Santiago de Compostela 18-22 Sep 2023

CKM 2023

12th INTERNATIONAL WORKSHOP ON THE CKM UNITARITY TRIANGLE

LFU in rare b decays

- update from LHCb -

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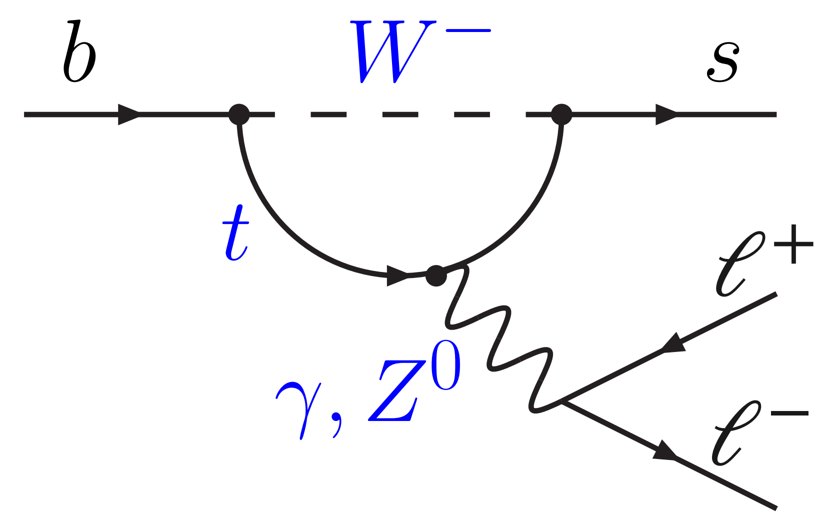
Rare $b \to s\ell^+\ell^-$ decays

An excellent test bench of SM flavour



- **Rare** FCNC with decay rate < 10^{-6}
  - Forbidden at tree level → loop factor
  - Suppressed by small CKM elements
  - $\mathcal{O}$(10 TeV) NP could enter at the same order as SM
- **Friendly** to experiments
  - Charged leptons
  - Normalisation from charmonium
  - Several complementary decay channels → $B \to K^*\gamma$, $B \to K^{(*)}\ell^+\ell^-$, $B_s \to \phi\gamma$, $B_s \to \phi\ell^+\ell^-$, $\Lambda_b \to pK^-\ell^+\ell^-$, …
  - Several complementary observables → Branching ratios, angular analyses, SM symmetry tests

Huge LHCb contribution in the last decade

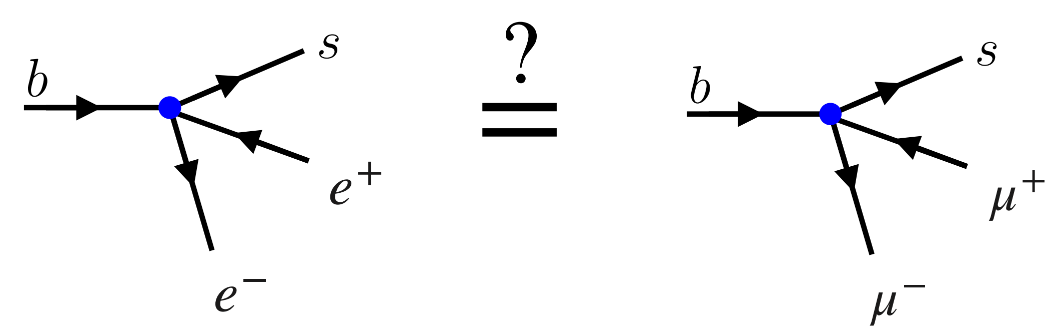
→ check out talks from Ulrik Egede and Andrea Mauri

LFU tests in $b \to s\ell^+\ell^-$

- **Lepton Flavour Universality** is an exact symmetry of the SM (modulo small lepton Yukawas)
- Accidental symmetry, easily broken beyond the SM
- LFU violation could shed light on the flavour puzzle

- Use rare $b \to s\ell^+\ell^-$ transitions to test if LFU holds at very high energy scale

Hiller & Kruger Phys.Rev.D 69 (2004) 074020



- **Very precise predictions**
  - QCD uncertainty cancels to 10^{-4}
  - Up to ~1% QED correction uncert.

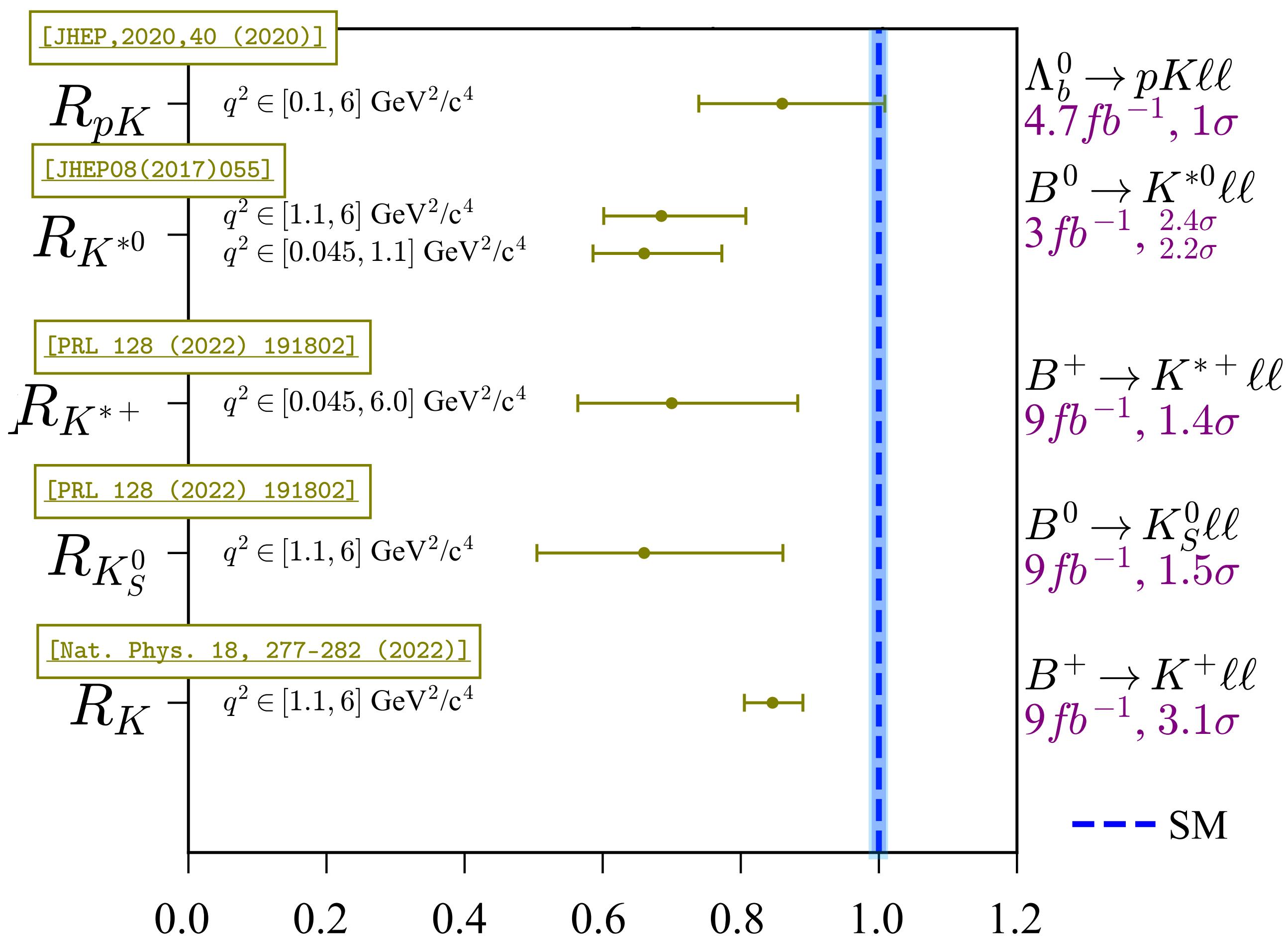
Bordone et al Eur.Phys.J.C 76 (2016) 8, 440

$$R_{H_s} = \frac{\mathrm{BR}\left(H_b \to H_s \mu^+\mu^-\right)}{\mathrm{BR}\left(H_b \to H_s e^+e^-\right)} \overset{\text{SM}}{=} 1.00 \pm 0.01$$

Before Dec 2022

LHCb measurements before Dec 2022

(other experiments have lower precision)



$$R_X = \frac{\mathcal{B}(b \to s\mu\mu)}{\mathcal{B}(b \to see)}$$

Check out results from Belle (II) in Bob Kowalewski's talk

- Coherent deviations from LFU, albeit statistically limited and only from one experiment

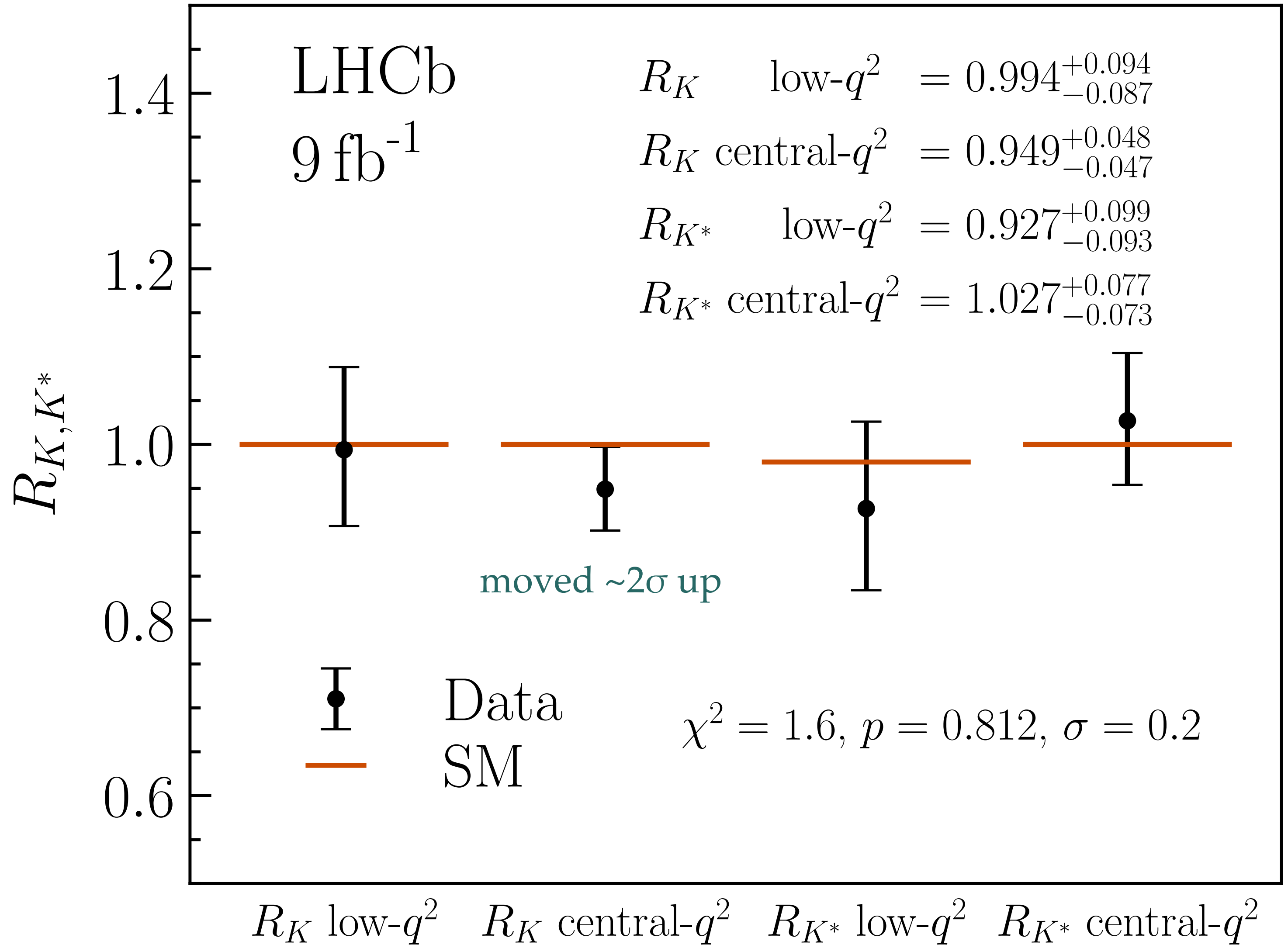
- **Huge excitement in our community**
- A large number of BSM models explaining the anomalies (Leptoquarks, heavy Z′, …)
- No one questioning the SM predictions

New results from Dec 2022

Phys.Rev.D 108 (2023) 3, 032002
Phys.Rev.Lett. 131 (2023) 5, 051803

- New simultaneous analysis of the two most sensitive channels $B \to K^{(*)}\ell\ell$
- Tighter selection, better background modelling and other improvements
- Additional MisID component identified thanks to simult. analysis

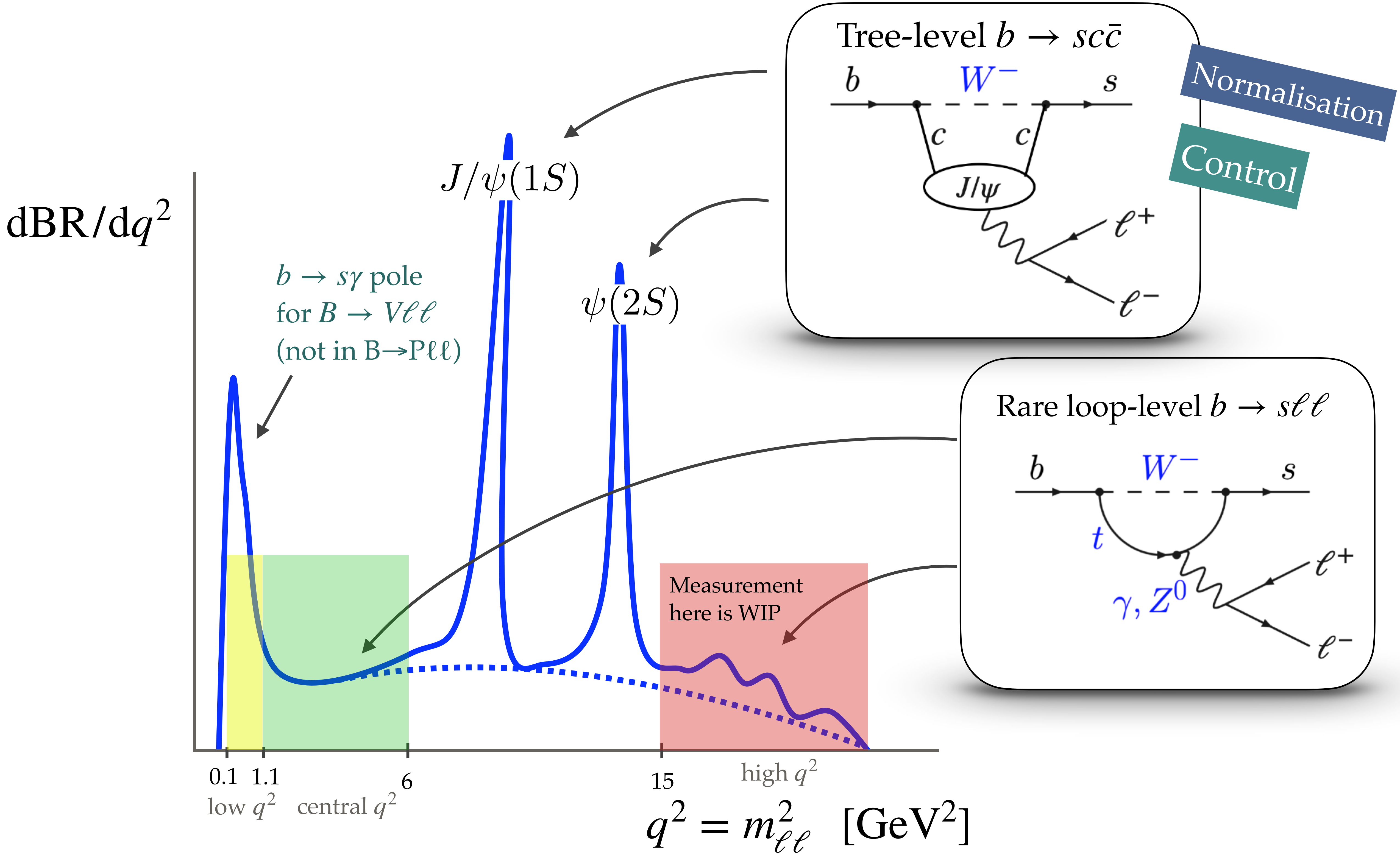
- **Most precise measurement to date**
- **The LFU anomaly has faded away**



LFU test in $b \to s\ell\ell$ at LHCb

- the state of the art -

q^2 spectrum of $b \to s\ell\ell$



Efficiency correction

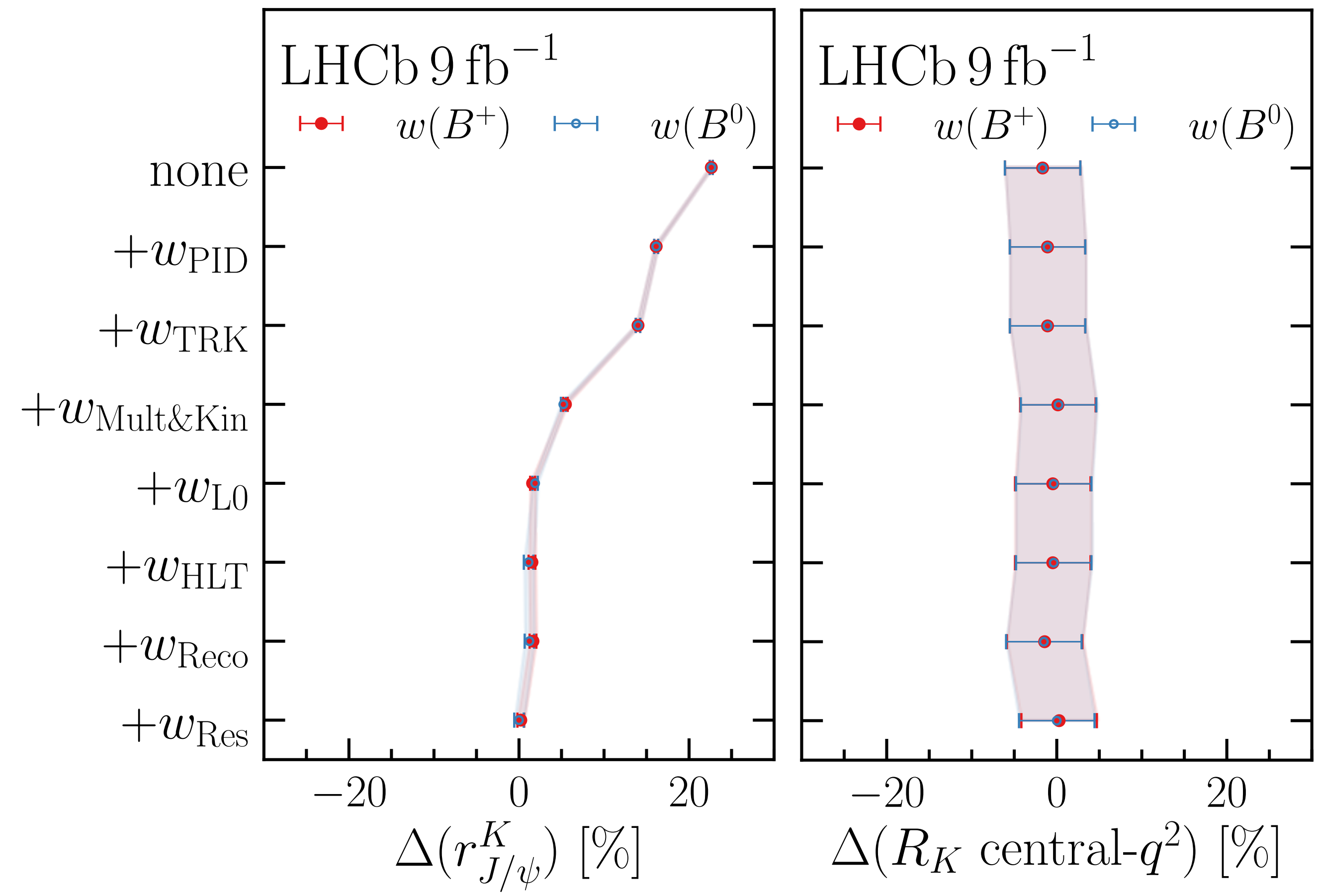
Phys.Rev.D 108 (2023) 3, 032002
Phys.Rev.Lett. 131 (2023) 5, 051803

- Redefine R_K assuming LFU in $J/\psi \to \ell\ell$

$$R_K = \frac{\frac{\mathcal{N}}{\varepsilon}(B \to K\mu\mu)}{\frac{\mathcal{N}}{\varepsilon}(B \to Kee)} \times \frac{\frac{\mathcal{N}}{\varepsilon}\left(B \to K\, J/\psi(ee)\right)}{\frac{\mathcal{N}}{\varepsilon}\left(B \to K\, J/\psi(\mu\mu)\right)}$$

$$r_{J/\psi}^{-1} \equiv \frac{\Gamma(J/\psi \to e^+e^-)}{\Gamma(J/\psi \to \mu^+\mu^-)} = 1$$

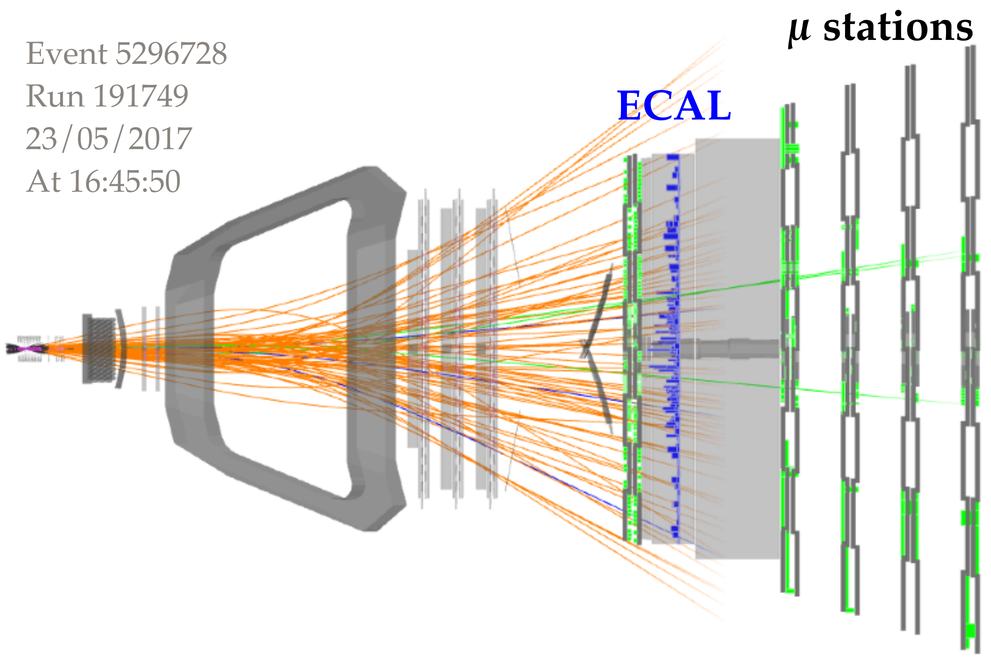
- Muons-electrons efficiency differences calibrated with very thorough MC corrections
- Weights for PID, tracking, event multiplicity, trigger, reconstruction efficiency, mass resolution
- **Double ratio remains very stable**



Electrons at LHCb

Int.J.Mod.Phys. A 30, 1530022 (2015)

Selection efficiency

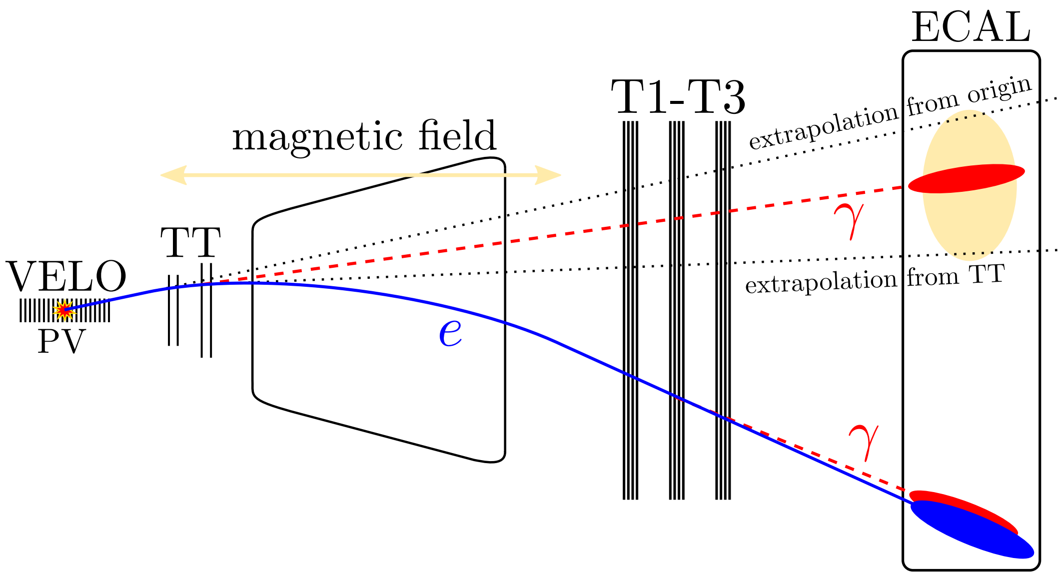


- Efficiency bottleneck at hardware trigger:
  - $p_{\mathrm{T}}(\mu^{\pm}) > 1.5 - 1.8$ GeV
  - $E_{\mathrm{T}}(e^{\pm}) > 2.5 - 3.0$ GeV

$$\frac{\epsilon(B^+ \to K^+\mu^+\mu^-)}{\epsilon(B^+ \to K^+e^+e^-)} \sim 3$$

⇒ **Electron channel yield drives the stat uncertainty on $R_{K^{(*)}}$**

Momentum measurement



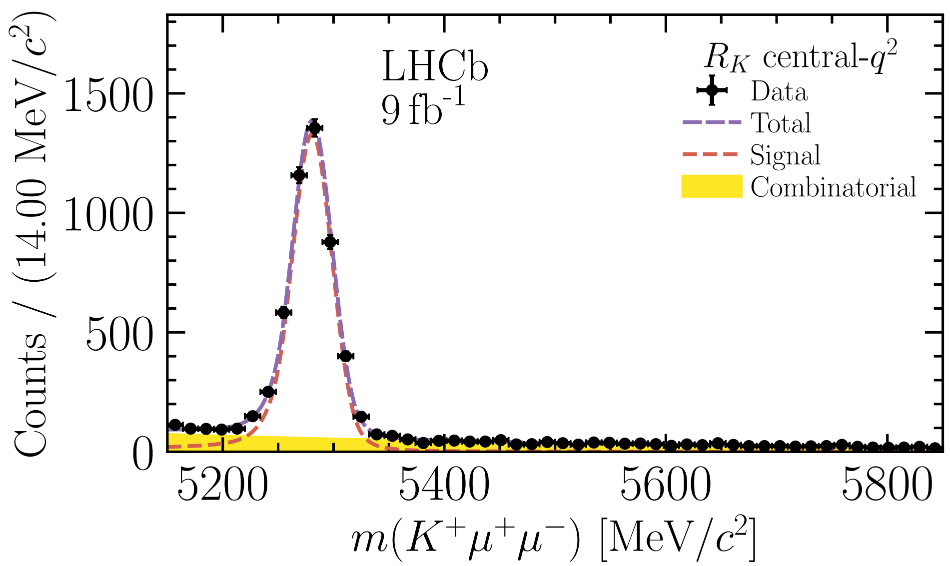
- ~0.4 X_0 of material before the magnet → energy loss to bremsstrahlung
- Brem recovery algorithm in place but has limited efficiency

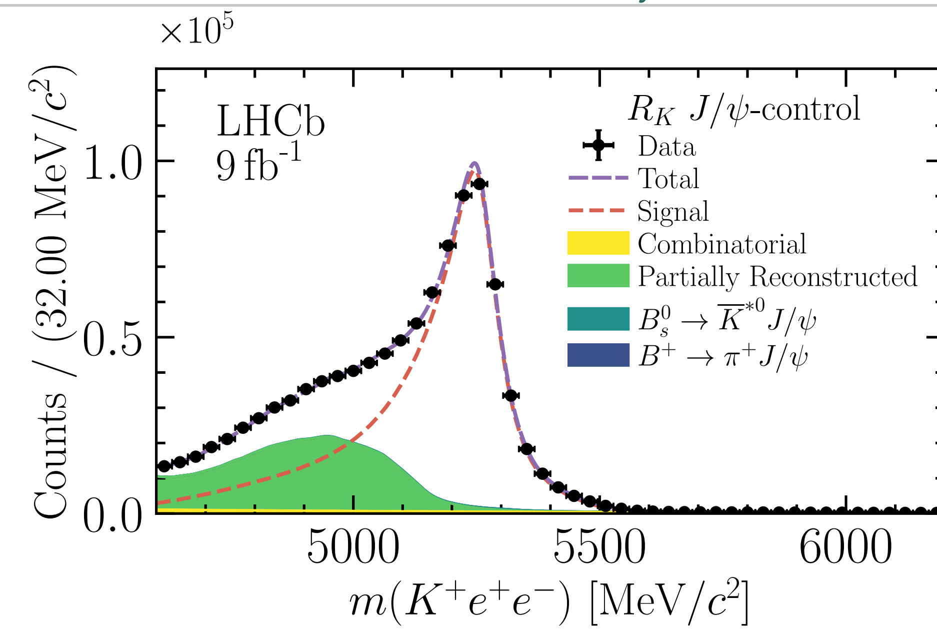
⇒ **Electron channel has worse *B* mass resolution**

⇒ **higher background rate**

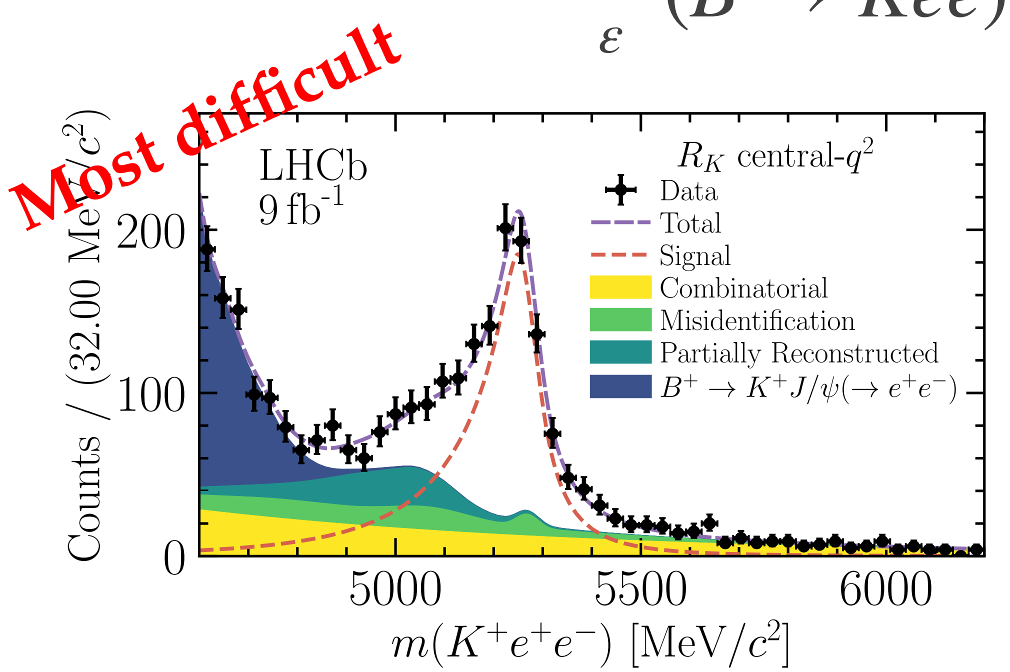
Signal yields

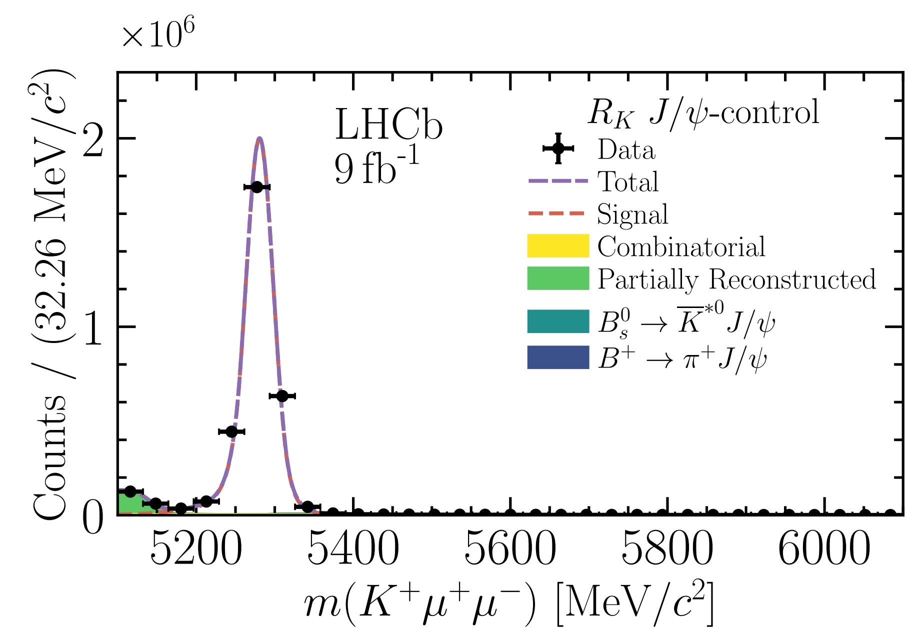
[Phys.Rev.D 108 (2023) 3, 032002](#)
[Phys.Rev.Lett. 131 (2023) 5, 051803](#)





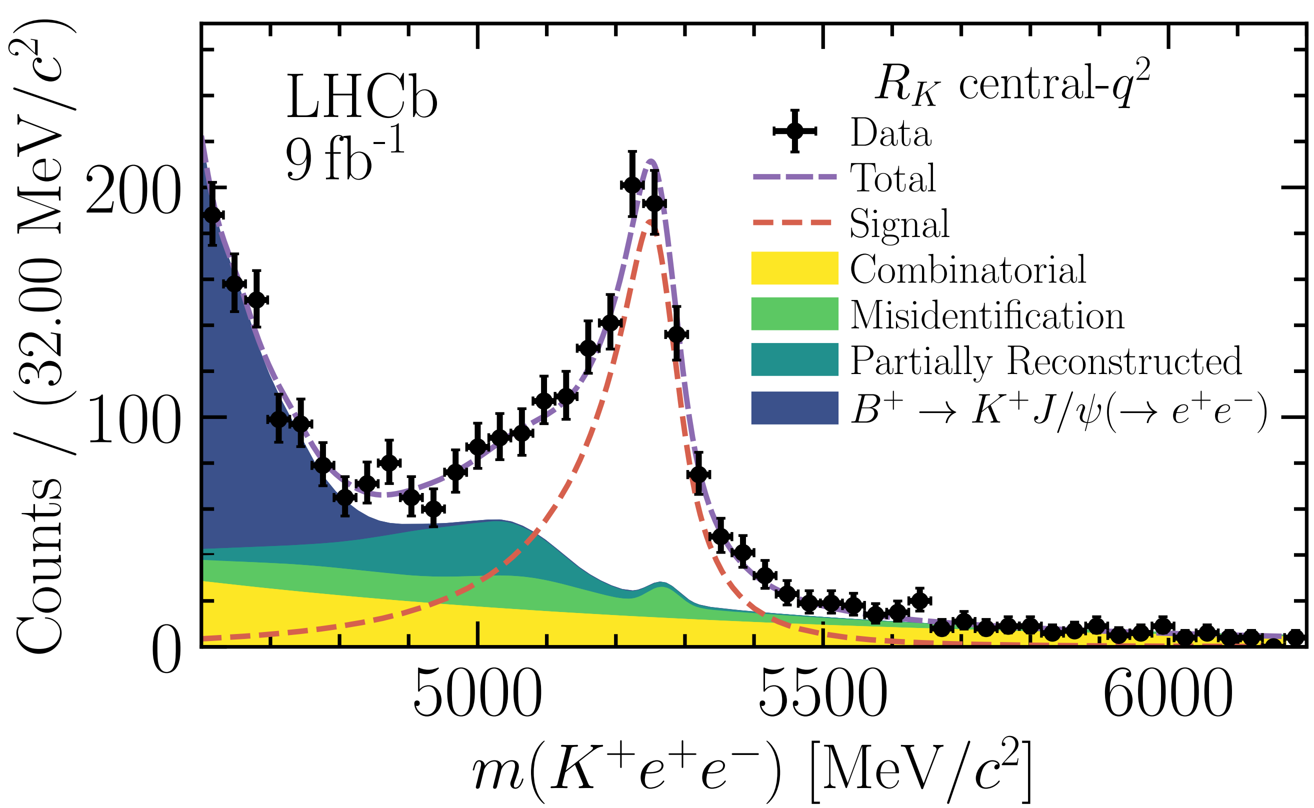
$$R_K = \frac{\frac{\mathcal{N}}{\varepsilon}\left(B \to K\mu\mu\right)}{\frac{\mathcal{N}}{\varepsilon}\left(B \to Kee\right)} \times \frac{\frac{\mathcal{N}}{\varepsilon}\left(B \to K\, J/\psi(ee)\right)}{\frac{\mathcal{N}}{\varepsilon}\left(B \to K\, J/\psi(\mu\mu)\right)}$$





Electrons fit

Phys.Rev.D 108 (2023) 3, 032002
Phys.Rev.Lett. 131 (2023) 5, 051803



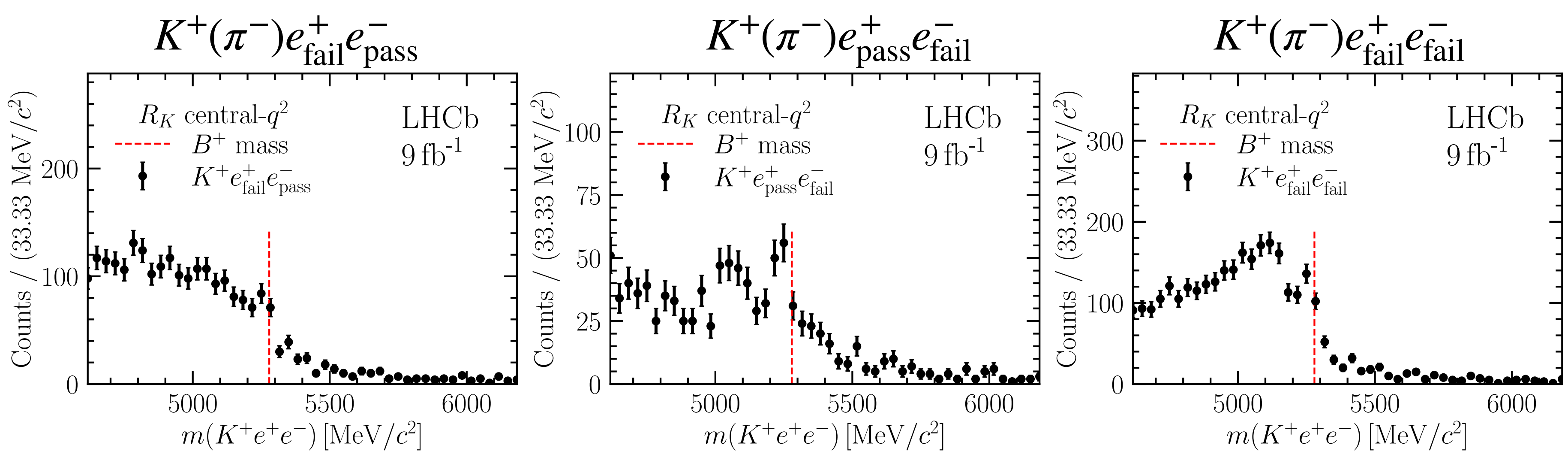
- $B \to K\,J/\psi$ leakage at low $m(ee)$ determined from control channel fit
- Combinatorial background modelled with exponential modified by part-reco selection
- **Part. reco. $B \to Kee$+hadrons**
  - Constrained from the signal yield of the $B^0 \to K^{*0}ee$ channel
  - Procedure accounts for the extrapolation to the full $m(K\pi)$ spectrum
- **Backgrounds from $e^{\pm}$ misID**

…see next slide

Electron misID

Phys.Rev.D 108 (2023) 3, 032002
Phys.Rev.Lett. 131 (2023) 5, 051803

- Dependence of 4-channels result on PID requirement
  $\Rightarrow$ misID component not negligible
- Yield and shape of misID component taken from data control regions enriched in $\pi \to e$ and $K \to e$ misID

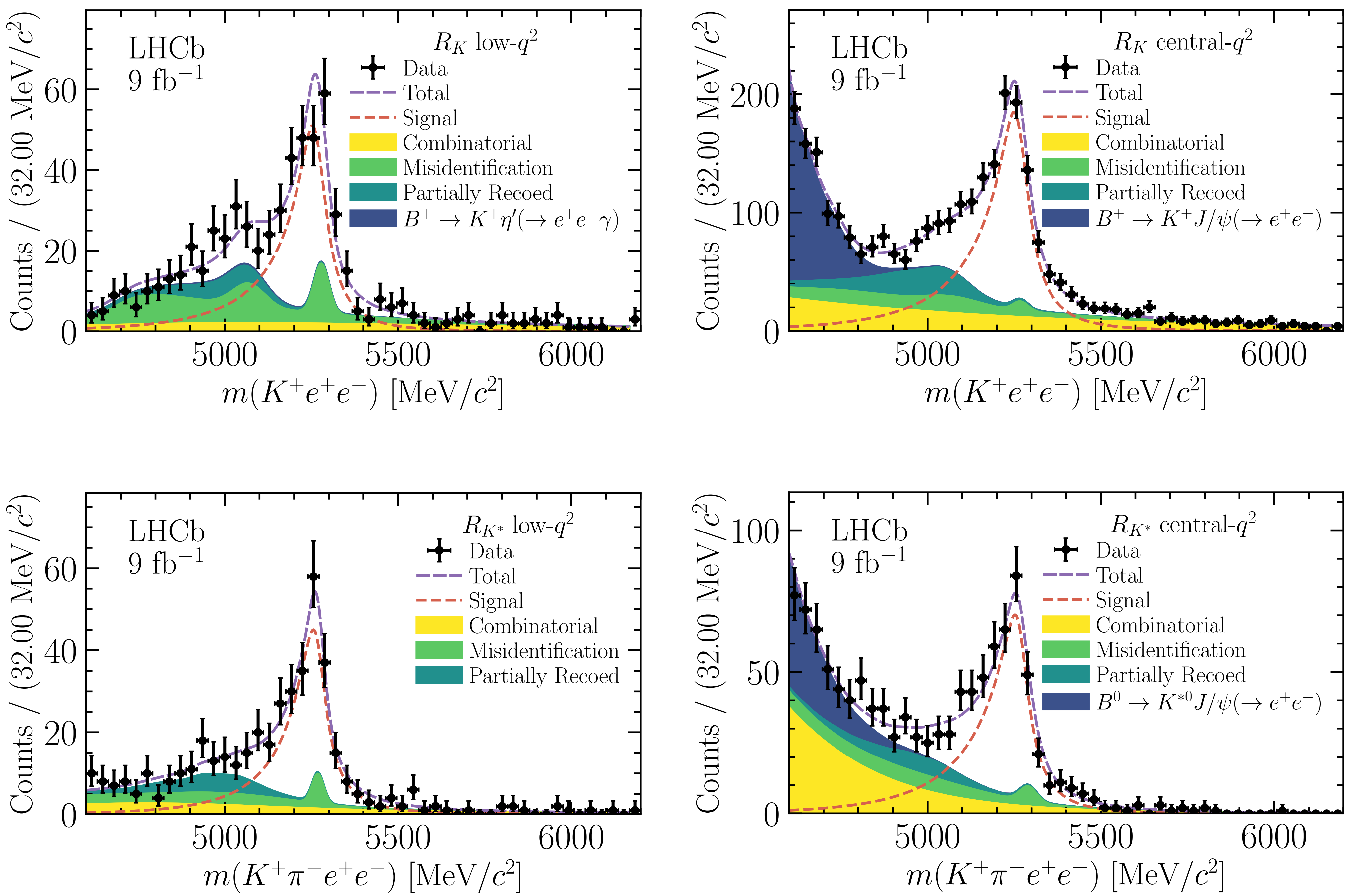


- Transfer function to signal region taken from pure K/π samples
- Procedure validated to 2% precision using peaking backgrounds $\bar{D}^0 \to K^+\pi^-$ and $B \to K^+h^+h^-$

Electron mass fits

Phys.Rev.D 108 (2023) 3, 032002
Phys.Rev.Lett. 131 (2023) 5, 051803

low-q^2 central-q^2

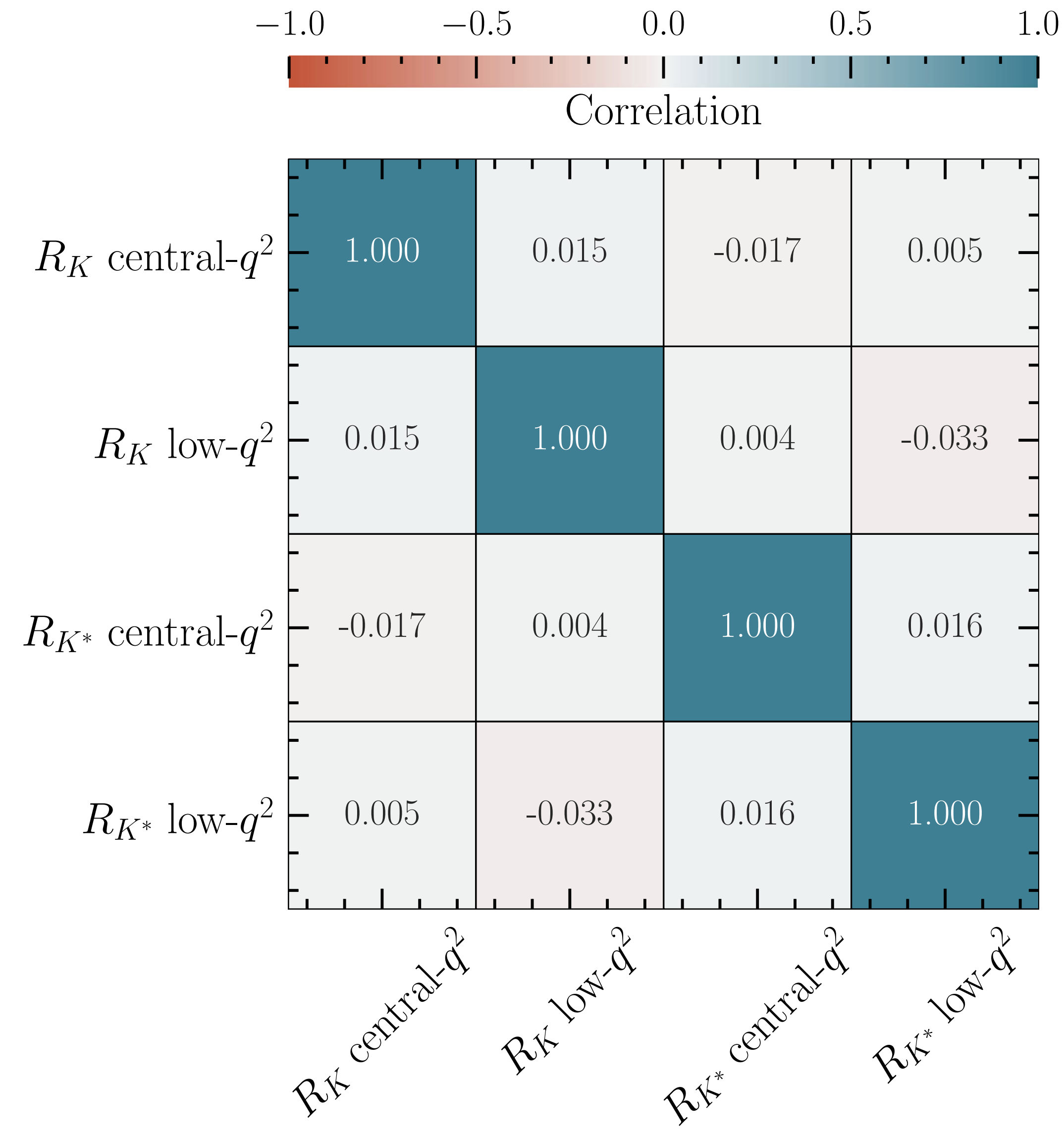


Results

Phys.Rev.D 108 (2023) 3, 032002
Phys.Rev.Lett. 131 (2023) 5, 051803

$$\text{low-}q^2 \begin{cases} R_K = 0.994^{+0.090}_{-0.082}(\text{stat})\,^{+0.029}_{-0.027}(\text{syst}), \\ R_{K^*} = 0.927^{+0.093}_{-0.087}(\text{stat})\,^{+0.036}_{-0.035}(\text{syst}), \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K = 0.949^{+0.042}_{-0.041}(\text{stat})\,^{+0.022}_{-0.022}(\text{syst}), \\ R_{K^*} = 1.027^{+0.072}_{-0.068}(\text{stat})\,^{+0.027}_{-0.026}(\text{syst}), \end{cases}$$



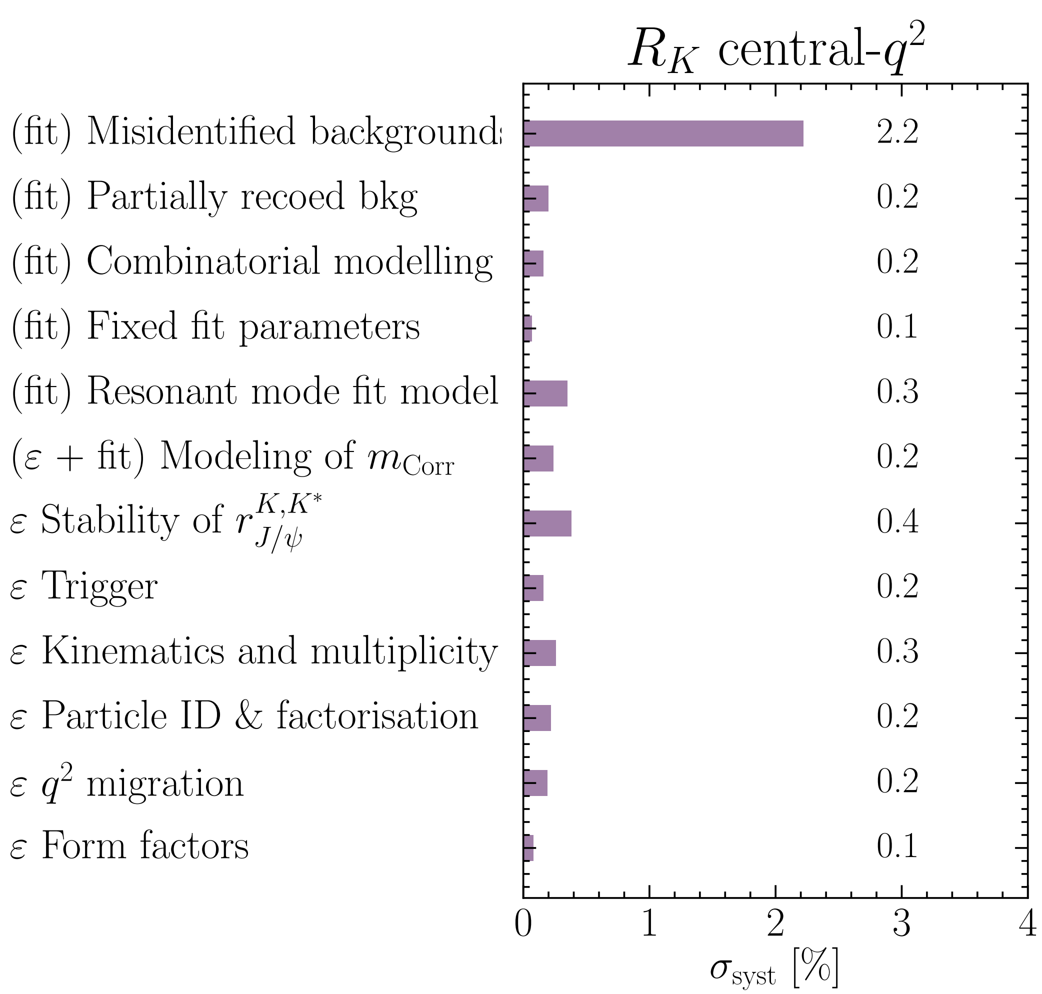
Still statistically dominated!

Towards the ultimate precision

[Phys.Rev.D 108 (2023) 3, 032002](#)
[Phys.Rev.Lett. 131 (2023) 5, 051803](#)

Let's consider only the central-q^2 R_K

$$R_K = 0.949^{+0.042}_{-0.041}\,(\text{stat})\,^{+0.022}_{-0.022}\,(\text{syst})$$



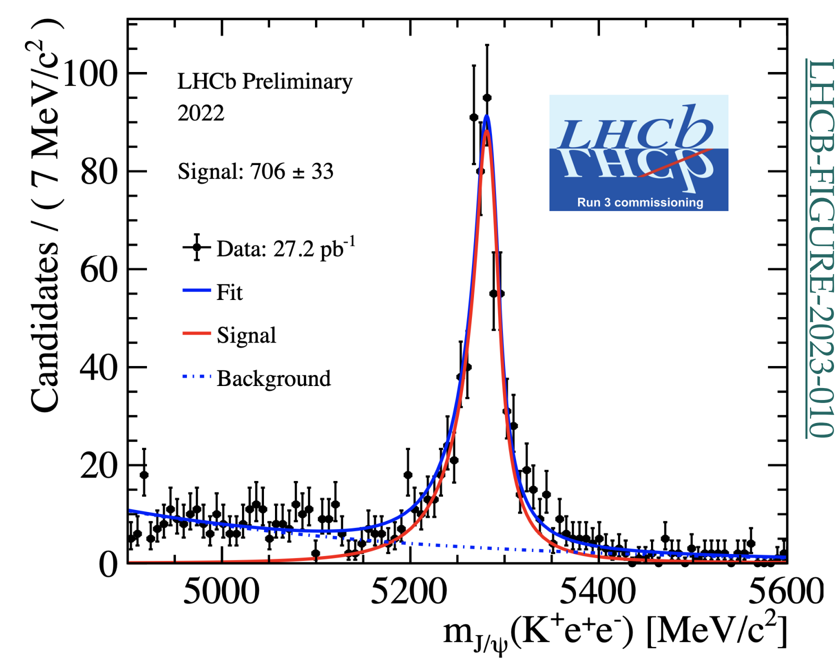
Theory uncertainty < 1%

Bordone et al [Eur.Phys.J.C 76 (2016) 8, 440](#)

[TDR LHCb upgrade I](#)

- LHCb recently upgraded to collect data at ~5× luminosity
  - Commissioning phase
  - Aim at collecting ~50 fb^{-1}

$B \to K\, J/\psi(ee)$ from 2022 data



- LHCb Phase II upgrade
  - Framework TDR and Physics case
  - Another ~10× higher lumi
  - Will reach theory uncertainty in R_K

Other channels and observables

- Tests at higher q^2 are WIP
- **Angular LU test** with $B^0 \to K^* \ell^+ \ell^-$
  - Can disentangle BSM contributions with different Lorentz structure
- Lots of potential in Λ_b decays
- Can test also rarer $b \to d\ell\ell$

CERN-LHCC-2018-027

R_X precision	9fb^{-1}
~~R_K~~	~~0.043~~
~~$R_{K^{*0}}$~~	~~0.052~~
R_ϕ	0.130
R_{pK}	0.105
R_π	0.302
~~$R_{K^0_S}$~~	~~0.26~~
~~$R_{K^{*+}}$~~	~~0.22~~

+ we are exploring high q^2

S.Glashow et al Phys.Rev.Lett. 114 (2015) 091801

- LFU violation implies LFV

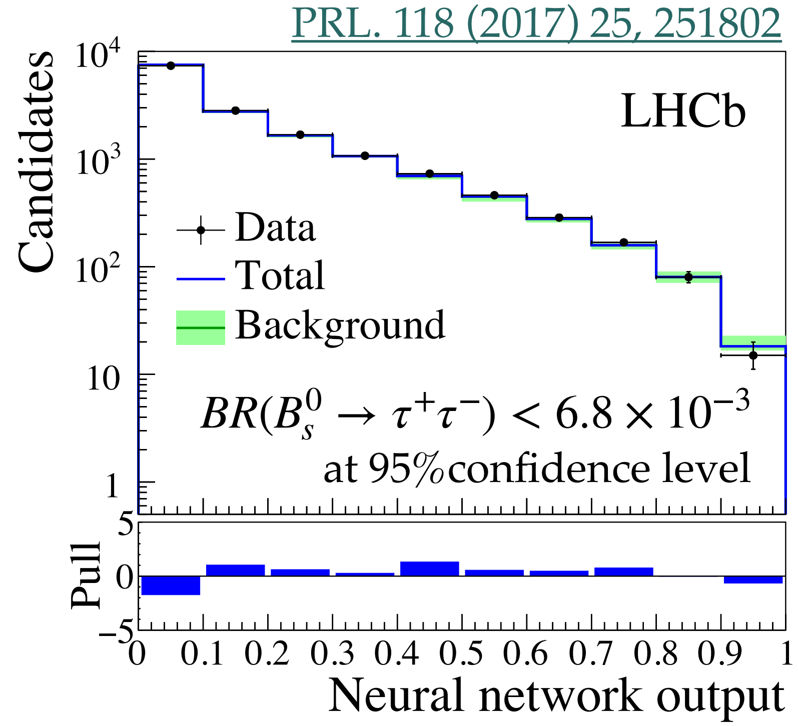
  → LFV searches in G.Mohanty's talk

Other leptons?

Tests with $b \to s\tau\tau$

- **Extremely challenging** $\tau^+\tau^-$ reconstruction at LHCb
- Searched for $B^0_{(s)} \to \tau^+\tau^-$ (Run 1)

PRL. 118 (2017) 25, 251802



- Search for $B \to K^{(*)}\tau\tau$ is WIP

Study $b \to s\nu\bar{\nu}$

- **Probably impossible** at LHCb
- Recent excess observed by Belle2
  $BR(B \to K^+\nu\bar{\nu}) = (2.40 \pm 0.67) \times 10^{-5}$

See S.Stefkova's talk

- ν flavour unidentified anyhow
- Interpretation relies on interplay with LFU results in charged leptons

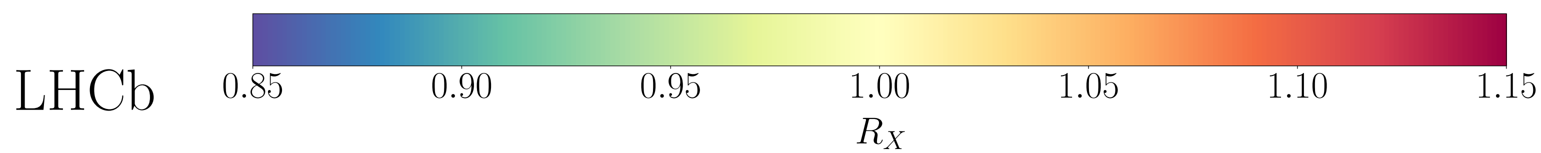
e.g. see Bause et al, ArXiv:2309.00075

Conclusions

- New simultaneous analysis of R_K and R_{K^*}
  - World's most precise test of LFU in $b \to s\ell\ell$
  - Results are compatible with LFU
- Presented state-of-the-art LFU tests in $b \to s\ell\ell$
  - Analysis tools ready to bring this to ultimate precision
  - Data from LHCb upgrades will reduce both stat and syst
- Additional LFU tests on the way:
  - Other hadronic channels and angular observables
  - Tests with $b \to d\ell\ell$ and searches for $b \to s\tau\tau$
- Very important set of measurements that will continue to test the SM LFU symmetry at higher and higher energy

BACKUP

PID requirements scans



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

DLL(e): *combination of sub-detectors delta-log-likelihood for π/e*

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

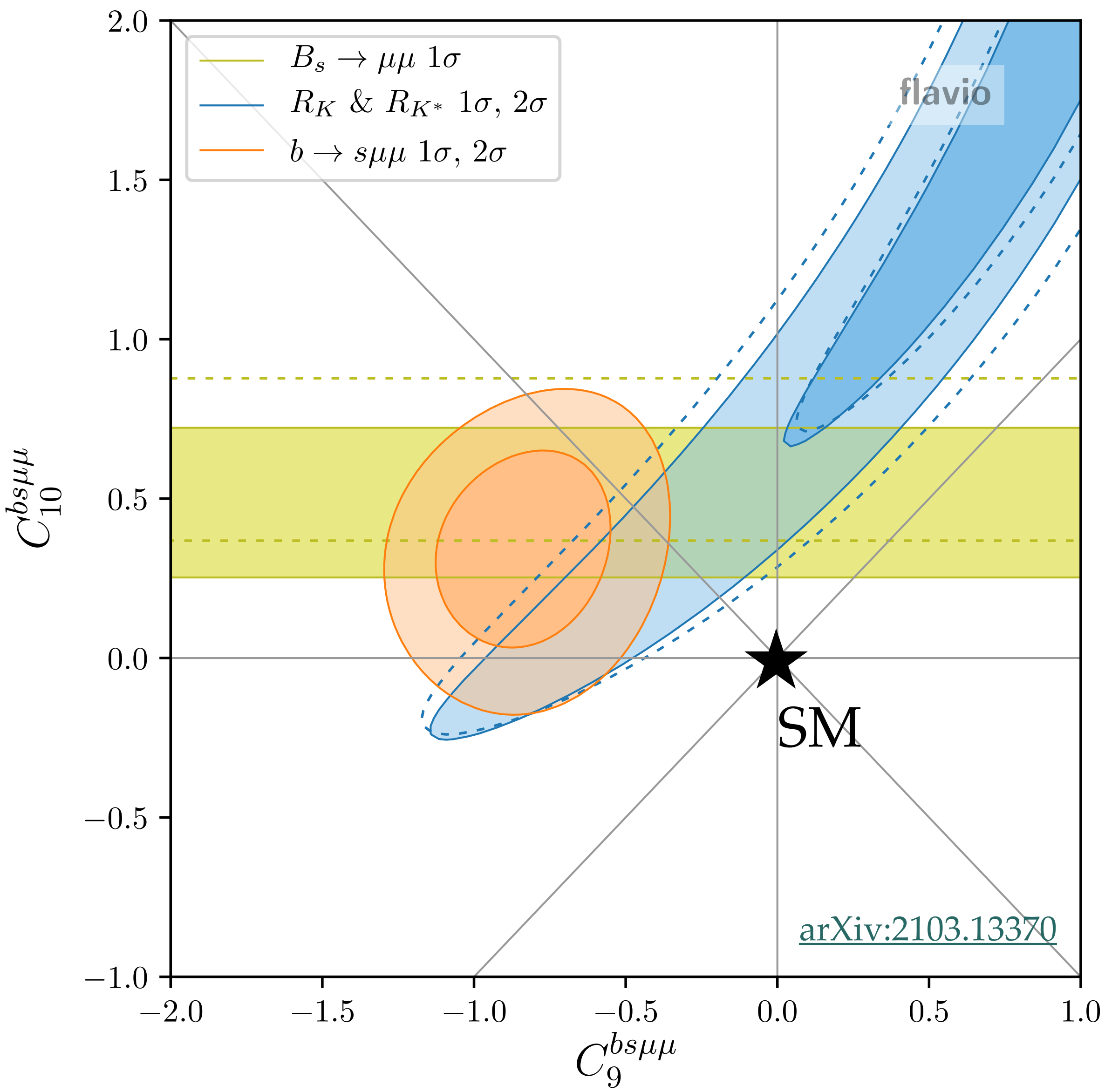
	ProbNN(e) > 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	1.127 ± 0.100	1.119 ± 0.099	1.116 ± 0.099	1.103 ± 0.098	1.097 ± 0.097	1.083 ± 0.095	1.097 ± 0.099	1.113 ± 0.101	1.119 ± 0.103
DLL(e) > 5	1.021 ± 0.074	1.016 ± 0.074	1.016 ± 0.075	0.997 ± 0.073	1.016 ± 0.076	1.001 ± 0.075	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

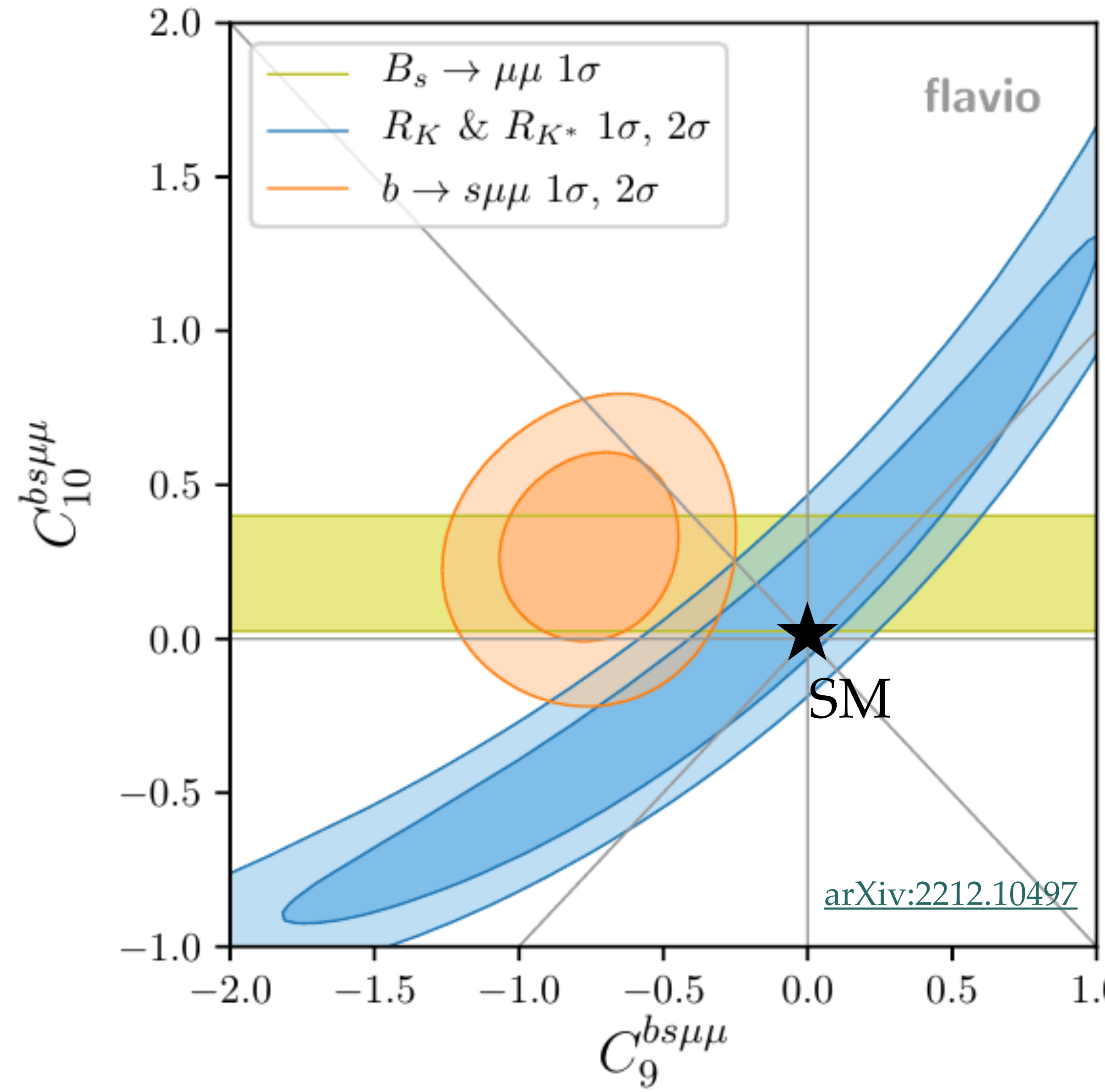
ProbNN(e): *neural-net based e-ID score*

Tightening selection in electron PID without specific treatment of electron misidentified backgrounds exhibited a coherent pattern

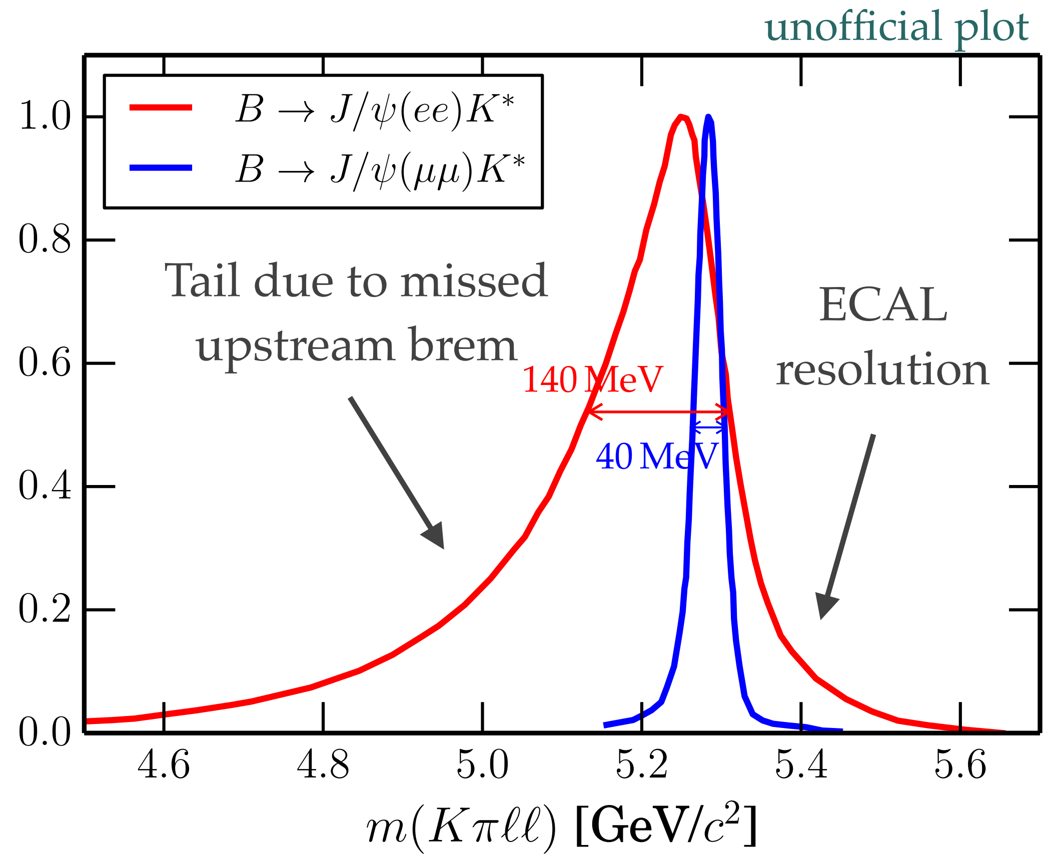
No more coherent pattern

2021 → 2023





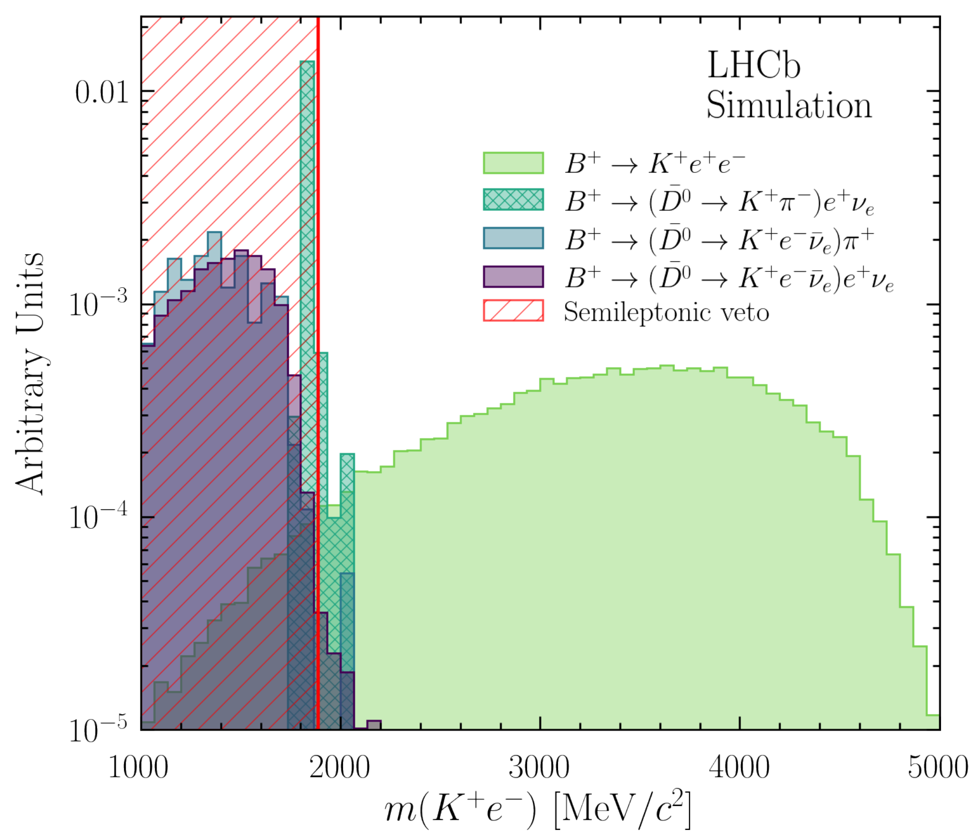
B mass resolution



Reducing backgrounds in electrons

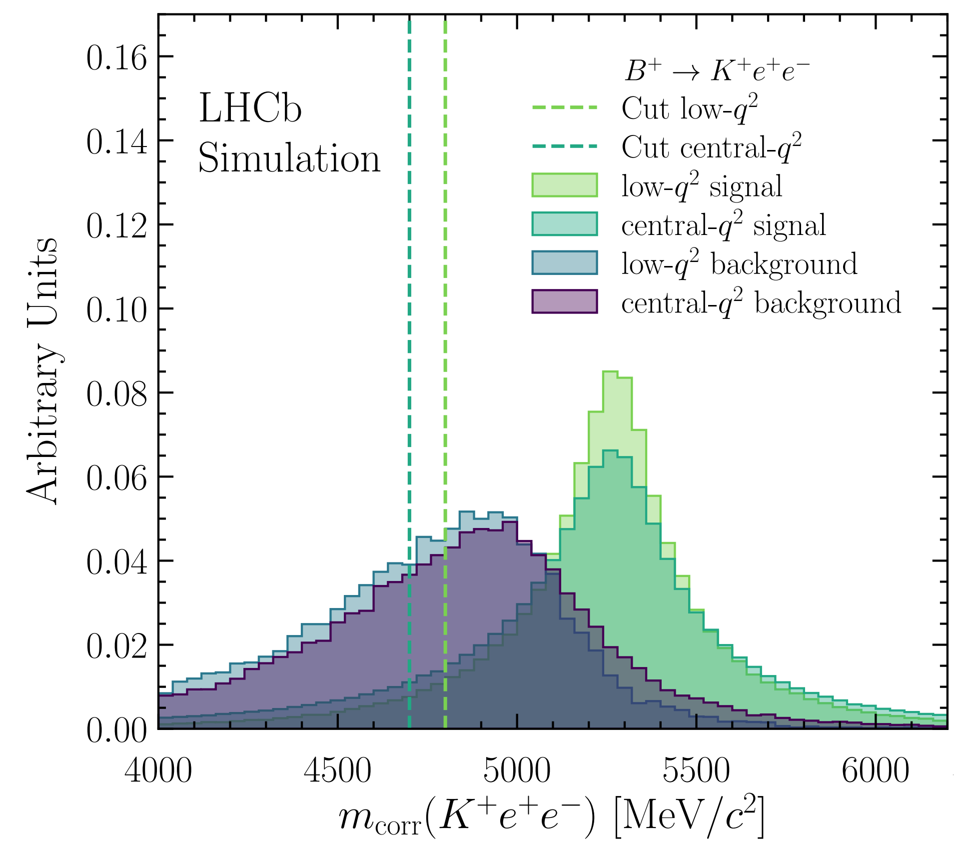
Phys.Rev.D 108 (2023) 3, 032002
Phys.Rev.Lett. 131 (2023) 5, 051803

Vetoes



- Efficient kinematic+PID criteria to reduce specific backgrounds
- e.g.: veto $b \to c \to s$ cascade ($\epsilon < 4\%$)

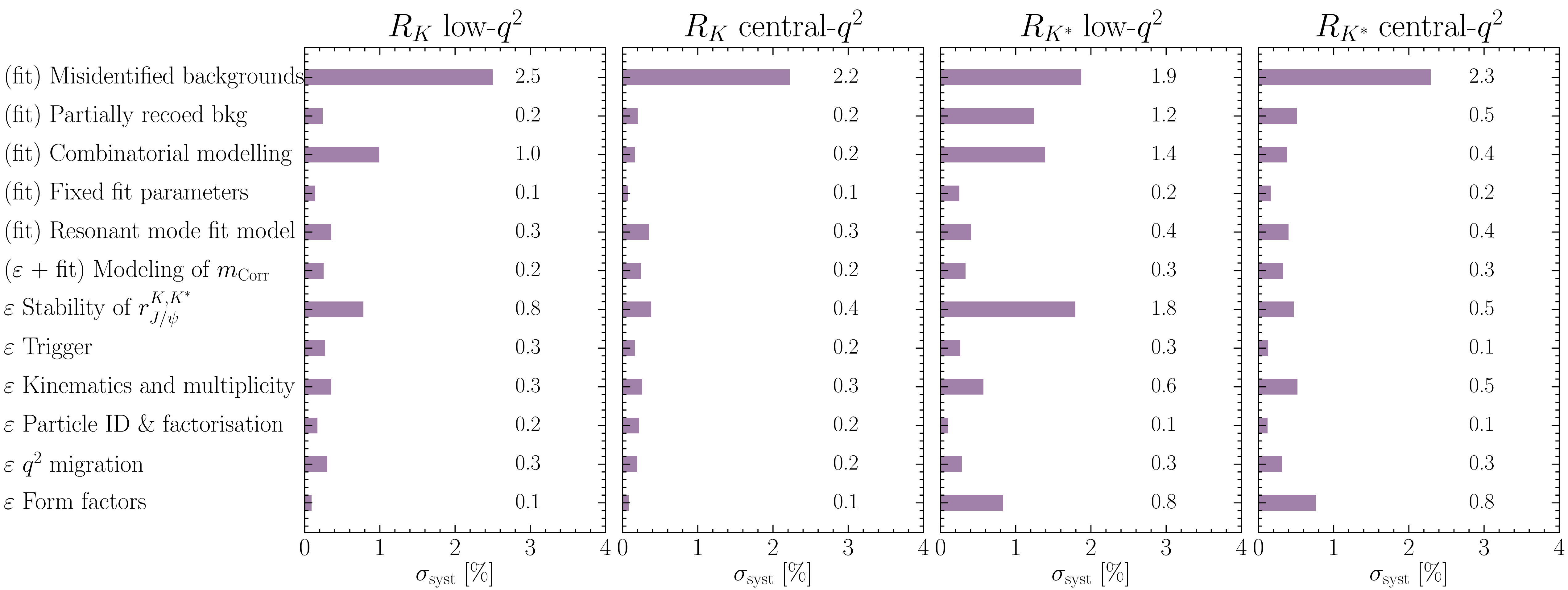
MVA selection



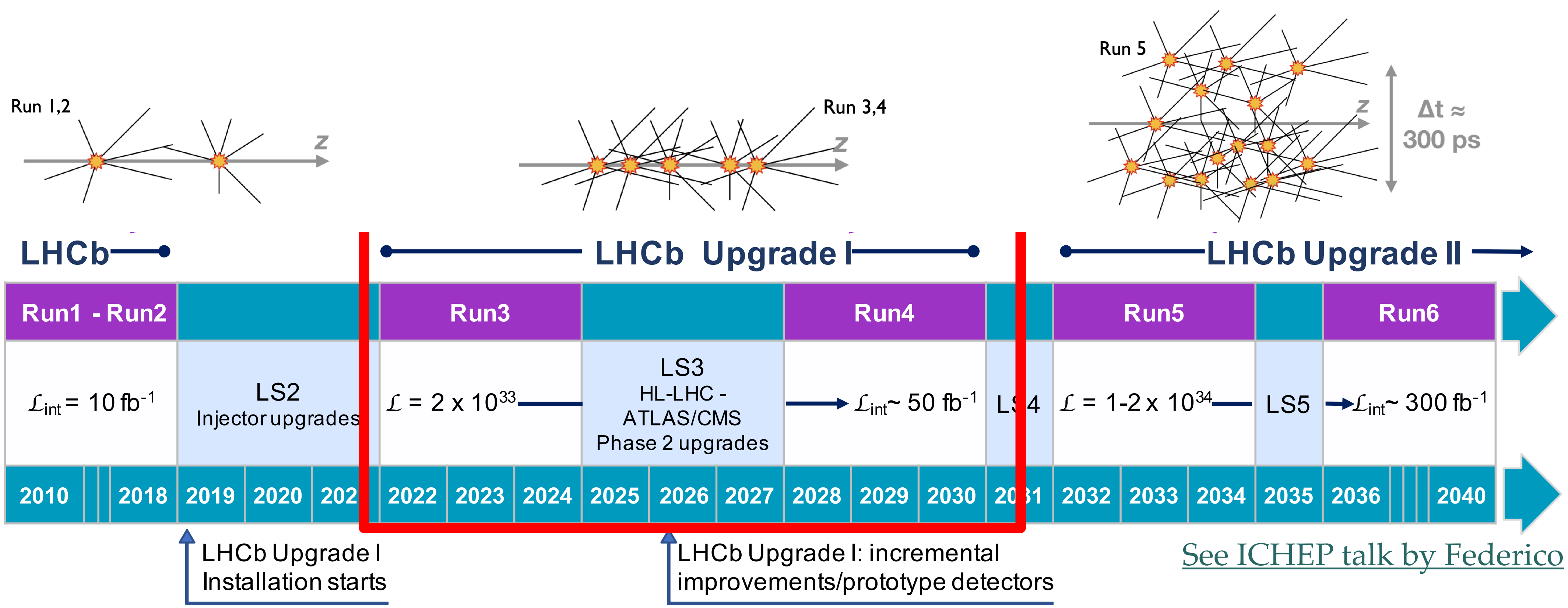
- Partially reconstructed background
  - MVA trained on vertex and track isolation
  - Cut on minimum of B corrected mass
- Combinatorial background
  - MVA trained on kinematics and vertices
  - Used for both muons and electrons

Systematics

Phys.Rev.D 108 (2023) 3, 032002
Phys.Rev.Lett. 131 (2023) 5, 051803



LHCb Upgrade II



See ICHEP talk by Federico