b-hadron production and properties at LHCb

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On behalf of the LHCb collaboration

Outline

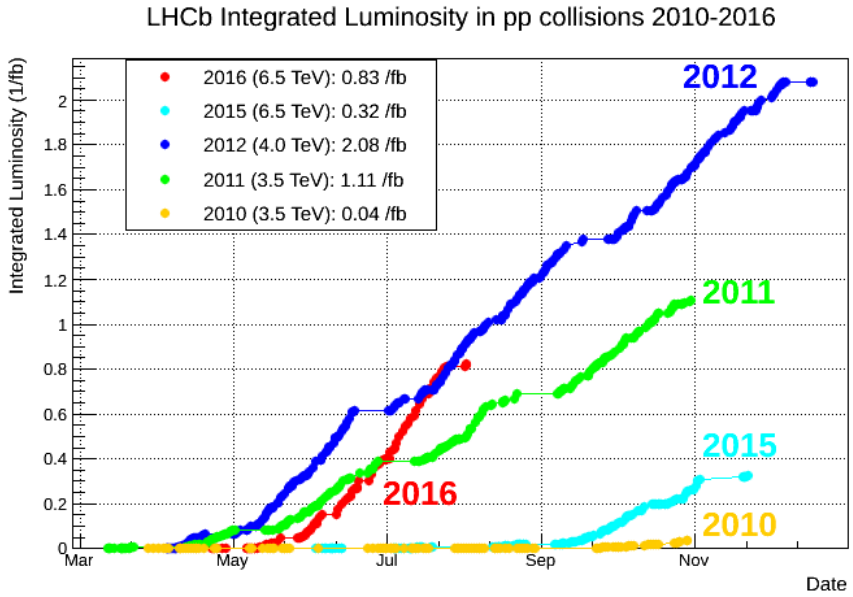
- Quarkonia
- B_c physics
- b-hadrons
- Summary and outlook

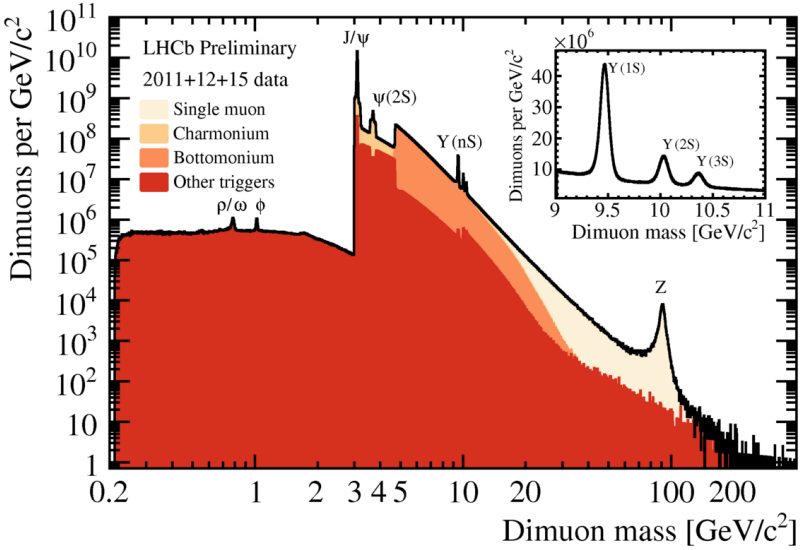
Impossible to present everything in 25 minutes hence focus on more recent results

See also related LHCb talks by

V. Belyaev, *LHCb results on associated production of heavy hadrons*
G. Cavallero, *LHCb results on exotic spectroscopy*
D. Craik, *LHCb results on heavy quark spectroscopy*
R. Silva Coutinho, *LHCb charm, bottom and top production in the forward region*
C. Voss *LHCb results on baryonic B decays*

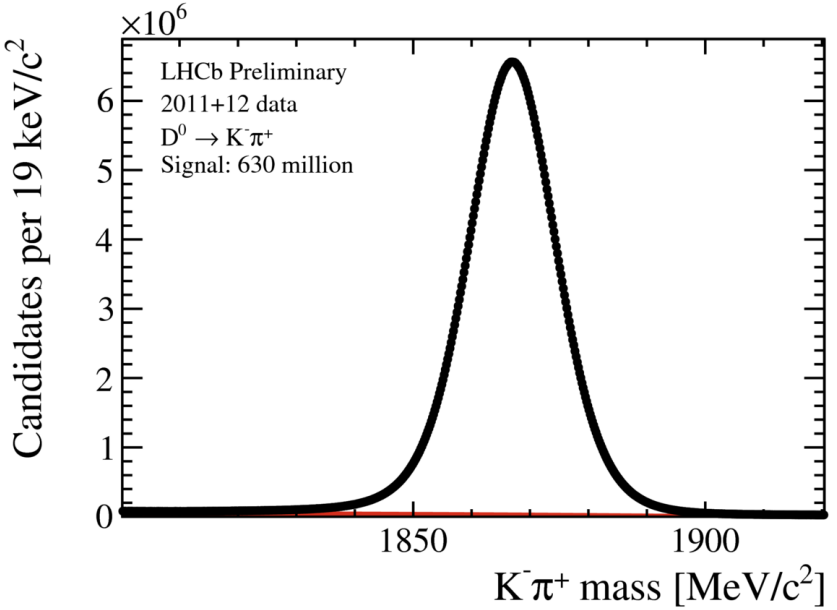
Introduction





Today results from Run 1
plus J/ψ from Run 2

Exploit excellent dimuon trigger
Capabilities plus unique hadron
triggering and PID



LHCb-CONF-2016-005

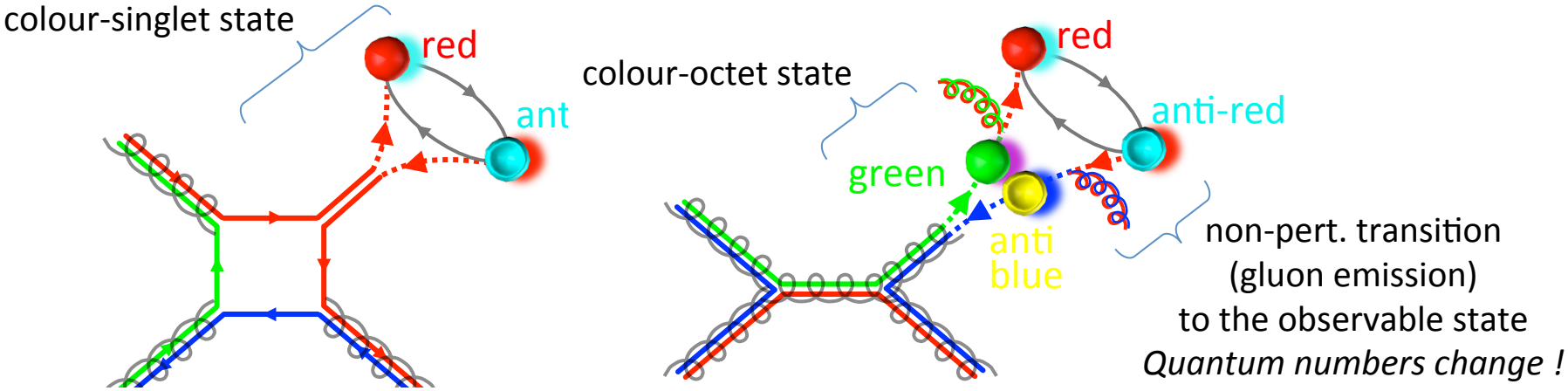
Quarkonia motivation

Colour Singlet Model at NLO known to underestimate production cross-section

- Better agreement with NNLO* calculations

NRQCD approach better agreement with data, but Long Distance Matrix Elements (LDMEs) have to be determined from the data

- Cross-sections agree with data, but predicts large transverse polarization whilst data shows small polarization



Figures by Pietro Faccioli

LHCb scorecard

Process	Centre-of-mass energy [TeV]				
	2.76	5	7	8	13
η_c cross-section	No	No	Done	Done	To do
J/ψ cross-section	Done	To do	Done	Done	Done
J/ψ polarization	No	No	Done	To do	To do
ψ(2S) cross-section	To do	To do	Done	To do	To do
ψ(2S) polarization	No	No	Done	To do	To do
χ_c production	No	No	Done	To do	To do
χ_b production	No	No	Done	Done	To do
ϒ(nS) cross-section	Done	To do	Done	Done	To do
ϒ(nS) polarization	No	No	To do	To do	To do

Unique To LHCb

Done

To do

No

Today J/ψ production @13TeV

http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_B_Q.html

J/ψ cross-section at 13 TeV

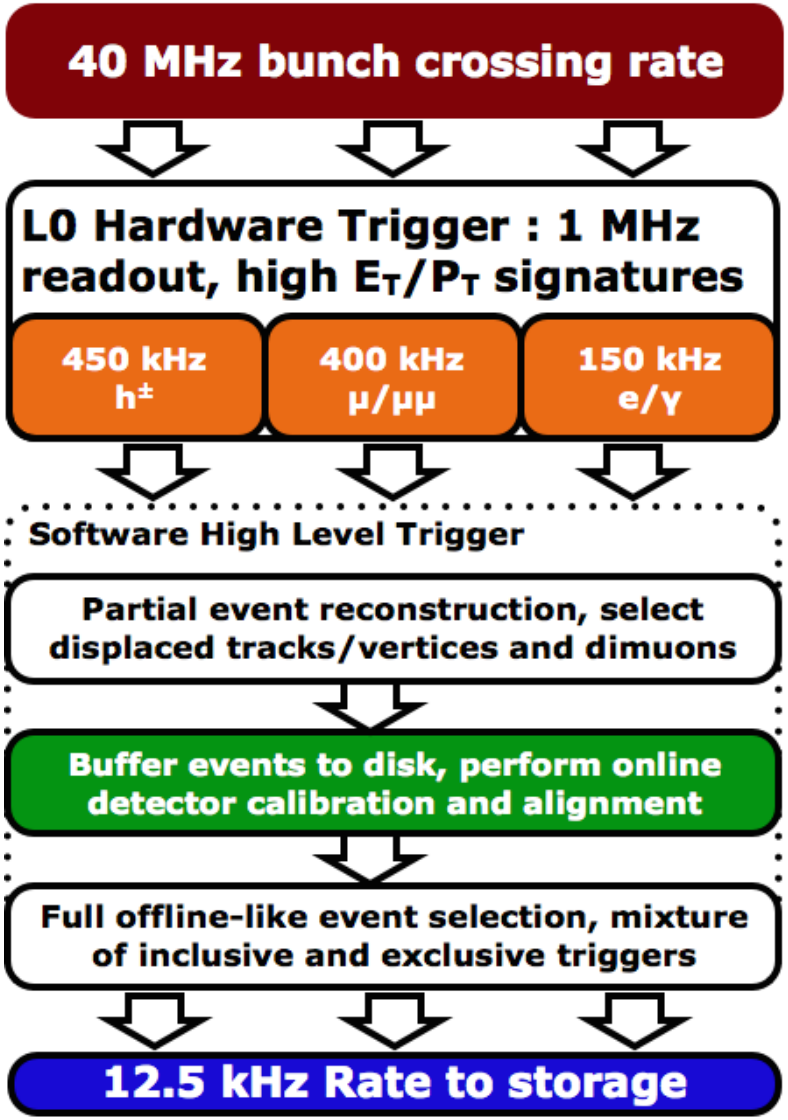
Total of 4.97 ± 0.19 pb^{-1} pp collision data collected in early July 2015

Use new turbo trigger stream (arxiv:1604.05596)

Offline quality reconstructed candidates directly from trigger

Decrease event size, increase output rate by an order of magnitude

Take candidates selected by muon trigger lines with invariant mass consistent with J/ψ



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J/ψ production analysis

Measure double differential cross-section

- Both prompt and J/ψ from b-hadron decay cross-sections
- Ratio of 13 and 8 TeV cross-section measurements (partially cancel out experimental and theory uncertainties)
- Estimate of b production cross-section at 13 TeV

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$$\frac{d^2\sigma}{dydp_T} = \frac{N(J/\psi \to \mu^+\mu^-)}{\mathcal{L} \cdot \epsilon_{tot} \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-) \cdot \Delta y \cdot \Delta p_T}$$

Fit to mass distribution

5 bins from 2 - 4.5 in y
14 bins from 0-14 GeV/c in pt

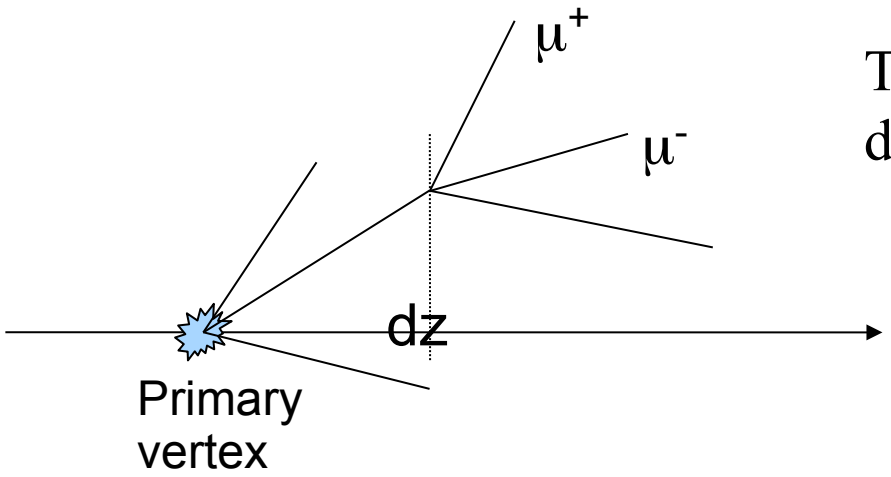
Luminosity
3.05 ± 0.12 pb^{-1}

Efficiency from MC+ data driven corrections for tracking, trigger PID
Assume zero polarization

5.961 ± 0.033 %

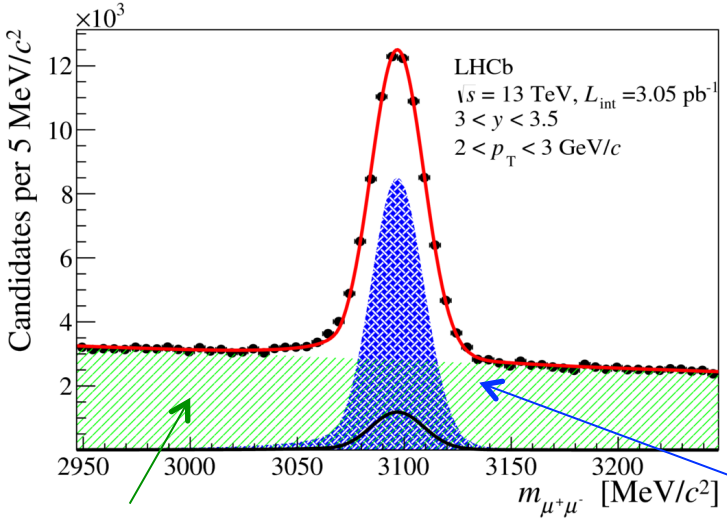
J/ψ fit details

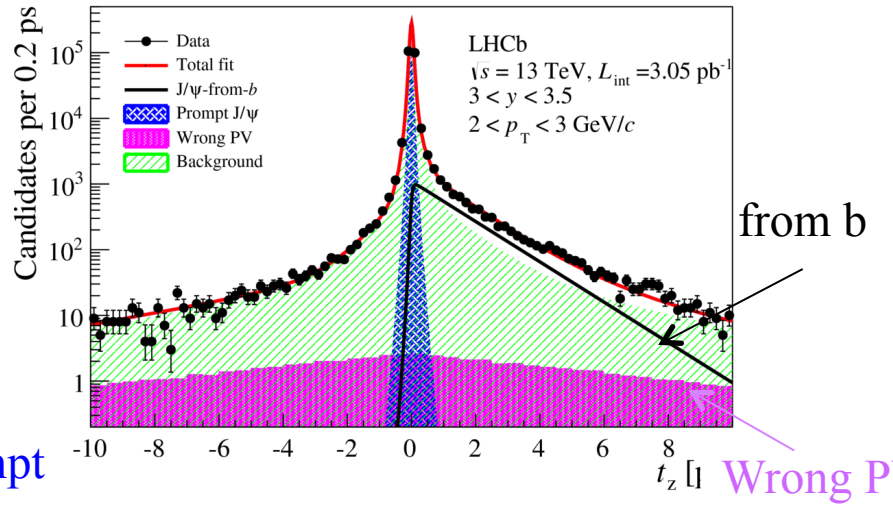
Unbinned simultaneous maximum likelihood fit to M(J/ψ) and tz for each bin



To separate J/ψ from prompt and b decays:

$$tz = \frac{dz}{p_z^{J/\psi}} \cdot m^{J/\psi}$$



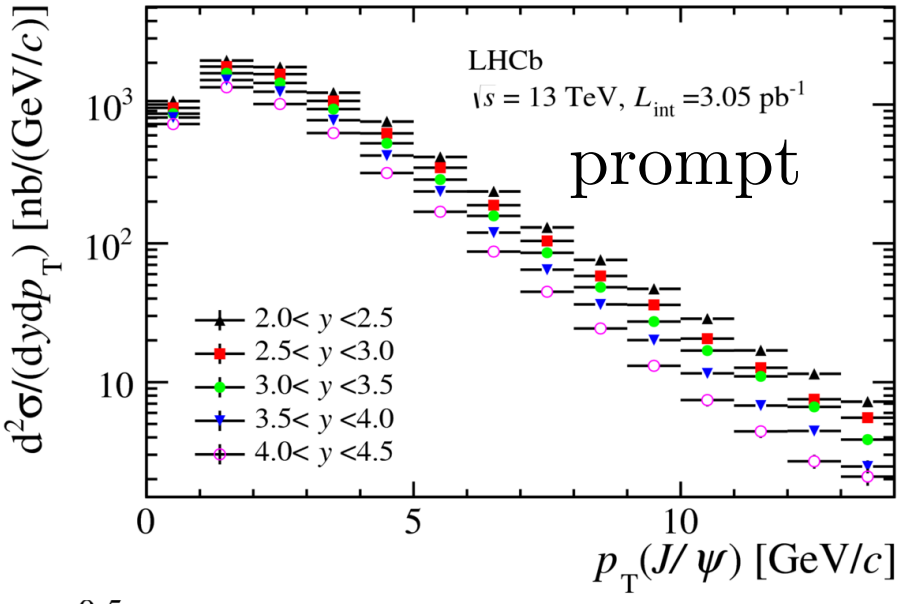


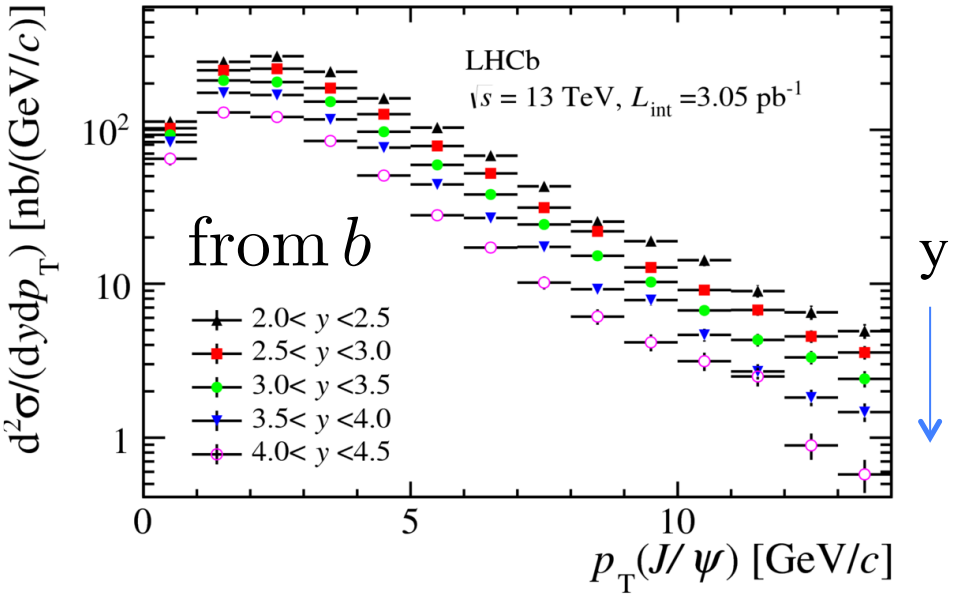
prompt

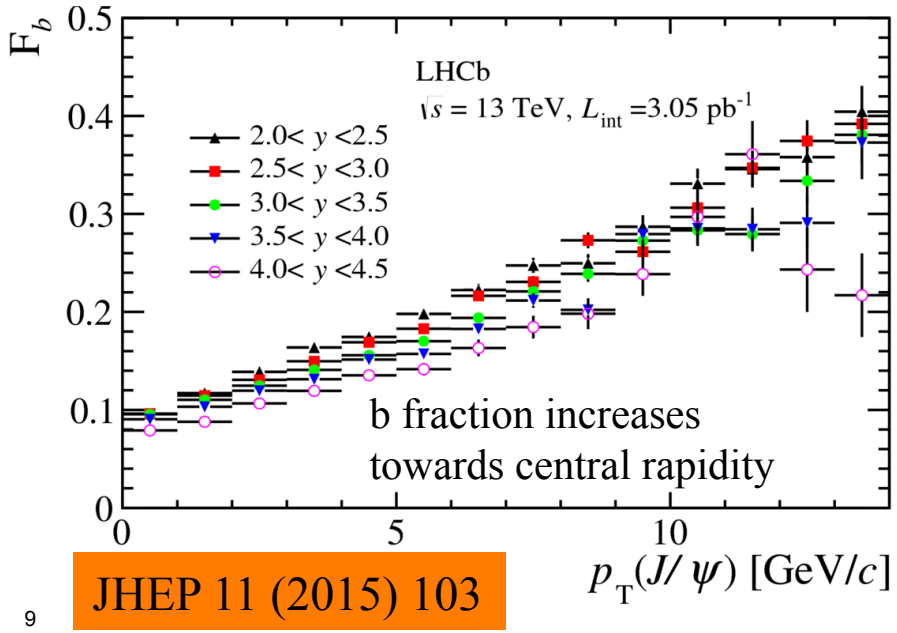
Combinatorial background

Wrong PV

J/ψ cross-sections







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$p_T < 14\,\mathrm{GeV}/c,\ 2.0 < y < 4.5$

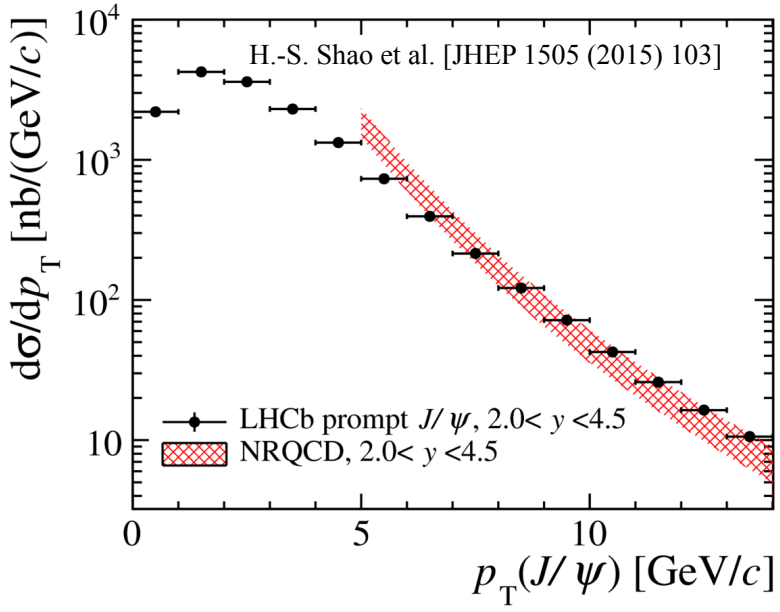
$\sigma(\text{prompt } J/\psi) = (15.30 \pm 0.03 \pm 0.86)\mu\text{b}$

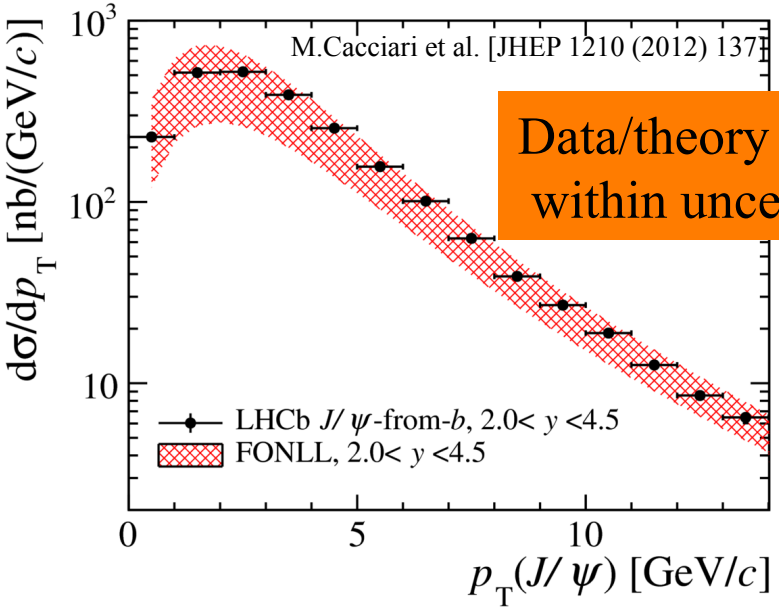
$\sigma(J/\psi \text{ from } b) = (2.34 \pm 0.01 \pm 0.13)\mu\text{b}$

Naïve extrapolation to 4 using Pythia 6

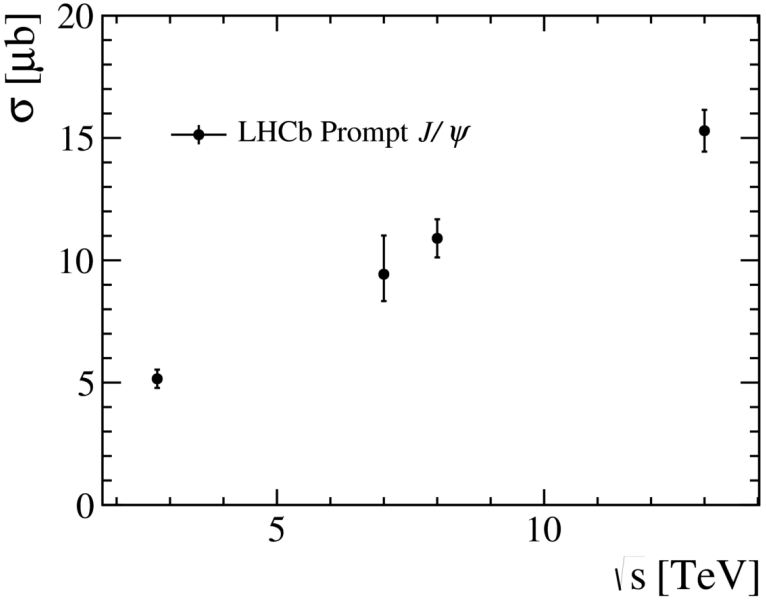
$\sigma(pp \to b\bar{b}X) = 515 \pm 2 \pm 53\,\mu\text{b}$

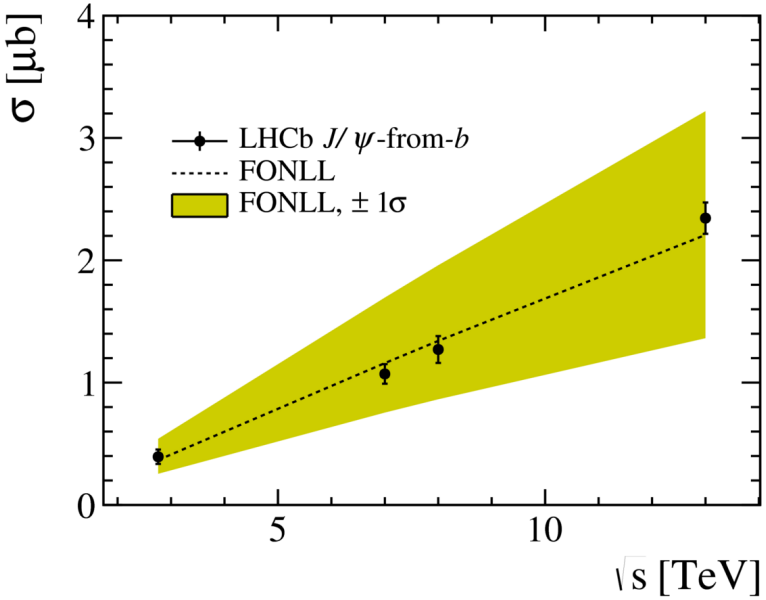
J/ψ: Comparison to theory





Data/theory agree within uncertainties

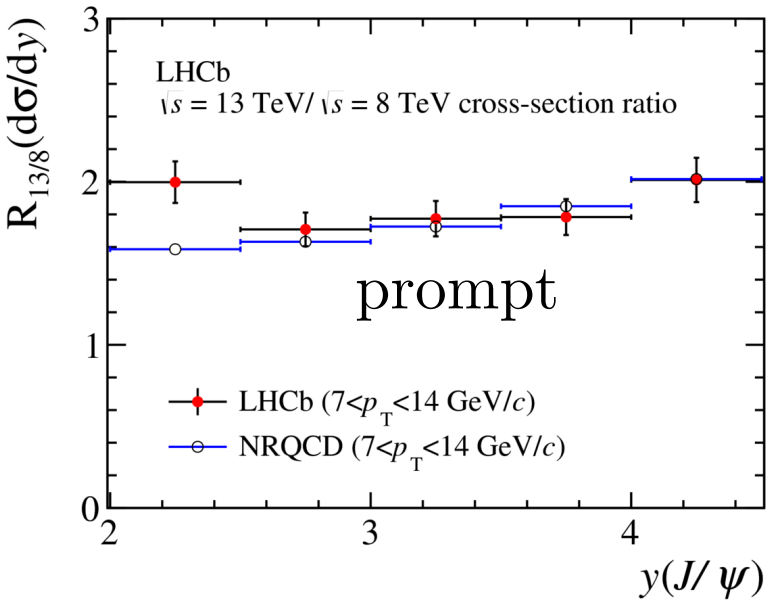


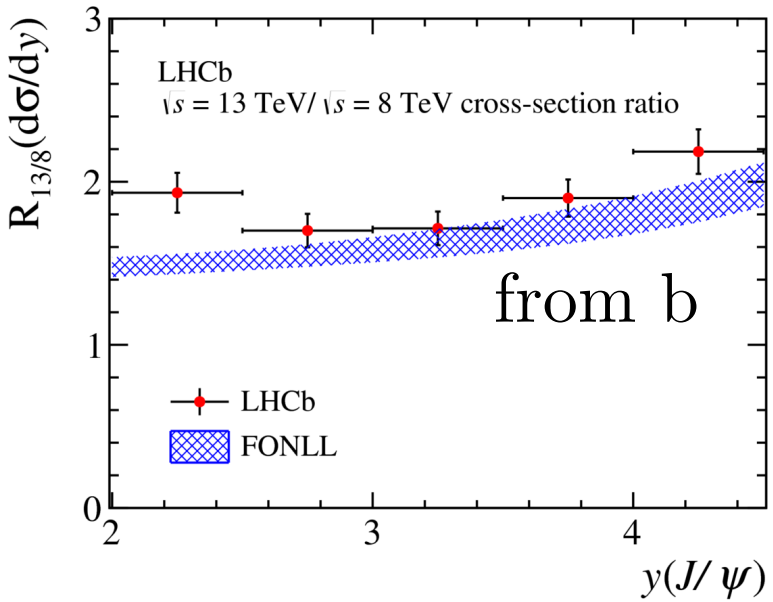


J/ψ: Cross-section ratios

Experimental (and theory) uncertainties cancel in cross-section ratio to 8 TeV measurement [JHEP 06 (2013) 064]

Quantity	Systematic uncertainty	
Luminosity	4.6%	30% cancelled
Trigger	1.5 %	50% cancelled
Muon ID	2.2%	
Tracking	1%	50% cancelled
Signal shape	2%	up to 80% cancelled for some bins
p_T-y-spectrum, MC stat. (t_z fits)	1-8%	



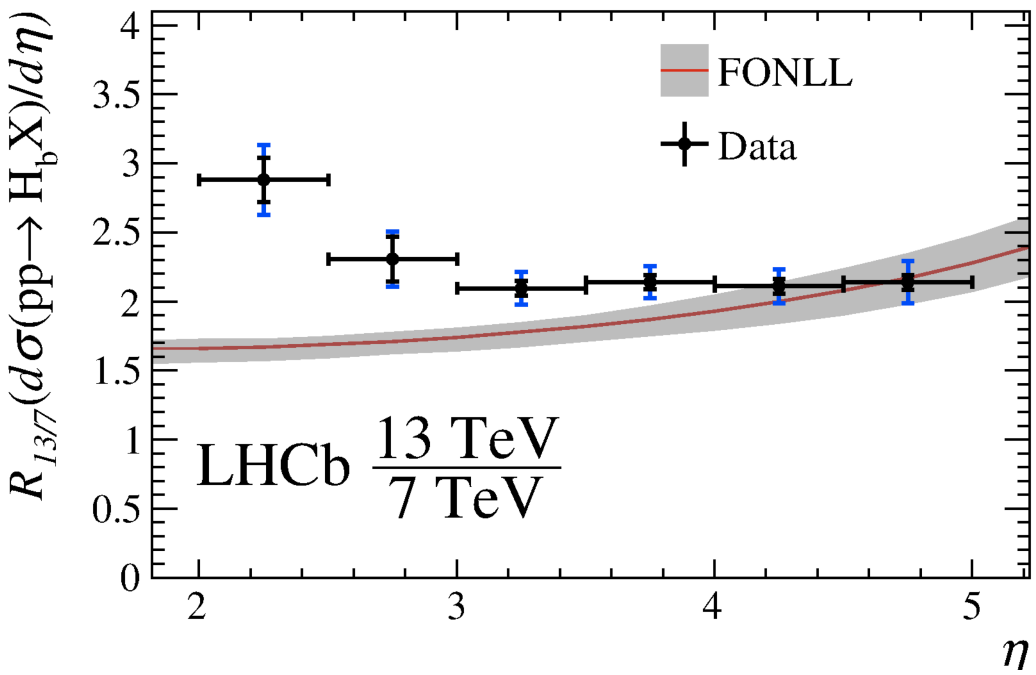


b cross-section ratios from semi-leptonic decays

J/ψ Data/theory ratios agree well at high y, low y less well

Trend that theory underestimates increase in cross section seen in data also seen seen in b cross-section measurement using semi-leptonic decays

LHCb-PAPER-2016-031



More details in talk of R. Silva Coutinho

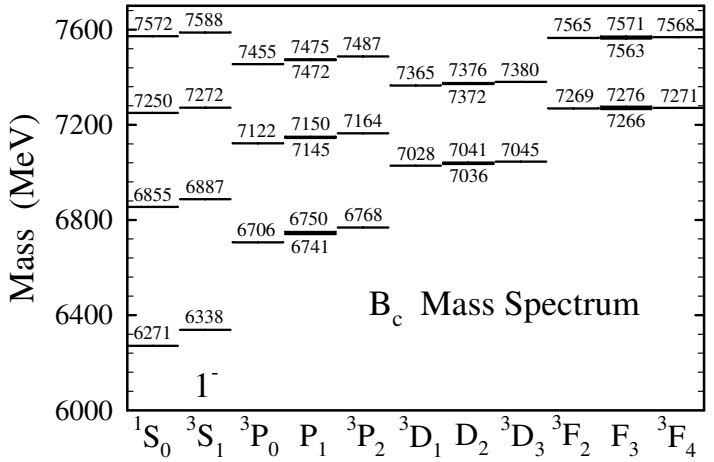
B_c physics

Ground state is unique meson containing two heavy quarks decaying weakly

Ideal testing ground for QCD models

LHCb has had big impact in this area

From Godfrey, PRD 70, 054017



- Mass from average of LHCb measurements is 6274.67 ± 1.2 MeV/c^2
- Lifetime 511.4 ± 9.3 fs
- 9 new decay modes !

Today present two recent analyses

Measurement of BR($B_c^+ \rightarrow J/\psi K^+$)/BR($B_c^+ \rightarrow J/\psi \pi^+$), arxiv:1607.06823

Study of $B_c^+ \rightarrow K^+K^-\pi^+$ and evidence for $B_c^+ \rightarrow \chi_{c0}\,\pi^+$ arxiv:1607.06134

For $B \rightarrow pp\pi^+$ see talk of C. Haen

$B_c^+ \rightarrow J/\psi K^+$

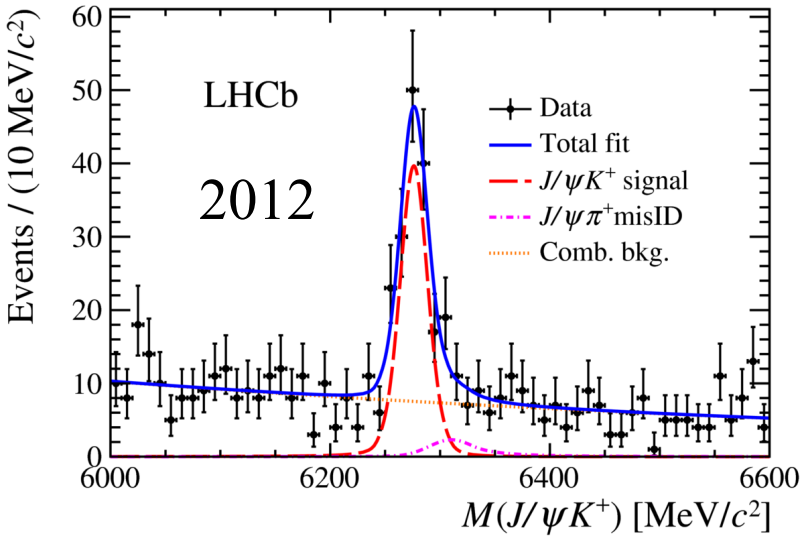
arxiv:1607.06823

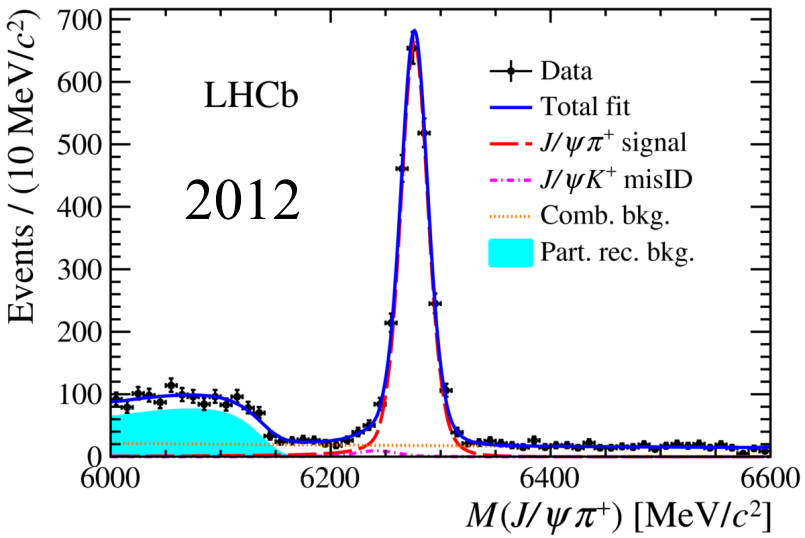
Mode first observed by LHCb using 1 fb^{-1} of data (JHEP 09 (2103) 75)

CKM suppressed b → cus transition

New update to full Run 1 dataset (3 fb^{-1})

Normalize to $B_c^+ \rightarrow J/\psi\pi^+$





$B_c^+ \rightarrow J/\psi K^+$

- Simultaneous fit to signal and normalization channels
- In Run 1 3207 +/- 64 total of $B_c^+ \rightarrow J/\psi\pi^+$ candidates

Main systematic from treatment of partially reconstructed backgrounds

	7 TeV	8 TeV
Signal model	0.5%	0.8%
Combinatorial background	1.1%	0.5%
Partially reconstructed background	3.3%	3.2%
Misidentification background	0.2%	0.0%
Particle identification efficiency	0.2%	0.1%
Detector material	0.3%	0.3%
Total	3.5%	3.4%

stat syst

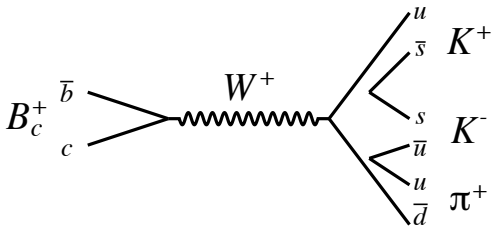
$$R_{K/\pi} = 0.079 \pm 0.007 \pm 0.003$$

Agrees with previous LHCb results and range of theory predictions

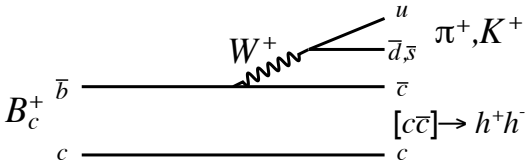
$B_c^+ \rightarrow K^+K^-\pi^+$

arxiv:1607.06134

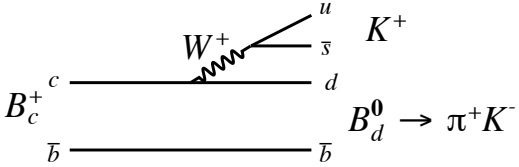
$\bar{b}c \rightarrow W^+ \rightarrow u\bar{q}\ (q = d, s)$



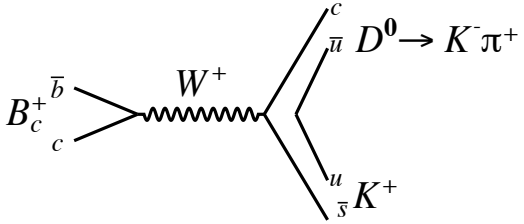
$B_c^+ \rightarrow [c\bar{c}](\rightarrow h_1^+ h_1^-)h_2^+$



$B_c^+ \rightarrow B_q^0(\rightarrow h_1^+ h_2^-)h_3^+$



$B_c^+ \rightarrow D^0(\rightarrow K\pi)h^+\ (h = \pi,\ K)$

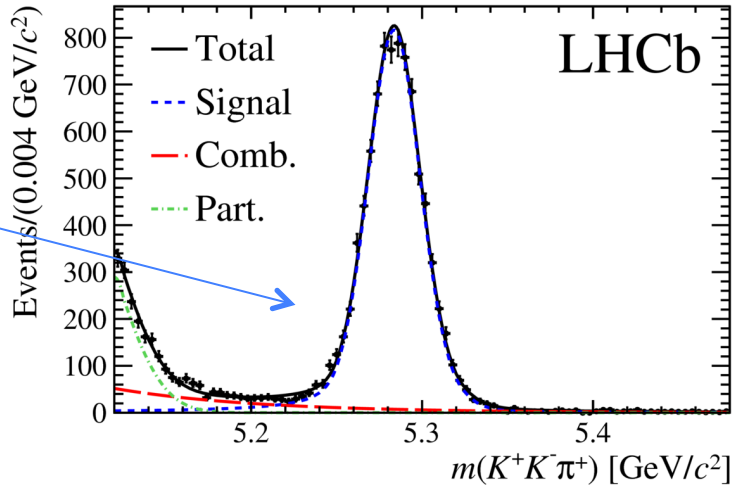


$B^+ \rightarrow \overline{D}^0(\rightarrow K^+K^-)\pi^+$

For normalization use

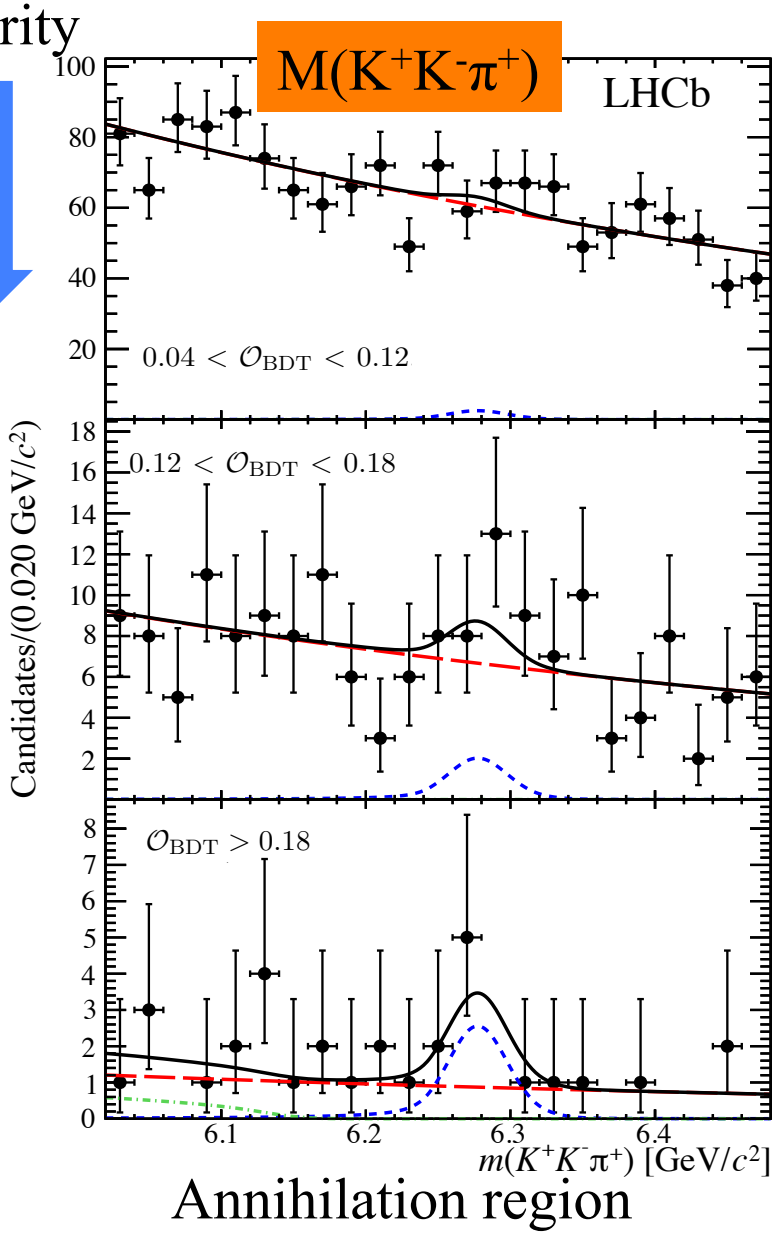
And measure

$$R_f \equiv \frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \rightarrow f)$$



$B_c^+ \rightarrow K^+K^-\pi^+$

Purity



Annihilation region

Explore interesting areas of phase space separately, starting with annihilation region

$$\bar{b}c \rightarrow W^+ \rightarrow u\bar{q} \ (q = d, s)$$

$$m(K^-\pi^+) < 1.834\,\mathrm{GeV}/c^2$$

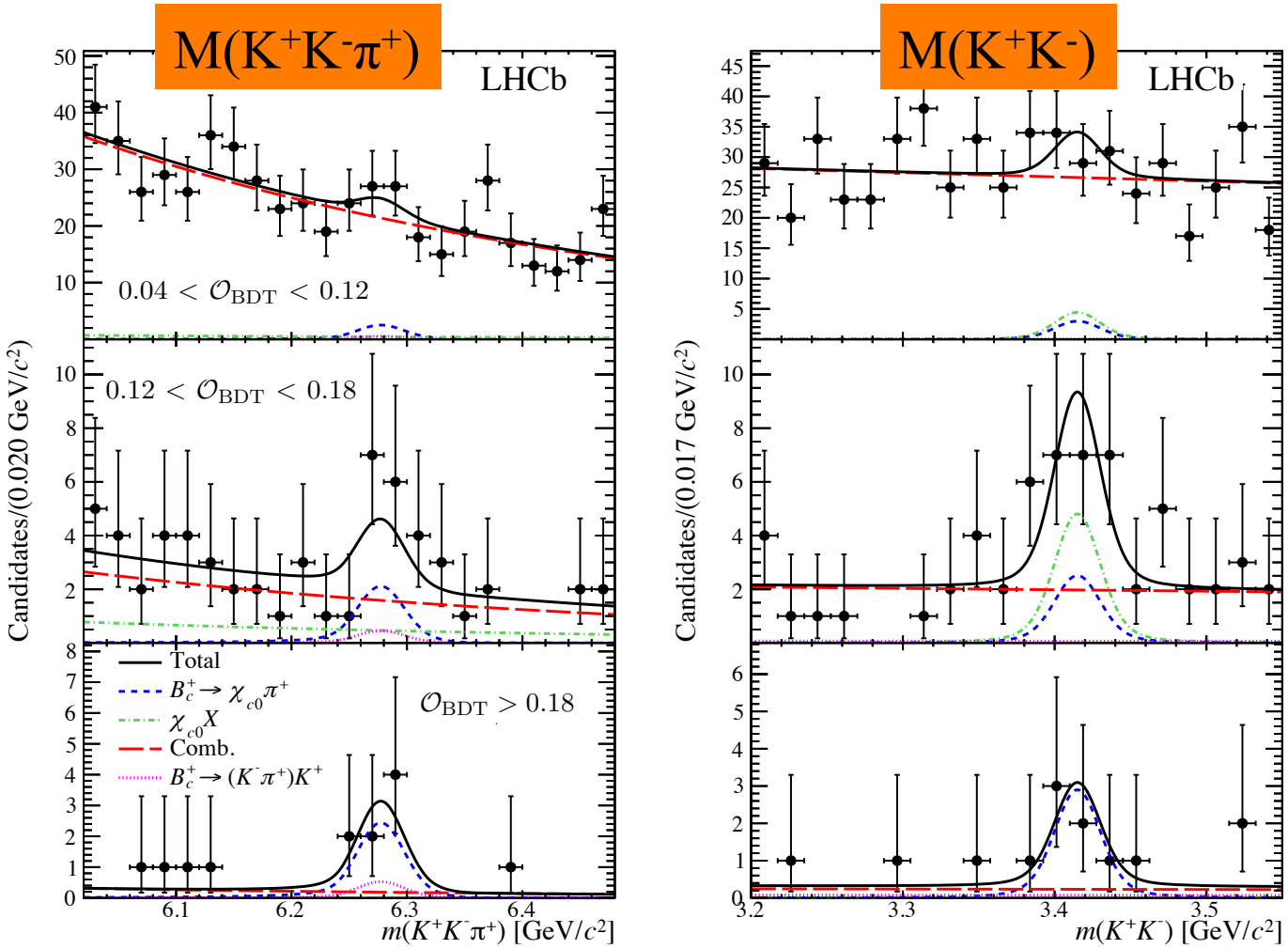
To enhance sensitivity analysis is done in 3 bins of output of BDT trained to discriminate signal

$$N_c = 20.8^{+11.4}_{-9.9}$$

2.4 σ significance

$B_c^+ \rightarrow K^+K^-\pi^+$

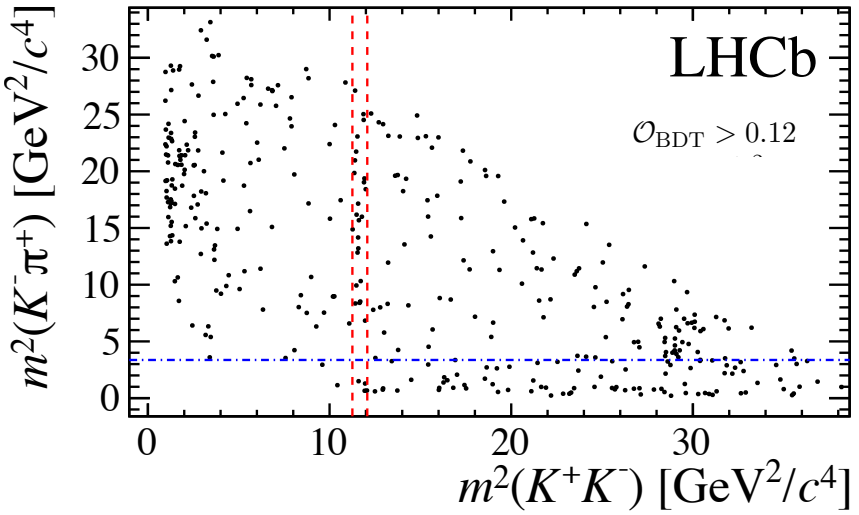
Purity

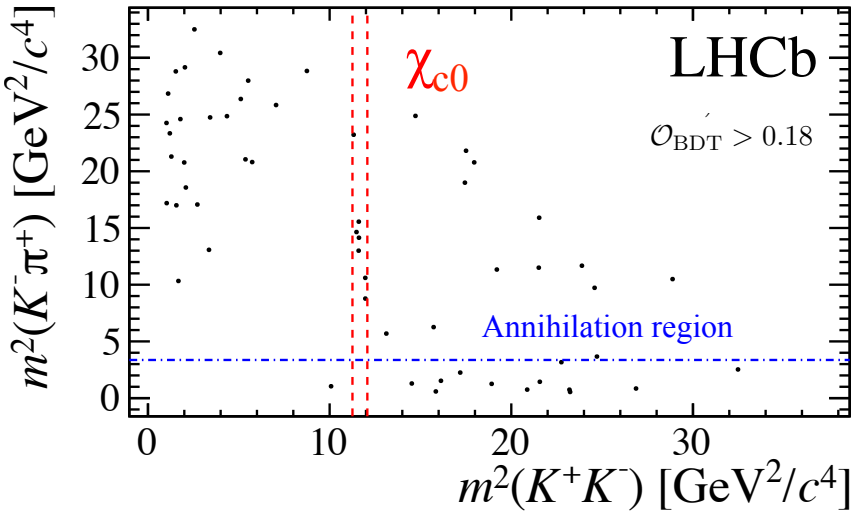


Charmonium region

4.5 evidence for $B_c^+ \rightarrow \chi_{c0}\,\pi^+$

$B_c^+ \rightarrow K^+K^-\pi^+$





Systematics

Source	$R_{\mathrm{an},KK\pi}$	$R_{\chi_{c0}\pi}$
Normalisation yield	1.3	1.3
Event distribution	1.6	–
Fit model	2.4	2.3
BDT shape	5.0	2.9
PID	1.0	1.0
Simulation	0.8	0.8
Detector acceptance	0.4	0.3
B_c^+ lifetime	2.0	2.0
Hardware trigger	1.5	1.4
Fiducial cut	0.1	0.1
Branching fractions	3.6	6.2
Total	7.5	7.8

$$\frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to \chi_{c0}\pi^+)$$

$$(9.8^{+3.4}_{-3.0}(\mathrm{stat}) \pm 0.8(\mathrm{syst})) \times 10^{-6}$$

$$R_{\mathrm{an},KK\pi} < 15(17) \times 10^{-8}$$

(Expected to be at $10^{-9} - 10^{-8}$ level)

$$R_{B_s^0\pi} \equiv \frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to B_s^0\pi^+) < 4.5(5.4) \times 10^{-3}$$

$$R_{D^0K} \equiv \frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to D^0K^+) < 1.3(1.6) \times 10^{-6}$$

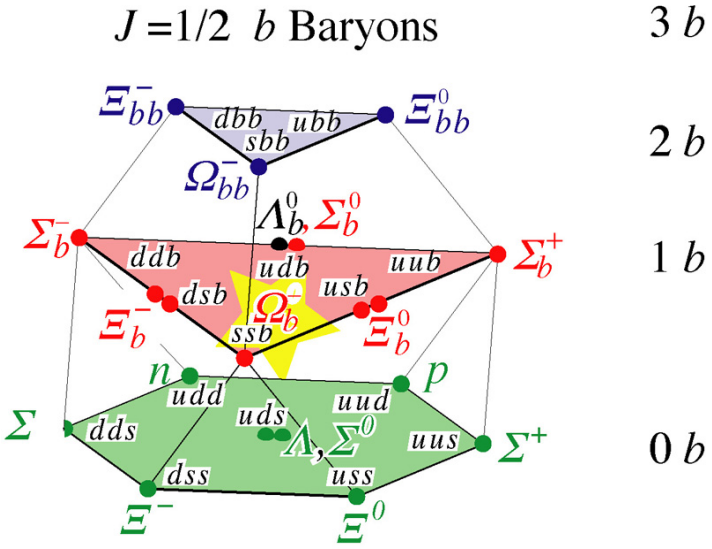
b-baryons

Until LHC startup very poorly explored

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

Excited Λ_b states seen by LHCb PRL. 109:172003 (2012)

Excited Ξ_b states also seen by LHCb (JHEP 05 (2016) 161), PRL 114 (2015), 062004. Neutral state seen by CMS.



Measurements of properties probe QCD

- Mass measurements probe the quark model
- Lifetime measurements test of HQET prediction $\tau_{\Omega_b^-} \simeq \tau_{\Xi_b^-} > \tau_{\Xi_b^0} \approx \tau_{\Lambda_b^0}$

$\Lambda_b \rightarrow \psi(2S)pK^-$

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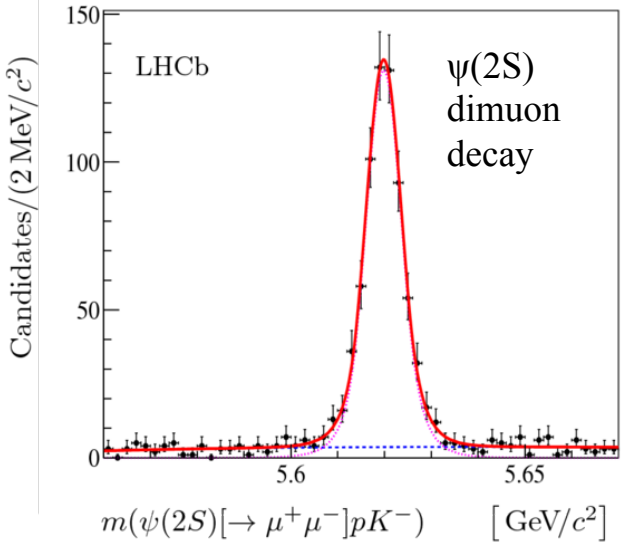
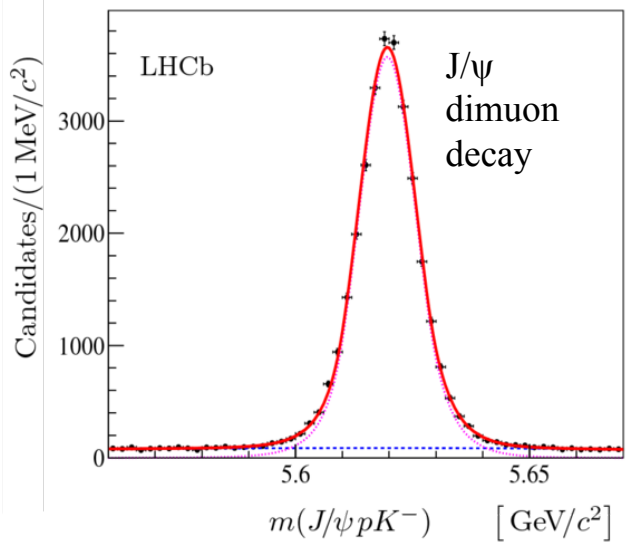
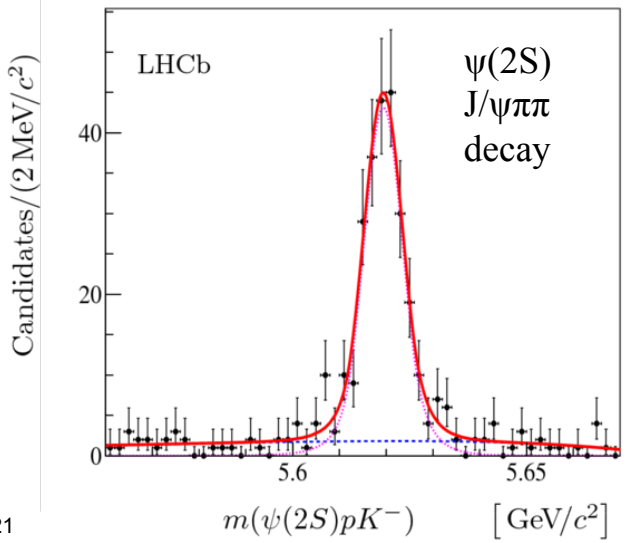
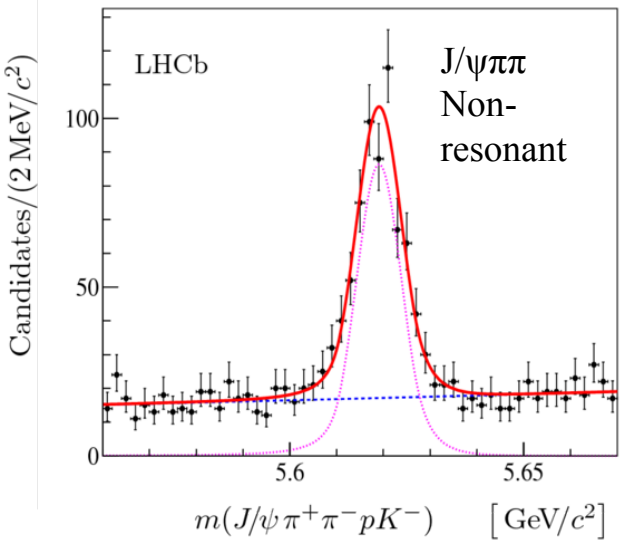




First observation of these modes using Run 1 dataset

Channel	$N(\Lambda_b^0)$
$\Lambda_b^0 \to J/\psi pK^-$	$28\,834 \pm 204$
$\Lambda_b^0 \to \psi(2S)[\to \mu^+\mu^-]pK^-$	665 ± 28
$\Lambda_b^0 \to \psi(2S)[\to J/\psi\pi^+\pi^-]pK^-$	231 ± 17
$\Lambda_b^0 \to J/\psi\pi^+\pi^- pK^-$	793 ± 36





$\Lambda_b \rightarrow J/\psi\pi^+\pi^-pK^-$

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Combination of ψ(2S) modes gives

$$R^{\psi(2S)} = \frac{\mathcal{B}(\Lambda_b^0 \to \psi(2S)pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, pK^-)} = (20.70 \pm 0.76 \pm 0.46 \pm 0.37) \times 10^{-2}$$

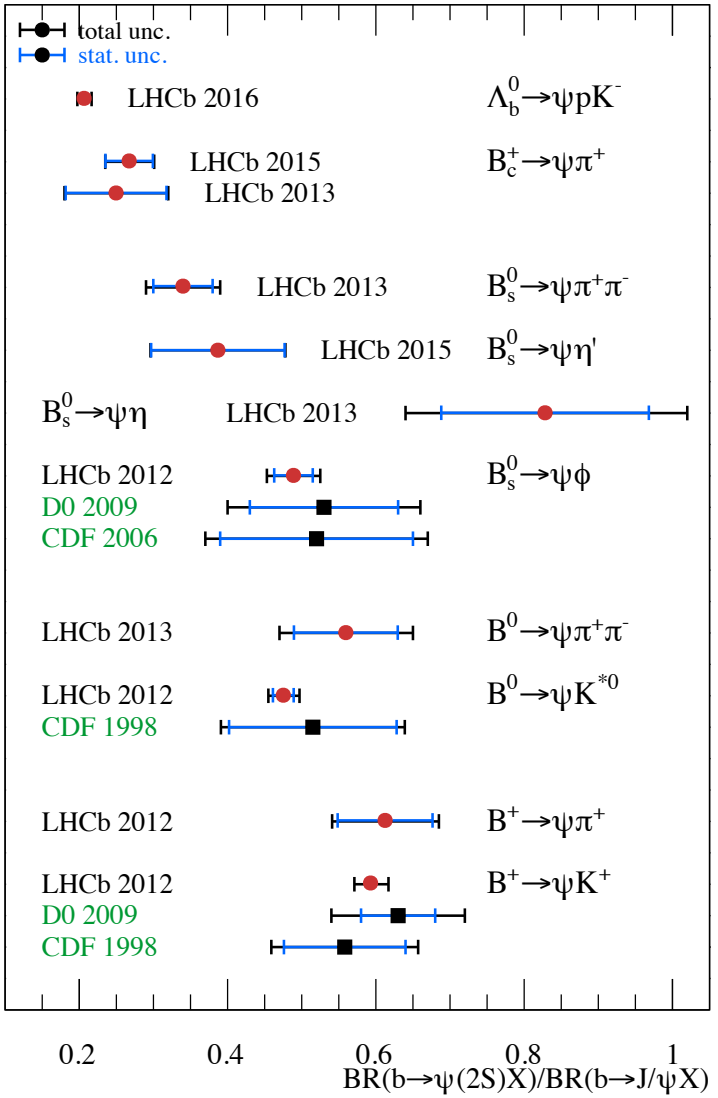
Excluding intermediate resonances

$$R^{J/\psi\pi^+\pi^-} = \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\,\pi^+\pi^- pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, pK^-)} = (20.86 \pm 0.96 \pm 1.34) \times 10^{-2}$$

Also determine

$$\frac{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}{\mathcal{B}(\psi(2S) \to J/\psi\,\pi^+\pi^-)} = (2.30 \pm 0.20 \pm 0.12 \pm 0.01) \times 10^{-2}$$

Most precise direct determination of this ratio



$\Lambda_b \rightarrow J/\psi\pi^+\pi^-pK^-$

Low Q-value of these decays allows for precision measurement of Λ_b mass

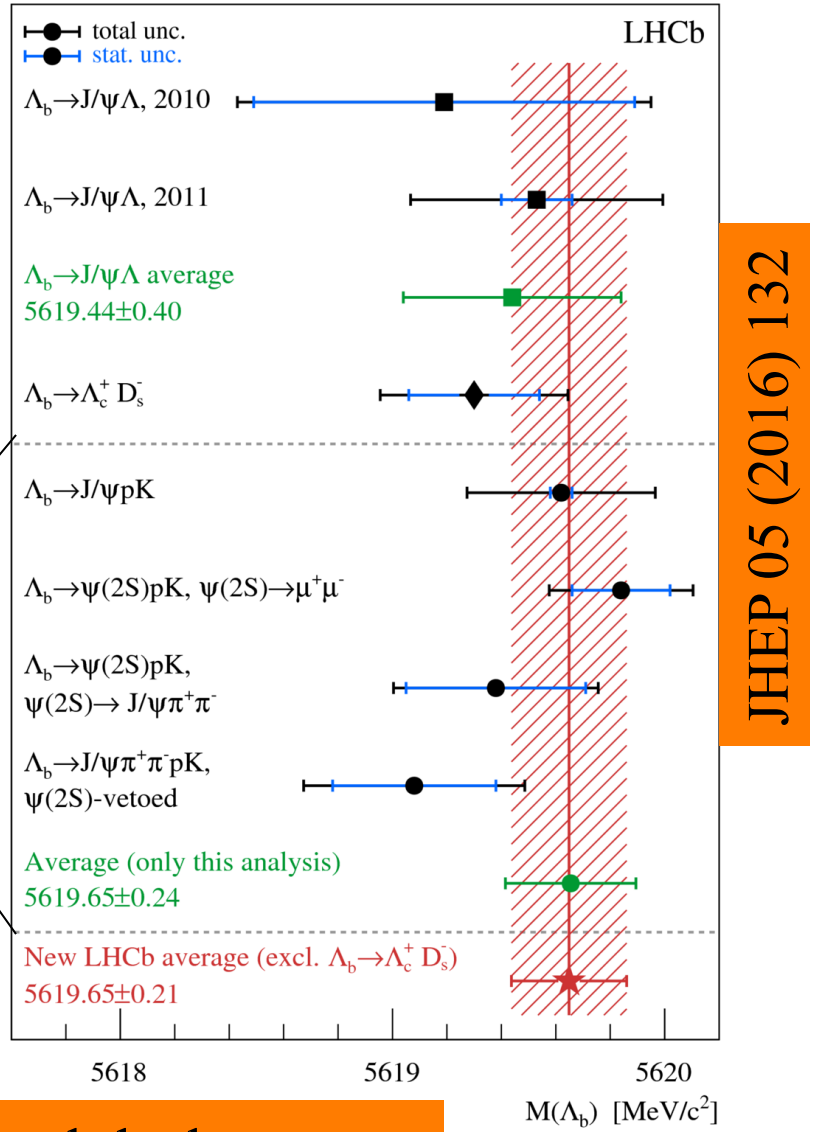
Complement with measurement using normalization mode (large dataset but higher statistics)

This gives:

$$M(\Lambda_b^0) = 5619.65 \pm 0.17 \pm 0.17\,\text{MeV}/c^2$$

LHCb combination

$$M(\Lambda_b^0) = 5619.65 \pm 0.16 \pm 0.14\,\text{MeV}/c^2$$



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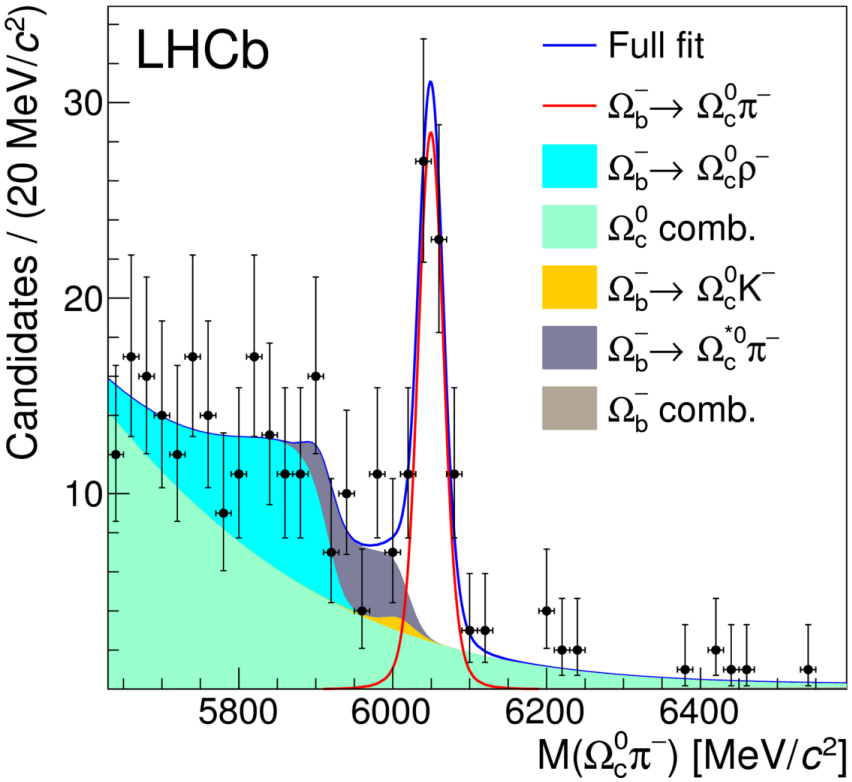
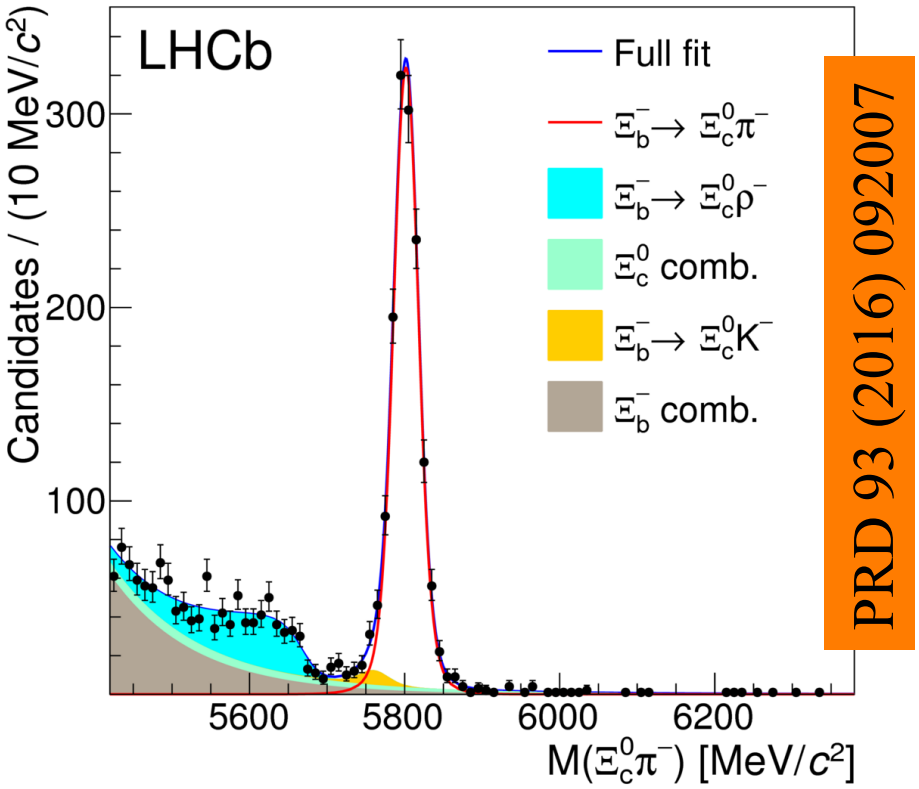
Most precise direct measurement of any b-hadron mass

Ω^-_b mass and lifetime

63 +/- 9 Ω^-_b ➔ $\Omega_c{}^0\pi^-$ candidates observed in Run 1 data





Make relative measurement of lifetime/mass difference using the mode $\Xi_b{}^-$ ➔ $\Xi_c{}^0\pi^-$ as normalization

Ω_b^- mass and lifetime

Systematic uncertainties on acceptance cancel in ratio between signal and normalization

$$m_{\Omega_b^-} - m_{\Xi_b^-} = 247.3 \pm 3.2 \pm 0.5\,\mathrm{MeV}/c^2,$$
$$m_{\Omega_b^-} = 6045.1 \pm 3.2 \pm 0.5 \pm 0.6\,\mathrm{MeV}/c^2$$

Consistent with previous LHCb/CDF measurements
Inconsistent with D0 result

$$\frac{\tau_{\Omega_b^-}}{\tau_{\Xi_b^-}} = 1.11 \pm 0.16 \pm 0.03,$$
$$\tau_{\Omega_b^-} = 1.78 \pm 0.26 \pm 0.05 \pm 0.06\ \mathrm{ps}$$

Consistent with previous measurements
More data will allow precision probe of HQET

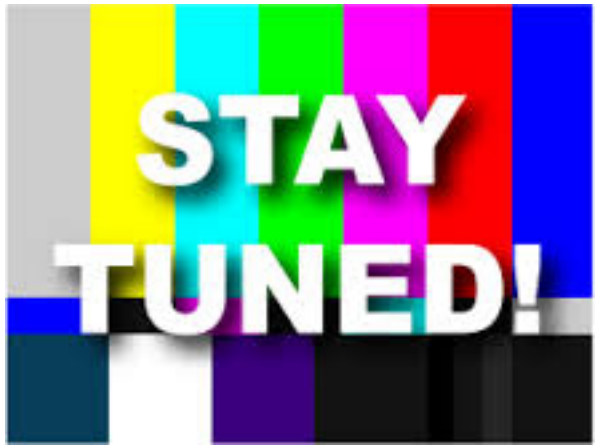
Summary + Outlook

LHCb has made wide range of measurements of quarkonia and b-hadrons

- Comprehensive set of results related to quarkonia production
- Detailed studies of B_c^+ meson and b-baryons

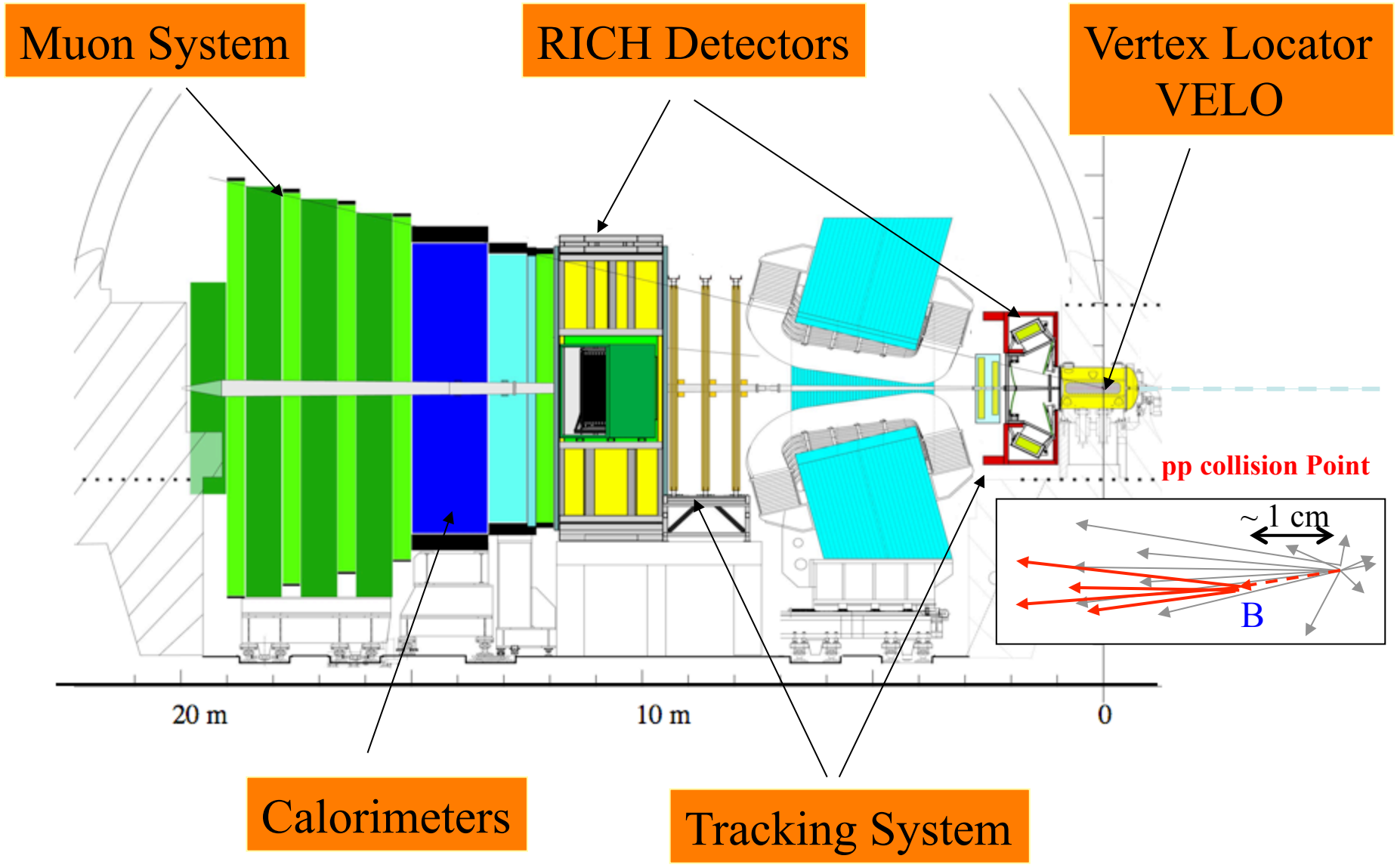
A lot more to come exploiting Run 1 and large Run 2 dataset being collected now:

- Complete quarkonia program
- Further studies of b-baryon properties
- More B_c^+ decay modes



Backup

The LHCb Detector



J/ψ selection

Trigger selection

L0: trigger on muon with high pt

HLT1: two muon candidates with high invariant mass and momenta

HLT2: Turbo stream. Mass 300 MeV window around J/ψ candidate from HLT1

Offline

Muon identification and track quality requirements

Λ_b mass