MIRCO DORIGO (CERN and INFN-TS)

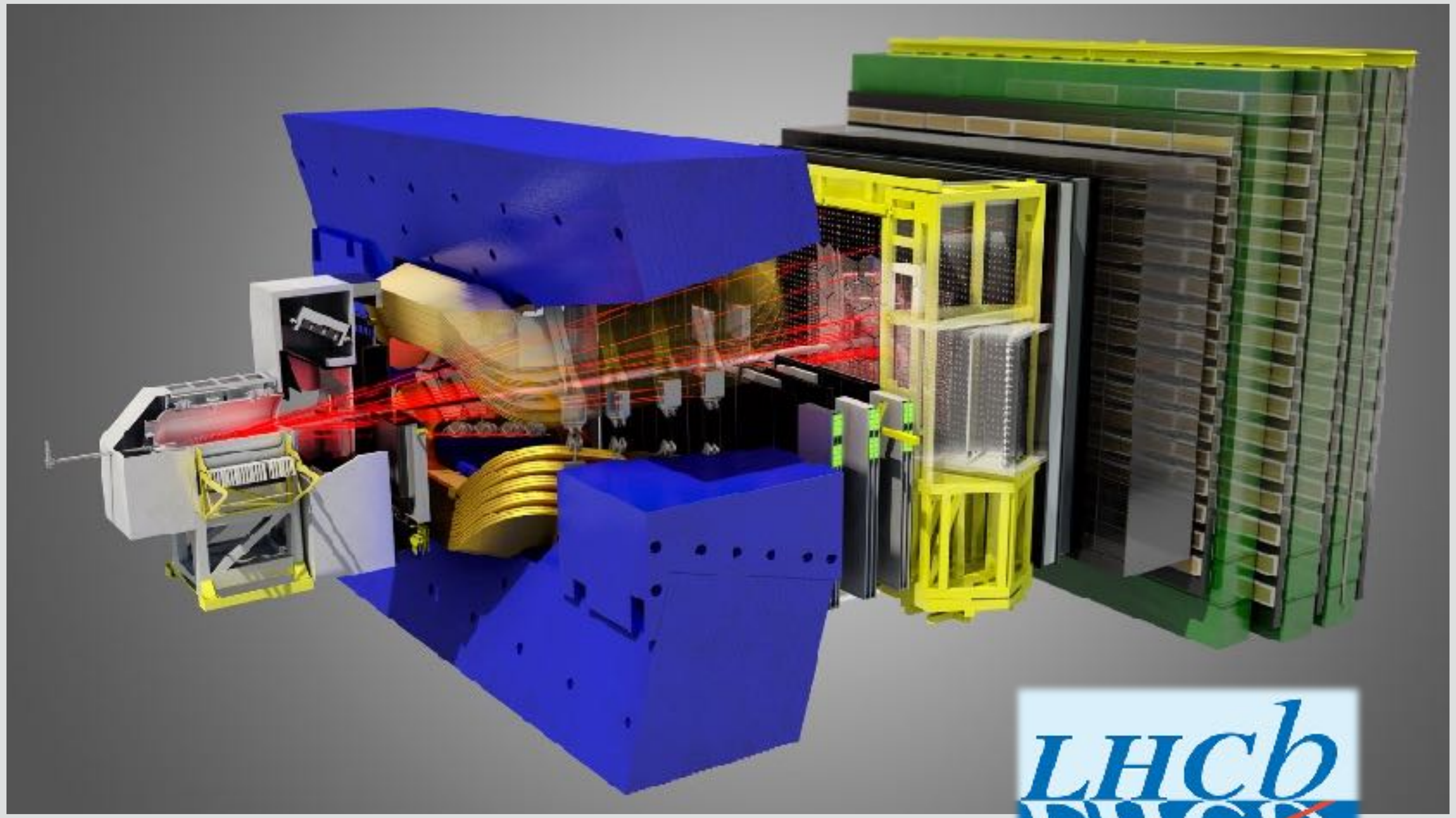
on behalf of the LHCb collaboration

B PROPERTIES, LIFETIMES, AND B_c DECAYS AT LHCb

BEAUTY 2018 - LA BIODOLA, MAY 6–12 2018

CONTENTS

- **B properties: focus on Bs lifetime.** For other recent results on b hadron properties (baryons) see Sheldon Stone's talk on Monday.
- **Bc decays: two recent searches**
- **Using data from LCHb**. Ideal for
  - lifetime measurement (large boost, precise FD and p measurements)
  - B_c searches (large b production, all b hadron species)



σ_{IPx}~20μm

σ_p/p~0.5-0.8%

PID $\varepsilon_K = 95\%$, $\varepsilon_\mu = 98\%$,

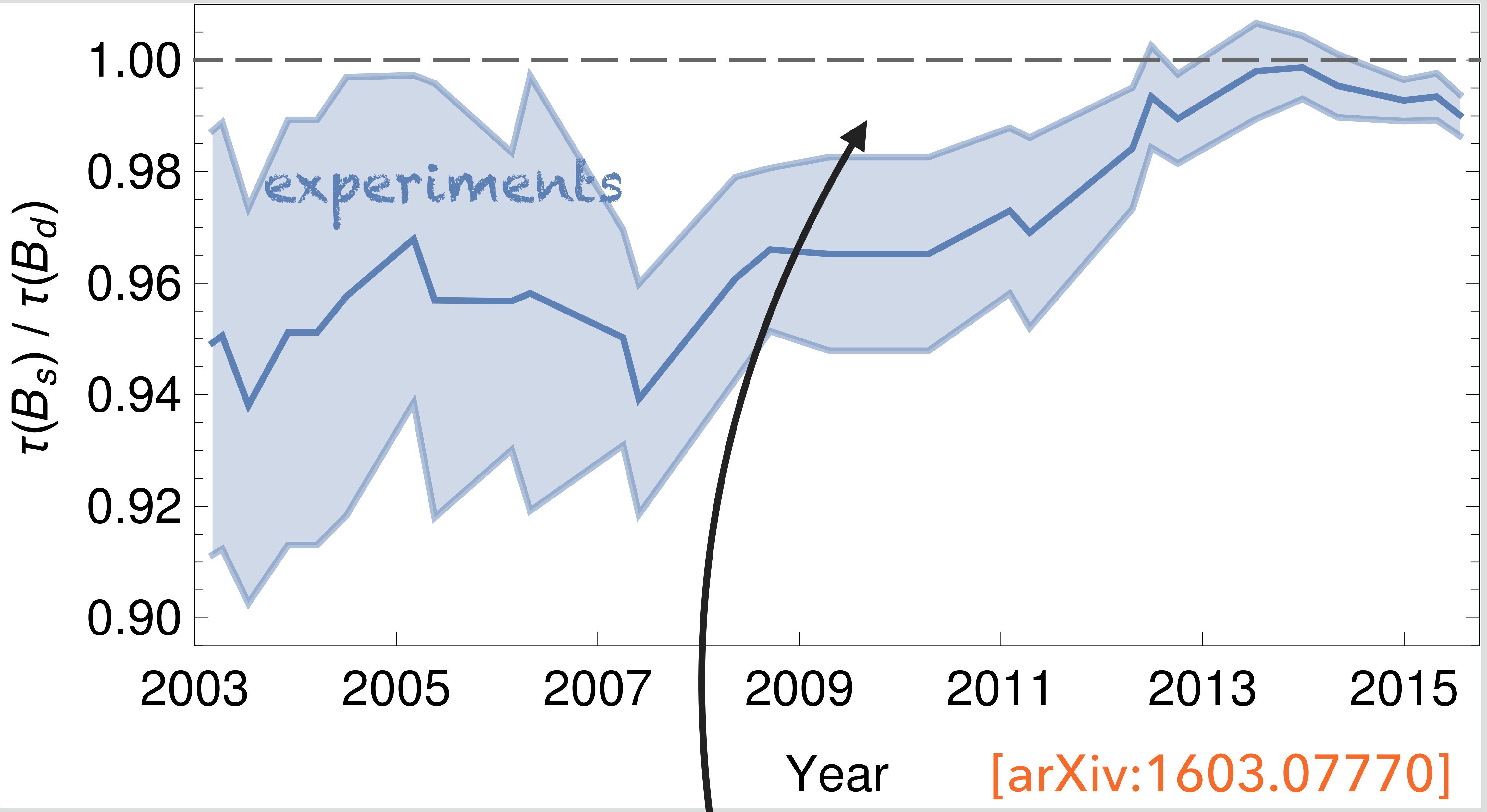
$misid_{\pi\to K} = 5\%$

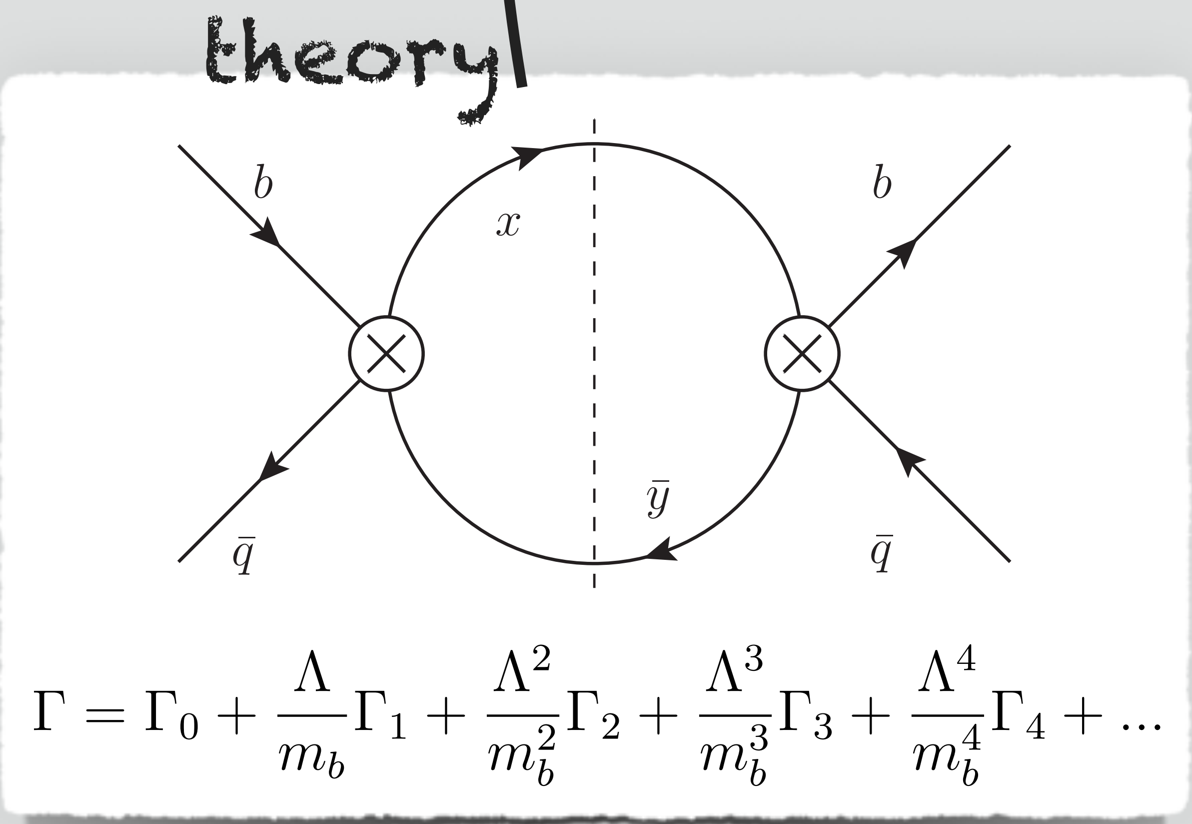
$misid_{K\to\mu} = 0.6\%$,

$misid_{\pi\to\mu} = 0.3\%$

LIFETIMES

- Supporting measurements to sharpen our theoretical tools and to build confidence on experimental methods
- Test the heavy-quark expansion model: the best predictive tool for inclusive quantities in the dynamics of heavy mesons.
- $\tau(B_s^0)/\tau(B^0)$ has key discriminating power as corrections nearly vanish.
- Data value 0.990 ± 0.004 agree well with the 0.9994 ± 0.0025 prediction [JHEP 12 (2017) 068]. Want to improve data precision.





SEMILEPTONIC

- Semileptonic (SL) decays $B_s^0 \to D_s^- \mu^+ X \nu_\mu$ provide huge sample.
- Reminder: with nonzero width-difference "B_s lifetime" is not uniquely defined. SL decays give access to the flavour-specific lifetime.

$$\tau_s^{\mathrm{fs}} = \frac{1}{\Gamma_s}\left[\frac{1+(\Delta\Gamma_s/2\Gamma_s)^2}{1-(\Delta\Gamma_s/2\Gamma_s)^2}\right]$$

- Challenging.
  - **Biased decay-time** determination from the observed decay length.
  - **Broad B mass**, spoiling separation from background and between the various signals within the inclusive final state.

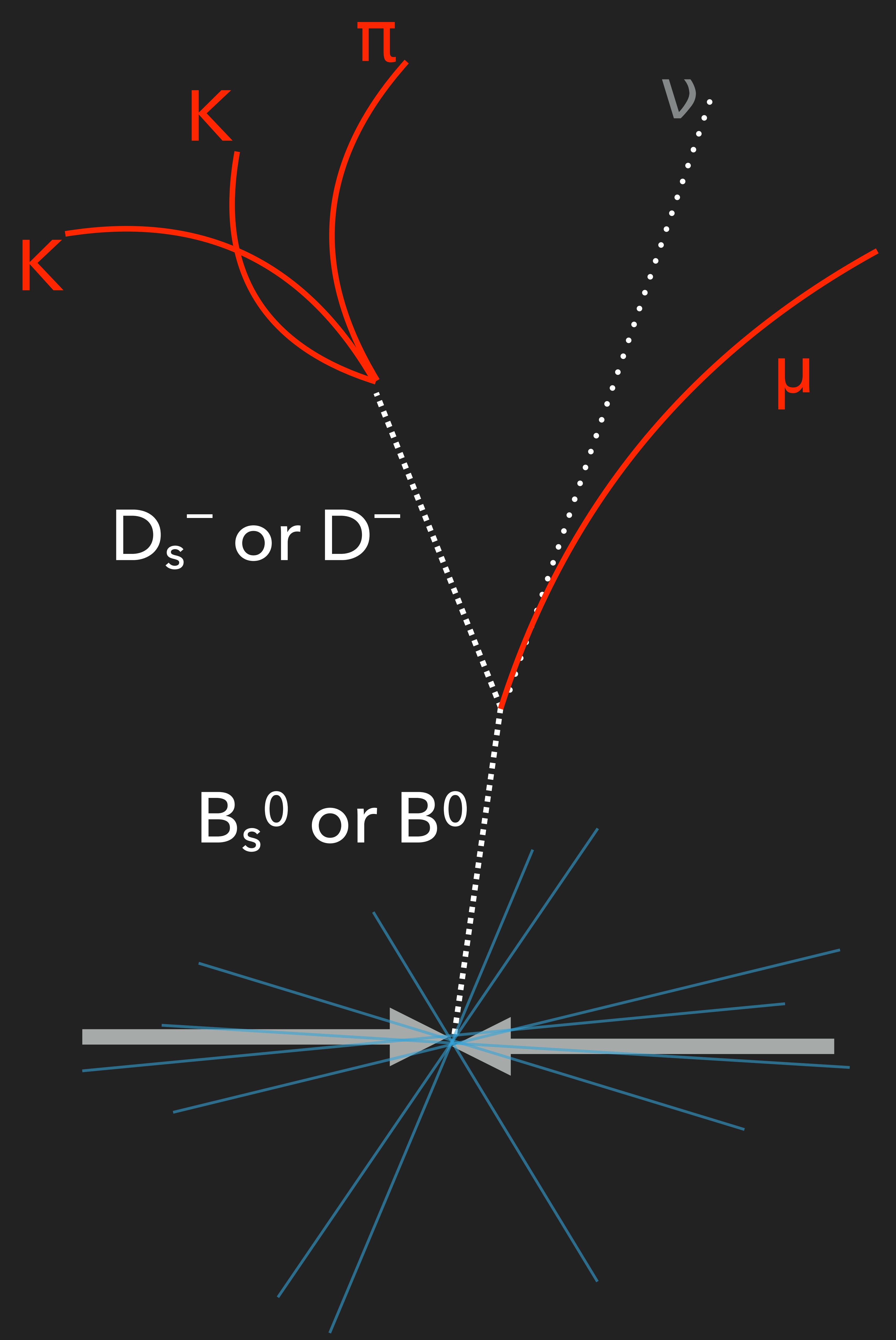
NOVEL METHOD

- τ_s^{fs} from change in B_s^0 yield vs decay time, relative to the yield of B^0 decays **reconstructed in the same final state.**

$$B^0_{(s)} \to D^-_{(s)} \mu^+ X \nu_\mu$$

- Name of the game: **minimize B_s^0-to-B^0 differences** of the selection efficiency vs the decay-time.

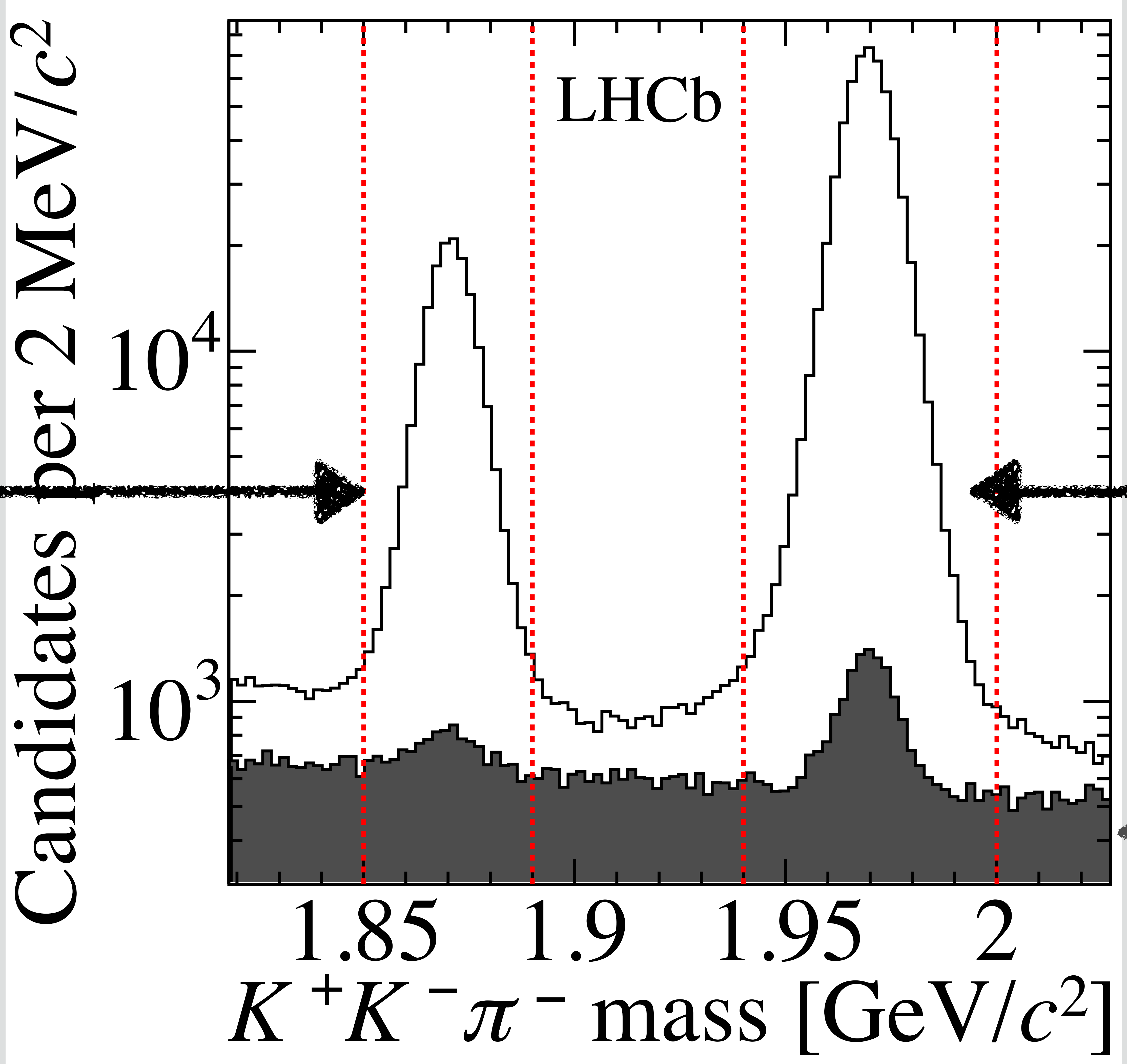
- Extract $\Delta = 1/\tau_s^{fs} - 1/\tau_{B0}$.
  Precise value of τ_{B0} as input.



SIGNAL SAMPLE

[PRL 119 (2017) 101801]

140K D^- candidates



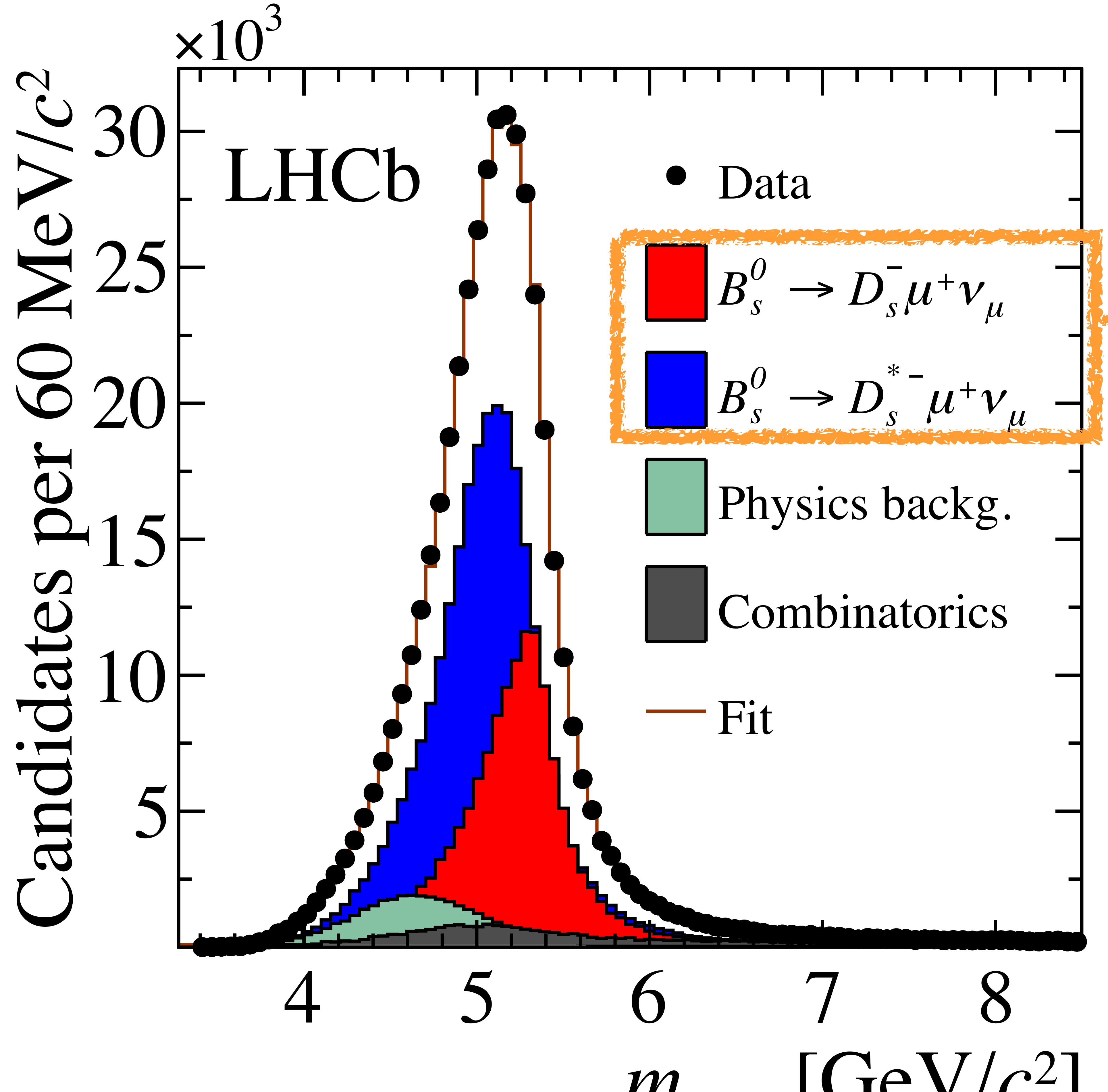
470K D_s^- candidates

← background ($D^\pm\mu^\pm$ combination)

SAMPLE COMPOSITION

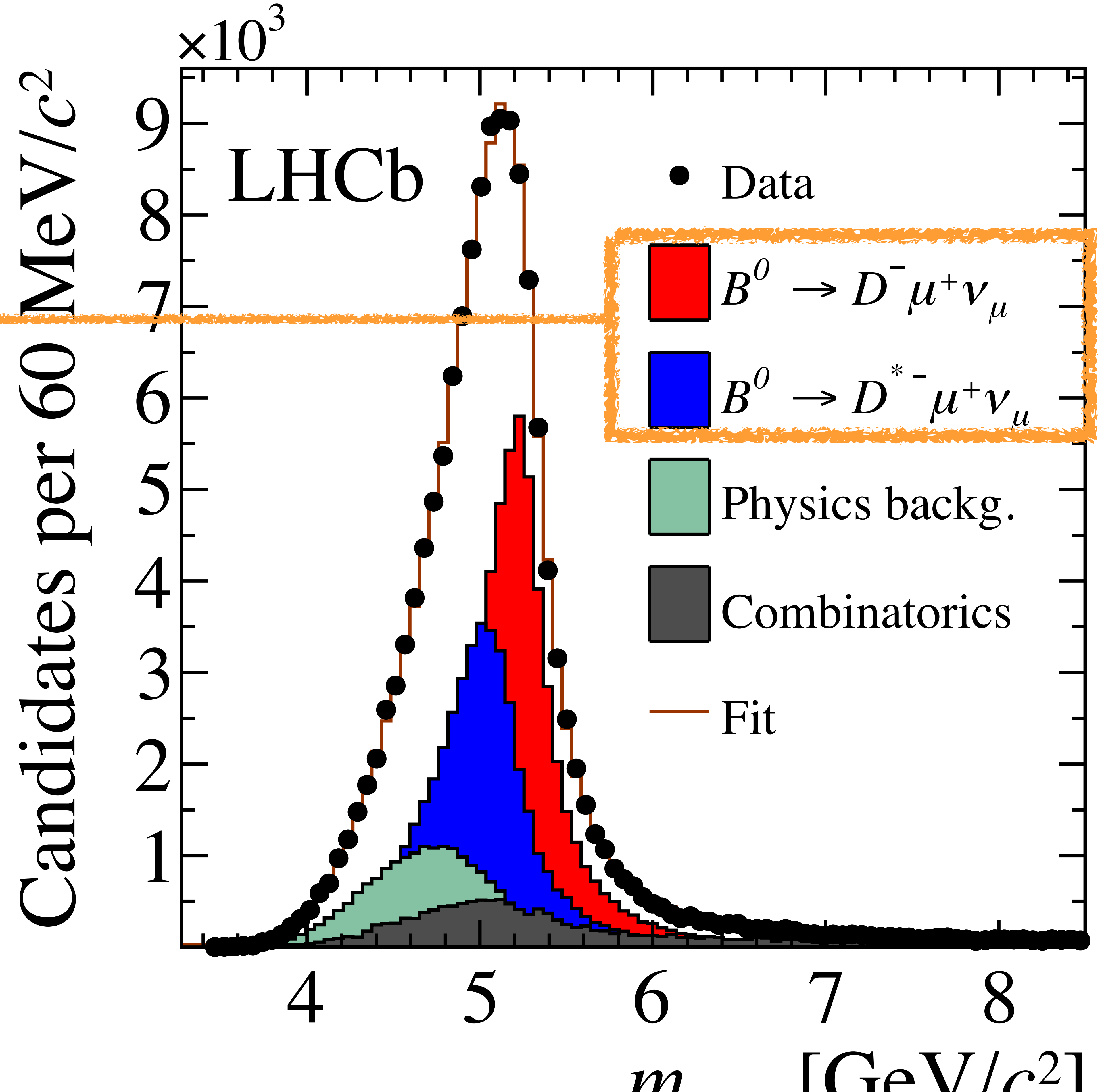
B_s^0 sample

B^0 sample serves also as validation: composition known from B-factories



[PRL 119 (2017) 101801]

Signal

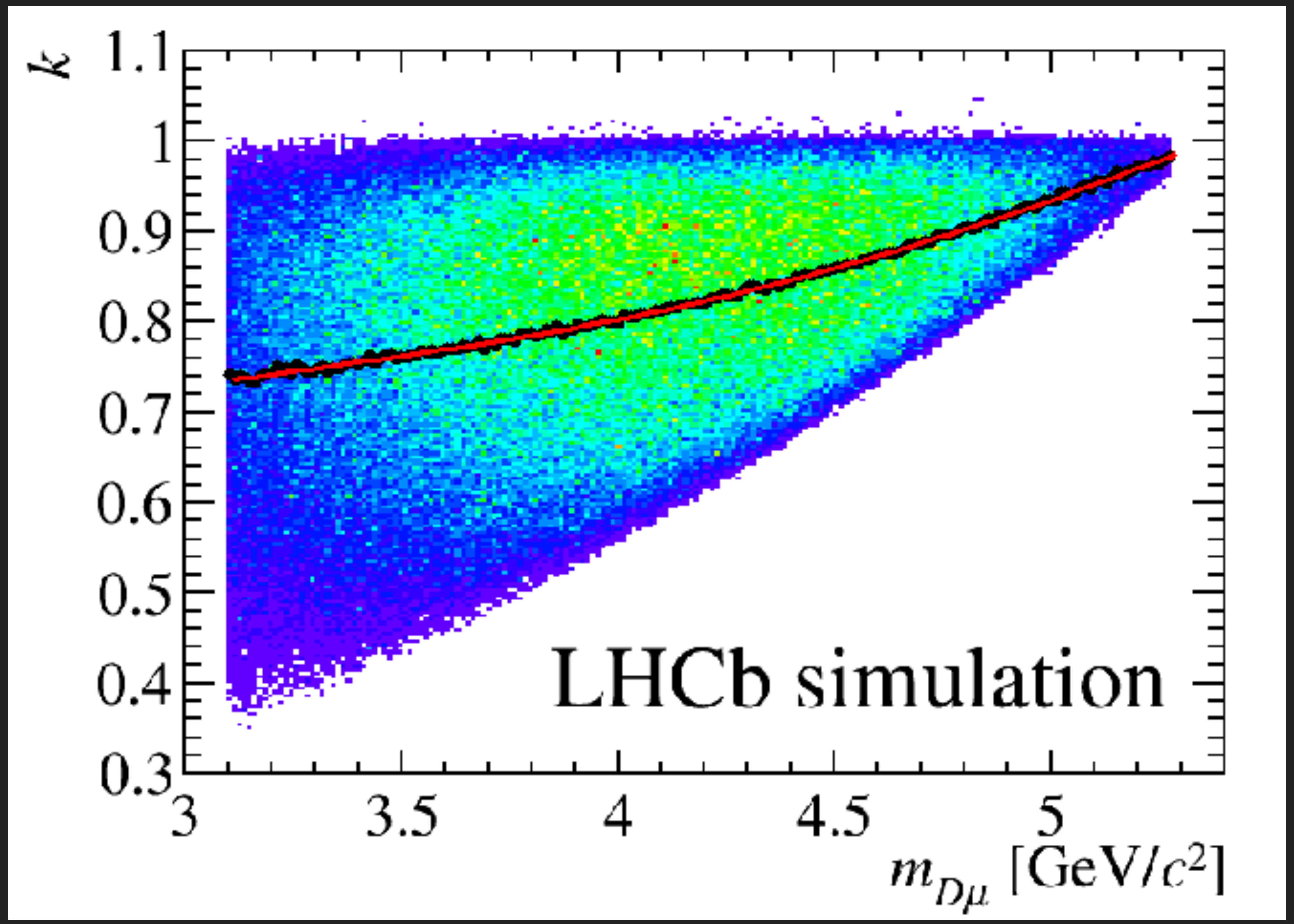


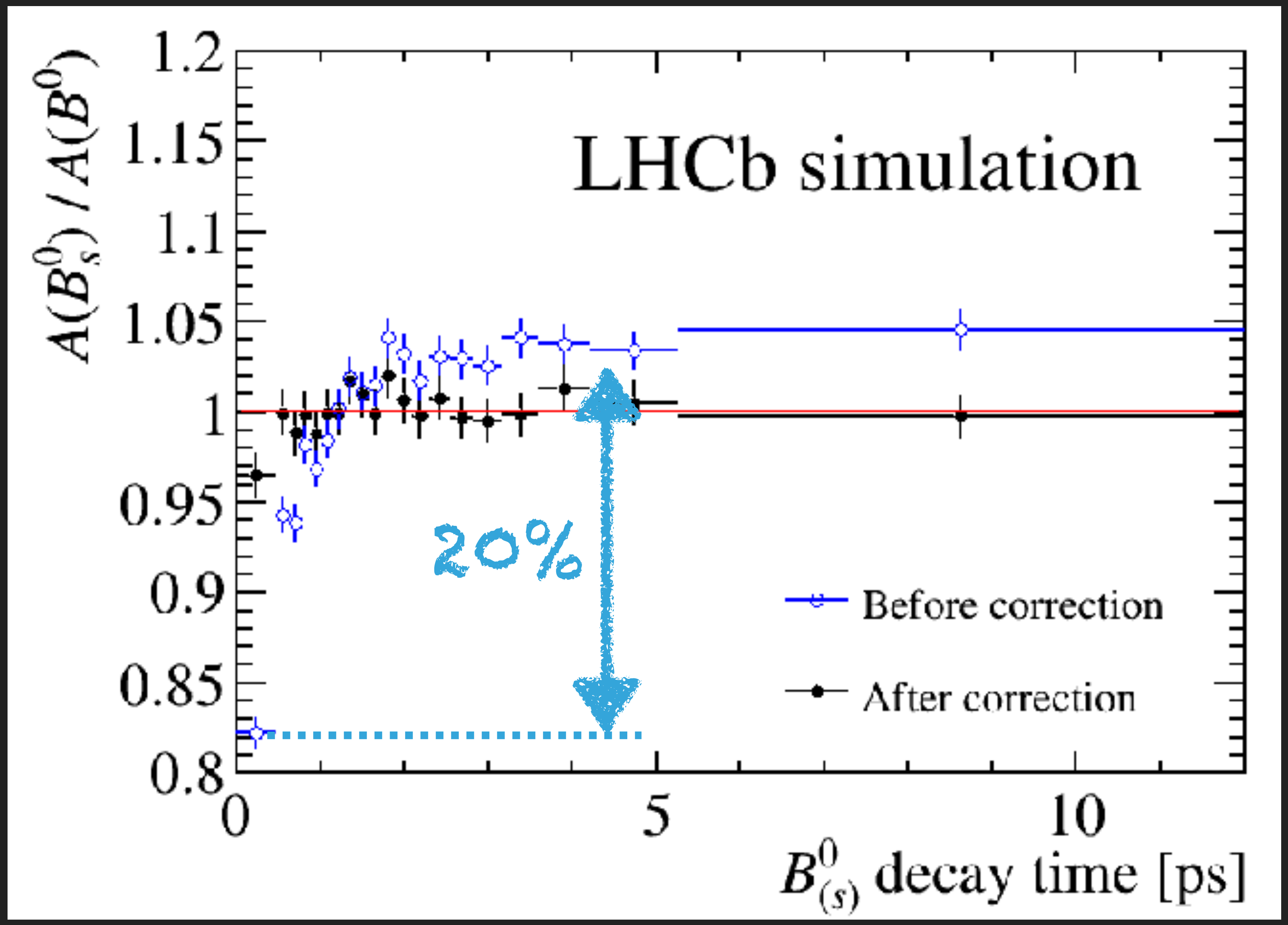
[PRL 119 (2017) 101801]

CORRECTING THE DATA

1. Unreconstructed ν momentum biases the decay-time determination. Correct observed momentum for average missing momentum as determined in simulation:
   k = p(Dμ)/p(B) [fermilab-thesis-2006-18]

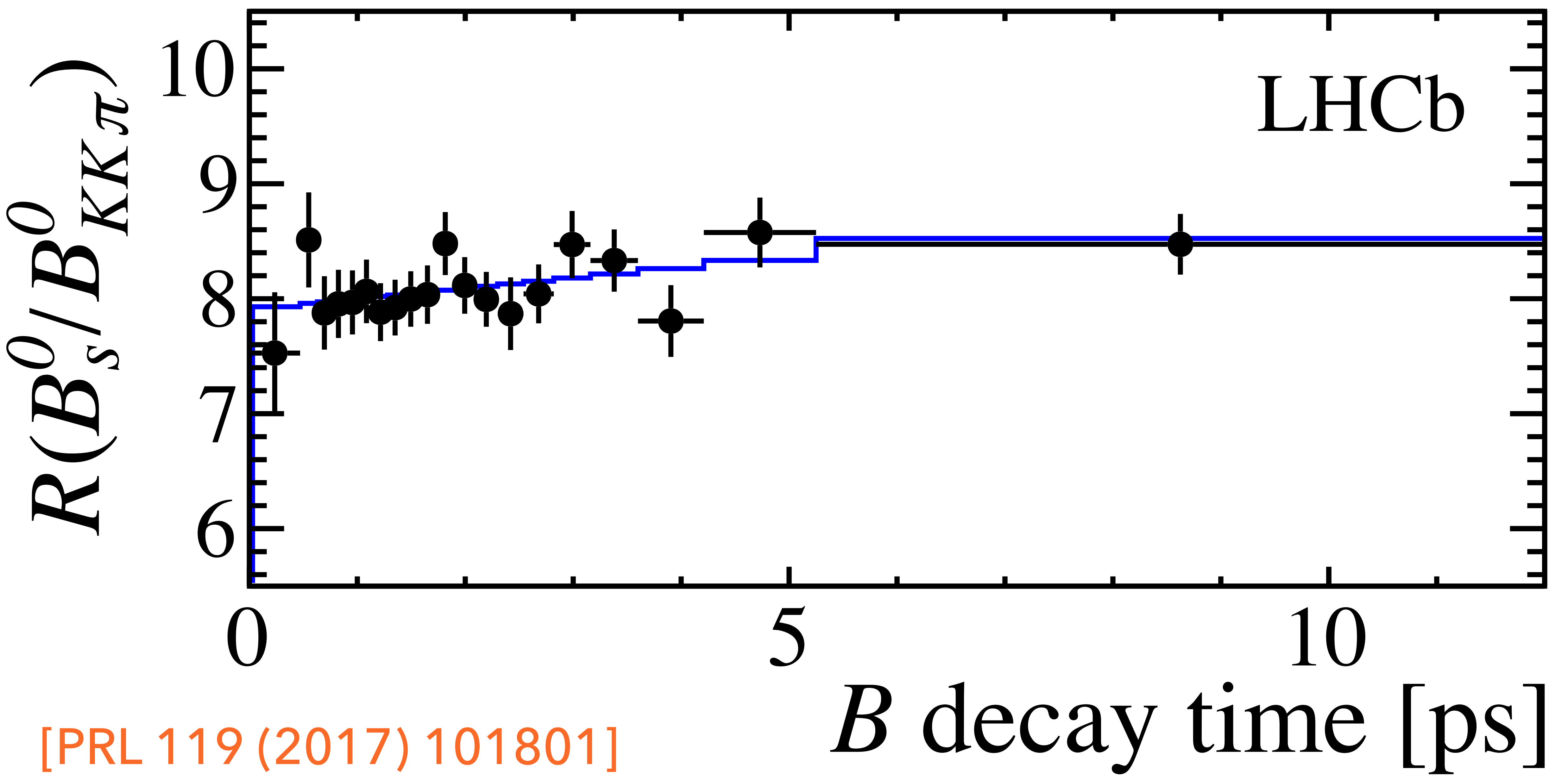
2. Want uniform signal-to-reference efficiency ratio as a function of decay time. Known 2x difference between D_s^- and D^- lifetime introduces about 20% non uniformities. Equalise the D decay time distributions.





[PRL 119 (2017) 101801]

RESULT



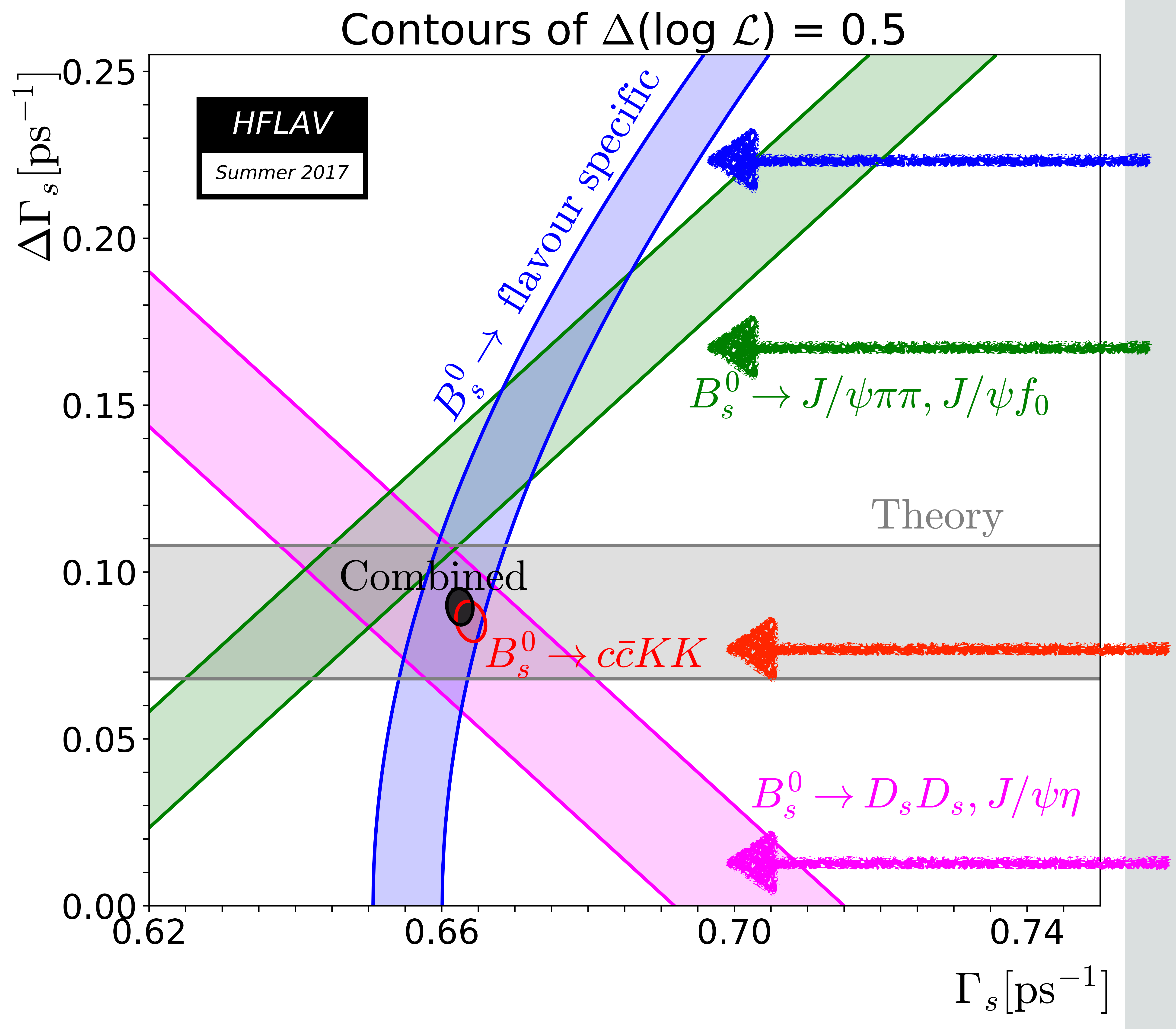
[PRL 119 (2017) 101801]

$$\tau_s^{\rm fs} = 1.547 \pm 0.013 \pm 0.010 \pm 0.004(\tau_{B^0})\ \rm ps$$

15% better than world's best. Halved the systematic of previous-best SL result.

- Agree with and improve previous determinations.
- Precision limited by the size of the reference sample. Ample chances for improvement with new data.
- Systematic dominated by the modelling in simulation of the signal.
- Method potential extends well beyond lifetimes. Method is suitable for other experiments too.

(SOME) LHCb LIFETIMES



$B_s^0 \to D\mu X$ [PRL 119 (2017) 101801]

$B_s^0 \to D_s\pi$ [PRL 113 (2014) 172001]

$B_s^0 \to J/\psi f_0$ [PRL 109 (2012) 152002]

$B_s^0 \to J/\psi\phi$ [PRL 114 (2015) 041801]

$B_s^0 \to J/\psi KK$ [JHEP 08 (2017) 037]

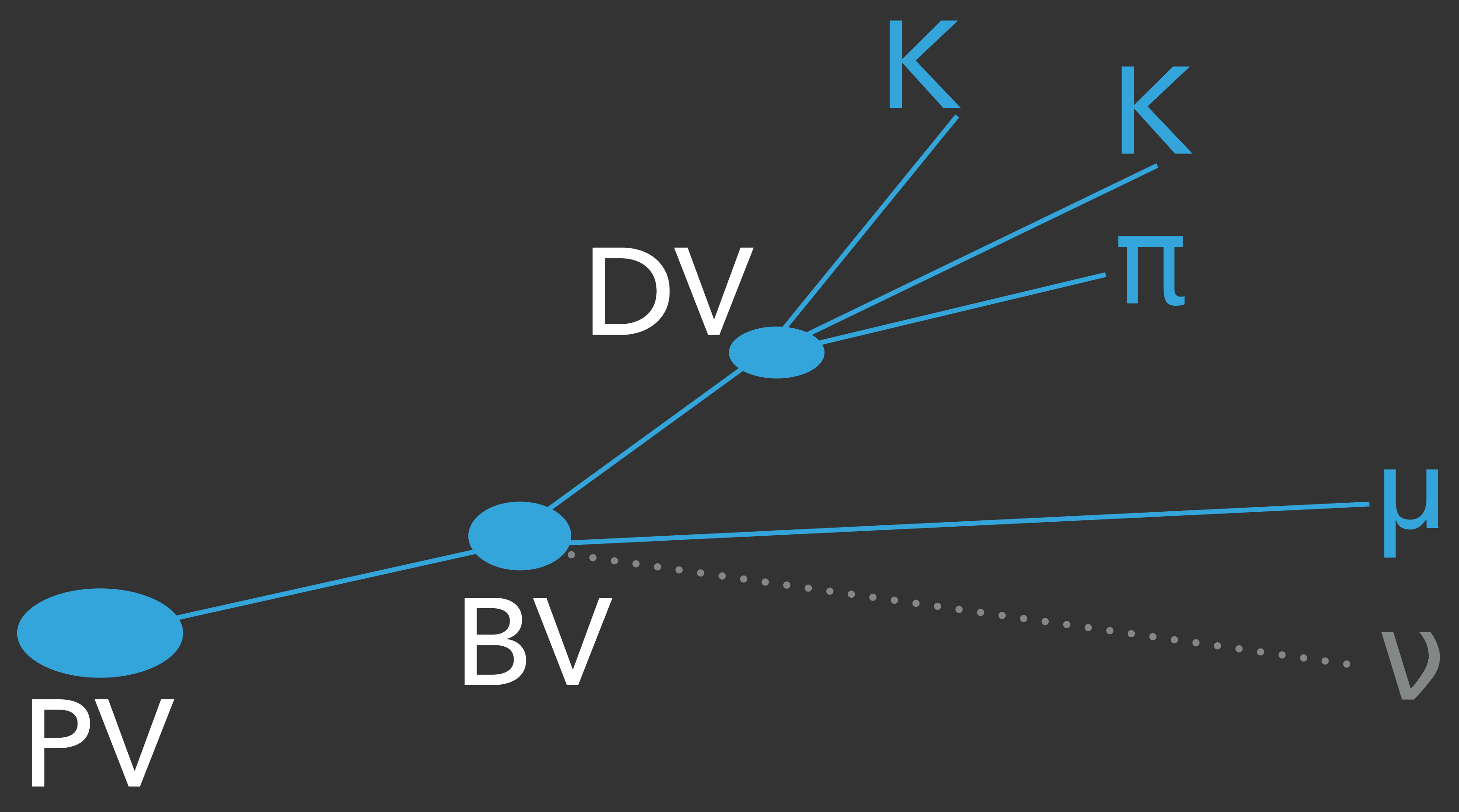
$B_s^0 \to \psi(2S)\phi$ [PLB 762 (2016) 253]

See Greig Cowan's talk on Monday

$B_s^0 \to J/\psi\eta$ [PLB 762C (2016) 484]

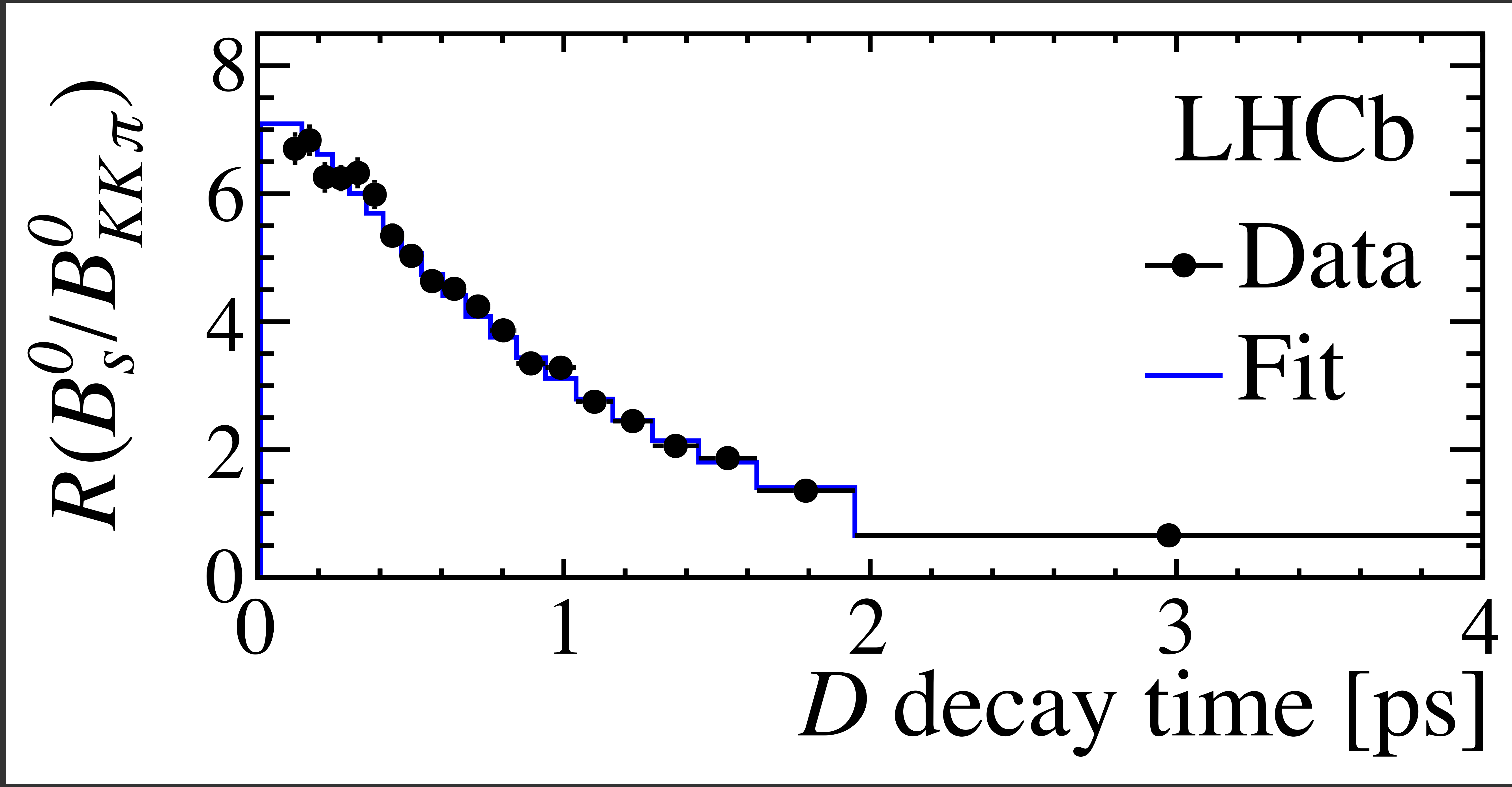
$B_s^0 \to D_s D_s$ [PRL 112 (2014) 111802]

BONUS



- Fit of composition in D decay time bin and then fit the resulting signal-to-reference yield ratio.
- Use precise D^- lifetime as input to obtain the D_s^- lifetime.
- Include a 4% relative acceptance correction and 110 fs decay-time resolution
- Agreement with world's average.

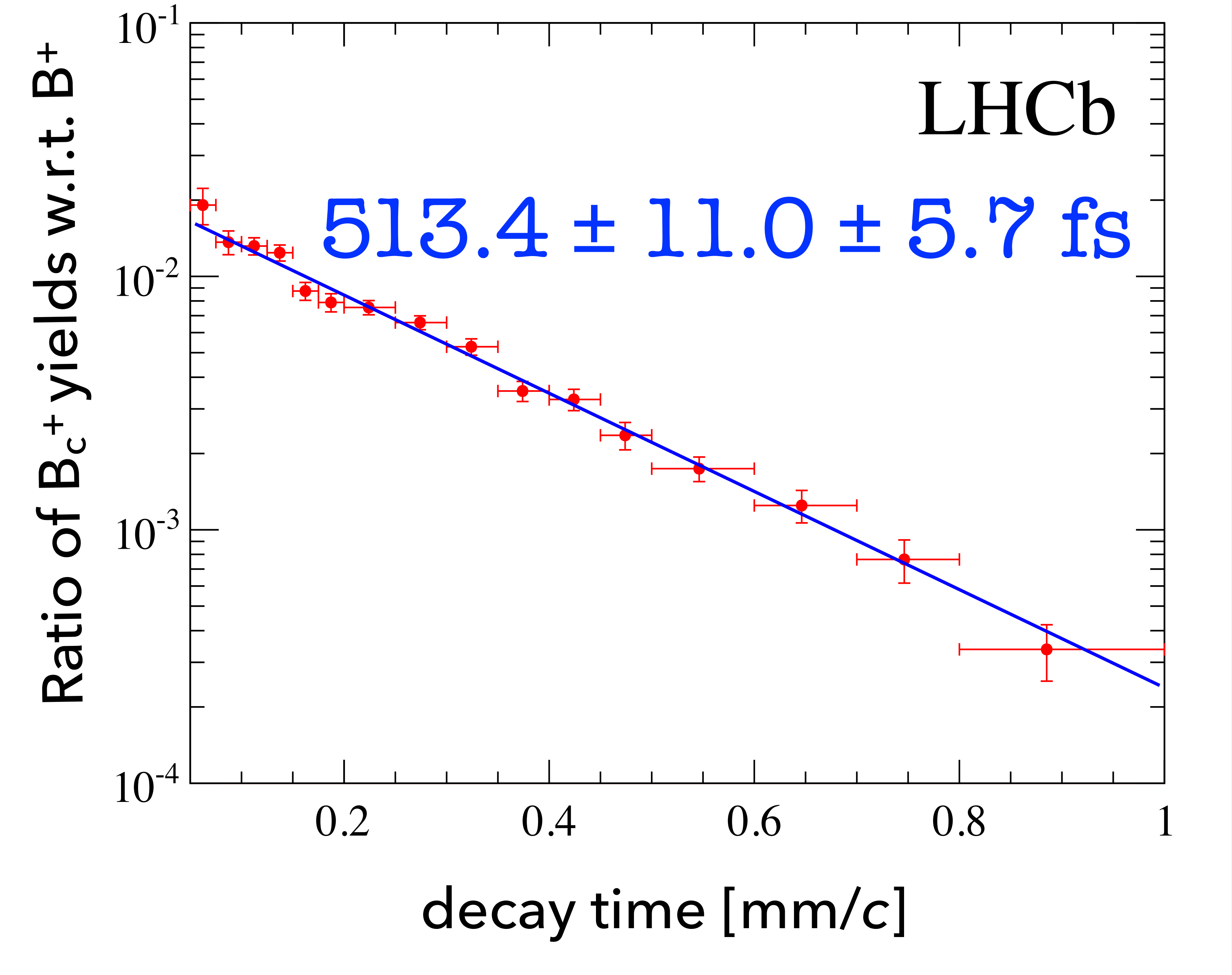
[PRL 119 (2017) 101801]



$$\tau_{D_s} = 0.5064 \pm 0.0030 \pm 0.0017 \pm 0.0017(\tau_D)\ \text{ps}$$

Improved by factor of 2 the precision of the world's best result

ON THE B_c SECTOR



- B_c first observation by CDF in '98 [PRL 81, 2432].
  Least studied of all B mesons.
  Only 16 decay modes established so far.

- Small production, about O(0.1%) of all b hadrons.
  Yet, several results from LHCb:

  ✓ Mass, PRL 109, 232001 (2012).

  ✓ Lifetime, PLB 742 (2015) 29-37; EPJ C74 (2014) 2839.

  ✓ New decays: PRD 95, 032005 (2017); PRL 118, 111803 (2017); PRD 94, 091102 (2016); PLB 759, 313 (2016); PRL 113, 152003 (2014); JHEP 1405 (2014) 148; JHEP 1311 (2013) 094; PRL 111, 181801 (2013); JHEP09(2013)075; PRD 87, 11 (2013) 112012; PRD 87, 071103 (2013); PRL 108, 251802 (2012).

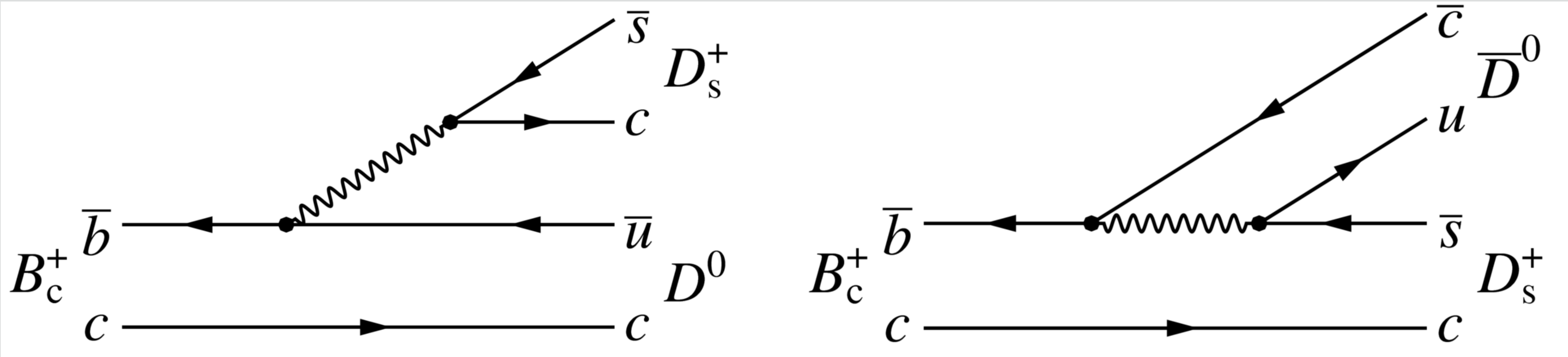
- Will focus on **two recent searches of B_c and $B_c(2S)$ decays**.

DECAYS INTO DD MESONS

- CP violation not observed yet in B_c^+ decays. $B_c^+ \to D^{(*)+} D^{(*)}$ decays, where D is $D^0_{(s)}$ or $\overline{D^0}$, proposed to measure γ [PRD 62, 057503; PRD 65, 034016].
- Ratio of interfering suppressed and favoured amplitudes expected to be about 1. Enhanced CP asymmetries w.r.t. $B^+ \to DK$ decays.
- Attempt a first observation. Expectation of BRs are around 10^{-6} for most modes.

Cabibbo-suppressed, colour-allowed

Cabibbo-favoured, colour-suppressed



$$r_{B_c^+} \equiv |A(B_c^+ \to D^0 D_s^+)/A(B_c^+ \to \overline{D}^0 D_s^+)| \approx 1$$

[PRD 62 (2000) 057503]

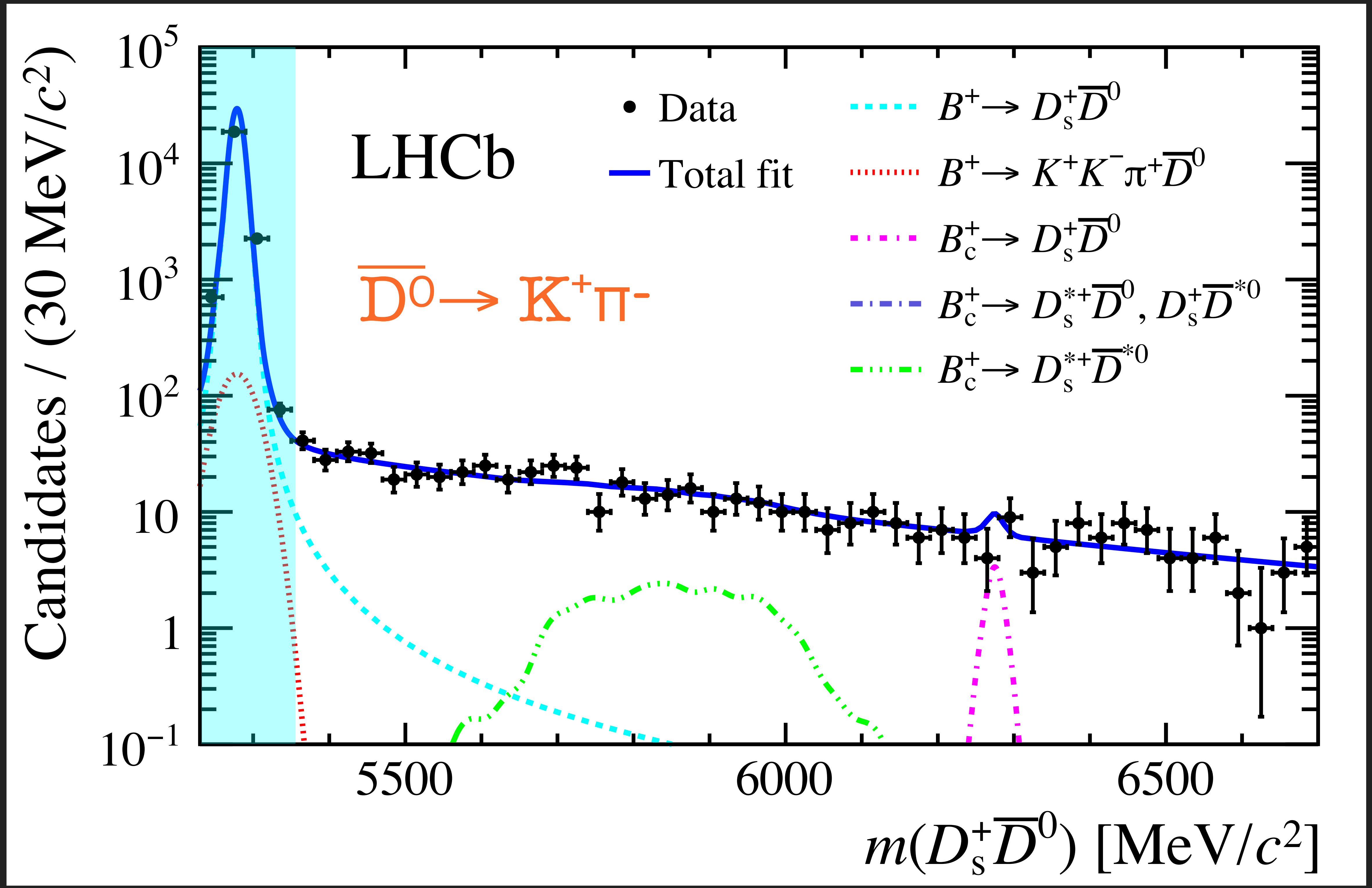
Channel	Prediction for the branching fraction $[10^{-6}]$			
$B_c^+ \to D_s^+ \overline{D}^0$	2.3 ± 0.5	4.8	1.7	2.1
$B_c^+ \to D_s^+ D^0$	3.0 ± 0.5	6.6	2.5	7.4
$B_c^+ \to D^+ \overline{D}^0$	32 ± 7	53	32	33
$B_c^+ \to D^+ D^0$	0.10 ± 0.02	0.32	0.11	0.32

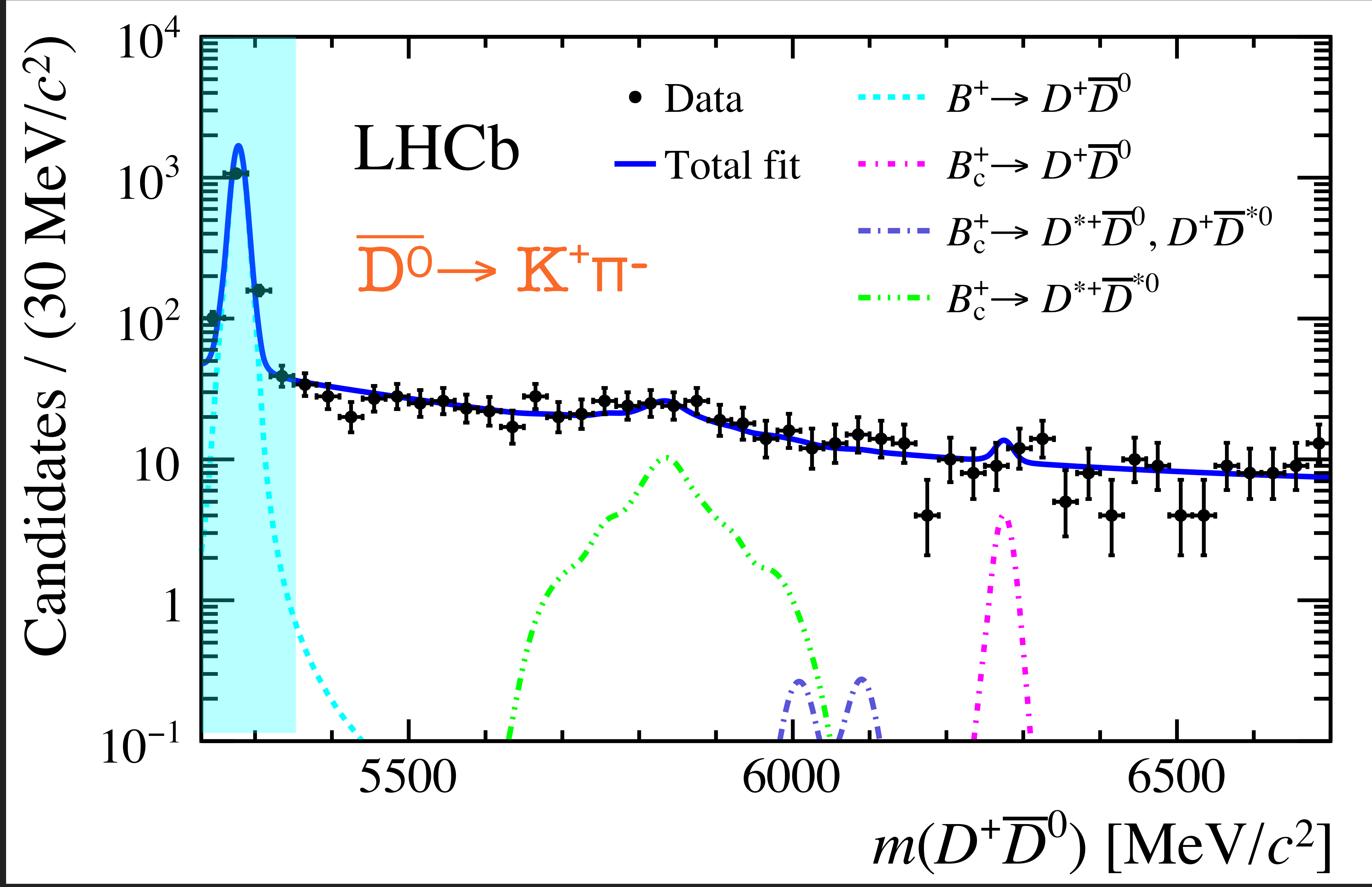
[PRD 86 (2012) 074019; arXiv:hep-ph/0211021; PLB 555 (2003),189; PRD 73 (2006), 054024]

DECAYS INTO DD MESONS

- Use 3 fb^{-1} of data collected at 7 and 8 TeV.
- Reconstruct $D_s^+ \to K^+K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$.
- **Normalise to the B⁺ modes**: 34K $D_s\overline{D^0}$, 0.5K D_sD^0, 1.9K $D^+\overline{D^0}$, 40 D^+D^0

[arXiv:1712.04702]





DECAYS INTO DD MESONS

- No signal found, extract limits at 90% [95%] CL.

[arXiv:1712.04702]

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^+ \overline{D}^0)}{\mathcal{B}(B^+ \to D_s^+ \overline{D}^0)} = (3.0 \pm 3.7) \times 10^{-4}\ [< 0.9\,(1.1) \times 10^{-3}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^+ D^0)}{\mathcal{B}(B^+ \to D_s^+ \overline{D}^0)} = (-3.8 \pm 2.6) \times 10^{-4}\ [< 3.7\,(4.7) \times 10^{-4}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D^+ \overline{D}^0)}{\mathcal{B}(B^+ \to D^+ \overline{D}^0)} = (8.0 \pm 7.5) \times 10^{-3}\ [< 1.9\,(2.2) \times 10^{-2}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D^+ D^0)}{\mathcal{B}(B^+ \to D^+ \overline{D}^0)} = (2.9 \pm 5.3) \times 10^{-3}\ [< 1.2\,(1.4) \times 10^{-2}].$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^{*+} \overline{D}^{*0})}{\mathcal{B}(B^+ \to D_s^+ \overline{D}^0)} = (3.2 \pm 4.3) \times 10^{-3}\ [< 1.1\,(1.3) \times 10^{-2}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^{*+} D^{*0})}{\mathcal{B}(B^+ \to D_s^+ \overline{D}^0)} = (7.0 \pm 9.2) \times 10^{-3}\ [< 2.0\,(2.4) \times 10^{-2}],$$

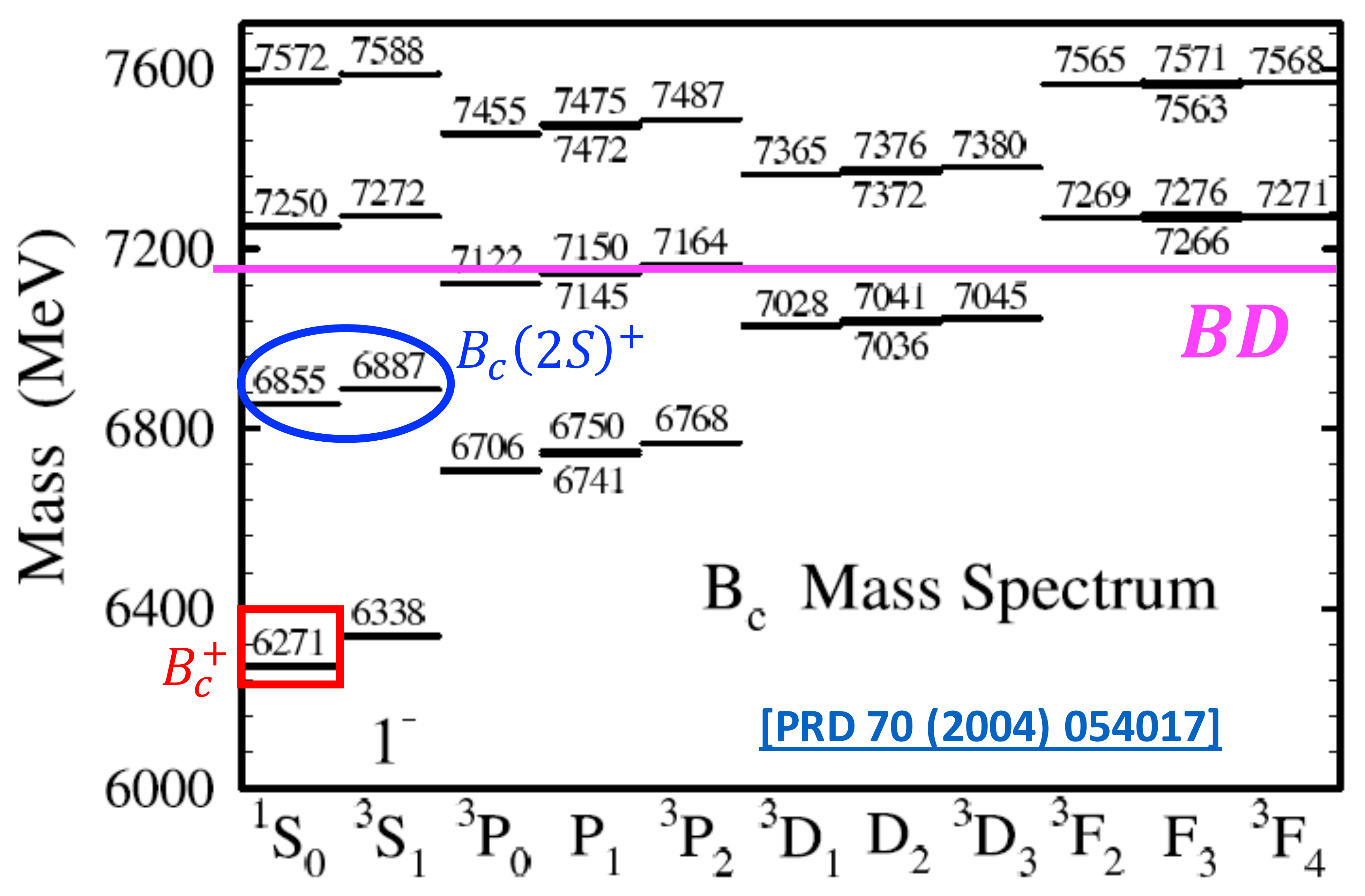
$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D^{*+} \overline{D}^{*0})}{\mathcal{B}(B^+ \to D^+ \overline{D}^0)} = (3.4 \pm 2.3) \times 10^{-1}\ [< 6.5\,(7.3) \times 10^{-1}],$$

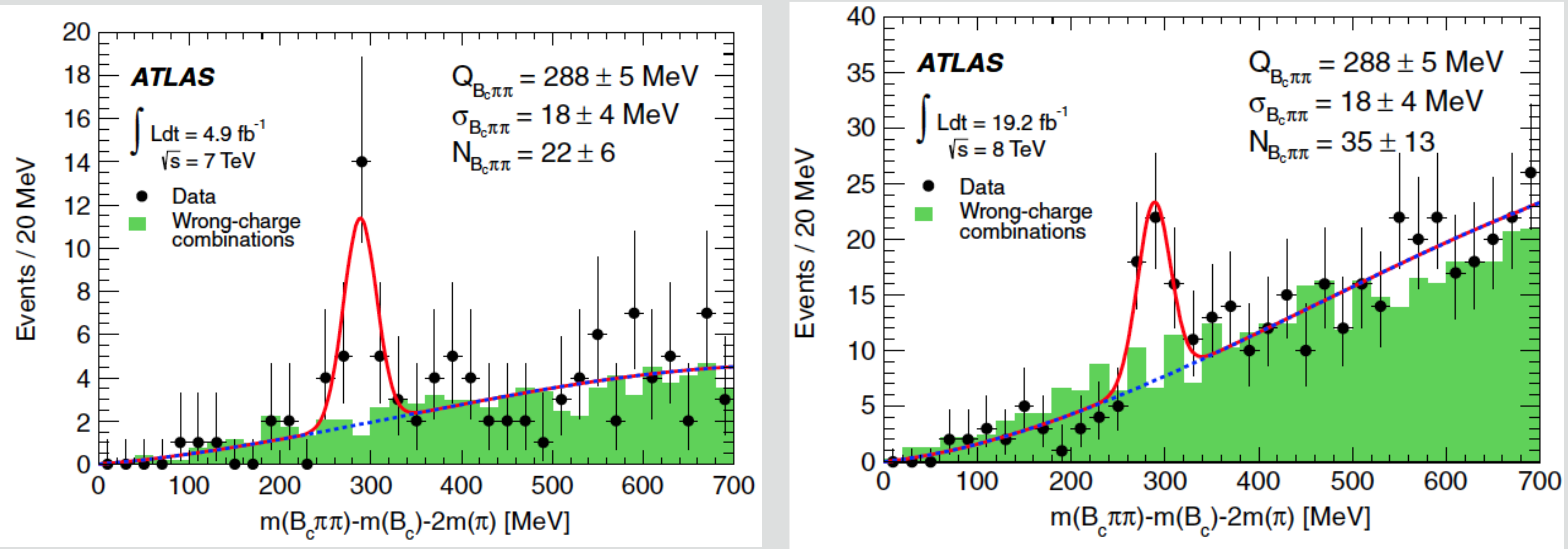
$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D^{*+} D^{*0})}{\mathcal{B}(B^+ \to D^+ \overline{D}^0)} = (-4.1 \pm 9.1) \times 10^{-2}\ [< 1.3\,(1.6) \times 10^{-1}].$$

- Upper limits also for combination of decays into a $D_s D^{0*}$ and $D_s{}^* D^0$ final states.
- Assuming f_c/f_u about 1%, extract limits on the B_c^+ decays BRs: far above the predictions – e.g. $BR(B_c^+ \to D^+ \overline{D}^0) < 6.0 \times 10^{-4}$ at 90% CL.

SEARCH FOR EXCITED B_c

- A rich mass spectrum predicted by various QCD potential models and Lattice QCD.
- States below BD threshold can only undergo radiative or hadronic transitions to the ground state B_c^+ which decays weakly.
- ATLAS observed $B_c(2S)^+$ using ~330 $B_c^+ \to J/\psi\pi^+$ decays. No discrimination between
  - $B_c(2^1S_0)^+ \to B_c^+\pi^+\pi^-$
  - $B_c(2^3S_1)^+ \to B_c^{*+}(\to B_c^+\gamma)\pi^+\pi^-$

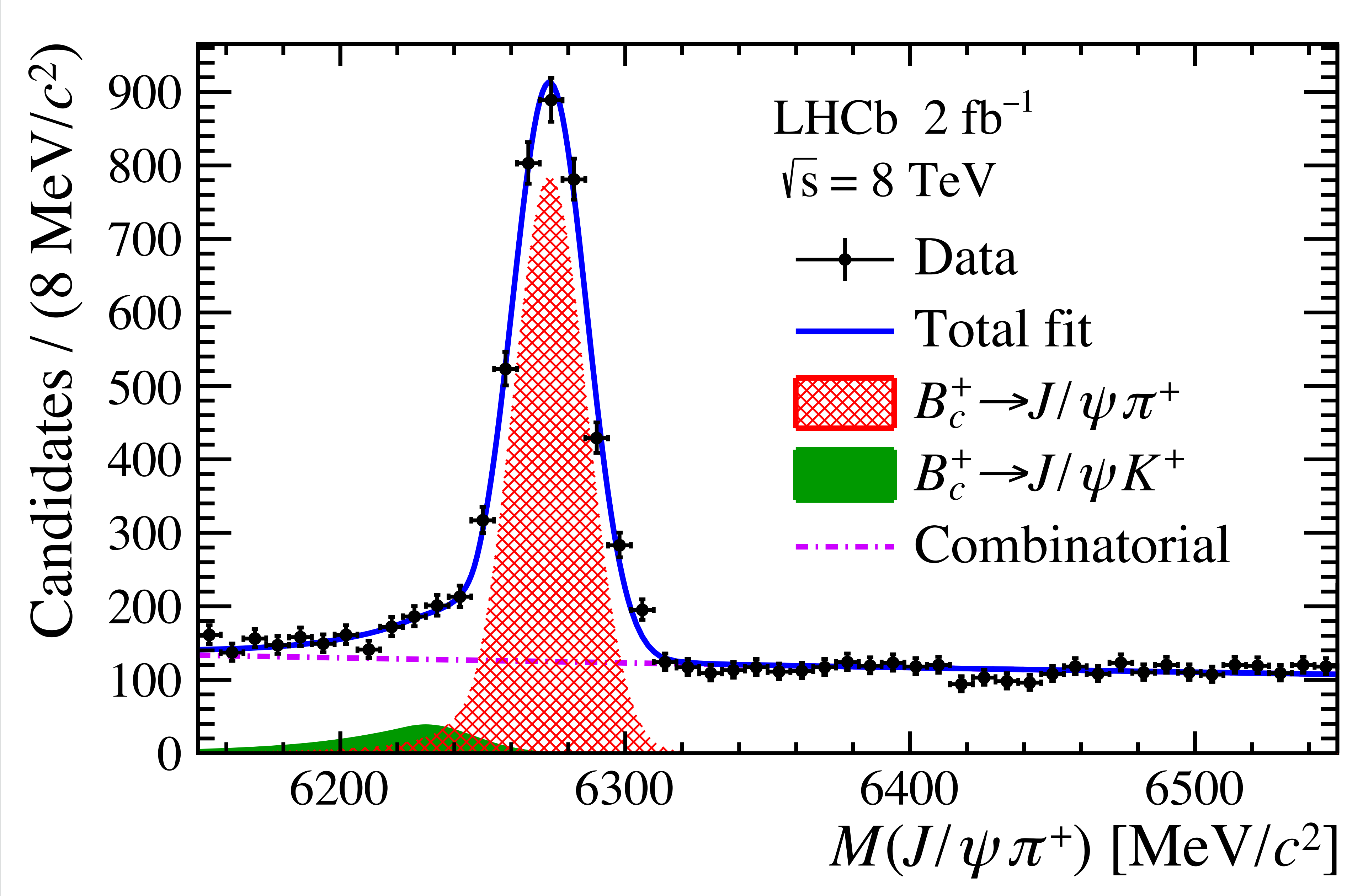




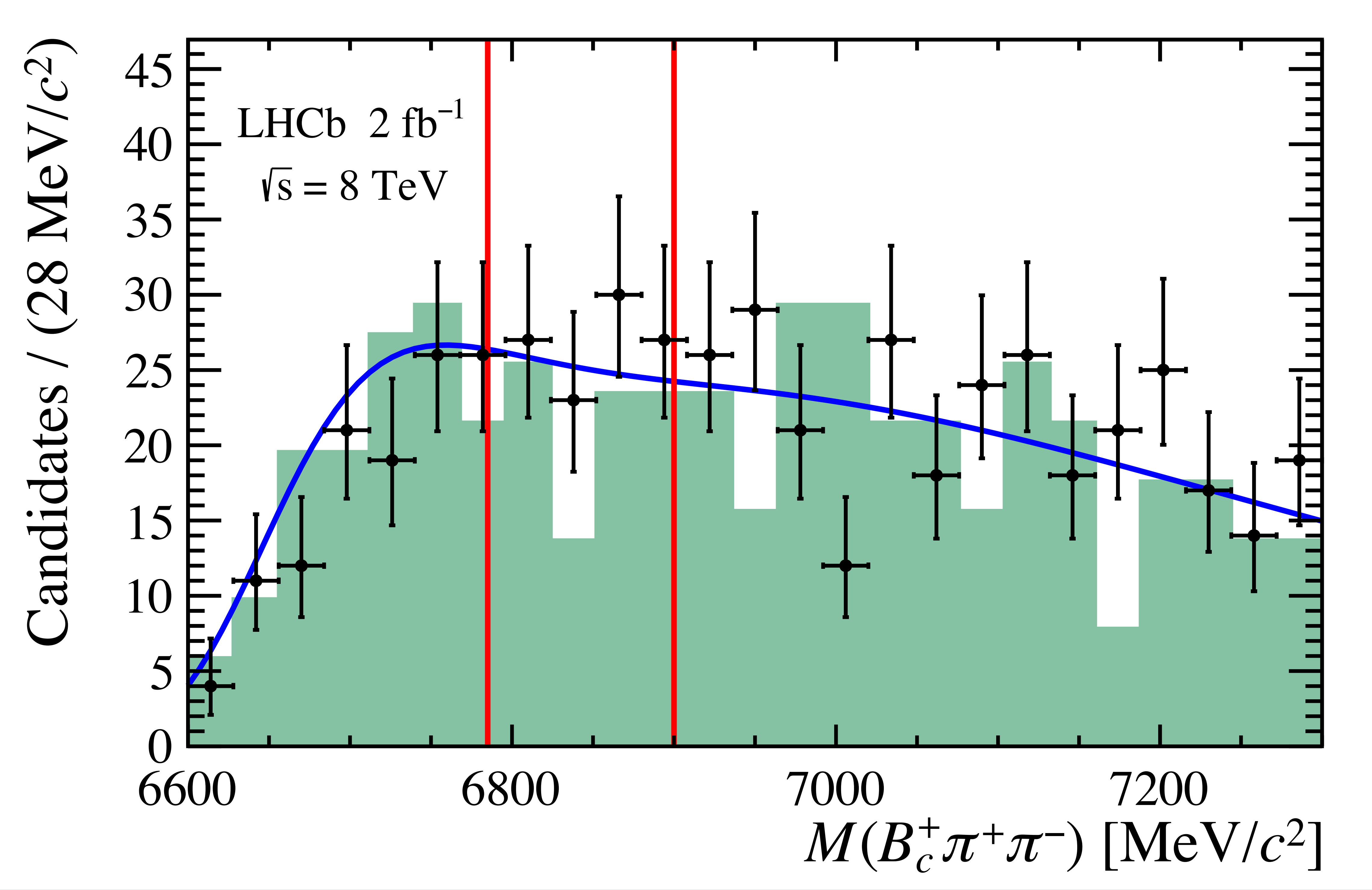
[PRL 113 (2014) 12004]

SEARCH FOR EXCITED B_c

- Use 2 fb^{-1} collected at 8 TeV. Reconstruct about 3300 $B_c^+ \to J/\psi\pi^+$ decays, selected with a BDT exploiting vertex displacement and kinematics of daughter particles.



[JHEP 01 (2018) 138]



- Attach $\pi^+\pi^-$ pairs to form the excited state candidates. Categorise them with a MLP exploring angles between B_c and $B_c(2S)$ candidates. No signal found.

SEARCH FOR EXCITED B_c

- Put limits on $\mathcal{R} = \frac{\sigma_{B_c^{(*)}(2S)^+}}{\sigma_{B_c^+}} \cdot \mathcal{B}(B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-)$

  and compared with the ATLAS measurement.

	$\sqrt{s} = 7\,\text{TeV}$	$\sqrt{s} = 8\,\text{TeV}$	
ATLAS	$(0.22 \pm 0.08\,(\text{stat}))/\varepsilon_7$	$(0.15 \pm 0.06\,(\text{stat}))/\varepsilon_8$	[PRL 113 (2014) 12004]
LHCb	–	$< [0.04, 0.09]$	[JHEP 01 (2018) 138]

- $\varepsilon_{7,8}$ is the efficiency to reconstruct $B_c(2S)^+$ w.r.t. the B_c^+ signals.
  It's ≤1, but much larger than that of LHCb.

- LHCb upper limits at 95% CL in the vicinity of the ATLAS peak at ~6842 MeV/c.

- The LHCb and ATLAS measurements are compatible in case of large values of $\varepsilon_{7,8}$.

CONCLUSION

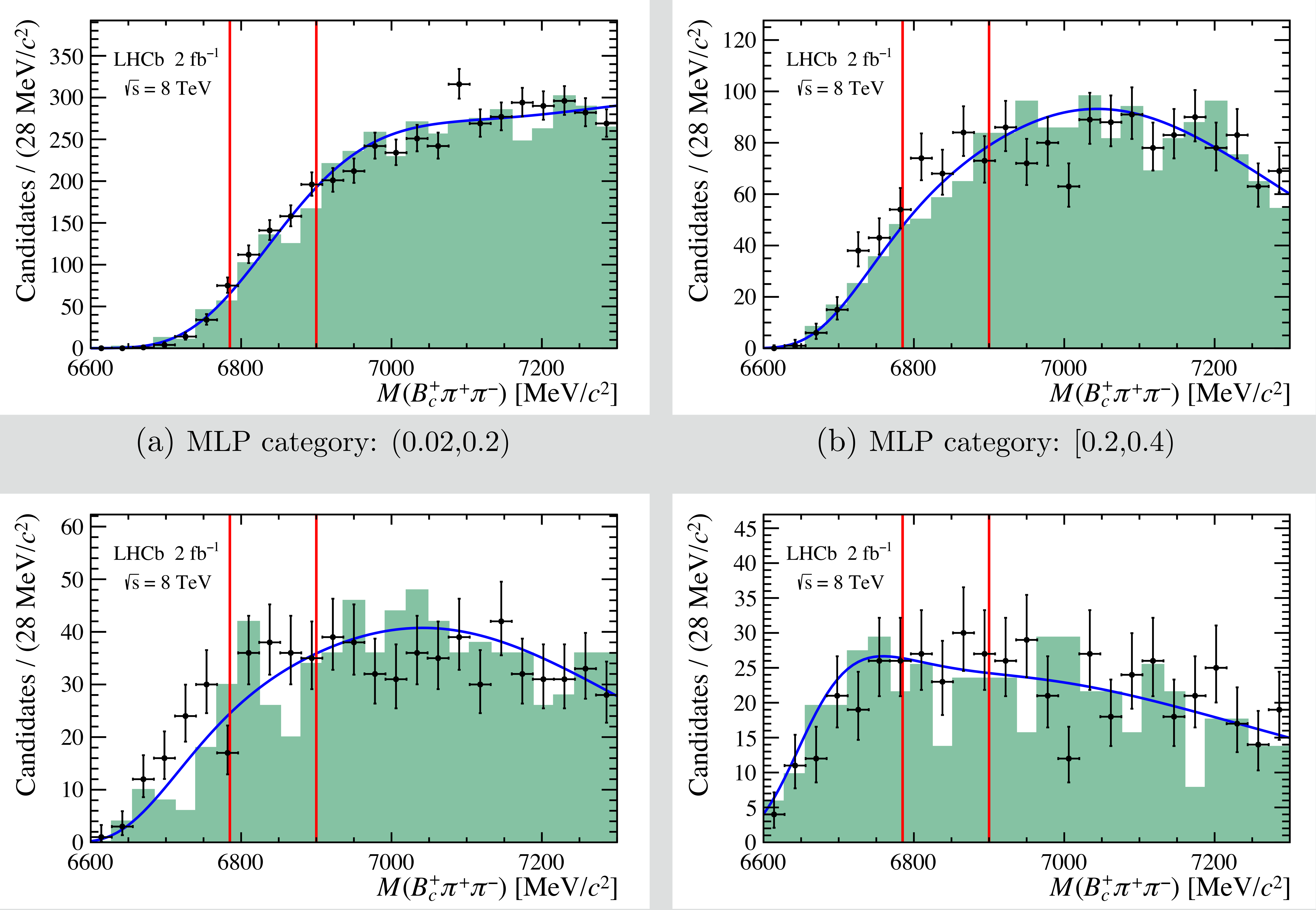
- LHCb reports a novel data-driven method for competitive B-lifetime measurements with SL decays: precision improved by 15% in B_s^0 FS lifetime and 2x in D_s lifetime [PRL 119 (2017) 101801].
- LHCb contributed with a number of new B_c decays observed.
  Keep searching:
  - no signal of $B_c \rightarrow DD$ decays yet [arXiv:1712.04702].
  - no signal of excited $B_c(2S)$ states [JHEP 01 (2018) 138].
  - see Patrick Owen's talk, LFU test with $B_c^+ \rightarrow J/\psi\ \tau\nu$ and $B_c^+ \rightarrow J/\psi\ \mu\nu$ decays [PRL 120, 121801 (2018)].
- Full Run 2 data set soon ready to explore new avenues and observations.

BACKUP

SEARCH FOR EXCITED B_c

- Categorise them with a MLP exploring angles between B_c and $B_c(2S)$ candidates.

[JHEP 01 (2018) 138]



(a) MLP category: (0.02,0.2)
(b) MLP category: [0.2,0.4)
(c) MLP category: [0.4,0.6)
(d) MLP category: [0.6,1.0]

SEARCH FOR EXCITED B$_c$

[JHEP 01 (2018) 138]

$$\mathcal{R} = \frac{\sigma_{B_c^{(*)}(2S)^+}}{\sigma_{B_c^+}} \cdot \mathcal{B}(B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-)$$
$$= \frac{N_{B_c^{(*)}(2S)^+}}{N_{B_c^+}} \cdot \frac{\varepsilon_{B_c^+}}{\varepsilon_{B_c^{(*)}(2S)^+}},$$

efficiency $\varepsilon_{B_c^+}$ is determined to be 0.0931 ± 0.0005

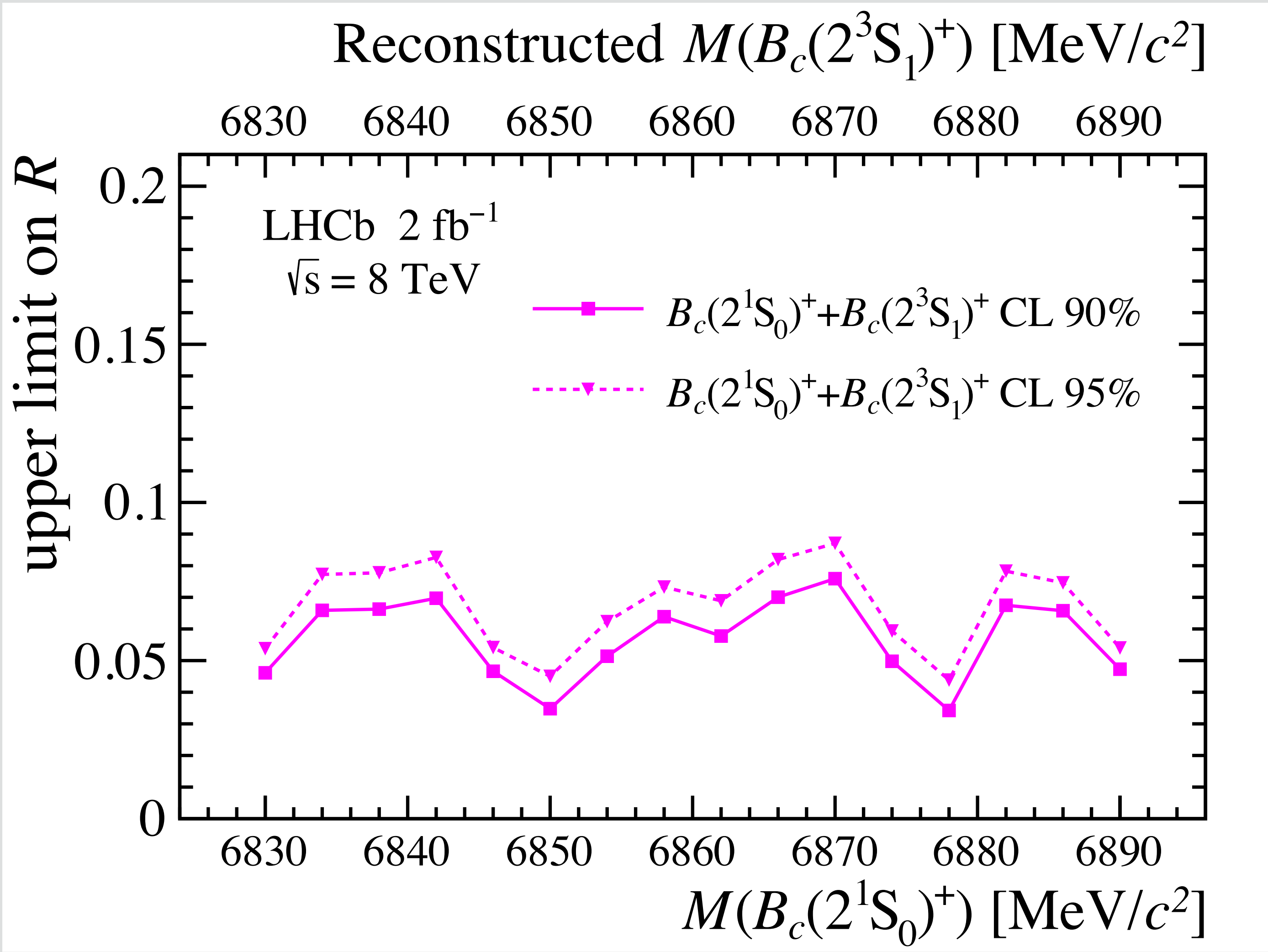
MLP category	$(0.02, 0.2)$	$[0.2, 0.4)$	$[0.4, 0.6)$	$[0.6, 1.0]$
		Efficiencies in %		
$B_c(2S)^+$	0.148 ± 0.006	0.140 ± 0.006	0.130 ± 0.006	0.256 ± 0.008
$B_c^*(2S)^+$	0.118 ± 0.003	0.140 ± 0.004	0.144 ± 0.004	0.288 ± 0.005

SEARCH FOR EXCITED B_c

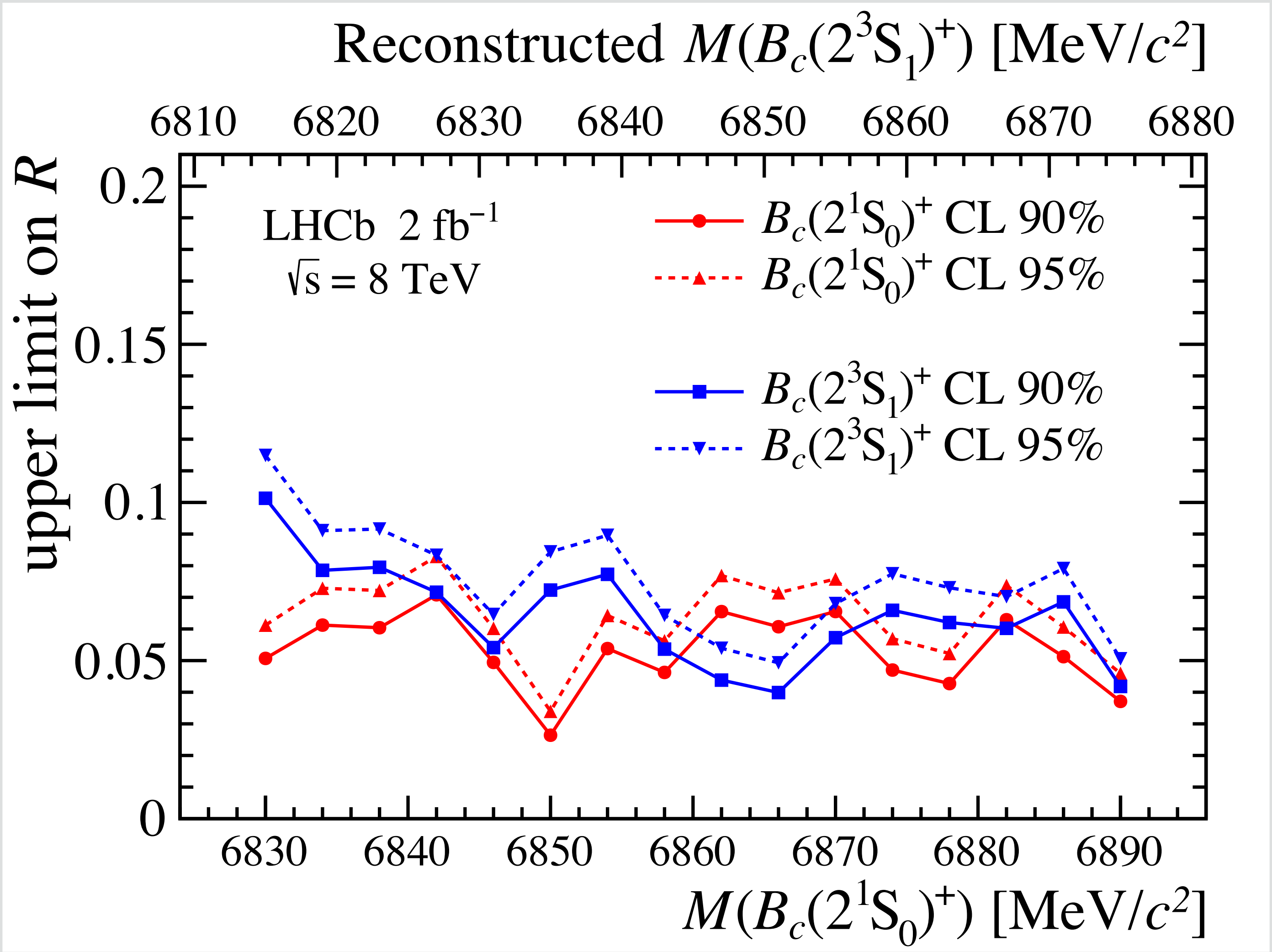
[JHEP 01 (2018) 138]

- Scan over different mass hypotheses for overlapping $B_c(2^1S_0)^+$ and $B_c(2^3S_1)^+$ and put limits on

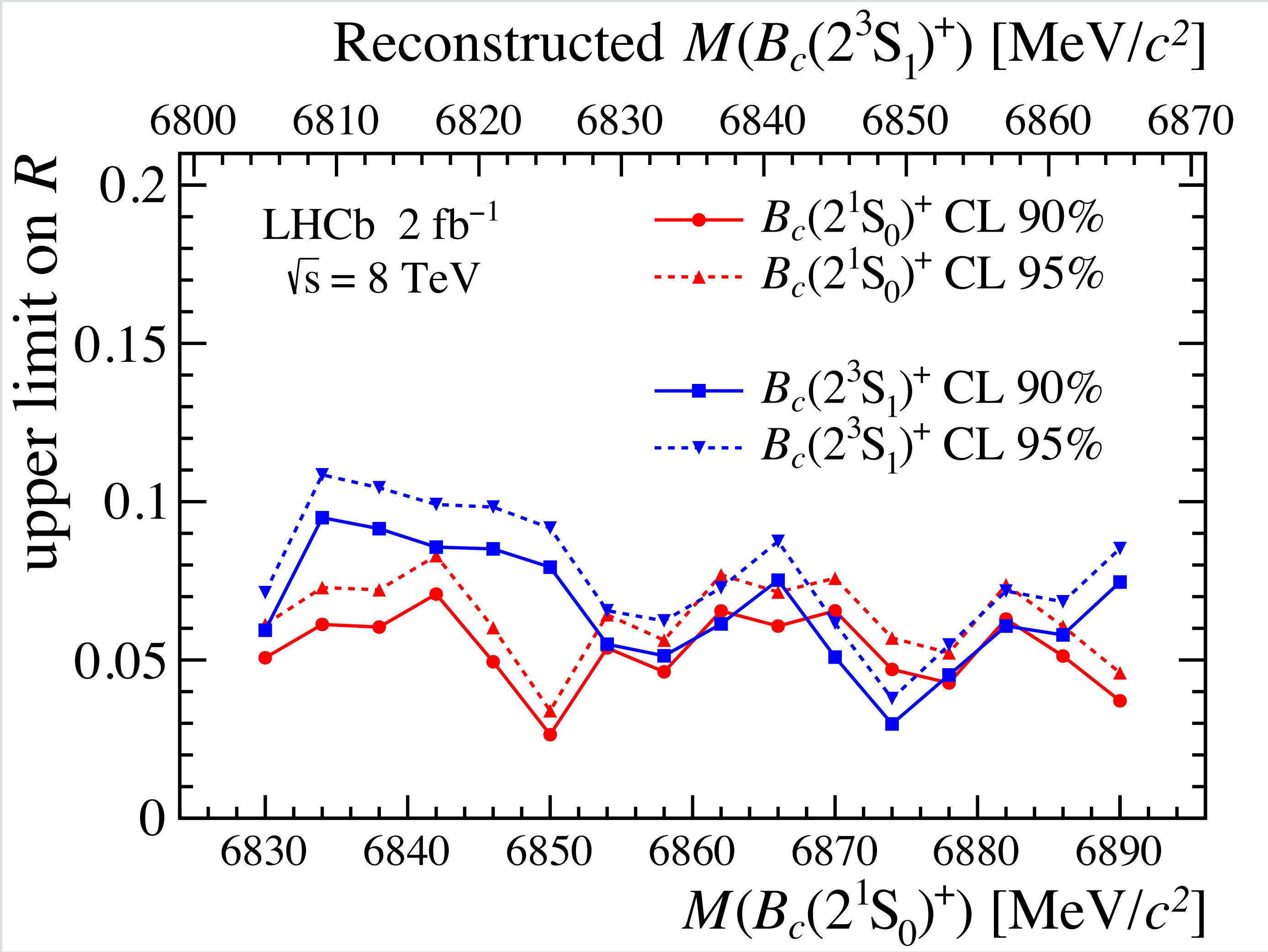
$$\mathcal{R} = \frac{\sigma_{B_c^{(*)}(2S)^+}}{\sigma_{B_c^+}} \cdot \mathcal{B}(B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-)$$



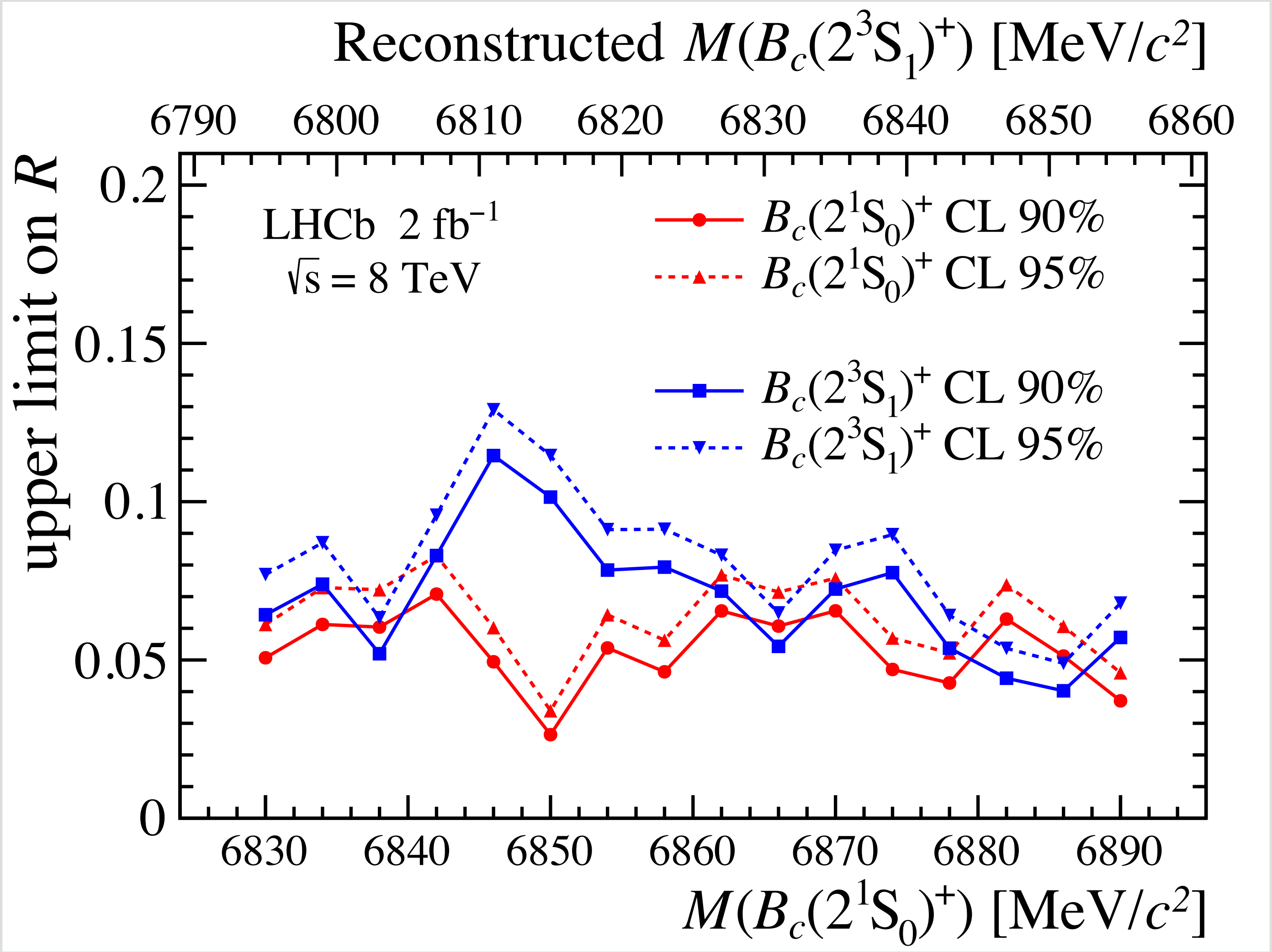
(a) $\Delta M = 0\,\text{MeV}/c^2$



(b) $\Delta M = 15\,\text{MeV}/c^2$



(c) $\Delta M = 25\,\text{MeV}/c^2$



(d) $\Delta M = 35\,\text{MeV}/c^2$

SEARCH FOR EXCITED B_c

[JHEP 01 (2018) 138]

$$\mathcal{R} = \frac{\sigma_{B_c^{(*)}(2S)^+}}{\sigma_{B_c^+}} \cdot \mathcal{B}(B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-) = \frac{N_{B_c^{(*)}(2S)^+}}{N_{B_c^+}} \cdot \frac{\varepsilon_{B_c^+}}{\varepsilon_{B_c^{(*)}(2S)^+}},$$

	$\sqrt{s} = 7\,\text{TeV}$	$\sqrt{s} = 8\,\text{TeV}$
ATLAS	$(0.22 \pm 0.08\,(\text{stat}))/\varepsilon_7$	$(0.15 \pm 0.06\,(\text{stat}))/\varepsilon_8$
LHCb	–	$< [0.04, 0.09]$

Table 1: Summary of the predictions for the $\mathcal{R}$ values.

	Ref. for $\mathcal{B}$ prediction	$\mathcal{R}_{B_c(2S)^+}$	$\mathcal{R}_{B_c^*(2S)^+}$
BCVEGPY with listed settings	[5]	0.02	0.04
	[7]	0.02	0.05
Production according to Ref. [5]	[5]	0.02	0.04
Production according to Ref. [6]	[5]	0.04	0.09
	[7]	0.05	0.12