Flavour Anomalies: What's Cooking in Rare and Semileptonic B Decays?

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24^e Congrès Générale de la Société Française de Physique
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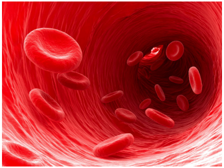
The Building Blocks of our Universe

[size ≈ 0.2m]

$\Rightarrow$

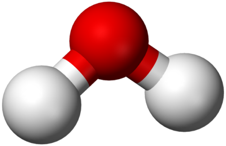
Cells



[size ≈ 6×10^{-6}m]

$\Rightarrow$

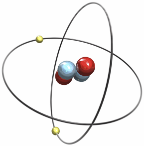
Molecule



[size > 0.74×10^{-10}m]

$\Downarrow$

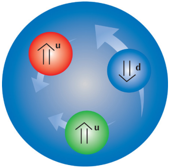
Atom



[size ≈ 31×10^{-12}m]

$\Leftarrow$

Nucleus



[size ≈ 1.5×10^{-15}m]

$\Leftarrow$

Elementary Particles

[size < 10^{-22}m]

Standard Model of Elementary Particles

Many Questions Remain . . .

Neutrino Masses?

Family Symmetry?

Matter–Anti-Matter Asymmetry?

Standard Model

Strong CP Problem?

Hierarchy Problem?

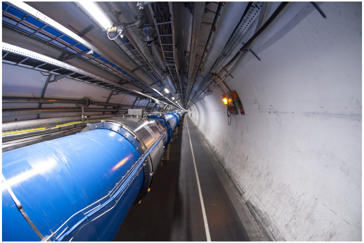
Quantize Gravity & General Relativity?

Neutrinos: Dirac or Majorana?

Dark Matter & Dark Energy?

The Large Hadron Collider

Searching for New Physics at the LHC



LHC Mission Objectives

✓ Search for the Higgs boson

× Search for evidence of Beyond the Standard Model Physics

Two Complementary Strategies

Direct Searches (Energy Frontier):

Search for new on-shell resonances

- *Bump*-hunting
  - Select x leptons + y jets (= observed decay products)
  - Require some missing energy (= undetected decay products)

Indirect Searches (Precision Frontier):

Search for anomalies in SM quantities

- Higgs Sector
- (Heavy) Flavour Sector
  - CP Violation & CKM Matrix
  - **Rare & Semileptonic Decays**

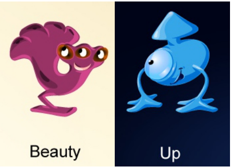
The Holy Grail: A $5\,\sigma$ Deviation

- σ = Total uncertainty on measurement (or difference with SM prediction)
- Arbitrary choice, but standard practice in particle physics

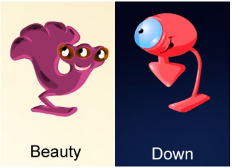
σ	Probability	$1-$ Probability	Used for
$1\,\sigma$	68.26 %	31.73 %	Quoted Uncertainties
$2\,\sigma$	95.45 %	4.55 %	
$3\,\sigma$	99.73 %	0.27 %	Evidence for New Physics
$4\,\sigma$	99.99 %	6.33×10^{-5}	
$5\,\sigma$	99.99 %	5.73×10^{-7}	Observation of New Physics

B Meson Family

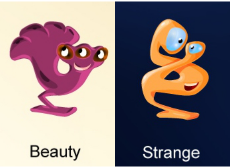
$B^+ = |\bar{b}u\rangle$



$B^0_d = |\bar{b}d\rangle$

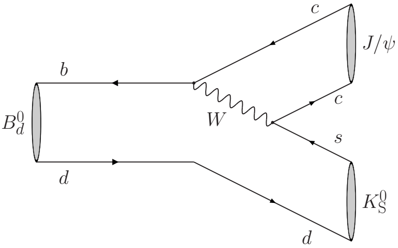


$B^0_s = |\bar{b}s\rangle$



- Unstable particles (lifetime $\approx 1.5 \times 10^{-12}$ seconds)
- More than 250 different decay paths
- Observables: branching fractions, asymmetries, angular correlations, . . .
- Allows us to probe many SM parameters

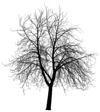
$\Rightarrow$ Perform high precision tests of SM



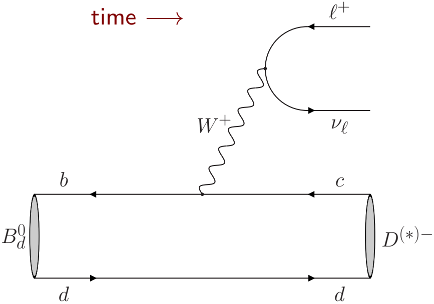
Semileptonic $b \to c\ell^- \bar{\nu}_\ell$ Decays

Semileptonic $b \to c\ell^-\bar{\nu}_\ell$ Decays

Tree-Level Transitions



1. $B_d^0 \to D^{(*)-} e^+ \nu_e$
2. $B_d^0 \to D^{(*)-} \mu^+ \nu_\mu$
3. $B_d^0 \to D^{(*)-} \tau^+ \nu_\tau$



Standard Model Decays

- Relatively simple final state
- Theoretically well understood
- No difference in behaviour between the lepton families $\ell^+ \in \{e^+, \mu^+, \tau^+\}$

Lepton Flavour Universality

Semileptonic $b \to c\ell^- \bar{\nu}_\ell$ Decays

Lepton Flavour Universality

- Accurate predictions for the $B_d^0 \to D^{(*)-}\ell^+\nu_\ell$ branching ratios
- **Only** difference is the lepton mass
- Allows us to test Lepton Flavour Universality

→ Ratio of branching fractions ($\ell^+ \in \{e^+, \mu^+\}$)

$$R(D) \equiv \frac{\mathcal{B}(B_d^0 \to D^- \tau^+ \nu_\tau)}{\mathcal{B}(B_d^0 \to D^- \ell^+ \nu_\ell)} \stackrel{\text{SM}}{=} 0.300 \pm 0.008\,, \qquad R(D^*) \equiv \frac{\mathcal{B}(B_d^0 \to D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B_d^0 \to D^{*-} \ell^+ \nu_\ell)} \stackrel{\text{SM}}{=} 0.252 \pm 0.003$$

FLAG, EPJC77 (2017), 112, arxiv:1607.00299
S.Fajfer *et al.*, PRD85 (2012) 094025, arxiv:1203.2654

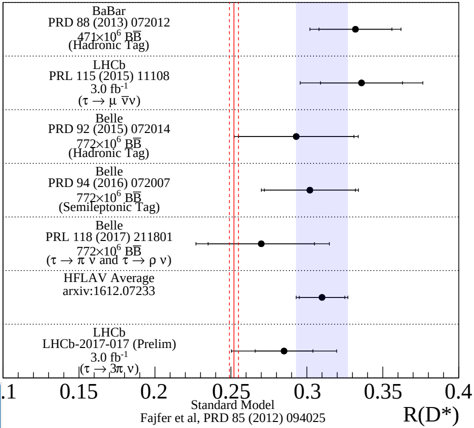
Challenging Measurements:

1. Missing energy due to the neutrino
2. τ decays inside the detector

- $B_d^0 \to D^{*-}\ell^+\nu_\ell$ is experimentally easier than $B_d^0 \to D^-\ell^+\nu_\ell$

Measurement of $R(D^*)$

- $\approx 2/3$ of the times D^{*-} decays into $D^0\pi_S^-$
- The presence of this slow pion (π_S^-) is very useful to suppress background
- Advantage over $B_d^0 \to D^-\ell^+\nu_\ell$

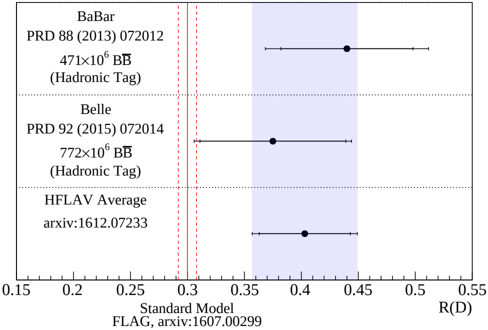


Measured by

- 3 different experiments: BaBar, Belle & LHCb
- Different decay channels
- Different techniques
- **All** above the SM prediction
- Significance: $3.4\,\sigma$

Measurement of $R(D)$

- More challenging due to feeddown from excited D^{**} resonances
- Final state entwined with $B_d^0 \to D^{*-}\ell^+\nu_\ell \Rightarrow$ large correlation

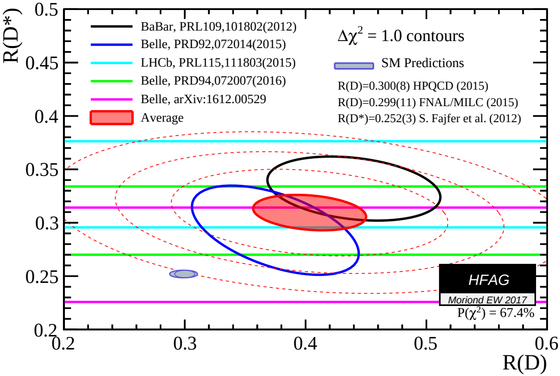


Measured by

- 2 different experiments: BaBar & Belle
- **Both** above the SM prediction
- Significance: $2.2\,\sigma$
- LHCb is also planning a measurement

Combined $R(D^*)$–$R(D)$ Fit

3.9 σ deviation from SM



SM Expectation:	Experimental Average:	Sig.
$R(D^*) = 0.252 \pm 0.003$	$R(D^*) = 0.310 \pm 0.015\,(\text{stat}) \pm 0.008\,(\text{syst})$	$3.4\,\sigma$
$R(D) = 0.300 \pm 0.008$	$R(D) = 0.403 \pm 0.040\,(\text{stat}) \pm 0.024\,(\text{syst})$	$2.2\,\sigma$

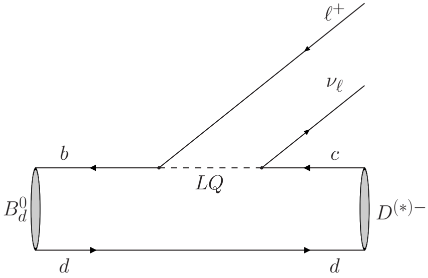
FLAG, arxiv:1607.00299

S. Fajfer *et al.*, arxiv:1203.2654

HFLAV, arxiv:1612.07233

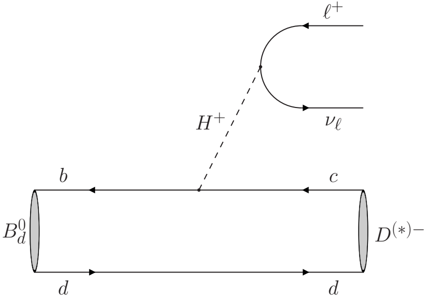
Possible Explanations

LeptoQuark Models



- Model allows direct interaction between quarks and leptons

2 Higgs Doublet Models

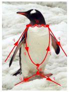


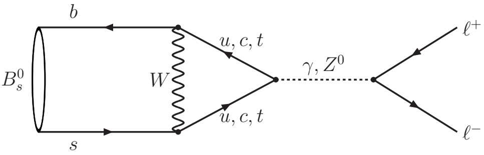
- Model now contains 5 Higgs particles (SM only has 1)
- Charged Higgs interaction

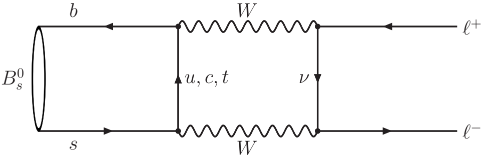
Rare $b \to s\ell^+\ell^-$ Transitions

Rare $b \to s\ell^+\ell^-$ Transitions

Flavour Changing Neutral Current







1. $B^0_{d/s} \to \mu^+\mu^-$
2. $B^+ \to K^+\ell^+\ell^-$
3. $B^0_d \to K^{*0}\ell^+\ell^-$
4. Many more possibilities

Standard Model Decays

- Forbidden at Tree level

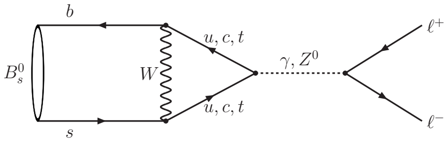
$\Rightarrow$ Loop suppressed

- Sensitive to new physics contributions

The Decay $B \to \mu^+\mu^-$

Theory Calculations

- Only leptons in the final state
- Theoretically well understood
- Accurate SM predictions



$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) \stackrel{\text{SM}}{=} (1.06 \pm 0.09) \times 10^{-10}\,, \qquad \mathcal{B}(B_s^0 \to \mu^+\mu^-) \stackrel{\text{SM}}{=} (3.65 \pm 0.23) \times 10^{-9}$$

Bobeth *et al.*, PRL 112 (2014) 101801, arxiv:1311.0903

- Special interest: the ratio $\mathcal{B}(B_d^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$
  (Is there New Physics? Is it *minimal flavour violating* or not?)

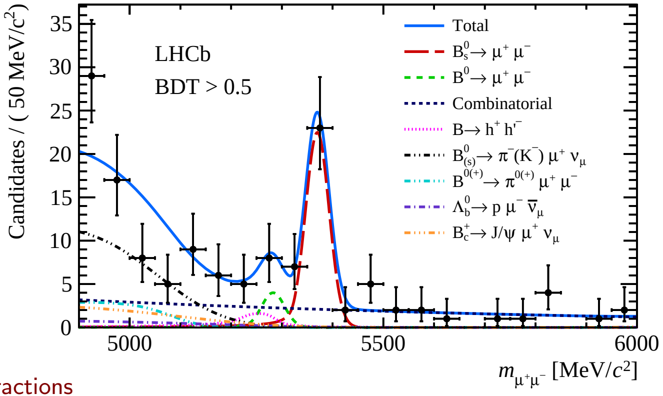
Experimental Status

- Active search since '80s
- 2014: First observation of $B_s^0 \to \mu^+\mu^-$ using LHC Run 1 data
  CMS+LHCb, Nature 522 (2015) 68, arxiv:1412.6433
- Recent update from LHCb, including data from LHC Run 2

The Decay $B \to \mu^+\mu^-$

LHCb, PRL 118 (2017) 191801, arxiv:1703.05747

- LHCb's excellent mass resolution allows to separate B_d^0 and B_s^0 signals



Branching Fractions

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,(\text{stat})\,^{+0.3}_{-0.2}\,(\text{syst})) \times 10^{-9} \qquad (7.8\sigma)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5\,^{+1.2}_{-1.0}\,(\text{stat})\,^{+0.2}_{-0.1}\,(\text{syst})) \times 10^{-10} \qquad (1.6\sigma)$$

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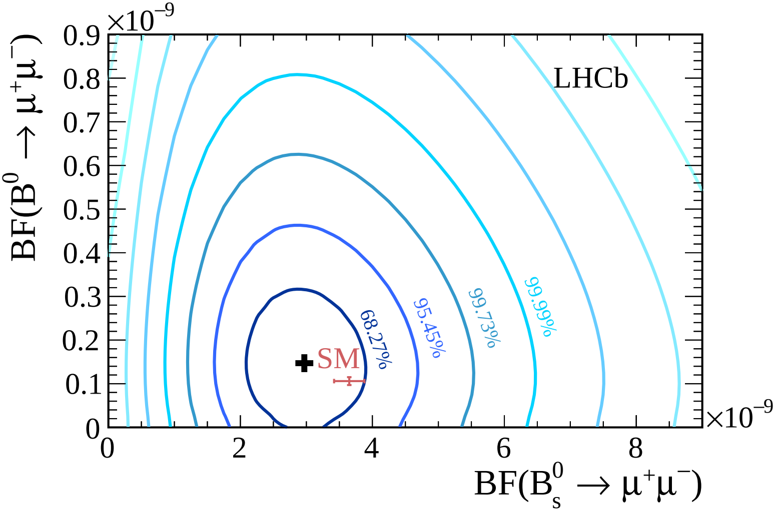
The Decay $B \to \mu^+\mu^-$

LHCb, PRL 118 (2017) 191801, arxiv:1703.05747

- Good agreement with the SM expectation
- But better precision is needed regarding $\mathcal{B}(B_d^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$



The Decay $B^+ \to K^+\ell^+\ell^-$

Testing Lepton Flavour Universality

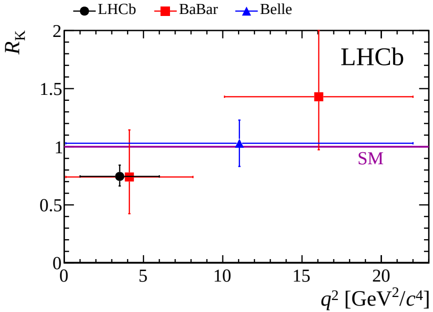
- Compare the branching ratios for electrons and muons
- Theoretically very precisely known

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \overset{\text{SM}}{\to} 1$$

- Using Run 1 data, LHCb finds

$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

- Significance: 2.6σ
- LHCb is working on an update including LHC Run 2 data



LHCb, PRL 113 (2014) 151601, arxiv:1406.6482

- q^2 = mass of the $\ell^+\ell^-$ system

The Decay $B_d^0 \to K^{*0}\ell^+\ell^-$

Another Test of Lepton Flavour Universality

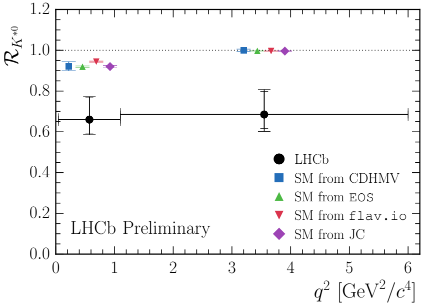
- Compare the branching ratios for electrons and muons
- Theoretically precisely known

$$R_{K^*} = \frac{\mathcal{B}(B_d^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B_d^0 \to K^{*0}e^+e^-)} \stackrel{\text{SM}}{\to} 1$$

- Using Run 1 data, LHCb finds

$$R_{K^*}|_{[0.045,1.1]} = 0.66^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst})$$
$$R_{K^*}|_{[1.1,6.0]} = 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst})$$

- Significance: $2.2\sigma + 2.5\sigma$

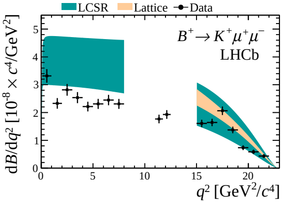


LHCb, arxiv:1705.05802

- q^2 = mass of the $\ell^+\ell^-$ system

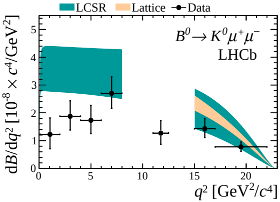
Other $b \to s\mu^+\mu^-$ Branching Fractions

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



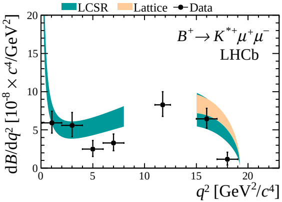
- Also used for R_K

$B_d^0 \to K^{*0}\mu^+\mu^-$



- Also used for R_{K^*}

$B^+ \to K^{*+}\mu^+\mu^-$



LHCb, JHEP06 (2014) 133, arxiv:1403.8044

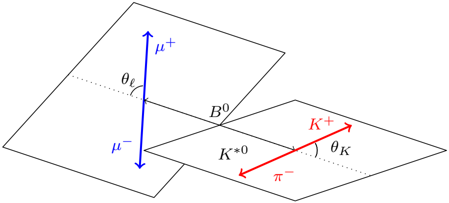
- Measure branching fractions as a function of q^2
- All are below the theory predictions

$\Rightarrow$ Same trend as for R_K and R_{K^*}

The Decay $B_d^0 \to K^{*0}\mu^+\mu^-$ (yet again)

Angular Observables

- K^{*0} is a Spin 1 particle (Excited version of K^0 particle)
- Angular correlations between the decay products

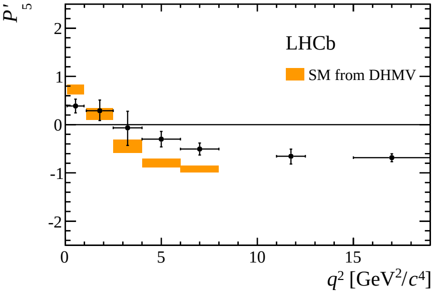


- Many additional observables to look at, complementing the branching fraction
- Of interest here: the one named "P_5'" (optimised for NP searches)

The Decay $B_d^0 \to K^{*0}\mu^+\mu^-$ (yet again)

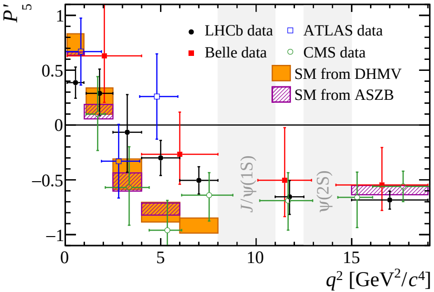
- Measured by 4 different experiments: Belle, LHCb, ATLAS, CMS
- Most precise measurement from LHCb

LHCb Only



LHCb, JHEP02 (2016) 104, arxiv:1512.04442

All Together



Belle, arxiv:1604.04042

ATLAS, ATLAS-CONF-2017-023

CMS, CMS-PAS-BPH-15-008

- Significance: 3.4 σ
  - Ongoing discussion about the interpretation and theory predictions
  - Situation is not as clear cut as for the R-measurements

Puzzling Tensions in $b \to s\ell^+\ell^-$ Transitions

The Pieces

- R_K, R_{K^*}, branching fractions, P_5'

The Puzzle

- Individual "discrepancies" only have significance between 2 and 3 σ
- Can simply be statistical fluctuations

$\Rightarrow$ Why the excitement?

- They do seem to point in the same direction ...
- So what if ... we put all the pieces together?

Effective Field Theory Framework

- Describe all decays in a model-independent way: Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = \frac{\overbrace{G_F}^{\text{Fermi Constant}}}{\sqrt{2}} \sum_{j=u,c} \underbrace{V_{jd}^* V_{jb}}_{\text{CKM Elements}} \left[\sum_k \underbrace{(C_k^{\text{SM}} + C_k^{\text{NP}})}_{\text{Wilson Coefficients}} \overbrace{\mathcal{O}_k}^{\text{Operator}} + C_k' \mathcal{O}_k' \right]$$

G. Buchalla *et al.*, RMP 68 (1996) 1125, `arxiv:9512380[hep-ph]`

- Does not favour any particular New Physics model
- Matching to specific NP models can be done later

Ingredients:

- Coupling constants & CKM elements
- Wilson coefficients contain all perturbative short-distance effects
  - ⇒ For specific models: Can be calculated within perturbation theory
  - ⇒ C_k^{NP} **Free parameters** in the fit to the data
- Operators contain all non-perturbative long-distance effects
  - Semileptonic operators: $\mathcal{O}_9$ (vector) and $\mathcal{O}_{10}$ (axial-vector)
  - Primed operators have mirrored (L ↔ R) chirality

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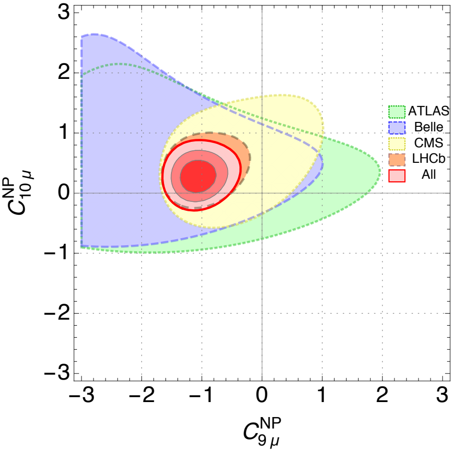
Hints for New Physics?

- Best fit model has Wilson coefficient
  $$C_9^{\text{NP}} = -1$$
- Significance: $\approx 5\,\sigma$
- Suggests lepton universality violation

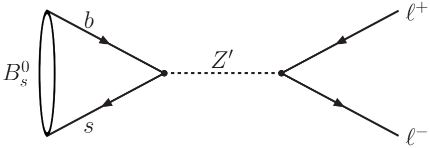
- What can explain this?
  1. Statistical fluctuations
  2. Not-yet-understood SM effects
  3. New Physics
- Way forward?
  - Increase the statistics
  - Additional observables
  - Additional decay channels



B. Capdevila *et al.*, arxiv:1704.05340

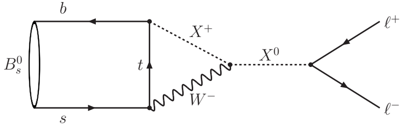
Possible Explanations

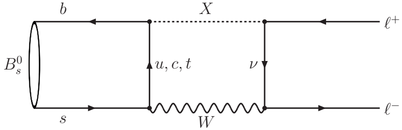
Z'-Models



- New tree level processes

2HDM or LeptoQuarks





- Additional loop contributions

Challenge

- Simultanously explain the tensions in $b \to s\ell^+\ell^-$ transitions and $R(D^*)$–$R(D)$
  - New physics at tree-level and at loop-level

$\Rightarrow$ Different orders of magnitude

Conclusion

- Possible first hints for beyond the SM physics
- Discrepancy in $R(D^*)$–$R(D)$
- Puzzling tensions in $b \to s\ell^+\ell^-$ transitions
- Something is cooking . . . hopefully it's tasty New Physics