B-flavour anomalies in $b \to sll$ and $b \to c l \nu$ transitions at LHCb

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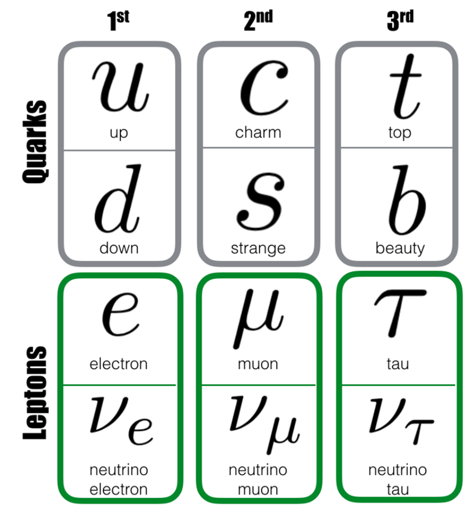
Overview of the situation

The study of **heavy-flavour hadron decays** allows the **indirect search for beyond-the-SM physics** at large mass scales.



Two sets of anomalies have been seen in the **B sector**.
* They seem to form a **coherent pattern**.
* They seem to be **flavour-dependent**. → Connection with the flavour structure of the SM?

Neutral currents

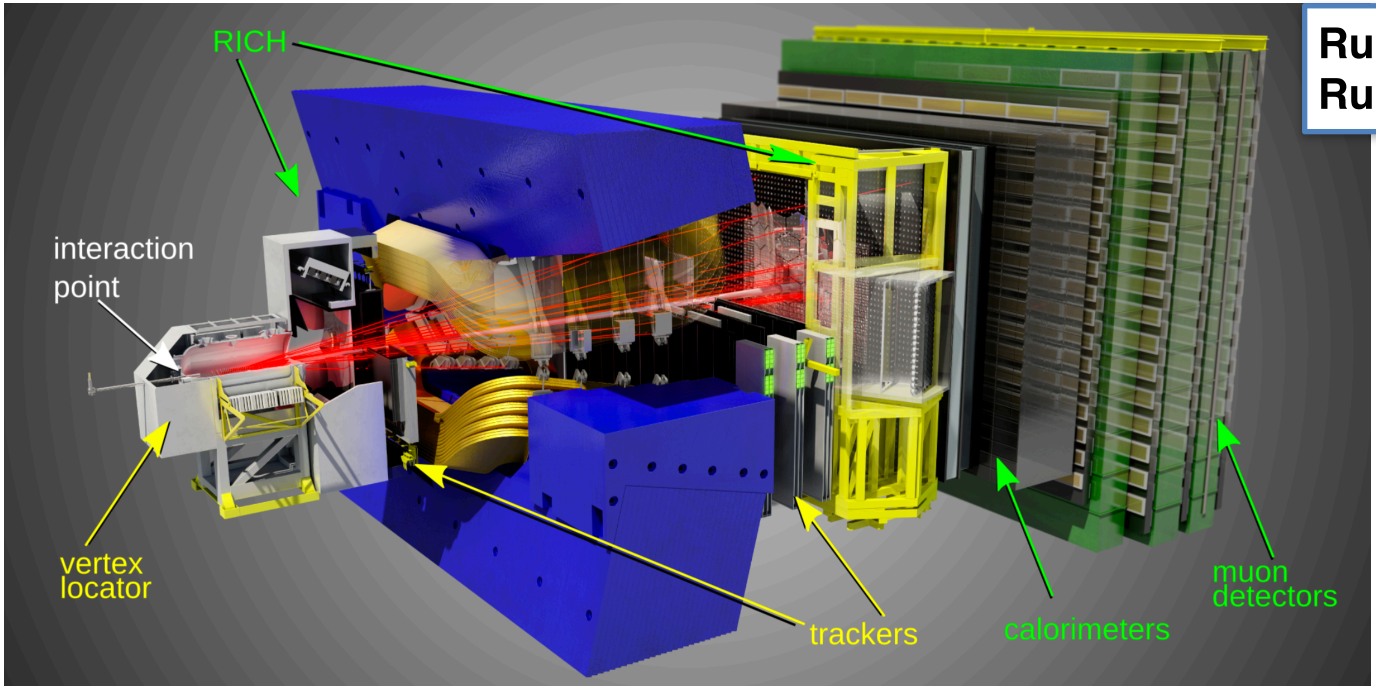
* Only occur in loops, BR $\lesssim 10^{-6}$.
* New contributions can enhance SM-suppressed amplitudes.

Charged currents

* Tree level, BR ~ few %.
* Clean SM predictions.

Proposed new models for combined explanations: **leptoquarks**, **Z'**, …

The LHCb detector

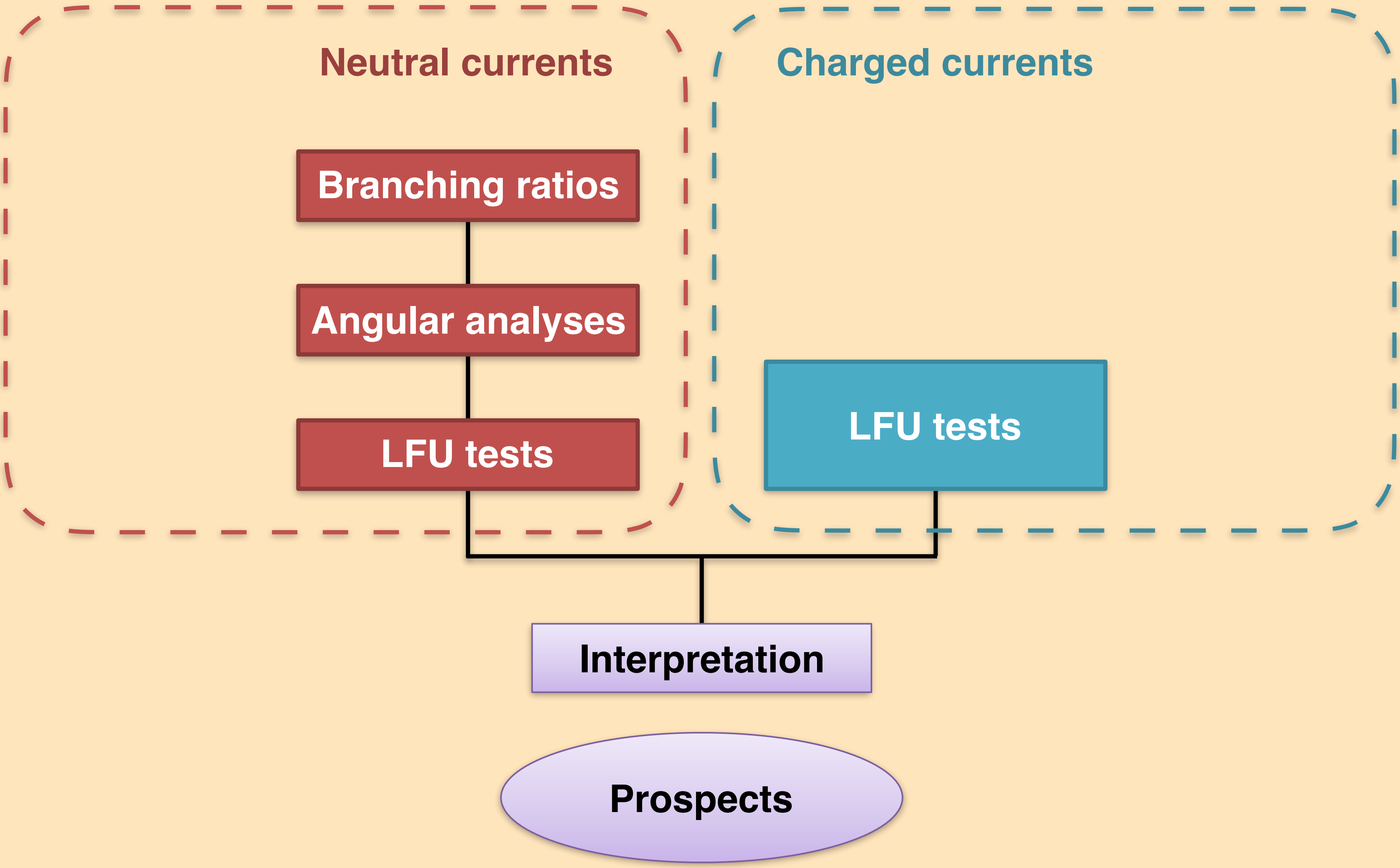


Run 1: 2010-2012
Run 2: 2015-2018

2018 (13 TeV): 2.19 /fb
2017 (13 TeV): 1.71 /fb
2016 (13 TeV): 1.67 /fb
2015 (13 TeV): 0.33 /fb
2012 (8 TeV): 2.08 /fb
2011 (7 TeV): 1.11 /fb
2010 (7 TeV): 0.04 /fb

- Large amount of *b* hadrons produced, σ_b=(144 ± 1 ± 21) μb at 13TeV
- Forward spectrometer for *b*- and *c*-hadron decays (2<η<5)
  - Good vertex and impact parameter resolution (σ(IP)~20 μm)
  - Excellent momentum resolution ($\delta p/p$ = [0.5 - 1] % p<200 GeV)
  - Excellent charged particle identification (μ ID 97% for (π→μ) misID of 1-3%)

Contents of the talk



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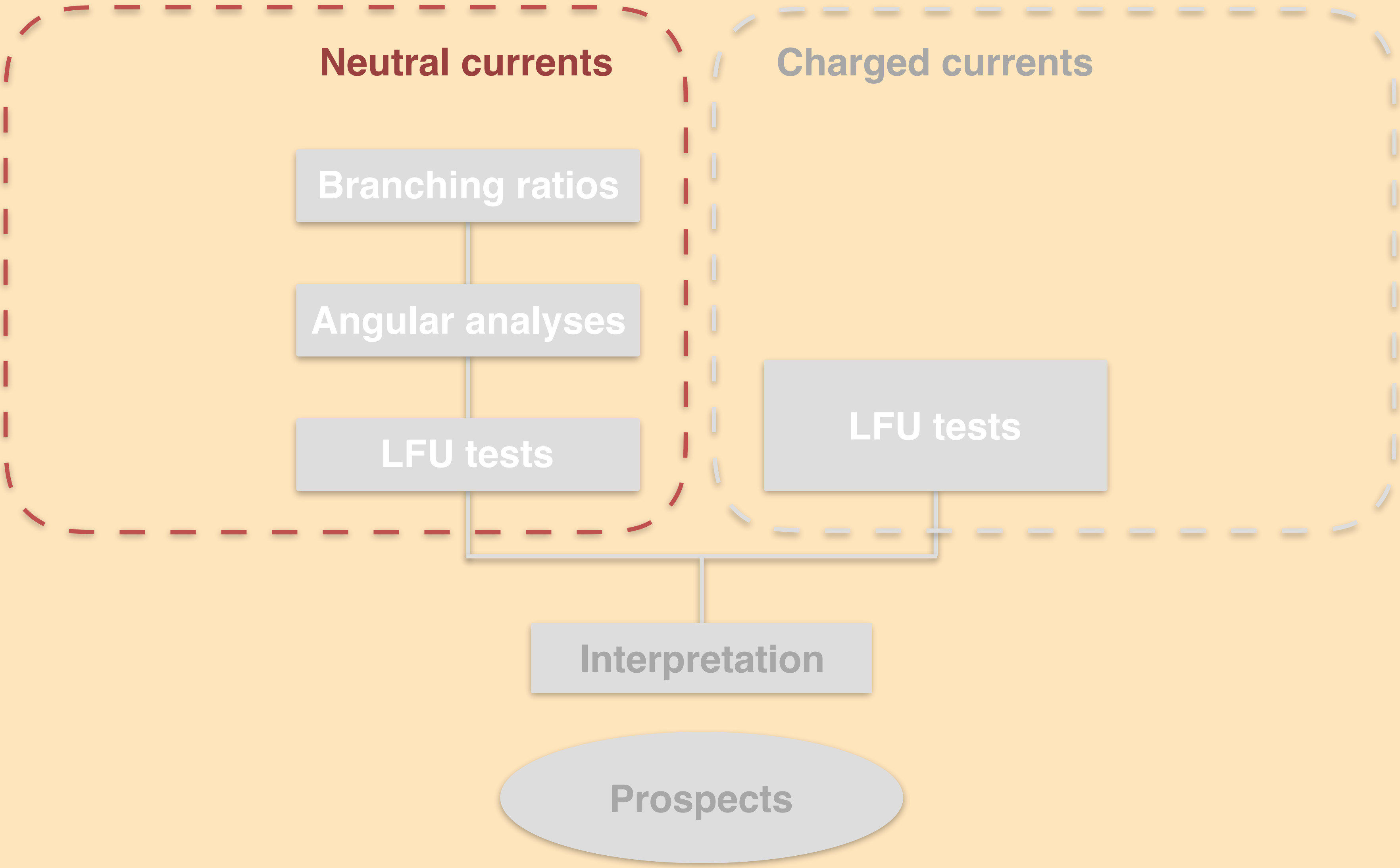

Phenomenological treatment

The anomalies are studied in a common and model-independent framework, using the **effective-Hamiltonian** formalism:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^{*} \frac{e^2}{16\pi^2} \sum_i \mathcal{C}_i \mathcal{O}_i$$

Local operator: $\mathcal{O}_i$

Wilson coefficient ("effective coupling"): $\mathcal{C}_i$

$$\Delta\mathcal{H}_{\text{NP}} = \frac{\kappa}{\Lambda^2_{\text{NP}}} \mathcal{O}_i$$

Flavour-violating coupling: κ

NP scale: Λ_{NP}

- BSM processes can modify the effective Hamiltonian by
  - Modifying Wilson coefficients of operators present in SM
  - Introducing new operators
  - Making Wilson coefficients dependent on the lepton flavour

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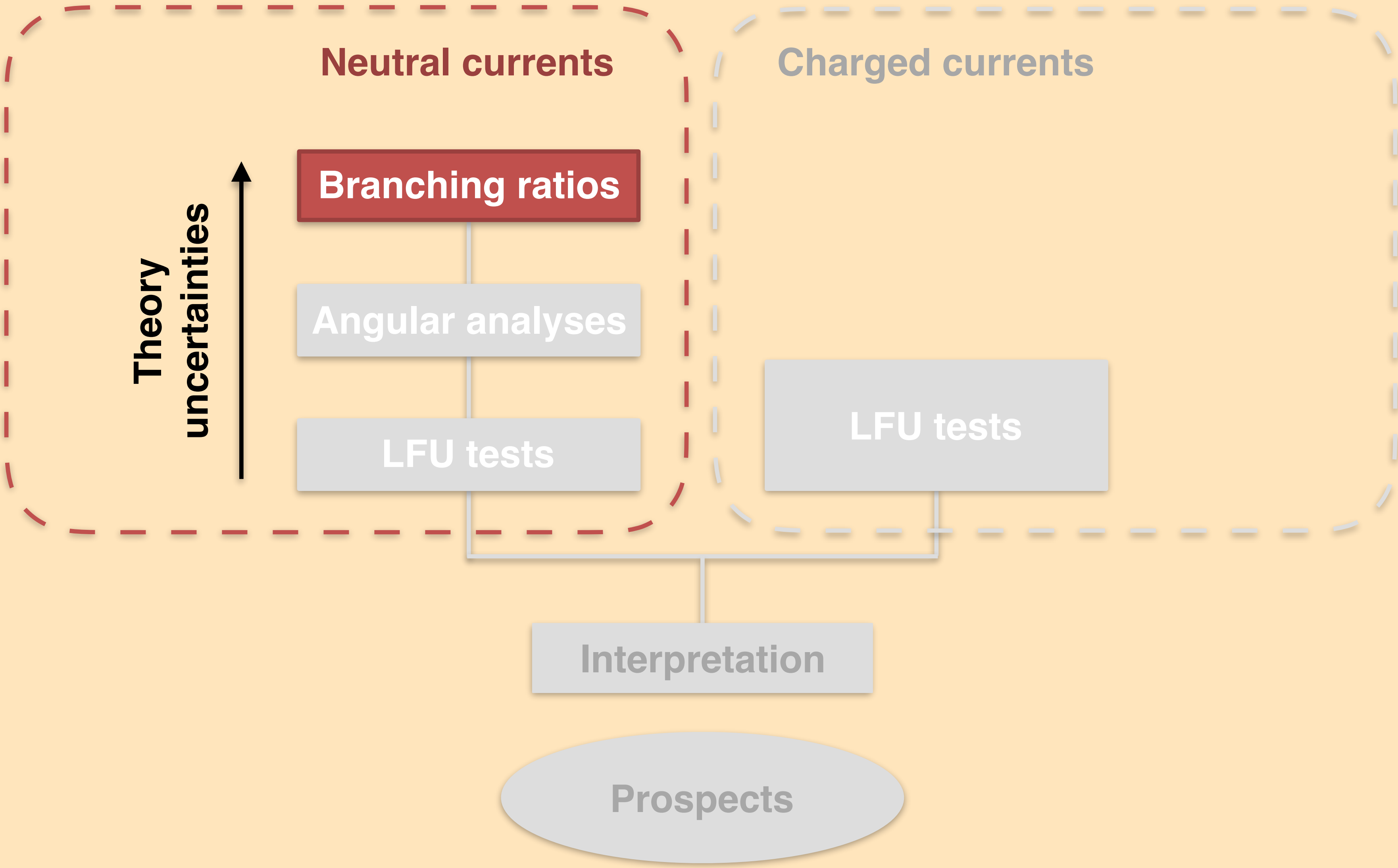


The very-rare-decay $B^0_{(s)} \to \mu^+\mu^-$

Loop and helicity suppressed.
Only C_{10} contributes in the SM.

PRL 118,191801 (2017) (LHCb)

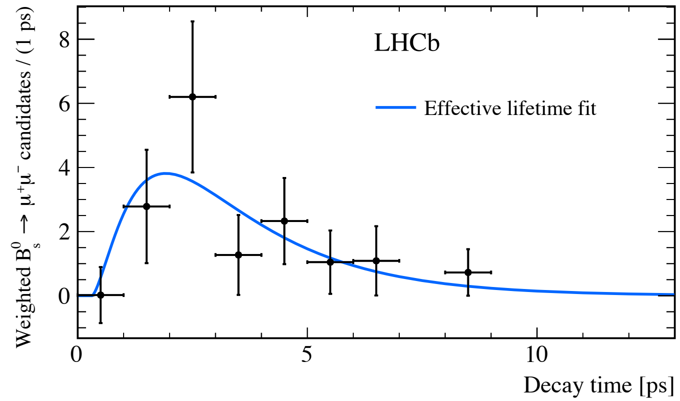
- Latest measurement from LHCb uses Run1 ($3fb^{-1}$) and Run2 ($1.4\ fb^{-1}$) data

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9} \quad \mathbf{7.8\sigma}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ at 90\% CL} \quad \mathbf{1.9\sigma}$$

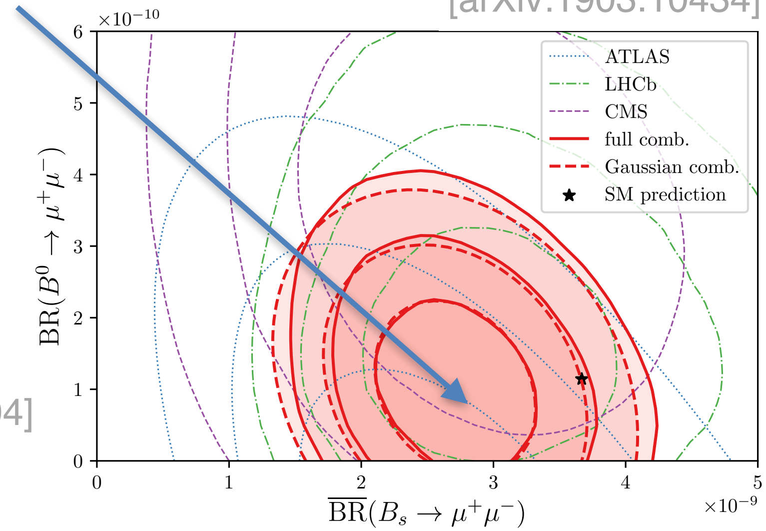
- First measurement of the effective lifetime

$$\tau_{eff}(B^0_s \to \mu^+\mu^-) = (2.04 \pm 0.44 \pm 0.05)\ \text{ps}$$

provides complementary constraints



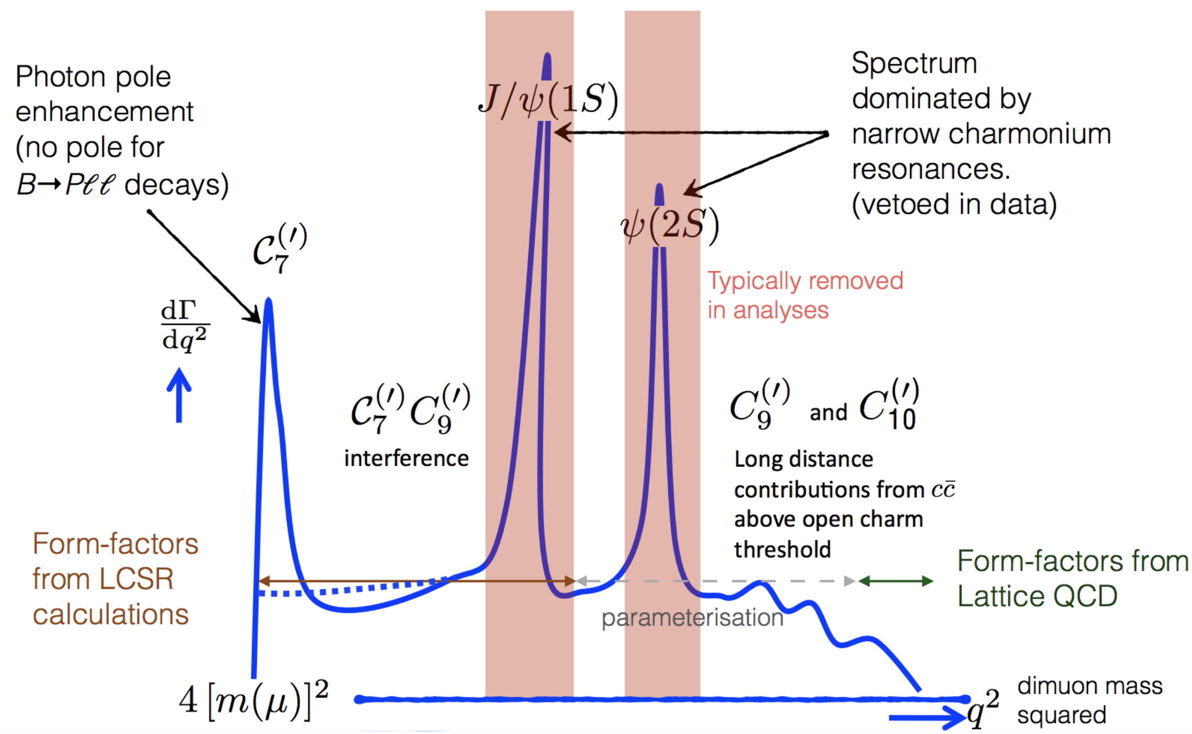
$\mathscr{B}(B^0_s \to \mu^+\mu^-)$: ~2σ from SM [arXiv:1903.10434]

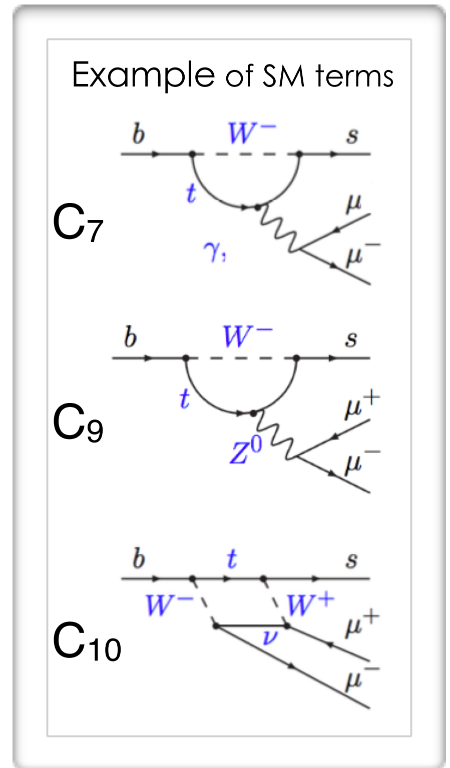


Combination with recent CMS [PRL111(2013)101804] and ATLAS [arXiv:1812.03017] measurements.

Study of b→sl⁺l⁻ transitions

Different regions of $q^2 = M(l^+l^-)^2$ give sensitivity to different **Wilson Coefficients**.

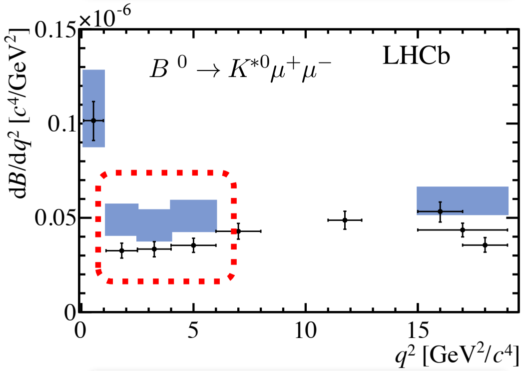




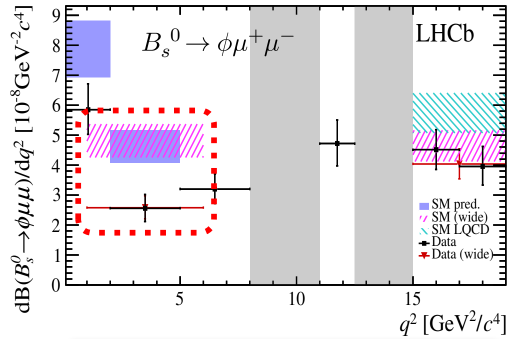
The regions of the **J/ψ and ψ(2S) resonances** correspond to tree-level decays, assumed to be SM-like. They are vetoed in the analyses and used as control regions.

Branching fractions for b→sμ⁺μ⁻

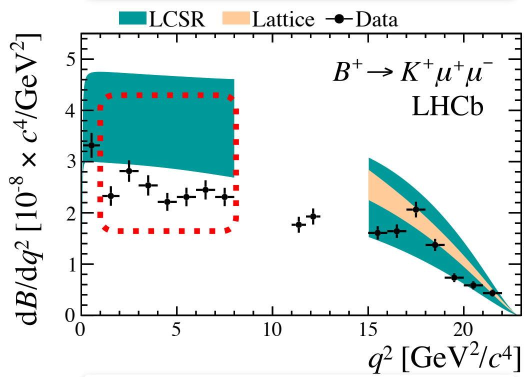
JHEP 11 (2016) 047, LHCb



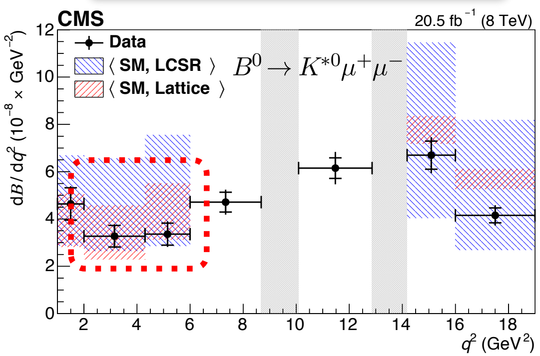
JHEP 09 (2015) 179, LHCb



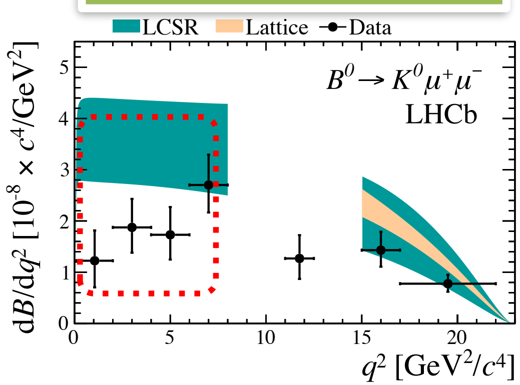
JHEP 06 (2014) 133, LHCb



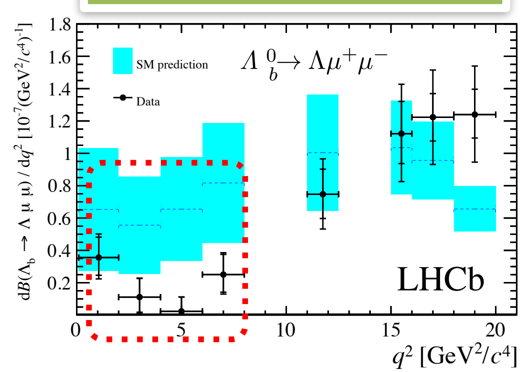
PLB 753,424 (2016), CMS



JHEP 06 (2014) 133, LHCb



JHEP 06 (2015) 115, LHCb



Data systematically below SM predictions, tensions at **1-3σ level**.
Large hadronic theory uncertainties.

Evidence for the decay $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$

JHEP 07 (2018) 020

B_s counterpart of $B^0 \to K^{*0}\mu^+\mu^-$.

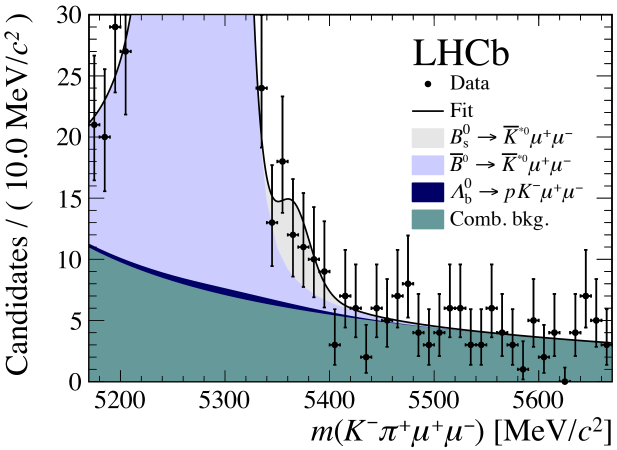
Heavily suppressed b→dll transition,
SM BR ∈ [3,4] x 10^{-8}. [EPJ C73 (2013) 10, 2593]
[JHEP 07 (2018) 020] [PRD 98, 094012 (2018)]

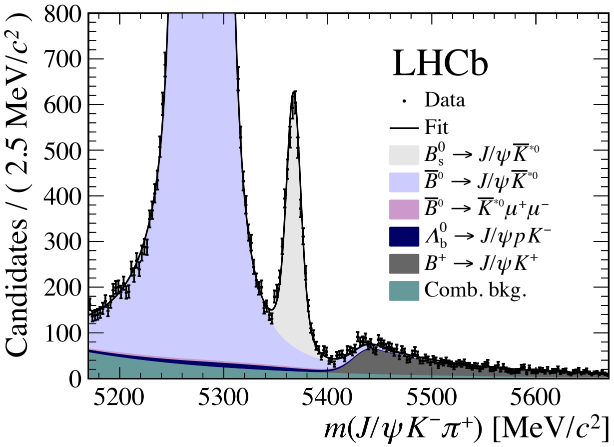
Run1 + part of Run2, 4.6 fb^{-1}.

BR measured relative to $B_s^0 \to J/\psi \overline{K}^{*0}$.

First evidence at 3.4σ, BR consistent with SM.

This study **sets the ground** for detailed analyses in the LHCb Upgrade.





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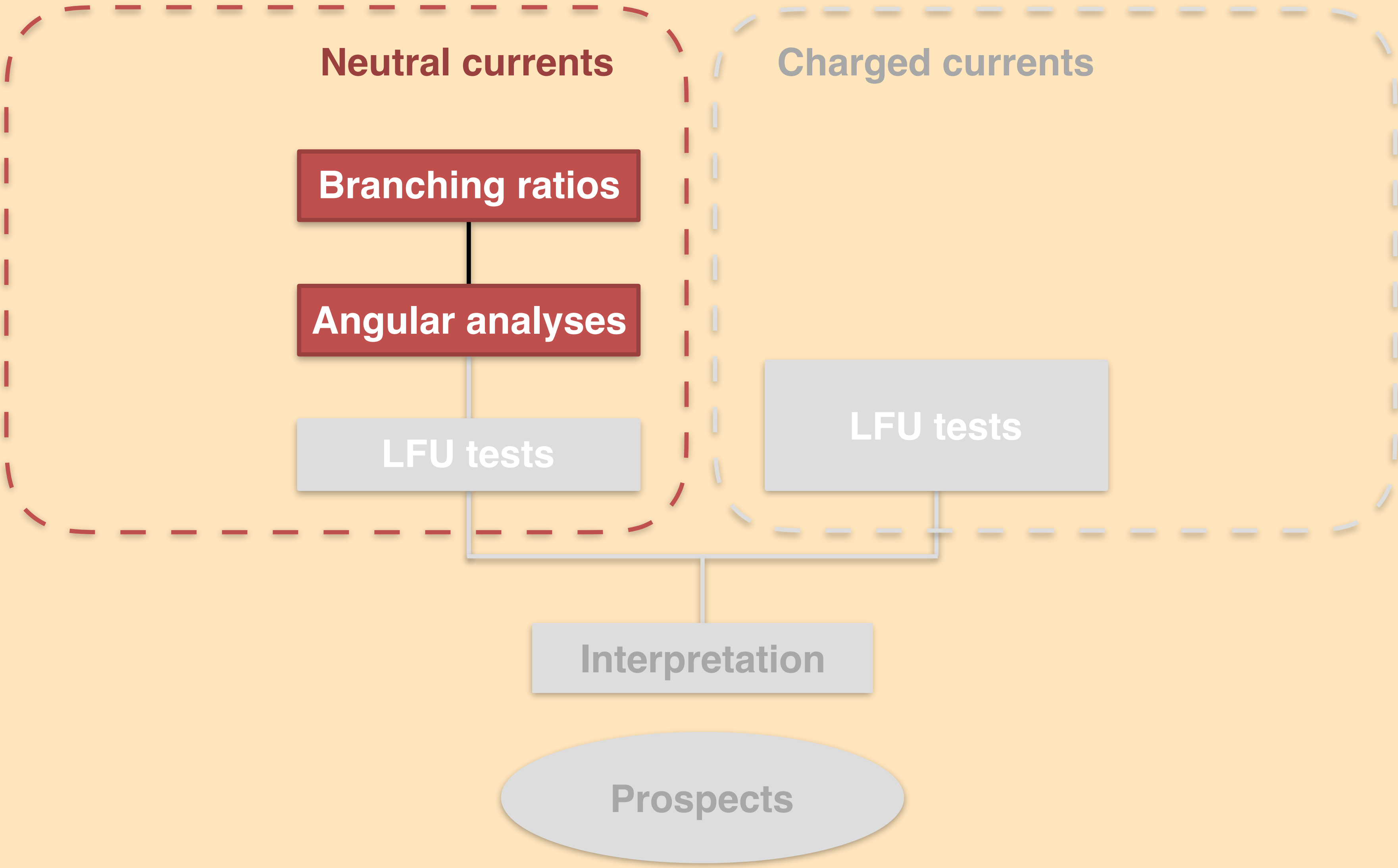
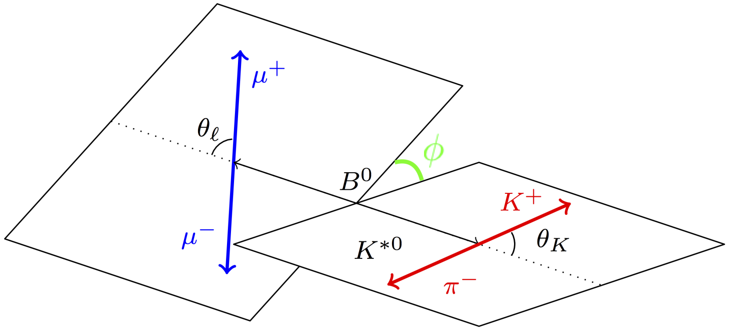


Angular analysis of $\mathrm{B}^0 \to \mathrm{K}^{*0}\mu^+\mu^-$

Decay rate described in terms of three helicity angles and q²:

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



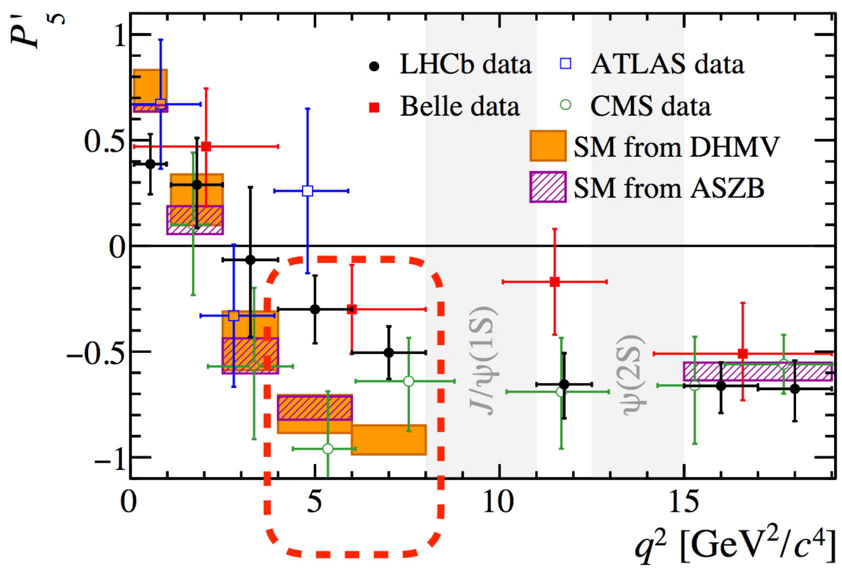
F_L, A_{FB} and S_i are combinations of polarization amplitudes and depend on Wilson coefficients ($\mathrm{C}_7^{(\prime)}, \mathrm{C}_9^{(\prime)}, \mathrm{C}_{10}^{(\prime)}$) and form factors.

Optimized observables, where form factors cancel at leading order:

$$P_5' \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

[JHEP, 1305:137 (2013)]

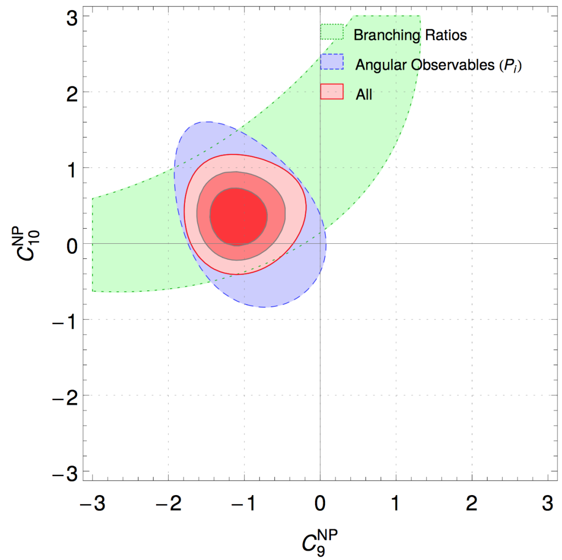
Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$



PRL 118 (2017) 111801 (Belle)
PLB 781 (2018) 517541 (CMS)
JHEP 10 (2018) 047 (ATLAS)

JHEP 02 (2016) 104 (LHCb)

Local SM tension of 2.8 and 3.0 σ
Global (LHCb only) $\longrightarrow$ 3.4 σ



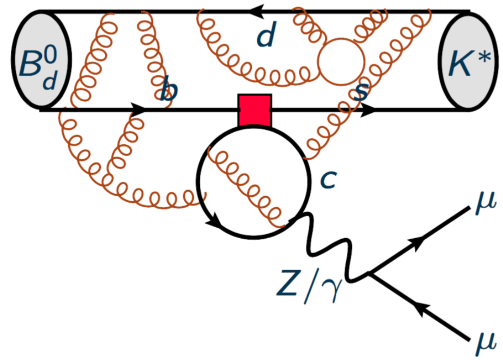
[JHEP06 (2016) 092]

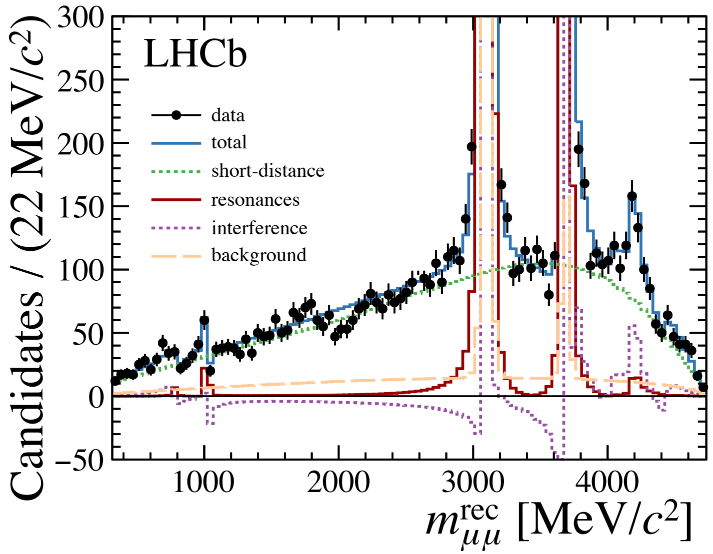
Both branching fractions and P_5' discrepancies can be explained with a shift in either C_9 or C_9/C_{10} simultaneously.

Charm-loop contribution

- The charm loop causes a contribution to C_9 difficult to estimate.

- This effect can be considered as that of the sum of the tails of the resonances + open charm.





Phases in $B^+ \to K^+\mu\mu$

EPJ C77 (2017) 161

Fit to m($\mu\mu$) to determine the interference between "rare mode" and resonances.

- J/ψ-"rare mode" phase difference compatible with ±π/2
- interference far from the pole mass is small

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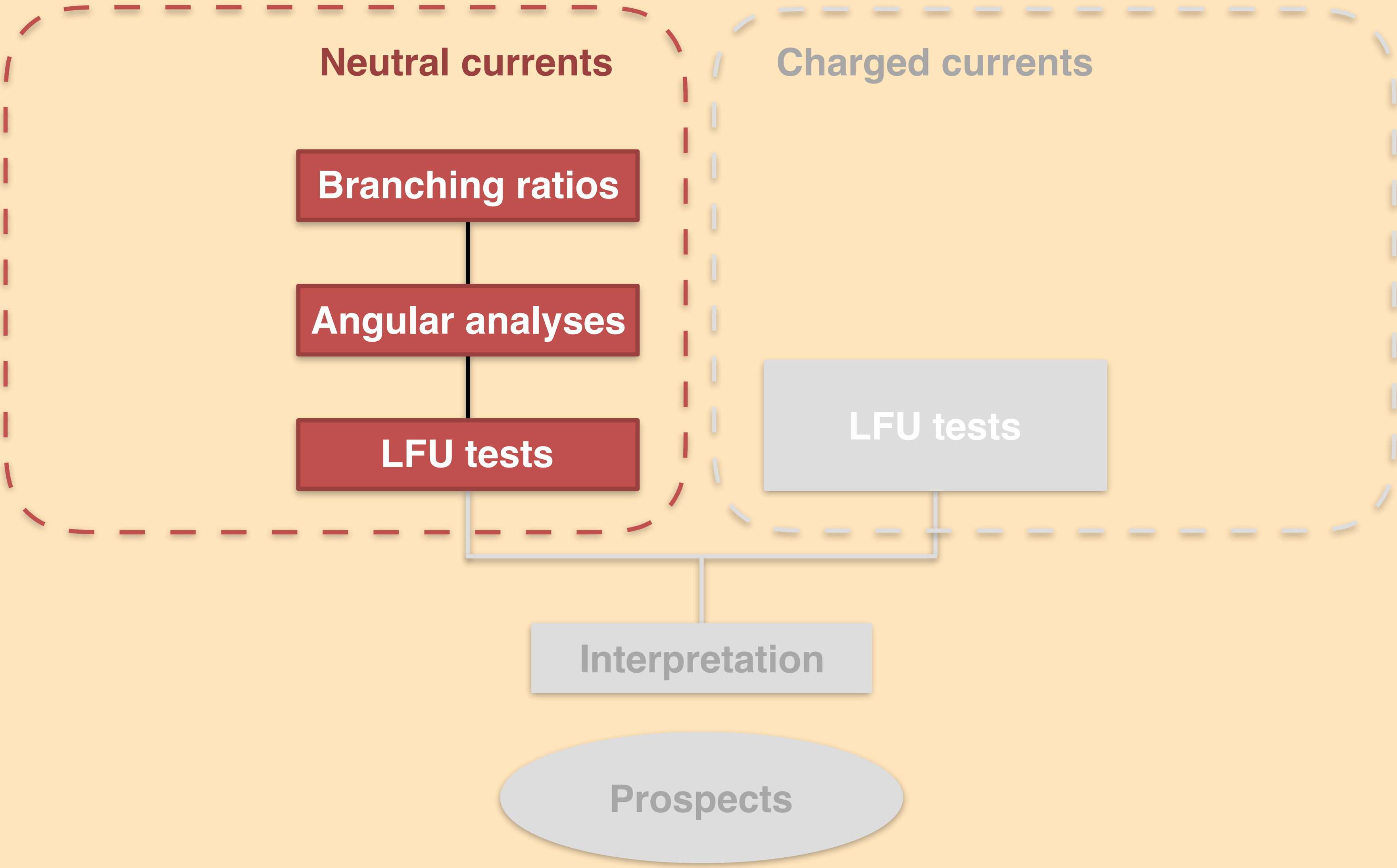


Lepton-flavour-universality tests

The SM is lepton universal: electroweak couplings are the same for **e/μ/τ**.
This can be different if NP is present.
For rare decays, focus on **muons vs. electrons**.

Ratios of branching fractions represent clean tests of LFU.

- SM prediction:

EPJ C76 (2016) 8 440

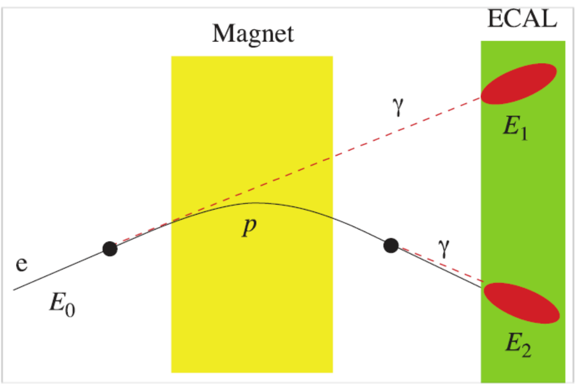
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} = 1 \pm \mathcal{O}(10^{-2})$$

taking the ratio cancels most uncertainties in hadronic transitions

Challenges for electrons at LHCb:

- Lower trigger and reconstruction efficiency.

- Bremsstrahlung strongly affects the q^2, B invariant mass and momentum resolutions.
→ Partial energy recovery adding photons.



Measurement of R(K)

PRL 122 (2019) 191801

Re-analysis of Run 1 data
(improved reconstruction and re-optimised analysis strategy)

Addition of 2015 + 2016 data

Previous measurement: [PRL 113,151601 (2014)]

Data sample **increased in a factor ~2**, with respect to the previous analysis

Three trigger types for the electron sample: focused on **electrons**, focused on **hadrons** and **signal independent**.

Efficiency computed using simulation that is calibrated with control channels in data.

Measurement via a **double ratio**, to further reduce uncertainties:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))}$$

Measurement of R(K)

PRL 122 (2019) 191801

To check the description of the efficiency, several tests are performed.

Measurement of R(ψ(2S)), expected to be 1:

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

Result: $R_{\psi(2S)} = 0.986 \pm 0.013 \;(\mathrm{stat+syst})$

Measurement of the single ratio $r_{J/\psi}$ predicted to be

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))} = 1 \qquad \text{(within 0.4\%)}$$

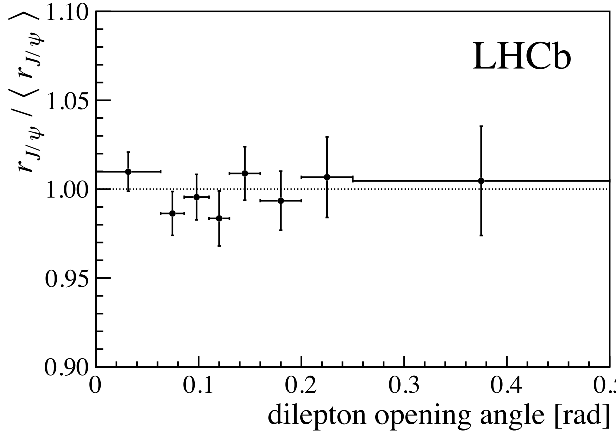
Strong test of the procedure, as both muons and electrons have to be under control.

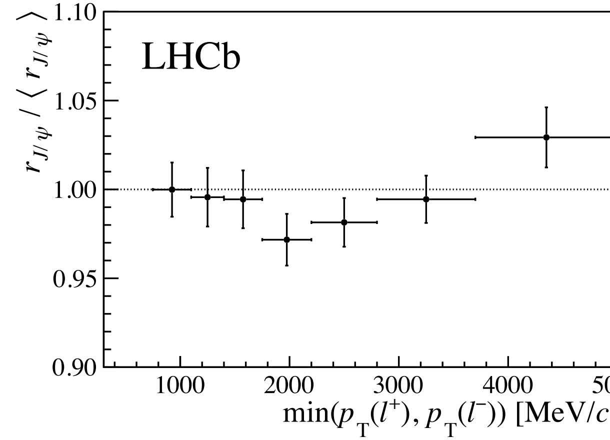
Result: $r_{J/\psi} = 1.014 \pm 0.035 \;(\mathrm{stat+syst})$

Measurement of R(K)

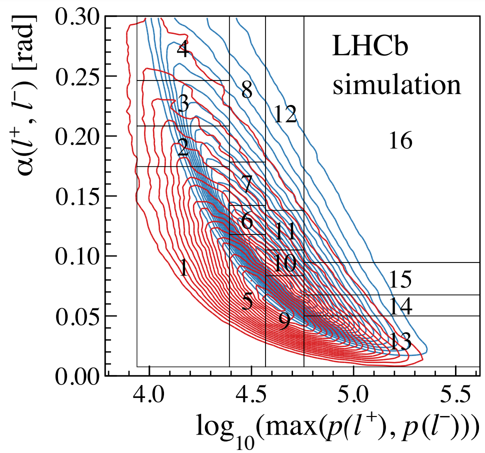
PRL 122 (2019) 191801

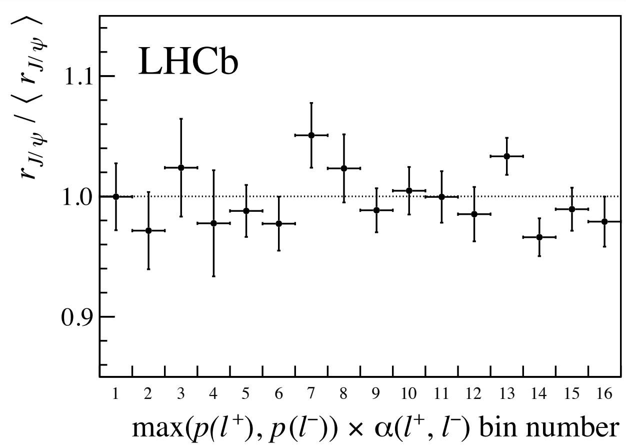
Measurement of $r_{J/\psi}$ in **1D bins** of kinematic variables.





Measurement of $r_{J/\psi}$ in **2D bins** of kinematic variables.



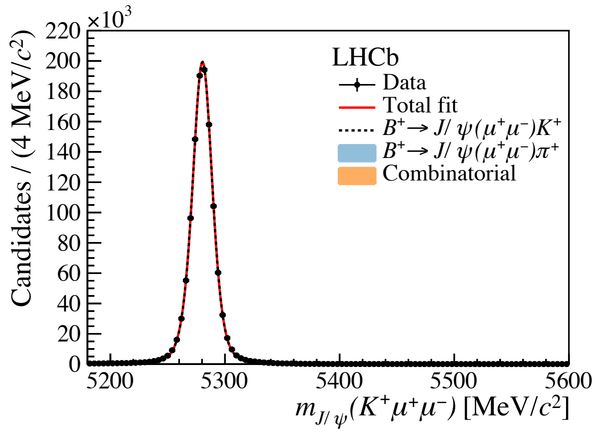


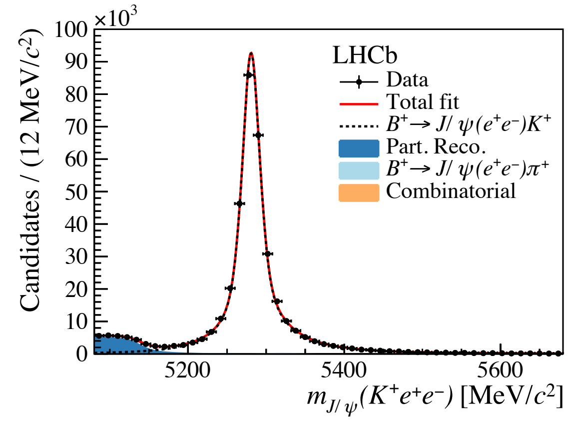
Measurement of R(K)

PRL 122 (2019) 191801

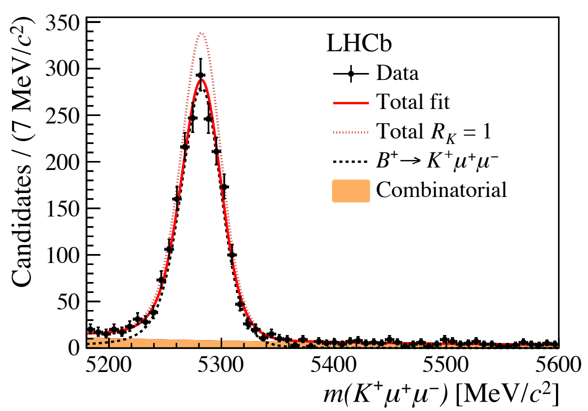
Yields extracted via invariant-mass fits.

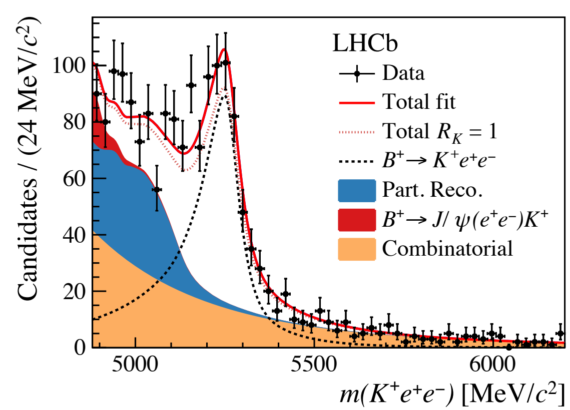
Resonant modes





Rare mode





Measurement of R(K)

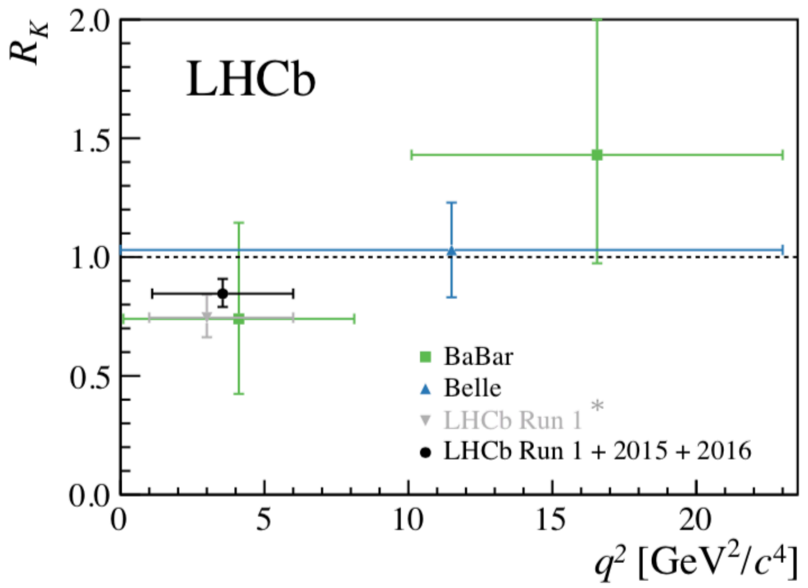
PRL 122 (2019) 191801

$$R_{K\,\text{Run1}}^{\text{new}} = 0.717\,^{+0.083}_{-0.071}\,(\text{stat})\,^{+0.017}_{-0.016}\,(\text{syst})$$

$$R_{K\,\text{Run2}} = 0.928\,^{+0.089}_{-0.076}\,(\text{stat})\,^{+0.020}_{-0.017}\,(\text{syst})$$

↓

$$R_K = 0.846\,^{+0.060}_{-0.054}\,(\text{stat})\,^{+0.014}_{-0.016}\,(\text{syst})$$



Updated result compatible with the SM at the **2.5σ level** (previously 2.6σ)

- Run 1 and Run 2 results compatible at the 1.9σ level.
- $\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ compatible with previous measurement. [JHEP06 (2014) 133]

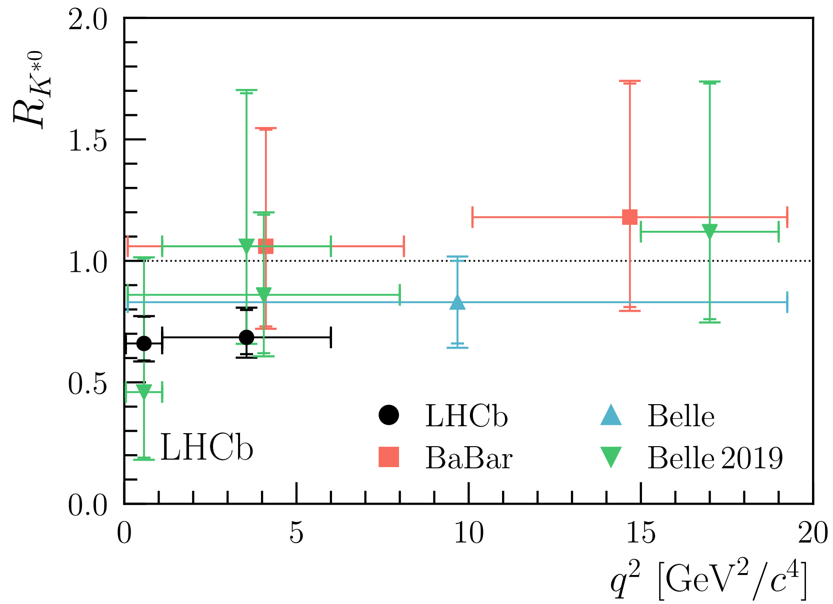
Measurement of R(K*)

$$R(K^*) = \frac{\mathscr{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathscr{B}(B^0 \to K^{*0}e^+e^-)} \frac{\mathscr{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}{\mathscr{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))}$$

LHCb Run 1 measurement:

JHEP 08 (2017) 055, LHCb

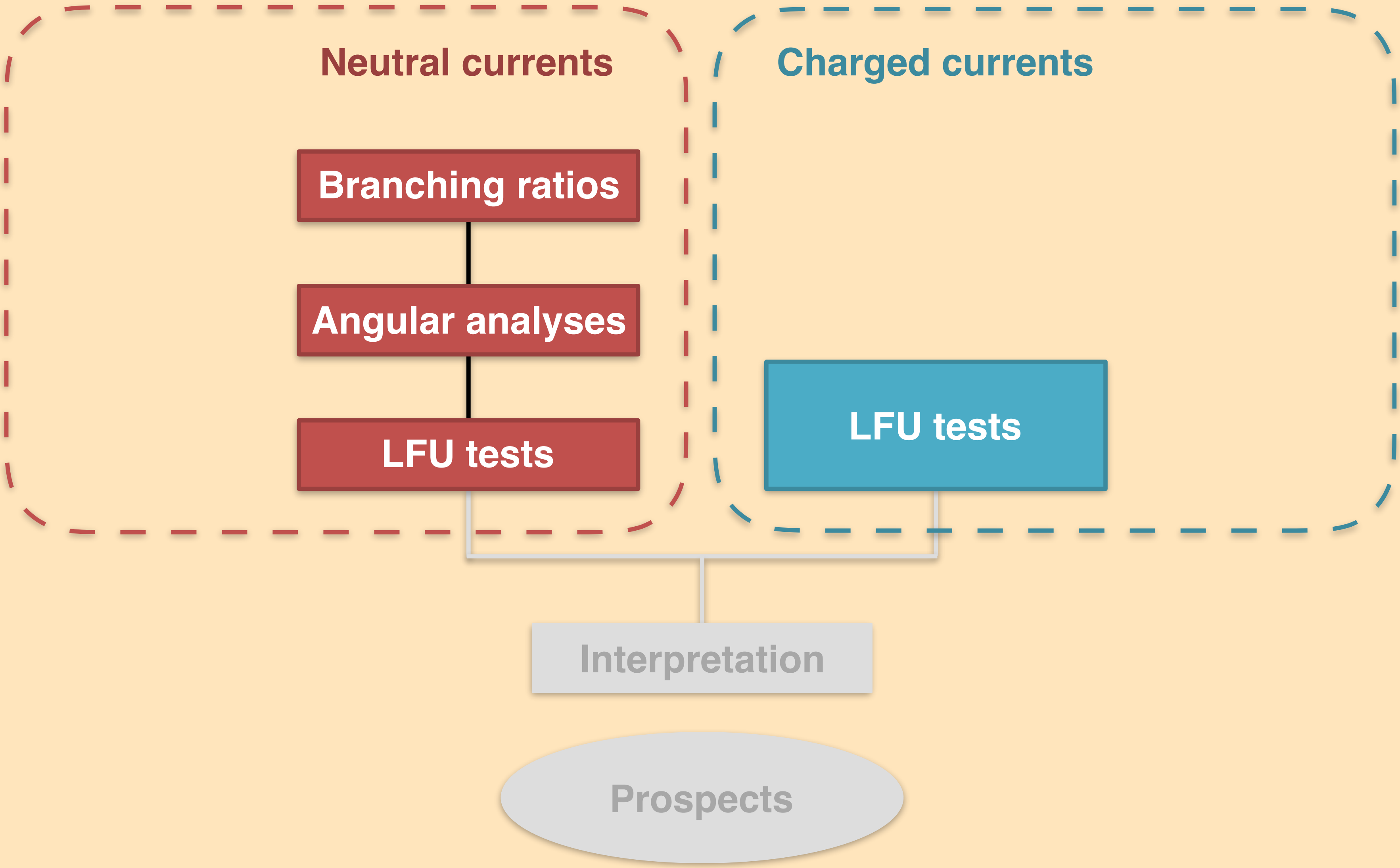
$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07} \pm 0.03 & \text{for } 0.045 < q^2 < 1.1 \text{ GeV}^2 \\ 0.69^{+0.11}_{-0.07} \pm 0.05 & \text{for } 1.1 < q^2 < 6.0 \text{ GeV}^2 \end{cases}$$



2.5(2.4)σ tension with the SM

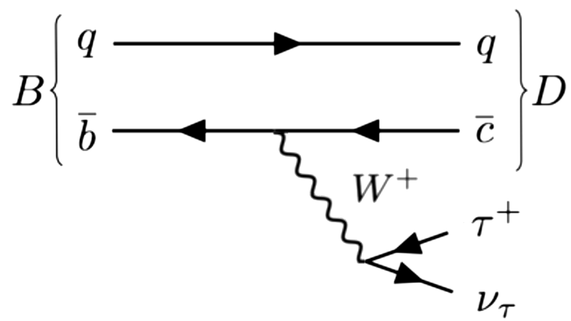
Recent updated measurement from Belle. [arXiv:1904.02440]

Contents of the talk



LFU in charged currents

- **Tree-level** decays in the SM.
- Very large data samples.
- Theoretically very clean.
- **μ/τ deviations** observed by three experiments (LHCb, Belle, BaBar).



$$R(\mathcal{H}_c) = \frac{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \tau \nu_\tau)}{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \mu \nu_\mu)}$$

$$\mathcal{H}_b = B^0, B^+_{(c)}, \Lambda_b^0, B_s^0 \ldots$$

$$\mathcal{H}_c = D^*, D^0, D^+, D_s, \Lambda_c^{(*)}, J/\psi \ldots$$

LHCb: Difficult decay reconstruction due to **missing neutrinos**.

Rest-frame approximation:

$$(\gamma\beta_z)_B = (\gamma\beta)_{D^*\mu} \Rightarrow (p_z)_B = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$

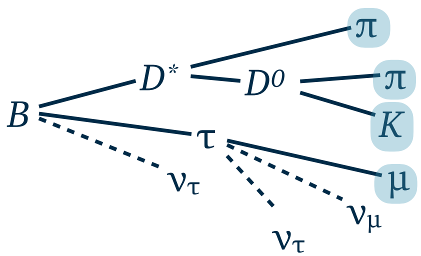
18% resolution on the B momentum.

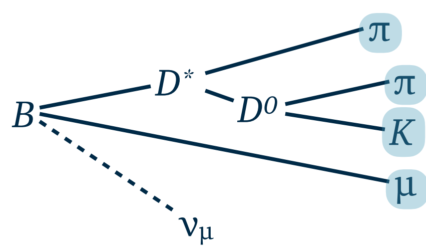
Muonic R(D*)

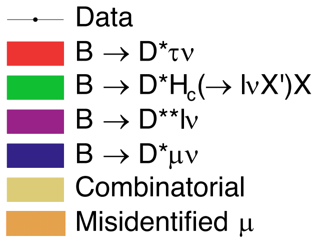
PRD 115,111803 (2015), LHCb

Reconstruction of the tauon as: $\tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$

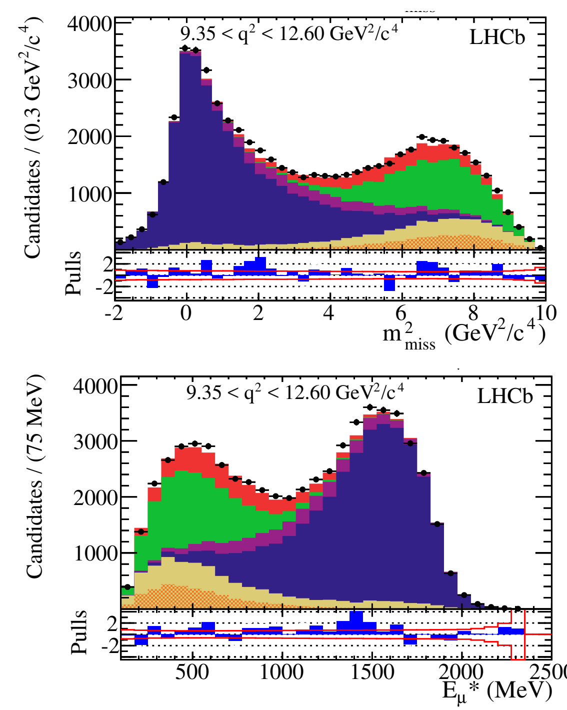
Signal and normalization have the same visible final state.







Projections in one bin of q²



Measurement via a 3D fit to data.

Set of variables

- E_μ
- q^2
- m^2_{miss}

$$R_{D^*} = 0.336 \pm 0.027 \pm 0.030$$

The result is **2.1σ above the SM**

Hadronic R(D*)

PRD 97,072013 (2018), LHCb

PRL 120,171802 (2018), LHCb

Reconstruction of the tauon as: $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)$

Normalized with respect to $B^0 \to D^{*-}\pi^+\pi^-\pi^+$

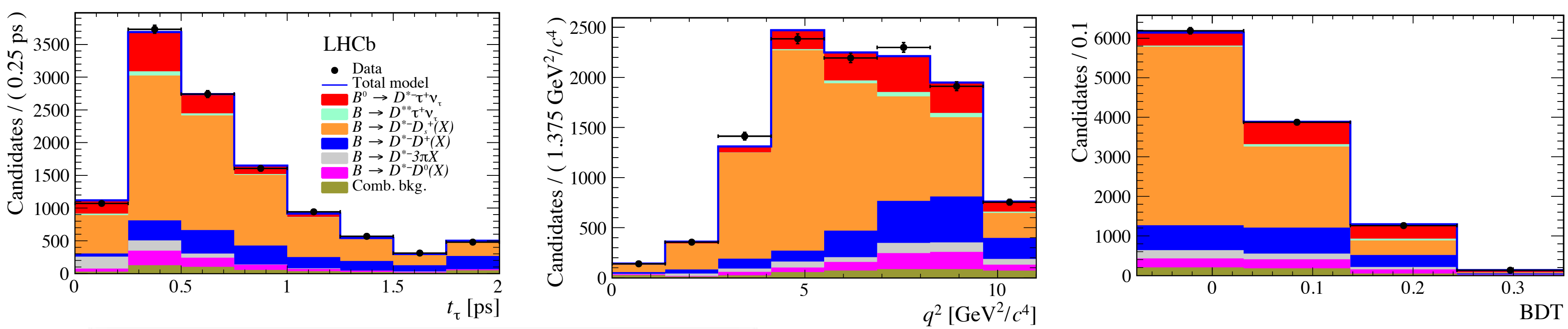
$$K_{had}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}, \quad \mathbf{R(D^*)} = K_{had}(D^*)\times\frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)$ from a **3D binned template fit**.

$\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)$ from an un-binned fit to $M(D^{*-}\pi^+\pi^-\pi^+)$.

$\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)$ and $\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$ external, from the PDG.

Set of variables
- t_τ
- q^2
- BDT output

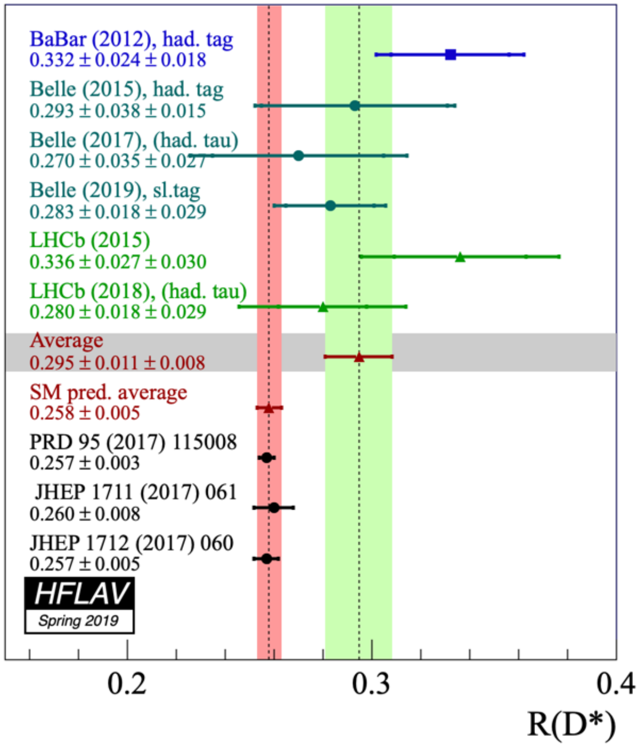


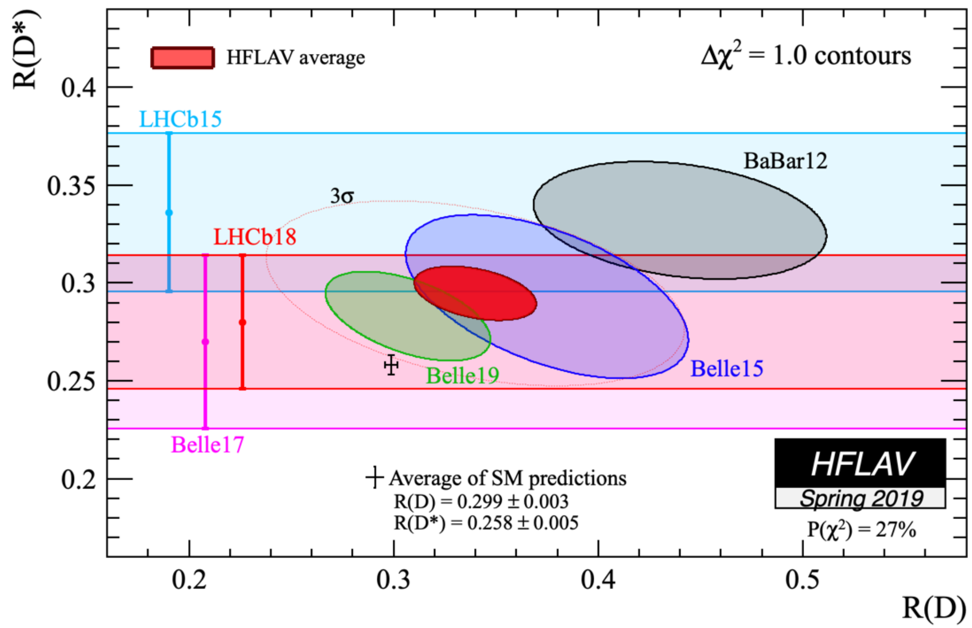
$R(D^*) = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$

External branching ratios

The result is **~1σ above the SM**

R(D) and R(D*) combination





New R(D) and R(D*) measurement by Belle.
[arXiv:1904.08794]

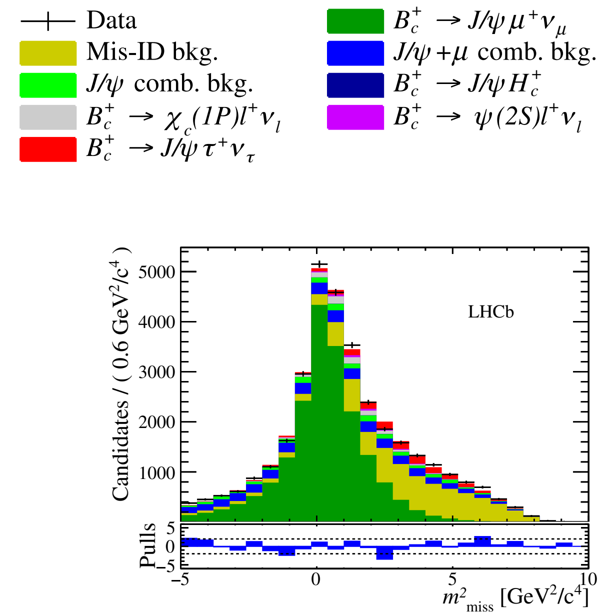
New world average for R(D) and R(D*) at 3.1σ from the SM

Measurement of R(J/ψ)

PRL 120,121801 (2018), LHCb

Similar decay, change of spectator quark (c instead of u or d).

$$R_{J/\psi} \equiv \frac{\mathcal{B}\left(B_c \to J/\psi\, \tau\nu\right)}{\mathcal{B}\left(B_c \to J/\psi\, \mu\nu\right)}$$



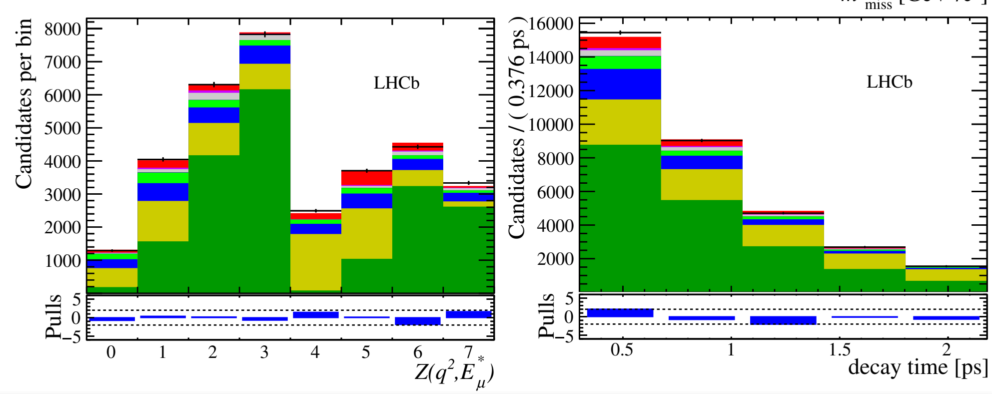
Form factors not constrained from B factories.

$R^{SM}_{J/\psi} \in [0.25, 0.28]$

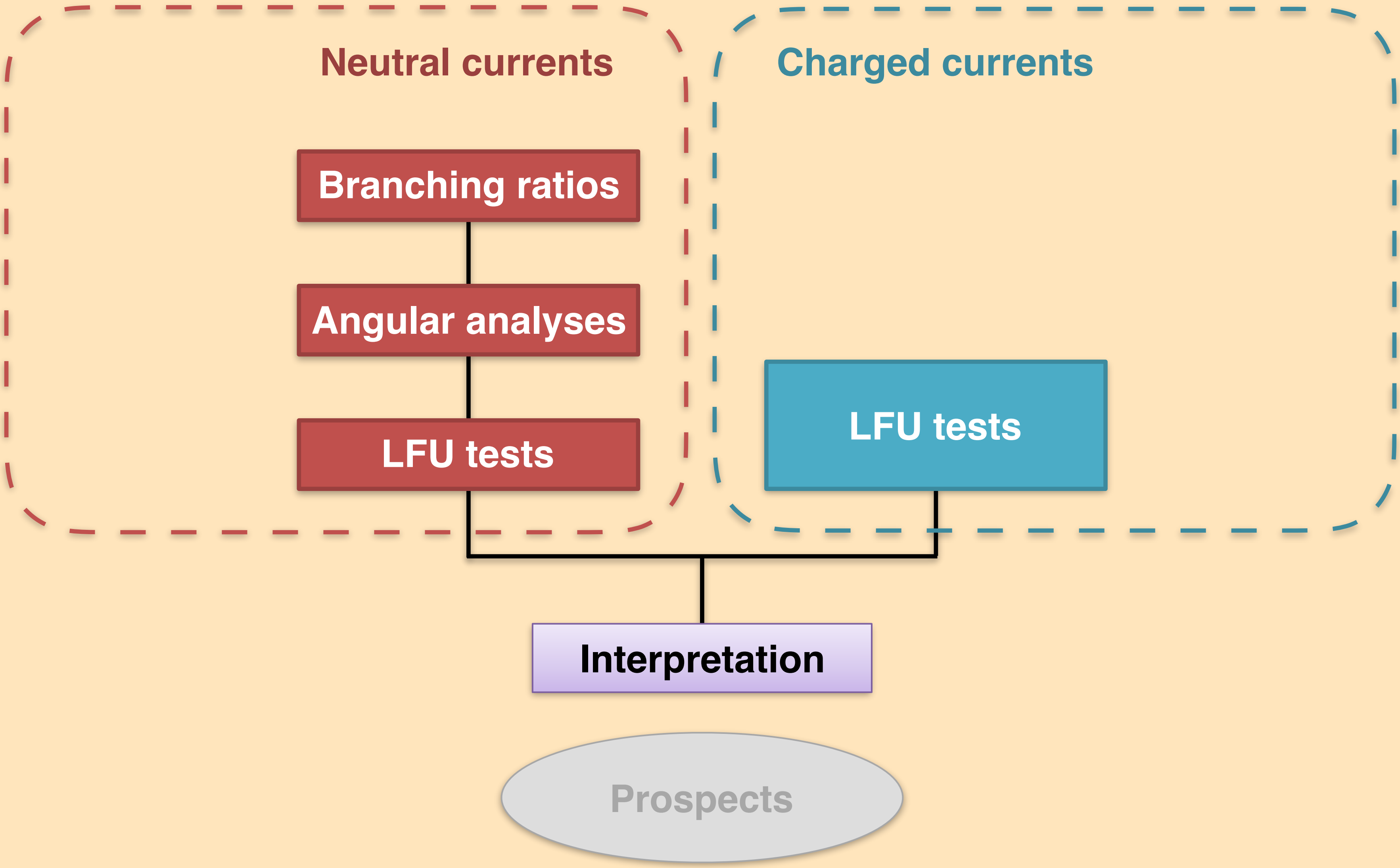
Measurement via a 3D fit: m^2_{miss}, t_B, $Z(q^2, E^*_\mu)$

- $\tau \to \mu\nu\nu$
- $J/\psi \to \mu\mu$
- $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$

$\sim 2\sigma$ above SM

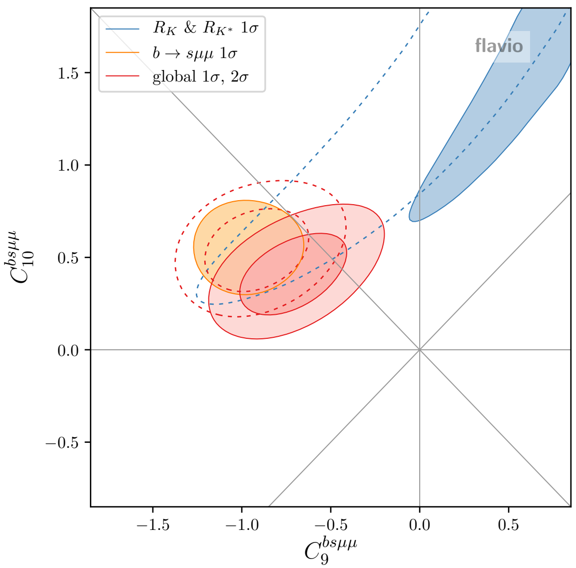


Contents of the talk



Phenomenological interpretation

[arXiv:1903.10434]

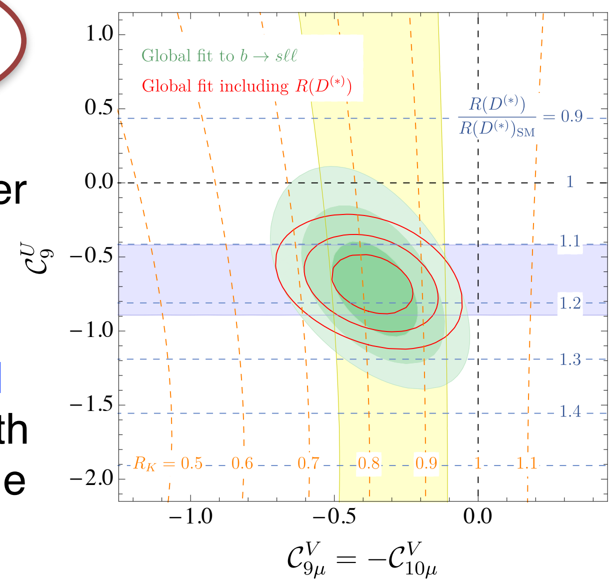


See the talk by Joaquin Matias

No dramatic changes after newest LFU results.

Interesting new possible interplay between neutral and charged currents, with NP in b→clν playing a role in the b→sll anomalies.

[arXiv:1903.09578]



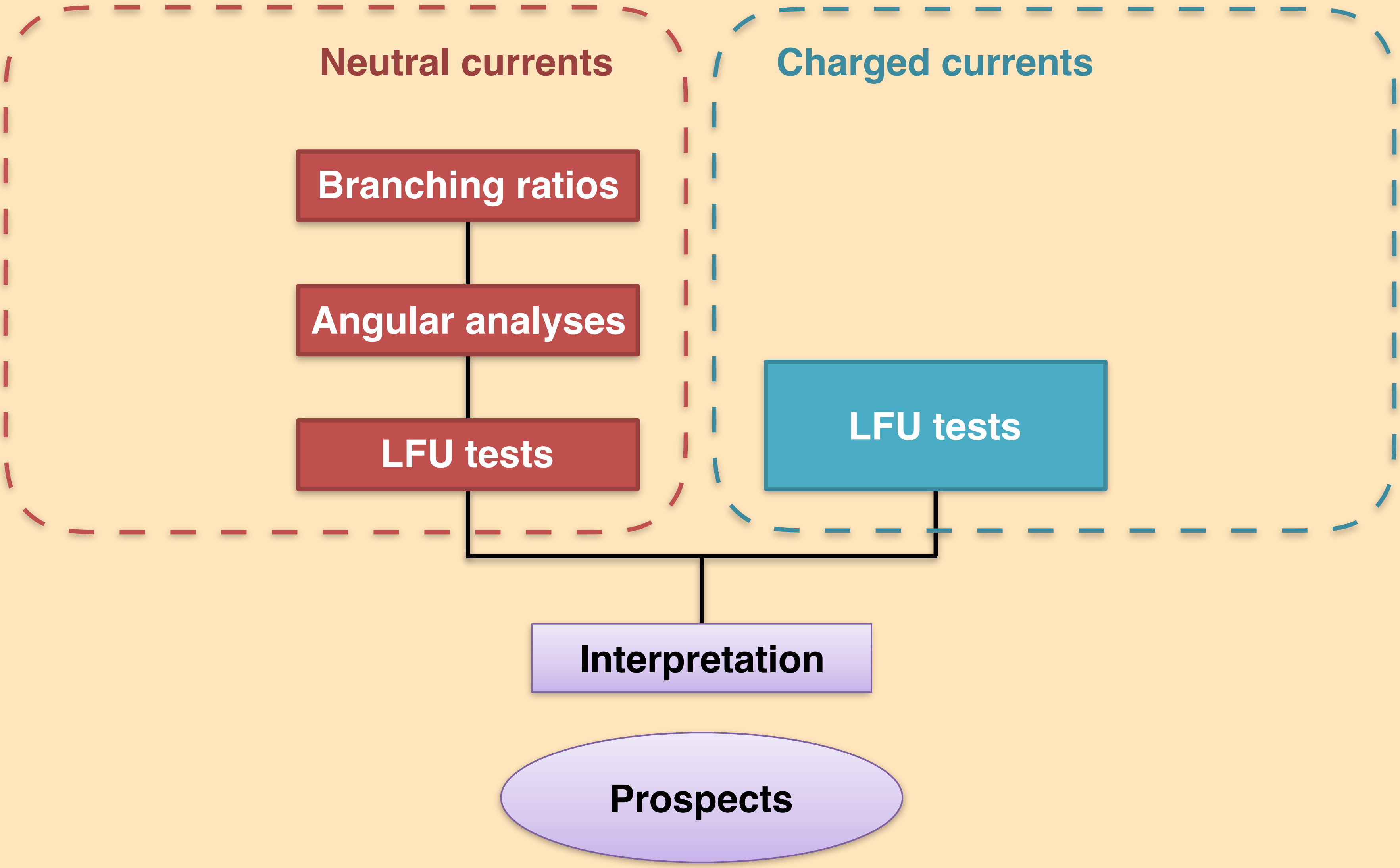
Complementary measurements: **lepton flavour violation (LFV)**

Many NP models that would explain the anomalies predict sizable branching fractions in charged LFV decays.

Recent LHCb results on $B^+ \to K^+\mu^\pm e^\mp$ and $B^0_{(s)} \to \tau^\pm\mu^\mp$.

See the talk by Cedric Meaux

Contents of the talk



Near-term prospects for b→sll

- R(K*) measurement with full Run 1 + Run 2 (previously only Run 1).
- R(K) measurement with full Run 1 + Run 2 (previously Run 1 + 2015 + 2016).
- $B^0 \to K^* \mu^+ \mu^-$ angular analysis.
- New ratios: R(ϕ), R(K$\pi\pi$), R($\Lambda^{(*)}$), …
- $B^0 \to K^* e^+ e^-$ angular analysis: non-LFU angular asymmetries $\Delta P_i'$.
- Direct measurement of Wilson Coefficients from data, via amplitude analysis of $B^0 \to K^* \mu^+ \mu^-$.

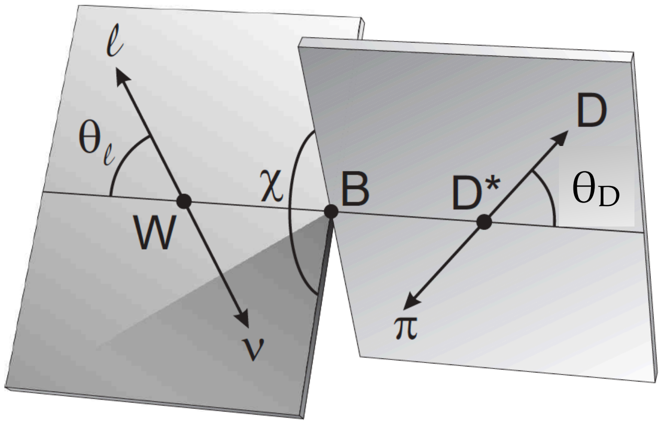
Near-term prospects for $b \to c l \nu$

- Simultaneous measurement of $R(D^0)$ and $R(D^*)$ (Run 1).
- Simultaneous measurement of $R(D^+)$ and $R(D^*)$ (Run 2).
- New ratios: $R(\Lambda_c)$, $R(D_s)$, …
- Updated analyses: addition of Run 2 data; hadronic versions of the muonic analyses.

Next step: angular analyses

Allow to differentiate among different possible new models.

Challenging due to the resolution on the angular variables, but very large data samples available.



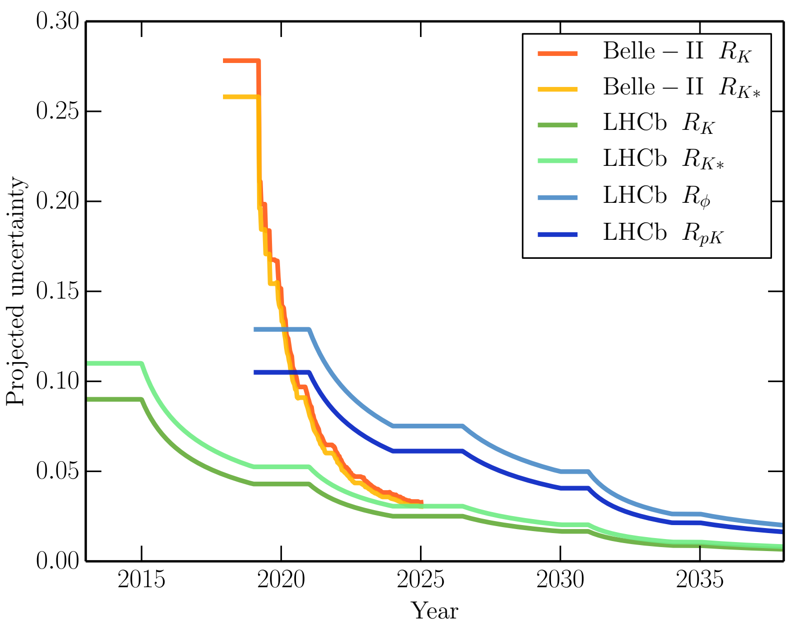
Long-term prospects

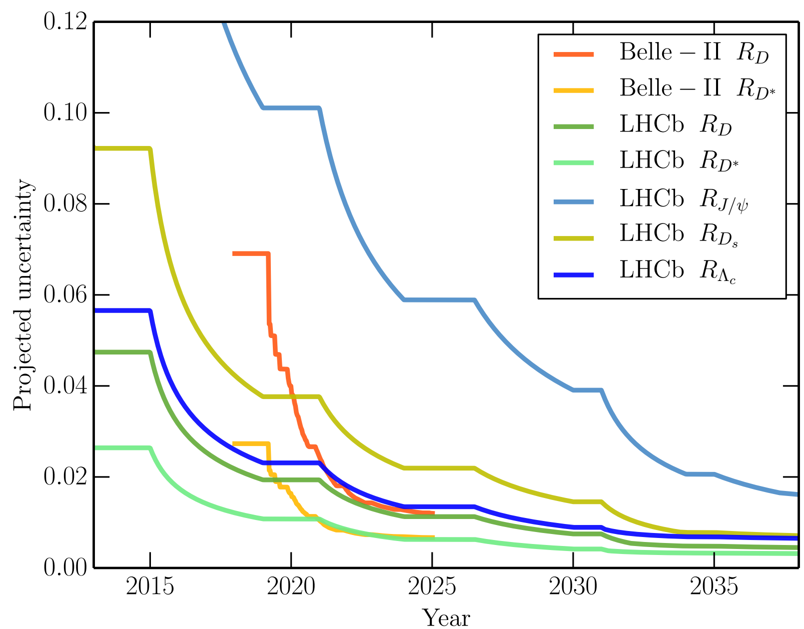
Interplay between the **LHCb Upgrades** and **Belle II**.

Large reduction of the uncertainty on the LFU measurements.

Experiment	2018	2021	2024	2025	2037
Belle-II	—	5 ab^{-1}		50 ab^{-1}	
LHCb	9 fb^{-1}		23 fb^{-1}		300 fb^{-1}

[Journal of Physics G, 46, 2 (2018)]





Summary and conclusions

- Very interesting pattern of anomalies in neutral and charged currents.
- Still larger data samples are needed to understand their nature.
- Several measurement updates using Run 2 data and new measurements to come in the near future.
- The LHCb Upgrades and Belle II will allow to further clarify the situation and, if the anomalies are due to beyond-the-SM physics, to disentangle between different scenarios.