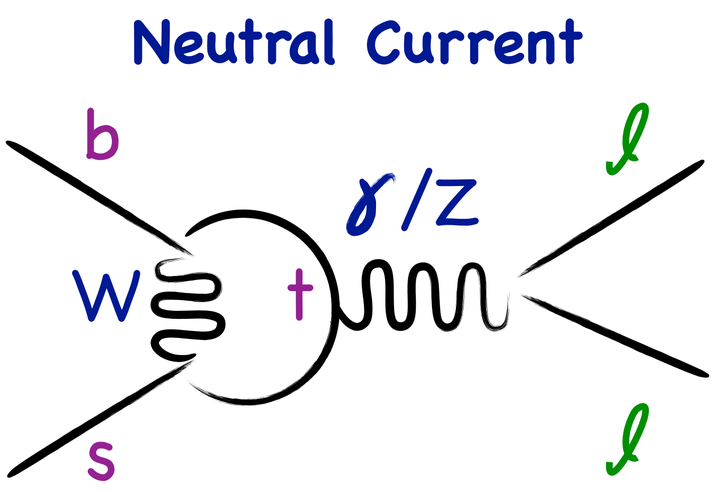
Flavour anomalies at LHCb

Andrea Mauri
On behalf of the LHCb collaboration

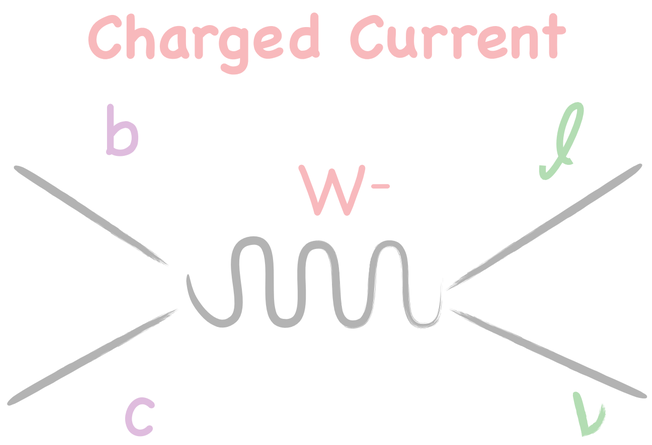
XVth Quark Confinement and the Hadron Spectrum conference
Stavanger 1-6 August 2022

Flavour anomalies

- **Flavour Changing Neutral Current (FCNC)**
  - e.g. $b \to s\ell\ell$ processes
  - very rare, BR $\sim \mathcal{O}(10^{-6})$ or lower



- **Charged Current (CC)**
  - e.g. $b \to c\ell\bar{\nu}$ decays
  - tree level: BR ~ few %

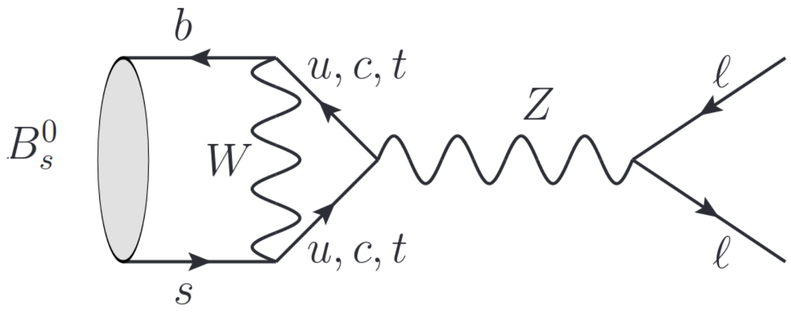


$B_s \to \mu^+\mu^-$

- A golden channel in flavour physics
  - Very rare 10^{-9} BR (helicity suppressed)
  - Precise 4% BR theoretical prediction

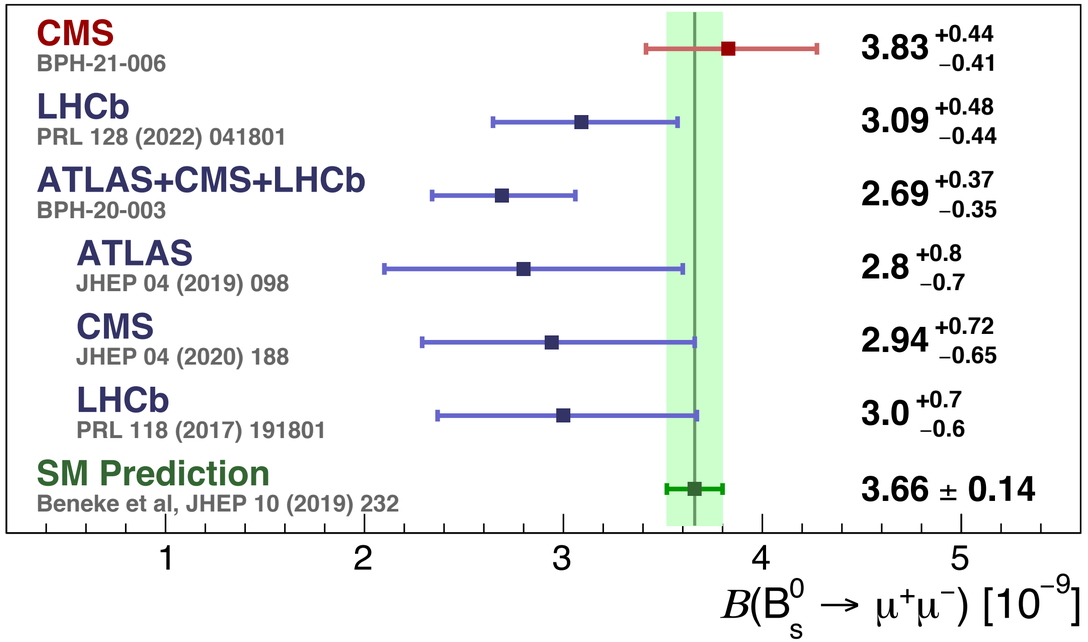
    Beneke et al. JHEP 10 (2019) 232

    Kozachuk et al., PRD 97 (2018) 053007



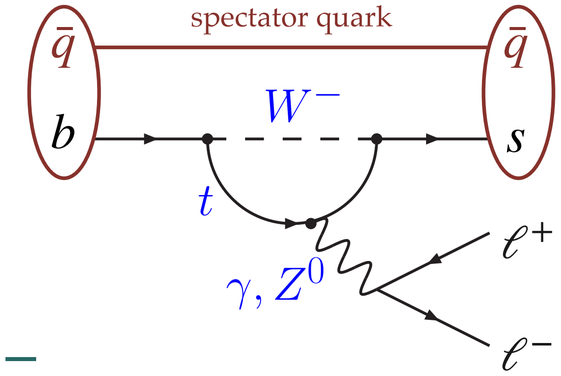
+ box diagram involving neutrinos

CERN seminar 26 Jul 2022

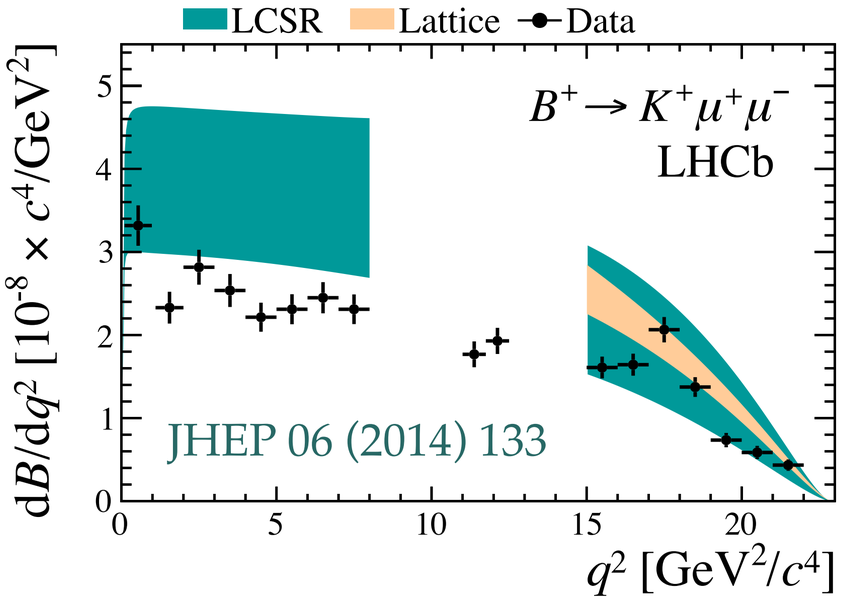


$b \to s\ell\ell$ branching ratios

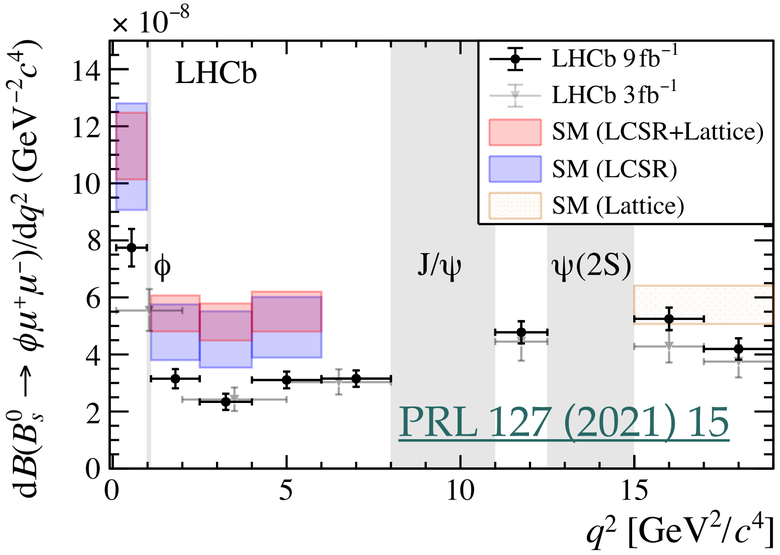
- $b \to s\mu\mu$ BF consistently lower than SM
  - Large form factors uncertainties (20-30%)



$B^+ \to K^+\mu^+\mu^-$

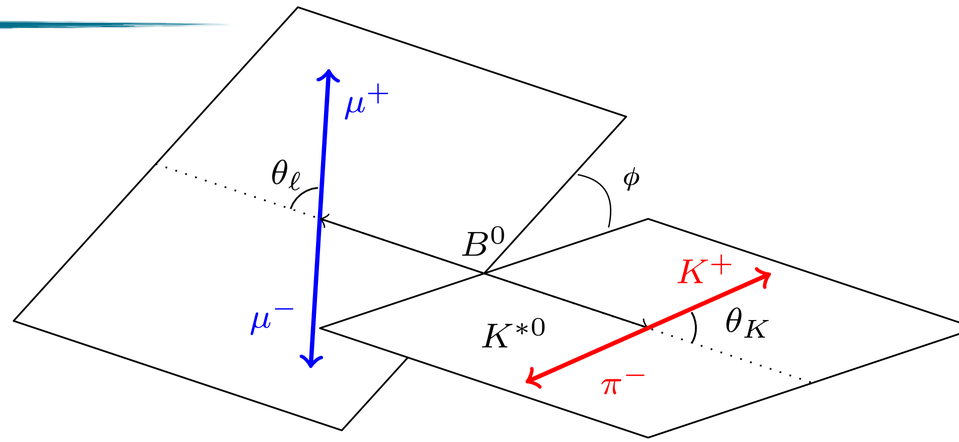


$B_s \to \phi\mu^+\mu^-$

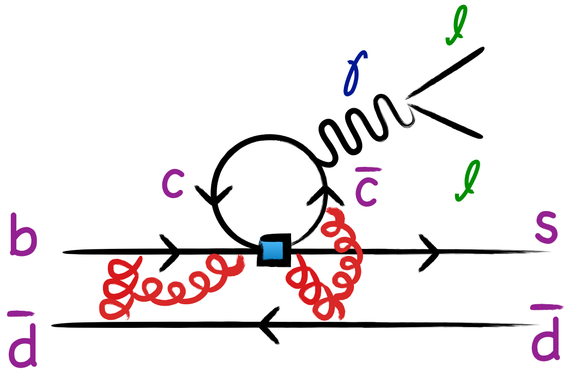


$b \to s\ell\ell$ angular analyses

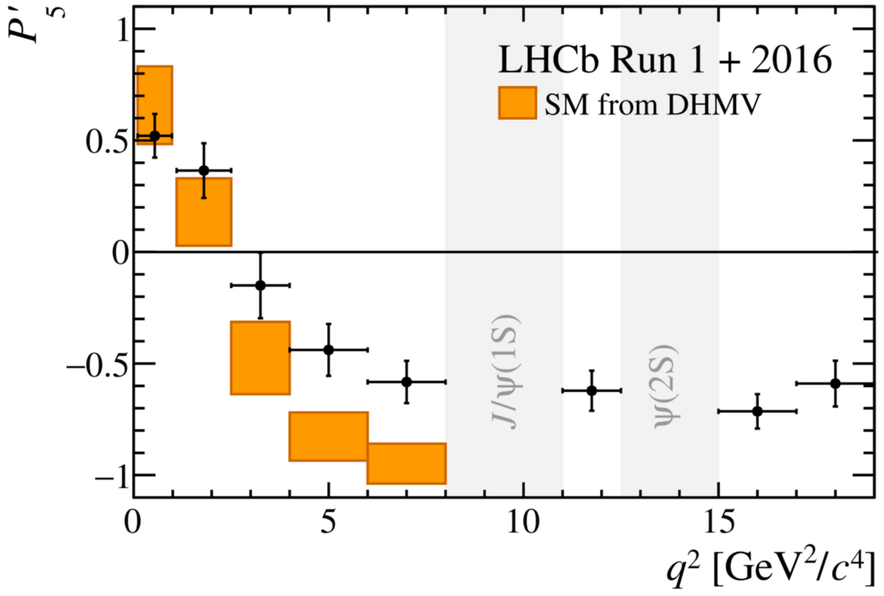
- $B^0 \to K^{*0}\ell^+\ell^-$ 4-body decays provide rich structure to be studied
  - Described by 3 angles and q^2



- We can measure many **angular observables** in bins of q^2
  - Optimized observables, e.g. P_5'
    - Form-factor uncertainty partly cancels
    - SM prediction still tricky due to charm-loop contributions



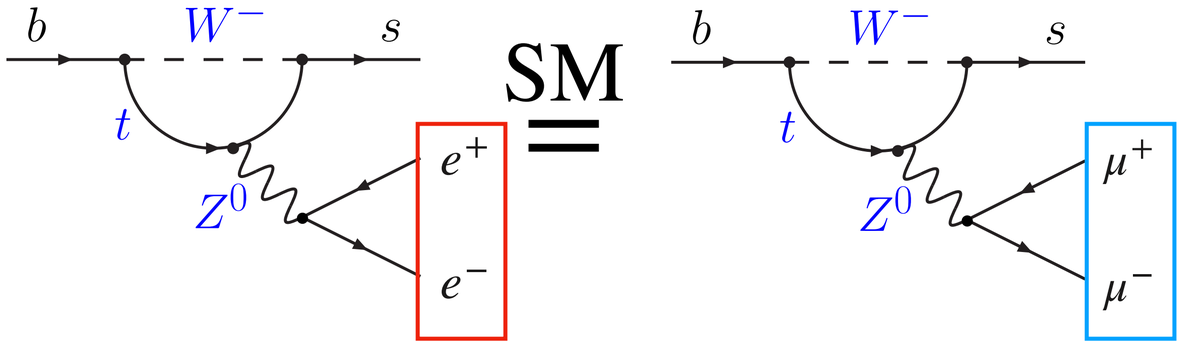
PRL 125(2020)011802

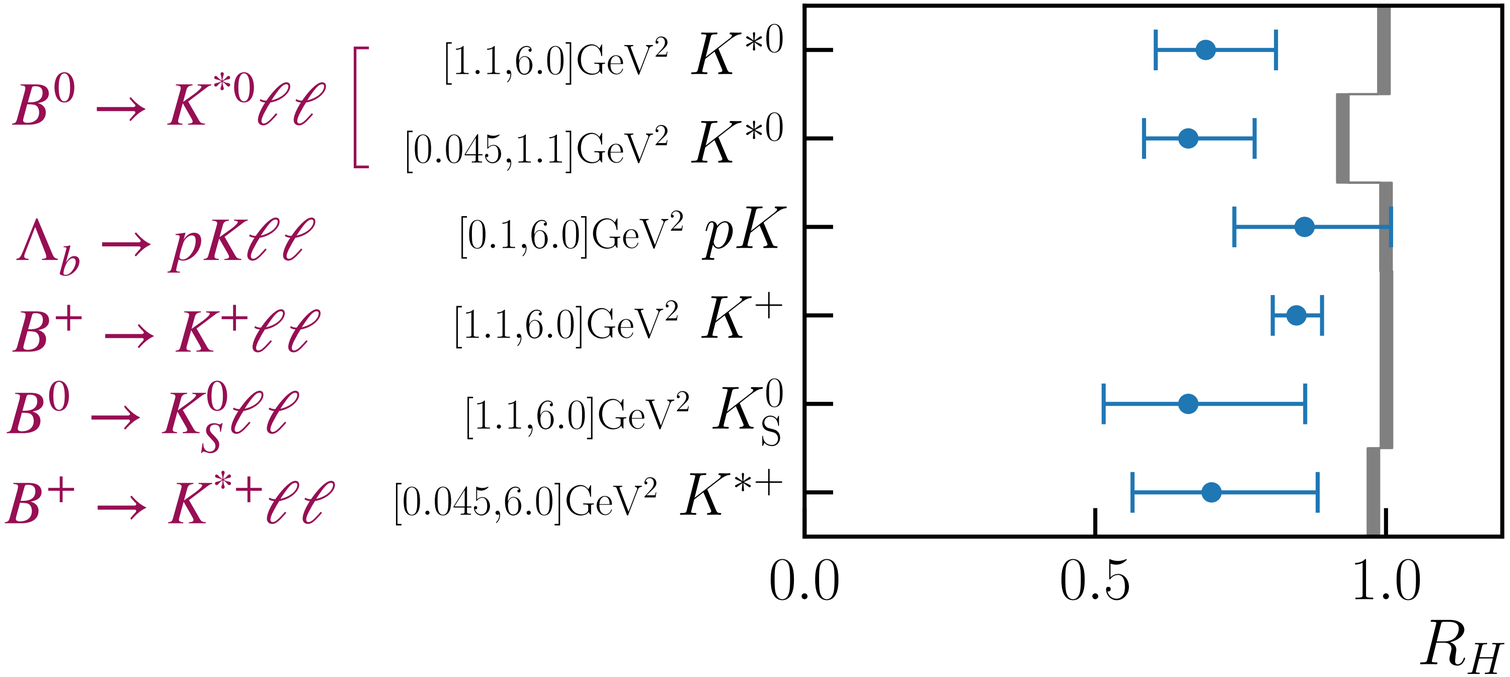


LFU test in $b \to s\ell\ell$ decays

- $b \to s\ell^+\ell^-$ is Lepton Universal in the SM
- Prediction are uncontroversial and very precise

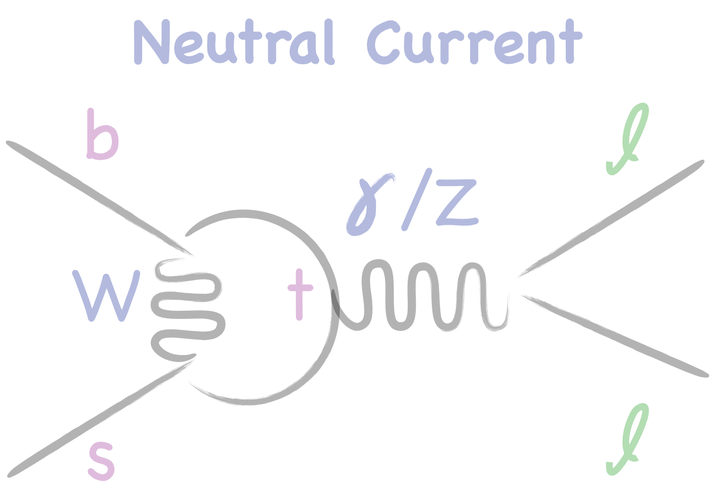
$$R_{H_s} = \frac{\mathrm{BR}\left(H_b \to H_s\mu^+\mu^-\right)}{\mathrm{BR}\left(H_b \to H_s e^+e^-\right)} \overset{\mathrm{SM}}{=} 1.00 \pm 0.01$$



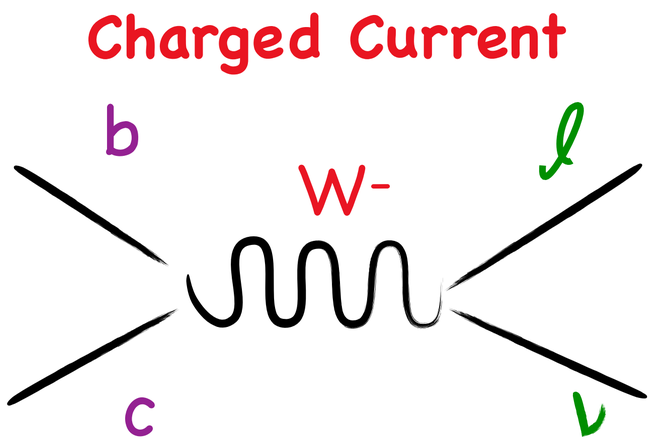


Flavour anomalies (CC)

- **Flavour Changing Neutral Current (FCNC)**
  - e.g. $b \to s\ell\ell$ processes
  - very rare, BR $\sim \mathcal{O}(10^{-6})$ or lower



- **Charged Current (CC)**
  - e.g. $b \to c\ell\bar{\nu}$ decays
  - tree level: BR ~ few %



R(D) - R(D*)

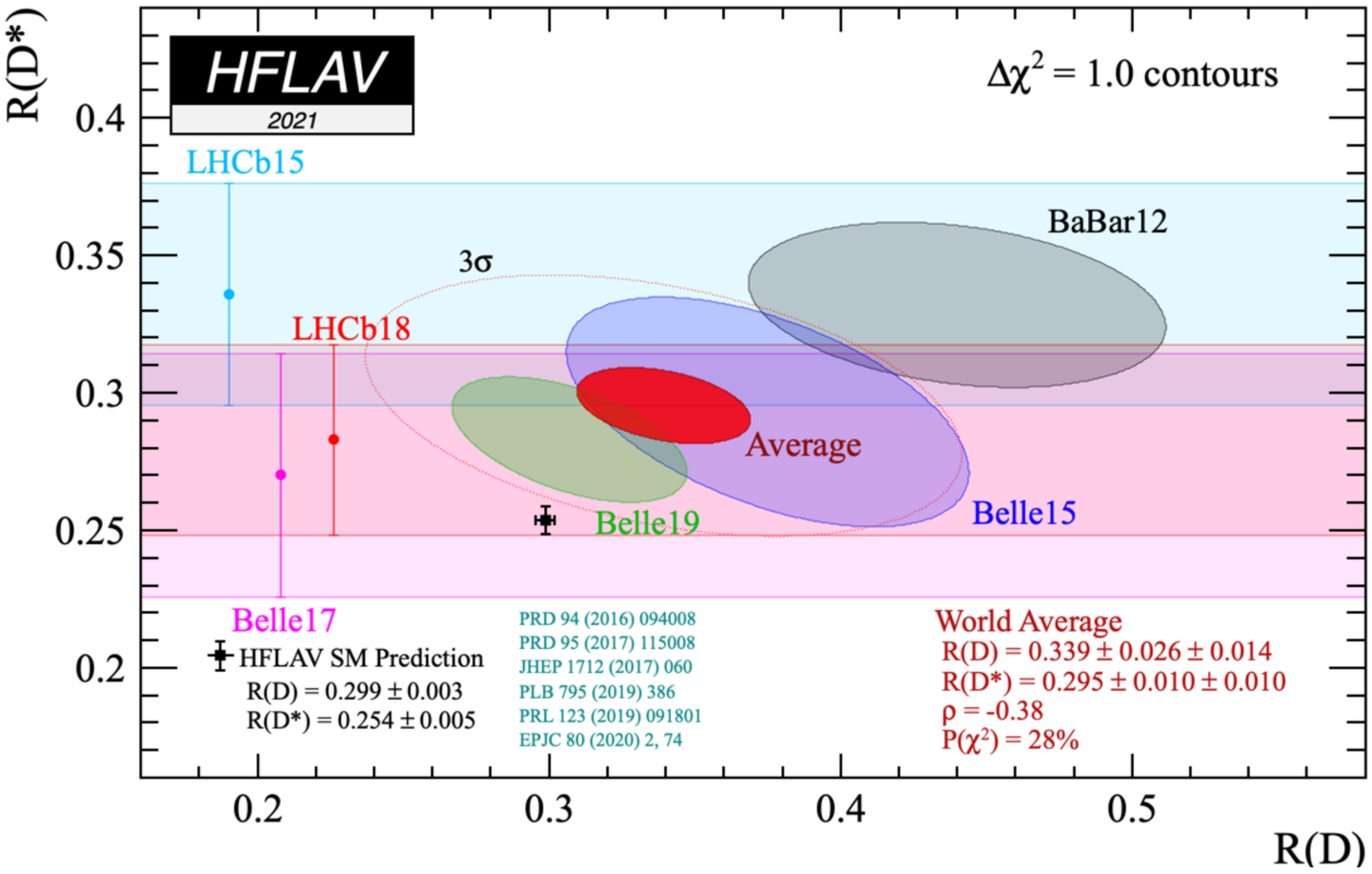
- LFU with **taus**

$$R(D) = \frac{\mathcal{B}(B^0 \to D\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D\ell\nu_\ell)}$$

$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^*\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^*\ell\nu_\ell)}$$

$\ell = e, \mu$ for B-factories

$\ell = \mu$ for LHCb



Combination of R(D) and R(D*) 3.3 σ away from SM

Conclusion

- FCNC
  - $b \to s\mu\mu$ Branching ratios
  - $b \to s\mu\mu$ Angular analyses
  - $B_s \to \mu^+\mu^-$ + LFU tests μ/e

Deviation $O(20\%)$ on SM **loop-order** processes

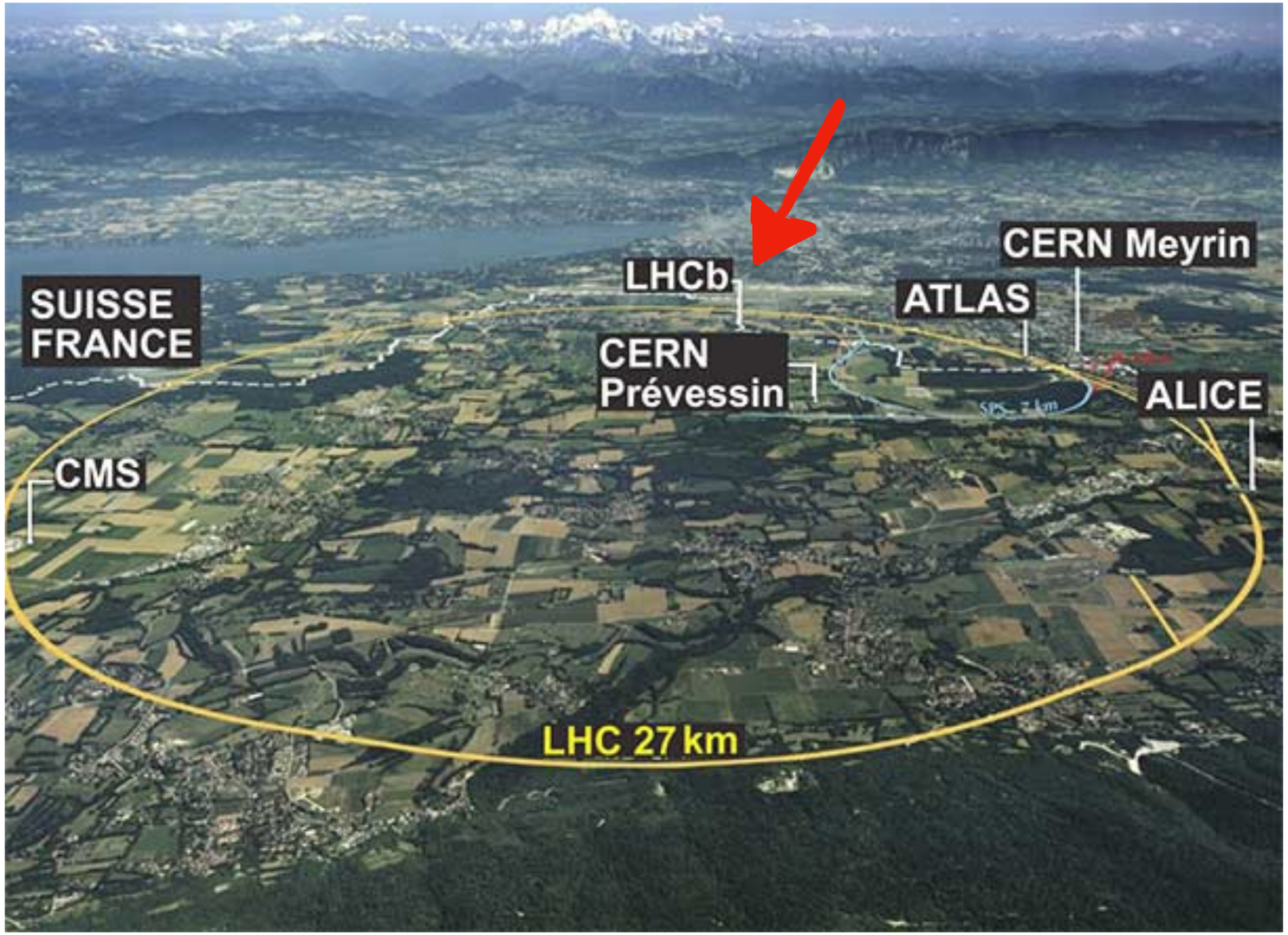
- CC: $b \to c\ell\bar{\nu}$
  - LFU tests τ/μ

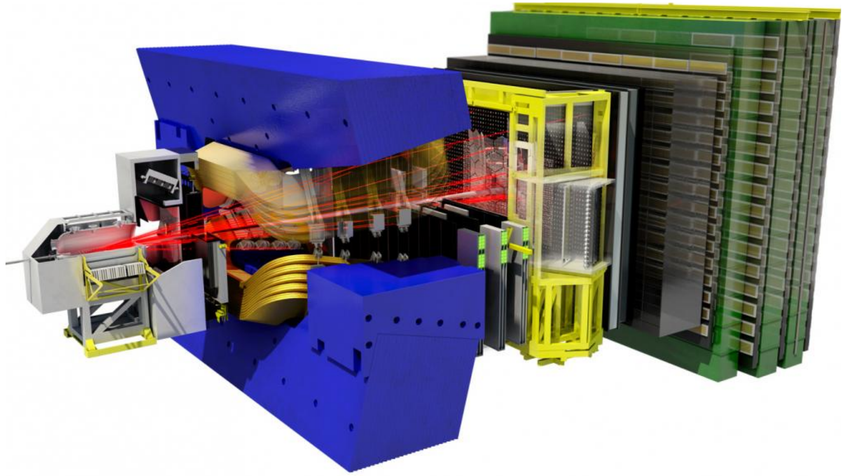
Deviation $O(20\%)$ on SM **tree-level** processes

Hierarchical pattern?
NP couples more strongly to **3rd** generation..?

Backup

LHCb


SUISSE
FRANCE
LHCb
CERN
Prévessin
ATLAS
CERN Meyrin
ALICE
CMS
LHC 27 km



LHCb

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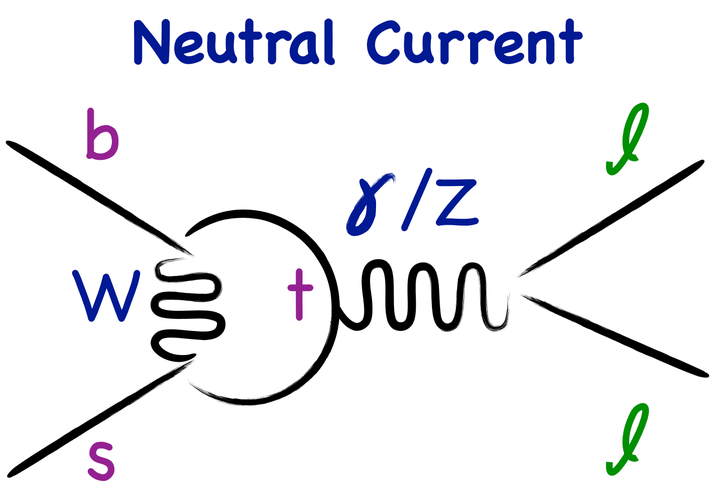

★ **Excellent experimental probe**
  - No neutrinos involved!
  - Several complementary observables
  - Several complementary decay channels

→ Branching ratios / Angular analyses / Lept. Flav. Univ. test

Fully leptonic $B_s \to \mu^+\mu^-$

- A golden flavour physics channel
  - Very rare 10^{-9} BR (helicity suppressed)
  - Precise 4% BR theoretical prediction

Beneke et al. JHEP 10 (2019) 232
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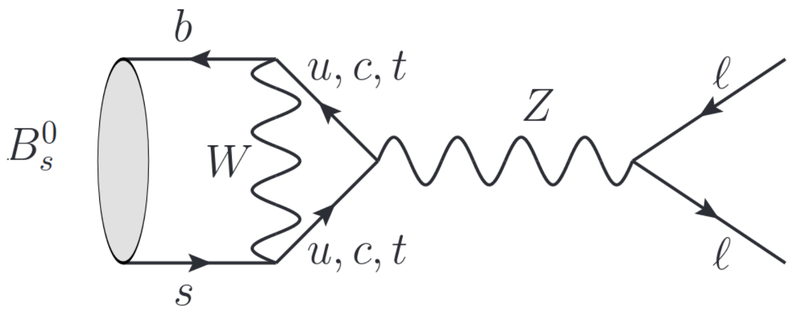
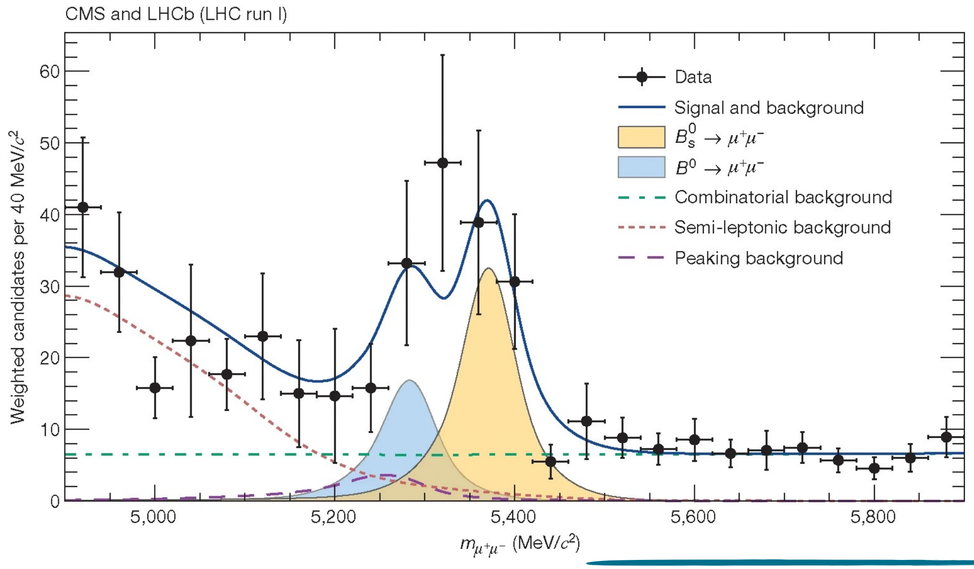


+ box diagram involving neutrinos

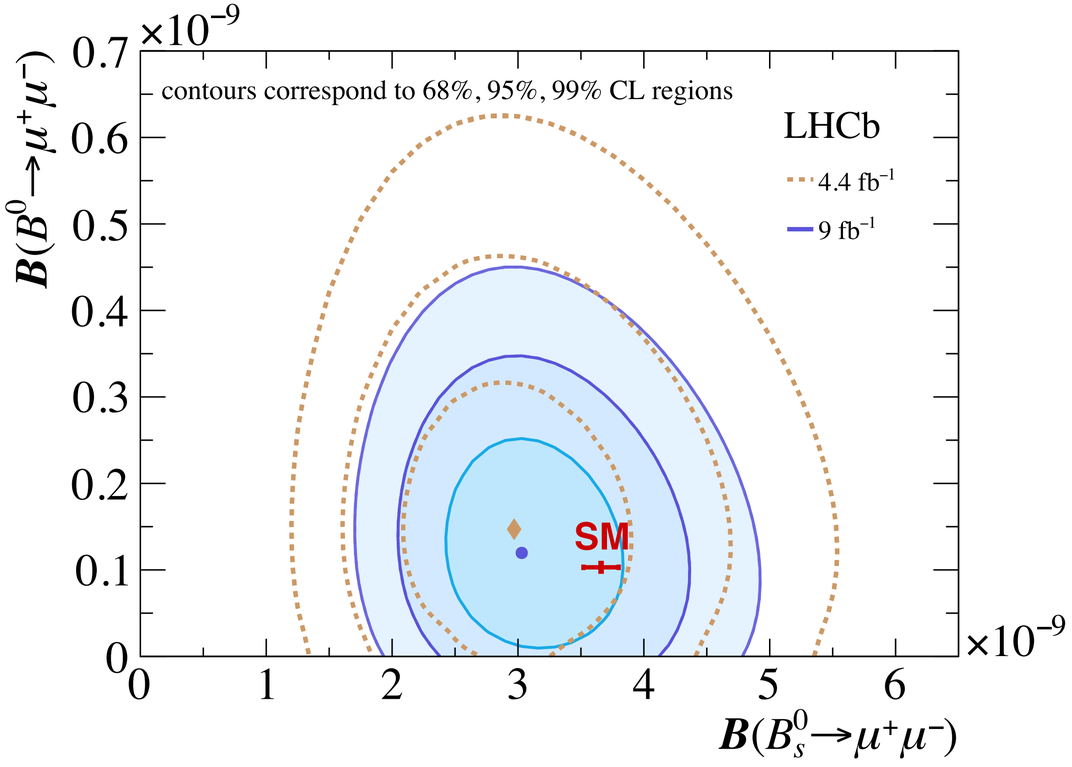
- Searched since the 80's and firstly observed in 2014 by LHCb + CMS (Run 1)

Nature 522 (2015) 68

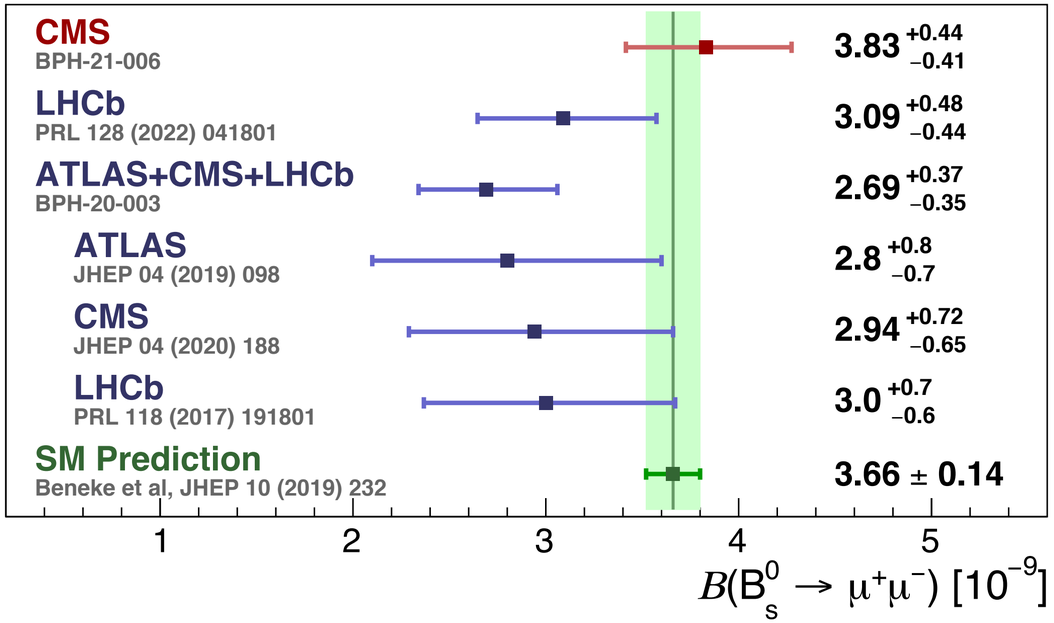


Fully leptonic $B_s \to \mu^+\mu^-$

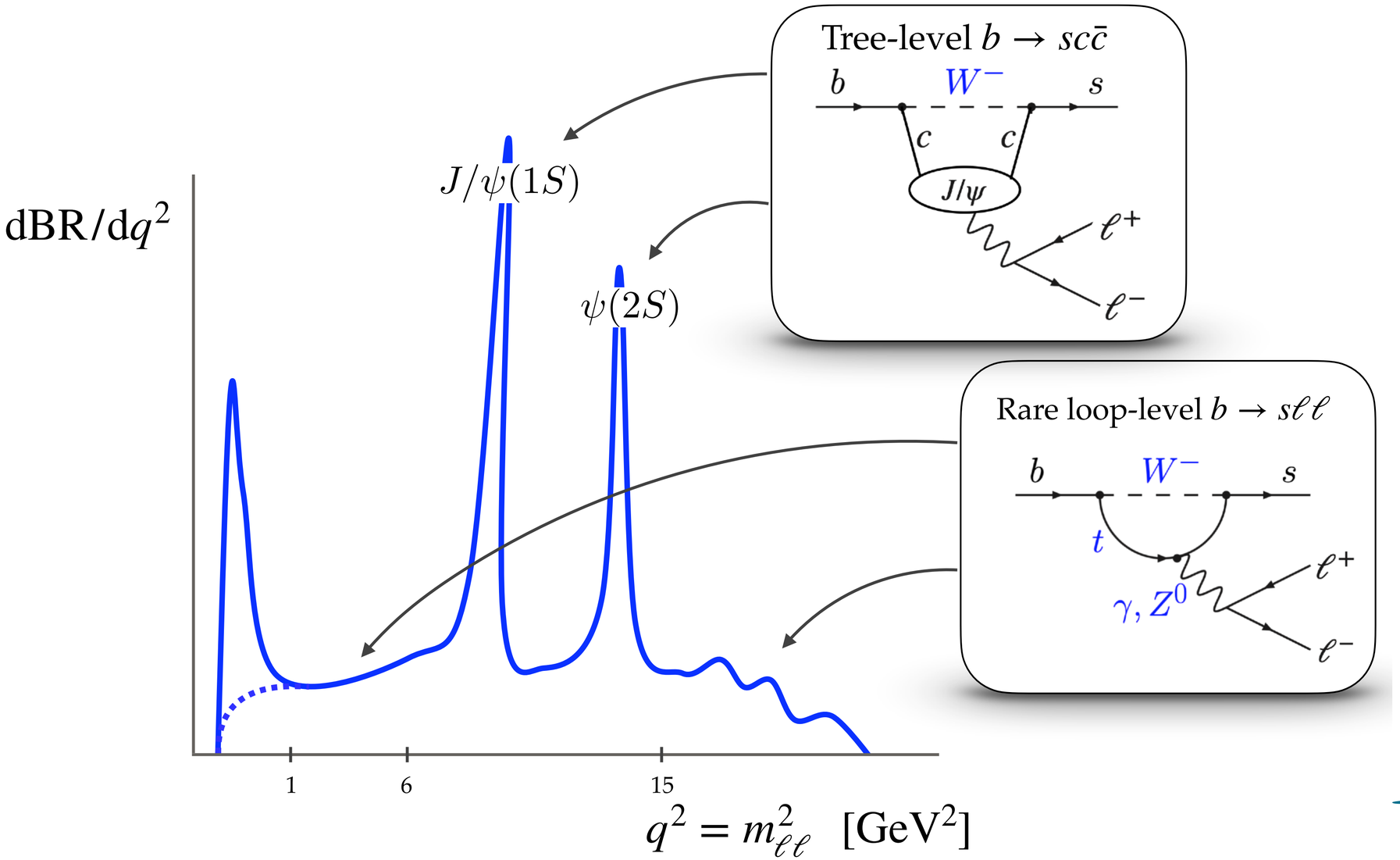
- Since first observation
  - updated LHCb Run1 + Run2 PRL 128(2022)041801 PRD 105(2022)012010
  - updated CMS Run1 + Run2 CMS-PAS-BPH-21-006



CERN seminar 26 Jul 2022

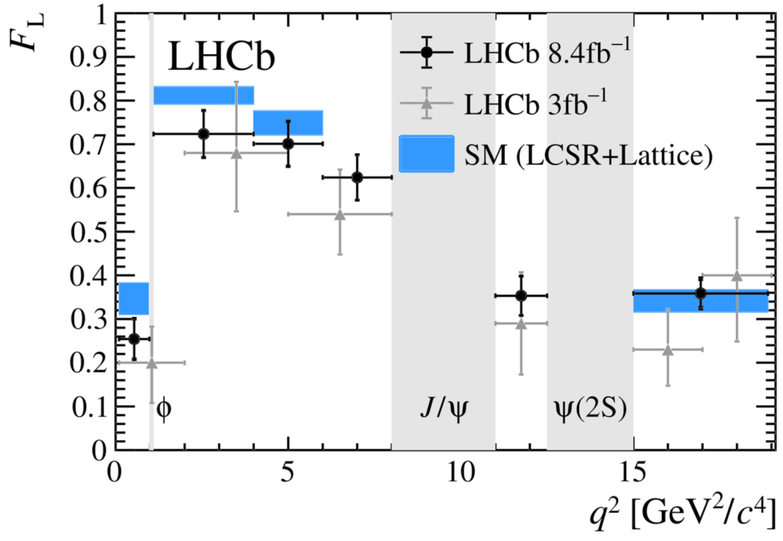


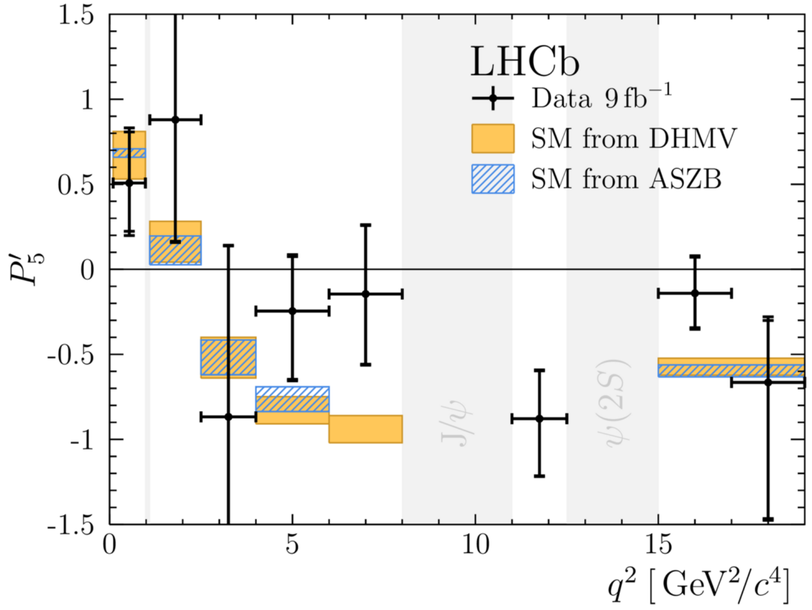
$b \to s\ell\ell$ semileptonic decays



$b \to s\ell\ell$ angular analyses

- Recent results:
  - $B^0 \to K^{*0}\mu^+\mu^-$ with 6/fb (~4600 events)
  - $B^+ \to K^{*+}\mu^+\mu^-$ with 9/fb (~700 events)
  - $B_s \to \phi\mu^+\mu^-$ with 9/fb (~1900 events)



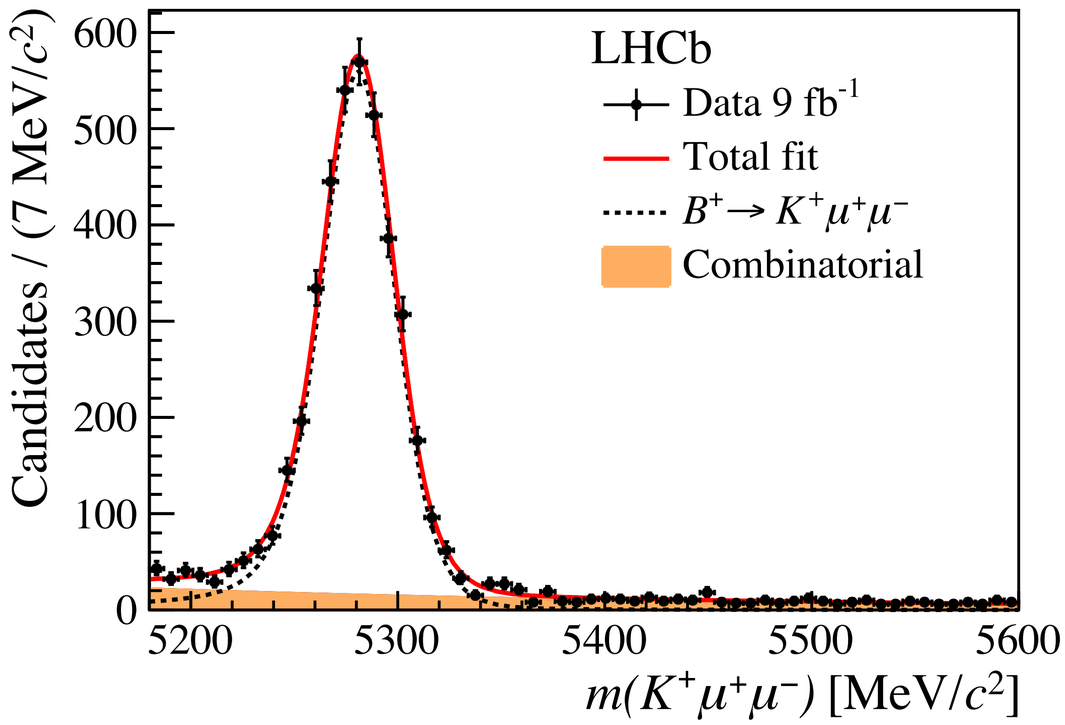


Electron VS muons in LHCb

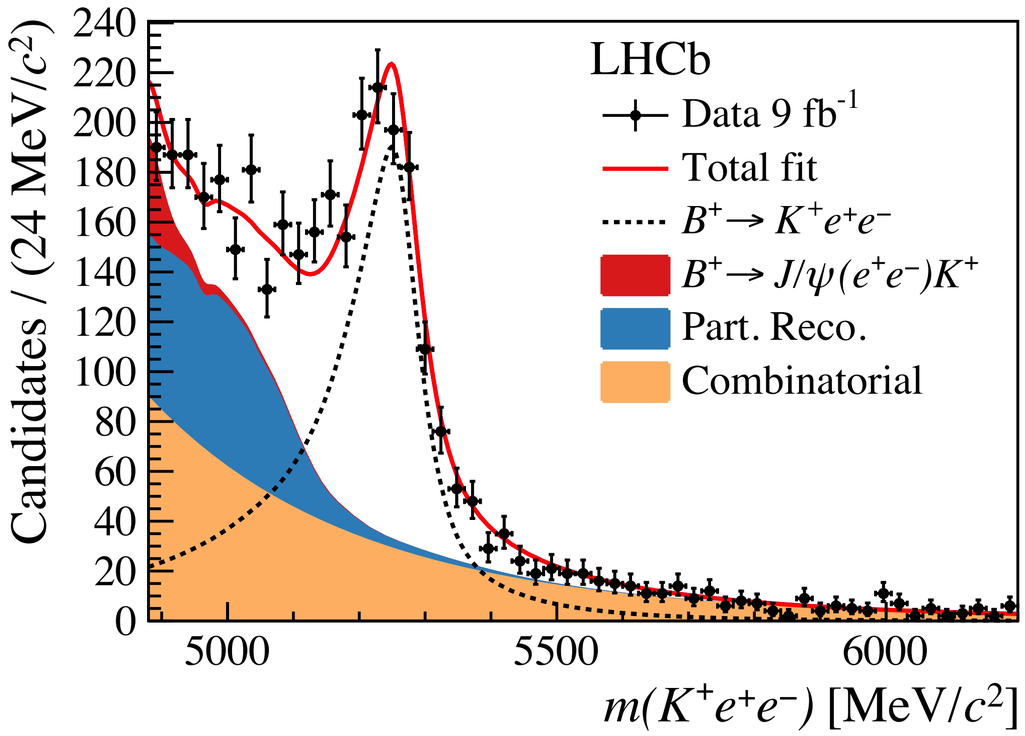
Nature Physics 18, (2022) 277-282

$$R_K = \frac{Br(B^+ \to K^+\mu^+\mu^-)}{Br(B^+ \to K^+e^+e^-)} = 0.846^{+0.042}_{-0.039}(\text{stat})^{+0.013}_{-0.012}(\text{syst})$$

Muons

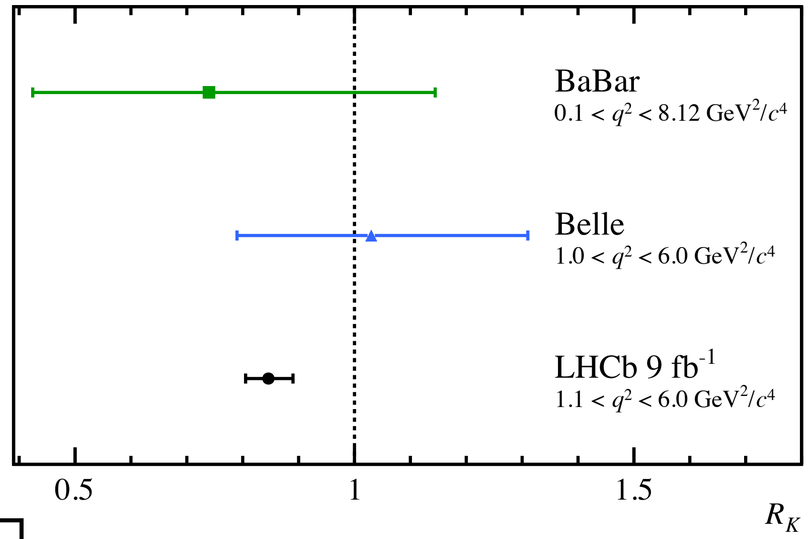


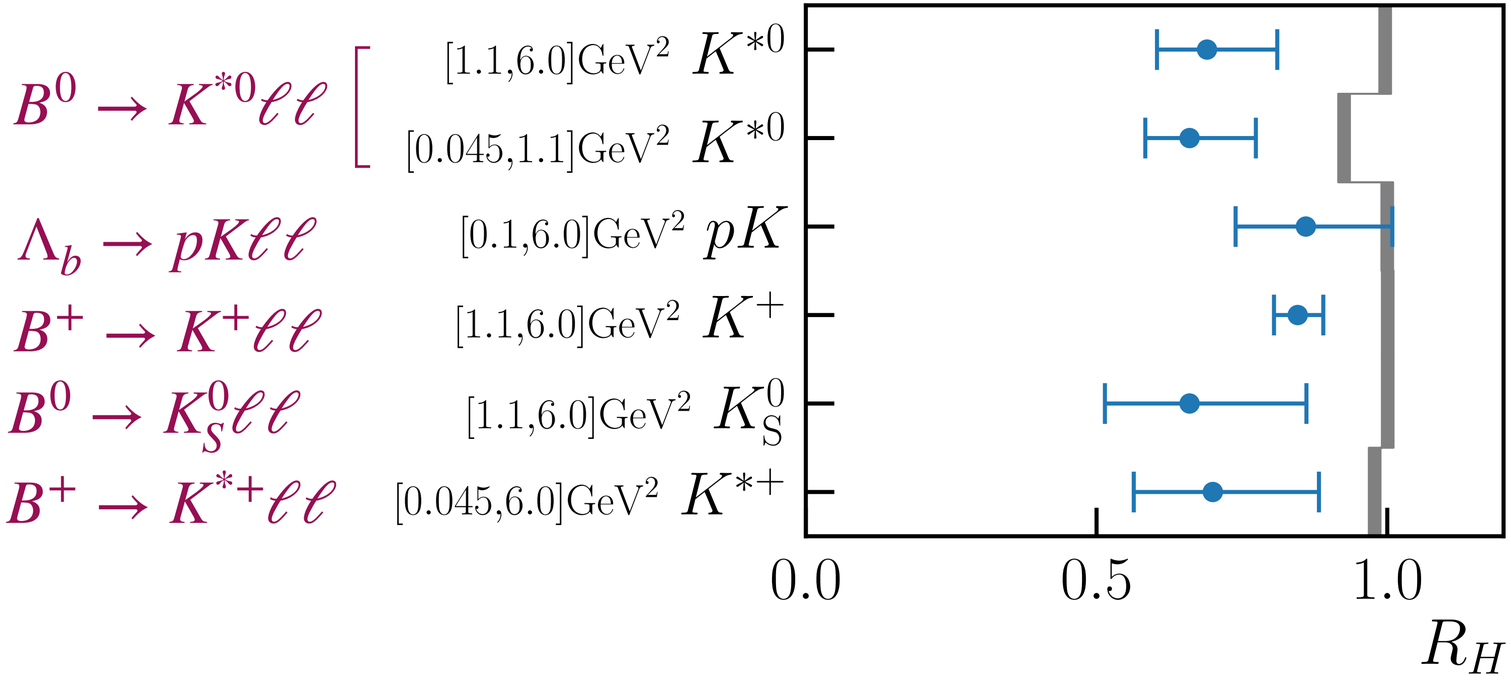
Electrons



R values

- Measurement much more precise than previous experiments
- Measured in several $b \to s\ell^+\ell^-$ channels
- It confirmed, would be a clear sign of NP





R_{D^*} @LHCb

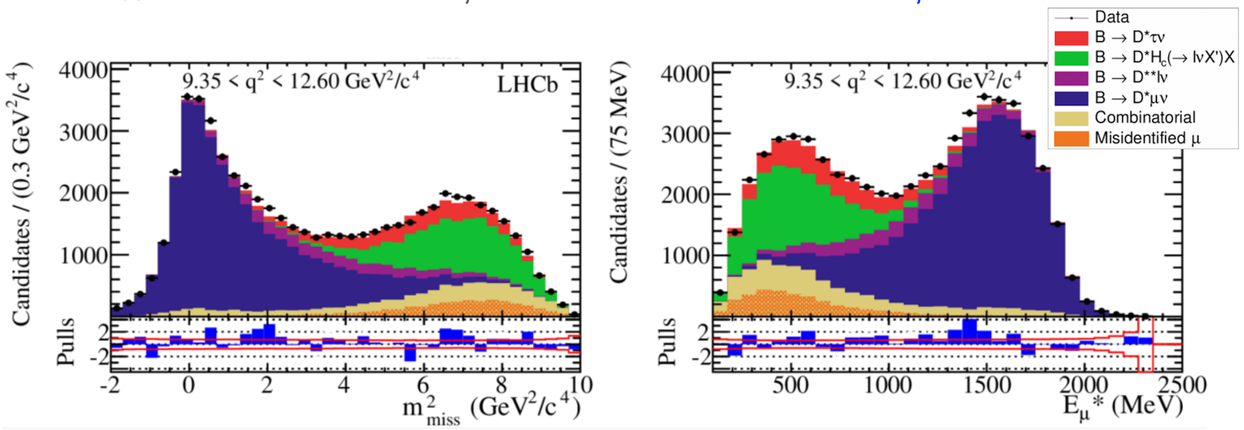
Run1 3fb^{-1}

'Muonic' $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

PRL 115 (2015) 111803

Fit variables:

$m^2_{\text{miss}} = (p_B - p_{D^*} - p_\mu)^2$, $q^2 = (p_B - p_{D^*})^2$, E^*_μ in B rest frame



- E^*_μ spectrum softer when μ comes from the τ decay
- $m^2_{\text{miss}} = 0$ in $B \to D^* \mu \nu_\mu$

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

2.1σ **above than SM**

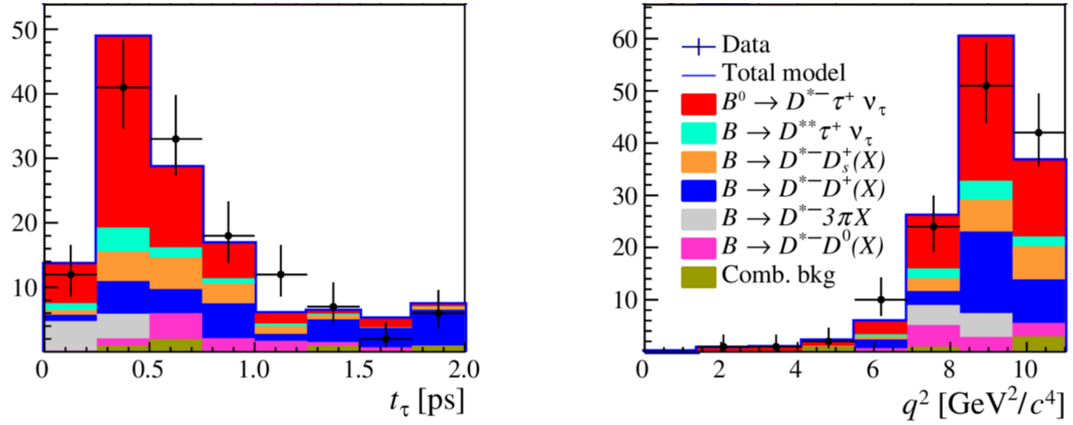
'Hadronic' $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$, $\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$

PRL 120 (2018) 171802

Fit variables:

$\text{BDT}_{\text{output}}$, $q^2 = (p_B - p_{D^*})^2$, t_τ τ decay time

Projections in the bin with the hardest $\text{BDT}_{\text{output}}$

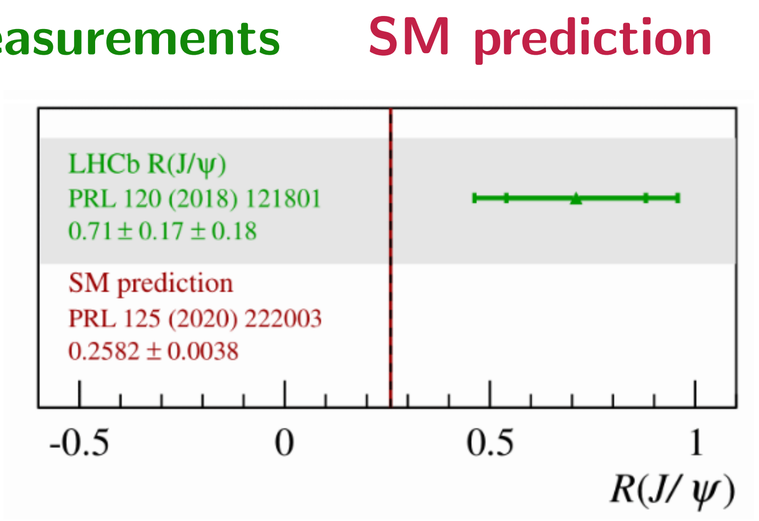


$$\mathcal{R}(D^*) = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$$

$\sim 1\sigma$ **above the SM**

$b \to c\ell\bar{\nu}$ LFU ratios

- LFU with **taus**
  - Muonic tau decays: $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$
  - Hadronic tau decays: $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$



Muonic:

$$R(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$$ 2.1σ above SM

PRL 115, 111803 (2015)

$$R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$$ 2σ above SM

PRL 120, 121801 (2018)

Hadronic:

$$R(D^*) = 0.280 \pm 0.018(\text{stat}) \pm 0.026(\text{syst}) \pm 0.013(\text{ext})$$ 1σ

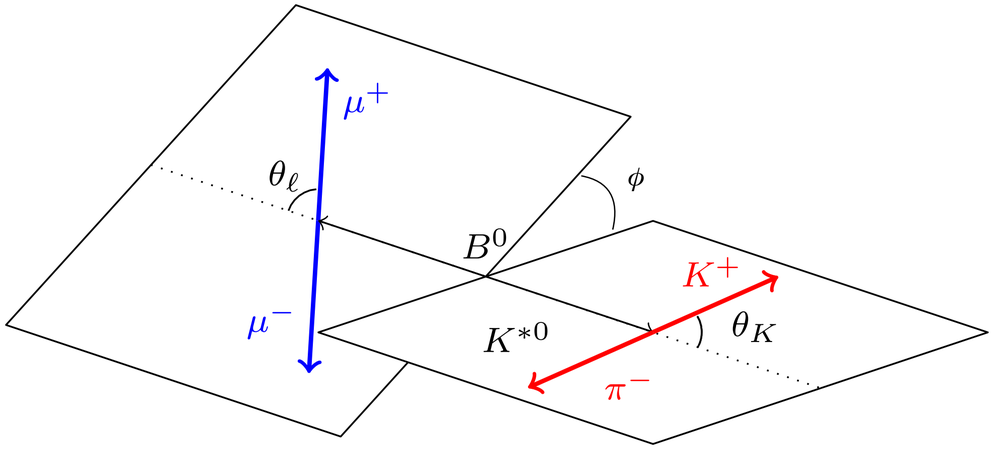
PRL 120, 171802 (2018)

$$R(\Lambda_c^+) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059(\text{ext})$$ 1σ

PRL 128, 191803 (2022)

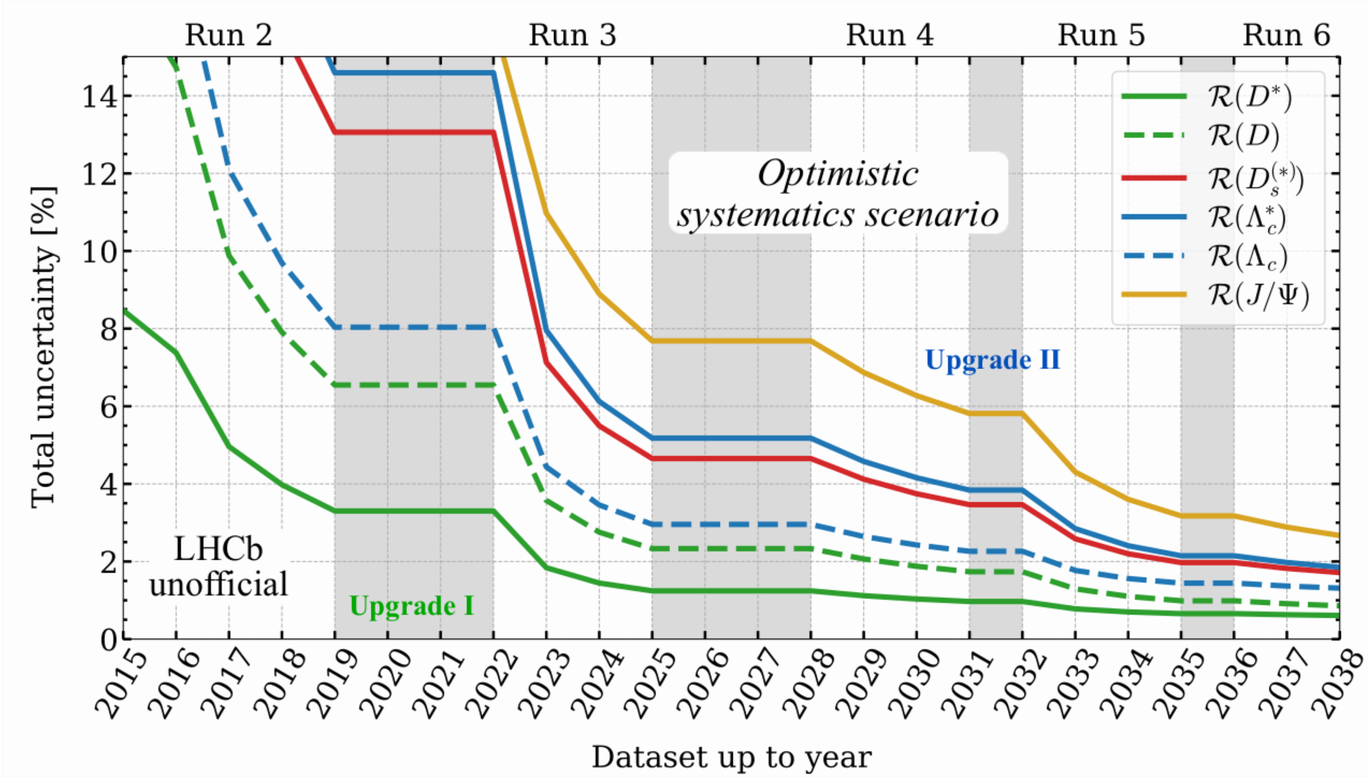
$B \to K^* \mu^+ \mu^-$ angular distributions

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



prospects

- $R(D^+)$
- $R(D^*)$ - $(e-\mu)$
- Combined $R(D^*) - R(D^0)$
- $R(D^{**})$
- $R(D_s^*)$
- $R(\Lambda_c^{**})$



[arXiv:2101.08326, arXiv:1808.08865]

- Exploring new observables beyond the branching fraction ratios, *e.g.* angular observables to determine spin structure of potential new physics
  - $B \to D^* \mu(\tau)\nu$ - muonic and hadronic