Universität Zürich[UZH]

Searches for NP with Rare, Semileptonic and Radiative Decays of Heavy Flavour Hadrons at the LHC

Julián García Pardiñas[1]
(on behalf of LHCb, CMS and ATLAS)

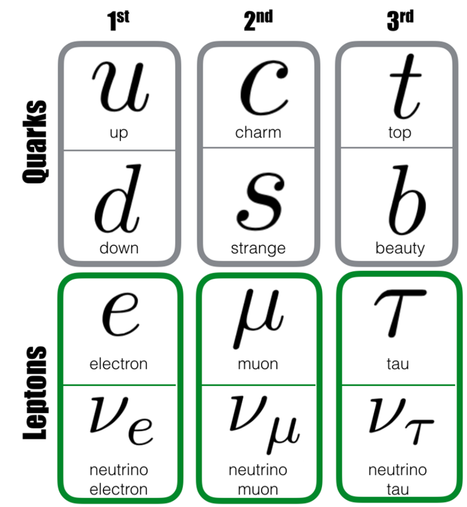
[1]Universität Zürich (UZH), Switzerland

La Thuile 2019

Vallée d’Aoste, Italy
March 13th, 2019

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 are **flavour-dependent**. → Connection with the flavour structure of the SM?

Rare decays (neutral currents)

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

Semileptonic decays (charged currents)

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

Proposed new models for a combined explanation: **leptoquarks**, **Z'**, **charged Higgs**, …

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

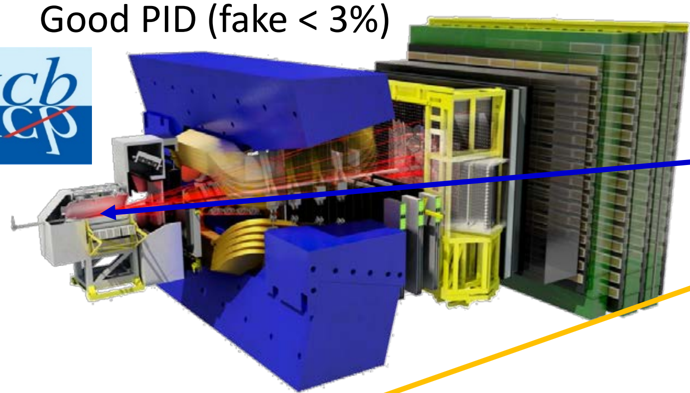
NP scale: Λ_{NP}

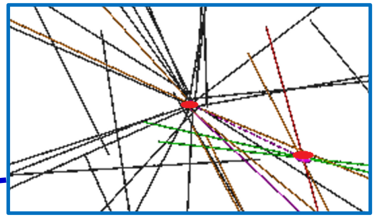
- BSM processes can modify the effective Hamiltonian by
  - Modifying Wilson coefficients of operators present in SM
  - Introducing new operators
  - Making Wilson coefficients dependent on the lepton flavour

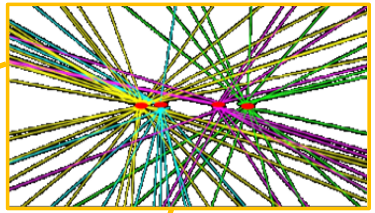
Experimental search at the LHC

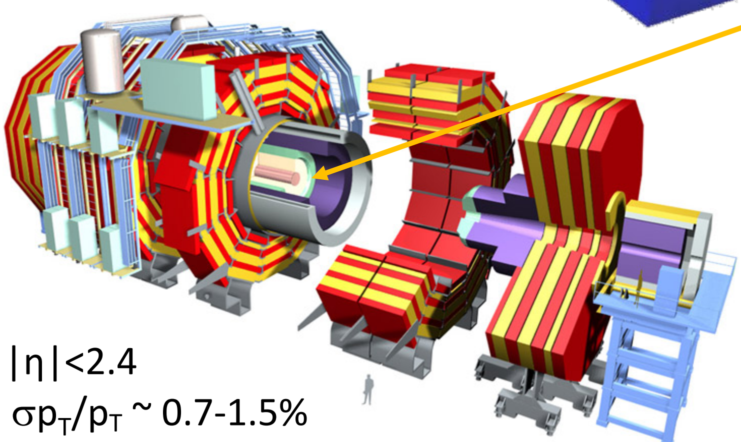
Run 1: 2010-2012
Run 2: 2015-2018

$2<\eta<5$
$\sigma p/p \sim 0.5$-1%
$\sigma IP_{\perp} \sim 15$-$50\ \mu m$
Good PID (fake < 3%)



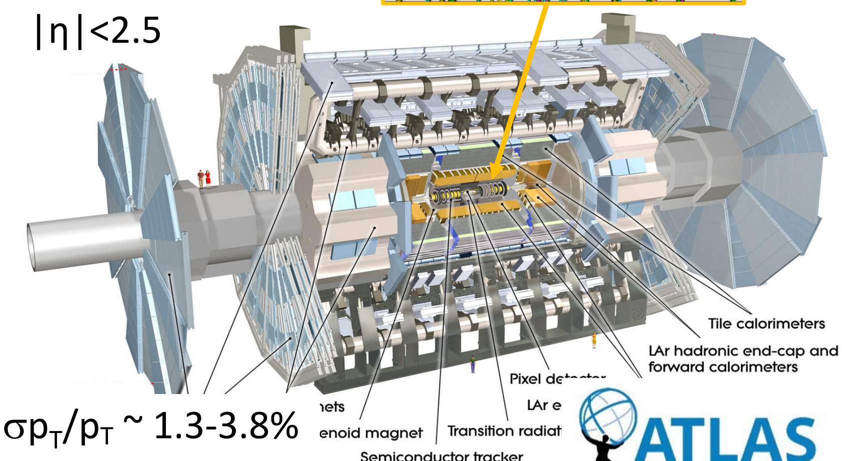






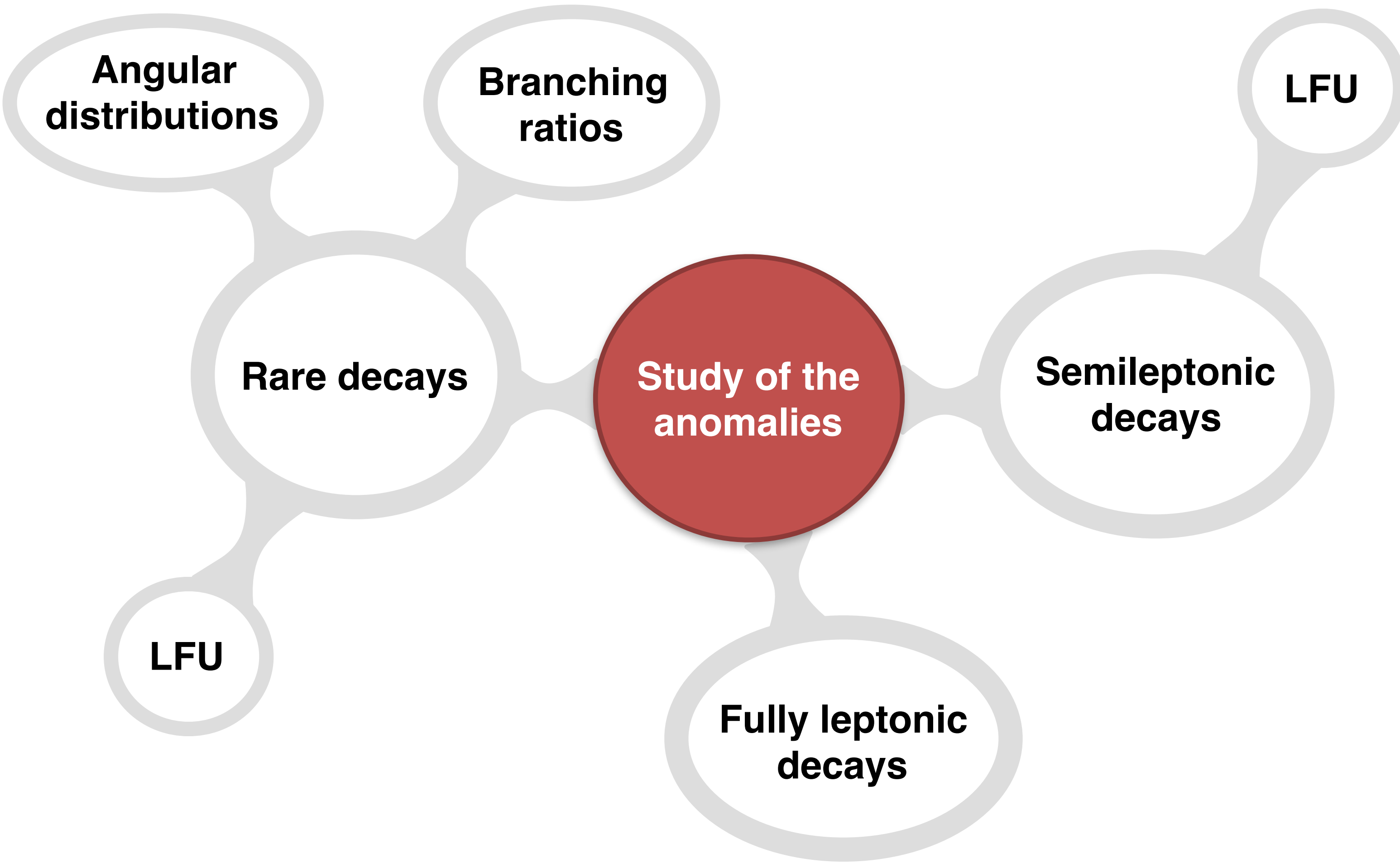
$|\eta|<2.4$
$\sigma p_T/p_T \sim 0.7$-1.5%
$\sigma IP_{\perp} \sim 25$-$100\mu m$
Very good PID (fake < 0.1%)

$|\eta|<2.5$

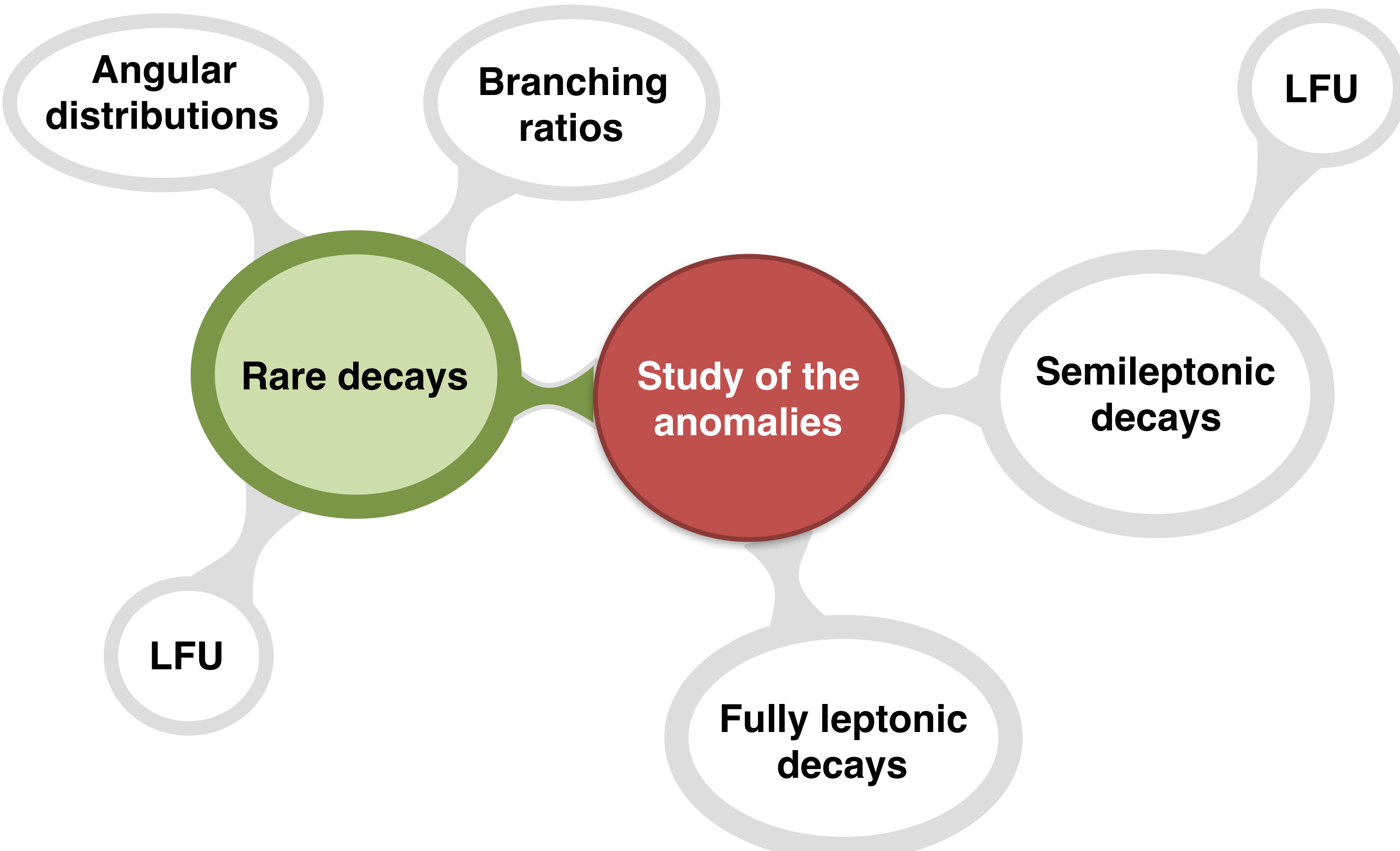


$\sigma p_T/p_T \sim 1.3$-3.8%
$\sigma IP_{\perp} \sim 25$-$100\mu m$

Map of the anomalies

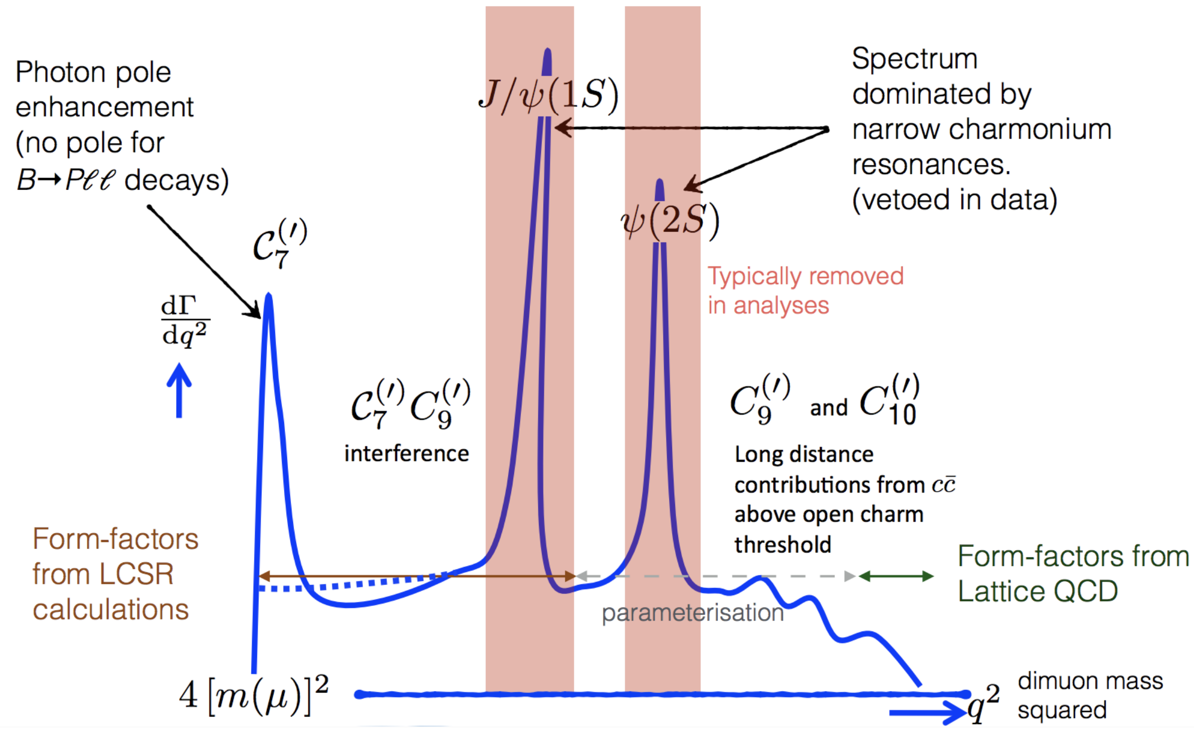


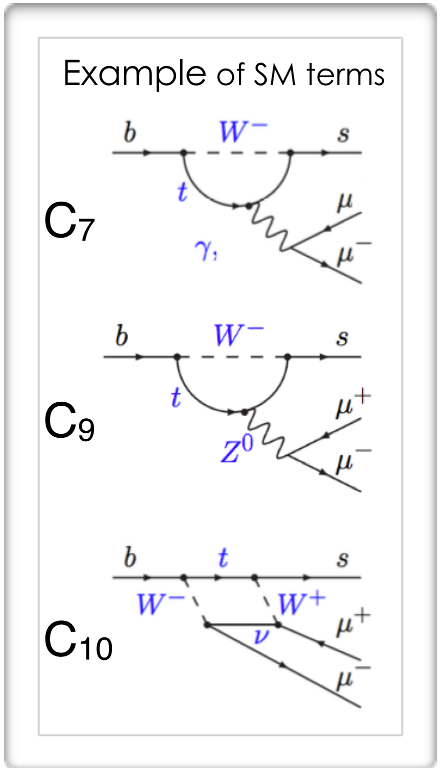
Map of the anomalies



Study of b→sll: q² spectrum

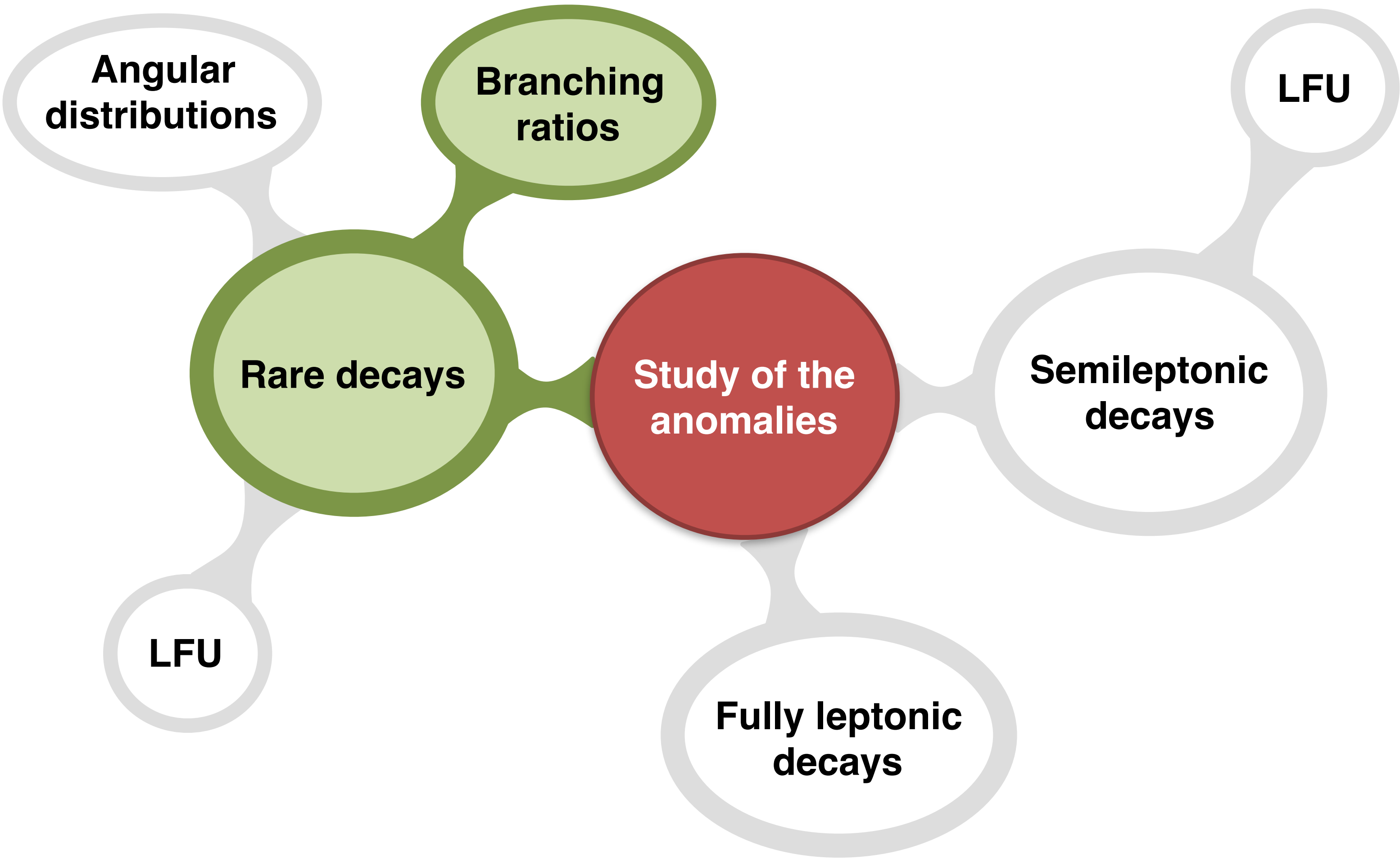
Different regions of $q^2 = M(l^+l^-)^2$ give sensitivity to different **Wilson Coefficients**.





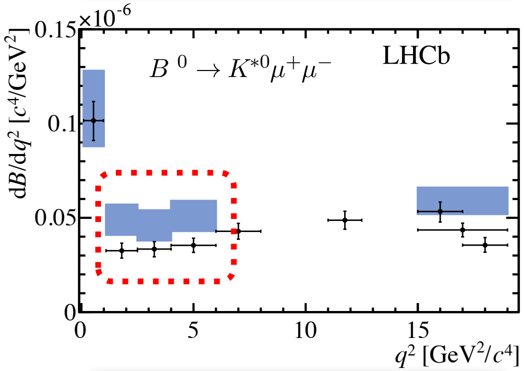
The regions of the **J/ψ and ψ(2S) resonances** correspond to tree-level decays, assumed to be SM-like. They are vetoed in the analyses and used as control regions.

Map of the anomalies

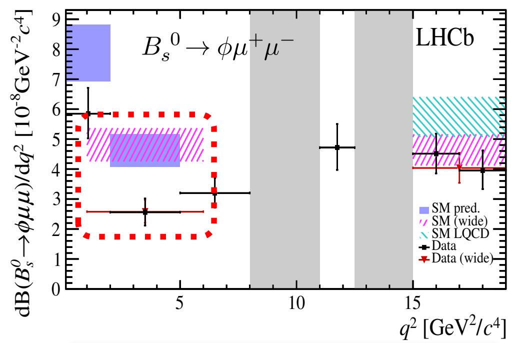


Differential branching ratios

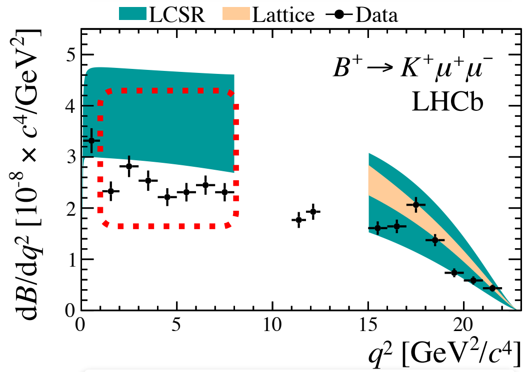
JHEP 11 (2016) 047, LHCb



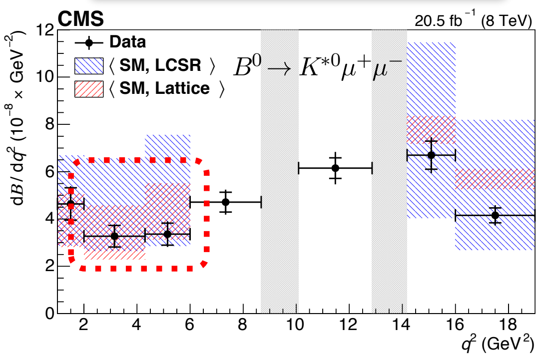
JHEP 09 (2015) 179, LHCb



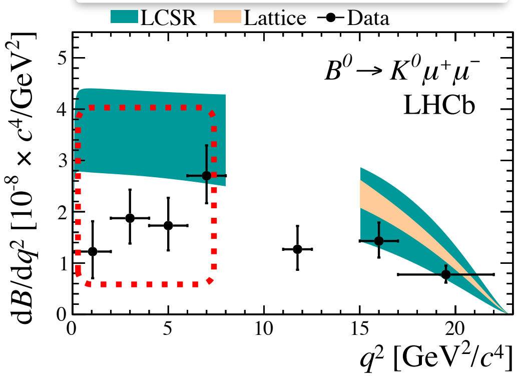
JHEP 06 (2014) 133, LHCb



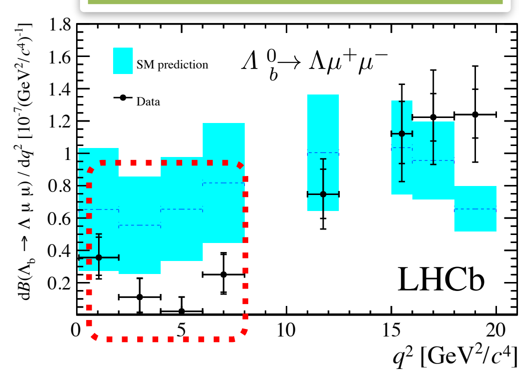
PLB 753,424 (2016), CMS



JHEP 06 (2014) 133, LHCb



JHEP 06 (2015) 115, LHCb



Data consistently below SM predictions, tensions at 1-3σ level.
Sizable hadronic theory uncertainties.

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

JHEP 07 (2018) 020 (LHCb)

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

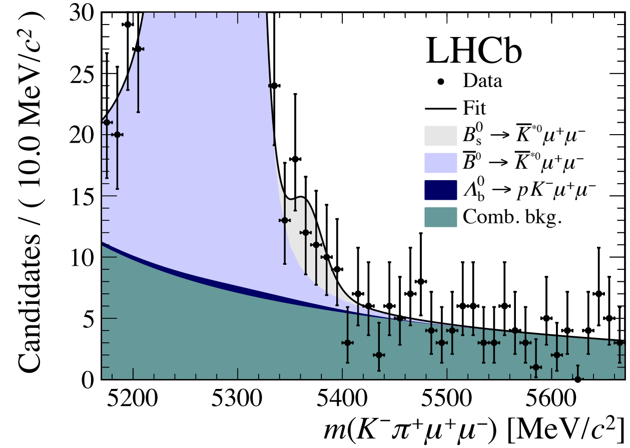
Heavily suppressed b→dll transition,
SM BR ∈ [3,4] x 10^{-8}. [EPJ C73 (2013) 10, 2593]
[JHEP 07 (2018) 020] [PRD 98, 094012 (2018)]

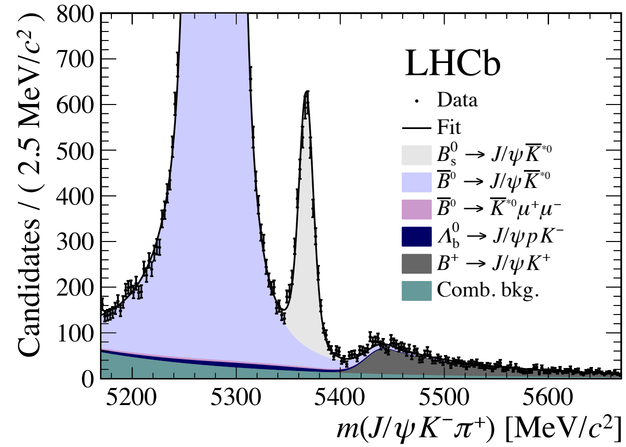
Run1 + part of Run2, 4.6 fb^{-1}.

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

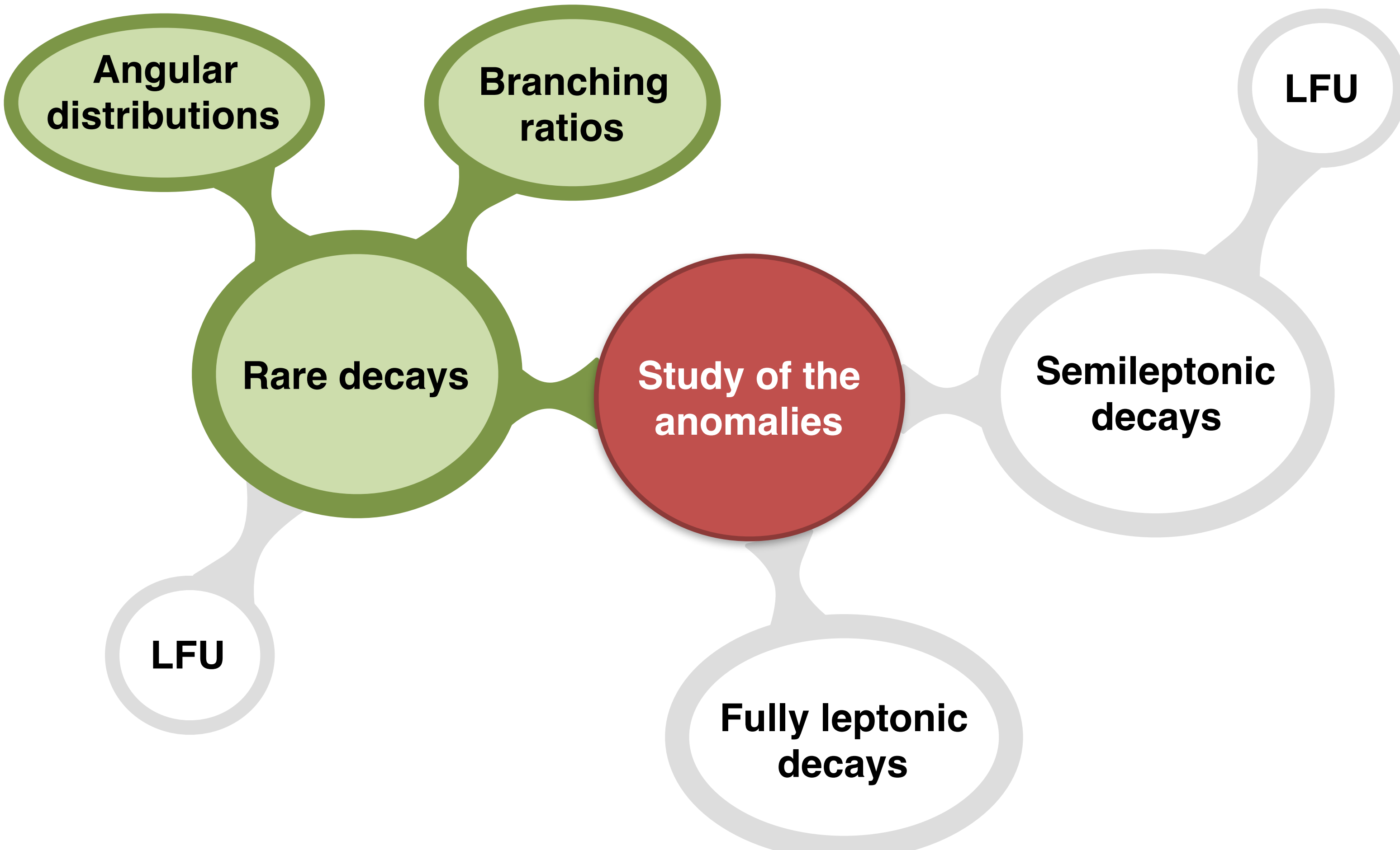
First evidence at 3.4 σ, BR consistent with SM.

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





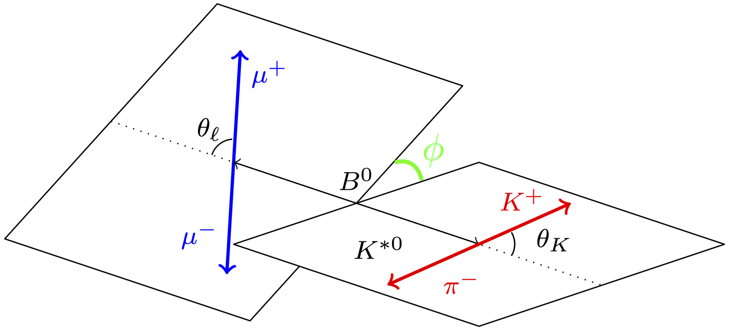
Map of the anomalies



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

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

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



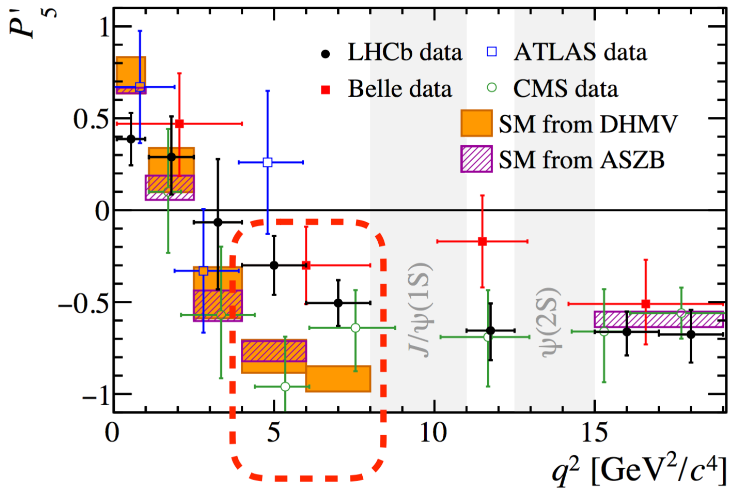
F_L, A_{FB} and S_i are combinations of polarization amplitudes and depend on Wilson coefficients ($C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$) and form factors.

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)]

Measurements



JHEP 02 (2016) 104 (LHCb)

PRL 118 (2017) 111801 (Belle)

JHEP 10 (2018) 047 (ATLAS)

PLB 781 (2018) 517541 (CMS)

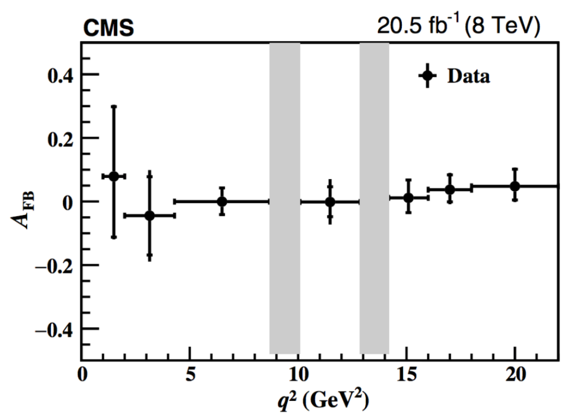
Local SM tension of 2.8 and 3.0 σ

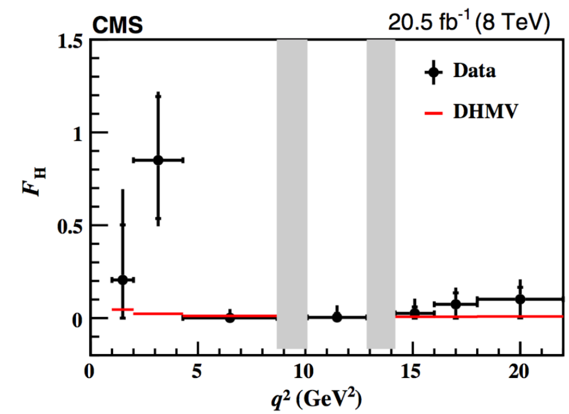
Global (LHCb only) $\longrightarrow$ 3.4 σ

Other recent studies of B decays

Angular analysis of $B^+ \to K^+\mu^+\mu^-$, 20.5 fb^{-1} (CMS, 2018): results consistent with the SM.

PRD 98 (2018) 112011 (CMS)





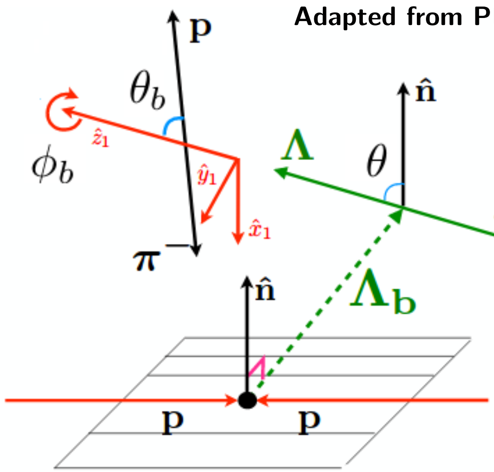
Angular analysis of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$

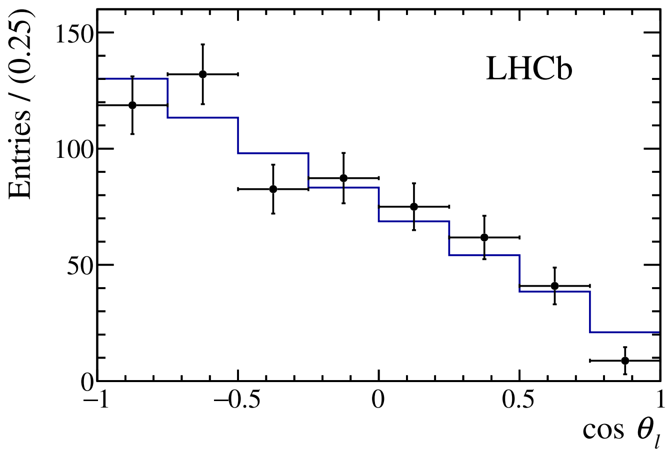
- Run1 + 1/2 Run2 (5 fb^{-1}) → 600 candidates.
- High q^2 region [15-20] GeV^2.
- Decay rate as a function of **5 angles and q^2**.
- First measurement of the **full set of angular observables**, determined with the **method of moments**.

$$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2}\sum_i^{34} K_i f_i(\vec{\Omega})$$

JHEP 09 (2018) 146 (LHCb)

Adapted from PRD97(2018)072010





Observables combined afterwards to construct asymmetries:

$$A_{FB}^{\ell} = \frac{3}{2}K_3 = -0.39 \pm 0.04 \pm 0.01$$

$$A_{FB}^{h} = K_4 + \frac{1}{2}K_5 = -0.30 \pm 0.05 \pm 0.02$$

Compatible with SM

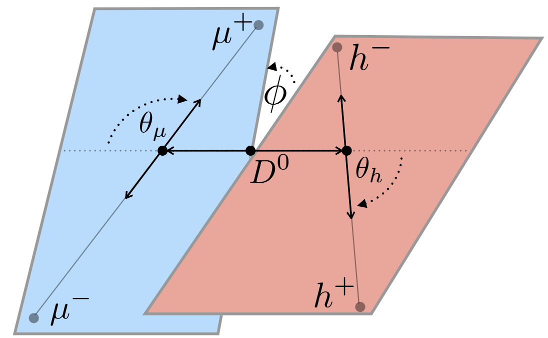
$$A_{FB}^{\ell h} = \frac{3}{4}K_6 = +0.25 \pm 0.04 \pm 0.01$$

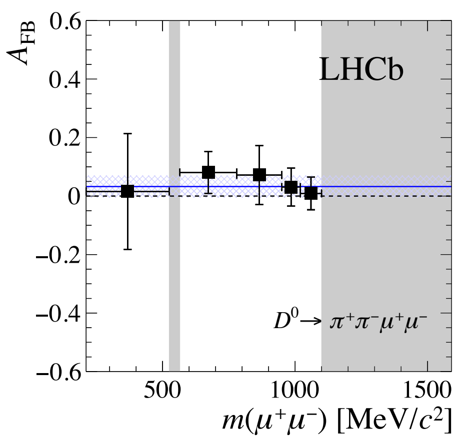
2.6 σ from SM

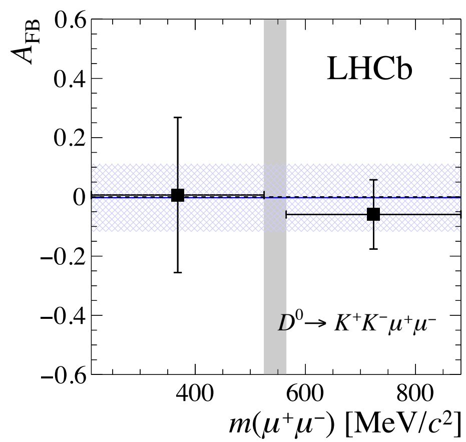
Angular and CP asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$

- Run1 + 1/2 Run2 (5 fb^{-1}).
- Two decays studied: **$D^0 \to \pi^+\pi^-\mu^+\mu^-$** and **$D^0 \to K^+K^-\mu^+\mu^-$**.
- **$c \to u\mu^+\mu^-$** transitions, highly suppressed in the SM.
  [PRD 83: 114006 (2011)]
- Measure **FB, triple-product and CP asymmetries**.
- Asymmetries measured via **fits to $M(h^+h^-\mu^+\mu^-)$**.

PRL 121 (2018) 091801 (LHCb)





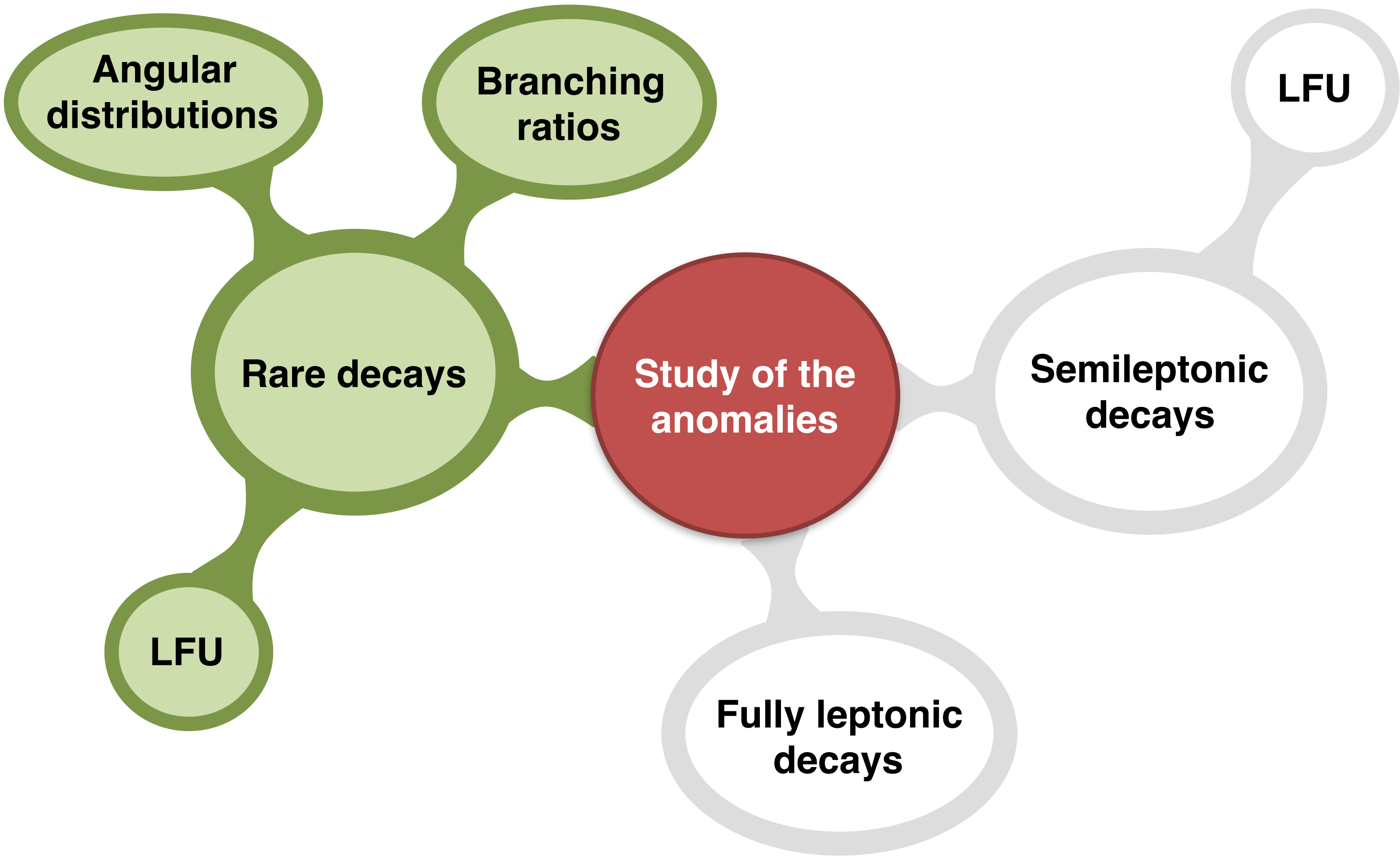


$$
\begin{aligned}
A_{FB}(D^0 \to \pi^+\pi^-\mu^+\mu^-) &= (\ \ 3.3 \pm 3.7 \pm 0.6)\%, \\
A_{2\phi}(D^0 \to \pi^+\pi^-\mu^+\mu^-) &= (-0.6 \pm 3.7 \pm 0.6)\%, \\
A_{CP}(D^0 \to \pi^+\pi^-\mu^+\mu^-) &= (\ \ 4.9 \pm 3.8 \pm 0.7)\%, \\
A_{FB}(D^0 \to K^+K^-\mu^+\mu^-) &= (0 \pm 11 \pm 2)\%, \\
A_{2\phi}(D^0 \to K^+K^-\mu^+\mu^-) &= (9 \pm 11 \pm 1)\%, \\
A_{CP}(D^0 \to K^+K^-\mu^+\mu^-) &= (0 \pm 11 \pm 2)\%,
\end{aligned}
$$

Consistent with zero and with the SM.

Additionally, asymmetries determined **in bins of q^2**. → Also consistent with SM.

Map of the anomalies



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.
Ratios of branching fractions represent clean tests of LFU.

- SM prediction:

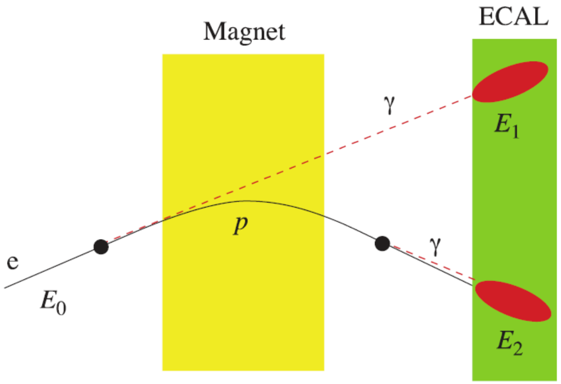
EPJ C76 (2016) 8 440

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

taking the ratio cancels most uncertainties in hadronic transitions

LHCb is much better at muons than at electrons.

- Less efficient trigger for electrons.
- Bremsstrahlung strongly affects the resolution.
- Partial energy recovery adding photons.



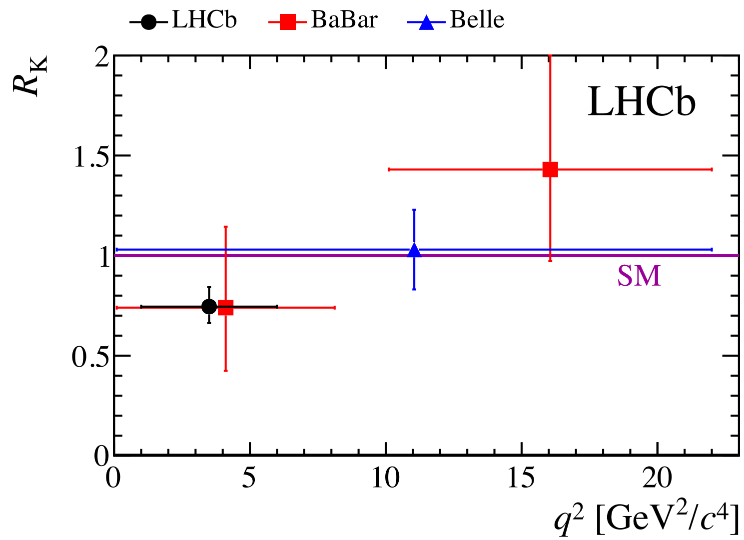
- Experimentally measured as double ratio:

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

most of the systematics cancel out

Measurements

PRL 113,151601 (2014), LHCb

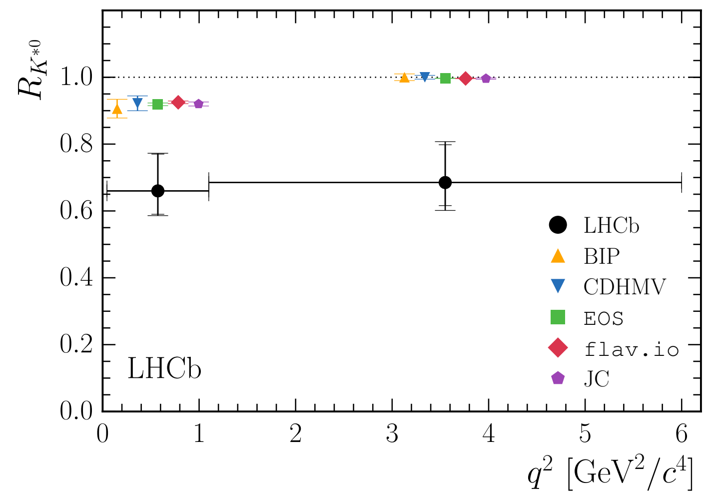


PRD 86, 032013 (2012), BaBar
PRL 103, 171801 (2009), Belle

$$R(K) = 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

2.6 σ tension with the SM

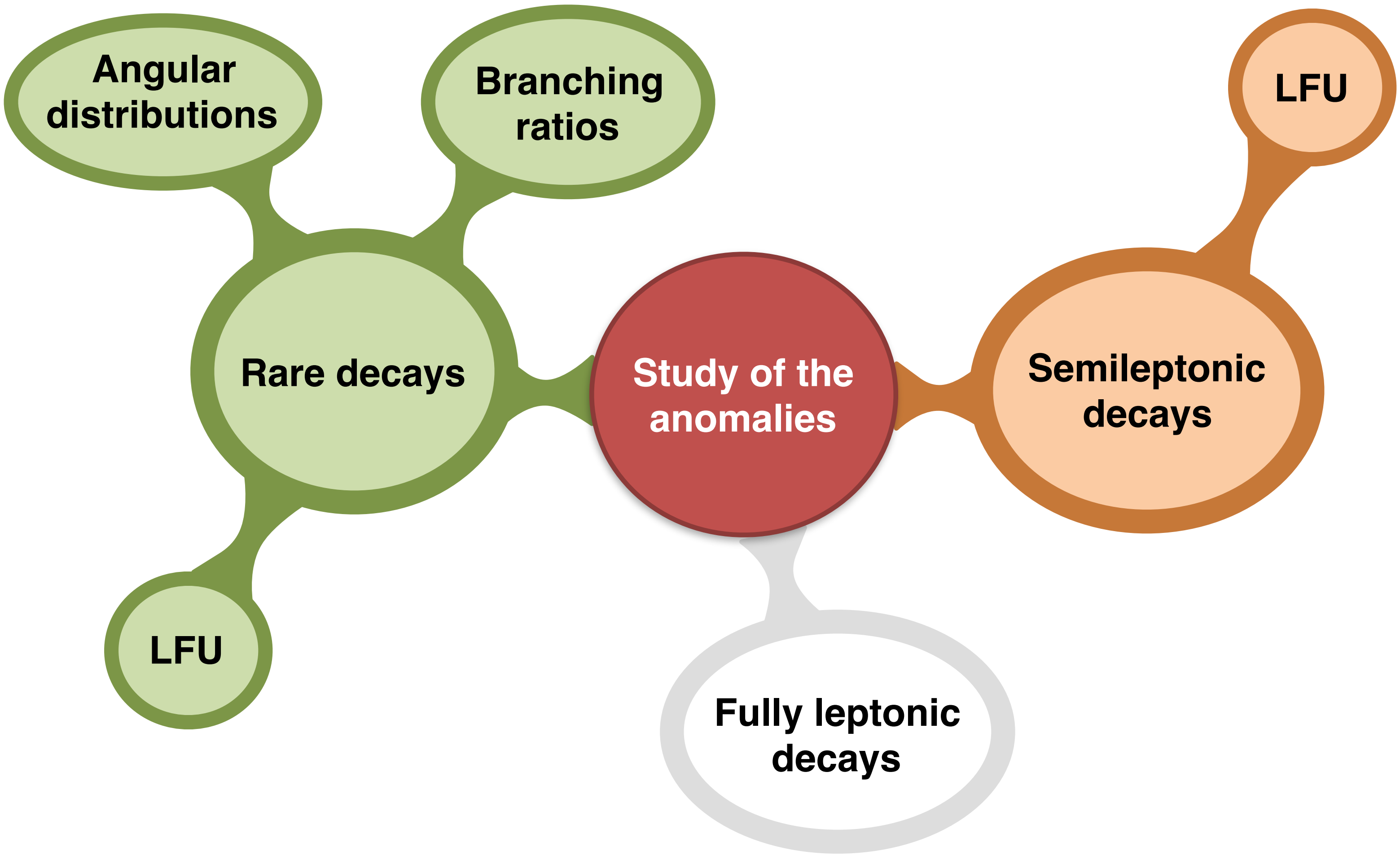
JHEP 08 (2017) 055, LHCb



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

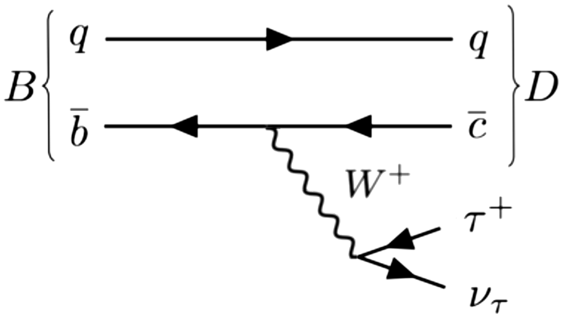
2.1 (2.4) σ tension with the SM

Map of the anomalies



LFU in semileptonic decays

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



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

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

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

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.

Components separated in multi-dimensional fits (q^2, missing mass, muon energy …).

LHCb measurements of R(D*)

Two complementary measurements with different methods and systematic uncertainties.

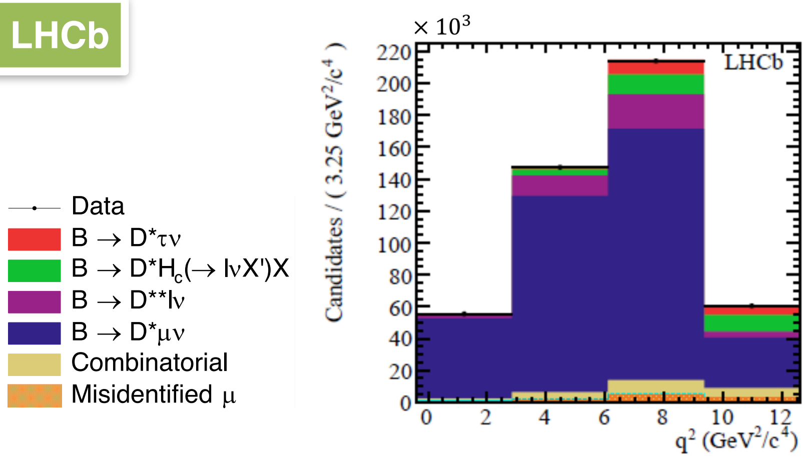
PRD 115,111803 (2015), LHCb

Muonic R(D*)

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

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

2.1σ above the SM



PRL 120,171802 (2018), LHCb **PRD 97,072013 (2018), LHCb**

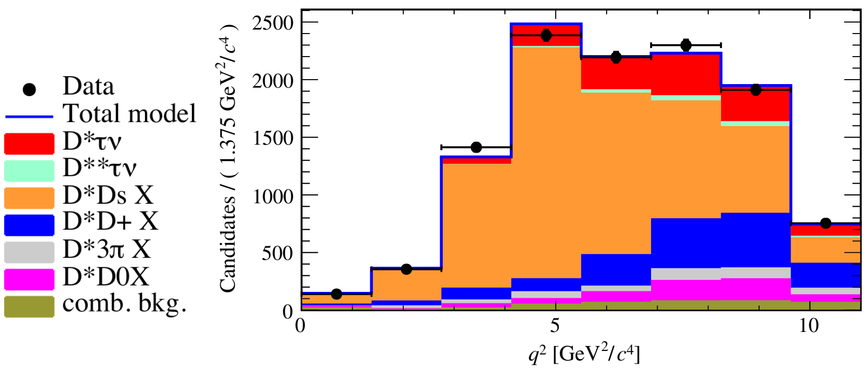
Hadronic R(D*)

$\tau^- \to \pi^+ \pi^- \pi^- (\pi^0)$

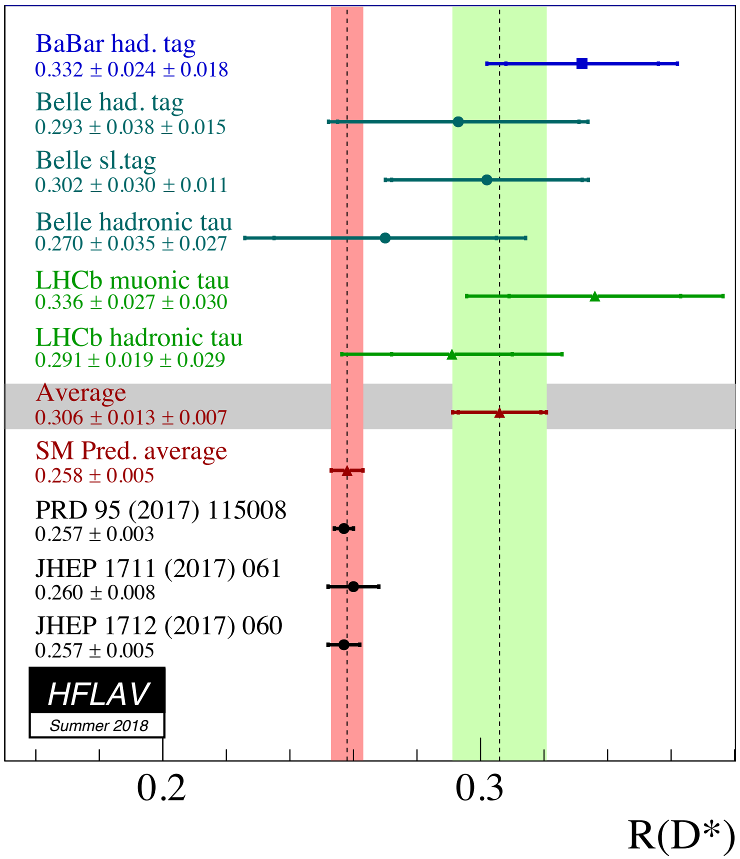
External branching ratios

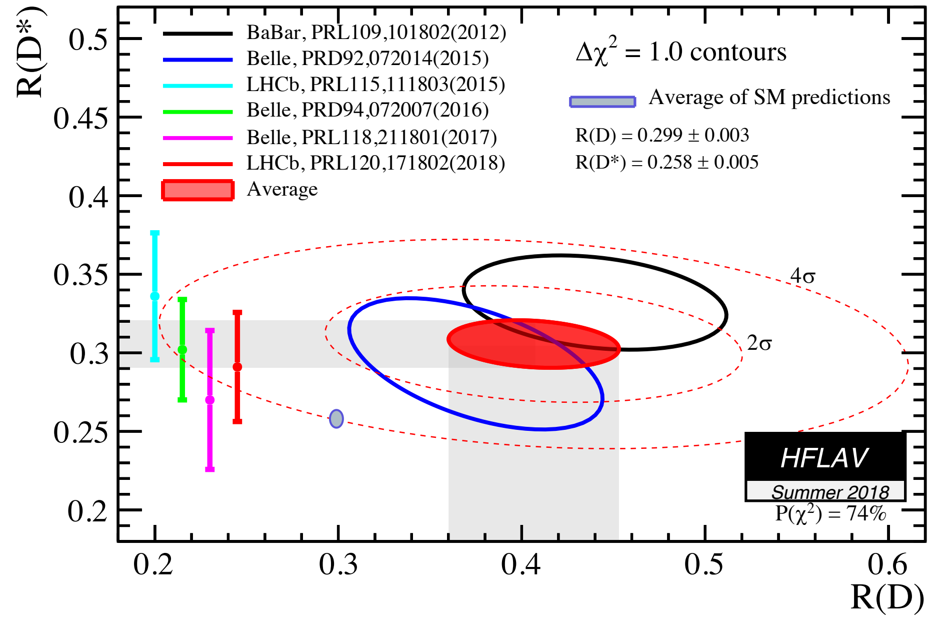
$R_{D^*} = 0.286 \pm 0.019 \pm 0.025 \pm 0.021$

1σ above the SM



World average for $R(D^{(*)})$





Tension with SM prediction:

2.3σ in R(D)
3.0σ in R(D*)
3.8σ combined

Measurement of R(J/ψ)

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.

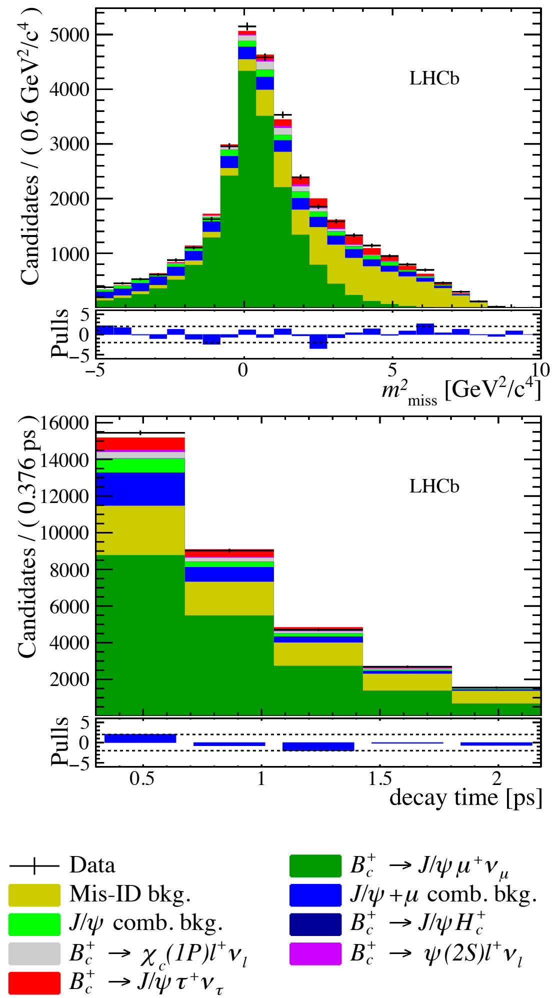
$R^{SM}_{J/\psi} \in [0.25, 0.28]$

PRL 120,121801 (2018), LHCb

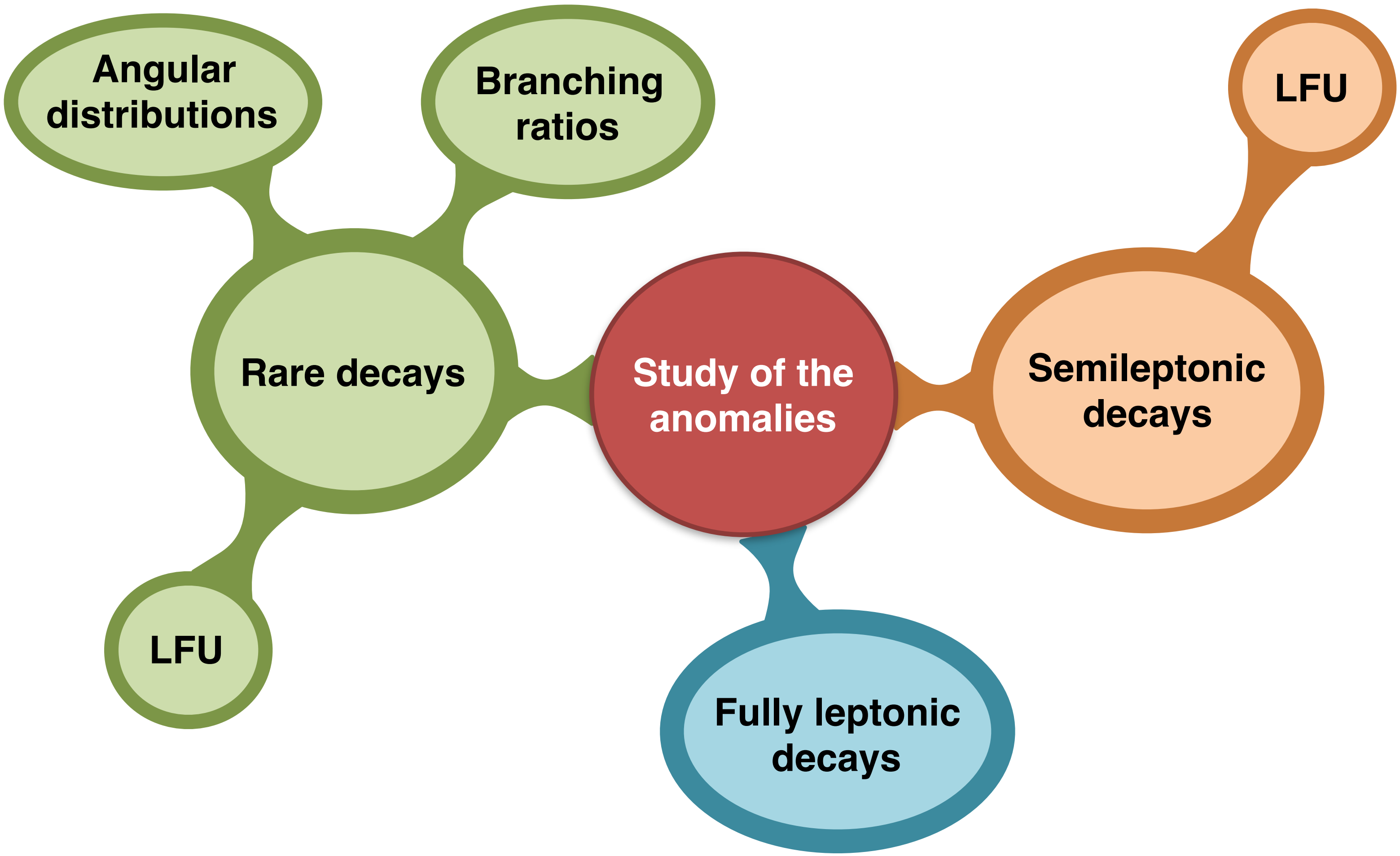
LHCb analysis:

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

$\sim 2\sigma$ above SM



Map of the anomalies



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

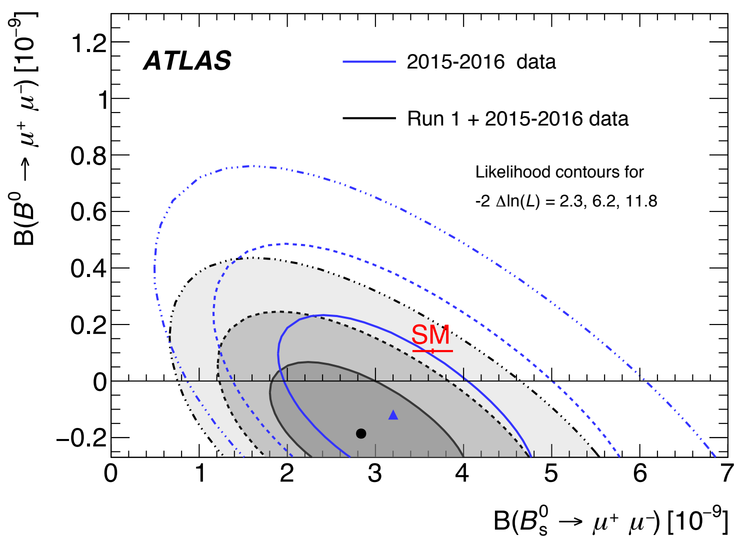
Loop and helicity suppressed. Theoretically very clean. Only C_{10} contributes in the SM.

Results compatible with the SM.

arXiv:1812.03017 (2018) (ATLAS)

26.3 fb^{-1} from Run II, combined with Run I.

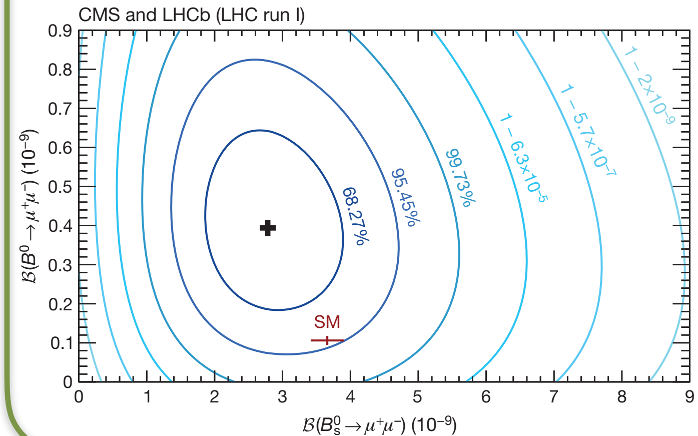
4.6σ significance for the B_s decay.



Nature 522,68-72 (2015) (LHCb+CMS)

LHCb & CMS: Run 1 dataset

- Observation of $B^0_s \to \mu^+\mu^-$ (6.2 σ)
- Evidence for $B^0 \to \mu^+\mu^-$ (3.0 σ)



PRL 118,191801 (2017) (LHCb)

LHCb 3+1.4 fb^{-1} run I+II

- First single experiment observation
  - 7.9σ significance $B^0_{(s)} \to \mu^+\mu^-$
- Effective lifetime of $B^0_{(s)} \to \mu^+\mu^-$

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

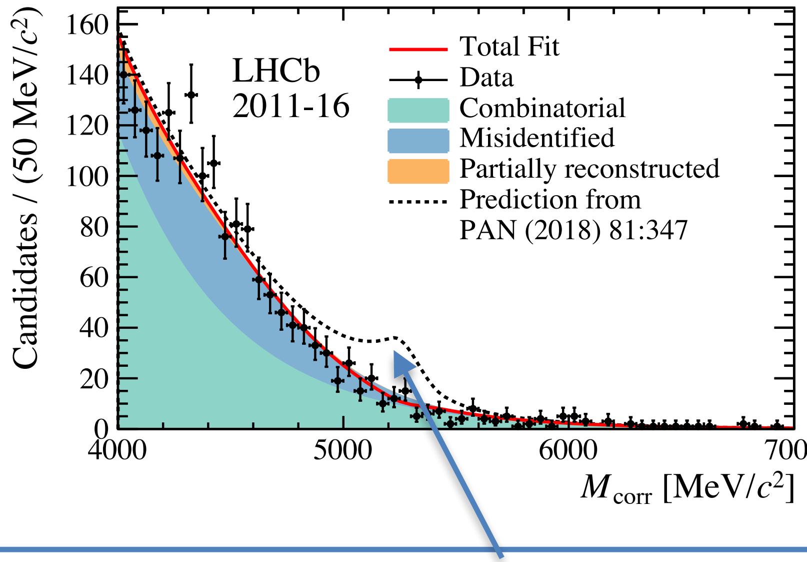
Search for $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$

Highly-suppressed decay, $BR \propto |V_{ub}|^2$.

arXiv:1812.06004 (2018) LHCb

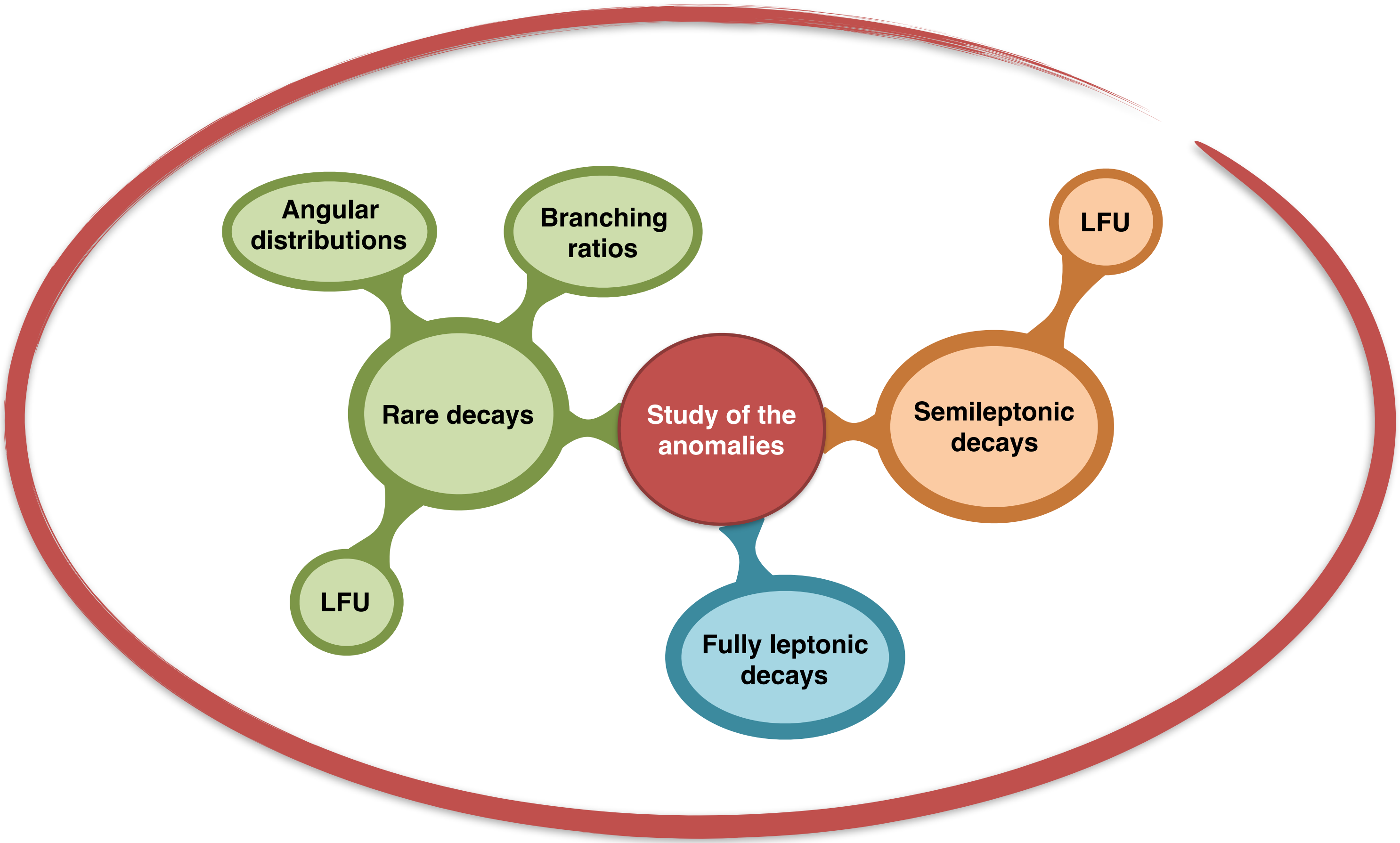
LHCb analysis:

* Run1+2016: 4.7 fb^{-1}
* Reconstruct B meson using corrected mass: $m_{B_{corr}} = \sqrt{m_{3\mu}^2 + p_T'^2} + p_T'$
* Veto J/ψ and ψ(2S), and require $\min(q(\mu^+,\mu^-)) < 960\,\mathrm{MeV}/c^2$
* Normalise to $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ (yield from invariant-mass fit).



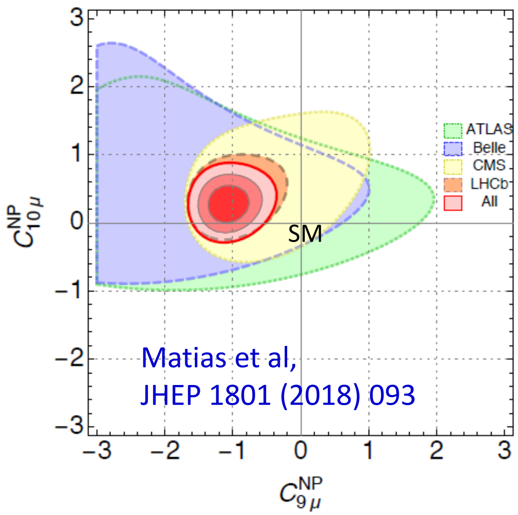
No signal is seen. Set upper limit of 1.6 x 10^{-8} at 95% CL. [PAN (2018) 81:347]
In tension with the prediction of BR ≈ 1.3 x 10^{-7}, based on the vector-dominance model.

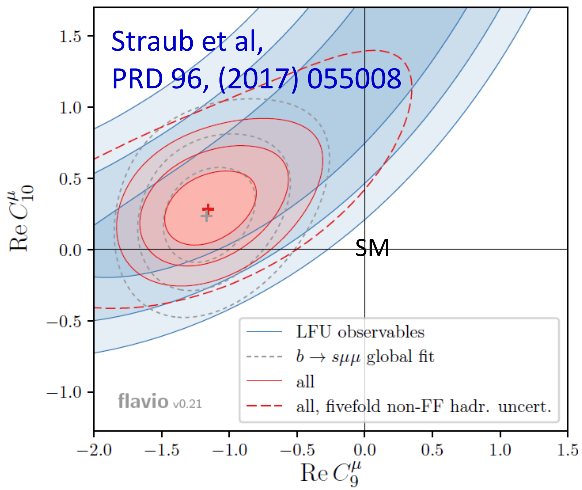
Map of the anomalies

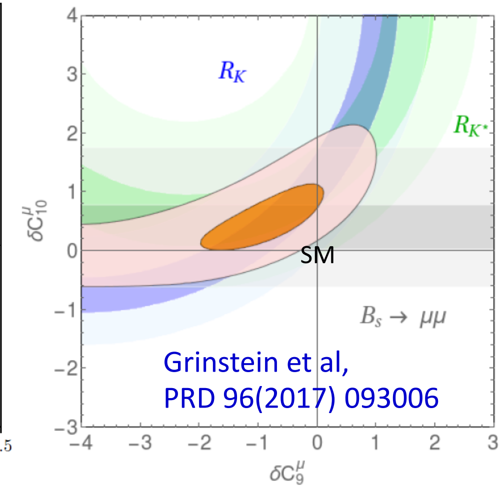


Combined explanation for rare decays

See the talks from **Javier Virto** and **Javier Fuentes Martín**.







The pattern of deviations is consistent with a shift of Wilson coefficients C_9 and C_{10}, which deviate from the SM values by **around 5σ**.

Independent fits made by many groups favor $\Delta C_9 = -1$ or $\Delta C_9 = -\Delta C_{10}$.

Near-term prospects

LHCb

Rare decays:

- Run 2 R(K) (coming very soon!)
- Run 2 R(K*)

} 1.5 - 1.8 improved precision

- New ratios: R(K$\pi\pi$), R(ϕ), R(pK), …
- Updated $B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular analysis
- Radiative decays: mixing-induced CP violation in $B_s^0 \rightarrow \phi\gamma$ (coming soon!)
- Studies of LFV in beauty- and charm-hadron decays

Semileptonic decays:

- New ratios (muonic-τ): R(D^0), R(D^+), R(Λ_c), R(D_s), …
- Hadronic-τ versions: R(D), R(D*), R(Λ_c), …

CMS

Rare decays:

- Fit of the full angular distribution of $B^0 \rightarrow K^{*0}\mu^+\mu^-$, including S-wave
- R(K) and R(K*)

Conclusions

- Very interesting **set of deviations in the B system**.
  - Rare decays ($b \to sll$ transitions)
  - Semileptonic decays ($b \to cl\nu$ transitions)
- No significant deviation from a single measurement, but the combination points to a coherent pattern.
- Some analyses using part of **Run2 data** presented, but many more to come.
  - The increased precision can turn hints into strong evidences.

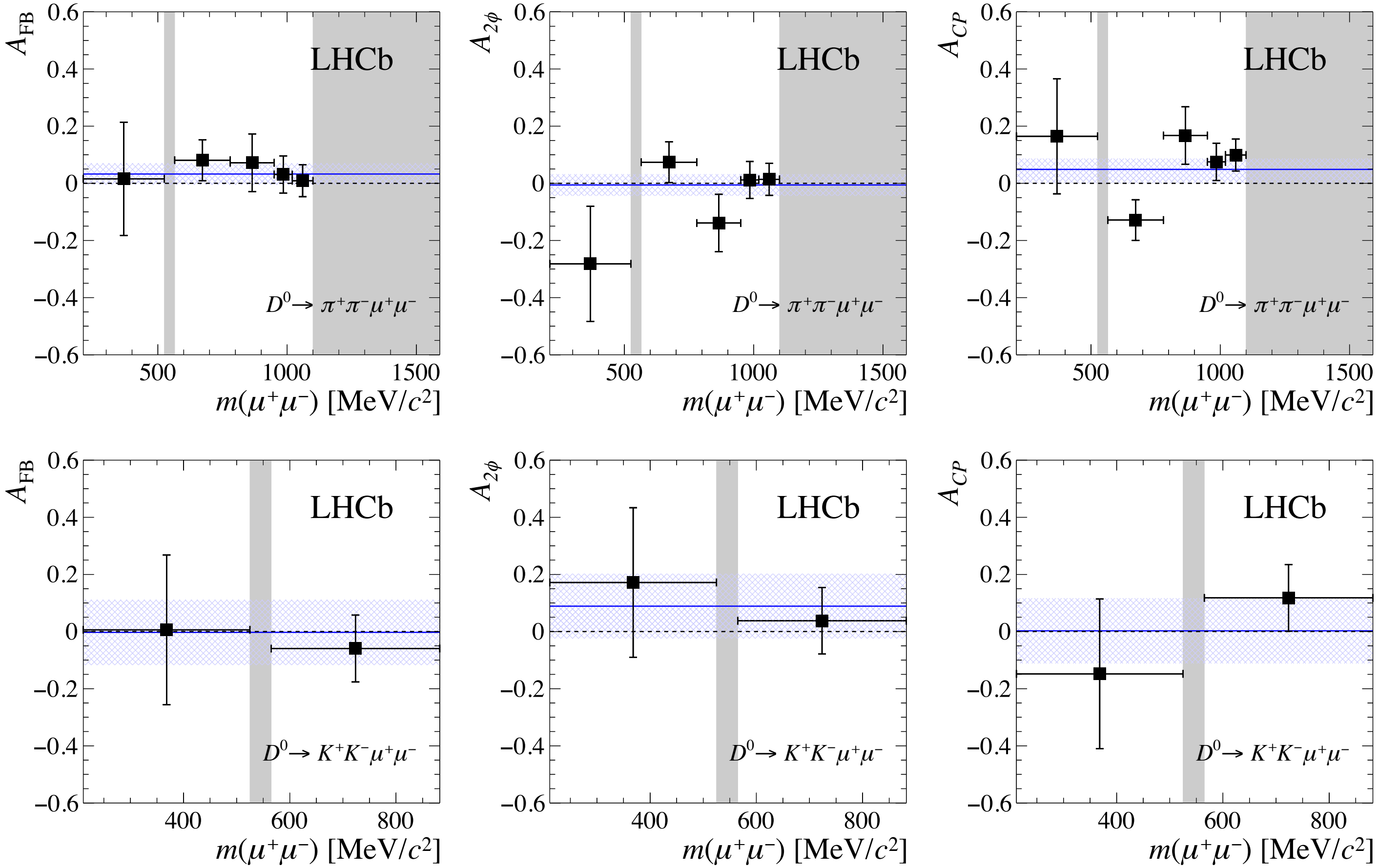
Some long-term prospects

- Charge-current decays in LHCb: move from the measurement of integrated R ratios to the study of **angular distributions**.
- **Belle II and upgraded LHCb**: perform very precise measurements of the relevant observables.

Backup slides

Angular and CP asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$

Asymmetries as a function of q²



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

Loop and helicity suppressed. Theoretically very clean. Only **C_{10}** contributes in the SM.

- SM prediction [C. Bobeth *et al.*, PRL 112, 101801 (2014)]

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Results compatible with the SM.

arXiv:1812.03017 (2018) (ATLAS)

New result from ATLAS.

26.3 fb^{-1} from Run II:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(3.2^{+1.1}_{-1.0}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.3 \times 10^{-10}$$

Combination with Run I:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}$$

(4.6σ significance for this decay)

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$$

Nature 522,68-72 (2015) (LHCb+CMS)

LHCb & CMS: Run 1 dataset

- Observation of $B^0_s \to \mu^+\mu^-$ (6.2 σ)
- Evidence for $B^0 \to \mu^+\mu^-$ (3.0 σ)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.0^{+1.6}_{-1.4}) \times 10^{-10}$$

PRL 118,191801 (2017) (LHCb)

LHCb 3+1.4 fb^{-1} run I+II

- First single experiment observation
  - 7.9σ significance $B^0_{(s)} \to \mu^+\mu^-$

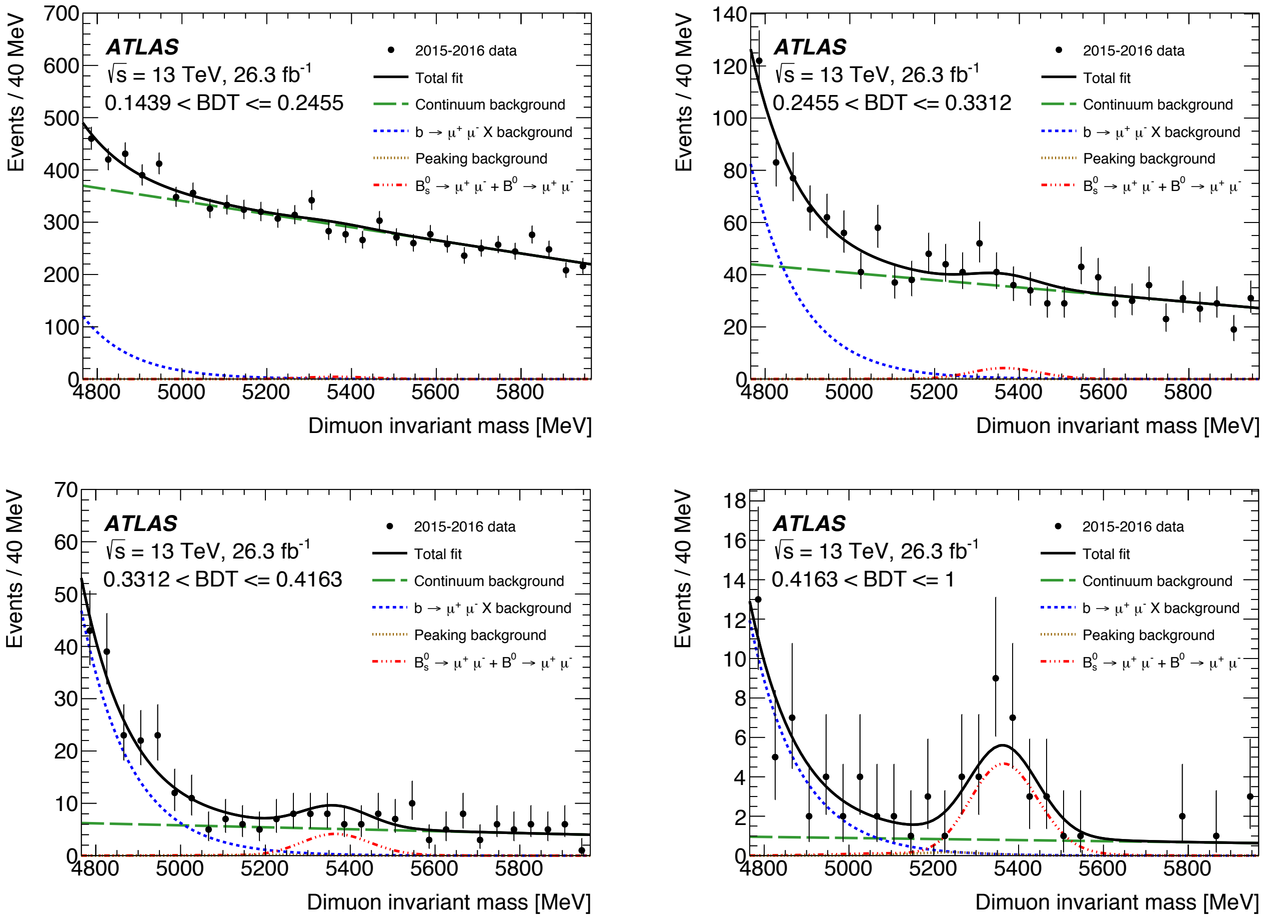
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$$

- Effective lifetime of $B^0_{(s)} \to \mu^+\mu^-$

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

ATLAS study of $B^0_{(s)} \to \mu^+\mu^-$

Invariant-mass plots in four BDT bins.



Long-term prospects

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