LFU and other anomalies in b-hadron decays

Carla Marin

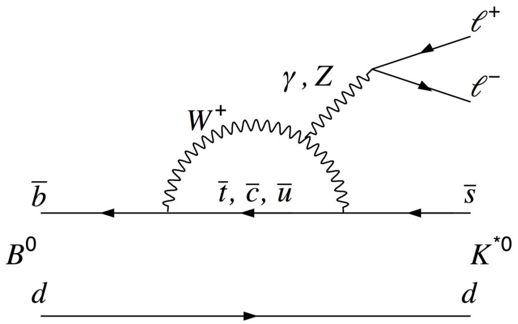
on behalf of the LHCb collaboration + results from Belle (II)

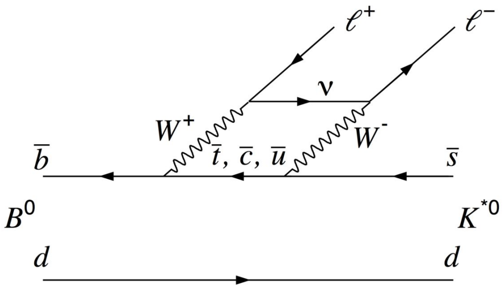
Overview

- Rare b-hadron decays
- Recent results
  - Branching ratios (BR)
  - Angular observables
  - Lepton Flavour Universality (LFU)
- Prospects

Rare b → sll decays

- Flavour-Changing Neutral-Currents sensitive to indirect effects of New Physics (NP) in loops
- Access to much larger scales than direct searches
- Tests of couplings to 3rd generation b-quarks



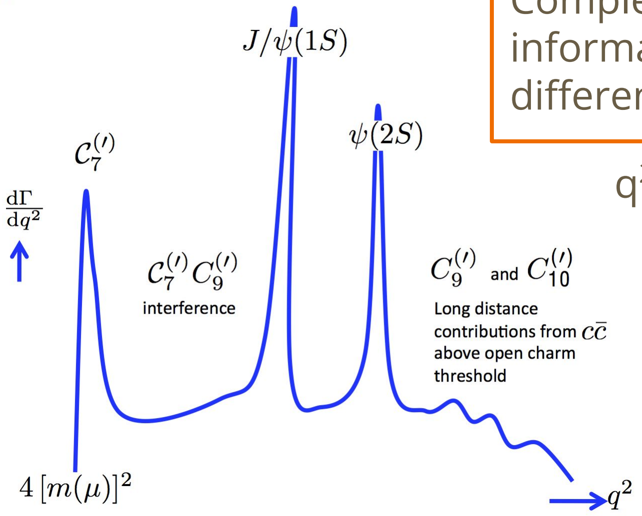


Effective Hamiltonian

Model independent description of b → sll decays:

$$H_{eff} \propto V_{tb} V_{ts}^* \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

$$O_7^{(\prime)} \propto (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$
$$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu l)$$
$$O_{10}^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu \gamma_5 l)$$
$$O_S^{(\prime)} \propto (\bar{s} P_{L(R)} b)(\bar{l} l)$$
$$O_P^{(\prime)} \propto (\bar{s} P_{L(R)} b)(\bar{l}\gamma_5 l)$$



Complementary information in different q^2 regions

$q^2 = (m_{ll})^2$

Observables

Phenomenology perspective

- **BR**: affected by hadronic uncertainties
- **Angular observables**: first-order form-factor cancellations
- **LFU**: full cancellations in the SM

Observables

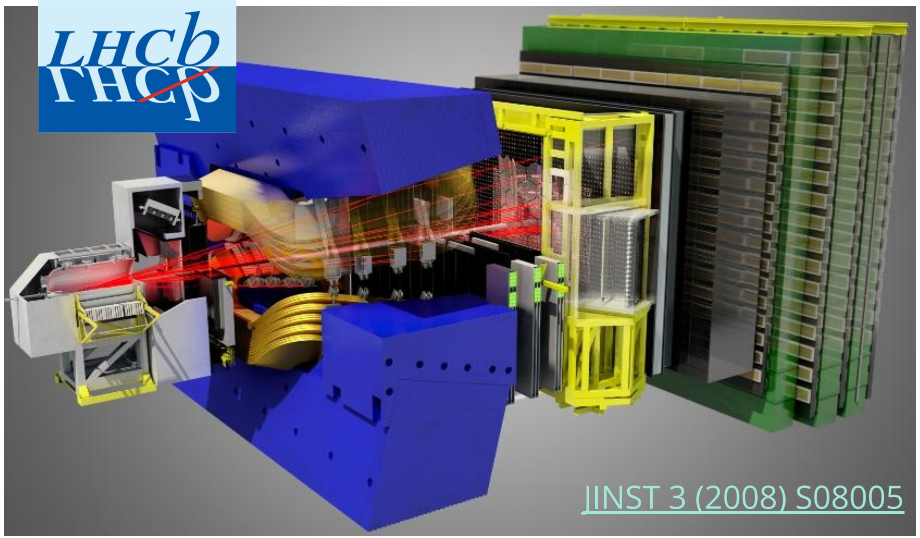
Phenomenology perspective

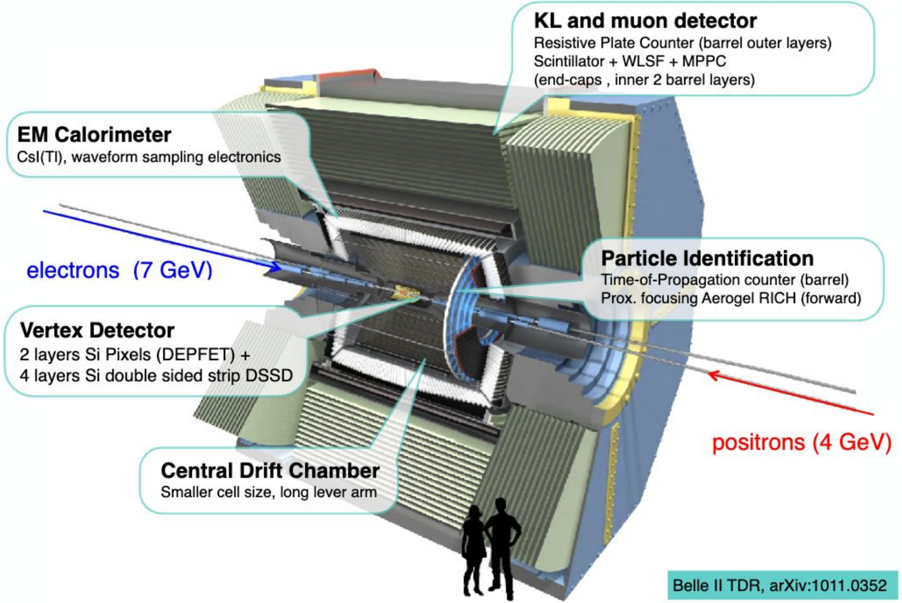
- **BR**: affected by hadronic uncertainties
- **Angular observables**: first-order form-factor cancellations
- **LFU**: full cancellations in the SM

Experimental perspective

- **BR**: simple extraction, good control of efficiencies through control modes
- **Angular observables**: need to control acceptance, many parameters require large yields
- **LFU**: need control of $e^{\pm}$ vs $\mu^{\pm}$ efficiencies - very challenging at hadron machines

Experiments: b-physics



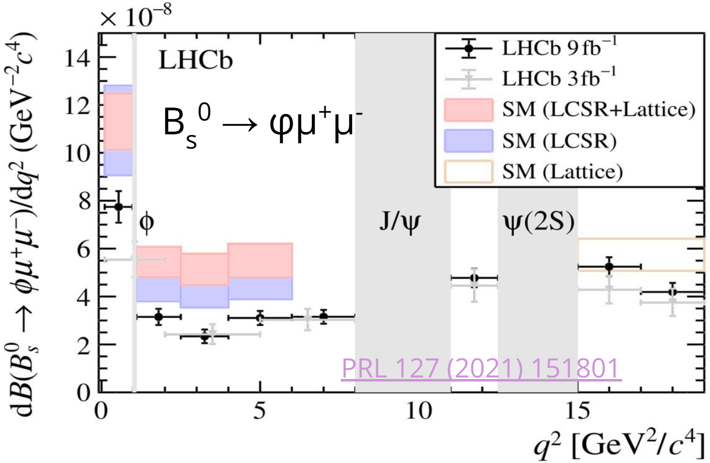


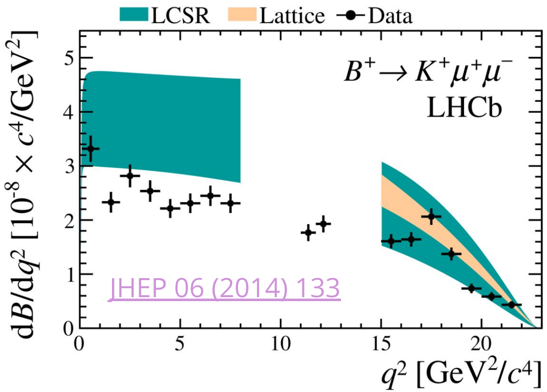
- pp collisions: high background
- 3+6fb^{-1}: all species (σ_{B+}~43/87μb) @7/13 TeV)
- forward spectrometer
- excellent PID, momentum, IP performance

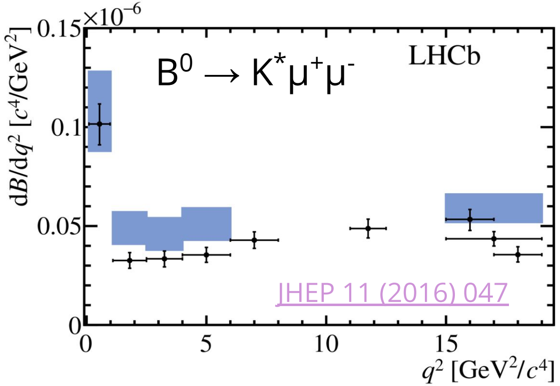
- e^+e^- collisions: very clean environment
- 1 ab^{-1} + 400 fb^{-1}: B^0, B^+ (B_s) (σ_B ~ 10^9/ab^{-1})
- hermetic detector, large coverage
- excellent PID, tagging power

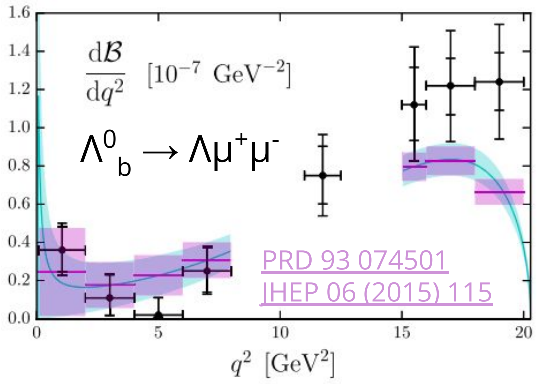
Branching ratios

Trend: $b \to s\mu^+\mu^-$ BR systematically lower than SM predictions





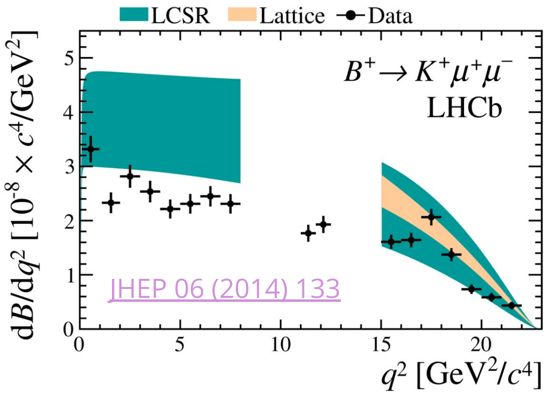


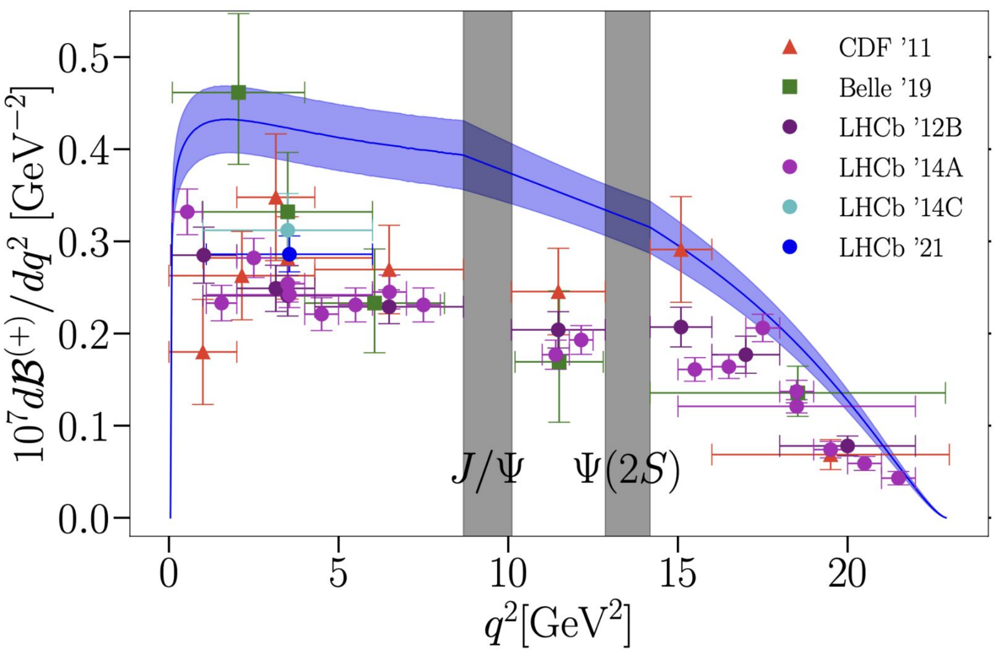


Branching ratios

Trend: $b \to s\mu^+\mu^-$ BR systematically lower than SM predictions

NEW LQCD FF for B → K: better precision, increased tension! See talk by C. Bouchard





Angular observables

Range of observables sensitive to different WCs

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

$B_d \rightarrow K^*\mu^+\mu^-$
[Altmannshofer et al.]

F_L: H longitudinal polarisation

A_{FB}: di-lepton forward-backward asymmetry

S_i: CP-averaged observables

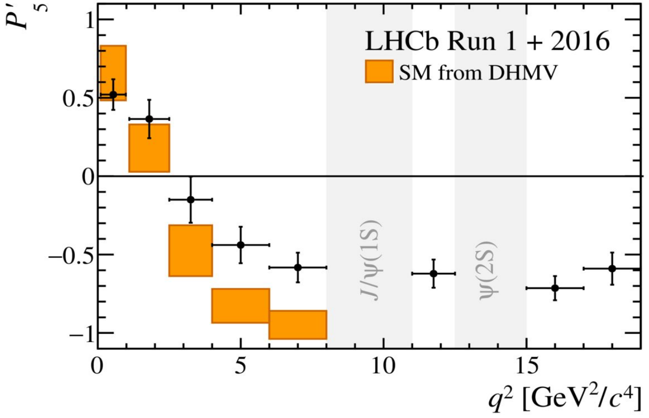
"Clean" basis: cancellation of Form Factors at leading order [Descotes-Genon et al.]

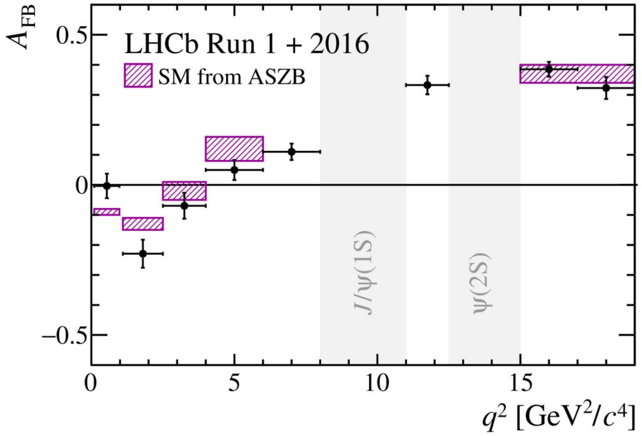
$$P_5' = S_5/\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}$$

Angular analysis of $B^0 \to K^* \mu^+ \mu^-$

PRL 125 (2020) 011802

Most precise by LHCb: Run 1 + 2016 data





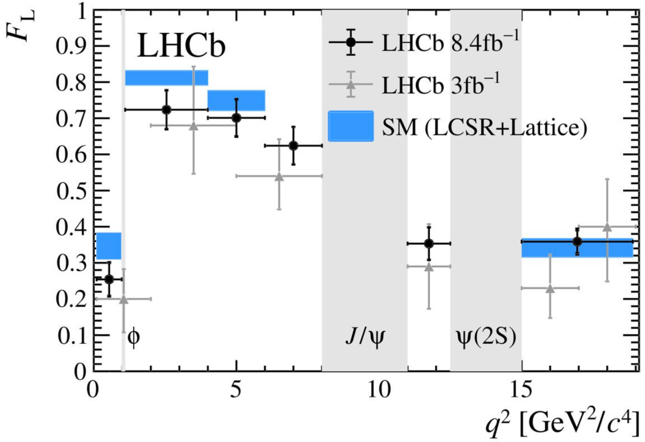
2.7 - 3.3 σ preference for NP with negative C_9^{NP}

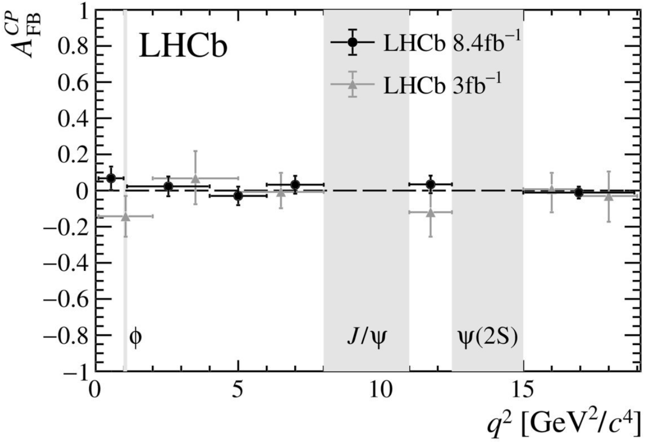
Angular analysis of $B_s^0 \to \phi\mu^+\mu^-$

JHEP 11 (2021) 043

Only LHCb, uses full dataset

⚠️ CP asymmetries in untagged rate: indistinguishable B_s and $\bar{B}_s$ decays





Compatible with SM but preference for negative C_9^{NP} at 1.9σ

Lepton Flavour Universality tests

Leptons of different species couple identically to electroweak bosons in SM
$\rightarrow$ Lepton Flavour Universality (LFU)

Measure ratio of same b $\rightarrow$ sll process with muons and electrons in final state:

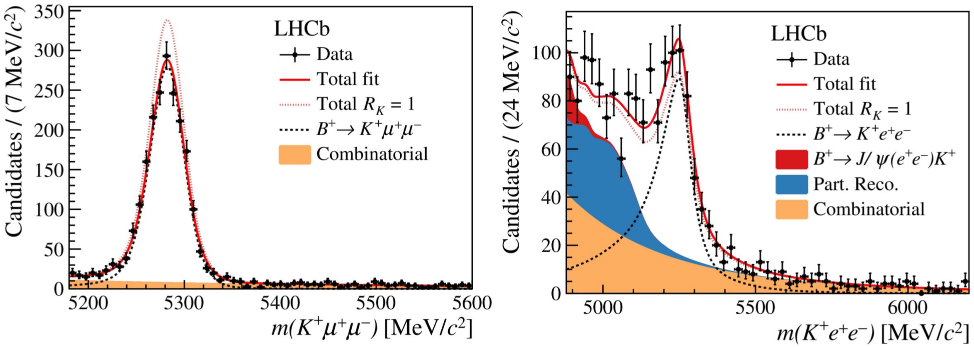
$$R_H \equiv \frac{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \to He^+e^-)}{dq^2} dq^2}$$

H = K^+, K^{0*}, K^0_S, K^{0+} ...

Hadronic uncertainties cancel in ratio $\rightarrow$ very clean theory prediction

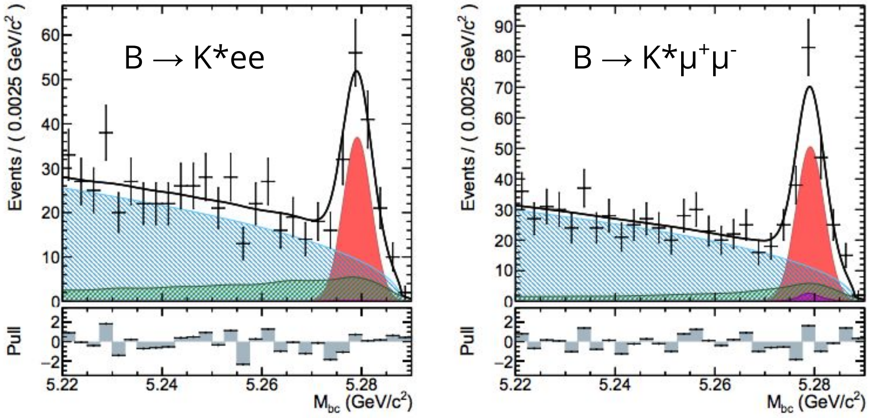
b → sll with electrons

A challenge at LHCb



PRL 122 (2019) 191801

Much more similar to muons at Belle



PRL 126 161801 (2021)

b → sll with electrons at LHCb

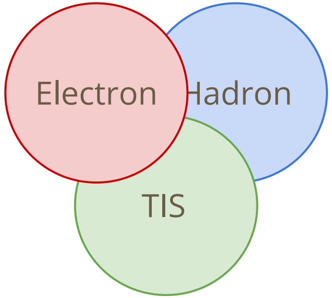
Hardware trigger

Larger ECAL occupancy → tighter thresholds for electrons:

- e p_T > 2700/2400 MeV in 2012/2016
- μ p_T > 1700/1800 MeV in 2012/2016

[LHCb-PUB-2014-046, 2019 JINST 14 P04013]

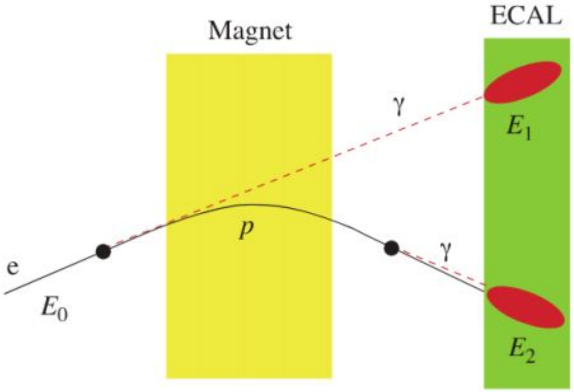
Mitigate with events triggered independently of the signal (TIS) (and hadron trigger)



Interaction with detector material

Electrons radiate much more Bremsstrahlung

Recovery procedure in place



- miss some photons and add fake ones
- ECAL resolution worse than tracking

→ worse mass resolution for electron modes

How do we measure LFU at LHCb?

$$R_H = \frac{BR(B \to H\mu^+\mu^-)}{BR(B \to He^+e^-)}$$

In SM:

$$R_K = 1.0000 \pm 0.0001$$ [Bordone et al.]

Experimentally:

$$R_H = \frac{N(B \to H\mu^+\mu^-)}{N(B \to He^+e^-)} \times \frac{\epsilon(B \to He^+e^-)}{\epsilon(B \to H\mu^+\mu^-)}$$

from mass fit — from MC and calibration samples

Exploit the well tested LFU in J/ψ modes

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

- as stringent cross-check
- to build double ratio at LHCb → cancel systematic effects

$$R_H = \frac{\dfrac{N(B \to H\mu^+\mu^-)}{N(B \to HJ/\psi(\mu^+\mu^-))}}{\dfrac{N(B \to He^+e^-)}{N(B \to HJ/\psi(e^+e^-))}} \times \frac{\dfrac{\epsilon(B \to He^+e^-)}{\epsilon(B \to HJ/\psi(e^+e^-))}}{\dfrac{\epsilon(B \to H\mu^+\mu^-)}{\epsilon(B \to HJ/\psi(\mu^+\mu^-))}}$$

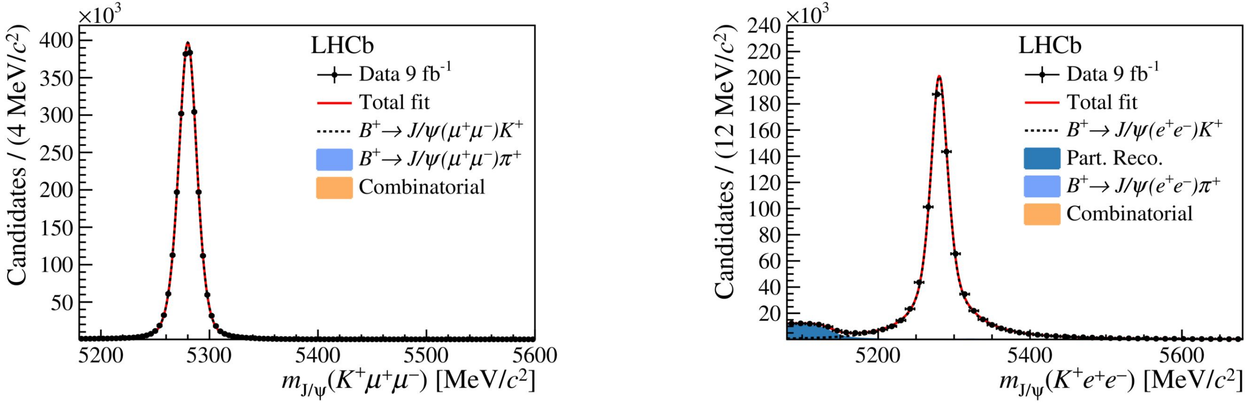
Nature Physics 18, (2022) 277-282

R_K with full LHCb data

Stringent cross-checks with $B^+ \to J/\psi K^+$

- shows that even absolute electron and muon efficiencies are understood

$$r_{J/\psi} = 0.981 \pm 0.020$$

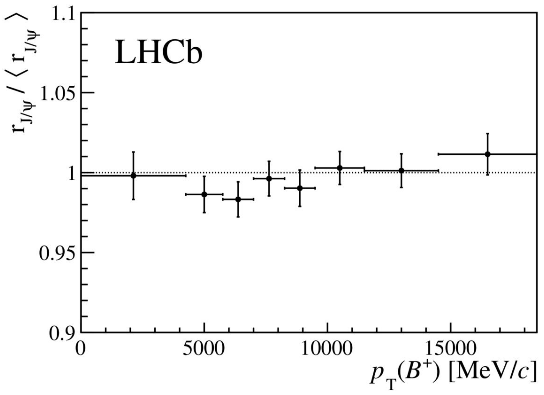


constraint m(ll) to J/ψ mass → strong improvement of mass resolution

Nature Physics 18, (2022) 277-282

R_K with full LHCb data

Check phase-space dependency: trends and $B^+ \to \psi(2S) K^+$ decays



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

$$\boxed{R_{\psi(2S)} = 0.997 \pm 0.011}$$

Effect of simulation corrections is small thanks to the double ratio:

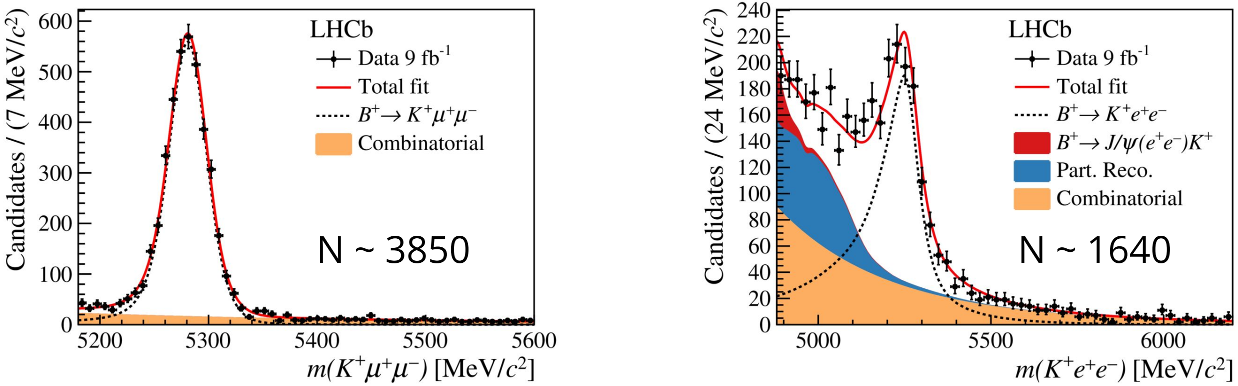
- R_K: (+3 ± 1)%
- $R_{J/\psi}$: 20%

Nature Physics 18, (2022) 277-282

R_K with full LHCb data

Measurement in $1.1 < q^2 < 6.0\ \text{GeV}^2$ with Run 1+2 datasets

R_K from simultaneous fit to $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ candidates



$$R_K(1.1 < q^2 < 6.0\,\text{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$

most precise LFU measurement in $b \to sll$!

Tension with SM at 0.10% (3.1σ)

PRL 128, 191802

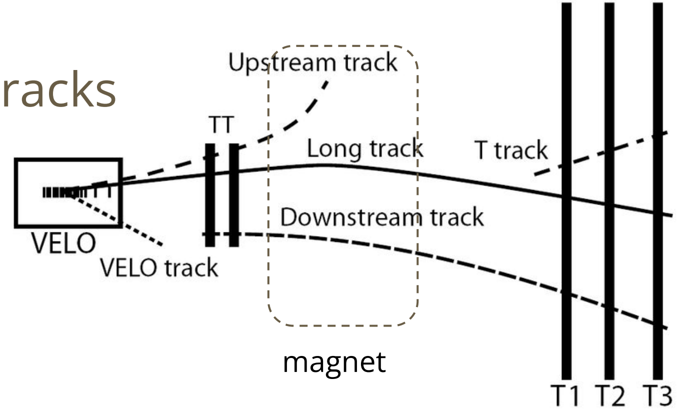
R_K and R_{K^*} with neutral Kaons

Isospin partners $B^0 \rightarrow K^0_S\, l^+l^-$ and $B^+ \rightarrow K^{*+}\, l^+l^-$

- only explored by Belle/BaBar before, more challenging at LHCb
- no unambiguous observation of electron modes by any experiment

Use full dataset and follow R_K strategy, with some particularities:

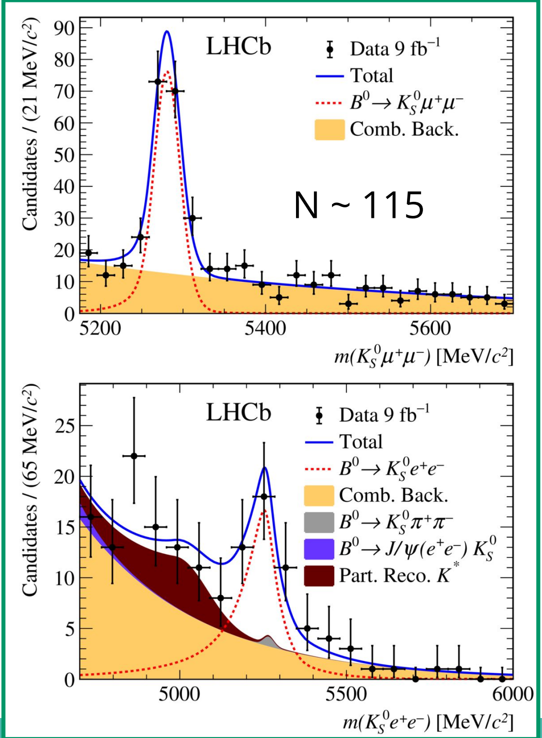
- reconstruct $K^0_S \rightarrow \pi^+\pi^-$ and $K^{*+} \rightarrow K^0_S\pi^+$
- reconstruct K^0_s from long and downstream tracks
- still smaller yields due to long-lived K^0_S



PRL 128, 191802

R_K and R_{K^*} with neutral Kaons

Separate fits to B^0 and B^+ decays, simultaneous for muons and electrons

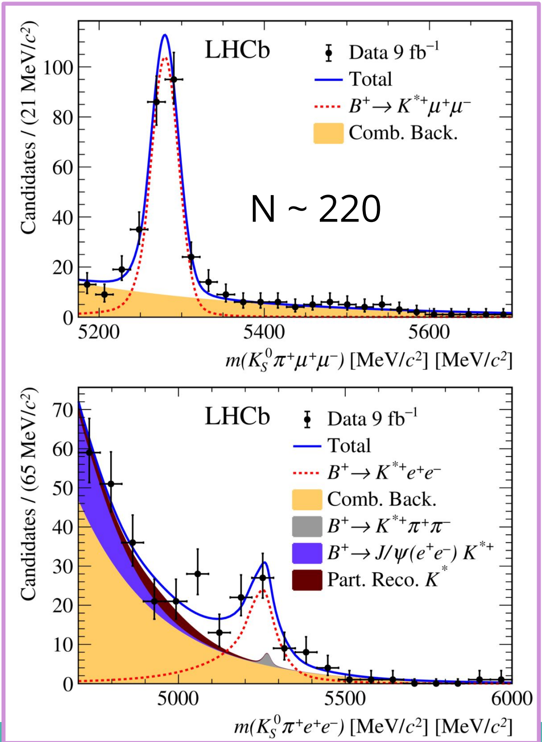


Electron mode significance of 5.3 and 6.0σ → 1st observation

$$R_{K_S^0} = 0.66\,^{+0.20}_{-0.14}\,(\text{stat.})\,^{+0.02}_{-0.04}\,(\text{syst.})$$

$$R_{K^{*+}} = 0.70\,^{+0.18}_{-0.13}\,(\text{stat.})\,^{+0.03}_{-0.04}\,(\text{syst.})$$

Most precise results, consistent with SM at 1.5 and 1.4σ



Overview of LHCb LFU measurements

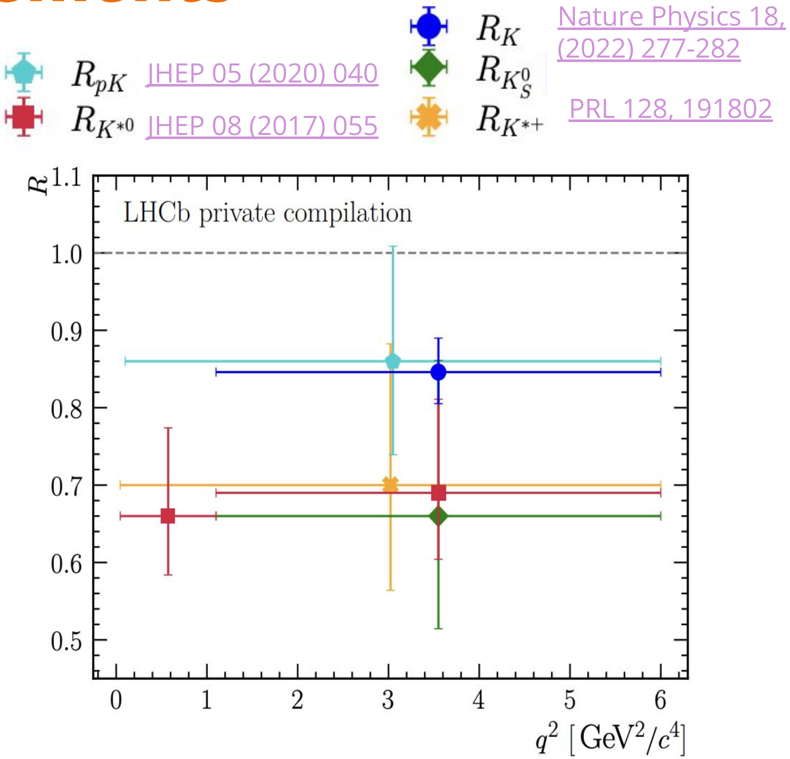
Working on final results with full Run 2 data

Unified analysis of R_K and R_{K*} ongoing

- Final Run 1 + 2 results
- Deeper understanding LFU
- High priority for collaboration

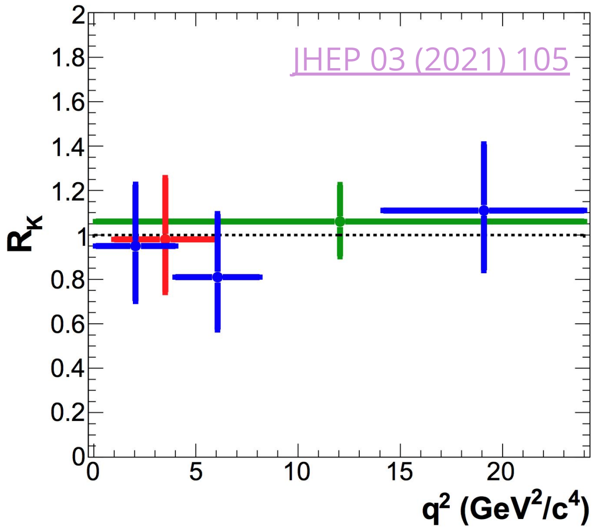
Updates and new measurements:

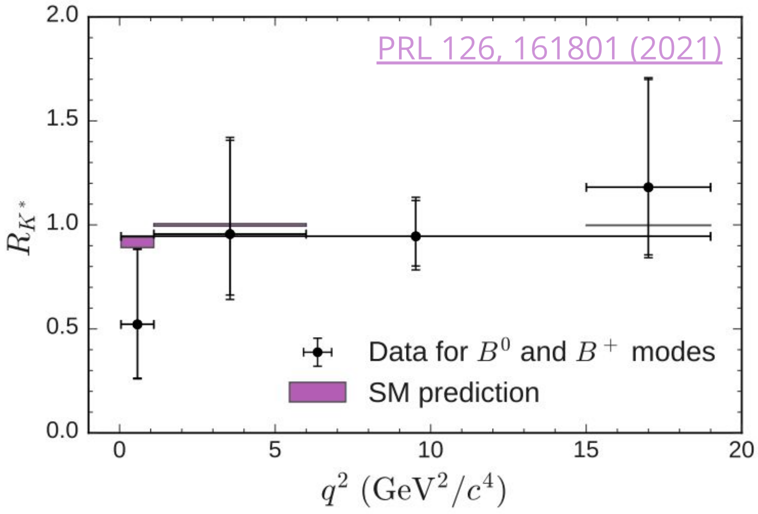
- R_{pK} full Run 1+2
- R_φ, $R_{K\pi\pi}$, etc.



Results from Belle

Weighted average of charged and neutral modes in various q^2 bins:





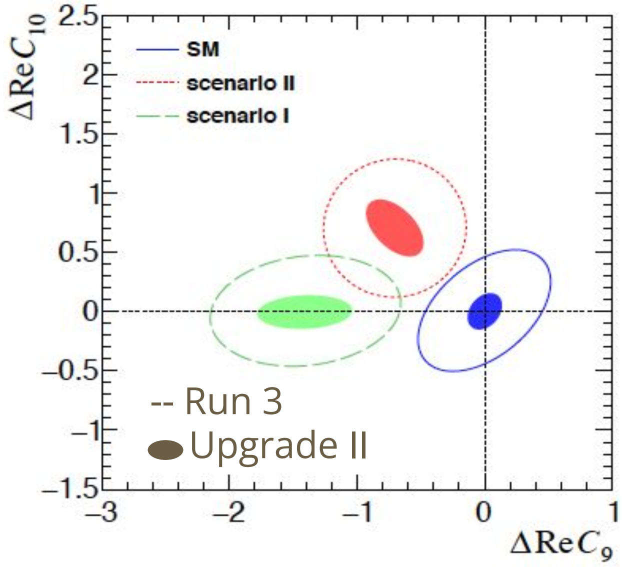
Results compatible with SM and LHCb measurements
Statistically limited → looking forward Belle II results!

Future prospects for LFU tests at LHCb

LHC schedule:

- Run 3: 2022 - 2025 → LHCb upgraded
- Run 4: 2028 - 2030
- Run 5 (HL-LHC): > 2032 → LHCb Upgrade II

	Run 3		Run 4	Upgrade II
R_X precision	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
R_K	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	0.052	0.031	0.020	0.008
R_ϕ	0.130	0.076	0.050	0.020
R_{pK}	0.105	0.061	0.041	0.016
R_π	0.302	0.176	0.117	0.047



$$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu l)$$

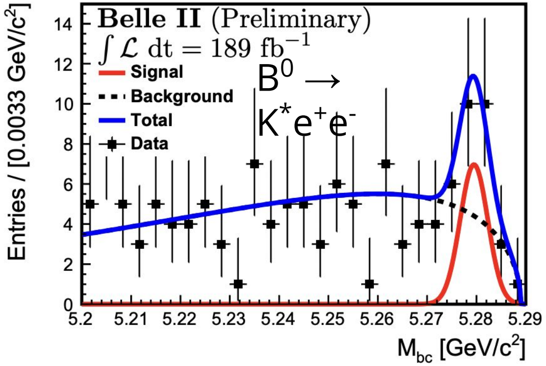
$$O_{10}^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu \gamma_5 l)$$

See talk by S. Prell

Prospects for Belle II

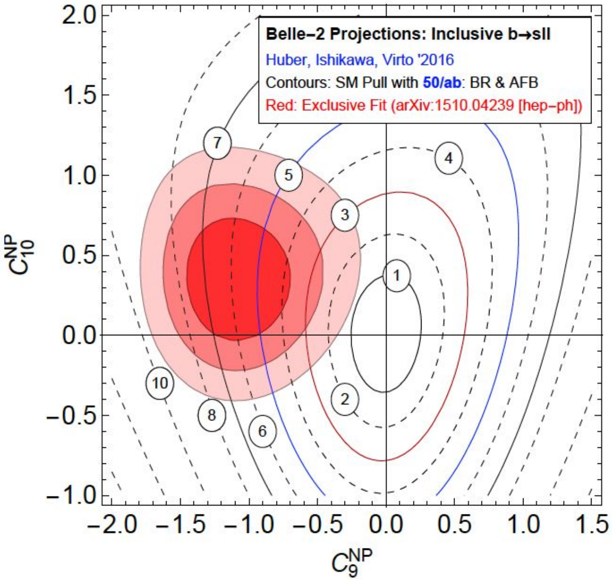
First b → sll and $r_{J/\psi}$ results w/ 189 fb^{-1}, looking forward to LFU tests

arXiv:2206.05946



Observable	Belle II	Belle (2021)
$R_{K^+}(J/\psi)$	$1.009 \pm 0.022 \pm 0.008$	$0.994 \pm 0.011 \pm 0.010$
$R_{K^0_S}(J/\psi)$	$1.042 \pm 0.042 \pm 0.008$	$0.993 \pm 0.015 \pm 0.010$

arXiv:2207.11275



Belle II Physics Book

Summary & conclusions

Rare b → sll decays provide stringent tests of NP

- Interesting tensions in b → sll transitions could be a hint of NP
- Latest results cannot confirm neither deny them
- Updates with more data and new modes under development
  - Precise results from other experiments awaited

Interpretation of results: talks by P. Stangl, M. Fedele and W. Altmannshofer
Many other studies of rare b-hadron decays: see talks by G. Frau and L. Martel

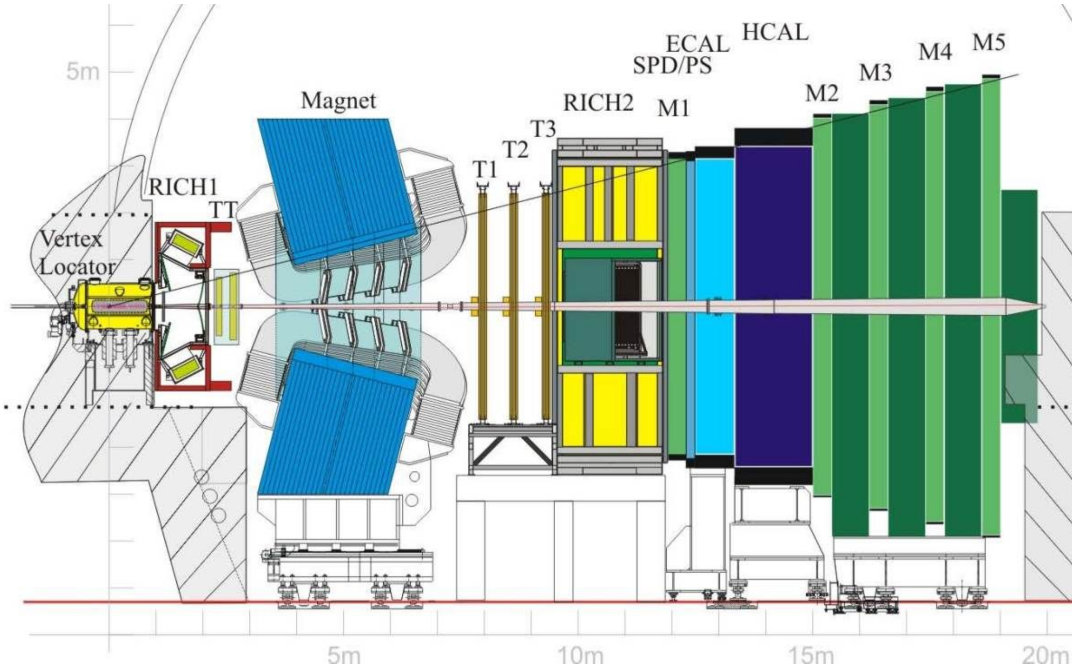
Stay tuned!

Thanks for the attention

BACK-UP

JINST 3 (2008) S08005

Experimental setup: LHCb



$\Delta p / p = 0.5 - 1.0\%$
$\Delta IP = (15 + 29/p_T[GeV])\ \mu m$

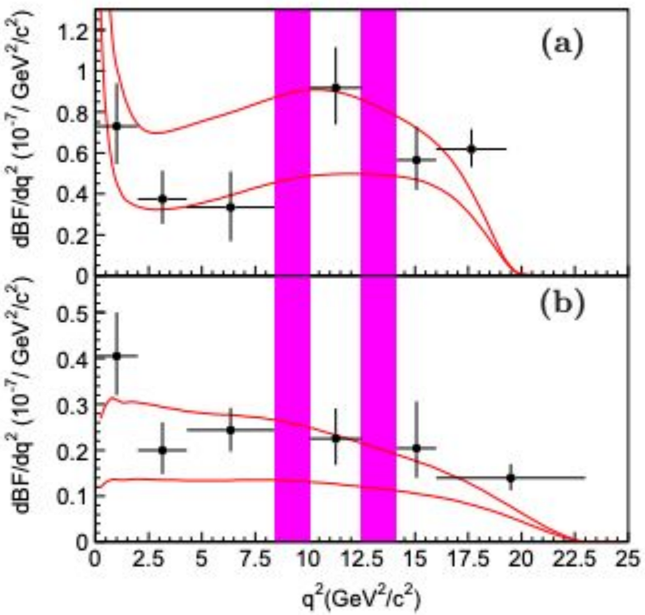
$\Delta E/E_{ECAL} = 1\% + 10\% / \sqrt{E[GeV]}$

Electron ID ~90% for ~5% $h \to e^{\pm}$ mis-id probability

Muon ID ~ 97% for 1-3% $\pi \to \mu$ mis-id probability

b ⟶ sll BR at Belle

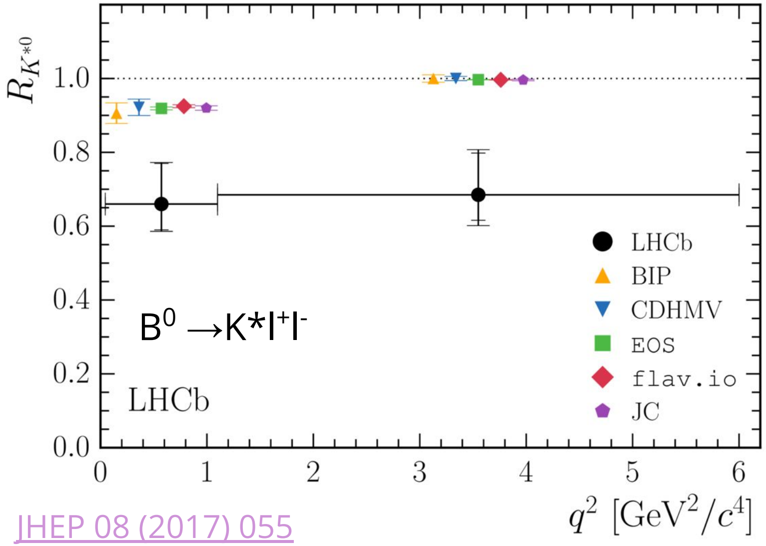
$B \to K^{*}l^{+}l^{-}$



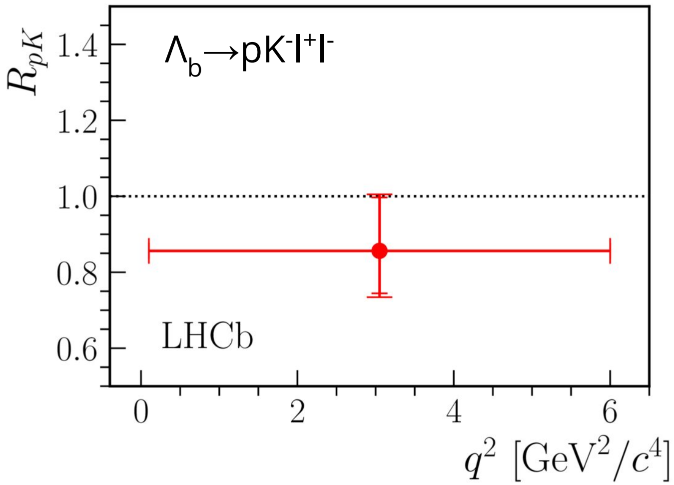
PRL 103, 171801 (2009)

$B \to Kl^{+}l^{-}$

R_{K*} and R_{pK}



JHEP 08 (2017) 055

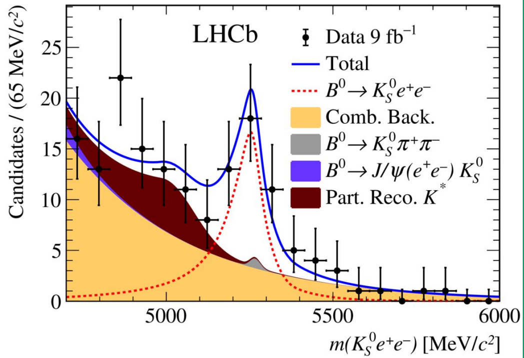


JHEP 05 (2020) 040

arXiv:2110.09501

R_K and R_{K^*} with neutral Kaons

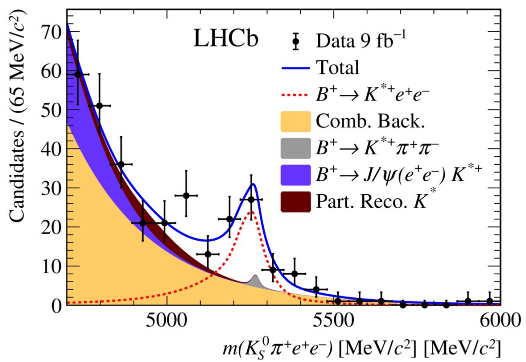
Separate fits to B^0 and B^+ decays, simultaneous for muons and electrons



Electron mode significance of 5.3 and 6.0σ → 1st observation

$e^\pm$ misId backgrounds are included in the fits

dB/dq^2 measured for first time in electron modes, in q^2 bins [1.1, 6.0] and [0.045, 6.0] GeV^2/c^4



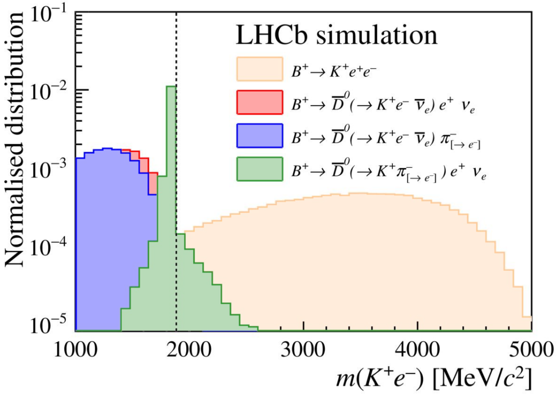
$$\frac{d\mathcal{B}\,(B^0 \to K^0 e^+e^-)}{dq^2} = (2.6 \pm 0.6\,(\text{stat.}) \pm 0.1\,(\text{syst.})) \times 10^{-8}\ \text{GeV}^{-2}c^4$$

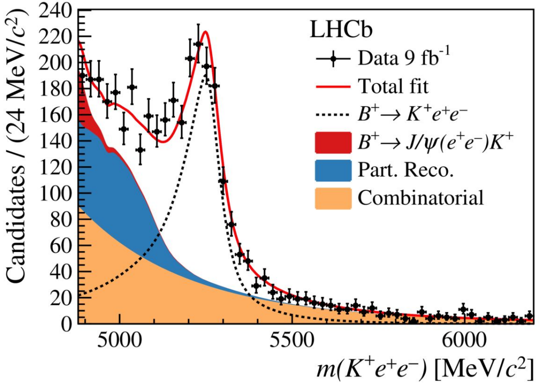
$$\frac{d\mathcal{B}\,(B^+ \to K^{*+} e^+e^-)}{dq^2} = \left(9.2\,^{+1.9}_{-1.8}\,(\text{stat.})^{+0.8}_{-0.6}\,(\text{syst.})\right) \times 10^{-8}\ \text{GeV}^{-2}c^4$$

Nature Physics 18, (2022) 277-282

R_K with full LHCb data

Cannot apply J/ψ mass constraint to rare mode → worse resolution → larger backgrounds for electron mode. Dedicated vetoes to minimise them.





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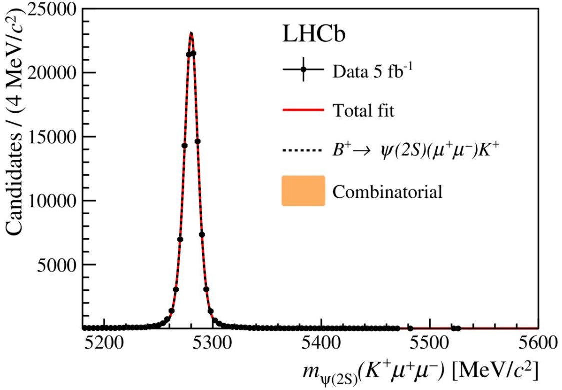
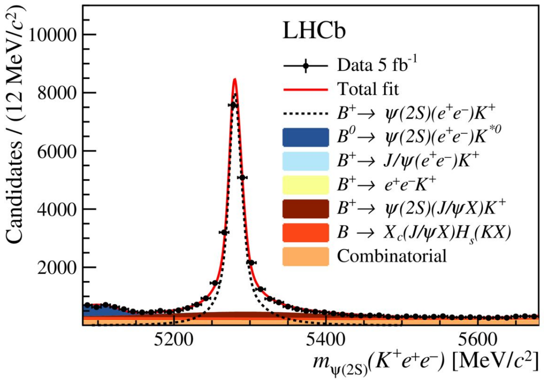
$R_{\psi(2S)}$ cross-check

Stringent cross-checks with $B^+ \to J/\psi K^+$ and $B^+ \to \psi(2S) K^+$ decays

$$R_{\psi(2S)} = 0.997 \pm 0.011$$ (double-ratio)





Constraint m(ll) to J/ψ or ψ(2S) mass → strong improvement of mass resolution

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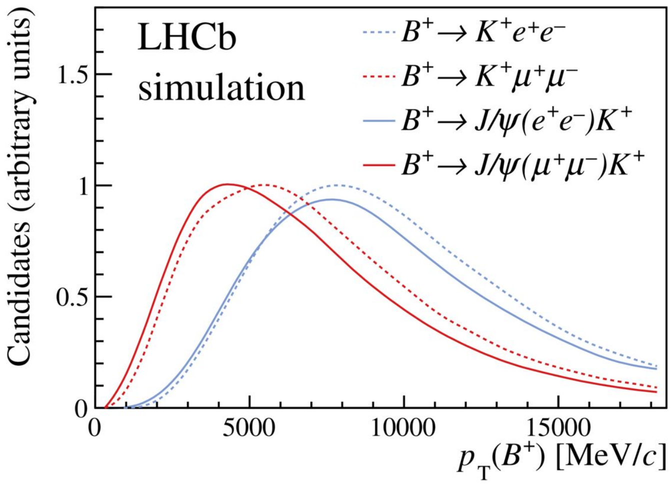
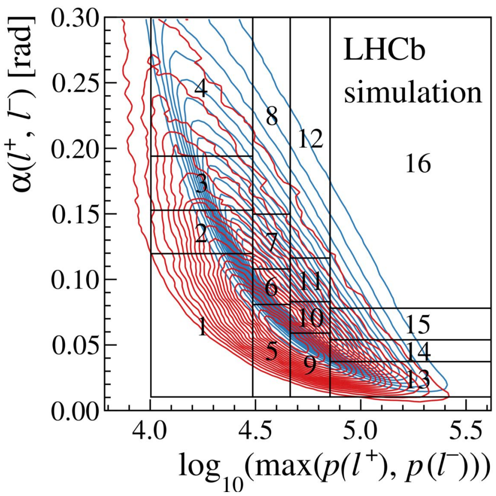
R_K: $r_{J/\psi}$ cross-checks





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R_K systematics

Detailed study of systematic uncertainties:

Fit model	1%
Calibration sample size	1%
Trigger, PID and B kinematics calibration	< 0.1%
q^2 distribution and resolution	negligible

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R_K: significance