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Explaining the Flavour Anomalies with New Physics

Corfu, 05.09.2017

Outline

- Introduction:

  New Physics and Flavour anomalies

  – $b \to s\mu\mu$

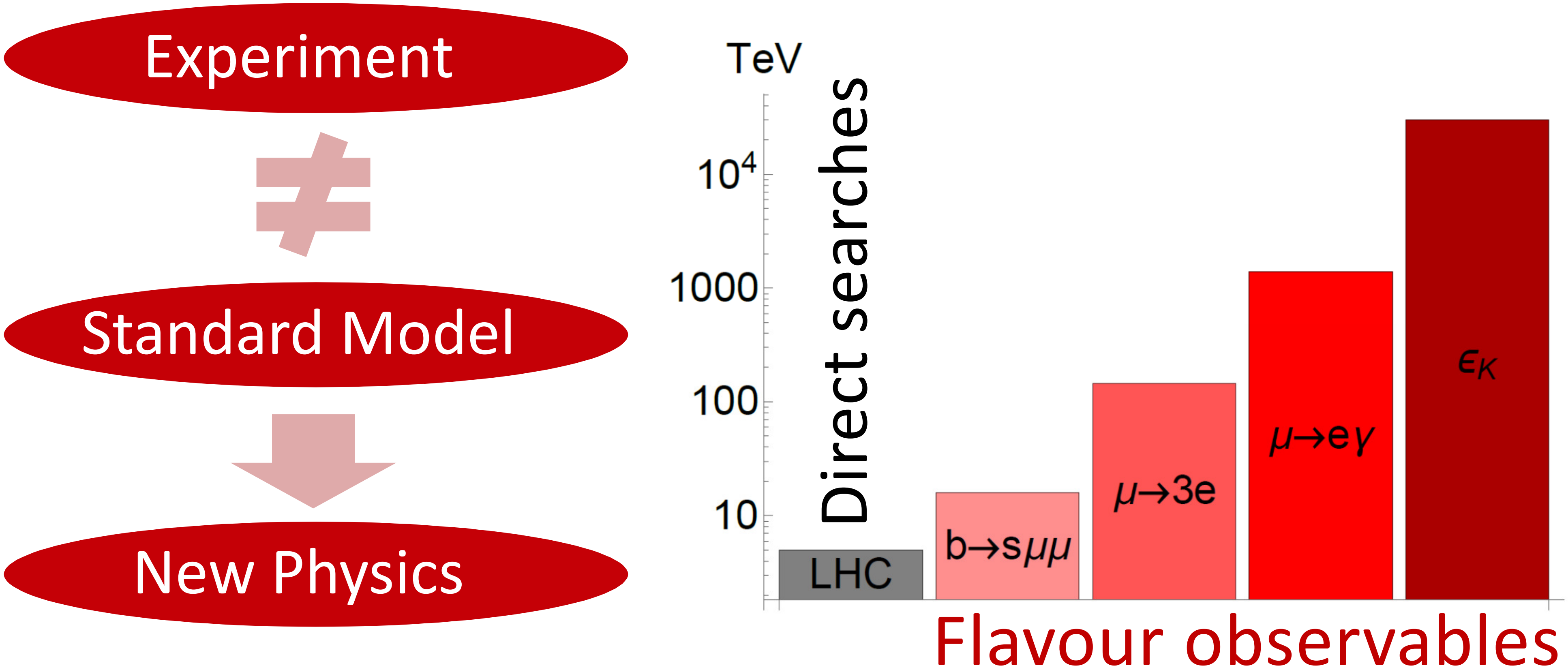
  – $b \to c\tau\nu$

  – a_μ

  – Z' explanations for $b \to s\mu\mu$
- Simultaneous explanations with LQs
- Conclusions

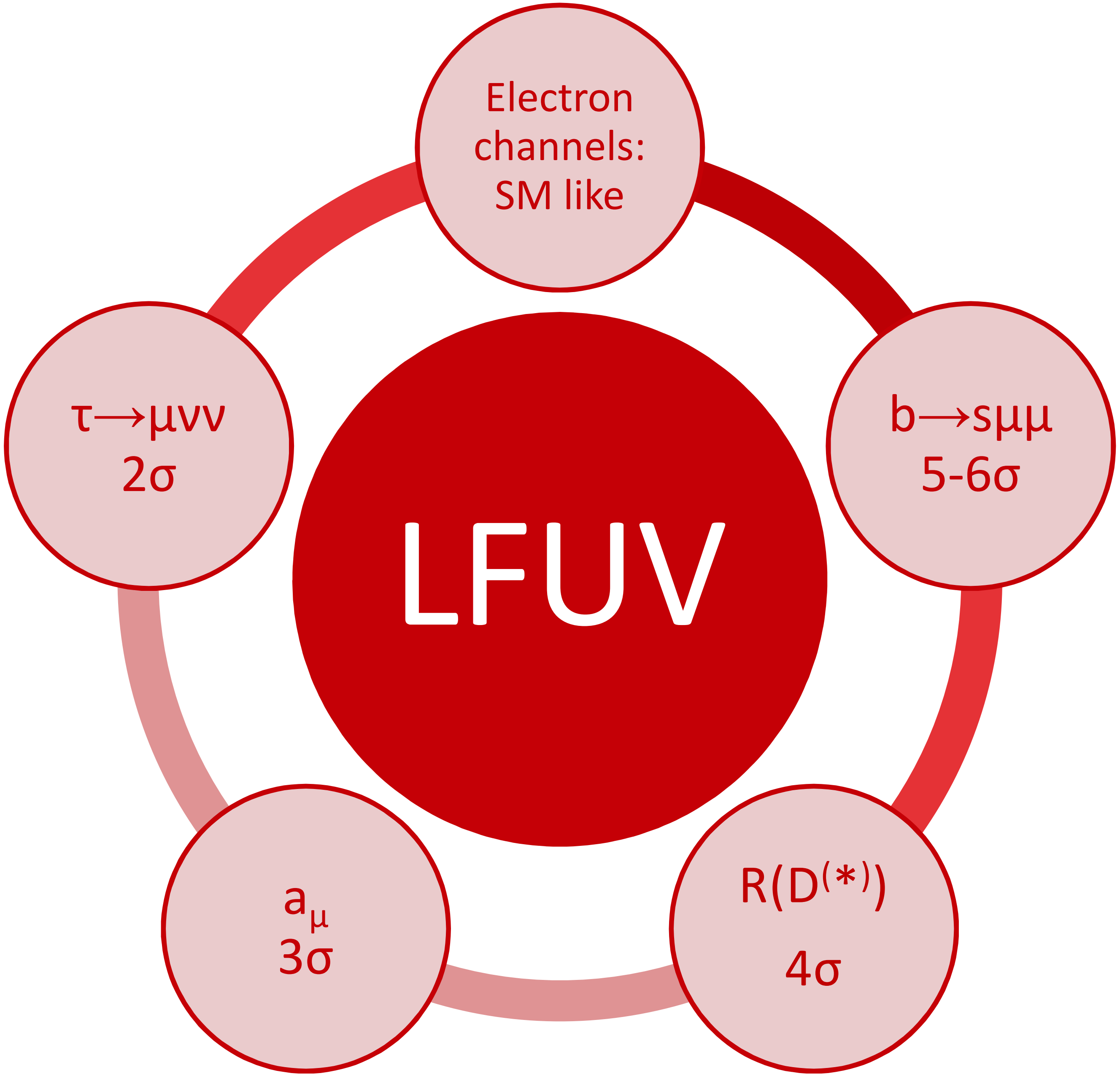
Finding NP in Flavour Observables

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



Flavour observables are sensitive to higher energy scales than collider searches

Hints for LFUV



Lepton Flavour Universality Violation (LFUV)

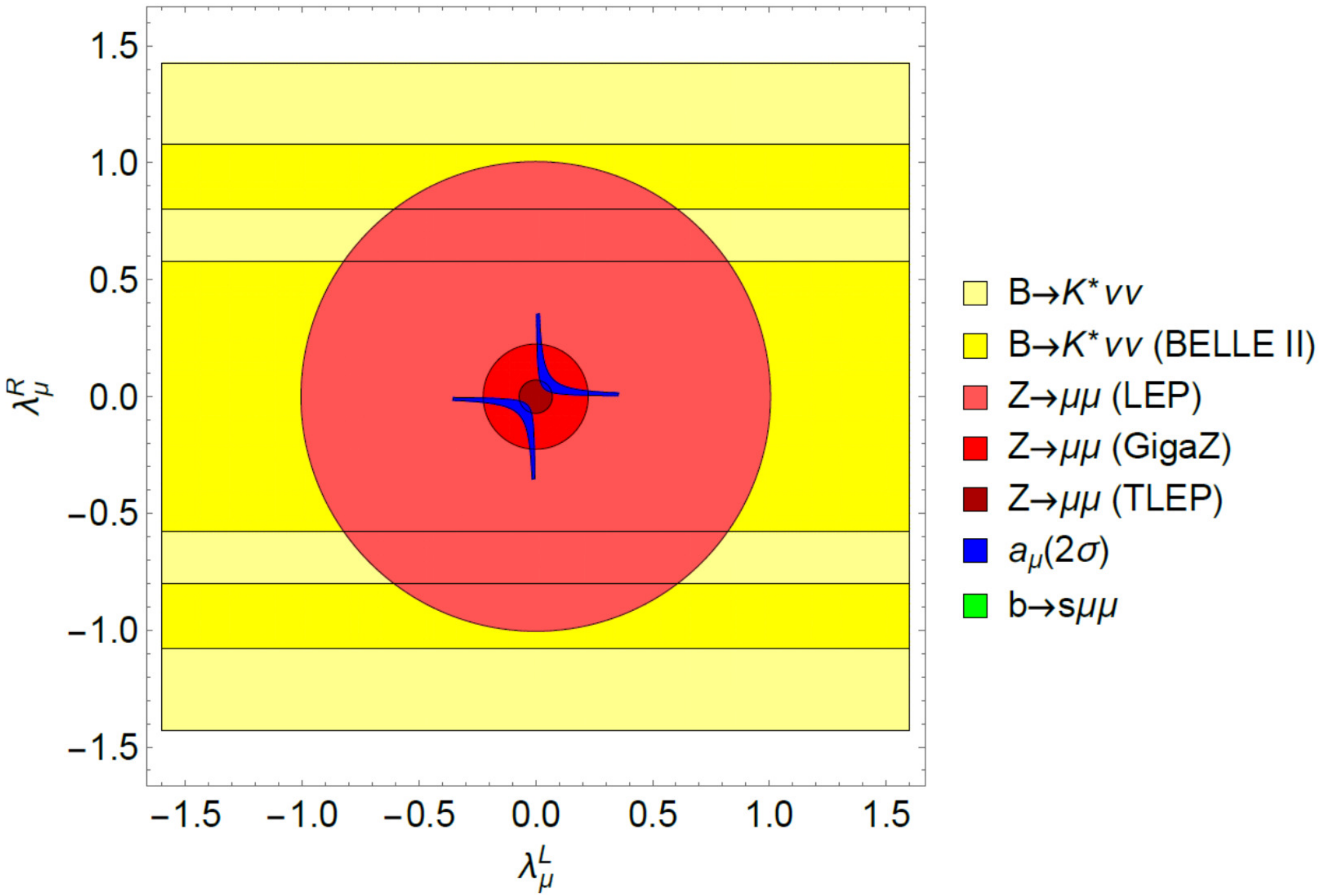
a_μ explanations

- MSSM e.g. D. Stockinger, hep-ph/0609168
  - tan(ß) enhanced slepton loops
- Scalars e.g. A. Broggio et at. arXiv:1409.3199 A.C. et al. arXiv:1507.07567
  - Light scalars with enhanced muon couplings
- Z' e.g. W. Altmannshofer, C. Chen, P.S.B. Dev, A. Soni, arXiv:1607.06832, …
  - Very light with τμ couplings (m_τ enhancement)
- Leptoquarks e.g. A. Djouadi, T. Kohler, M. Spira, J. Tutas, Z.Phys. C46 (1990)
  - m_t enhaned effects E. Leskow, A.C., G. D'Ambrosio, D. Müller arXiv:1612.06858

Chiral enhancement or very light particles

Scalar Leptoquarks in a_μ

- Chirally enhanced effects via top-loops



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

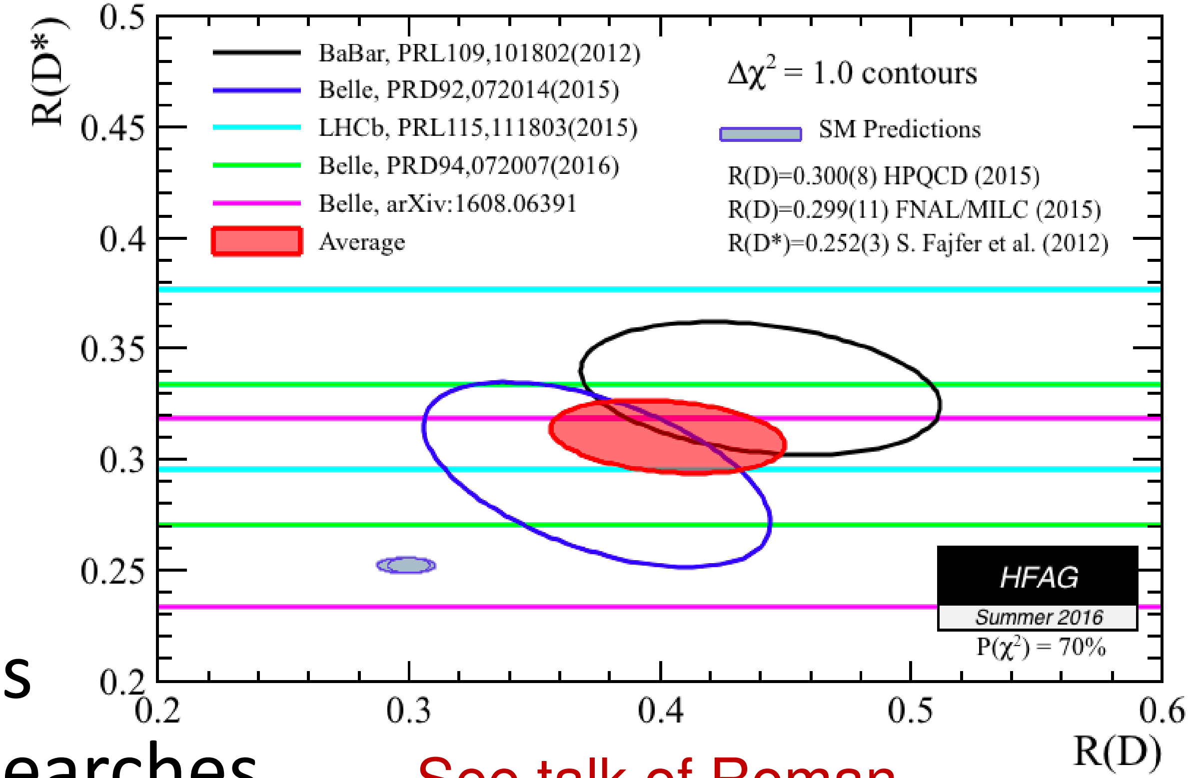
Left-, right-handed muons-top coupling

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

Z→μμ at future colliders

R(D) & R(D*)

- Charged scalars
  - Problems with q^2 distributions and B_c lifetime
- W'
  - Strong constraints from direct LHC searches
- Leptoquark
  - Strong signals in $qq \to \tau\tau$ searches



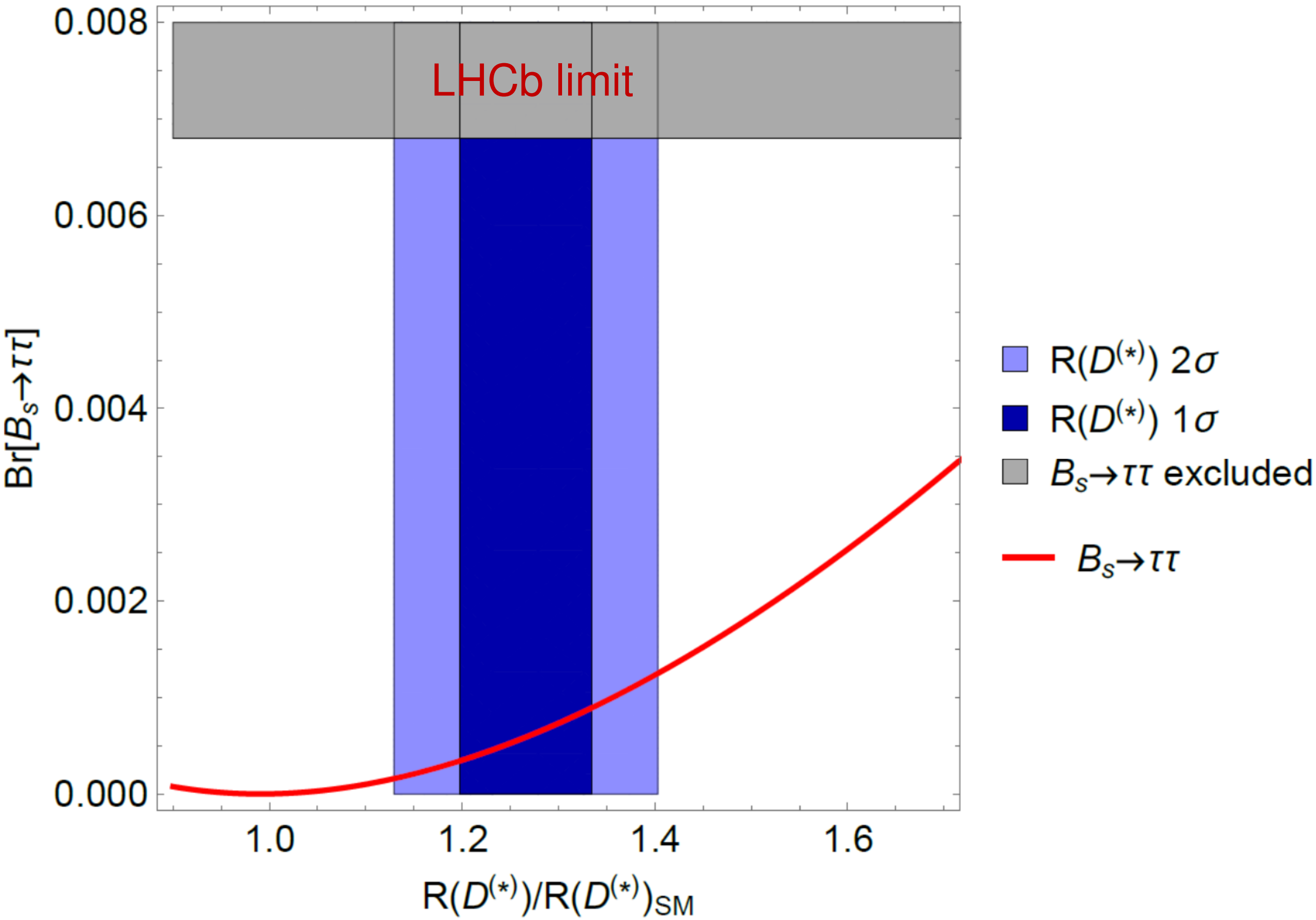
See talk of Roman

Faroughy et al. arXiv:1609.07138

Large tree-level effect needed
Explanation difficult

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

- Large couplings to the second generation needed in order avoid collider and EW precision bounds
- Cancellation in $b \to s\nu\nu$ needed: $C^{(1)} \approx C^{(3)}$



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

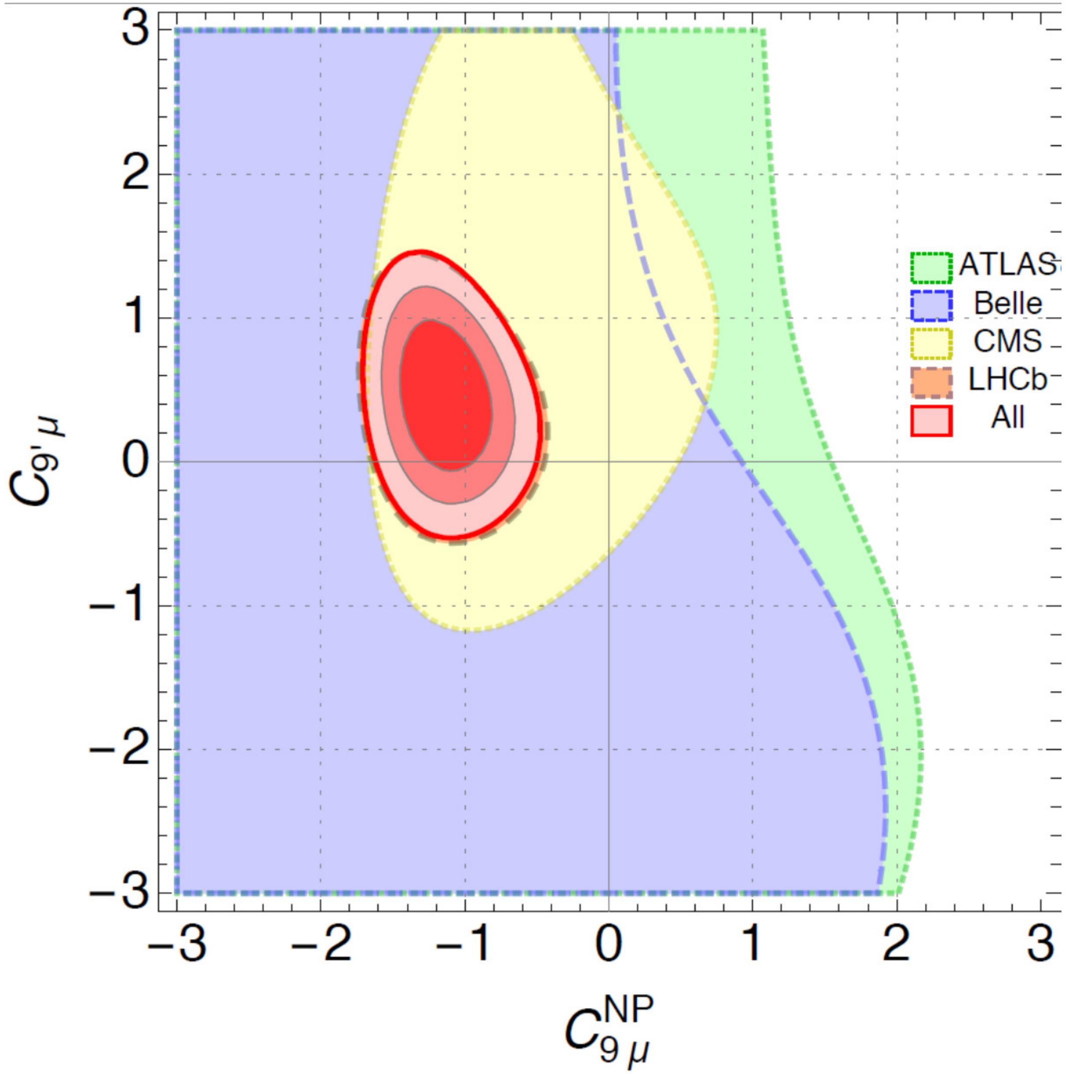
b→sμμ model-independent analysis

- Several 2-3σ deviations in more than 130 observables
  - P5'
  - R(K)
  - R(K*)
  - $B_s \to \phi\mu\mu$
- 6 NP operators

See talk of Nazila

$$O_{9\mu}^{(\prime)} = \bar{s}\gamma^{\mu}P_L b\,\bar{\mu}\gamma_{\mu}\left(\gamma^5\right)\mu$$

Model independent fit 4-6 σ better than SM



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

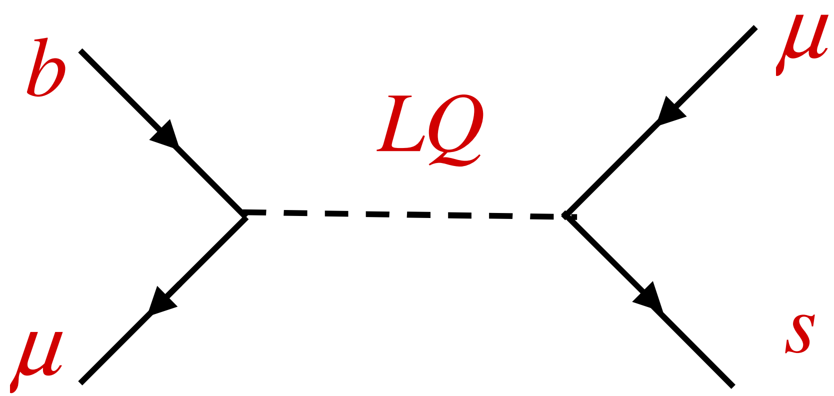
$b \to s\mu\mu$ explanations

- Z' See talk of Stephen King

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

- Leptoquarks

Gudrun Hiller, Martin Schmaltz
arXiv:1411.4773
B. Gripaios, M. Nardecchia, S.A. Renner.
arXiv:1412.1791
D. Bečirević, N. Košnik, O. Sumensari,
R. Zukanovich Funchal, arXiv:1608.07583
L. Calibbi, AC. T. Ota, PRL 2015
...



- Loop effects

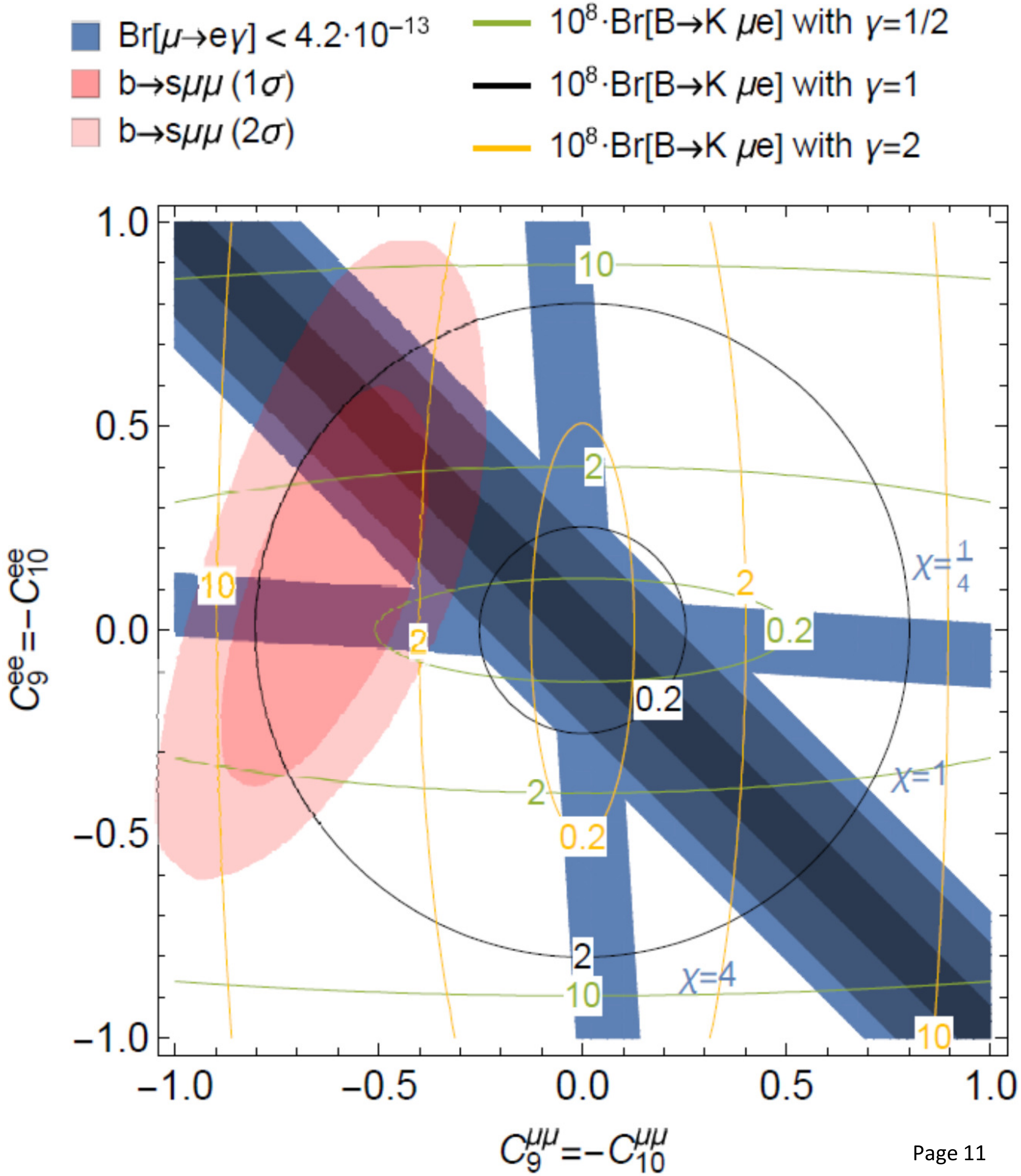
B. Gripaios, M. Nardecchia, S. Renner, arXiv:1509.05020

Even high scale NP explanations possible

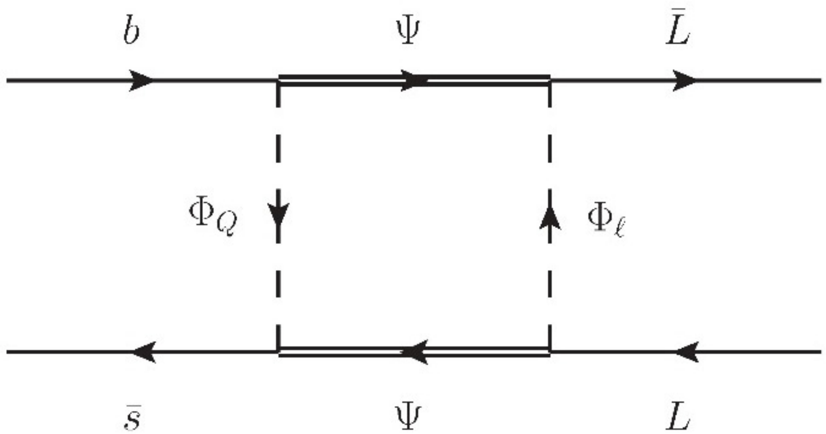
R(K), R(K*) and μ→eγ with LQs

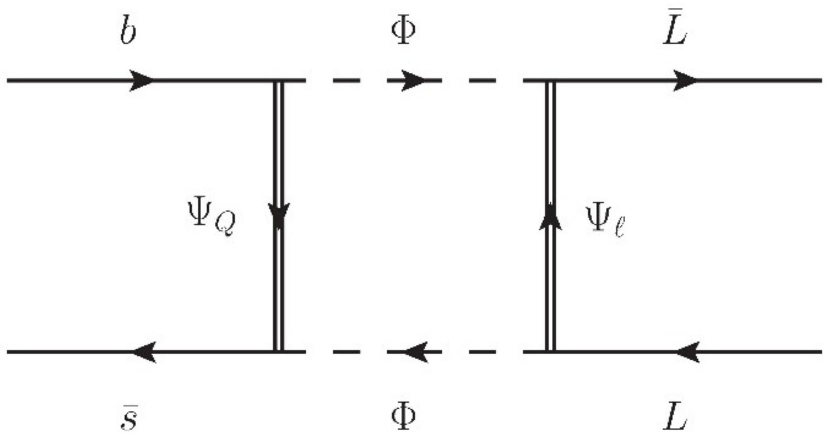
- Three LQs give a good fit
  - Scalar triplet
  - Vector singlet
  - Vector triplet
- Simultaneous effect in b→sμμ and b→see generate μ→eγ

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

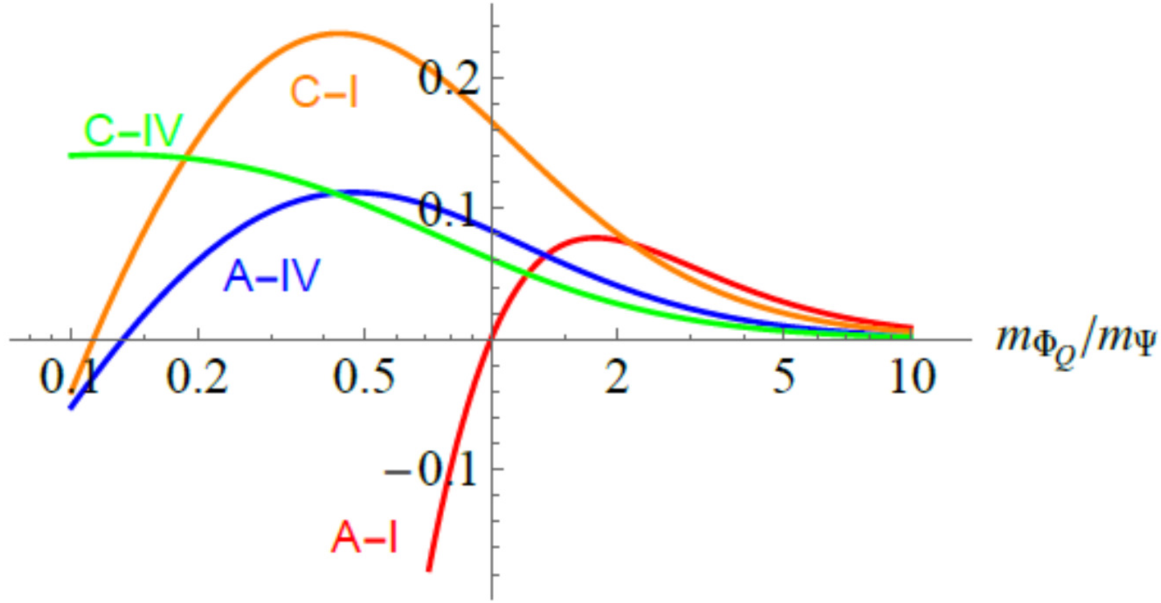
$SU(3)$	Φ_Q, Ψ_Q	Φ_ℓ, Ψ_ℓ	Ψ, Φ
A	3	1	1
B	1	$\bar{3}$	3
C	3	8	8
D	8	$\bar{3}$	3

2x6x4 possibilities

Pere Arnan, A.C., Lars Hofer and Federico Mescia, arXiv:1608.07832

b→sμμ and B_s mixing

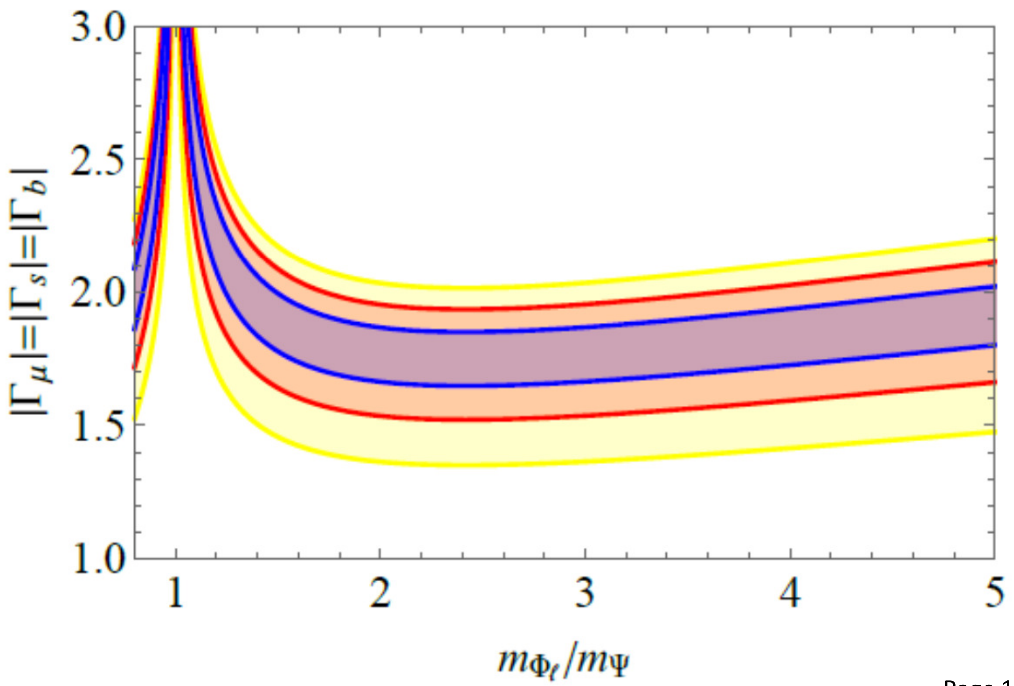
B_s mixing requires Majorana Fermions



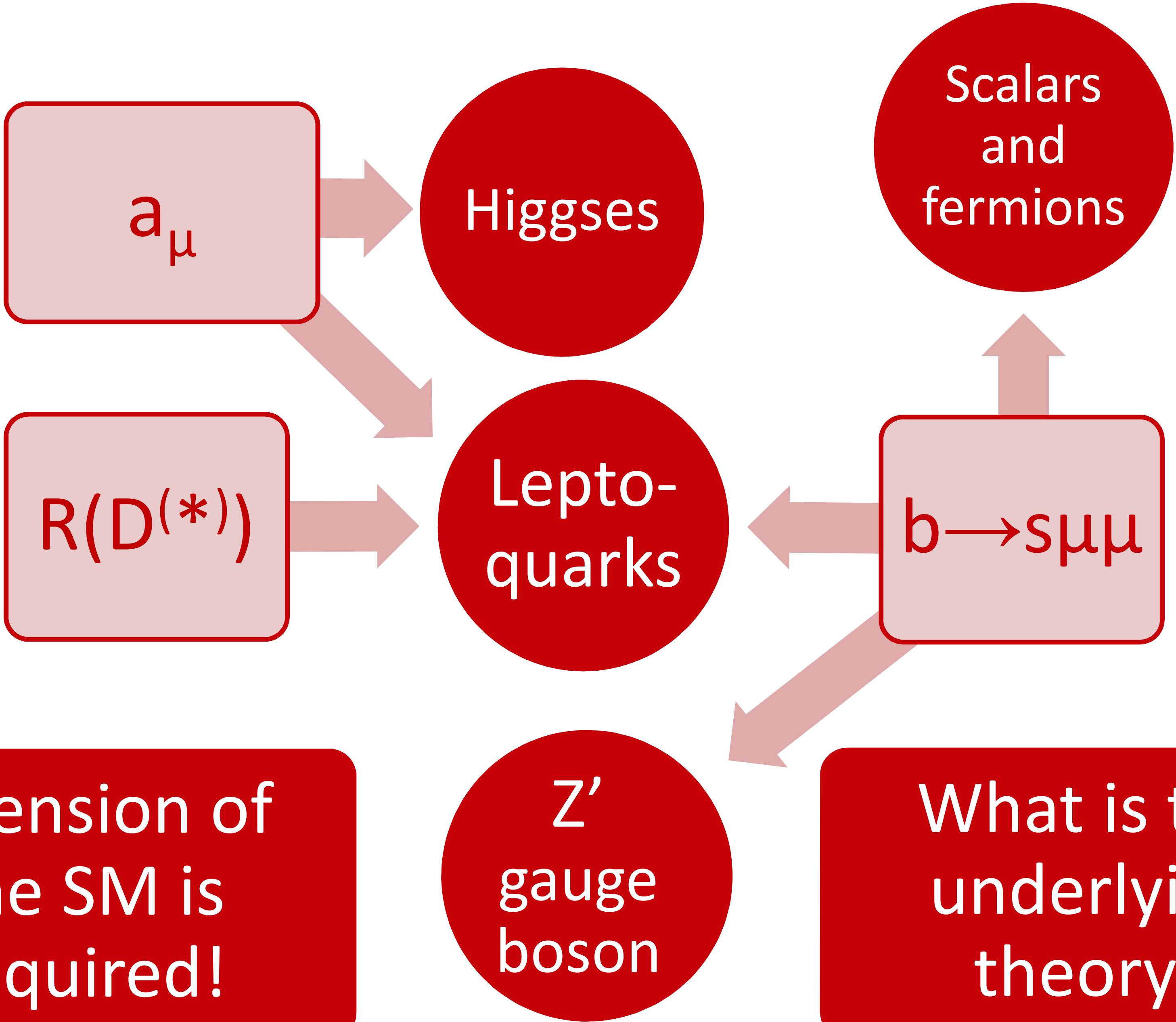
b→sμμ

	1σ		2σ
			3σ

Explanation with O(1) couplings



Implications for New Particles



Extension of the SM is required!

What is the underlying theory?

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Simultaneous Explanation of R(D), R(D*), a_μ and b→sμμ unsing Leptoquarks

Two Scalar Leptoquarks

AC, D. Mueller, T. Ota
arxiv:1703.09226
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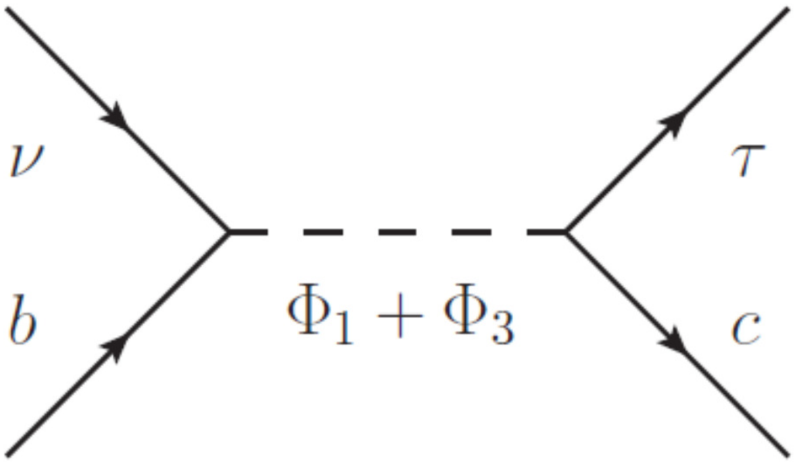
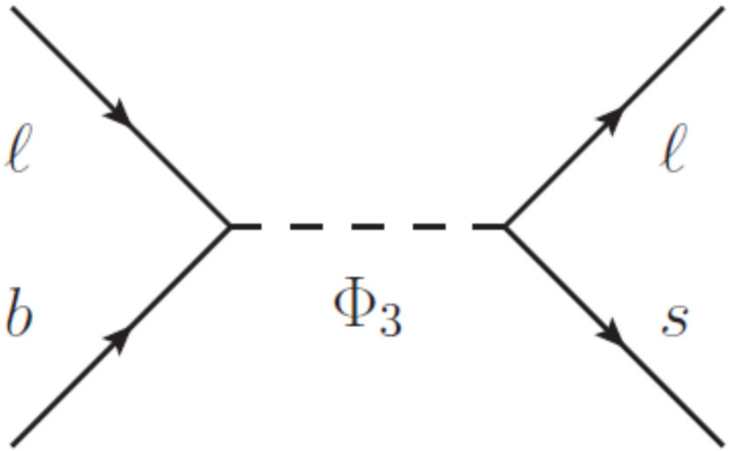
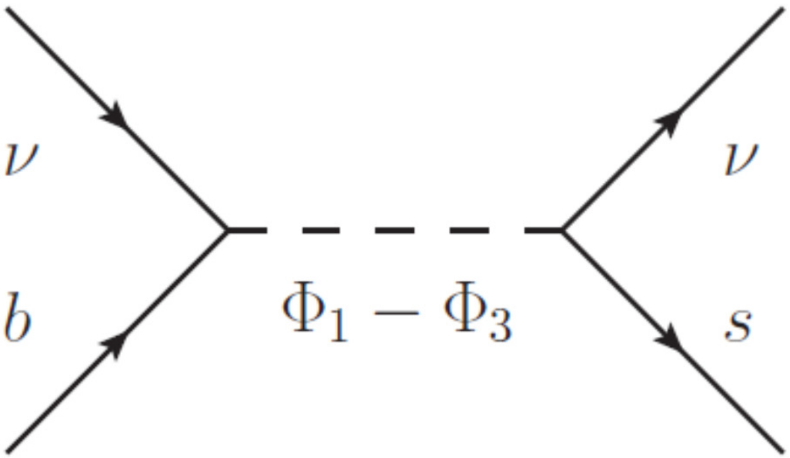
- Φ_1 scalar leptoquark singlet with Y=-2/3
- Φ_3 scalar leptoquark triplet with Y=-2/3



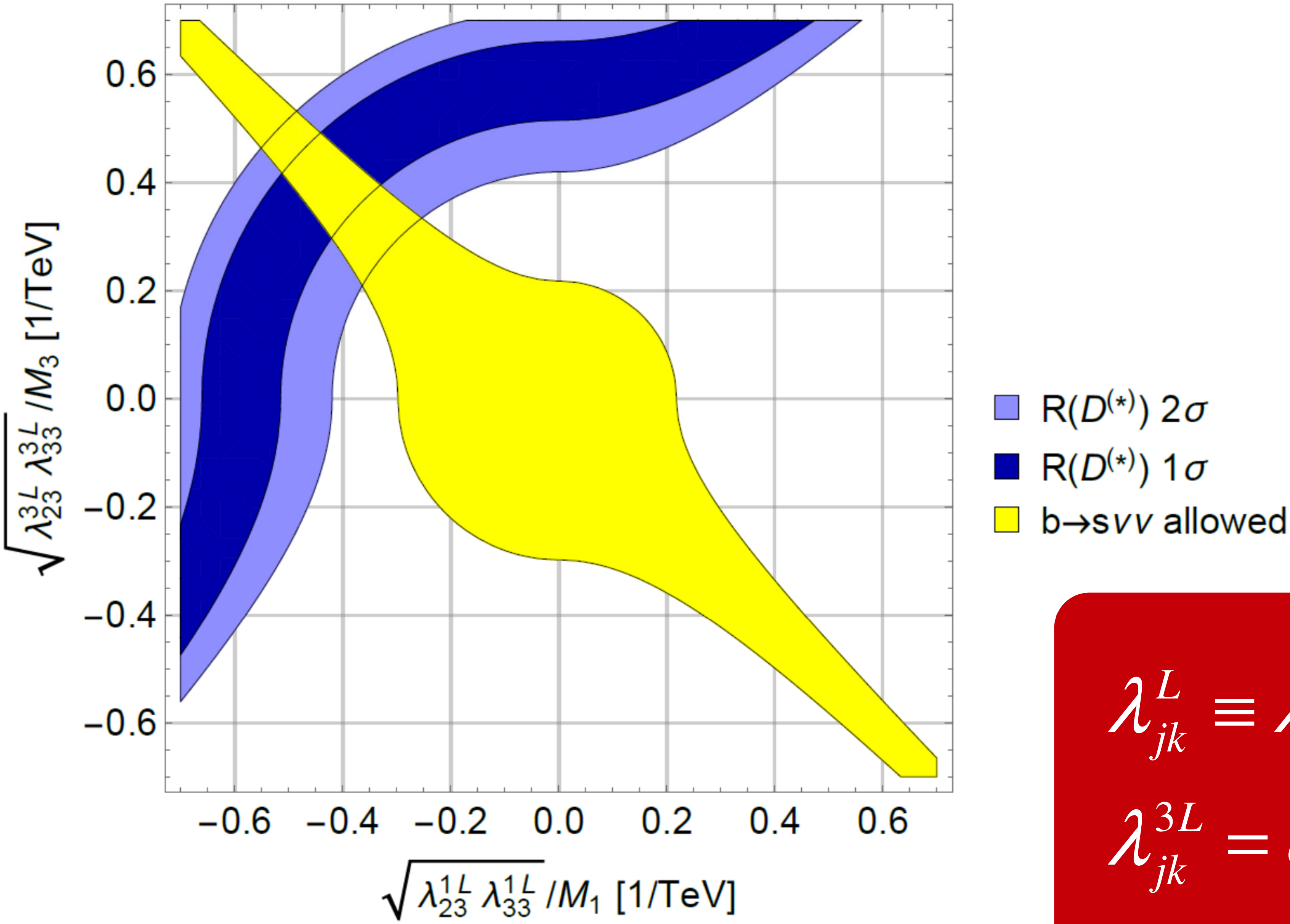




Constructive in R(D$^{(*)}$)

Destructive in b→sμμ

R(D$^{(*)}$), b→sνν with 2 Scalar LQs



$$\lambda_{jk}^{L} \equiv \lambda_{jk}^{1L}$$

$$\lambda_{jk}^{3L} = e^{i\pi j}\lambda_{jk}^{L}$$

R(D$^{(*)}$), b→sμμ and a_μ with 2 scalar LQs

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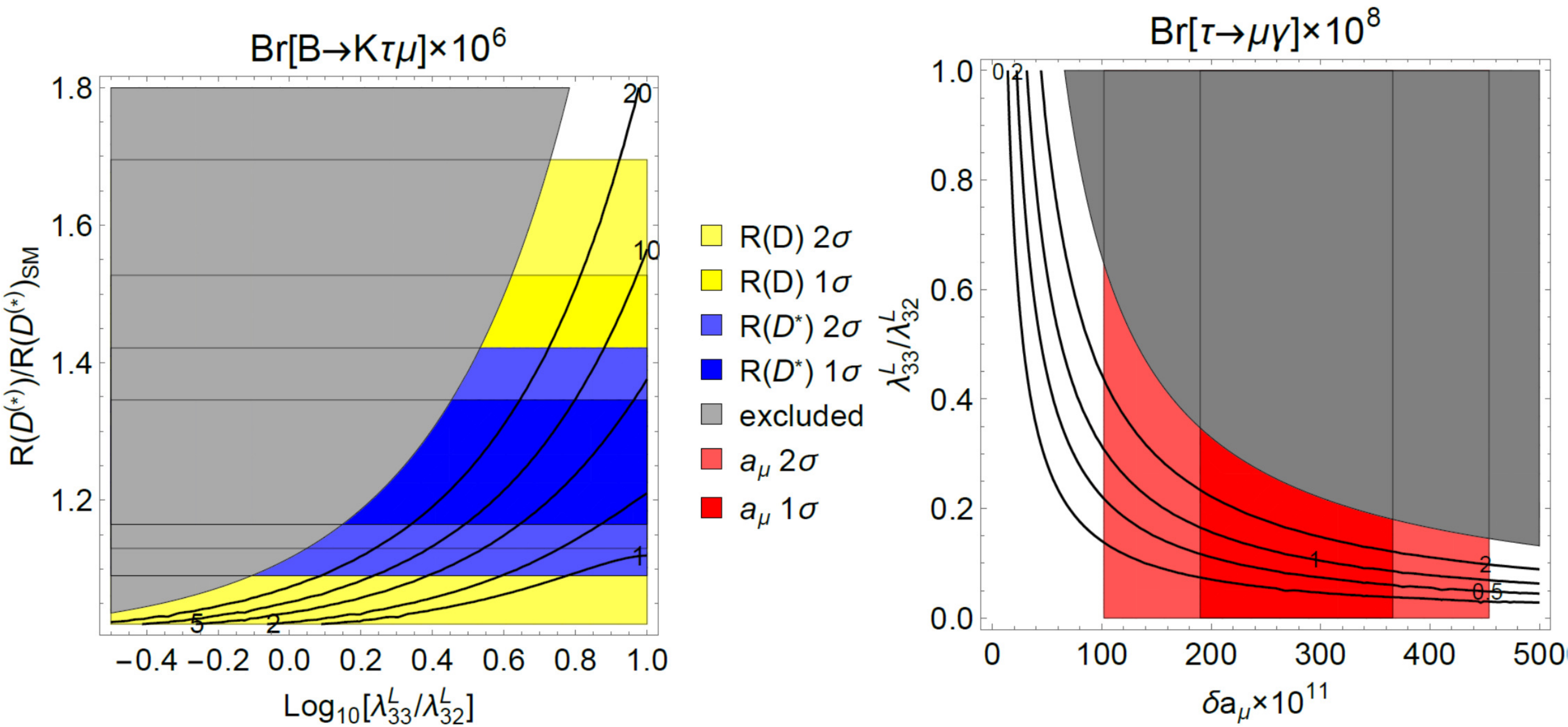
- Scalar leptoquark singlet + triplet with Y=-2/3
- Cancelation in b→sνν imposed



2 out of 3 can be explained

Vector Leptoquark SU(2) Singelet

- C_9=-C_{10} effect in b→sμμ
- Left handed vector current in R(D) and R(D*)
- No effect in b→sνν
- No proton decay
- Contained within the Pati-Salam model
- Massive vector bosons
  - Non-renormalizable without Higgs mechanism
  - Pati Salam not possible at the Tev scale because of K_L→μe and K→πμe

Good solution, but difficult UV completion

Pati-Salam + vector-like fermions

	$SU(4)$	$SU(2)_L$	$SU(2)_R$	$U(1)_{PQ}$
X_i^L	4	2	1	0
Y_i^L	4	2	1	0
Y_i^R	4	2	1	1
X_i^R	4	1	2	0
Z_i^R	4	1	2	0
Z_i^L	4	1	2	1
Σ	$\bar{4} \otimes 4$	1	1	- 1

L. Calibbi, AC and T. Li,
A model of vector leptoquarks in view of the B-physics anomalies
arXiv:1709.00692

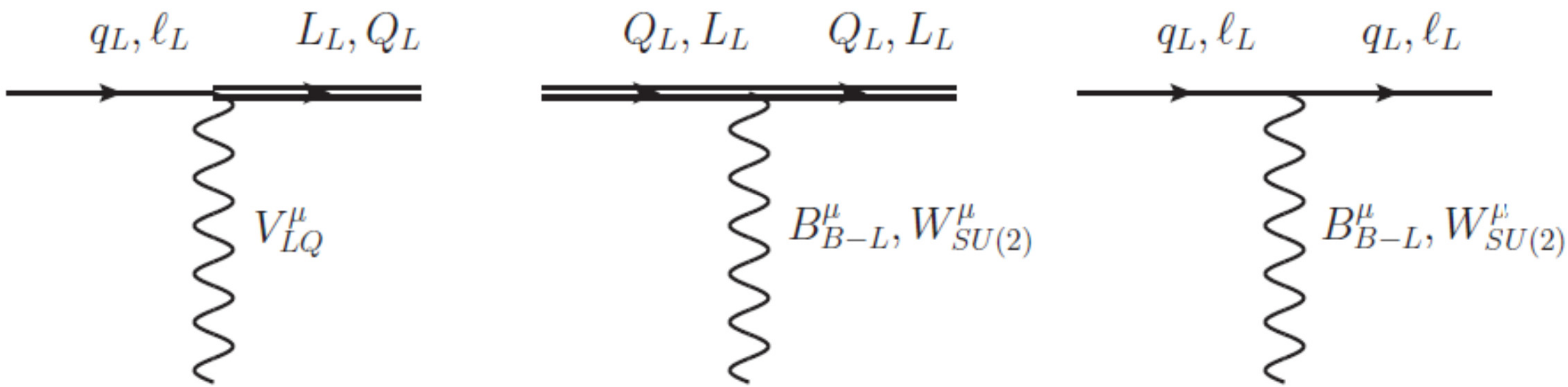
Pati-Salam + vector-like fermions

$$Y_R = \begin{pmatrix} Q'_R \\ L'_R \end{pmatrix}_i, \quad Y_L = \begin{pmatrix} Q_L \\ \ell_L \end{pmatrix}_i, \quad X_L = \begin{pmatrix} q_L \\ L_L \end{pmatrix}_i$$

$$L \supset -\left(m_{ij}^{Q} \overline{q}_{iL} + M_{ij}^{Q} \overline{Q}_{iL} \right) Q'_{jR} - \left(M_{ij}^{L} \overline{L}_{iL} + m_{ij}^{L} \overline{\ell}_{iL} \right) L'_{jR}$$

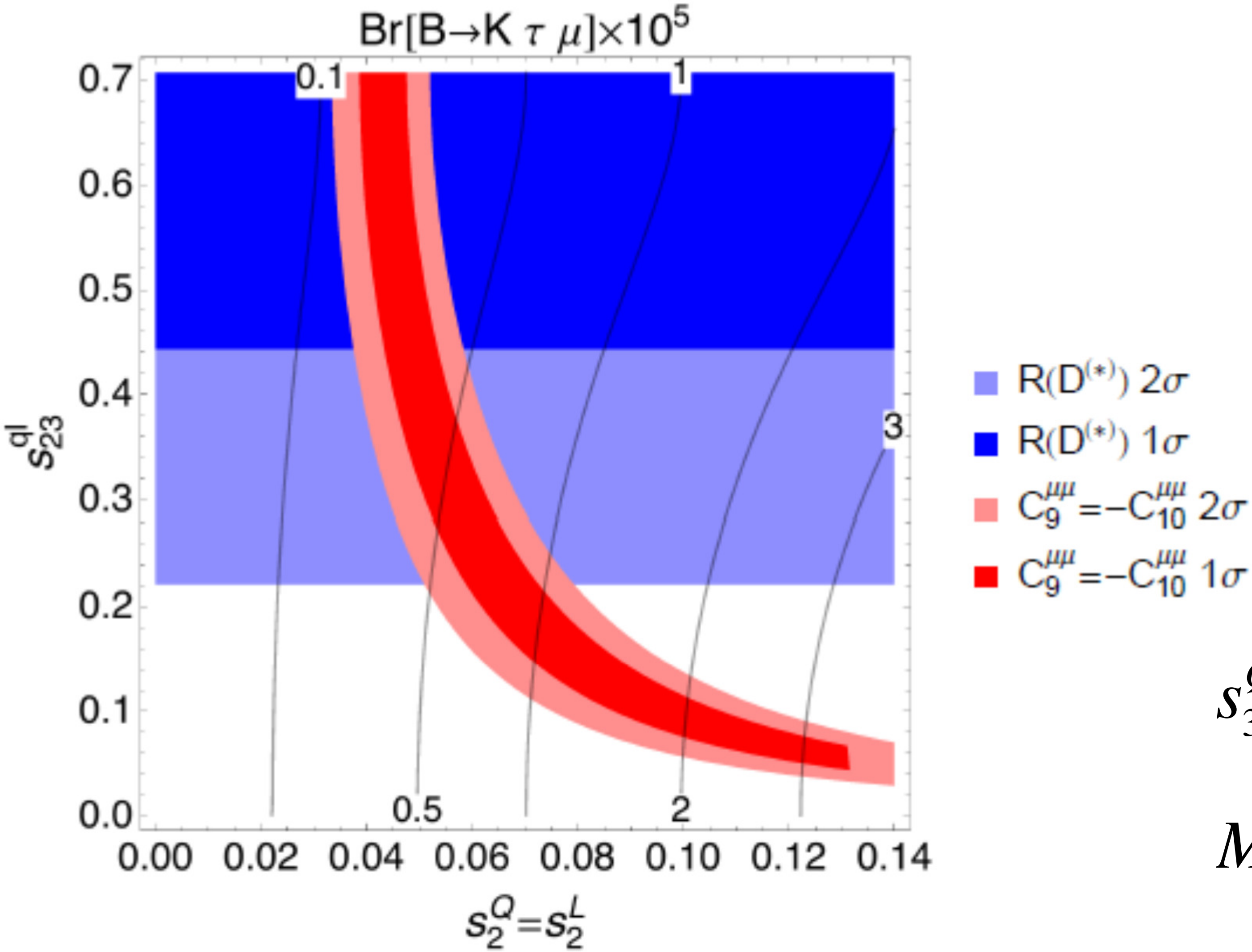
– 3 light generation (SM fermions)

– 3 heavy generation (vector like)



Only the LQ couples flavour violating

R(D$^{(*)}$) and b→sμμ



$$s_i^Q = \frac{\frac{m_{ii}^Q}{M_{ii}^Q}}{\sqrt{1 + \frac{m_{ii}^Q}{M_{ii}^Q}}}$$

$$s_3^Q = s_3^L = \frac{1}{\sqrt{2}}$$

$$M = 1.5\,TeV$$

Simultaneous explanation possible!
Can also account for the AMM of the muon

Outlook

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- P5' → $b \to d\mu\mu$
- R(D) & R(D*) → $b \to s\tau\tau$
- R(K) & R(K*) → $\mu \to e\gamma$
- R(D), R(D*) & a_μ → $\tau \to \mu\gamma$
- R(D), R(D*) & $b \to s\mu\mu$ → $b \to s\tau\mu$

Intersting experimental prospects

Conclusions

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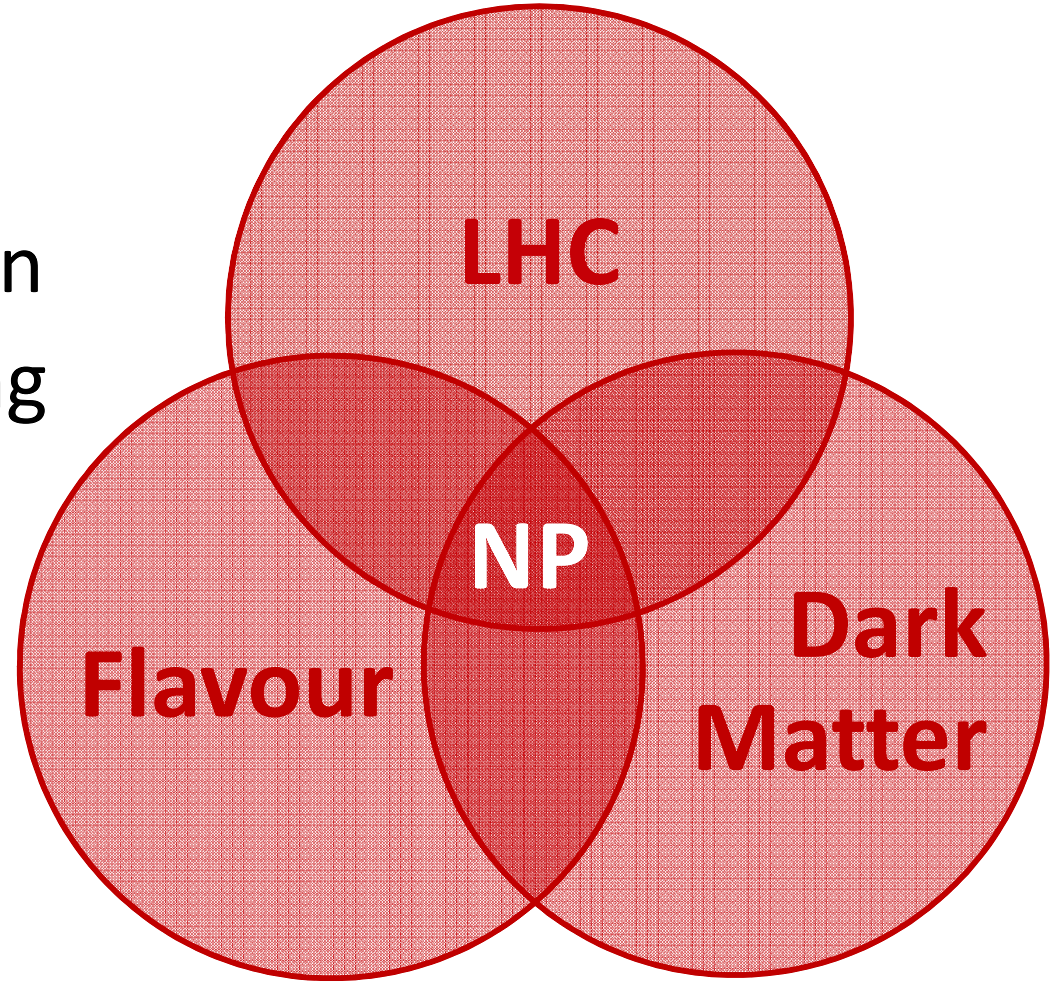
- Intriguing hints for Lepton Flavour Universality violating New Physics
- Leptoquarks are prime candidates for a solution
- Confirming or disproving the anomalies makes a model selection
- Predictions for flavor and LHC observables



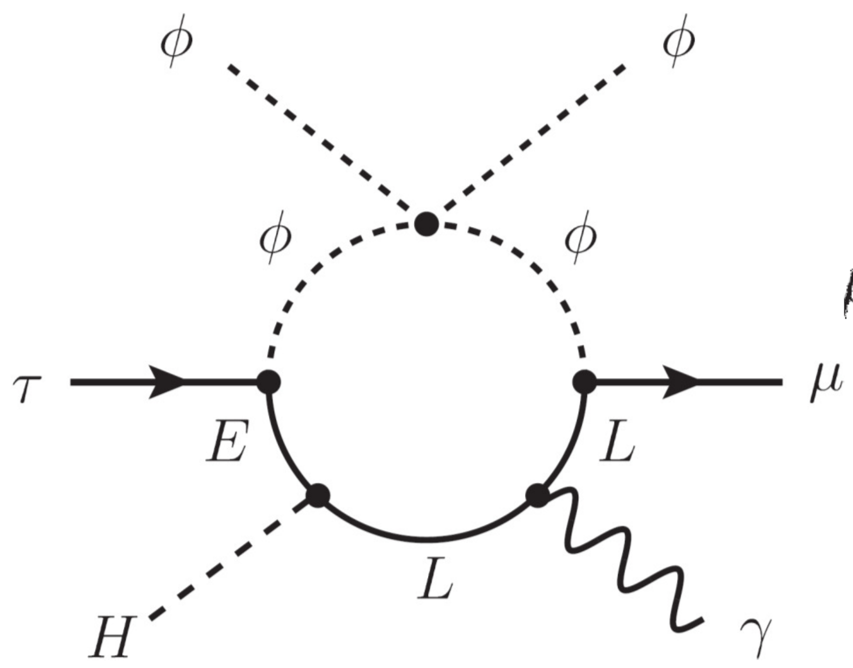
Exciting times in particle physics are ahead of us!

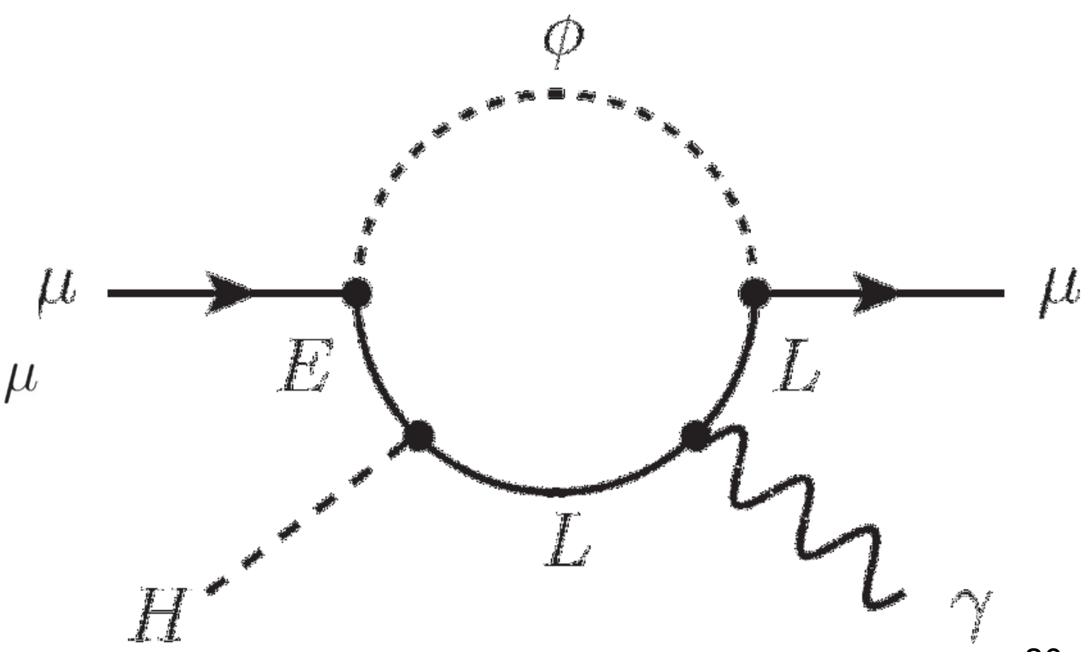
L_μ-L_τ model for a_μ

W. Altmannshofer, M. Carena, AC, 1604.08221

- L_μ-L_τ flavour symmetry
- Flavon couples to μ and τ
- $\tau \to \mu\gamma$ is protected
- a_μ is not protected
- Effects in $h \to \mu\mu$

Explanation of a_μ and b→sμμ





Solution with horizontal U(1) charges

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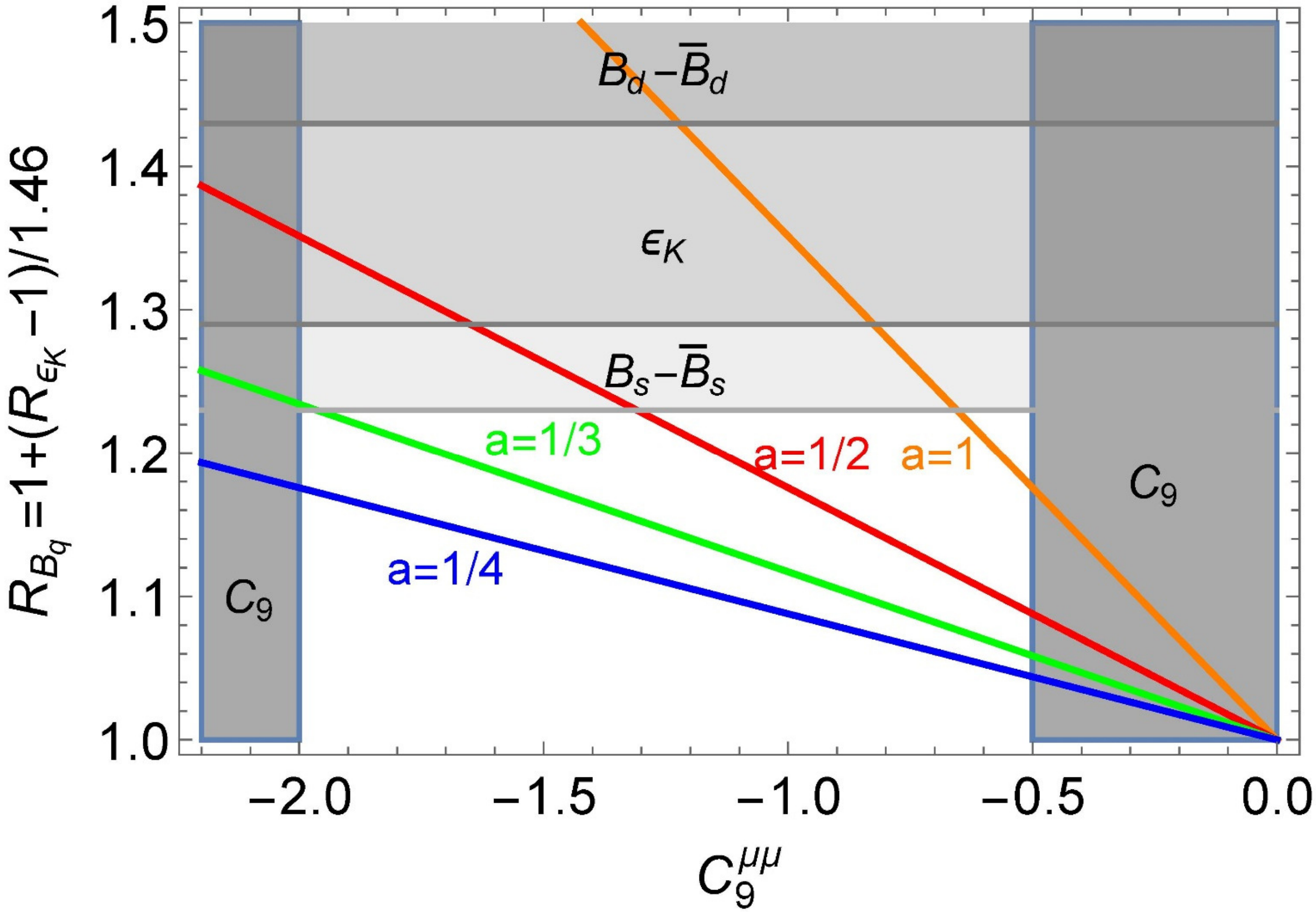
- Avoid vector-like quarks by assigning charges to baryons as well
  - Same mechanism in the quark and lepton sector
- L_μ-L_τ in lepton sector
  - Good symmetry for the PMNS matrix
  - Effect in $C_9^{\mu\mu}$ but not C_9^{ee}
- First two quark generations must have the same charges because the large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

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

ΔF=2: Z' contribution

$$R_{B_q} = \frac{\Delta m_{B_q}}{\Delta m_{B_q}^{SM}}$$

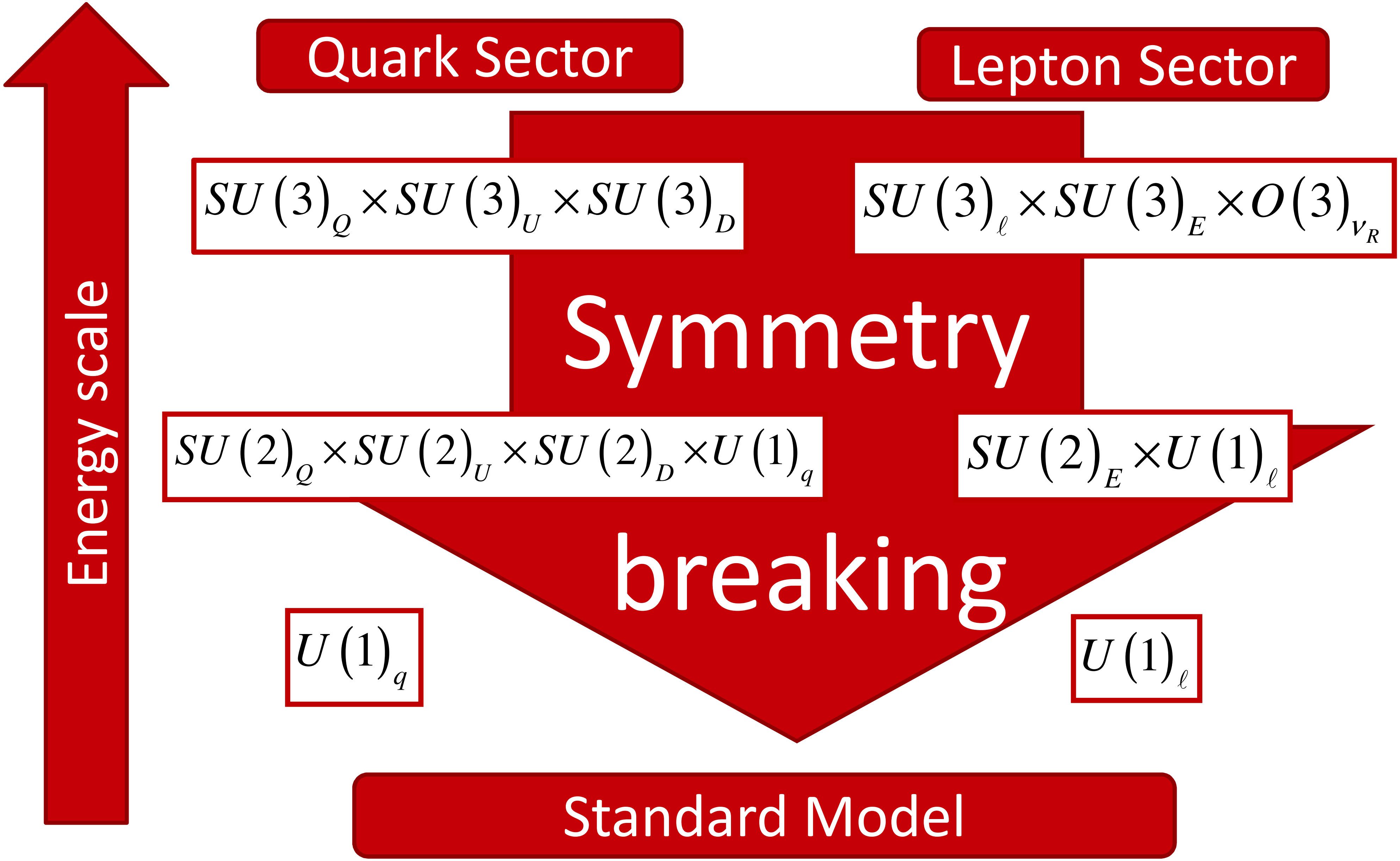
$$R_{\varepsilon_K} = \frac{\varepsilon_K}{\varepsilon_K^{SM}}$$



Necessarily constructive, but Higgs effects and be destructive.

Dynamical explanation of the charges

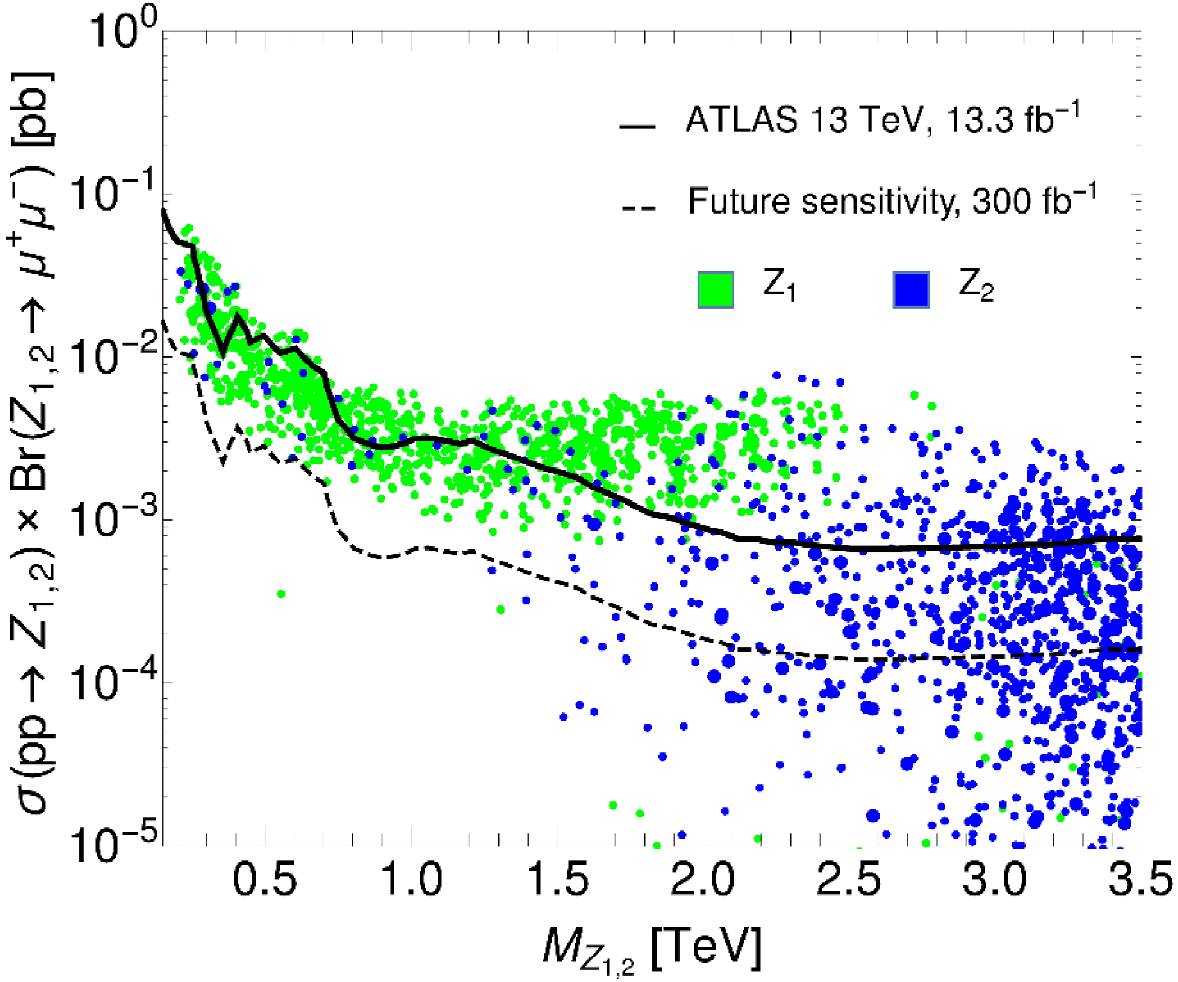
A.C., J. Fuentes-Martin, A. Greljo and G. Isidori arXiv:1611.02703



Solution with two Z's

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

Low energy phenonenology unchanged



Different collider signatures