



# Studies of the CKM matrix elements and b-hadron production using semileptonic decays at LHCb

A wide-angle photograph of the Seoul skyline at night. The city is densely packed with buildings of various heights, all illuminated with a variety of lights. In the foreground, a bridge spans a river, its structure reflected in the water. On the right side of the image, a tall, illuminated tower stands atop a hill, its light reaching high into the dark sky.

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on behalf of the LHCb collaboration  
ICHEP 2018, 4-11 July 2018, Seoul**

# Outline

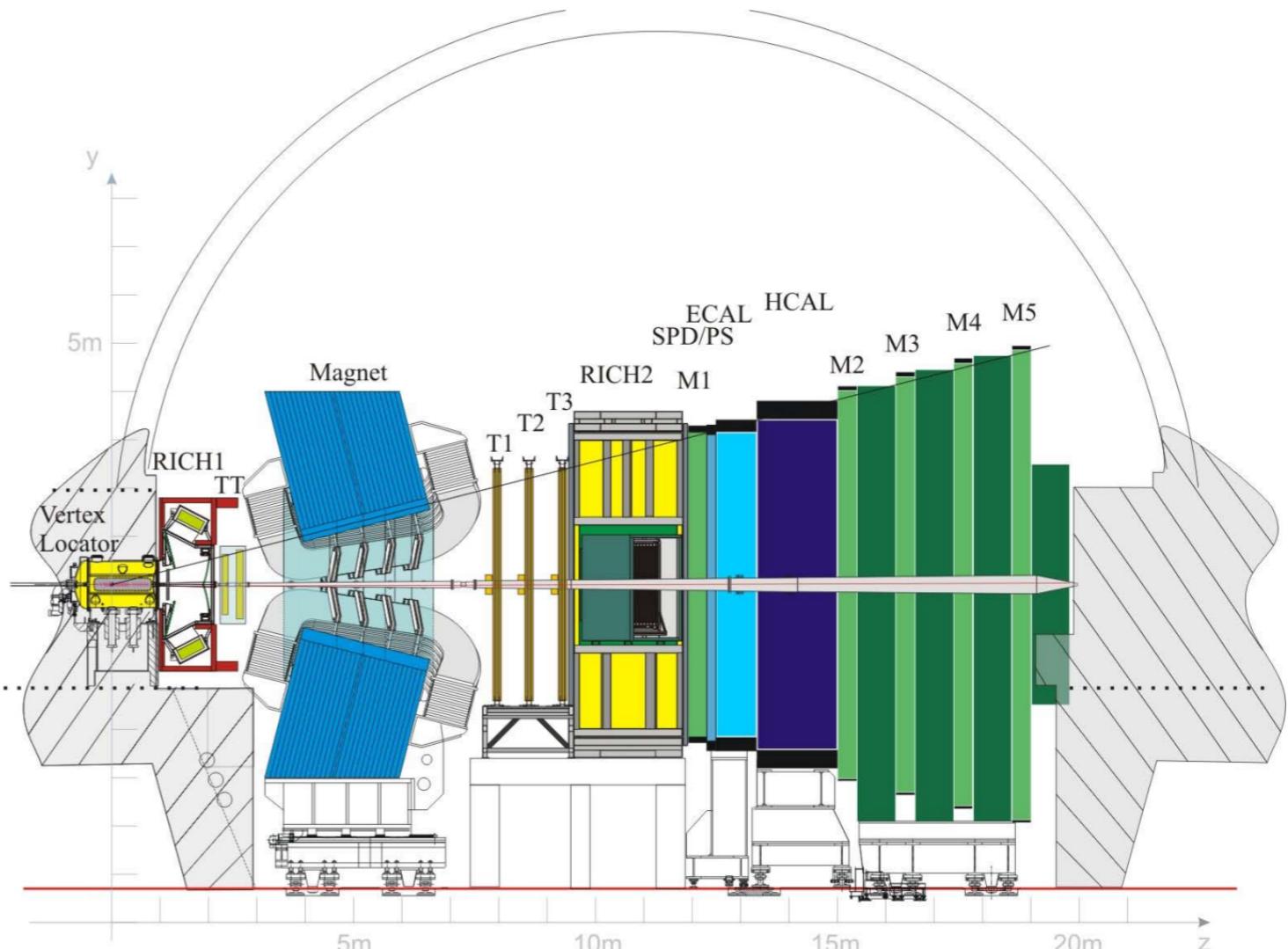
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- LHCb and the  $B$  momentum reconstruction.
- $V_{ub}$  from  $\Lambda_b$  decays.
- $\Lambda_b \rightarrow \Lambda_c$  form factor measurement.
- $f(D^0, D^{*0}, D^{**})$  fractions from  $B$  decays.
- Lifetime measurements.
  - $B_s, D_s$  and  $\Omega_c$
- Conclusions.

# The LHCb detector

[Int.J.Mod.Phys A30(2015)]

- Single-arm forward spectrometer  $2 < \eta < 5$
- Excellent momentum and mass resolution.
- Unique particle identification capabilities
- Optimised for beauty and charm physics
  - low  $p_T$  trigger thresholds

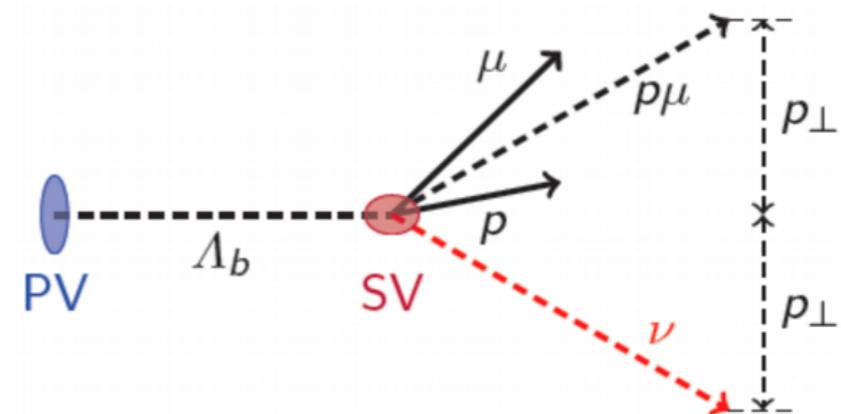


# Reconstructing the $B$ momentum

- LHCb is not hermetic + hadron environment.
  - $B$  momentum can be approximated by  $p_z(B) \sim \frac{m_b}{m_{vis}} p_z(\text{vis})$
- The momentum can be solved up to a two-fold ambiguity. Choose best solution i.e. with multivariate regression [[arXiv:1611.08522](#)]
- Allows to reconstruct variables as missing mass,  $q^2, \dots$
- Alternatively, use corrected mass [[PRL.80:660-665,1998](#)]

$$m_{corr} = \sqrt{m_{vis}^2 + p_\perp^2} + p_\perp$$

- Provide  $\sim 20\%$  resolution on discriminating variables.



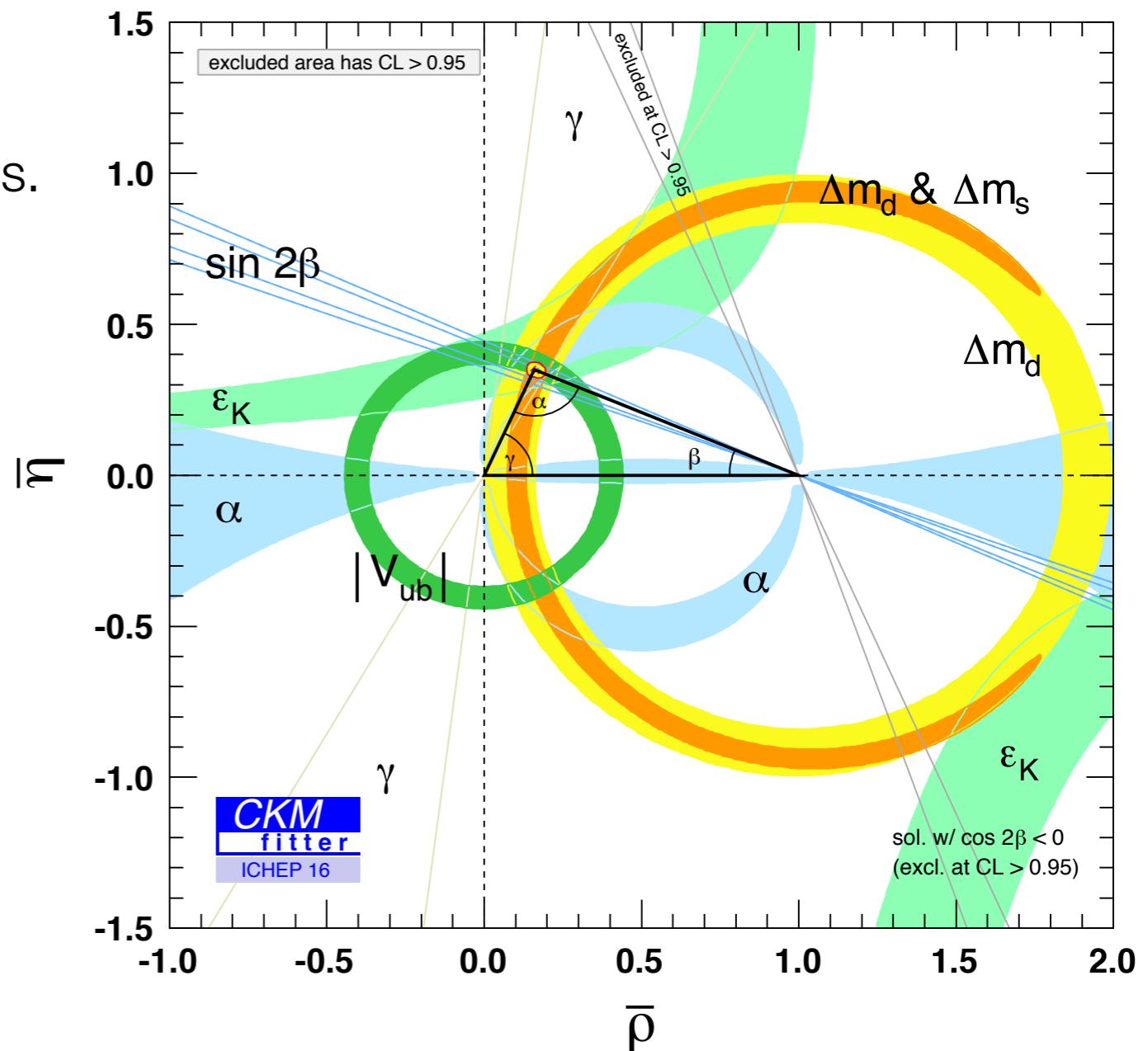
# $V_{ub}$ from $\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu$

[Nature Phys 10(2015)1038]

- One side of the CKM matrix.
- Long standing discrepancy between inclusive and exclusive measurements.
- Can be determined from  $b \rightarrow ul^+\nu_l$  transitions.

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+\mu^-\bar{\nu}_\mu)} R_{FF}$$

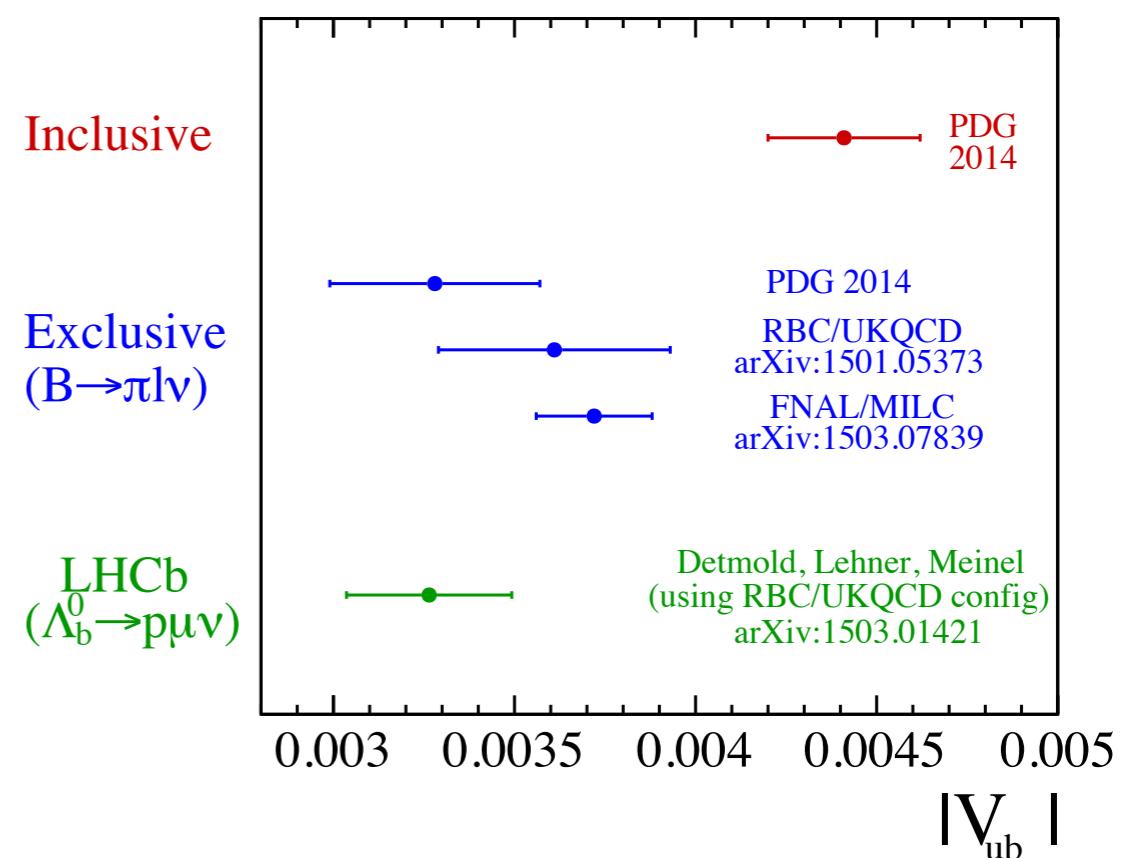
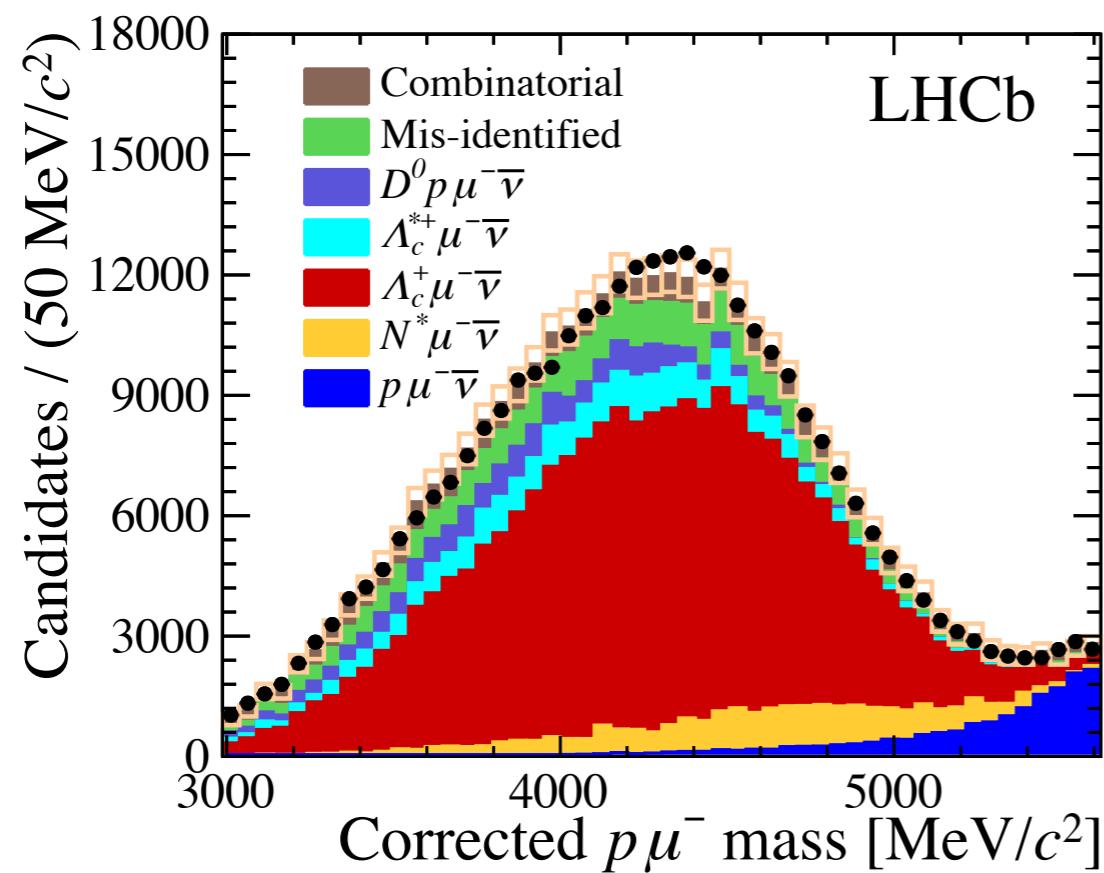
- Where  $R_{FF}$  is the ratio of form factors extracted from lattice.
- Get  $V_{cb}$  from exclusive decays.



# $V_{ub}$ from $\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu$

[Nature Phys 10(2015)1038]

- Use the corrected mass as discriminating variable.
- Measurement performed at low recoil  $q^2 > 15 \text{ GeV}^2$ .



- LHCb result is aligned with the exclusive measurements.

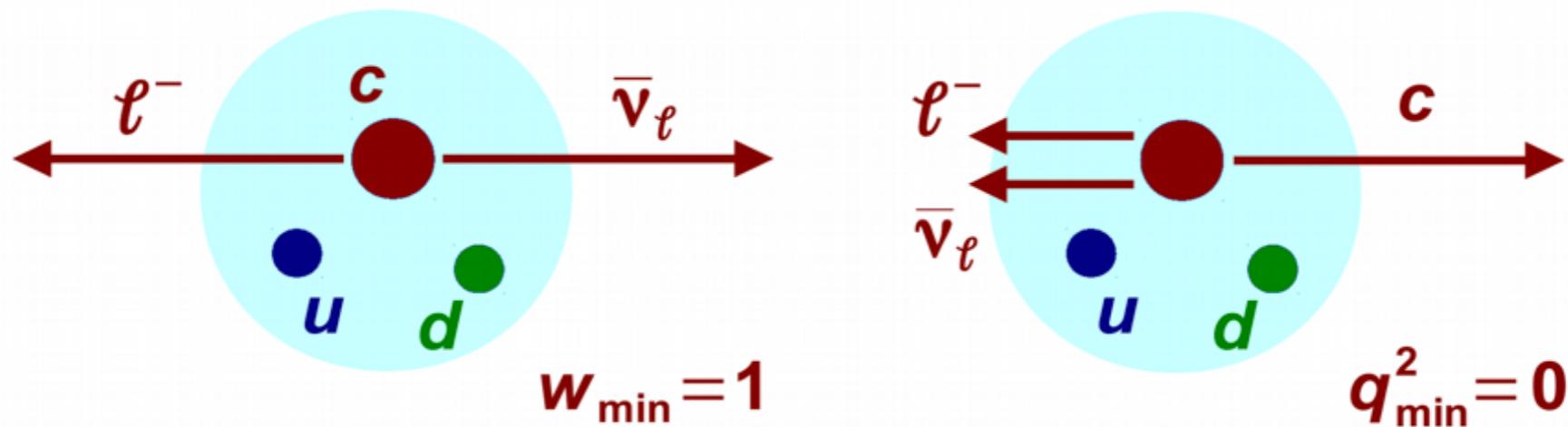
# $\Lambda_b^0 \rightarrow \Lambda_c^+$ form factors

[PRD96(2017)112005]

- Check precise predictions from lattice QCD.
- Proof of principle of LHCb's potential to measure FF.
- Existing measurement from DELPHI with 50% uncertainties. [PLB585, 63(2004)]
- In Heavy Quark Limit, FF reduces to a single Isgur-Wise function. [PLB232, 113(1989)]

$$\xi_B(w) = 1 - \rho^2(w - 1) + \frac{1}{2}\sigma^2(w - 1)^2 + \dots \quad \text{with} \quad w = \frac{m_{\Lambda_b^0}^2 + m_{\Lambda_c^+}^2 - q^2}{2m_{\Lambda_b^0}m_{\Lambda_c^+}}$$

- At zero recoil ( $w = 1$ ), is expected to have modest high-order corrections in the expansion  $\rightarrow$  precise determination of  $\rho^2$  and  $\sigma^2$ .

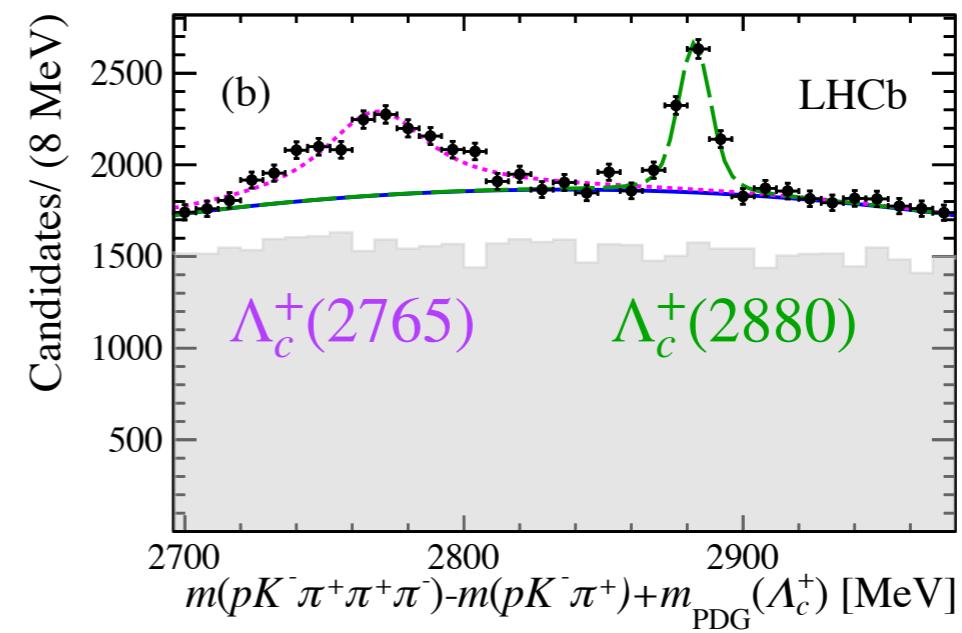
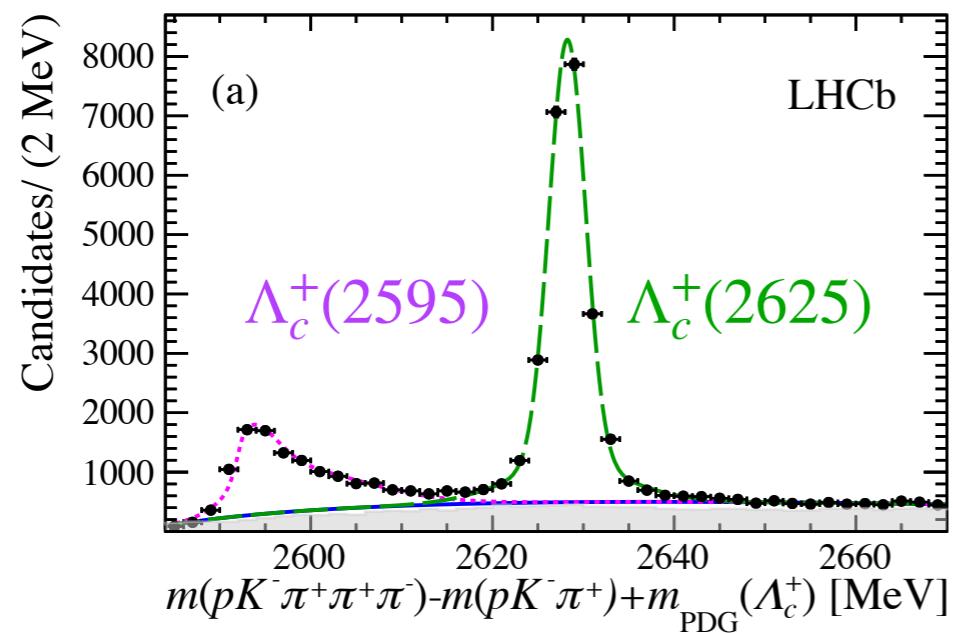
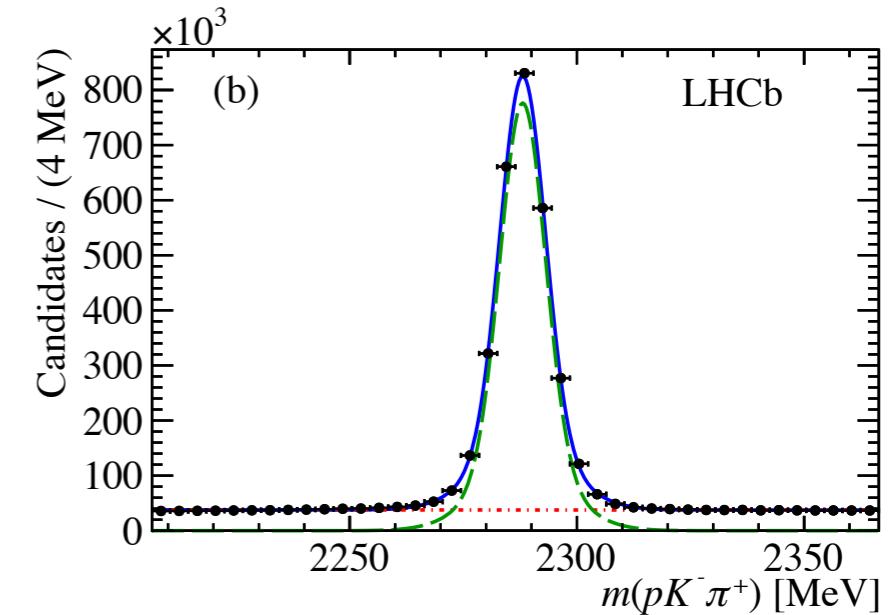


Courtesy of: O. Steinkamp

# $\Lambda_b^0 \rightarrow \Lambda_c^+$ form factors

[PRD96(2017)112005]

- Large sample of  $\Lambda_c^+ \rightarrow pK\pi$  (2.7M) interpreted as  $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\nu X$  with negligible contamination from prompt.
- Background from excited  $\Lambda_c^+$  are determined from data using the decay  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^+ \pi^- \mu^- \bar{\nu}_\nu X$ .
- Correct the excited  $\Lambda_c^+$  yields by the efficiency and subtract to the raw yield.



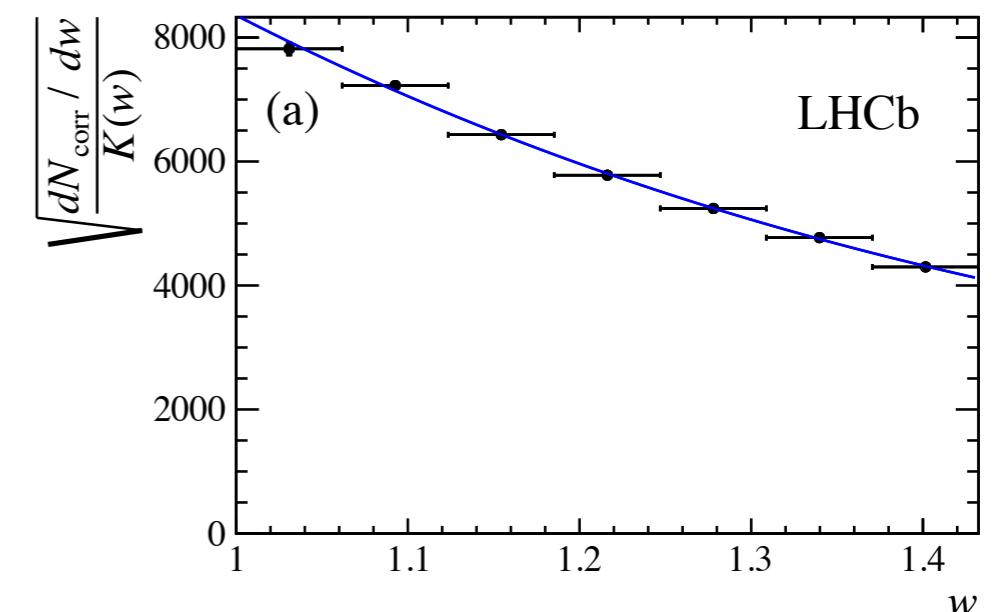
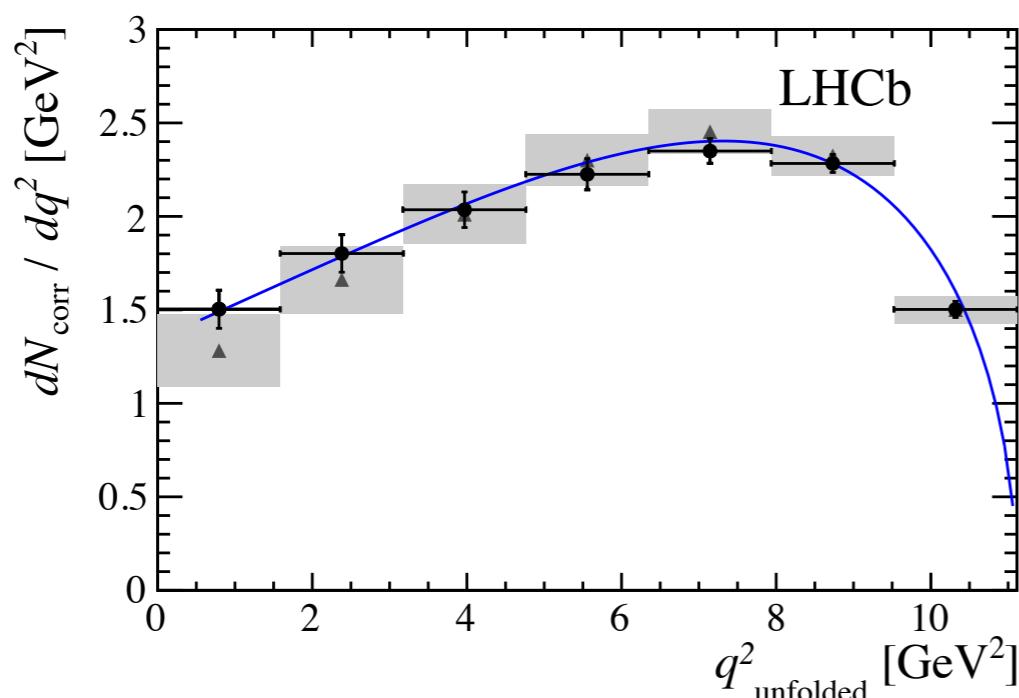
# $\Lambda_b^0 \rightarrow \Lambda_c^+$ form factors

[PRD96(2017)112005]

- Use the  $w$  solution that provides the smallest  $\Lambda_b^0$  momentum.
- Extract  $\rho^2$  and  $\sigma^2$  through a  $\chi^2$  fit using a Taylor expansion.

$$\rho^2 = 1.63 \pm 0.07(\text{stat}) \pm 0.08(\text{syst})$$

- Most precise value and compatible with theory.  
[PRD 73, 094002 \(2006\)](#)  
[PLB 629, 27 \(2005\)](#)  
[PRD 57, 6948 \(1998\)](#)



Shape consistent with theory:

Lattice QCD [PRD92(2015)034503]

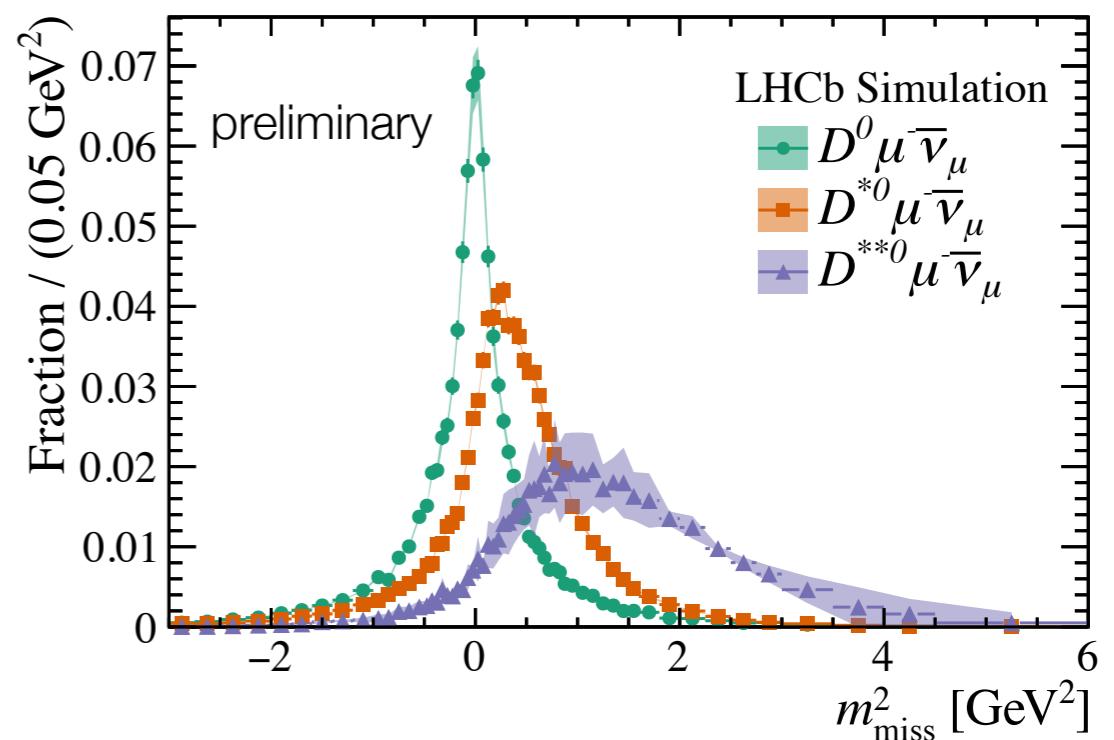
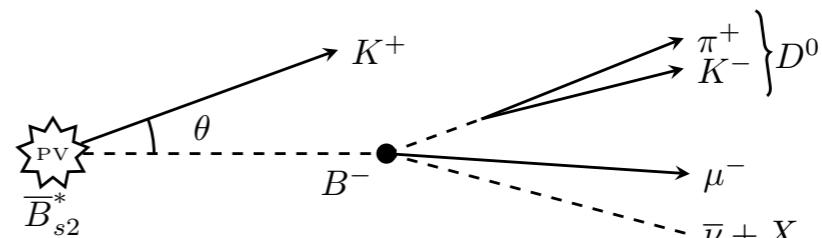
**Single FF in z expansion**  
[arXiv:hep-ph/0606023]

# $f(D^0, D^{*0}, D^{**})$ from $B^- \rightarrow D^0 X \mu^- \bar{\nu}_\mu$

[LHCb-PAPER-2018-024]

(NEW) in preparation

- The fractions of  $D^0, D^{*0}, D^{**}$  produced in semileptonic decays are uncertain.
- Discrepancy between exclusive and inclusive measurements account for 1% absolute.
  - Accurate measurement is fundamental as they are backgrounds to  $R(D^{(*)})$ .
- Use  $B^-$  candidates from  $B_{s2}^{*0} \rightarrow B^- K^+$ .
  - Good knowledge of the  $B^-$  direction (independent of decay).
  - Pay a factor 100 in statistics.
- Reconstruct  $D^0 \rightarrow K\pi$  and distinguish excited states through the missing mass.

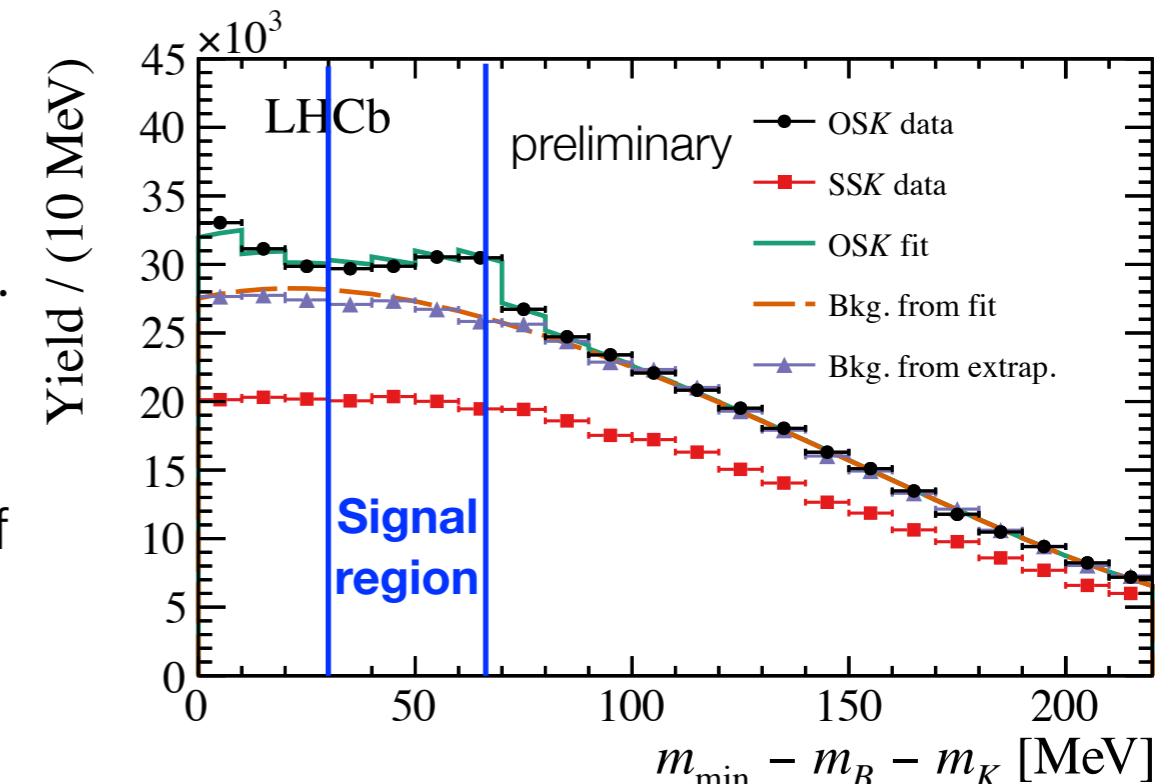
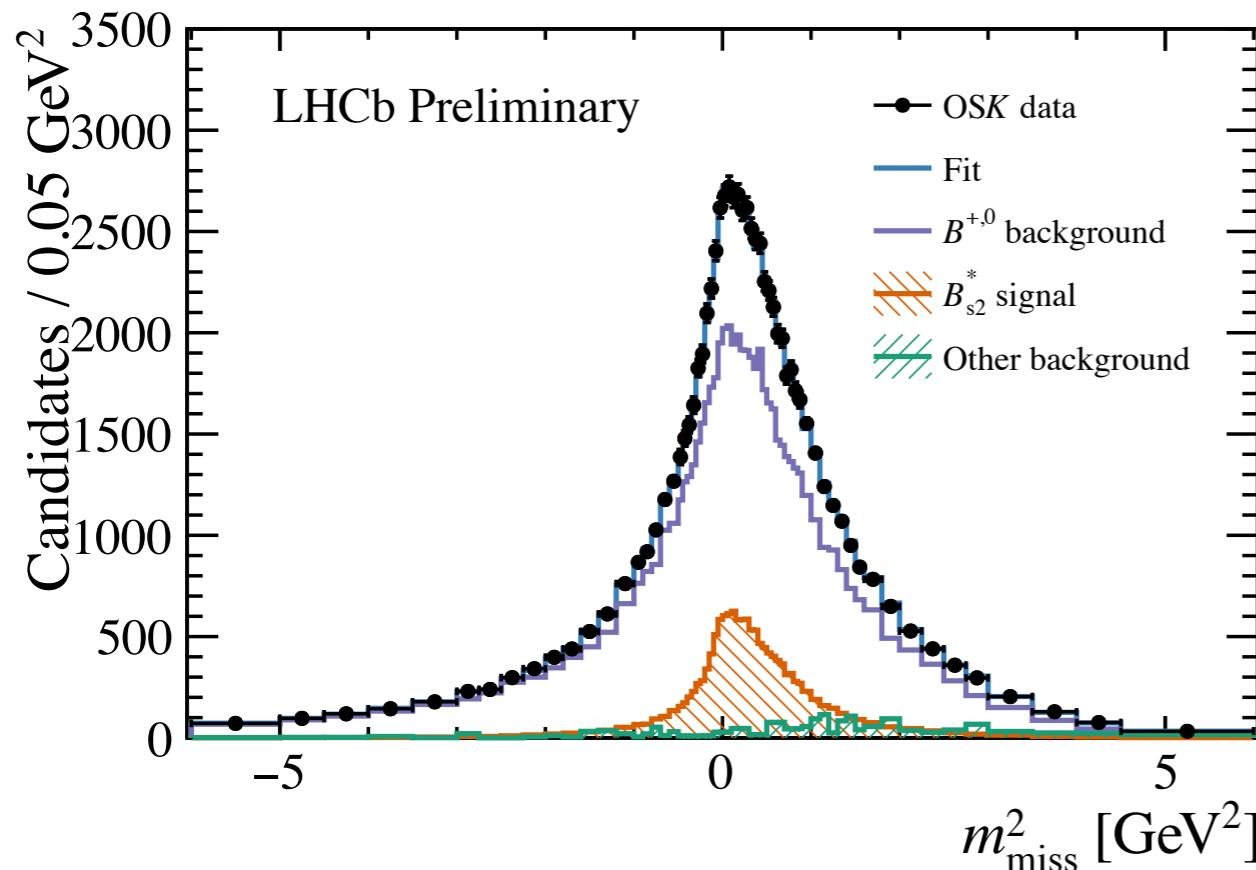


# $f(D^0, D^{*0}, D^{**})$ from $B^- \rightarrow D^0 X \mu^- \bar{\nu}_\mu$

[LHCb-PAPER-2018-024]

(NEW) *in preparation*

- Signal:  $B^- \rightarrow D^0 X \mu^- \bar{\nu}_\mu$
- Backgrounds:
  - Mainly from  $B^-$  and  $B^0$  decays not from  $B_{s2}^{*0}$ .
  - Modeled using data with same-sign  $K$ .
  - Smaller background derived with mixture of simulation and data-driven techniques.

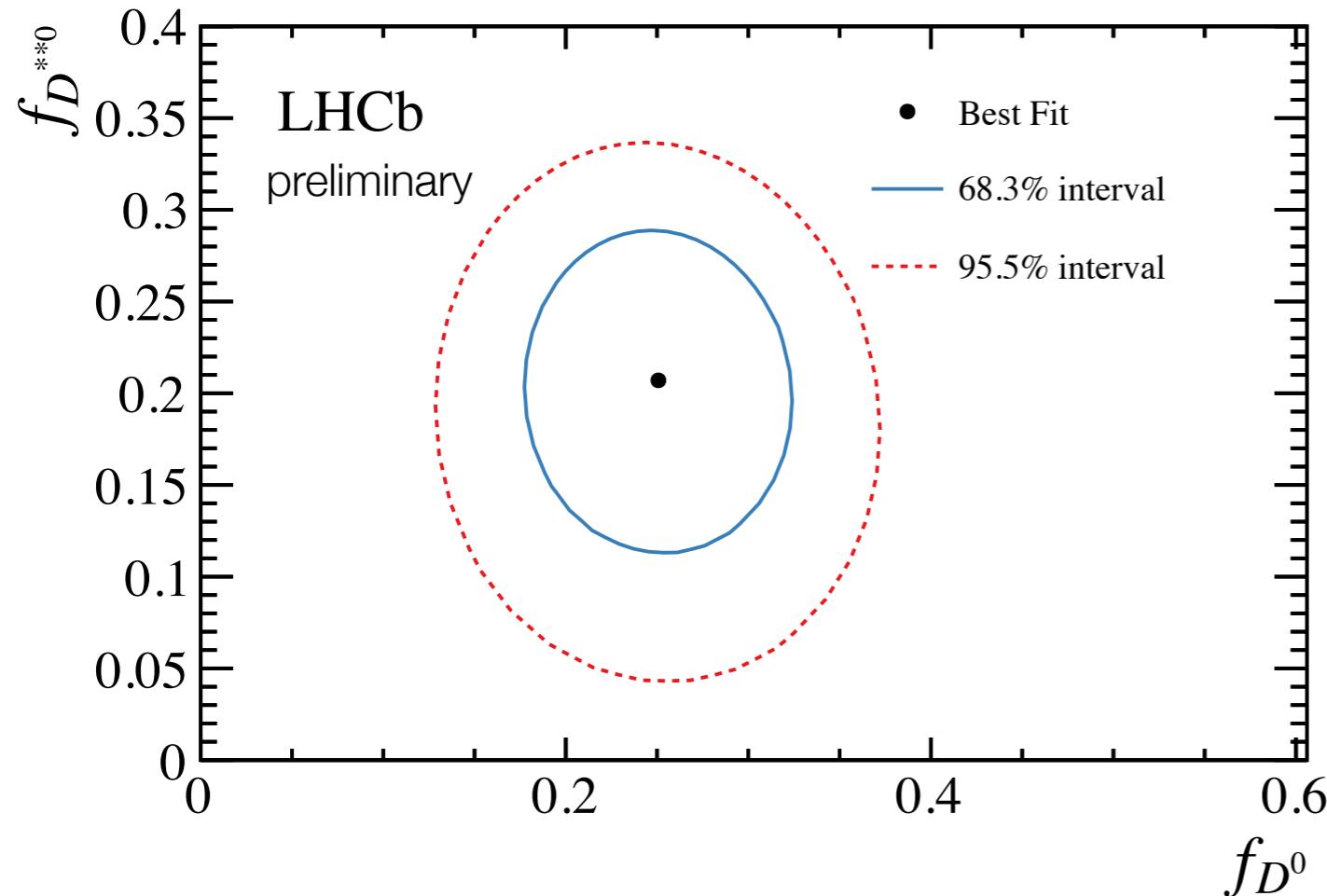


$m_{\text{min}}$  is the minimum mass necessary to yield real solutions, assuming that the  $B^- K^+$  pair comes from  $B_{s2}^{*0}$ .

# $f(D^0, D^{*0}, D^{**})$ from $B^- \rightarrow D^0 X \mu^- \bar{\nu}_\mu$

[LHCb-PAPER-2018-024]

(NEW) *in preparation*



$$f(D^0) = 0.25 \pm 0.05$$
$$f(D^{**}) = 0.21 \pm 0.07$$
$$f(D^{*0}) = 1 - f(D^0) - f(D^{**})$$

preliminary

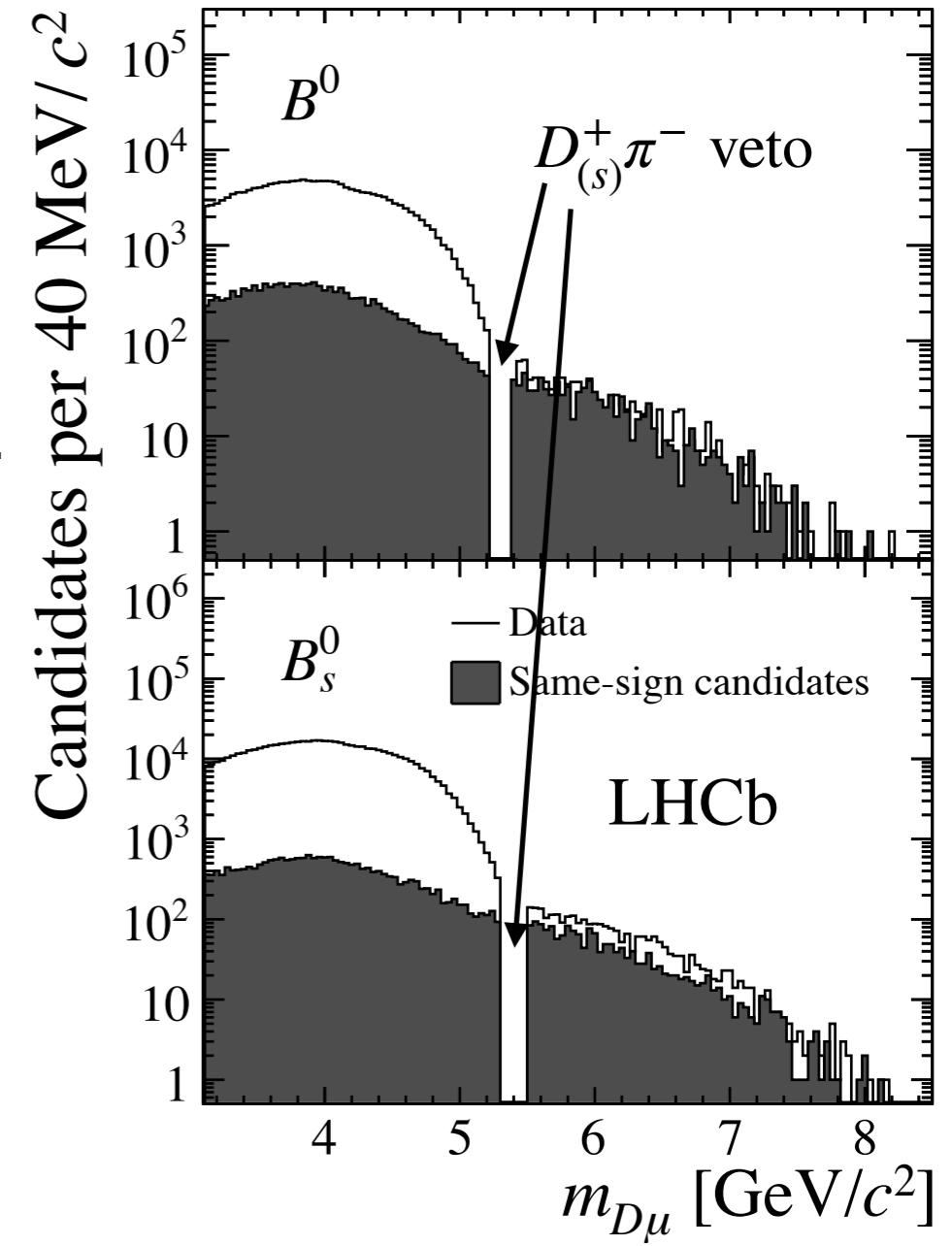
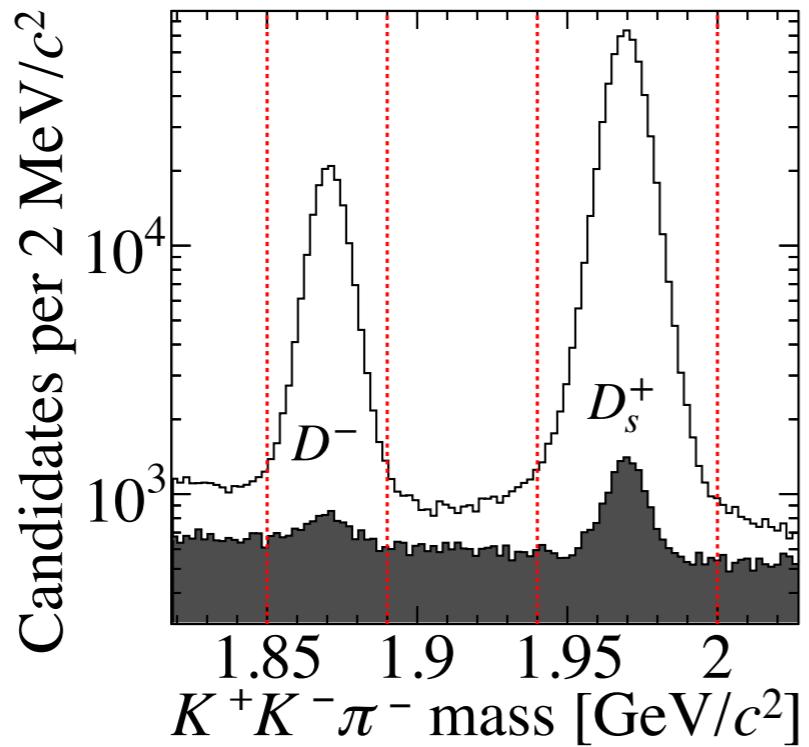
Not yet competitive with the B factories  
[PRD.76.051101]

Proves the potential of such measurements  
at LHCb using this technique.

# $B_s$ and $D_s$ lifetimes

[PRL119(2017)101801]

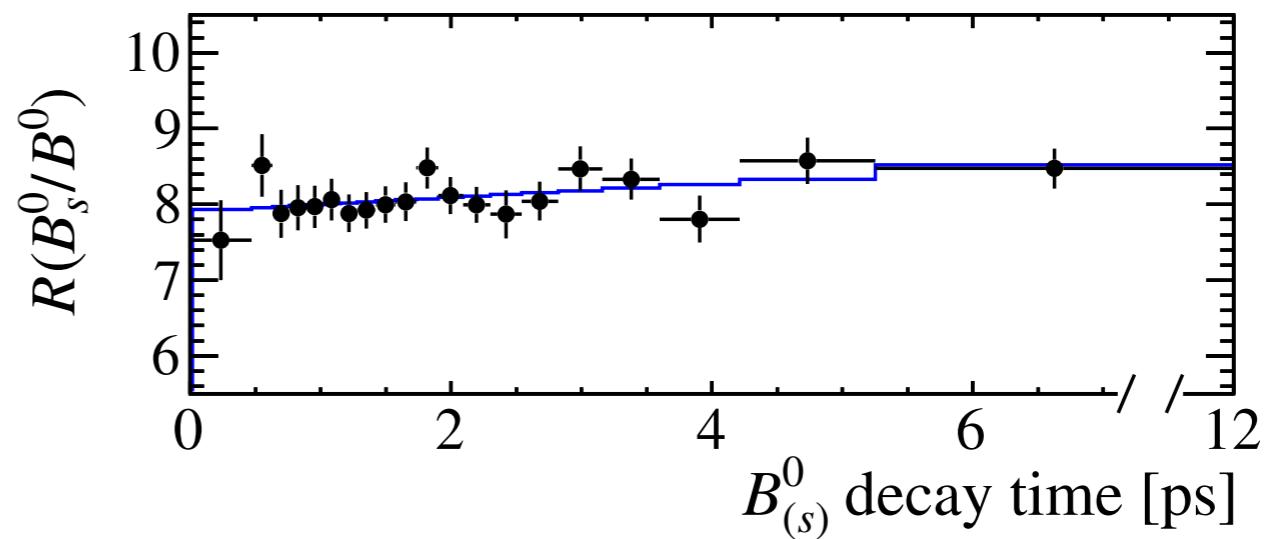
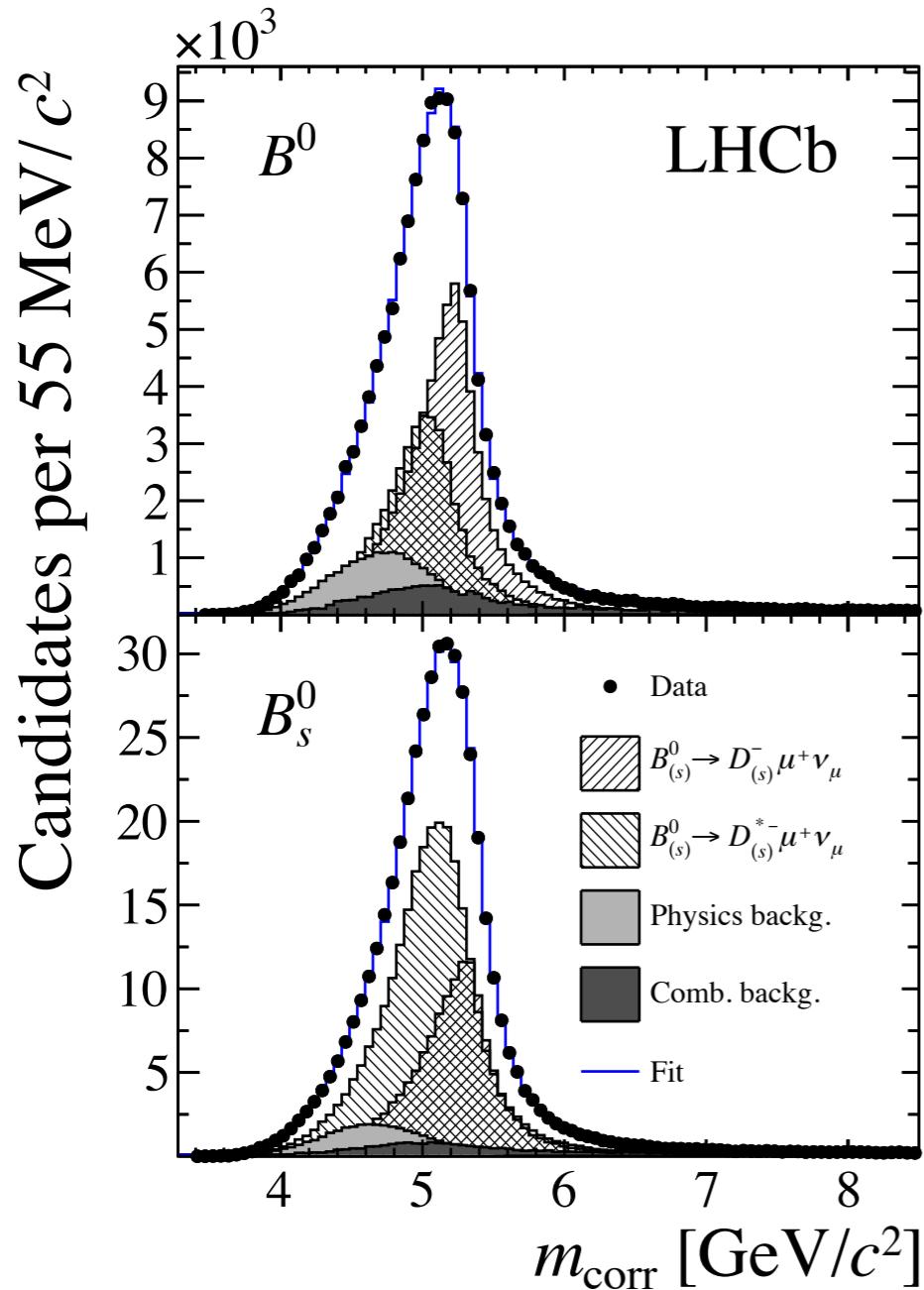
- Measure flavour-specific  $B_s$  lifetime in  $B_s \rightarrow D_s^{-(*)} \mu^+ \nu$ .
- Sensitive to decay width difference between heavy and light eigenstates.
- Large yield but systematics from missing bodies.
- Measurement relative to  $B^0 \rightarrow D^{-(*)} \mu^+ \nu$  with  $D_s/D^- \rightarrow K K \pi$ .



# $B_s$ and $D_s$ lifetimes

[PRL119(2017)101801]

- Evaluate the ratio of  $B_s/B^0$  in bins of lifetime. Access to  $\Delta_\Gamma(B) \equiv 1/\tau_{B_s}^{\text{fs}} - \Gamma_d$



$$\Delta_\Gamma(B) = -0.0115 \pm 0.0053(\text{stat}) \pm 0.0041(\text{syst}) \text{ ps}^{-1}$$

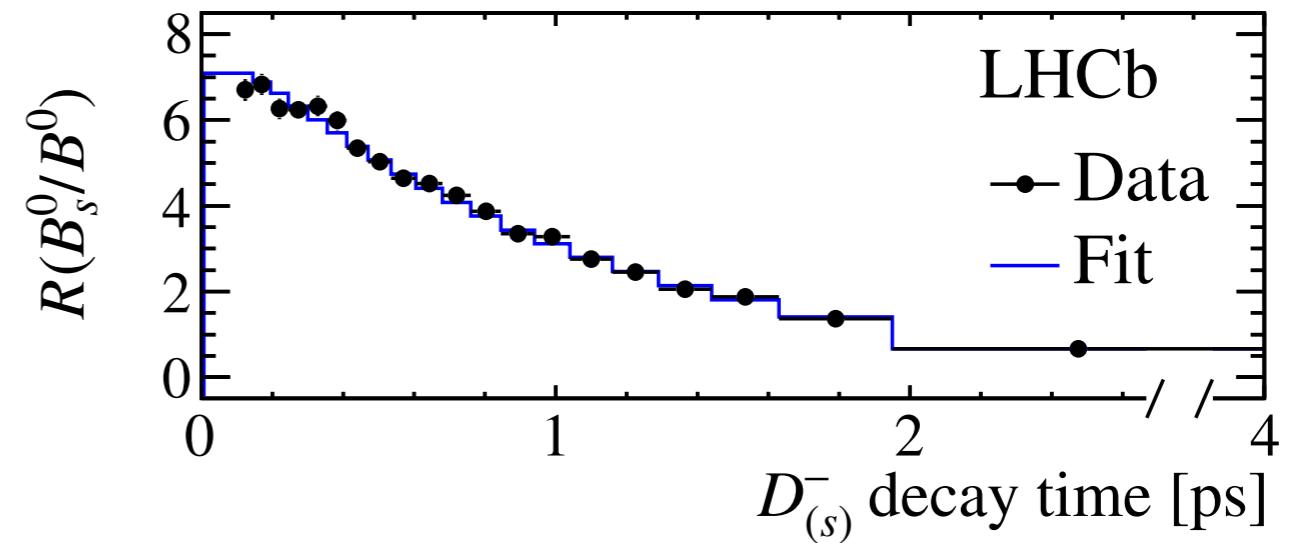
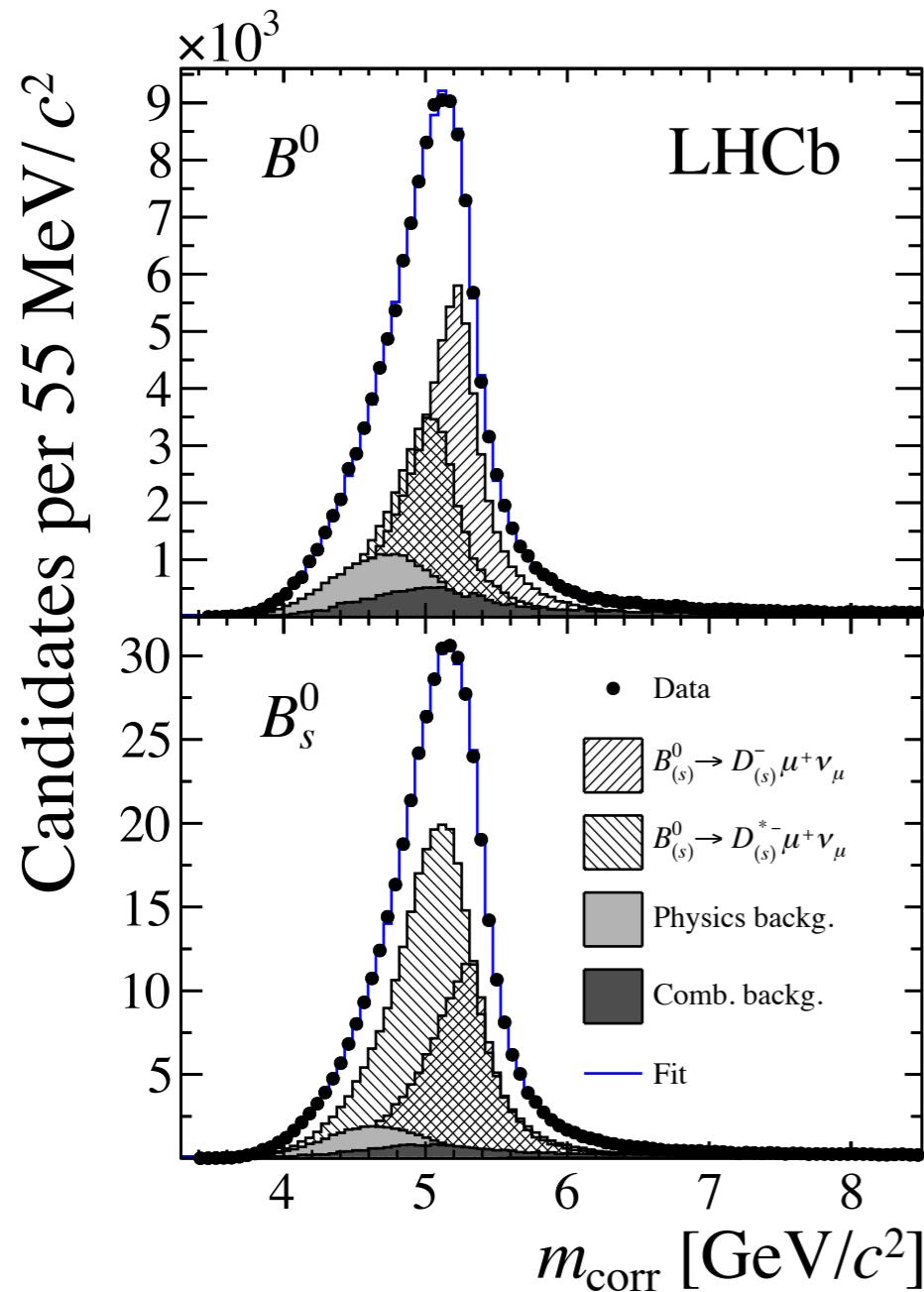
$$\tau_{B_s} = 1.547 \pm 0.013(\text{stat}) \pm 0.0010(\text{syst}) \pm 0.0010(\tau_B) \text{ ps}$$

Most precise determination by using this novel technique.

# $B_s$ and $D_s$ lifetimes

[PRL119(2017)101801]

- As a by-product, we can do the same for the charm meson.



$$\Delta\Gamma(D) = 1.0131 \pm 0.0117(\text{stat}) \pm 0.0065(\text{syst}) \text{ ps}^{-1}$$

$$\tau_{D_s} = 0.5046 \pm 0.0030(\text{stat}) \pm 0.0017(\text{syst}) \pm 0.0017(\tau_D) \text{ ps}$$

Most precise determination by using this novel technique.

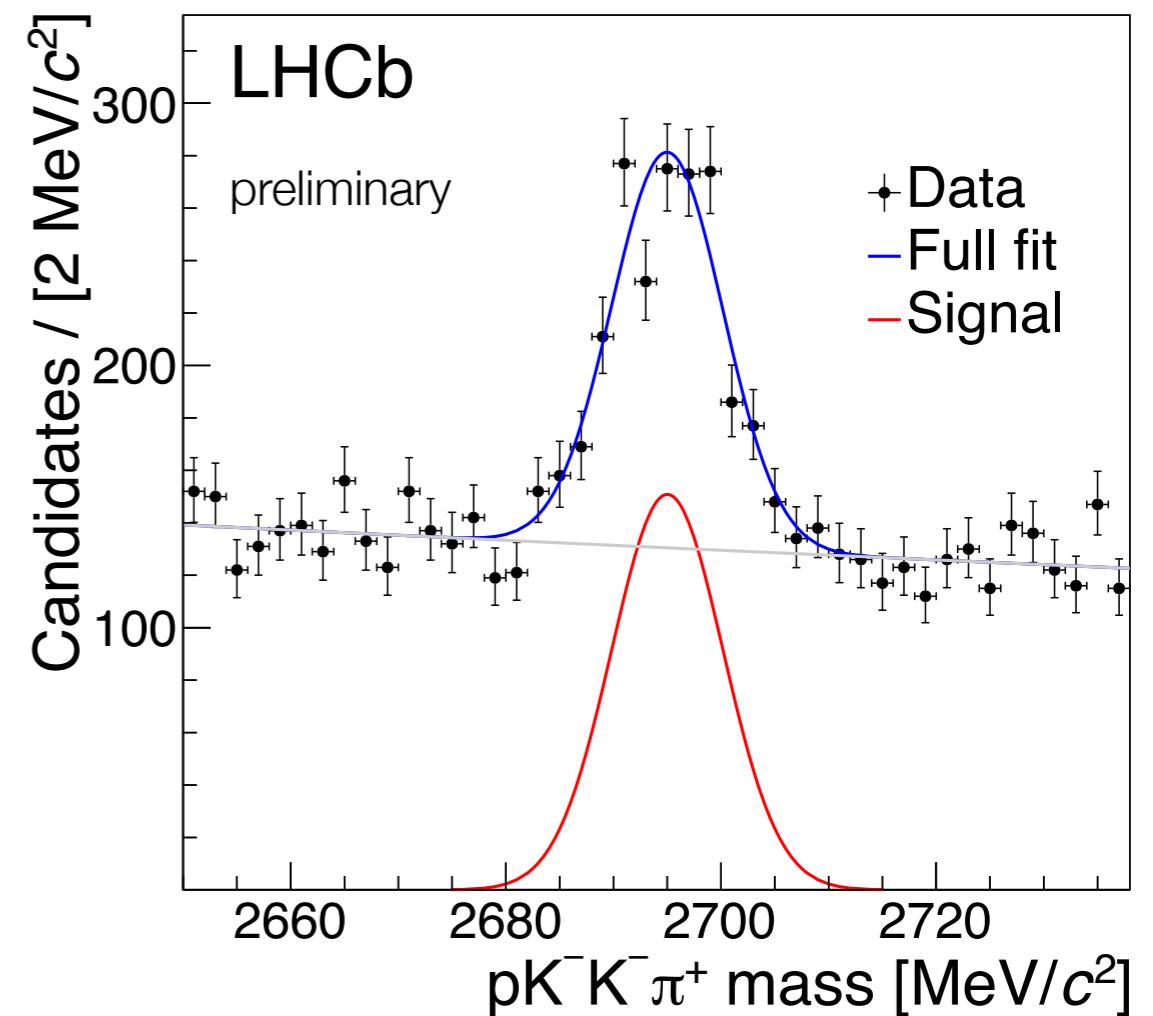
# $\Omega_c$ lifetime

[LHCb-PAPER-2018-028]

(NEW) *in preparation*

- Charmed-baryon lifetimes are less well known than mesons ( $\sim 17\%$  for  $\Omega_c$ ).
- Expected hierarchy  $\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$  takes into account effects not present in mesons. e.g.: spin contribution of spectator system, constructive Pauli interference [[Rin. Nuovo Cim. 26N7 \(2003\) 1](#)].

- Measurement uses  $\Omega_b \rightarrow \Omega_c \mu \nu$  with  $\Omega_c \rightarrow p K K \pi$
- Minimise systematic uncertainties by measuring relative to the  $D^+$  lifetime from  $B^0 \rightarrow D^+ \mu \nu X$ .



# $\Omega_c$ lifetime

[LHCb-PAPER-2018-028]  
*(NEW) in preparation*

- Almost 1k selected  $\Omega_c$  candidates.

- Largest sample for lifetime measurements by 1 order of magnitude.

$$\frac{\tau_{\Omega_c^0}}{\tau_{D^+}} = 0.258 \pm 0.023(\text{stat}) \pm 0.010(\text{syst})$$

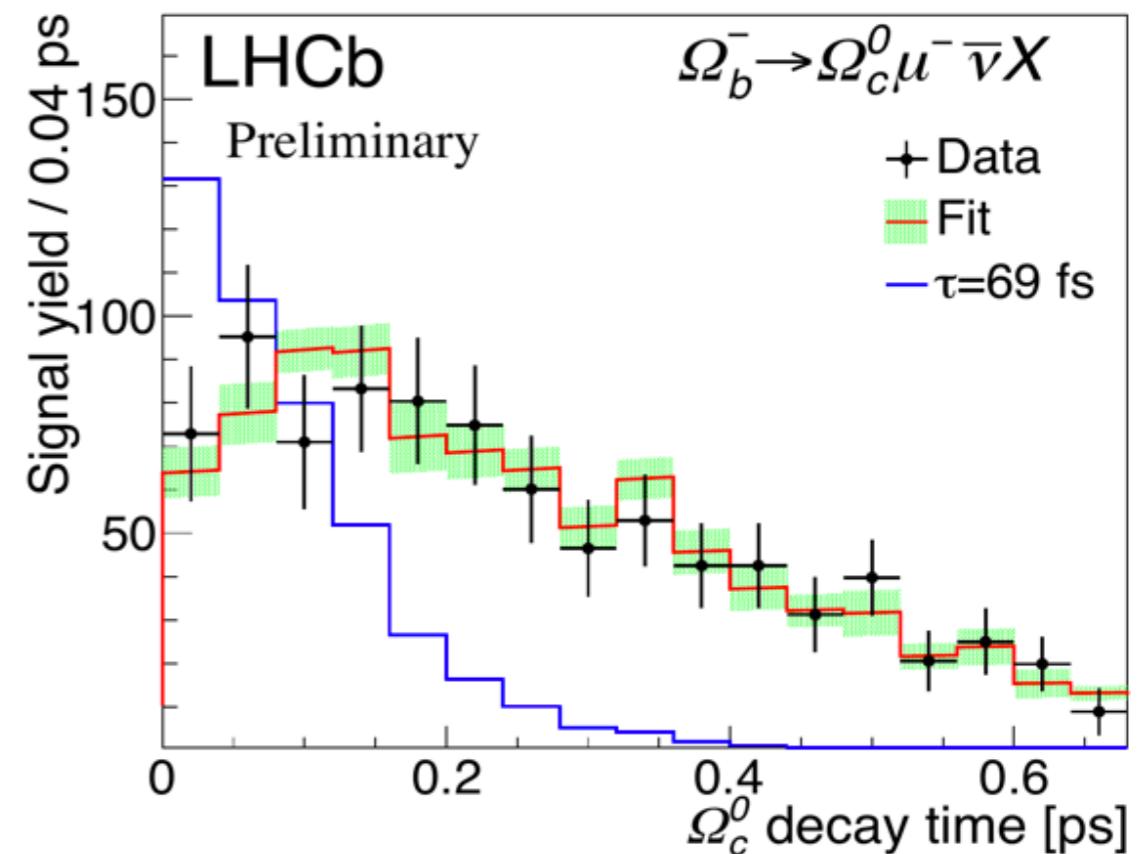
$$\tau_{\Omega_c^0} = 268 \pm 24(\text{stat}) \pm 10(\text{syst}) \pm 2(\tau_{D^+}) \text{ fs}$$

- Lifetime is four times larger than the current PDG average => new hierarchy.

$$\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$$

- Possible interpretations:

- Smaller interference between ss pair.
- Major role of spin of ss system.
- Missing higher order corrections in HQE.



# Conclusions

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- Semileptonic decays are not an easy task on a non-hermetic detector in a hadron environment.
  - New techniques developed in the last years make possible to do precision measurements.
- No new results for  $V_{ub}$  from LHCb.
  - Expect to have a new result from  $B^+ \rightarrow \mu^+\mu^-\mu^+\nu$  by the end of the summer, and later for  $B_s \rightarrow K^-\mu^+\nu_\mu$ .
- In the meantime:
  - New measurements of  $\Lambda_b \rightarrow \Lambda_c$  form-factors.
  - Most precise measurement of  $B_s$  and  $D_s$  lifetimes.
  - Interesting puzzle from  $\Omega_c$  lifetime.
  - New method to extract the fractions of  $B^- \rightarrow DX\mu\nu$  decays.