New results on lepton universality tests from LHCb

Shanzhen Chen

IHEP, CAS

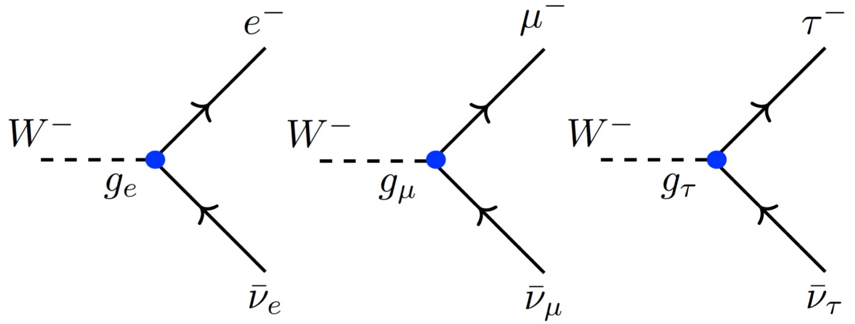
IAS Program on High Energy Physics - Mini-workshop on Experiment/Detector

Outline

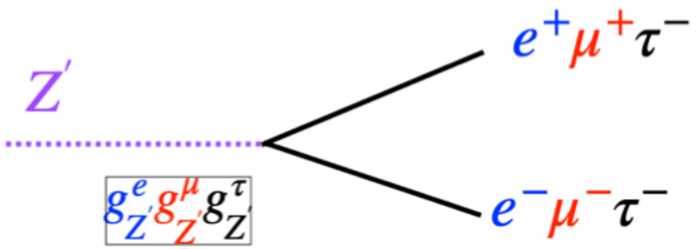
- Lepton flavour universality (LFU) and the LHCb detector
- b →clν: R(D) and R(D*)
- b →sll: R(K) and R(K*)
- Prospects and Conclusions

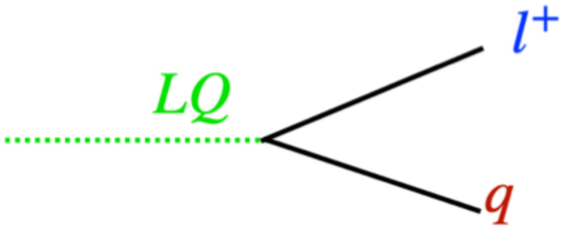
Lepton Flavour Universality in the Standard Model

- Lepton Flavour Universality: In SM, EW couplings are independent from lepton flavours



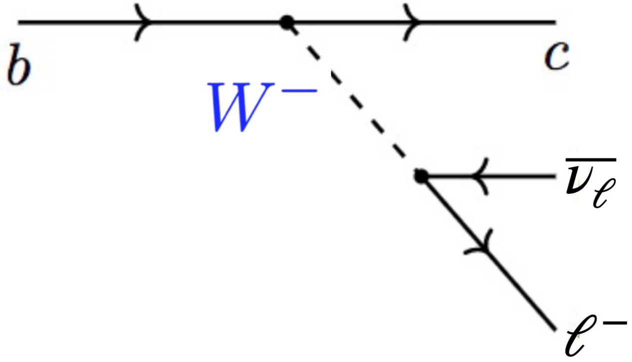
- Extensively verified in $Z \to ll$, $\tau \to l\nu\nu$, $J/\psi \to ll$, $\pi \to l\nu$, $K \to \pi l\nu$
- BSM new particles can break LFU at high energy scale



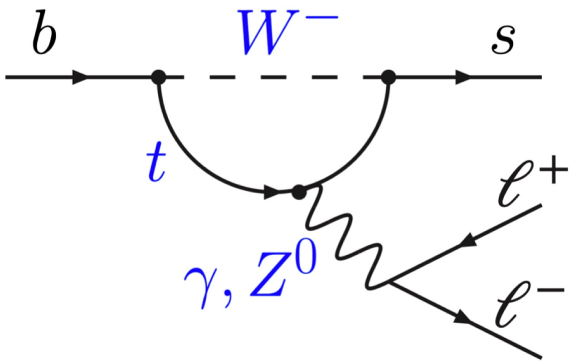


Lepton flavour universality tests with B decays

- LFU tests in b →clν at LHCb
  - Large branching fraction, tree level processes
  - Missing neutrino makes it experimentally challenging
  - e.g., R(D(∗)) = B($\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$) / B($\bar{B} \to D^{(*)}\mu^-\bar{\nu}_\mu$)

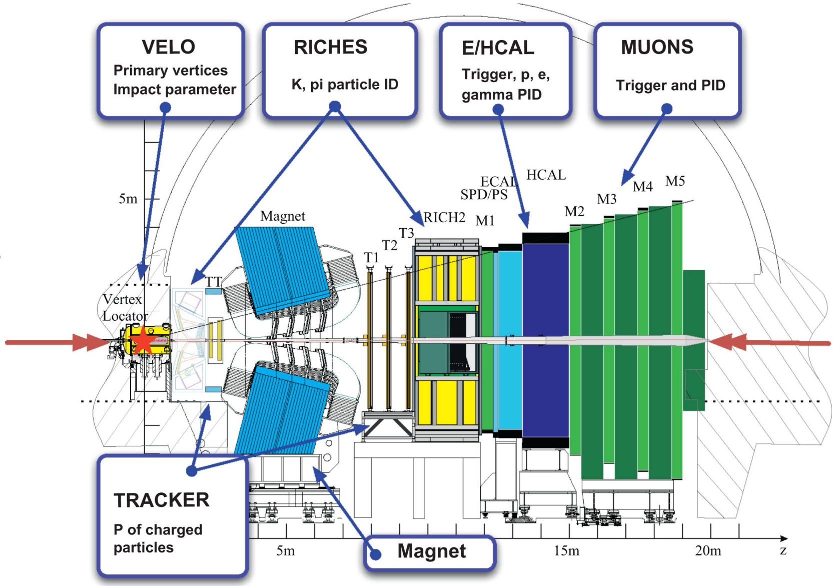


- LFU tests in b →sll at LHCb
  - branching fraction ~ O(10^{-6}), suppressed at tree level
  - Highly sensitive to NP
  - e.g., R(K(∗)) = B($\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)$)/($\mathcal{B}(B \to K^{(*)}e^+e^-)$)



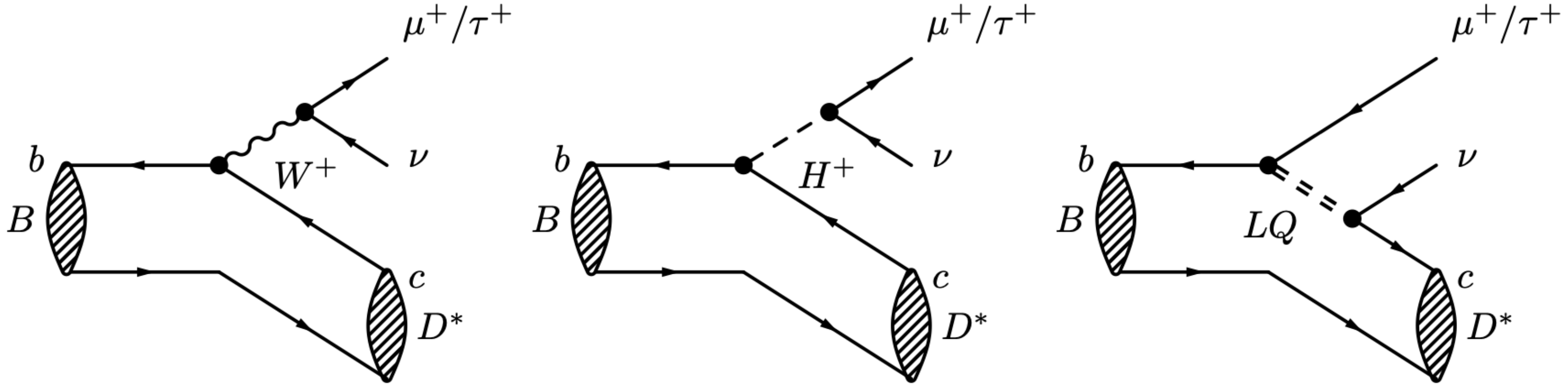
The LHCb experiment

- LHCb is dedicated for flavour physics studies, but also serve as a forward general-purpose detector
  - forward arm spectrometer with unique coverage in pseudorapidity ($2 < \eta < 5$)
  - catching 27% of b-quarks in 4% of solid angle
  - precision measurements in beauty and charm sectors
    - momentum resolution $\Delta p / p$ = 0.5% at < 20 GeV/c to 1.0% at 200 GeV/c
    - IP resolution (15+29/pT[GeV]) μm for high-pT tracks
    - decay time resolution 45 fs for Bs ->J/ψ φ and Bs ->Ds π
    - Particle ID with calorimeters, muon system and Cherenkov detectors (RICH)
  - Extended physics program to QCD, EW, direct searches
  - Participation in heavy ion runs
    - Unique operation mode as fixed-target experiment



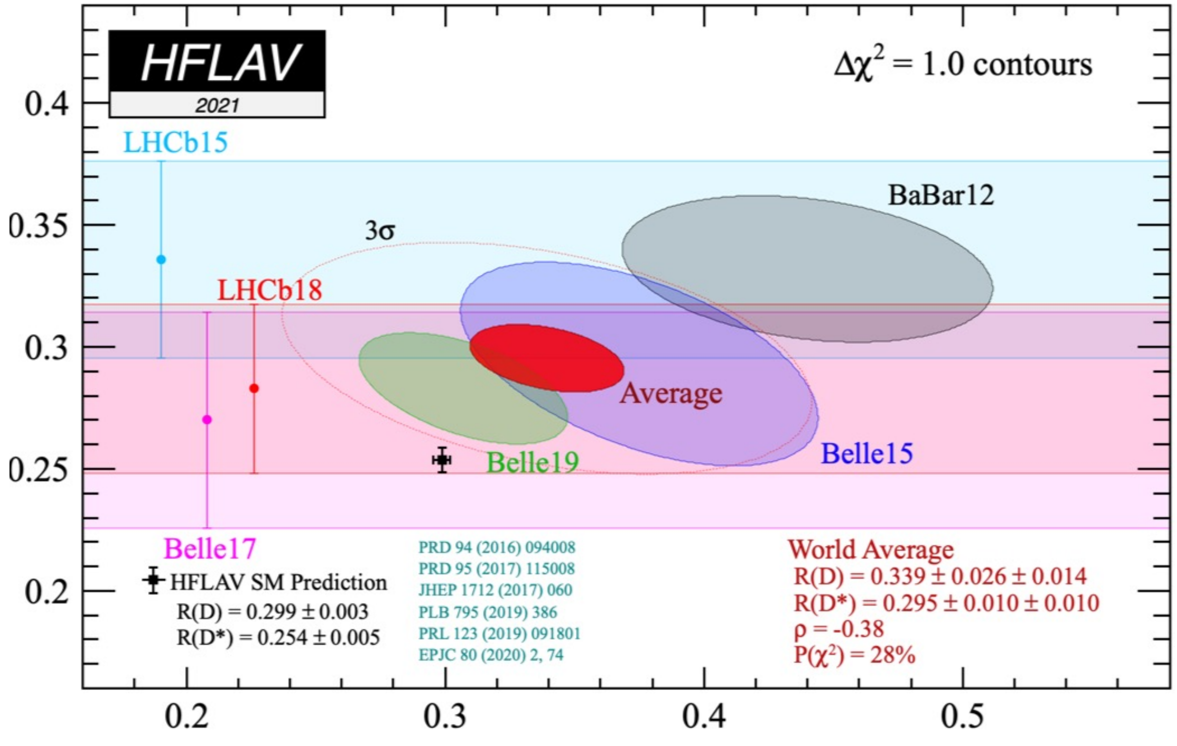
LFU tests in b → clν

- $R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c l \bar{\nu}_l)}$, where at LHCb l=μ, (at B-factories l=μ, e)
- $H_c = D^{*,+}, D^0, D^+, D_s^+, \Lambda_c^+, J/\psi$
- $H_b = B^0, B^+, B_s^0, B_c, \Lambda_b \ldots$
- R(D*) and R(D) :
  - Studied with $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ and $\bar{B} \to D^{(*)}\mu^-\bar{\nu}_\mu$,
  - Ratio R(D(∗)) = B($\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$) / B($\bar{B} \to D^{(*)}\mu^-\bar{\nu}_\mu$) is sensitive to e.g charged Higgs, leptoquarks



R(D*) and R(D)

- Previous measurements from LHCb and b-factories are combined



▸ **Using muonic $\tau \rightarrow \mu\nu\nu$** [PRL 115,111803 (2015)]

✦ $R(D^*) = 0.336 \pm 0.027 \pm 0.030$

(2.1σ above SM)

▸ **With 3-prong hadronic** [PRD 97, 072013 (2018)]

$\tau^+ \rightarrow \pi^+\pi^-\pi^+(\pi^0)\overline{\nu_\tau}$ [PRL 120, 171802 (2018)]

✦ $R(D^*) = 0.280 \pm 0.018 \pm 0.026 \pm 0.013$

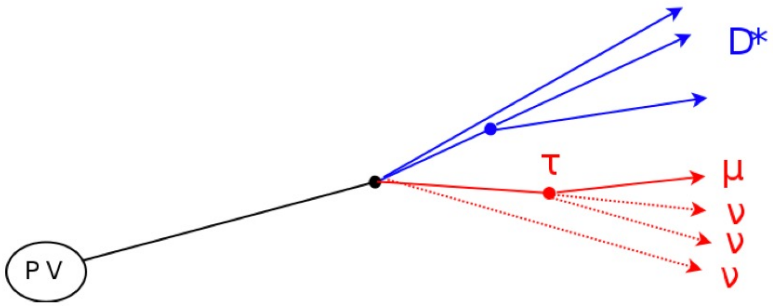
(1σ above SM)

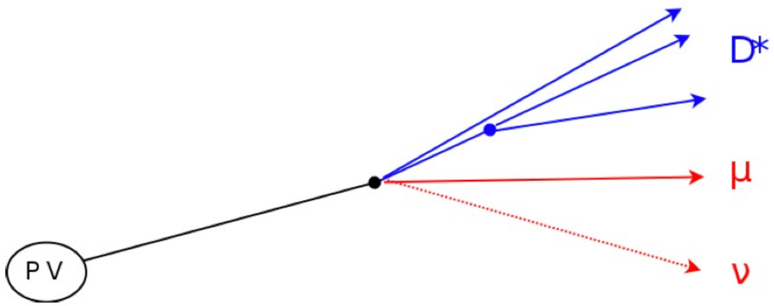
Combined results: Longstanding 3.3.σ hint of a deviation from lepton universality

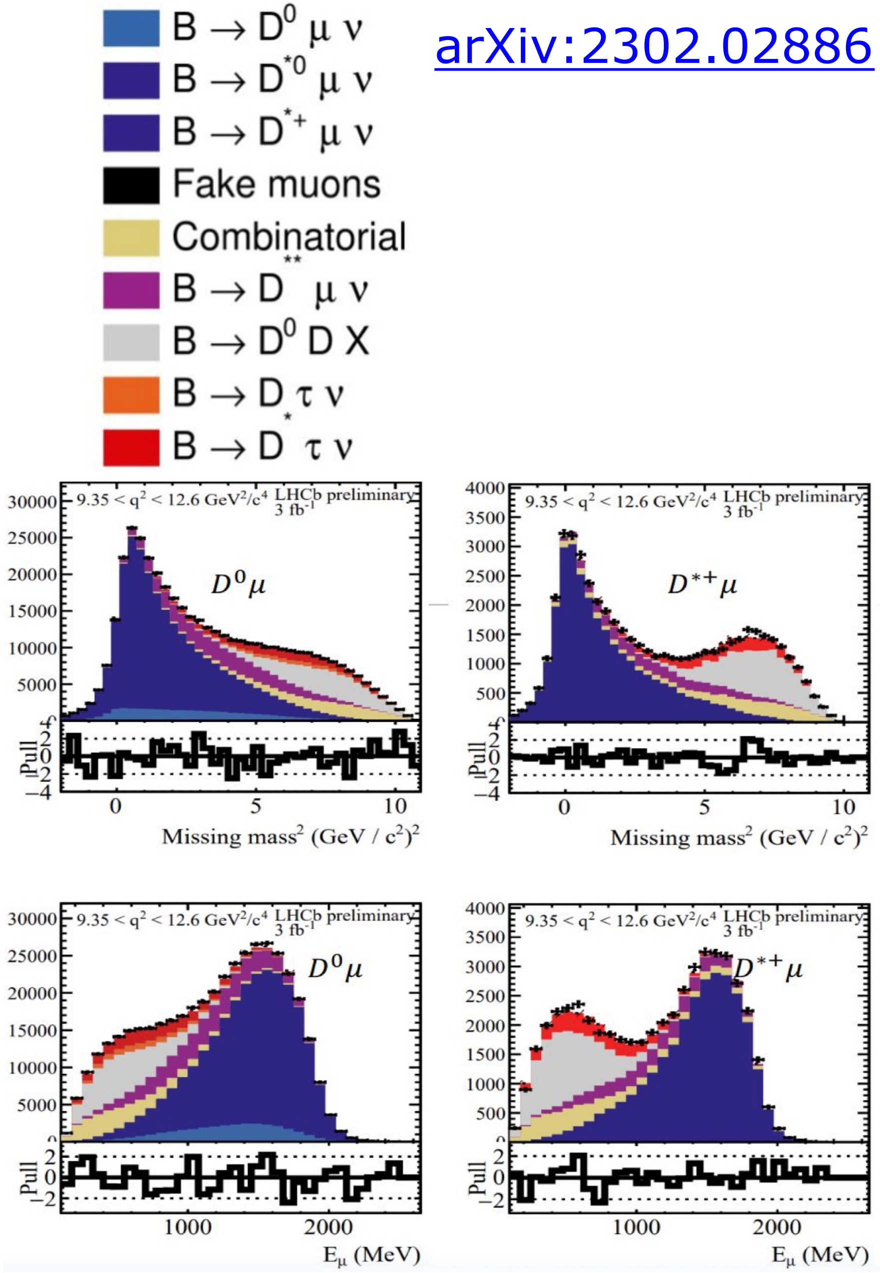
New study

[arXiv:2302.02886](https://arxiv.org/abs/2302.02886)

- $R(D^{(*)}) = \frac{\mathcal{B}(B\to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(B\to D^{(*)}l\bar{\nu}_l)}$, $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$, $D^* \to (D \to \pi K)\pi$
- Simultaneously measure R(D) and R(D*) with Run 1 data
  - Higher branching fraction and higher efficiency due to inclusion of not fully reconstructed D*
- Experimental challenges: neutrinos - 3 for $(\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu)\ \bar{\nu}_\tau$
  - No narrow peak to fit (in any distribution)
- $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ $\bar{B} \to D^{(*)}\mu^-\bar{\nu}_\mu$

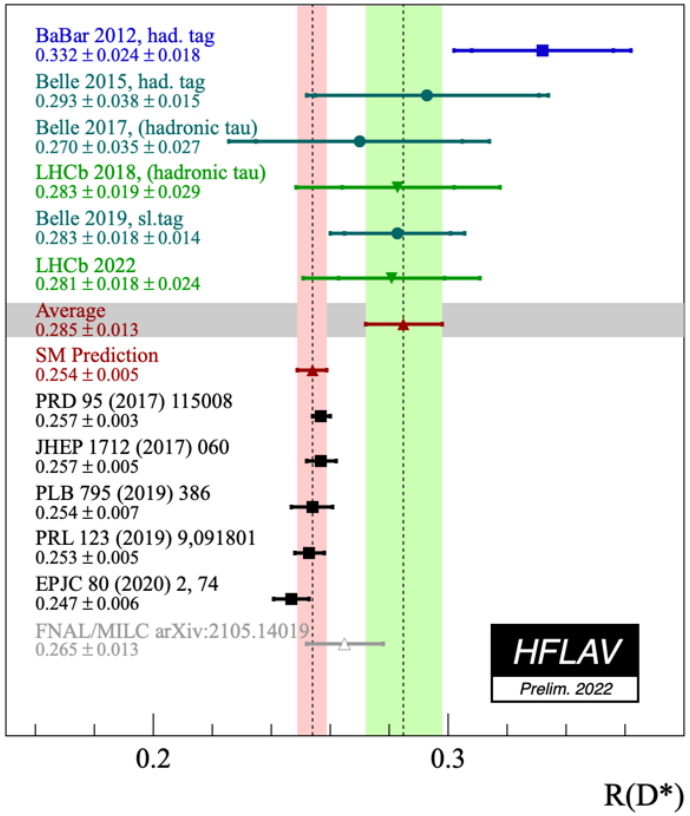


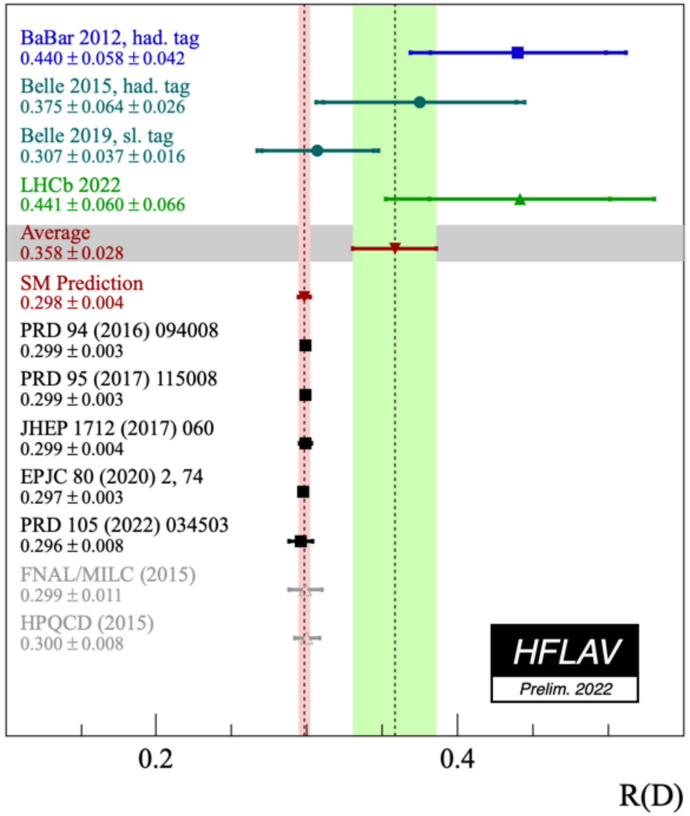




Results

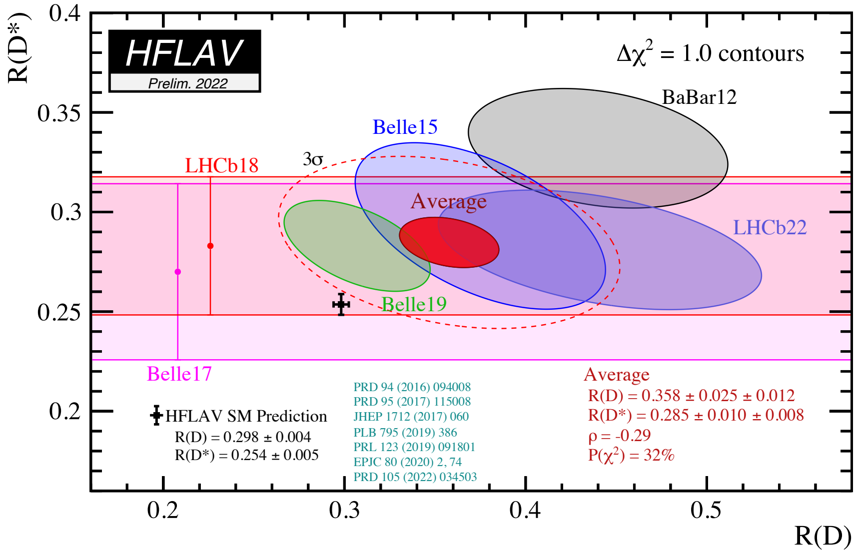
- Simultaneous fit to 8 samples
  - Signal sample + 3 control sample,
  - for both D^0 and D^*
- $R(D*)$=0.281 ± 0.018 ± 0.024
- $R(D)$=0.441 ± 0.060 ± 0.066
- slightly lower $R(D*)$,
  slightly higher $R(D)$,
- 1.9σ above SM





New combined result:

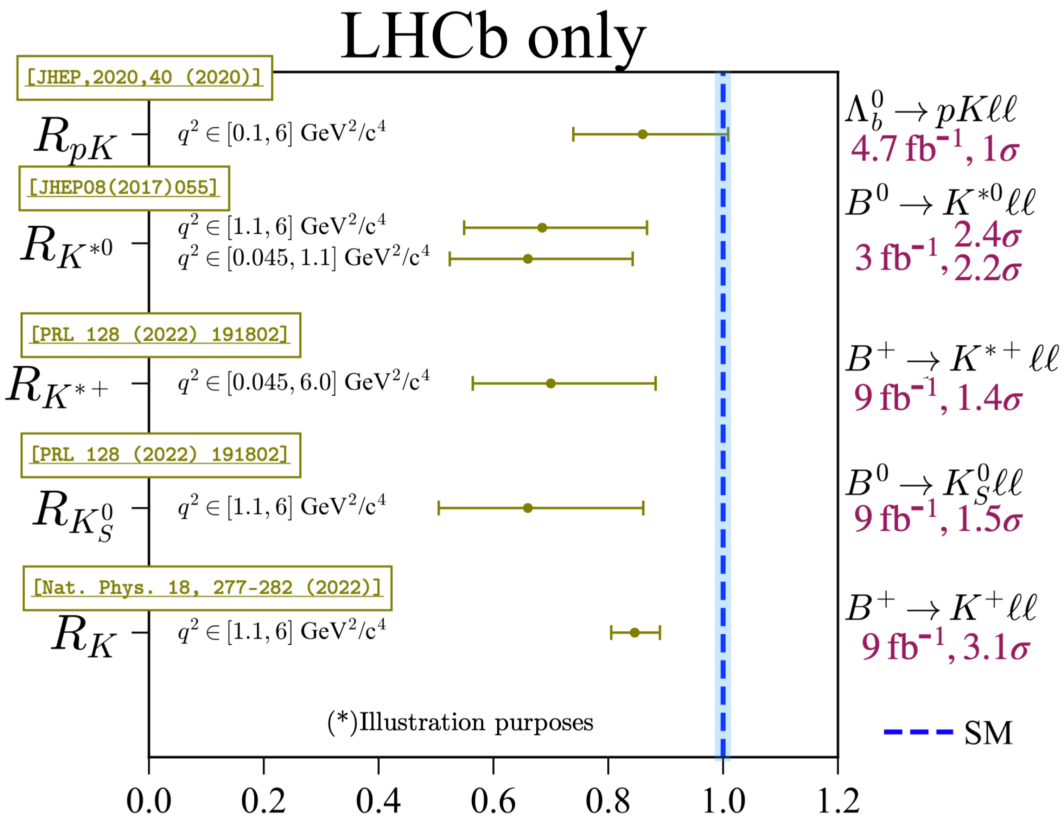
3.3σ → 3.2σ above SM



LFU tests in b->sll

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

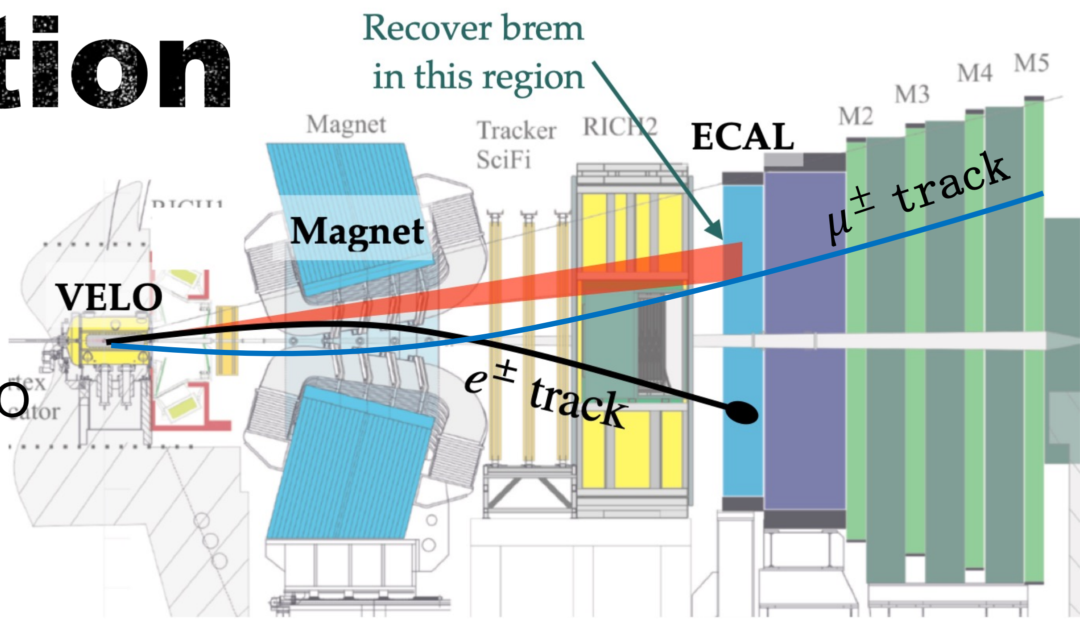
- Coherent pattern of tension to SM in LFU tests with b-> sll trasitions
  - Measure differential branching fraction vs dilepton invariant mass
- RX ratio extremely well predicted in SM
  - Cancelation of hadronic uncertainties at 10^{-4}
  - O(1%) QED correction [Eur.Phys.J.C 76(2016)8]
- Any departure from unity is a clear sign of New Physics

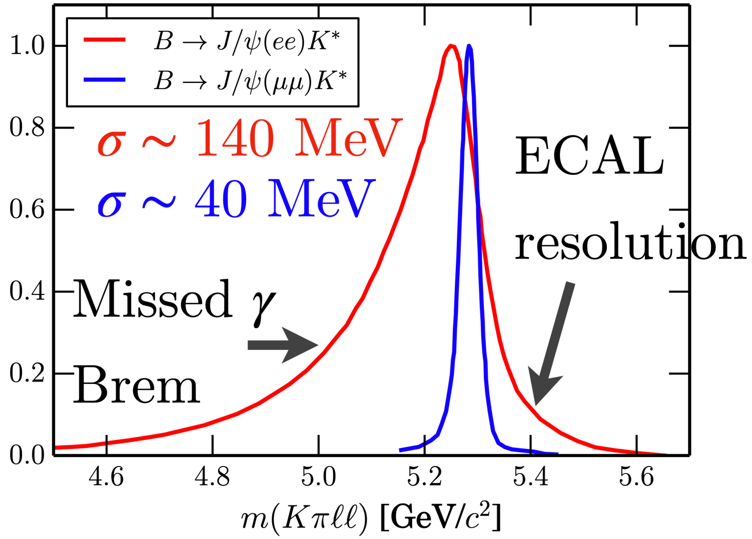


$q^2 = m^2(ll)$

Event reconstruction

- Electrons at LHCb
  - Emit bremmshtralung γ, high occupancy in ECAL
  - ECAL tight trigger thresholds and ID mostly from CALO
  - ε_{reco} and $\frac{\sigma_p}{p}$ worse than μ
- Muon at LHCb
  - Negligible bremmshtralung, MUON has low occupancy
  - Muon soft trigger thresholds and ID mostly from MUON
  - Excellent ε_{reco} and $\frac{\sigma_p}{p}$
- Overall, a ratio of ~ 3:1 of reconstructed muons to electrons in LHCb in Run1/2 data taking





arXiv:2212.09153
arXiv:2212.09152

New R(K) and R(K*) study

- Full Run 1 + Run 2 data
- $R_{K^{(*)}} = \dfrac{\int_{q^2 min}^{q^2 max} \frac{d\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2 min}^{q^2 max} \frac{d\mathcal{B}(B\to K^{(*)}e^+e^-)}{dq^2} dq^2}$
- Experimentally accessible through a double-ratio measurement
  - Use resonant-J/ψ mode as normalization to cancel out most of ε systematics in e/μ differences. Resonant-J/ψ mode also used for ε calibration
- $R_{K^{(*)}} = \dfrac{\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B\to J/\psi(\to\mu^+\mu^-)K^{(*)})} \Big/ \dfrac{\mathcal{B}(B\to K^{(*)}e^+e^-)}{\mathcal{B}(B\to J/\psi(\to e^+e^-)K^{(*)})}$
- $R_{K^{(*)}}$ measured in two q² regions

$$\begin{cases} \text{low-}q^2 : q^2 \in [0.1, 1.1]\,\text{GeV}^2/c^4 \\ \text{central-}q^2 : q^2 \in [1.1, 6.0]\,\text{GeV}^2/c^4 \end{cases}$$

Misidentified background in electron mode

- By tighten the PID requirement to electrons, the R(K$^{(*)}$) measurement shifts towards 1

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

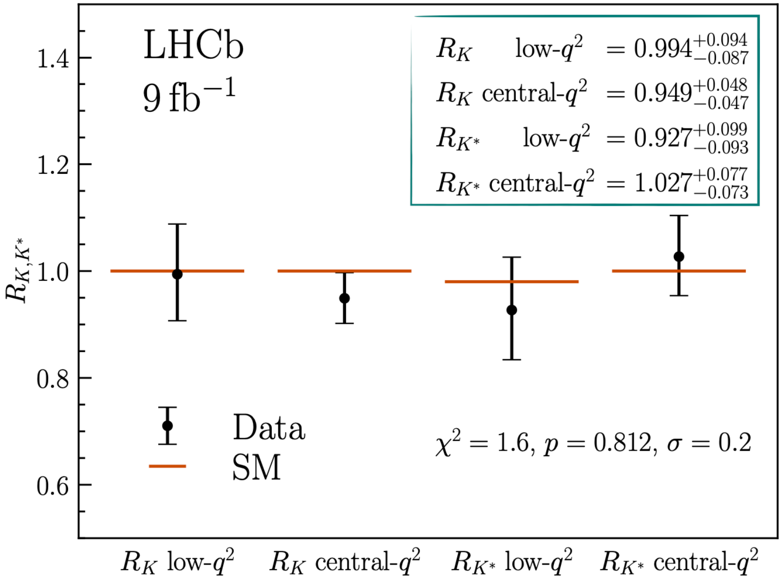
	ProbNN(e) > 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	1.127 ± 0.100	1.119 ± 0.099	1.116 ± 0.099	1.103 ± 0.098	1.097 ± 0.097	1.083 ± 0.095	1.097 ± 0.099	1.113 ± 0.101	1.119 ± 0.103
DLL(e) > 5	1.021 ± 0.074	1.016 ± 0.074	1.016 ± 0.075	0.997 ± 0.073	1.016 ± 0.076	1.001 ± 0.075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

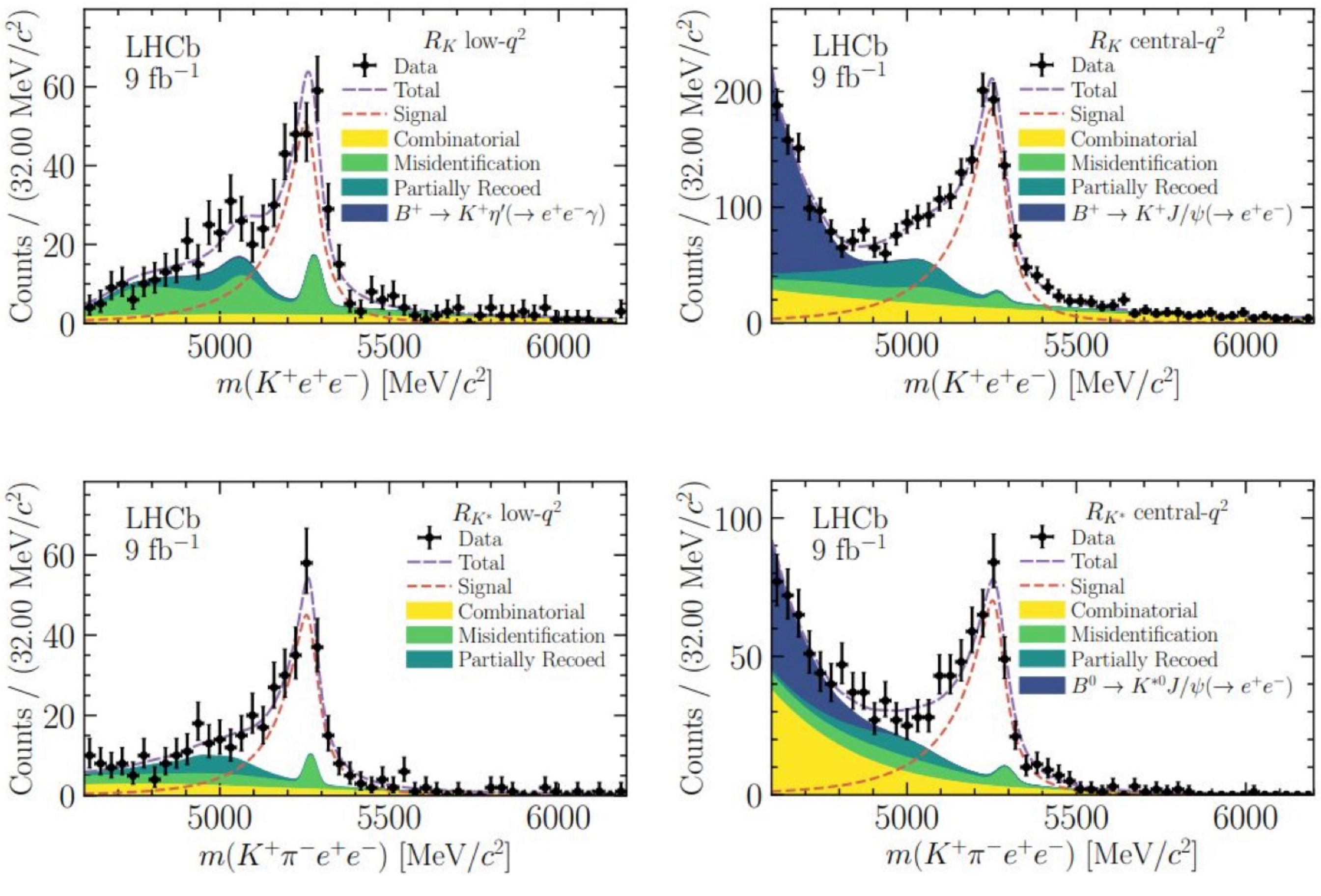
ProbNN(e): *neural-net based e-ID score*

- A new inclusive data-driven treatment of misidentified background implemented

Results

- Most precise and accurate LFU test in b -> sll trasition
- Compatible with SM with a simple χ^2 test on 4 measurement at 0.2 σ
  - *Previous R(K) results superseded*

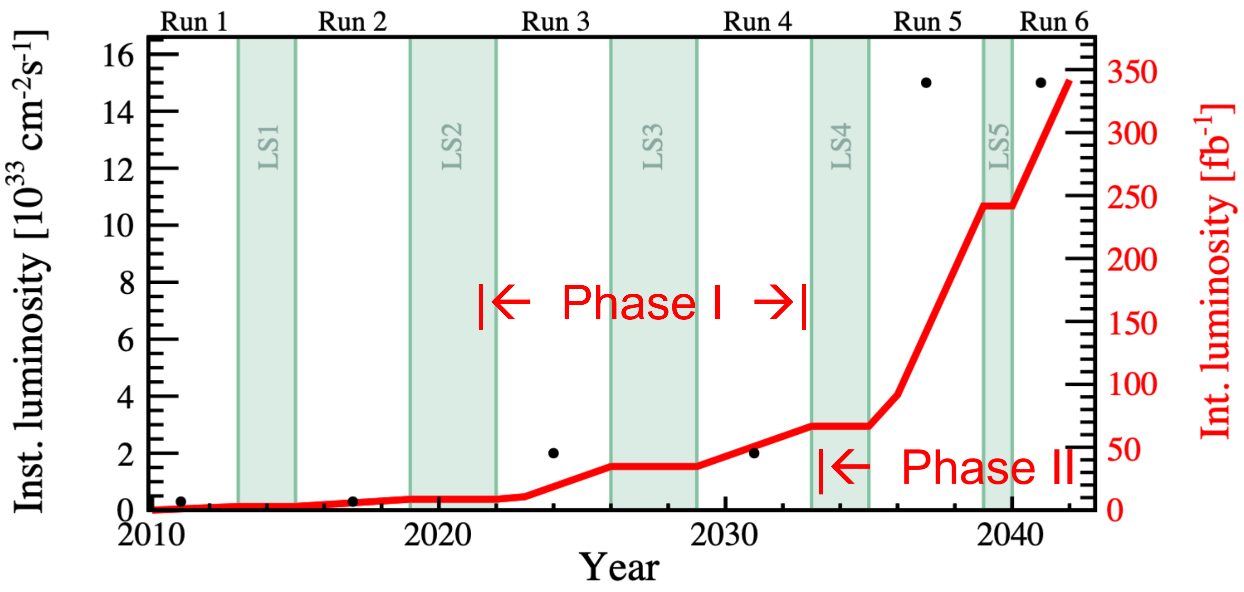




LHCb upgrade(s)

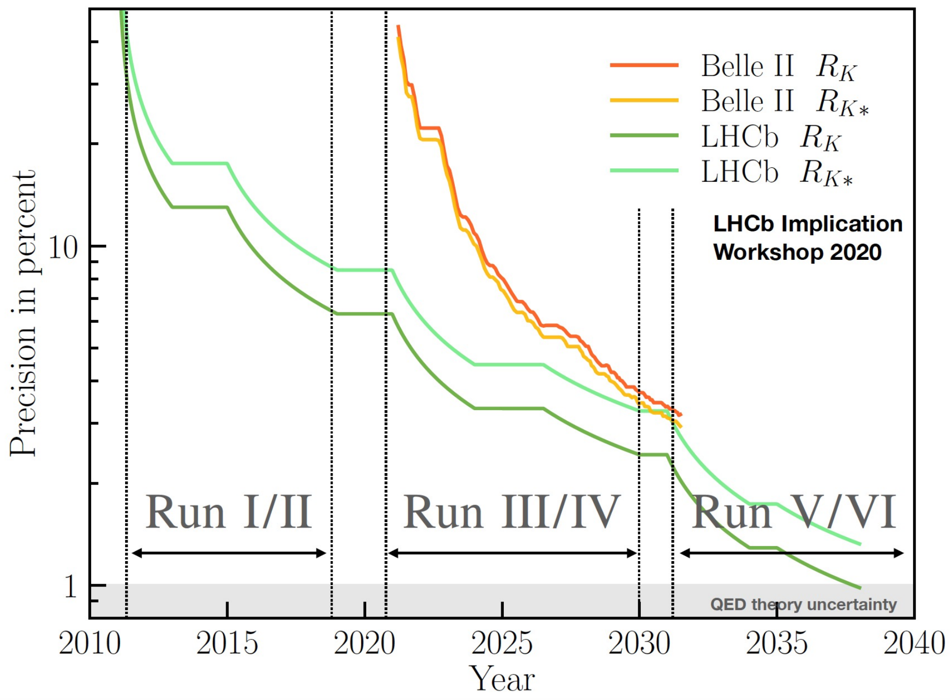
- Physics programme limited by detector, NOT by LHC
- Phase I Upgrade
  - a brand new detector!
  - L_{peak} = $2x10^{33}$ cm^{-2} s^{-1}
  - L_{int} = ~ 50 fb^{-1} during Run 3 & 4
- Phase II Upgrade
  - L_{peak} = $1.5x10^{34}$ cm^{-2} s^{-1}
  - L_{int} = ~ 300 fb^{-1} during Run 5 & 6, Install in LS4 (2033)
  - Some smaller detector consolidation and enhancements in LS3 (2026)
  - Potentially the only general purpose flavour physics facility in world on this timescale

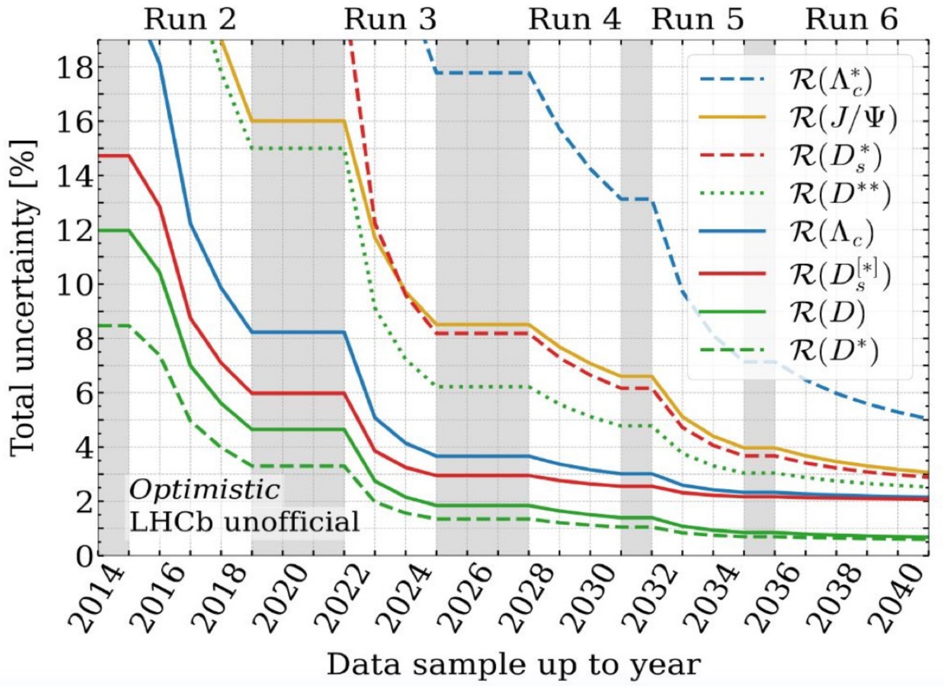
schedule updated beginning of 2022



LFU tests Prospects

- By scaling the uncertainties with luminosity, prospects on future LFU tests ability at LHCb can be obtained





Conclusions

- Lepton Flavour Universality tests are a clean probe to NP, complementing the direct researches
- R(D*) and R(D) studies:
  - 1.9.σ away from SM
  - Combined results with B-factories: 3.2σ hint of a deviation from lepton universality
- R(K) and R(K*) study:
  - Compatible with SM at 0.2σ
  - Previous R(K) results superseded
- Run III of LHCb has started, more data to come