ON LEPTON FLAVOR UNIVERSALITY VIOLATION

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u. of cincinnati & CERN

based on Kamenik, Soreq, JZ, 1704.06005

2017 CERN-CKC workshop, June 2 2017

UPSHOT

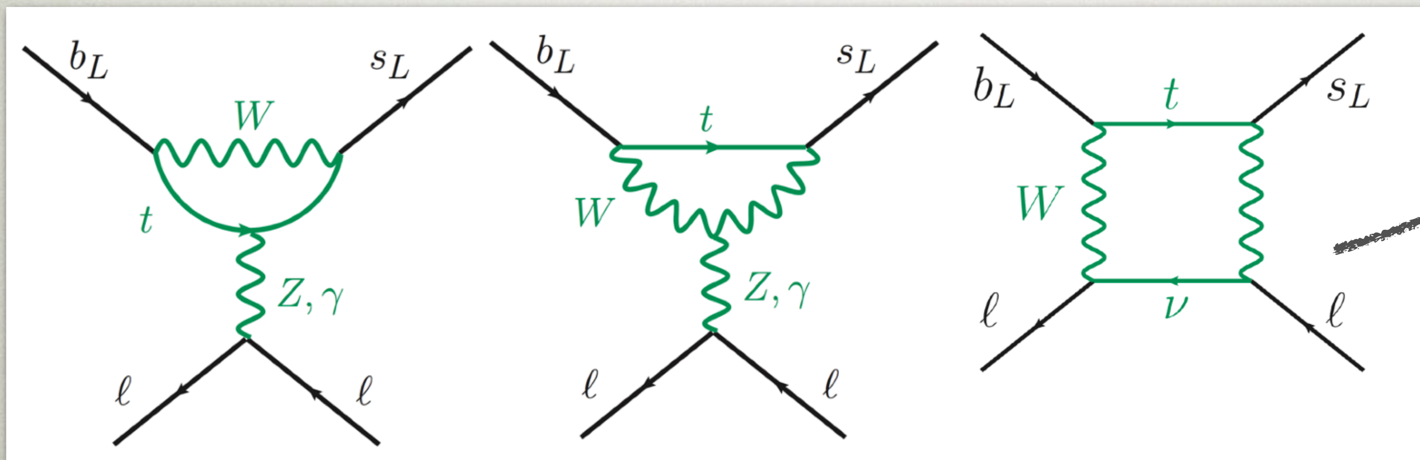
- $b \to sll$ flavor anomaly
  - theoretically clean, ~4σ excess
  - does it make sense?
    - reasonable scale for NP models*

*mostly face the I. I. Rabi's, "Who ordered that?", muon question

EXPERIMENTAL SITUATION

- at present two significant anomalies in B physics
- $b \to c\tau\nu$: excess of more than 4σ
  - no easy model building
- $b \to sll$: focus of this talk

$$G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C_{9(10)} \bar{s}_L \gamma^\mu b_L \; \bar{\ell} \gamma_\mu (\gamma_5) \ell$$



$$C_9^{\rm SM} \approx -C_{10}^{\rm SM}$$

  - in the SM $b \to see$ the same as $b \to s\mu\mu$
    - Lepton Flavor Universality in the SM

$b \to sll$: EXPERIMENT

- three clean observables: R_K and R_{K^*}

two bins

$$R_K = \left.\frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}\right|_{[1,6]\mathrm{GeV}^2}$$

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^*\mu^+\mu^-)}{\mathrm{BR}(B \to K^*e^+e^-)}$$

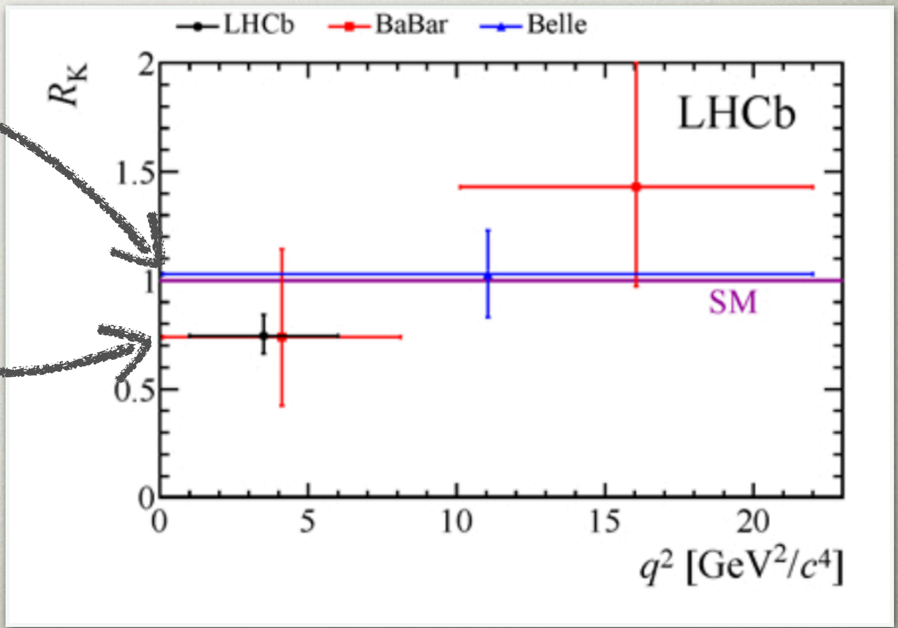
- 2.6σ anomaly in R_K

Bordone, Isidori, Pattori, 1605.07633

SM: $R_K = 1.00 \pm 0.01$

exp: $R_K = 0.745 \pm 0.082$

LHCb,1406.6482 (3.0 fb^{-1} @7+8TeV)

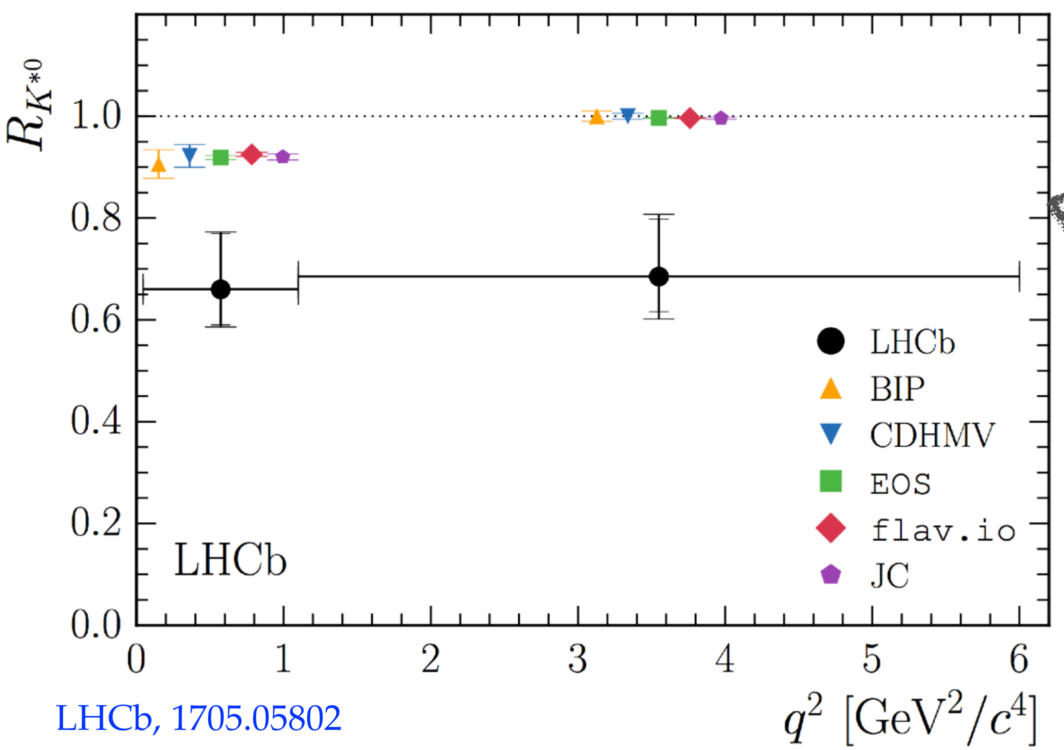


$b \to sll$: EXPERIMENT

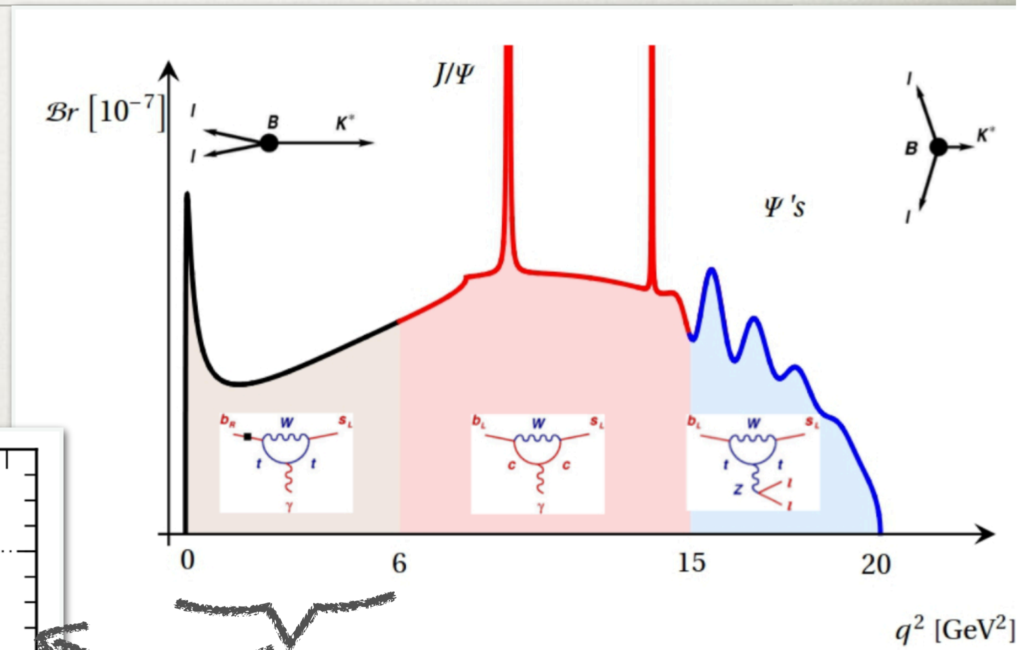
- 2 bins in R_{K^*}

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^* \mu^+ \mu^-)}{\mathrm{BR}(B \to K^* e^+ e^-)}$$

- 2.2-2.5σ deviation in each



LHCb, 1705.05802



experiment: LHCb, 1705.05802 (3.0 fb^{-1} @7+8TeV)

$$R_{K^*[0.045,\ 1.1]\ \mathrm{GeV}^2} = 0.660^{+0.110}_{-0.070} \pm 0.024,$$

$$R_{K^*[1.1,\ 6]\ \mathrm{GeV}^2} = 0.685^{+0.113}_{-0.069} \pm 0.047,$$

WHAT DO WE LEARN?

see, e.g., Alonso, Grinstein, Martin Camalich, 1407.7044

- R_K can only be explained by NP in

$$\mathcal{O}_9^{(\prime)\ell} = \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma^\mu P_{L(R)}b)\,(\bar{\ell}\gamma_\mu\ell),\qquad \mathcal{O}_{10}^{(\prime)\ell} = \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma^\mu P_{L(R)}b)\,(\bar{\ell}\gamma_\mu\gamma_5\ell)$$

  - scalar currents constrained by $B_S \to ll$

- R_K and R_{K^*} different parity, complementary info, e.g. for central bin

$$R_K \simeq 1 + 2\frac{\mathrm{Re}\, C^{\rm BSM}_{b_{L+R}(\mu-e)_L}}{C^{\rm SM}_{b_L\mu_L}}\qquad R_{K^*} \simeq R_K - 4p\frac{\mathrm{Re}\, C^{\rm BSM}_{b_R(\mu-e)_L}}{C^{\rm SM}_{b_L\mu_L}}$$

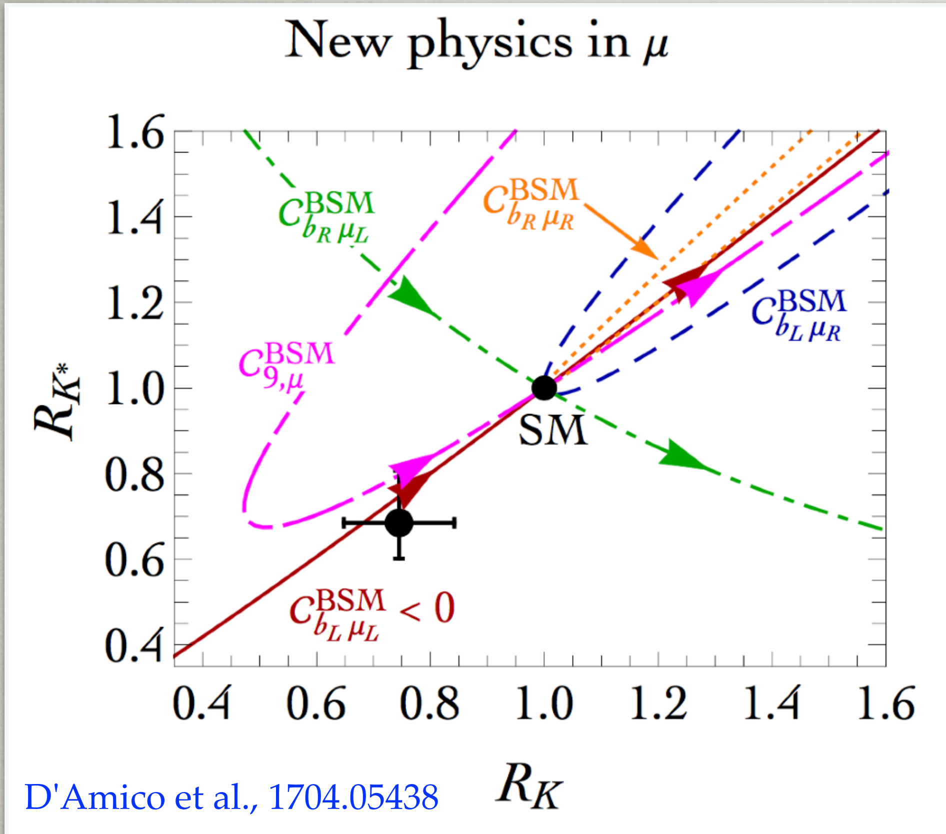
- NP can be either in muons or electrons

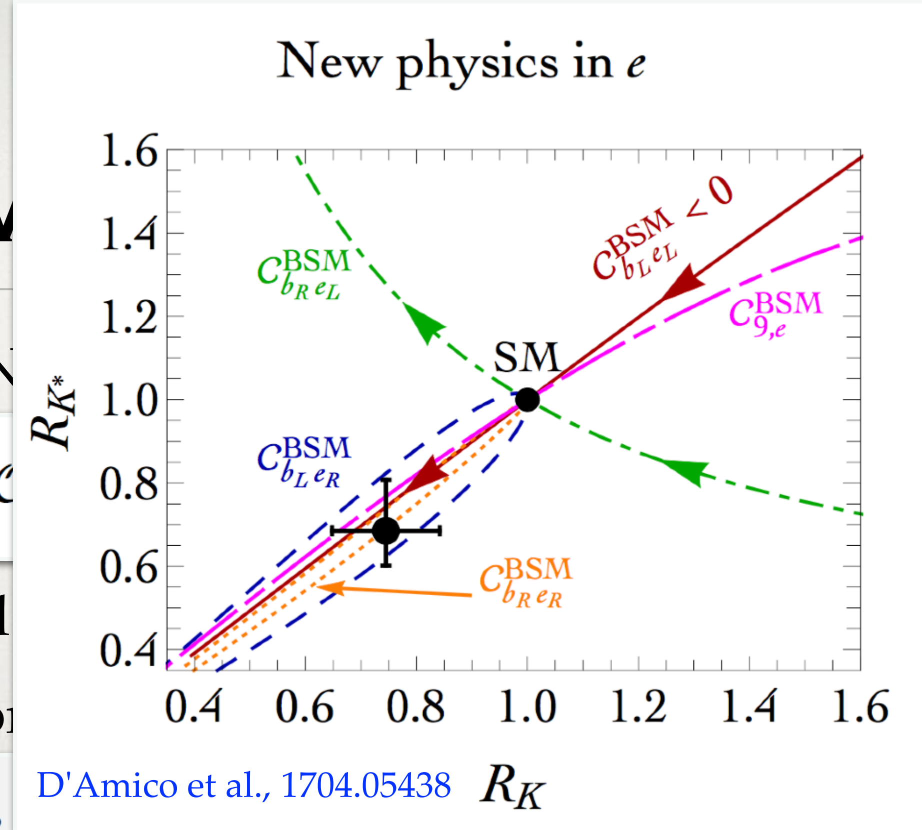
see, e.g., D'Amico et al., 1704.05438

  - in both cases $(\bar{s}b)_L$ ok
  - for electrons also $(\bar{s}b)_R(\bar{e}e)_R$ possible (from quadratic dep.)

- combined signif. from "clean" observables $>4\sigma$

Altmannshofer, Stangl, Straub, 1704.05435; D'Amico, Nardecchia, Panci, Sannino, Strumia, Torre, Urbano, 1704.05438; Capdevila, Crivellin, Descotes-Genon, Matias, Virto, 1704.05340; Hiller, Nisandzic, 1704.05444; Geng, Grinstein, Jager, Martin Camalich, Ren, Shi, 1704.05446; Chobanova, Hurth, Mahmoudi, Neshatpour, Santos, 1705.10730





$R_K \simeq 1 + 2 \ldots \; C^{\rm SM}_{b_L\mu_L}$ $\quad$ $R_{K^*} \simeq R_K - 4p \ldots \; C^{\rm SM}_{b_L\mu_L}$

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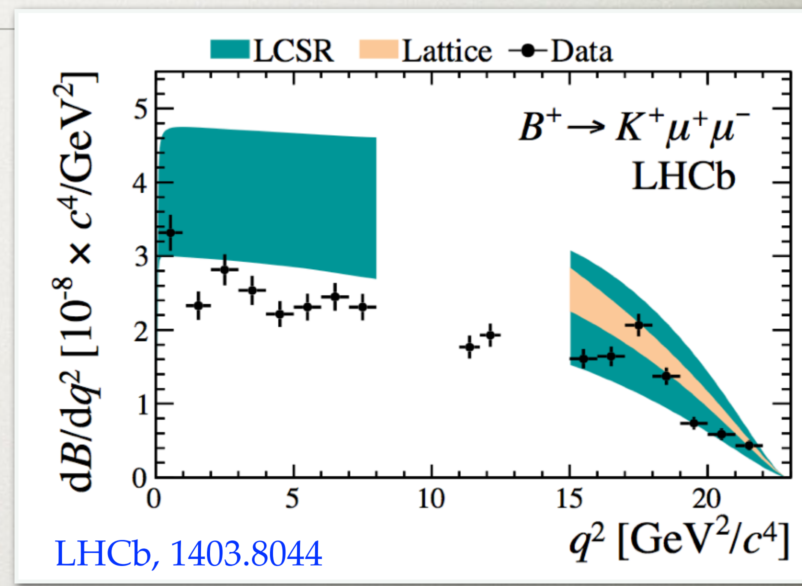
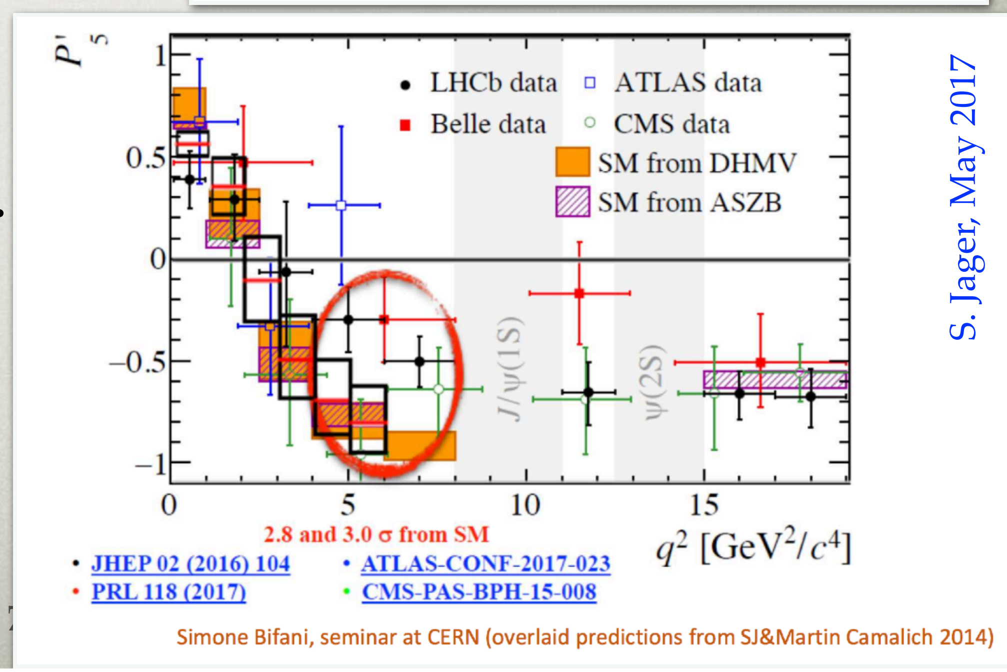
GLOBAL FITS

- in principle much more info
  - $Br(B \to K^{(*)}\mu\mu)$, $Br(B_s \to \phi\mu\mu)$, $Br(B \to X_s\mu\mu)$
  - angular obs. in $B^0 \to K^{*0}\mu\mu$, $B_s \to \phi\mu\mu$
- these are "dirty" observables
  - require form factors predict. (QCD sum rules), charm loops, nonfactor. contribs.
- prefer NP in muons





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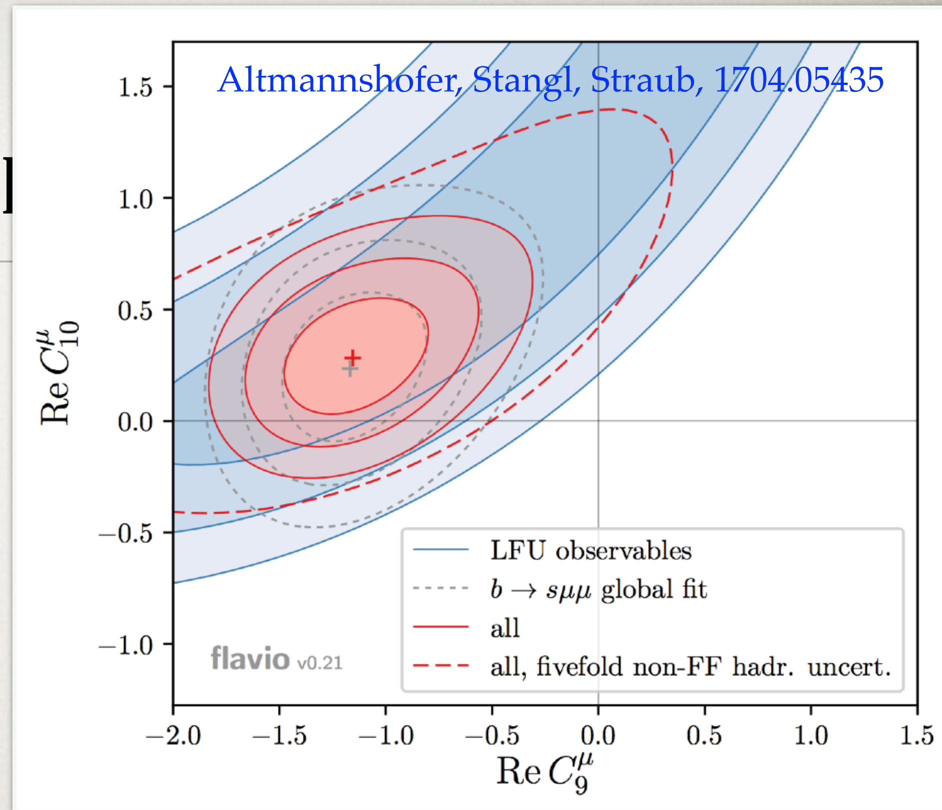
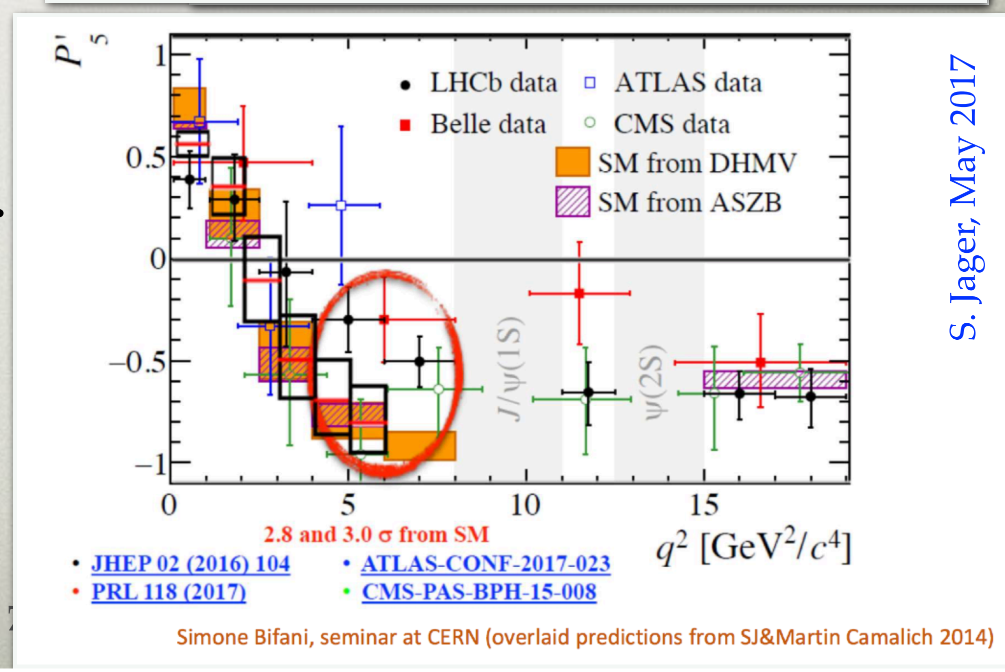




WHAT KIND OF NP?

- from now on will assume that NP in $b \to s\mu\mu$
- what is the NP scale?
  - the Wilson coeffs. in previous slides

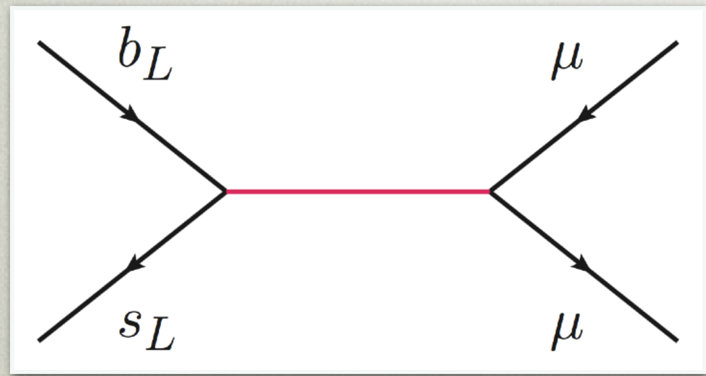
$$V_{tb}V_{ts}^* \frac{\alpha_{\text{em}}}{4\pi v^2} C_I = \frac{C_I}{(36\,\text{TeV})^2}$$

$C_I^{NP} \sim O(1)$

- types of NP
  - tree level (heavy or light)
  - loop level

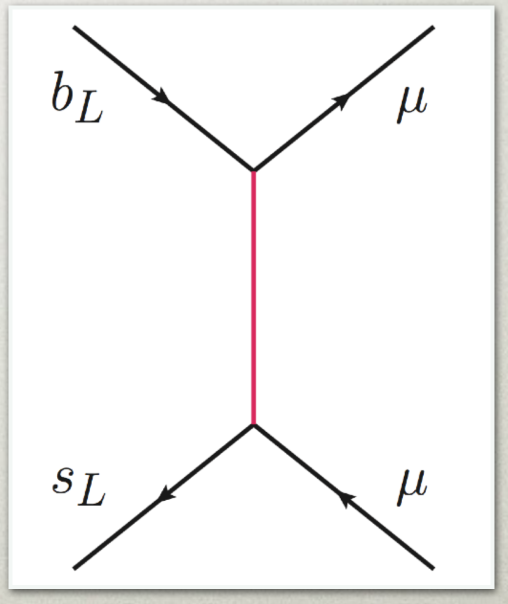
TREE LEVEL

- two distinct types:
- mediated by a Z'
  - $SU(2)_L$ singlet or triplet



Altmannshofer, Straub, 1308.1501;
Altmannshofer, Gori, Pospelov, Yavin, 1403.1269;
Greljo, Isidori, Marzocca, 1506.01705;
+many refs.

- leptoquark
  - spin 0 or 1



see, e.g., Hiller, Nisandzic, 1704.05444;
Hiller, Schmaltz, 1411.4773; +many refs

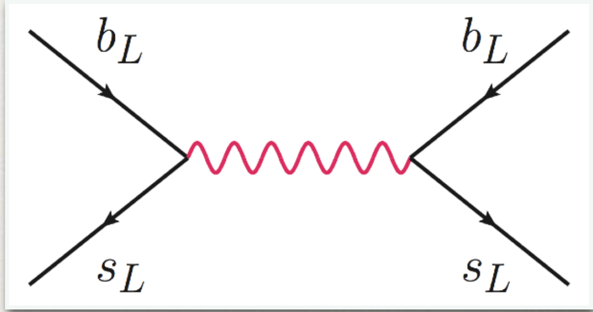
GENERAL CONSIDERTATIONS ABOUT Z'

Altmannshofer, Straub, 1308.1501; 1411.3161

- nontrivial constraint from B_s mixing

$$\frac{g_{bsZ'}}{m_{Z'}} \lesssim \frac{0.01}{2.5\ \mathrm{TeV}}$$

compare: $V_{ts} \simeq 0.04$

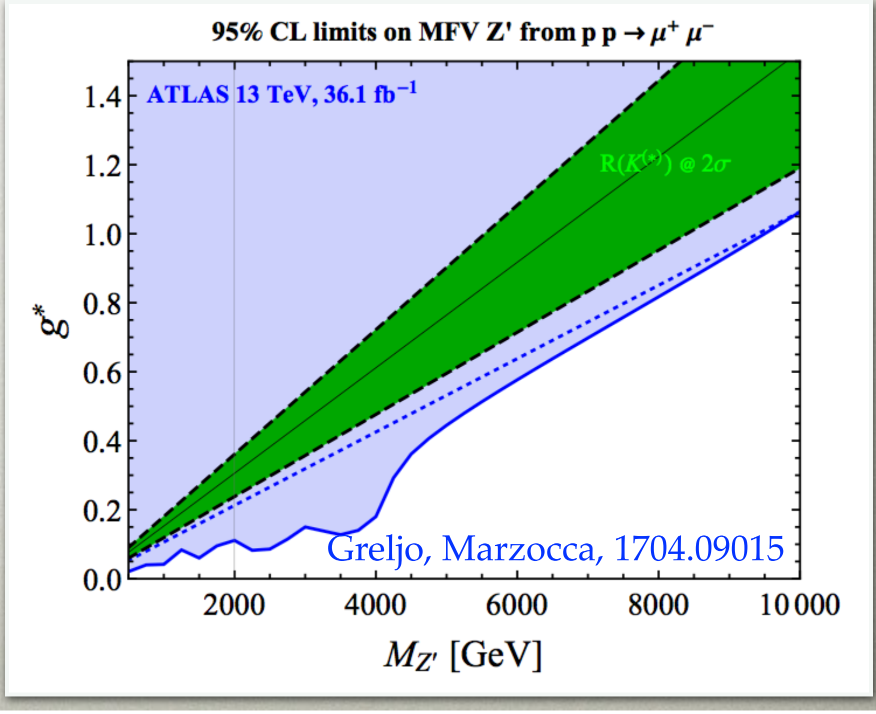


- bounds from ATLAS, CMS from $pp \to Z' \to \mu\mu$
  - e.g., for MFV ansatz

Greljo, Marzocca, 1704.09015

$$c^{(3,1)}_{Q_i Q_j L_{22}} \sim \left(\mathbf{1} + \alpha Y_u Y_u^\dagger + \beta Y_d Y_d^\dagger\right)_{ij}$$

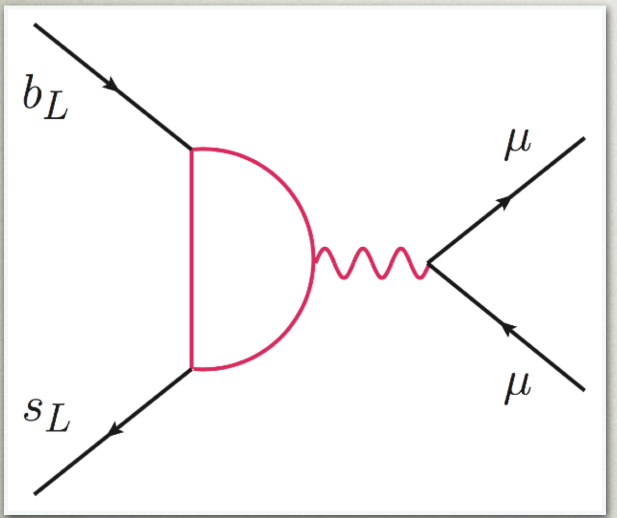
$$J_\mu = g_Q^{(1),ij}(\bar{Q}_i \gamma_\mu Q_j) + g_L^{(1),kl}(\bar{L}_k \gamma^\mu L_l)$$



LOOP LEVEL

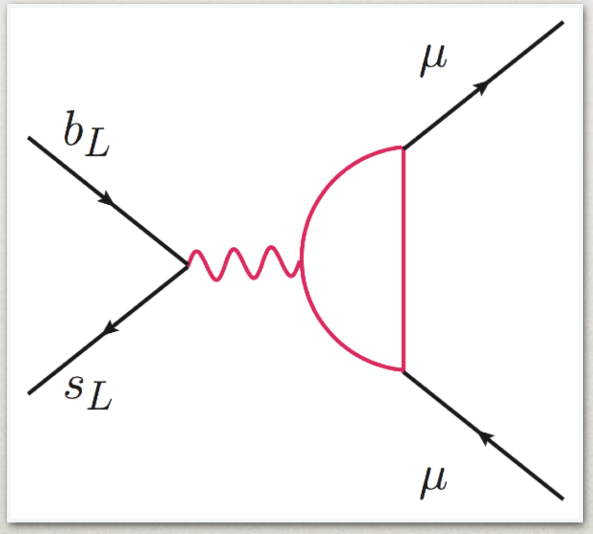
- three distinct options

- Z′ w/ loop to bs



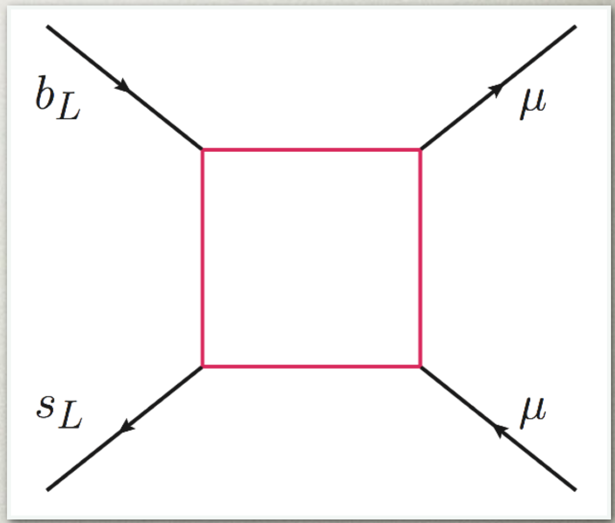
Kamenik, Soreq, JZ, 1704.06005

- Z′ w/ loop to $\mu\mu$



Bélanger, Delaunay, 1603.03333

- box w/ NP fields



Gripaios, Nardecchia, Renner, 1509.05020;
Bauer, Neubert, 1511.01900;
Becirevic, Sumensari, 1704.05835

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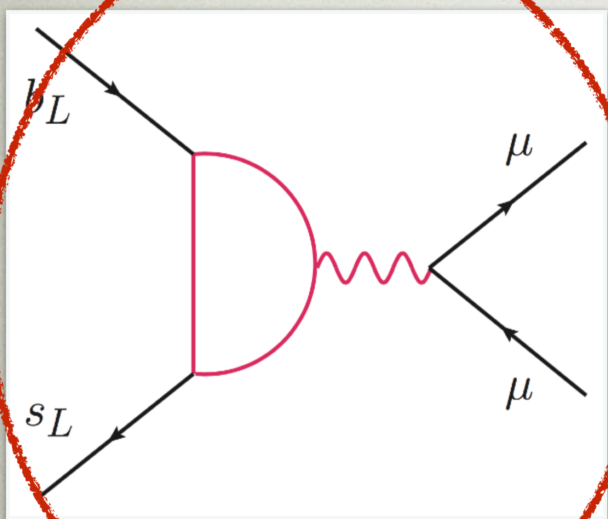

Kamenik, Soreq, JZ, 1704.06005

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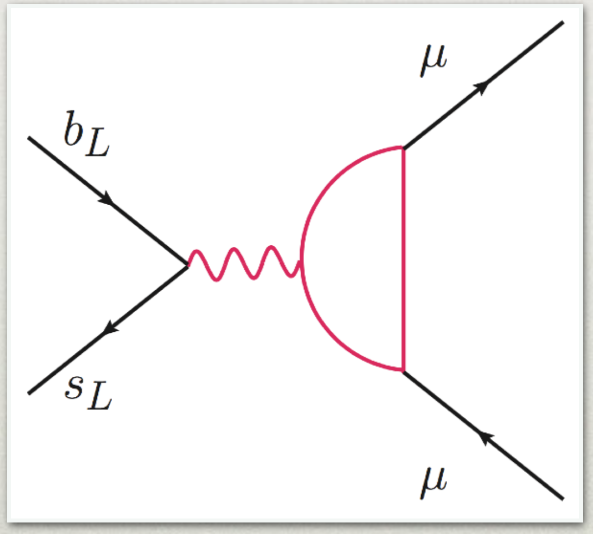

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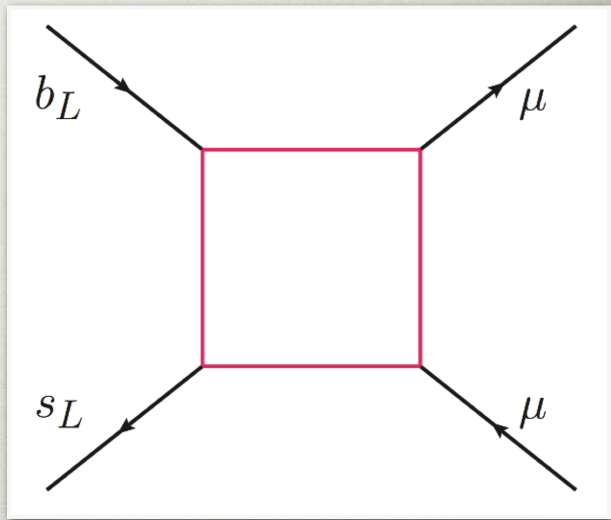
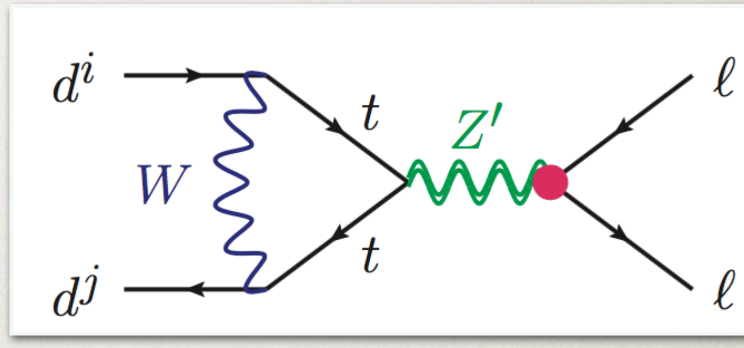


Gripaios, Nardecchia, Renner, 1509.05020; Bauer, Neubert, 1511.01900; Becirevic, Sumensari, 1704.05835

TOP-PHILIC Z'

Kamenik, Soreq, JZ, 1704.06005

- where is the flavor structure coming from?
- why the $(\bar{s}b)_{V\text{-}A}$ chiral structure?
- automatic for top-philic Z'
  - $b \to s$ due to SM W in the loop



  - avoids contraints from dimuon resonance searches

$$c^{(3,1)}_{Q_{ij}L_{22}} \sim \left(\not{1} + \alpha Y_u Y_u^\dagger + \beta Y_d Y_d^\dagger\right)_{ij}$$

  - MFV structure: all FV due to CKM
    - there is a correlated signal in $K \to \pi\nu\nu$

cf. NA62 reach: 10% of the SM

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \simeq (8.4 \pm 1.0) \times 10^{-11} \times \frac{1}{3}\sum_{\ell}\left|1 + 0.11(C_9^{\ell,\mathrm{NP}} - C_{10}^{\ell,\mathrm{NP}})\right|^2$$

SM value

see also Bordone, Buttazzo, Isidori, Monnard, 1705.10729

MINIMAL U(1)' MODEL

Kamenik, Soreq, JZ, 1704.06005

- new U(1)' gauge symmetry
  - scalar $\Phi \sim (1,1,0,q')$ $\quad \Phi = (\phi + \tilde{v})/\sqrt{2}$
  - vectorlike fermion $T' \sim (3, 1, 2/3, q')$ ← $SU(3)\times SU(2)\times U(1)\times U(1)'$
  - all the SM fields singlets under U(1)'
- interactions with the SM through only three terms

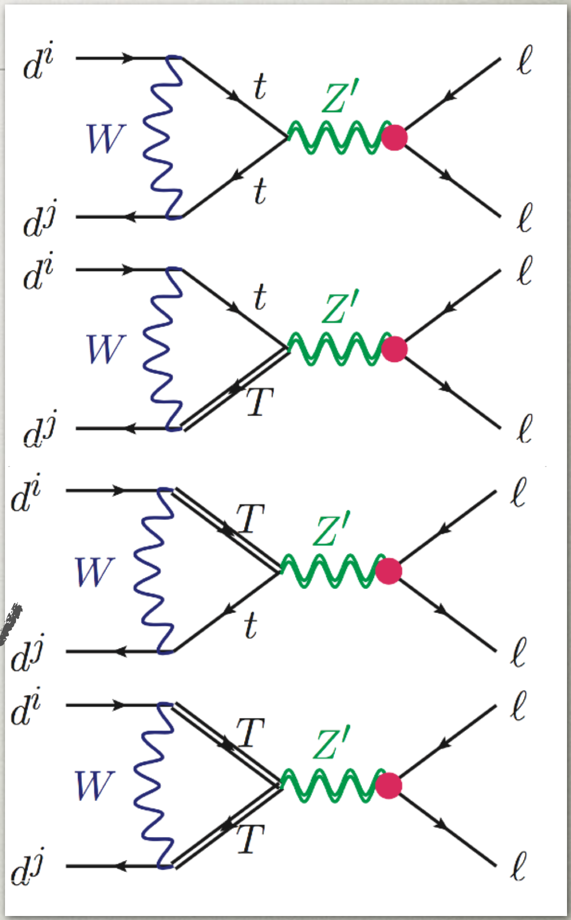
$$\mathcal{L}_{\rm mix} = -\lambda' |\Phi|^2 |H|^2 - \epsilon B^{\mu\nu} F'_{\mu\nu} - (y_T^i \bar{T}' \Phi u_R^i + \text{h.c.})$$

  - assume alignment with the SM up Yukawa

$$y_u^{ij} \sim \text{diag}(0, 0, y_t) \qquad y_T^i \sim (0, 0, y_T^t)$$

  - for us the interesting limit $|y_T^t| \gg \lambda', \varepsilon$

SIZE OF $b \to s\mu\mu$



- t–T mass matrix

$$\mathcal{M}_u^{t-T'} = \begin{pmatrix} y_t v/\sqrt{2} & 0 \\ y_T^t \tilde{v}/\sqrt{2} & M_T \end{pmatrix}$$

- the mixing angles for the two chiralities

$$\theta_R \sim y_T^t \tilde{v}/M_T \qquad \theta_L \sim \theta_R v/M_T$$

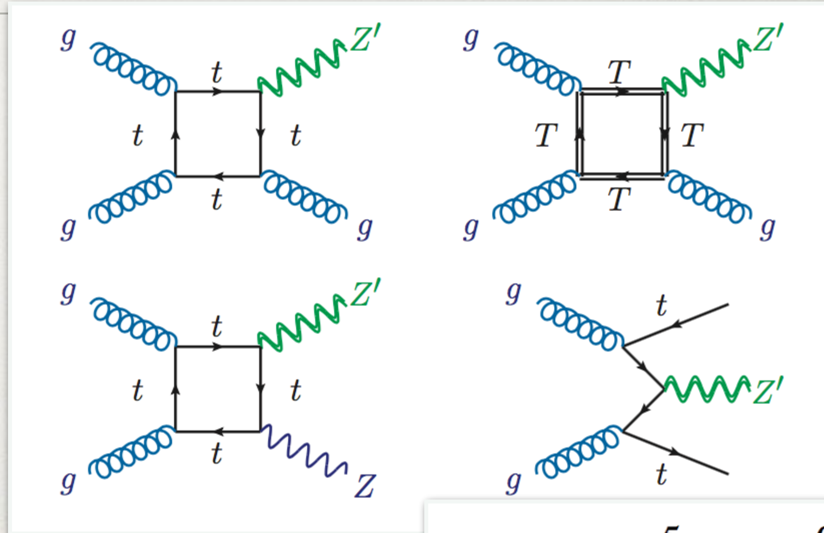
  - main effects due to mixing with t_R
- the induced $b \to sll$

$$C_{9,10}^{\mu,\text{NP}} = \frac{1}{2} q' q'_{\mu,V,A} \frac{m_t^2}{m_{Z'}^2} \frac{\tilde{g}^2}{e^2} s_R^2 \log\left(\frac{m_T^2}{m_W^2}\right) + \dots,$$

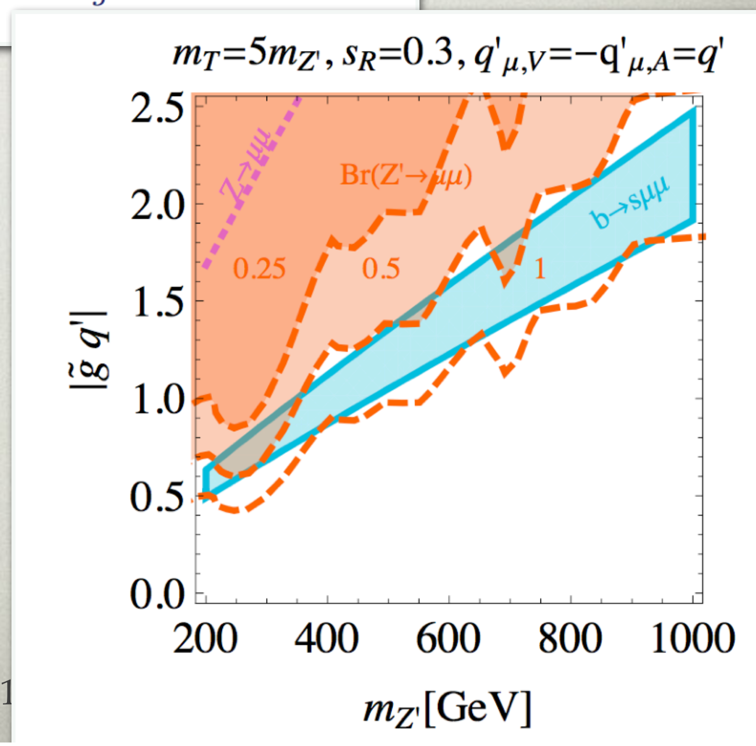
  - fits the anomaly for $m_{Z'} \sim O(500\ \text{GeV})$, $\tilde{g}q' \sim O(1)$
- couplings to muons due to mixing with vectorlike leptons
  - depending on the details could explain $(g\text{-}2)_\mu$

Kamenik, Soreq, JZ, 1704.06005

DIRECT SEARCHES



- important contraints from dimuon searches
- production channels:
  - tree level $pp \to \bar{t}tZ'$,
  - 1-loop: $pp \to ZZ', jZ'$
- depends on $Br(Z' \to \mu\mu)$
  - e.g. below $\bar{t}t$ threshold:
    - coupling to $\mu_L \quad \Rightarrow Br(Z' \to \mu\mu)=0.5$
    - coupling to $\mu_L, \tau_L \Rightarrow Br(Z' \to \mu\mu)=0.25$
- interesting possible searches at CMS, ATLAS:
  - $pp \to \bar{t}t(Z' \to \mu\mu),\ \bar{t}t(Z' \to \tau\tau),\ \bar{t}t(Z' \to \bar{t}t)$

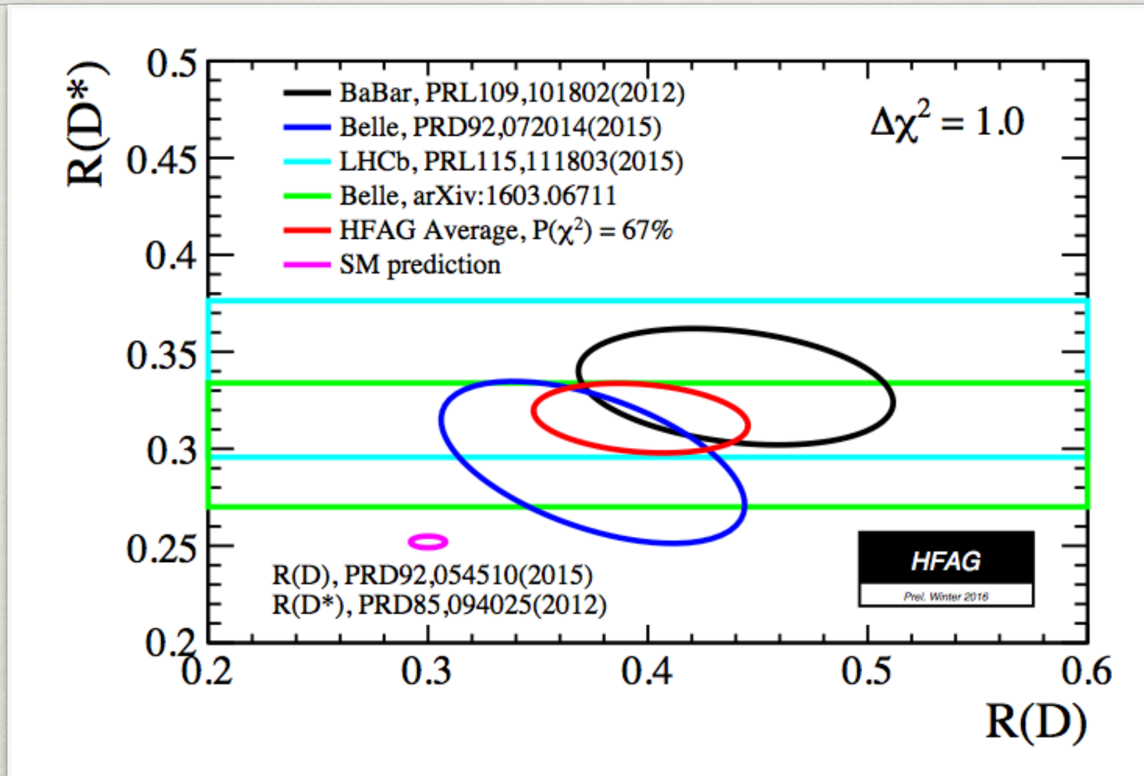


CONCLUSIONS

- LFU violation anomaly in $b \to sll$ stands at present at $\sim 4\sigma$
- reasonable NP models can explain it
  - showed a top-philic Z' as a representative of a new class of NP models

BACKUP SLIDES

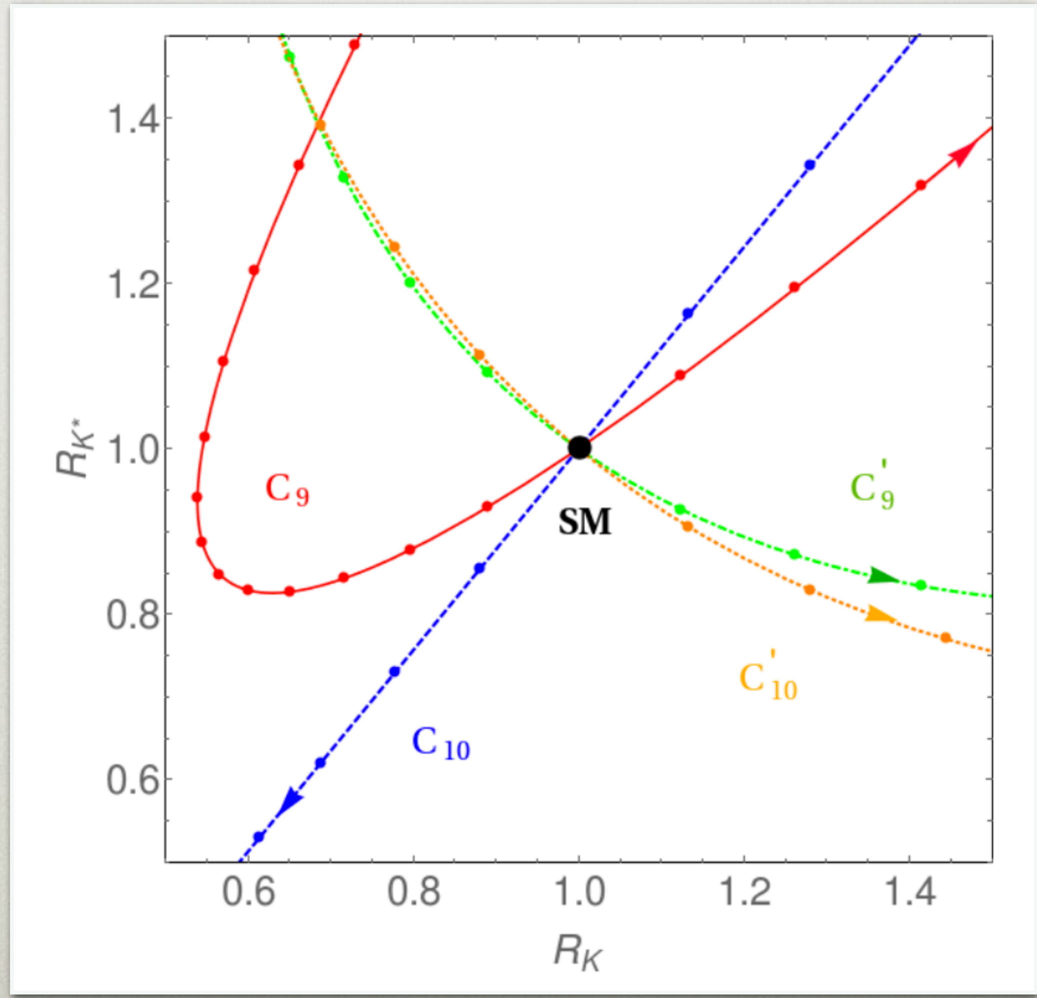
$b \to c\tau\nu$



	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375^{+0.064}_{-0.063} \pm 0.026$	$0.293^{+0.039}_{-0.037} \pm 0.015$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Exp. average	0.388 ± 0.047	0.321 ± 0.021
SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50 ab^{-1}	± 0.010	± 0.005

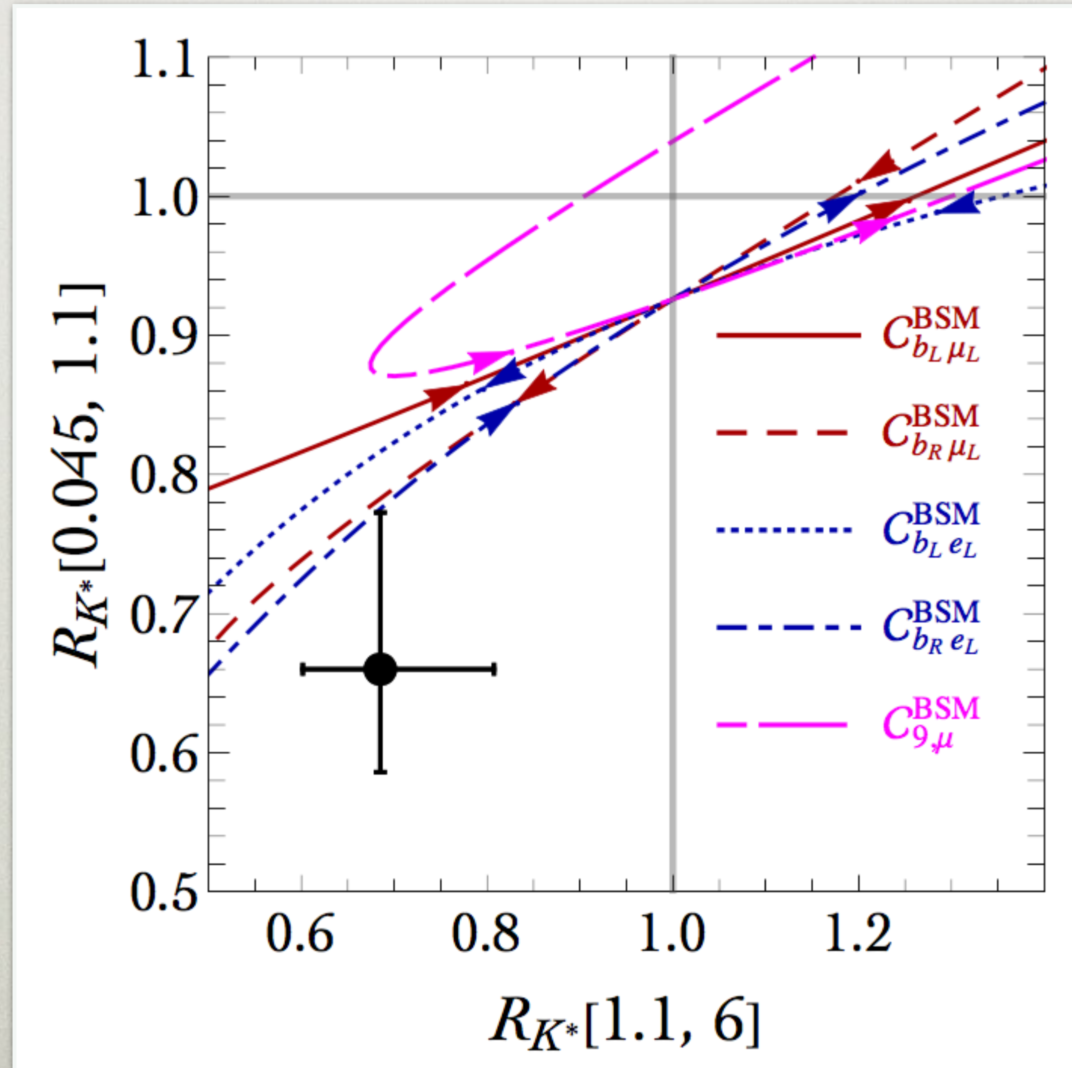
R_K vs. R_{K^*}

Geng et al, 1704.05446



LOW Q2 BIN

D'Amico et al., 1704.05438



LEPTOQUARKS

Hiller, Nisandzic, 1704.05444

- R_K vs. R_{K^*} selects only three leptoquarks
  - scalar S_3 and vectors

label	representation	Wilson coefficient	Relation	$R_{K^{(*)}}$
$\tilde{S}_2$	$(3, 2, 1/6)$	C_{RL}	$C'_9 = -C'_{10}$	$R_K < 1,\ R_{K^*} > 1$
S_3	$(\bar{3}, 3, 1/3)$	$C_{LL}^{\rm NP}$	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1.$
S_2	$(3, 2, 7/6)$	C_{LR}	$C_9 = C_{10}$	$R_K \simeq R_{K^*} \simeq 1$
$\tilde{S}_1$	$(\bar{3}, 1, 4/3)$	C_{RR}	$C'_9 = C'_{10}$	$R_K \simeq R_{K^*} \simeq 1$

label	representation	Wilson coefficient	Relation	$R_{K^{(*)}}$
V_1	$(3, 1, 2/3)$	$C_{LL}^{\rm NP}$	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1$
		C_{LR}	$C_9 = +C_{10}$	$R_K \simeq R_{K^*} \simeq 1$
V_2	$(3, 2, -5/6)$	C_{RL}	$C'_9 = -C'_{10}$	$R_K < 1,\ R_{K^*} > 1$
		C_{RR}	$C'_9 = +C'_{10}$	$R_K \simeq R_{K^*} \simeq 1$
V_3	$(3, 3, -2/3)$	$C_{LL}^{\rm NP}$	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1$