Tensions in flavor physics?

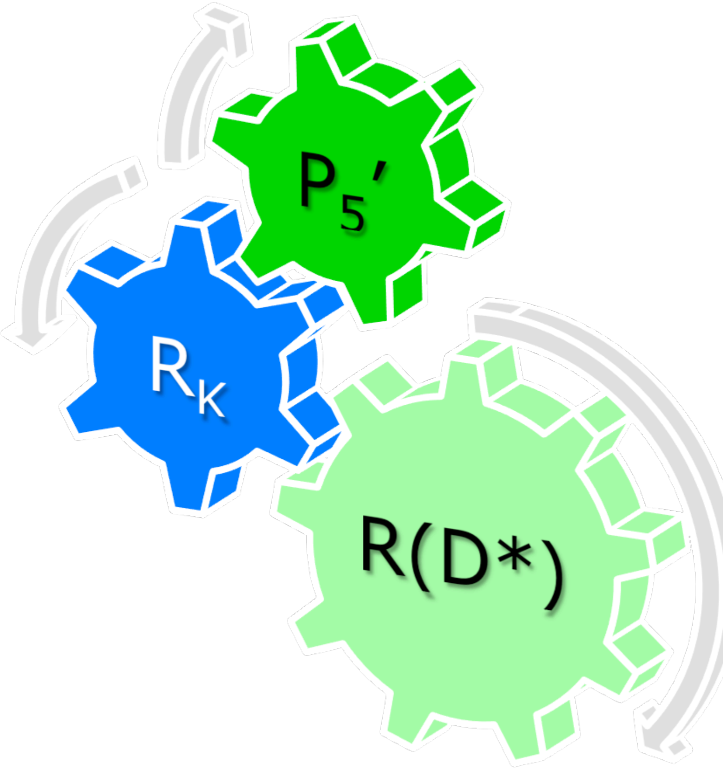
Niels Tuning

12 Dec 2015


INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS
CERNCOURIER
VOLUME 55 NUMBER 9 NOVEMBER 2015
Tensions in the Standard Model

Outline: the jargon

- What are the measurements?



- What are the interpretations?

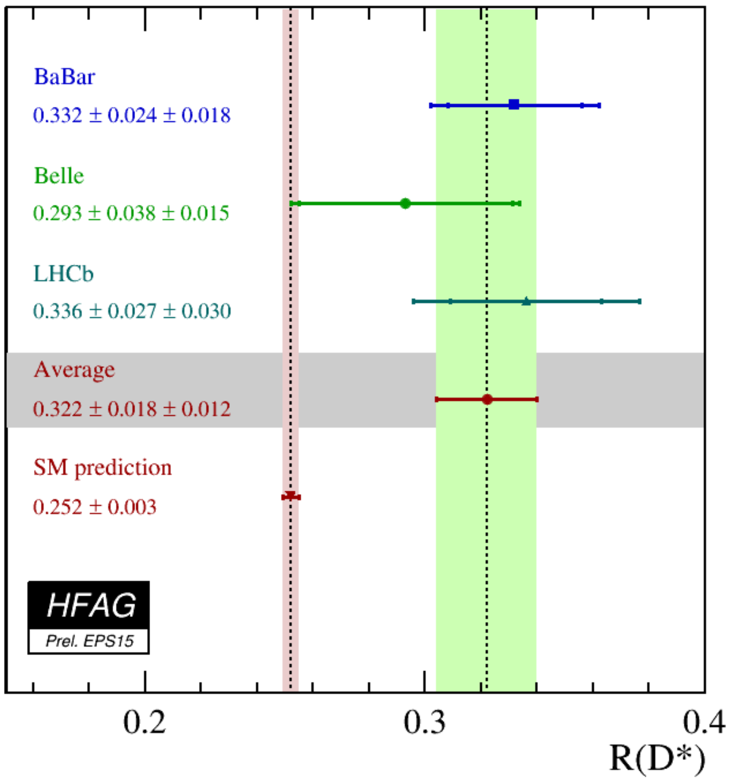
C_9

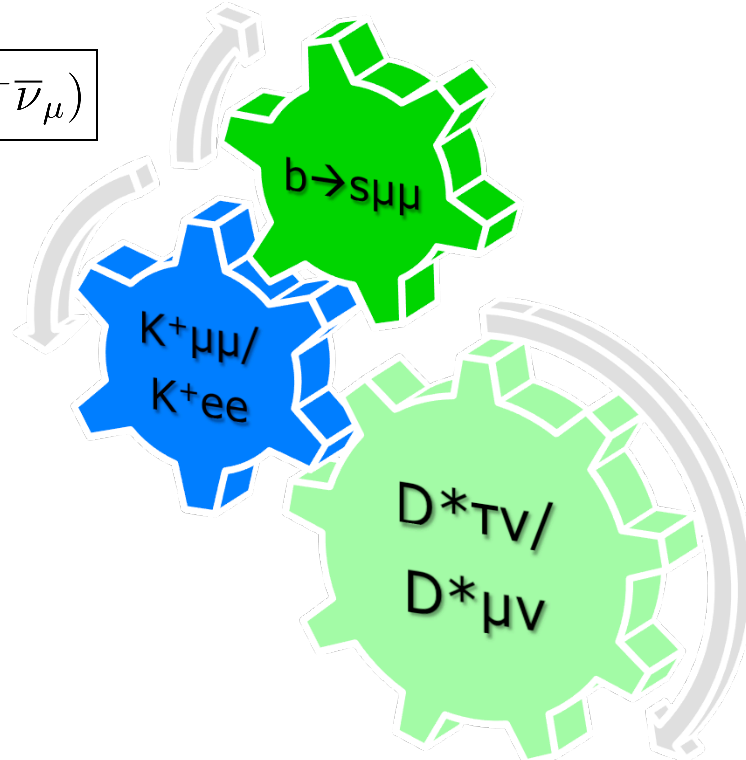
The measurements: R(D*)

- See previous talk by Greg!

$$\mathcal{R}(D^*) \equiv \mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$$

arXiv:1506.08614



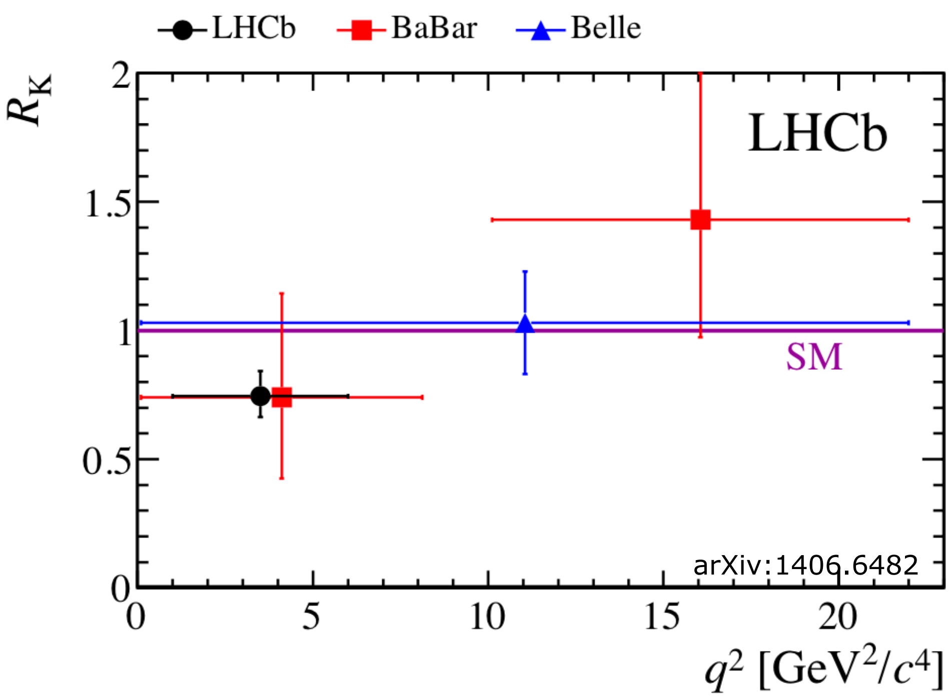


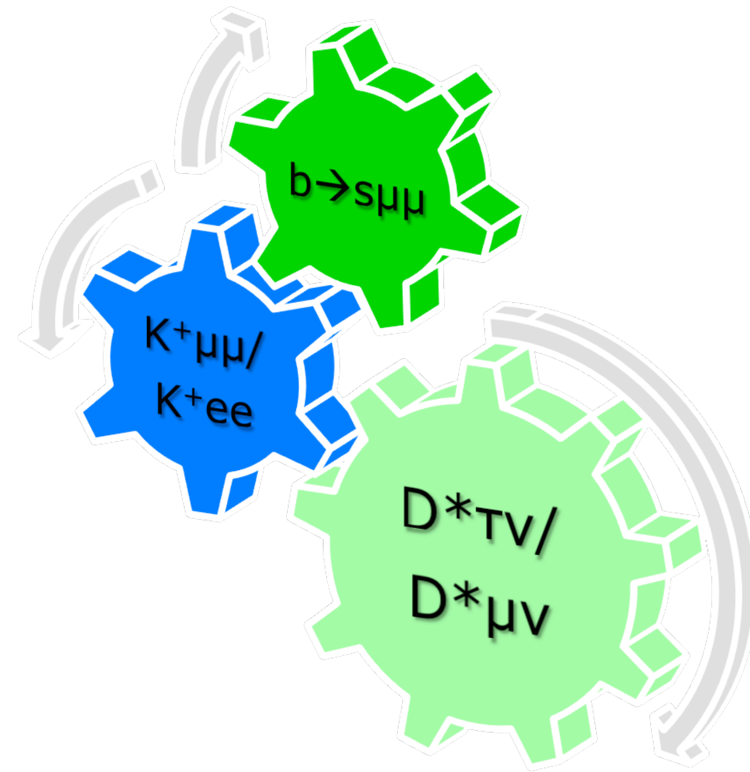
$$R(D^*) = 0.322 \pm 0.018\,(\text{stat}) \pm 0.012\,(\text{sys})$$

The measurements: R_K

- More lepton-flavor universality violation?

$$R_K = \frac{\Gamma(B^+ \to K^+ \mu^+ \mu^-)}{\Gamma(B^+ \to K^+ e^+ e^-)}$$

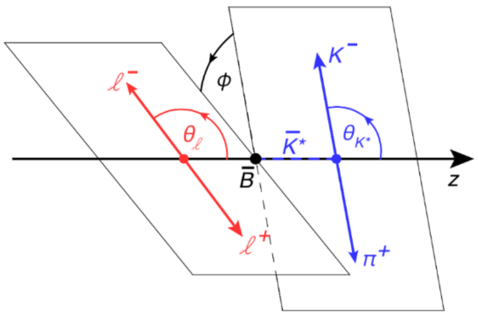


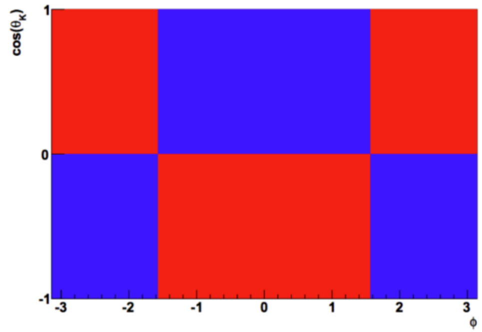


$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

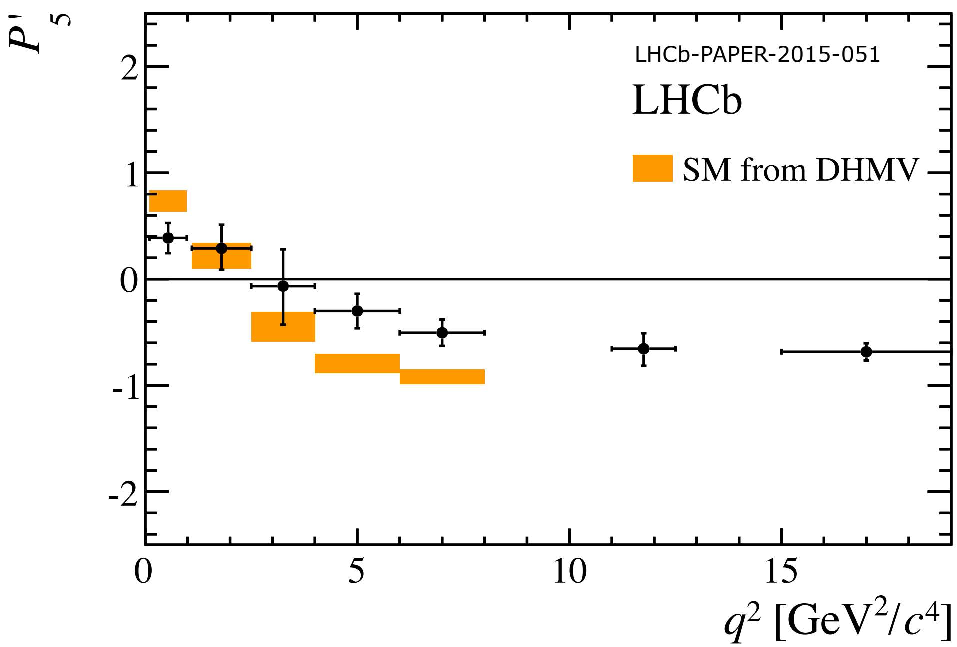
The measurements: P_5'

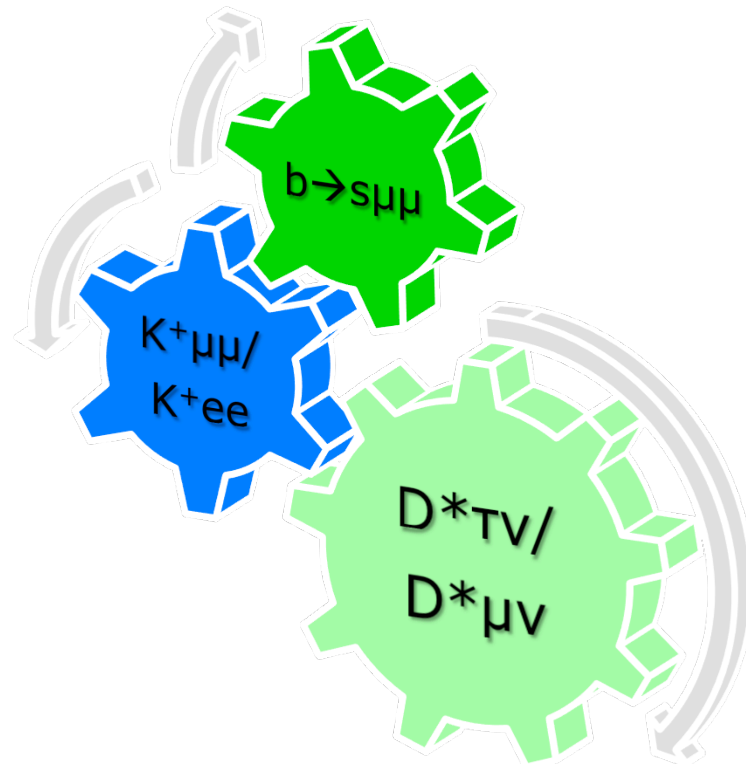
- More deviations in flavor-changing neutral current?





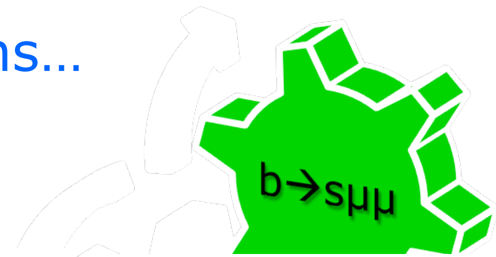
Counting S_5: blue minus red

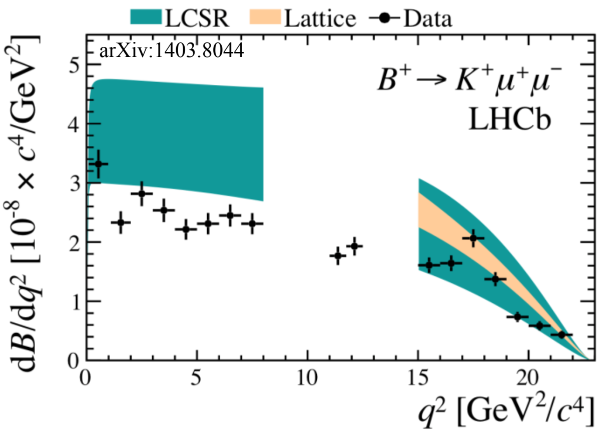


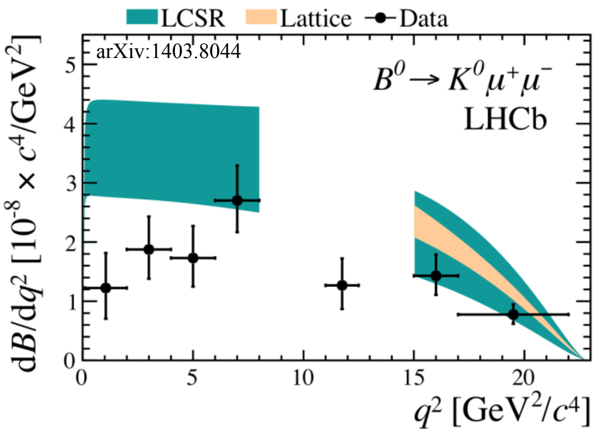


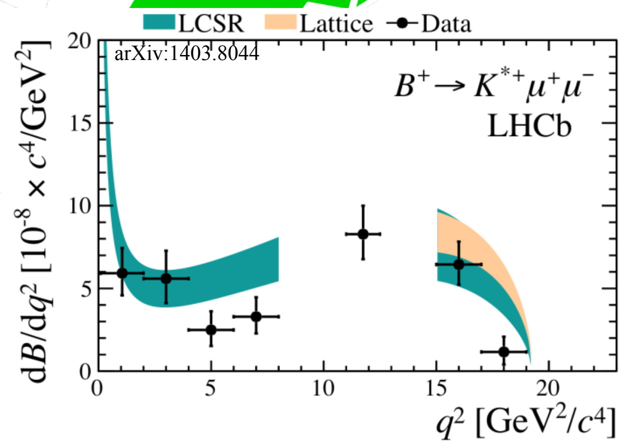
The measurements: P_5' and more!

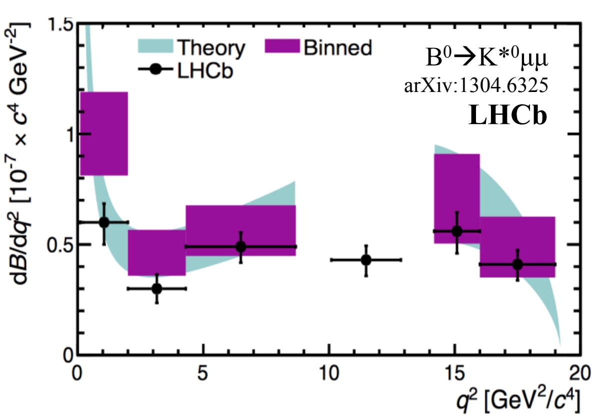
- More deviations in flavor-changing neutral current?
  - ➢ *All* decay rates are below predictions…

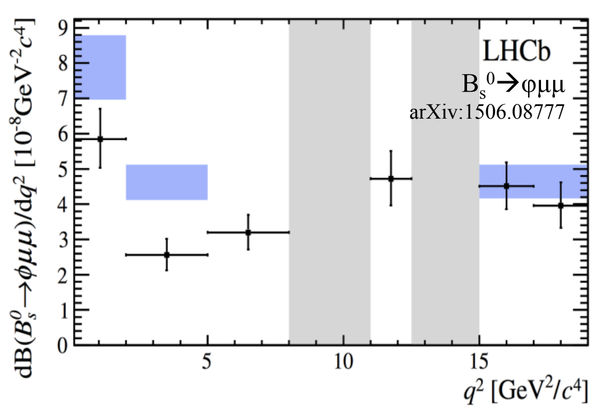


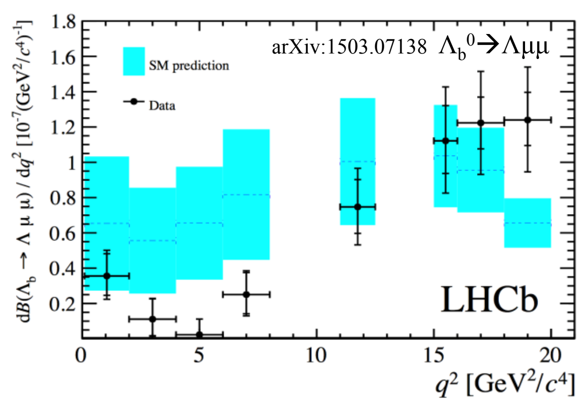




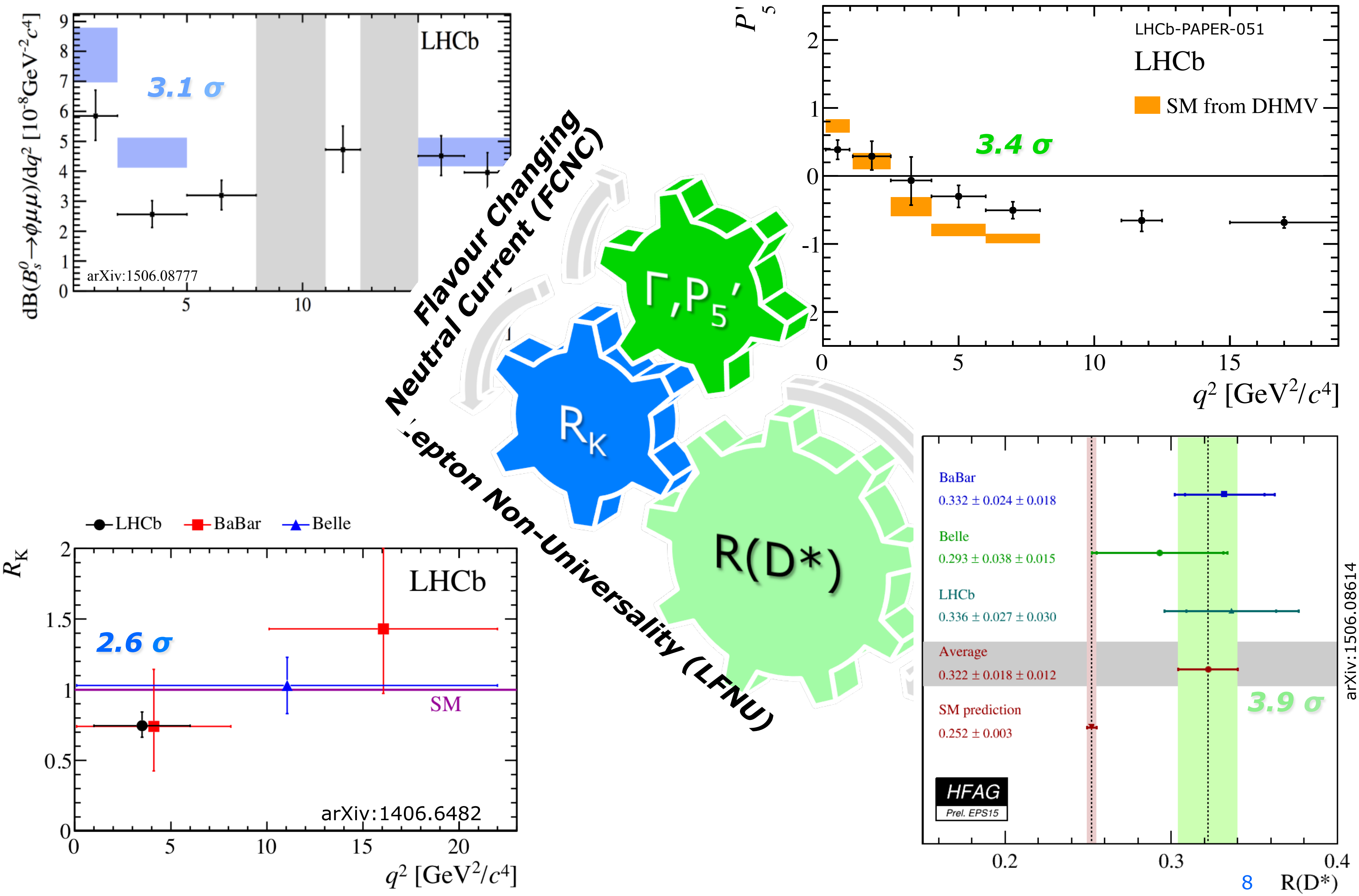








Tensions


LHCb
3.1 σ
arXiv:1506.08777
$dB(B_s^0 \to \phi\mu\mu)/dq^2$ [10^{-8}GeV$^{-2}c^4$]
LHCb-PAPER-051
LHCb
SM from DHMV
3.4 σ
P'_5
q^2 [GeV^2/c^4]
Flavour Changing Neutral Current (FCNC)
Γ,P5'
RK
R(D*)
Lepton Non-Universality (LFNU)
LHCb
BaBar
Belle
R_K
2.6 σ
SM
arXiv:1406.6482
q^2 [GeV^2/c^4]
BaBar
0.332 ± 0.024 ± 0.018
Belle
0.293 ± 0.038 ± 0.015
LHCb
0.336 ± 0.027 ± 0.030
Average
0.322 ± 0.018 ± 0.012
SM prediction
0.252 ± 0.003
HFAG
Prel. EPS15
3.9 σ
arXiv:1506.08614
R(D*)

More Measurements

"Interesting" recent measurements at LHCb:

- ✓ *R(D*) and R(D):* *Lepton universality* $B \rightarrow D^{(*)}\tau\upsilon$ / $B \rightarrow D^{(*)}\mu\upsilon$
- ✓ R_K: *Lepton universality* $B \rightarrow Kee$ / $B \rightarrow K\mu\mu$
- ✓ P_5': *Angular observable* $B^0 \rightarrow K^*\mu\mu$
- ✓ $\Gamma(b \rightarrow s\ \mu\mu)$ *Decay rates of* $B_{(s)} \rightarrow K(\varphi)\mu\mu$

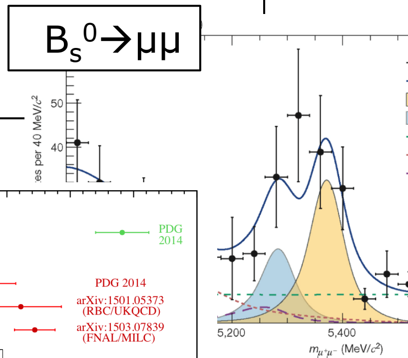
More Measurements

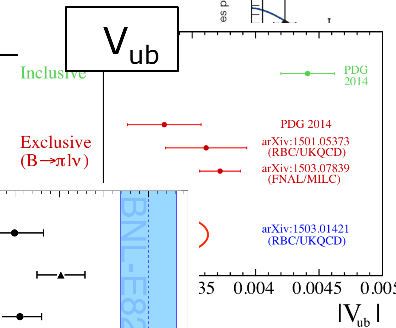
"Interesting" recent measurements at LHCb:

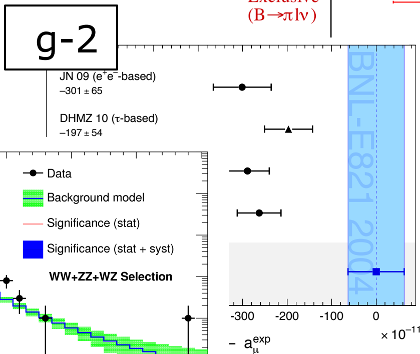
- ✓ R(D*) and R(D): *Lepton universality $B \to D^{(*)}\tau\nu$ / $B \to D^{(*)}\mu\nu$*
- ✓ R_K: *Lepton universality $B \to Kee$ / $B \to K\mu\mu$*
- ✓ P_5': *Angular observable $B^0 \to K^*\mu\mu$*
- ✓ $\Gamma(b \to s\,\mu\mu)$ *Decay rates of $B_{(s)} \to K(\varphi)\mu\mu$*

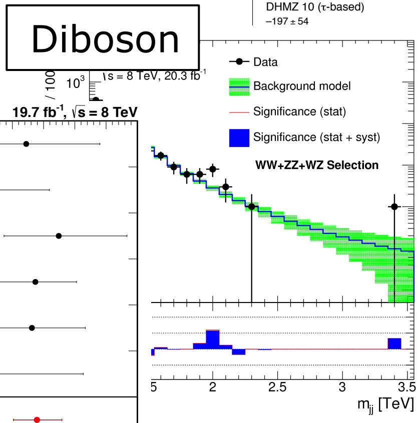
Other interesting measurements and constraints:

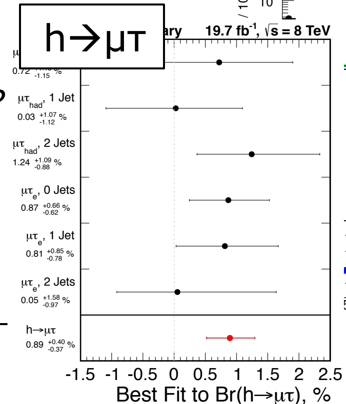
- ✓ $BR(B^0 \to \mu\mu)$: *high?*
- ✓ V_{ub}: incl vs excl: *different?*
- ✓ g-2 *high?*
- ✓ ~~Diboson~~ resonance Diphoton *high?*
- ✓ $H \to \tau\mu$ *high?*
- ✓ ε'/ε *x10 high?*
- ❑ B-mixing
- ❑ $\tau \to \mu\mu\mu$
- ❑ $\mu \to e\gamma$









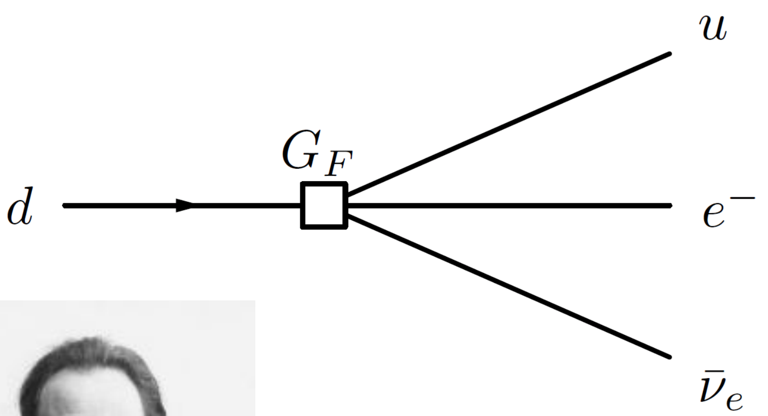


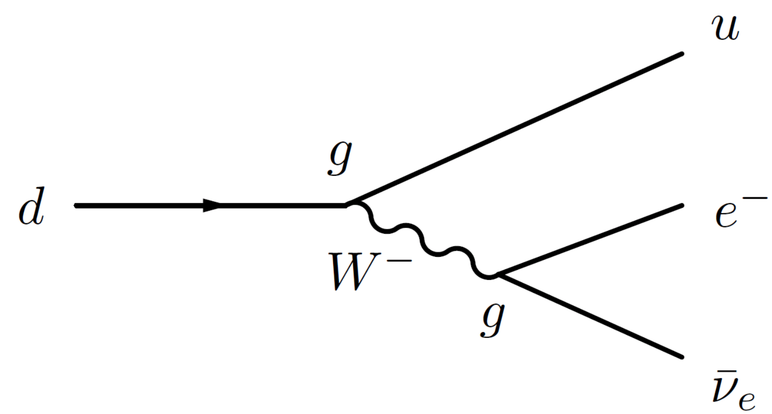
LHCb/CMS Nature 522, 68 (2015)	
LHCb	arXiv:1504.01568
BNL E821	PDG
ATLAS	arXiv:1506.00962
CMS	PAS-HIG-14-005

http://www.foksuk.nl/

Effective couplings

- Historical example:



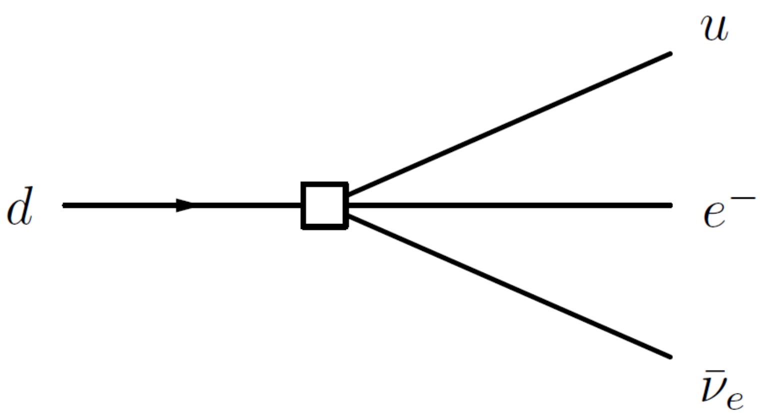


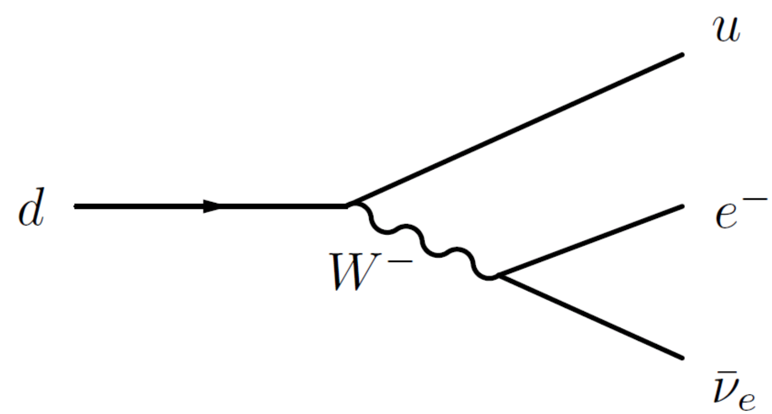
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

- Both are correct, depending on the energy scale you consider

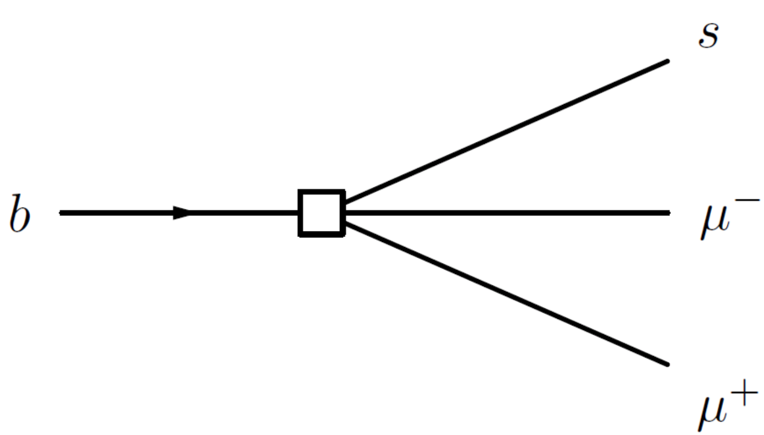
Effective couplings

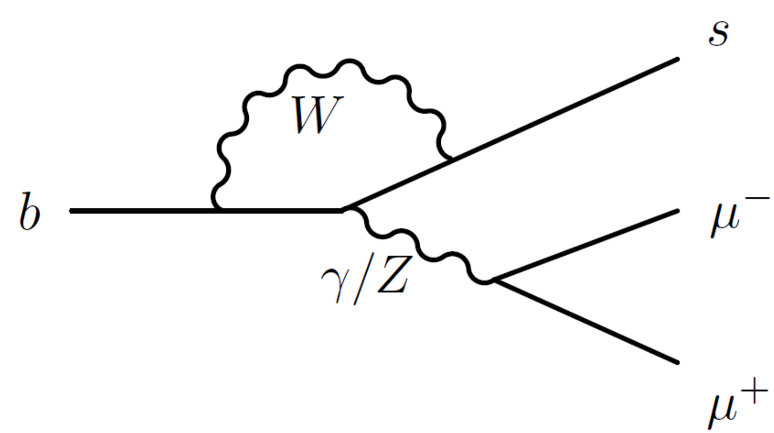
- Historical example





- Analog: *Flavour-changing neutral current*

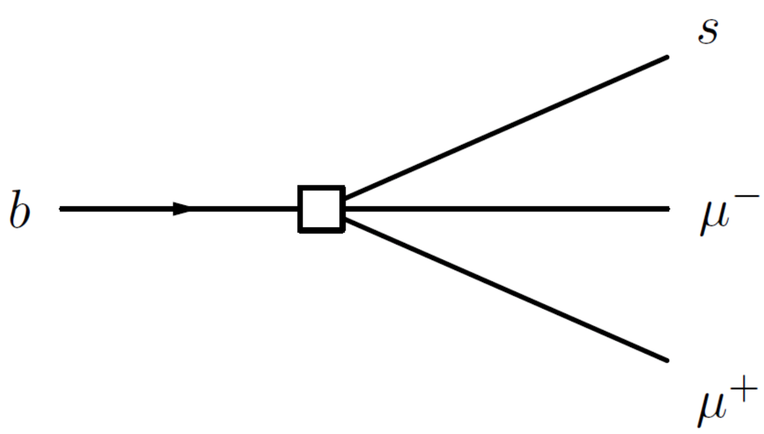


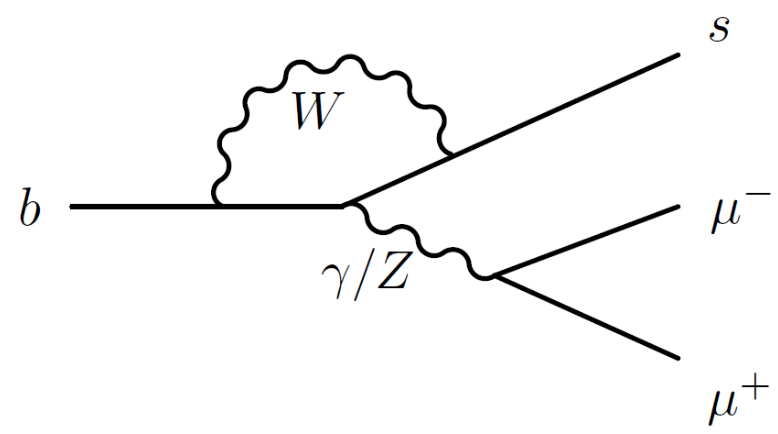


Effective couplings

- Effective coupling can be of various "kinds"
  - Vector coupling
  - Axial coupling
  - Left-handed coupling (V-A)
  - Right-handed (to quarks)
  - …

$$\mathcal{H}_{\text{eff}} = \frac{G_{\text{F}}}{\sqrt{2}} V_{\text{CKM}} \sum_i C_i(\mu) Q_i$$





Effective couplings

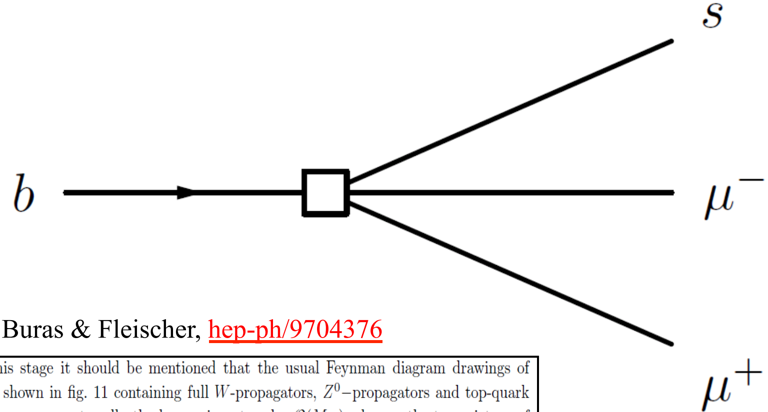
- Effective coupling can be of various “kinds”
  - Vector coupling: C_9
  - Axial coupling: C_{10}
  - Left-handed coupling (V-A): C_9-C_{10}
  - Right-handed (to quarks): C_9', C_{10}', …
  - …

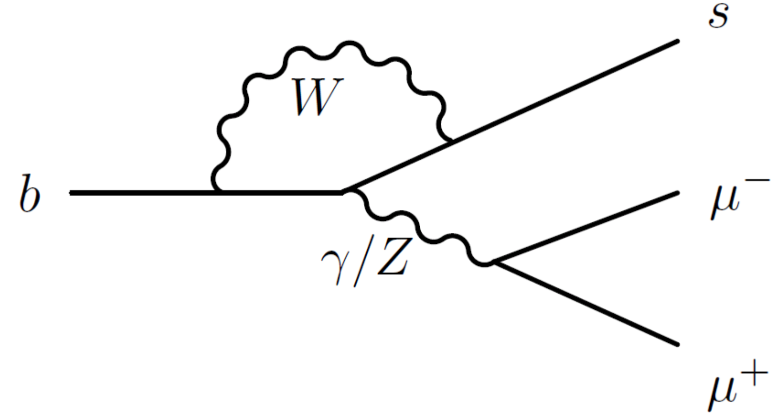
$$\mathcal{H}_{\rm eff} = \frac{G_{\rm F}}{\sqrt{2}} V_{\rm CKM} \sum_i C_i(\mu) Q_i$$

See e.g. Buras & Fleischer, hep-ph/9704376

Semi–Leptonic Operators (fig. 11f):

$$Q_{9V} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_V \qquad Q_{10A} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_A$$





From Buras & Fleischer, hep-ph/9704376

At this stage it should be mentioned that the usual Feynman diagram drawings of the type shown in fig. 11 containing full W-propagators, Z^0–propagators and top-quark propagators represent really the happening at scales $\mathcal{O}(M_{\rm W})$ whereas the true picture of a decaying hadron is more correctly described by the local operators in question. Thus, whereas at scales $\mathcal{O}(M_{\rm W})$ we have to deal with the full six-quark theory containing the photon, weak gauge bosons and gluons, at scales $\mathcal{O}(1\,{\rm GeV})$ the relevant effective theory contains only three light quarks u, d and s, gluons and the photon. At intermediate energy scales $\mu = \mathcal{O}(m_b)$ and $\mu = \mathcal{O}(m_c)$ relevant for beauty and charm decays, effective five-quark and effective four-quark theories have to be considered, respectively.

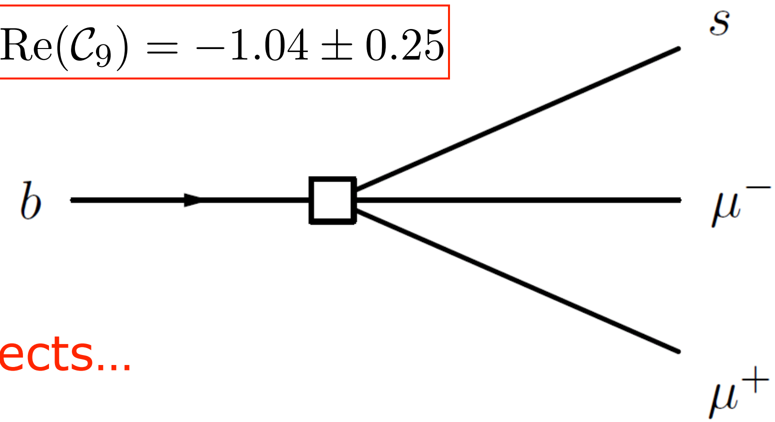
“the true picture of a decaying hadron is more correctly described by the local operators”

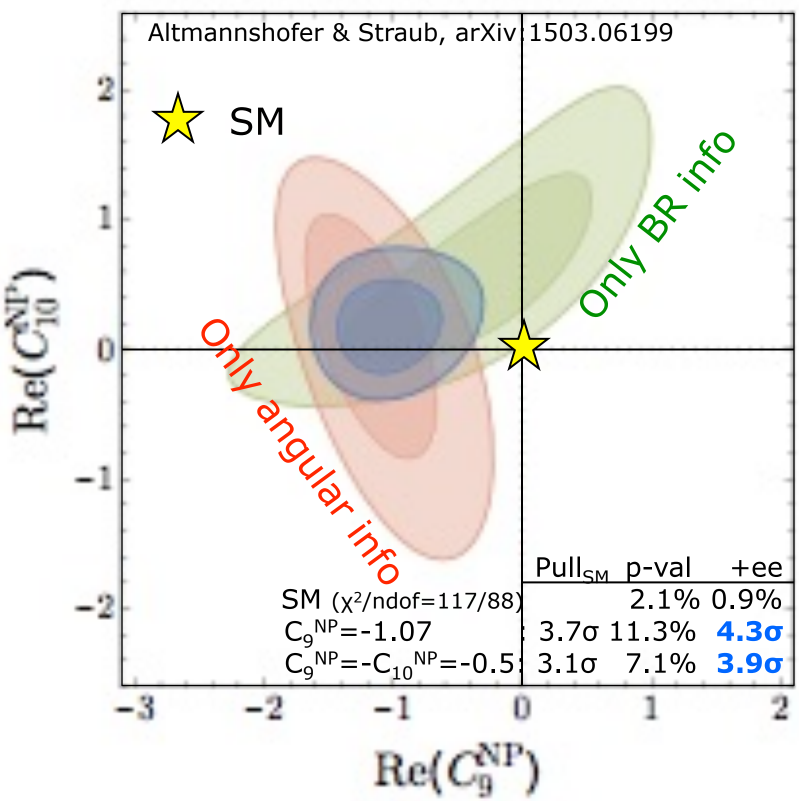
Theory: 1) Model independent fits

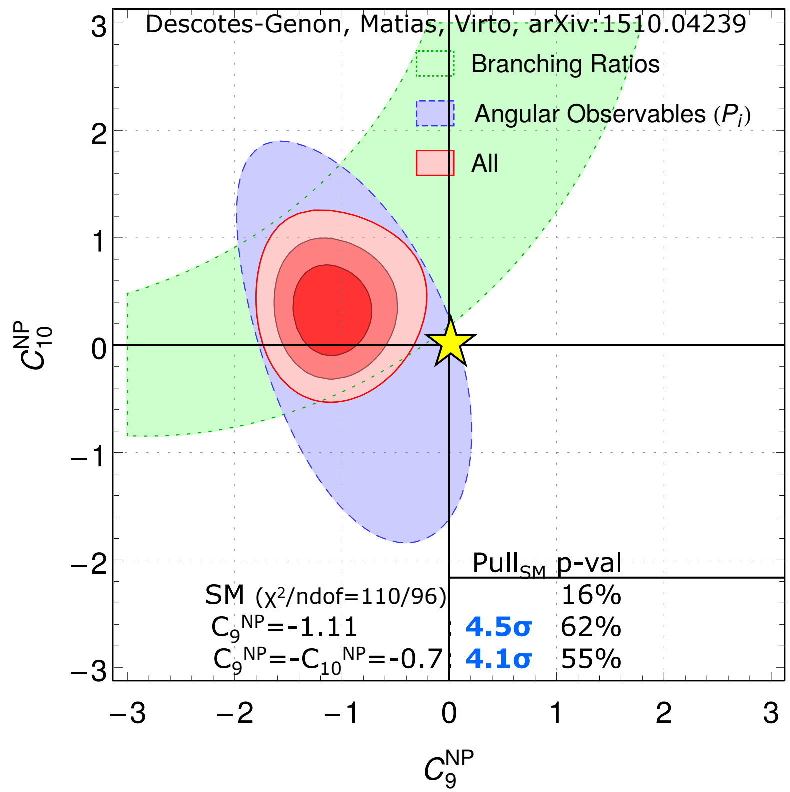
- C_9^{NP} deviates from 0 by >4σ
- Independent fits by more groups
  - $C_9^{NP}=-1$
  - $C_9^{NP}=-C_{10}^{NP}$
- Caveat: debate on charm-loop effects…

LHCb-PAPER-2015-051

$$\Delta\mathrm{Re}(\mathcal{C}_9) = -1.04 \pm 0.25$$







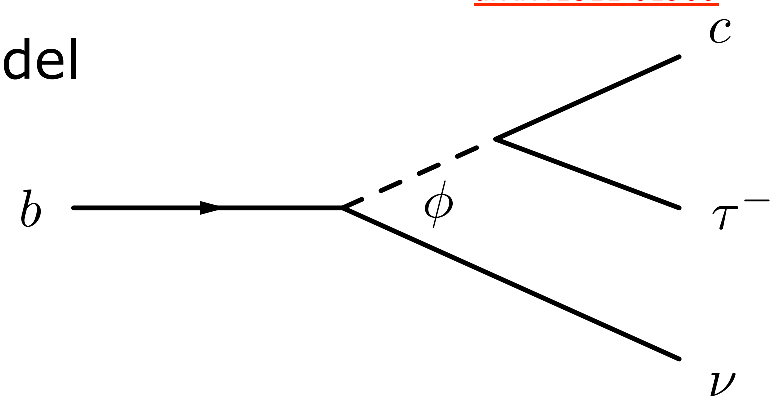
Theory: 2) Leptoquarks

One Leptoquark to Rule Them All:
A Minimal Explanation for $R_{D^{(*)}}$, R_K and $(g-2)_\mu$

Martin Bauer[a] and Matthias Neubert[b,c]

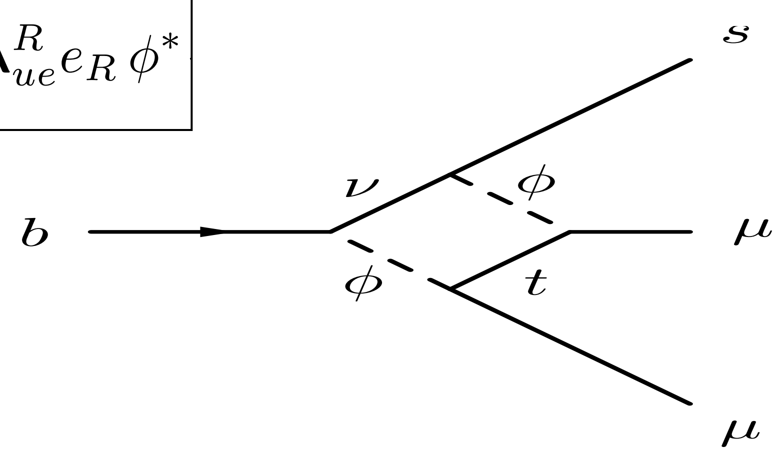
arXiv:1511.01900

- Example: "Bauer/Neubert" model
  - Leptoquark m_Δ ~ 1 TeV
  - g-2
  - R(D*)
  - R_K
  - b→c : tree level, b→s : loop level



$$\mathcal{L}_\phi \ni \bar{u}_L^c \boldsymbol{\lambda}_{ue}^L e_L\, \phi^* - \bar{d}_L^c \boldsymbol{\lambda}_{d\nu}^L \nu_L \phi^* + \bar{u}_R^c\, \boldsymbol{\lambda}_{ue}^R e_R\, \phi^*$$

- Predictions:
  - 1σ effects on BR(Z→*μμ)*
  - B-mixing affected
  - (BR(*h*→*τμ)*~10^{-7})



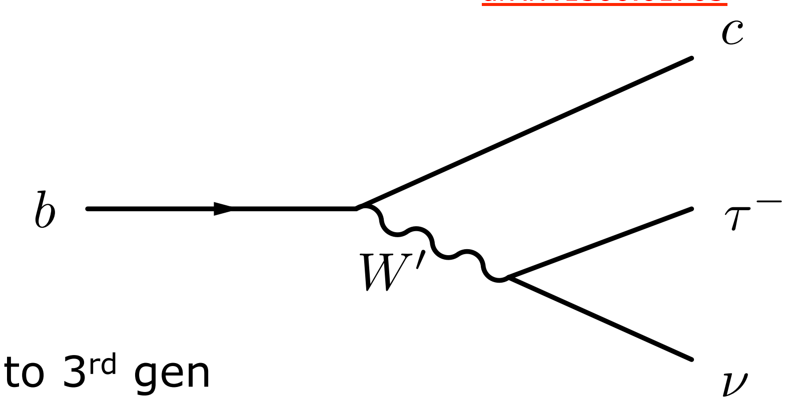
Theory: 3) heavy Z’

On the breaking of Lepton Flavor Universality in B decays

Admir Greljo[a,b], Gino Isidori[a,c], David Marzocca[a]

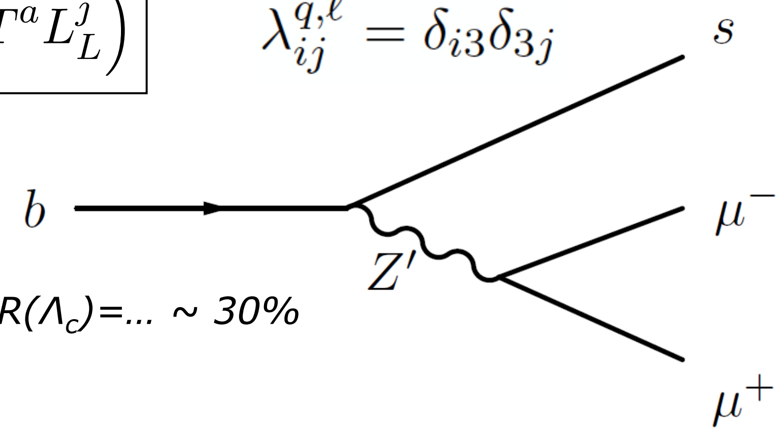
arXiv:1506.01705

- Example: “Isidori” model
  - New Z’ boson
  - Relatively simple model
  - Describes all (most?) data
  - Extra $SU(2)_L$ symmetry, coupling to 3[rd] gen

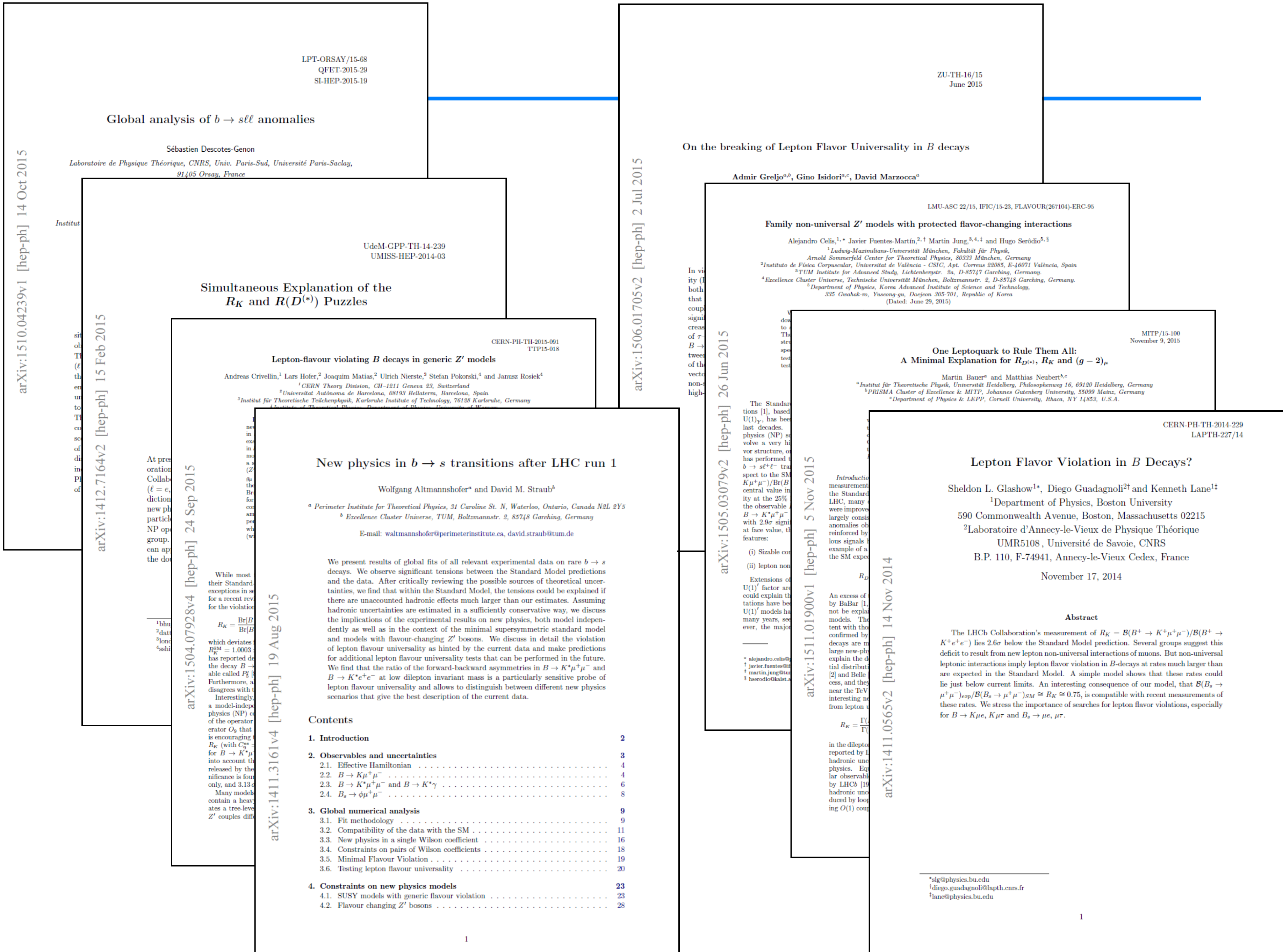


$$J^a_\mu = g_q \lambda^q_{ij} \left(\bar{Q}^i_L \gamma_\mu T^a Q^j_L \right) + g_\ell \lambda^\ell_{ij} \left(\bar{L}^i_L \gamma_\mu T^a L^j_L \right)$$

$$\lambda^{q,\ell}_{ij} = \delta_{i3}\delta_{3j}$$



- Predictions:
  - $C^{NP}_{10}=-C^{NP}_9$
  - τ,μ difference universal: $R(D)=R(D^*)=R(\Lambda_c)=\ldots \sim 30\%$
  - e, μ difference: ~1-2%
  - B-mixing: 10% deviations from SM
  - τ→μμμ not far from present bound
  - No coupling to bosons, so cannot explain diboson excess…
  - Z’→tt,bb,ττ not very easy in ATLAS, most stringent constraint from m(Z’→ττ)>300 GeV, ruling out most minimal version of this model!


LPT-ORSAY/15-68
QFET-2015-29
SI-HEP-2015-19

Global analysis of $b \to s\ell\ell$ anomalies

Sébastien Descotes-Genon

Laboratoire de Physique Théorique, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France

arXiv:1510.04239v1 [hep-ph] 14 Oct 2015

UdeM-GPP-TH-14-239
UMISS-HEP-2014-03

Simultaneous Explanation of the R_K and $R(D^{(*)})$ Puzzles

arXiv:1412.7164v2 [hep-ph] 15 Feb 2015

CERN-PH-TH-2015-091
TTP15-018

Lepton-flavour violating B decays in generic Z' models

Andreas Crivellin,[1] Lars Hofer,[2] Joaquim Matias,[2] Ulrich Nierste,[3] Stefan Pokorski,[4] and Janusz Rosiek[4]

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[2] Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain
[3] Institut für Theoretische Teilchenphysik, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany

arXiv:1504.07928v4 [hep-ph] 24 Sep 2015

New physics in $b \to s$ transitions after LHC run 1

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We present results of global fits of all relevant experimental data on rare $b \to s$ decays. We observe significant tensions between the Standard Model predictions and the data. After critically reviewing the possible sources of theoretical uncertainties, we find that within the Standard Model, the tensions could be explained if there are unaccounted hadronic effects much larger than our estimates. Assuming hadronic uncertainties are estimated in a sufficiently conservative way, we discuss the implications of the experimental results on new physics, both model independently as well as in the context of the minimal supersymmetric standard model and models with flavour-changing Z' bosons. We discuss in detail the violation of lepton flavour universality as hinted by the current data and make predictions for additional lepton flavour universality tests that can be performed in the future. We find that the ratio of the forward-backward asymmetries in $B \to K^*\mu^+\mu^-$ and $B \to K^*e^+e^-$ at low dilepton invariant mass is a particularly sensitive probe of lepton flavour universality and allows to distinguish between different new physics scenarios that give the best description of the current data.

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1

arXiv:1411.3161v4 [hep-ph] 19 Aug 2015

ZU-TH-16/15
June 2015

On the breaking of Lepton Flavor Universality in B decays

Admir Greljo[a,b], Gino Isidori[a,c], David Marzocca[a]

arXiv:1506.01705v2 [hep-ph] 2 Jul 2015

LMU-ASC 22/15, IFIC/15-23, FLAVOUR(267104)-ERC-95

Family non-universal Z' models with protected flavor-changing interactions

Alejandro Celis,[1,*] Javier Fuentes-Martín,[2,†] Martin Jung,[3,4,‡] and Hugo Serôdio[5,§]

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[5] Department of Physics, Korea Advanced Institute of Science and Technology, 335 Gwahak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea
(Dated: June 29, 2015)

arXiv:1505.03079v2 [hep-ph] 26 Jun 2015

MITP/15-100
November 9, 2015

One Leptoquark to Rule Them All:
A Minimal Explanation for $R_{D^{(*)}}$, R_K and $(g-2)_\mu$

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arXiv:1511.01900v1 [hep-ph] 5 Nov 2015

CERN-PH-TH-2014-229
LAPTH-227/14

Lepton Flavor Violation in B Decays?

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November 17, 2014

Abstract

The LHCb Collaboration's measurement of $R_K = \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$ lies 2.6σ below the Standard Model prediction. Several groups suggest this deficit to result from new lepton non-universal interactions of muons. But non-universal leptonic interactions imply lepton flavor violation in B-decays at rates much larger than are expected in the Standard Model. A simple model shows that these rates could lie just below current limits. An interesting consequence of our model, that $\mathcal{B}(B_s \to \mu^+\mu^-)_{exp}/\mathcal{B}(B_s \to \mu^+\mu^-)_{SM} \cong R_K \cong 0.75$, is compatible with recent measurements of these rates. We stress the importance of searches for lepton flavor violations, especially for $B \to K\mu e$, $K\mu\tau$ and $B_s \to \mu e$, $\mu\tau$.

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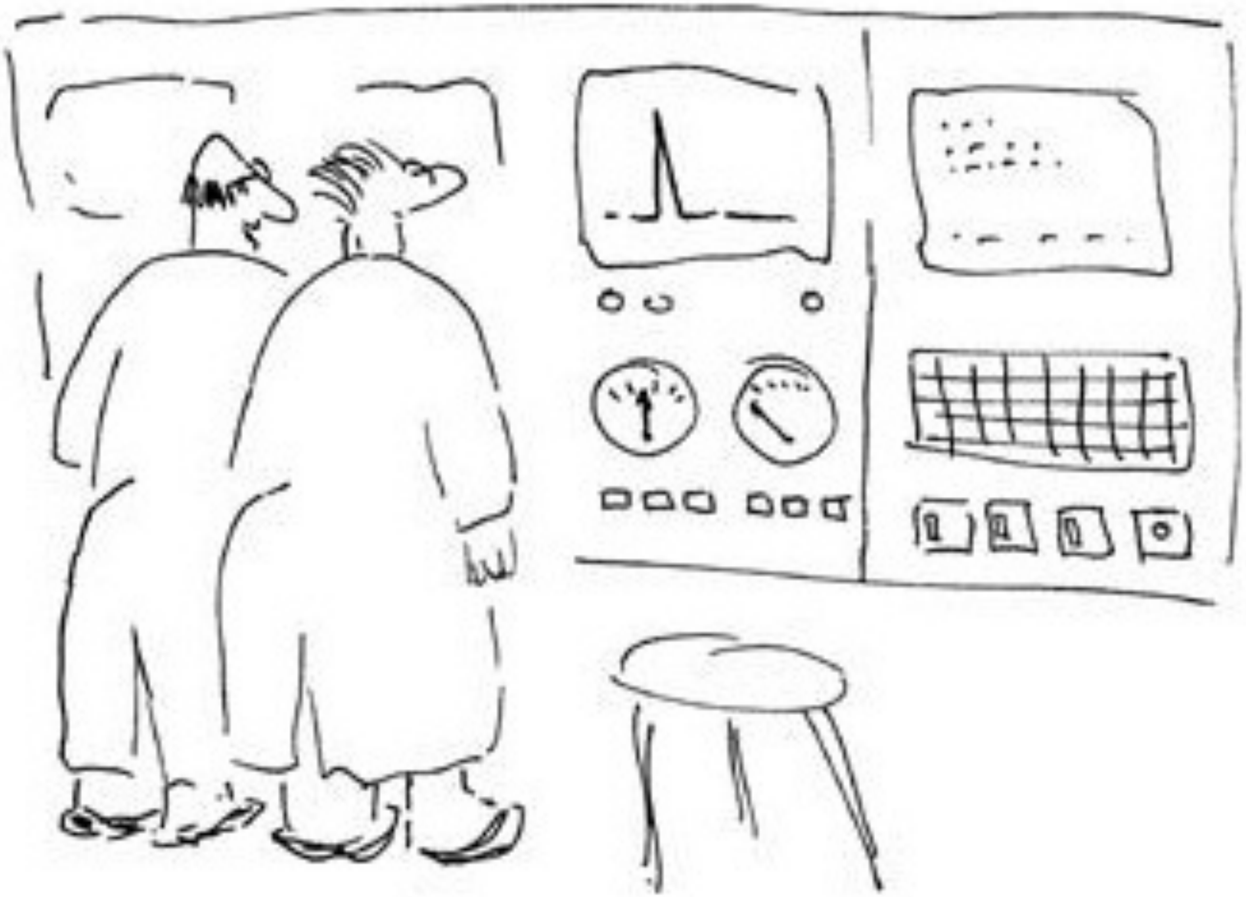
arXiv:1411.0565v2 [hep-ph] 14 Nov 2014

Interpretations

Shown	Authors	Model	Input	Predictions/ Result	arXiv
☑	Descotes-Genon, Matias, Virto	Model independent	*$b\to sll$, $b\to s\gamma$*	• $C_9^{NP}=-1$ • $C^{NP}_{10}=-C^{NP}_9$	1307.5683 1510.04239
☑	Altmannshofer, Straub	Model independent	*$b\to sll$, $b\to s\gamma$*	• $C_9^{NP}=-1$ • $C^{NP}_{10}=-C^{NP}_9$	1411.3161 1503.06199
☐	Glashow, Guadagnoli, Lane	Z'	*$B^0\to K^*\mu\mu$, R_K, $B_s^0\to\mu\mu$*	LFNU → LFV	1411.0565 1507.01412
☐	Bhattacharya, Datta, London, Shivashankara	Z', W'	*R_K, $R(D^*)$*	R(D)=R(D*)	1412.7164
☐	Crivellin, Hofer, Matias, Nierste, Pokorski, Rosiek	Z'	*$B\to K^*\mu\mu$, R_K ($\tau\to 3\mu$, $\mu\to e\gamma$, g-2, B-mix)*	1) $C^{NP}_{10}=0$ 2) $C^{NP}_{10}=-C^{NP}_9$ Limits on *$B\to(K)\mu e$*. ($h\to\mu\nu$ 1503.03477)	1504.07928
☐	Celis, Fuentes-Martin, Jung, Serodio	Z'	*$B^0\to K^*\mu\mu$, R_K*	$R_K=R_{K^*}$	1505.03079
☑	Greljo, Isidori, Marzocca	Z' ,W'	*$B^0\to K^*\mu\mu$, R_K, $R(D^*)$, $\tau\to 3\mu$, B-mix, $B\to X\nu$*	*R(D)=R(D*), $D\mu\nu/De\nu$* ~ 1-2%	1506.01705
☐	Buras, Butazzo, Knegjens De Fazio	Z' $SU(3)_L$	*ε'/ε, $K_L\to\mu\mu$, $B_s^0\to\mu\mu$*	*$K\to\pi\nu\nu$, $B^0\to K^*\mu\mu$ $m_{Z'}$~3 TeV*	1507.08672 1512.02869
☐	Hiller, Schmaltz	Leptoquark	*R_K, $b\to s\mu\mu$*		1408.1627
☐	Bečirević, Fajfer, Košnik	Leptoquark (scalar, or vector)	*$BR(B\to K\mu\mu)$, $B_s^0\to\mu\mu$*	$C_9'=-C_{10}'$, $R_K=0.88$	1503.09024 1511.06024
☐	Freytsis, Ligeti, Ruderman	Leptoquark (scalar/vector)	*$R(D^*)$,$B^+\to\tau\nu$*	*B^+/B^- CPV, $D\to\pi\nu\nu$~10^{-5}*	1506.08896
☑	Bauer, Neubert	Leptoquark (scalar)	*R_K, $R(D^*)$, g-2 (B-mix, $\tau\to\mu\gamma$, $D\to\mu\mu$)*	$BR(Z\to\mu\mu)$, *B-mix*	1511.01900

Conclusions

- Many tantalyzing hints
- This time, they seem to point in the same direction…
- One parameter needs adjustment (C_9)



WELL, EITHER WE'VE FOUND THE Z' BOSON,
OR MARCEL'S JUST PUT THE KETTLE ON

Z'

THE FORCE AWAKENS

BOSON

12 December

Single bins with deviations >1.9σ

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7\ \frac{d\text{BR}}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{d\text{BR}}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{d\text{BR}}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7\ \frac{d\text{BR}}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

Altmannshofer & Straub, arXiv:1503.06199