Bottom production, spectroscopy, lifetime

Jibo HE
on behalf of the LHCb collaboration,
including results from the ALICE, ATLAS, CMS and CDF collaborations

CERN

Physics in Collision 2013 @ IHEP (Beijing), 06/09/2013

Outline

- Includes new results made public since PIC2012, please refer to S. Argiro's talk [link] on PIC2012 for old results
- Bottom production
  - Inclusive measurements, using electron, charmonium
  - Exclusive measurements, b meson, Λ_b^0, B_c^+
- Bottom spectroscopy
  - B^{**}, B_s^{**}, b-baryon and B_c^+ masses
- Bottom lifetime
  - B_s^0, Λ_b^0 and B_c^+ lifetimes
- My apologies in case I miss your favorite results

Bottom production

Bottom production

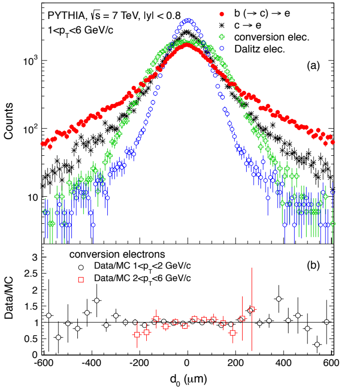
- Measurements of heavy flavor production provides important tests of QCD
  - Parton distribution function
  - Hard parton scattering
  - Fragmentation
- Production cross-section at new energies also required to guide relevant studies, e.g., search for new physics
- Measurements of heavy flavor production in *pp* collisions provide mandatory baseline for nucleus-nucleus collisions

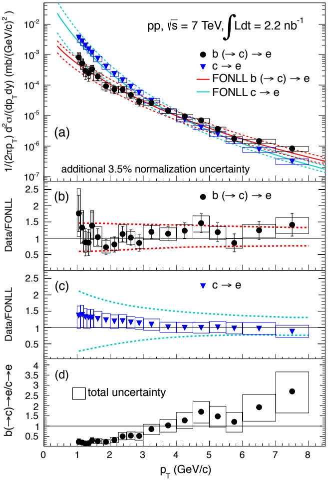
Bottom production using electron

[ALICE, PLB 721 (2013) 13]

- Different sources of electrons separated using impact parameter
- Bottom and charm differential cross-section described well by FONLL prediction

[M. Cacciari et al., JHEP 10 (2012) 137]

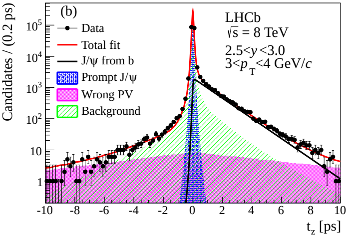


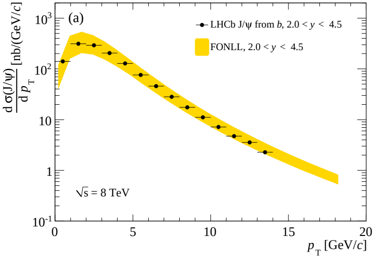


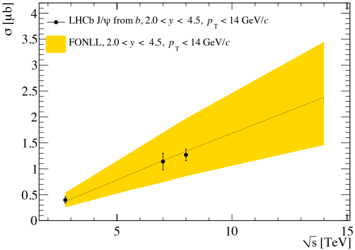
Bottom production using J/ψ

[LHCb, EPJC 71 (011) 1645] [LHCb, JHEP 02 (2013) 041] [LHCb, JHEP 06 (2013) 064]

- LHCb measured bottom production using $b \to J/\psi X$ at $\sqrt{s} = 2.76$ and 8 TeV, apart from that at 7 TeV
- $b \to J/\psi X$ separated from prompt J/ψ using $t_z = \frac{(z_{J/\psi} - z_{\text{PV}}) \times M_{J/\psi}}{p_z}$
- Good agreements with FONLL



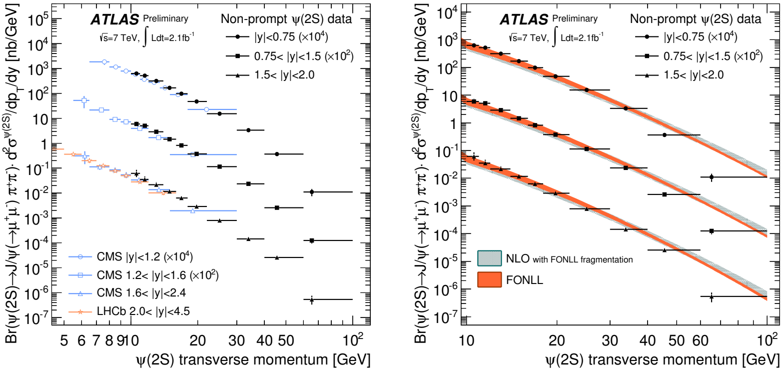




Bottom production using $\psi(2S)$

[ATLAS-CONF-2013-094] [CMS, JHEP 02 (2012) 011] [LHCb, EPJC 72 (2012) 2100]

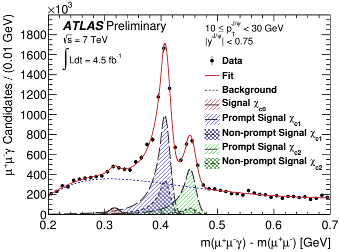
- ATLAS measured bottom production using $b \to \psi(2S)X$ with $\psi(2S) \to J/\psi(\mu\mu)\pi^+\pi^-$, overlaid with CMS and LHCb results (note: different rapidity ranges)
- Compared to NLO and FONLL, some discrepancy for high p_{T}?

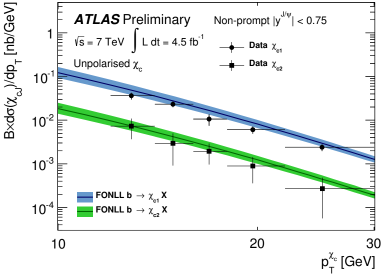


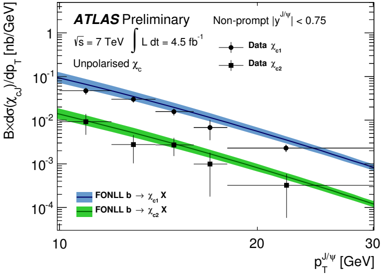
Bottom production using χ_c

[ATLAS, ATLAS-CONF-2013-095]

- ATLAS measured bottom production using $b \to \chi_c X$ with $\chi_c \to J/\psi(\mu\mu)\gamma(e^+e^-)$



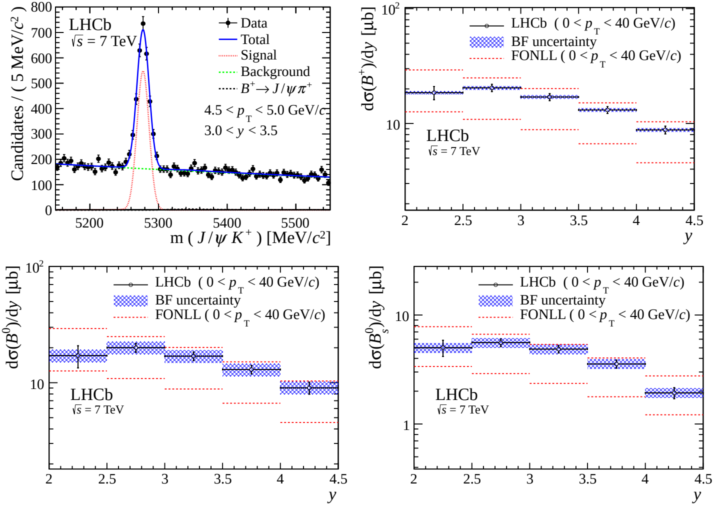




b meson production

[LHCb, JHEP 08 (2013) 117]

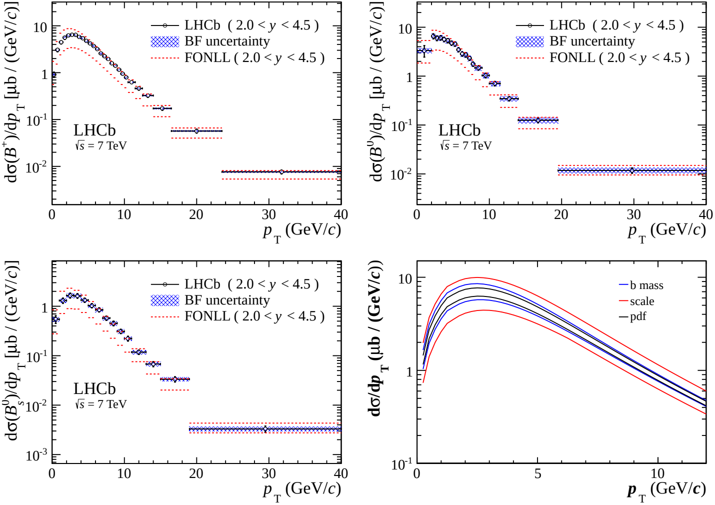
- LHCb measured $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, and $B_s^0 \to J/\psi \phi$ production for $2 < y(B) < 4.5$, in agreement with FONLL



b meson production (cont.)

[LHCb, JHEP 08 (2013) 117]

- $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}$, good agreement with FONLL
- Theo. uncertainty includes m_b, $\mu_{\mathrm{R}}, \mu_{\mathrm{F}}$ and PDF

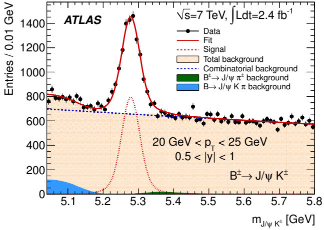


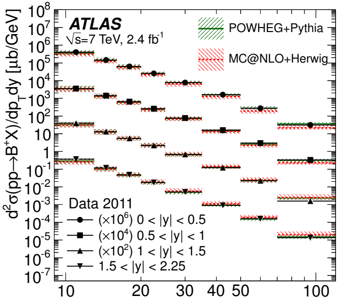
B^+ production by ATLAS

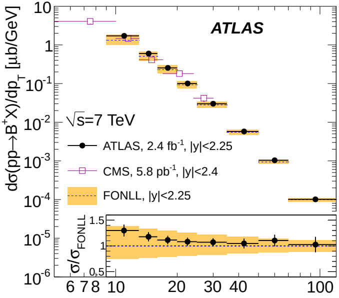
[ATLAS, arXiv:1307.0126] [CMS PRL 106 (2011) 112001]

- ATLAS measured $B^+ \to J/\psi K^+$ in the central region
- Compared to CMS results, FONLL, POWHEG, and MC@NLO

[M. Cacciari et al., JHEP 10 (2012) 137]



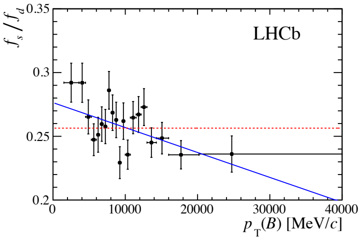


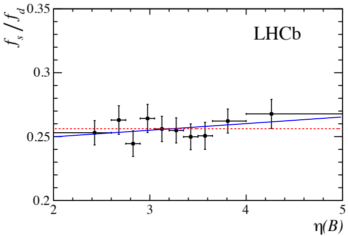


f_s/f_d

[LHCb, JHEP 04 (2013) 001]

- f_s/f_d needed for normalization of $B_s^0 \to \mu^+\mu^-$
- LHCb updated measurement of f_s/f_d with $B_s^0 \to D_s^-\pi^+$ and $B^0 \to D^-K^+$ using 2011 data (1 fb^{-1})
- Evidence (3σ) of dependence on $p_{\mathrm{T}}(B_s^0)$, while no indication of dependence on $\eta(B_s^0)$

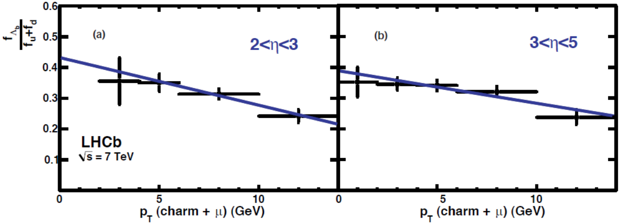


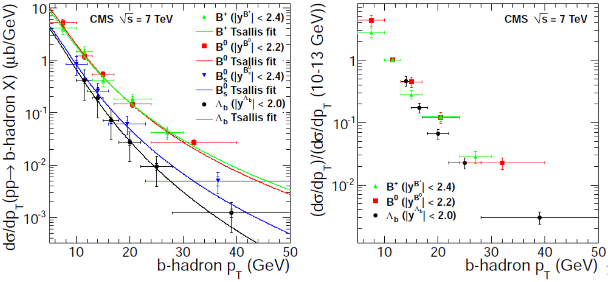


Λ_b^0 production

[CMS, PLB 714 (2012) 136] [LHCb, PRD 85 (2012) 032008]

- Measured with semileptonic decay modes (LHCb), and exclusive decay modes (CMS), $f_{\Lambda_b}/(f_u + f_d)$ has significant p_T dependence

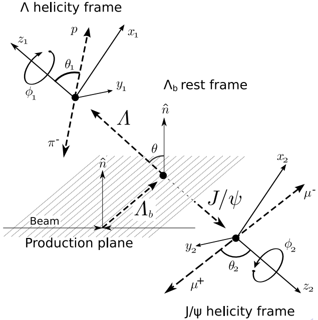




Λ_b^0 production polarization

[LHCb, PLB 724 (2013) 27] [ATLAS, ATLAS-CONF-2013-071]

- Λ_b^0 longitudinal polarization vanishes ($\mathcal{P}$-conservation of QCD) while transverse polarization could be as large as 20%
- Angular analysis of $\Lambda_b^0 \to J/\psi(\mu\mu)\Lambda(p\pi)$ allows to measure
  - Polarization and decay helicity amplitudes $\mathcal{M}_{J/\psi,\Lambda}$ ($\mathcal{M}_{+1/2,0}$, $\mathcal{M}_{-1/2,0}$, $\mathcal{M}_{-1/2,-1}$, $\mathcal{M}_{+1/2,+1}$)
  - Parity-violating asymmetry parameter $\alpha_b = |\mathcal{M}_{+1/2,0}|^2 - |\mathcal{M}_{-1/2,0}|^2 + |\mathcal{M}_{-1/2,-1}|^2 - |\mathcal{M}_{+1/2,+1}|^2$



Λ_b^0 production polarization (cont.)

[LHCb, PLB 724 (2013) 27] [ATLAS, ATLAS-CONF-2013-071]

- Results of LHCb and ATLAS

Variable	LHCb	ATLAS
α_b	$0.05 \pm 0.17 \pm 0.07$	$0.28 \pm 0.16 \pm 0.06$
$\mathcal{M}_{+1/2,0}$	$0.01 \pm 0.04 \pm 0.03$	$0.17^{+0.12}_{-0.17} \pm 0.06$
$\mathcal{M}_{-1/2,0}$	$0.57 \pm 0.06 \pm 0.03$	$0.59^{+0.06}_{-0.07} \pm 0.04$
$\mathcal{M}_{-1/2,-1}$	$0.51 \pm 0.05 \pm 0.02$	$0.79^{+0.04}_{-0.05} \pm 0.02$
$\mathcal{M}_{+1/2,+1}$	$-0.10 \pm 0.04 \pm 0.03$	$0.08^{+0.13}_{-0.08} \pm 0.05$

- J/ψ and Λ from Λ_b^0 decay are highly polarized
- Parity-violating asymmetry parameter α_b in agreement with most predictions, but not with the HQET prediction

Method	Value	Reference
Factorization	-0.1	Cheng, PRD 56 (1997) 2799
Factorization	-0.18	Fayyazuddin and Riazuddin, PRD 58 (1998) 014016
Covariant oscillator quark model	-0.21	Mohanta et al., Prog.Theor.Phys 101 (1999) 959
Perturbative QCD	-0.17 to -0.14	Chou, Shih, Lee, PRD 65 (2002) 074030
Factorization (HQET)	0.78	Ajaltouni, Conte, Leitner, PLB 614 (2005) 165
Light front quark model	-0.20	Wei, Ke, Li, PRD 80 (2009) 094016

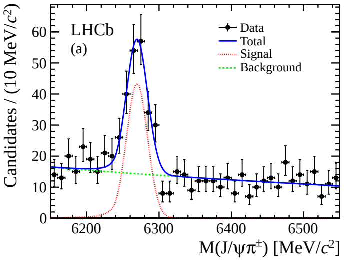
B_c^+ production

[LHCb, PRL 109 (2012) 232001]

- B_c^+, two different heavy flavor quarks, production more difficult than other b mesons
- Production cross-section at 7 TeV measured with $B_c^+ \to J/\psi\pi^+$ using 0.37 fb^{-1} of data

$$R_{c/u} = \frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+) \times \mathcal{B}(B^+ \to J/\psi K^+)}$$
$$= (0.68 \pm 0.10 \pm 0.03 \pm 0.05(\tau_{B_c^+}))\%$$

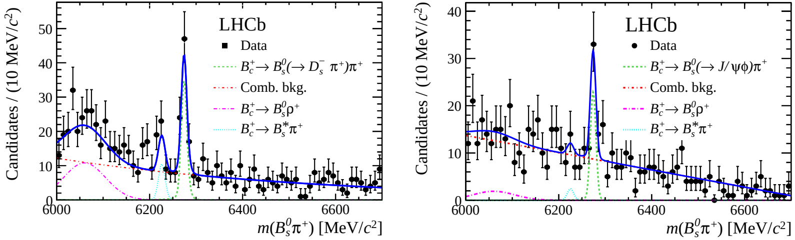
for $p_{\mathrm{T}}(B) > 4$ GeV/c and $2.5 < \eta(B) < 4.5$



B_c^+ production (cont.)

[LHCb, arXiv:1308.4544]

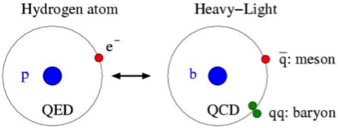
- LHCb measured $\frac{f_c}{f_s} \cdot \mathcal{B}(B_c^+ \to B_s^0 \pi^+)$ using 2011 + 2012 data, for $2 < \eta(B) < 5$.
- Measured with $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to J/\psi\phi$ independently, results consistent with each other
- Combined results
  $\frac{f_c}{f_s} \cdot \mathcal{B}(B_c^+ \to B_s^0 \pi^+) = \left(2.37 \pm 0.31 \pm 0.11 \,^{+0.17}_{-0.12}\,(\tau_{B_c^+})\right) \times 10^{-3}$



- First observation of $B_c^+ \to B_s^0 \pi^+$

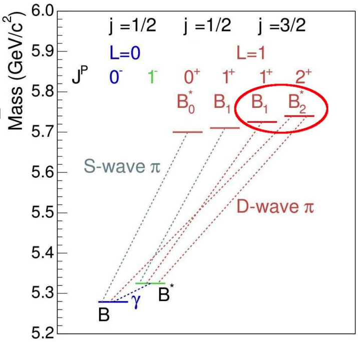
Bottom spectroscopy

- *B* mesons are heavy-light system of QCD



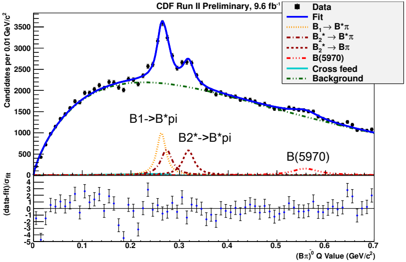
- States characterized by three quantum numbers

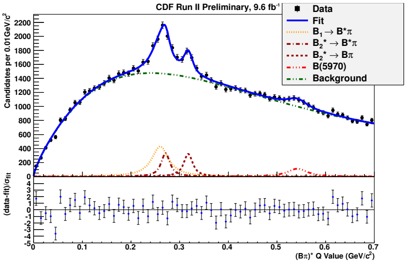
$\vec{L}$	Orbital angular momentum
$\vec{j} = \vec{L} + \vec{s}_{u,d,s}$	Light quark angular momentum
$\vec{J} = \vec{j} + \vec{s}_b$	Total angular momentum

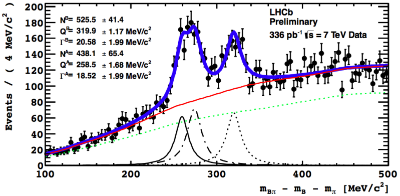


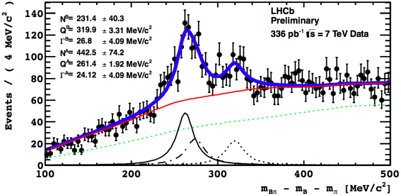
[CDF, EPS2013] [LHCb, LHCb-CONF-2011-053]

- Searched with $B^+\pi^-$ (left), $B^0\pi^+$ (right)
- Evidence of $B(5970)$? More investigations ongoing



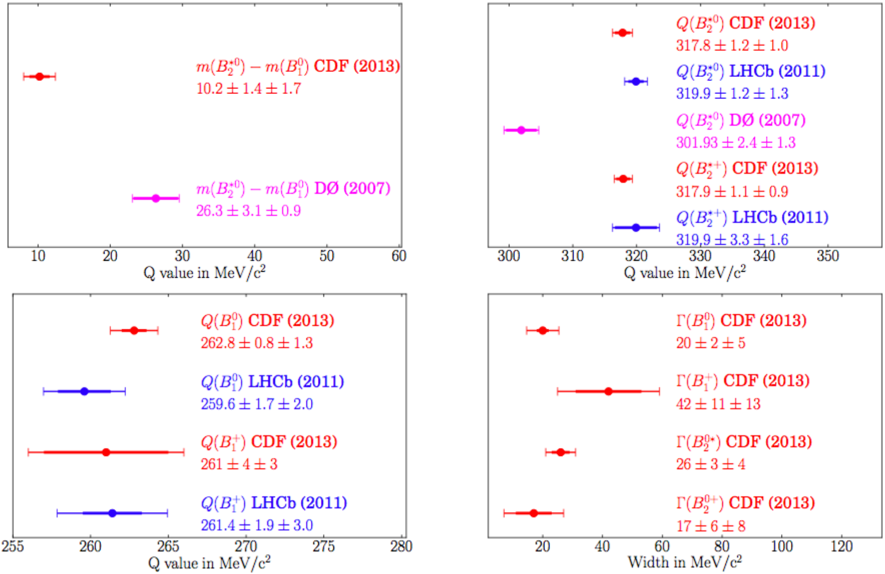






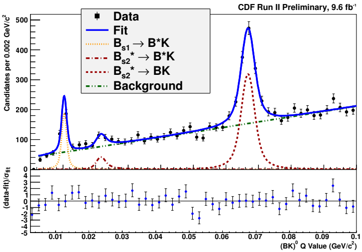
B^{**}, comparison

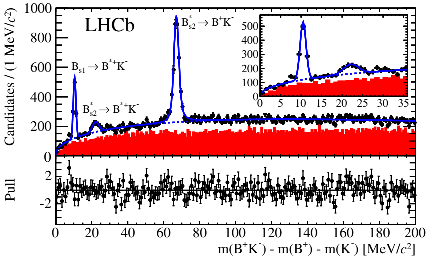
[M. Kambeitz, EPS2013]



[CDF, EPS 2013] [LHCb, PRL 110 (2013) 151803]

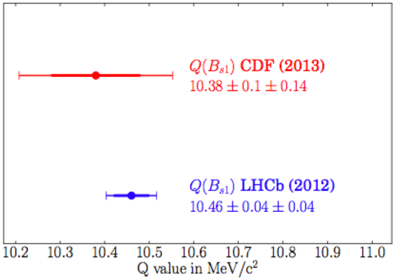
- Searched with B^+K^-

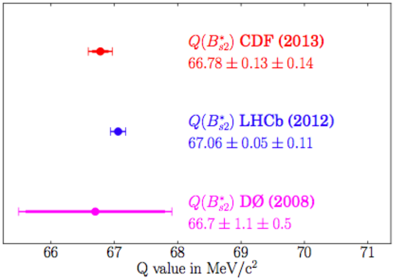


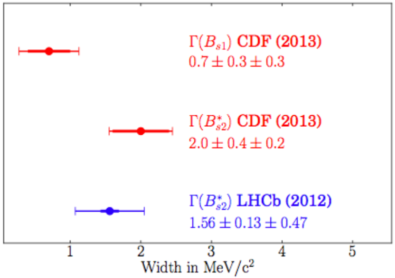


B_s^{**}, comparison

[M. Kambeitz, EPS2013]



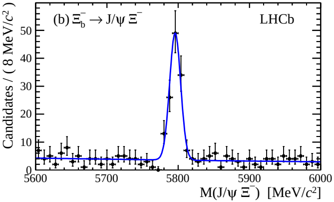


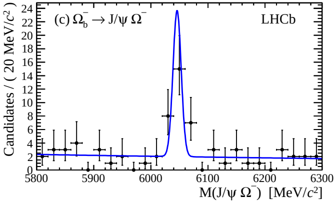


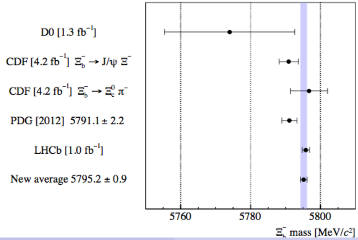
Ξ_b^-, Ω_b^-

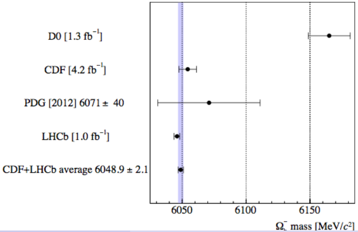
[LHCb, PRL 110 (2013) 182001] [CDF, PRD 80 (2009) 072003] [D0, PRL 101 (2008) 232002]

- Big discrepancy between CDF and D0 for Ω_b mass
  - CDF: $6054.4 \pm 6.8 \pm 0.9$ MeV D0: $6165 \pm 10 \pm 13$ MeV
  - Theo: 6052.1 ± 5.6 MeV [M. Karlinera et al., Annals Phys.324 (2009) 2]
- LHCb measured with 1 fb^{-1} of data, in agreement with CDF result





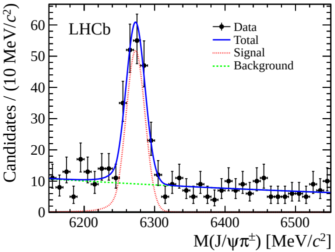


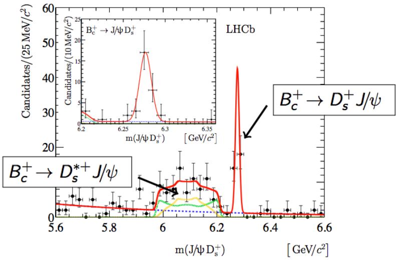


B_c^+ mass

[LHCb, PRL 109 (2012) 232001] [LHCb, PRD 87 (2013) 112012]

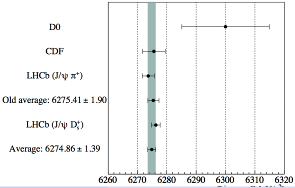
- LHCb measured B_c^+ mass with $B_c^+ \to J/\psi\pi^+$ ($0.37\ \text{fb}^{-1}$)
  - $M(B_c^+) = 6273.7 \pm 1.3\,(\text{stat}) \pm 1.6\,(\text{syst})$ MeV
- With $B_c^+ \to J/\psi D_s^+$ ($3\ \text{fb}^{-1}$)
  - $M(B_c^+) = 6276.28 \pm 1.44(\text{stat}) \pm 0.36(\text{syst})$ MeV





- Consistent with lattice QCD: $M(B_c^+) = 6278(4)(8)$ MeV

[HPQCD, PRD 86 (2012) 094510]



Bottom lifetime

Bottom lifetime

- Decay of *b*-hadrons dominated by the weak decay of *b*-quark
- $\tau(B^0) \sim \tau(B^+) \sim \tau(B_s^0) \sim \tau(\Lambda_b^0)$, when ignoring contribution of lighter quarks
- Heavy Quark Expansion (HQE), decay rate of H_b

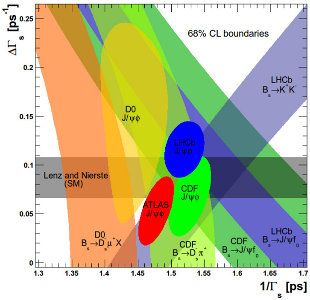
$$\Gamma_{H_b \to f} = |CKM|^2 \sum_n c_n^{(f)} \left(\frac{\Lambda_{\text{QCD}}}{m_b} \right)^n \langle H_b | O_n | H_b \rangle$$

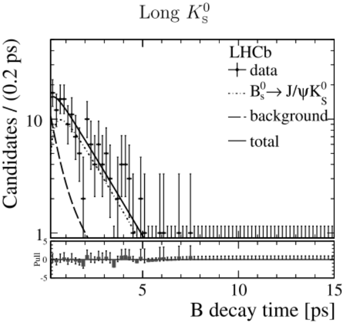
  - $c_n^{(f)}$, coefficients of OPE, can be calculated perturbatively
  - All non-perturbative physics shifted into $\langle H_b | O_n | H_b \rangle$, can be calculated using lattice QCD, or QCD sum rules, or related to other observables via HQE

B_s^0 lifetime

[ATLAS, JHEP 12 (2012) 072] [LHCb, NPB 873 (2013) 275]

- Due to B_s^0 mixing, two mass eigenstates $m_{\mathrm{H}}, m_{\mathrm{L}}$, with different lifetimes $\tau_{\mathrm{H}} = 1/\Gamma_{\mathrm{H}}, \tau_{\mathrm{L}} = 1/\Gamma_{\mathrm{L}}$
- Effective lifetime $\tau_{B_s^0} = 1/\Gamma_s$, $\Gamma_s = (\Gamma_{\mathrm{H}} + \Gamma_{\mathrm{L}})/2$ is sensitive to $\Delta\Gamma_s$ and mixing induced $\mathcal{CP}$-violating phase ϕ_s for CP-eigenstates
- Apart from measuring $B_s^0 \to K^+K^-$, and $B_s^0 \to J/\psi f_0(980)$, LHCb also measured $B_s^0 \to J/\psi K_{\mathrm{S}}^0$ effective lifetime, $\tau^{\mathrm{eff}}_{J/\psi K_{\mathrm{S}}^0} = 1.75 \pm 0.12 \pm 0.05$ ps (ref: $\tau^{\mathrm{eff}}_{J/\psi K_{\mathrm{S}}^0}|_{\mathrm{SM}} = 1.639 \pm 0.022$ ps)

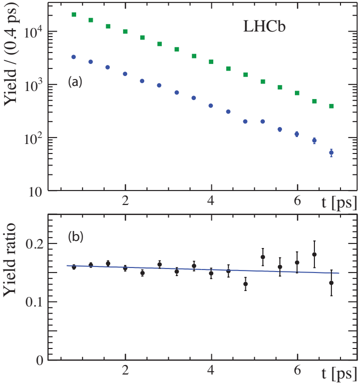


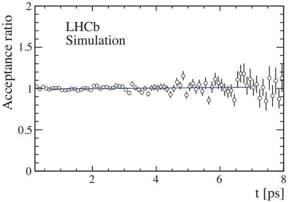


Λ_b^0 lifetime

[LHCb, PRL 111 (2013) 102003]

- Long-standing discrepancy between experiment and theory, eventually resolved with recent results from Tevatron and LHC
- Take LHCb measurement as example, $\tau(\Lambda_b^0)/\tau(B^0)$ measured using $\Lambda_b^0 \to J/\psi pK$, and $B^0 \to J/\psi K^*$, in 16 bins of decay time
- Verified on simulation that the ratio of acceptance is flat

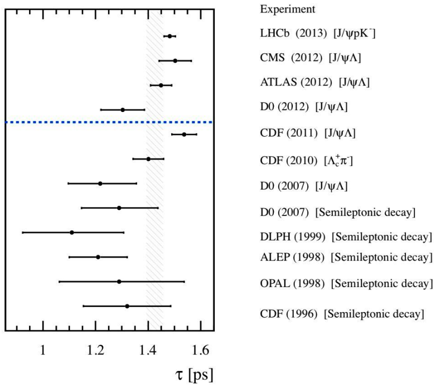




Λ_b^0 lifetime (cont.)

[LHCb, PRL 111 (2013) 102003]

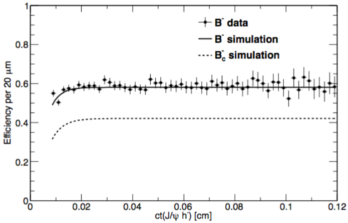
- LHCb measured
  - $\tau(\Lambda_b^0)/\tau(B^0) = 0.976 \pm 0.012 \pm 0.006$
  - $\tau(\Lambda_b^0) = 1.482 \pm 0.018 \pm 0.012$ ps

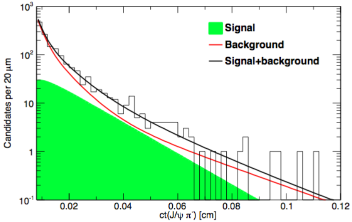


B_c^+ lifetime

[CDF, PRD 87 (2013) 011101 (R)]

- Both b, c quarks decay, or annihilate, $\tau(B_c^+) \sim \frac{1}{3}\tau(B^0)$
- B_c^+ lifetime was measured using semi-leptonic decays, before CDF did it with exclusive $B_c^+ \to J/\psi\pi^+$ (6.7 fb^{-1})
- Acceptance from MC, and verified on simulation





- $\tau(B_c^+) = 0.452 \pm 0.048 \pm 0.027$ ps, consistent with previous measurements

Summary

- Many new results on bottom production, spectroscopy, and lifetimes
- Experimental measurements agree with theoretical predictions well, while in some cases, the experimental precision is much better
- More accurate theoretical prediction needed, possible to reduce theo. uncertainties? E.g.
  - Uncertainty due to μ_{R} and μ_{F}
  - Branching fractions, ratio of BRs $\frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)}$
- Many new results will come soon, stay tuned