LFU measurements: challenges and future prospects

Beyond the flavour anomalies, IPPP Durham

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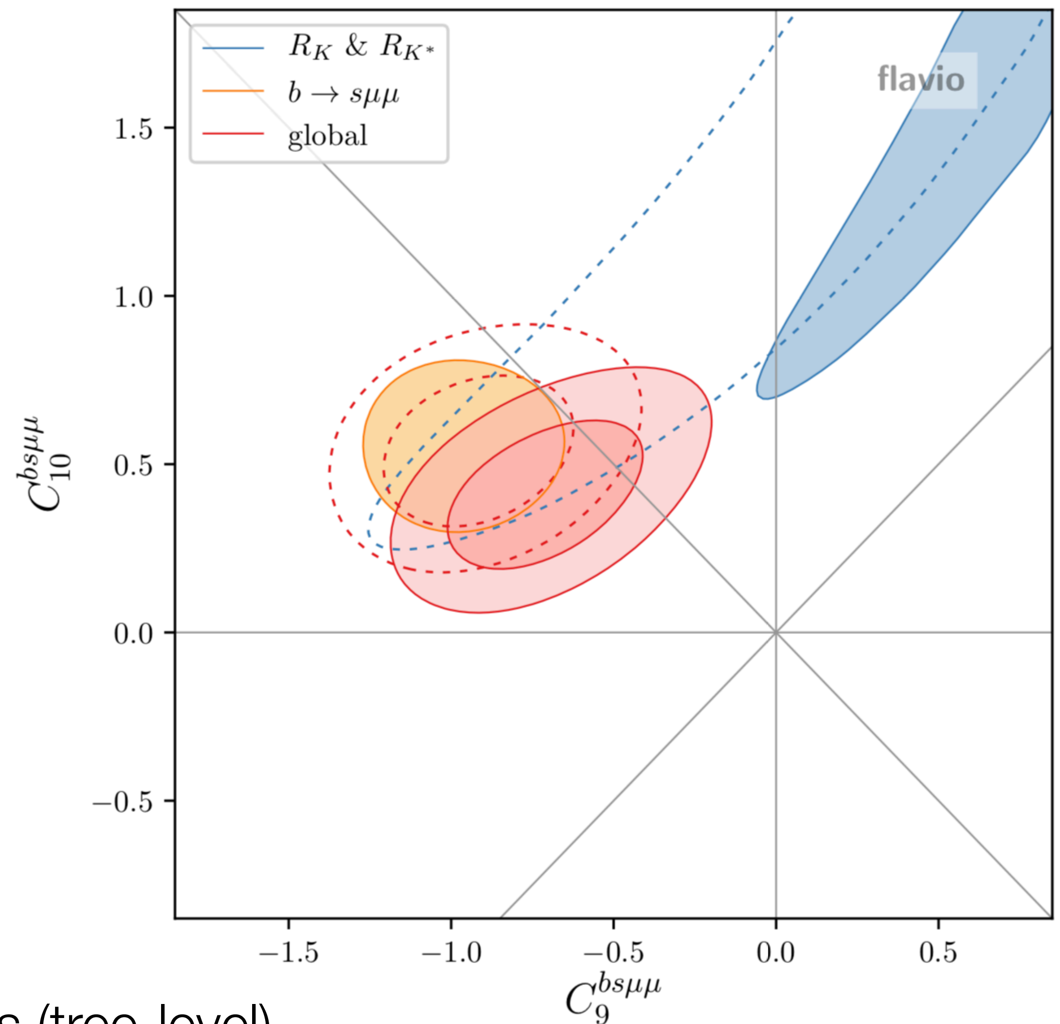
April, 2020

Lepton Flavour Universality tests

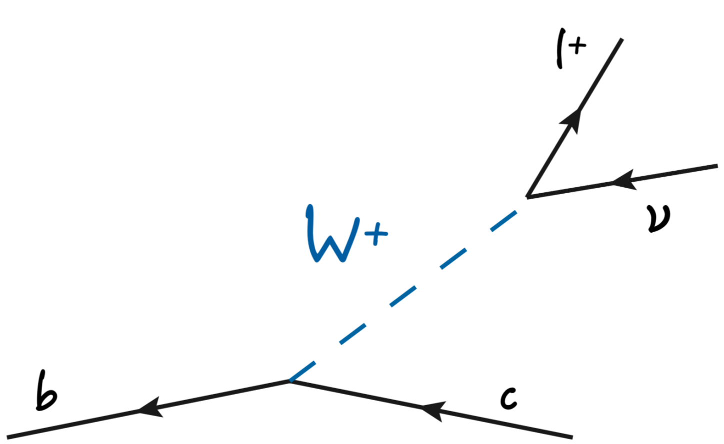
In the Standard Model, couplings of the gauge bosons to the **L**eptons are **F**lavour **U**niversal

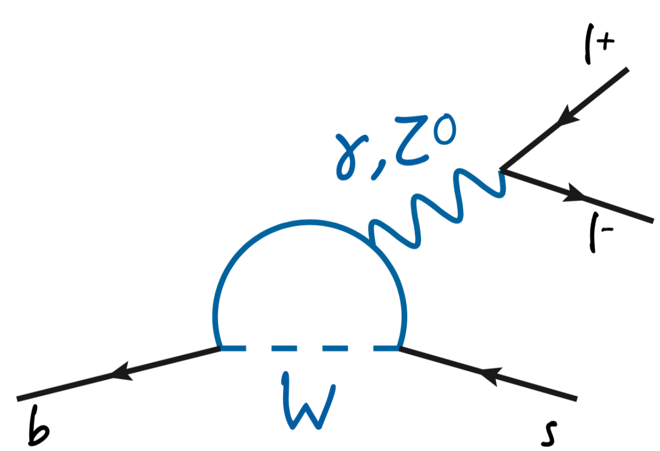
Thoroughly tested in the past:

- $Z \to \ell\ell$ and $W \to \ell\nu$ measurements
- Semileptonic decays of π, K and D mesons
- Leptonic decays
- Quarkonia ($J/\psi \to ee, \mu\mu$)
- **B-meson anomalies**
  - Flavour Changing Charged Current $b \to c\ell\nu$ decays (tree-level)
  - Flavour Changing Neutral Current **$b \to s\ell\ell$ transitions (loop-level)**



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



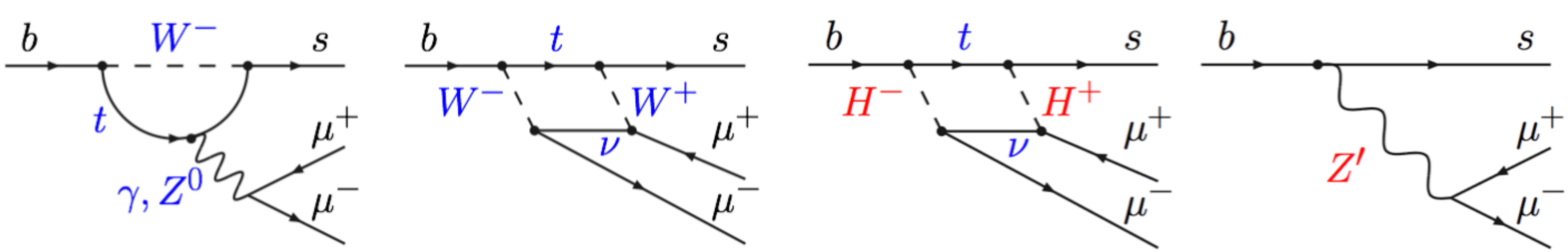


What do we measure?

$B^{+,0}$, B_S, Λ_b

$K, K^*, \phi, pK \ldots$

$$R_{H_s} = \frac{\int \frac{d\Gamma(B \to H_s \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \to H_s e^+ e^-)}{dq^2} dq^2} \overset{SM}{\cong} 1$$



Standard Model

New Physics

Differential in q^2

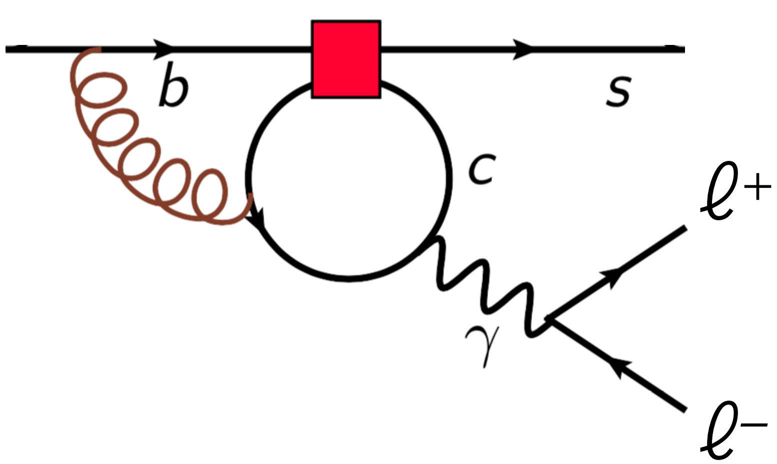
- Perform the measurement in bins of $q^2 \equiv m(\ell\ell)$

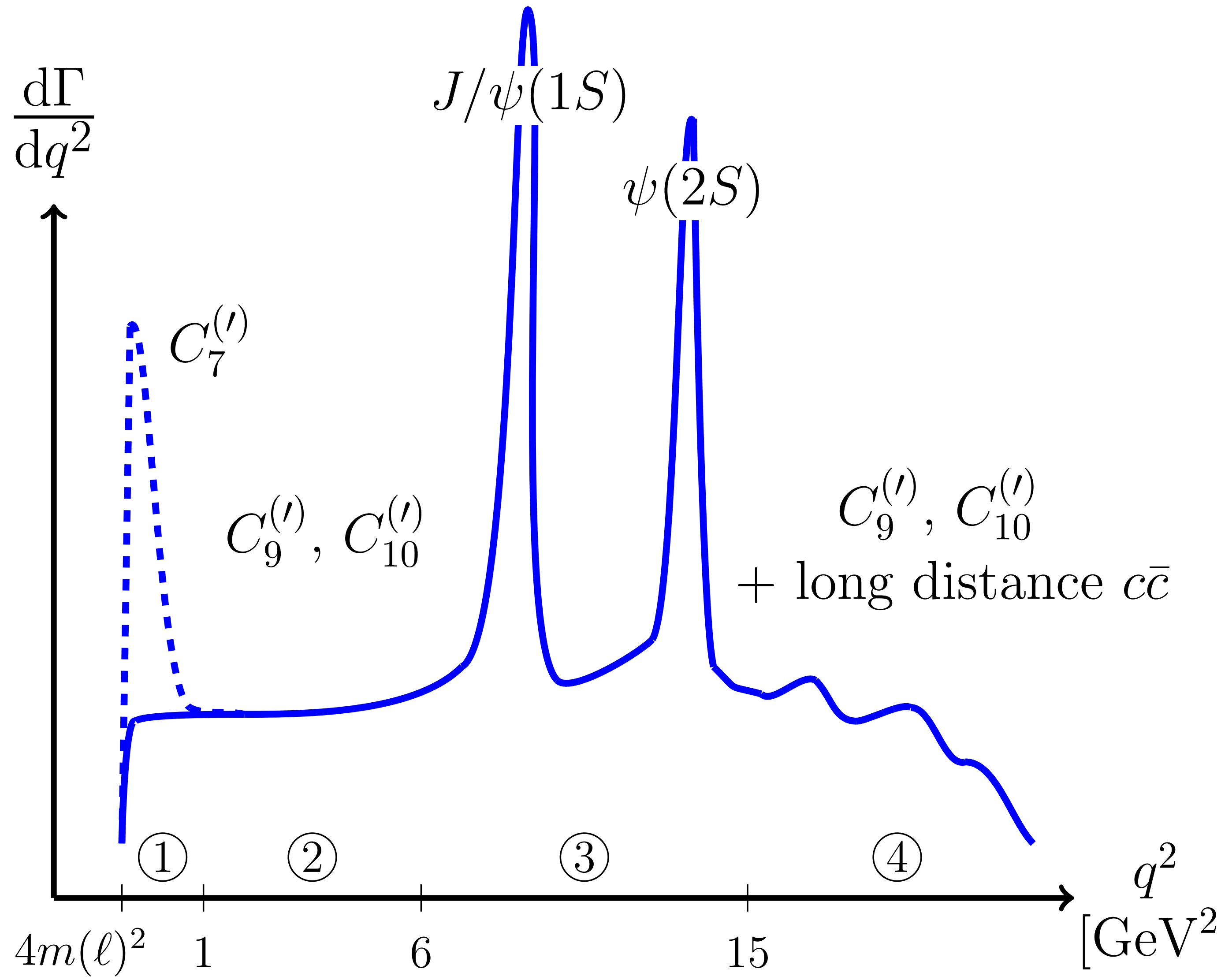
  ① low-q^2: [0.045, 1.1] GeV²/c⁴

  ② central-q^2: [1.1, 6] GeV²/c⁴

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\alpha_e}{4\pi} \sum [C_i\mathcal{O}_i + C_i'\mathcal{O}_i']$$

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





What data?

R(K)* [low, central q^2]

Lumi = 3/fb

Analyses ongoing

LHCb upgrade

Run 1	LS1	Run 2	LS2	Run 3	LS3	
2010-2012	2013-2014	2015-2018	2018-2020	2021-2024	2025-2027	…

R(K) [central q^2]

Lumi = 3/fb

R(K) [central q^2]

- Re-analysis of Run 1 sample
- Added 2015-2016 data (higher σ_{bb})

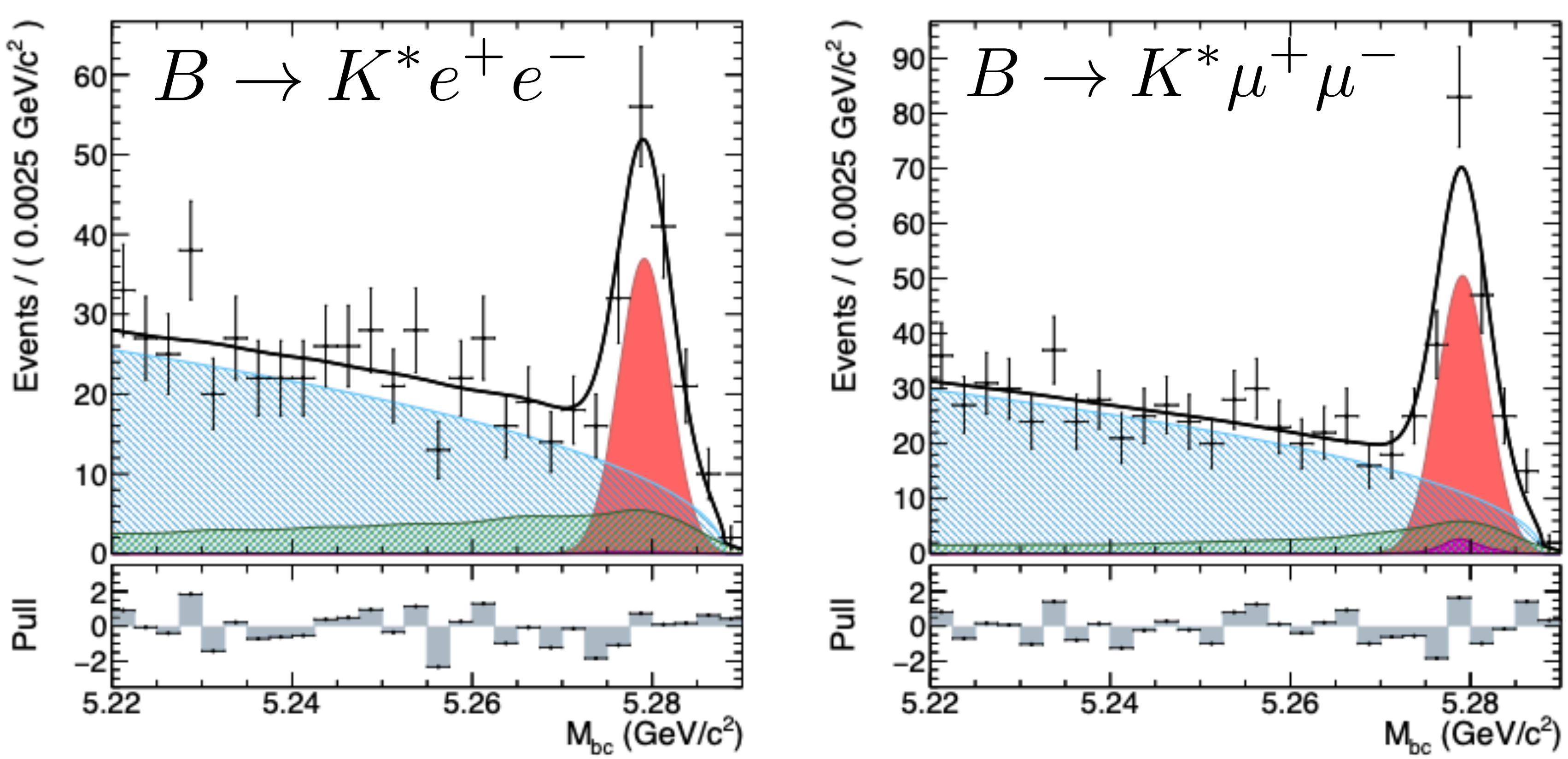
Lumi = 5/fb

New measurements of *R(K)* and *R(K*)* [low, central, high q^2]

Lumi = 711/fb Υ(4S) (772×10^6 BB events)

R(K) and R(K*) at Belle

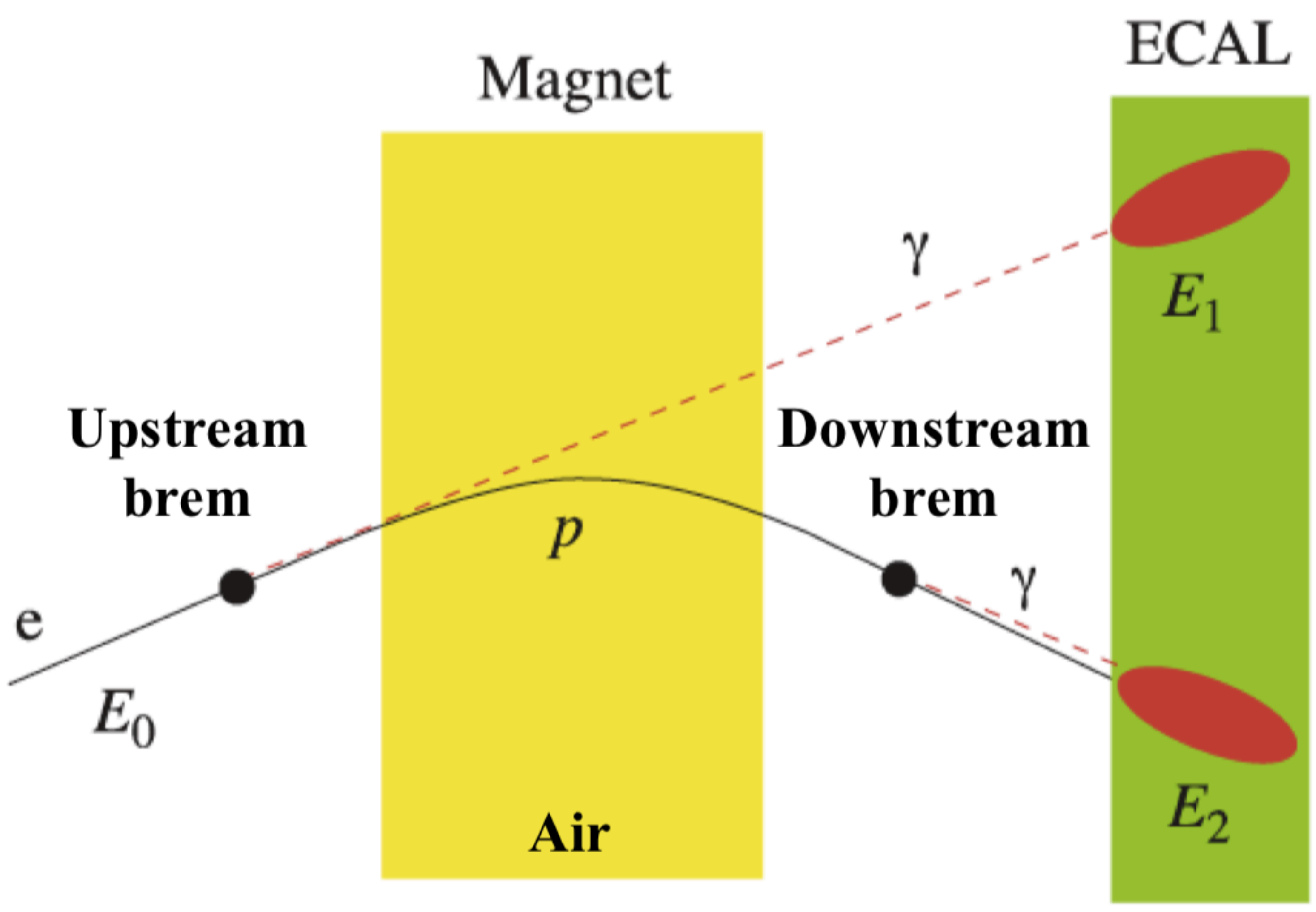
- Clean environment from ee collisions
- Similar reconstruction performance for muons and elections
- Good performance on neutrals [K_S, $K^{*0}(K_S\pi^0)$, $K^{*+}(K^+\pi^0$, $K_S\pi^+)$]
- Limited statistics



[Belle, arXiv:1904.02440]

LFU tests at LHCb

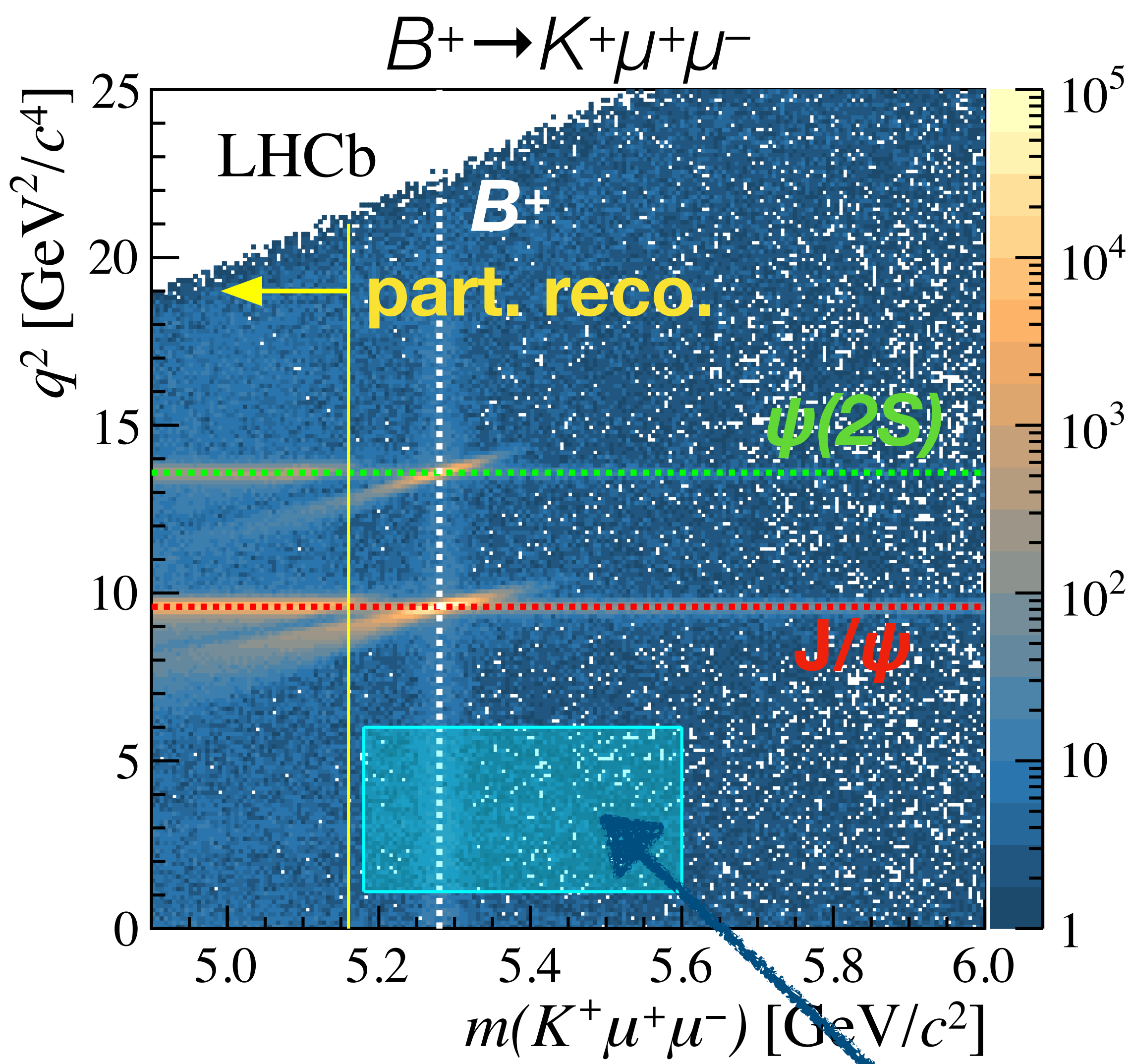
- Large b production, $\sigma(pp\rightarrow b\bar{b})$~600$\mu$b @ 13TeV
- Experimental challenge: very different performance for e and μ
  - Electrons lose a large fraction of their energy through Bremsstrahlung

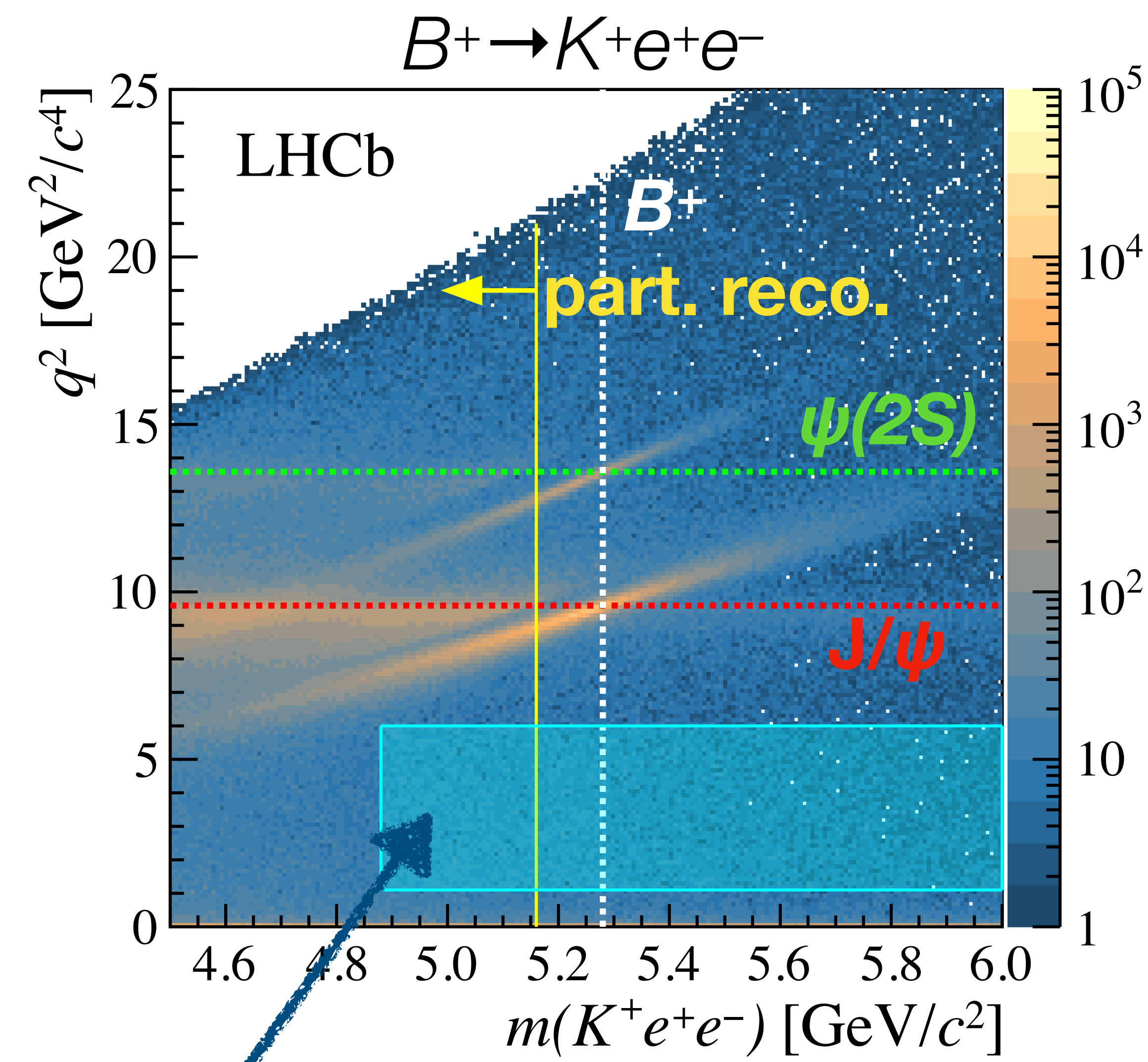


- Bremsstrahlung recovery: Look for photon clusters in the calorimeter (ET > 75 MeV) compatible with electron direction before magnet

Momentum & mass resolution

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





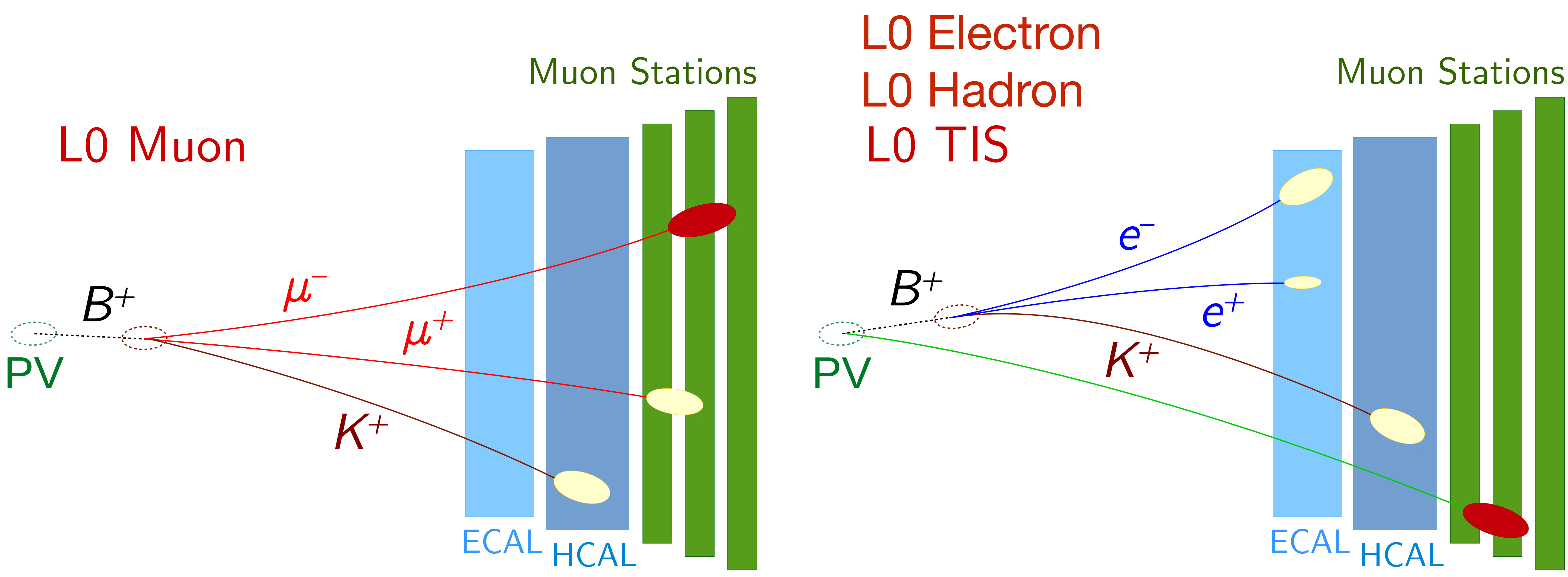
Signal regions

[PRL 122 (2019) 191801]

Trigger

[PRL 122 (2019) 191801]

- Very different trigger signatures: Lower trigger efficiency for electrons



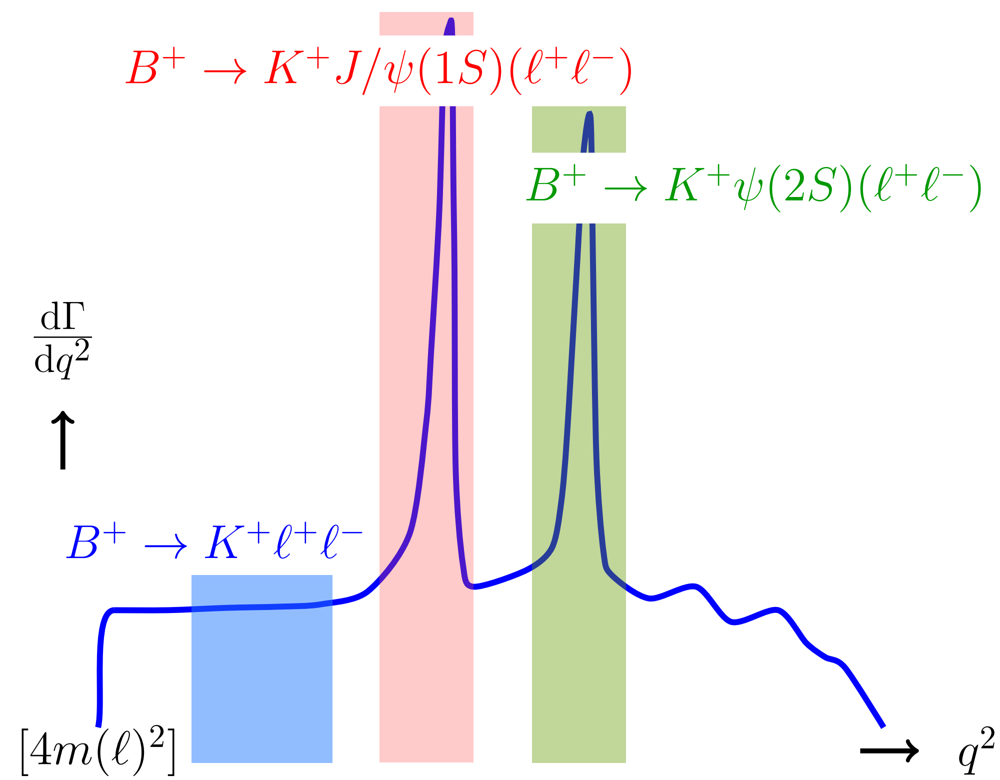
Analysis strategy

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

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

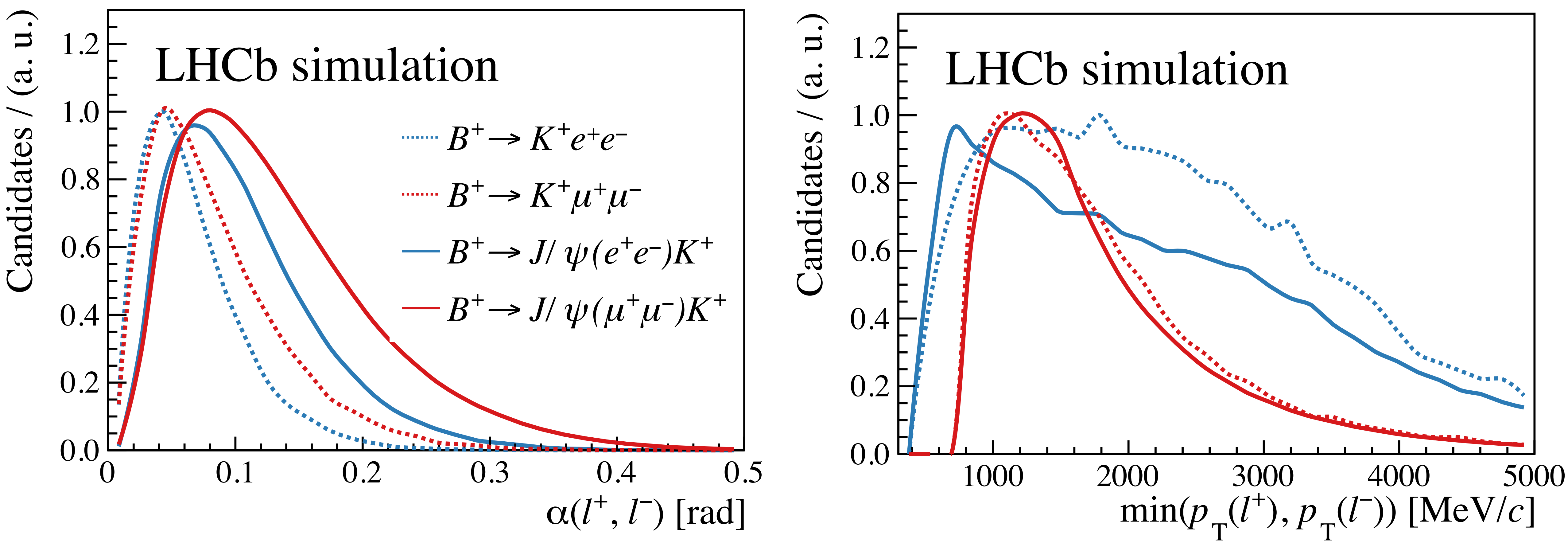
$$= \frac{N(K^+\mu\mu)}{N(K^+J/\psi(\mu\mu))} \cdot \frac{N(K^+J/\psi(ee))}{N(K^+ee)}$$

$$\frac{\varepsilon(K^+J/\psi(\mu\mu))}{\varepsilon(K^+\mu\mu)} \cdot \frac{\varepsilon(K^+ee)}{\varepsilon(K^+J/\psi(ee))}$$



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)



$\Longrightarrow$ Systematic uncertainties cancel to a large extent

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 ($D^{*+} \to D^0(K^-\pi^+)\pi^+$...) [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

Cross-checks

[PRL 122 (2019) 191801]

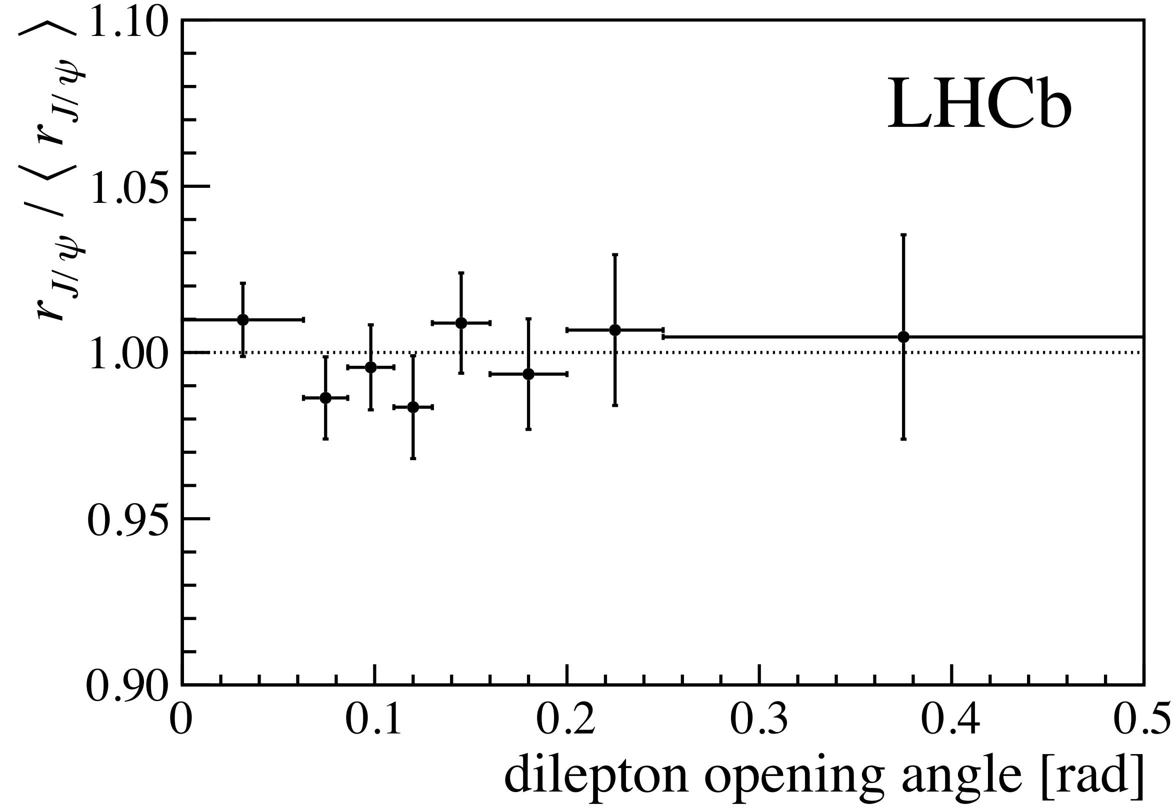
- To ensure good understanding of the efficiencies check

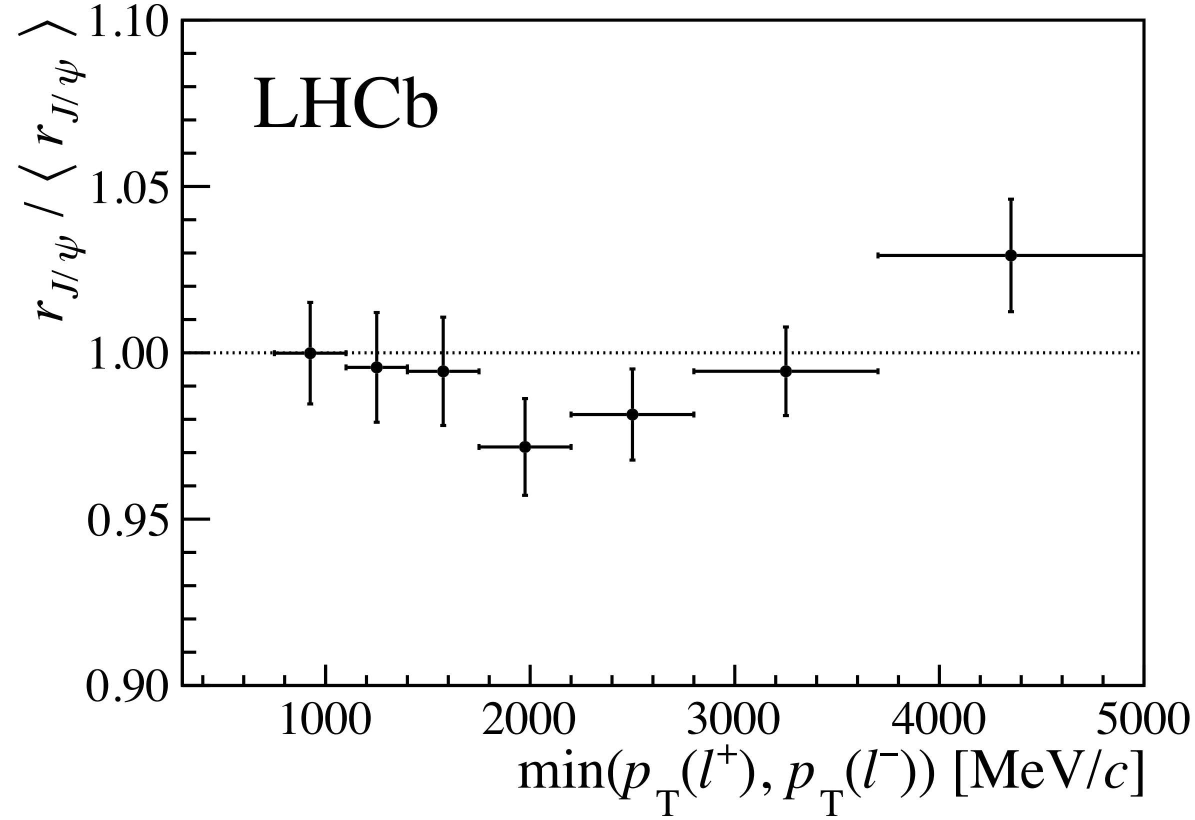
$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = 1$$

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

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

- Cross-checks done independently for samples corresponding to different years and trigger categories

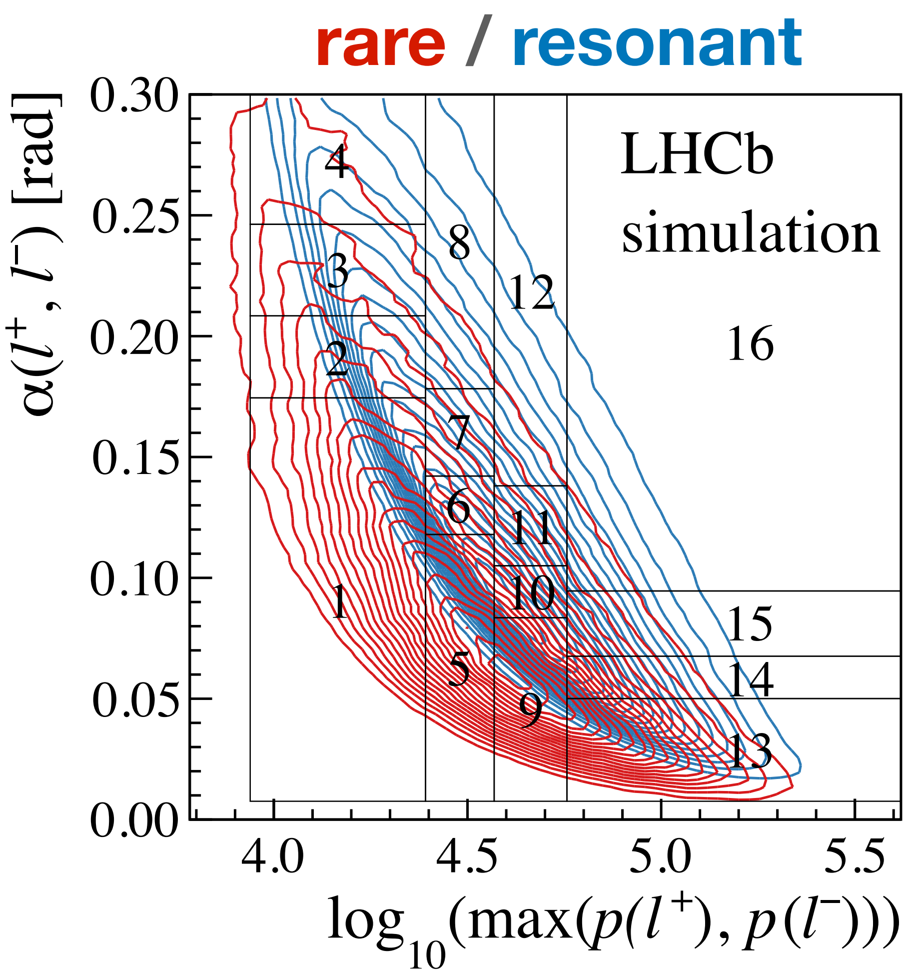


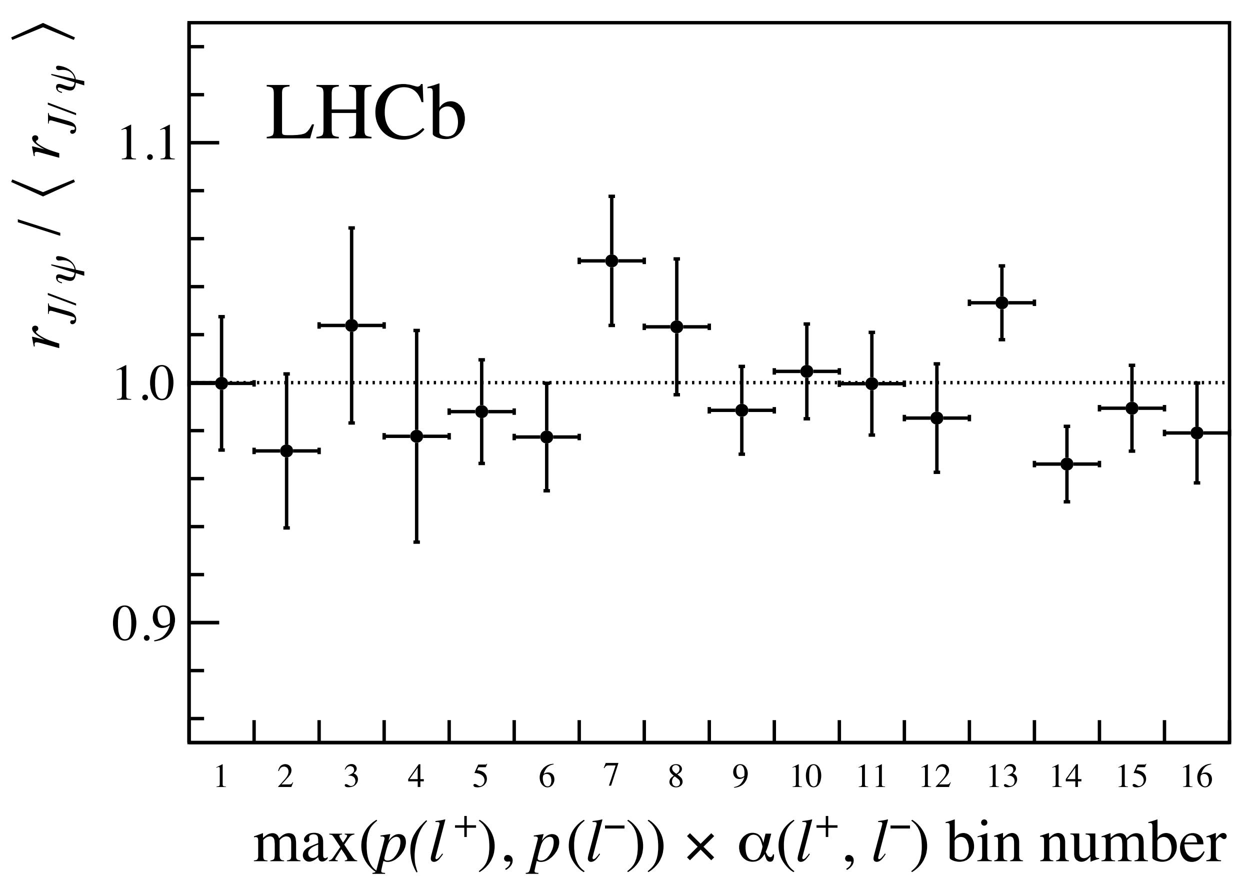


Cross-checks (II)

[PRL 122 (2019) 191801]

- $r_{J/\psi}$ is also checked in 2D 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…

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

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

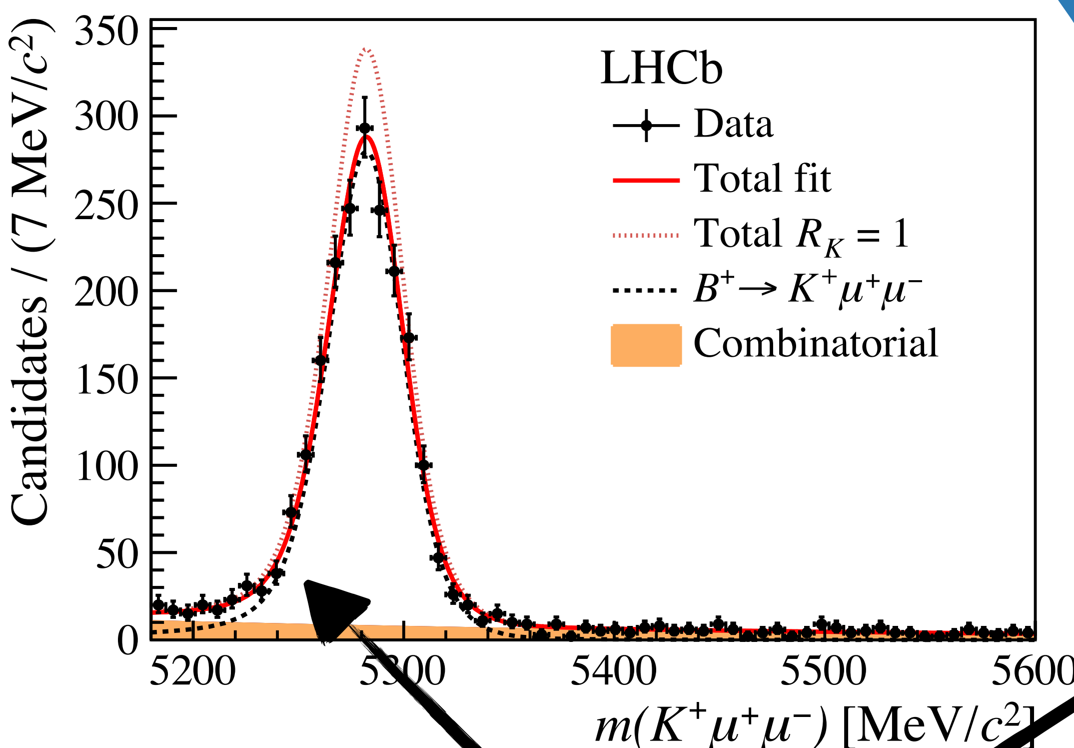
- … and that the BR of the rare muon mode is in agreement with previous measurements.
- <u>All cross-checks done independently for Run 1 and Run 2 samples and 3 trigger categories</u> and excellent agreement found

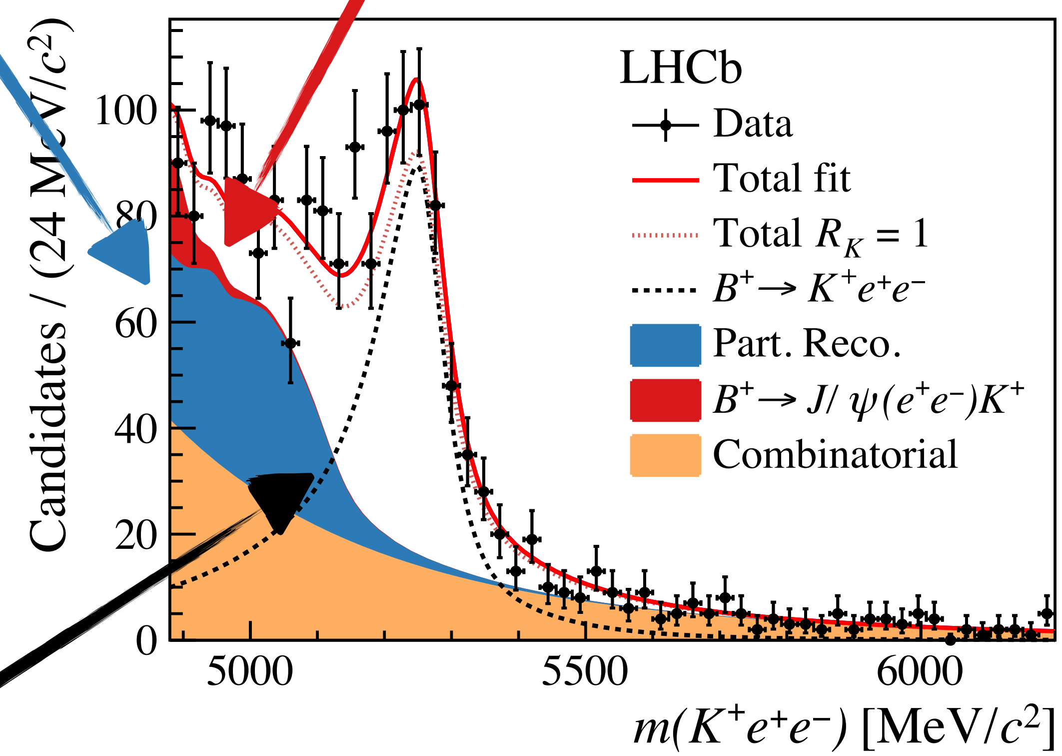
Extraction of the yields

[PRL 122 (2019) 191801]

Partially reconstructed background: $B \to K^{**}e^+e^-$, where $K^{**}=K(\pi)$, $K\pi(\pi)$,…

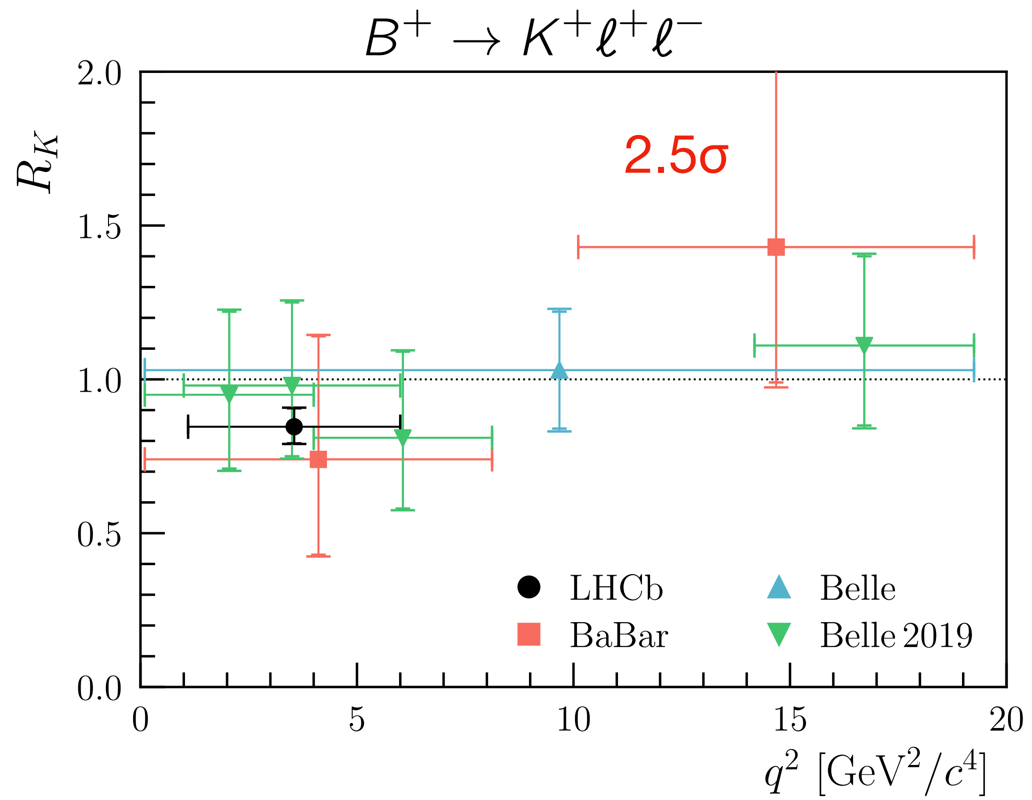
Leakage from $B \to K\, J/\psi(ee)$ constraint from the fit to the resonant mode

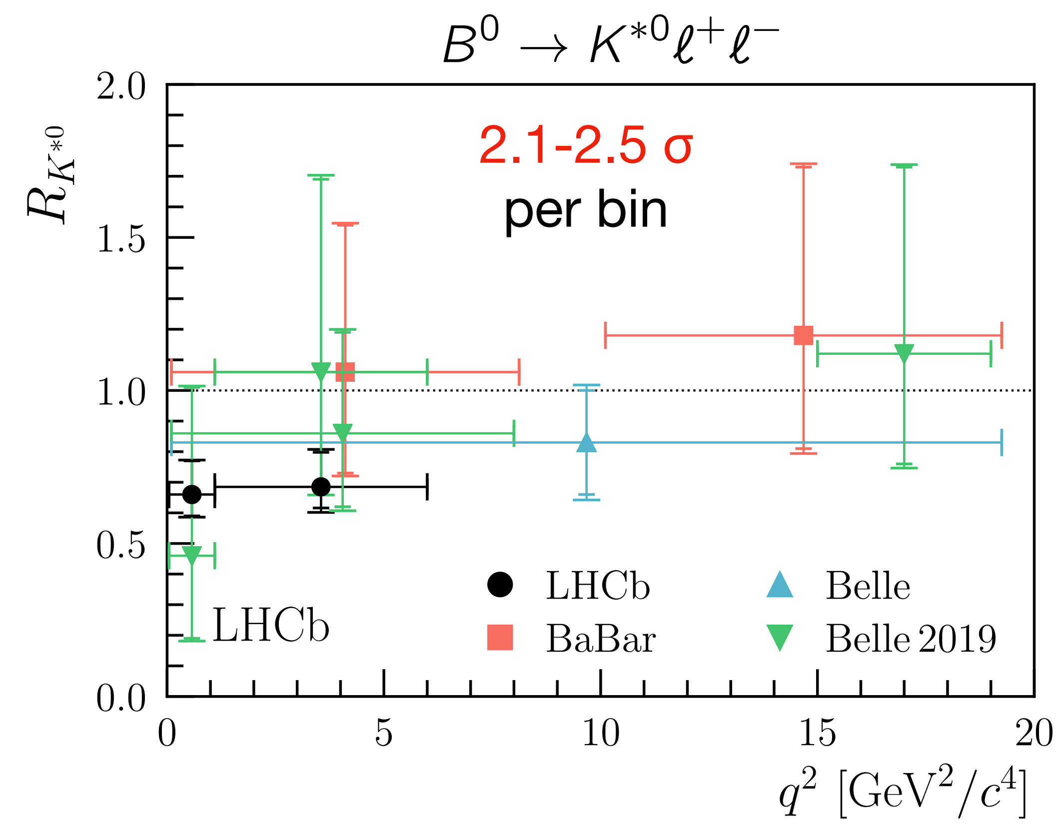




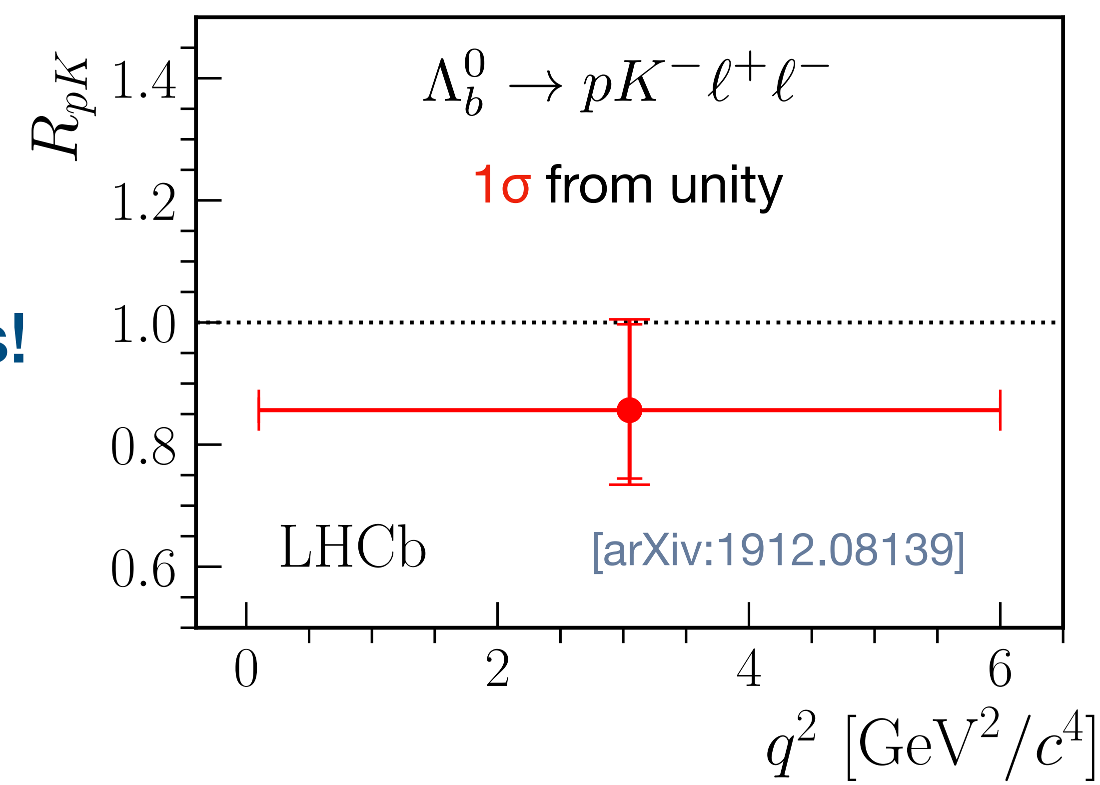
Different signal shape between muons and electrons:
- worse mass resolution (recovered γ)
- longer radiative tail (non-recovered γ)

Status on LFU ratios





- Values consistently below the SM, but significance still low
- **New measurement using baryon decays!**



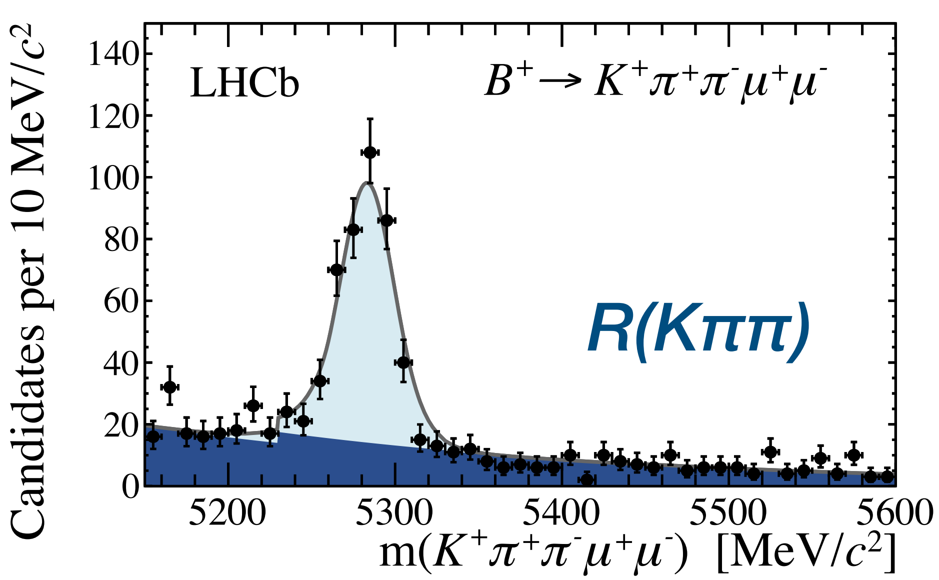
[BaBar, PRD 86 (2012) 032012]
[Belle, arXiv:1908.01848]
[Belle, arXiv:1904.02440]
[Belle, PRL 103 (2009) 171801]
[LHCb, PRL 122 (2019) 191801]
[LHCb, PRL 113 (2014) 151601]
[LHCb, JHEP 08 (2017) 055]

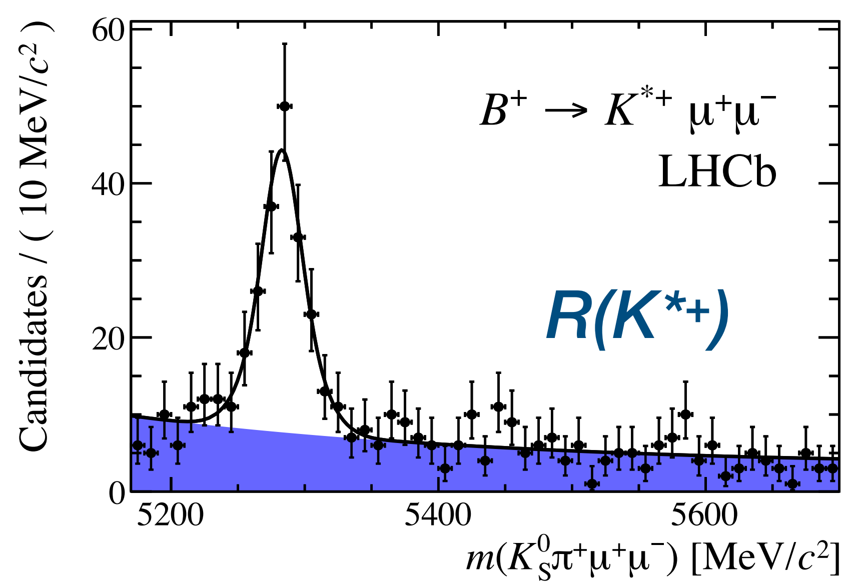
In the short term future…

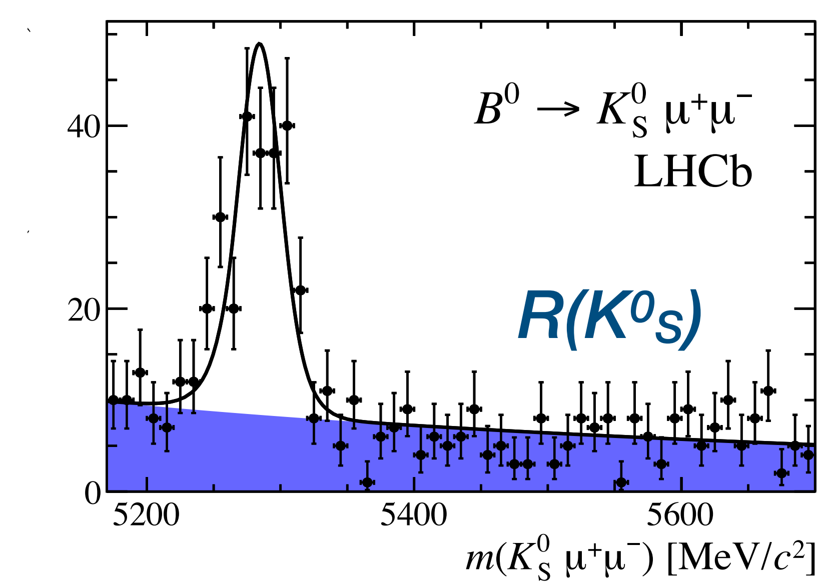
- LHCb full Run 2 dataset ~ 4 times number of B's available in Run1
  - updates of R(K) and R(K*) coming [**low-**, central and **high-q^2**]
  - many LFU test in different penguin decays in which the muon modes are well established

Expected precision	$9\ \text{fb}^{-1}$
$R_K\ [1-6]\text{GeV}/c^2$	0.043
R_{K^*}	0.052
R_{pK}	0.098
R_ϕ	0.110

[LHCb-PUB-2018-009]

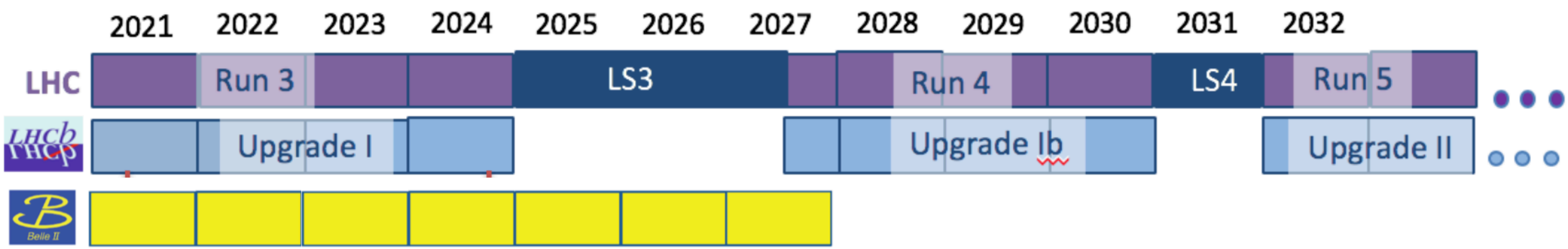






What next?

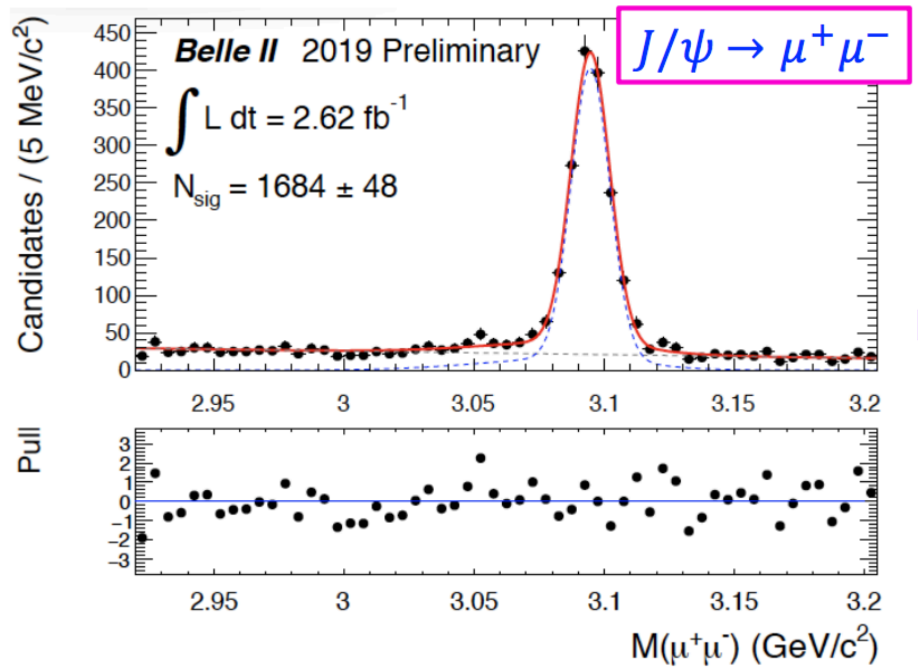
[CERN-LHCC-2011-001, updated with latest news]

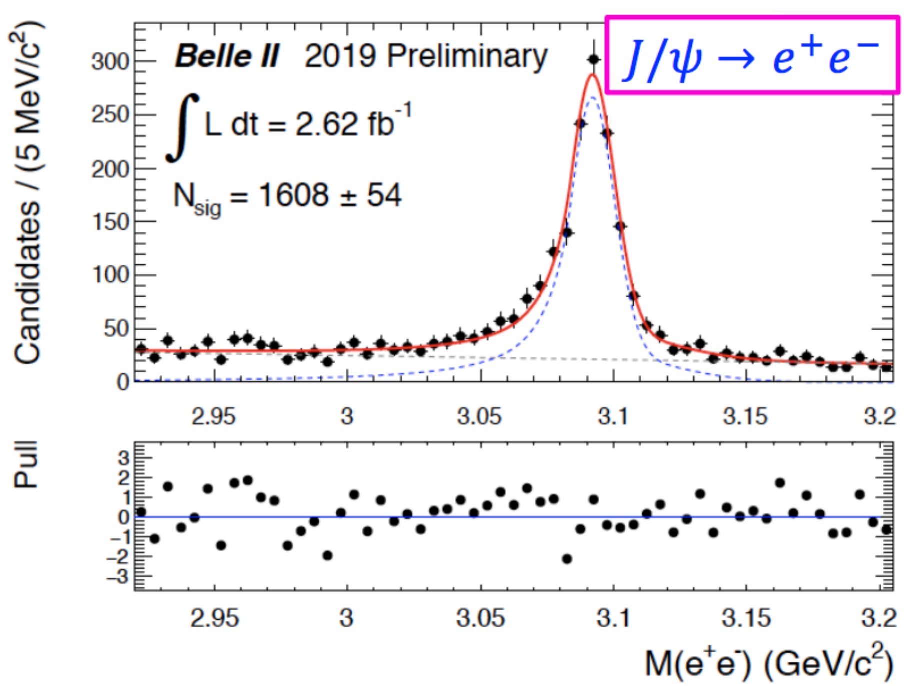


- **LHCb is in the process of upgrading to a new detector**
  - will operate at much higher luminosity with improved efficiency (make all trigger decisions in software)
  - will accumulate ~**50 fb^{-1} of data**
- **A second phase of the Upgrade** in LS4 is also planned to profit from even higher luminosities at the **HL-LHC** (increase data sample up to 300 fb^{-1} for LHCb)
- **Belle II** started up last year, **will accumulate ~50 ab^{-1}** until 2027

R(K) and R(K*) prospects in Belle II

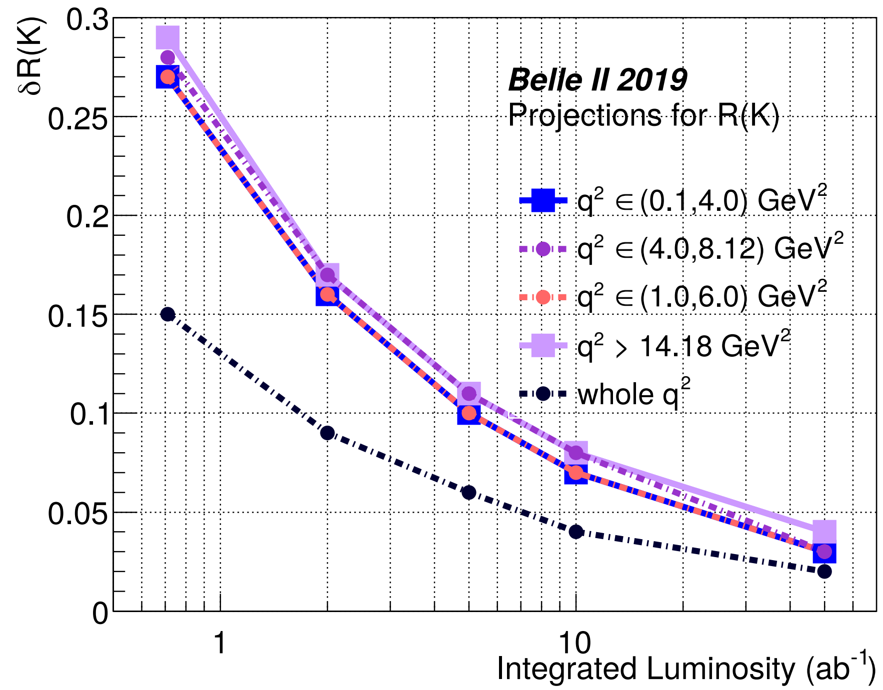
Bremsstrahlung effect is mild: similar resolution and efficiencies as muons!

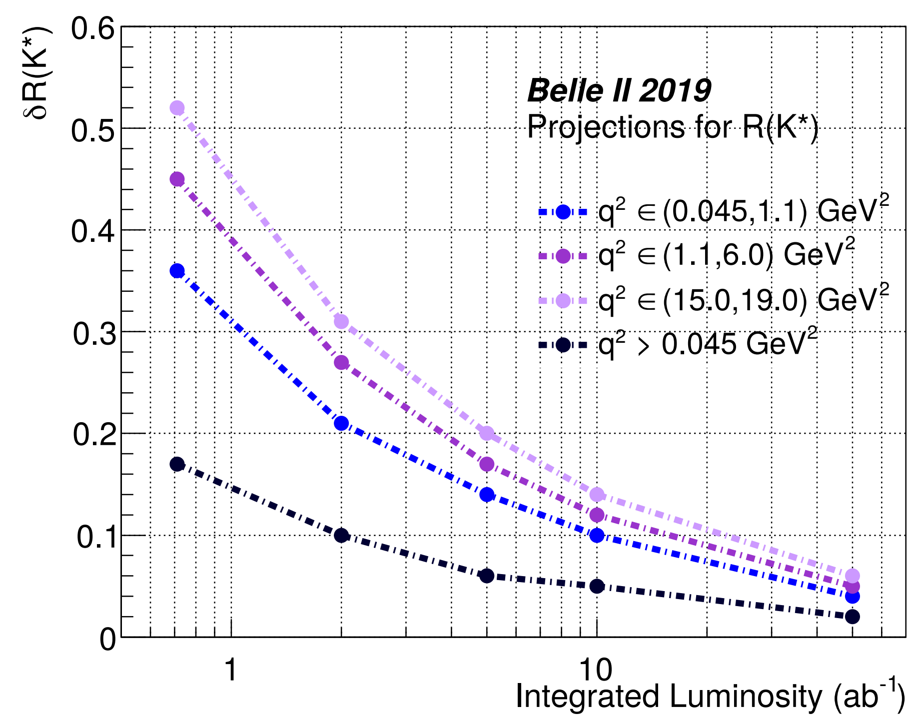




BELLE2-TALK-CONF-2019-157

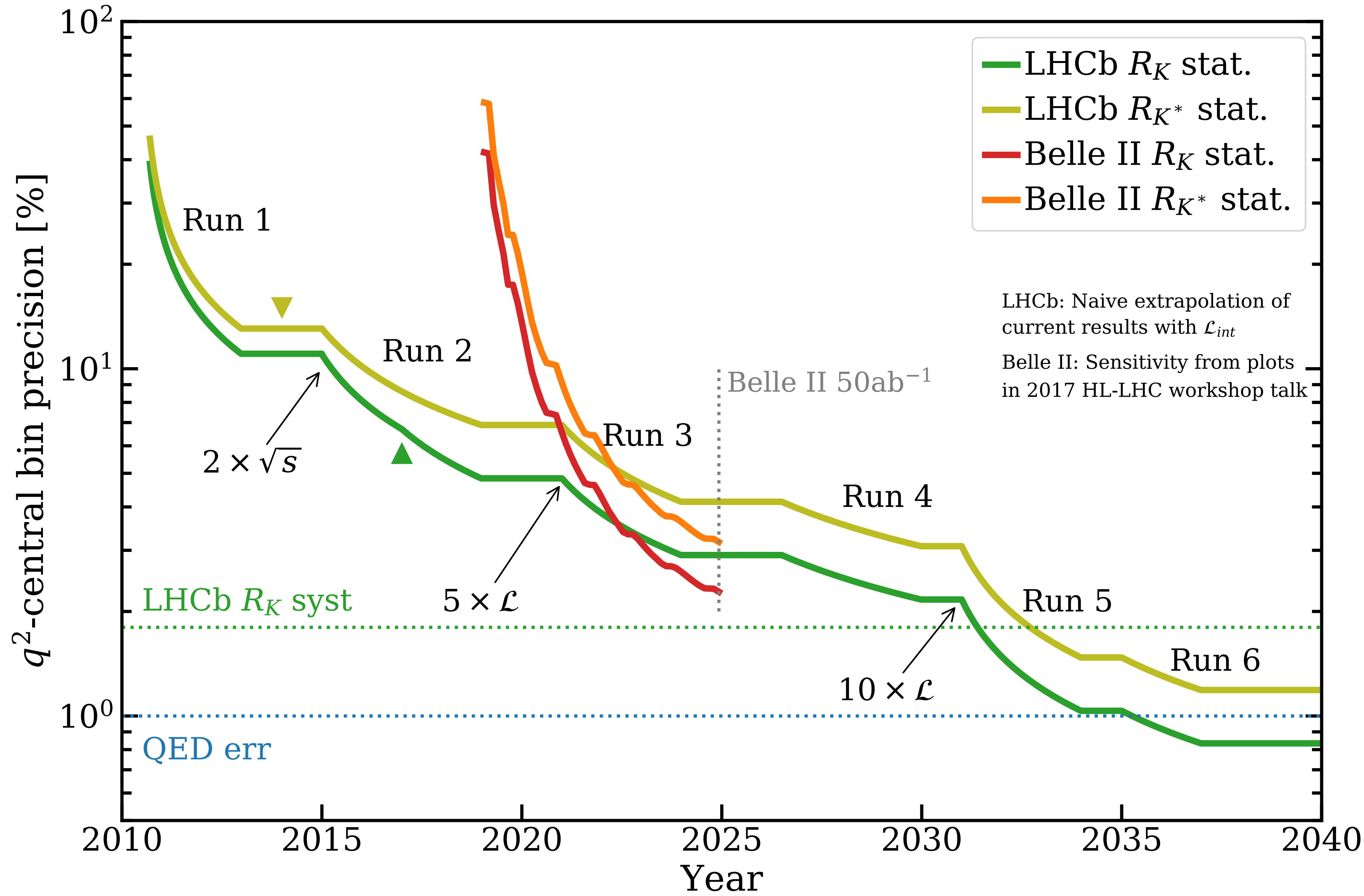
Precision scales with luminosity: systematic less than 1% (of which 0.4% is lepton ID)





BELLE2-TALK-CONF-2019-097

R(K) and R(K*) prospects in LHCb



- Assumes unchanged performance throughout the plot

Experimental challenges in Upgrade I

- In LHCb, for the electrons:

  - the tracker is used to measure the momentum;

  - the calorimeter provides electron identification and Bremsstrahlung recovery

- **Upgraded LHCb will be running at higher luminosity => increase in pile-up**
  - **Tracking**: we have a factor 4 more of tracks on average, so default reconstruction algorithms need to cut harder
  - **Calorimetry:** removal of Pre-Shower and SPD, ECAL unchanged

    => worst electron identification performance

    => it is more difficult for the Brem recovery algorithm to find the correct photons

    => higher Brem tails, both on left and right side

  Combinatorial background will be higher, physics background will be more smeared

- On the bright side: **Removal of hardware trigger (L0)**

  => recover efficiency lost in the L0 and the L0 related systematic errors disappear

Many studies on dedicated tuning for electrons ongoing

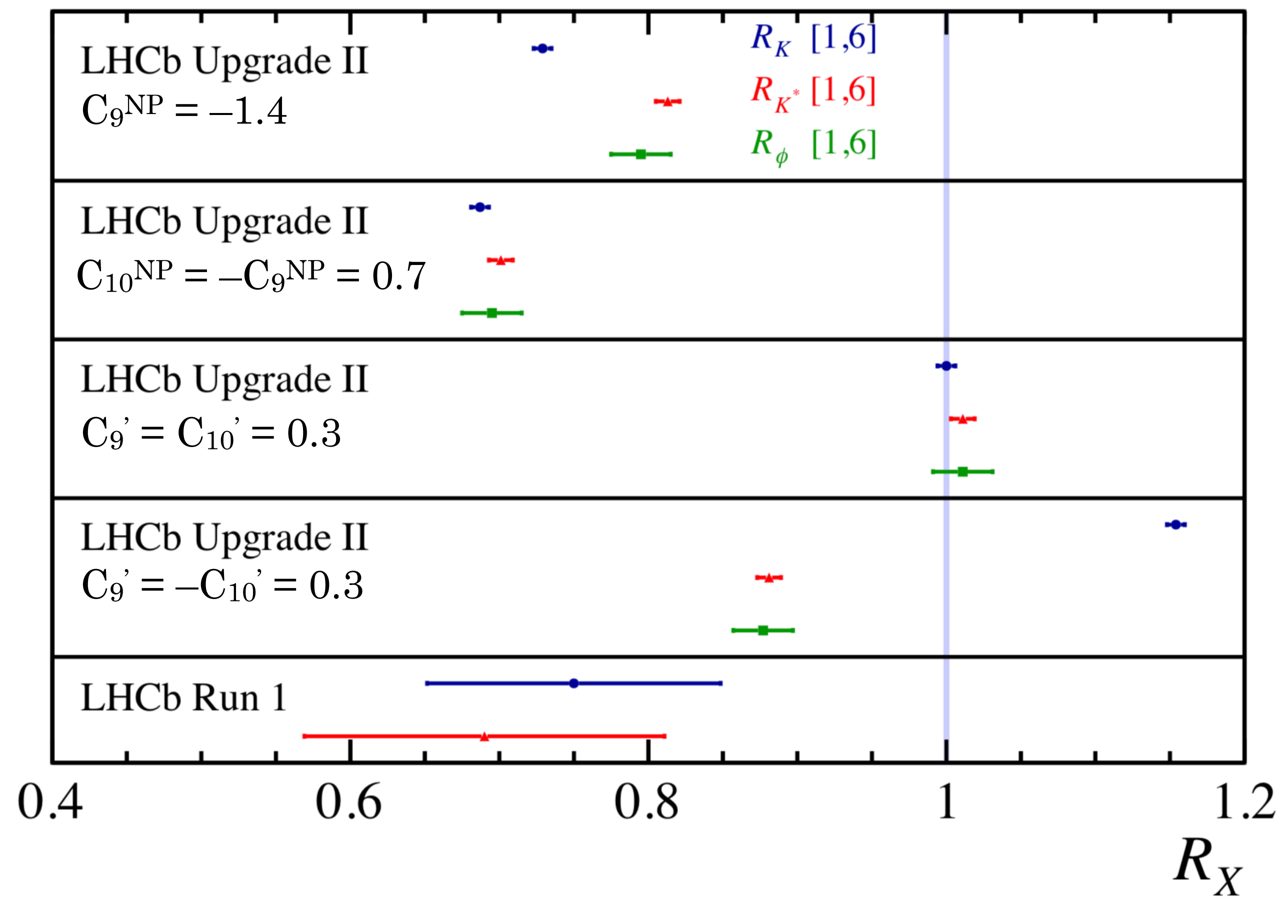
to keep the efficiency at current level

LFU with LHCb upgrade-II

[LHCb-PUB-2018-009]

- With 300/fb, 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 ~ 1%
- Start probing LFU ratios in $b \to d \ell \ell$ transitions

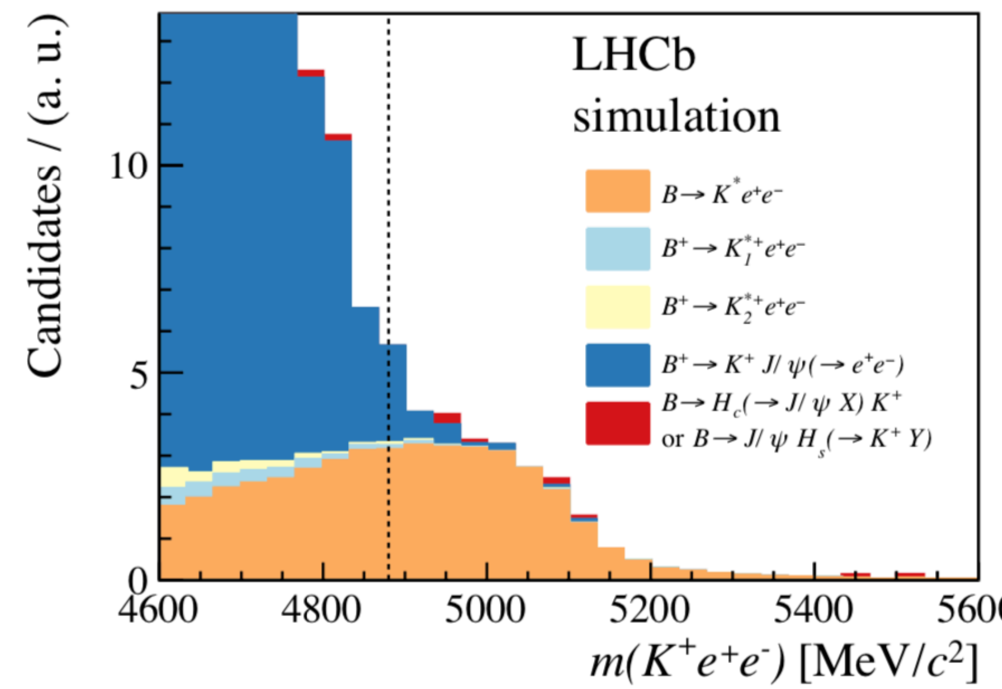
Luminosity	$\sigma(R_\pi)$
9 fb^{-1}	0.302
23 fb^{-1}	0.176
50 fb^{-1}	0.117
300 fb^{-1}	0.047



R_X systematics

- Residual backgrounds
  - Shape of partially reconstructed backgrounds can be studied in the data ($H_b \to H_s^{**} e^+ e^-$ BR's and amplitude structure)
- Corrections to simulation
  - Easier calibration in absence of hardware trigger
  - Larger control samples
- Upgrade II: calorimeter upgrade will have an impact on these effects
  - Less amount of material?
  - Better calorimeter granularity?

[PRL 122 (2019) 191801]



[JHEP 08 (2017) 055]

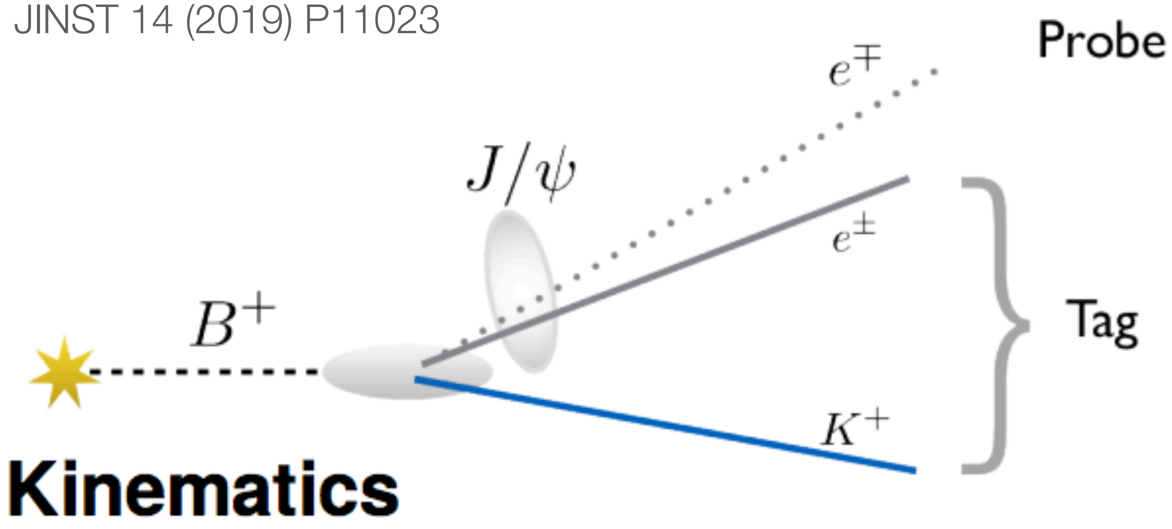
	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass 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
$r_{J/\psi}$ ratio	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

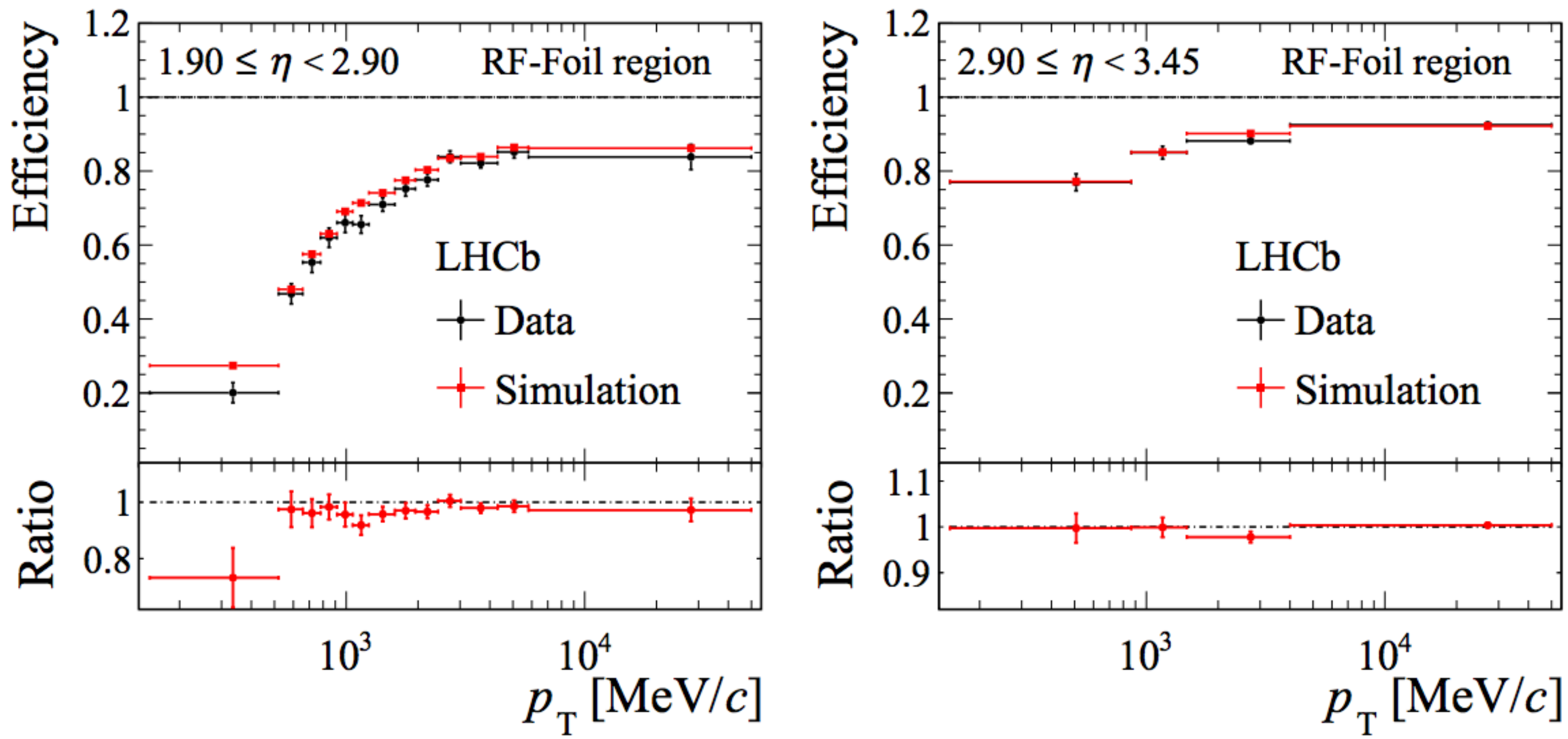
Improving systematics for electrons at LHCb

A new data driven method for measuring electron reconstruction efficiency has been developed, using kinematically constrained VELO tracks from $B^+ \to J/\psi\,(ee)\,K^+$:

- direction inferred from VELO segment;
- probe momentum inferred from J/ψ mass constraint;
- B mass with J/ψ mass constraint used to extract signal.

JINST 14 (2019) P11023





Allows measuring branching ratios with electrons in final state with a systematic uncertainty lower than 1%

Angular LFU tests

- 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

First angular analyses of B->K*ee at low q2, with 124 events (Run I) measures FL with an absolute statistical precision of ~6%

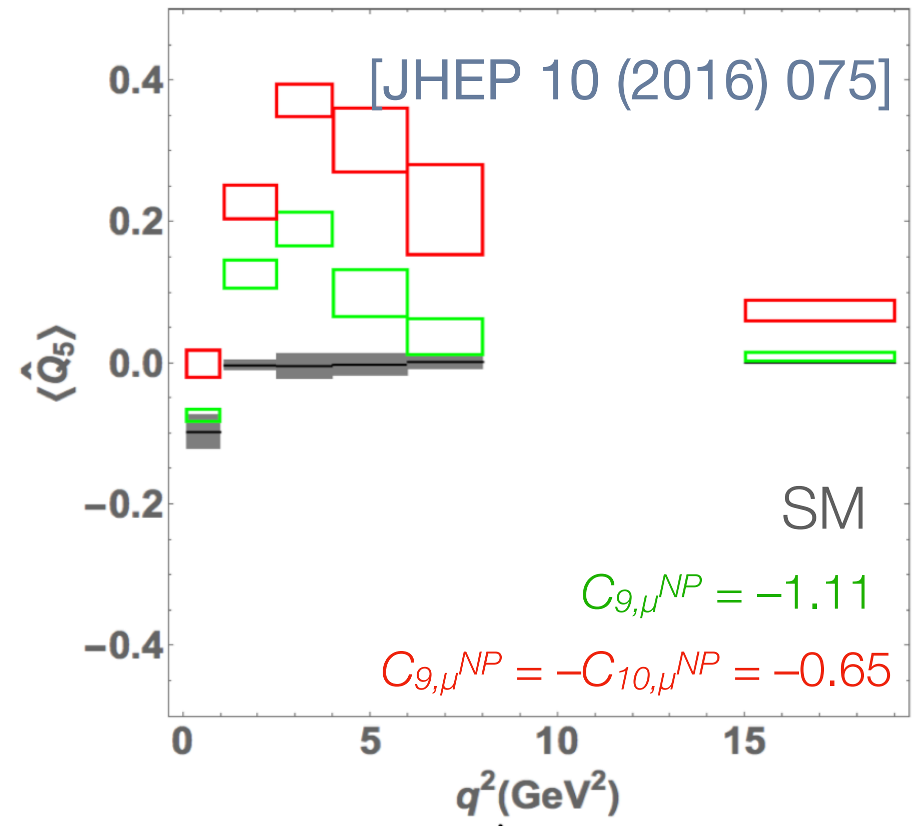
Run1 angular analysis of B->K*mm, with 624 events in the central bin, mesures FL with an absolute statistical precision of ~3%

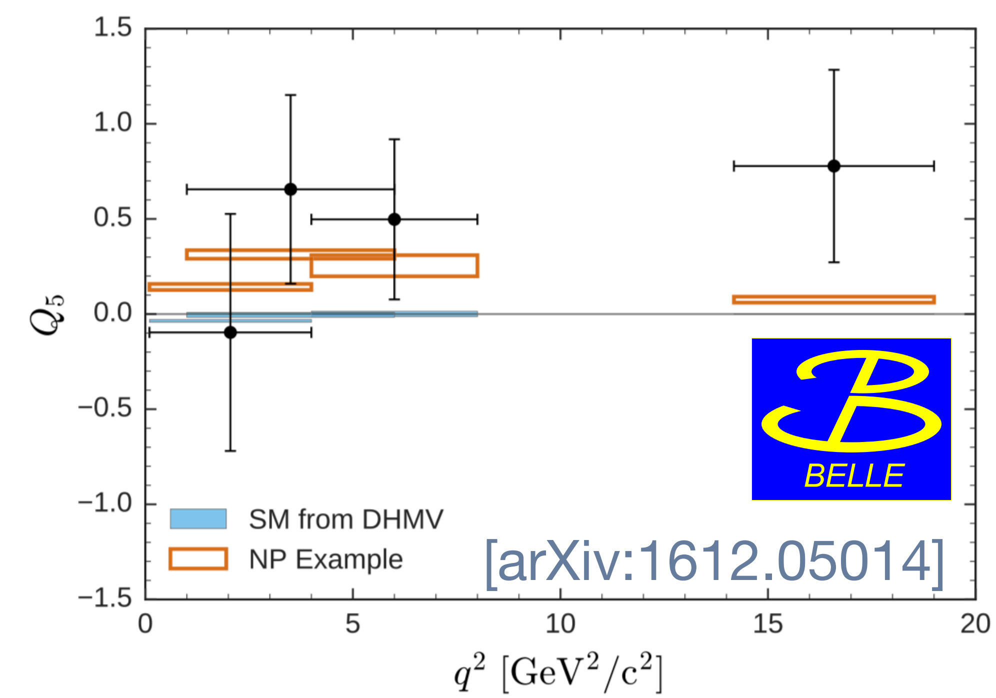
=> **With ~500 events expected in Run1+2 for B->K*ee in the central q2, a first angular LFU test should be possible.**

Key is controlling angular efficiency shape and the background pollution for the electrons.

LHCb-PAPER-2014-066, « low q2 angular analysis »

Source	$\sigma(F_L)$	$\sigma(A_T^{(2)})$	$\sigma(A_T^{Im})$	$\sigma(A_T^{Re})$
Acceptance modelling	0.013	0.038	0.035	0.031
Combinatorial background	0.006	0.030	0.029	0.038
PR background	0.019	0.011	0.007	0.009
$B^0 \to K^{*0}\gamma$ contamination	0.003	0.004	0.003	0.002
Fit bias	0.008	-	-	0.010
Total systematic uncertainty	0.03	0.05	0.05	0.05
Statistical uncertainty	0.06	0.23	0.22	0.18





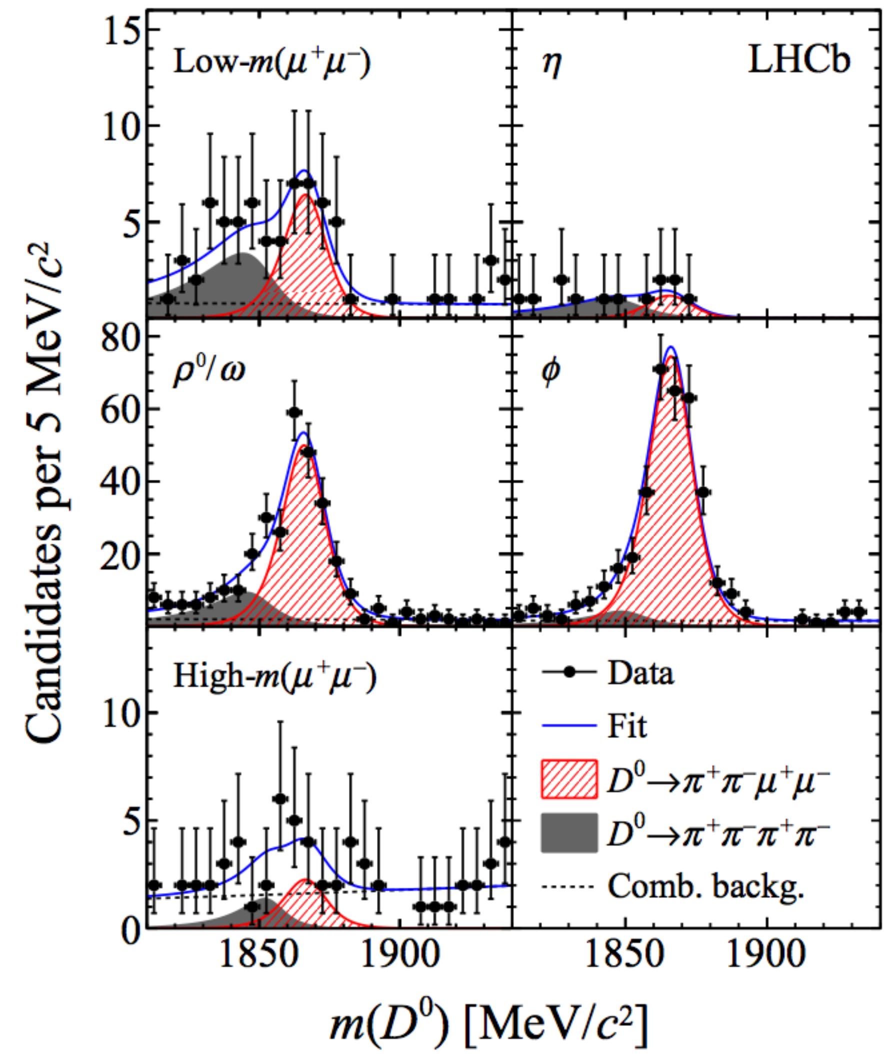
LFU tests with Charm?

- LHCb has a large production of charm mesons
- LFU tests could be performed in rare charm decays in Upgrade I and Upgrade II
- The most promising channels:

  - $D^0 \to K\pi\ell\ell$, $D^0 \to \pi\pi\ell\ell$, $D^0 \to KK\ell\ell$

- Requires a careful tuning of the trigger and improved capabilities of reconstructing low pT electrons.
- Would this kind of measurements be useful in the global picture? Can we learn anything about the SD contributions?

[arXiv: 1707.08377]



Summary

- LHCb has many test of LFU in the pipeline using the full Run 2 dataset, that will hopefully help to resolve the current situation
- LHCb Upgrade I & II, open the door to large improvements in many LFU ratios and new ways to test LFU
  - Removal of hardware trigger will improve efficiencies, but
  - larger pile-up makes analyses with electrons more challenging
  - Possible improvements in the detector for Upgrade II under investigation could have large impact in LFU analyses
- Belle 2 will soon enter the LFU game, with very different experimental systematics

Backup

In the short term future…

[C. Rovelli,
Heavy Flavor Physics Workshop,
Roma, Feb 17th 2020]

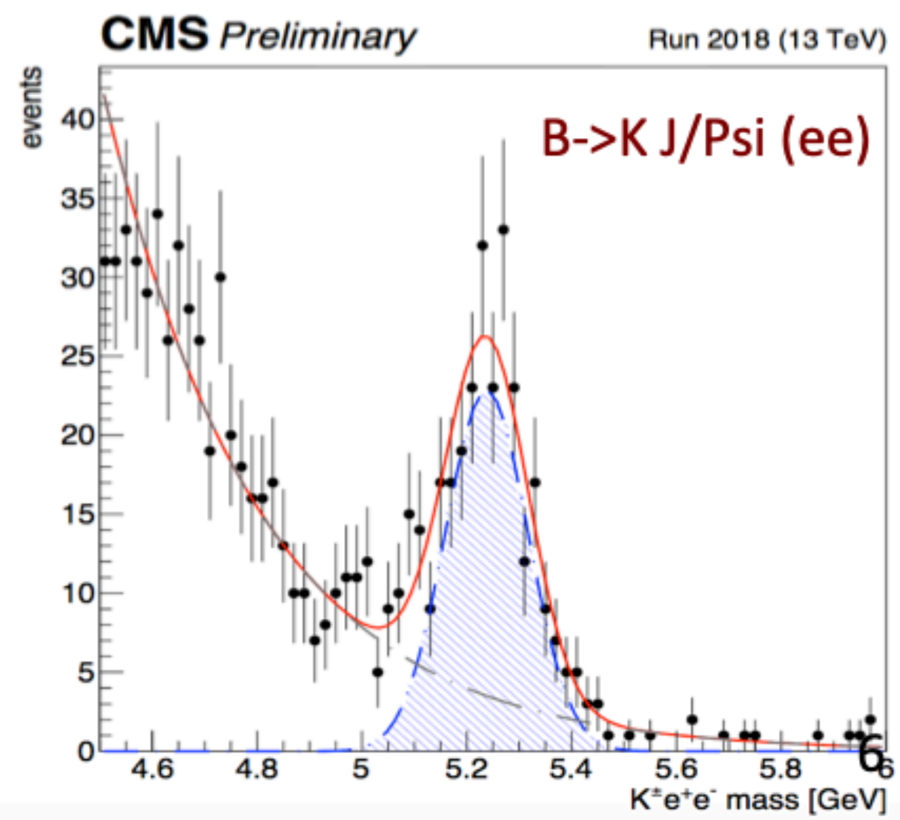
B parking data sample

~1.2*10^10 events recorded during June–Nov 2018 with high purity triggers

Average pile-up lower than typical CMS events (typically 20 PU).

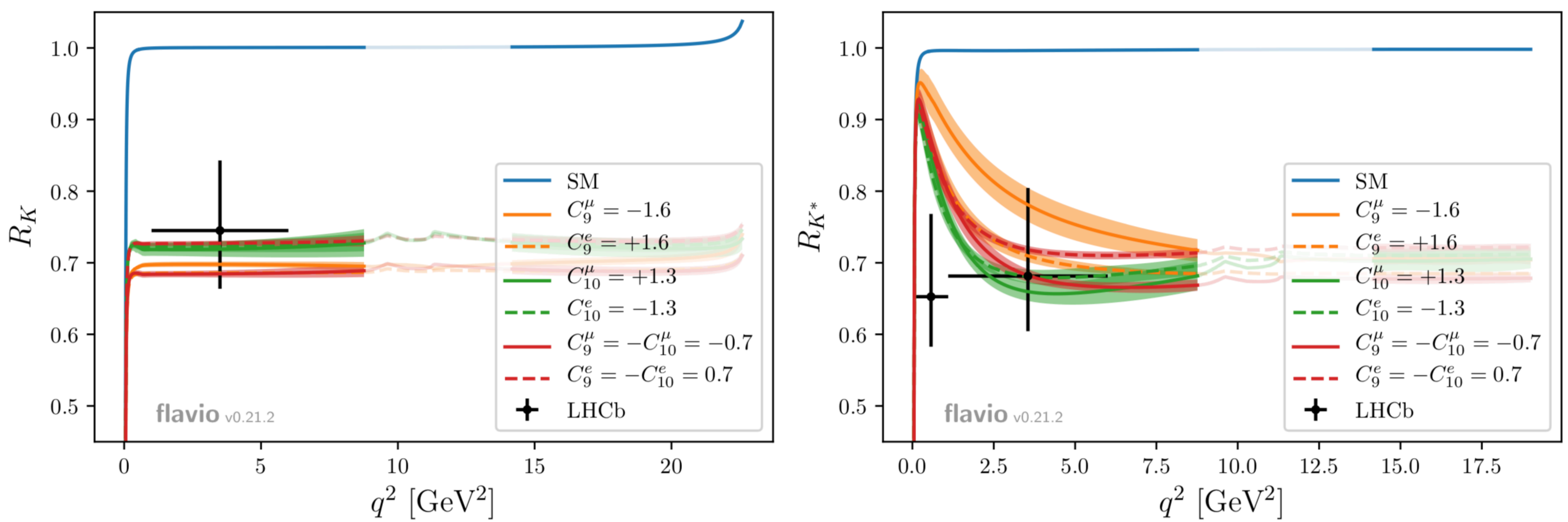
Huge rates => cannot reconstruct promptly @ Tier0
Parked in RAW format and reconstruction done during LS2 (now ready!)

B_d^0	4.99×10^9
$B^\pm$	4.99×10^9
B_s	1.56×10^9
b baryons	1.56×10^9
B_c	1.25×10^7
B hadrons total	1.25×10^{10}



Other q^2 bins

- Probe different kinematic regimes were similar deviations are predicted by most NP models.
  - High-q2 bin: Different background composition makes it a bit trickier (leakage from *J/ψ*, *ψ(2S)* and excited states)
  - R(K) low-q2: Experimentally easier but less stat. gain w.r.t. R(K*)



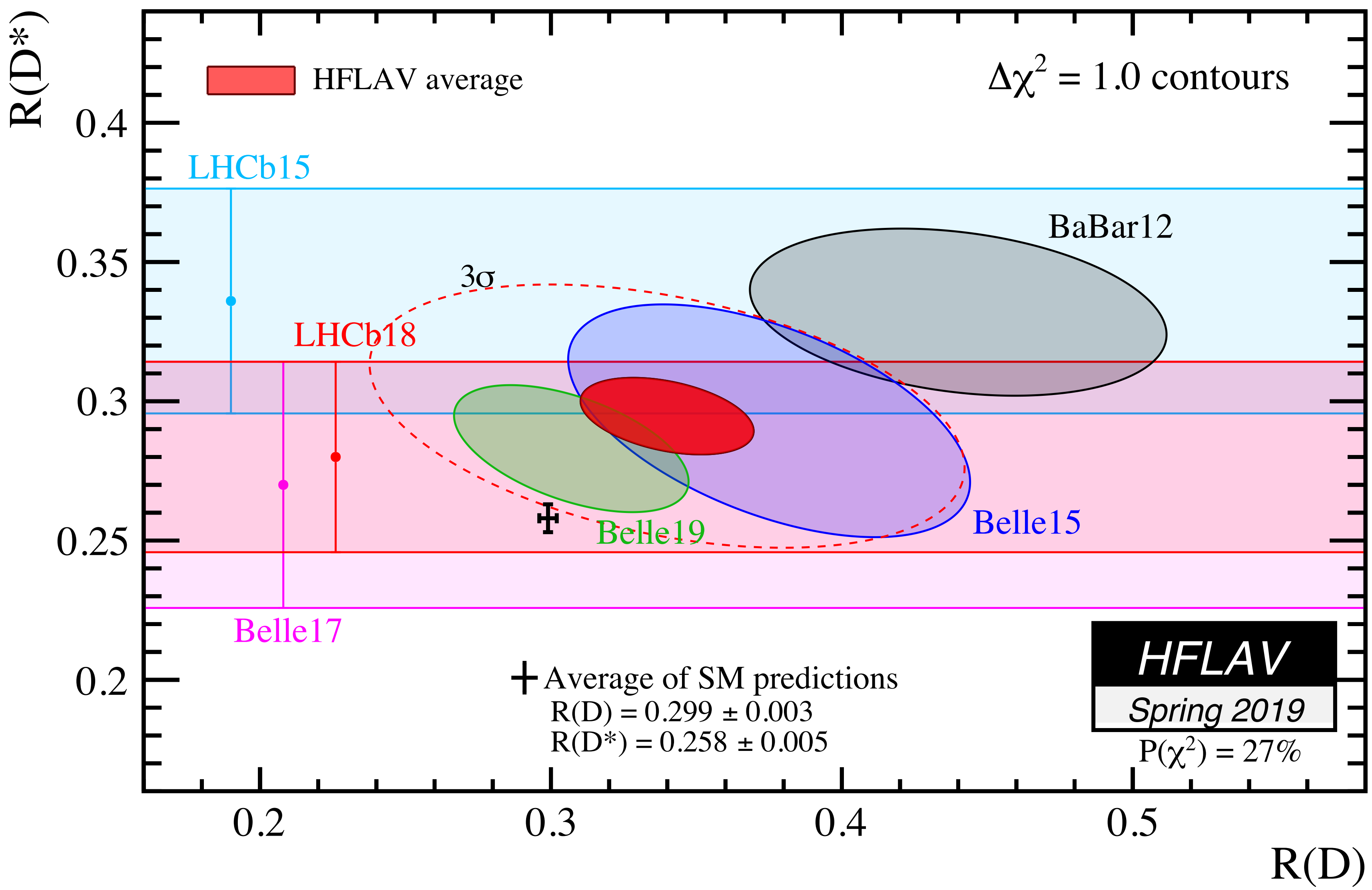
[PRD96(2017)055008]

R(D) and R(D*) combination

Combining with results from the B-factories:

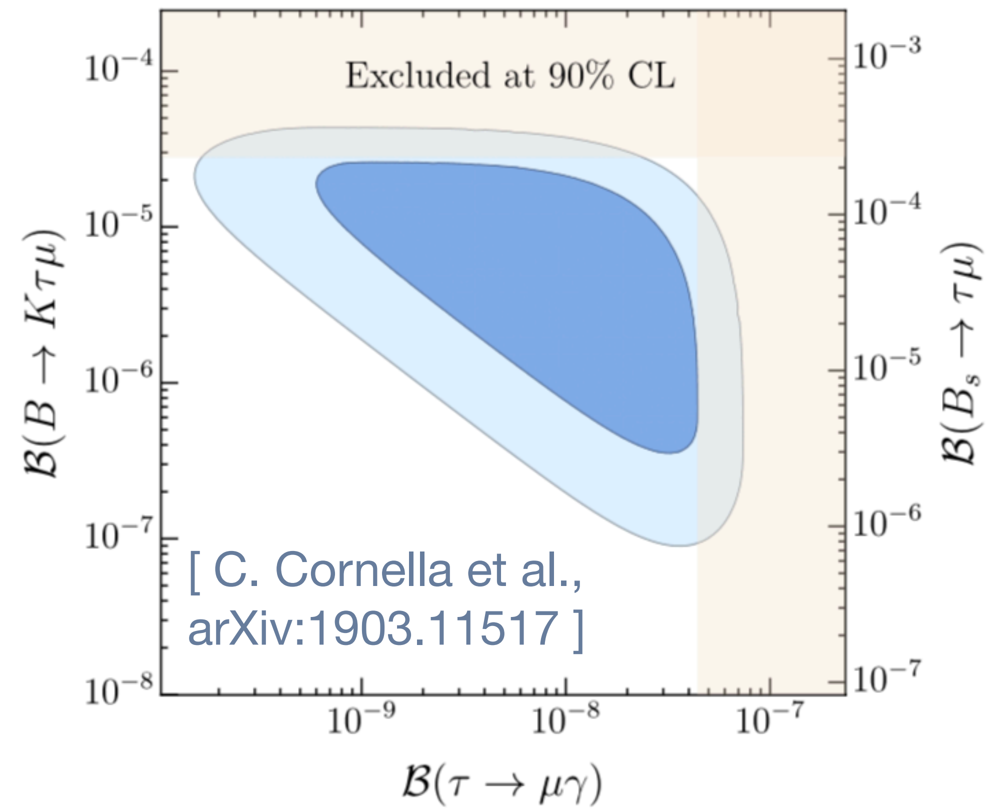
→ Global tension with the SM prediction of **3.08σ**

[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 ($B \to \ell\ell'$, $B \to K\ell\ell'$,…)
  - e.g. vector lepto-quark contributing at tree-level to R(D*) and at loop-level to R_K



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

Mode	Limit	90% CL	95% CL
$B^0_s \to \tau^\pm\mu^\mp$	Observed	3.4×10^{-5}	4.2×10^{-5}
	Expected	3.9×10^{-5}	4.7×10^{-5}
$B^0 \to \tau^\pm\mu^\mp$	Observed	1.2×10^{-5}	1.4×10^{-5}
	Expected	1.6×10^{-5}	1.9×10^{-5}

First limit in the Bs mode

[LHCb-PAPER-2019-016]

See V. Bellee's talk for more details