中国科学院大学
University of Chinese Academy of Sciences

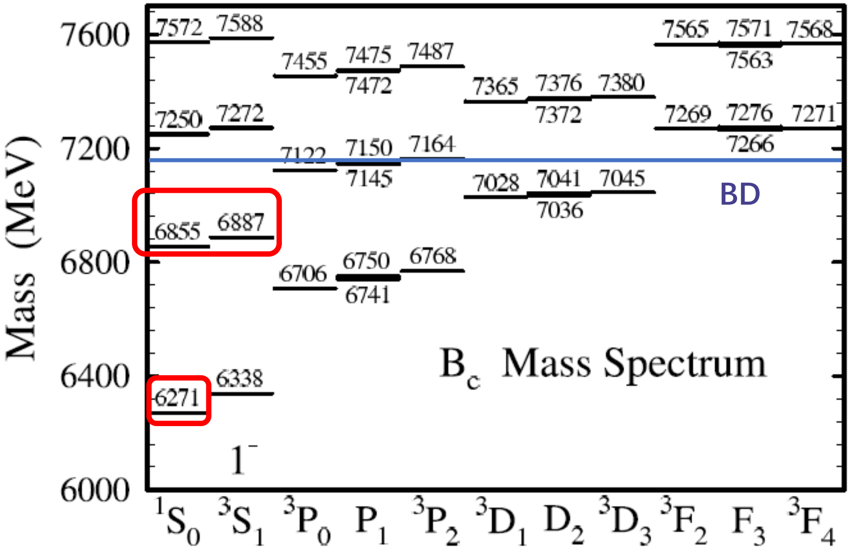
Recent results of B_c physics at LHCb

Yanting Fan
on behalf of LHCb collaboration
University of Chinese Academy of Science (CN)

The 5th China LHC Physics Workshop
24 October 2019

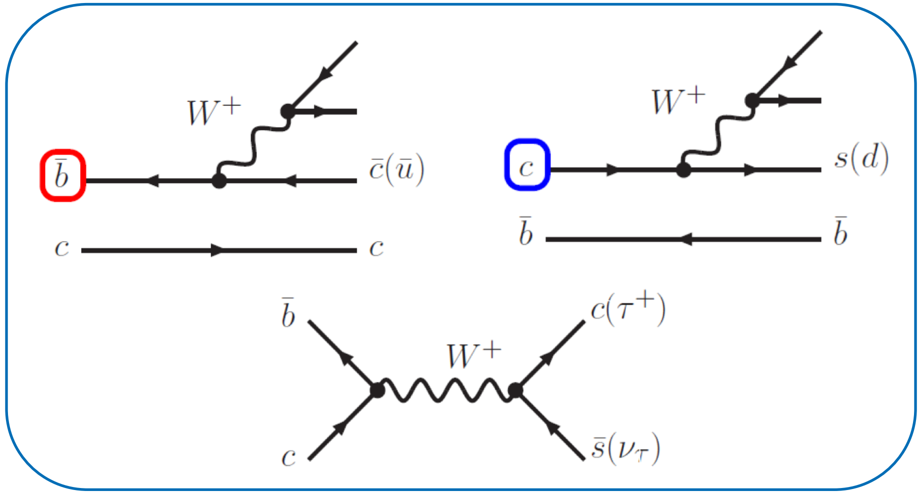
B_c physics

[PRD 70 (2004) 054017]

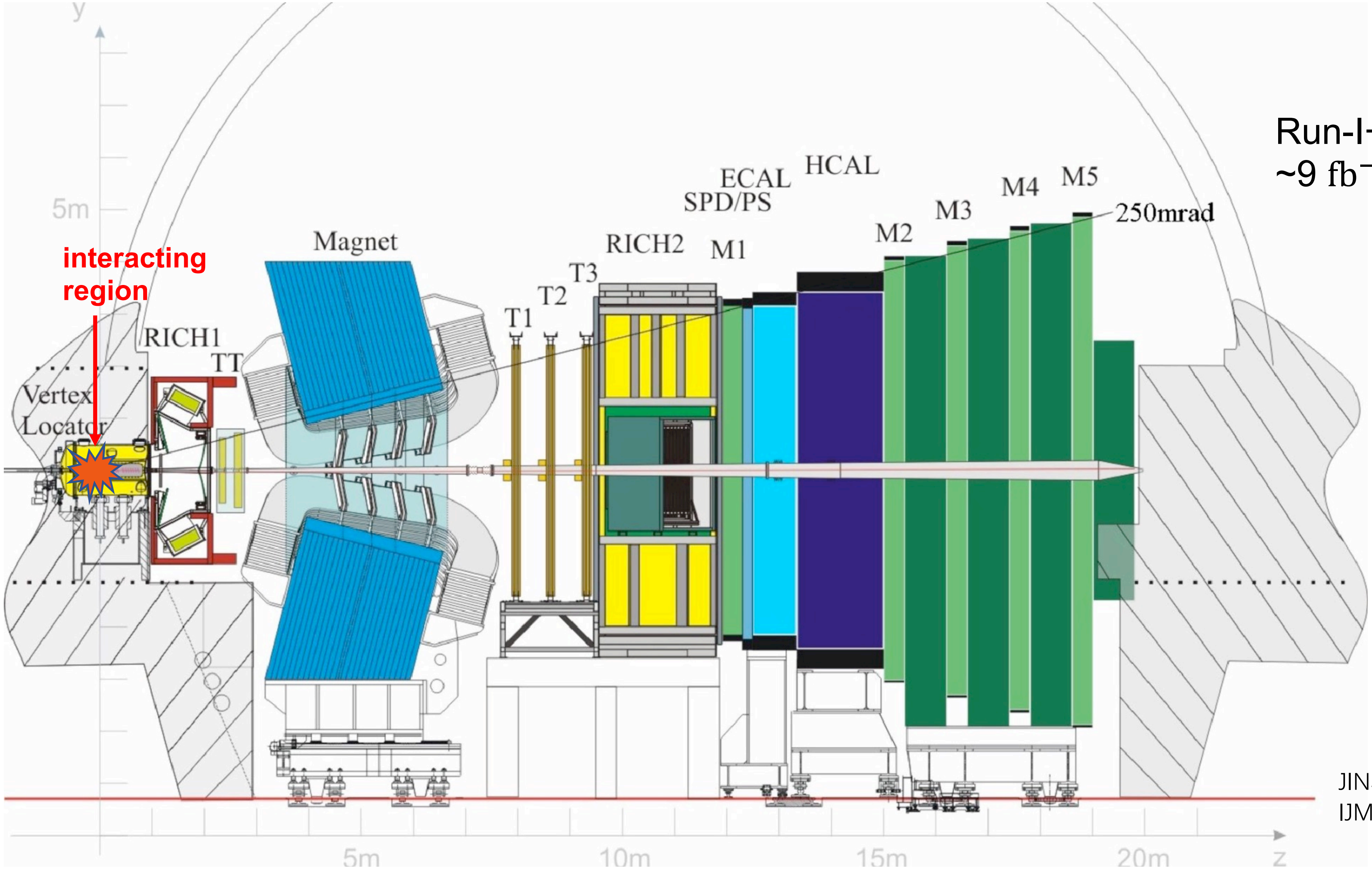


- B_c: unique mesons consist of two different heavy flavor quarks, ideal testing for QCD models (mass, lifetime, branching fractions, etc)
- Ground state decays weakly; states under BD threshold decay to 1S states only through radiative or hadronic transitions
- First observed in CDF; Only B_c^+ and $B_c(2S)$ have been observed so far

- $\sigma(B_c^+)_{LHC}/\sigma(B_c^+)_{Tevatron} \sim \mathcal{O}(10)$
- Rich B_c^+ decay modes:
  - $\bar{b} \to \bar{c}W^+$(~20%)
  - $c \to sW^+$ (~70%)
  - $c\bar{b} \to W^+$ (~10%)



LHCb detector



Run-I+Run-II
~9 fb^{-1} for data-taking

JINST 3 (2008) S08005)
IJMPA 30 (2015) 1530022

B_c studies at LHCb

Mass & spectroscopy	$M(B_c^+ \to J/\psi\pi^+)$		[PRL 109 (2012) 232001]	
	$M(B_c^+ \to J/\psi D_s^+)$		[PRD 87 (2013) 112012]	
	$M(B_c^+ \to J/\psi p\bar{p}\pi^+)$		[PRL 113 (2014) 152003]	
	$M(B_c^+ \to J/\psi D^0 K^+)$		[PRD 95 (2017) 032005]	
	$M(B_c^*(2S)^+ \to B_c^+\pi^+\pi^-)$, $M(B_c(2S)^+ \to B_c^+\pi^+\pi^-)$ (evidence)		[PRL 122 (2019) 232001]	
Lifetime	$\tau(B_c^+ \to J/\psi\mu^+\nu_\mu X)$		[EPJC 74 (2014) 2839]	
	$\tau(B_c^+ \to J/\psi\pi^+)$		[PLB 742 (2015) 39]	
Production	$\sigma(B_c^+)\cdot\mathcal{B}(B_c^+ \to J/\psi\pi^+)/\sigma(B^+)\cdot\mathcal{B}(B^+ \to J/\psi K^+)$		[PRL 109 (2012) 232001] 7TeV [PRL 114 (2015) 132001] 8TeV	
	$\sigma(B_c^+)/\sigma(B_s^0)\cdot\mathcal{B}(B_c^+ \to B_s^0\pi^+)$		[PRL 111 (2013) 181801]	
	$\sigma(B_c^+)/\sigma(B^+)\cdot\mathcal{B}(B_c^+ \to D^0K^+)$		[PRL 118 (2017) 111803]	
Decay	$B_c^+ \to \psi(2S)\pi^+$	[PRD 87 (2013) 071103(R)] [PRD 92 (2015) 072007]	$B_c^+ \to J/\psi K^+$	[JHEP 09 (2013) 075] [JHEP 09 (2016) 153]
	$B_c^+ \to p\bar{p}\pi^+$(upper limit)	[PLB 759 (2016) 313]	$B_c^+ \to K^+K^-\pi^+$(upper limit)	[PRD 94 (2016) 091102(R)]
	$B_c^+ \to J/\psi D^{(*)}K^{*0}$	[PRD 95 (2017) 032005]	$B_c^+ \to D^0K^+$	[PRL 118 (2017) 111803]
	$\mathcal{B}(B^+ \to J/\psi\tau^+\nu_\tau)/\mathcal{B}(B^+ \to J/\psi\mu^+\nu_\mu)$	[PRL 120 (2018) 121801]	$B_c^+ \to D_{(s)}^{(*)+}\bar{D}^{(*)0}, D_{(s)}^{(*)+}D^{(*)0}$ (upper limit)	[NPB 930 (2018) 563]

Searches for new B_c decays

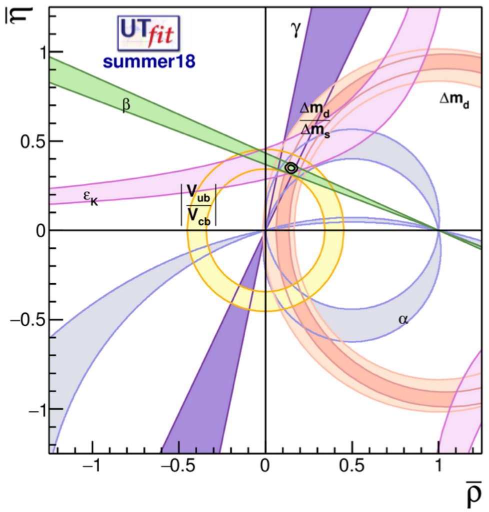
B_c^+ decays into two charmed mesons

[NPB 930 (2018) 563]

Motivation

Measure the unitarity triangle angle γ in the CKM Matrix to reveal signs of new physics

$$\gamma \equiv \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$$

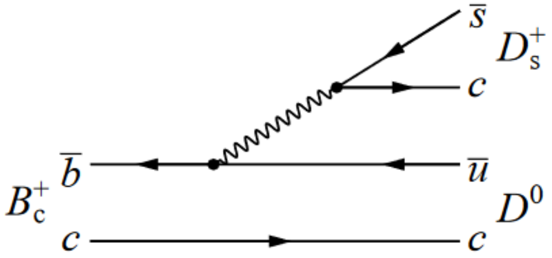


Way to measure γ:

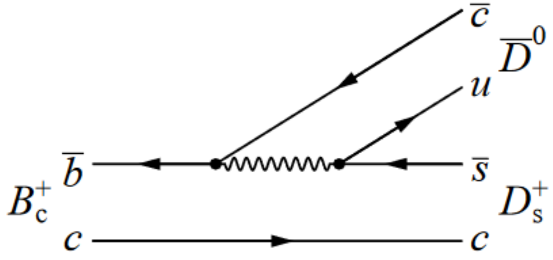
1. CP asymmetry (The best measurement for $B^+ \to \bar{D}^0 K^+, D^0 K^+$)
2. Angular distributions method
3. Using decays:
   - Decay with two charm mesons: $B_c^+ \to D_{(s)}^+ \bar{D}^0, D_{(s)}^+ D^0$
   - Decay with one excited charm meson: $B_c^+ \to D_s^{*+} \bar{D}^0, D_s^{*+} D^0, D_{(s)}^+ D^{*0}, D_{(s)}^+ \bar{D}^{*0}$
   - Decay with two excited charm mesons: $B_c^+ \to D_{(s)}^{*+} \bar{D}^{*0}, D_{(s)}^{*+} D^{*0}$

Channel	Prediction for the branching fraction $[10^{-6}]$ Ref. [9]	Ref. [10]	Ref. [11]	Ref. [12]
$B_c^+ \to D_s^+ \bar{D}^0$	2.3 ± 0.5	4.8	1.7	2.1
$B_c^+ \to D_s^+ D^0$	3.0 ± 0.5	6.6	2.5	7.4
$B_c^+ \to D^+ \bar{D}^0$	32 ± 7	53	32	33
$B_c^+ \to D^+ D^0$	0.10 ± 0.02	0.32	0.11	0.32

(V_{ub}) Color-favoured



(V_{cb}) Color-supressed



B_c^+ decays into two charmed mesons

[NPB 930 (2018) 563]

Data: full Run-I data, 3 fb^{-1}

Decay modes:

$$B_c^+ \to D_{(s)}^+ D^0, D_{(s)}^+ \overline{D}^0$$

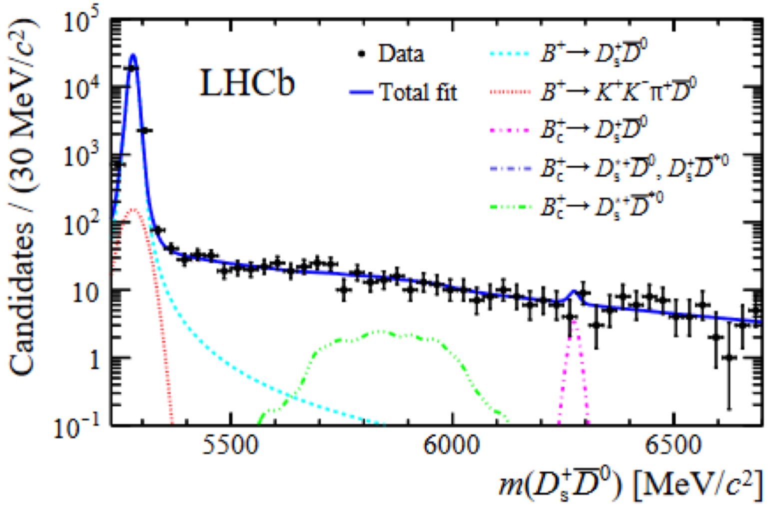
weighted sum of branching fractions

$$B_c^+ \to D_{(s)}^{*+} D^0, D_{(s)}^{*+} \overline{D}^0$$
$$B_c^+ \to D_{(s)}^+ D^{*0}, D_{(s)}^+ \overline{D}^{*0}$$

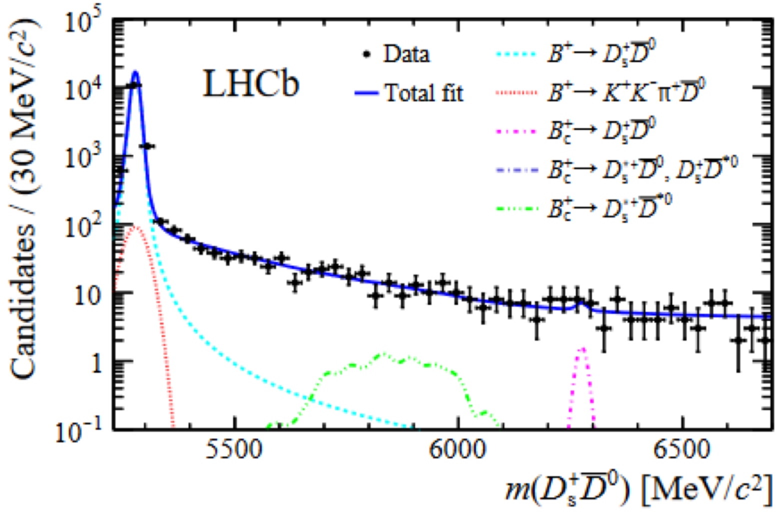
$$B_c^+ \to D_{(s)}^{*+} D^{*0}, D_{(s)}^{*+} \overline{D}^{*0}$$

Charm mesons reconstructed:

$$D^0 \to K^-\pi^+$$
$$D^0 \to K^-\pi^+\pi^-\pi^+$$
$$D^+ \to K^-\pi^+\pi^+$$
$$D_s^+ \to K^+K^-\pi^+$$



Fits for mass spectrum, with $D^0 \to K^-\pi^+$



Fits for mass spectrum, with $D^0 \to K^-\pi^+\pi^-\pi^+$

B_c^+ decays into two charmed mesons

[NPB 930 (2018) 563]

Result:

No evidence of signal for any of the decay modes

The upper limits are @90% (95%) CL:

With two charm mesons

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D_s^+\overline{D}^0)}{\mathcal{B}(B^+\to D_s^+\overline{D}^0)} = (\ \ 3.0\pm3.7)\times10^{-4}\ [<0.9\,(1.1)\times10^{-3}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D_s^+D^0)}{\mathcal{B}(B^+\to D_s^+\overline{D}^0)} = (-3.8\pm2.6)\times10^{-4}\ [<3.7\,(4.7)\times10^{-4}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D^+\overline{D}^0)}{\mathcal{B}(B^+\to D^+\overline{D}^0)} = (\ \ 8.0\pm7.5)\times10^{-3}\ [<1.9\,(2.2)\times10^{-2}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D^+D^0)}{\mathcal{B}(B^+\to D^+\overline{D}^0)} = (\ \ 2.9\pm5.3)\times10^{-3}\ [<1.2\,(1.4)\times10^{-2}].$$

With two excited charm mesons

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D_s^{*+}\overline{D}^{*0})}{\mathcal{B}(B^+\to D_s^+\overline{D}^0)} = (\ \ 3.2\pm4.3)\times10^{-3}\ [<1.1\,(1.3)\times10^{-2}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D_s^{*+}D^{*0})}{\mathcal{B}(B^+\to D_s^+\overline{D}^0)} = (\ \ 7.0\pm9.2)\times10^{-3}\ [<2.0\,(2.4)\times10^{-2}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D^{*+}\overline{D}^{*0})}{\mathcal{B}(B^+\to D^+\overline{D}^0)} = (\ \ 3.4\pm2.3)\times10^{-1}\ [<6.5\,(7.3)\times10^{-1}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D^{*+}D^{*0})}{\mathcal{B}(B^+\to D^+\overline{D}^0)} = (-4.1\pm9.1)\times10^{-2}\ [<1.3\,(1.6)\times10^{-1}].$$

With one excited charm meson

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D_s^{*+}\overline{D}^0)+\mathcal{B}(B_c^+\to D_s^+\overline{D}^{*0})}{\mathcal{B}(B^+\to D_s^+\overline{D}^0)} = (-0.1\pm1.5)\times10^{-3}\ [<2.8\,(3.4)\times10^{-3}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D_s^{*+}D^0)+\mathcal{B}(B_c^+\to D_s^+D^{*0})}{\mathcal{B}(B^+\to D_s^+\overline{D}^0)} = (-0.3\pm1.9)\times10^{-3}\ [<3.0\,(3.6)\times10^{-3}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to (D^{*+}\to D^+\pi^0,\gamma)\overline{D}^0)+\mathcal{B}(B_c^+\to D^+\overline{D}^{*0})}{\mathcal{B}(B^+\to D^+\overline{D}^0)} = (\ \ 0.2\pm3.2)\times10^{-2}\ [<5.5\,(6.6)\times10^{-2}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to (D^{*+}\to D^+\pi^0,\gamma)D^0)+\mathcal{B}(B_c^+\to D^+D^{*0})}{\mathcal{B}(B^+\to D^+\overline{D}^0)} = (-1.5\pm1.7)\times10^{-2}\ [<2.2\,(2.8)\times10^{-2}].$$

Upper limits are consistent with the theoretical expectations.

Test of lepton universality with semileptonic B_c decays

BR of semileptonic B_c^+ decays

[PRL 120 (2018) 121801]

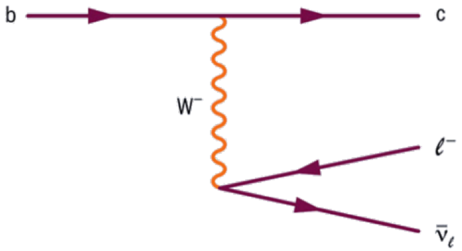
Motivation

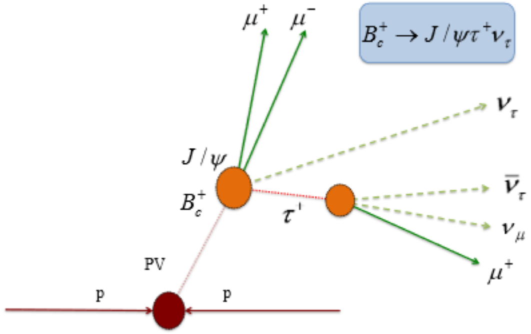
Test the Standard Model (SM) and search for new effects beyond the SM

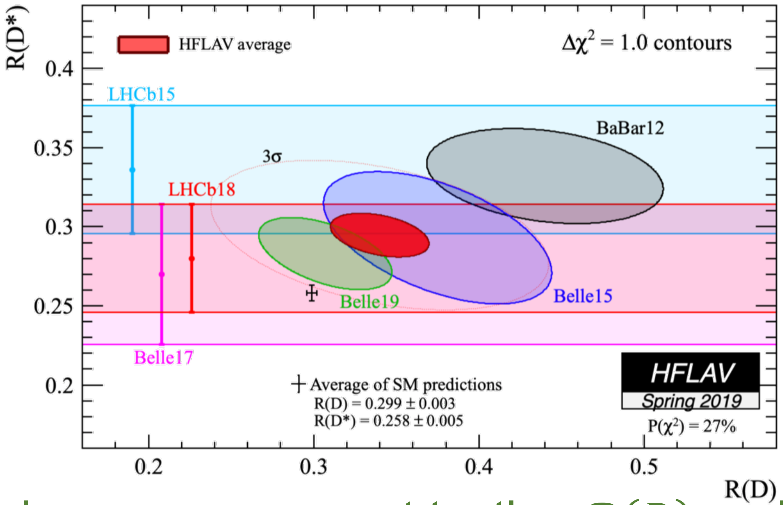
$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}$$

Lepton universality:

Decays of b-quark hadrons proceed through tree-level diagrams in which a virtual W boson decays into a lepton–neutrino pair.
Same behavior for all the leptons in the SM prediction, test with semileptonic decays and leptonic decays.
Ratio provided in semileptonic decays: $R(D), R(J/\psi)$







Previous measurement testing $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

Ideal for semitaunic decays:

1. Tree level processes in theoretical models
2. New physics in weak couplings with charged Higgs, leptoquarks, or vector bosons
3. Test for LU in loop level of EW

BR of semileptonic B_c^+ decays

[PRL 120 (2018) 121801]

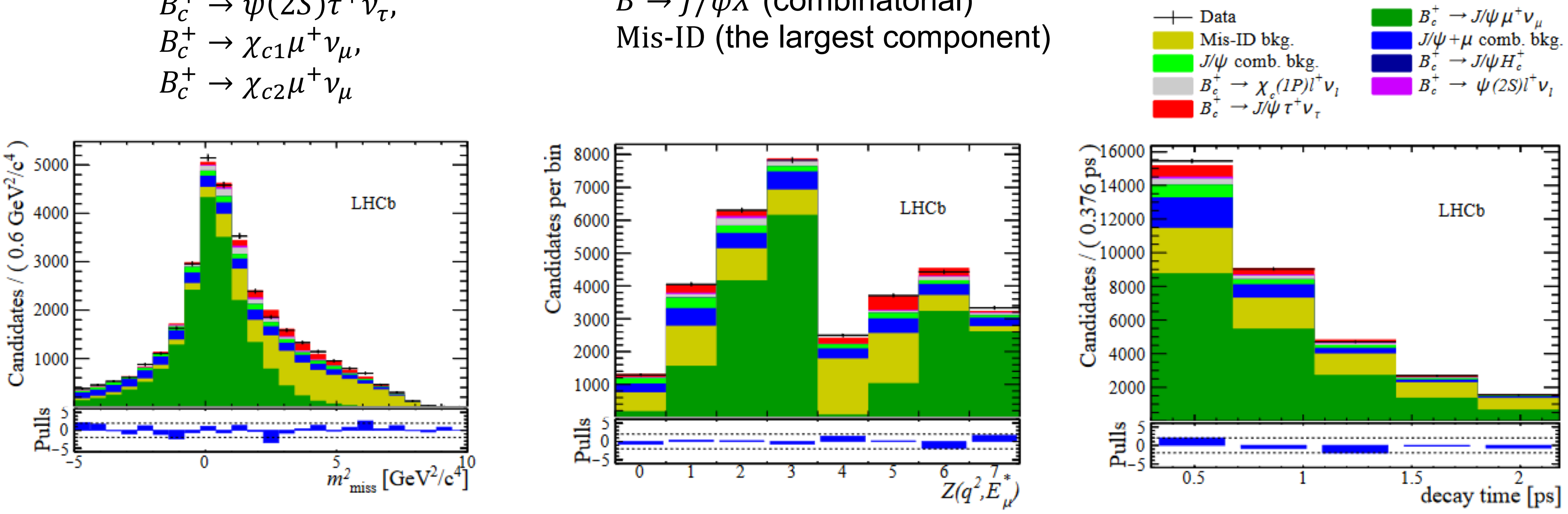
Data: full Run-I data, 3 fb^{-1}

Simulation templates:

$B_c^+ \to \psi(2S)\mu^+\nu_\mu$,
$B_c^+ \to \psi(2S)\tau^+\nu_\tau$,
$B_c^+ \to \chi_{c1}\mu^+\nu_\mu$,
$B_c^+ \to \chi_{c2}\mu^+\nu_\mu$

Backgrounds:

$B_c^+ \to J/\psi H_c X$
$B \to J/\psi X$ (combinatorial)
Mis-ID (the largest component)



BR of semileptonic B_c^+ decays

[PRL 120 (2018) 121801]

Result:

First measurement of $R(J/\psi)$, result within 2σ with the theoretical predictions
SM expectation ~0.25-0.28 depending on form-factors

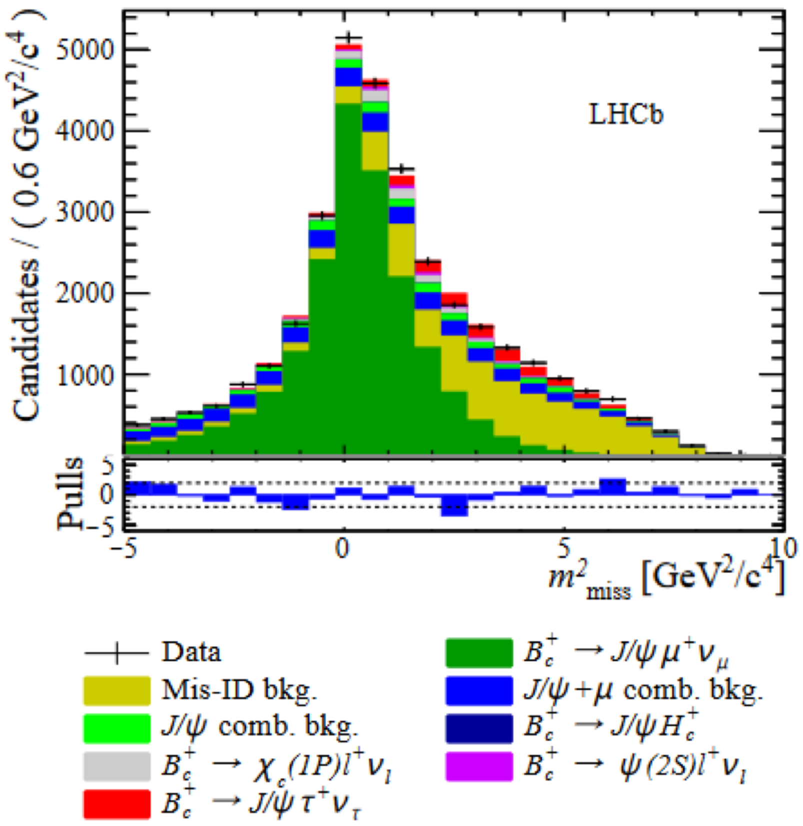
$$f(q^2) = \frac{1}{1 - q^2/M_{\text{pole}}^2} \sum_{k=0}^{K} a_k z(q^2)^k$$

Ratio of branching fractions measured:

$$\mathcal{R}(J/\psi) = 0.71 \pm 0.17(stat) \pm 0.18(syst)$$

Result higher than the SM prediction

Signal yield: 1400 $\pm$ 300
Normalization: 19140 $\pm$ 340



Observation of excited B_c^+ state

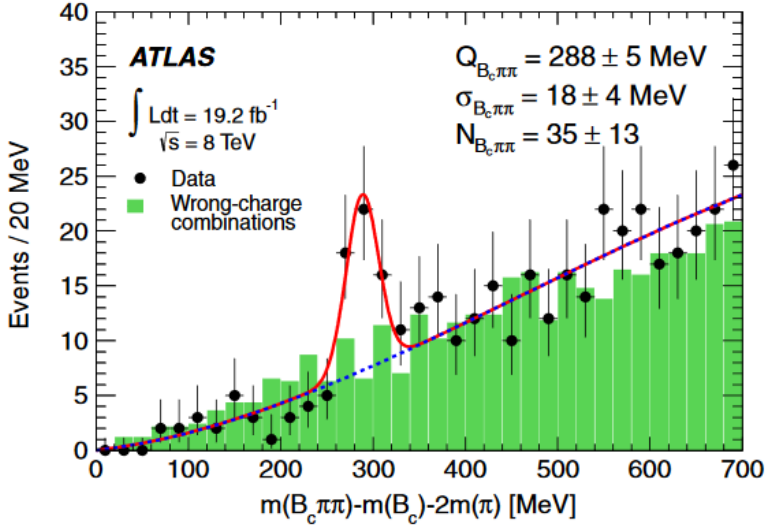
Observation of an excited B_c^+ state

[PRL 122 (2019) 232001]

Motivation

Get more knowledge about B_c^+ mass spectrum. The first excited state of B_c^+ of has been observed, measuring with the most precise $B_c(2S)^+$ mass to date.

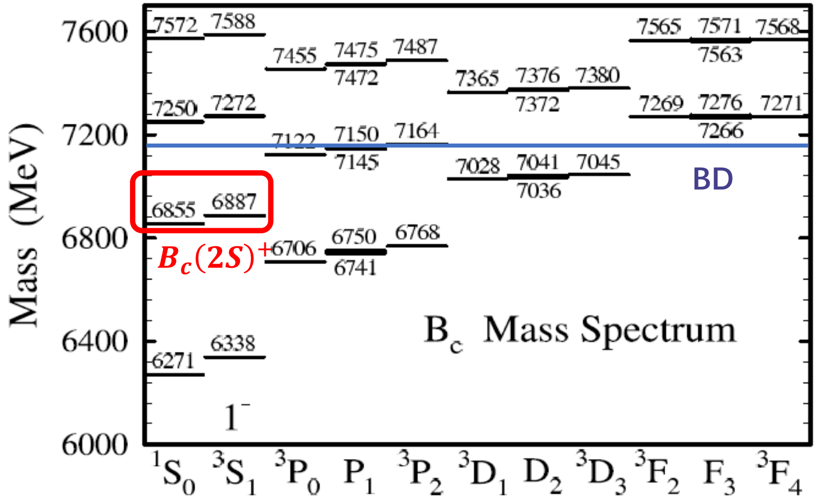
First observation of $B_c(2S)^+$ structure by ATLAS with $B_c^+\pi^+\pi^-$ final state without distinguishing different states; $M(B_c^+) = 6842 \pm 4 \pm 5$ MeV/c^2.



[PRL 113, 212004]

Abundant spectrum of B_c, the excited states still remain to be observed more

[PRD 70 (2004) 054017]



Observation of an excited B_c^+ state

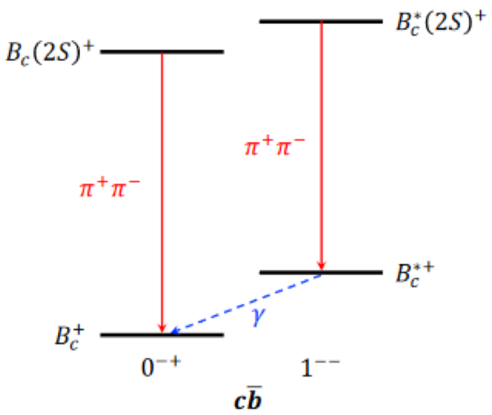
[PRL 122 (2019) 232001]

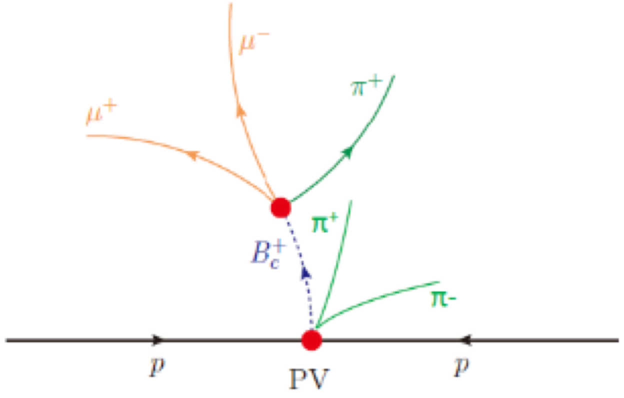
Data: Run-I and Run-II data, 8.5 fb^{-1}
About seven times larger statistics than ATLAS

Decay modes:

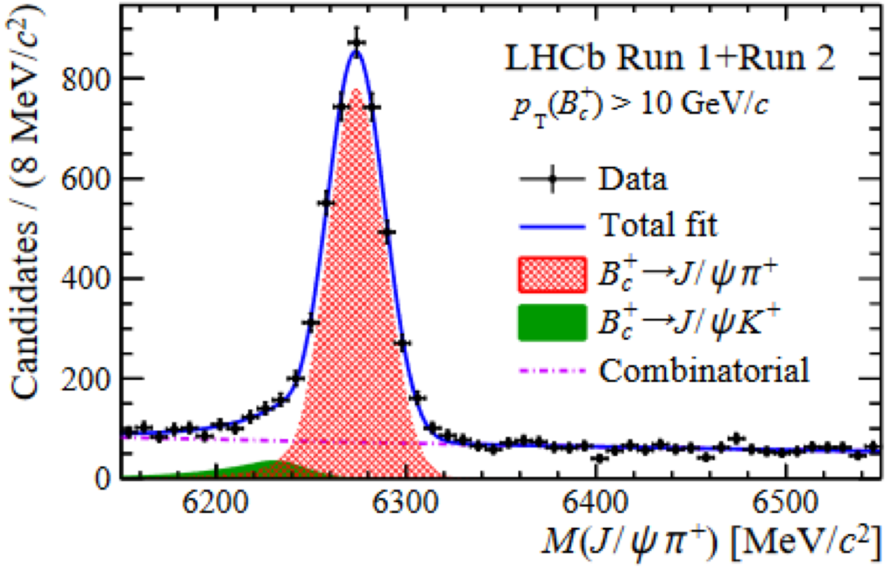
$$B_c^*(2S)^+ \to B_c^*(1S)^+(\to B_c^+(\to J/\psi\pi^+)\gamma)\pi^+\pi^-$$
$$B_c(2S)^+ \to B_c^+\pi^+\pi^-$$

Excited states:
Small decay widths (~keV) with cascade radiative or pionic decays to the ground state;





Reconstructed B_c^+ candidates with $J/\psi\pi^+$ decay
B_c^+ signal yield: 3785 ± 73



Observation of an excited B_c^+ state

[PRL 122 (2019) 232001]

Result:

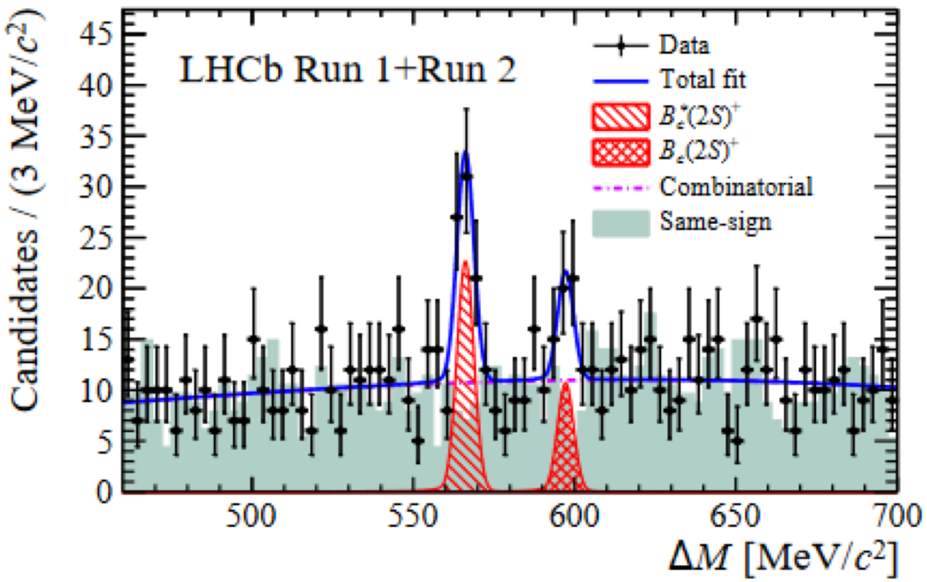
$M(B_c^*(2S)^+) = 6841.2 \pm 0.6(stat) \pm 0.1(syst) \pm 0.8(B_c^+)$ MeV/c^2

With a global (local) significance ~6.3σ (6.8σ)

$M(B_c(2S)^+) = 6872.1 \pm 1.3(stat) \pm 0.1(syst) \pm 0.8(B_c^+)$ MeV/c^2

With a global (local) significance ~2.2σ (3.2σ)

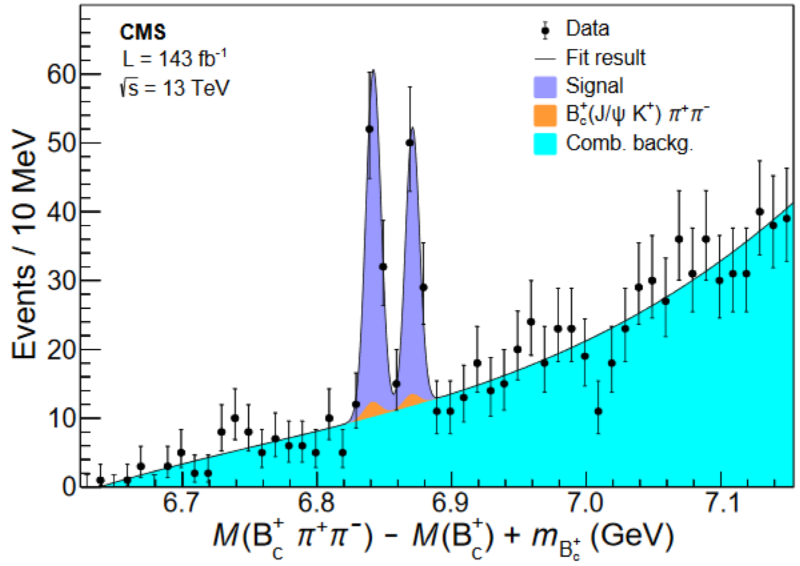
The additional source of uncertainty comes from limited knowledge of B_c^+



Mass spectrum of $\Delta M = M(B_c^+\pi^+\pi^-) - M(B_c^+)$ for $B_c^*(2S)^+$ and $B_c(2S)^+$:

$B_c^*(2S)^+$:
Signal yield: 51 ± 10

$B_c(2S)^+$:
Signal yield: 24 ± 9



[PRL 122, 132001 (2019)]

Compared with CMS results

$$M(B_c(2S)^+) = 6871.0 \pm 1.2(stat) \pm 0.8(syst) \pm 0.8(B_c^+) \text{ MeV}/c^2$$

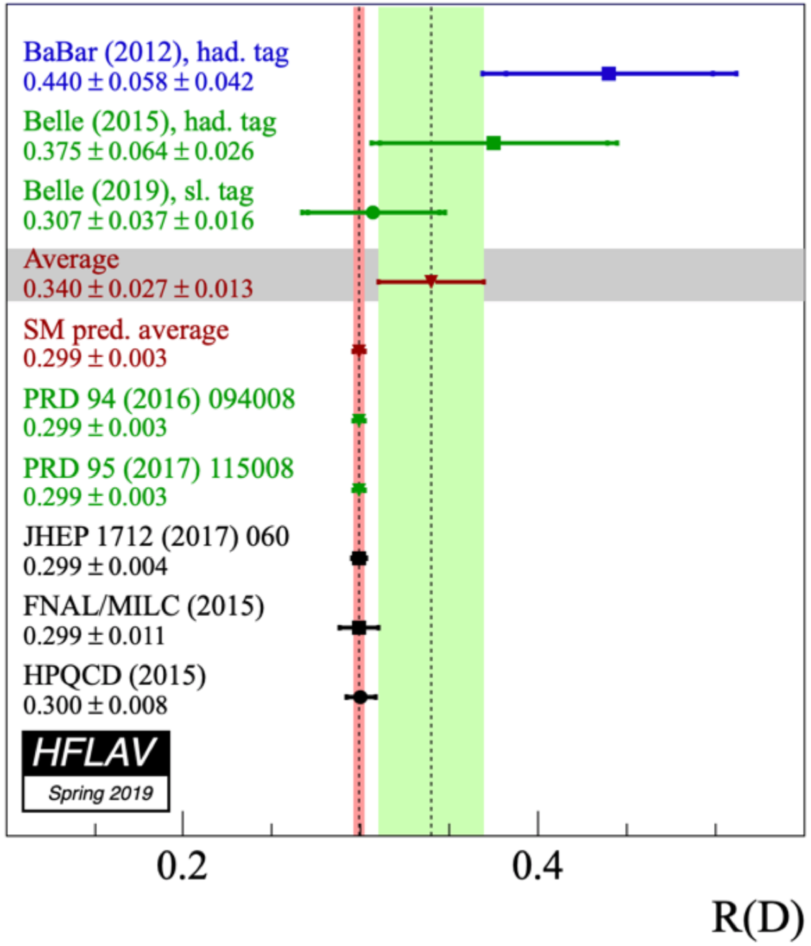
The results are all within the range of the theoretical predictions.

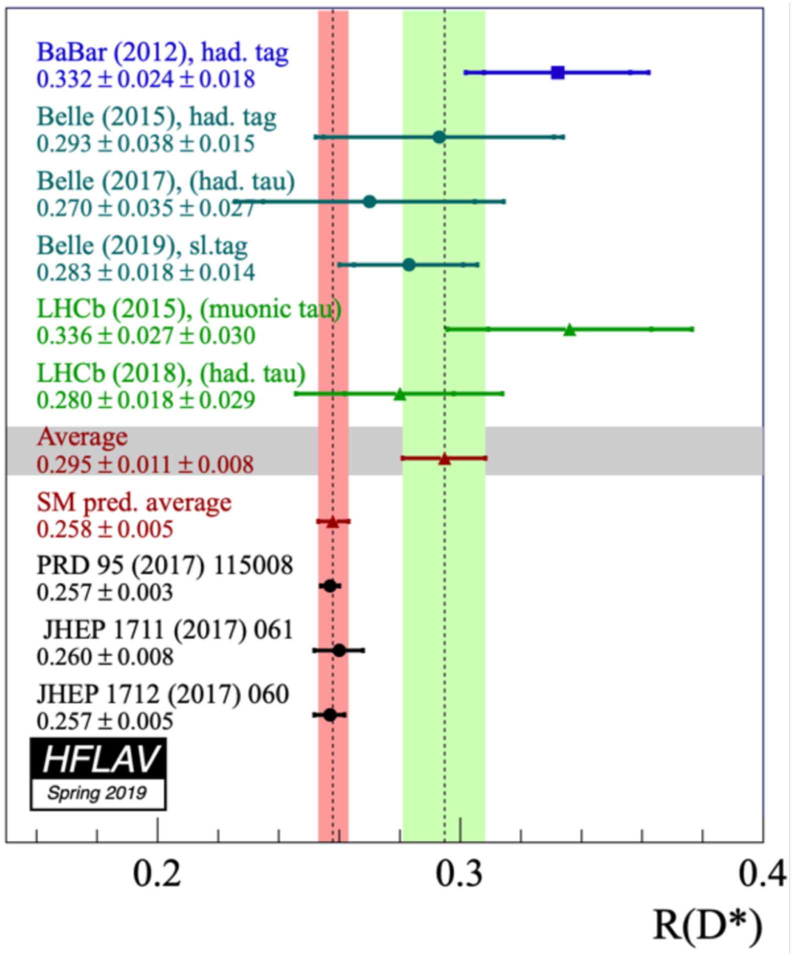
Summary

- LHCb has made big progress on B_c studies (mass, lifetime, production and decays) with Run-I and Run-II data
- A newly decay of B_c has been searched for and studied
  - To measure the unitarity triangle angle γ with an upper limit, waiting for the future studies
- A test of lepton flavor universality with semileptonic B_c decay
  - Within 2 standard deviations agreement with the theoretical predictions
  - Higher than the SM prediction
- Observation of an excited B_c^+ state
  - Previously contributed by ATLAS
  - Fascinating results from both LHCb and CMS
  - Observation of $B_c^*(2S)^+$, with an evidence of $B_c(2S)^+$

Backup

Average of R(D) and R(D*)





Multidimensional histogram

3 kinematic quantities in the multidimensional histogram:

$$m_{miss}^2 = (p_{B_c^+} - p_{J/\psi} - p_\mu)^2$$

$$q^2 = (p_{B_c^+} - p_{J/\psi})^2$$

E_μ^*： the unpaired-muon energy in the B_c^+ rest frame