

# Lepton Flavour Universality measurements at LHCb

$b \rightarrow s\ell\ell$  2019, Lyon

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Paula Álvarez Cartelle

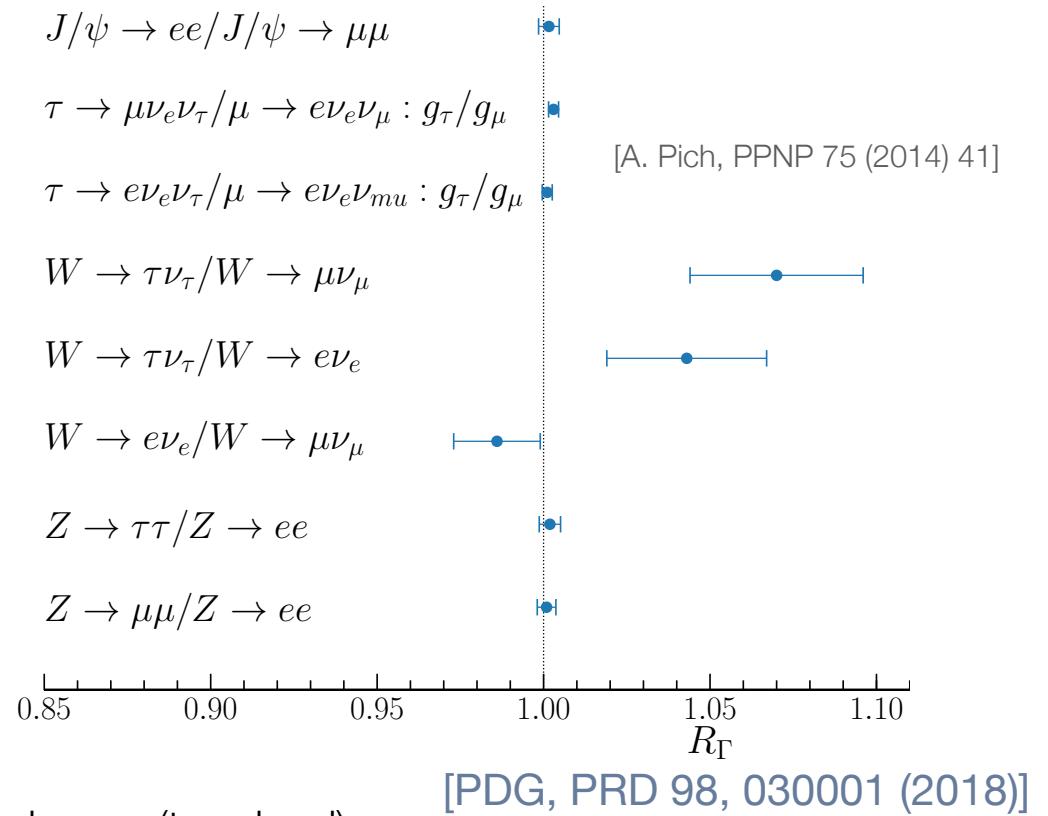
September, 2019

# LFU tests

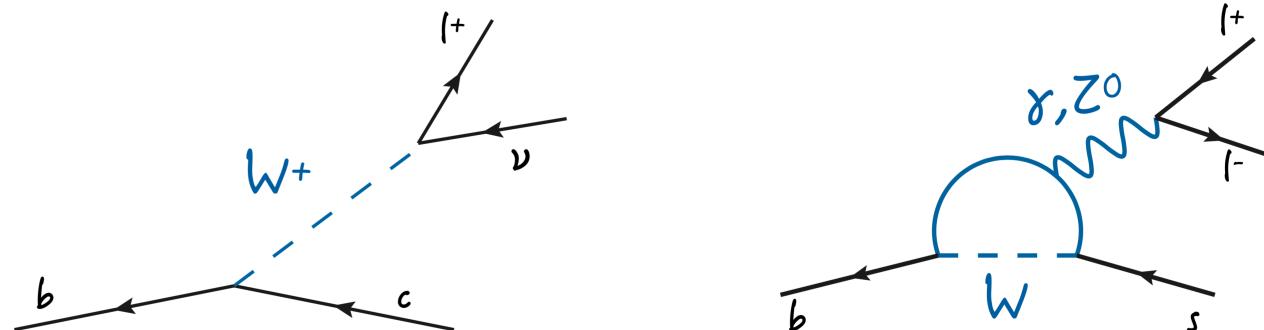
LFU has been thoroughly tested in the past:

- $Z \rightarrow \ell\ell$  and  $W \rightarrow \ell\nu$  measurements
- Semileptonic decays of  $\pi$ ,  $K$  and  $D$  mesons
- Leptonic decays
- Quarkonia ( $J/\psi \rightarrow ee, \mu\mu$ )
- **B-meson decays**

- ▶ Flavour Changing Charged Current  $b \rightarrow c\bar{\ell}\nu$  decays (tree-level)
- ▶ Flavour Changing Neutral Current  **$b \rightarrow s\bar{\ell}\ell$  transitions (loop-level)**

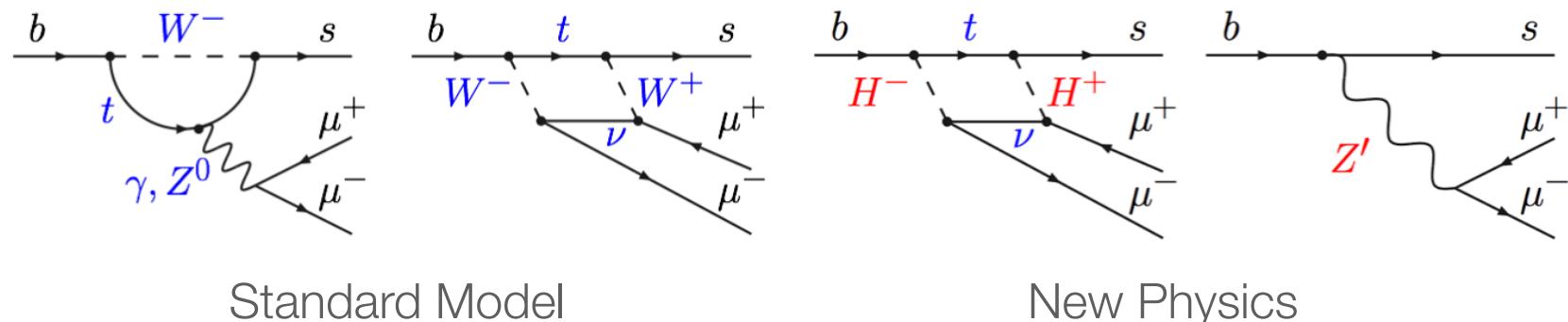


[PDG, PRD 98, 030001 (2018)]



# What do we want to measure?

$$R_{H_s} = \frac{\int \frac{d\Gamma(B \rightarrow H_s \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \rightarrow H_s e^+ e^-)}{dq^2} dq^2} \stackrel{SM}{\approx} 1$$

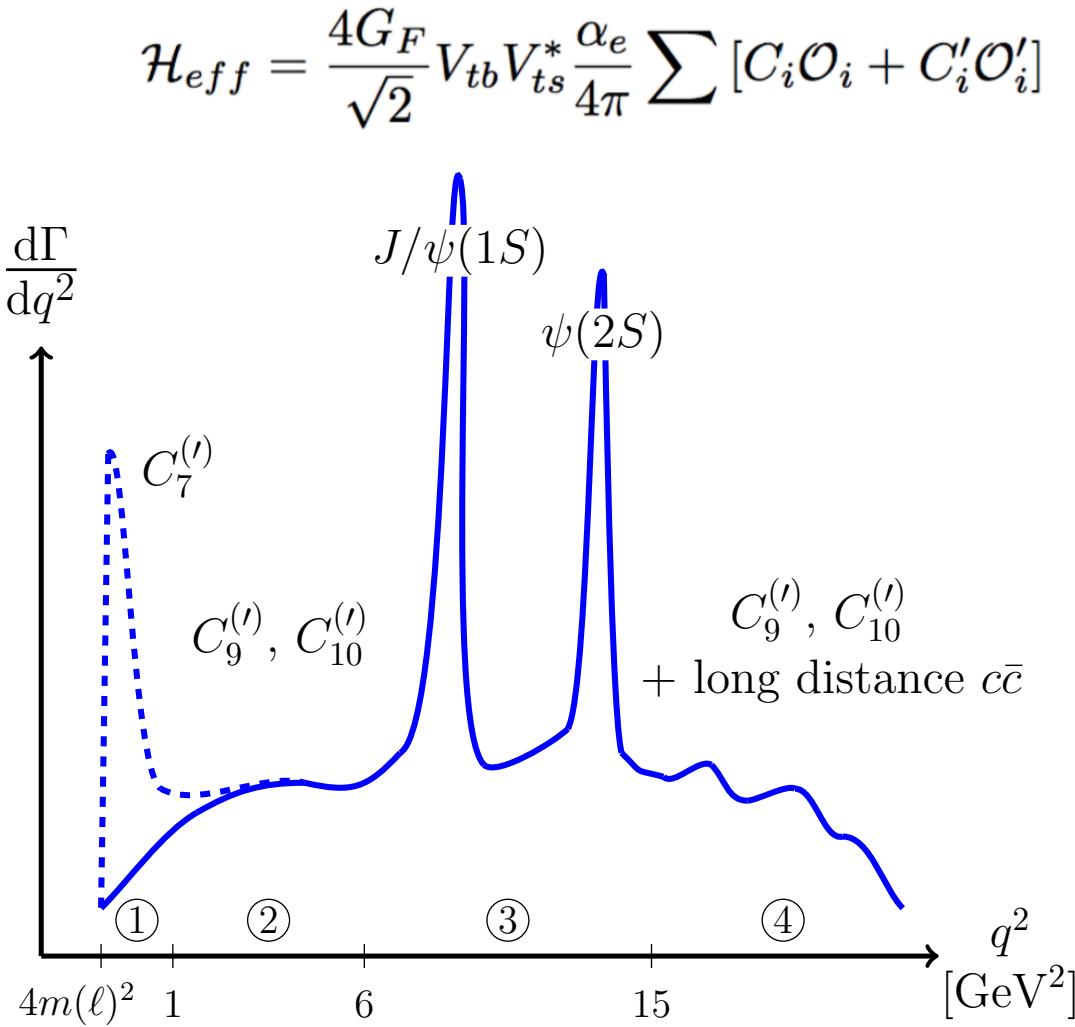
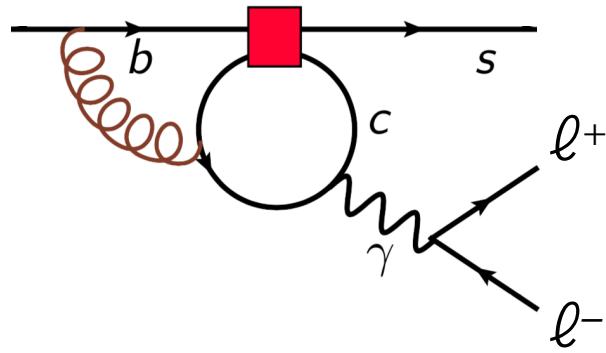


# Differential in $q^2$

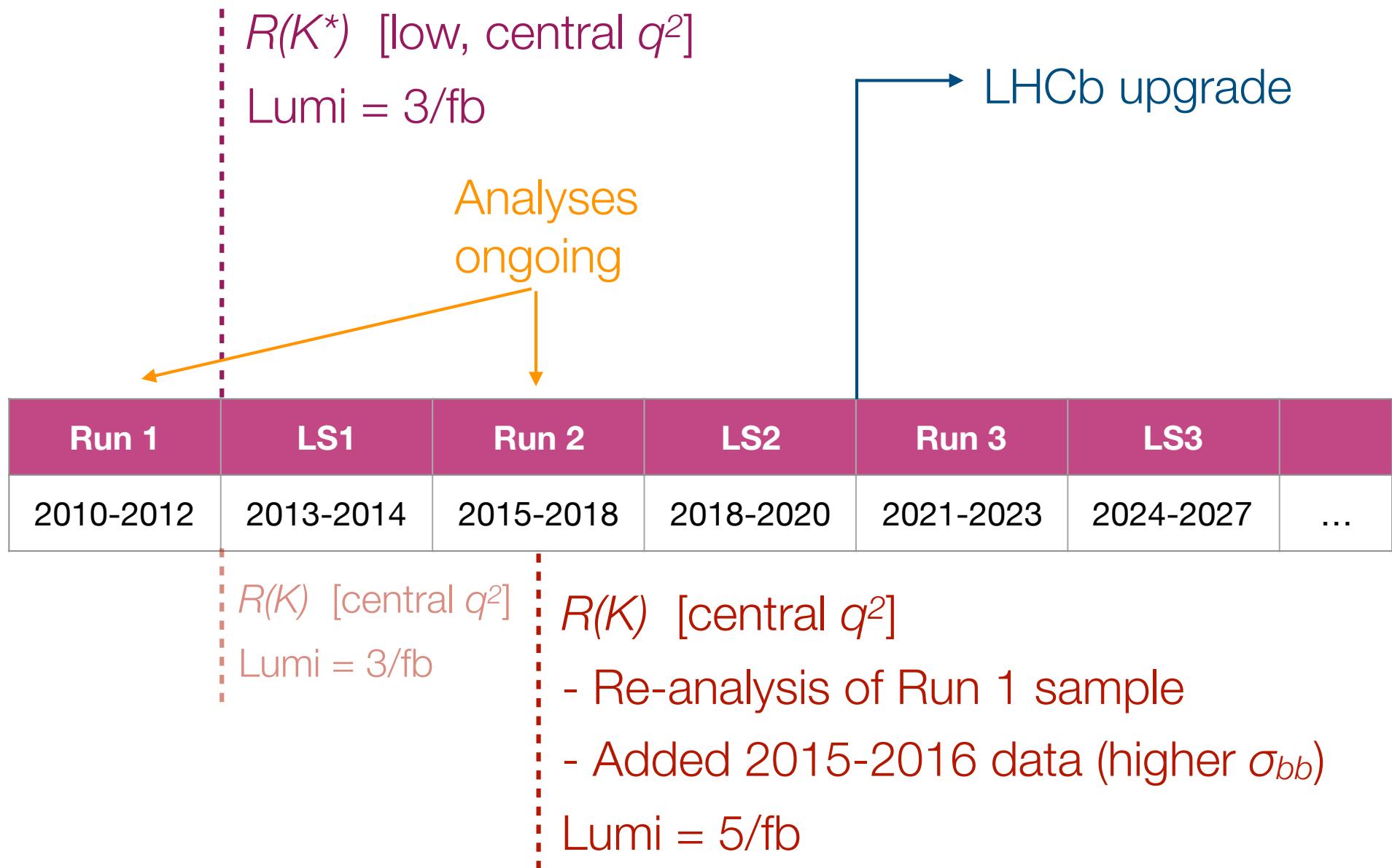
- Perform the measurement in bins of  $q^2 \equiv m(\ell\ell)$

- ① low- $q^2$ : [0.045, 1.1]  $\text{GeV}^2/\text{c}^4$
- ② central- $q^2$ : [1.1, 6]  $\text{GeV}^2/\text{c}^4$

- Veto the  $q^2$  regions close to the resonances ③ where the charm-loop dominates

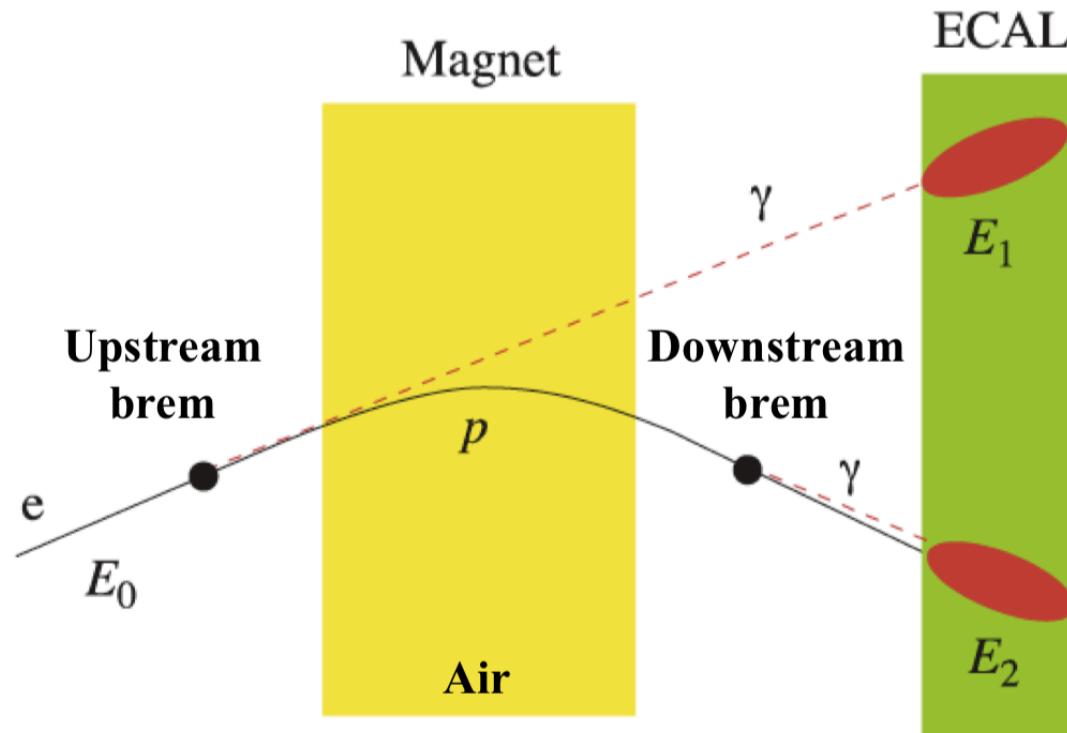


# What data?



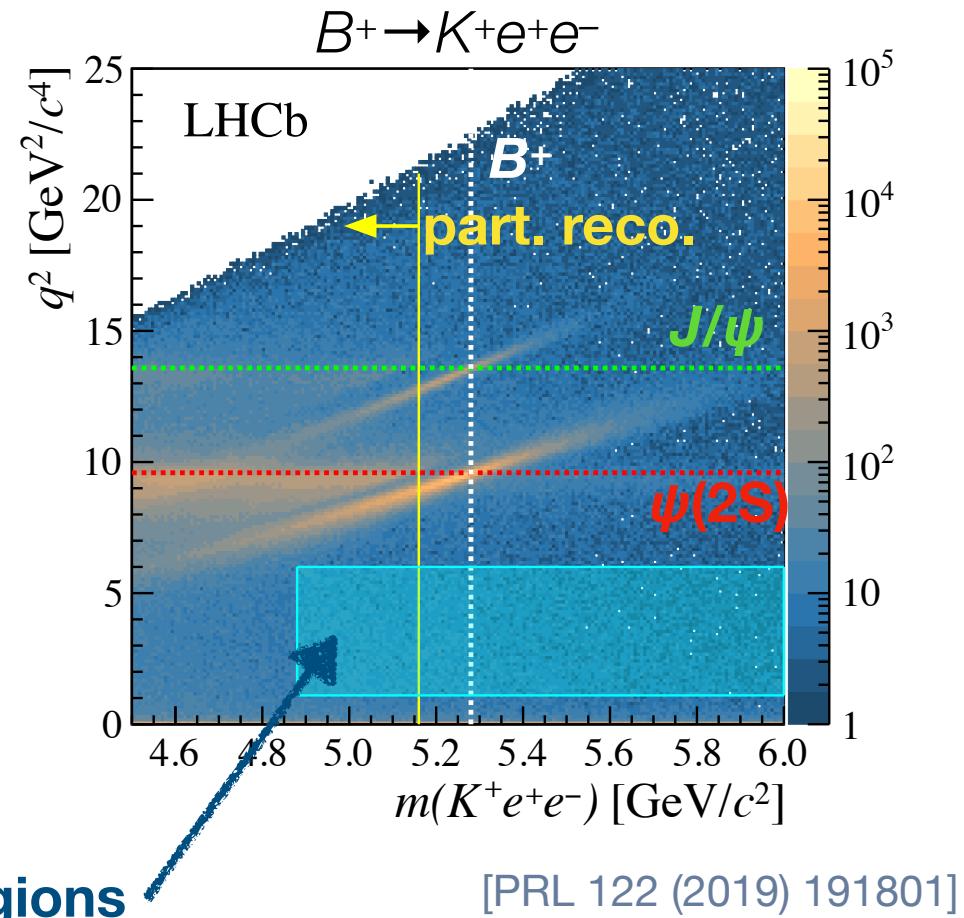
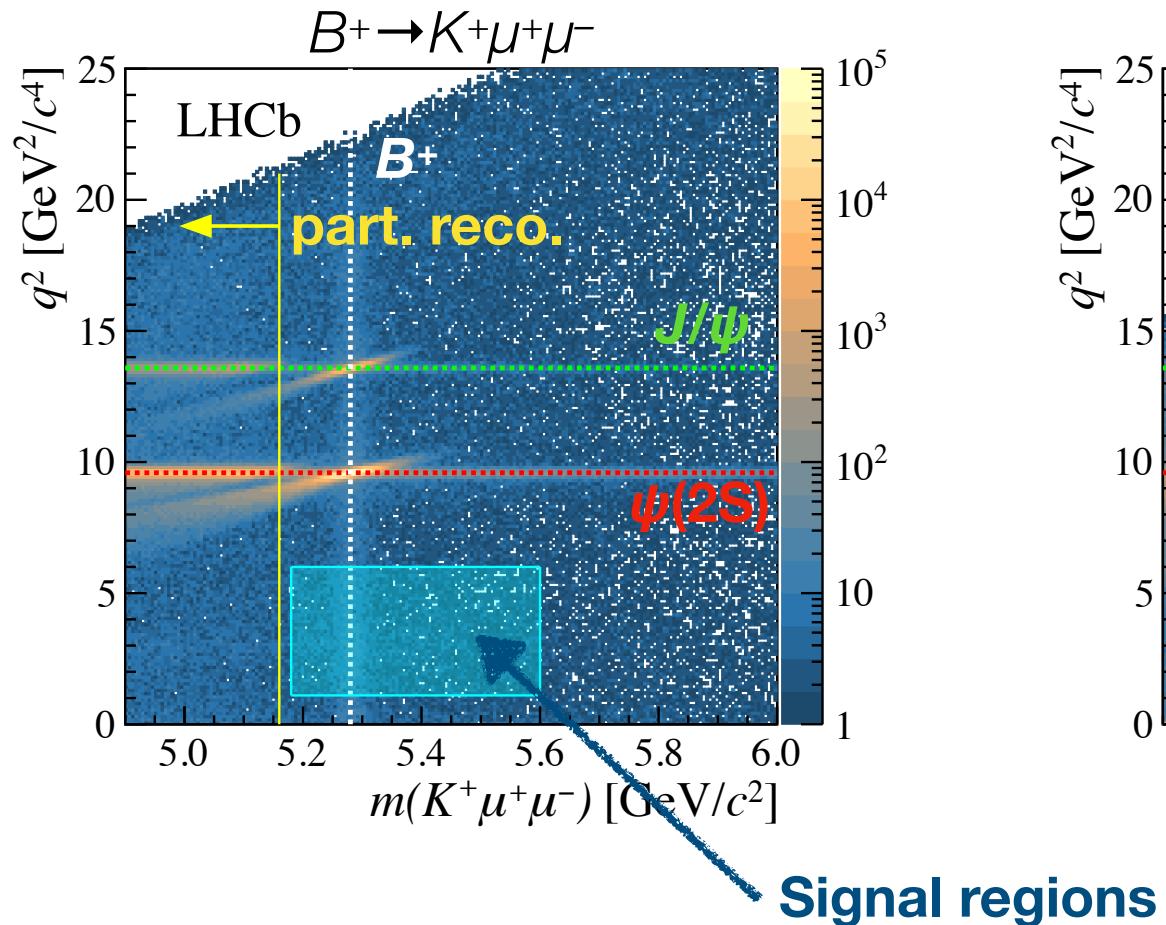
# Experimental challenge - electrons

- Electrons lose a large fraction of their energy through Bremsstrahlung radiation
  - ▶ Bremsstrahlung recovery: Look for photon clusters in the calorimeter ( $ET > 75$  MeV) compatible with electron direction before magnet



# Momentum & mass resolution

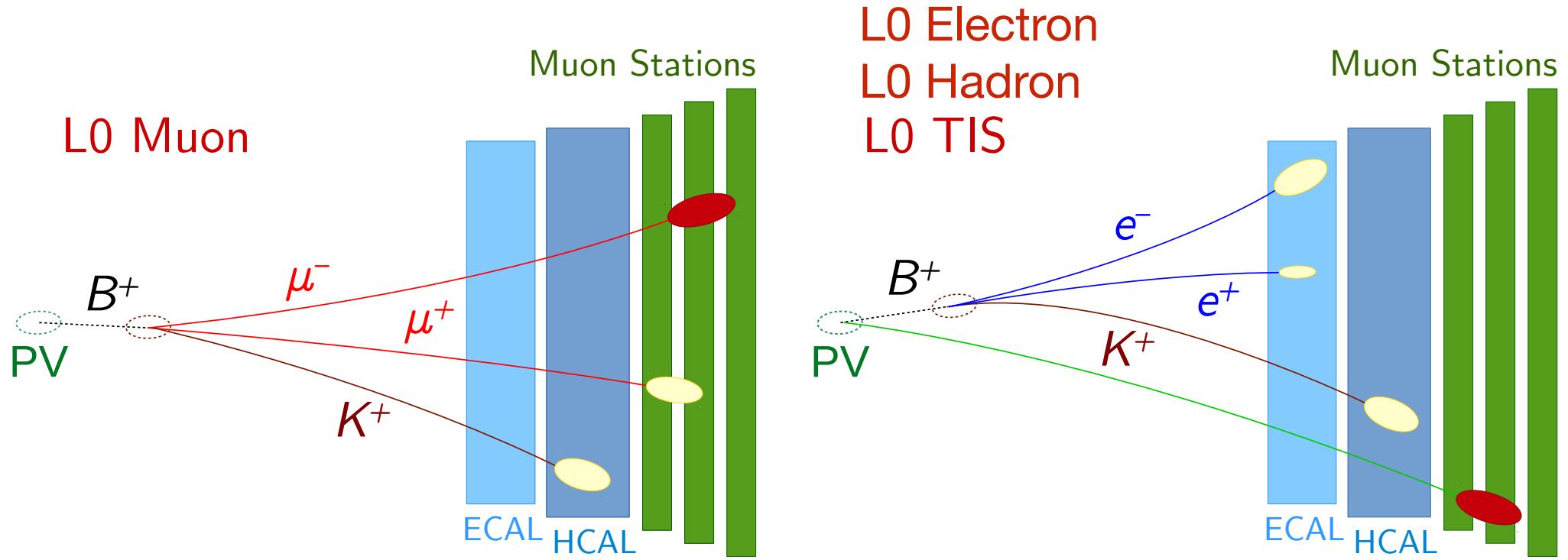
- After Brem. recovery, still worse resolution for electrons
  - ▶ lower reconstruction and PID efficiencies
  - ▶ worse signal-background separation



# Trigger

[PRL 122 (2019) 191801]

- Very different trigger signatures: Lower trigger efficiency for electrons

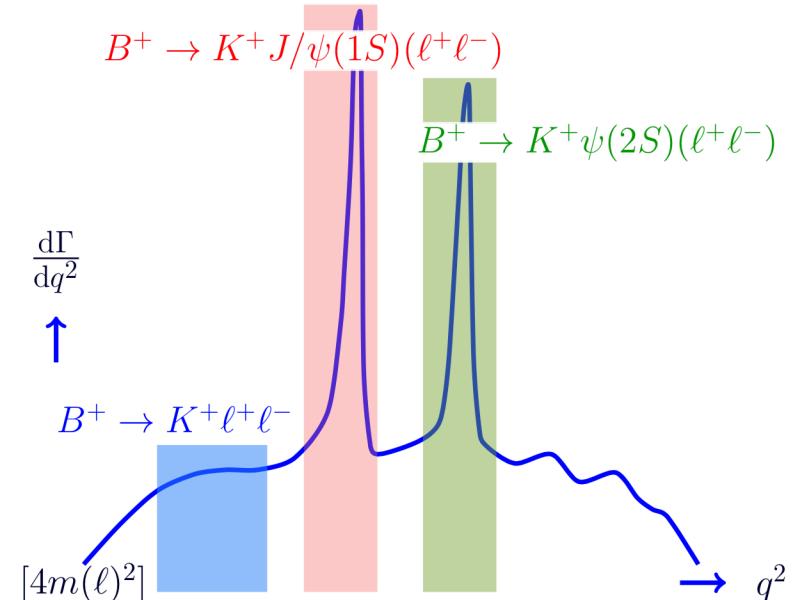


# Analysis strategy

- Get differences between muons and electrons fully under control
  - Measurement performed as a double ratio between **rare** and **resonant** modes to cancel most systematics

$$\begin{aligned}
 R_K &= \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi(\mu^+ \mu^-))} \Big/ \frac{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi(e^+ e^-))} \\
 &= \frac{N(K^+ \mu\mu)}{N(K^+ J/\psi(\mu\mu))} \cdot \frac{N(K^+ J/\psi(ee))}{N(K^+ ee)} \\
 &\quad \frac{\varepsilon(K^+ J/\psi(\mu\mu))}{\varepsilon(K^+ \mu\mu)} \cdot \frac{\varepsilon(K^+ ee)}{\varepsilon(K^+ J/\psi(ee))}
 \end{aligned}$$

Two ingredients needed: Efficiencies and yields.



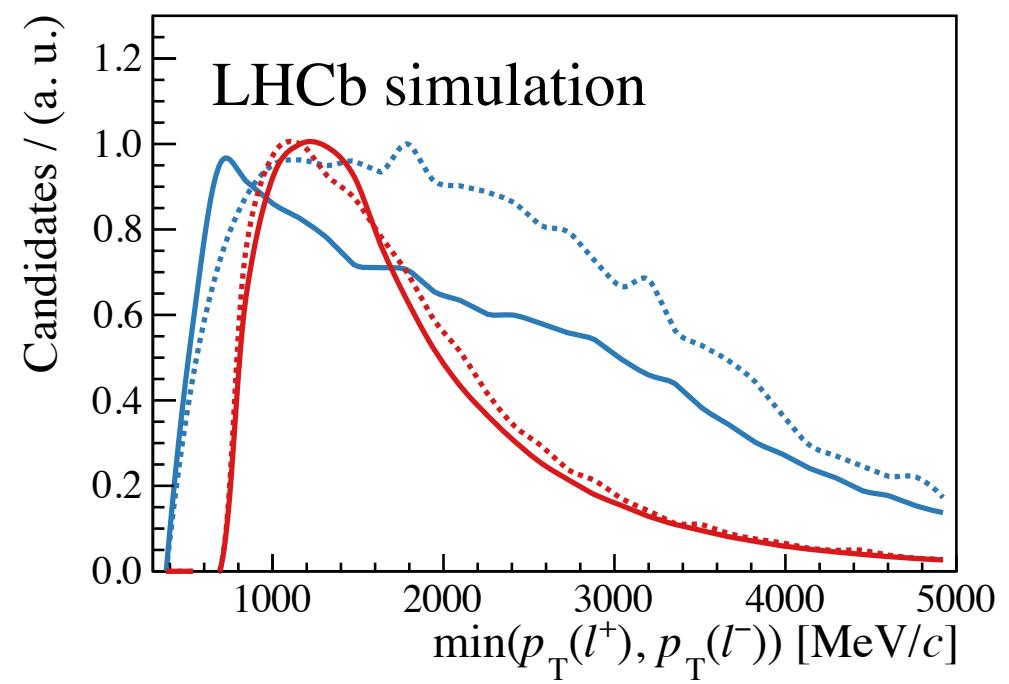
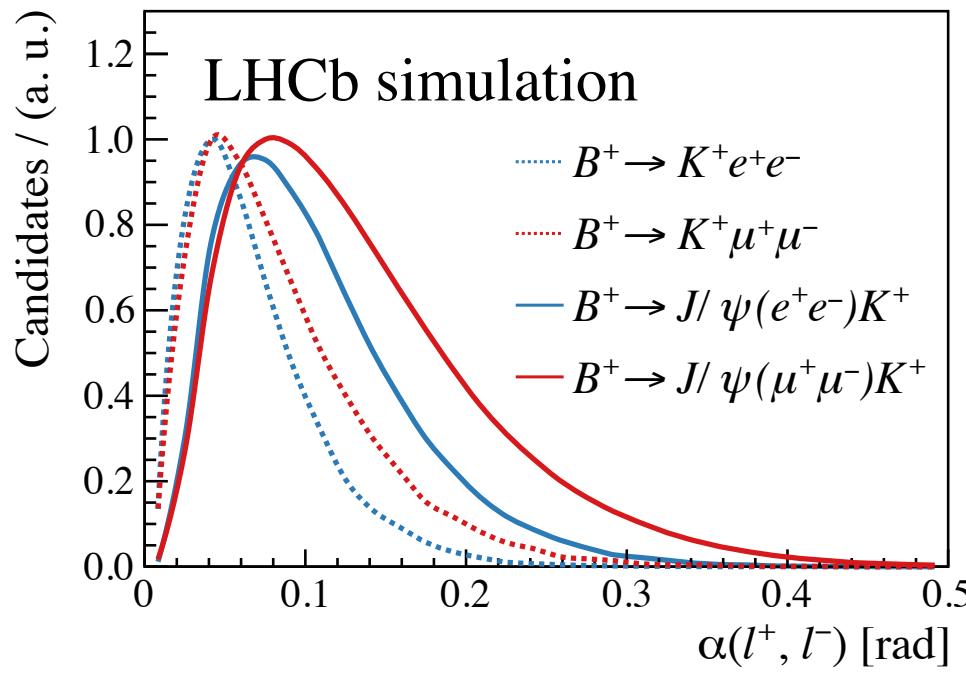
# Data-driven calibration of the efficiencies

Ratio of efficiencies determined with simulation carefully calibrated using control channels selected from data:

- Particle ID calibration
  - ▶ Tune particle ID variables for diff. particle species using kinematically selected calibration samples ( $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+ \dots$ ) [EPJ T&I(2019)6:1]
- Calibration of  $q^2$  and  $m(K^+e^+e^-)$  resolutions
  - ▶ Use fit to  $m(J/\psi)$  to smear  $q^2$  in simulation to match that in data
- B+ kinematics
  - ▶ correct simulation to describe kinematics of B's produced at LHCb
- Trigger efficiency
  - ▶ Determine trigger efficiency using tag-and-probe method in normalisation modes

# The magic of the ‘double-ratio’

- Large overlap between resonant (—) and rare (···) modes in variables relevant for the detector response (due to the large boost of B's produced at LHCb)



⇒ Systematic uncertainties cancel to a large extent

# Cross-checks

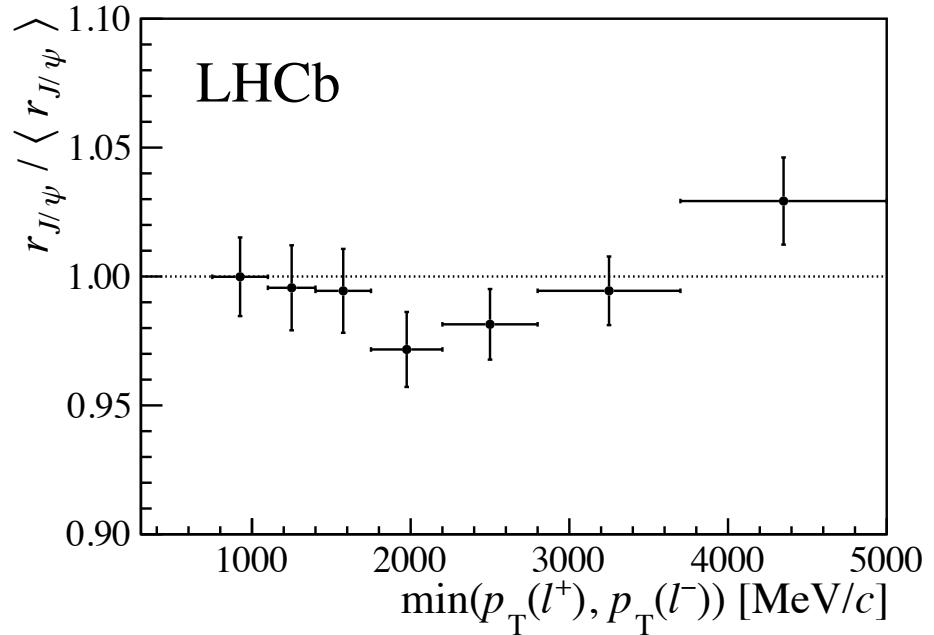
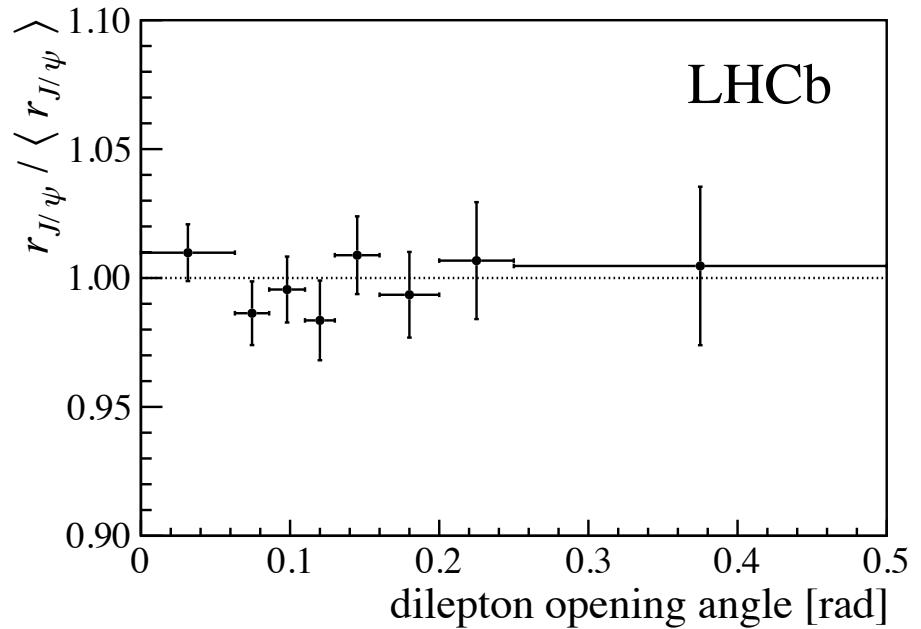
[PRL 122 (2019) 191801]

- To ensure good understanding of the efficiencies check

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \rightarrow K^+ J/\psi(\mu^+ \mu^-))}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi(e^+ e^-))} = 1$$

$$r_{J/\psi} = 1.014 \pm 0.035 \text{ (stat + syst)}$$

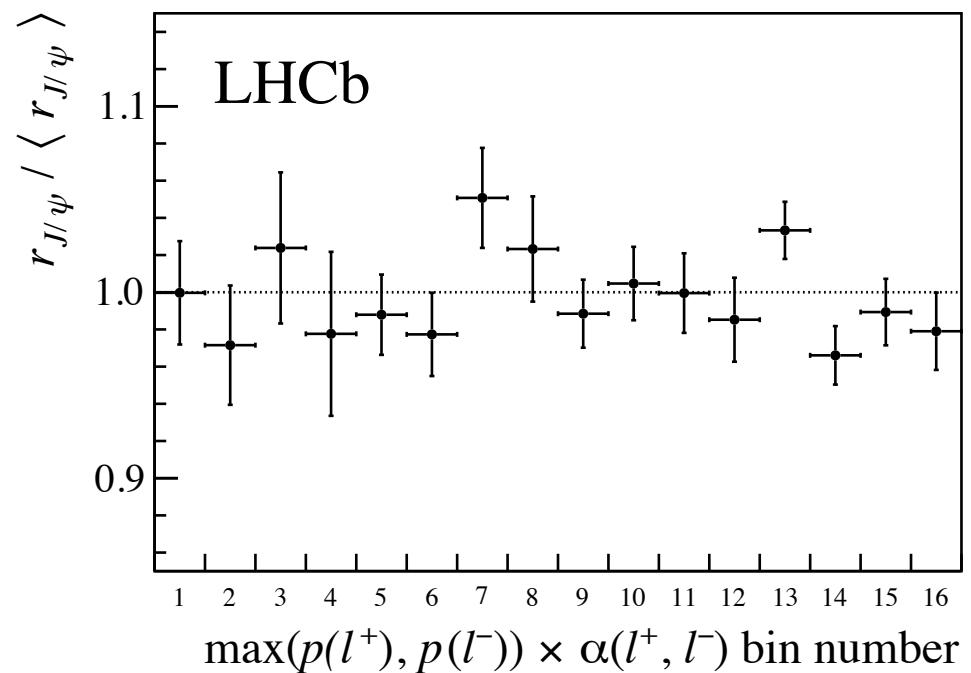
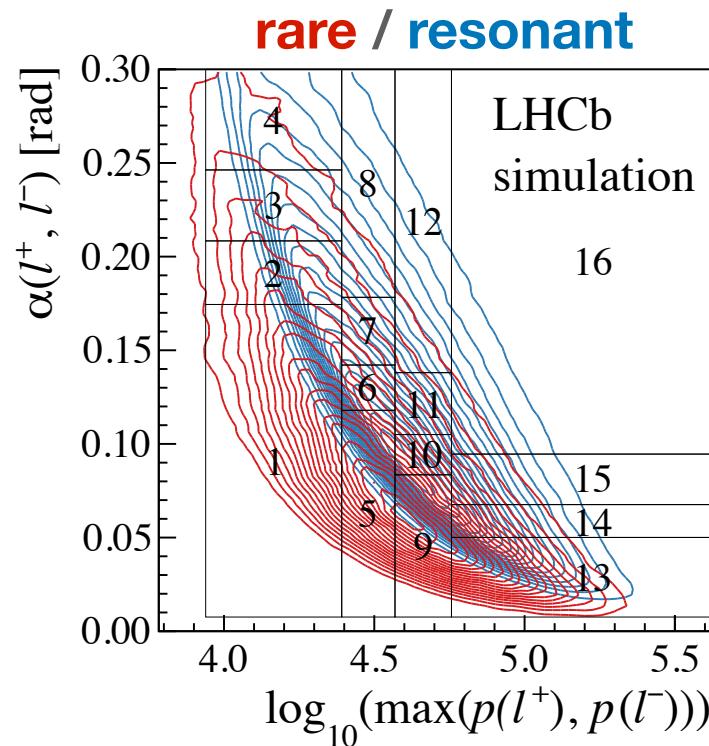
- Checked that efficiencies are understood in all kinematic regions  $\Rightarrow r_{J/\psi}$  is flat for all variables examined
- Cross-checks done independently for Run 1 and Run 2 samples and excellent agreement found



# Cross-checks (II)

[PRL 122 (2019) 191801]

- $r_{J/\psi}$  is also checked in 2D to check to look for correlated mismodelling of the efficiencies:
  - ▶ Choose  $q^2$ -dependent variables relevant for the detector response.



# Cross-checks (III)

[PRL 122 (2019) 191801]

- Checked also the double ratio...

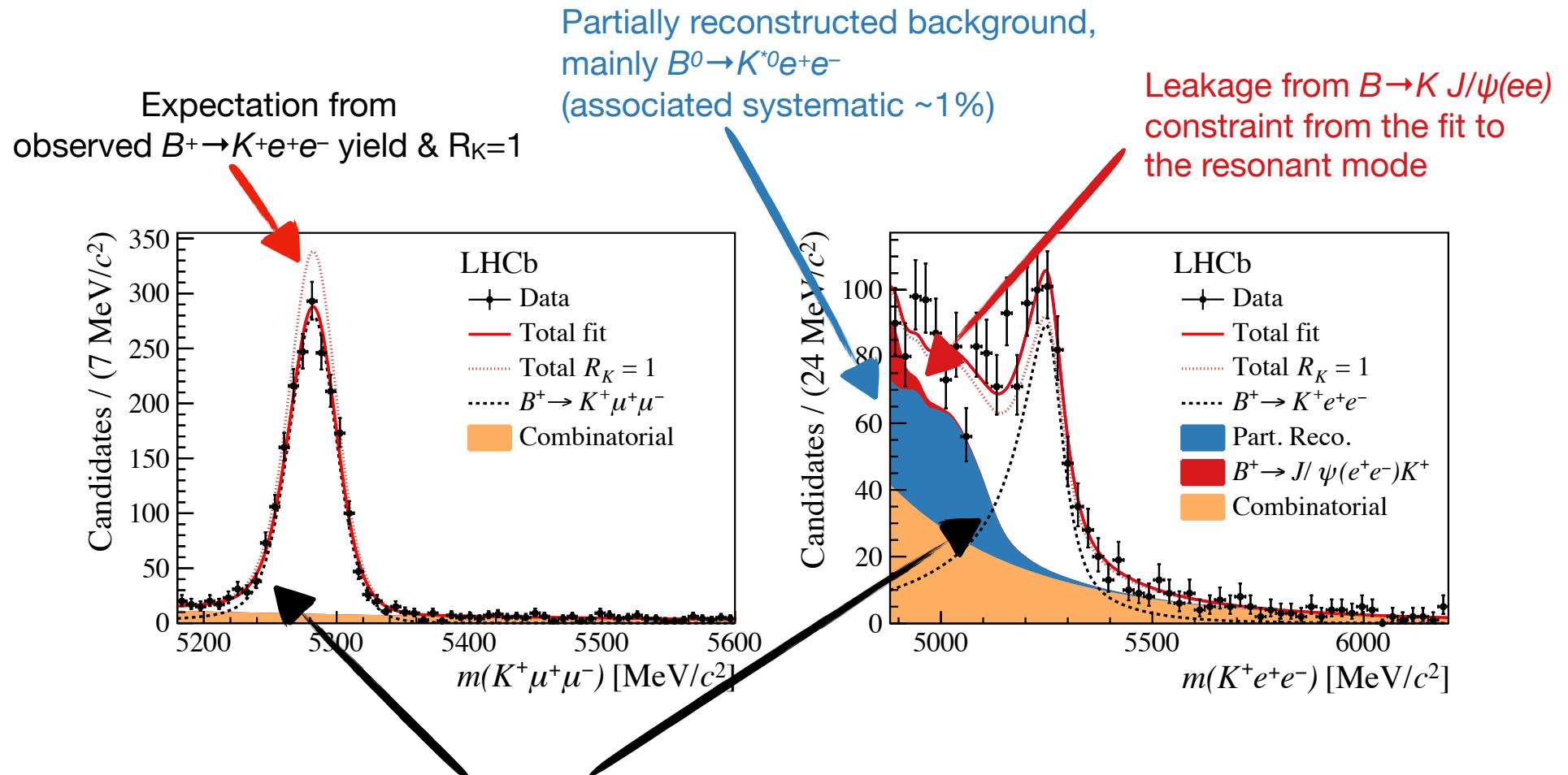
$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \rightarrow K^+ \psi(2S)(\mu^+ \mu^-))}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi(\mu^+ \mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \rightarrow K^+ \psi(2S)(e^+ e^-))}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi(e^+ e^-))}$$

$$R_{\psi(2S)} = 0.986 \pm 0.013 \text{ (stat + syst)}$$

- ... and that the BR of the rare muon mode is in agreement with previous measurements.
- All cross-checks done independently for Run 1 and Run 2 samples and 3 trigger categories and excellent agreement found

# Extraction of the yields

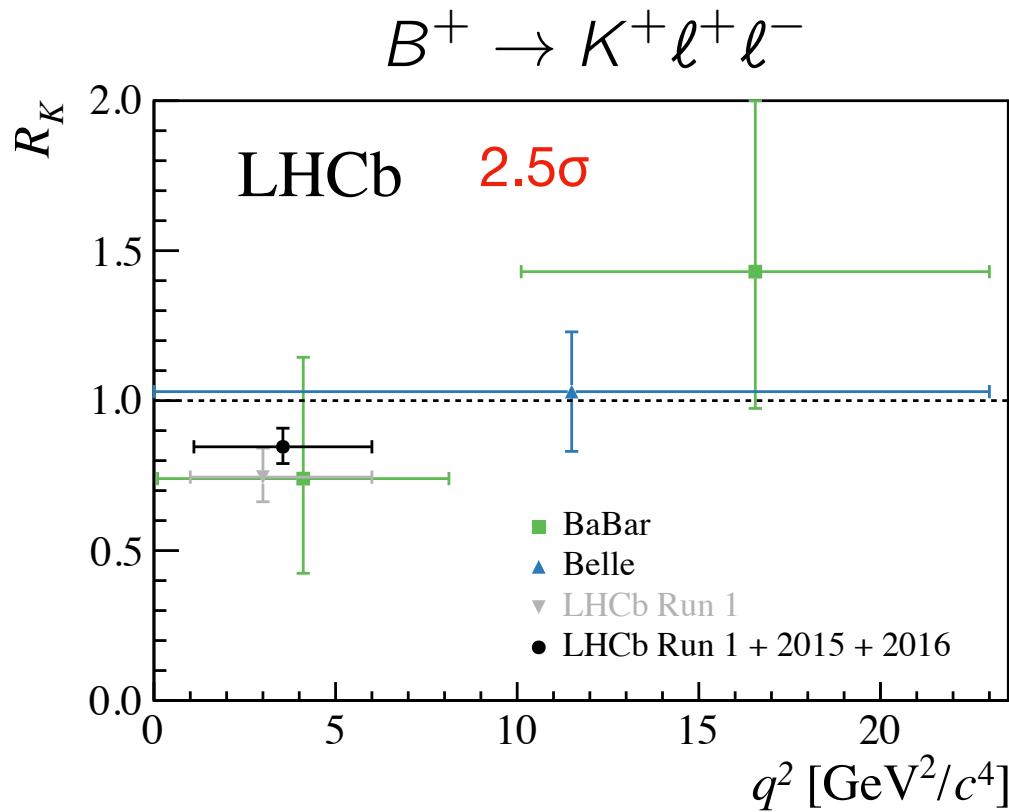
[PRL 122 (2019) 191801]



Different signal shape between muons and electrons:

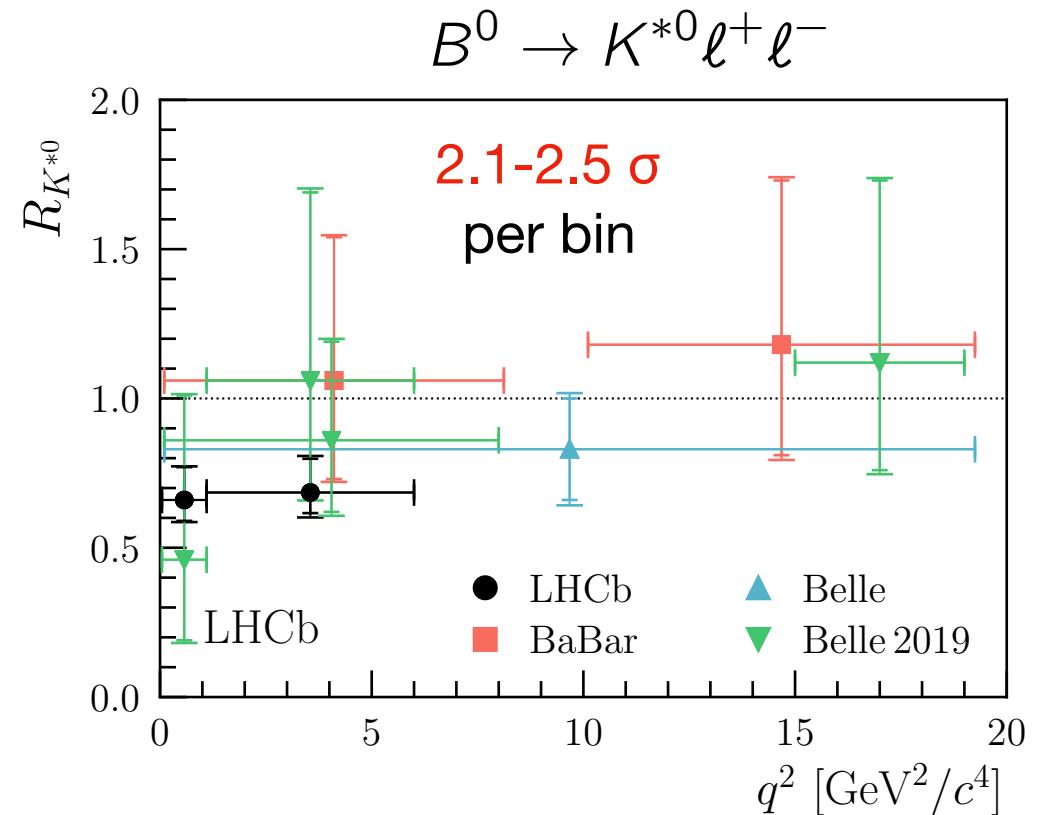
- worse mass resolution (recovered  $\gamma$ )
- longer radiative tail (more Bremsstrahlung)

# Results



$$R_K^{\text{old Run1}} = 0.745^{+0.090}_{-0.074} (\text{stat}) \pm 0.036 (\text{syst})$$

$$R_K = 0.846^{+0.060}_{-0.054} (\text{stat})^{+0.014}_{-0.016} (\text{syst})$$



$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07} (\text{stat}) \pm 0.03 (\text{syst}) & \text{low } q^2 \\ 0.69^{+0.11}_{-0.07} (\text{stat}) \pm 0.05 (\text{syst}) & \text{central } q^2 \end{cases}$$

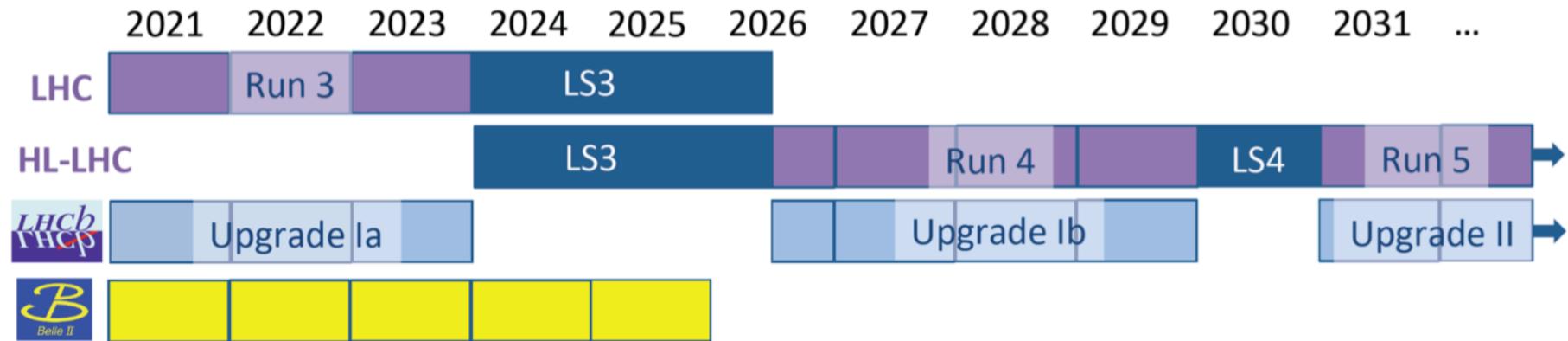
[PRL 122 (2019) 191801]  
[LHCb, PRL 113 (2014) 151601]

[LHCb, JHEP 08 (2017) 055]  
[BaBar, PRD 86 (2012) 032012]

[Belle, PRL 103 (2009) 171801]  
[Belle, arXiv:1904.02440]

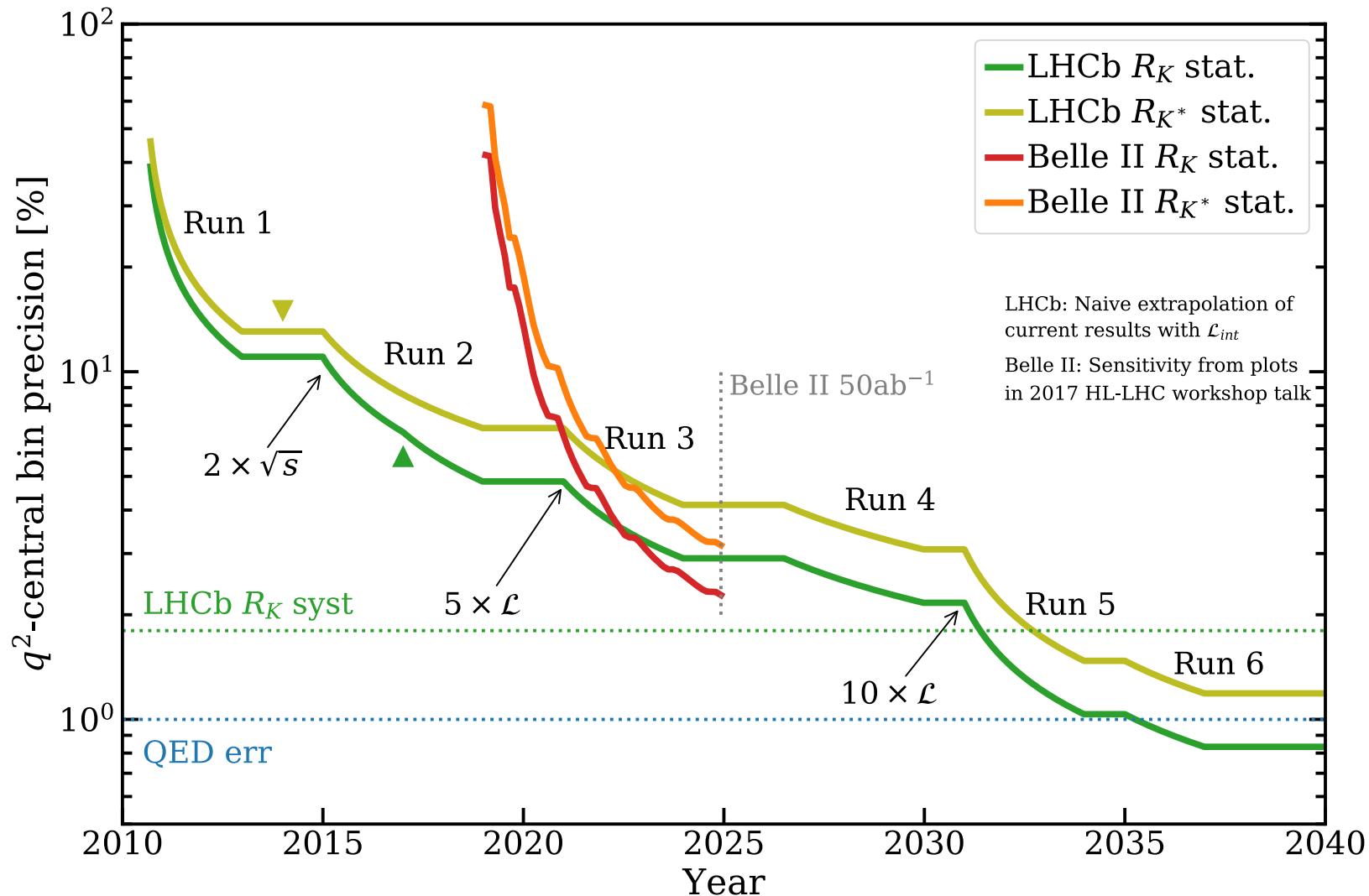
# What next?

[ CERN-LHCC-2011-001 ]



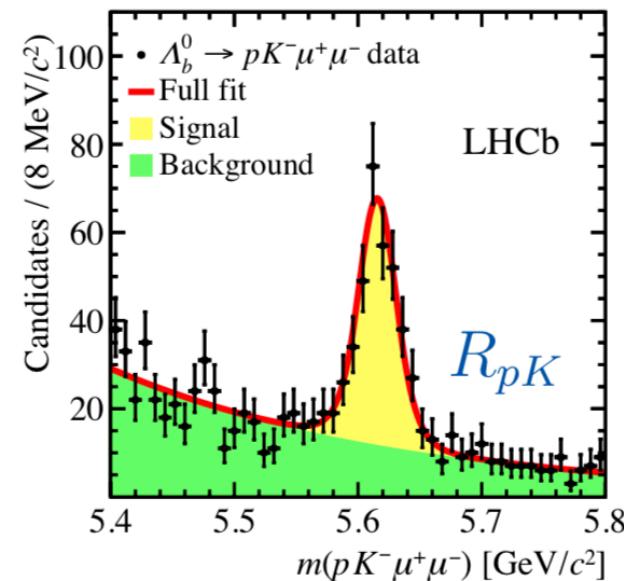
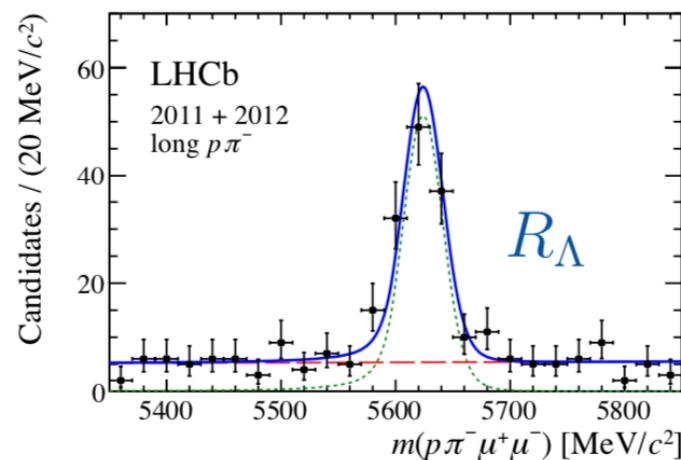
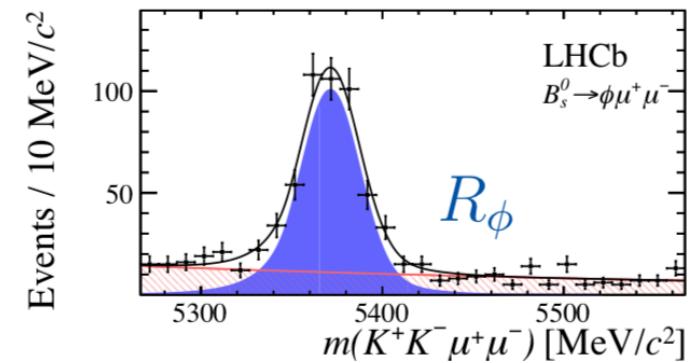
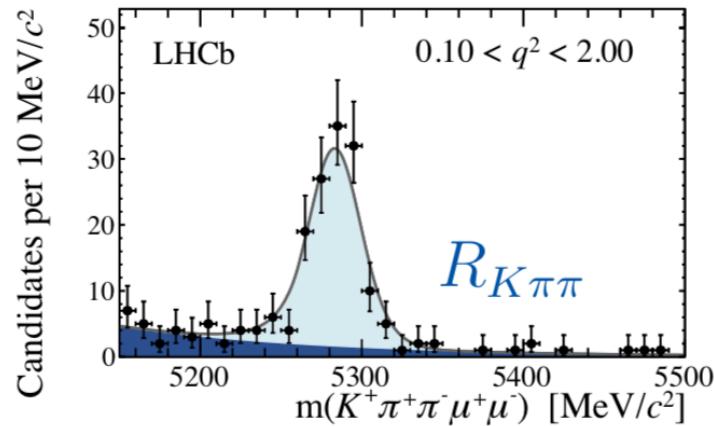
- **LHCb full Run 2 dataset ~ 4 times number of B's available in Run1**
  - ▶ updates of  $R(K)$  and  $R(K^*)$  coming
- **LHCb is in the process of upgrading to a new detector**
  - ▶ will operate at much higher luminosity with improved efficiency (make all trigger decisions in software)
  - ▶ will accumulate  $50 \text{ fb}^{-1}$  of data
- **A second phase of the Upgrade** in LS4 is also planned to profit from even higher luminosities at the **HL-LHC** (increase data sample up to  $300 \text{ fb}^{-1}$  for LHCb)

# Prospects for $R(K)$ and $R(K^*)$



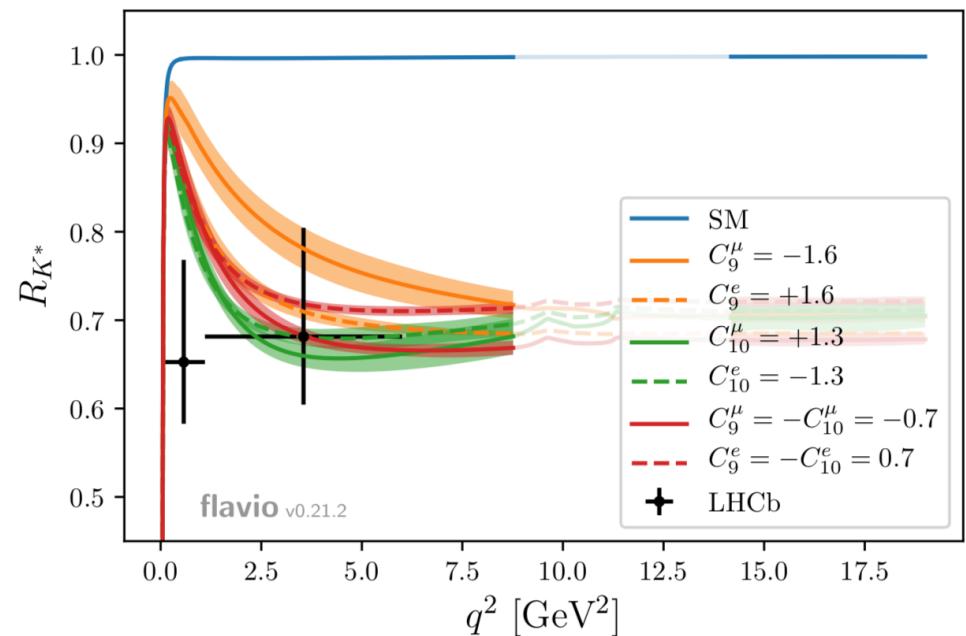
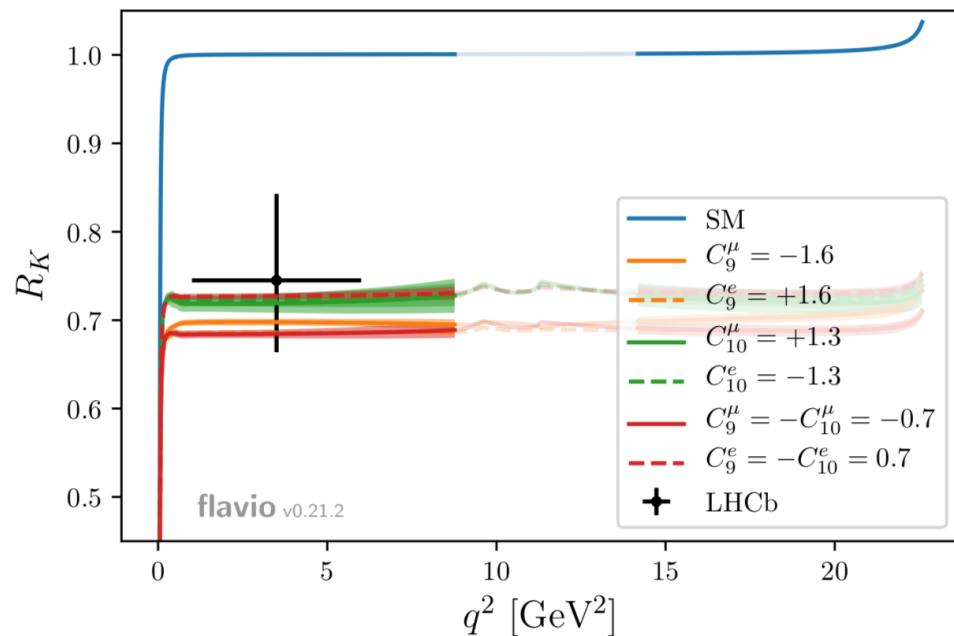
# Other LFU ratios

- Extending LFU test to many other penguins decays  
(muon decays well established)



# Other $q^2$ bins

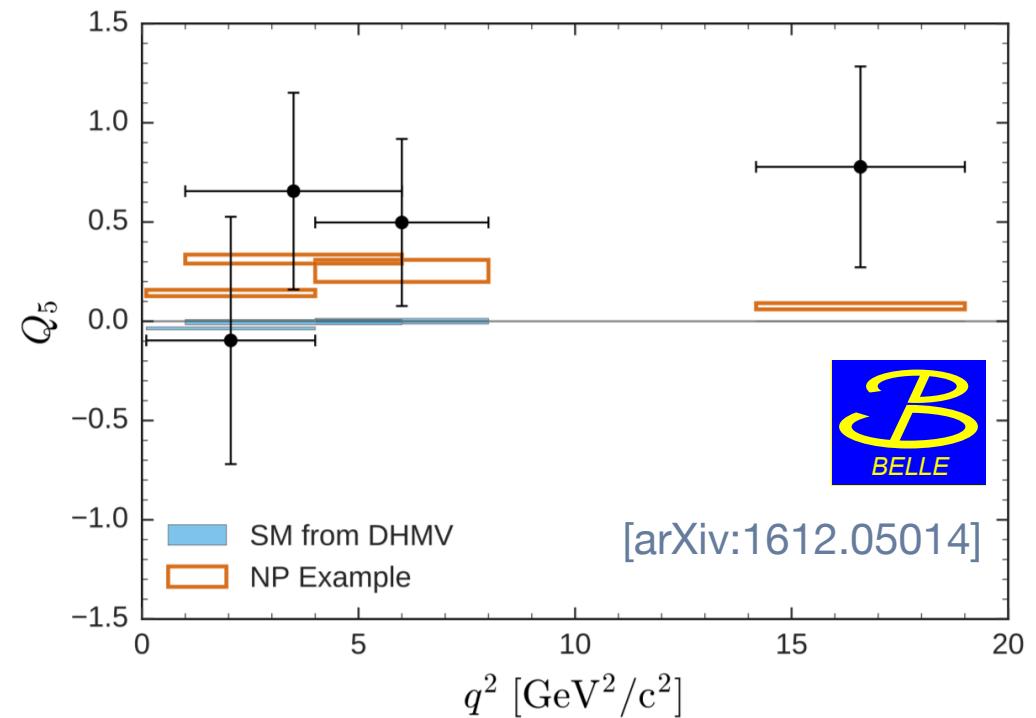
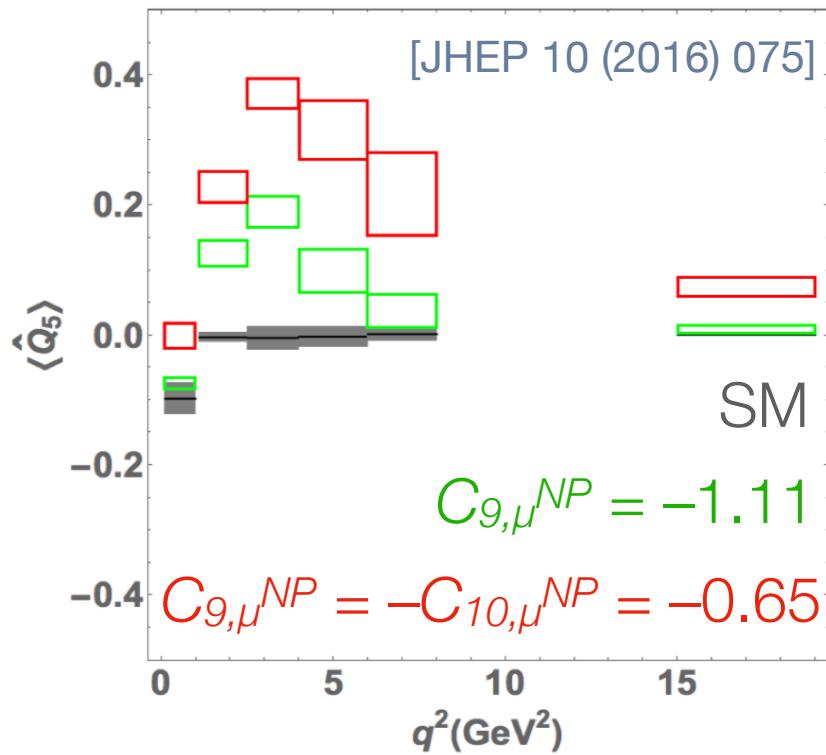
- Probe different kinematic regimes where similar deviations are predicted by most NP models.
  - ▶ High- $q^2$  bin: Different background composition makes it a bit trickier (leakage from  $J/\psi$ ,  $\psi(2S)$  and excited states)
  - ▶  $R(K)$  low- $q^2$ : Experimentally easier but less stat. gain w.r.t.  $R(K^*)$



[PRD96(2017)055008 ]

# LFU with angular observables

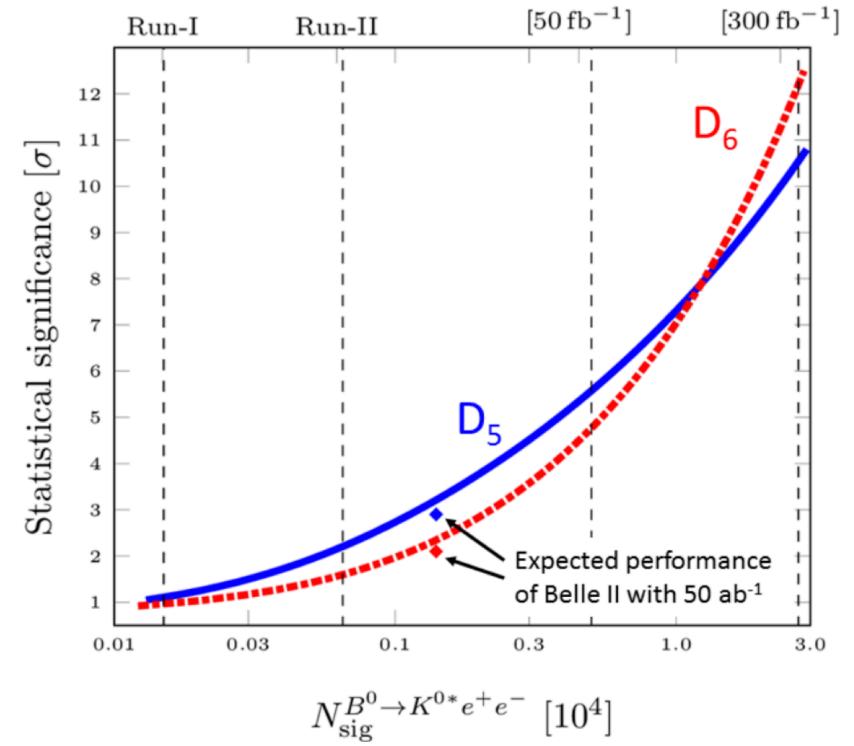
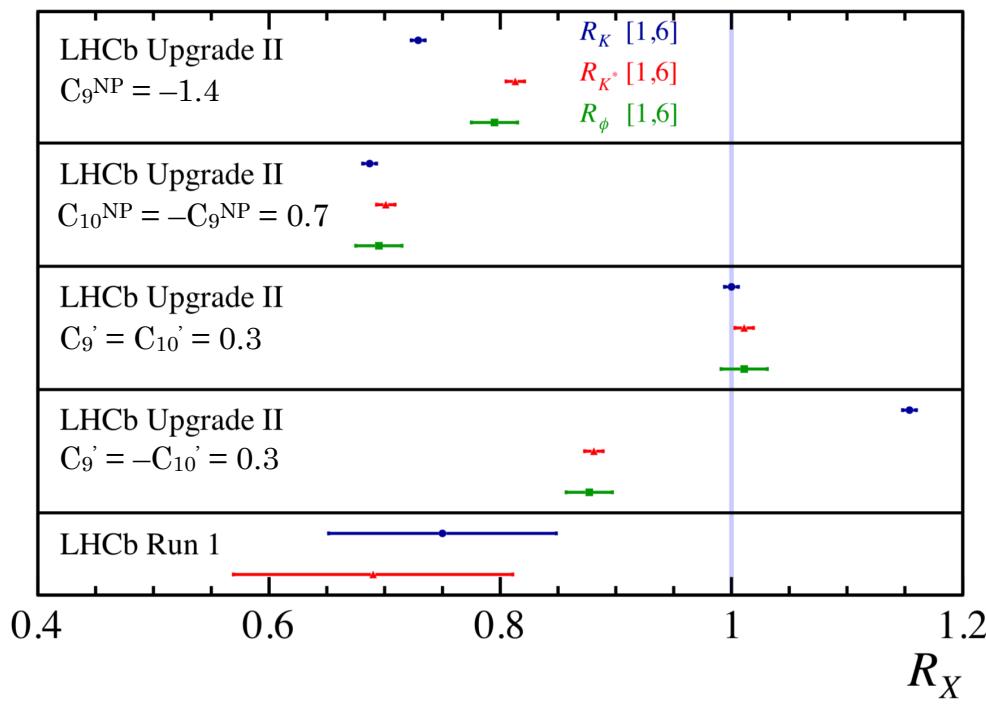
- Difference in angular observables between muons and electrons (e.g.  $Q_5 = P'_5(\mu) - P'_5(e)$ )
  - ▶ Complementary sensitivity to NP effects
  - ▶ Very different experimental systematics



# LFU with LHCb upgrade-II

[LHCb-PUB-2018-009]

- Access to different LFU ratios and angular observables with excellent precision: **allow to distinguish between different NP scenarios**
  - Need to drive systematics in electrons below  $\sim 1\%$



# Conclusions

- ▶ Since last  $b \rightarrow s \ell \ell$  workshop, LHCb has updated the measurement of  $R(K)$  adding part of Run 2 data, but result does not provide a definitive picture.
- ▶ Upcoming measurements with full Run 2 statistics will help to resolve the current situation.
- ▶ Ongoing and future upgrades, open the door to different ways of testing LFU in penguin decays that will potentially give us information about the nature of New Physics.



# Backup

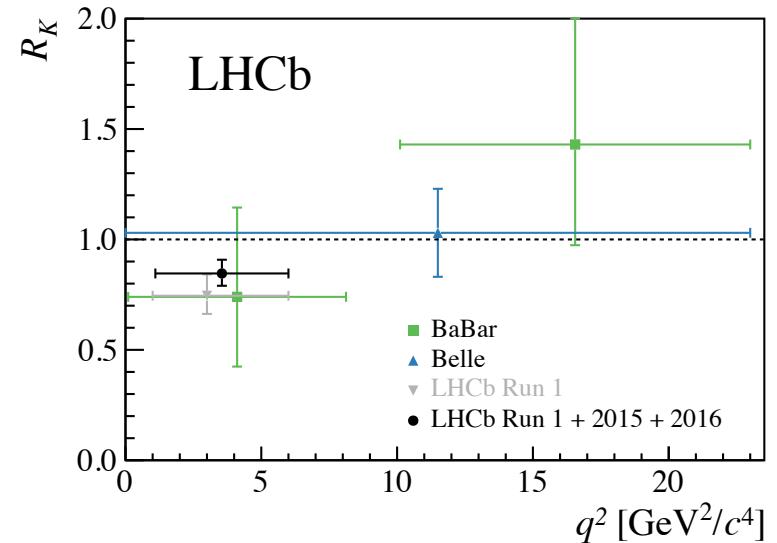
# New $R_K$ result

[PRL 122 (2019) 191801]

Reanalysing 2011-2012 and adding 2015 and 2016:

$$R_K = 0.846^{+0.060}_{-0.054} \text{ (stat)}^{+0.014}_{-0.016} \text{ (syst)}$$

compatible with the SM expectation at **2.5  $\sigma$ .**



- Main systematics:
  - ▶ Uncertainty on the fit shape
  - ▶ Calibration of  $B^+$  kinematics and trigger efficiencies

- If Run 1 and Run 2 samples were fitted separately

$$R_K^{\text{old Run1}} = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)}$$

$$R_K^{\text{new Run1}} = 0.717^{+0.083}_{-0.071} \text{ (stat)}^{+0.017}_{-0.016} \text{ (syst)}$$

$$R_K^{\text{2015 + 2016}} = 0.928^{+0.089}_{-0.076} \text{ (stat)}^{+0.020}_{-0.016} \text{ (syst)}$$

⇒ Accounting for correlations:

- ▶ Previous Run 1 vs this Run 1 result  $< 1\sigma$
- ▶ Run 1 vs 2015+2016:  $1.9\sigma$

# $R(K)$ systematics

- Efficiency calibration
    - Dependence with tag, in tag-and-probe determinations;
    - Parameterisation bias (e.g. factorisation of PID efficiencies for kaons and electrons) tag and trigger bias;
    - Dependence of  $q^2$  and  $m(K^+e^+e^-)$  resolution with  $q^2$
    - Inaccuracies in material description in simulation (tracking efficiency)
  - Statistics of simulation and calibration samples
    - Bootstrapping method that takes into account correlations between calibration samples and final measurement
  - Choice of fit model
    - Associated signal and partially reconstructed background shape
- Total relative systematic of 1.7% in the final  $R_K$  measurement ⇒ Expected to be statistically dominated

# $R(K^*)$ systematics

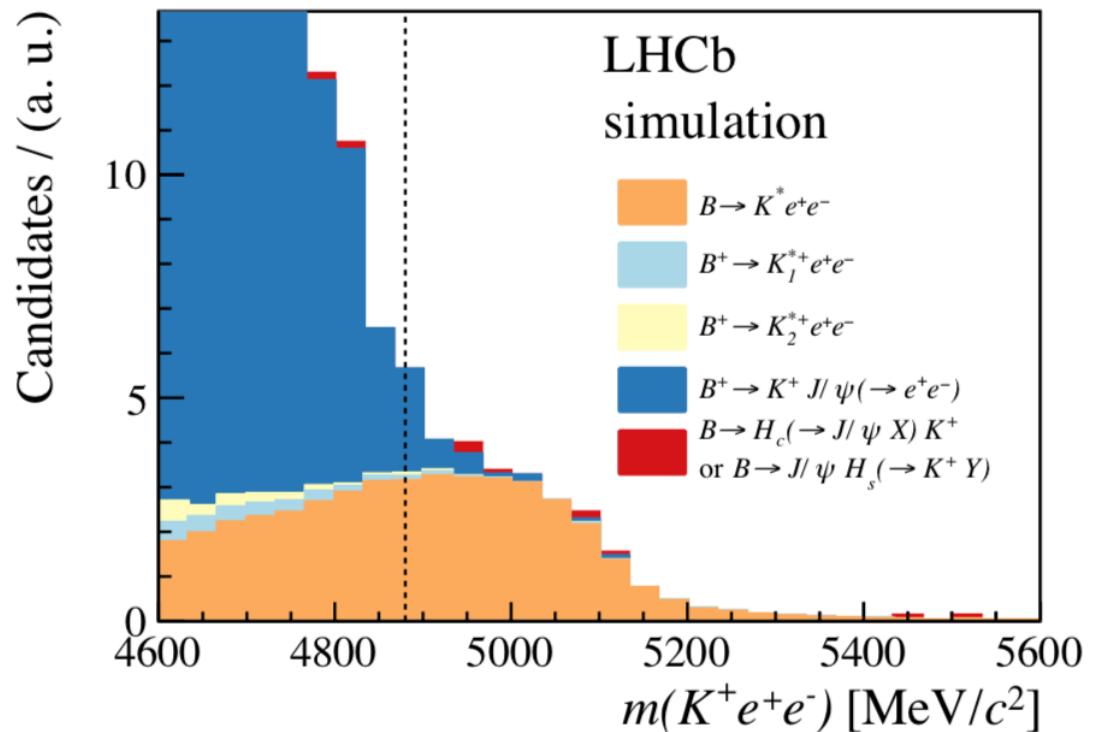
Trigger category	low- $q^2$			central- $q^2$		
	L0E	L0H	L0I	L0E	L0H	L0I
<b>Corrections to simulation</b>	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
<b>Kinematic selection</b>	2.1	2.1	2.1	2.1	2.1	2.1
<b>Residual background</b>	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ flatness	1.6	1.4	1.7	0.7	2.1	0.7
<b>Total</b>	4.0	6.1	5.5	6.4	7.5	6.7

# Fit window for $B^+ \rightarrow K^+ e^+ e^-$

[PRL 122 (2019) 191801]

Remaining backgrounds:

- Combinatorial
- $B^+ \rightarrow K^+ J/\psi(e^+e^-)$
- Partially reconstructed  
 $B \rightarrow KX\ell\ell$  decays



Choose the  $m(K^+e^+e^-)$  window so that the contribution from partially reconstructed decays is dominated by  $B^0 \rightarrow K^{*0}e^+e^-$ ,

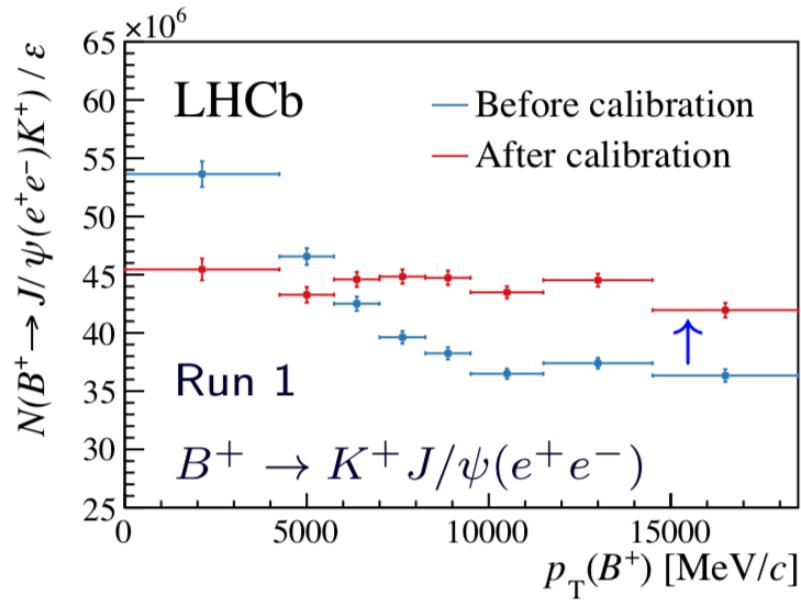
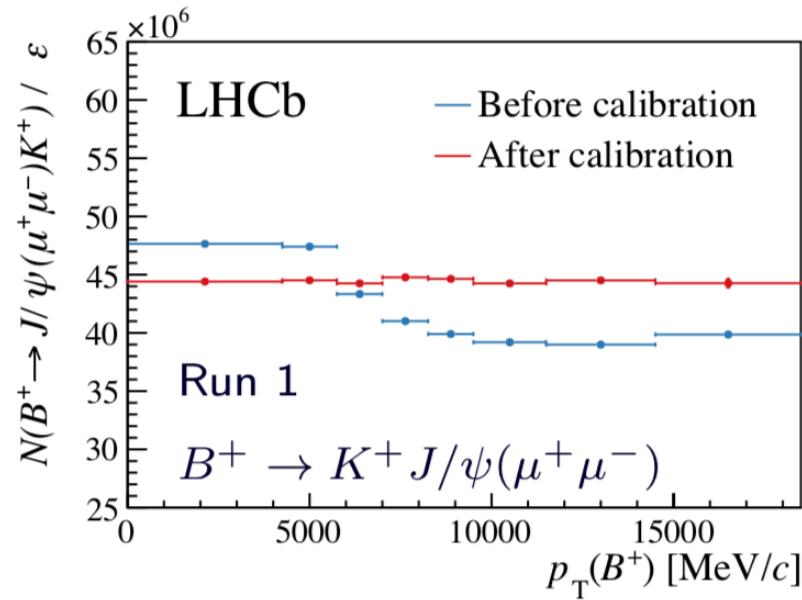
→ Included the contribution from  $B \rightarrow K^{**}e^+e^-$  decays,  $K^{**} \equiv \{K_1, K_2^{*0(+)}\}$ , as a systematic

$$\mathcal{B}(B \rightarrow K^{**}e^-e^-) = \mathcal{B}(B^0 \rightarrow K^{*0}e^-e^-) \cdot \mathcal{B}(B \rightarrow K^{**}J/\psi) / \mathcal{B}(B^+ \rightarrow K^{*0}J/\psi)$$

# Efficiency calibration summary

[LHCb-PAPER-2019-009]

- After calibration, very good data/MC agreement in all key observables



- Calibrate the simulation so that it describes correctly the kinematics of the  $B^+$ 's produced at LHCb.
- Compare distributions in data and simulation using  $B^+ \rightarrow K^+ J/\psi(\ell^+\ell^-)$  candidates.
- Iterative reweighing of  $p_T(B^+) \times \eta(B^+)$ , but also the vertex quality and the significance of the  $B^+$  displacement.

none

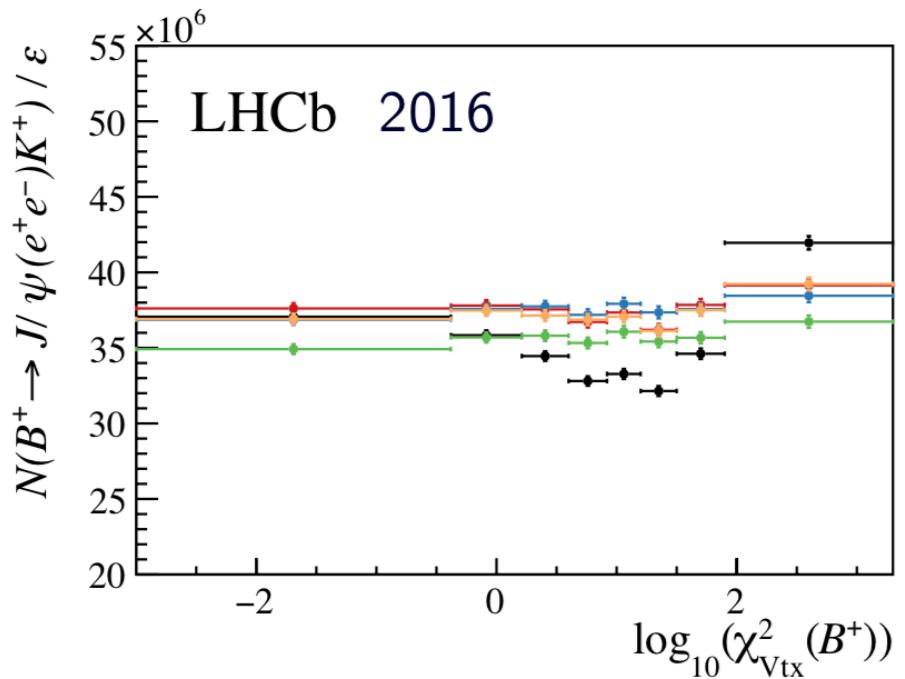
$\mu\mu$  LOMuon, nominal

$\mu\mu$  LOTIS

$ee$  LOElectron

$VTX\chi^2$ :  $ee$  LOElectron,  
 $p_T(B) \times \eta(B)$ ,  $IP\chi^2$ :  $\mu\mu$  LOMuon

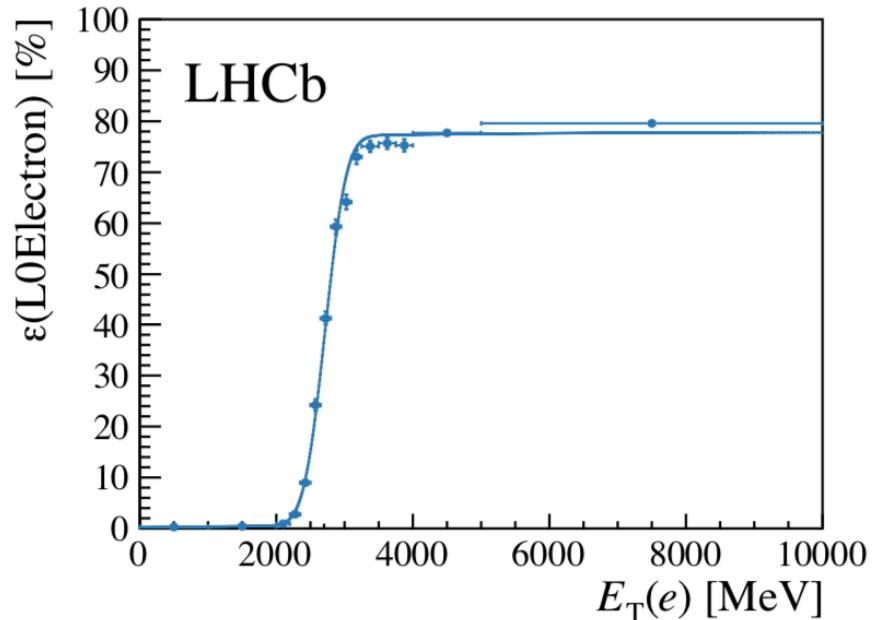
→ Systematic uncertainty from RMS between all these weights



# Trigger efficiency

The trigger efficiency is computed in data using  $B^+ \rightarrow K^+ J/\psi(\ell^+\ell^-)$  decays through a tag-and-probe method

[LHCb-PAPER-2019-009]



Especially for the electron samples, need to take into consideration some subtleties:

- dependence on how the calibration sample is selected,
- correlation between the two leptons in the signal.

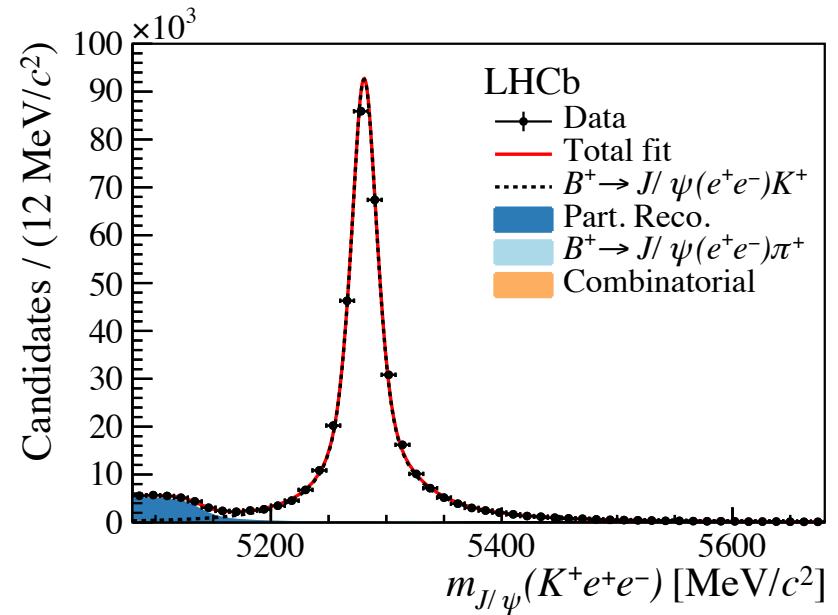
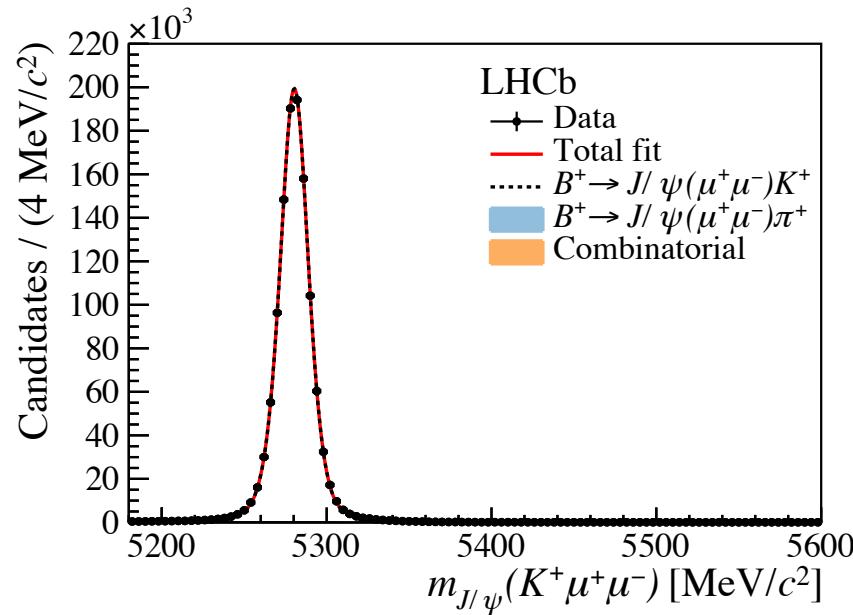
Repeat calibration with different samples/different requirements on the accompanying lepton

→ Associated systematic in the ratio of efficiencies is small

# Fit to the resonant modes

[PRL 122 (2019) 191801]

Yields for  $B^+ \rightarrow K^+ J/\psi(\ell^+\ell^-)$ , used as input for cross-checks and final determination of  $R_K$ , obtained from a fit to the  $J/\psi$ -constrained  $B$  mass



- Signal and background shapes determined from calibrated simulation
- Allow for a shift in the position in the signal peak and a scale factor to the resolution to float in the fit

# Simultaneous fit to extract $R_K$

- Get  $R_K$  directly as a parameter of the fit
- Perform simultaneous fit to  $m(K^+e^+e^-)$  and  $m(K^+\mu^+\mu^-)$  distributions

$$R_K = \frac{N_{K\mu\mu}^r}{N_{Kee}^{rt}} \cdot \frac{N_{J/\psi ee}^{rt}}{N_{J/\psi\mu\mu}^r} \cdot \frac{\varepsilon_{Kee}^{rt}}{\varepsilon_{K\mu\mu}^r} \cdot \frac{\varepsilon_{J/\psi\mu\mu}^r}{\varepsilon_{J/\psi ee}^{rt}}$$
$$= \frac{N_{K\mu\mu}^r}{N_{Kee}^{rt}} \cdot c_K^{rt},$$

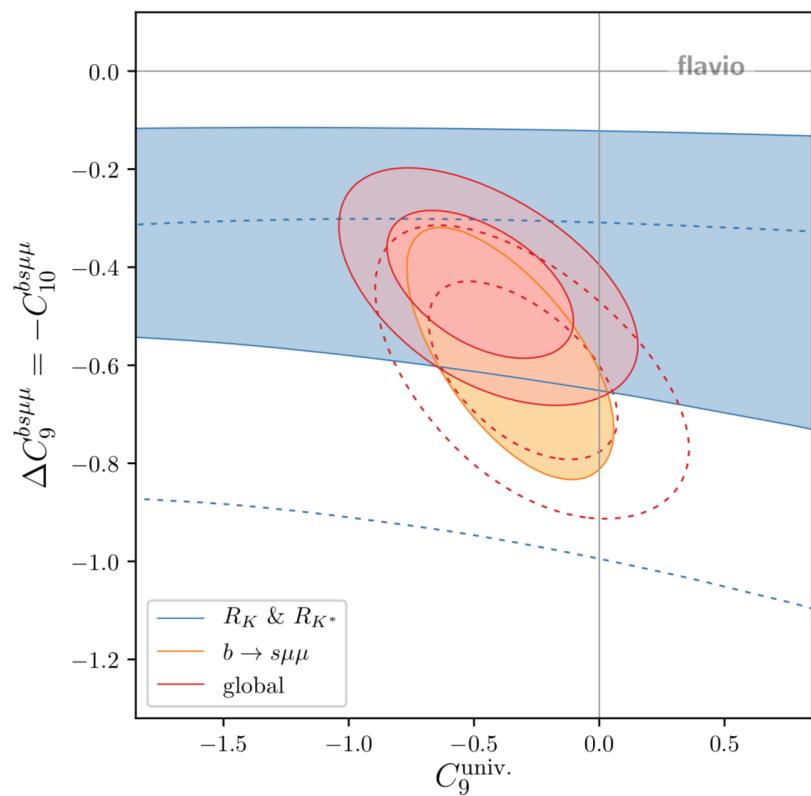
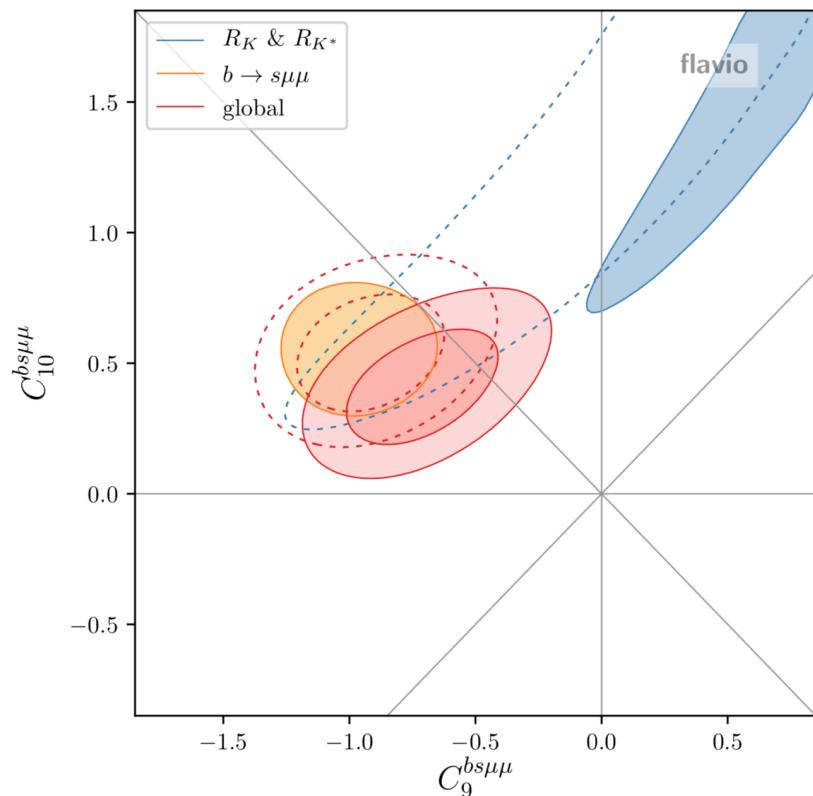
for  $r$  = Run 1, Run 2 and  $t$  = L0Electron, L0Hadron, L0TIS.

- $c_K^{rt}$  are included as a multidimensional Gaussian constraint, with uncertainties and correlations according to the  $6 \times 6$  covariance matrix  $\sigma$
- Partially reconstructed background comes essentially from  $B \rightarrow K^*e^+e^-$  and so it can be constrained using

$$\frac{N_{prc}^{r,t}}{N_{prc}^{r,eTOS}} = \frac{\varepsilon_{trig,mass}^{r,t}(K^*ee)}{\varepsilon_{trig,mass}^{r,eTOS}(K^*ee)} = r_{prc}^{rt}$$

# Impact on Global Fits

[ J. Aebischer et al., arXiv:1903.10434 ]

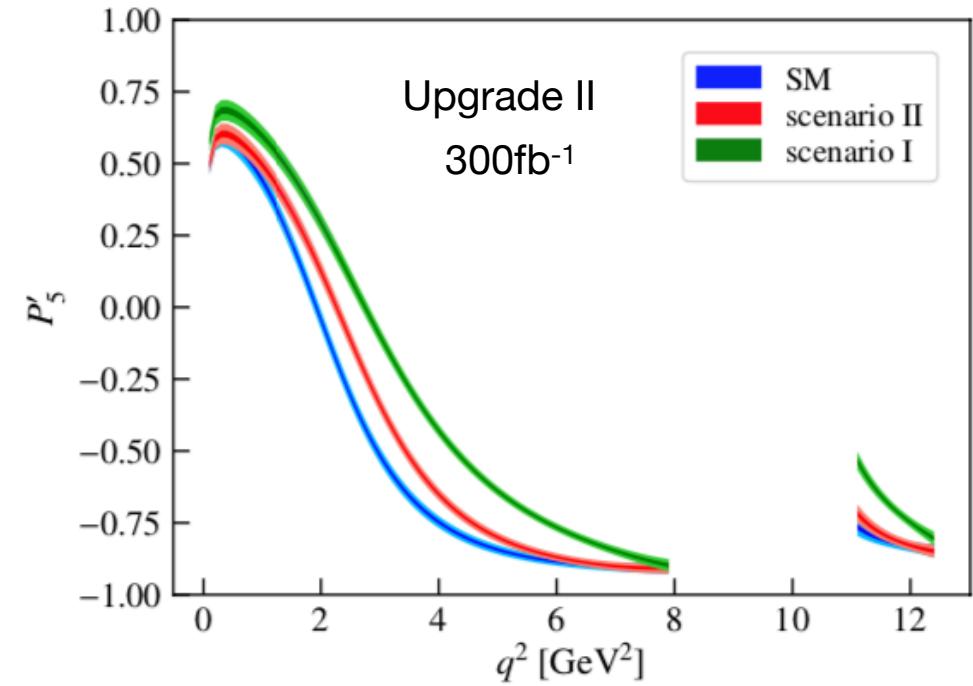
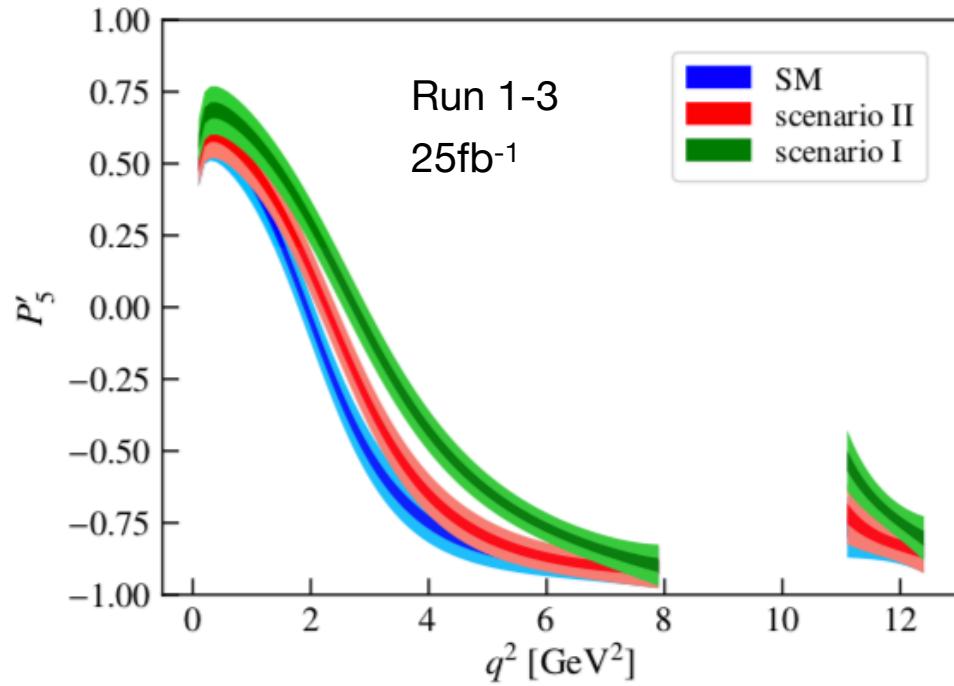


- Best fit point still in tension with the SM
- Worse compatibility between  $R_K$  ( $R_{K^*}$ ) &  $b \rightarrow s\mu\mu$  observables
- Muonic NP: Best fit closer to the SM,  $C_9 = -C_{10}$  still preferred
- Adding LF universal NP: Slight preference for universal shift in  $C_9$

[ M. Algueró et al., arXiv:1903.09578, A. K. Alok et al., arXiv:1903.09617,  
 M. Ciuchini et al., arXiv:1903.09632, Guido D'Amico et al., arXiv:1704.05438, and more ]

# Angular analyses prospects

- Parameterise and fit for form-factors together with effective couplings (Wilson coefficients) in a  $q^2$ -unbinned approach

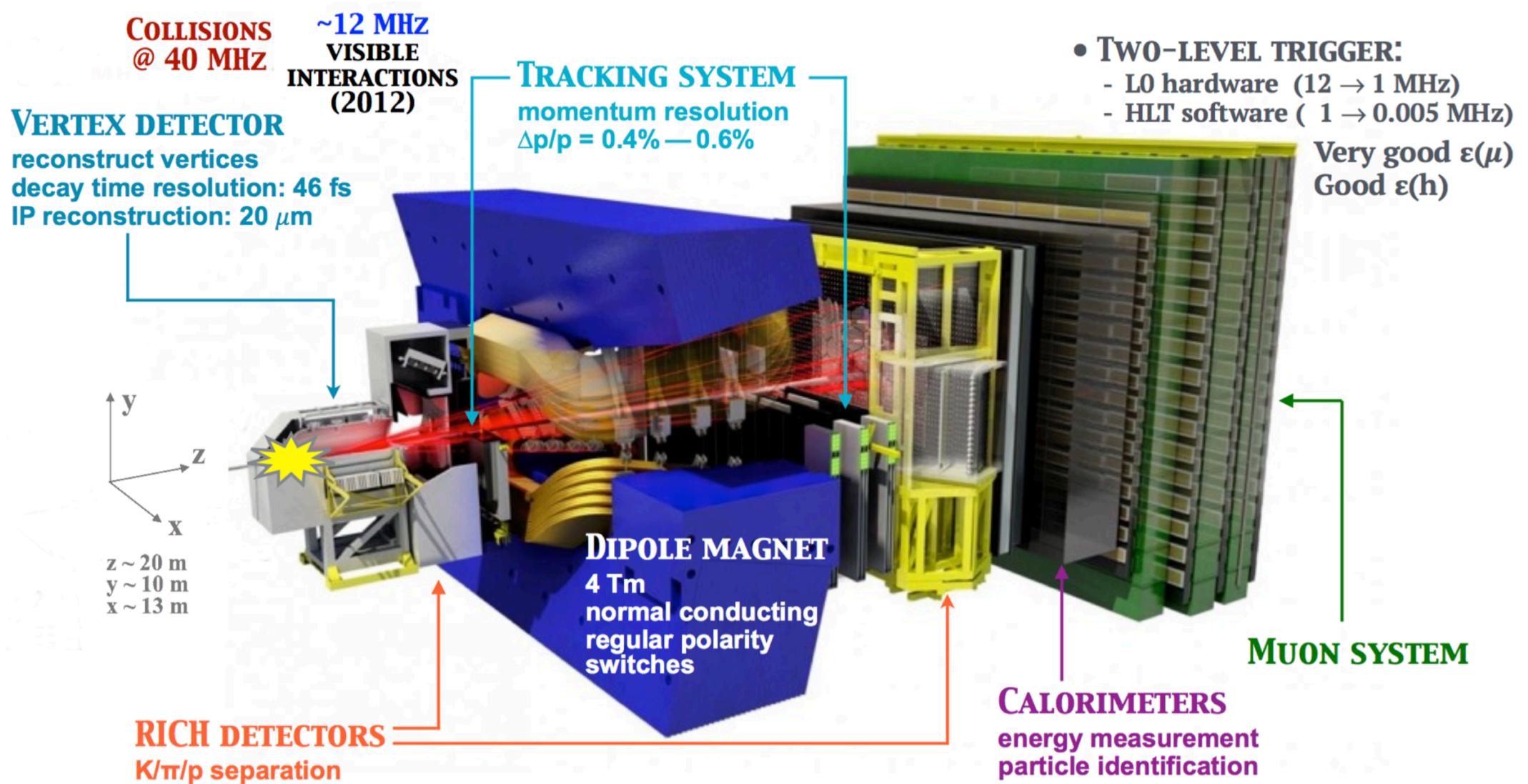


# LHCb Upgrade and beyond

Observable	Current LHCb	Run 3 (29 fb <sup>-1</sup> )	Upgrade II
<b>EW Penguins</b>			
$R_K$ ( $1 < q^2 < 6 \text{ GeV}^2 c^4$ )	0.1 [274]	0.025	0.007
$R_{K^*}$ ( $1 < q^2 < 6 \text{ GeV}^2 c^4$ )	0.1 [275]	0.031	0.008
$R_\phi, R_{pK}, R_\pi$	—	0.08, 0.06, 0.18	0.02, 0.02, 0.05
<b>CKM tests</b>			
$\gamma$ , with $B_s^0 \rightarrow D_s^+ K^-$	$(^{+17})_{-22}^\circ$ [136]	4°	1°
$\gamma$ , all modes	$(^{+5.0})_{-5.8}^\circ$ [167]	1.5°	0.35°
$\sin 2\beta$ , with $B^0 \rightarrow J/\psi K_S^0$	0.04 [606]	0.011	0.003
$\phi_s$ , with $B_s^0 \rightarrow J/\psi \phi$	49 mrad [44]	14 mrad	4 mrad
$\phi_s$ , with $B_s^0 \rightarrow D_s^+ D_s^-$	170 mrad [49]	35 mrad	9 mrad
$\phi_s^{ss\bar{s}s}$ , with $B_s^0 \rightarrow \phi \phi$	154 mrad [94]	39 mrad	11 mrad
$a_{sl}^s$	$33 \times 10^{-4}$ [211]	$10 \times 10^{-4}$	$3 \times 10^{-4}$
$ V_{ub} / V_{cb} $	6% [201]	3%	1%
<b><math>B_s^0, B^0 \rightarrow \mu^+ \mu^-</math></b>			
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	90% [264]	34%	10%
$\tau_{B_s^0 \rightarrow \mu^+ \mu^-}$	22% [264]	8%	2%
$S_{\mu\mu}$	—	—	0.2
<b><math>b \rightarrow c \ell^- \bar{\nu}_\ell</math> LUV studies</b>			
$R(D^*)$	0.026 [215, 217]	0.0072	0.002
$R(J/\psi)$	0.24 [220]	0.071	0.02
<b>Charm</b>			
$\Delta A_{CP}(KK - \pi\pi)$	$8.5 \times 10^{-4}$ [610]	$1.7 \times 10^{-4}$	$3.0 \times 10^{-5}$
$A_\Gamma (\approx x \sin \phi)$	$2.8 \times 10^{-4}$ [240]	$4.3 \times 10^{-5}$	$1.0 \times 10^{-5}$
$x \sin \phi$ from $D^0 \rightarrow K^+ \pi^-$	$13 \times 10^{-4}$ [228]	$3.2 \times 10^{-4}$	$8.0 \times 10^{-5}$
$x \sin \phi$ from multibody decays	—	$(K3\pi) 4.0 \times 10^{-5}$	$(K3\pi) 8.0 \times 10^{-6}$

Gains in precision many critical observables are expected

# The LHCb detector



# Full amplitude analyses of $B \rightarrow K^{(*)} \ell^+ \ell^-$

We can extract NP-sensitive observables and information on hadronic nuisances from the same fit to the data

- Full amplitude analysis of  $B \rightarrow K^+ \ell^+ \ell^-$
- Work ongoing to extend this to  $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ 
  - ▶ Several approaches proposed

[Hurth et al, JHEP11(2017)176], [Chrzaszcz et al, 1805.06378], [Blake et al, EPJC(2018)78:453]

