

Imperial College
London



Lepton Universality

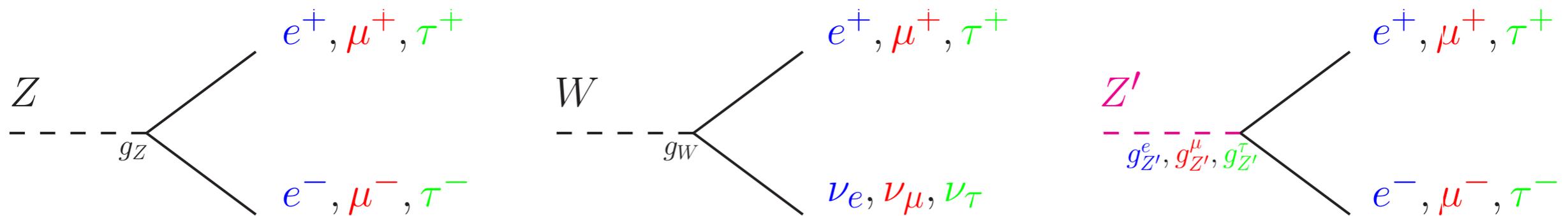
LHCP 2019, Puebla (Mexico)

Paula Álvarez Cartelle

on behalf of the ATLAS, CMS and LHCb collaborations

Lepton Flavour universality

- In the Standard Model, couplings of the gauge bosons to charged leptons are **Flavour Universal**
 - ▶ branching fractions of e , μ and τ differ only by phase space and helicity-suppressions



- Some extensions of the SM predict new particles that could break LFU (e.g. Z' , leptoquarks)
 - ▶ any significant observation of LFU violation is a direct sign for New Physics.

Testing LFU

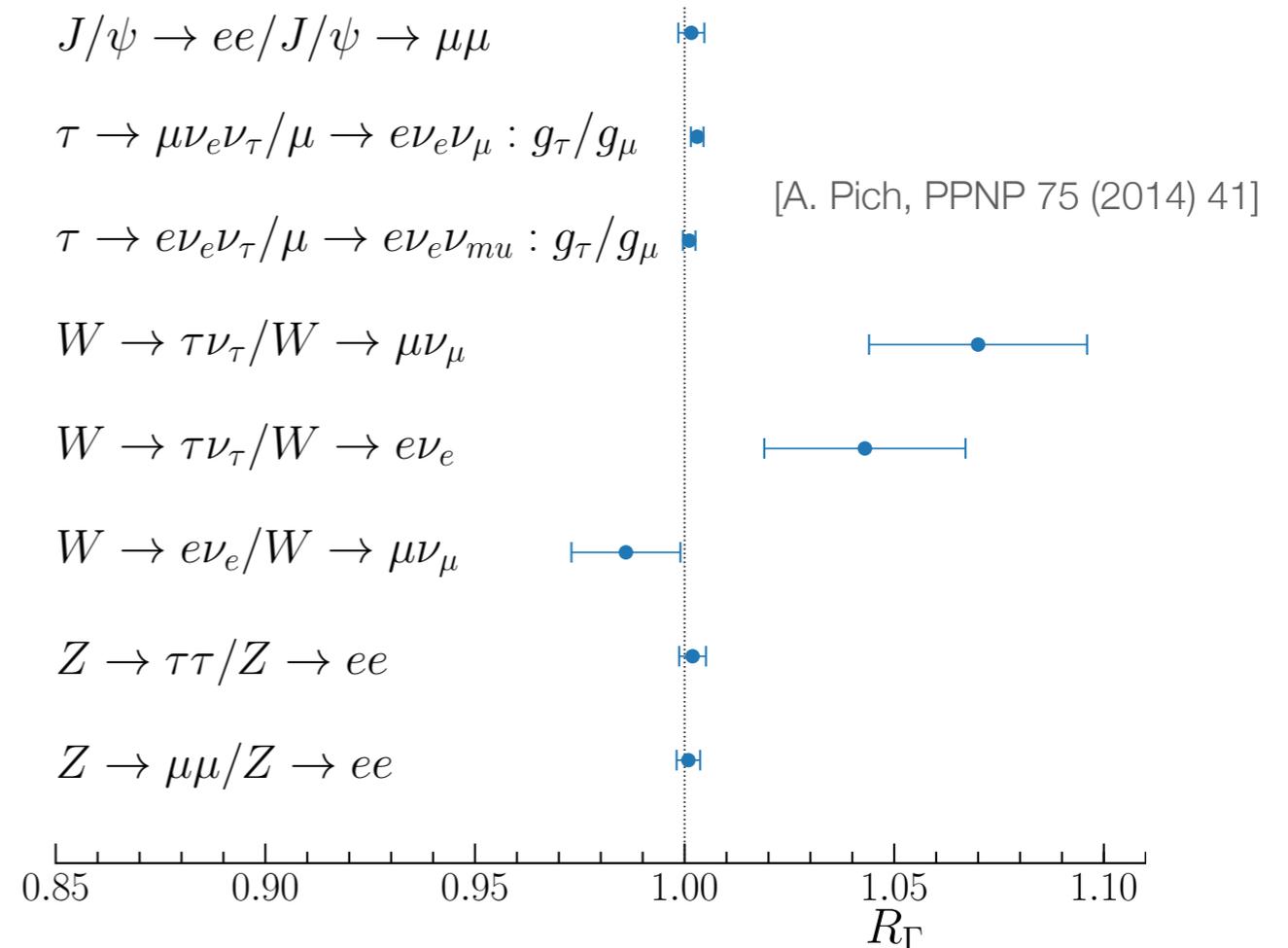
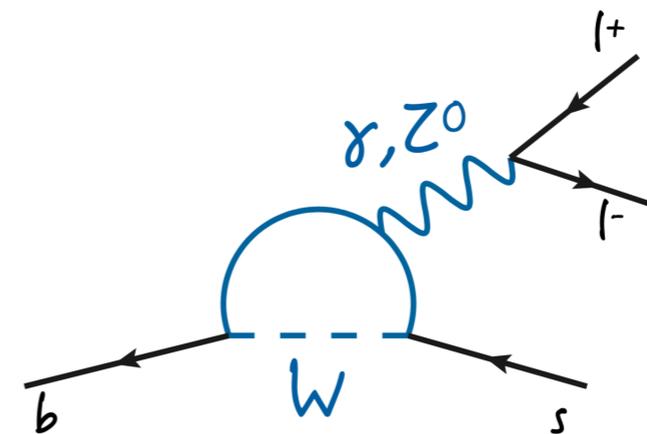
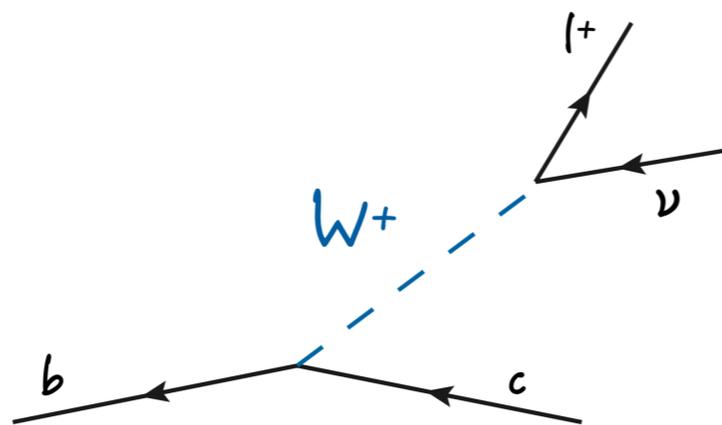
[PDG, PRD 98, 030001 (2018)]

Thoroughly tested in the past:

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

▶ Flavour Changing Charged Current **$b \rightarrow c\ell\nu$ decays (tree-level)**

▶ Flavour Changing Neutral Current **$b \rightarrow s\ell\ell$ transitions (loop-level)**



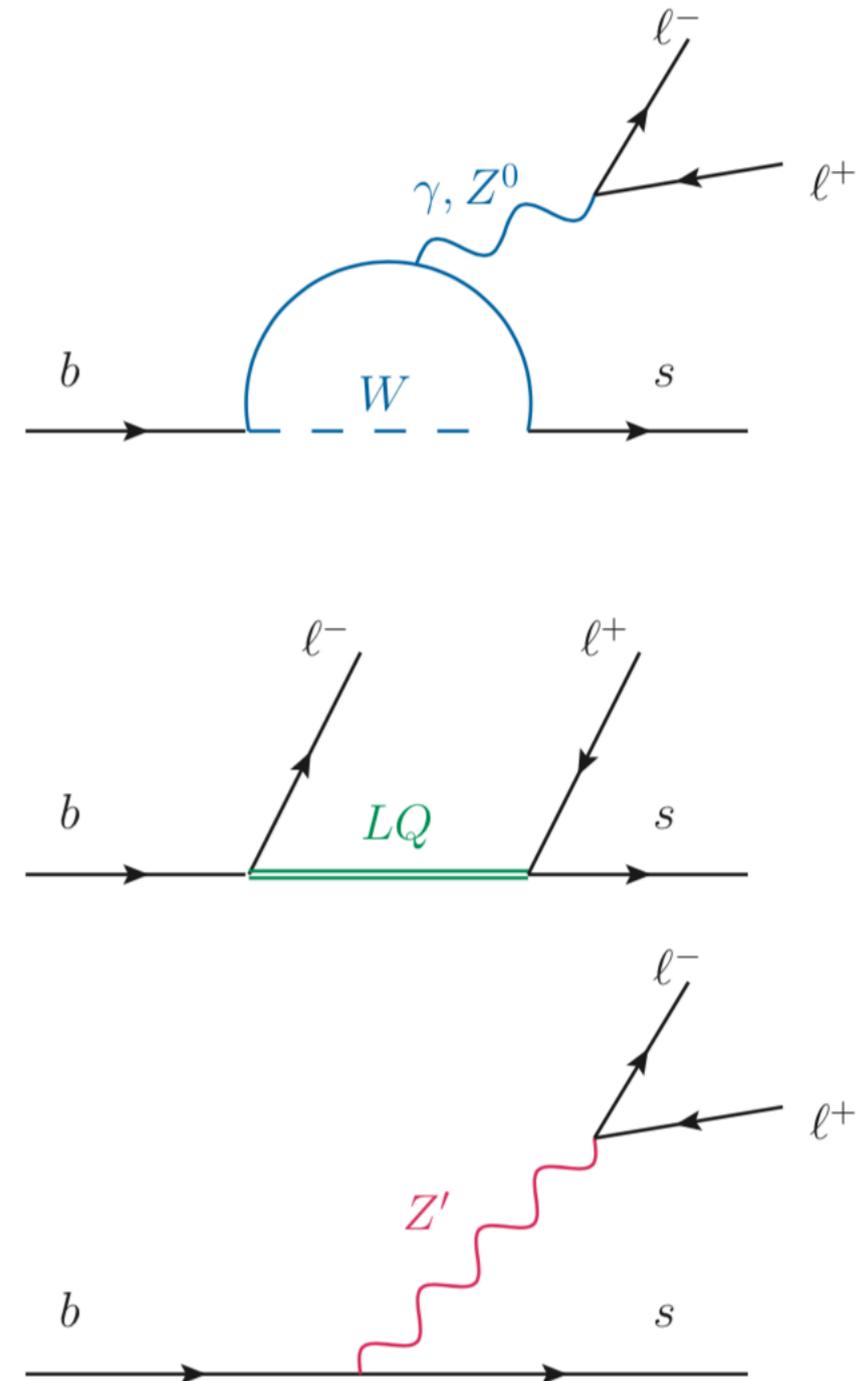
Flavour Changing Neutral Currents

FCNC are **suppressed in the SM**,

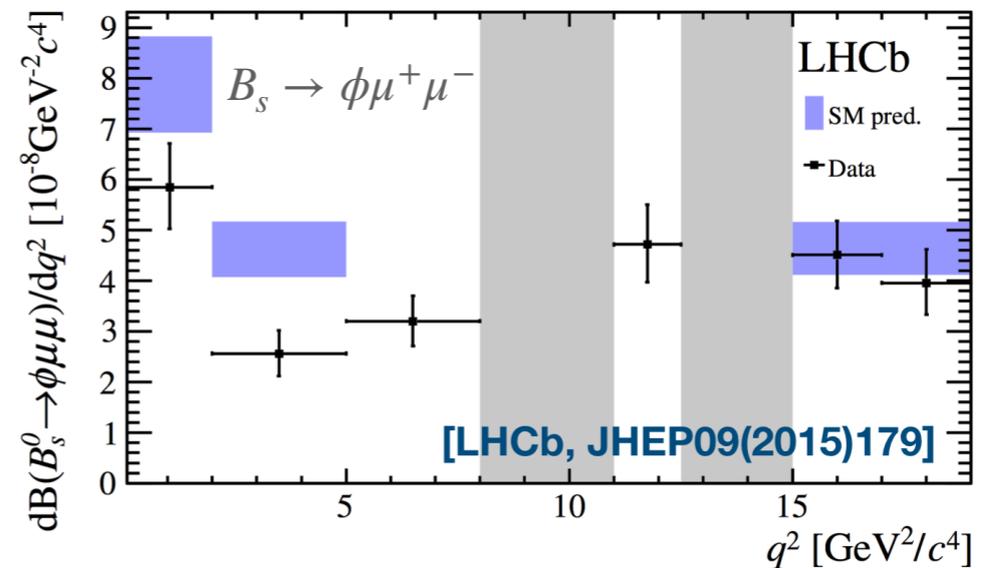
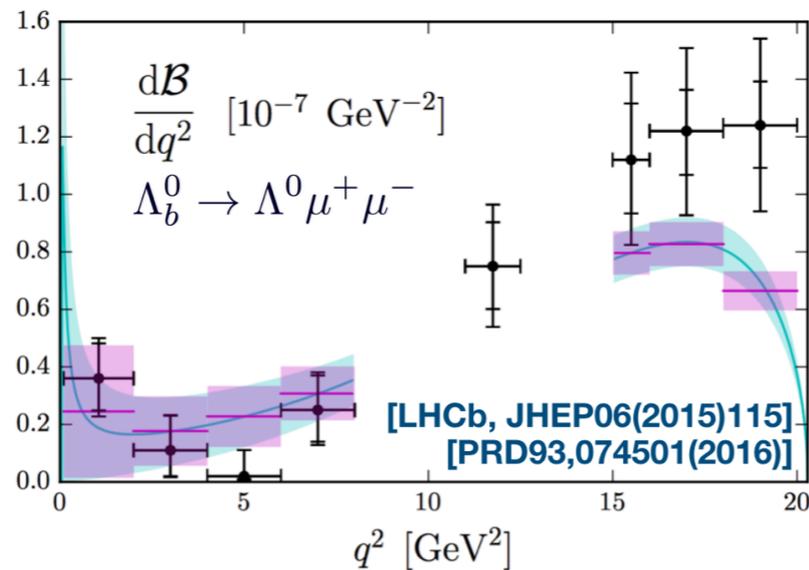
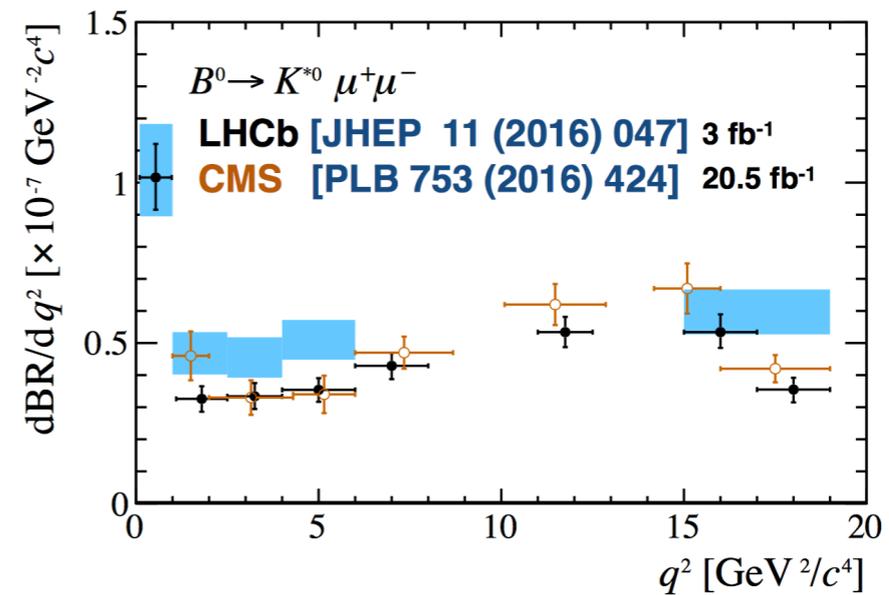
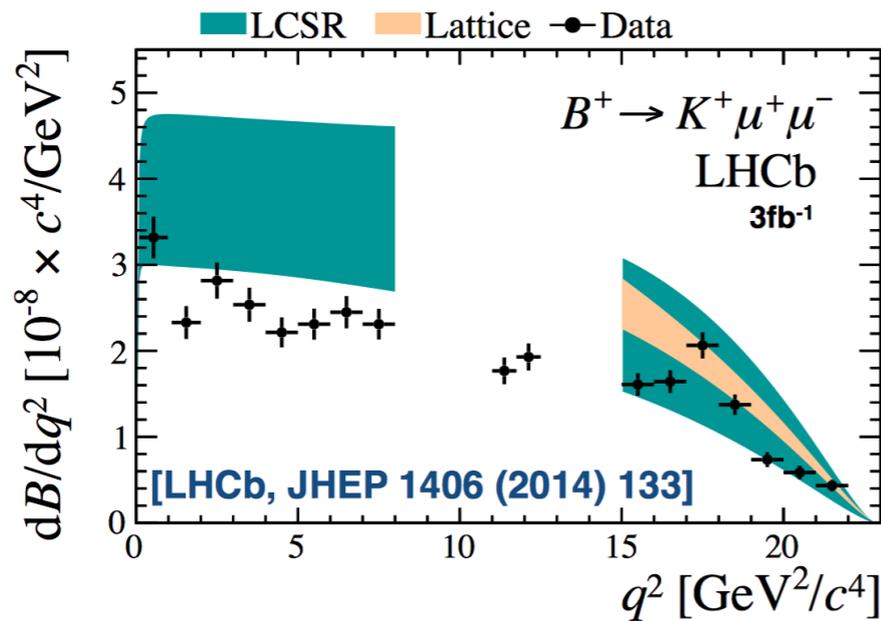
- only occur at loop level
- GIM suppressed
- left-handed chirality

but this is **not necessarily true in a New Physics** scenario.

Study many different kinds of observables (BR's, angular observables and LFU test) with different sensitivities to NP.

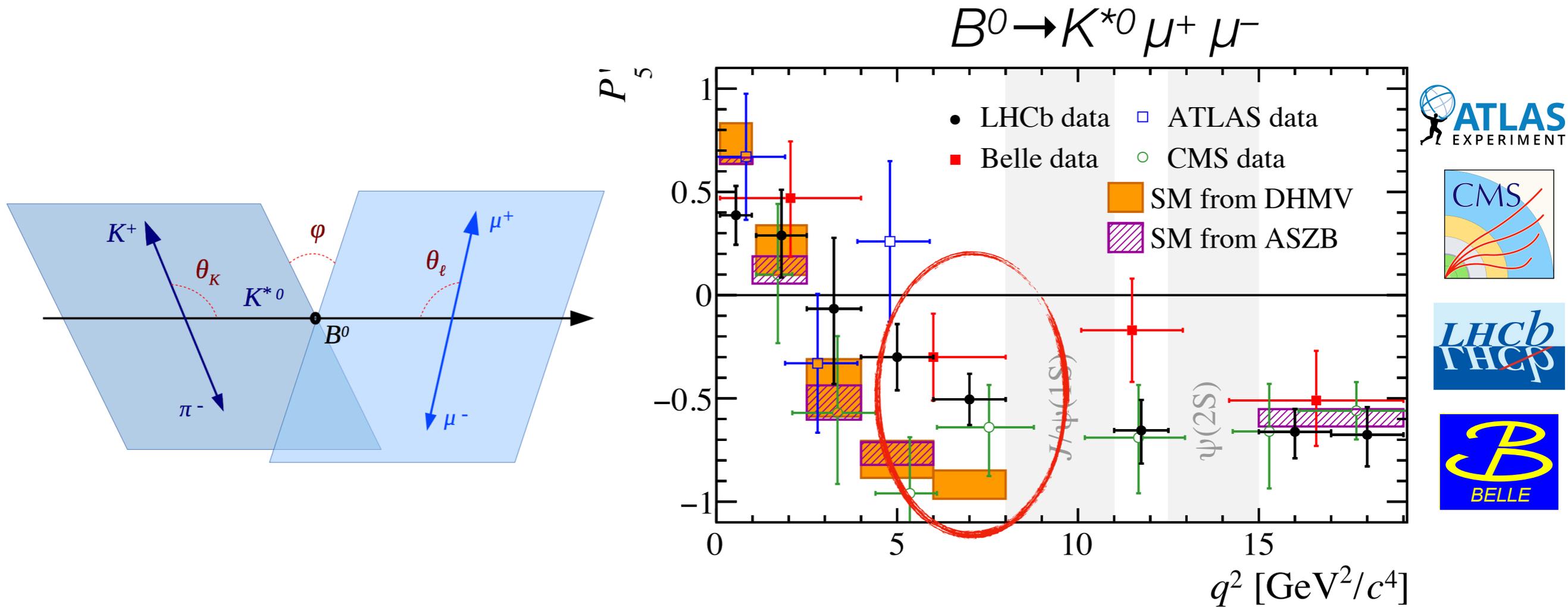


$b \rightarrow s \mu^+ \mu^-$ branching fractions



- Branching fractions consistently below the SM predictions at low $q^2 = [m(\ell\ell)]^2$ for several processes
- Considerable uncertainty in the SM prediction

Angular observables



- Give access to observables with reduced dependence on hadronic effects
[JHEP 1204 (2012) 104]
- LHCb finds deviation from the SM prediction at the level of 3.4σ

LHCb [JHEP 02 (2016) 104], CMS [PLB 781 (2018) 517], ATLAS [JHEP 10 (2018) 047],
BaBar [PRD 93 (2016) 052015], Belle [PRL 103 (2009) 171801], CDF [PRL 108 (2012) 081807]

Theoretical framework - Effective theory

Can describe these interactions in terms of an effective Hamiltonian that describes the full theory at lower energies (μ)

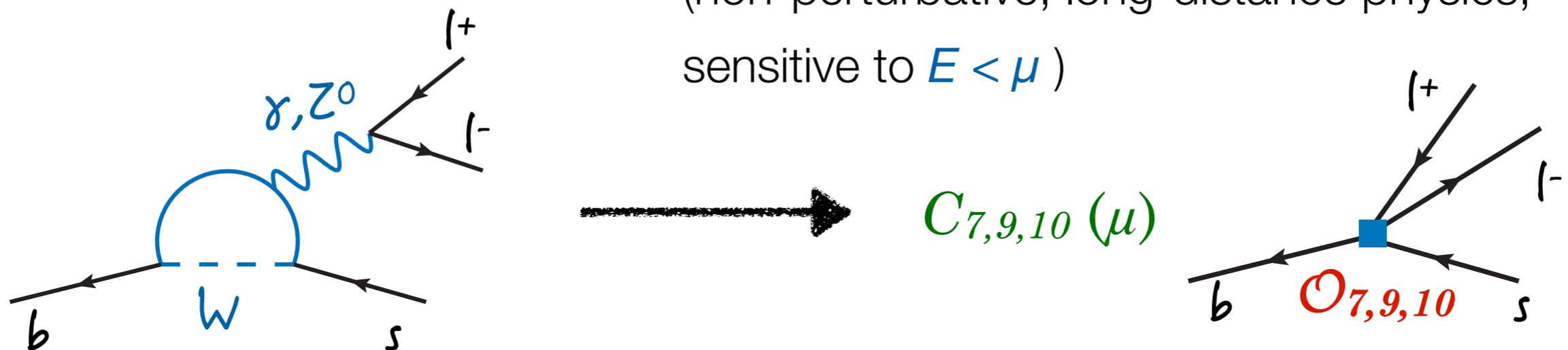
$$\mathcal{H}_{\text{eff}} \sim \sum_i C_i(\mu) \mathcal{O}_i(\mu)$$

$C_i(\mu)$ → Wilson Coefficients

(perturbative, short-distance physics, sensitive to $E > \mu$)

\mathcal{O}_i → Local operators

(non-perturbative, long-distance physics, sensitive to $E < \mu$)

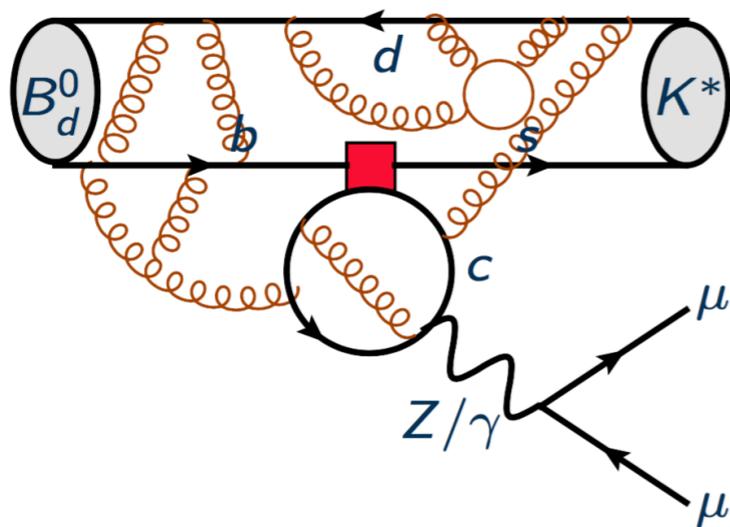


Contributions from NP will modify the measured value of the Wilson coefficients present in the SM or introduce new operators

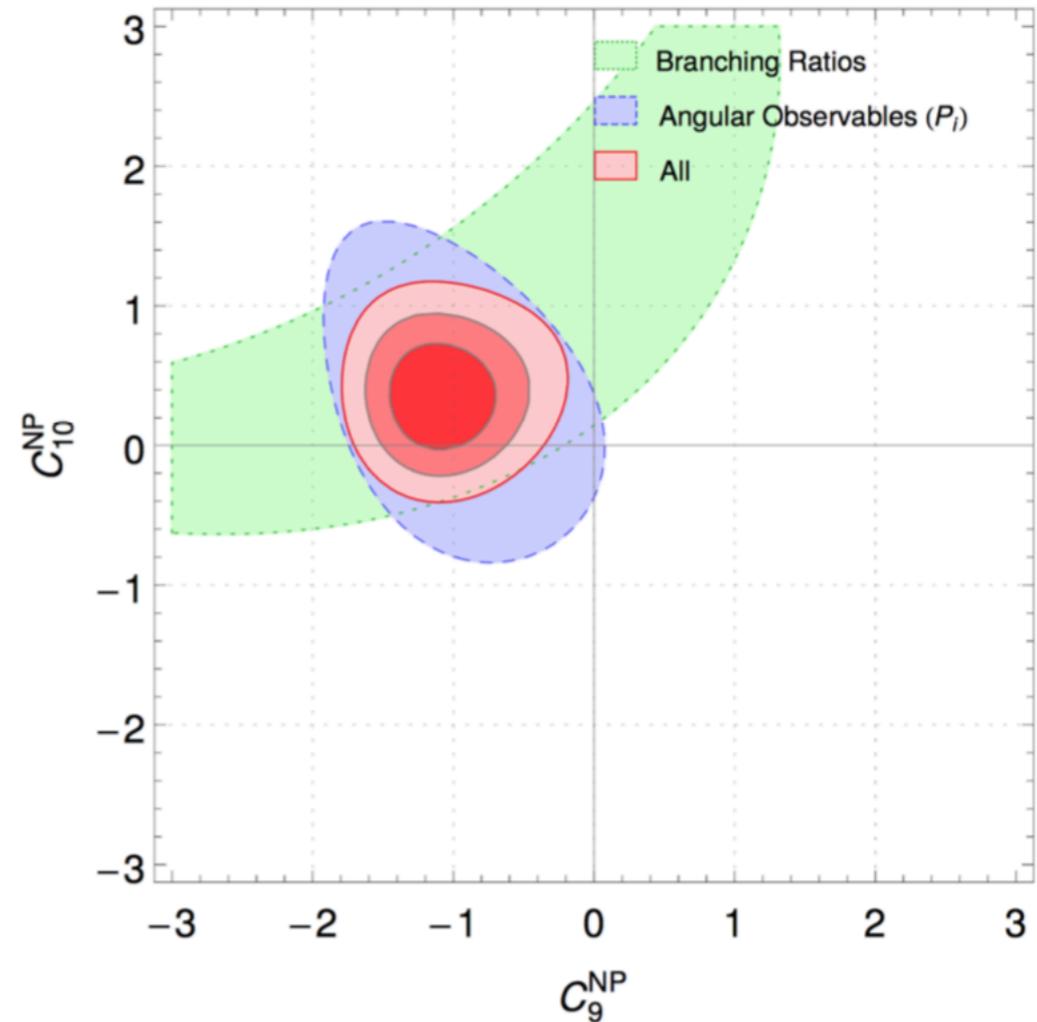
Global fits to $b \rightarrow s \mu^+ \mu^-$ observables

- Branching fractions and angular observables consistent
- Best fit prefers shifted **vector coupling C_9** (or C_9 and **axial-vector C_{10}**)

... could QCD effects mimic vector-like NP contribution?



[S. Descotes-Genon et al. JHEP06 (2016) 092]



[W. Altmannshofer et al. Phys. Rev. D96 (2017) 055008,
 B. Capdevila et al. JHEP 01 (2018) 093, T. Hurth et al. Phys. Rev. D96 (2017) 095034,
 G. D'Amico et al. JHEP 09 (2017) 010, L.-S. Geng et al. Phys. Rev. D96 (2017) 093006,
 M. Ciuchini et al. Eur. Phys. J. C77 (2017) 688,
 S. Jäger and J. Martin Camalich, Phys. Rev. D93 (2016) 014028 and many others]

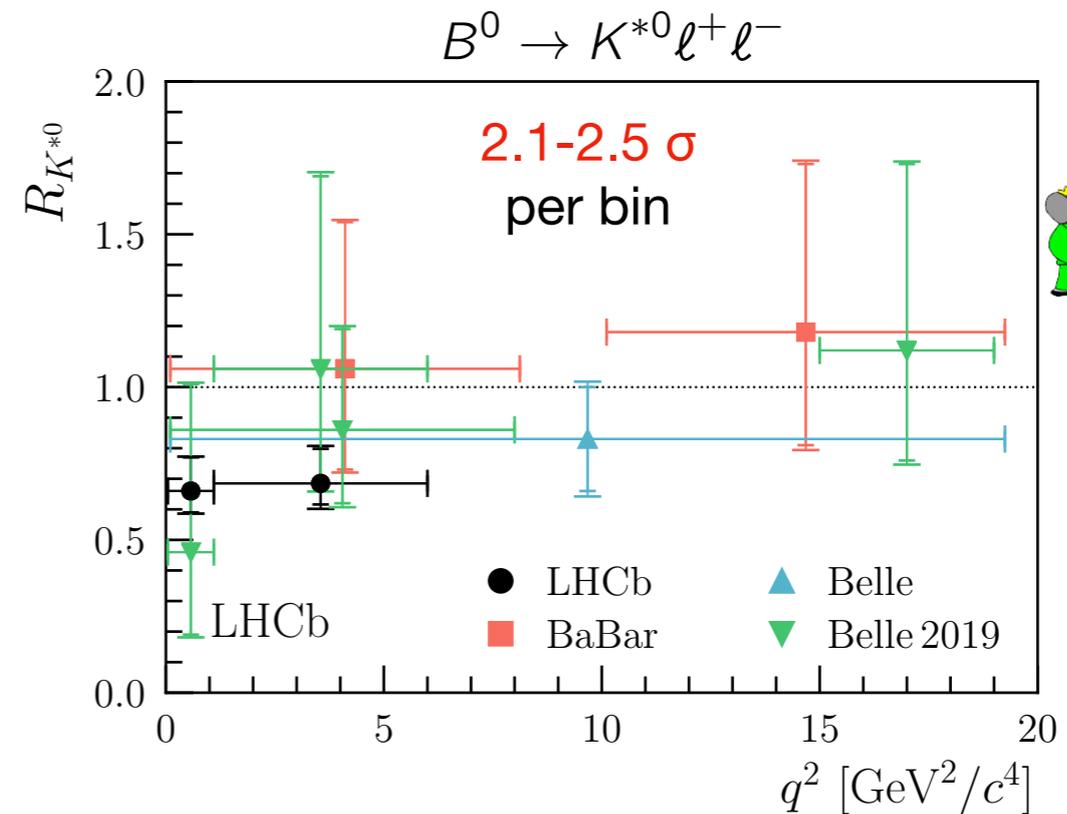
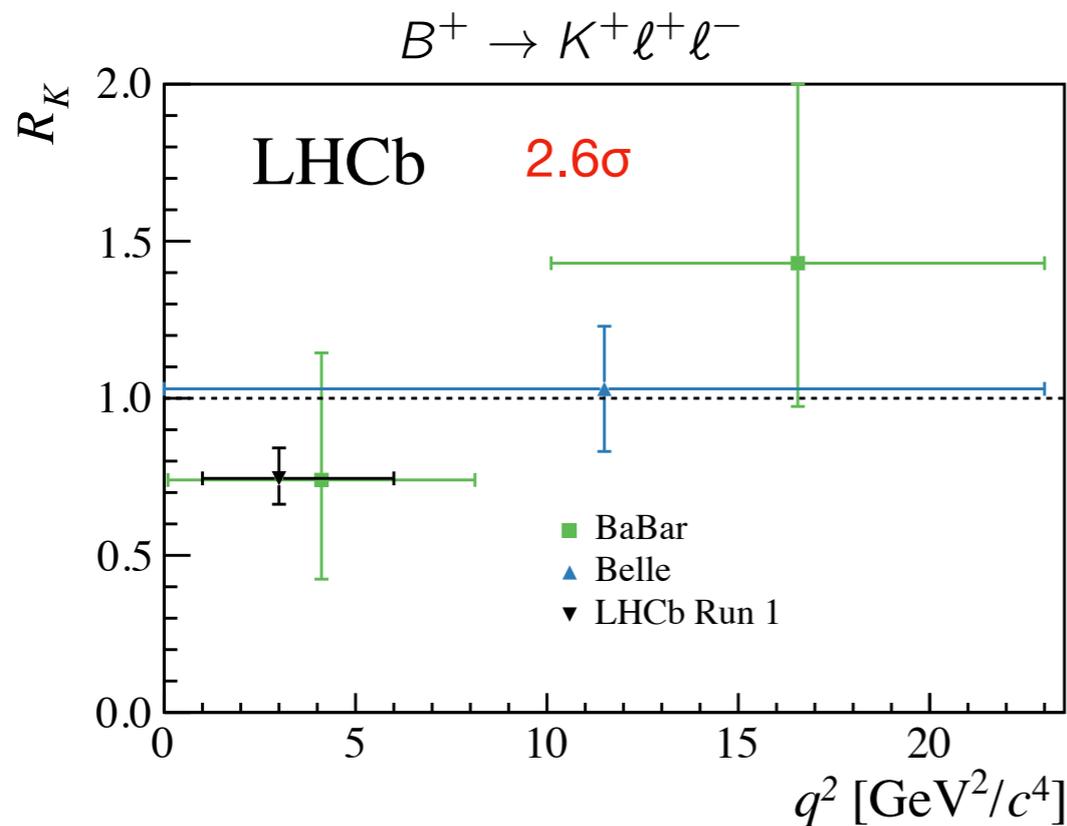
Lepton Flavour universality in $b \rightarrow s \ell \ell$

Ratios of muons/electrons are **extremely well predicted in the SM**

- ▶ Hadronic uncertainties of $O(10^{-4})$ [JHEP 07 (2007) 040]
- ▶ QED uncertainties can be $O(10^{-2})$ [EPJC 76 (2016) 8,440]

$$R_K = \frac{BR(B^+ \rightarrow K^+ \mu^+ \mu^-)}{BR(B^+ \rightarrow K^+ e^+ e^-)} \stackrel{\text{SM}}{\approx} 1$$

Any statistically significant deviation from 1 is a sign of New Physics



[LHCb, PRL 113 (2014) 151601] [LHCb, JHEP 08 (2017) 055]

[BaBar, PRD 86 (2012) 032012]

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

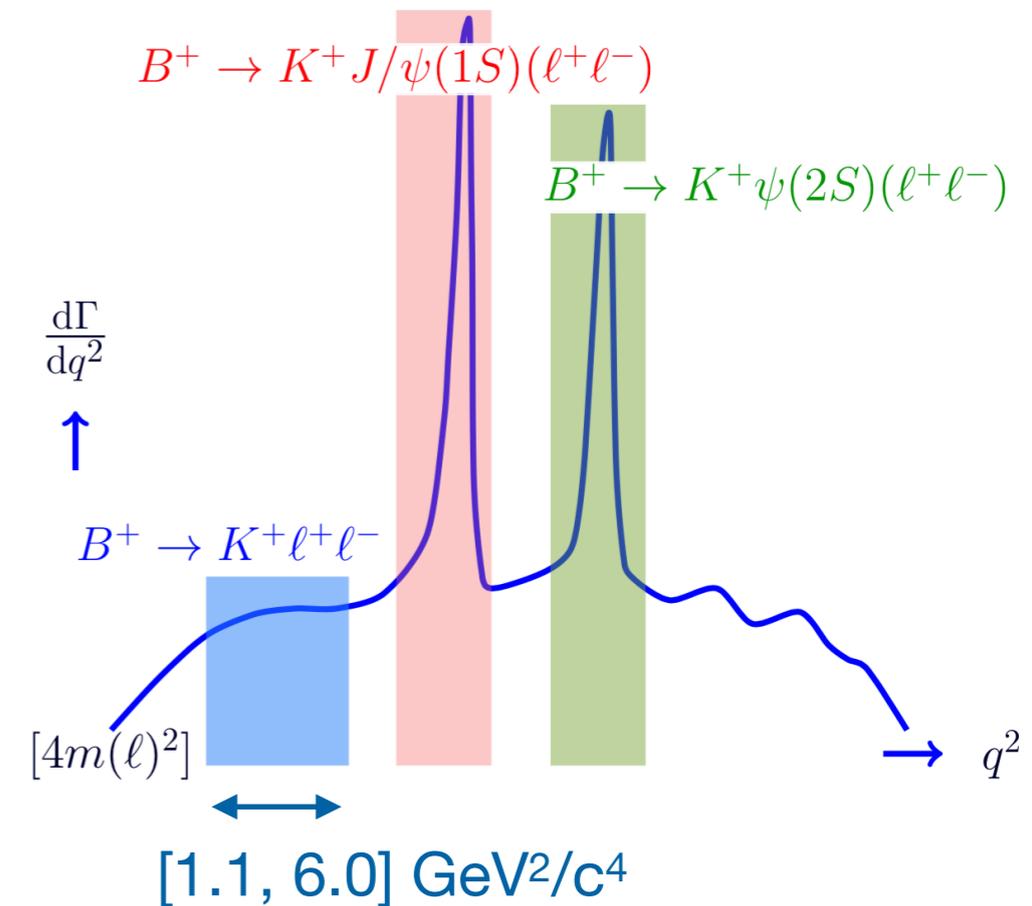
New measurement of R_K

[PRL 122 (2019) 191801]

- In total, this update uses \sim twice as many B's as previous analysis.
 - Re-optimised analysis of Run1 data (3fb^{-1})
 - Added 2015 & 2016 datasets from Run2 (2fb^{-1})

- Details of the analysis:

- Electrons and muons behave very differently in the LHCb detector due to larger Bremsstrahlung radiation for the electrons
 - Worse mass and q^2 resolution
 - Lower reconstruction efficiency
- Measurement performed as a double ratio between **rare** and **resonant** modes to cancel most systematics



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

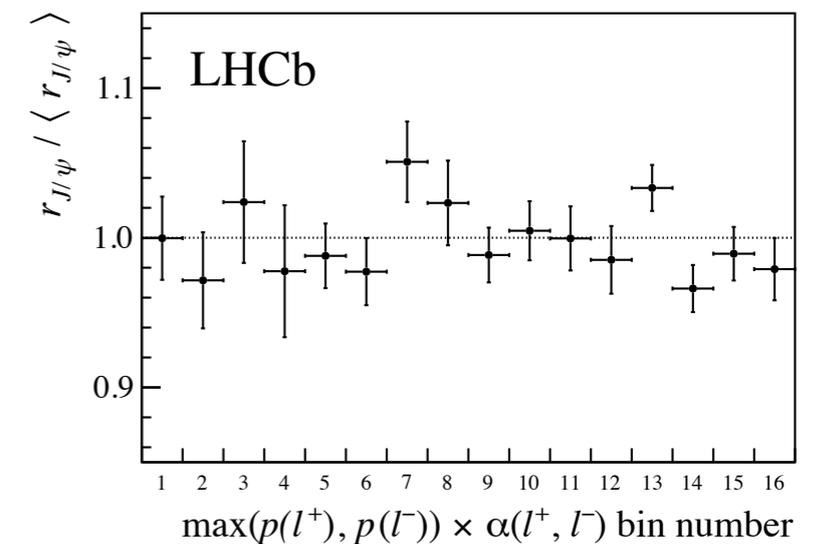
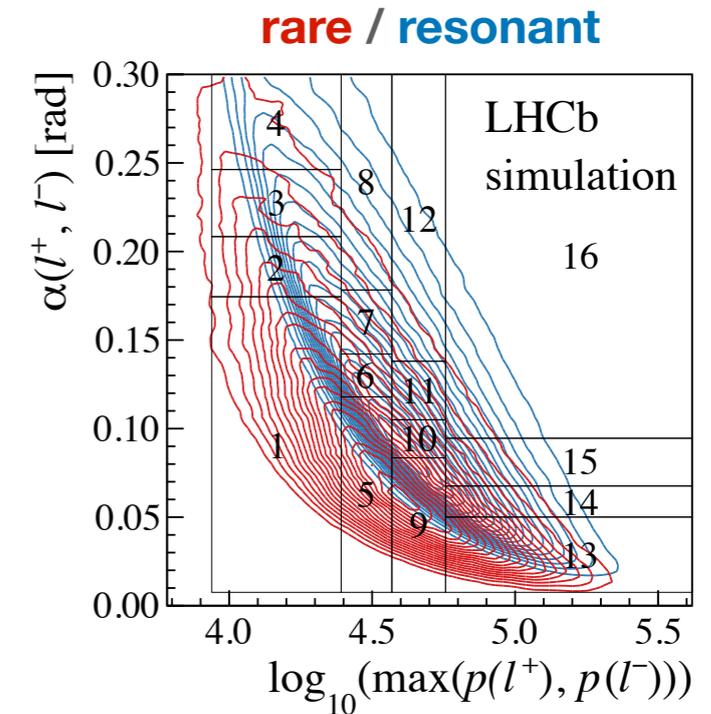
R_K systematics & cross-checks

- Efficiencies computed using simulation carefully calibrated using control channels selected from data
 - ▶ B^+ kinematics, particle-ID, trigger efficiency...
 - ▶ Small systematic associated due to **good cancellation in double ratio**
- Numerous cross-checks to ensure good understanding of the efficiencies, e.g. 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



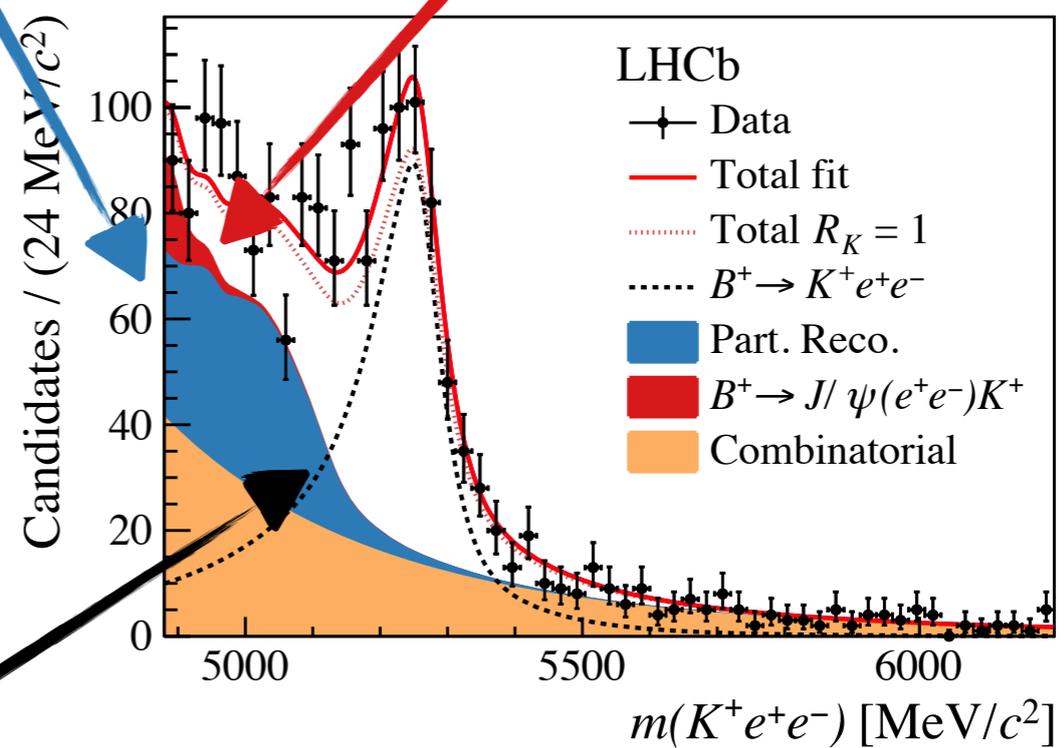
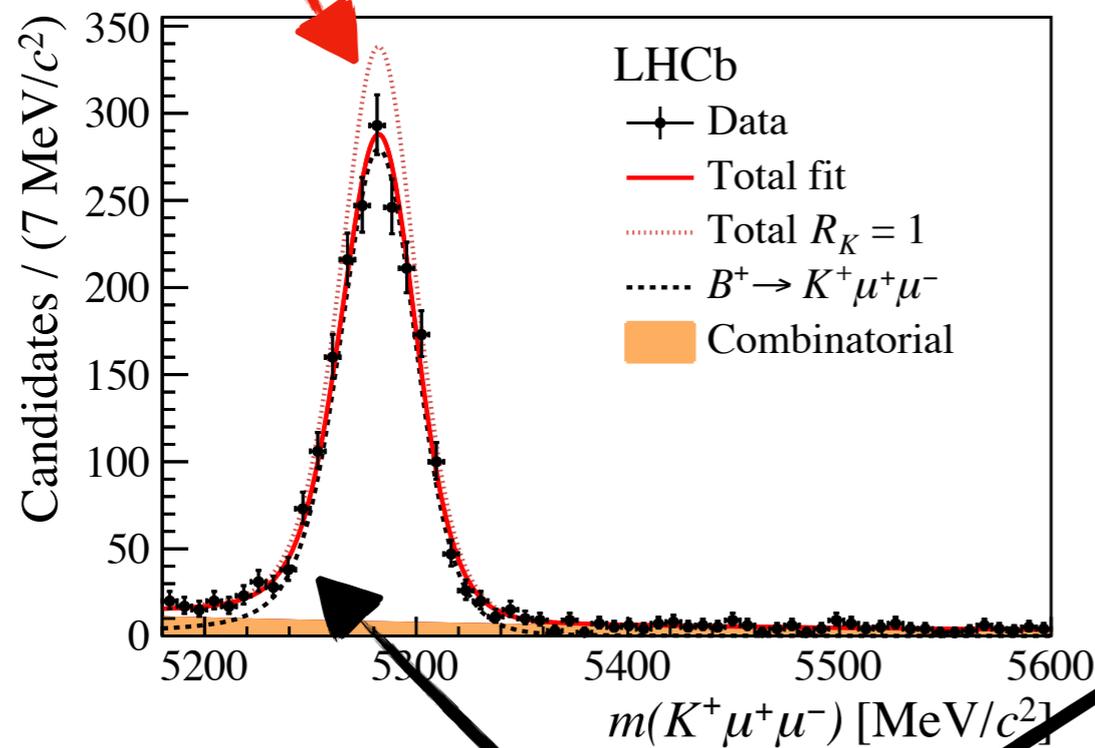
R_K simultaneous fit

[PRL 122 (2019) 191801]

Expectation from observed $B^+ \rightarrow K^+ e^+ e^-$ yield & $R_K=1$

Partially reconstructed background, mainly $B^0 \rightarrow K^{*0} e^+ e^-$

Leakage from $B \rightarrow K J/\psi(ee)$ constraint from the fit to the resonant mode

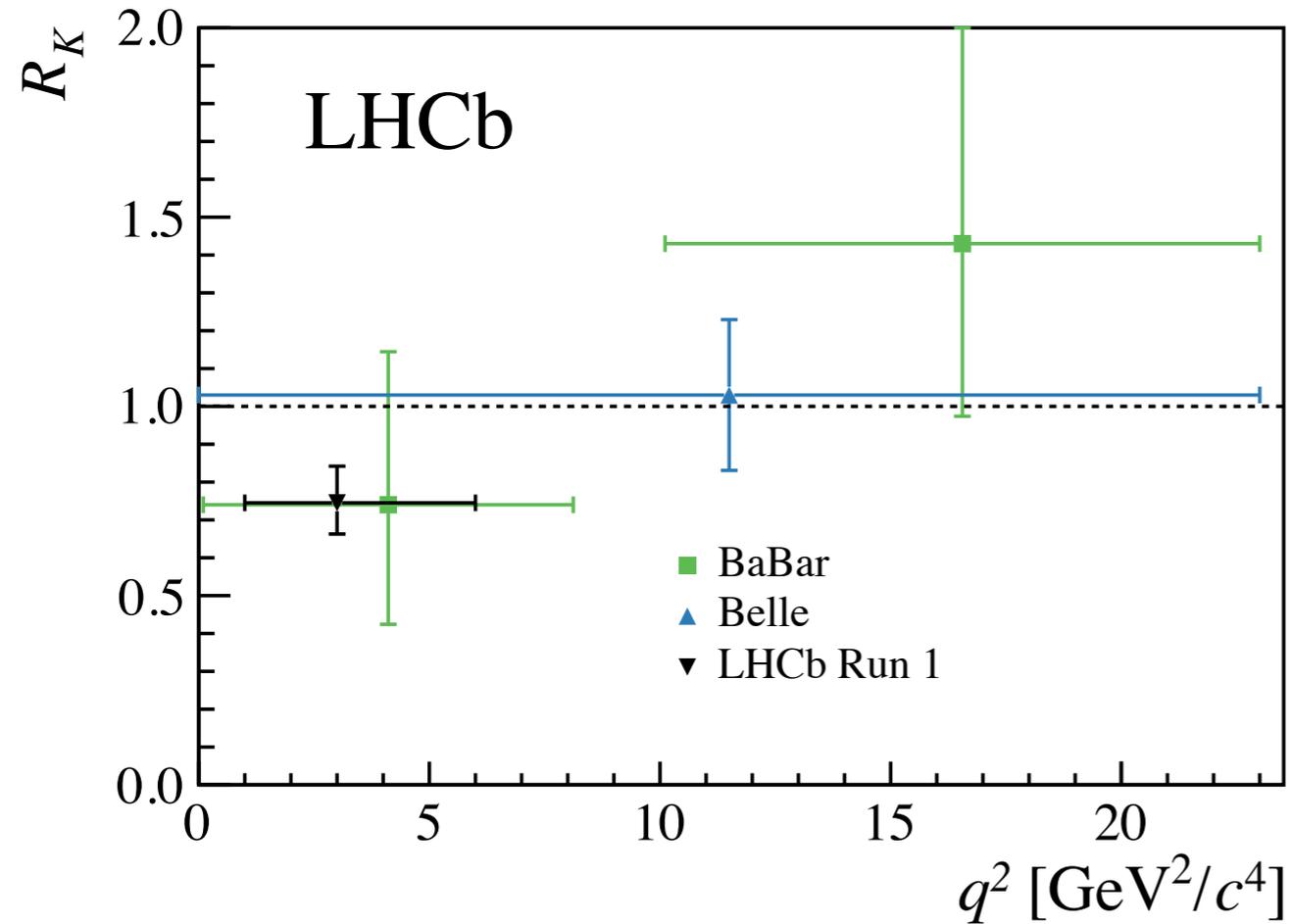


Different signal shape between muons and electrons:

- worse mass resolution (recovered γ)
- longer radiative tail (more Bremsstrahlung)

New R_K result

[PRL 122 (2019) 191801]



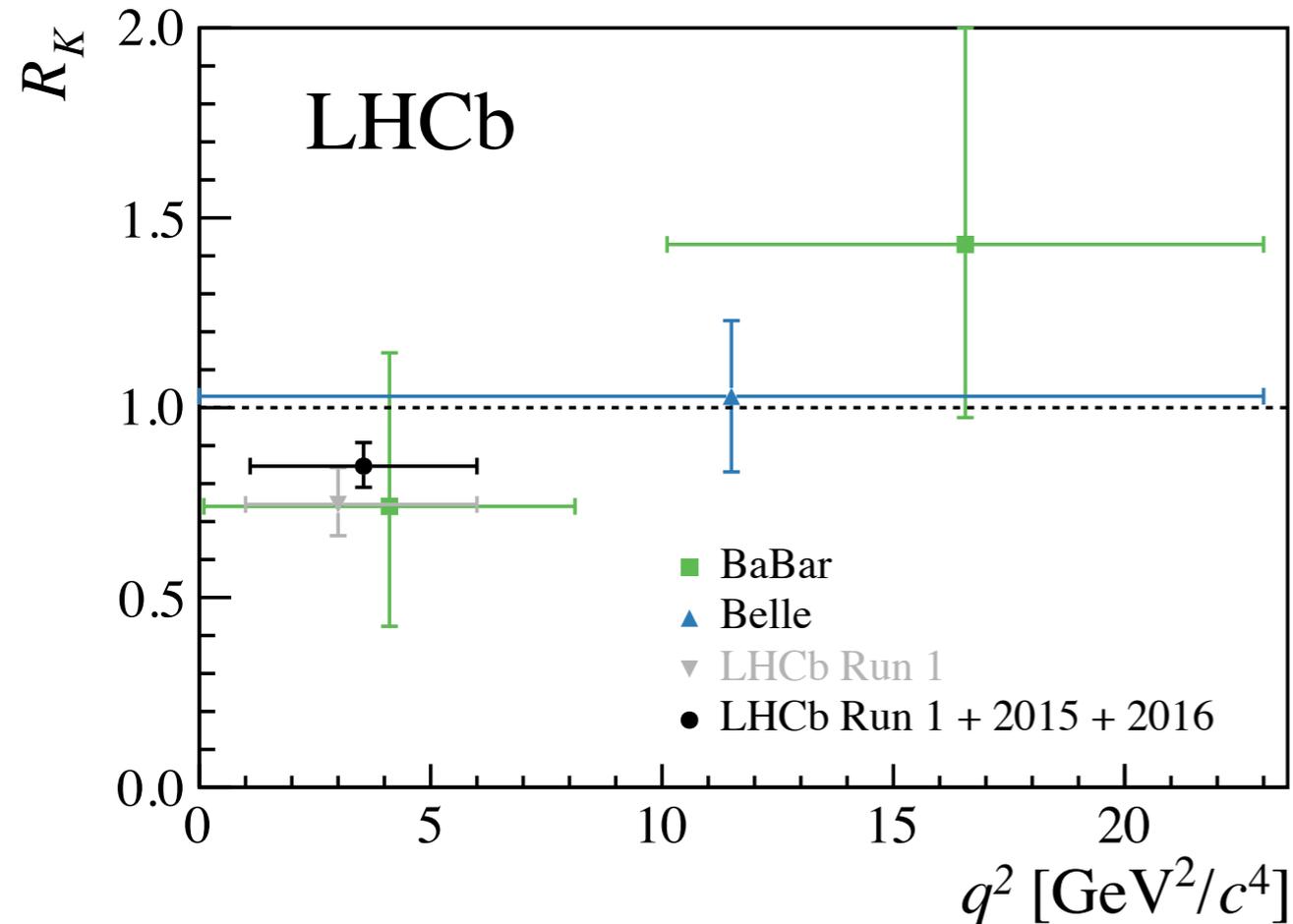
Using 2011-2012 data

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

compatible with the SM expectation at 2.6σ .

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[PRL 122 (2019) 191801]



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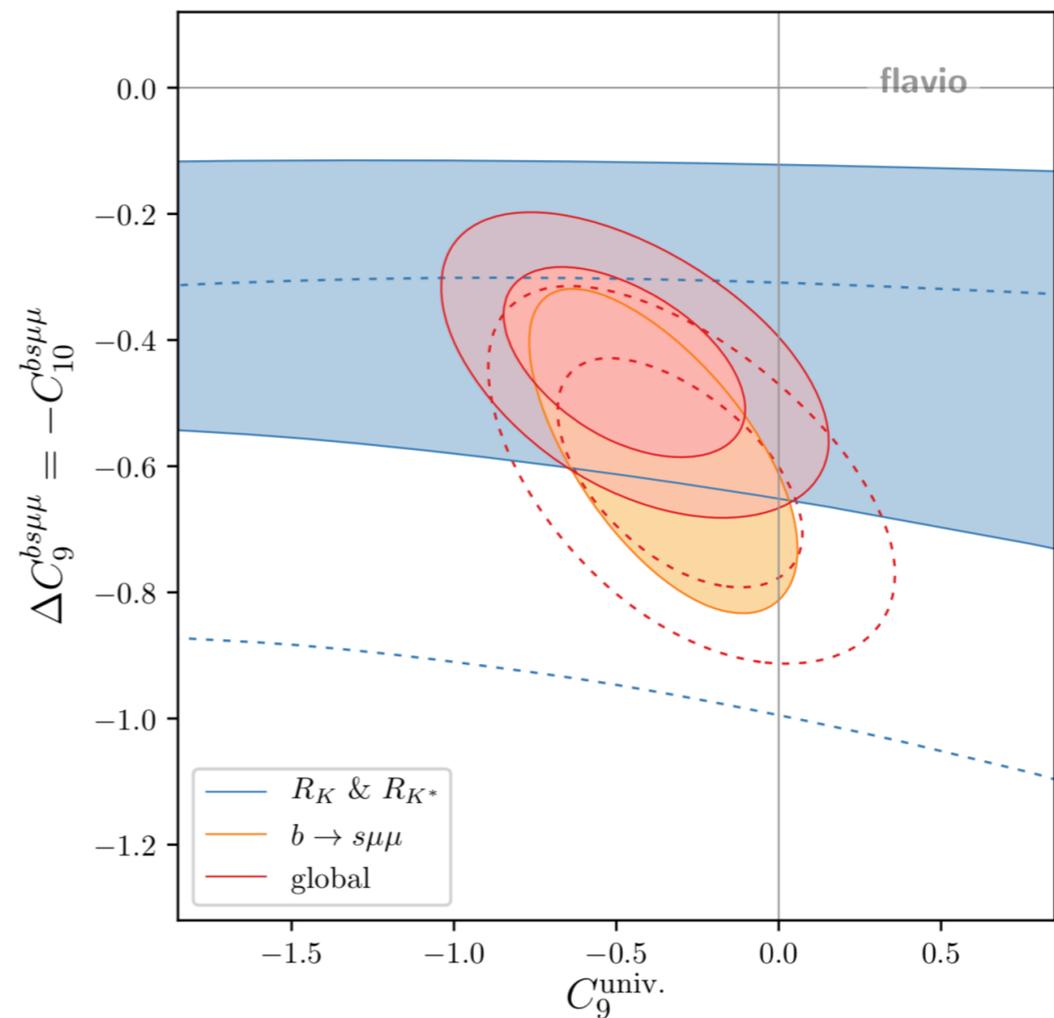
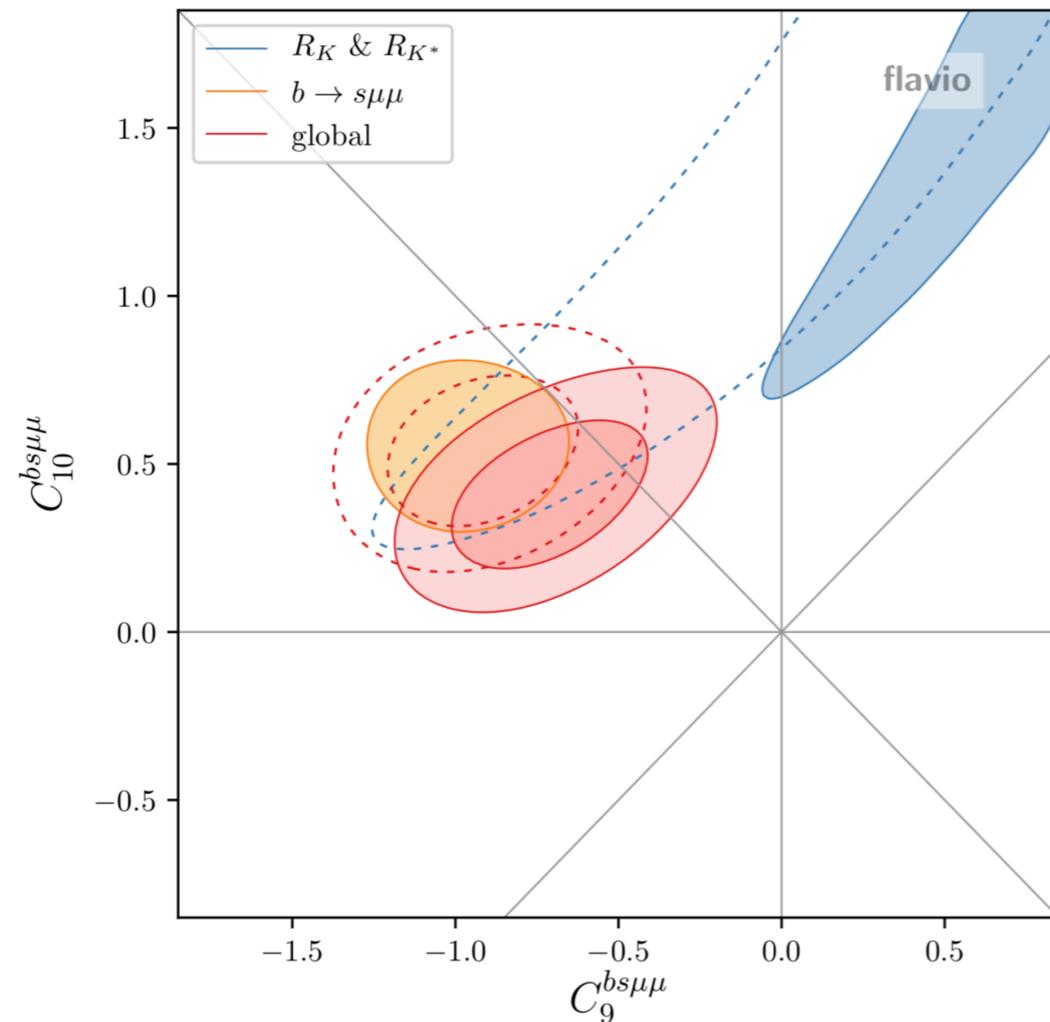
Reanalysing 2011-2012 data and adding 2015 and 2016

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

compatible with the SM expectation at **2.5σ** .

- Systematic is small due to **good cancellation in double ratio**
 - ▶ Uncertainty on the fit shape
 - ▶ Calibration of B^+ kinematics and trigger efficiencies

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

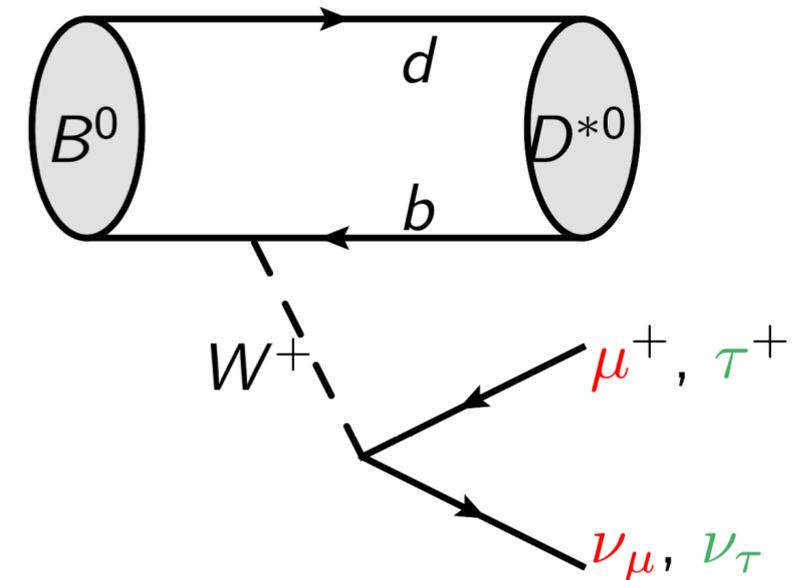
[M. Algueró et al., arXiv:1903.09578, A. K. Alok et al., arXiv:1903.09617, M. Ciuchini et al., arXiv:1903.09632, Guido D'Amico et al., arXiv:1704.05438, and more]

LFU in charged currents: $R(D^*)$ ratio

- Very clean observables in the SM

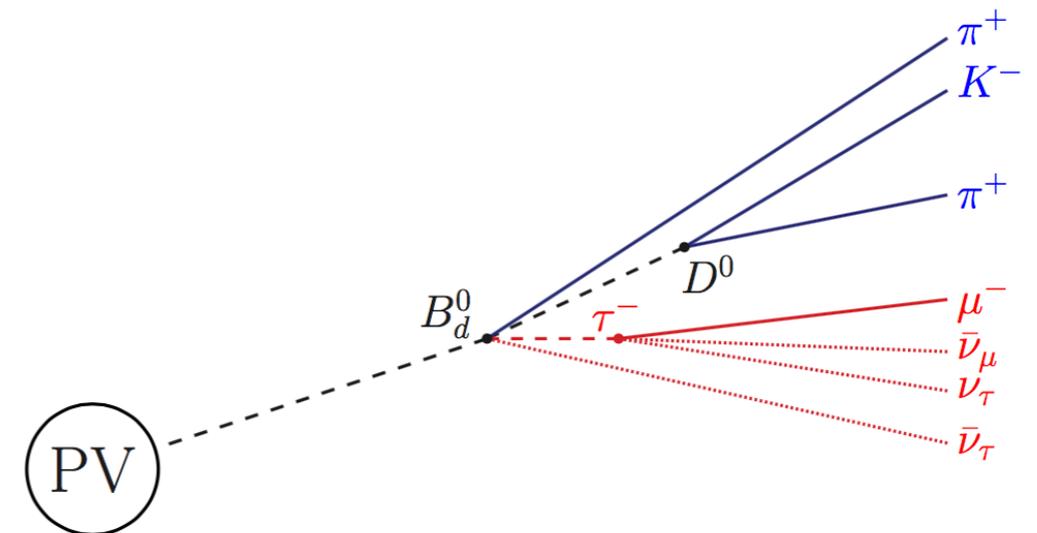
$$R(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)} \stackrel{SM}{=} 0.258 \pm 0.005$$

[HFLAV average]



- Challenging for LHCb due to the presence of multiple neutrinos
- Two LHCb measurements in Run1 (2011+2012) using different reconstructions of the τ decay

- ▶ $\tau \rightarrow \mu \nu \nu$ [LHCb, PRL 115 (2015) 111803]
- ▶ $\tau \rightarrow 3\pi(\pi^0)\nu$: [LHCb, PRL 120 (2018) 171802]
[LHCb, PRD 97 (2018) 072013]



- Also LFU test in $B_c \rightarrow J/\psi \ell \nu$ decays, $R(J/\psi)$
[LHCb, PRL 120 (2018) 121801]

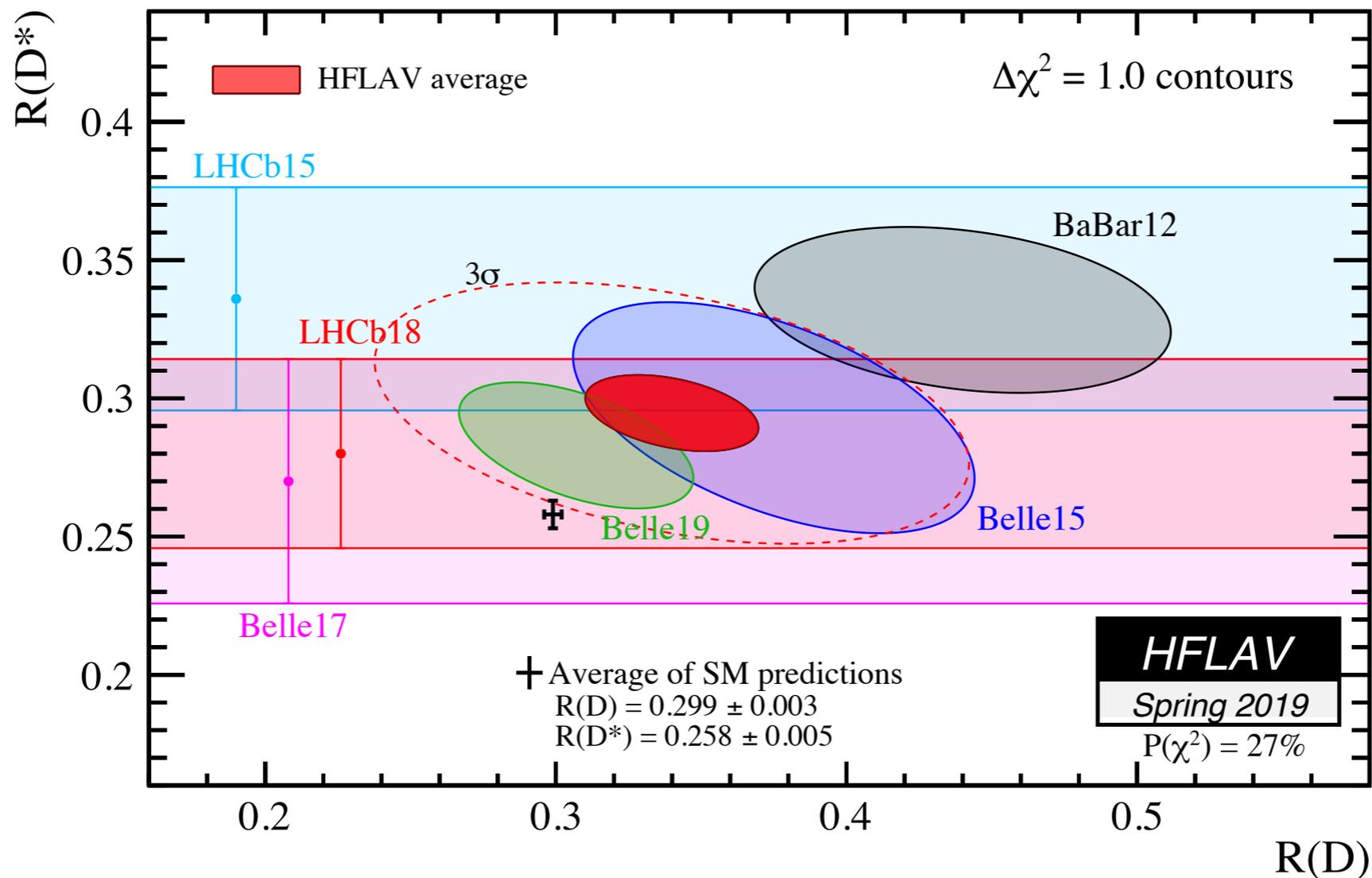
See A. Romero's talk for more details

R(D*) and R(D*) combination

Combining with results from the B-factories:

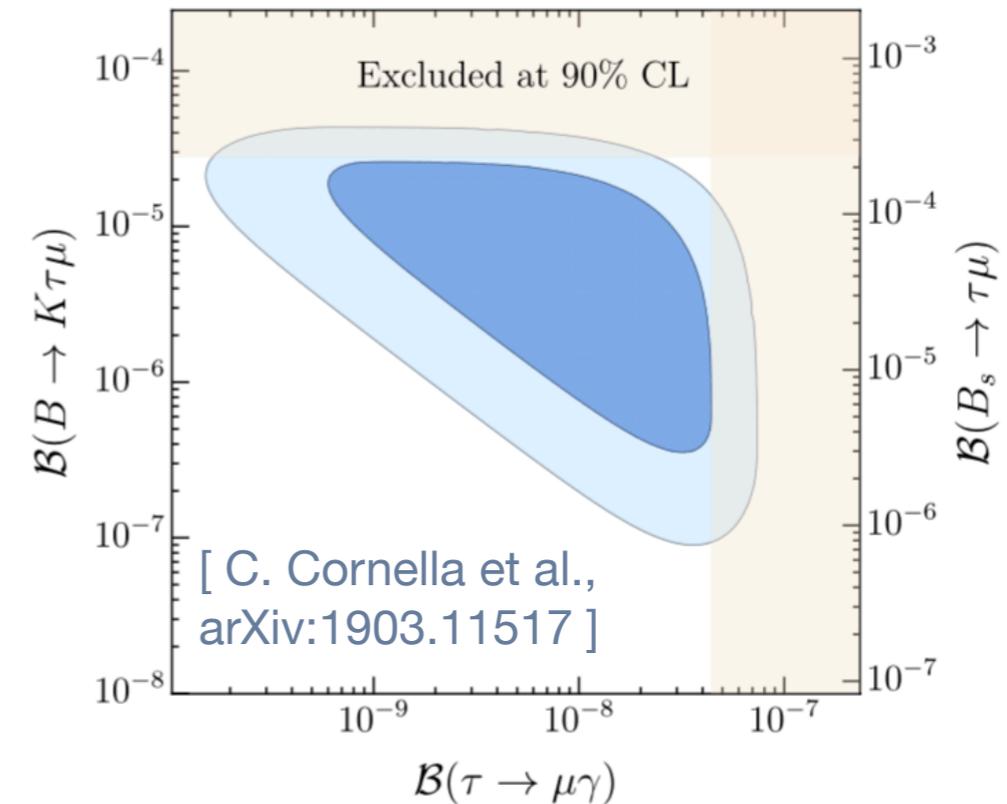
→ Global tension with the SM prediction of **3.08 σ**

- [BaBar, PRL 109,101802 (2012)]
- [LHCb, PRL 115 (2015) 111803]
- [Belle, PRD 92 (2015) 072014]
- [Belle, PRL 118 (2017) 211801]
- [LHCb, PRL 120 (2018) 171802]
- [Belle, arXiv:1904.08794v2 (2019)]



Link to Lepton Flavour Violation

- Attempts to explain tensions in FCCC and FCNC simultaneously, usually point to enhancements in LFV processes ($B \rightarrow \ell \ell'$, $B \rightarrow K \ell \ell'$, ...)
 - ▶ e.g. vector lepto-quark contributing at tree-level to $R(D^*)$ and at loop-level to R_K



- **New searches for $B_{(s)} \rightarrow \tau \mu$ with LHCb Run1 data**

Mode	Limit	90% CL	95% CL
$B_s^0 \rightarrow \tau^\pm \mu^\mp$	Observed	<u>3.4×10^{-5}</u>	4.2×10^{-5}
	Expected	3.9×10^{-5}	4.7×10^{-5}
$B^0 \rightarrow \tau^\pm \mu^\mp$	Observed	1.2×10^{-5}	1.4×10^{-5}
	Expected	1.6×10^{-5}	1.9×10^{-5}

First limit in the B_s mode



[LHCb-PAPER-2019-016]

See V. Bellee's talk for more details

Prospects on LFU tests



- LHCb full Run 2 dataset ~ 4 times number of B 's available in Run1
 - ▶ Updates of R_K and R_{K^*0} , and many other LFU ratios: R_ϕ , $R_{\rho K}$, $R(D)$, $R(\Lambda_c)$...
 - ▶ Angular analysis of $b \rightarrow s \ell \ell$ transitions also underway

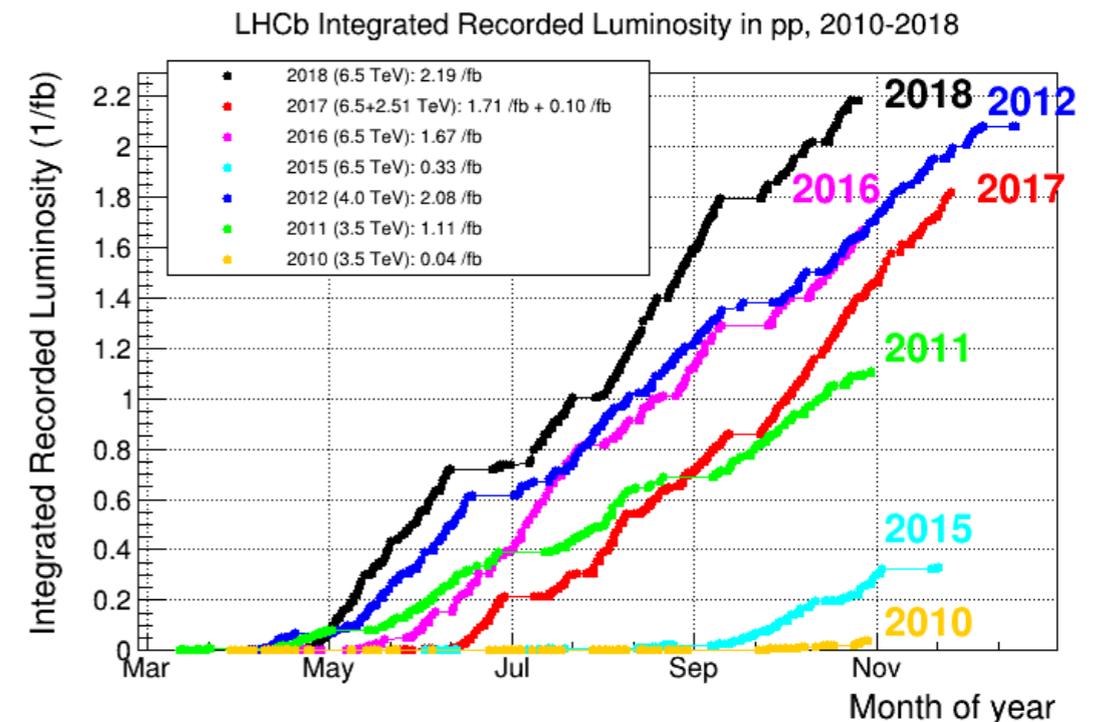


- CMS has collected a sample of 10^{10} B decays
 - ▶ With an effective low p_T electron reconstruction, should get a very competitive number of e.g. $B^+ \rightarrow K^+ e^+ e^-$ signal candidates
 - ▶ Expect systematics will be very different to those at LHCb e.g. no trigger effect and very different material distribution

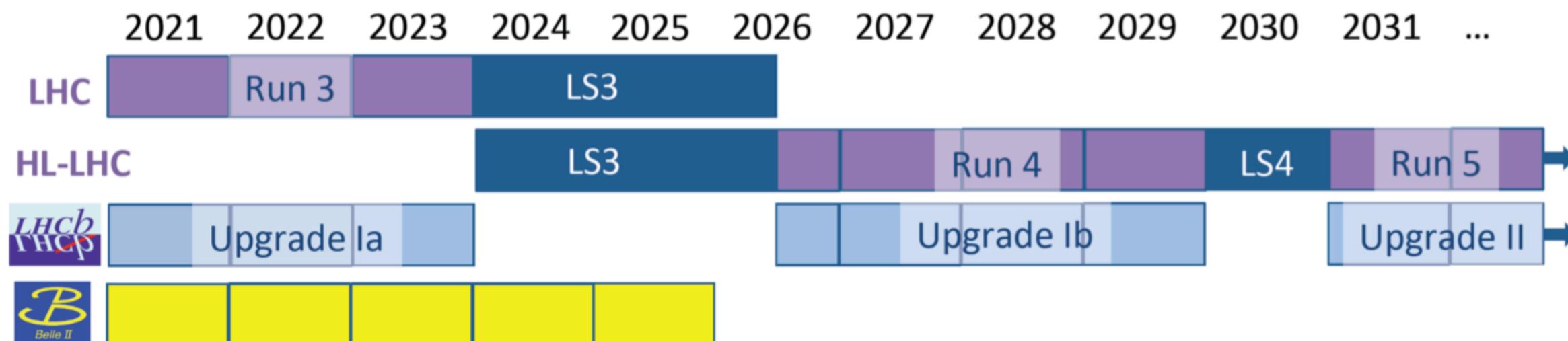


- ATLAS pursuing a similar strategy

- Belle II starting data-taking this year



Further into the future

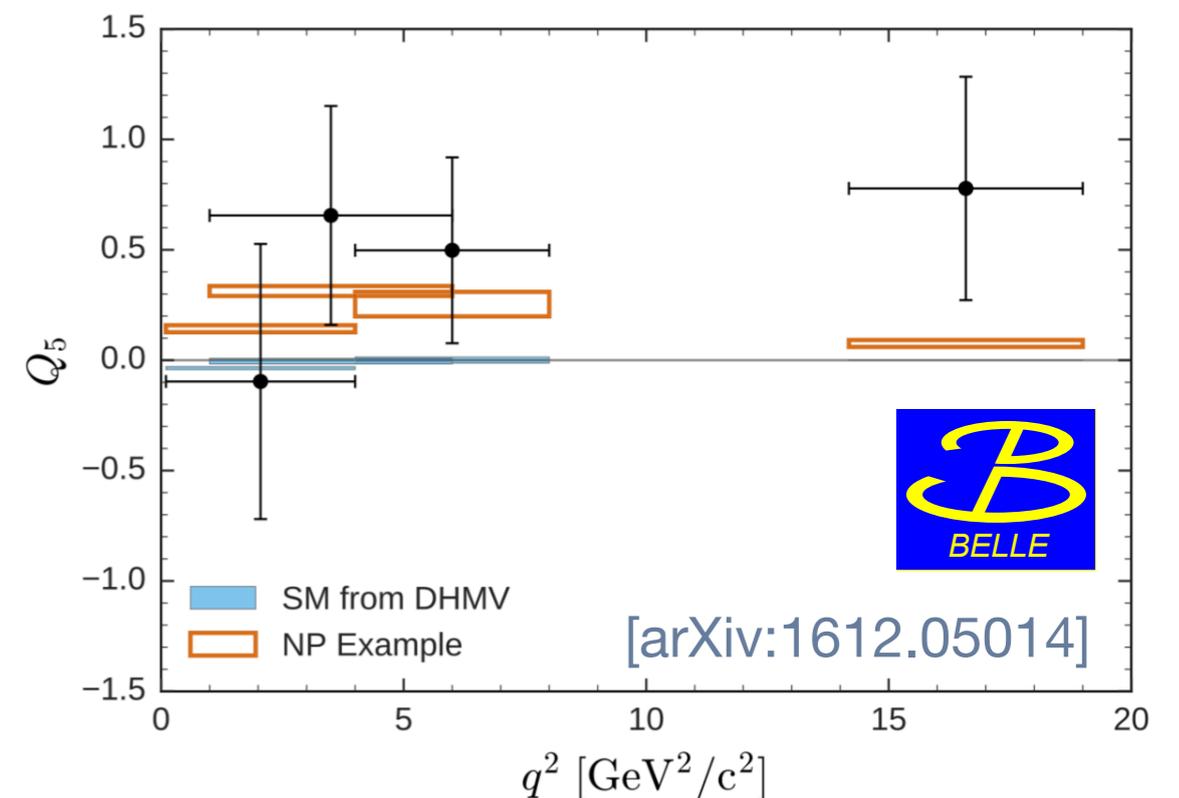
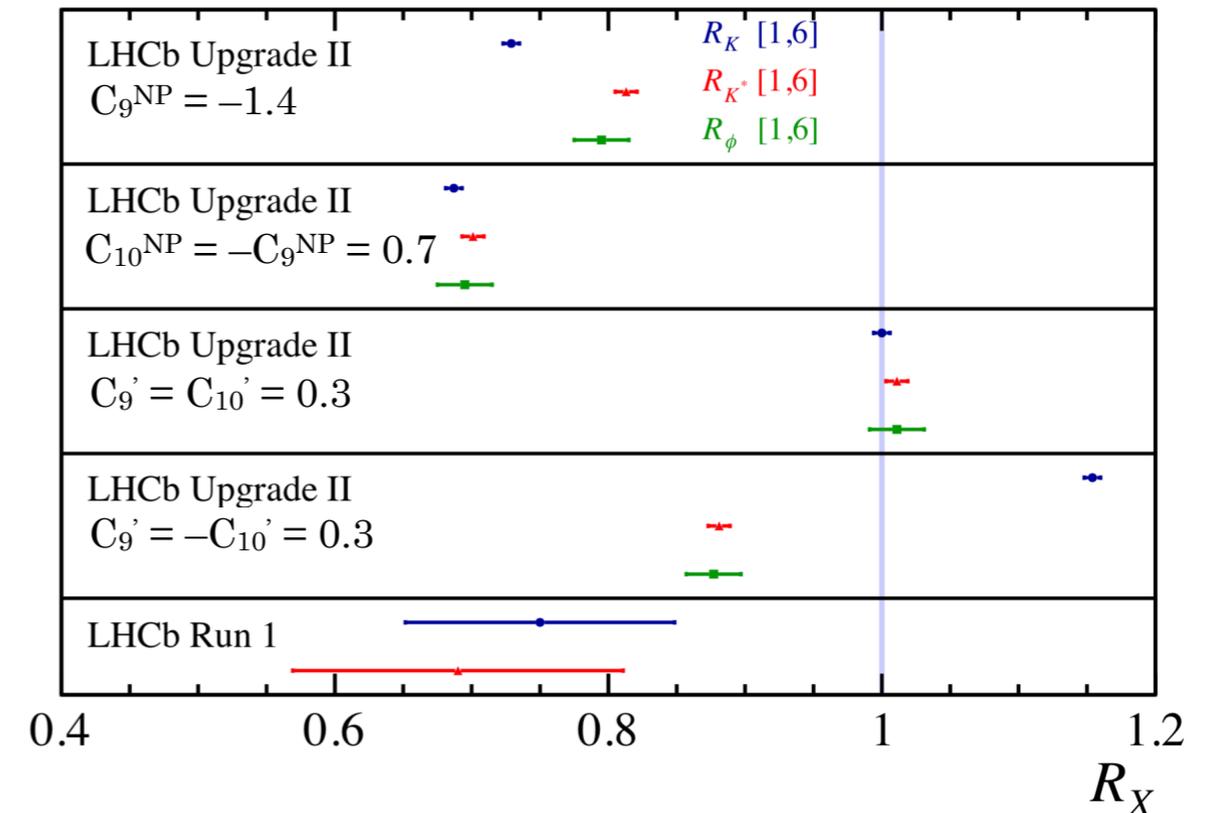


- LHCb is in the process of upgrading to a new detector
 - ▶ will operate at much higher luminosity with improved efficiency (make all trigger decisions in software)
 - ▶ will accumulate 50 fb^{-1} of data
- A second phase of the Upgrade in LS4 is also planned to profit from even higher luminosities at the HL-LHC (increase data sample up to 300 fb^{-1} for LHCb)

LFU with upgrade datasets

[LHCb-PUB-2018-009]

- Access to **different LFU ratios** with excellent precision: **allow to distinguish between different NP scenarios**
 - ▶ Need to drive systematics in electrons down to $\sim 1\%$
- LFU tests with **angular observables**
 - ▶ e.g. $Q_5 = P'_5(\mu) - P'_5(e)$
- Large benefits for **$R(H_c)$ ratios, specially with B_s, Λ_b and B_c hadrons**
 - ▶ complementary sensitivity to NP
 - ▶ Interplay between LHCb and Belle II



Summary

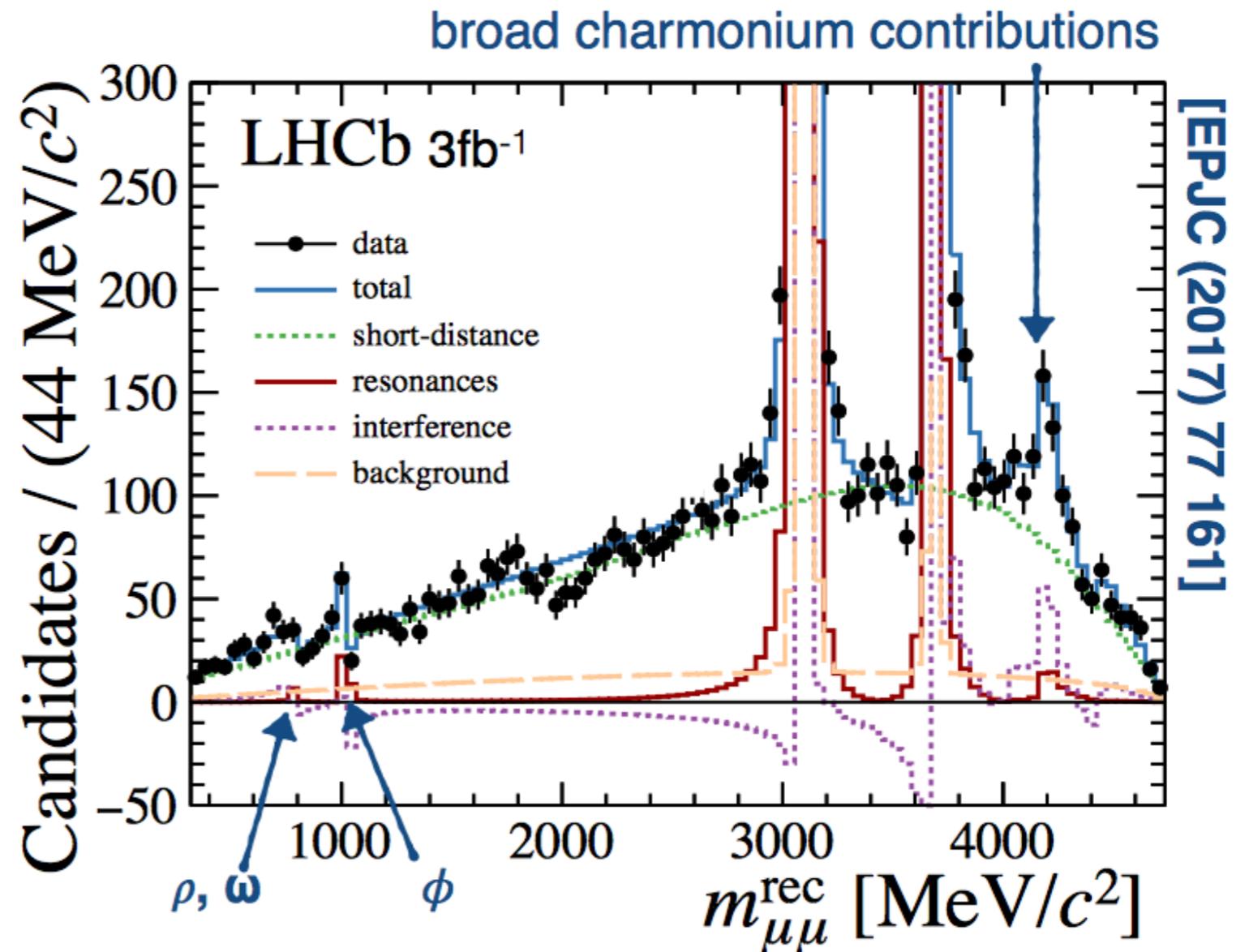
- ▶ Lepton Flavour Universality tests are theoretically pristine probes for New Physics
- ▶ Intriguing anomalies found in LFU tests using B-meson decays
 - ▶ tree-level $b \rightarrow c \ell \nu$ decays
 - ▶ loop-level $b \rightarrow s \ell \ell$ decays - pointing in the same direction as other $b \rightarrow s \mu \mu$ tensions
- ▶ Latest measurements yet to provide a definitive picture
- ▶ Upcoming measurements with full Run 2 statistics will help to resolve the current situation
- ▶ Ongoing and future experiment upgrades and the start-up of Belle II, opens the door to many improvements in precision, so interesting times are ahead!

Backup

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

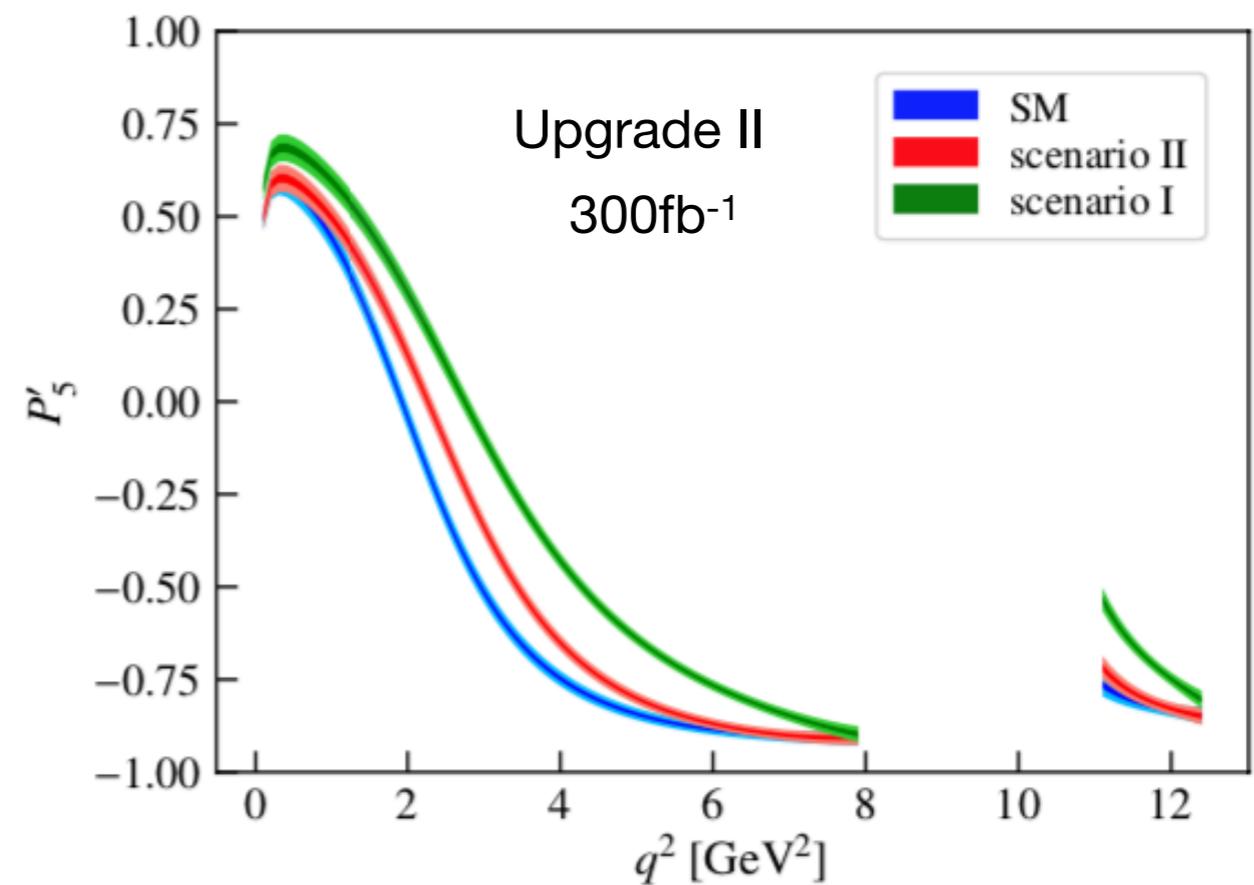
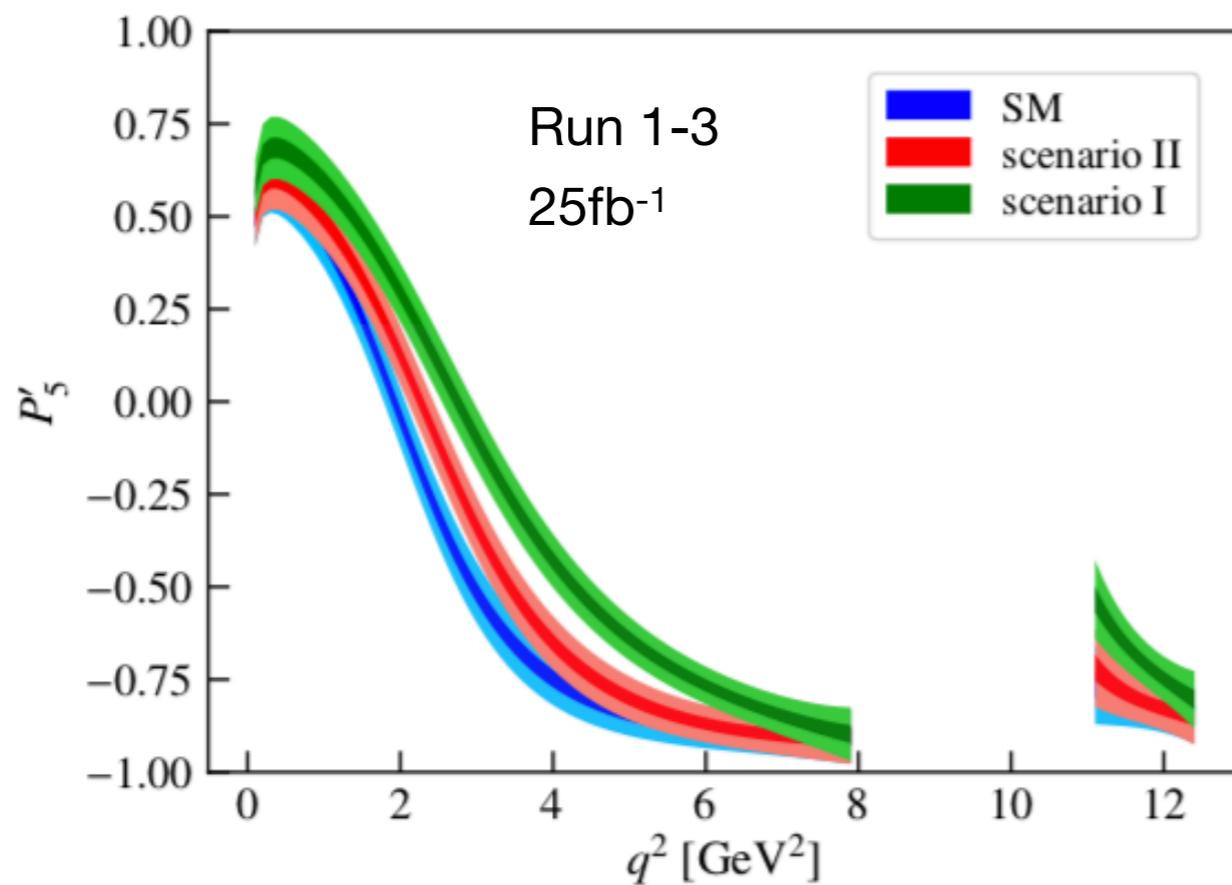
- Full amplitude analysis of $B \rightarrow K^+ \ell^+ \ell^-$
- Work ongoing to extend this to $B^0 \rightarrow K^{*0} \ell^+ \ell^-$
 - ▶ Several approaches proposed



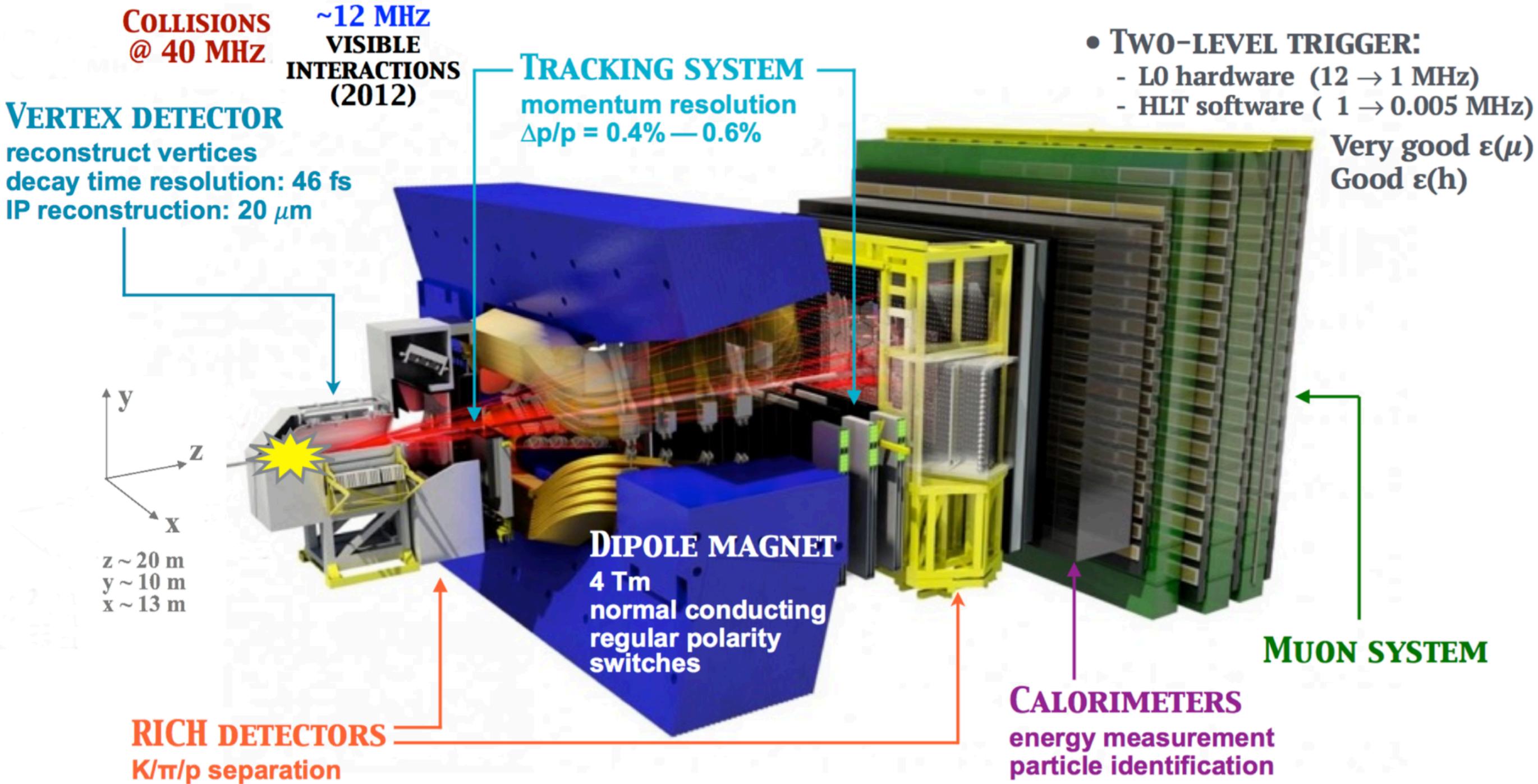
[Hurth et al, JHEP11(2017)176], [Chrzaszcz et al, 1805.06378], [Blake et al, EPJC(2018)78:453]

Angular analyses prospects

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



The LHCb detector



LHCb Upgrade and beyond

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

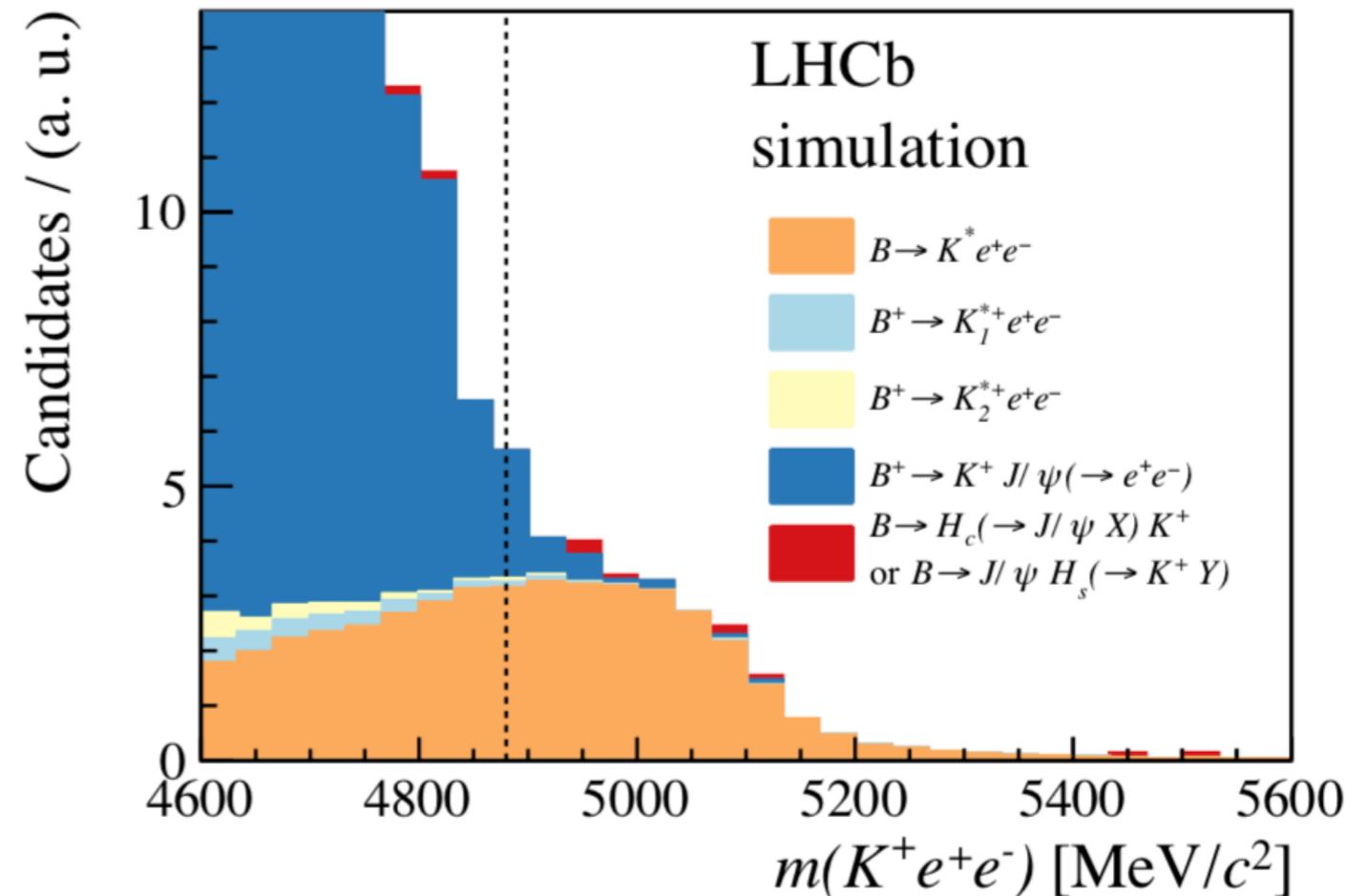
Gains in precision many critical observables are expected

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

[PRL 122 (2019) 191801]

Remaining backgrounds:

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



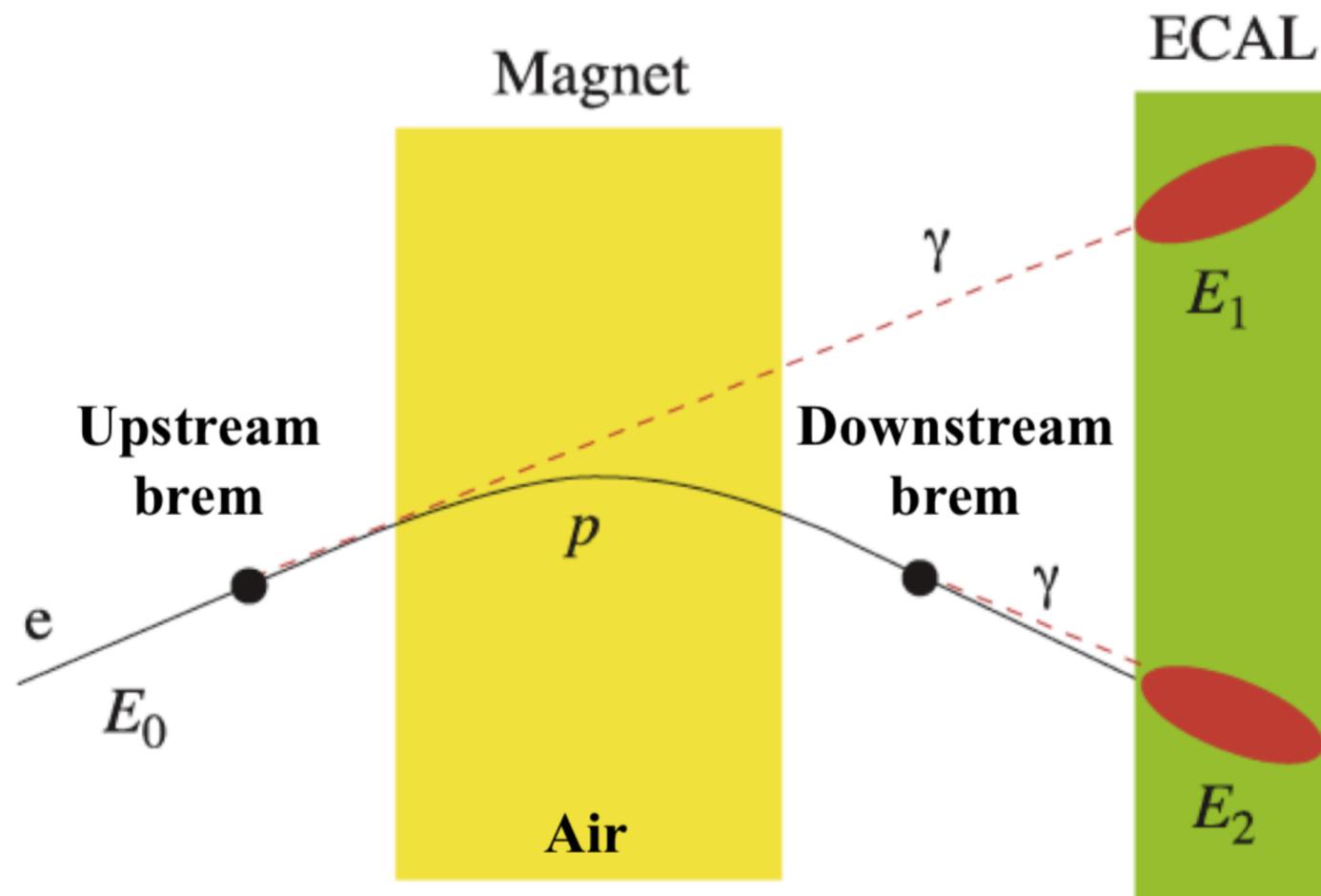
Choose the $m(K^+ e^+ e^-)$ window so that the contribution from partially reconstructed decays is dominated by $B^0 \rightarrow K^{*0} e^+ e^-$,

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

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

Electron reconstruction (I)

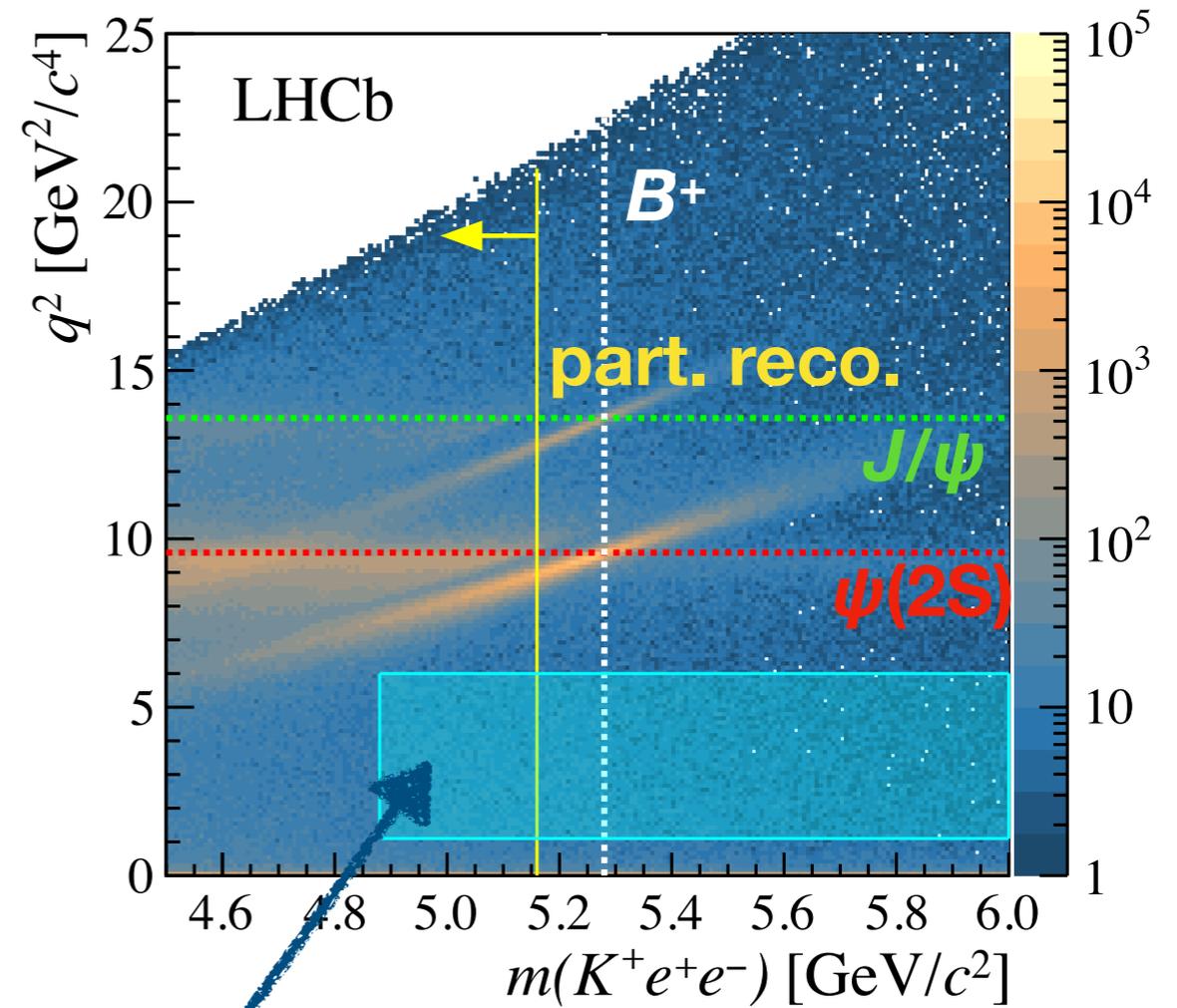
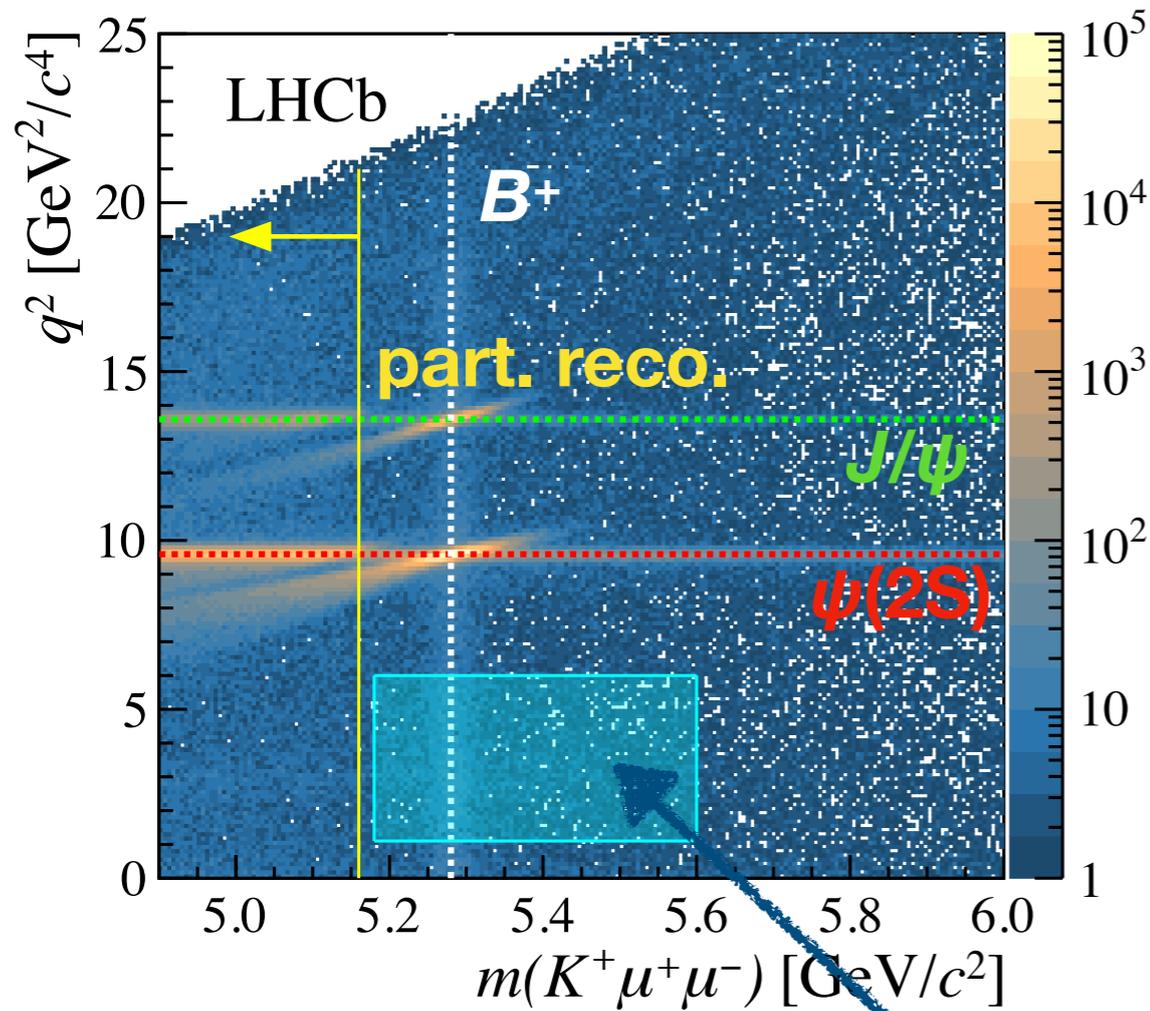
- Electrons lose a large fraction of their energy through Bremsstrahlung radiation
 - ▶ Bremsstrahlung recovery: Look for photon clusters in the calorimeter ($E_T > 75$ MeV) compatible with electron direction before magnet



Electron reconstruction (II)

[PRL 122 (2019) 191801]

- After Brem. recovery, still worse momentum/mass resolution for electrons

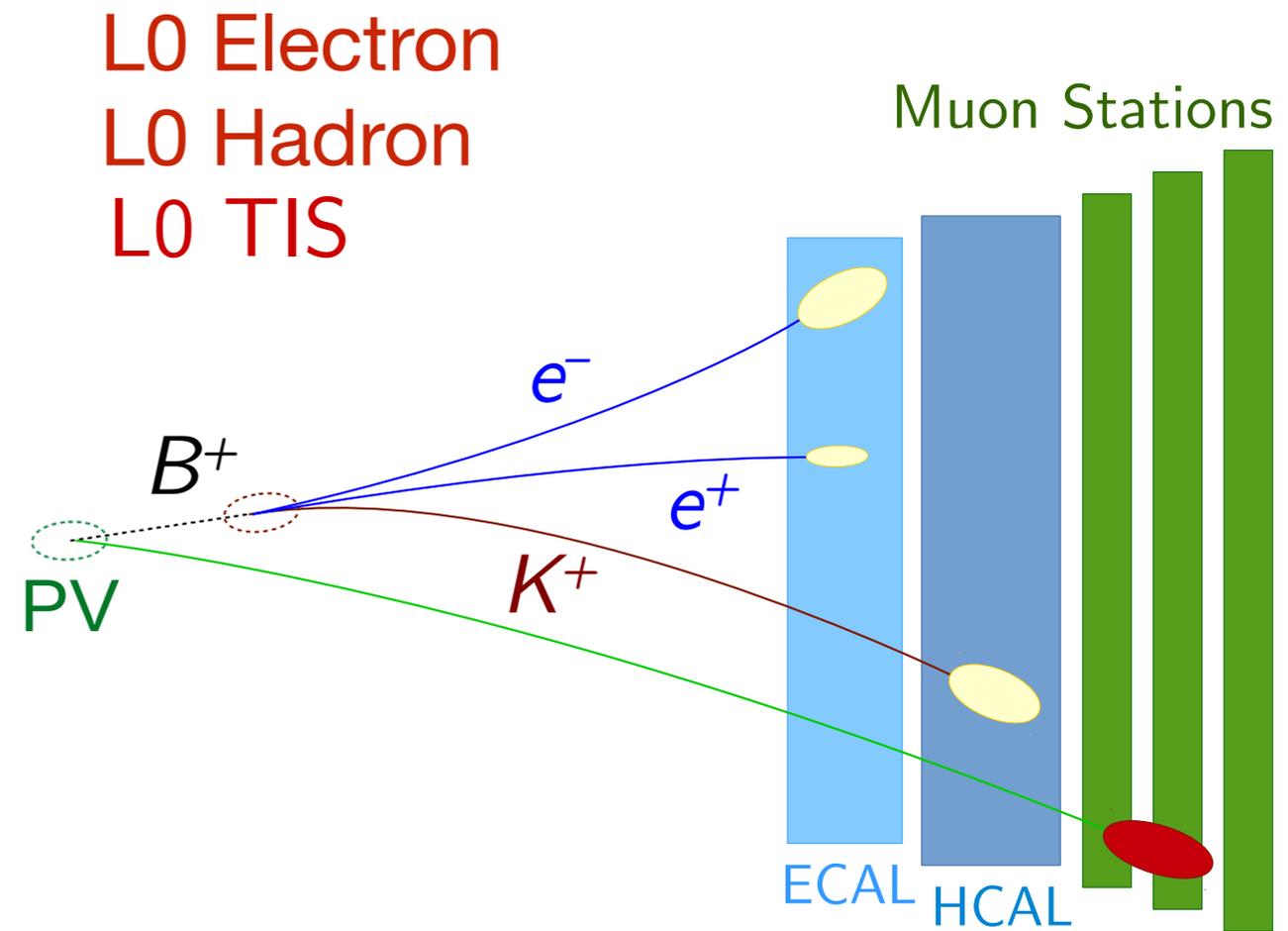
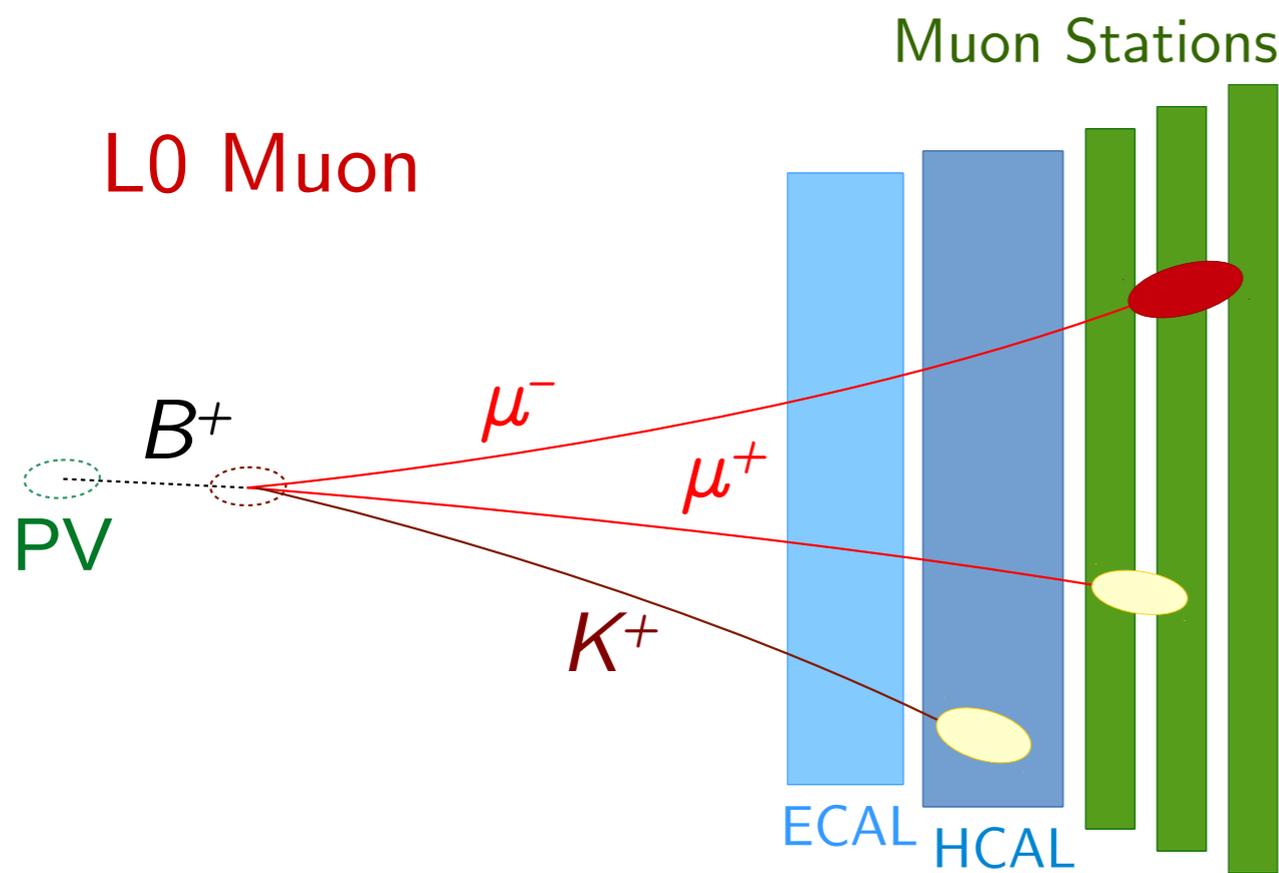


Signal regions

Electron reconstruction (III)

[PRL 122 (2019) 191801]

- Very different trigger signatures: Lower trigger efficiency for electrons

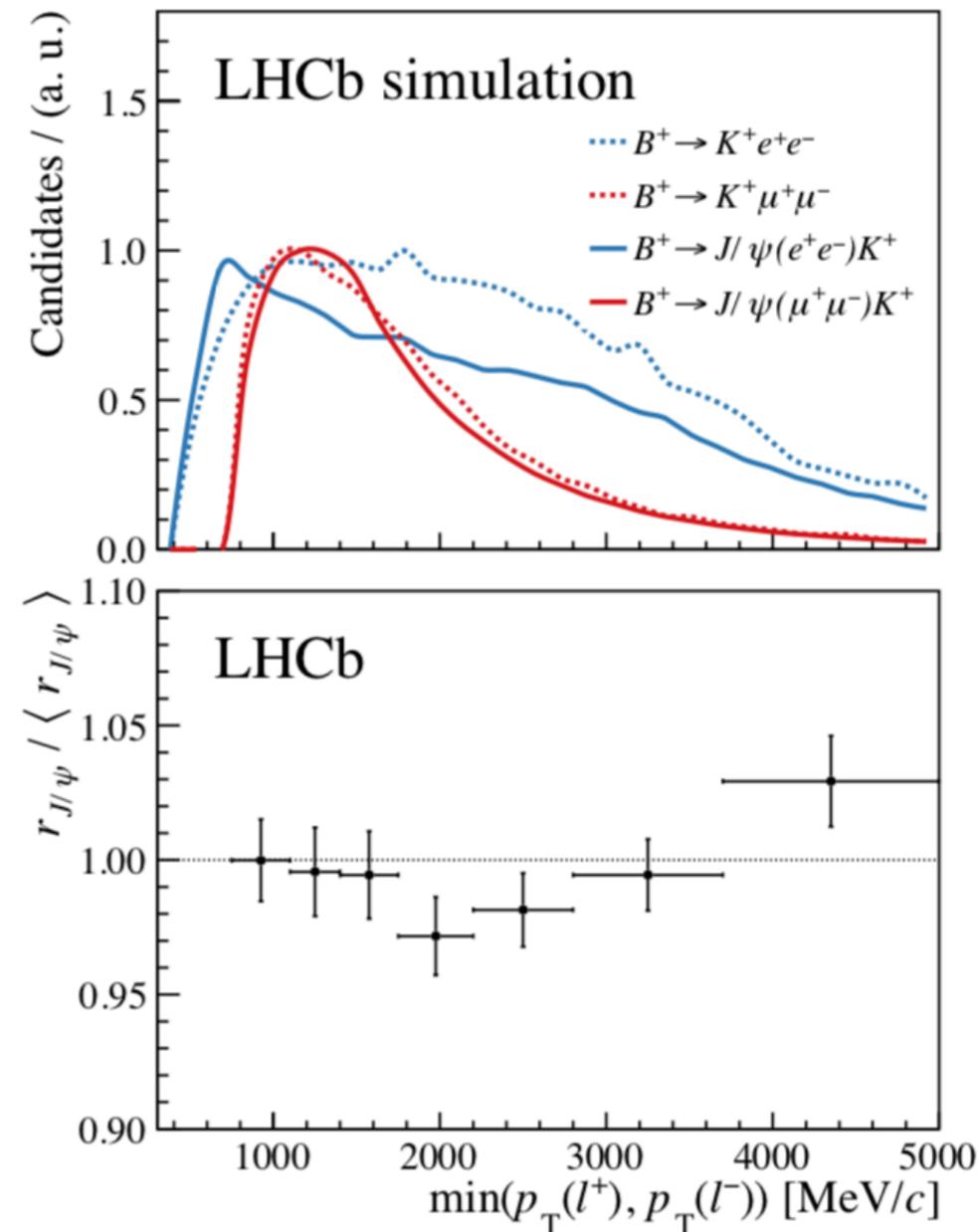
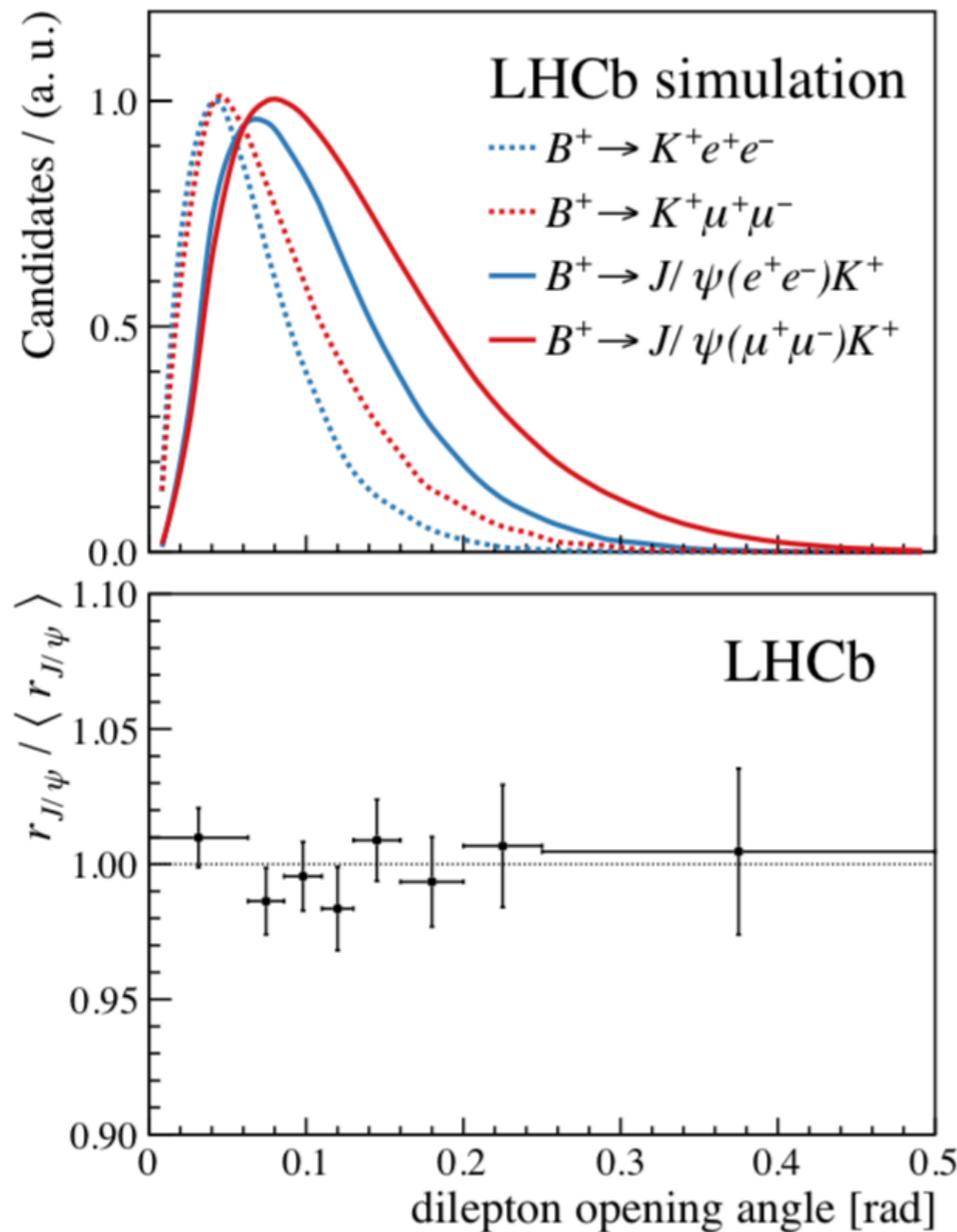


Cross-check 2: $r_{J/\psi}$ as a function of kinematics

Check that efficiencies are understood in all kinematic regions $\rightarrow r_{J/\psi}$ is flat for all variables examined

\rightarrow e.g. given expected $\min(p_T(l^+), p_T(l^-))$ spectra, bias expected on R_K if deviations are genuine rather than fluctuations is 0.1%

[PRL 122 (2019) 191801]



Cross-check 4 & 5

[PRL 122 (2019) 191801]

- Measurement of the double ratio

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

Result well compatible with unity:

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

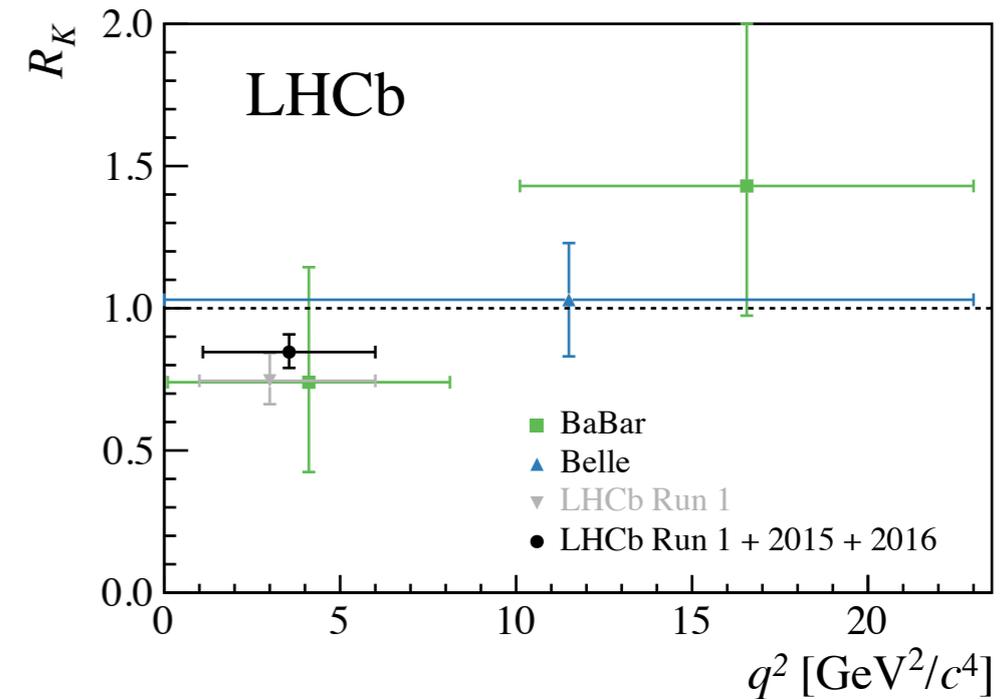
- Good compatibility found separately for Run 1 and Run 2 datasets, and in all trigger categories.
- Checked that the $\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$ is compatible with previous determination [LHCb JHEP06 (2014) 133], but less precise owing to the selection being optimised for R_K .
 - Good compatibility between the measurements in the Run 1 and Run 2 samples is also found.

R_K result

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 σ** .



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

- If Run 1 and Run 2 samples were fitted separately

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

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

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

⇒ Accounting for correlations:

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

BR($B^+ \rightarrow K^+ e^+ e^-$) at low q^2

[PRL 122 (2019) 191801]

Combining this measurement of R_K with $BR(B^+ \rightarrow K^+ \mu^+ \mu^-)$ from [LHCb, JHEP 06 (2014) 133]

$$\left. \frac{d\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{dq^2} \right|_{1.1 < q^2 < 6.0} = (28.6^{+2.0}_{-1.7} \pm 1.4) \times 10^{-9} \text{ c}^4 / \text{GeV}^2$$

- Most precise measurement of this BR to date
- Systematic uncertainty dominated by $BR(B^+ \rightarrow K^+ J/\psi)$
- $BR(B^+ \rightarrow K^+ \mu^+ \mu^-)$ with new sample:
 - ▶ Compatible with previous result [LHCb, JHEP 06 (2014) 133]
 - ▶ Compatibility between Run 1 and Run 2 results

