# Measurement of lepton universality parameters in $B^+ \to K^+ l^+ l^-$ and $B^0 \to K^{*0} l^+ l^-$ decays

2212.09153

LHCb collaboration

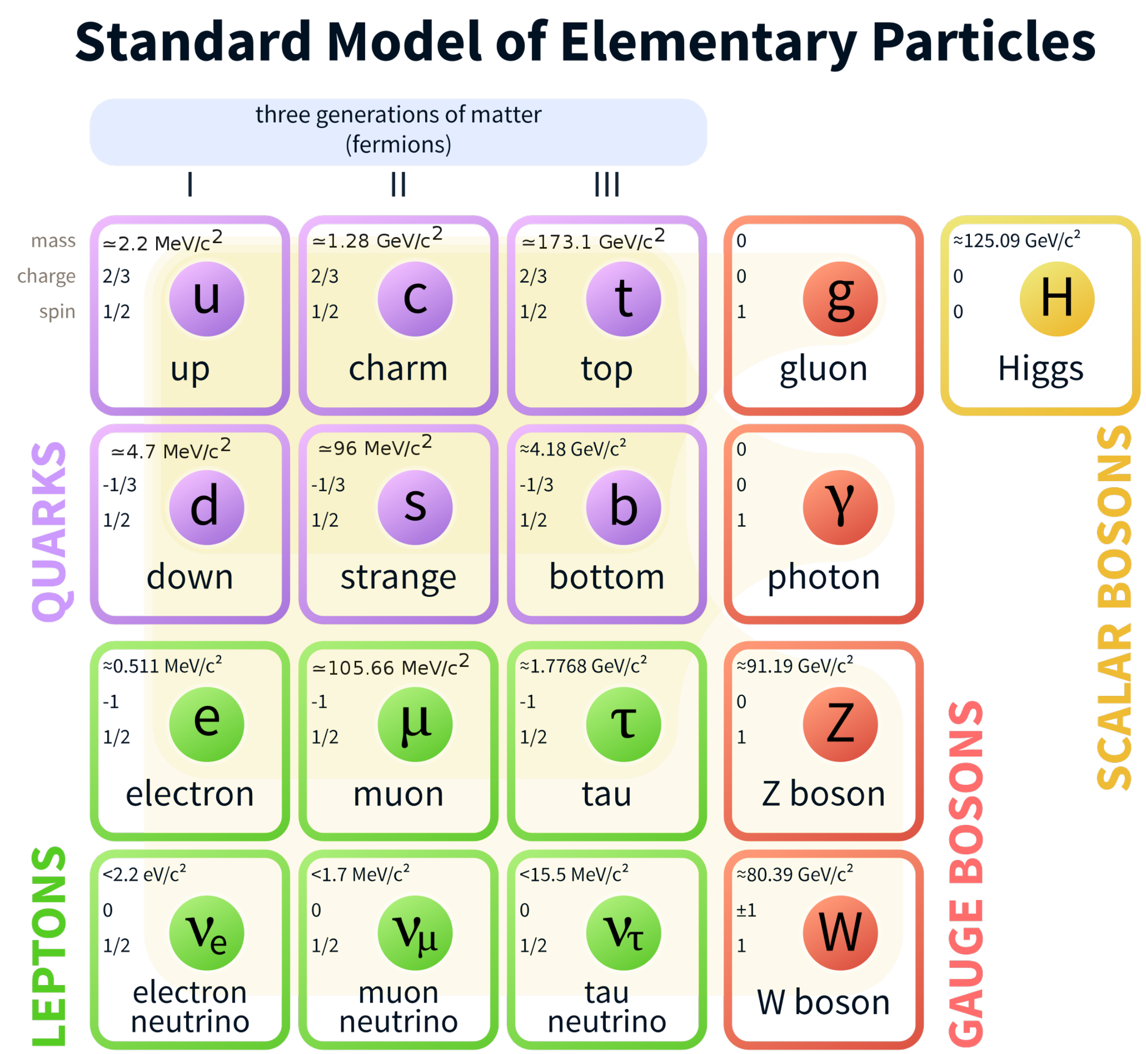
Slides are partially borrowed from the seminar of Renato Quagliani given on 20.12.2022

See also LHCb-PAPER-2022-046 submitted to PRL

BLTP Journal Club, presented by A. Bednyakov, 09.01.2023

# Lepton-Flavour Universality in the Standard Model

$$\mathscr{L}_{SM} = \mathscr{L}_{Gauge}(g_s, g, g') + \mathscr{L}_{Yukawa}(y_u, y_d, y_l) + \mathscr{L}_{Higgs}(\lambda, m_\Phi^2) + \dots$$




- **Gauge interactions are flavour universal**
- **Yukawa interactions are not, but due to Higgs mechanism the couplings are proportional to masses**

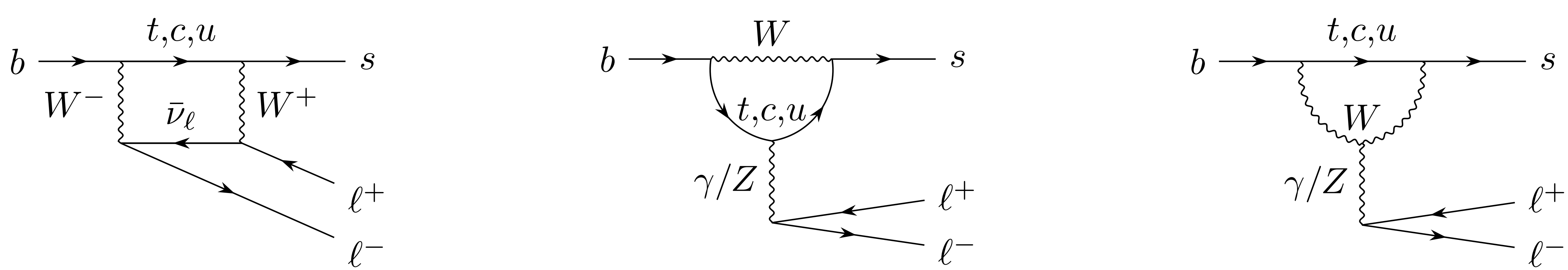
**In the SM, lepton flavour non-universal terms are due to the three lepton masses**

$$m_\tau : m_\mu : m_e = 3477 : 207 : 1$$

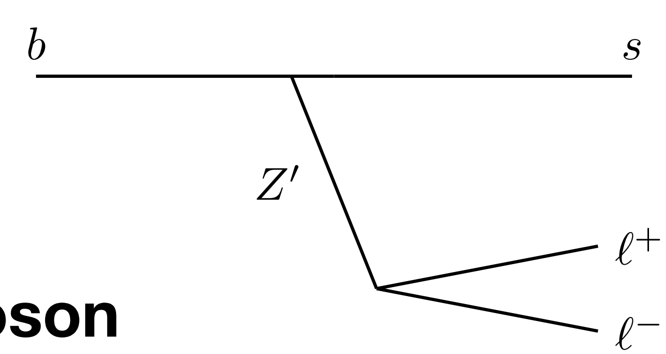
# FCNC transitions in the SM and New Physics

**Flavour-Changing-Neutral-Current processes are loop suppressed in the SM**

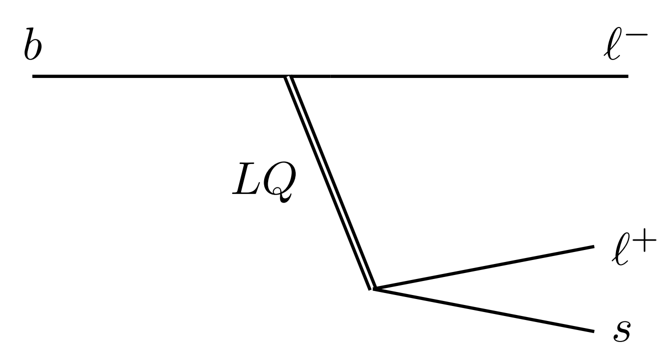
**Relevant examples (rare $b \to sll$ transitions):**




**New Physics can compete with the SM contribution, e.g.**




**Heavy Z'-boson**

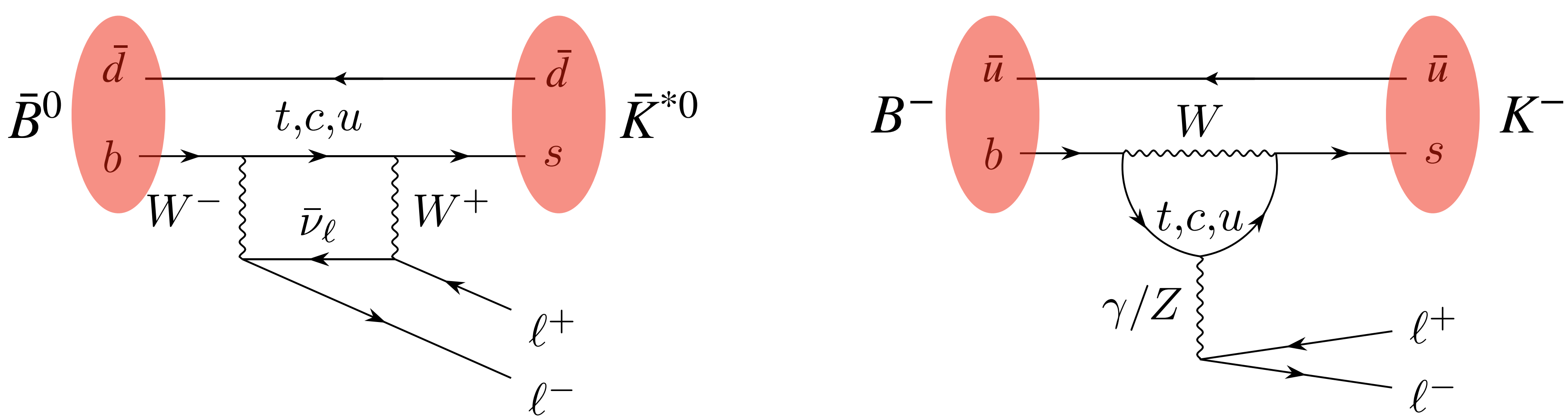



**LeptoQuarks**

# FCNC transitions in the SM and New Physics

$$m_B = 5279 \text{ MeV}$$
$$m_{K+} = 493 \text{ MeV}$$
$$m_{K^{*0}} = 895 \text{ MeV}$$

- **We deal with mesons, not quarks**
- **Large theoretical uncertainties in predictions: hadronic form-factors (10-20 %)**




- **Different processes $B \to Pll$ and $B \to Vll$ with pseudo scalar $P = K_S^0, K^\pm$ and vector $V = K^{*0,\pm}$ mesons in the final state (different FF!)**
- **Isospin partners**

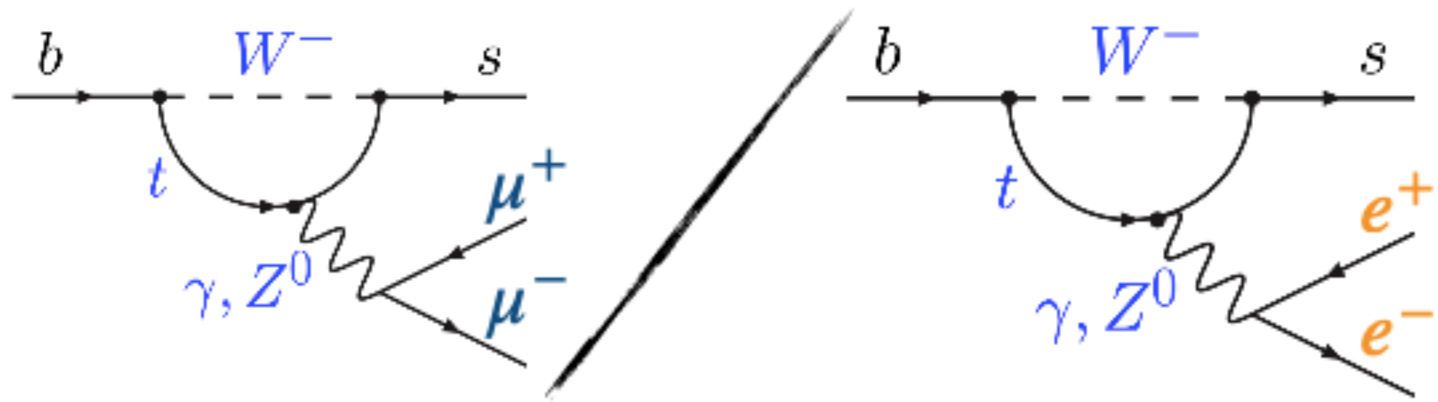
**2212.09153**

$$B^+ \to K^+ l^+ l^-$$
$$B^0 \to K^{*0}(\to K^+\pi^-) l^+ l^-$$

$$B^0 \to K_S^0 l^+ l^-$$
$$B^+ \to K^{*+}(\to K_S^0 \pi^+) l^+ l^-$$

# A Lepton-Universality Probe in FCNC b-s transitions

- **Given $B \to Xl^+l^-$ for some $X$, we can construct ratios $R_X$, corresponding to**




- **Small theoretical uncertainties because hadronic uncertainties cancel :**
  $R_X = 1$ **in the SM neglecting lepton masses**

- **Any departure from unity is a clear sign of New Physics**

# A Lepton-Universality Probe in FCNC b-s transitions

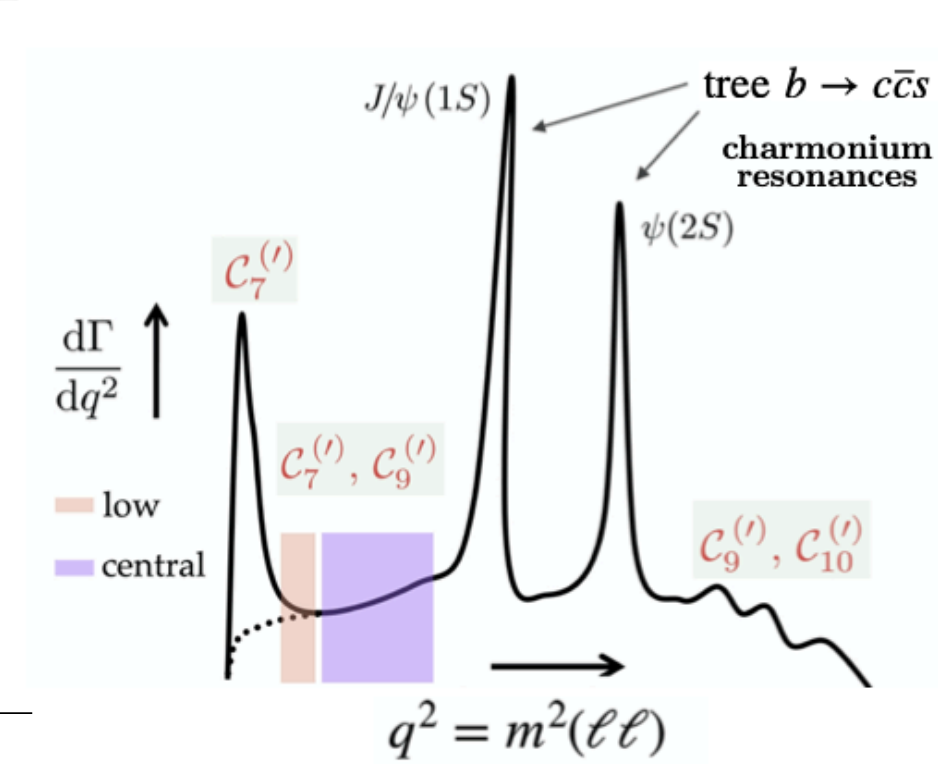
- **More precisely, one defines**

$$R_{K,K^*}(q_a^2, q_b^2) = \frac{\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

- **Invariant mass of lepton pair** $q^2 \equiv (p_{l^+} + p_{l^-})^2$

low-$q^2$ : $q^2 \in [0.1, 1.1]\,\mathrm{GeV}^2/c^4$

central-$q^2$ : $q^2 \in [1.1, 6.0]\,\mathrm{GeV}^2/c^4$

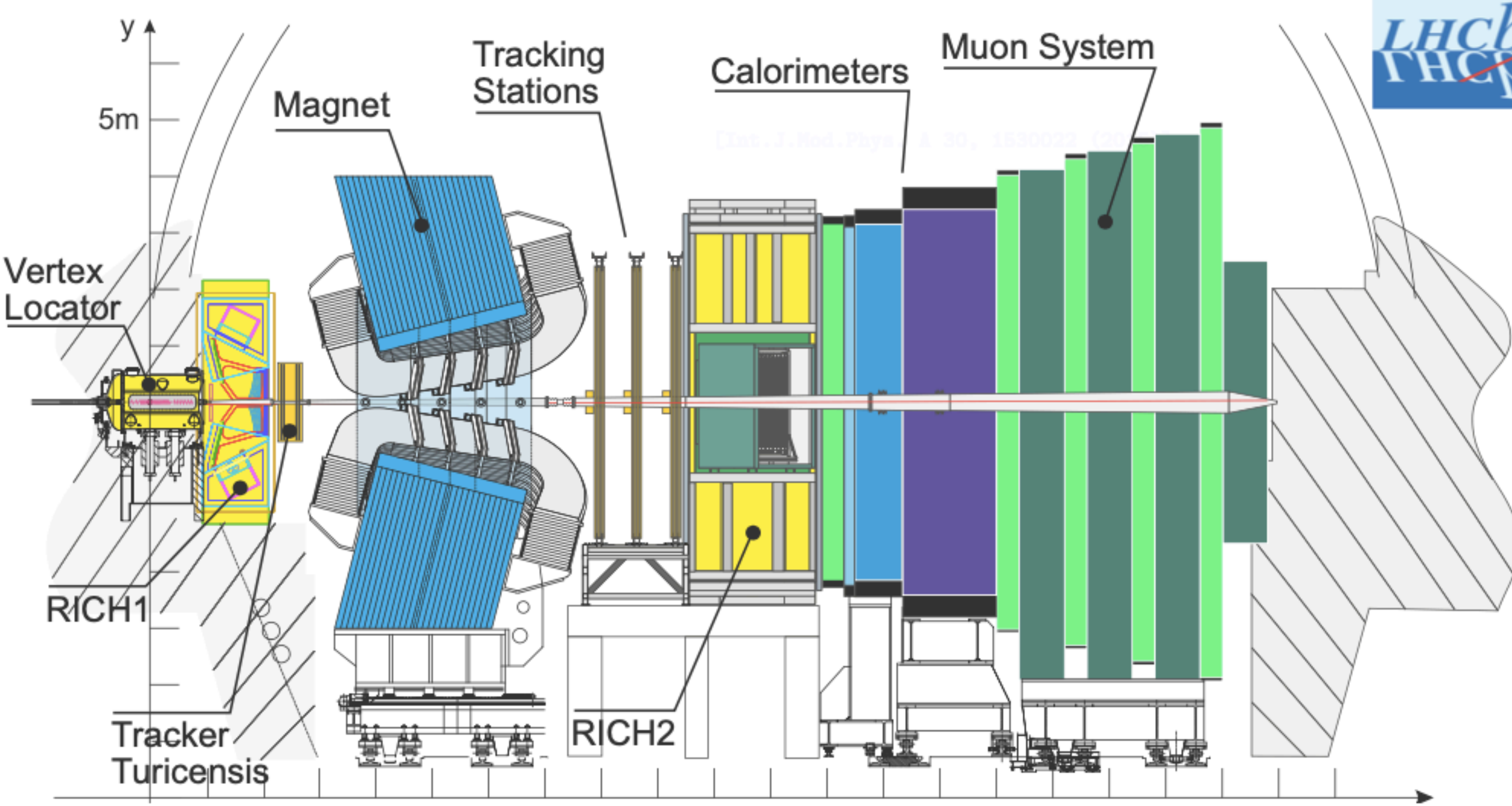



$q^2 \in [(2m_l)^2, (m_b - m_X)^2]$

**Flavio python code:**

| | $R_K$ low-$q^2$ | $R_K$ central-$q^2$ | $R_{K^*}$ low-$q^2$ | $R_{K^*}$ central-$q^2$ |
|---|---|---|---|---|
| SM prediction | 0.9936 | 1.0007 | 0.9832 | 0.9964 |
| SM uncertainty | 0.0003 | 0.0003 | 0.0014 | 0.0006 |

# LHCb detector at CERN



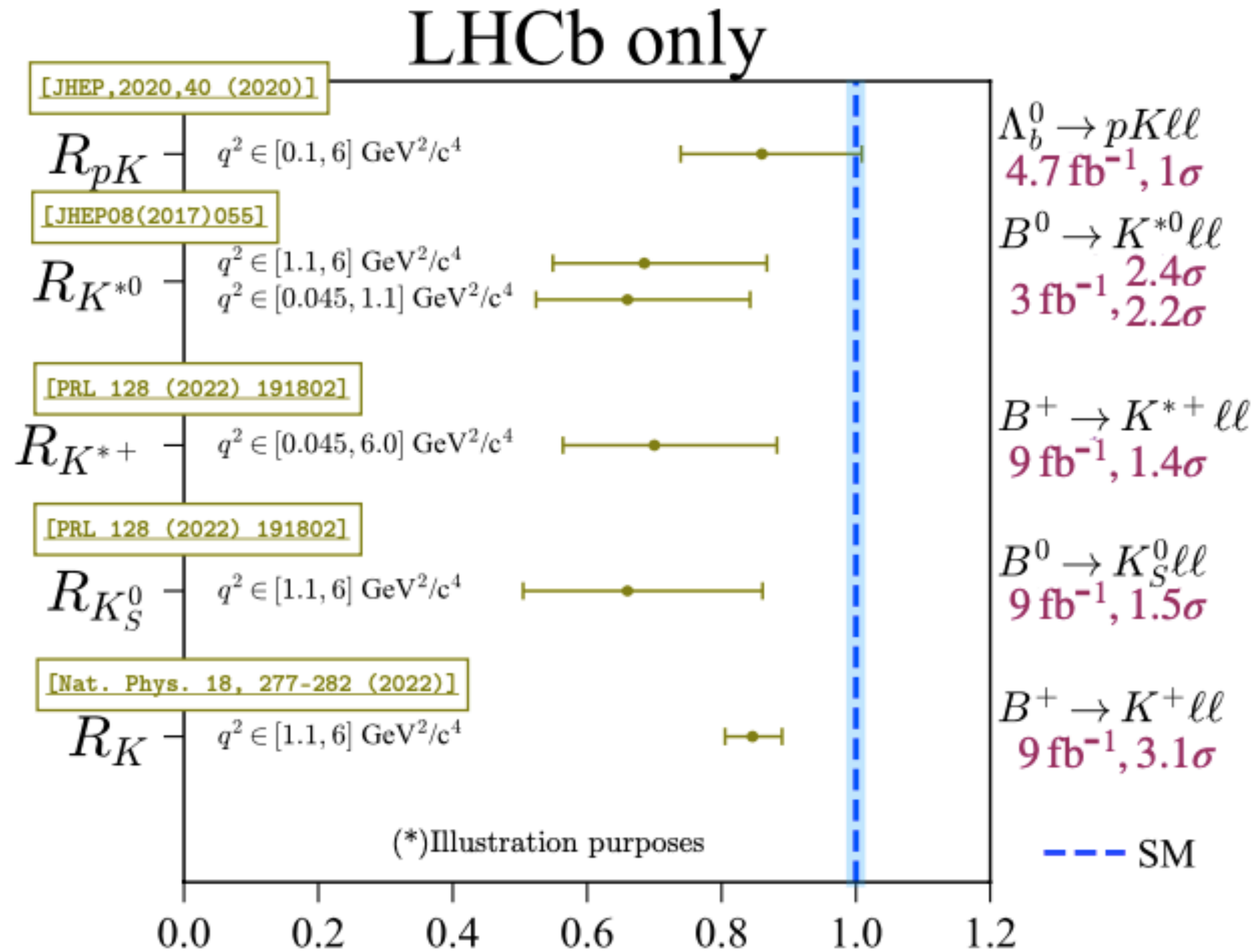
# $R_K$ and $R_{K^*}$: previous measurements

**First LHCb measurement (2014)**

$$R_K = 0.745^{+0.096}_{-0.082}$$

LHCb 3 $\text{fb}^{-1}$, 2.6$\sigma$
$1.1 < q^2 < 6\ \text{GeV}^2/c^4$
[PRL **113** 151601]

$\mathcal{O}(10^3)$
**theoretical papers trying to address the issue**




$$R_X = \frac{\mathcal{B}(b \to s\mu^+\mu^-)}{\mathcal{B}(b \to se^+e^-)}$$

**2212.09153 - first simultaneous LHCb analysis of $R_K$ and $R_{K^*}$!**

# LFU tests at LHCb

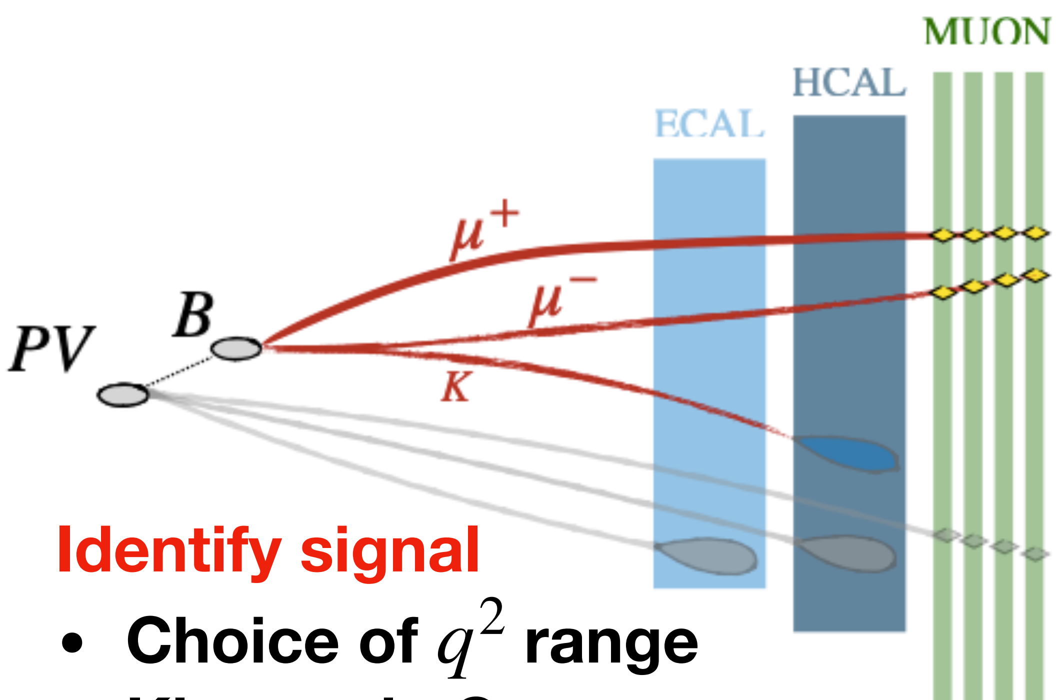
$$R_{K,K^*}(q_a^2, q_b^2) = \frac{\displaystyle\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\displaystyle\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2} \times \underbrace{\frac{\Gamma(J/\psi \to e^+e^-)}{\Gamma(J/\psi \to \mu^+\mu^-)}}_{\text{Measured to be 1}}$$

Phys. Lett. B731, 227 (2014)

$$R_{(K,K^*)} = \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)} \times \overbrace{\frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(e^+e^-))}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\mu^+\mu^-))}}^{r_{J/\psi}^{-1} = 1}$$

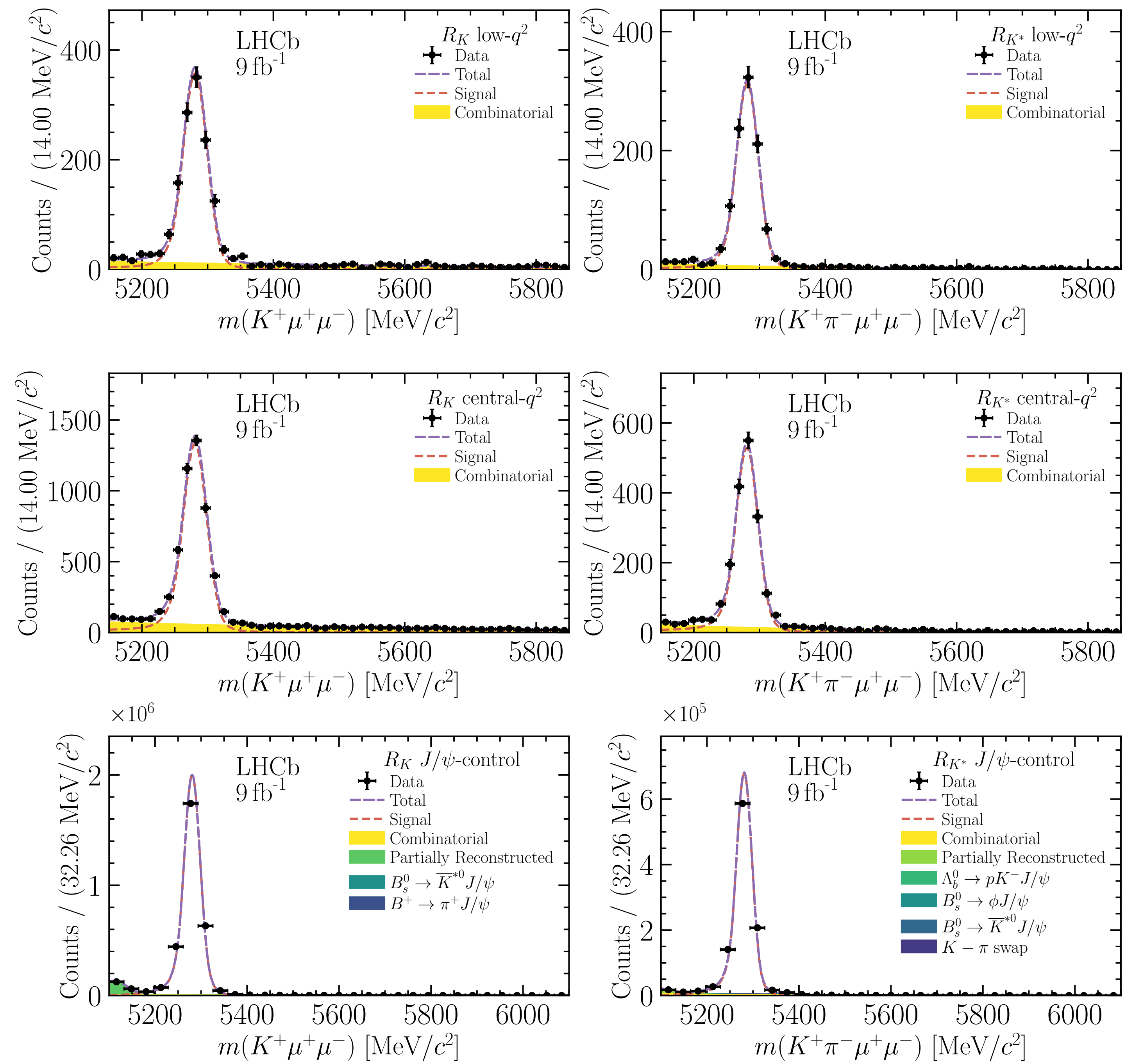
- $\mathcal{N}$ - from mass fits, efficiencies $\varepsilon$ are evaluated from data-driven corrected simulations
- Resonant $J/\psi$ mode is used to cancel (most of) systematical uncertainties in $\varepsilon$ determination + calibration

# LFU tests: challenges



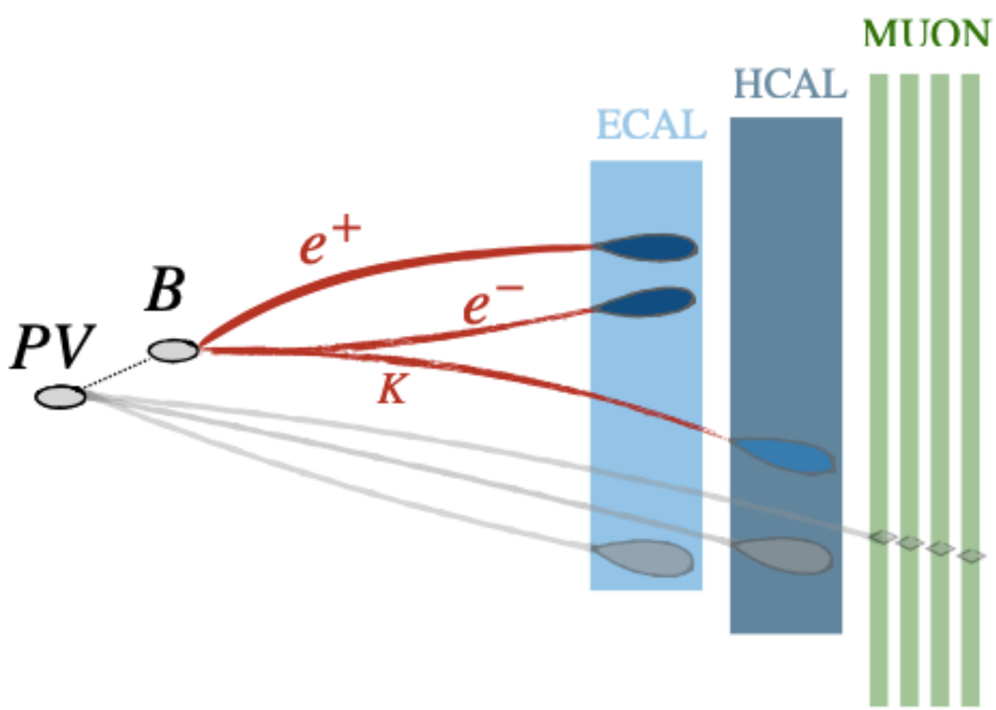

**Identify signal**
- Choice of $q^2$ range
- Kinematic Cuts
- **P**article **ID**entification
- ....

**Estimate background:**
- Combinatorial
- Partially reconstructed
- Exclusive
- **Misidentified**




**Clean mass fit for muons**

# LFU tests: challenges

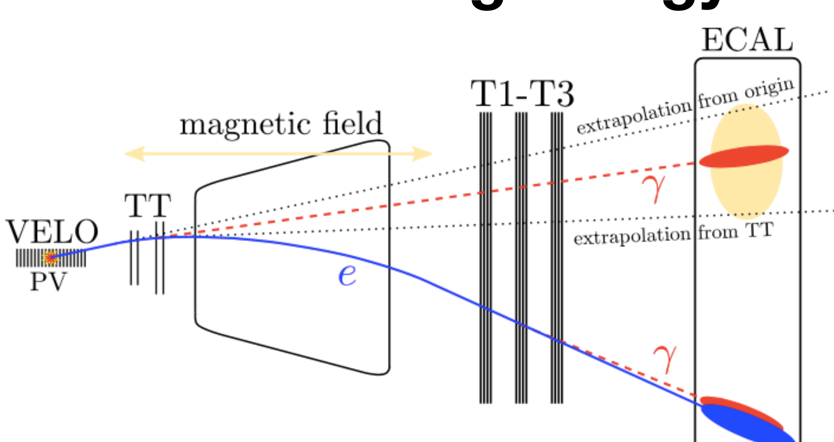


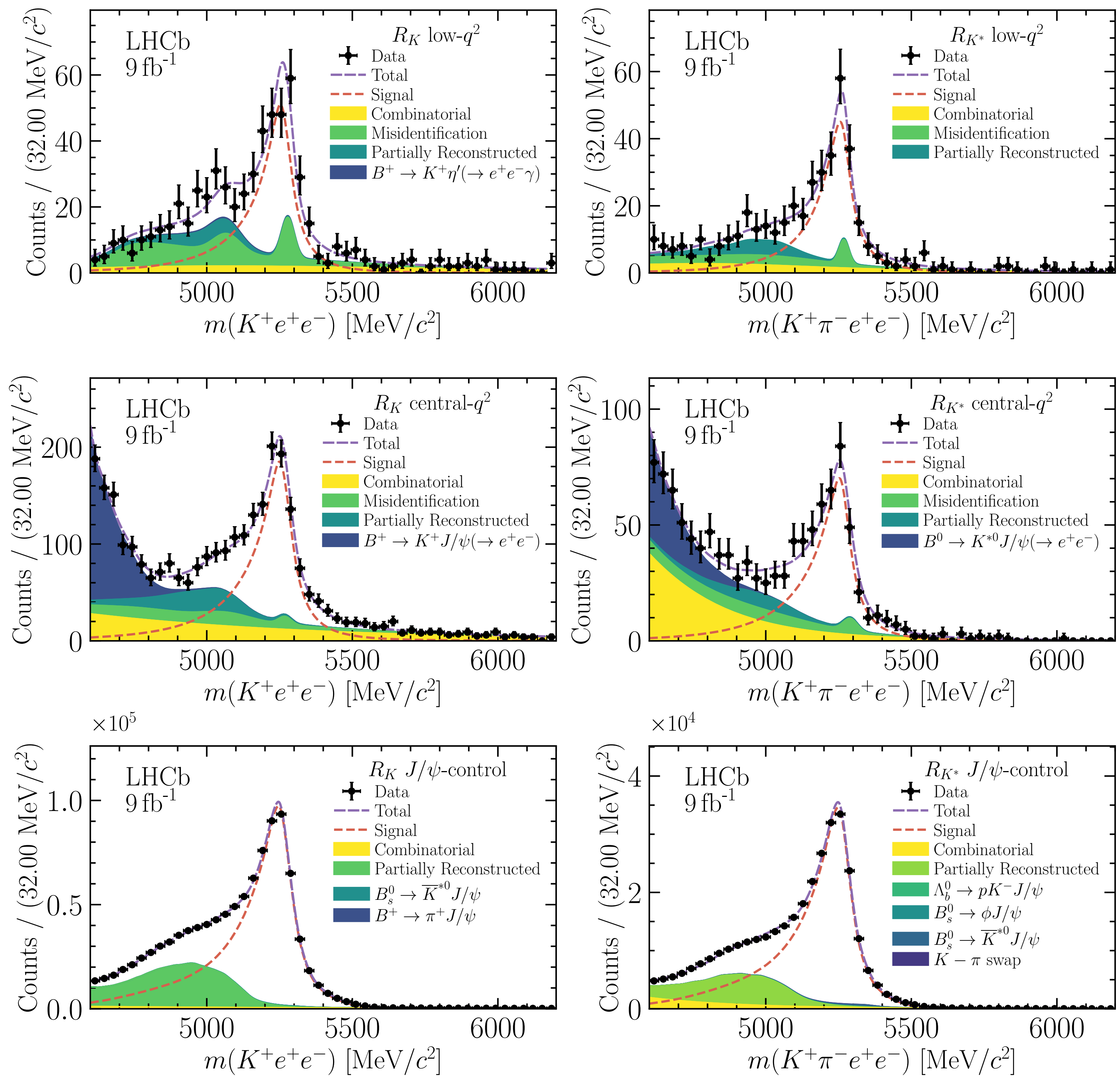

**Important systematic effect**

- **misidentification of $\pi^{\pm}, K^{\pm}$ as $e^{\pm}$**

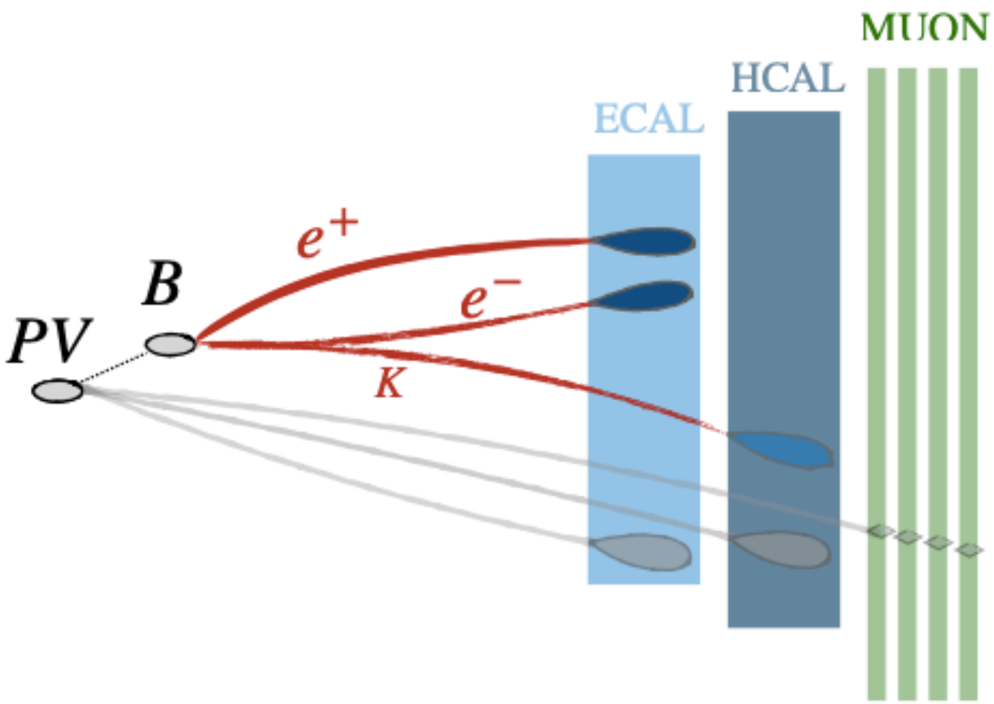
**Also take into account:**

- **bremsstrahlung energy loss**



# LFU tests: challenges

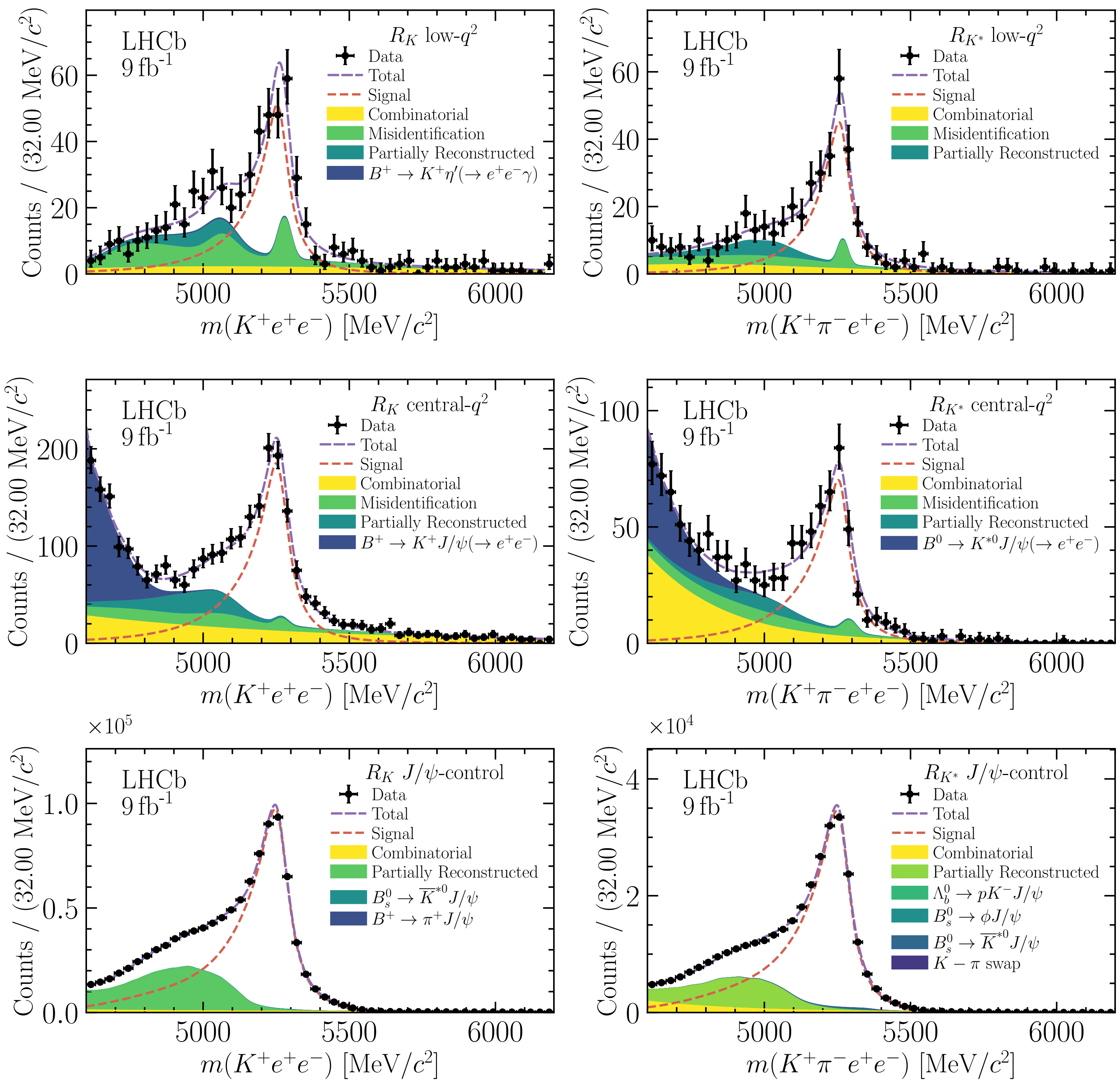



**Important systematic effect**

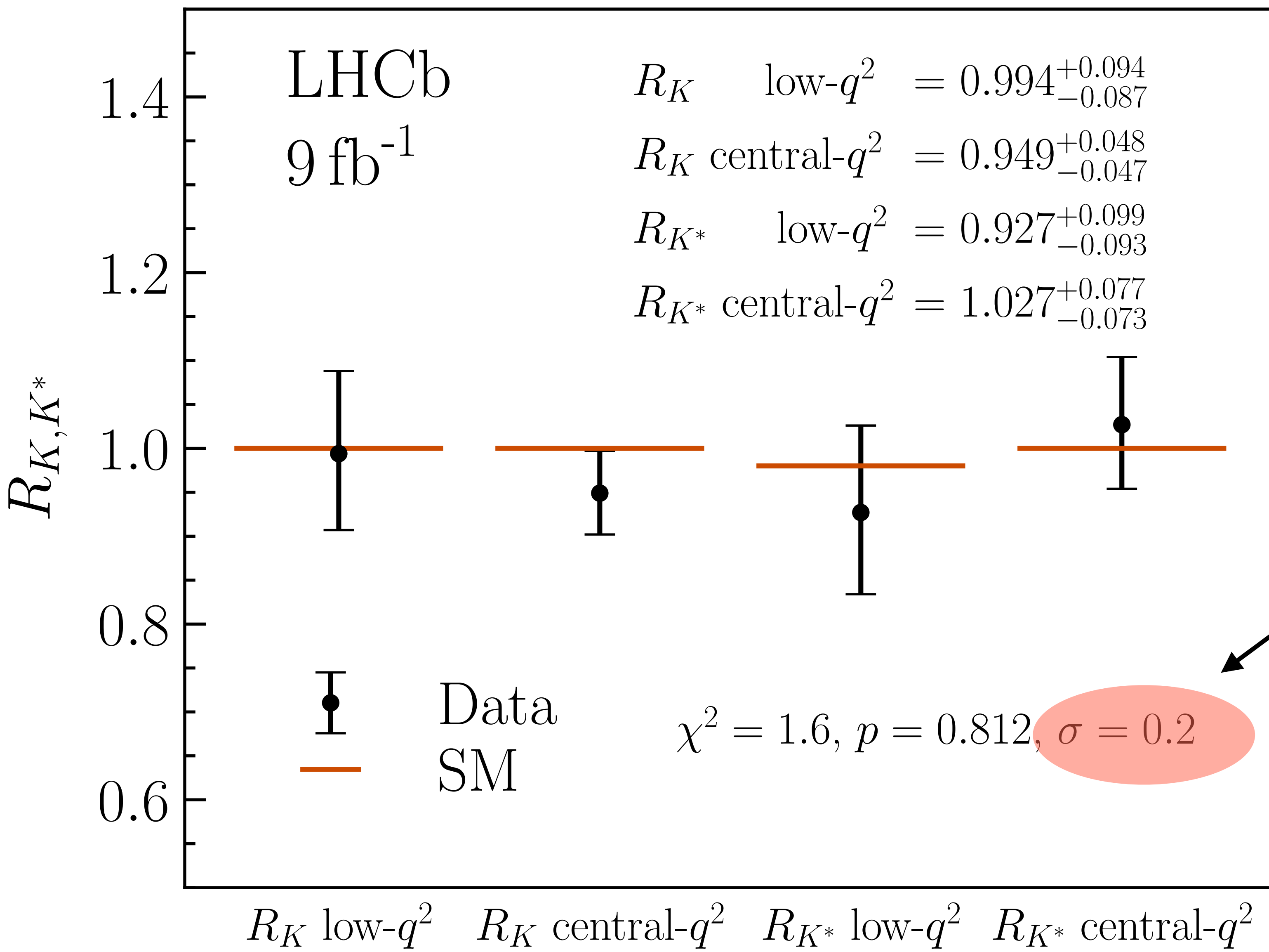
- **misidentification of $\pi^\pm, K^\pm$ as $e^\pm$**

| Sample | $\pi \to e$ | $K \to e$ |
|---|---|---|
| Run 1 | 1.78 (1.70) % | 0.69 (1.24) % |
| Run 2p1 | 0.83 (1.51) % | 0.18 (1.25) % |
| Run 2p2 | 0.80 (1.50) % | 0.16 (1.23) % |

**Previous analyses**



# $R_K$ and $R_{K^*}$: recent measurements




**Compatibility with the SM**

LHCb Run 1 (3 $fb^{-1}$, 2011-2012), Run 2P1 (2 $fb^{-1}$, 2015-2016), Run 2P2 (4 $fb^{-1}$, 2017-2018)

# $R_K$ and $R_{K^*}$: Recent vs Previous

- **Simultaneous analysis $R_K$ and $R_{K^*}$:**
  **additional handle on partially reconstructed background** $B^0 \to K^*(K^+\pi^-)e^+e^-$

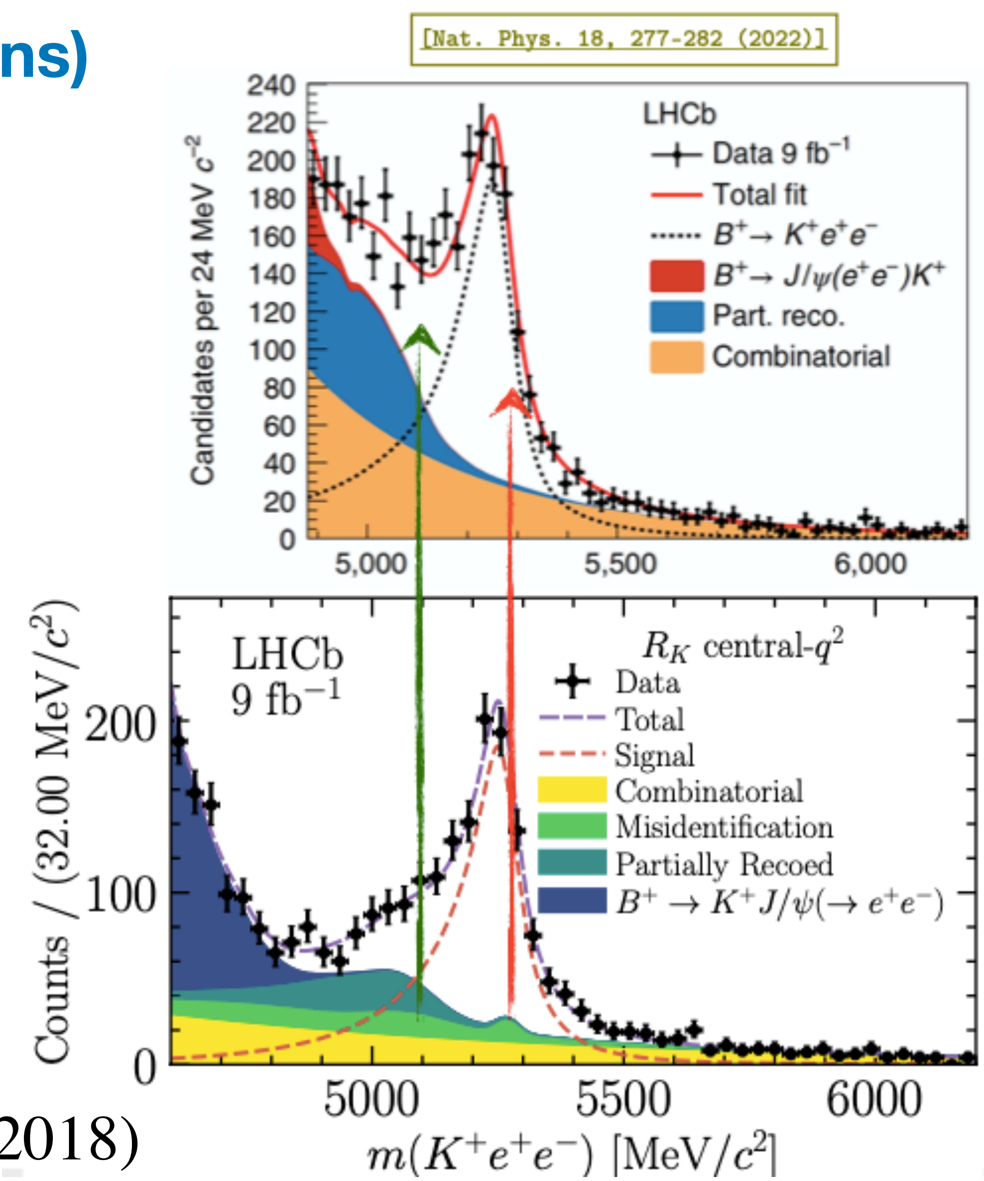
- **Tighter particle identification criteria (for electrons)**

- **New data-driven technique to estimate**
  **misidentified hadronic backgrounds**

$R_K = 0.846^{+0.042+0.013}_{-0.039-0.012}$ ⟶ $R_K = 0.949^{+0.042+0.022}_{-0.039-0.022}$

LHCb 9 $\text{fb}^{-1}$, **3.1$\sigma$**
$1.1 < q^2 < 6\ \text{GeV}^2/c^4$
**[Nat.Phys.18 277(2022)]**

LHCb 9 $\text{fb}^{-1}$, **0.2$\sigma$**
$1.1 < q^2 < 6\ \text{GeV}^2/c^4$
**[2212.09153]**




LHCb Run 1 (3 $\text{fb}^{-1}$, 2011-2012),
Run 2P1 (2 $\text{fb}^{-1}$, 2015-2016), Run 2P2 (4 $\text{fb}^{-1}$, 2017-2018)

# $R_K$ and $R_{K*}$: Recent vs Previous

- **Simultaneous analysis $R_K$ and $R_{K*}$:**
  **additional handle on partially reconstructed background $B^0 \to K^*(K^+\pi^-)e^+e^-$**

- **Tighter particle identification criteria (for electrons)**

- **New data-driven technique to estimate**
  **misidentified hadronic backgrounds**

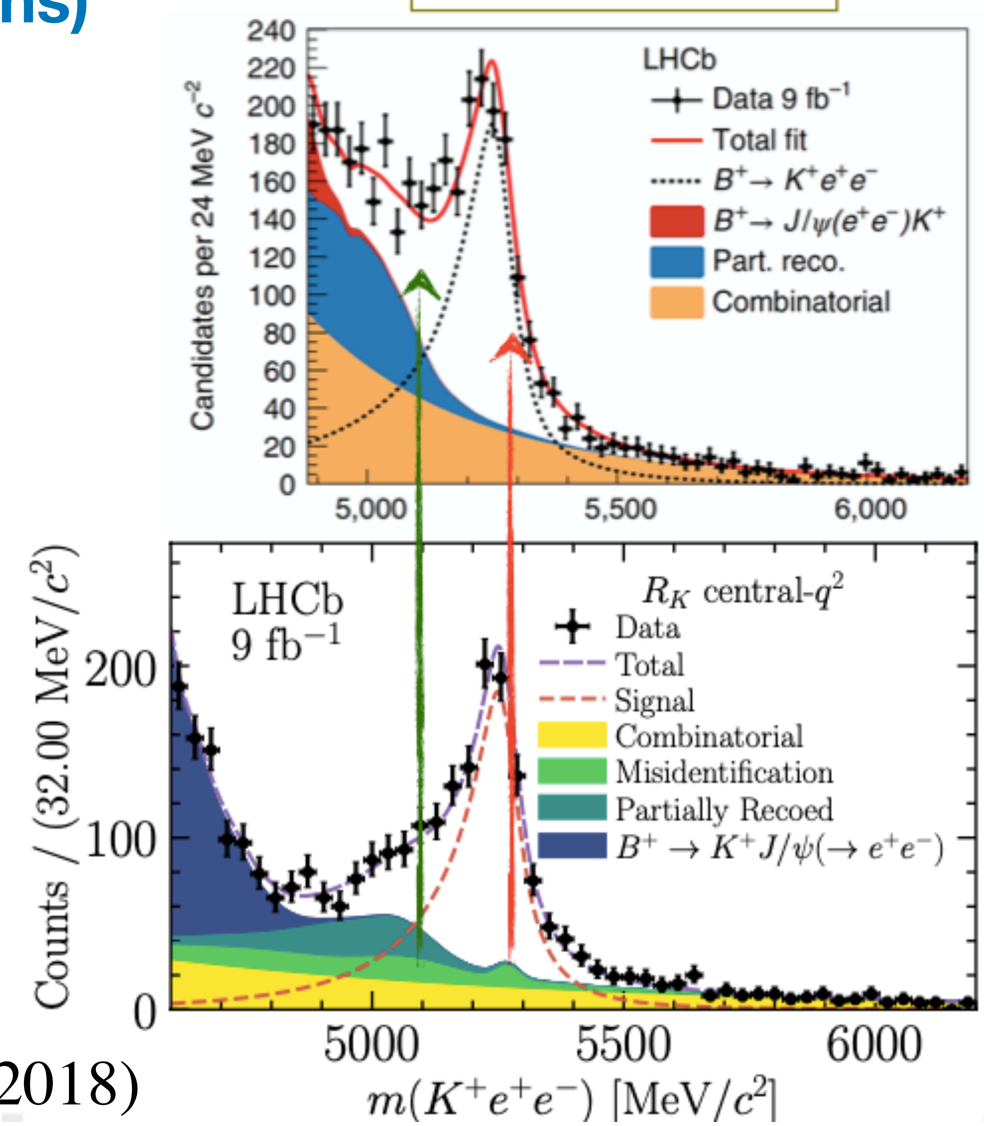
$R_{K*} = 0.69^{+0.11+0.05}_{-0.07-0.05}$

LHCb 3 fb$^{-1}$, **2.4-2.5$\sigma$**
$1.1 < q^2 < 6\ \mathrm{GeV}^2/c^4$
**[JHEP 08 (2017) 055]**

$R_{K*} = 1.027^{+0.072+0.027}_{-0.068-0.027}$

LHCb 9 fb$^{-1}$, **0.2$\sigma$**
$1.1 < q^2 < 6\ \mathrm{GeV}^2/c^4$
**[2212.09153]**

[Nat. Phys. 18, 277-282 (2022)]

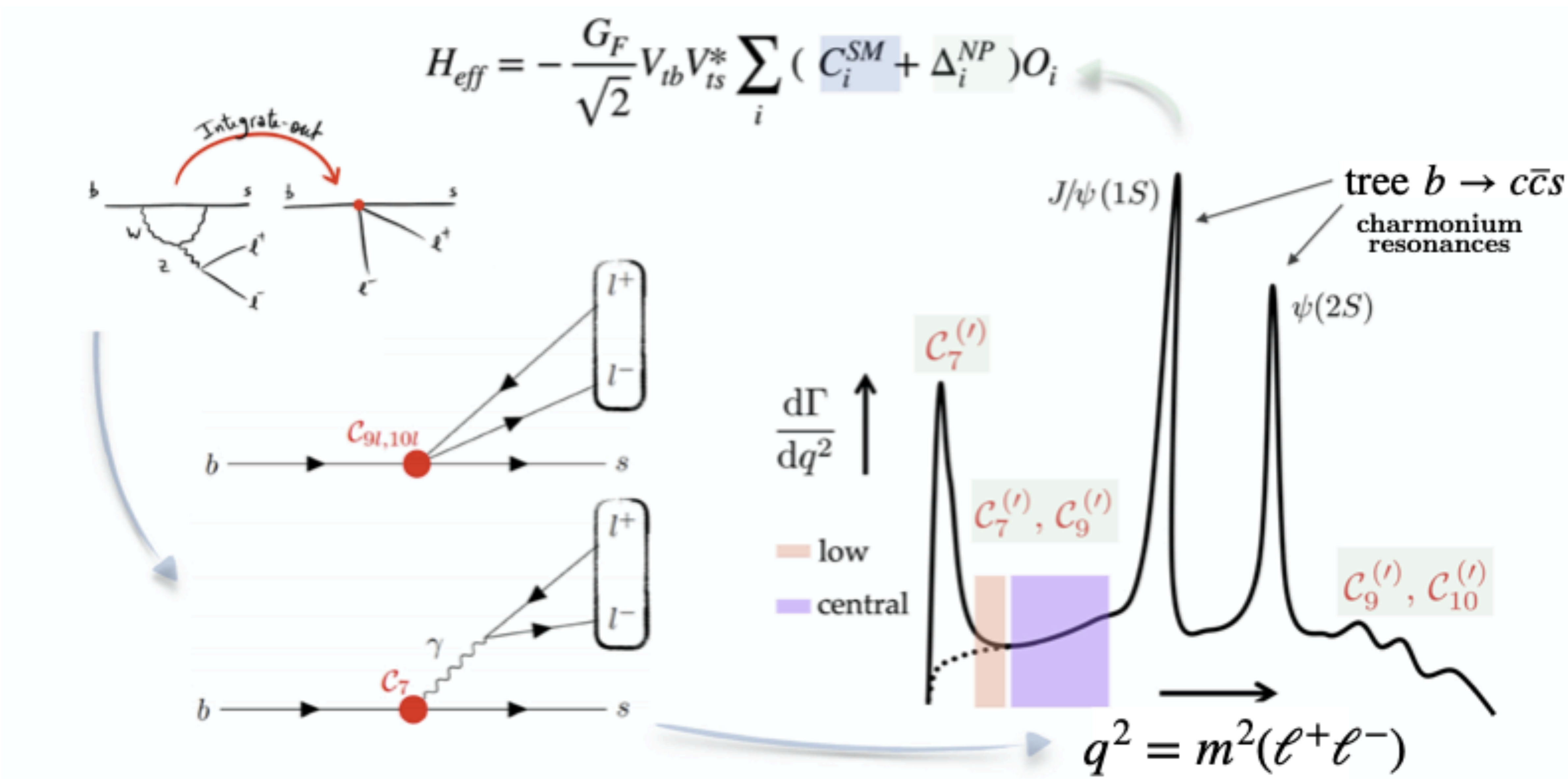



LHCb Run 1 (3 fb$^{-1}$, 2011-2012),
Run 2P1 (2 fb$^{-1}$, 2015-2016), Run 2P2 (4 fb$^{-1}$, 2017-2018)

# Conclusions

- A new systematical effect was discovered making the recent LHCb measurements in perfect agreement with the SM
- Previous anomalies in $R_K$ and $R_{K*}$ are not confirmed
- Yet, there are anomalies in other observables, e.g., in differential width and angular observables corresponding to $b \to s\mu^+\mu^-$ transitions

# Backup: Weak Effective Theory for $b \to s$



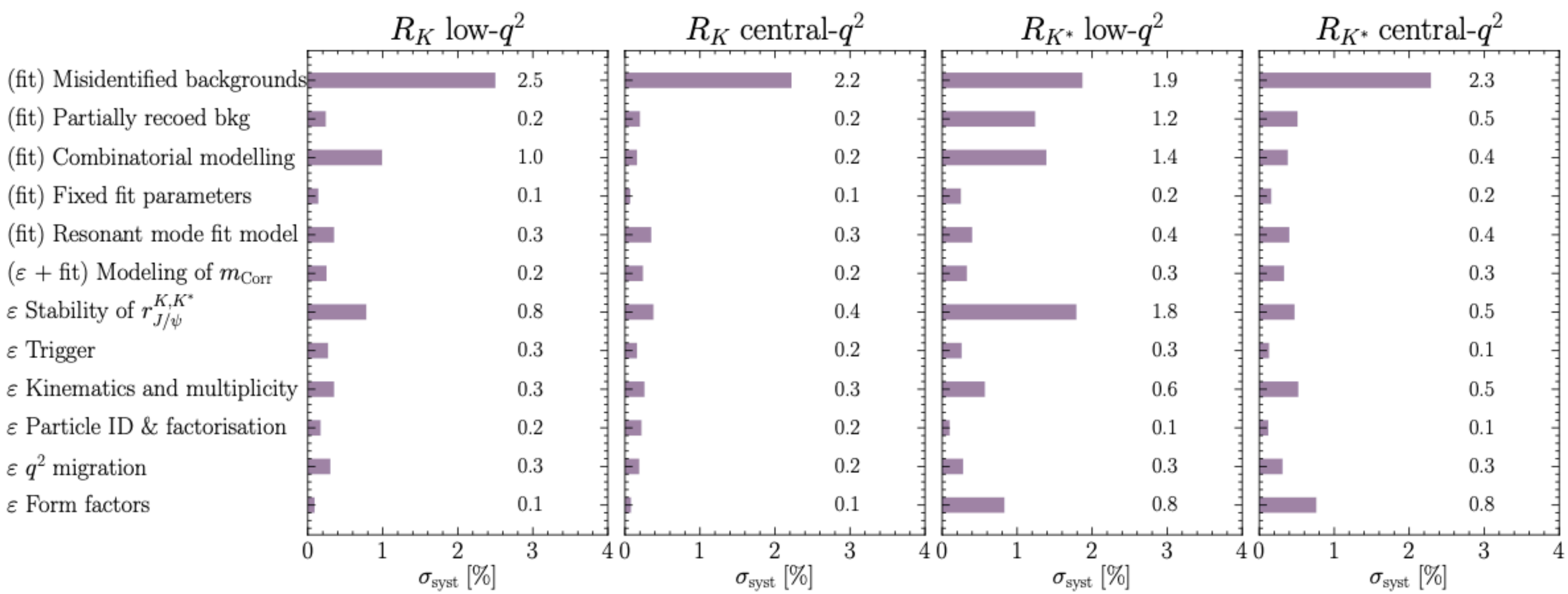

···· : with PseudoScalar $H_s$ in final state, $K_s^0, K^+$

— : with Vector $H_s$ in final state, $K^{*0}, K^{*+}, \phi, \ldots$

# Backup: Observed yield

| **LU observable** | **Muon ($\times 10^3$)** | **Electron ($\times 10^3$)** |
|---|---|---|
| low- $q^2$ $R_K$ | $1.25 \pm 0.04$ | $0.305 \pm 0.024$ |
| low- $q^2$ $R_{K^*}$ | $1.001 \pm 0.034$ | $0.247 \pm 0.022$ |
| central- $q^2$ $R_K$ | $4.69 \pm 0.08$ | $1.19 \pm 0.05$ |
| central- $q^2$ $R_{K^*}$ | $1.74 \pm 0.05$ | $0.443 \pm 0.028$ |
| $J/\psi$ $R_K$ | $(2.964 \pm 0.002) \times 10^3$ | $(7.189 \pm 0.015) \times 10^2$ |
| $J/\psi$ $R_{K^*}$ | $(9.733 \pm 0.010) \times 10^2$ | $(2.517 \pm 0.009) \times 10^2$ |

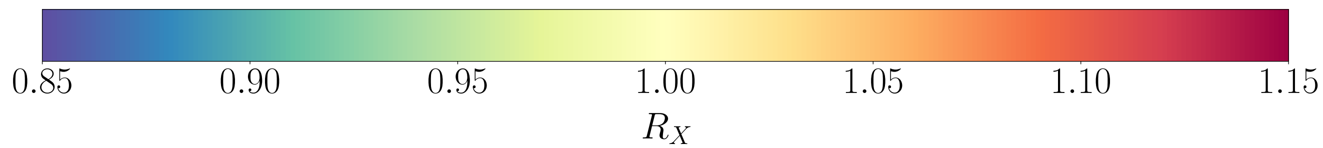
# Backup: systematics




- Dominant systematic from misidentified backgrounds estimation from data driven method
- Measurement still statistically dominated

# Backup: PID criteria

LHCb




$R_K$ low-$q^2$

| | ProbNN(e) $> 0.20$ | $> 0.25$ | $> 0.30$ | $> 0.35$ | $> 0.40$ | $> 0.45$ | $> 0.50$ | $> 0.55$ | $> 0.60$ |
|---|---|---|---|---|---|---|---|---|---|
| DLL(e) $> 7$ | 0.960 ± 0.097 | 0.971 ± 0.099 | 0.988 ± 0.102 | 0.997 ± 0.102 | 0.982 ± 0.100 | 0.973 ± 0.099 | 0.967 ± 0.099 | 0.967 ± 0.099 | 0.977 ± 0.102 |
| DLL(e) $> 5$ | 0.961 ± 0.086 | 0.964 ± 0.086 | 0.969 ± 0.088 | 0.983 ± 0.090 | 0.973 ± 0.089 | 0.981 ± 0.091 | 0.979 ± 0.092 | 0.961 ± 0.090 | 0.985 ± 0.095 |
| DLL(e) $> 2$ | 0.873 ± 0.073 | 0.904 ± 0.078 | 0.908 ± 0.079 | 0.958 ± 0.087 | 0.950 ± 0.086 | 0.954 ± 0.087 | 0.938 ± 0.086 | 0.940 ± 0.087 | 0.969 ± 0.093 |

$R_K$ central-$q^2$

| | ProbNN(e) $> 0.20$ | $> 0.25$ | $> 0.30$ | $> 0.35$ | $> 0.40$ | $> 0.45$ | $> 0.50$ | $> 0.55$ | $> 0.60$ |
|---|---|---|---|---|---|---|---|---|---|
| DLL(e) $> 7$ | 0.948 ± 0.051 | 0.944 ± 0.051 | 0.944 ± 0.051 | 0.939 ± 0.051 | 0.939 ± 0.051 | 0.941 ± 0.051 | 0.934 ± 0.051 | 0.935 ± 0.051 | 0.937 ± 0.052 |
| DLL(e) $> 5$ | 0.941 ± 0.044 | 0.938 ± 0.044 | 0.942 ± 0.044 | 0.933 ± 0.044 | 0.939 ± 0.045 | 0.951 ± 0.046 | 0.946 ± 0.046 | 0.953 ± 0.047 | 0.949 ± 0.048 |
| DLL(e) $> 2$ | 0.906 ± 0.040 | 0.902 ± 0.040 | 0.907 ± 0.040 | 0.895 ± 0.040 | 0.904 ± 0.041 | 0.916 ± 0.042 | 0.920 ± 0.043 | 0.925 ± 0.044 | 0.919 ± 0.044 |

$R_{K^*}$ low-$q^2$

| | ProbNN(e) $> 0.20$ | $> 0.25$ | $> 0.30$ | $> 0.35$ | $> 0.40$ | $> 0.45$ | $> 0.50$ | $> 0.55$ | $> 0.60$ |
|---|---|---|---|---|---|---|---|---|---|
| DLL(e) $> 7$ | 0.985 ± 0.112 | 0.982 ± 0.112 | 0.966 ± 0.109 | 0.952 ± 0.107 | 0.971 ± 0.111 | 0.975 ± 0.112 | 0.984 ± 0.114 | 0.970 ± 0.112 | 0.960 ± 0.111 |
| DLL(e) $> 5$ | 0.980 ± 0.097 | 0.993 ± 0.100 | 0.978 ± 0.099 | 0.979 ± 0.100 | 1.007 ± 0.103 | 1.014 ± 0.105 | 1.010 ± 0.106 | 1.010 ± 0.108 | 1.019 ± 0.110 |
| DLL(e) $> 2$ | 0.855 ± 0.080 | 0.848 ± 0.079 | 0.830 ± 0.076 | 0.847 ± 0.080 | 0.883 ± 0.086 | 0.901 ± 0.088 | 0.915 ± 0.089 | 0.925 ± 0.092 | 0.934 ± 0.117 |

$R_{K^*}$ central-$q^2$

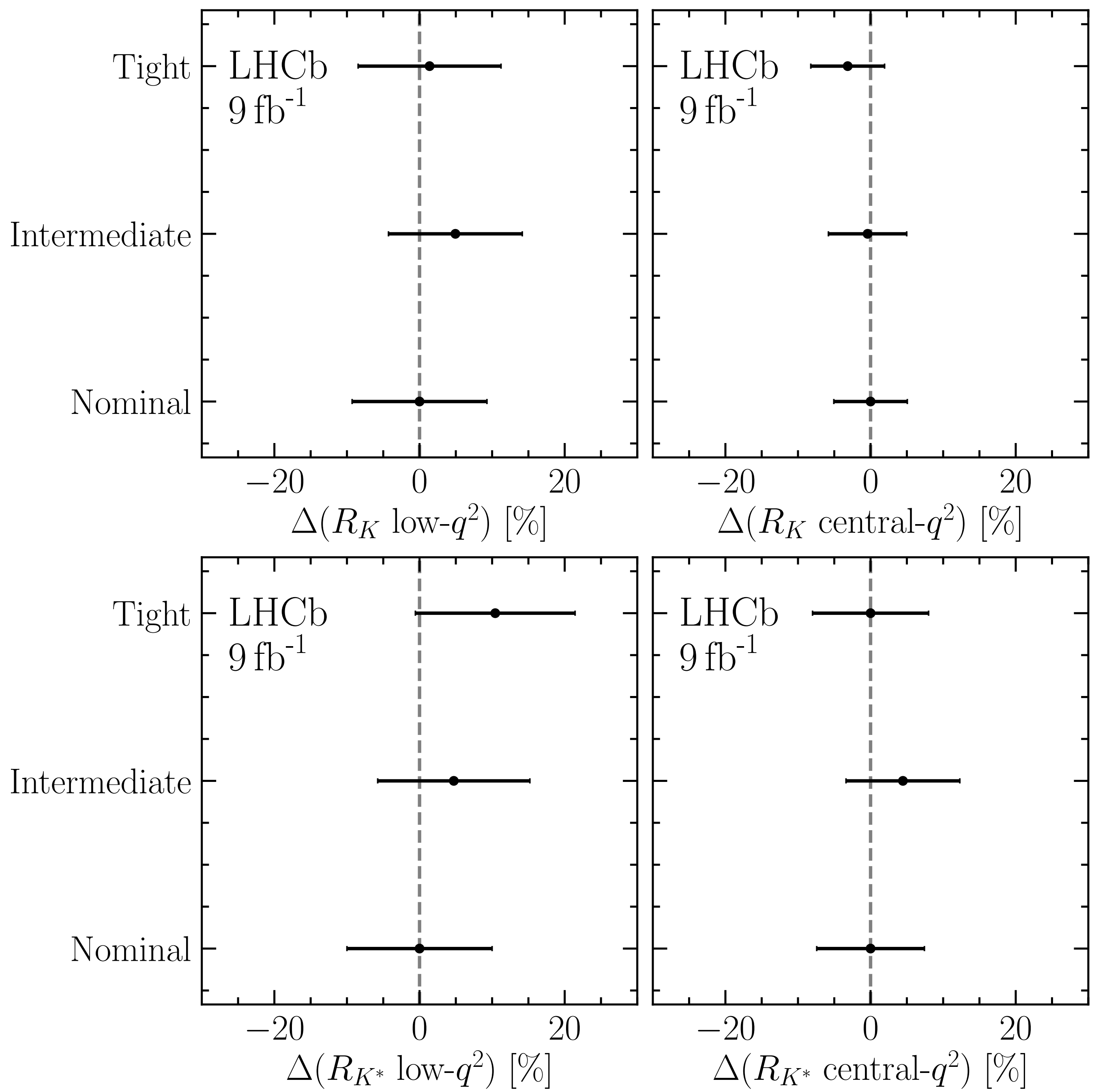
| | ProbNN(e) $> 0.20$ | $> 0.25$ | $> 0.30$ | $> 0.35$ | $> 0.40$ | $> 0.45$ | $> 0.50$ | $> 0.55$ | $> 0.60$ |
|---|---|---|---|---|---|---|---|---|---|
| DLL(e) $> 7$ | 1.127 ± 0.100 | 1.119 ± 0.099 | 1.116 ± 0.099 | 1.103 ± 0.098 | 1.097 ± 0.097 | 1.083 ± 0.095 | 1.097 ± 0.099 | 1.113 ± 0.101 | 1.119 ± 0.103 |
| DLL(e) $> 5$ | 1.021 ± 0.074 | 1.016 ± 0.074 | 1.016 ± 0.075 | 0.997 ± 0.073 | 1.016 ± 0.076 | 1.001 ± 0.075 | 1.012 ± 0.077 | 1.035 ± 0.081 | 1.049 ± 0.084 |
| DLL(e) $> 2$ | 0.965 ± 0.066 | 0.990 ± 0.069 | 0.986 ± 0.069 | 0.993 ± 0.071 | 1.024 ± 0.075 | 1.006 ± 0.073 | 1.014 ± 0.075 | 1.038 ± 0.079 | 1.039 ± 0.081 |

**DLL(x)** - the difference in log-likelihood between the given charged-species (x) hypothesis and the pion hypothesis

**ProbNN(x)** - output of artificial neural networks trained to identify each charged-particle species (x) (normalised between 0 and 1)

**Fits without the inclusion of misidentified background, but with different PID criteria**

# Backup: PID criteria + Misidentified background modelling




DLL(e) > 5 and ProbNN(e) > 0.5

DLL(e) > 3 and ProbNN(e) > 0.4,

DLL(e) > 2 and ProbNN(e) > 0.2

**Robustness against PID criteria tightening**

# Backup: Isospin partners

$$B^0 \to (K_S^0 \to \pi^+\pi^-)l^+l^- \qquad R_{K_S^0} = 0.66^{+0.20}_{-0.14}(\text{stat})^{+0.02}_{-0.04}(\text{syst})$$

$$B^+ \to K^{*+}( \to K_S^0\pi^+)l^+l^- \qquad R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(\text{stat})^{+0.03}_{-0.04}(\text{syst})$$

LHCb, $9\ \text{fb}^{-1}$, [Phys. Rev. Lett. 128, 191802 (2022)]

2110.09501

suffer from a reduced experimental efficiency at LHCb due to the presence of a $K_s^0$ meson in the final state.

# LHCb vs others