$	*BABAR*, Belle	2007	OK
Z(4430)	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B\to K(\pi^+\psi(2S))$	Belle	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^-\to\gamma(\Lambda_c^+\Lambda_c^-)$	Belle	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-\psi(2S))$	Belle	2007	NC!
Y_b(10888)	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^-\to(\pi^+\pi^-\Upsilon(nS))$	Belle	2010	NC!

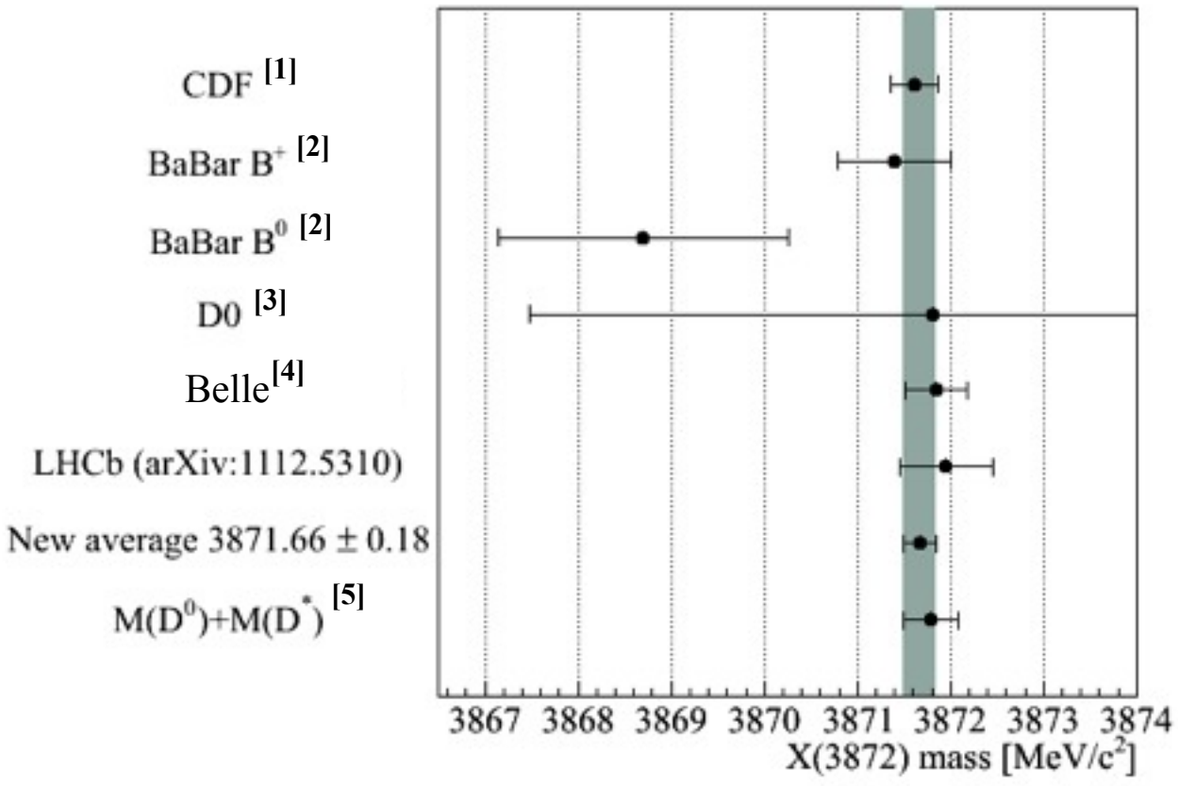
"Heavy quarkonium: progress, puzzles, and opportunities", arXiv:1010.5827

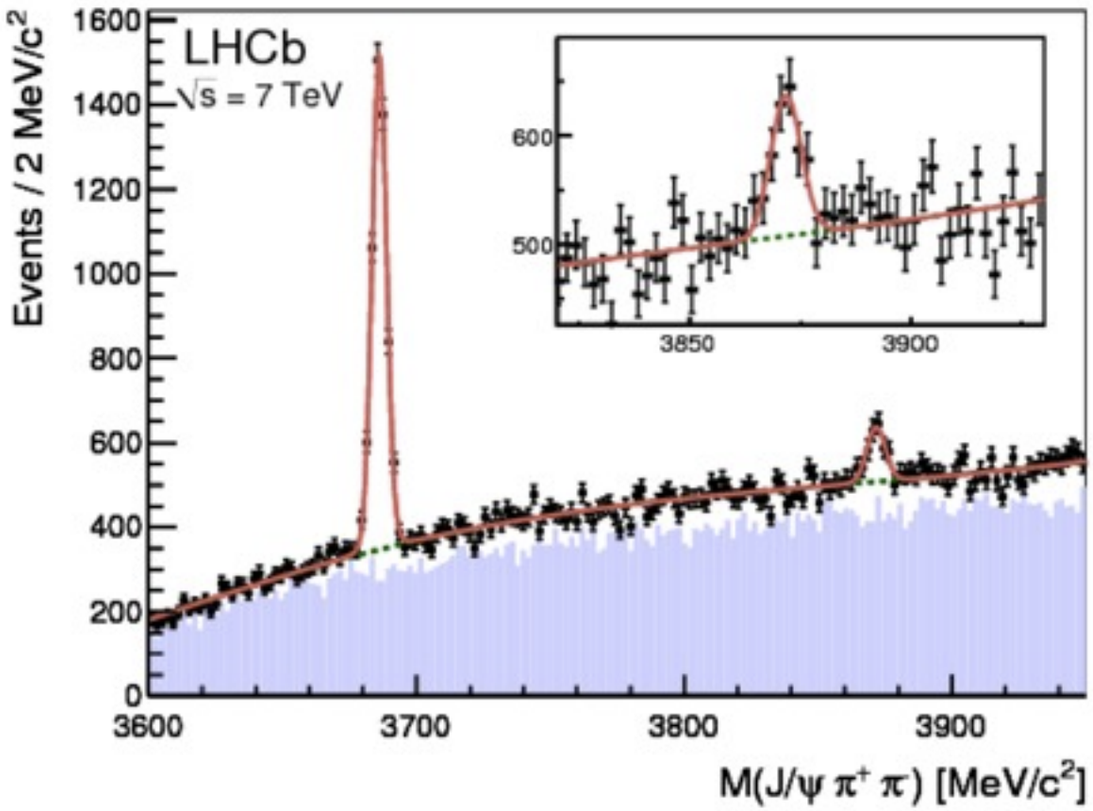
X(3872): Mass Measurement

LHCb-PAPER-2011-034
arXiv: 1112.5310
Submitted to Eur. Phys. J. C

➢ **In molecular state hypothesis, the mass should be below the $D^{*0}\overline{D^0}$ threshold**

➢ **Results shown in summary plot, more accuracy is desired to see if it is above, at, or below threshold**





➢ **First measurement in LHCb with 37 pb^{-1} data gives:**

$M_{x(3872)}$ = 3871.95 ± 0.48 (stat) ± 0.12 (syst) MeV

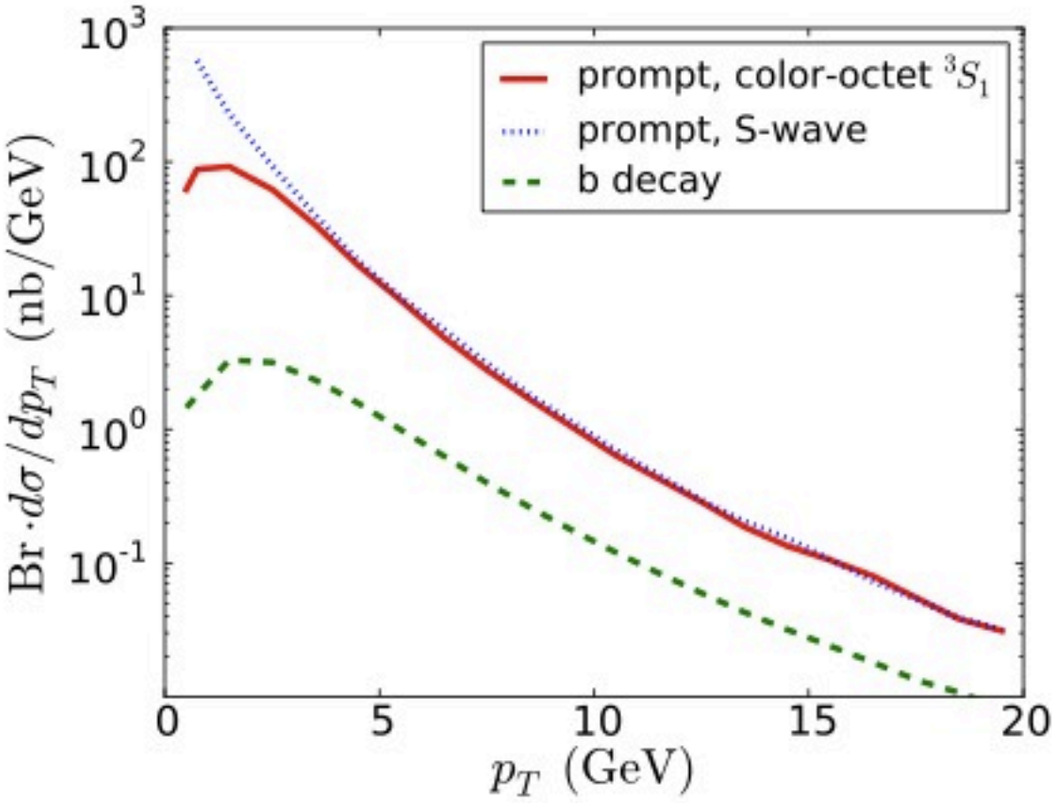
➢ **Further measurement with 1 fb^{-1} data ongoing to pin down the statistical error to ~0.12 MeV**

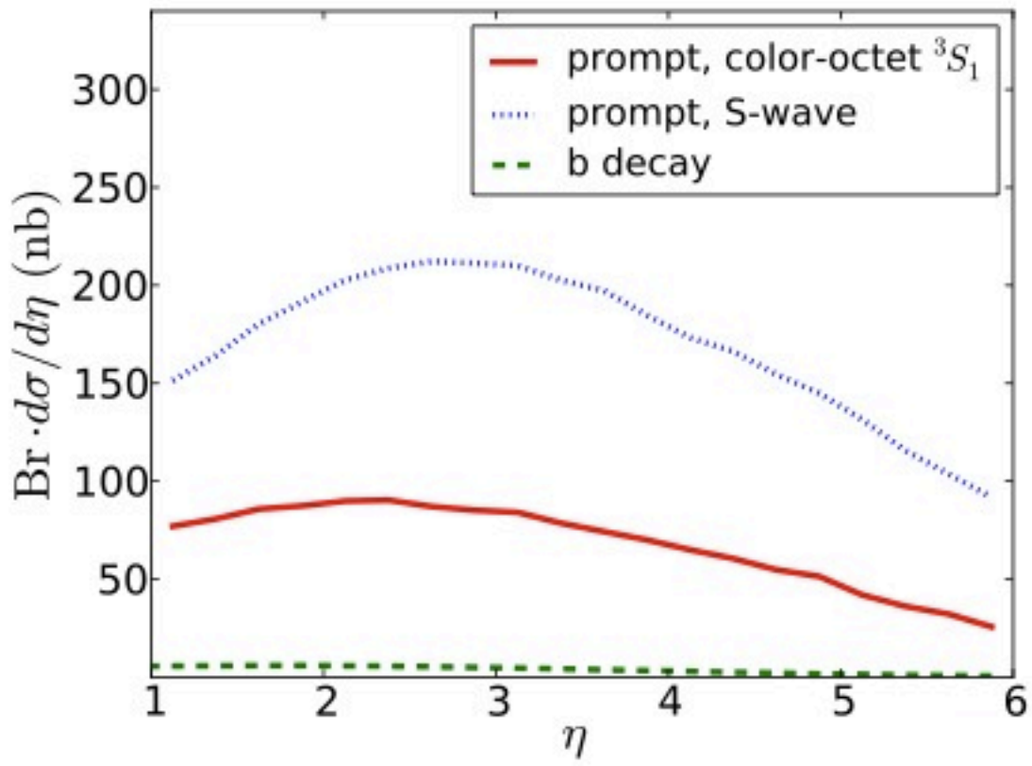
[1] CDF Collaboration, Phys. Rev. Lett. 103 (2009) 152001
[2] BABAR Collaboration, Phys. Rev. D77 (2008) 111101R
[3] D0 Collaboration, Phys. Rev. Lett. 93 (2004) 162002
[4] Belle Collaboration, Phys. Rev. D84 (2011) 052004R
[5] Particle Data Group, J. Phys. G37 (2010) 075021

X(3872) : Cross Section(1)

Cross section measurements also help in testing different models, calculations have been done for LHC using molecular nature and results from Tevatron

P. Artoisenet and E. Braaten; arXiv:0911.2016





☛ **The predictions in $\eta \in [2.5, 4.5]$ and $p_T \in [5, 20]$ GeV give**

➢ **Prompt + *b* cross section: 13 ± 2.7 nb**

☛ **Using 35 pb^{-1} data, LHCb made an inclusive cross section measurement**

X(3872) : Cross Section(2)

LHCb-PAPER-2011-034
arXiv: 1112.5310
Submitted to Eur. Phys. J. C

☛ **The measurement is done using:**

$$\sigma_{X(3872)} \times \mathcal{BR}(X(3872) \to J/\psi\pi^+\pi^-) = \frac{N_{X(3872)}}{\epsilon_{\rm tot} \times \mathcal{L}_{\rm int} \times \mathcal{BR}(J/\psi \to \mu^+\mu^-)}$$

➢ $N_{x(3872)}$, **the number of reconstructed** $X(3872) \to J/\psi(\to\mu^+\mu^-)\pi^+\pi^-$

➢ $\mathscr{L}_{int}$ **= 34.7 pb^{-1}, the integrated luminosity used**

➢ ϵ_{tot}, **the total reconstruction efficiency**

➢ $\mathscr{B}r(J/\psi\to\mu^+\mu^-)$, **the** $J/\psi\to\mu^+\mu^-$ **branching fraction**

☛ **We obtain the inclusive cross section in** $\eta \in [2.5, 4.5]$ **and** $p_T \in [5, 20]$ **GeV:**

$$\sigma_{X(3872)} \times \mathcal{BR}(\mathrm{X}(3872) \to \mathrm{J}/\psi\pi^+\pi^-) = 4.7 \pm 1.1(\mathrm{stat}) \pm 0.7(\mathrm{syst})$$

☛ **The measured value is 2.8σ smaller than the prediction in previous slide**

☛ **Measurements with 1 fb^{-1} is ongoing and we will separate prompt and *b* component and measure it as a function of p_T and η**

Search for X(4140) (1)

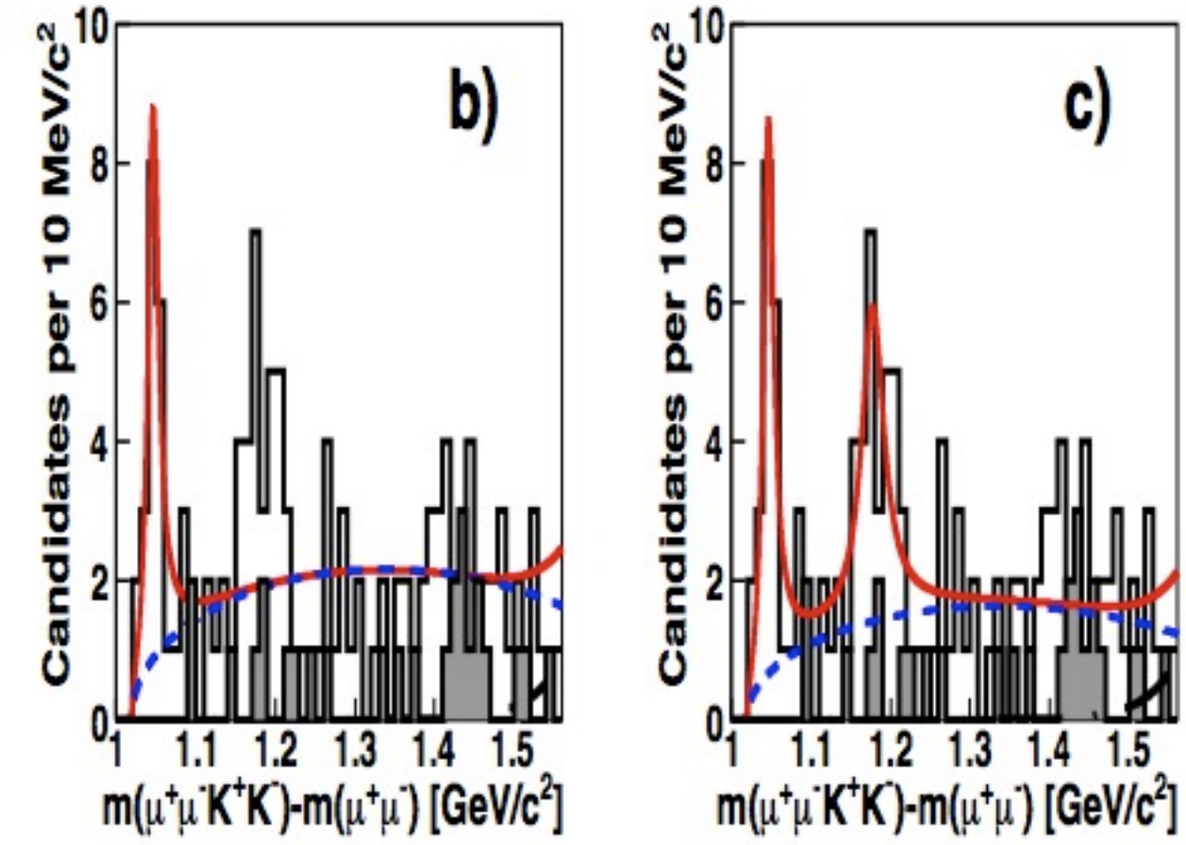
CDF observed a narrow structure *X(4140)→J/ψφ* (also named as *Y*(4140)) in *B→J/ψφK* decay with 6 fb^{-1} data

➢ In CDF, 19±6(stat)±3(syst) resonance events within 115±12(stat) reconstructed *B→J/ψφK* events: 3.8σ significance and mass:

$$M_{X(4140)} = 4143.4^{+2.9}_{-3.0}(stat) \pm 0.6(syst) MeV$$

➢ CDF data also suggested a second state with 22±8 events, 3.1σ significance at higher mass:

$$M = 4274.4^{+8.4}_{-6.7}(stat) \pm 1.9(syst) MeV$$

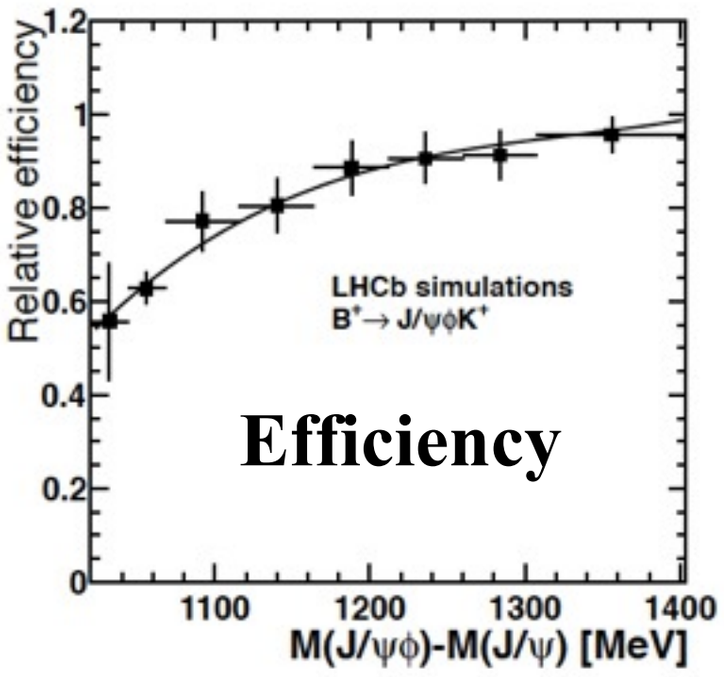


CDF Collaboration, arXiv:1101.6058

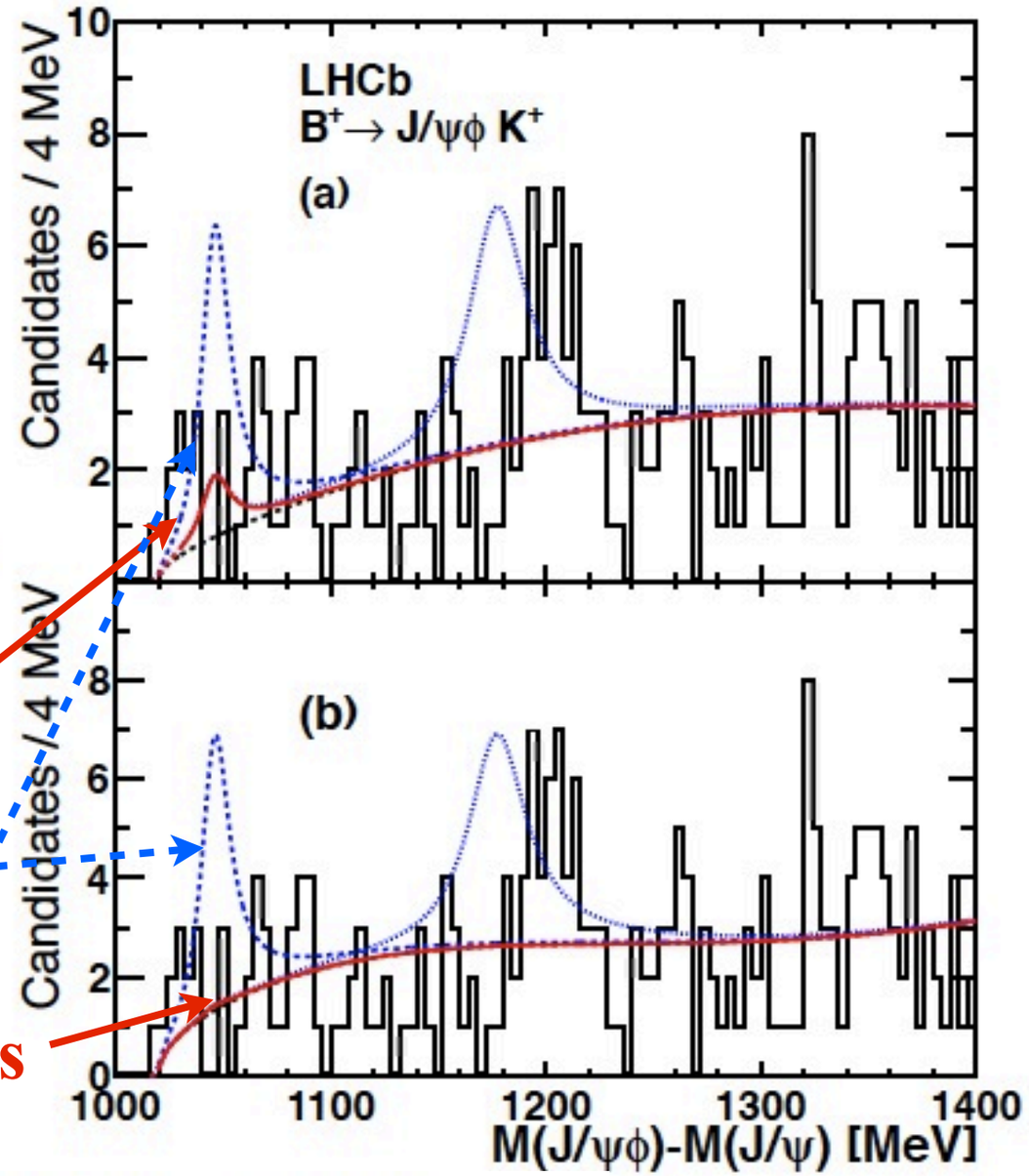
➢ With 0.38 fb^{-1} of data, LHCb also performed a search using 346 ± 20 reconstructed B→J/ψφK

Search for X(4140) (2)

LHCb-PAPER-2011-033
arXiv: 1202.5087
Submitted to Phys. Rev. D



Efficiency



3-body phase space background

7±5 events

Scaled from CDF:
35±9±6 events

0.6±7 events

Parabolic × 3-body phase space background

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

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

at 90% CL vs CDF:

2.4σ disagreement
0.149±0.039±0.024

0.17±0.06 (stat.)

Not Confirmed

Orbitally Excited $B_{(s)}^{**}$ Mesons

LHCb-CONF-2011-053
Preliminary

➢ **Compared to open charm meson excited states, little is known in B mesons.**

➢ **B^{**}_s and B^{**0} measured to some extent by Tevatron, while B^{**+} is missing in the story**

➢ **The search is done in LHCb by looking at invariant mass distributions of B^+K^-, $B^+\pi^-$ and $B^0\pi^+$ relative to threshold**

$$Q(h) = m(Bh) - m(B) - m(h)$$

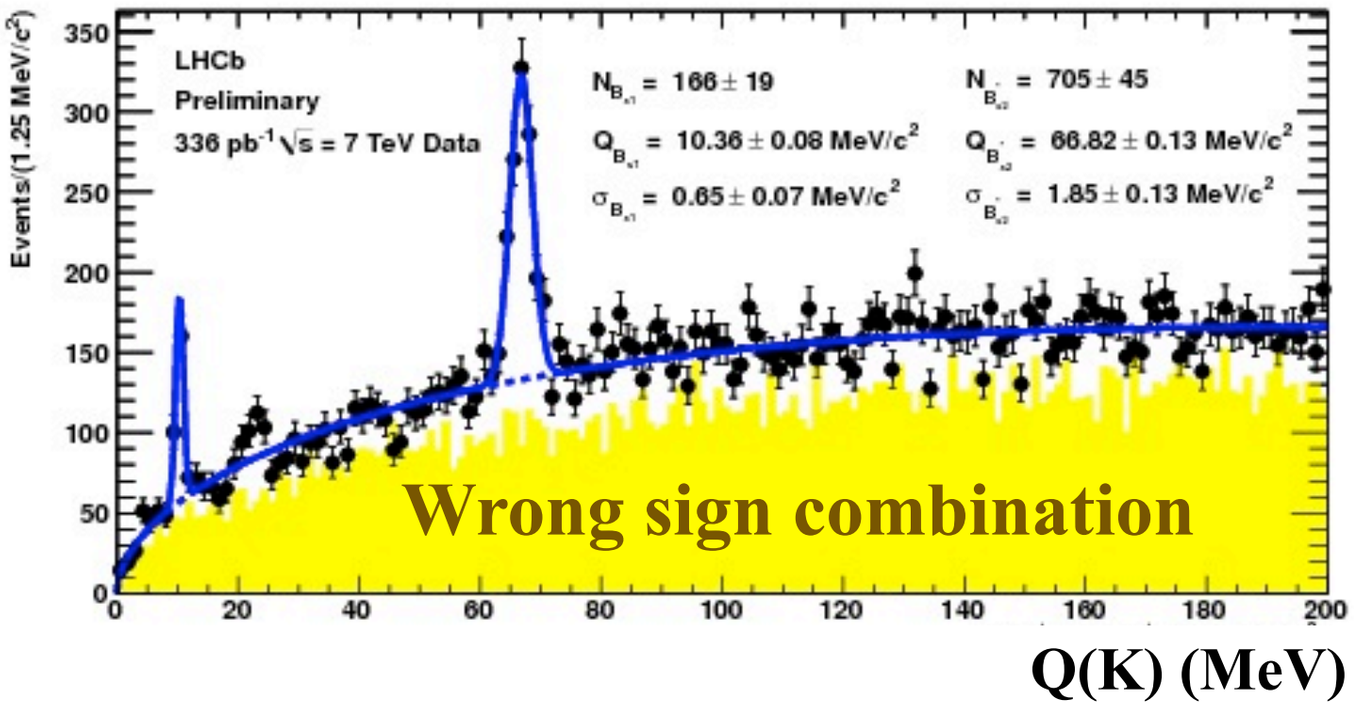
	K^-	π^-	π^+
$B^{(*)+}$	$B_{s1}(5830)^0$ $B_{s2}(5840)^0$	$B_1(5721)^0$ $B_2^*(5747)^0$	
$B^{(*)0}$			B^{**+}

➢ **Using B for reconstruction instead of B^*, and B^{**} mass may be shifted by 45.78±0.35 MeV (M(B^*) - M(B))**

Orbitally Excited B_s^{**} Mesons

LHCb-CONF-2011-053

Preliminary



➢ **Using $B^{(*)+} + K^-$ invariant mass**

➢ **Resolution ~ 1 MeV, larger than intrinsic widths**

➢ **Fit with Gaussian distribution for signals and threshold function ($Q^\alpha e^{-\beta Q}$) for background**

➢ **Measured masses**

$$M_{B_{s1}^0} = (5828.99 \pm 0.08_{\rm stat} \pm 0.13_{\rm syst} \pm 0.45^{B\,\rm mass}_{\rm syst})\ \text{MeV}$$
$$M_{B_{s2}^{*0}} = (5839.67 \pm 0.13_{\rm stat} \pm 0.17_{\rm syst} \pm 0.29^{B\,\rm mass}_{\rm syst})\ \text{MeV}$$

➢ **Significance**

$B^{(*)+} + K^-$	Significance
$B_{s1}^{*0} \to B^{*+} K^-$	12.5σ
$B_{s2}^{*0} \to B^{+} K^-$	22σ

Consistent with previous measurement

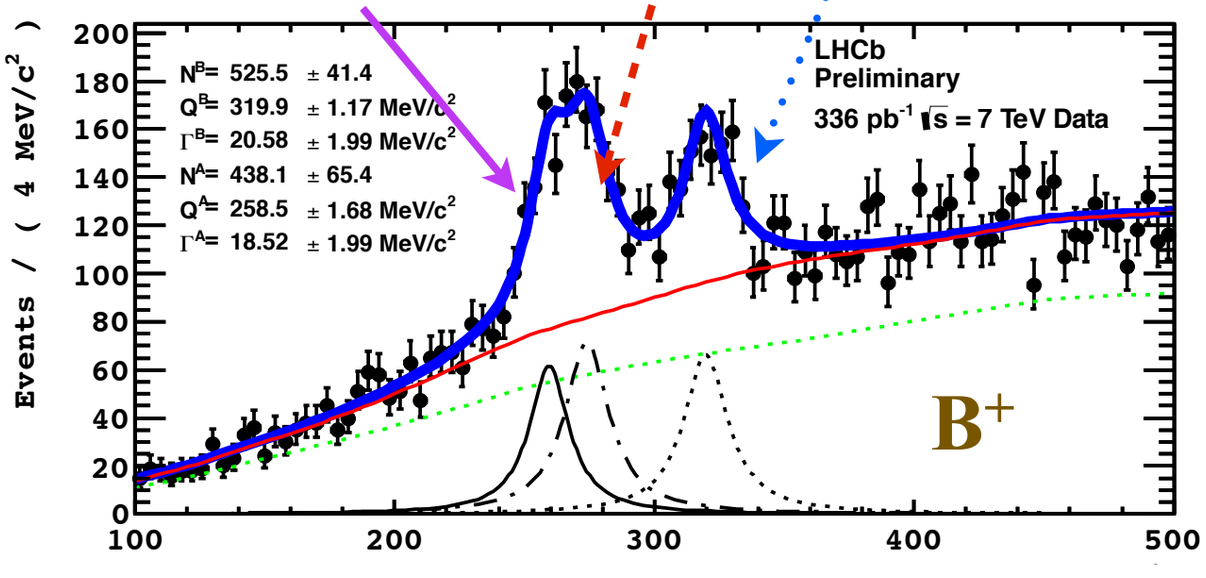
Orbitally Excited B^{**} Mesons(1)

LHCb-CONF-2011-053

Preliminary

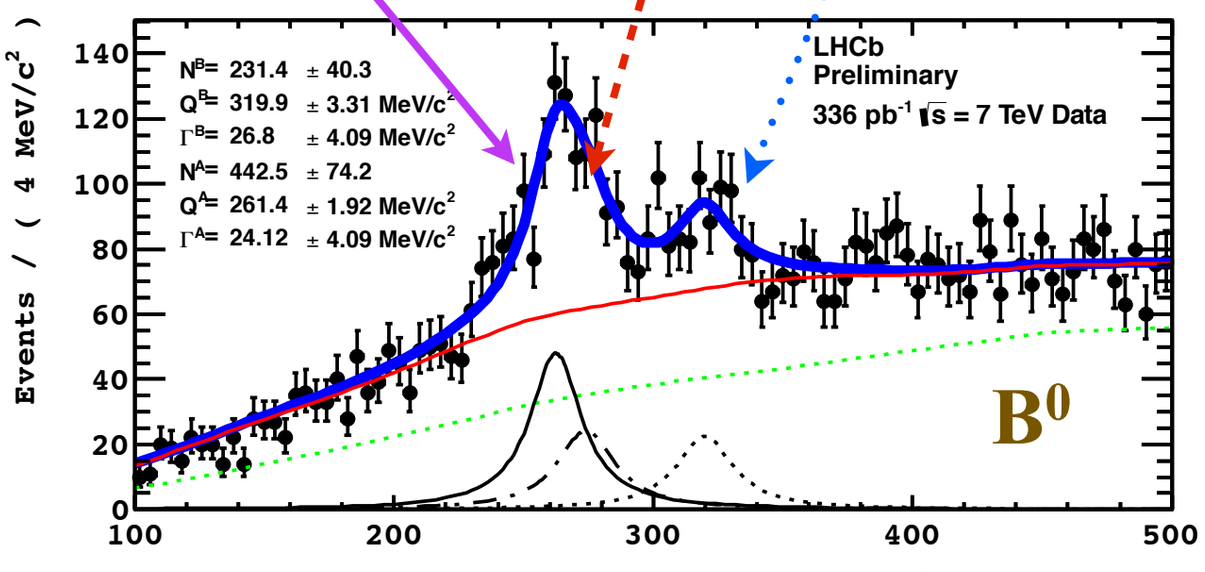
➢ $B_2^0 \to B^{*+}\pi^-$

➢ $B_1^0 \to B^{*+}\pi^-$ ➢ $B_2^0 \to B^+\pi^-$



➢ $B_2^+ \to B^{*0}\pi^-$

➢ $B_1^+ \to B^{*0}\pi^-$ ➢ $B_2^+ \to B^0\pi^-$



➢ **Resolution ~ 3 MeV, smaller than intrinsic widths**

➢ **Fit with Breit-Wigner function for signals**

➢ **Mass difference between two $B_2^{0(+)}$ channels fixed to 45.78 MeV;**
Width of $B_2^{0(+)}$ fixed to be the same when fitting its two channels;
Relative yields fixed to 0.93 ± 0.18 based on theoretical prediction[1][2];
Widths of B_1^0 and B_2^{*0} fixed to be 0.9 ± 0.2 based on prediction[3]

[1] M. Di Pierro and E. Eichten, Phys. Rev. D64 (2001) 114004
[2] Particle Data Group, J. Phys. G37 (2010) 075021
[3] A. F. Falk and T. Mehen, Phys. Rev. D53 (1996) 231-240

Orbitally Excited B^{**} Mesons(2)

LHCb-CONF-2011-053

Preliminary

➢ **Measured masses**

$$M_{B_1^0} = (5724.1 \pm 1.7_{\text{stat}} \pm 2.0_{\text{syst}} \pm 0.5^{B\,\text{mass}}_{\text{syst}})\ \text{MeV}$$

$$M_{B_1^+} = (5726.3 \pm 1.9_{\text{stat}} \pm 3.0_{\text{syst}} \pm 0.5^{B\,\text{mass}}_{\text{syst}})\ \text{MeV}$$

$$M_{B_2^{*0}} = (5738.6 \pm 1.2_{\text{stat}} \pm 1.2_{\text{syst}} \pm 0.3^{B\,\text{mass}}_{\text{syst}})\ \text{MeV}$$

$$M_{B_2^{*+}} = (5739.0 \pm 3.3_{\text{stat}} \pm 1.6_{\text{syst}} \pm 0.3^{B\,\text{mass}}_{\text{syst}})\ \text{MeV}$$

New identified states

➢ **Significance**

Significance	$B^{(*)+}$ + pion	$B^{(*)0}$ + pion
$B_1 \to B^*\pi$	13.5σ	9.9σ
$B_2^* \to B\pi$	8.0σ	4.0σ
$B_2^* \to B^*\pi$	2.6σ	0σ

➢ **Our measurements are consistent with the previous results and further extend the excited *B* spectrum into B^{**+}**

B_c System

➢ B_c meson: unique state in Standard Model formed by two heavy quarks of different flavours

➢ B_c production: $O(10)$ times more than Tevatron in LHC, cross section measurement ➠ Understanding of production mechanism

➢ B_c mass spectrum ➠ Quark model and pQCD test

➢ B_c decays: both heavy quarks can decay, lifetime only 1/3 of $B_{(s)}$ mesons

➢ B_c lifetime measurement ➠ Dynamics of heavy quark decay

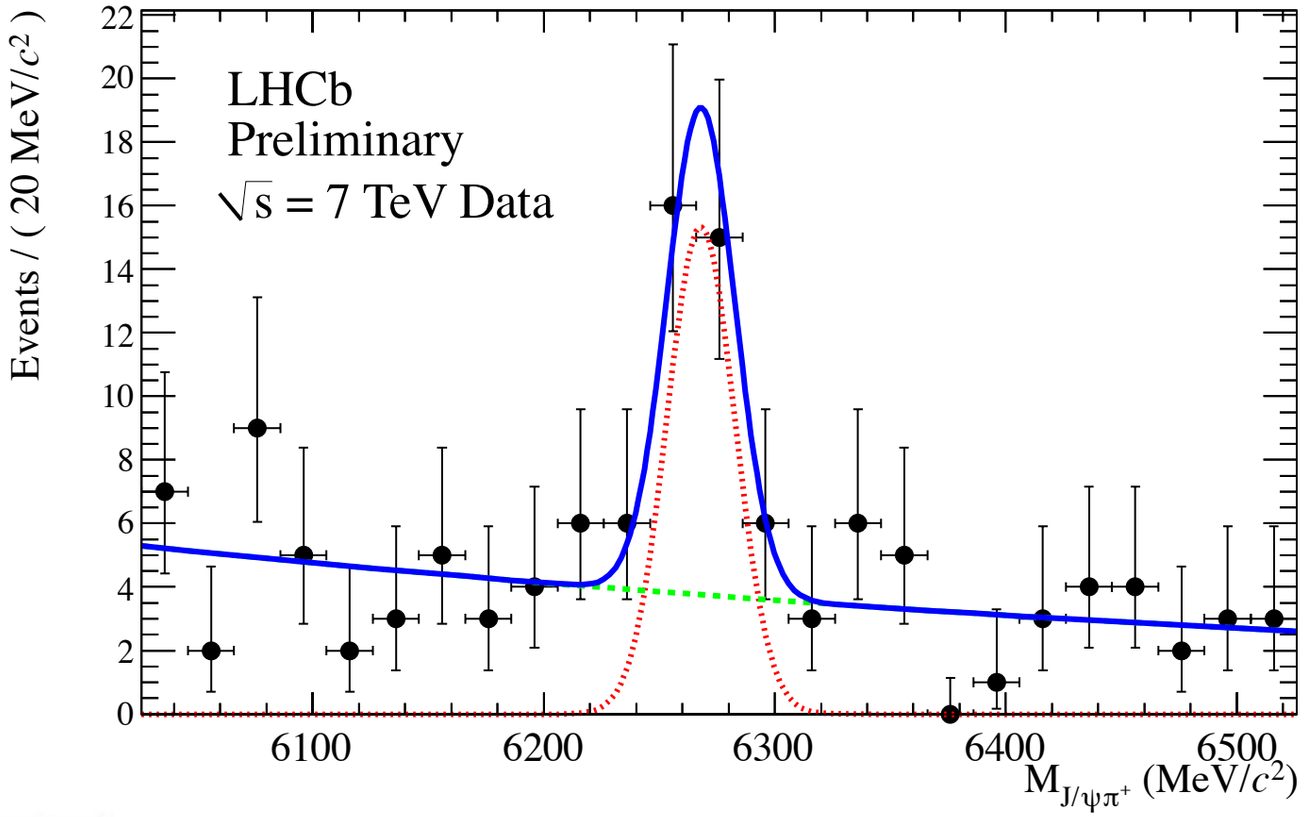
➢ Few decay channels observed, new continent to explore

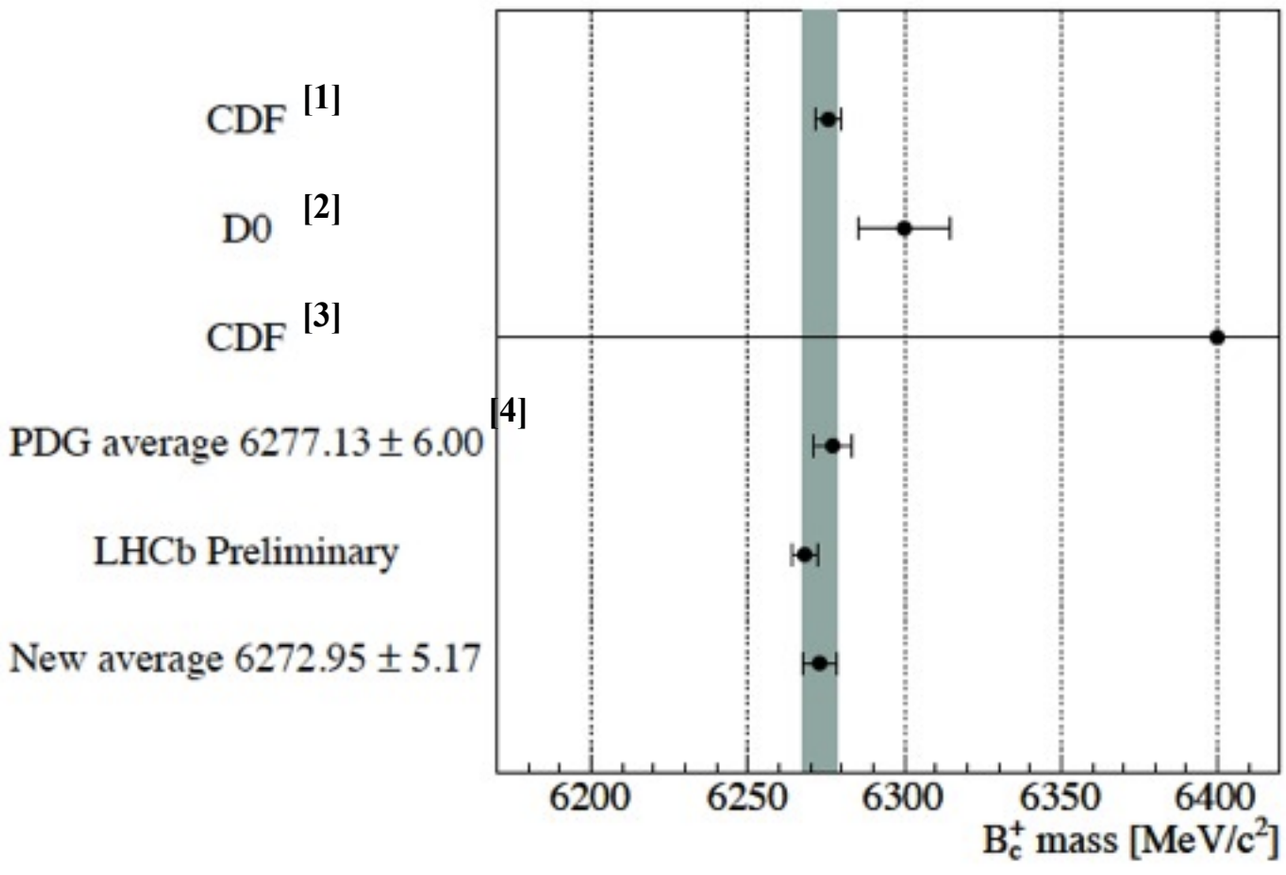
B_c Mass Measurement

LHCb-CONF-2011-027

Preliminary

- **Based on 35 pb^{-1} of data using $B_c^+ \to J/\psi\pi^+$ decay**
- **Signals: 28±7**
- **Fit with Gaussian + exponential background**





$M(B_c^+) = 6268.0 \pm 4.0(stat) \pm 0.6(syst)$ MeV

[1] CDF Collaboration, Phys. Rev. Lett. 100 (2008) 182002
[2] D0 Collaboration, Phys. Rev. Lett. 101 (2008) 012001
[3] CDF Collaboration, Phys. Rev. Lett. 81 (1998) 2432
[4] Particle Data Group, J. Phys. G37 (2010) 075021

B_c Cross Section

LHCb-CONF-2011-017

Preliminary

➢ **The measurement is done using $B^+ \to J/\psi K^+$ as reference channel**

$$\frac{\sigma(B_c^\pm) \times \mathrm{BR}(B_c^\pm \to J/\psi \pi^\pm)}{\sigma(B^\pm) \times \mathrm{BR}(B^\pm \to J/\psi K^\pm)} = \epsilon_{\mathrm{rel}} \times \frac{N(B_c^\pm)}{N(B^\pm)}$$

for $p_T(B) > 4$ GeV and $\eta \in [2.5, 4.5]$

➢ **ϵ_{rel} : the relative efficiency between B_c^+ and B^+ decays**

Obtained from Monte Carlo

Unknown spectrum of B_c^+ taken into account by binning efficiencies in p_T and η

$$\frac{\sigma(B_c^\pm) \times \mathrm{BR}(B_c^\pm \to J/\psi \pi^\pm)}{\sigma(B^\pm) \times \mathrm{BR}(B^\pm \to J/\psi K^\pm)} = (2.2 \pm 0.8_{\mathrm{stat}} \pm 0.2_{\mathrm{syst}})\%$$

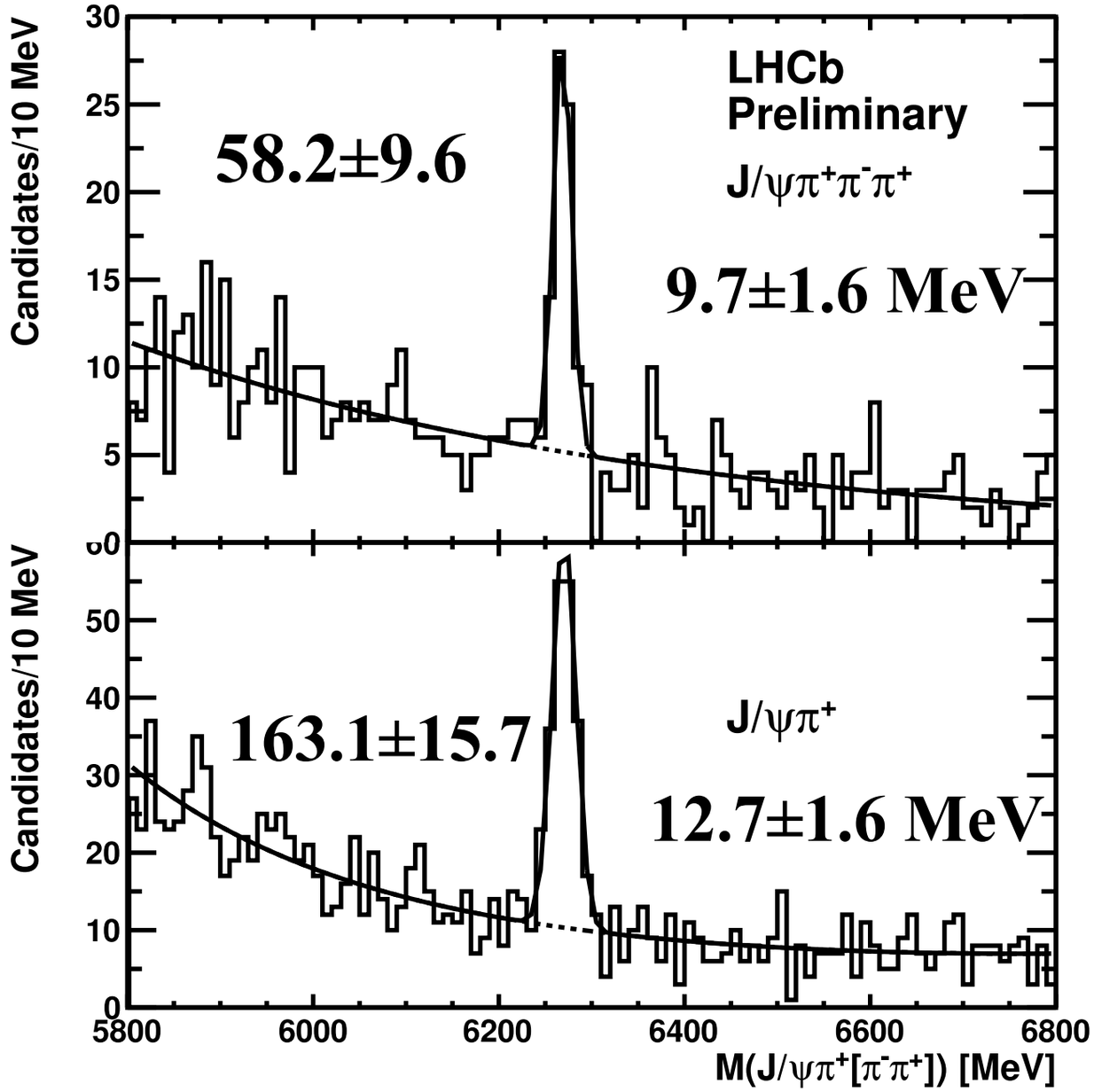
$B_c \to J/\psi\pi\pi\pi(1)$

LHCb-CONF-2011-040

Preliminary

➢ **The branching fraction is 1.5-2.3 times more than $B_c^+ \to J/\psi\pi^+$, though detection efficiency is ~10 times lower due to two extra pions**

➢ **The measurement is done with respect to $B_c^+ \to J/\psi\pi^+$ to test different phenomenological predictions**



➢ **By looking at difference between fit w/o signal, significance of signals is 6.8(11) sigma**

➢ **With the efficiency ratio of 0.119±0.006, we determine the branching fraction ratio to be 3.0±0.6(stat)±0.4(syst)**

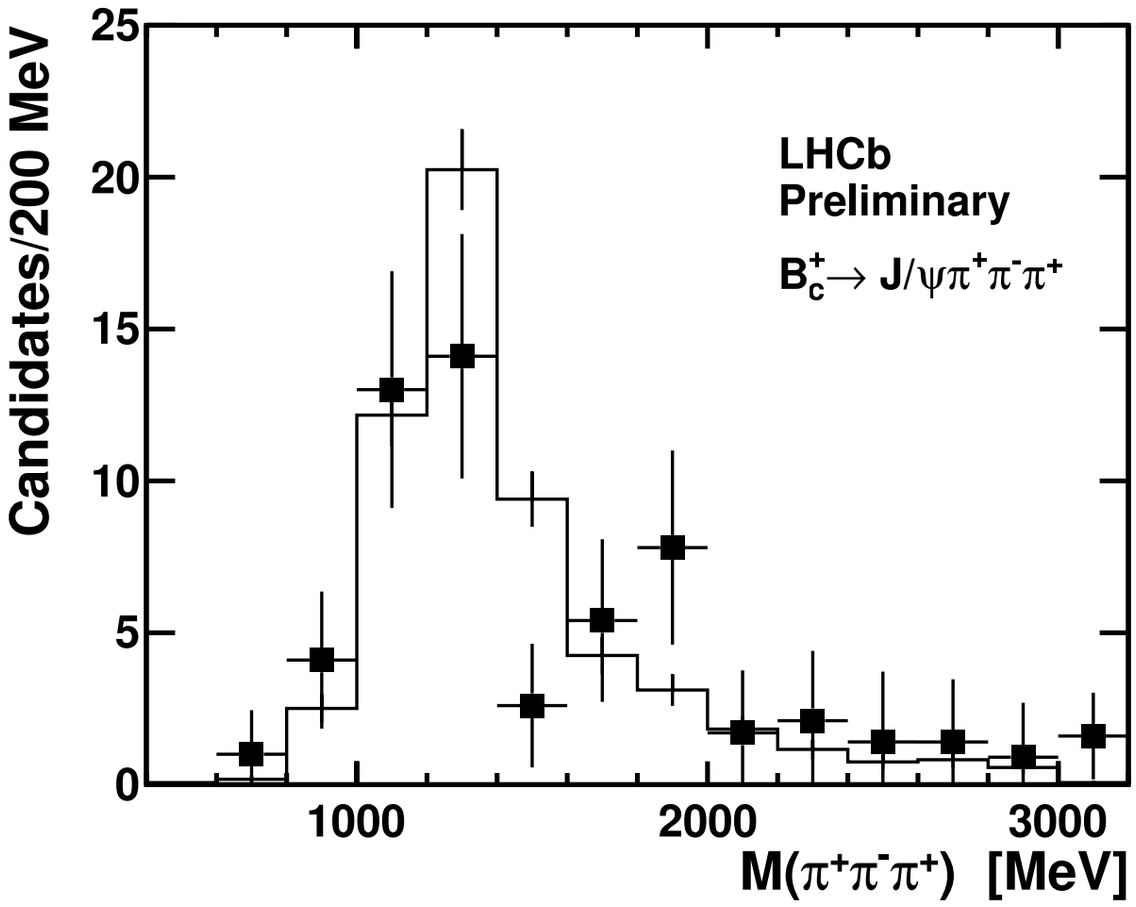
➢ **Our result favours prediction $\mathcal{B}r$ ratio ~ 2.3[1] using QCD sum rules**

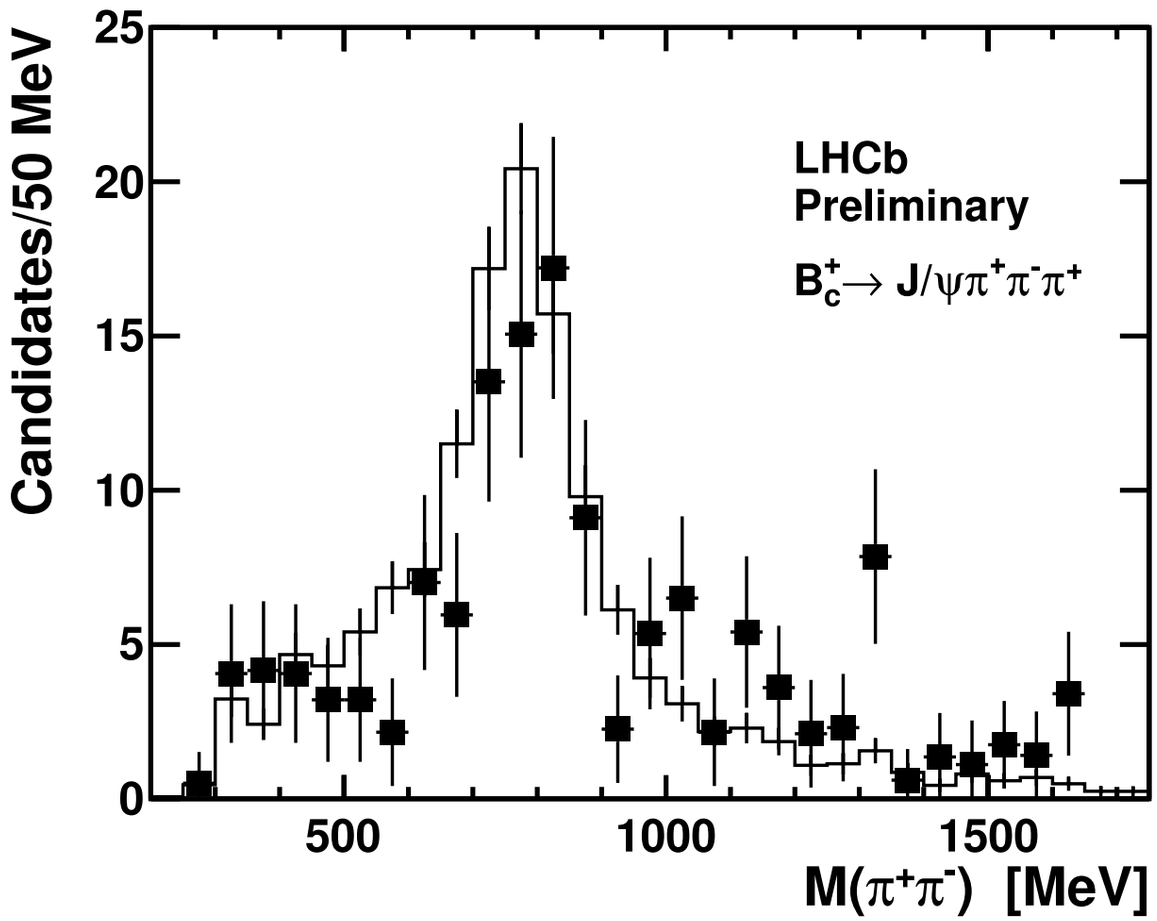
[1] A. K. Likhoded and A. V. Luchinsky, Phys. Rev. D81 (2010) 014015

$B_c \to J/\psi\pi\pi\pi(2)$

LHCb-CONF-2011-040

Preliminary





➢ **Background subtracted distributions of (3π) and (2π) invariant mass**

➢ **Dominated by $B_c^+ \to J/\psi a_1^+(1260)$ with $a_1^+(1260) \to \rho^0\pi^+$**

➢ **Need more statistics to observe $B_c^+ \to \psi(2S)\pi^+$ and $B_c^+ \to X(3872)\pi^+$ in the decay as in $B^+ \to J/\psi\pi^+\pi^+\pi^-$**

Conclusion and Prospect

Results shown are made with part of luminosity collected, lots of other measurements are ongoing with full 1 fb^{-1} data

- ***X, Y, Z* states:**

  First studies of *X(3872)* and *X(4140)* demonstrate potential of LHCb to explore exotic meson sector. Future results with larger data set will build on this

- **$B_{(s)}^{**}$ and B_c system:**

  LHCb has access to the poorly explored $B_{(s)}^{**}$ and B_c sector, and will significantly improve the knowledge of their properties and decays

BackUp Slides

X(3872): Systematic Uncertainties

➢ **Mass measurement**

Category	Source of uncertainty	Δm [MeV/c^2] $\psi(2S)$	$X(3872)$
Mass fitting	Natural width	–	0.01
	Radiative tail	0.02	0.02
	Resolution	–	0.01
	Background model	0.02	0.02
Momentum calibration	Average momentum scale	0.08	0.10
	η dependence of momentum scale	0.02	0.03
Detector description	Energy loss correction	0.05	0.05
Detector alignment	Track slopes	0.01	0.01
Total		0.10	0.12

➢ **Cross section measurement**

Source of uncertainty	$\Delta\sigma/\sigma$ [%]
$X(3872)$ polarization	2.1
$X(3872)$ decay model	1.0
$X(3872)$ decay width	5.0
Mass resolution	5.8
Background model	6.4
Tracking efficiency	7.4
Track χ^2 cut	2.0
Vertex χ^2 cut	3.0
Muon trigger efficiency	2.9
Global event cuts	3.0
Muon identification	1.1
Integrated luminosity	3.5
$J/\psi \to \mu^+\mu^-$ branching fraction	1.0
Total	14.3

Width and resolution

Background model

Tracking efficiency