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Theory Group of the Laboratory for Particle Physics

Flavour Physics in the Light of the Recent Anomalies

Hong Kong, 27.06.2017

Outline

- Introduction:

  New Physics and Flavour anomalies

  - $b \to s\mu\mu$ $B \to K^*\mu\mu$, $B_s \to \mu\mu$, $B \to K\mu\mu / B \to Kee$, ...
  - $b \to c\tau\nu$ $B \to D\tau\nu / B \to Dl\nu$ and $B \to D^*\tau\nu / B \to D^*l\nu$
  - a_μ anomalous magnetic moment of the muon
  - ε'/ε direct CP violation in Kaon decays
- Explanations of the anomalies
- Models for simultaneous explanations
- Conclusions

Physics Beyond the Standard Model

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- Dark Matter existence established at cosmological scales
  - New weakly interacting particles
- Neutrinos not exactly massless
  - Right-handed (sterile) neutrinos
- Matter anti-matter asymmetry
  - Additional CP violating interactions

New particles and interactions exist!

The SM must be extended!
What is the underlying fundamental theory?

Precision Flavour Physics

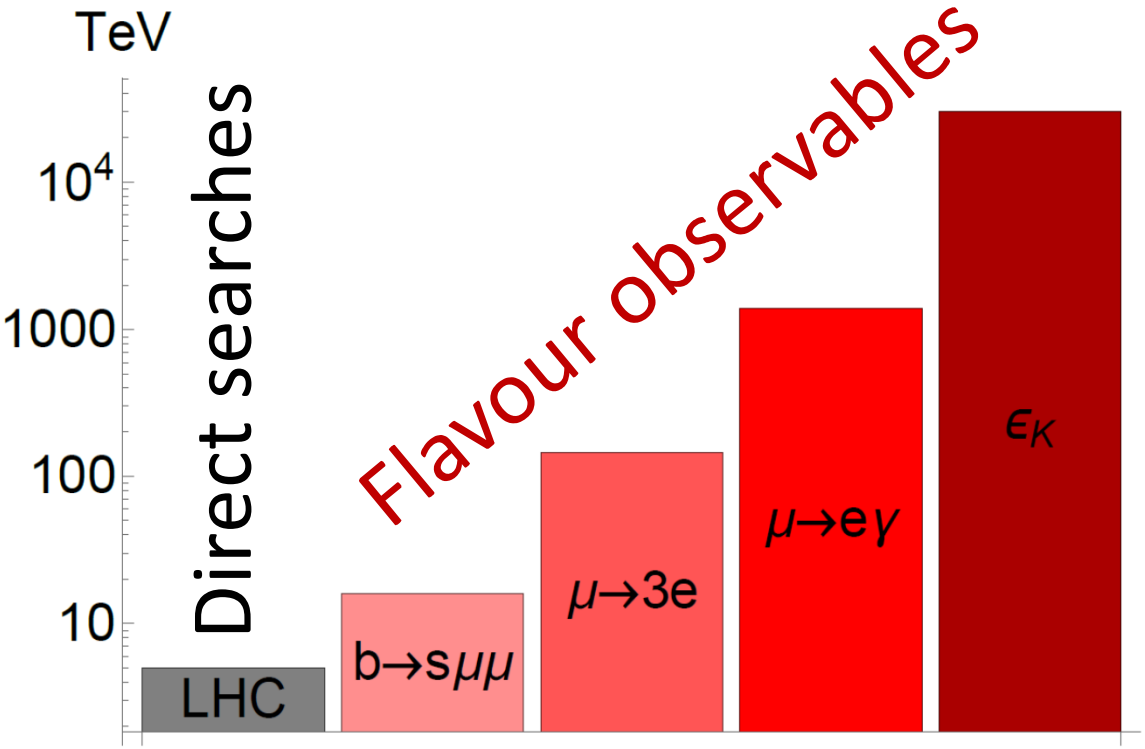
- At colliders one produces many (up to 10^{14}) heavy quarks or leptons and measures their decays into light flavours

Experiment

≠

Standard Model

New Physics



Flavour observables are sensitive to higher energy scales than collider searches

New Physics in the Flavour Sector

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2 Accelerators Find Particles That May Break Known Laws of Physics

The LHC and the Belle experiment have found particle decay patterns that violate the Standard Model of particle physics, confirming earlier observations at the BaBar facility

By Clara Moskowitz | September 9, 2015 | Véalo en español

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Democracy suffers a blow—in particle physics

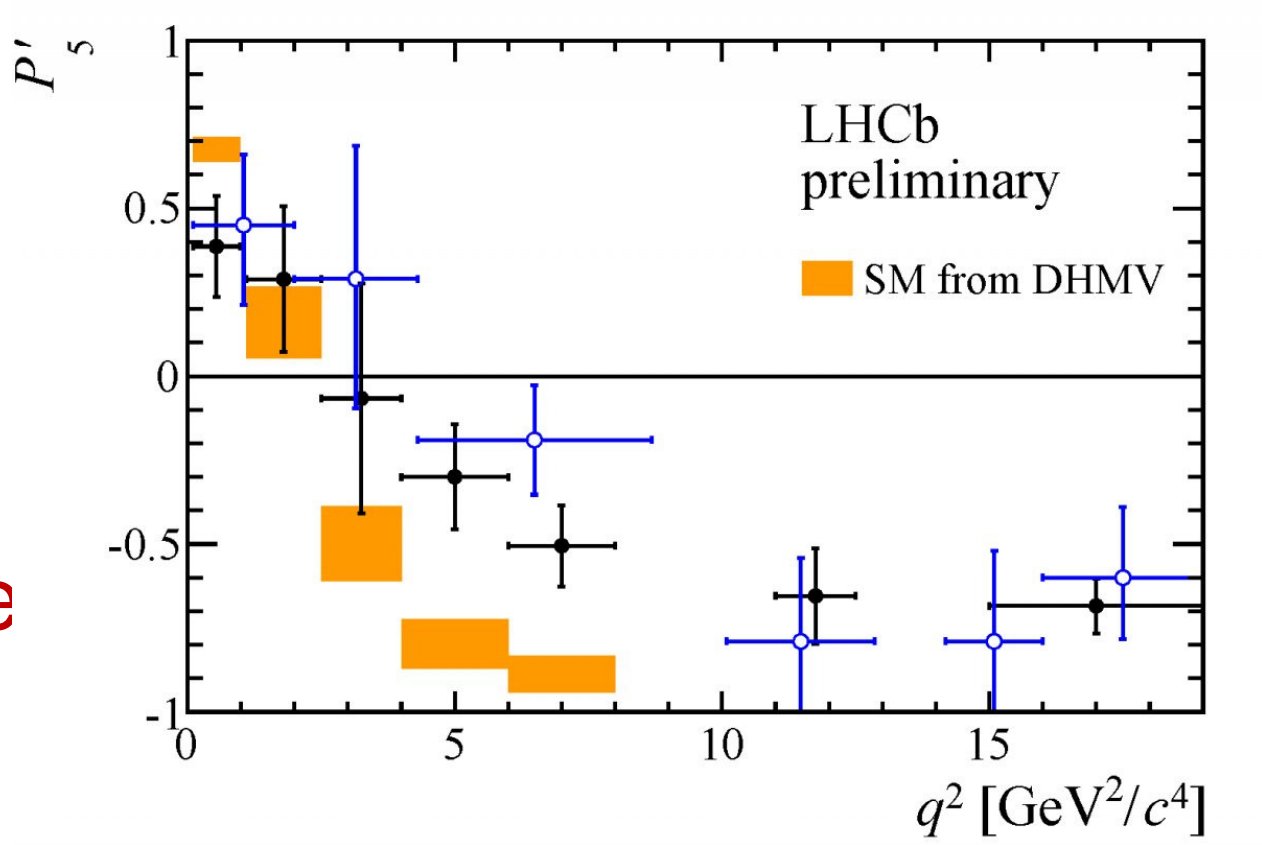
Three independent B-meson experiments suggest that the charged leptons may not be so equal after all.

Steven K. Blau 17 September 2015

Hints for New Physics in flavour observables

B→K*μμ

- LHCb 3σ deviation from the SM mostly in P5'
- Confirmed by BELLE and ATLAS (larger errors)
- CMS compatible with the SM (larger errors)
- Hadronic effects might be larger than expected



Hadronic uncertainties or NP?

R(K) = B→Kμμ/B→Kee

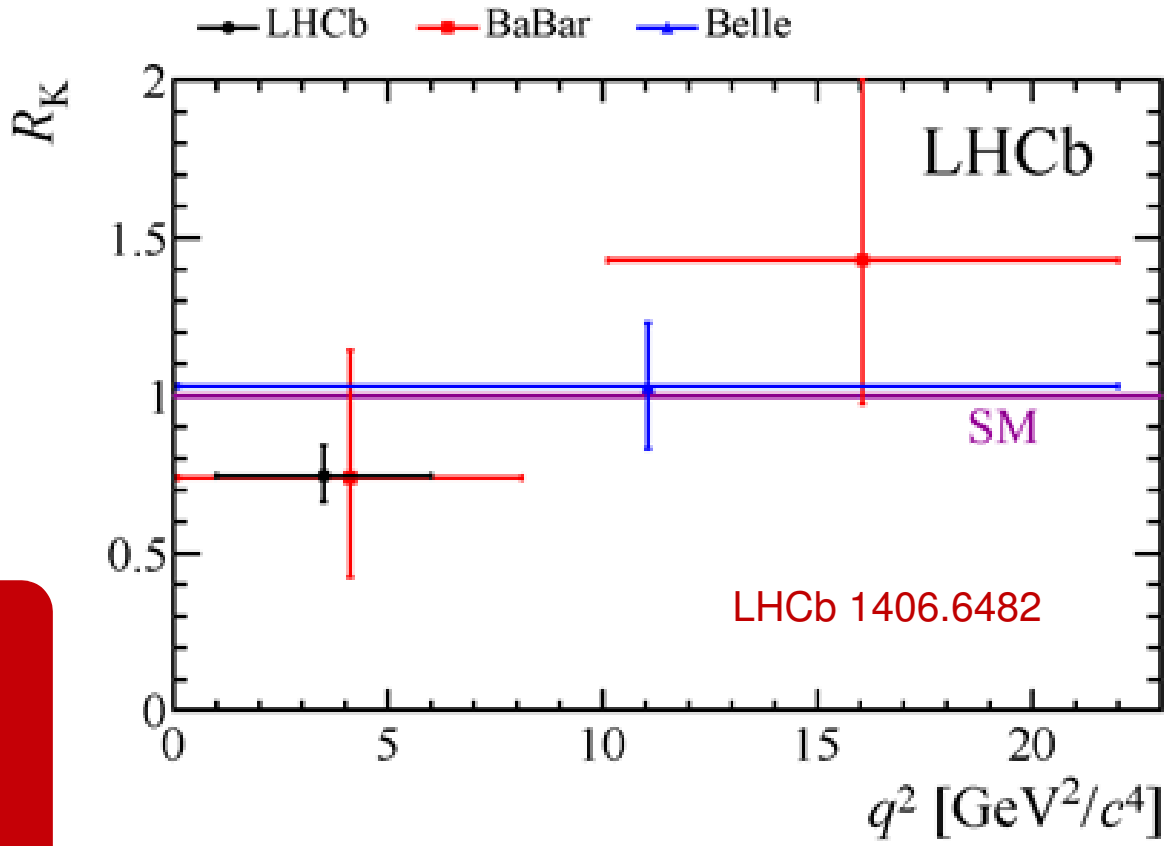
- Lepton flavour universality violation
- 2.6σ deviation from the theoretically rather clean SM expectation

C. Bobeth, G. Hiller, and
G. Piranishvili, 0709.4174

$$R_K^{\mathrm{SM}} = 1.0003 \pm 0.0001$$

$$R_K^{\mathrm{exp}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

Lepton Flaovur Violation in B decays?



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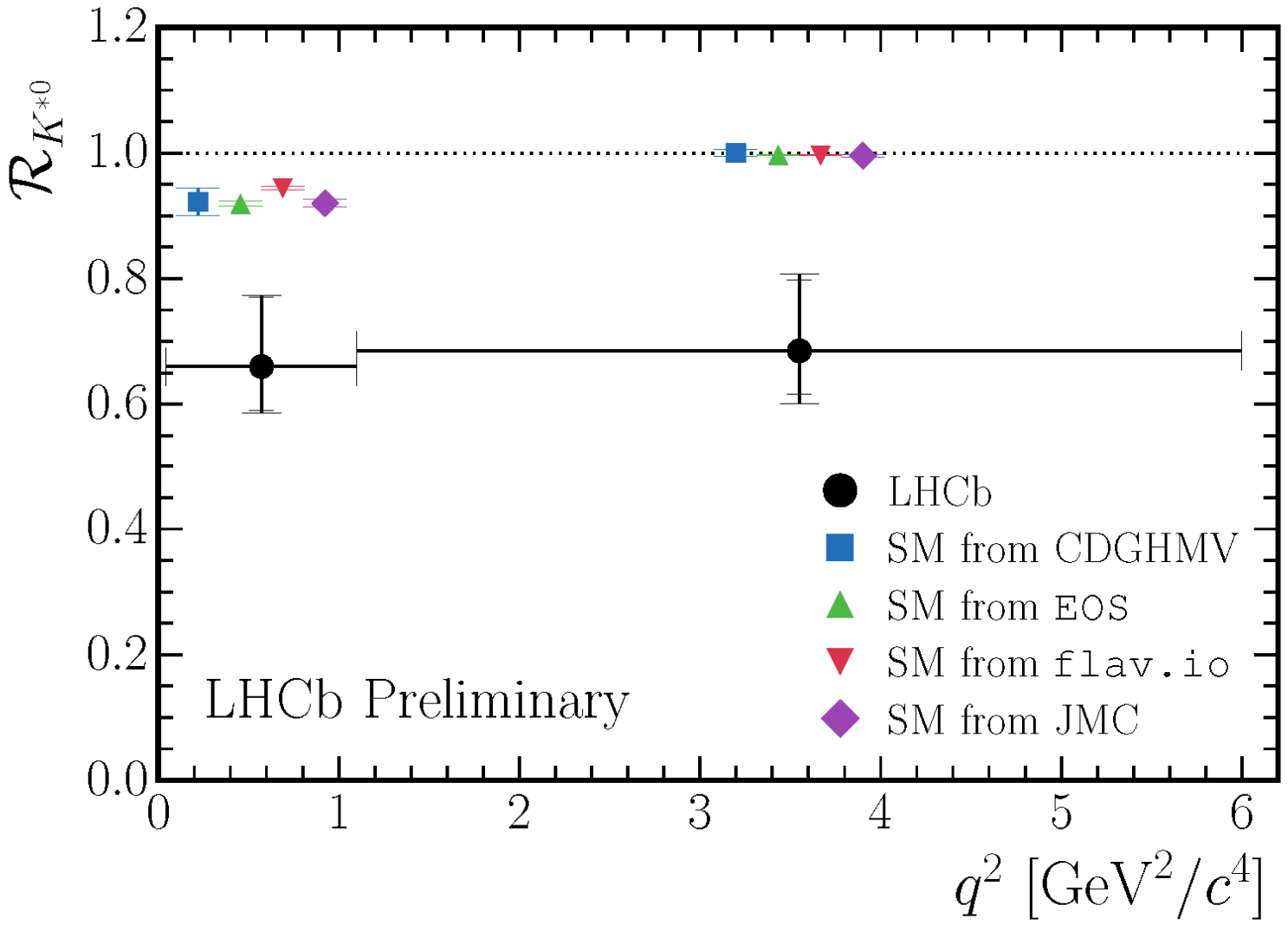
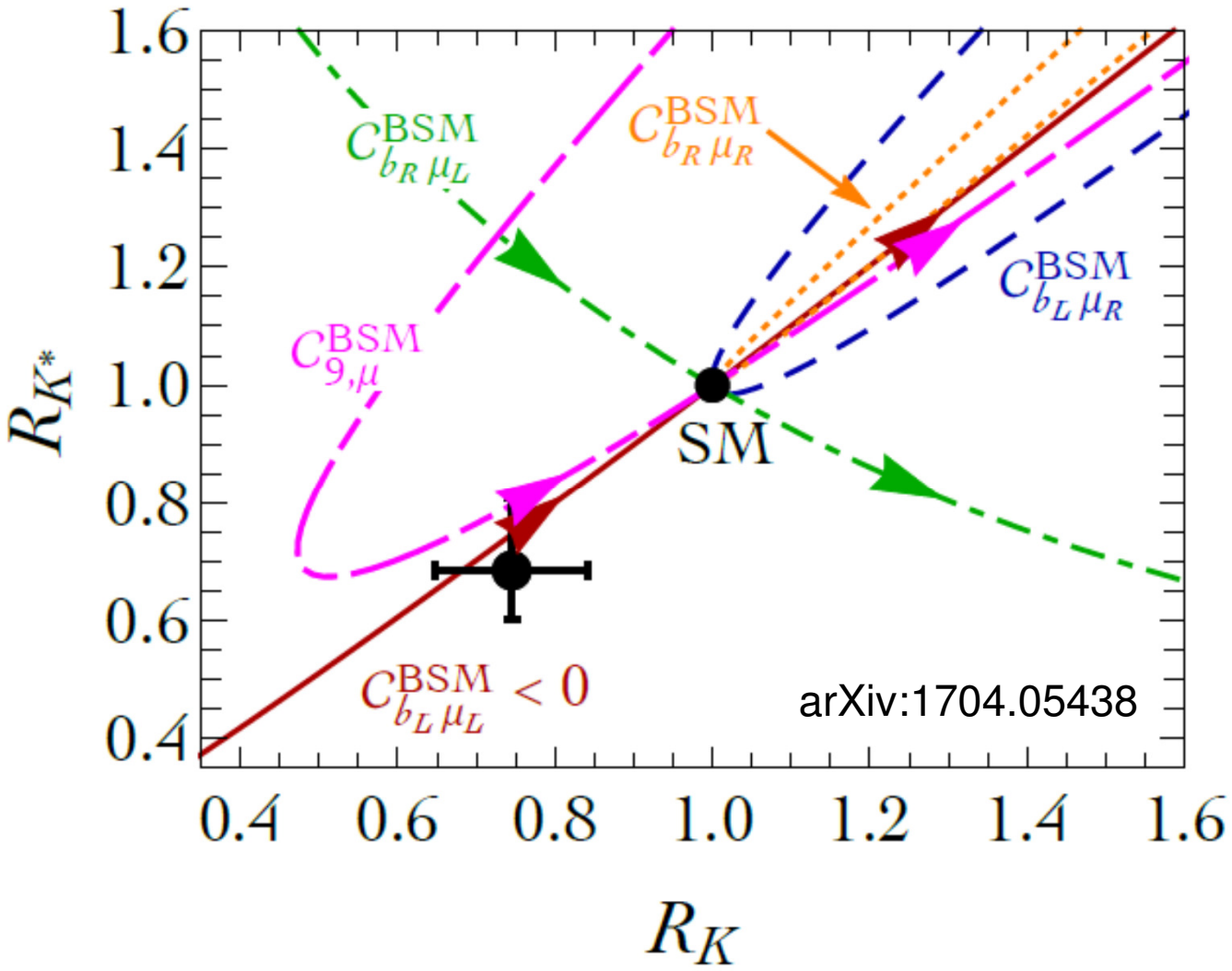
R(K*) = B→K*μμ/B→K*ee

- 2.2-2.4 σ in two bins



R(K) & R(K*)



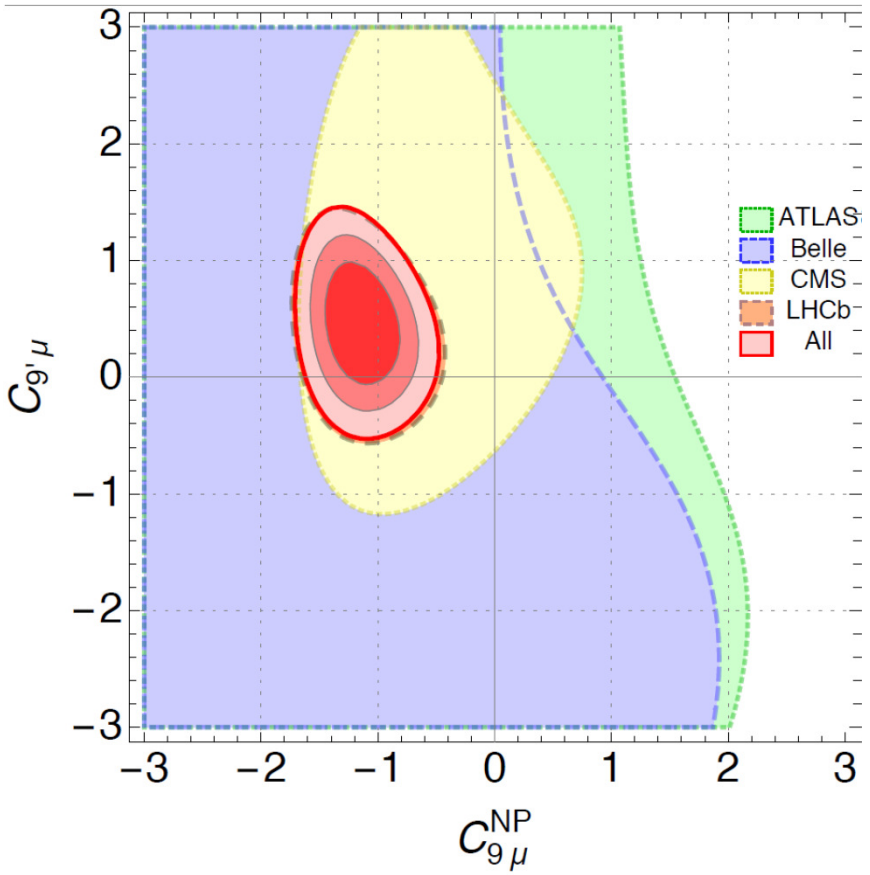
Combined ≈4 σ evidence for LFUV

Global fit to b→sμμ data

- Global analysis give a very good fit to data
- Good fit to data:
  - C_9
  - $C_9 = -C_{10}$
  - $C_9 = -C_9'$

$$O_9 = \bar{s}\gamma^\mu P_L b\,\bar{\ell}\gamma_\mu \ell$$

$$O_{10} = \bar{s}\gamma^\mu P_L b\,\bar{\ell}\gamma_\mu\gamma^5 \ell$$



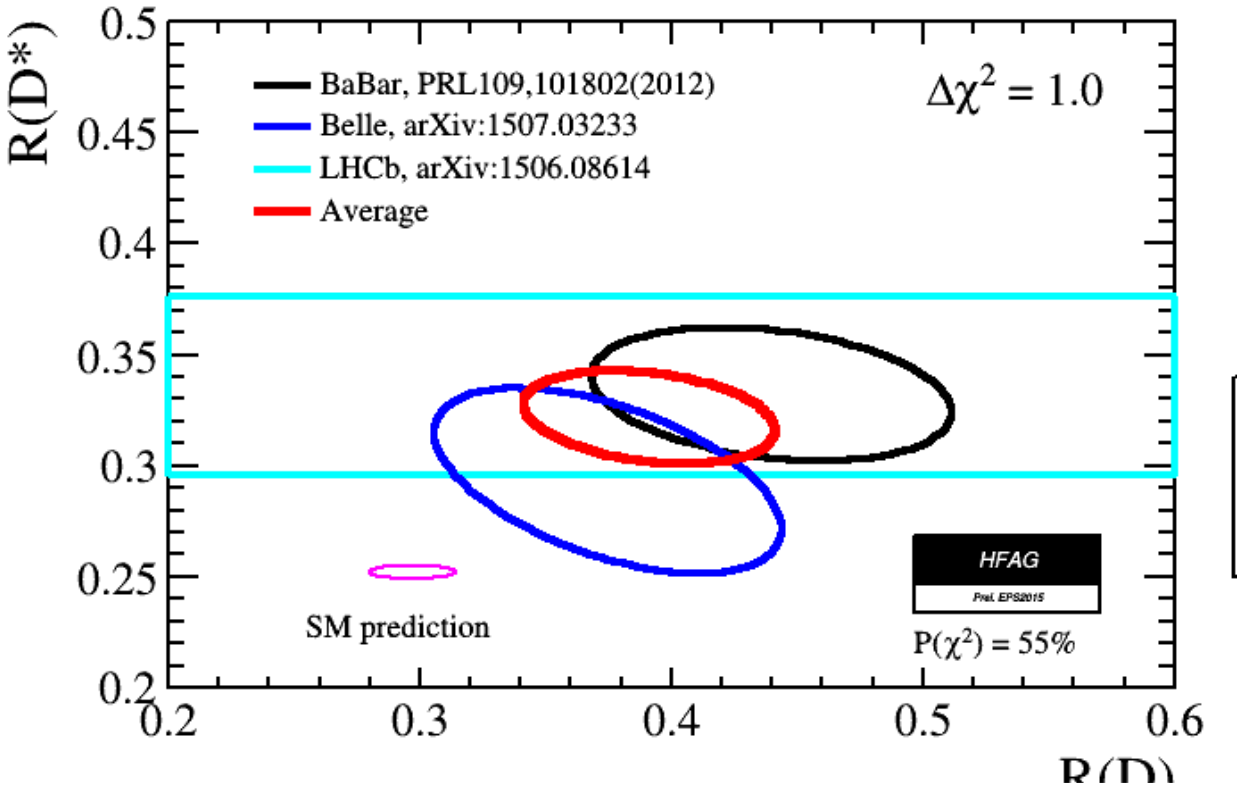
B. Capdevila, AC, S. Descotes-Genon, J. Matias and J. Virto, arXiv:1704.05340 [hep-ph].

New Physics fit is 5-6 σ better than the SM

Tauonic B decays

- Tree-level decays in the SM via W-boson

$$R\left(D^{(*)}\right) = B \to D^{(*)}\tau\nu \Big/ B \to D^{(*)}\ell\nu$$



All measurements above the SM prediction
≈4σ deviation

$\tau \to \mu\nu\nu$ and a_μ

- Tau decays

$$\mathrm{Br}\left[\tau \to \mu\nu\nu\right]_{\mathrm{exp}} = (17.41 \pm 0.04)\,\%$$

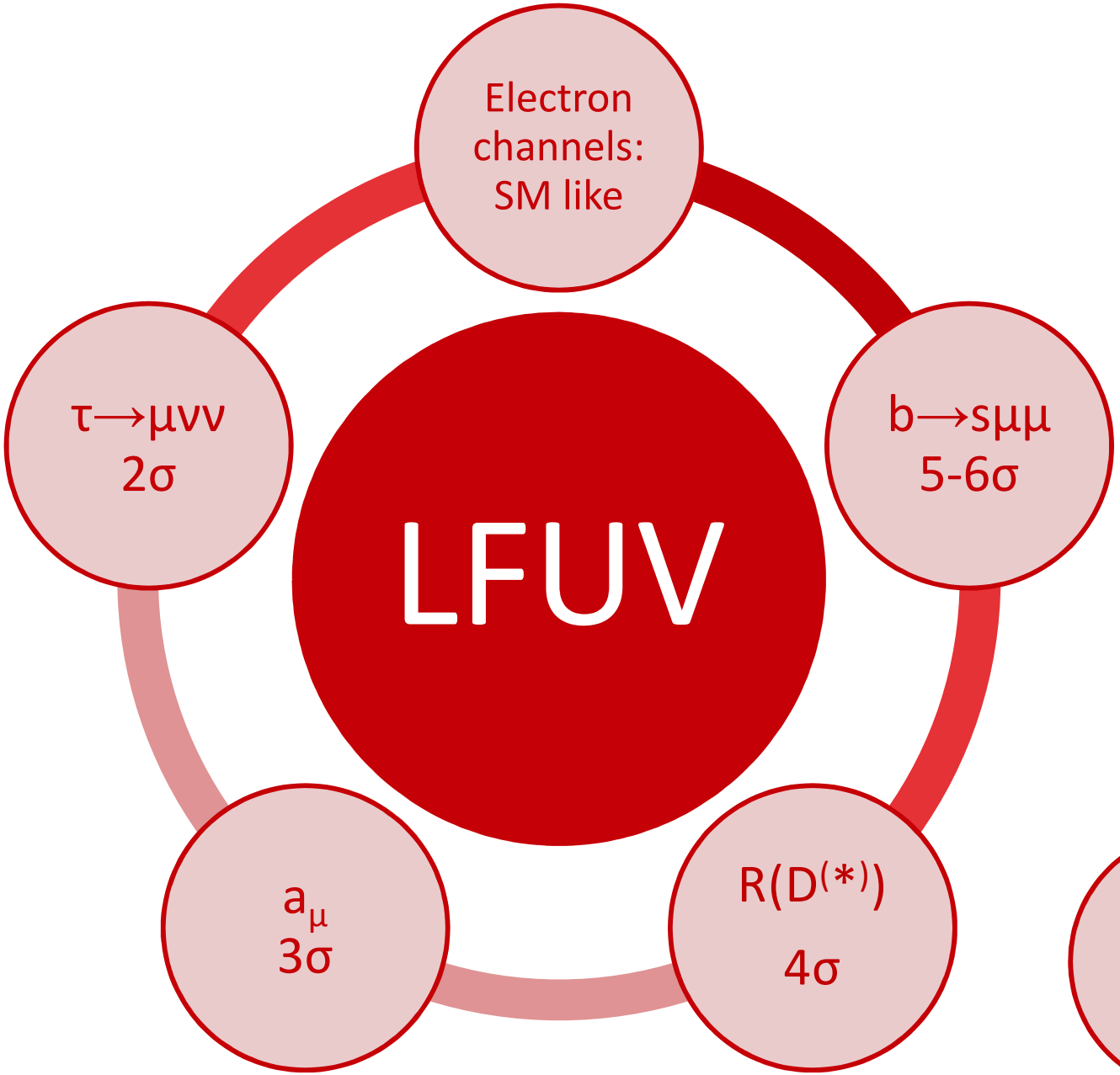
$$\Delta_{\tau\to\mu\nu\nu} = \frac{\mathrm{Br}\left[\tau \to \mu\nu\nu\right]_{\mathrm{exp}}}{\mathrm{Br}\left[\tau \to \mu\nu\nu\right]_{SM}} - 1 = (0.69 \pm 0.29)\,\%$$

- Anomalous magnetic moment of the muon

$$\Delta a_\mu = (236 \pm 87) \times 10^{-11}$$

2-3 σ deviation in the lepton sector

Hints for NP and LFUV



Lepton Flavour Universality Violation (LFUV)

+

ε'/ε ≈ 3σ

Talk of Vincenzo

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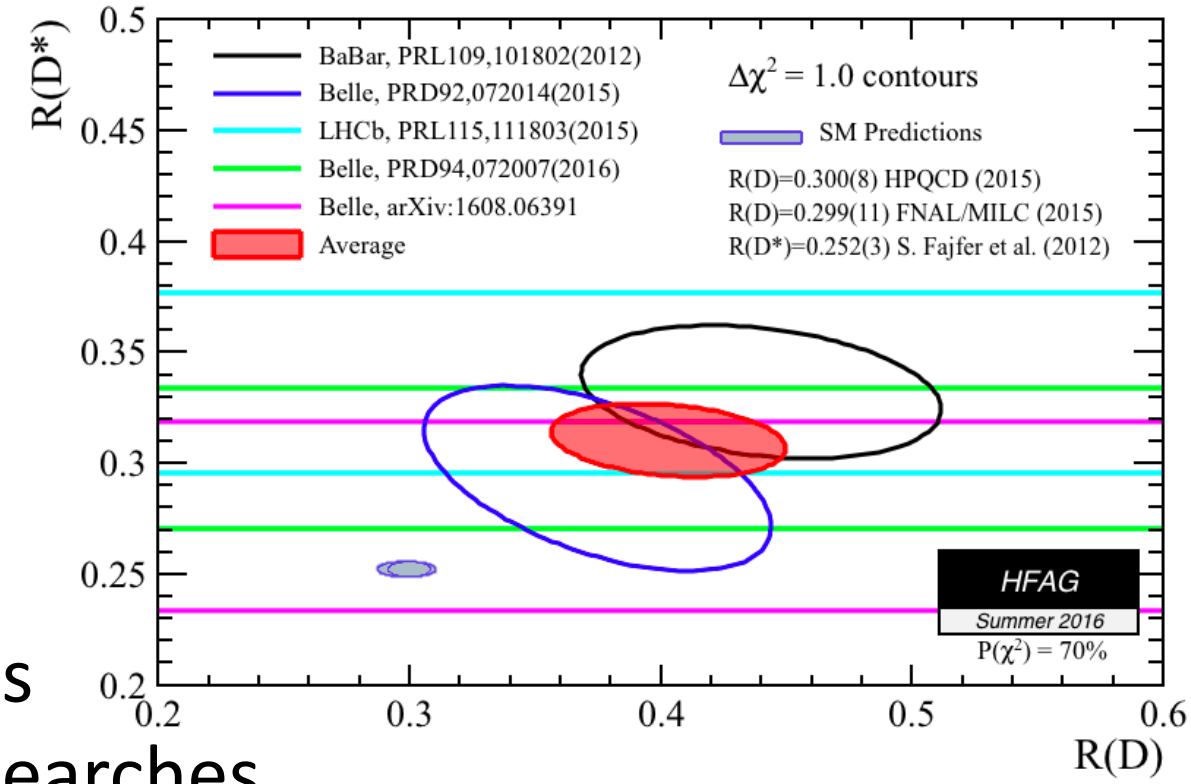
Explanations of the Anomalies

R(D) & R(D*)

- Charged scalars
  - Problems with q^2 distributions and B_c lifetime
- W'
  - Strong constraints from direct LHC searches



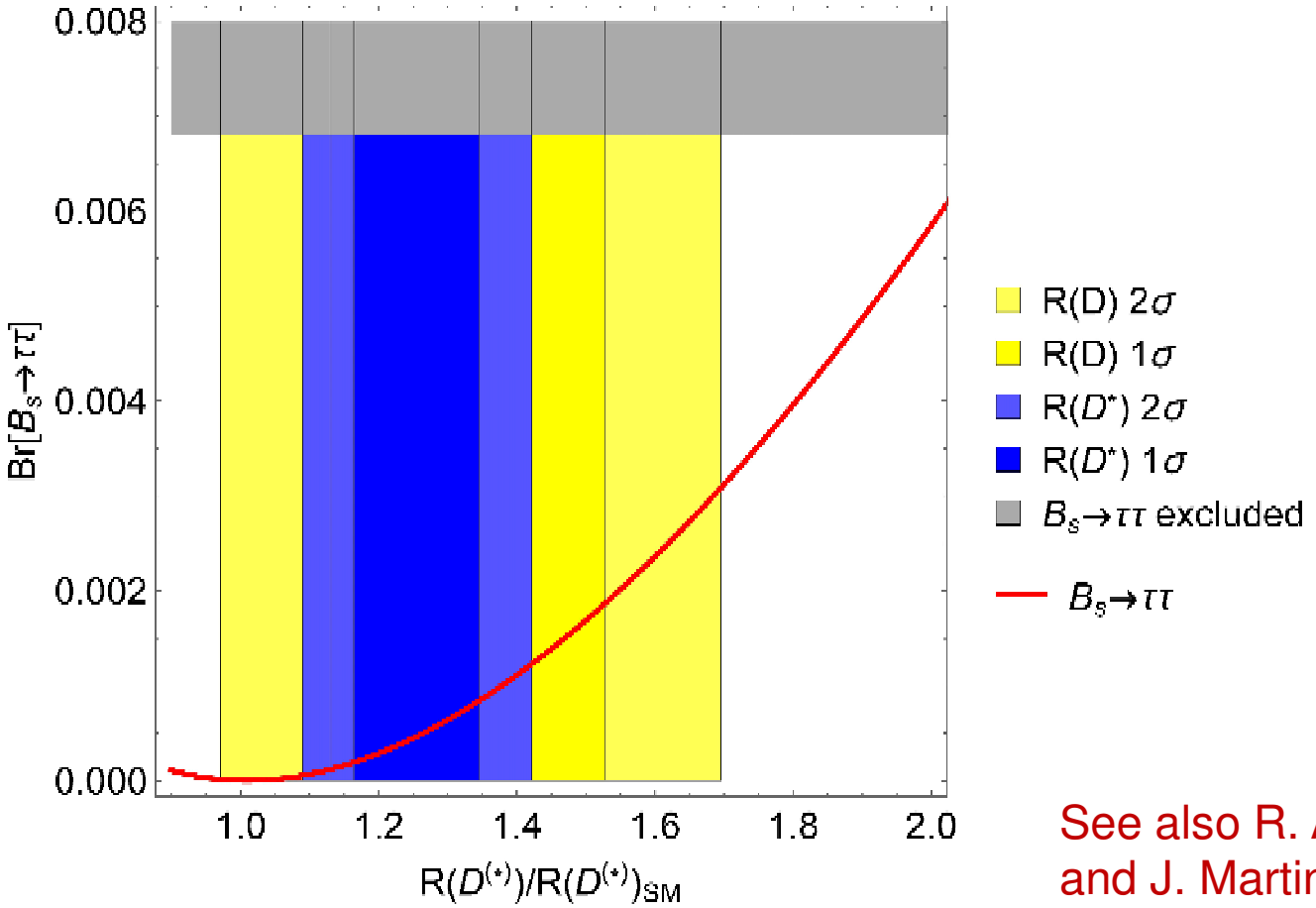
- Leptoquark see talk of Svjetlana
  - Strong signals in qq→ττ searches

Faroughy et al. arXiv:1609.07138

Explanation difficult

$R(D^{(*)})$ and $b\to s\tau\tau$ (model-independent)

- Large couplings to the second generation needed in order avoid collider bounds
- Cancelation in $b\to s\nu\nu$ needed: $C^{(1)}=C^{(3)}$



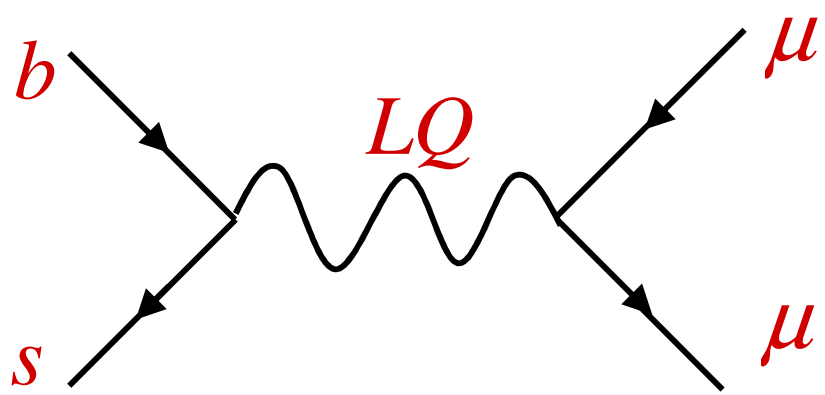
$B_s\to\tau\tau$ very strongly enhanced

See also R. Alonso, B. Grinstein and J. Martin Camalich, 1505.05164

b→sμμ explenation

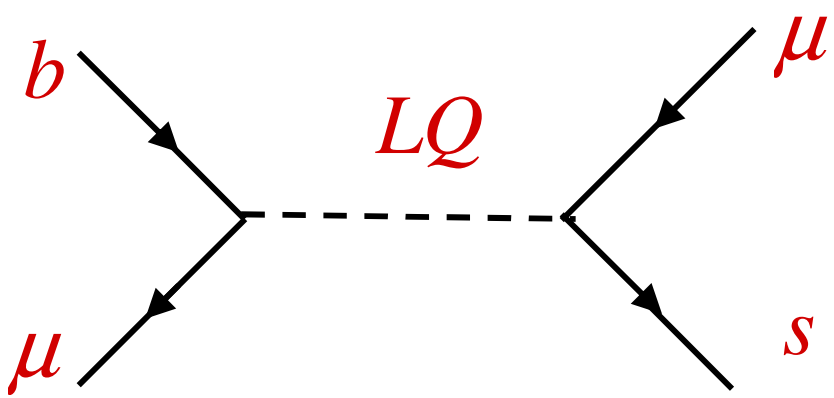
- Z' see also talk of Peter Cox

  U. Haisch et al. 1308.1959, Buras et al. 1311.6729
  W. Altmannshofer et al. 1403.1269,
  AC. et al. 1501.00993, ...



- Leptoquarks Talk of Svjetlana

  Gudrun Hiller, Martin Schmaltz.
  arXiv:1411.4773
  B. Gripaios, M. Nardecchia, S.A. Renner.
  arXiv:1412.1791
  D. Bečirević, N. Košnik, O. Sumensari,
  ...



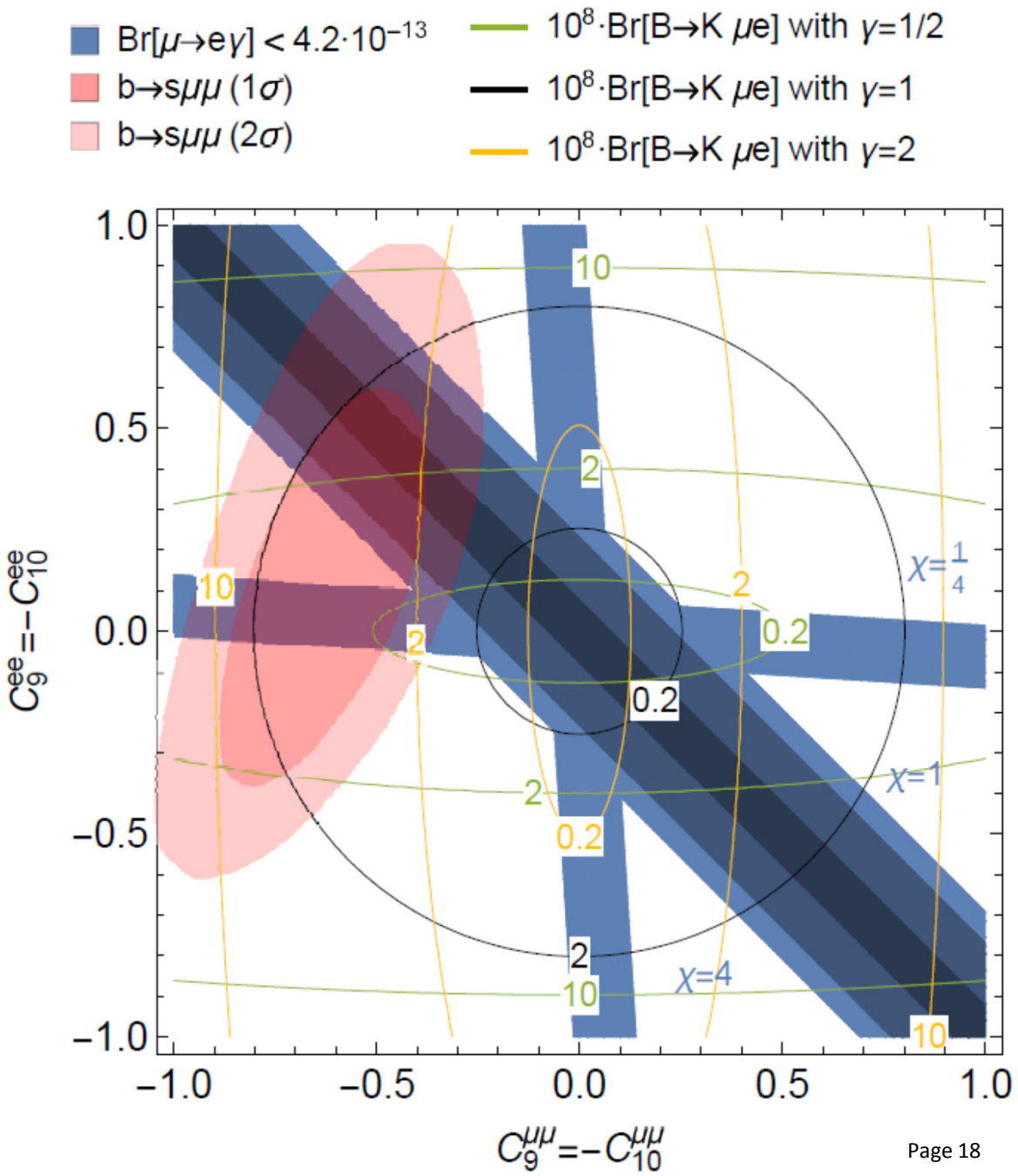
- Loop effects (more soon)

  B. Gripaios, M. Nardecchia, S. Renner, arXiv:1509.05020

Even high scale NP explanations possible

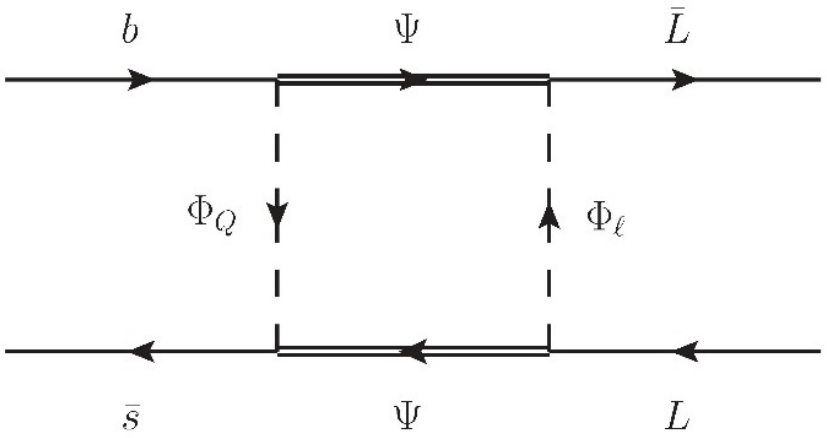
R(K), R(K*) and μ→eγ with LQs

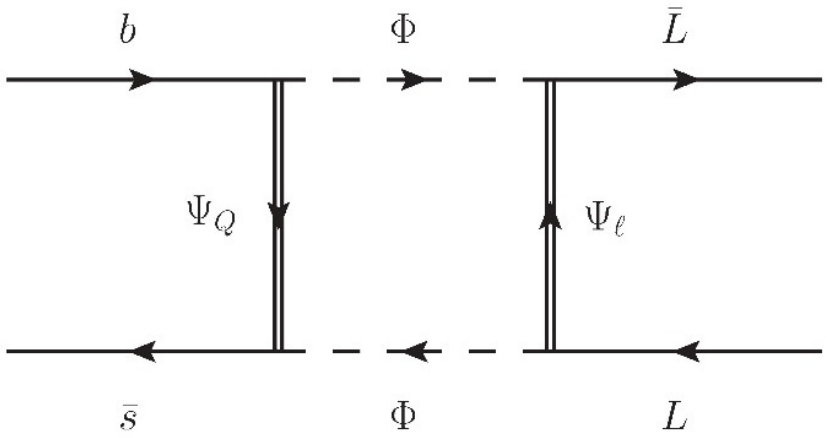
- Three LQs give a good fit
  - Scalar triplet
  - Vector singlet
  - Vector triplet
- Simultaneous effect in b→sμμ and b→see generate μ→eγ



AC, D. Mueller, A. Signer, Y. Ulrich, arXiv:1505.xxxx

New Scalars and Fermions in b→sμμ





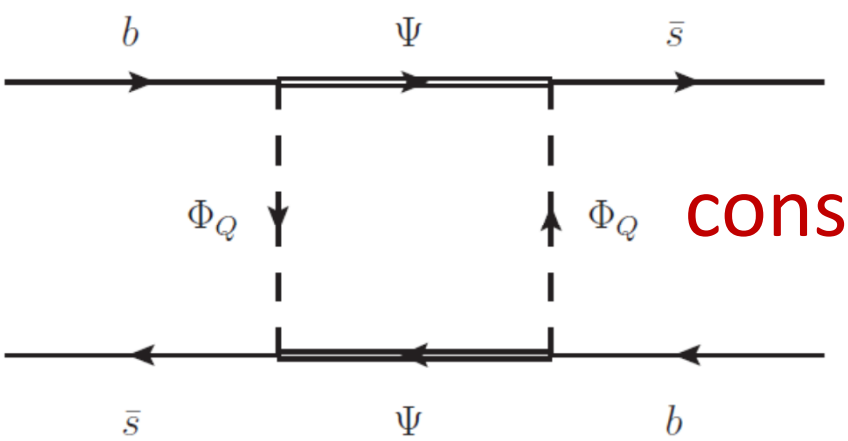
- Possible representations

$SU(2)$	Φ_Q, Ψ_Q	Φ_ℓ, Ψ_ℓ	Ψ, Φ
I	2	2	1
II	1	1	2
III	3	3	2
IV	2	2	3
V	3	1	2
VI	1	3	2

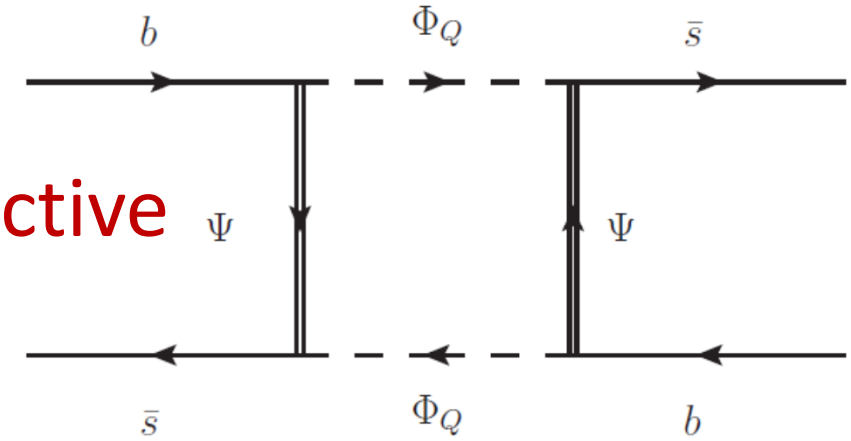
$SU(3)$	Φ_Q, Ψ_Q	Φ_ℓ, Ψ_ℓ	Ψ, Φ
A	3	1	1
B	1	$\bar{3}$	3
C	3	8	8
D	8	$\bar{3}$	3

2x6x4 possibilities

Constraints from B_s mixing

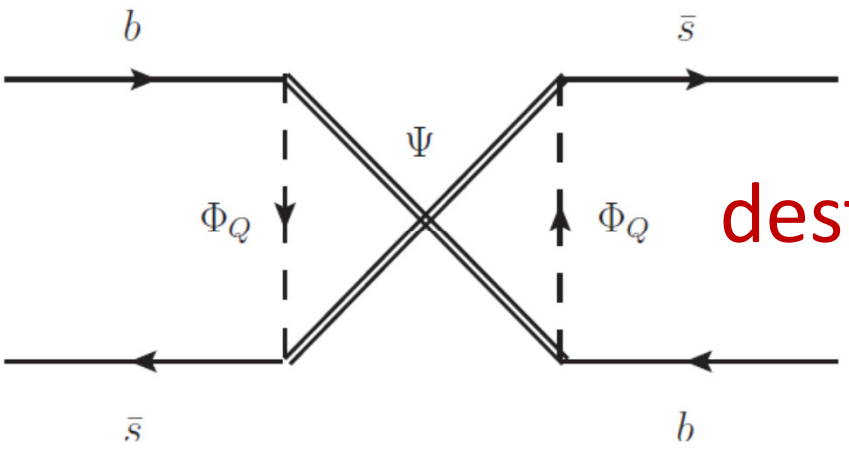


constructive

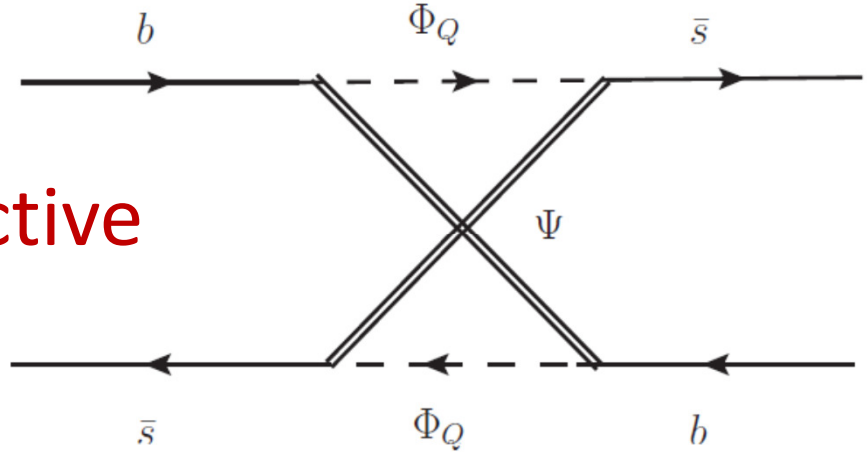


Lattice results prefers destructive interference MILC, 1602.03560

- Majorana representations



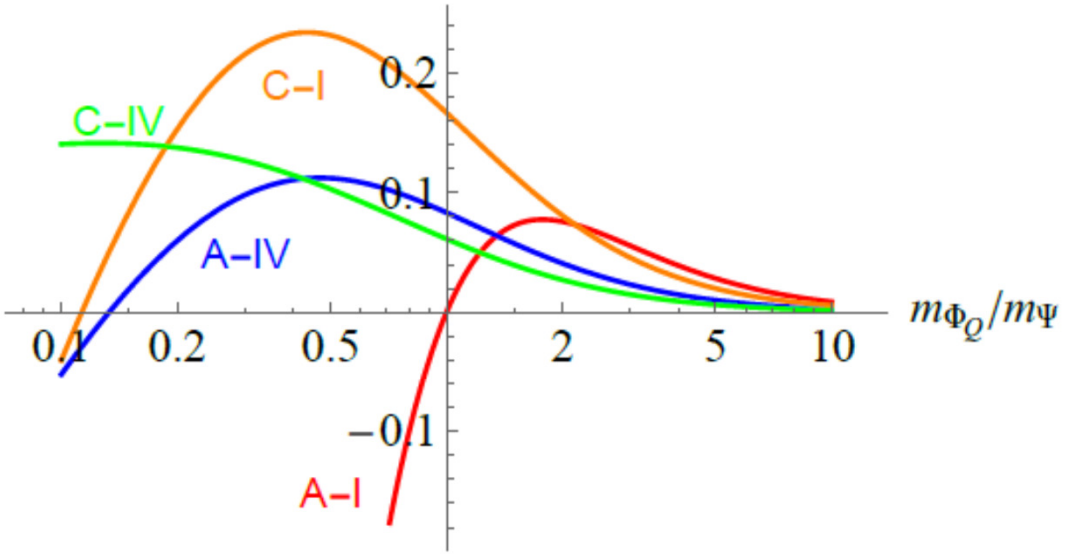
destructive



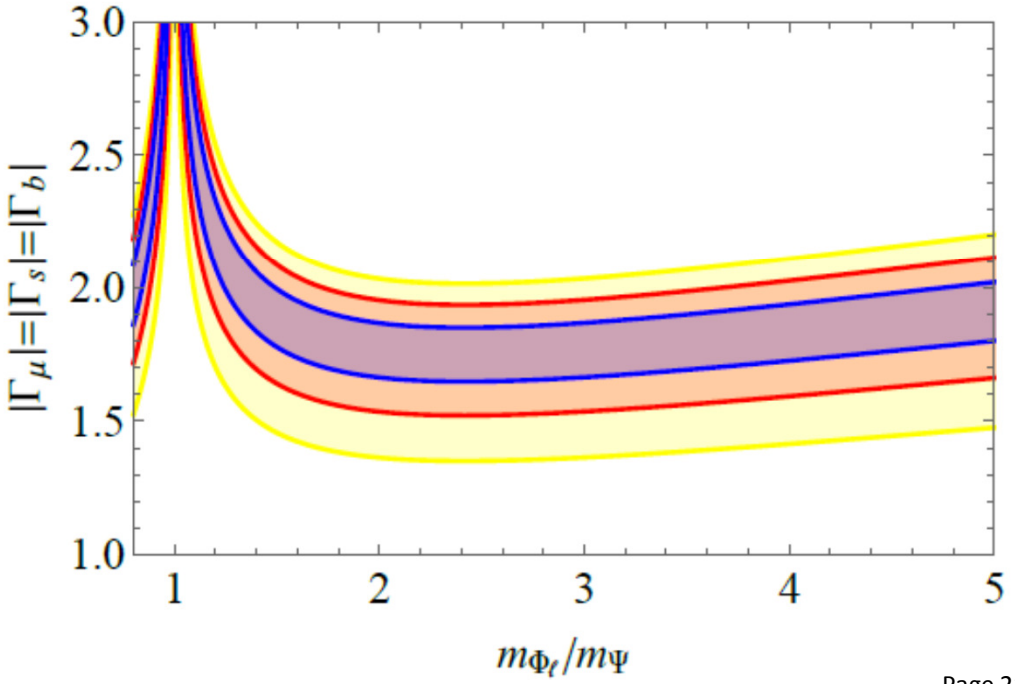
Destructive interference with Majorana fermions

$b \to s\mu\mu$ and B_s mixing

Relative effect in B_s mixing



$b \to s\mu\mu$ 3σ 1σ 2σ



Explanation with O(1) couplings

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Z’ bososns in b→sμμ

Z' solution for b→sμμ with VLQ

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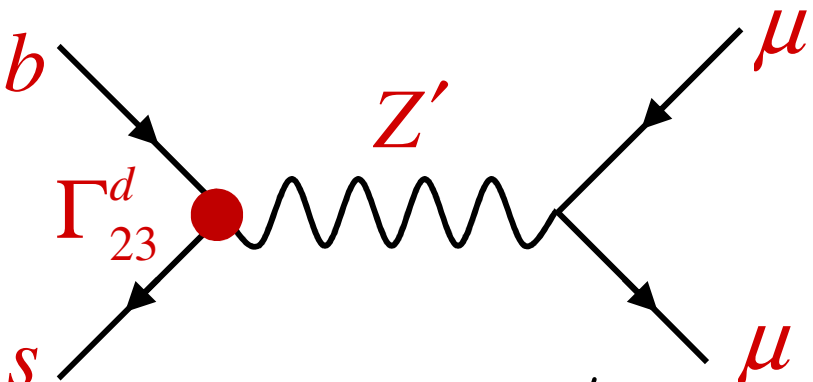
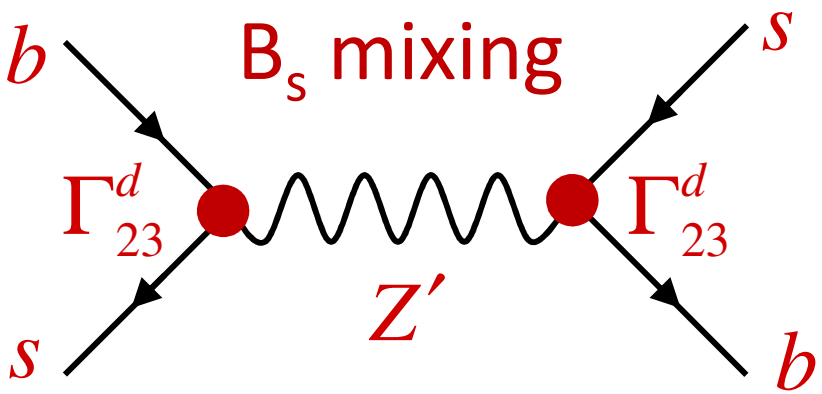
b→sμμ

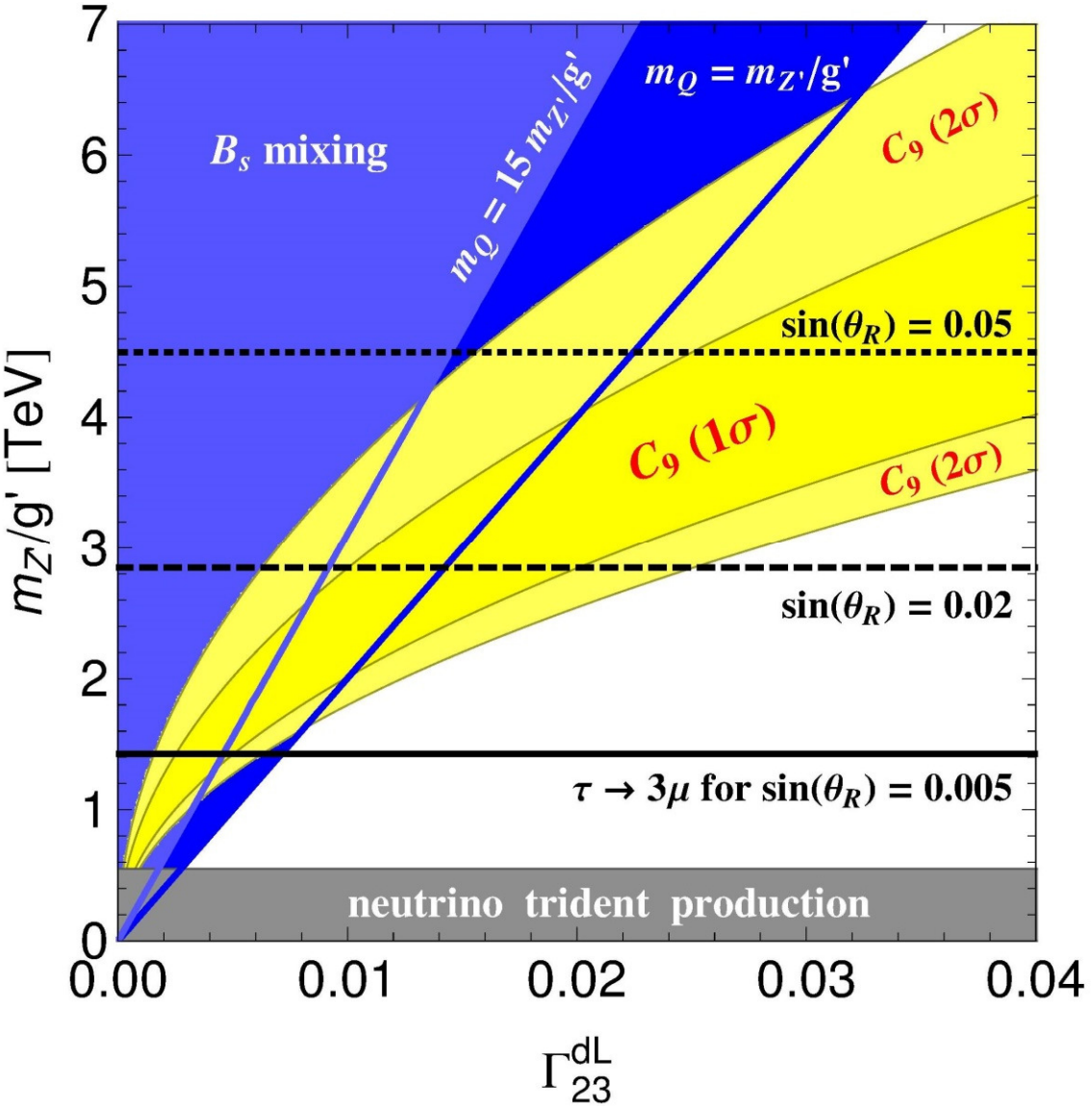


$$C_9^{\mu\mu} \propto \Gamma_{23}^{dL}\, g'^2 / m_{Z'}^2$$

B_s mixing



$$\frac{\Delta M_{12}}{M_{12}^{\mathrm{SM}}} \propto \left(\Gamma_{23}^{dL}\right)^2 g'^2 / m_{Z'}^2$$



allowed regions

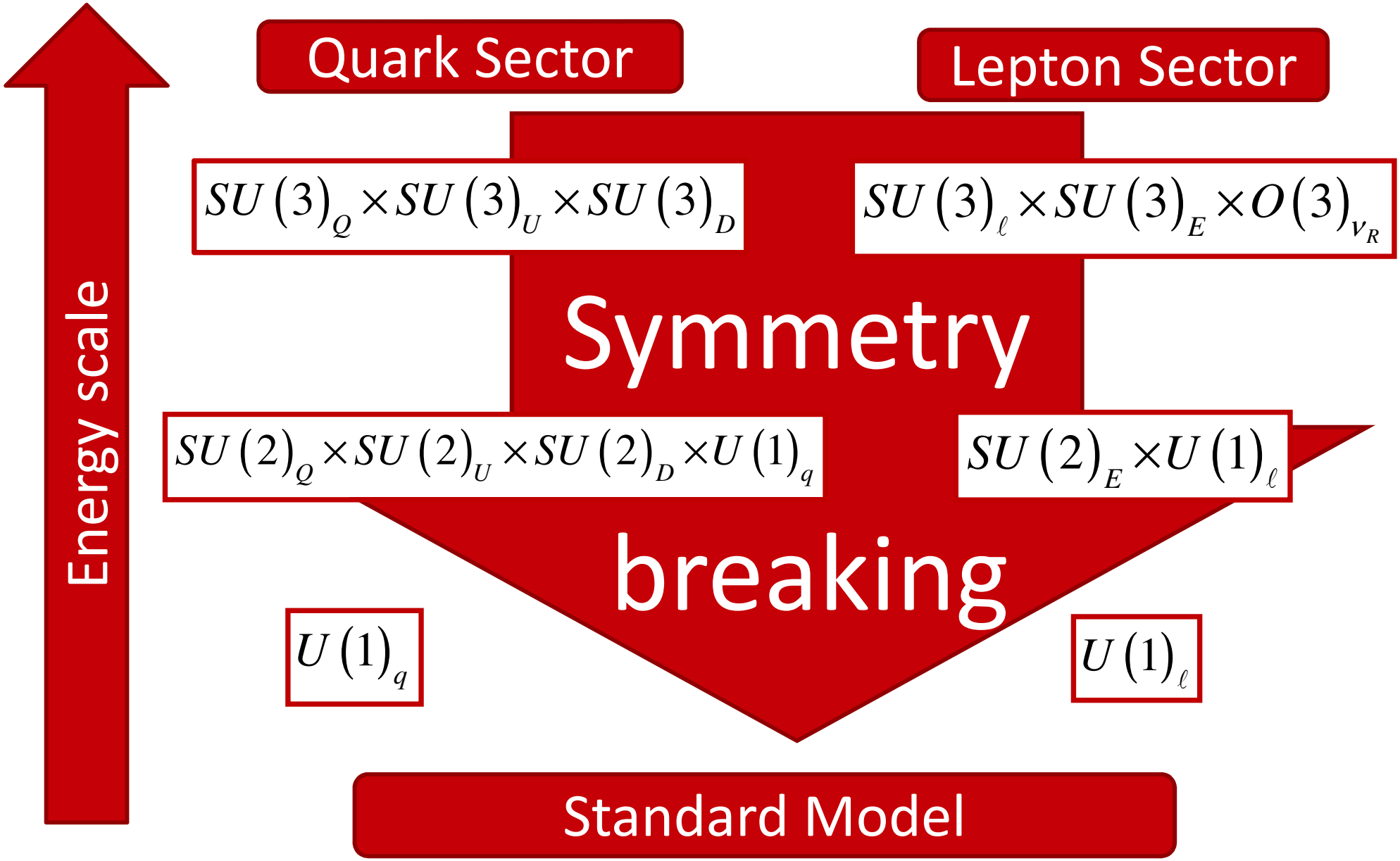
Solution with horizontal U(1) charges

- Avoid vector-like quarks by assigning charges to baryons as well
  - Same mechanism in the quark and lepton sector
- L_μ-L_τ in lepton sector
  - Good symmetry for the PMNS matrix
  - Effect in $C_9^{\mu\mu}$ but not C_9^{ee}
- First two quark generations must have the same charges because the large Cabibbo angle would lead to huge effect in Kaon mixing
- Anomaly freedom

Q(L)=(0,1,-1) Q(B)=(a,a,-2a)

Dynamical explanation of the charges

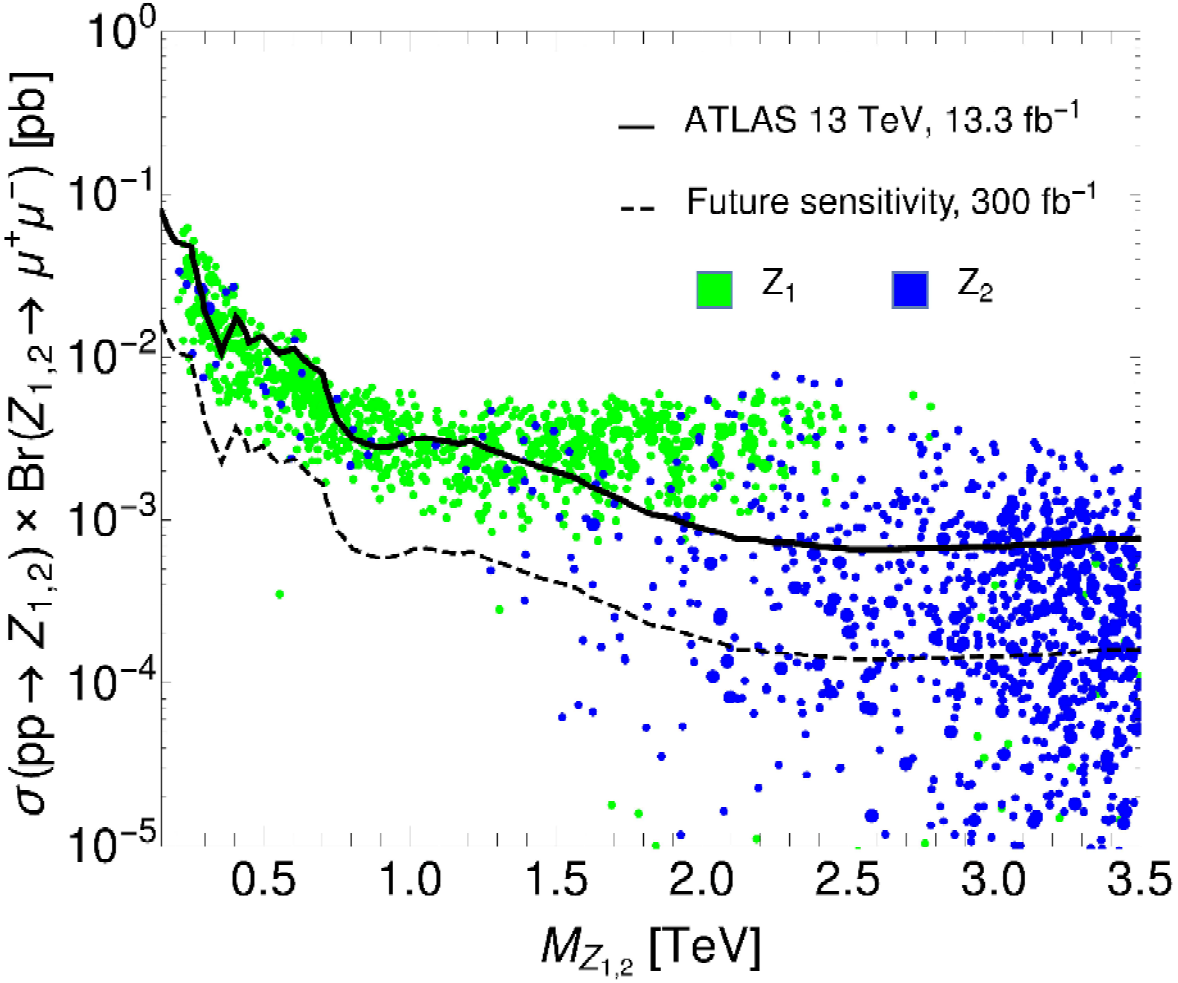
A.C., J. Fuentes-Martin, A. Greljo and G. Isidori arXiv:1611.02703



Solution with two Z's

- 2 Z' bosons
  - Z_1 coupling mainly to leptons
  - Z_2 coupling mainly to quarks

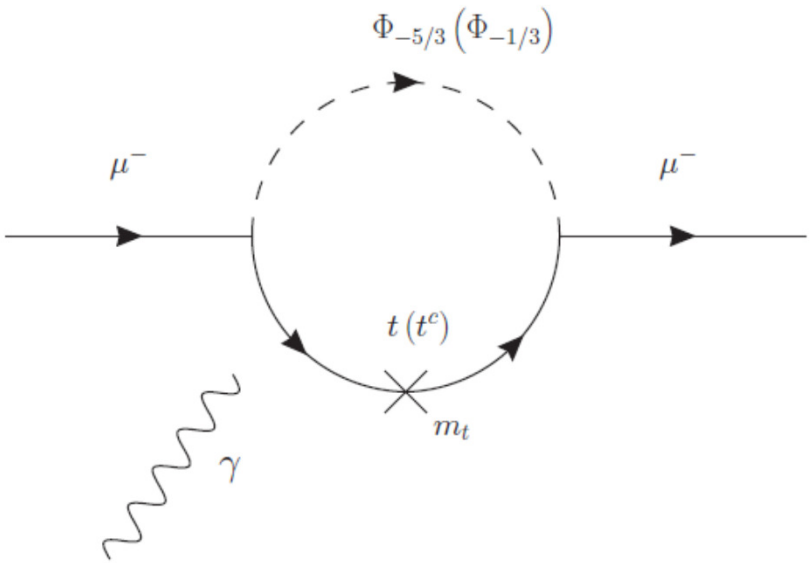
Low energy phenomenology unchanged



Different collider signatures

a_μ explanations

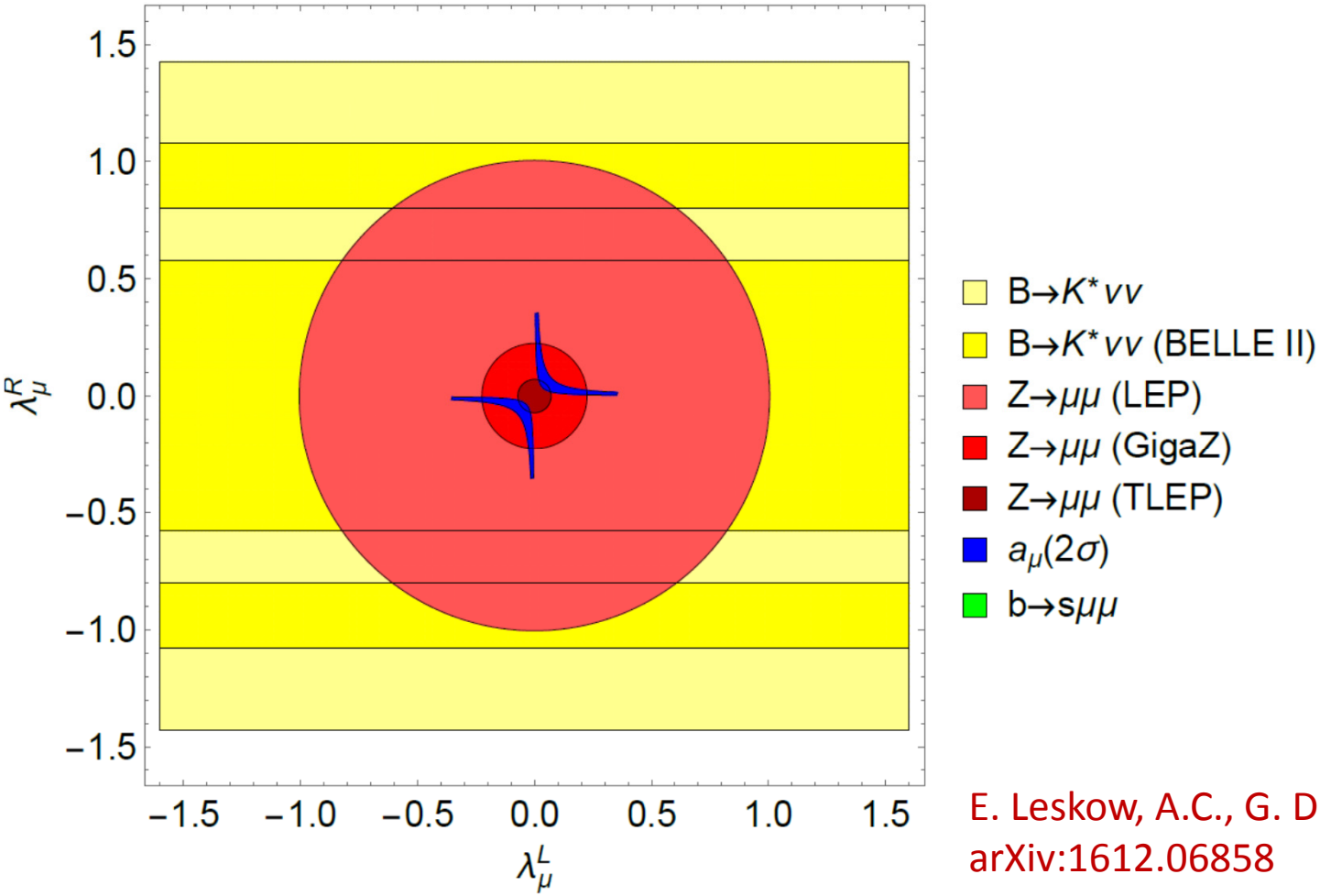
- MSSM e.g. D. Stockinger, hep-ph/0609168
  - tan(ß) enhancement
- Scalars (more later)
  - Light Higgses
- Z'
  W. Altmannshofer, C. Chen, P.S.B. Dev, A. Soni, arXiv:1607.06832
  - Very light with τμ couplings (m_τ enhancement)
- Leptoquarks (more now) A. Djouadi, T. Kohler, M. Spira, J. Tutas, Z.Phys. C46 (1990)
  - m_t enhaned effects



Chiral enhancement or very light particles

Leptoquarks in a_μ

- Chirally enhanced effects via top-quark loops



Left-, right-handed muons-top coupling

$$\lambda_\mu^{L,R}$$

E. Leskow, A.C., G. D'Ambrosio, D. Müller
arXiv:1612.06858

Z→μμ at future colliders

ε‘/ ε explanations

- W_R coupling

  see talk of Vincenzo

- Z’ and modified Z

  see talk of Christoph

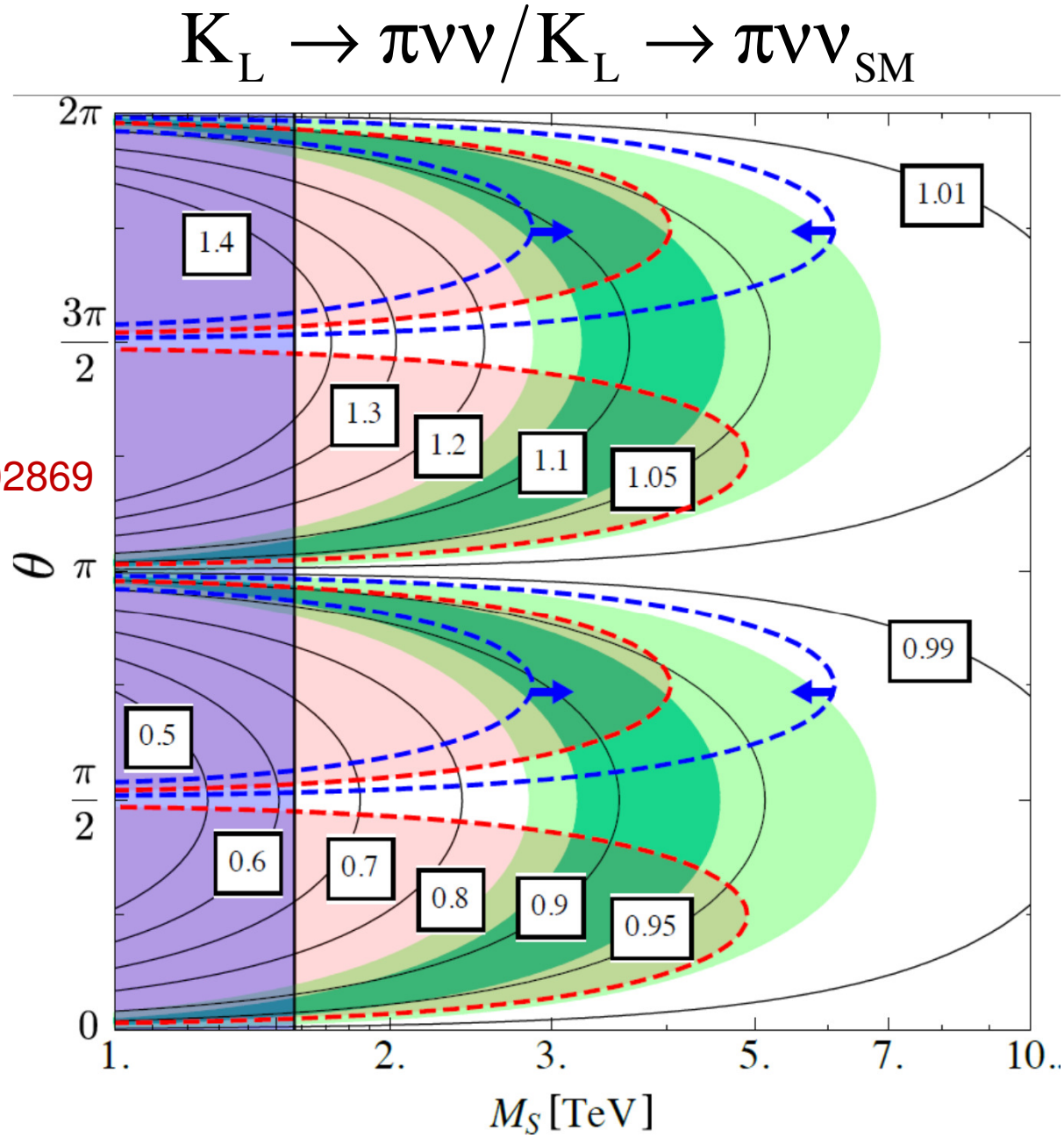
A. Buras, et al. arXiv:1507.08672
A. Buras, F. De Fazio, arXiv:1512.02869

- MSSM

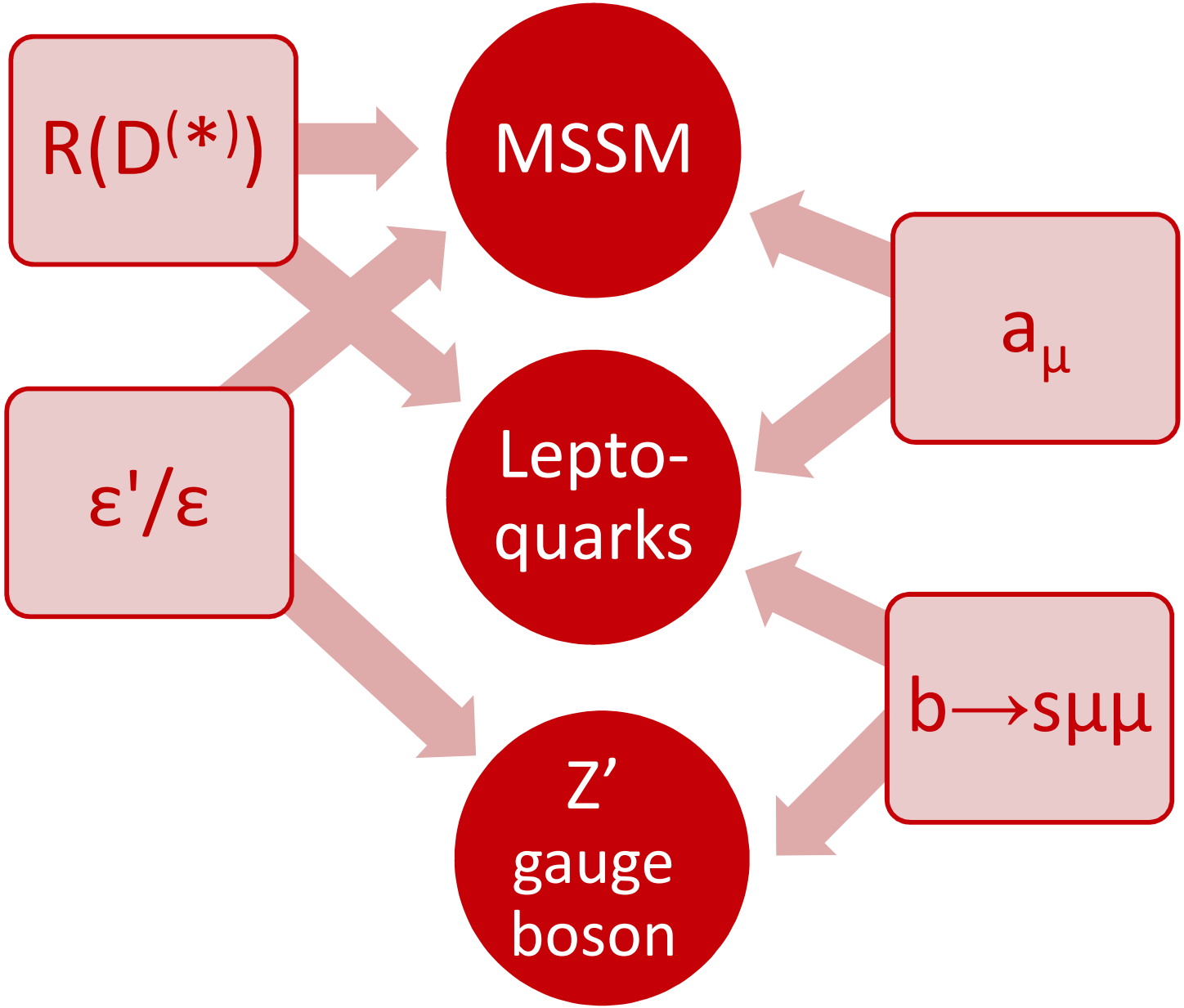
T. Kitahara, U. Nierste,
P. Tremper, arXiv:1604.07400
M. Endo, et al. arXiv:1608.01444
A. Crivellin, G. D'Ambrosio,
T. Kitahara and U. Nierste,
arXiv:1703.05786

LHC excluded

$\varepsilon' / \varepsilon$



Implications for New Particles



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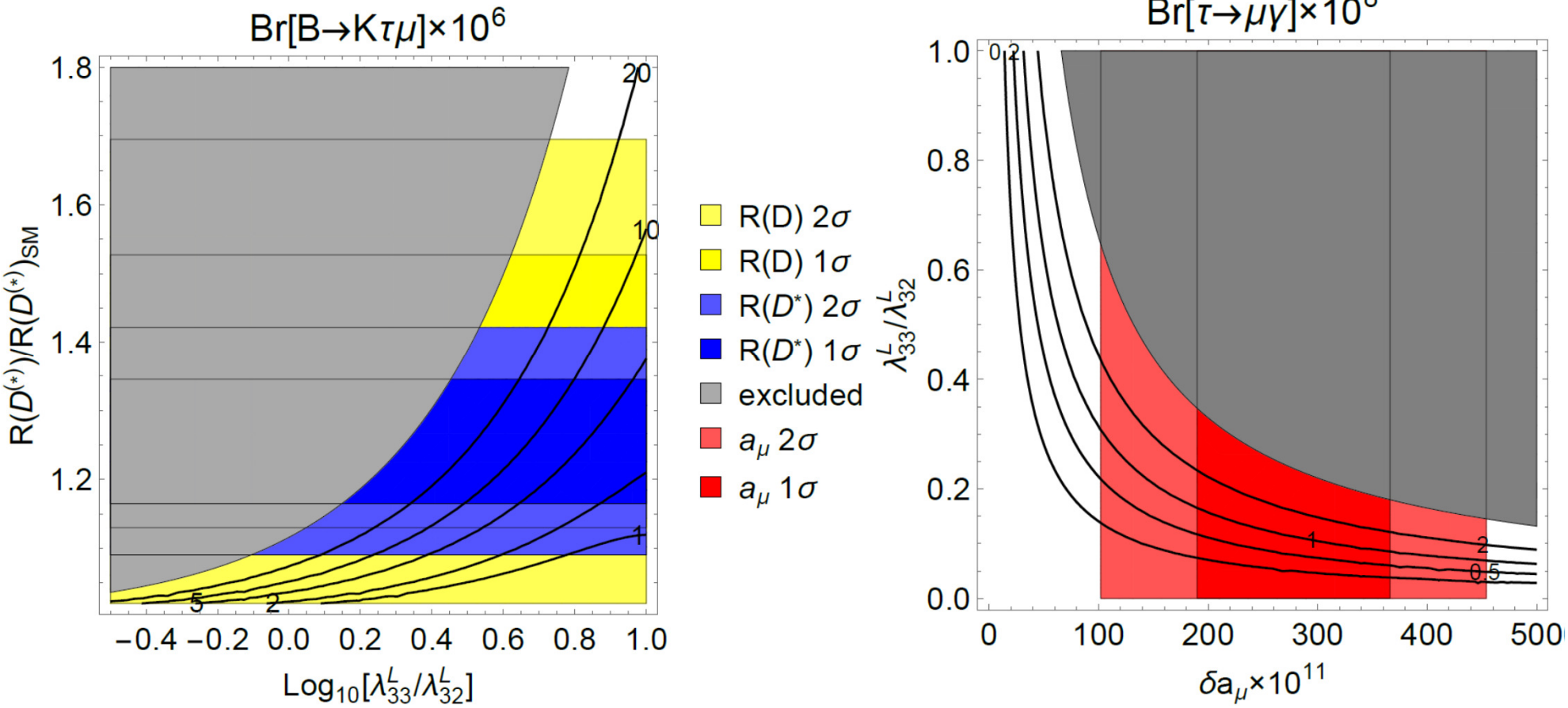
Simultaneous Explanation of R(D), R(D*), a_μ and $b \to s\mu\mu$

$R(D^{(*)})$, $b\to s\mu\mu$ and a_μ with LQs

- Scalar leptoquark singlet + triplet with Y=-2/3
- Cancelation in $b\to s\nu\nu$ imposed

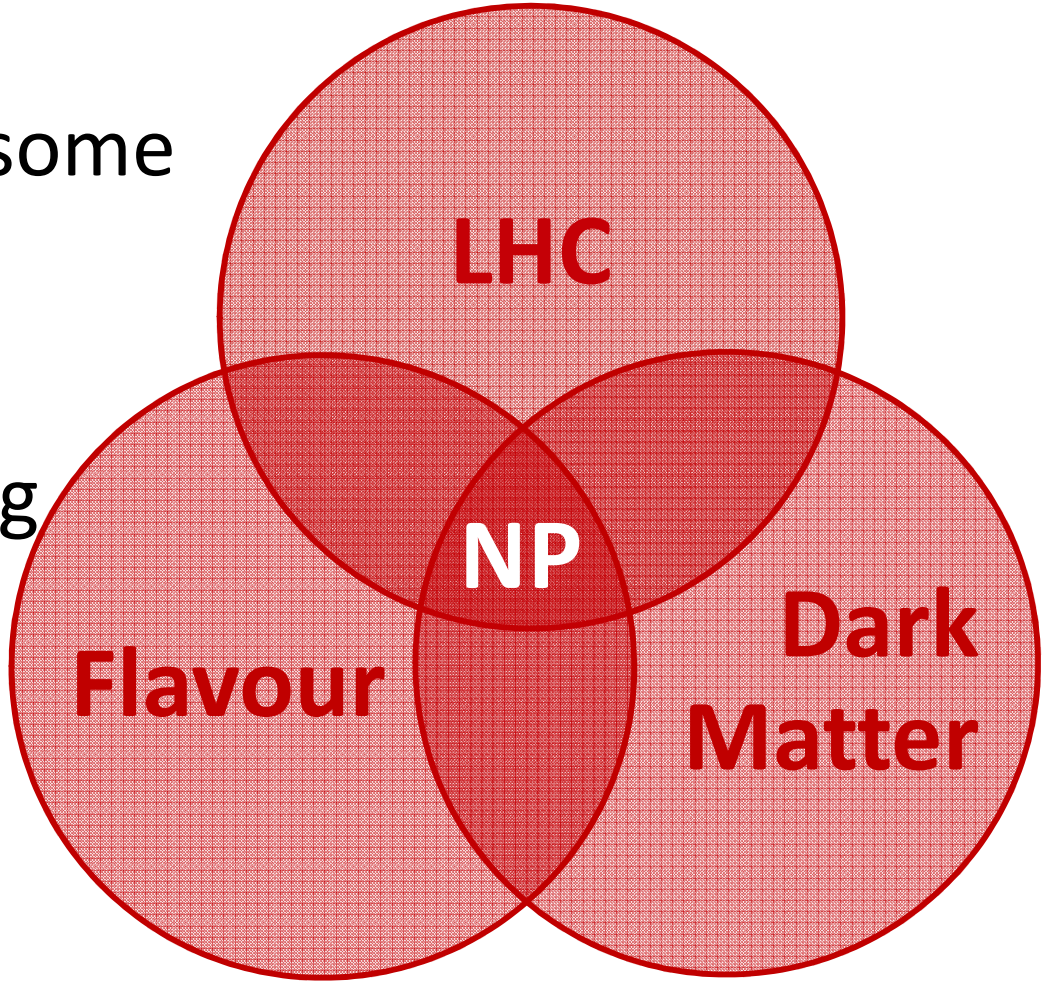


AC, D. Mueller, T. Ota arxiv:1703.09226

2 out of 3 can be explained

Conclusions

- Intriguing hints for Lepton Flavour Universality violating New Physics
- NP models can explain some of the anomalies simultaneously
- Confirming or disproving the anomalies makes a model selection
- Predictions for flavor and LHC observables



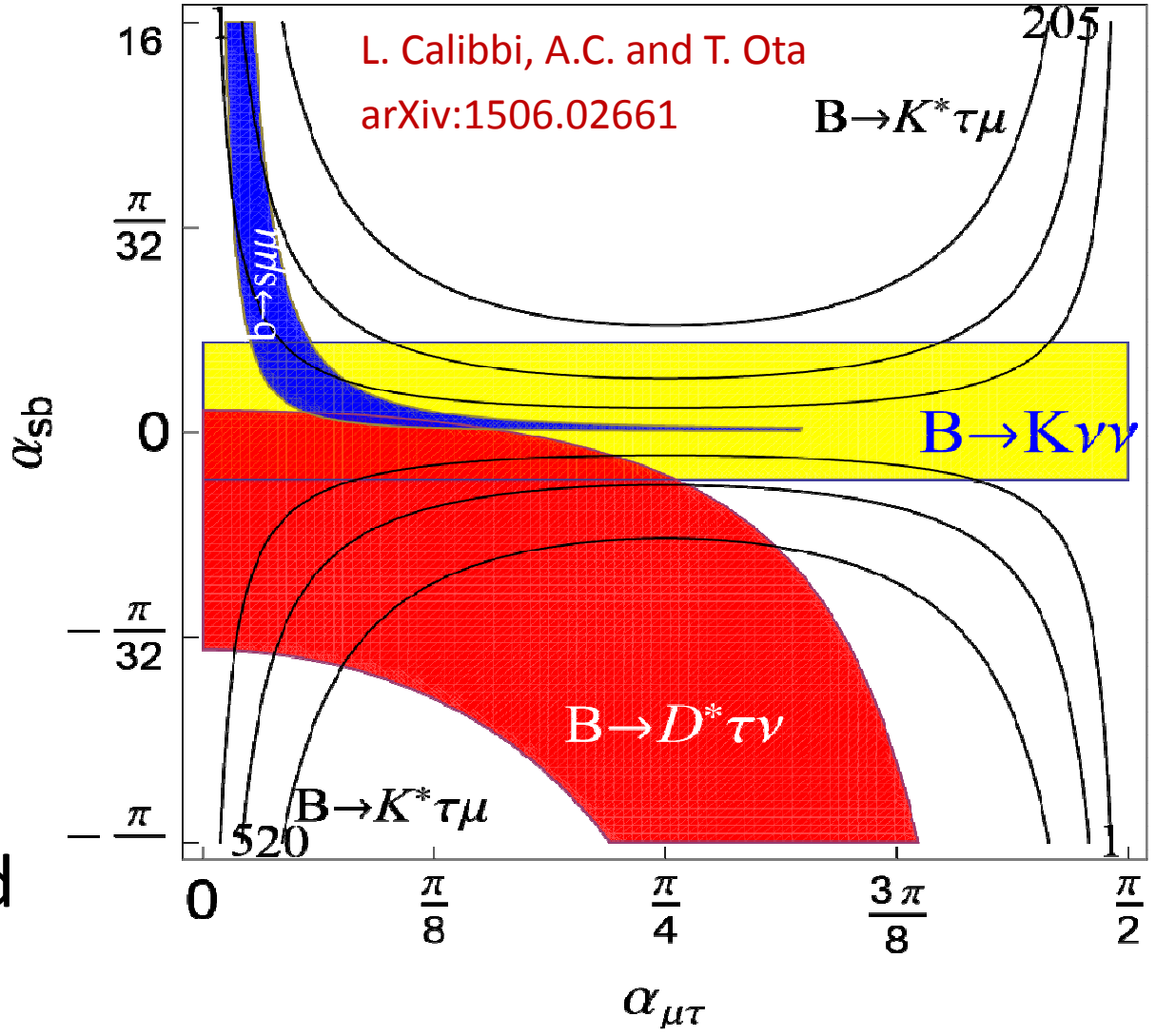
Exiting times in NP searches are ahead of us!

Leptoquarks in b→sμμ and b→cτν

Third generation couplings

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

α Misalignment between interaction and mass basis



Simultaneous explanation possible