b production, both as hadron and jets

Jean Wicht (CERN)
On behalf of the LHCb collaboration
Including results from ATLAS, CMS and LHCb

FPCP 2013 (Búzios, Brazil)
Tuesday 21st May 2013

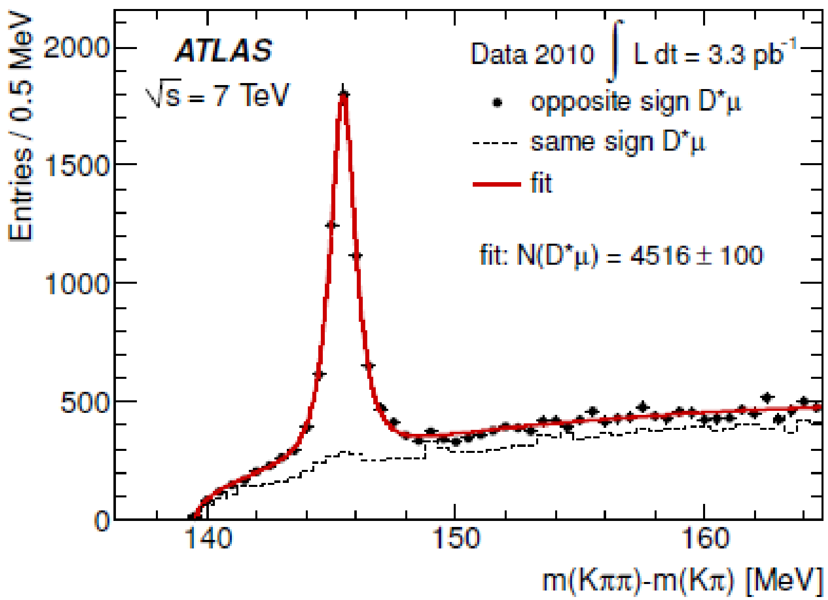
Outline

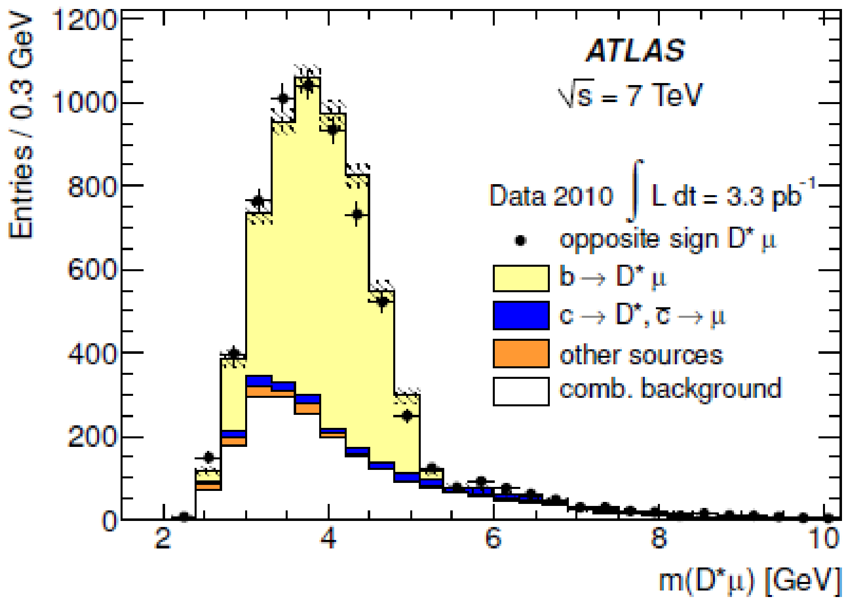
- **B hadrons**
  - **Cross-sections in pp collisions**
    - b-quark: concentrating on one recent result from ATLAS
    - B: concentrating on results on B^+ (ATLAS, CMS, LHCb)
    - b hadronization fractions (LHCb)
  - **Spectroscopy: concentrating on B baryons**
    - Two recent discoveries:
      - Excited Λ_b (LHCb)
      - Ξ_b (CMS)
    - Mass measurements
  - Λ_b production polarization (LHCb)
- **B jets**
  - Forward-central $b\bar{b}$ production asymmetry (LHCb)
  - Angular correlations between beauty jets (CMS)

b-hadron cross-section with D*μ (I)

ATLAS: 3 pb^{-1} @ 7 TeV
Nucl Phys B 864 (2012) 341

- Good test of QCD at high energy
  - ATLAS&CMS: b-quark production is often background for Higgs/SUSY searches
  - LHCb: how many B mesons will we get?
- Partial reconstruction of any b-hadron: **$D^*\mu$ with $D^*\rightarrow D^0\pi$ and $D^0\rightarrow K\pi$**



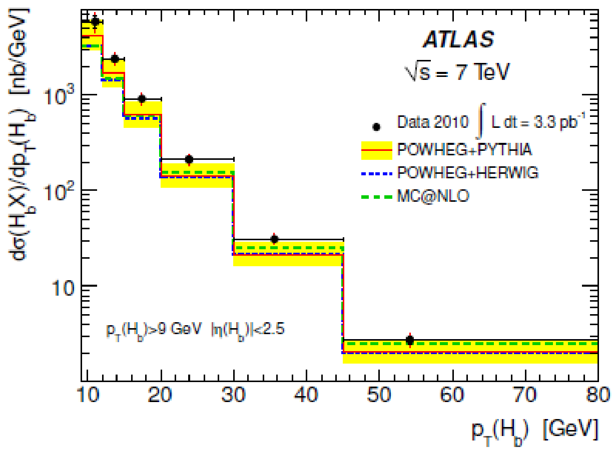


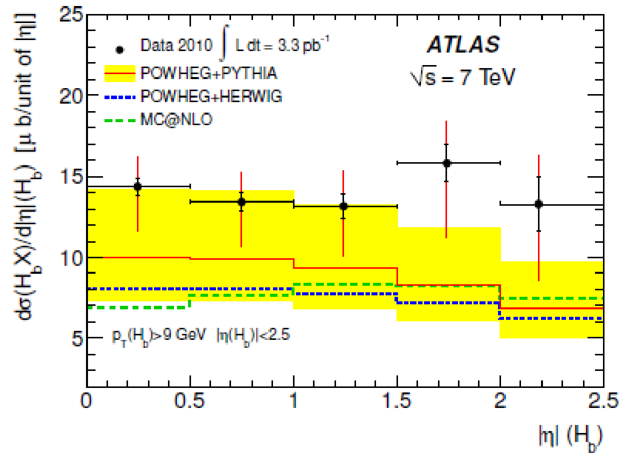
- Candidates first identified as opposite sign $D^*\mu$ excess in the D^* ΔM
  - Signal then extracted from $M(D^*\mu)$

b-hadron cross-section with $D^*\mu$ (II)

ATLAS: 3 pb^{-1} @ 7 TeV
Nucl Phys B 864 (2012) 341

- Cross-section measured in bins of p_T and η
- Unfolded distributions: correct p_T and η distributions to account for the not reconstructed particles kinematics, ie X from $pp \rightarrow H_b X$





- Decent overall agreement but hint of underestimation by NLO QCD predictions
- Extrapolated to full phase-space:

$$\mathrm{ATLAS}: \sigma(\mathrm{pp} \rightarrow \mathrm{H_b X})[\mu \mathrm{b}] = 360 \pm 9\ (\mathrm{stat}) \pm 34\ (\mathrm{syst}) \pm 25\ (\mathrm{BR}) \pm 12\ (\mathrm{lumi}) \pm 77\ (\mathrm{ext\&acc})$$

$$\mathrm{LHCb}: \sigma(\mathrm{pp} \rightarrow \mathrm{H_b X})[\mu \mathrm{b}] = 284 \pm 20\ (\mathrm{stat}) \pm 49\ (\mathrm{syst})$$

Good agreement with LHCb

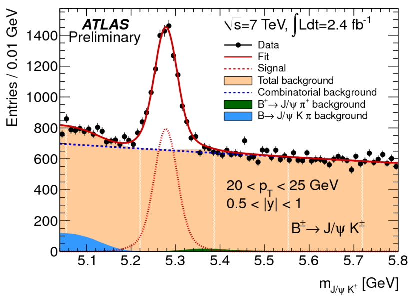
LHCb: 15 nb^{-1} @ 7 TeV
PLB 694 (2010) 209

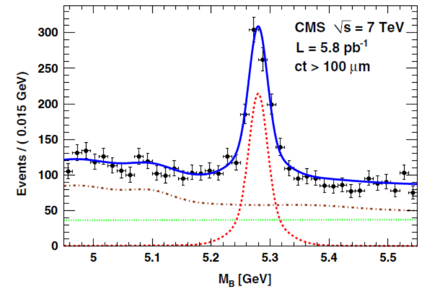
- CMS also measured b cross-section, but did not extrapolate

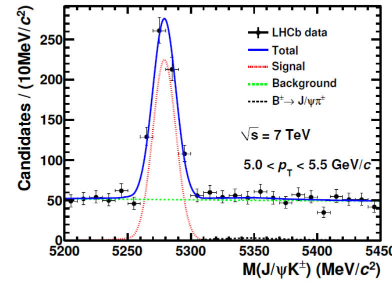
CMS: 28 pb^{-1} @ 7 TeV
JHEP 1206 (2012) 110

B-hadron production: B^+

Using $J/\psi(\mu\mu)K^+$



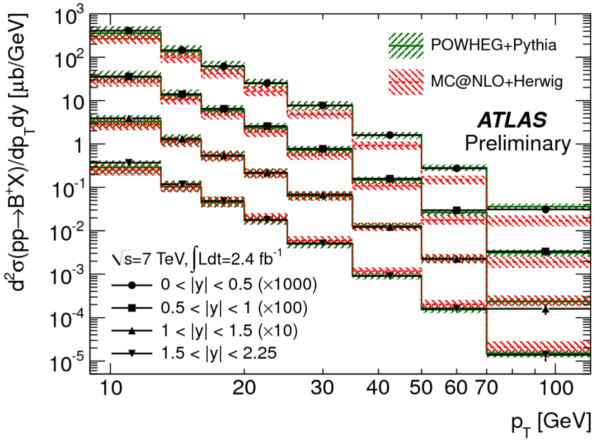


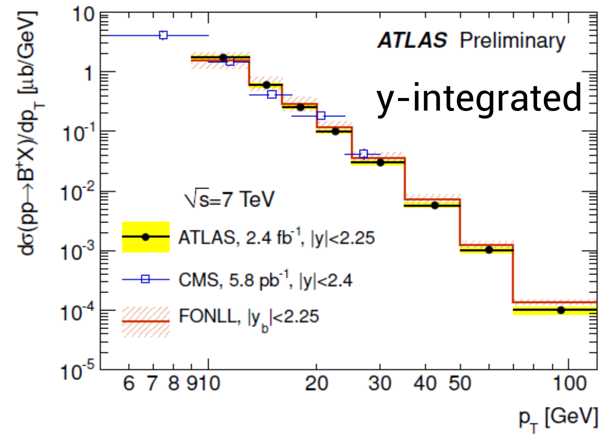


ATLAS: 2.4 fb^{-1} @ 7 TeV
ATLAS-CONF-2013-008

CMS: 5.8 pb^{-1} @ 7 TeV
PRL 106 (2011) 112001

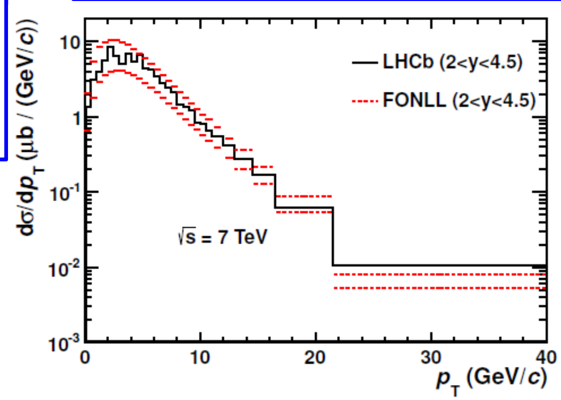
LHCb: 35 pb^{-1} @ 7 TeV
JHEP 1204 (2012) 093

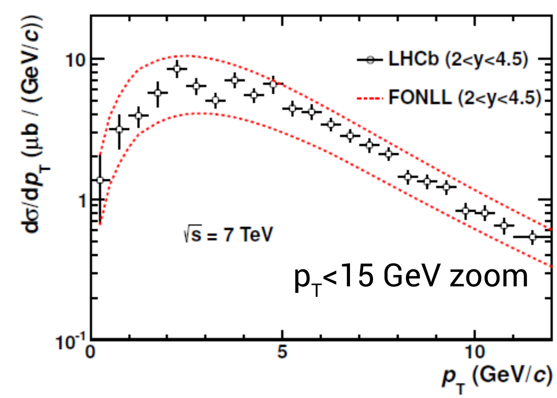




ATLAS data:
POWHEG+PYTHIA: good agreement
MC@NLO+HERWIG: predicts lower production cross-section and softer (harder) p_T spectrum at low (high) |y|

ATLAS (above): good agreement with FONLL and CMS
LHCb (below): also good agreement with FONLL





FONLL: Fixed Order + Next-to-Leading Log
http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html

B-hadron production: f_s/f_d (I)

LHCb: 1 fb^{-1} @ 7 TeV
arXiv:1301.5286

- LHCb wants to measure the f_q hadronization fractions
  to use the B^+/B^0 BF measured by the B-factories as calibration: eg $B_s \to \mu\mu$

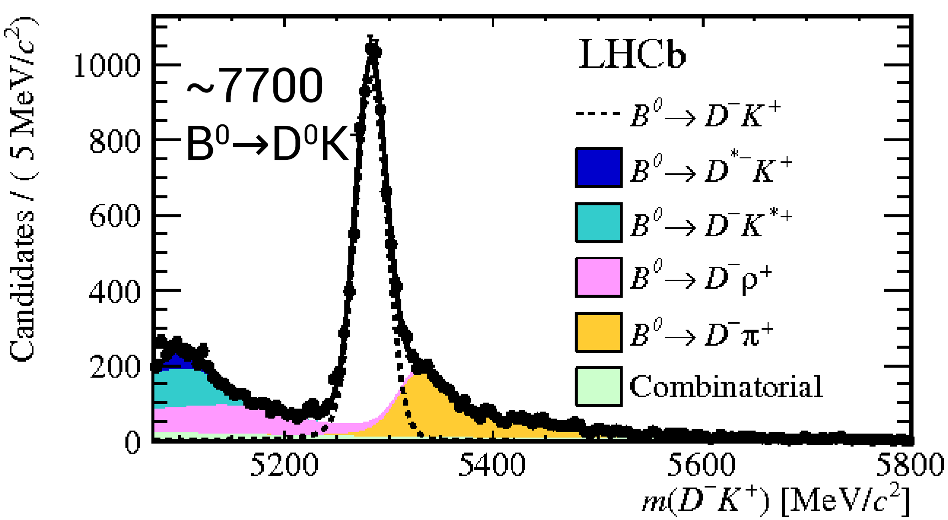
- f_s/f_d can be measured from the BF ratio:

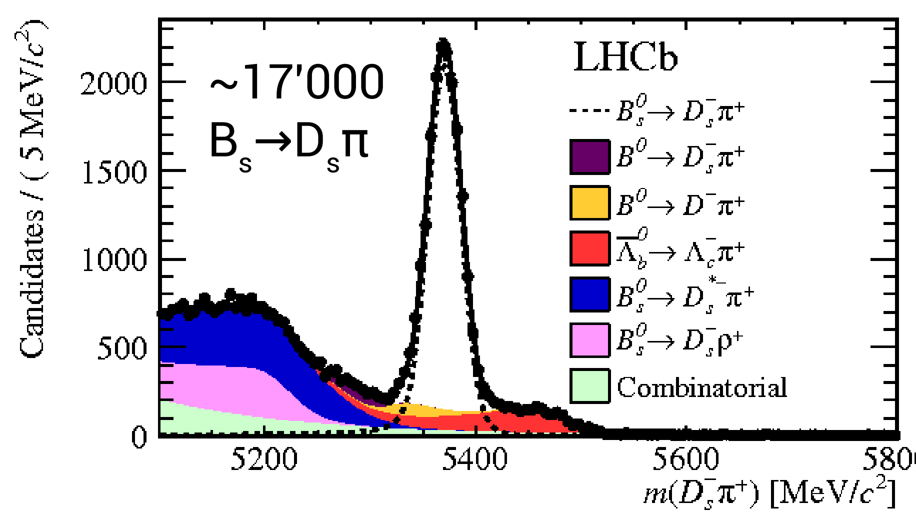
$$\frac{\mathcal{B}(B^0 \to D^- K^+)}{\mathcal{B}(B_s^0 \to D_s^- \pi^+)}$$

  which can be theoretically "cleanly" calculated

  Fleischer, Serra and Tuning, PRD82 (2010) 034038

  – Relevant signals with 1 fb^{-1}:

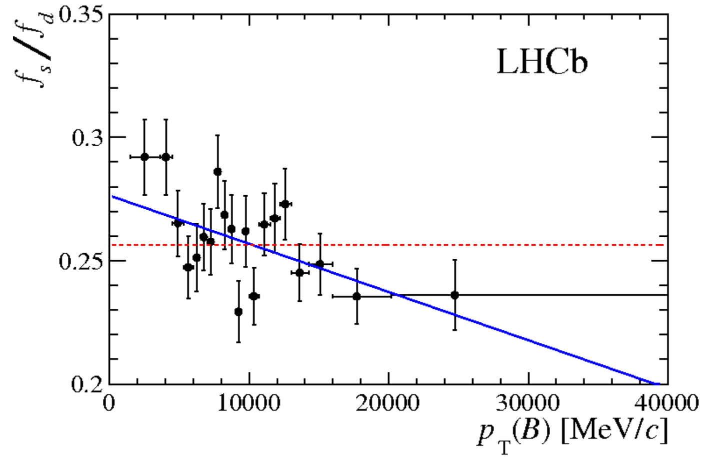


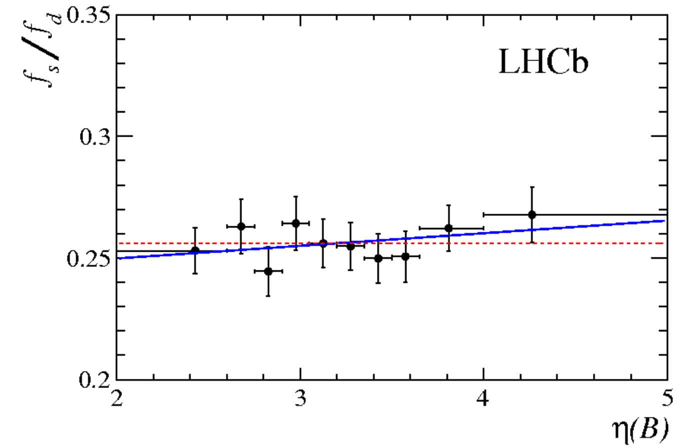


B-hadron production: f_s/f_d (II)

LHCb: 1 fb^{-1} @ 7 TeV
arXiv:1301.5286

Evidence for a small dependence of f_s/f_d with p_T and not with η





Overall, we obtain $$\frac{f_s}{f_d} = 0.238 \pm 0.004\ (\mathrm{stat}) \pm 0.015\ (\mathrm{syst}) \pm 0.021\ (\mathrm{theo})$$

Systematics: hardware trigger efficiency, PID
Theory: mostly $B_q \rightarrow D_q$ form factors

Also, f_Λ was measured with respect to f_u+f_d

LHCb: 3 pb^{-1} @ 7 TeV
PRD 85 (2012) 032008

$$\frac{f_{\Lambda_b^0}}{f_u + f_d} = (0.404 \pm 0.017\ (\mathrm{stat}) \pm 0.027\ (\mathrm{syst}) \pm 0.105\ (\mathrm{Br})) \times [1 - (0.031 \pm 0.004\ (\mathrm{stat}) \pm 0.003\ (\mathrm{syst})) \times p_T\ (\mathrm{GeV})]$$

Again, dependence on p_T was found, no on η

Assuming unitarity and $f_u=f_d$: **$f_u=f_d$=~33%, f_s=~8% and f_Λ=~27%**

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  - **Spectroscopy: concentrating on B baryons**
    - **Two recent discoveries:**
      - **Excited Λ_b (LHCb)**
      - **Ξ_b (CMS)**
    - **Mass measurements**
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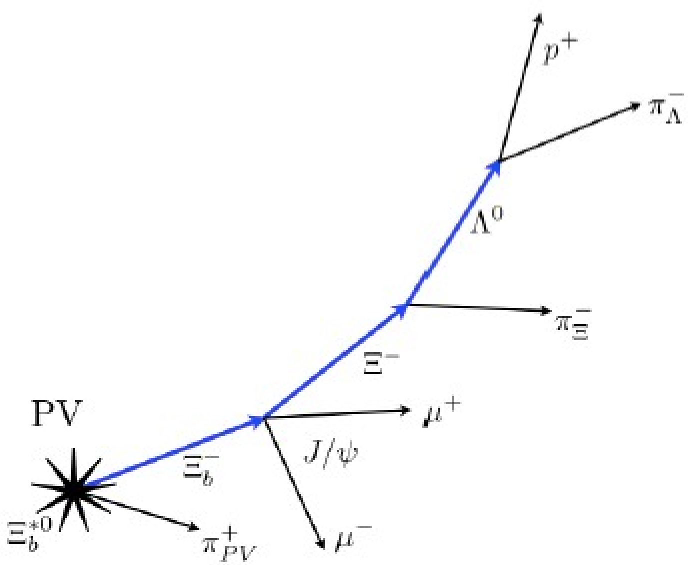
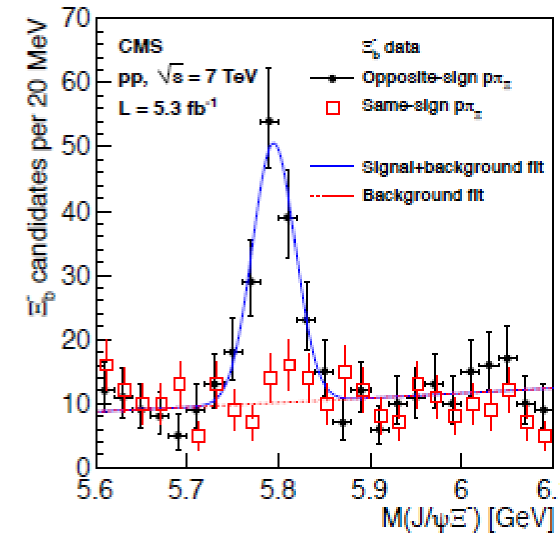
B-baryons spectroscopy (I)

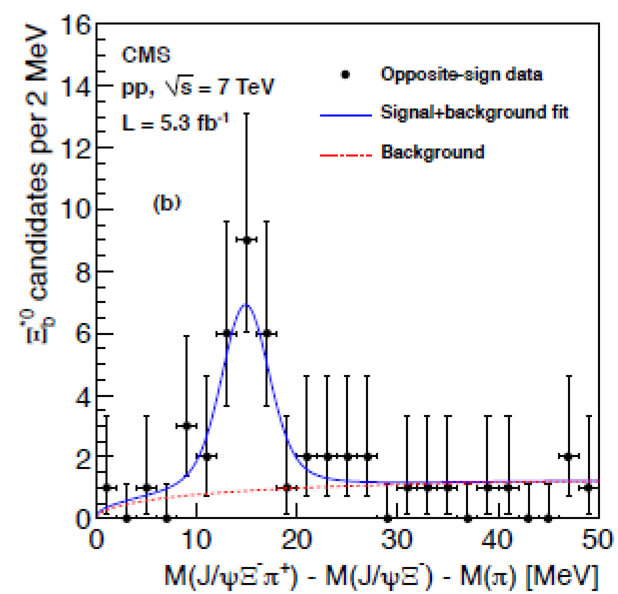
- **Test of the different QCD theories: HQET, perturbative, lattice, ...**
- Two recent discoveries:
- **Observation of Ξ_b^***

CMS: 5.3 fb^{-1} @ 7 TeV
PRL 108 (2012) 252002

  - Using ~110 $\Xi_b \to J/\psi \Xi$, look at $\Xi_b \pi$



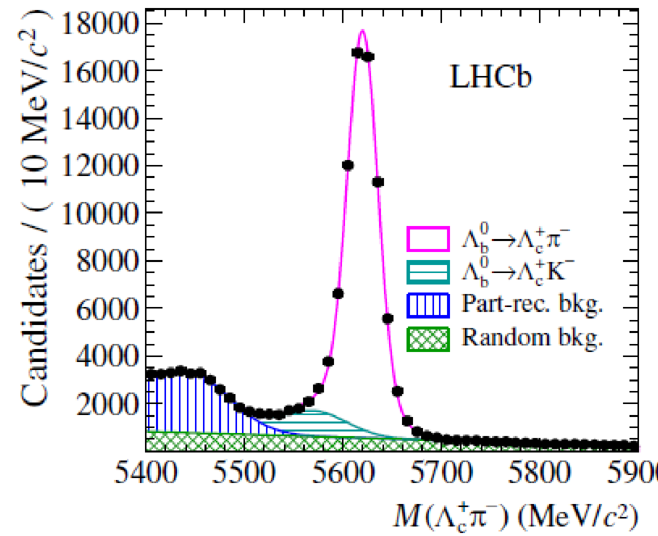


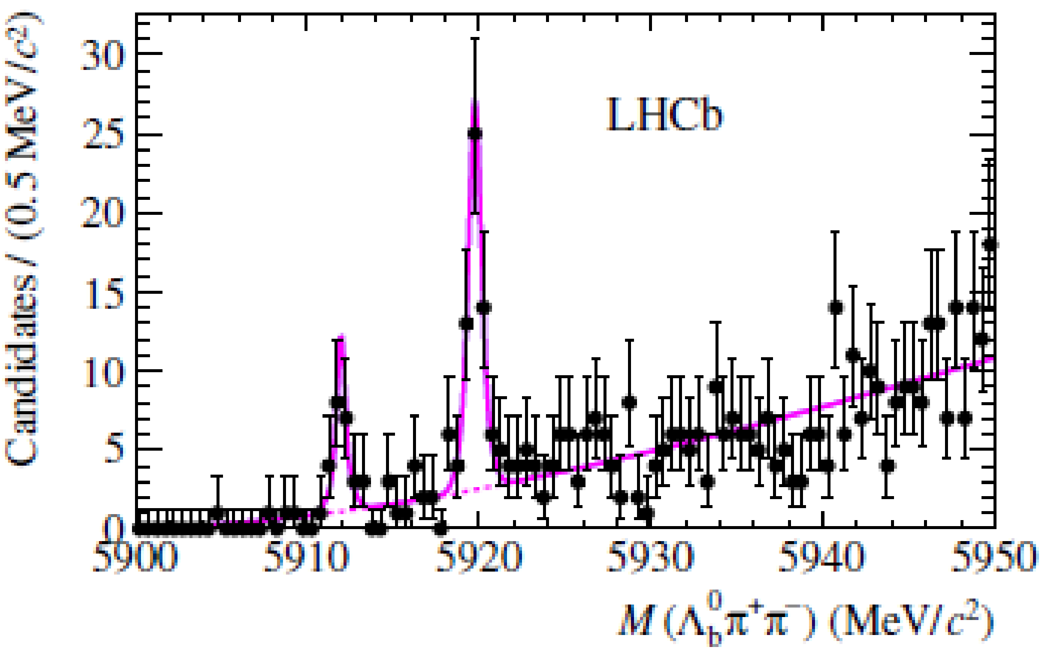


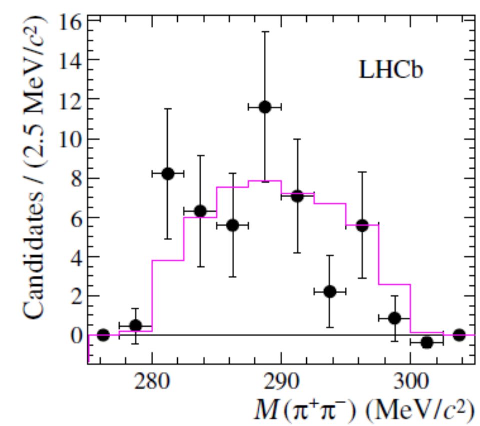
  - One narrow resonance (Γ=2.1±1.7 MeV):
    - 5945.0±0.7(stat)±0.3(syst)±2.7(PDG) MeV (6.9σ)
  - Assumed to be the $J^P=3/2^+$ companion of Ξ_b

B-baryons spectroscopy (II)

- **Excited Λ_b baryons** **LHCb: 1.0 fb^{-1} @ 7 TeV PRL 109 (2012) 172003**
  - Using large and clean sample of 70k $\Lambda_b \rightarrow \Lambda_c \pi$ decays, look at $\Lambda_b \pi\pi$
  - Two narrow resonance (Γ<1 MeV):
    - 5911.97±0.12±0.66 MeV (5.2σ)
    - 5919.77±0.08±0.66 MeV (10.2σ)
  - Assumed to be orbitally excited Λ_b



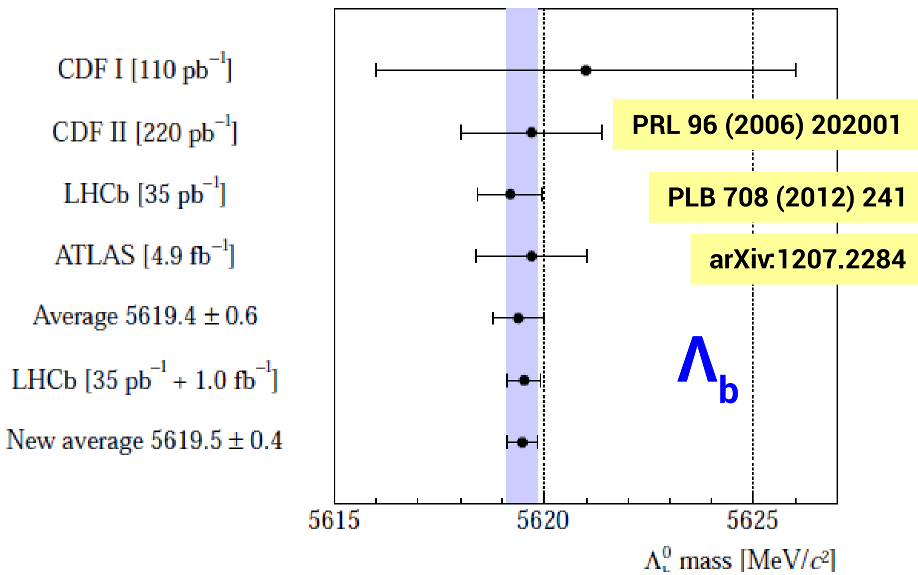


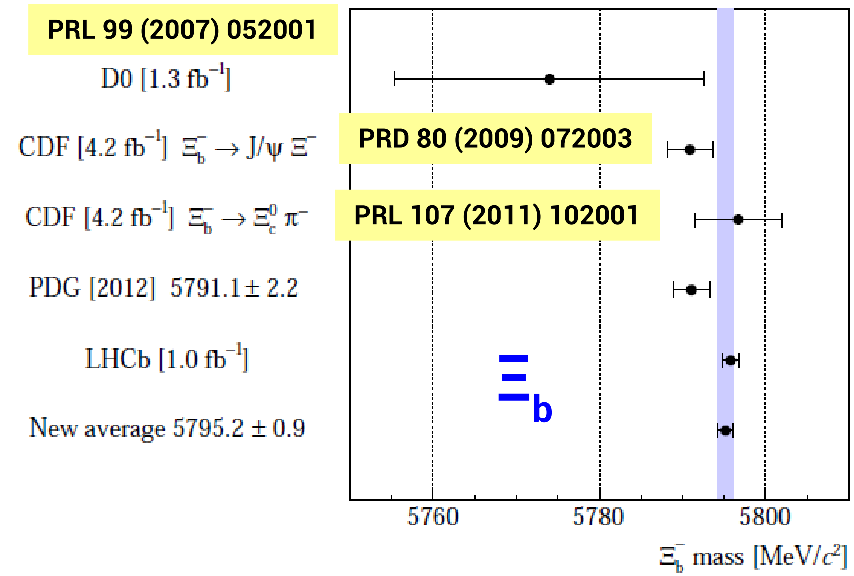


M(ππ) of the 2nd peak consistent with phase-space decay

B-baryons spectroscopy (II)

- Other B-baryons mass measurements, **LHCb is the front-runner**

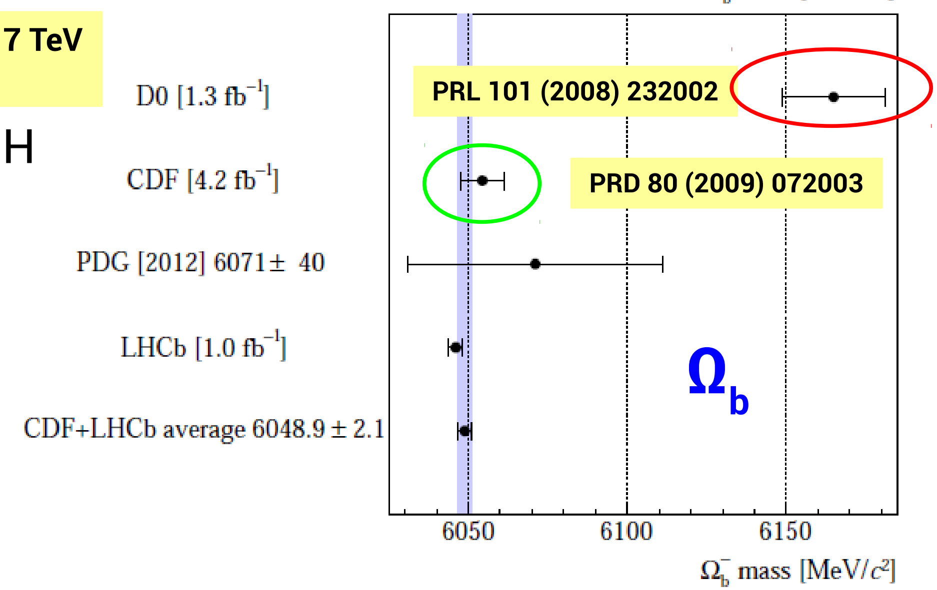




- Total uncertainty (LHCb 1fb-1)

LHCb: 1.0 fb^{-1} @ 7 TeV
arXiv:1302.1072

  - All modes reconstructed in $H_b \to J/\psi(\to \mu\mu)H$
  - Λ_b: ~0.5 MeV (systematics dominate: tracking calibration)
  - Ξ_b: ~1 MeV (not yet dominated)
  - Ω_b: ~2.5 MeV (not yet dominated)
    - OK with CDF, not D0



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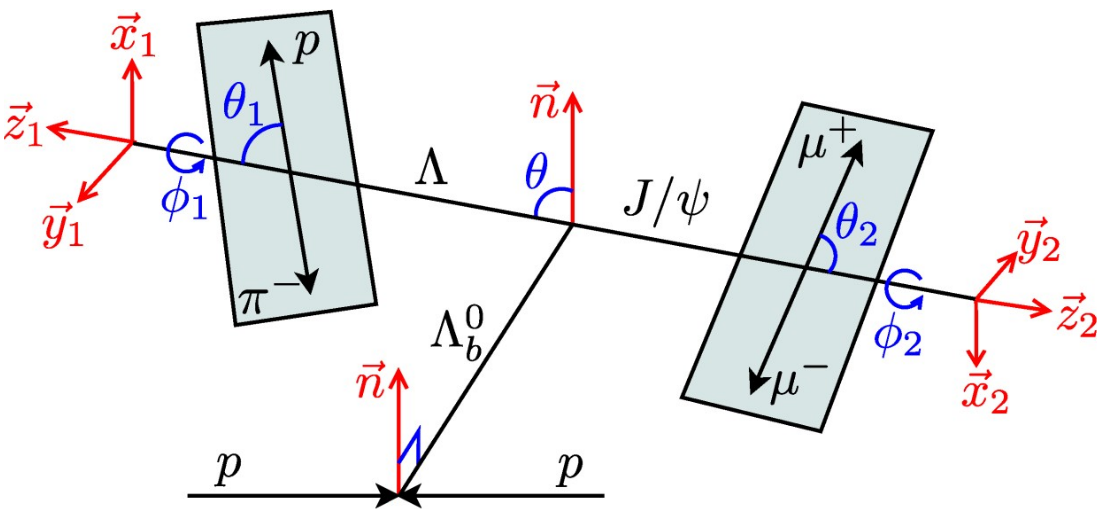
Λ_b production polarization (I)

LHCb: 1.0 fb^{-1} @ 7 TeV
arXiv:1302.5578

- Λ_b longitudinal polarization vanishes (parity conservation of QCD) but transverse polarization could be as large as 20% Ajaltouni, Conte, Leitner, PLB 614 (2005) 165
  - Measured in $e^-e^+\to Z^0\to bb$ (at LEP) using semi-leptonic decays but not yet at any hadron collider
- Angular analysis of $\Lambda_b\to J/\psi(\to\mu\mu)\Lambda(\to p\pi)$
  - Allows to measure the polarization together with the four decay helicity amplitudes: $\mathcal{M}_{+1/2,0}$, $\mathcal{M}_{-1/2,0}$, $\mathcal{M}_{-1/2,-1}$, $\mathcal{M}_{-1/2,+1}$



θ: polar angle of p_Λ in Λ_b rest-frame wrt $n=p_{\Lambda b0} x p_{beam}$
θ_1: polar angles of p_p in Λ rest-frame
θ_2: polar angles of p_μ in J/ψ rest-frame
ϕ_1 and ϕ_2: the azimuthal angles are integrated out

Four parameters to be measured simultaneously: polarization and three parameters describing the amplitudes:

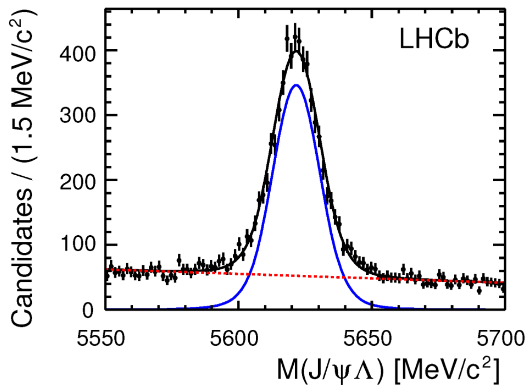
$$\alpha_b = |\mathcal{M}_{+1/2,0}| - |\mathcal{M}_{-1/2,0}| + |\mathcal{M}_{-1/2,-1}| - |\mathcal{M}_{+1/2,+1}|$$
$$r_0 = |\mathcal{M}_{+1/2,0}| + |\mathcal{M}_{-1/2,0}|$$
$$r_1 = |\mathcal{M}_{+1/2,0}| - |\mathcal{M}_{-1/2,0}|$$

α_b: P-violating asymmetry parameter of the $\Lambda_b\to J/\psi\Lambda$ decay

Λ_b production polarization (II)

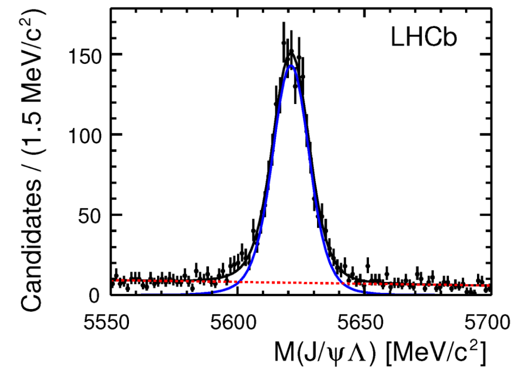
LHCb: 1.0 fb^{-1} @ 7 TeV
arXiv:1302.5578

Λ decay outside vertex detector



N_{sig}~5300
σ_{sig}~8 MeV

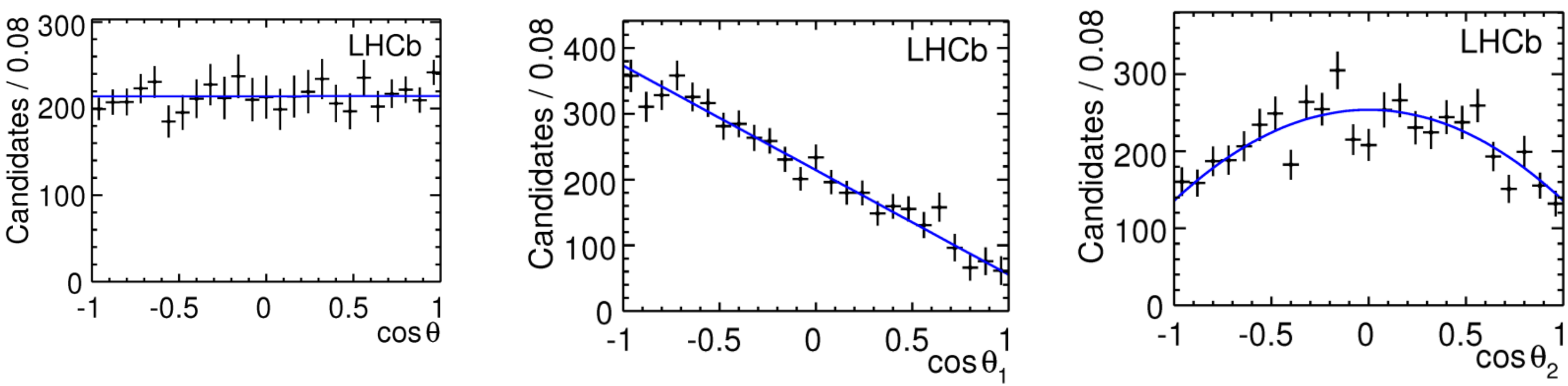
Λ decay inside vertex detector



N_{sig}~1900
σ_{sig}~6 MeV

Angular distribution is background subtracted and acceptance corrected

Shown for Λ decaying outside vertex detector



Most "interesting" distribution: cos θ
Flatness indicates no polarization

Λ_b production polarization (III)

LHCb: 1.0 fb^{-1} @ 7 TeV
arXiv:1302.5578

- Results

$$P_b = 0.05 \pm 0.07 \text{ (stat)} \pm 0.02 \text{ (syst)}$$
$$\alpha_b = 0.05 \pm 0.17 \text{ (stat)} \pm 0.07 \text{ (syst)}$$
$$r_0 = 0.58 \pm 0.02 \text{ (stat)} \pm 0.01 \text{ (syst)}$$
$$r_1 = -0.56 \pm 0.10 \text{ (stat)} \pm 0.05 \text{ (syst)}$$

Helicity amplitudes parametrization

$$\alpha_b = |\mathcal{M}_{+1/2,0}| - |\mathcal{M}_{-1/2,0}| + |\mathcal{M}_{-1/2,-1}| - |\mathcal{M}_{+1/2,+1}|$$
$$r_0 = |\mathcal{M}_{+1/2,0}| + |\mathcal{M}_{-1/2,0}|$$
$$r_1 = |\mathcal{M}_{+1/2,0}| - |\mathcal{M}_{-1/2,0}|$$

- P_b: first measurement in pp collisions
  - cannot exclude O(10%) value — Hiller, Knecht, Legger, Schietinger, PLB 649 (2007) 152
  - but disfavors 20% at the level of 2.7σ — Ajaltouni, Conte, Leitner, PLB 614 (2005) 165
- α_b: first measurement
  - In agreement with most predictions (-21% to -10%) but incompatible at 5.8σ 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

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Forward-central $b\bar{b}$ asymmetry (I)

LHCb: 1 fb^{-1} @ 7 TeV
LHCb-CONF-2013-001

- $t\bar{t}$ production asymmetry at Tevatron: $p\bar{p}$ collisions allow to distinguish forward-backward production

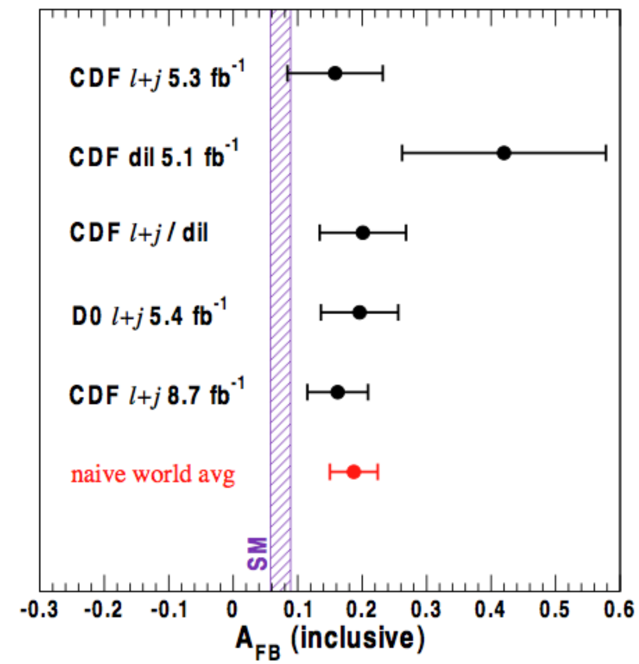
$$A_{\rm FB}^{t\bar{t}} = \frac{N_{\Delta y>0} - N_{\Delta y<0}}{N_{\Delta y>0} + N_{\Delta y<0}} \qquad \Delta y = y_t - y_{\bar{t}}$$

- At **LHC**: use **forward-central asymmetry**

$$A_{\rm FB}^{b\bar{b}} = \frac{N_{\Delta y>0} - N_{\Delta y<0}}{N_{\Delta y>0} + N_{\Delta y<0}} \qquad \Delta y = |y_b| - |y_{\bar{b}}|$$

  - Still provides useful constraints

Kawahala, Krohn, Strassler, arXiv:1108:3301

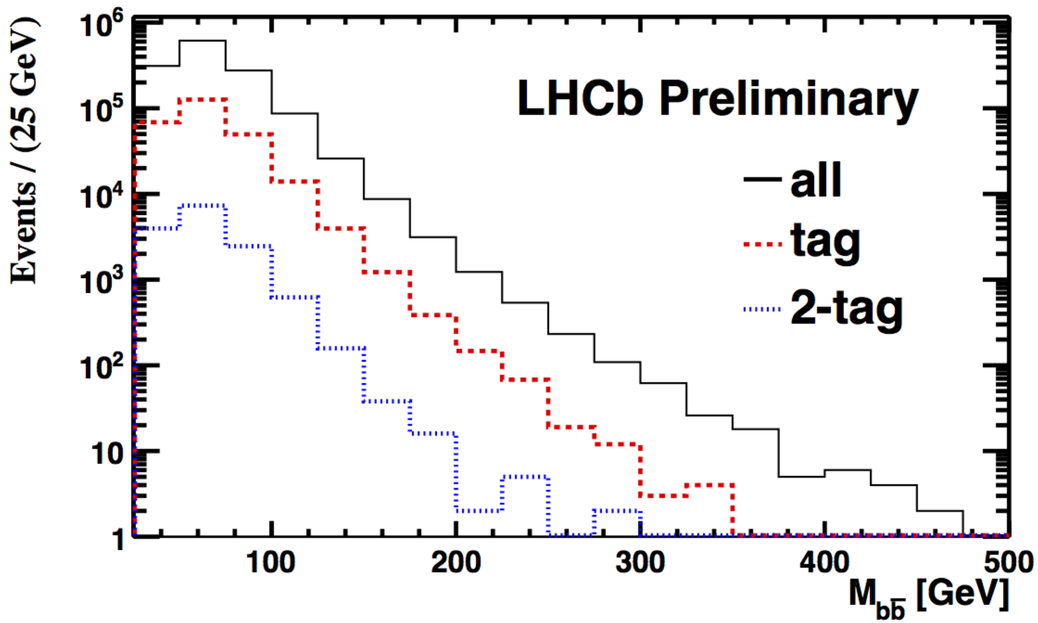


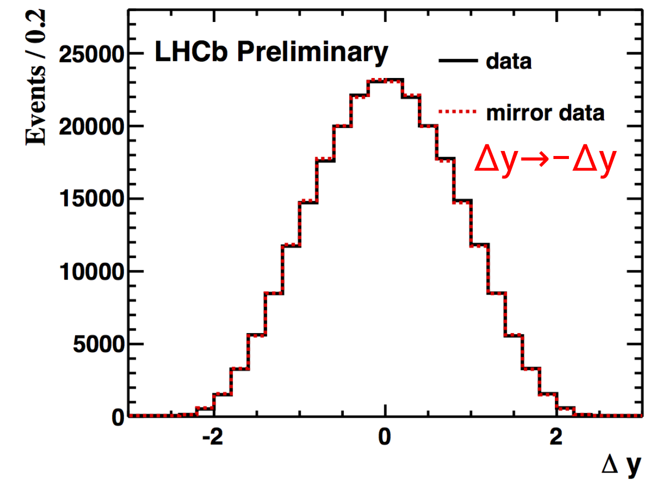
- **Selection**
  - Two high-p_T (>15 GeV) back-to-back ($\Delta\varphi$>2.5) b-tagged jets from the same primary pp vertex
  - **b-tagging**: only consider jets whose hardest displaced track is identified as a muon (muon charge identifies b quark flavor)
    - Calibrated using data: tagging purity compared with simulation
      - one b-quark reconstructed as a B^+ meson (J/ψK,Dπ)
      - doubly-tagged sample

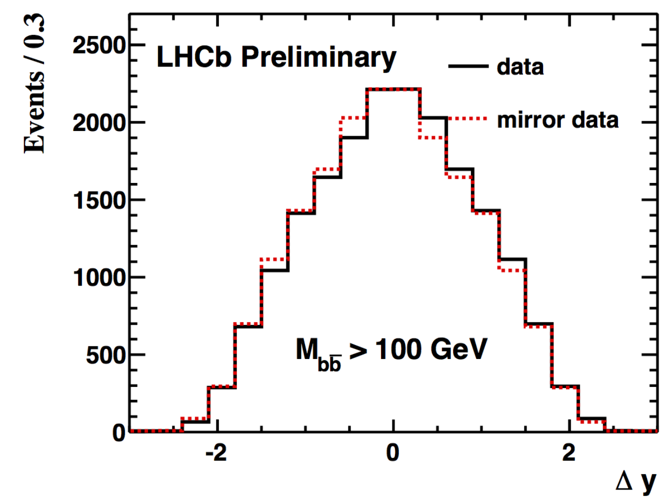
Forward-central $b\bar{b}$ asymmetry (II)

LHCb: 1 fb^{-1} @ 7 TeV
LHCb-CONF-2013-001

Mass of the selected di-jets







$$A_{\rm FB}^{b\bar{b}} = (0.5 \pm 0.5\ (\text{stat}) \pm 0.5\ (\text{syst}))\%$$

$$A_{\rm FB}^{b\bar{b}}(M_{b\bar{b}} > 100\ \text{GeV}) = (4.3 \pm 1.7\ (\text{stat}) \pm 2.4\ (\text{syst}))\%$$

- Systematic: mainly due to flavor tagging (can be reduced with more data)
- Result in agreement in SM
- Would like to measure for $M_{b\bar{b}}>2m_t$, but need more data

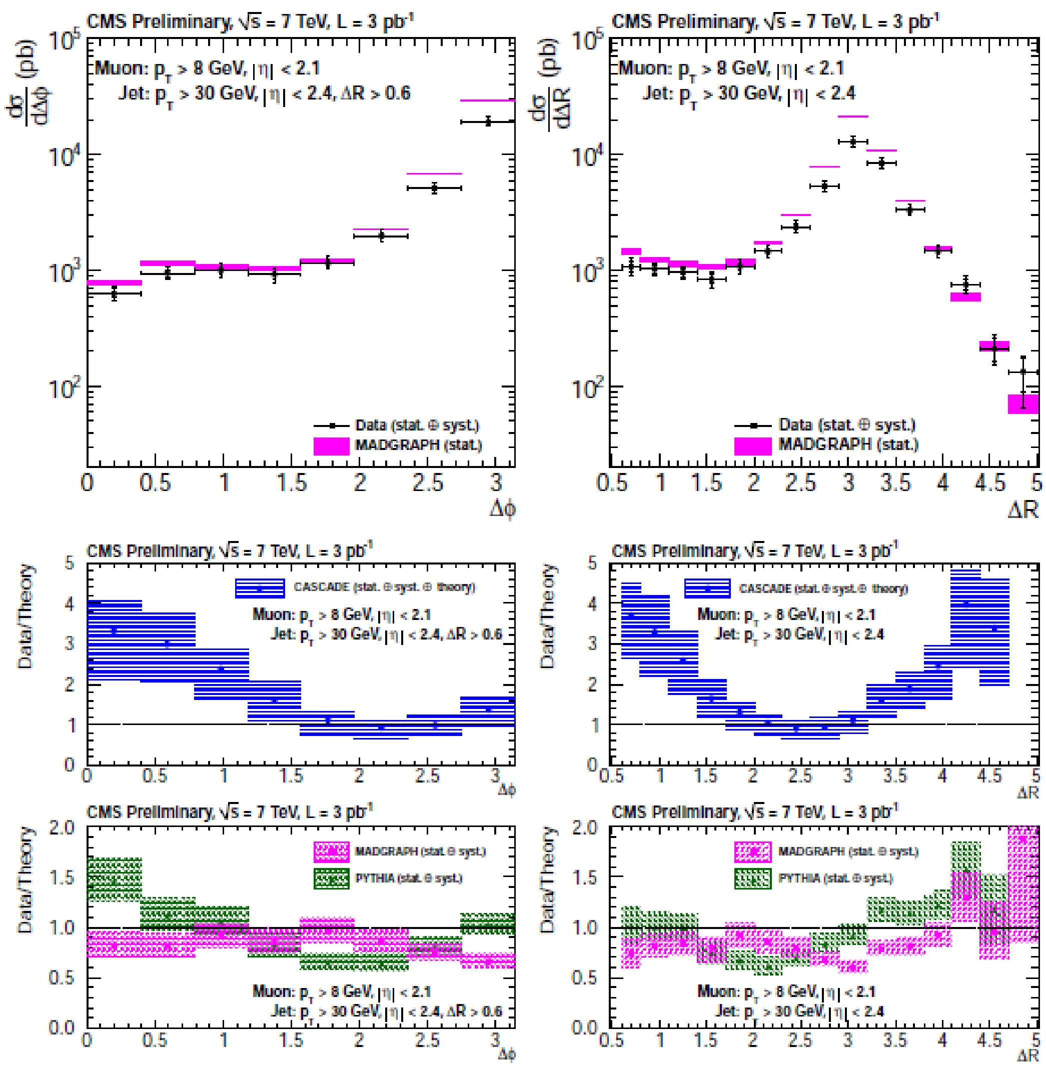
Beauty di-jet angular correlation (I)

CMS: 3 pb^{-1} @ 7 TeV
BPH-10-019

- Studying the hadroproduction of beauty quark pairs allows for a test pQCD
  - At lowest order, b and $\bar{b}$ quarks emitted back to back
  - At higher order, subprocesses with additional emitted gluons give rise to different topologies in the final state
    - Angular correlations sensitive to these subprocesses
- Hadroproduction of beauty di-jet expected to be a dominant background for many BSM processes
- Selection
  - B-hadrons have large semileptonic BR → Use of low-p_T single-muon trigger
    - Allows for a larger probe of beauty di-jet phase space than jet triggers
  - Measurements of the differential cross sections with respect to $\Delta\phi$ and ΔR (angular separation)

Beauty di-jet angular correlation (II)

CMS: 3 pb^{-1} @ 7 TeV
BPH-10-019



- Data compared to generators

	Total cross-section [nb]
Data	12.2 ± 0.2 (stat)$^{+1.6}_{-1.2}$ (syst)
PYTHIA	13.18 ± 0.02 (stat)
MADGRAPH	17.1 ± 0.1 (stat)
CASCADE	9.48 ± 0.04 (stat)$^{+1.93}_{-2.65}$ (syst)

- All need tuning
  - **MADGRAPH**: best description of the shape in the low angular region but overestimates total σ
  - **CASCADE**: region in disagreement in both ΔR and Δϕ and underestimates total σ
  - **PYTHIA**: disagreement in low Δϕ region but closer to total σ

Also found to be in good agreement with previous study: JHEP 1103 (2011) 136

PYTHIA: http://home.thep.lu.se/~torbjorn/Pythia.html
MADGRAPH: http://madgraph.phys.ucl.ac.be/
CASCADE: https://cascade.hepforge.org/

Summary

- **Many beautiful results presented:**
  - B hadrons
    - Cross-sections in pp collisions
      - b-quark: concentrating on one recent result from ATLAS
      - B: concentrating on results on B^+ (ATLAS, CMS, LHCb)
      - b hadronization fractions (LHCb)
    - Spectroscopy: concentrating on B baryons
      - Two recent discoveries:
        - Excited Λ_b (LHCb)
        - Ξ_b (CMS)
      - Mass measurements
    - Λ_b production polarization (LHCb)
  - B jets
    - Forward-central $b\bar{b}$ production asymmetry (LHCb)
    - Angular correlations between beauty jets (CMS)
- **LHC first run data not yet fully analyzed: more to come!**

Backups

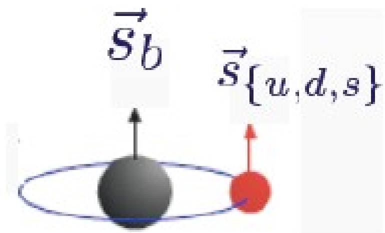
Excited B_s mesons (I)

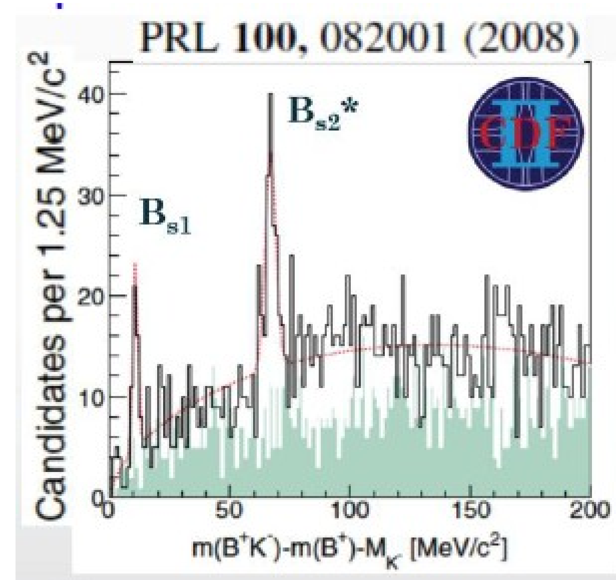
- Total angular momentum of B_s:

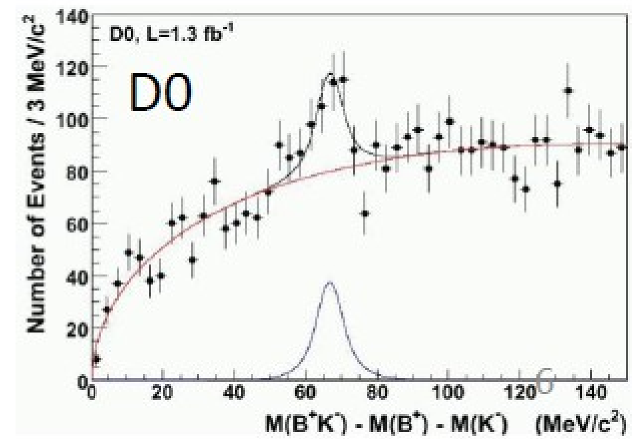
LHCb: 1.0 fb^{-1} @ 7 TeV
PRL 110 (2013) 151803

$$\vec{J} = \vec{j} + \vec{s}_b$$

$$\hookrightarrow = \vec{L} + \vec{s}_{u,d,s}$$







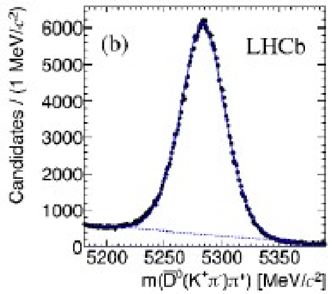
	j_s	J^P	B^+K^-	$B^{*+}K^-$	Mass (MeV/c^2)
B_{s0}^*	$1/2$	0^+	Yes	No	Unobserved
$B_{s1}^{'}$	$1/2$	0^+	No	Yes	Unobserved
B_{s1}	$3/2$	0^+	No	Yes	5829.4 ± 0.7
B_{s2}^*	$3/2$	0^+	Yes	Yes	5839.7 ± 0.6

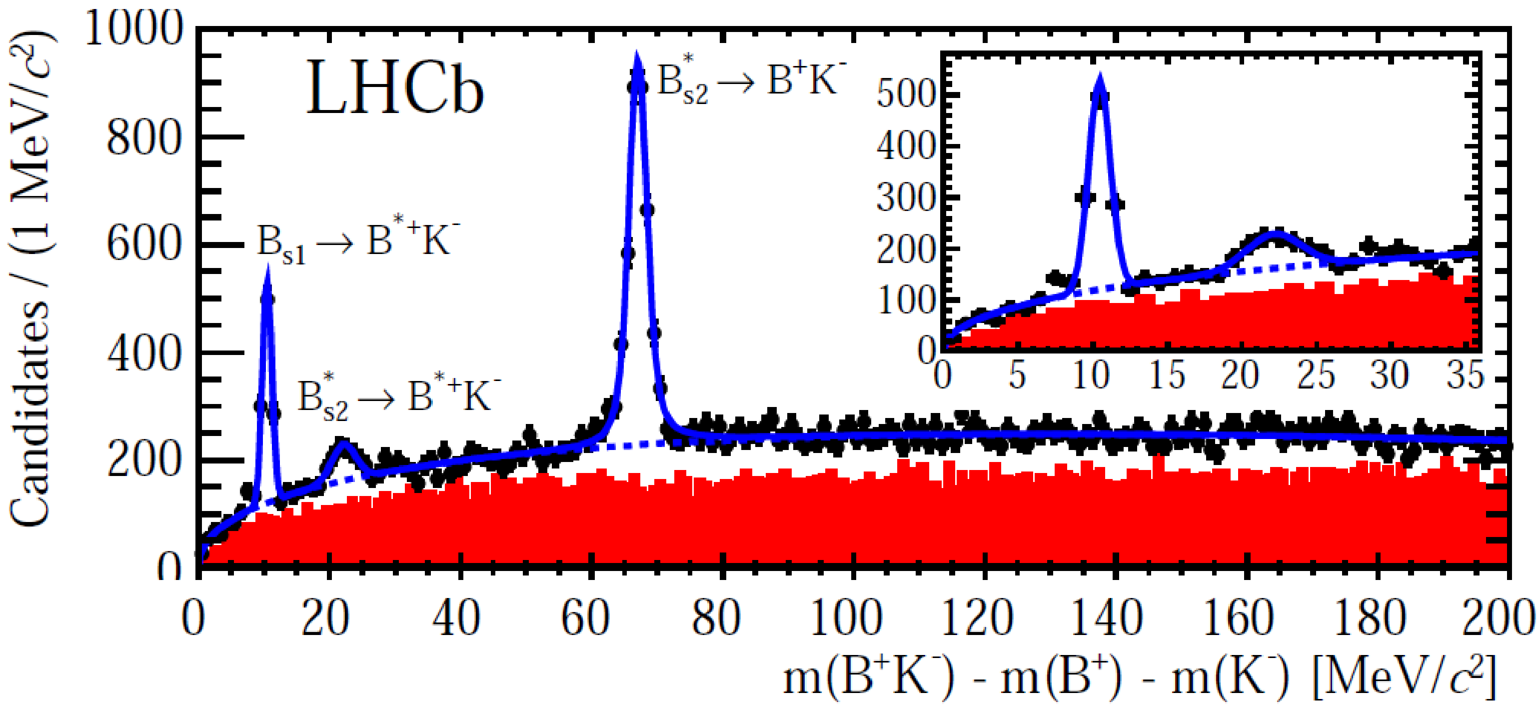
- CDF observed two narrow peaks in B^+K^- mass spectrum: B_{s2}^* and feed-down of $B_{s1} \rightarrow B^{*+}K^-$
- D0 confirmed only the first one

Excited B_s mesons (II)

LHCb: 1.0 fb^{-1} @ 7 TeV
PRL 110 (2013) 151803

- Study of orbitally excited B_s^* mesons decaying to $B^{+(*)}K^-$
- Clean sample of ~one million B^+
  - $J/\psi K^+$, **$D^0(K\pi)\pi^+$**, $D^0(K3\pi)\pi^+$, $D^0(K\pi)3\pi$
  - Reconstruct $B_s^* \to BK^+$





- $B_{s2}^* \to B^+K^-$ and $B_{s1} \to B^{*+}K^-$ peaks clearly observed
- Structure seen around ΔM~20 MeV, identified as $B_{s2}^* \to B^{*+}K^-$

Excited B_s mesons (III)

LHCb: 1.0 fb^{-1} @ 7 TeV
PRL 110 (2013) 151803

- We measure

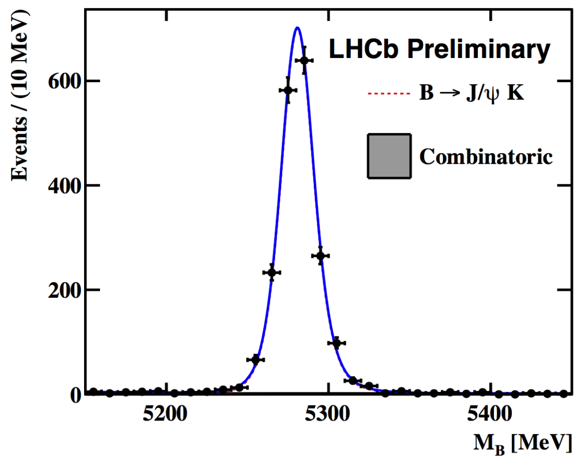
$$m(B^{*+}) = 5324.26 \pm 0.30\ (\mathrm{stat}) \pm 0.23\ (\mathrm{syst}) \pm 0.17\ (\mathrm{B^+\ mass})$$
$$m(B_{s1}) = 5828.40 \pm 0.04\ (\mathrm{stat}) \pm 0.04\ (\mathrm{syst}) \pm 0.41\ (\mathrm{B^{*+}\ mass})$$
$$m(B^*_{s2}) = 5839.99 \pm 0.05\ (\mathrm{stat}) \pm 0.11\ (\mathrm{syst}) \pm 0.17\ (\mathrm{B^+\ mass})$$
$$\Gamma(B^*_{s2}) = 1.56 \pm 0.13\ (\mathrm{stat}) \pm 0.47\ (\mathrm{syst})$$

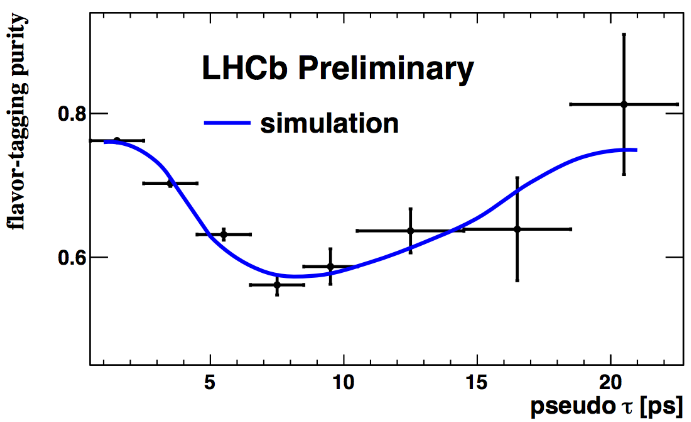
- Most precise mass measurements of B_{s1}, B_{s2}^* and B^{*+}
- First observation of B_{s2}^* (8σ) and measurement of its natural width
  - The $B^{*+}K^-$ final state and width favors $J^P=2^+$, as expected
- Confirmation of B_{s1} state which was observed by CDF but not by D0

Forward-central $b\bar{b}$ asymmetry (II)

LHCb: 1.0 fb^{-1} @ 7 TeV
LHCb-CONF-2013-001

- Jet energy correction
  - Particles out of acceptance: 20-30%
  - Missing ν's, track multiplicity: 10-20%
- Jet E resolution: 15-20%
- Flavor tagging: central part of the analysis
  - Purity: estimated in MC (73±2)%
    - Source of impurity: B oscillations, muons from charm decays, muon misID
  - Cross-check with data
    - Using fully reconstructed B^+ decays (J/ψK,Dπ) while the other b-quark is reconstructed in a jet
      - Agreement: purity (71.5±4.0)%
    - Using the doubly-tagged sample
      - b-hadron lifetime estimated using jet energy and flight distance
        - Agreement with simulation
      - Also in agreement: (70.7±0.4)%





Beauty di-jet angular correlation (III)

- beauty di-jet signal in data determined by bin-by-bin purity correction to selected events
  - fractional flavor content of the di-jet extracted from a system of 4 equations solved with pseudoexperiments and fitting the resulting distributions
  - overall signal purity from data: 0.933±0.017(stat)