UNIVERSITY OF CAMBRIDGE

Rare B Decays And Lepton Flavour Universality Tests at LHCb

Siim Tolk
on behalf of the LHCb collaboration

KAON 2016
Birmingham

Lepton Flavour Violation

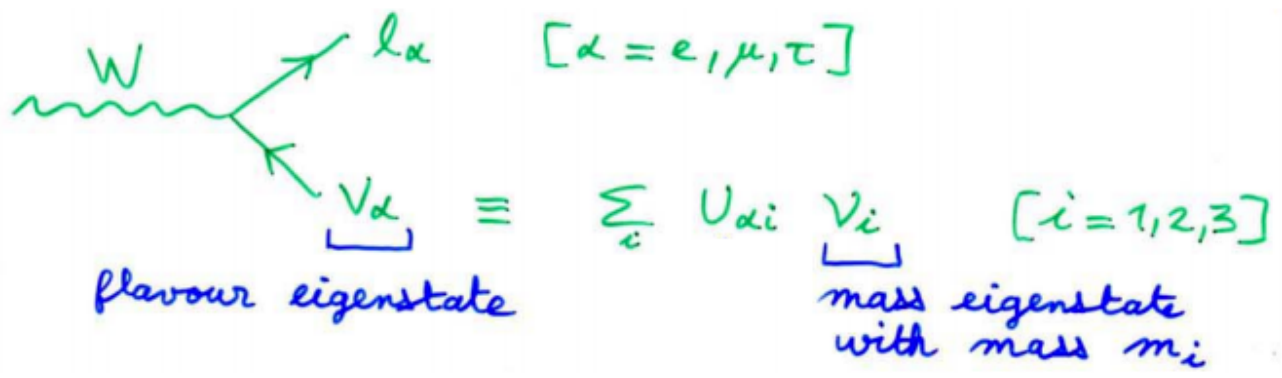
- Minimal Flavour Violation (MFV)

  The flavour changing transitions in Standard Model (SM) are governed by the CKM matrix, which applies to the quark sector (..QFV)

- Lepton Flavour Violation (LFV)

  Not present in the SM, present in the nature (at least) through neutrino mixing:

PRL 81 (1998) 1562



…at the level of **<O(10^{-40})**.

Large LFV is expected in numerous New Physics (NP) scenarios (Supersymmetry, Extra Dimension, Little Higgs)

Lepton Flavour Violation

- A subset of LFV searches in LHCb

$B_{(s)} \to e^{\pm}\mu^{\mp}$ **(1 fb^{-1})**

PRL 111 141801 (2013)

	BR($B_s^0 \to e^+\mu^-$) $\times 10^{-8}$ at 90% (95%) CL	BR($B^0 \to e^+\mu^-$) $\times 10^{-9}$ at 90% (95%) CL
Expected LHCb, 1 fb^{-1}	1.53 (1.95)	3.97 (4.95)
Observed LHCb, 1 fb^{-1}	1.11 (1.36)	2.8 (3.72)

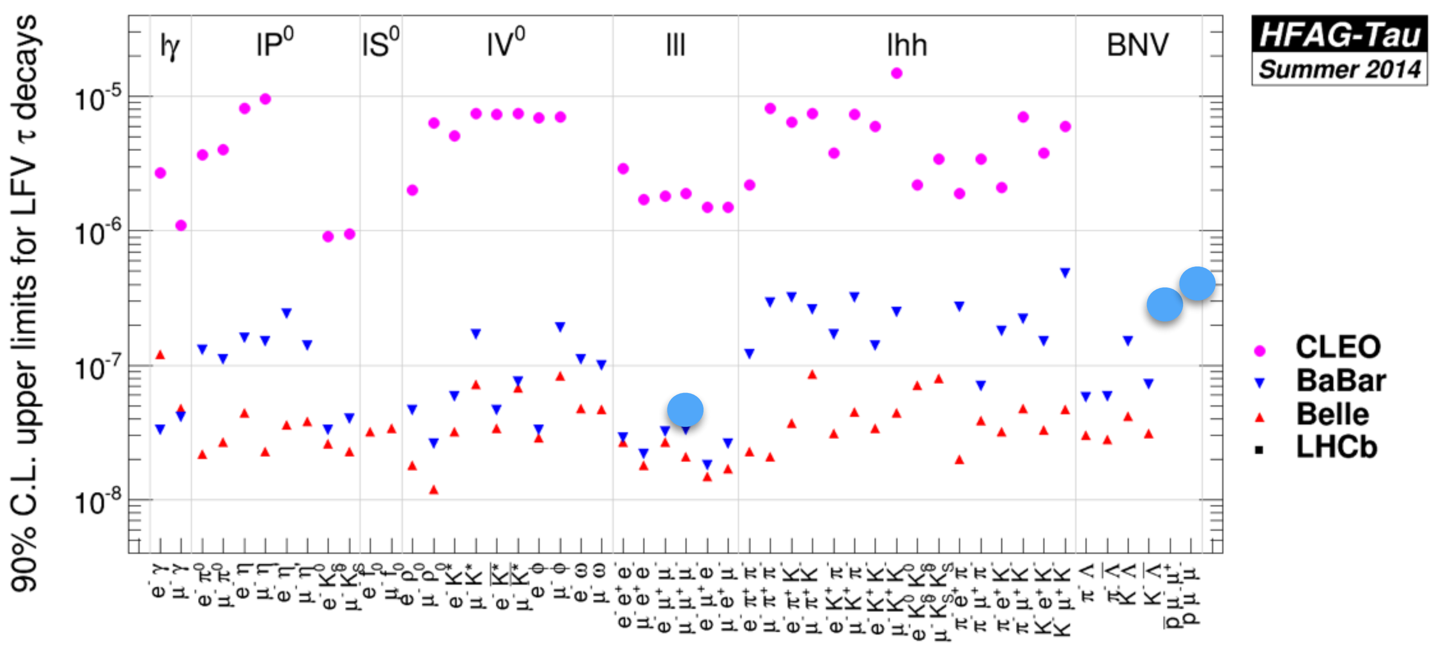
$D^0 \to e^{\pm}\mu^{\mp}$ **(3 fb^{-1})** $\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 1.5 \times 10^{-8}$ at 90% CL

PL B 754 (2016) 167

$\tau \to \mu\mu\mu$ **(3 fb^{-1})**

JHEP 02 (2015) 121

$\mathcal{B}(\tau^- \to 3\mu) < 4.6 \times 10^{-8}$ at 90% CL

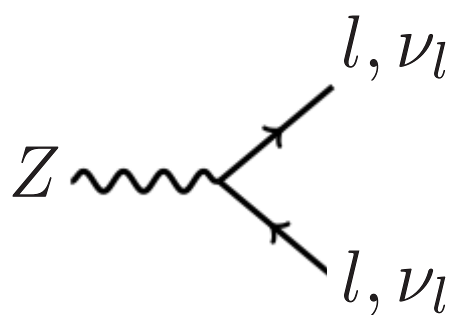


…no evidence for Lepton Flavour Violation

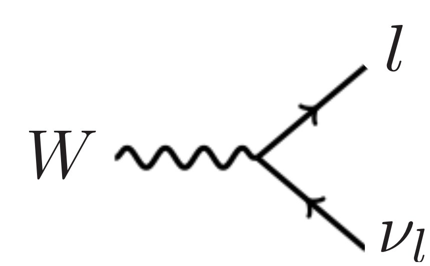
Lepton Flavour Universality

- Lepton Flavour Universality
  - In Standard Model, **lepton couplings** to gauge bosons are **identical**:

Neutral current:
$l = e, \mu, \tau$



Charged current:
$l = e, \mu, \tau$



  - The leptonic **branching fraction** (BF) only **differ due to lepton masses**
    ➤ Higgs couplings, phase space, level of helicity suppression
  - Lepton Universality has been thoroughly tested over the years at LEP, SLC, and many other experiments:

$$Z \to l^+l^- \quad W^\pm \to l^\pm\nu_l \quad \tau^\pm \to l^\pm\nu\bar{\nu} \quad \mu^\pm \to e^\pm\nu\bar{\nu}$$
$$K^\pm \to l^\pm\nu_l \quad K_L \to l^+l^- \quad K_S \to \pi^0 l^+l^- \quad K^\pm \to \pi^\pm l^\pm l^\mp$$
$$\pi^\pm \to l^\pm\nu_l$$

…and so far, found to hold.

Lepton Flavour Universality

- Lepton Flavour Universality Violation (LFUV)
  - The most stringent limits on LFUV involve the first two generations.

NP could easily evade the strong bounds from the direct searches while preserving the effect on heavy flavour

  - Many NP scenarios contain additional interactions and enhanced couplings to the third generation:
    - Examples: $A^0, H^\pm$, new vectors coupled to SM Higgs doublet, leptoquarks
  - The NP effects can be suppressed due to the MFV in pion and kaon decays

…assuming the NP is MFV, the ***kaon limits need to be improved by ~ O(1)*** *to probe the parameters space relevant in B decays.*

A. Crivellin et al, arXiv:1601.00970v3

Lepton Flavour Universality

- Lepton Flavour Universality Violation (LFUV)
  - The most stringent limits on LFUV involve the first two generations.

NP could easily evade the strong bounds from the direct searches while preserving the effect on heavy flavour

  - Many NP scenarios contain additional interactions and enhanced couplings to the third generation:
    - Examples: $A^0, H^{\pm}$, new vectors coupled to SM Higgs doublet, leptoquarks
  - The NP effects can be suppressed due to the MFV in pion and kaon decays

…assuming the NP is MFV, the ***kaon limits need to be improved by ~ O(1)*** *to probe the parameters space relevant in B decays.*

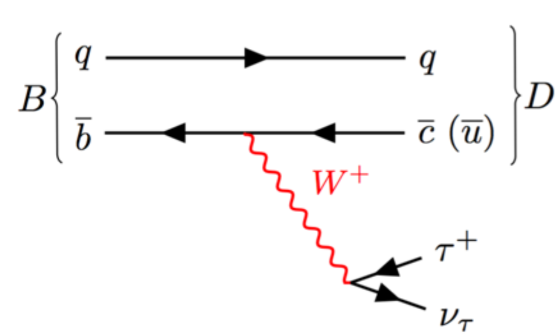
A. Crivellin et al, arXiv:1601.00970v3

Example of an **excellent LU test mode**:

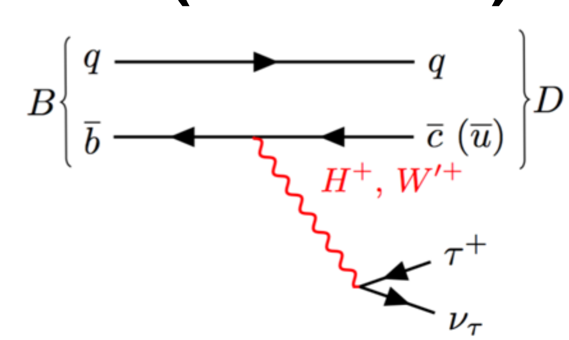
$$b \to c\tau\nu$$

not rare: BF~O(%)

SM



NP (tree level)



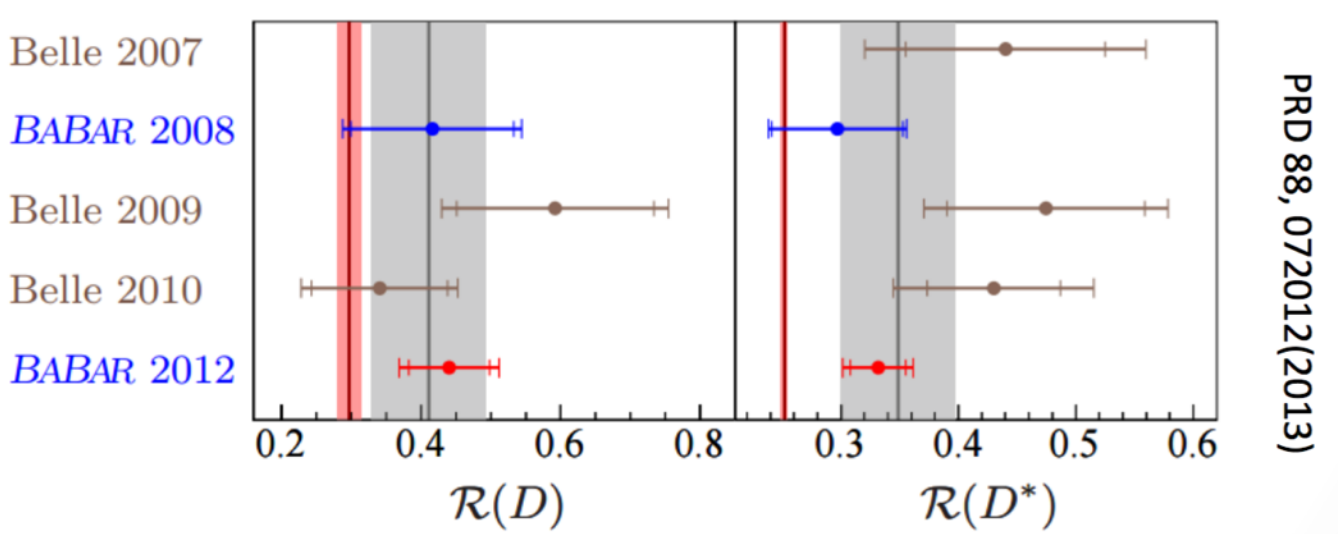
Lepton Flavour Universality Tests

$\mathcal{R}(D^*)$

$$\mathcal{R}(D^*) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$ **= 0.252(3)**

SM: PRD 85 094025 (2012)

- Semi-leptonic B decays are in general well understood in the SM
- Many **uncertainties can be significantly reduced in ratios**
  - theoretical (hadronic form factors, SM parametric)
  - experimental (D* reconstruction, particle identification and tracking)
- Babar and Belle measurements (pre 2015) show **deviations from SM:**



- R(D) and R(D*) combined: **3.7σ** (w.r.t. SM)

Lepton Flavour Universality Tests

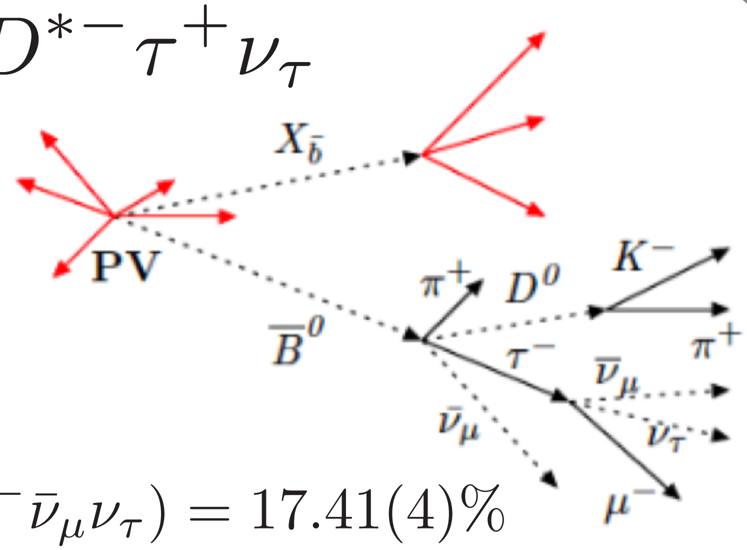
$\mathcal{R}(D^*)$ in LHCb

LHCB-PAPER-2015-025,arXiv:1506.08614

Extremely challenging in **hadronic environment**, requires a different strategy compared to Belle and Babar

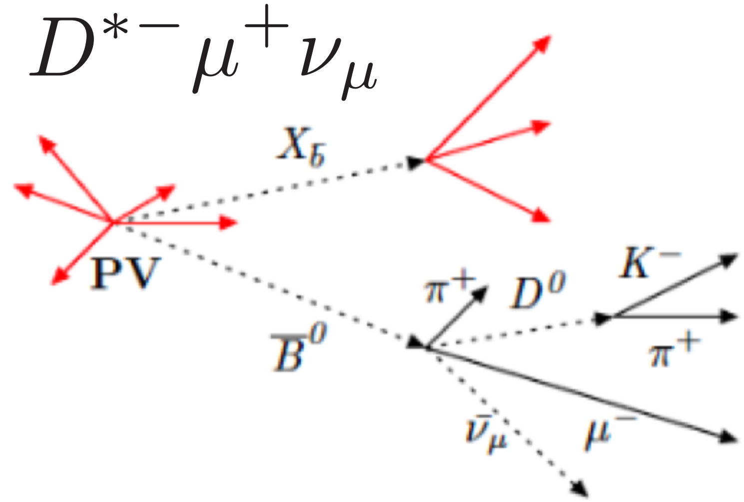
- Unknown B momentum
  - use the boost of the visible system and PV-SV separation
- Determine the ratio between decays to the **same (visible) final state:**

$B^0 \to D^{*-}\tau^+\nu_\tau$

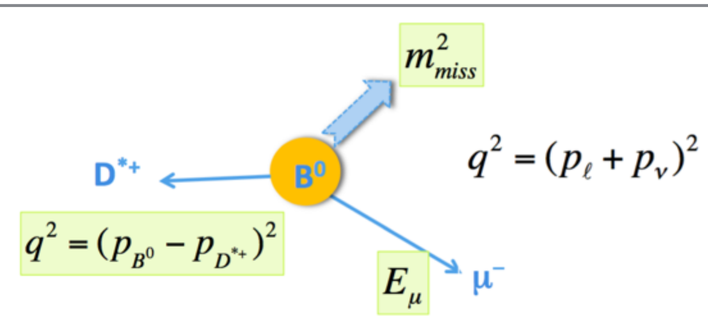


$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau) = 17.41(4)\%$

$B^0 \to D^{*-}\mu^+\nu_\mu$



- Separate the decays in B rest frame
  - missing mass, lepton pair recoil, lepton energy



Lepton Flavour Universality Tests

$\mathcal{R}(D^*)$ Results

LHCb $\mathcal{R}(D^*) = 0.336 \pm 0.027^{stat} \pm 0.030^{syst}$

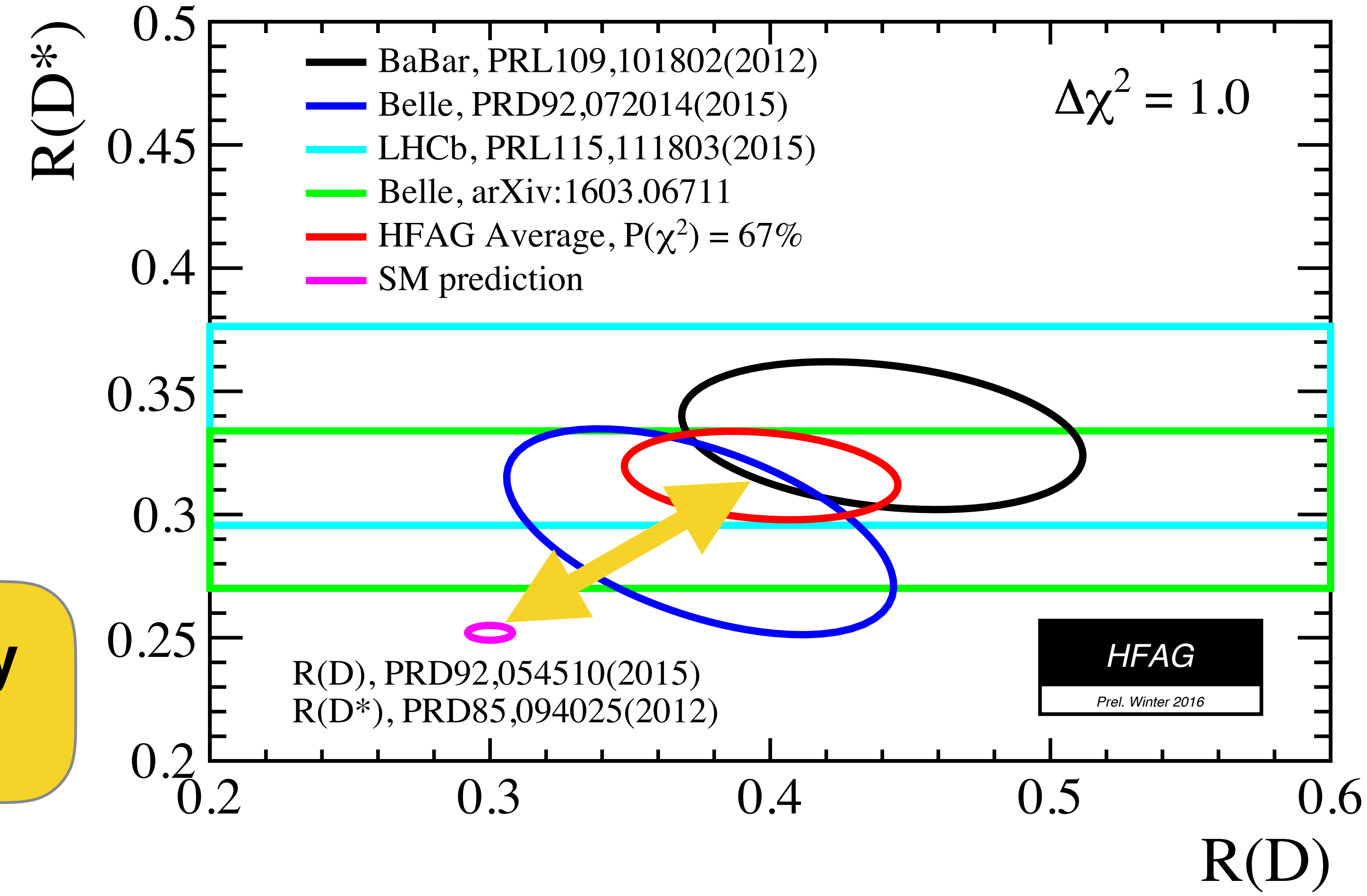
BaBar $\mathcal{R}(D^*) = 0.332 \pm 0.024^{stat} \pm 0.018^{syst}$

Belle $\mathcal{R}(D^*) = 0.293 \pm 0.038^{stat} \pm 0.015^{syst}$

Belle $\mathcal{R}(D^*) = 0.302 \pm 0.030^{stat} \pm 0.011^{syst}$

SM $\mathcal{R}(D^*) = 0.252 \pm 0.003$

Phys.Rev.D85(2012) 094025



Combined compatibility with SM : 4.0σ

$\mathcal{R}(D^*)$ Results

Excluding the newest (26/08) Belle result:

We report the measurement of $R(D^*)$ with hadronic τ decay modes $\tau^- \to \pi^- \nu_\tau$ and $\tau^- \to \rho^- \nu_\tau$ and the first measurement of P_τ in the decay $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$, using 772×10^6 $B\bar{B}$ data accumulated with the Belle detector. Our preliminary results are

$$R(D^*) = 0.276 \pm 0.034(\text{stat.})^{+0.029}_{-0.026}(\text{syst.}), \quad (14)$$

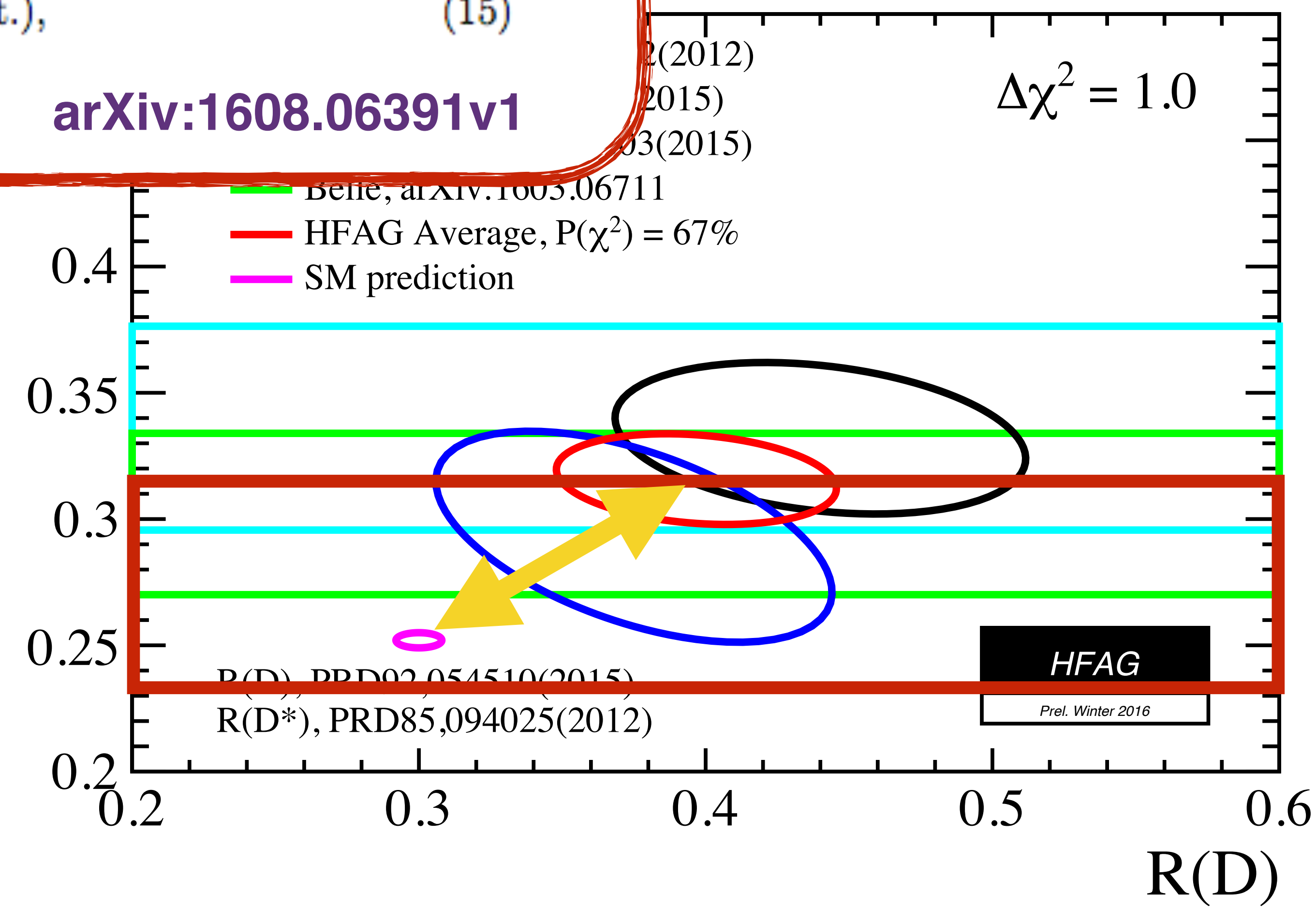
$$P_\tau = -0.44 \pm 0.47(\text{stat.})^{+0.20}_{-0.17}(\text{syst.}), \quad (15)$$

which is consistent with the SM prediction within 0.6σ.

arXiv:1608.06391v1

$(D^*) = 0.252 \pm 0.003$

ev.D85(2012) 094025



Combined compatibility with SM : 4.0σ

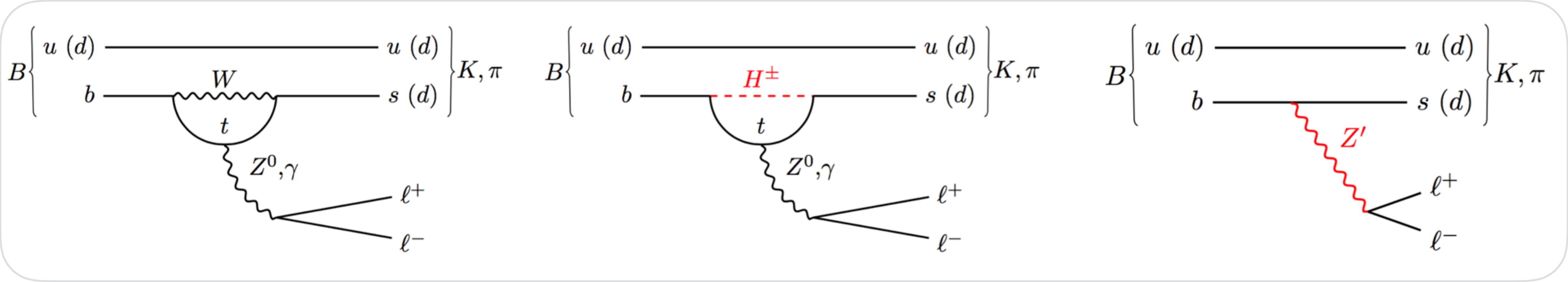
Lepton Flavour Universality Tests

$\mathcal{R}(D^*)$ is not the only place where we measure unexpected results…

- Another group of excellent Lepton Flavour Universality Tests involves a **flavour changing neutral current** transition:

$$b \to s\ l^+ l^-$$

- The BF's of FCNC decays **highly sensitive to various NP contributions**:



SM
(GIM suppressed at tree level penguin and box diagrams)

NP
(**loop** level)

NP
(**tree** level)

Lepton Flavour Universality Tests

$\mathcal{R}(K)$

- In the SM, the **ratio** between the leptonic B decays to kaons and leptons is precisely predicted in the SM:

$$\mathcal{R}(K)^{SM} \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 1 \pm \mathcal{O}(10^{-3})$$

(..due to phase space)

- R(K) is sensitive to new scalar and pseudo-scalar interactions or Z′ bosons, and **has been determined by the B-factories with a precision of 20-50%**:

Experiment	q^2 (GeV^2)	R_K
BaBar*	$0.1 - 16.0$	$1.00^{+0.31}_{-0.25} \pm 0.07$
	$0.1 - 8.12$	$0.74^{+0.40}_{-0.31} \pm 0.06$
	> 10.11	$1.43^{+0.65}_{-0.44} \pm 0.12$
Belle**	$0.00 - 16.0$	$1.03 \pm 0.19 \pm 0.06$

* PRD 86 (2012) 032012
** PRL 103 (2009) 171801

Lepton Flavour Universality Tests

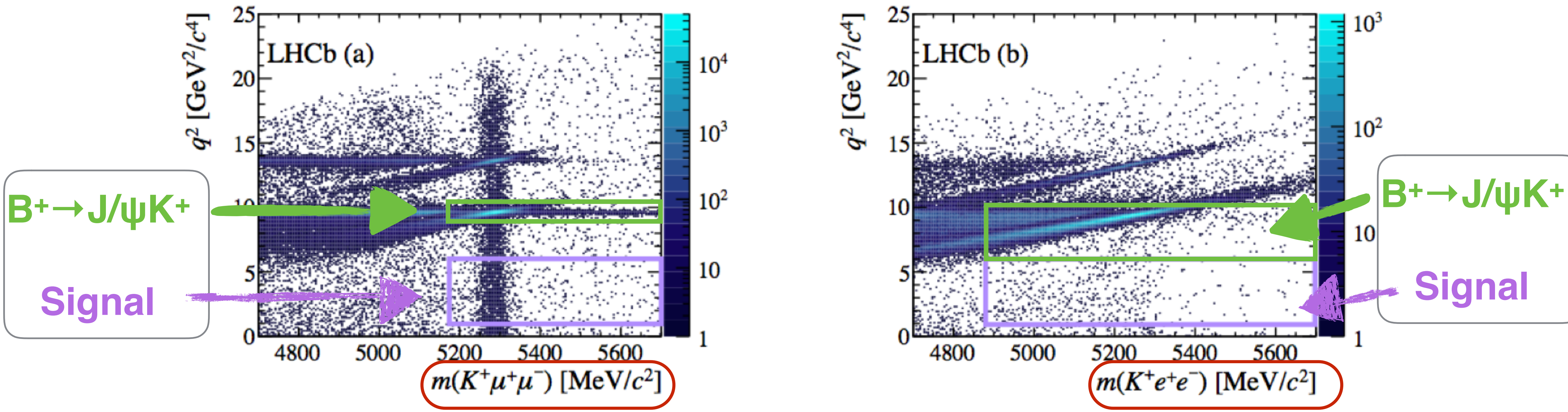
$\mathcal{R}(K)$ in LHCb

R(K) is determined in the **dilepton mass squared (q^2) range:** $1 < q^2 < 6\ GeV^2/c^4$

- excludes the resonant J/ψ region and higher ψ(2S) resonances
- makes precise theoretical estimates possible

..and **as a double ratio** w.r.t the respective resonant **$B^+ \to J/\psi K^+$** modes to cancel potential sources of systematics:

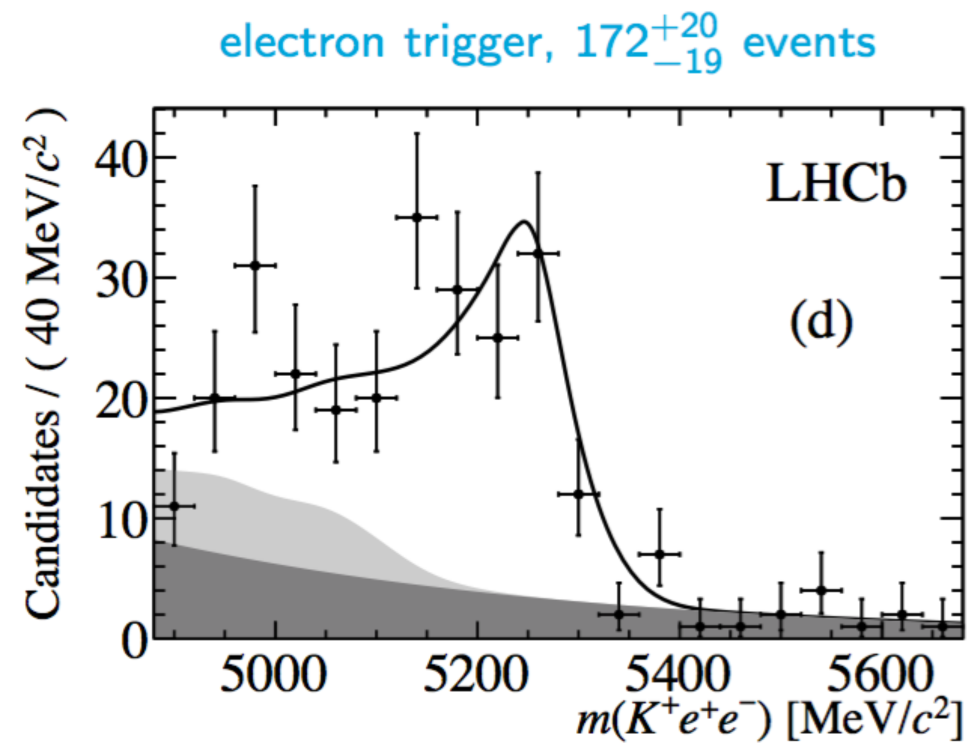
$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B^+ \to K^+ \mu\mu)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B^+ \to K^+ ee)}{dq^2} dq^2} = \left(\frac{N_{K\mu\mu}}{N_{Kee}}\right) \left(\frac{N_{KJ/\psi(ee)}}{N_{KJ/\psi(\mu\mu)}}\right) \left(\frac{\epsilon_{Kee}}{\epsilon_{K\mu\mu}}\right) \left(\frac{\epsilon_{KJ/\psi(ee)}}{\epsilon_{KJ/\psi(\mu\mu)}}\right)$$



Lepton Flavour Universality Tests

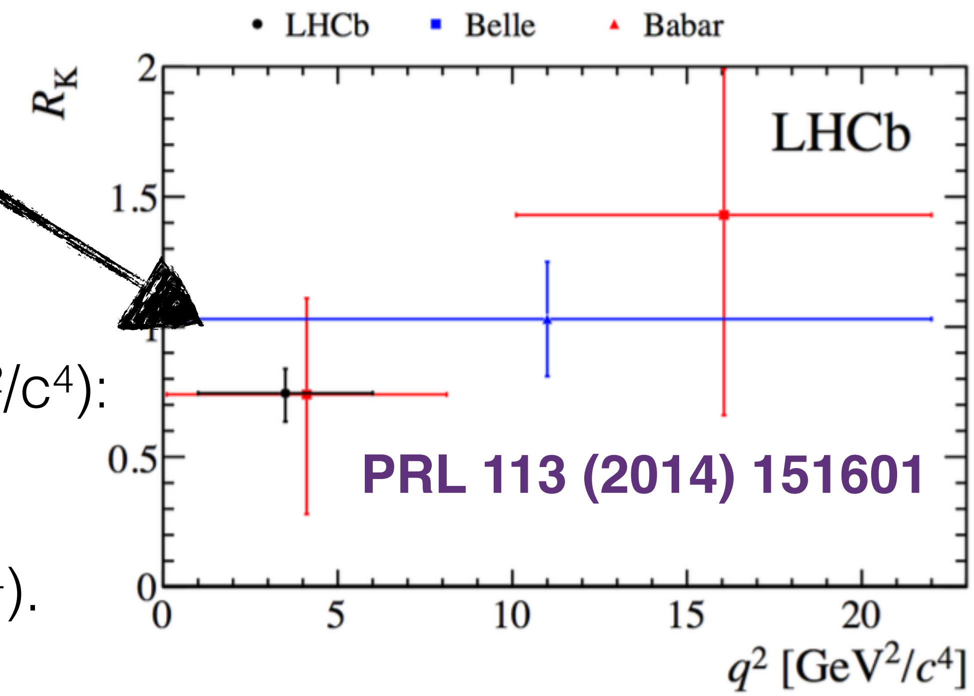
$\mathcal{R}(K)$ Results *(LHCb Run 1)*

- **Electrons are tricky**:
  - **efficiency** to detect an electron is 50% smaller
  - **mass distribution** of electron modes depends strongly on the associated photons
  - bremsstrahlung causes **migration** in the di-lepton mass squared range



$$\mathcal{R}(K) = 0.745^{+0.090}_{-0.074}(\texttt{stat}) \pm 0.036(\texttt{syst})$$

- most precise measurements up to date
- R(K) **compatible with the SM at 2.6σ**



PRL 113 (2014) 151601

- **Individual BF's (LHCb):**
  - ➤ **Electron mode BF agrees** with the SM (0<q²<6 GeV²/c⁴):

    $$\mathcal{B}(B^+ \to K^+e^+e^-) = [1.56^{+0.19}_{-0.15}(\texttt{stat})^{+0.06}_{-0.04}(\texttt{syst})] \times 10^{-7}$$

  - ➤ **Muon mode BF lower** than the SM (0<q²<15 GeV²/c⁴).

JHEP 06 (2014) 133

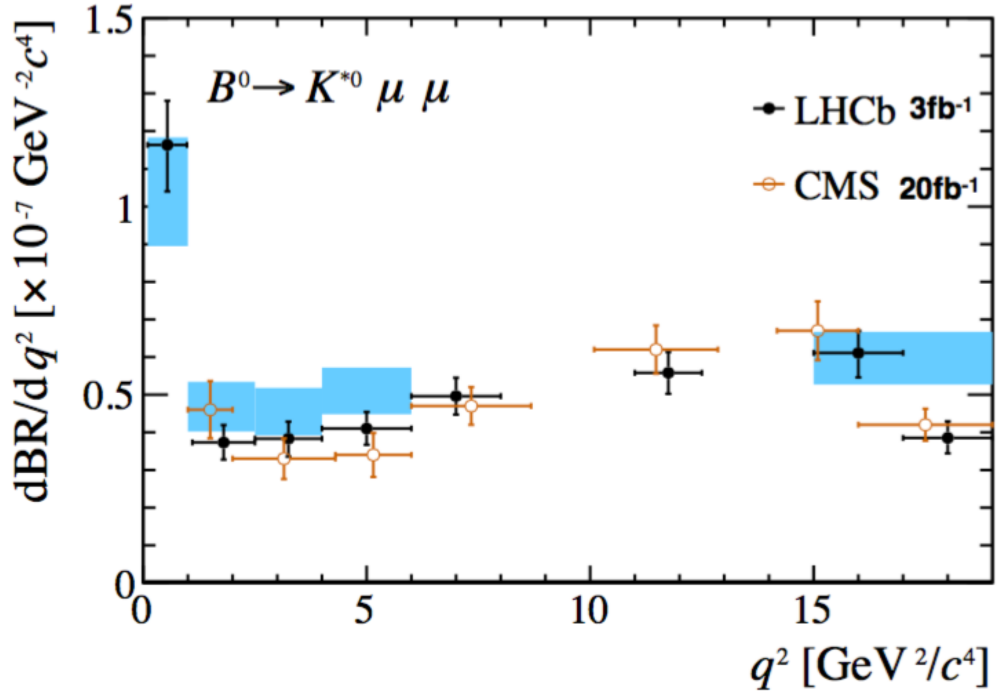
Individual B decays to leptons

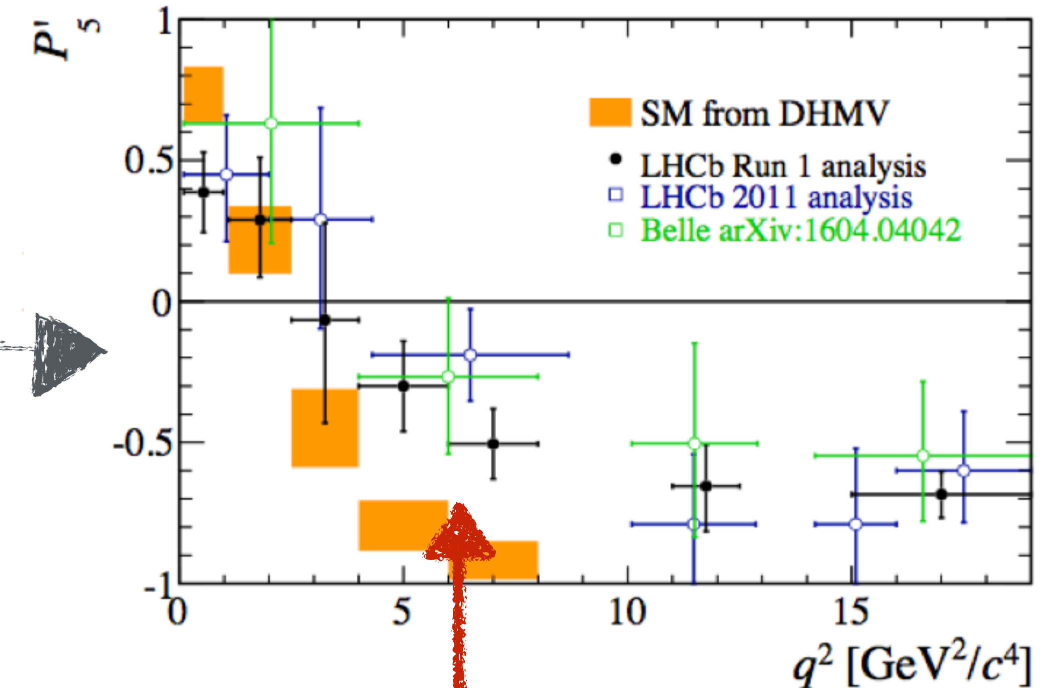
$$B^0 \to K^* \mu^+ \mu^-$$

- Measured **BF lower** than predicted by SM (though predictions have large uncertainties)

LHCb: arXiv:1606.04731, CMS: PLB 753 (2016) 424
SM: JHEP 01 (2012) 107 , PRL111 (2013) 162002, EPJC (2015) 75 382

- **Angular distributions** sensitive to NP effects
- 3 angles and di-lepton mass squared mapped to **optimised variables** to reduced form factor dependencies
- Significant local **tension in** one of the variables **P'_5**





Global fit at **3.4σ** from SM predictions

$$B^0 \to K^* e^+ e^-$$

- Very challenging (statistics, resolution, trigger)
- Simplified angular analysis performed (in agreement with SM)

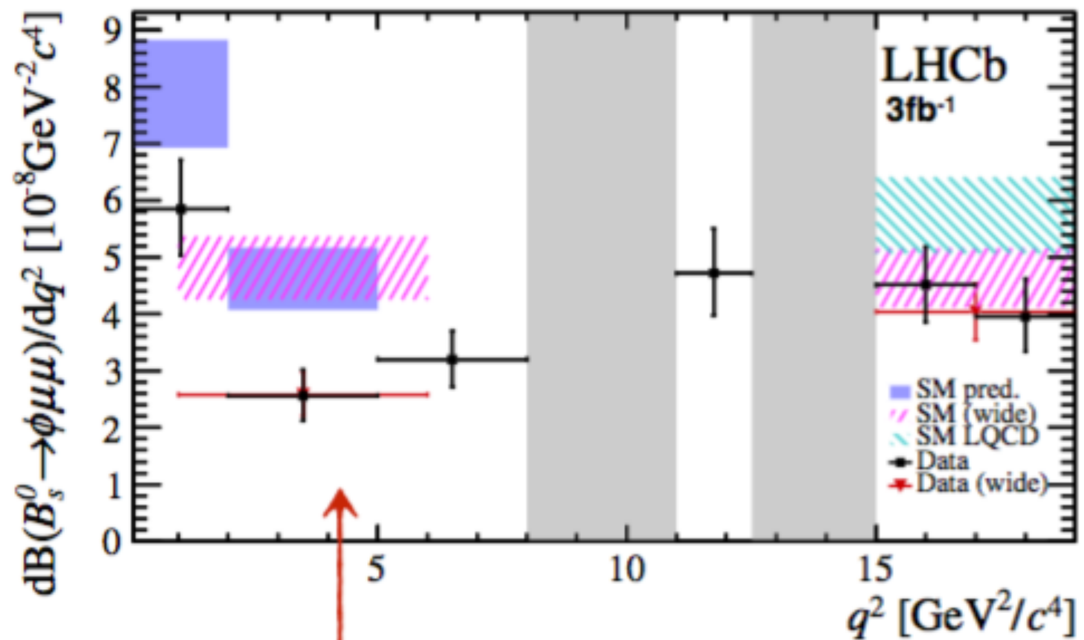
LHCb: Phys. Rev. D 93, 014028 (2016) ,
SM: PRD 93 (2016) 014028

Individual B decays to leptons

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

- **Narrow ϕ resonance simplifies selection**
- **Lower BF** than predicted in the SM
- Only CP averaged **angular observables** accessible (e.g. no P'_5), latter **in agreement**

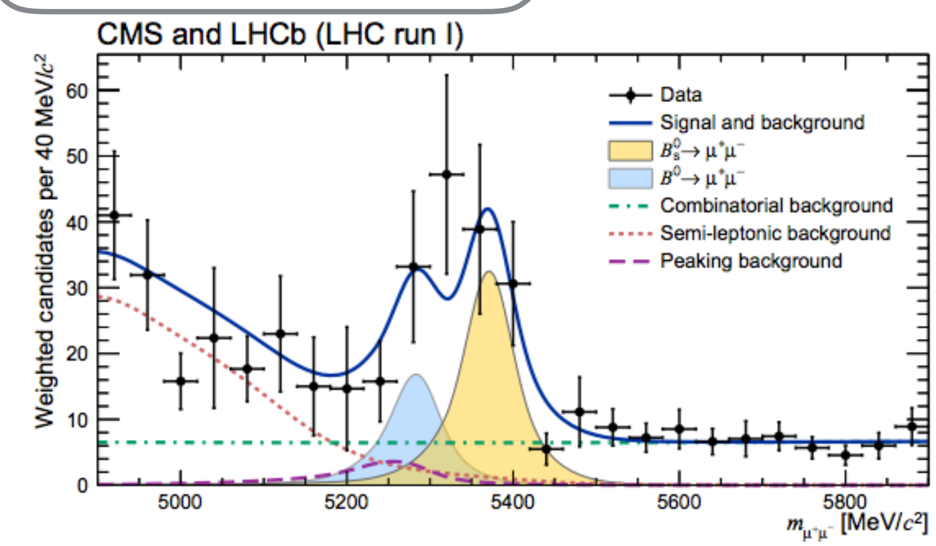
LHCb: JHEP 09 (2015) 179,
SM: EPJC (2015) 75 382, arXiv:1503.05534, PRD 89 (2014) 094501



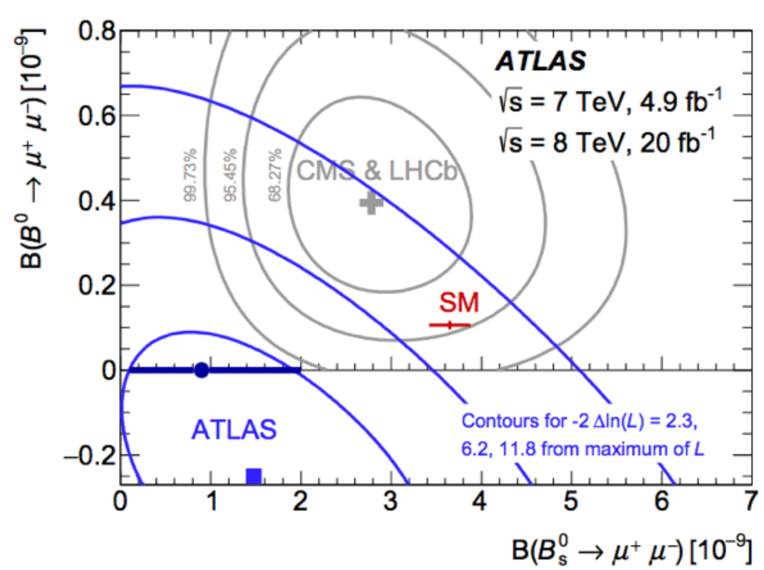
In a wide bin from $1 < q^2 < 6$ GeV$^2/c^4$, the data is $>3\sigma$ from the SM prediction

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

➤ **Similar (lower BF) trend** seen in other **b→sμ+μ-** processes
Compatibility with the SM 1.2σ for B_s (and 2.2σ for B^0)



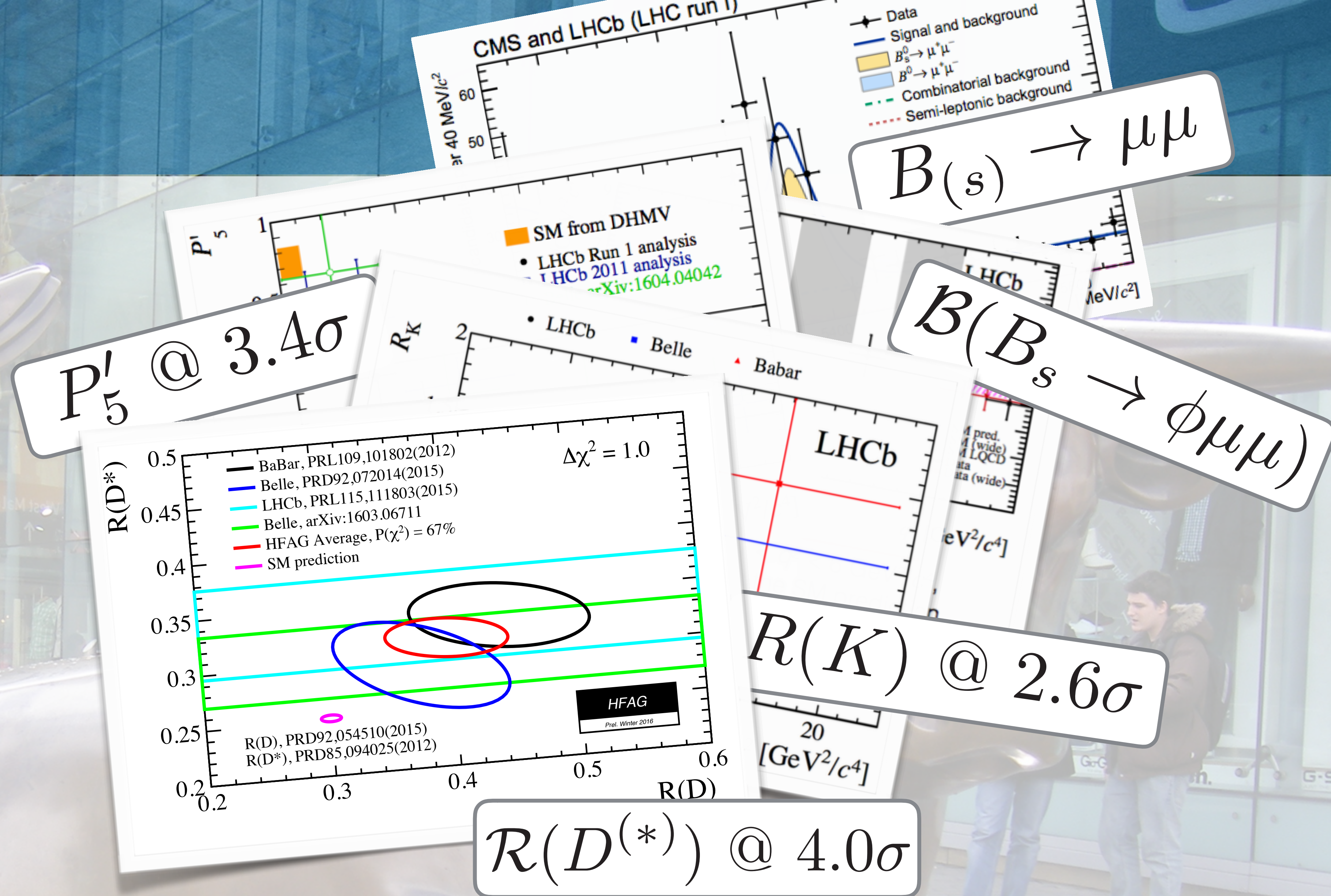
Nature 522, 68-72 (04 June 2015)

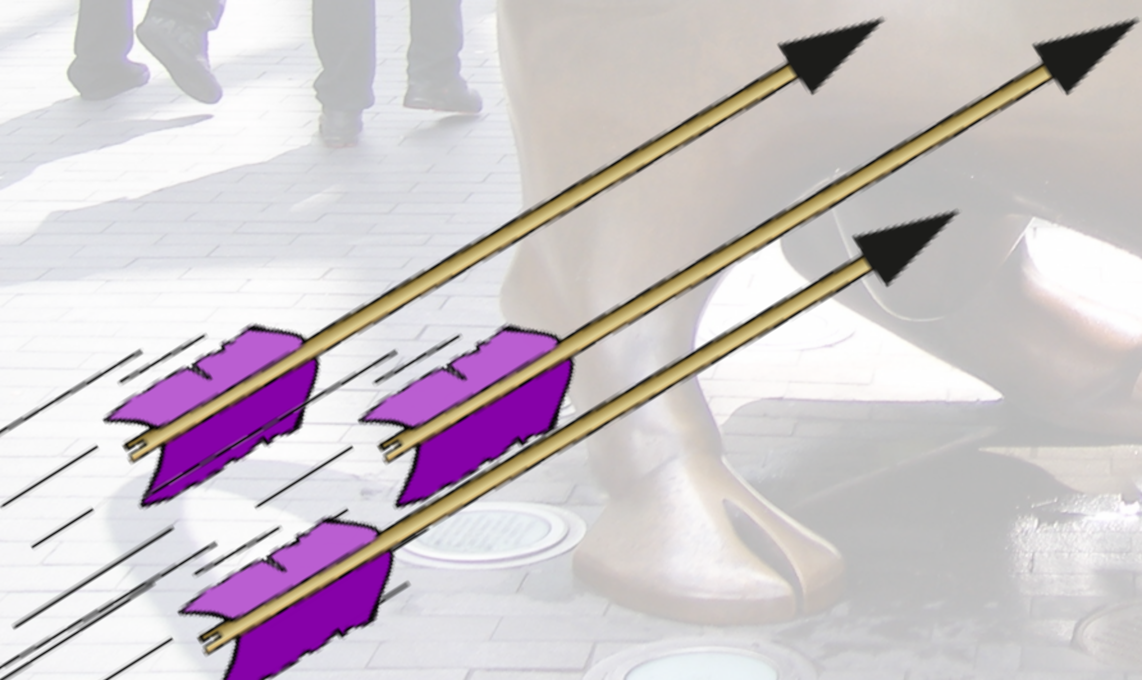


arXiv:1604.04263

$$B_{(s)} \to \tau\tau$$

…already next week at TAU!





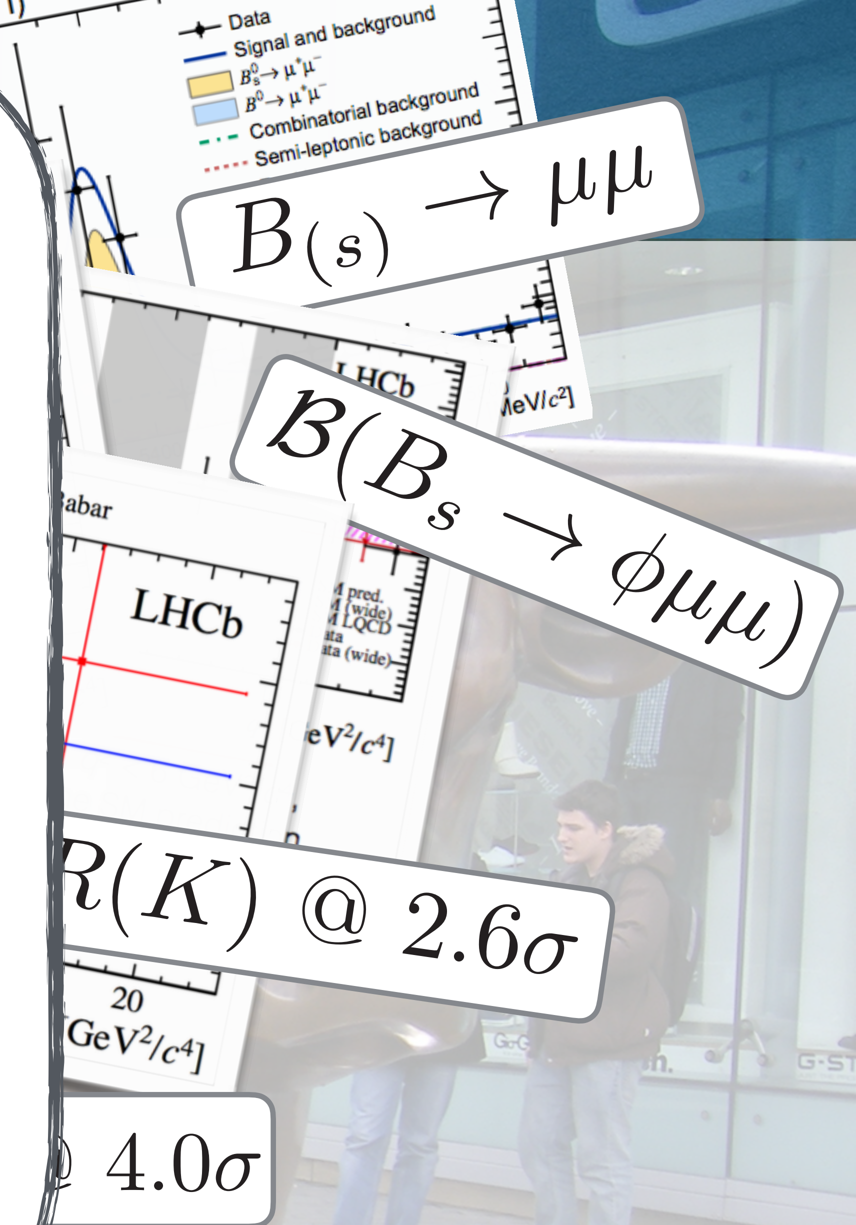
- **Global $b \to s l^+ l^-$ fits show 4-5σ tensions!**
  - $C_9^{NP} < 0$ **JHEP 06 (2016) 092 and many others**
- **Simultaneous explanations exist!**
  Leptoquarks, Z',..
  PRL 116 (2016) 141802, arXiv:1506.01705

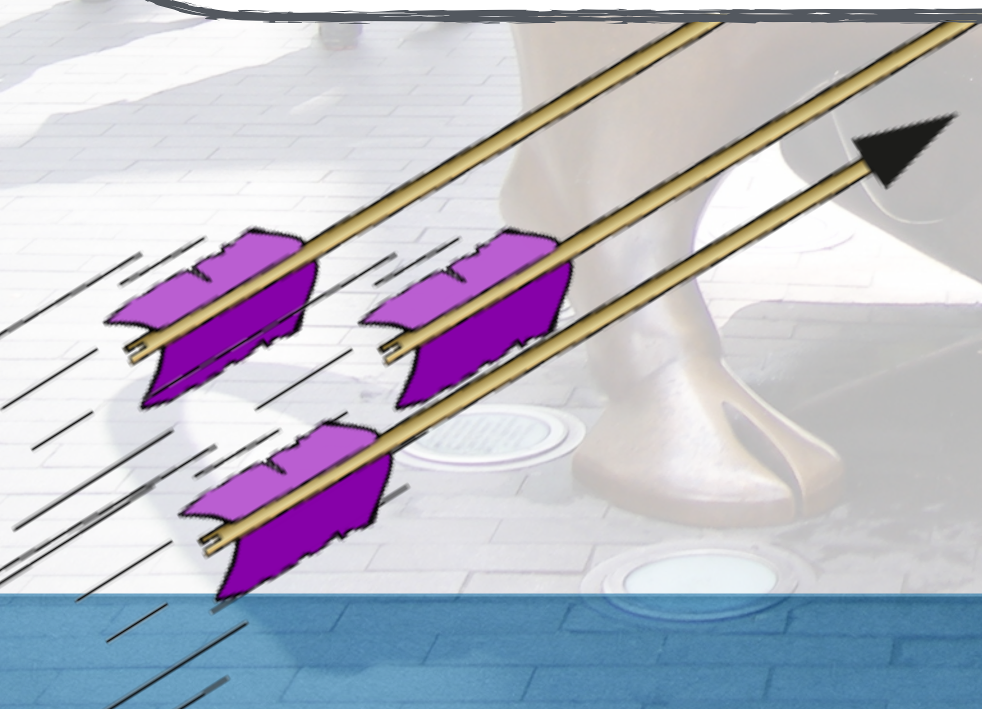
LHCb's schedule is busy…

- LHCb expected to collect **additional 5fb^{-1} in Run 2**
- Presented analysis will be **updated**.

- Many **new analysis** ongoing/foreseen at LHCb:
  - $R(D^*)$ using hadronic τ-decays
  - $R(D)$ measurement
  - Extend R to other mesons/baryons: $R(D_s)$ $R(\Lambda_c)$, $R(\Lambda_c^*)$
  - $R(K^*)$ with $B^0 \to K^* l^+ l^-$ and larger q^2 range
  - Electron-muon asymmetry in P'_5

Very interesting years ahead!





- **Global $b \to s l^+ l^-$ fits show 4-5σ tensions!**
  - $C_9^{NP} < 0$ **JHEP 06 (2016) 092 and many others**
- **Simultaneous explanations exist!** Leptoquarks, Z',..
  PRL 116 (2016) 141802, arXiv:1506.01705