PAUL SCHERRER INSTITUT

PSI

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Theory Group of the Laboratory for Particle Physics

Explaining the flavour anomalies with Leptoquarks

Obergurgel, 16.04.2018

Outline

- Introduction: The flavour anomalies
  - $b \to s\mu^+\mu^-$
  - $b \to c\tau\nu$
  - Anomalous magnetic moment of the muon a_μ

  Talks of Uli, Regis, Stefano, Vincenzo, …
- Simultaneous explanations with leptoquarks
  - 2 scalar leptoquarks
  - Vector leptoquark; gauged
  - Vector leptoqaurk; composite
- Conclusions and outlook

Physics Beyond the Standard Model

- Dark Matter existence established at cosmological scales

  Thursday session

  – New weakly interacting particles
- Neutrinos not exactly massless

  Talk of Frank Deppisch

  – Right-handed (sterile) neutrinos
- Matter anti-matter asymmetry

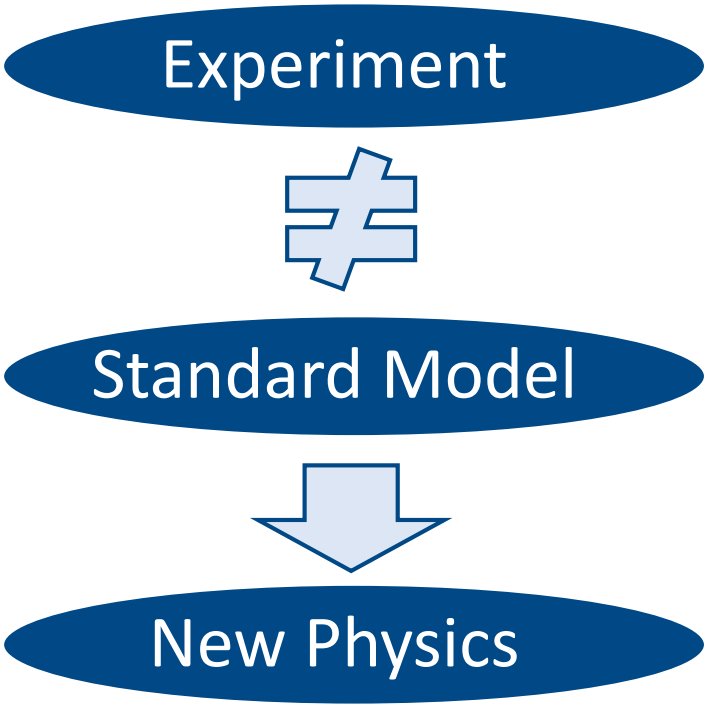
  – Additional CP violating interactions

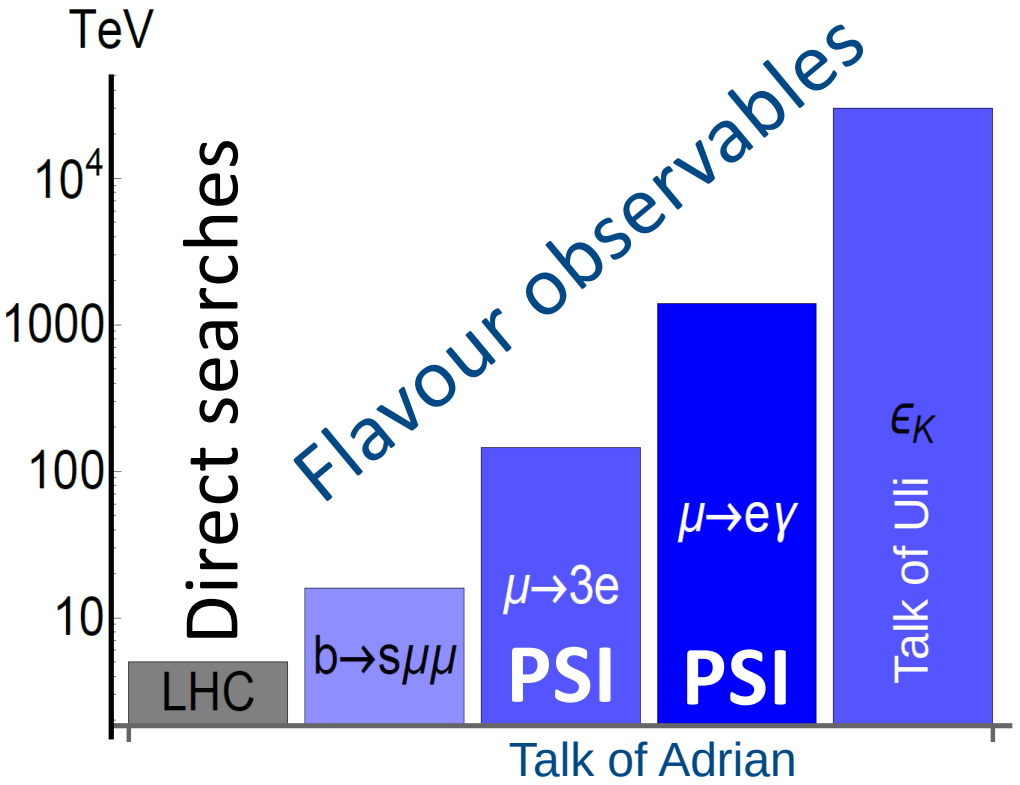
New particles and interactions exist!

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

Finding New Physics with Flavour

- 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

New Physics in the Flavour Sector

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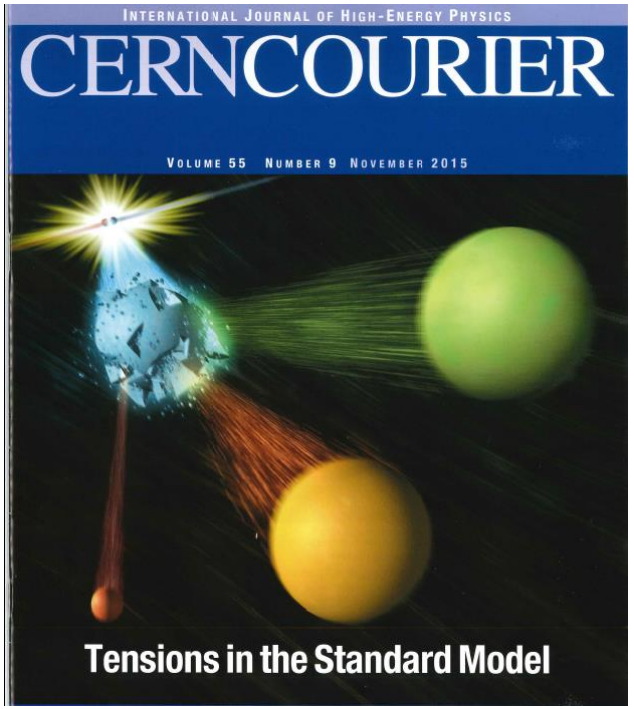
2 Accelerators Find Particles That May Break Known Laws of Physics

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

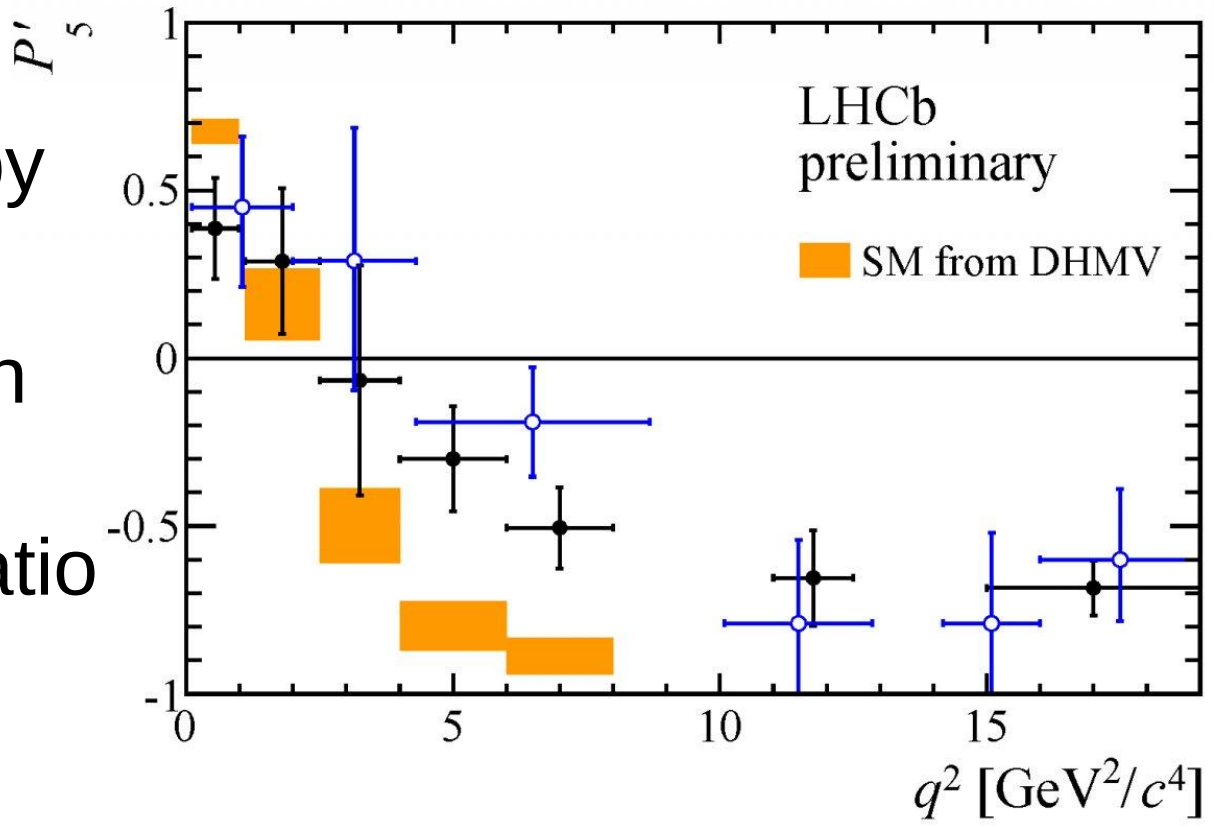
Three independent B-meson experiments suggest that the charged leptons may not be so equal after all.

Steven K. Blau 17 September 2015

Hints for New Physics in flavour observables

$P5'$ and $B_s \to \phi\mu\mu$

- LHCb 3σ deviation from the SM
- Confirmed by BELLE
- 2σ tension in the $B_s \to \phi\mu\mu$ branching ratio



Hadronic uncertainties or NP?

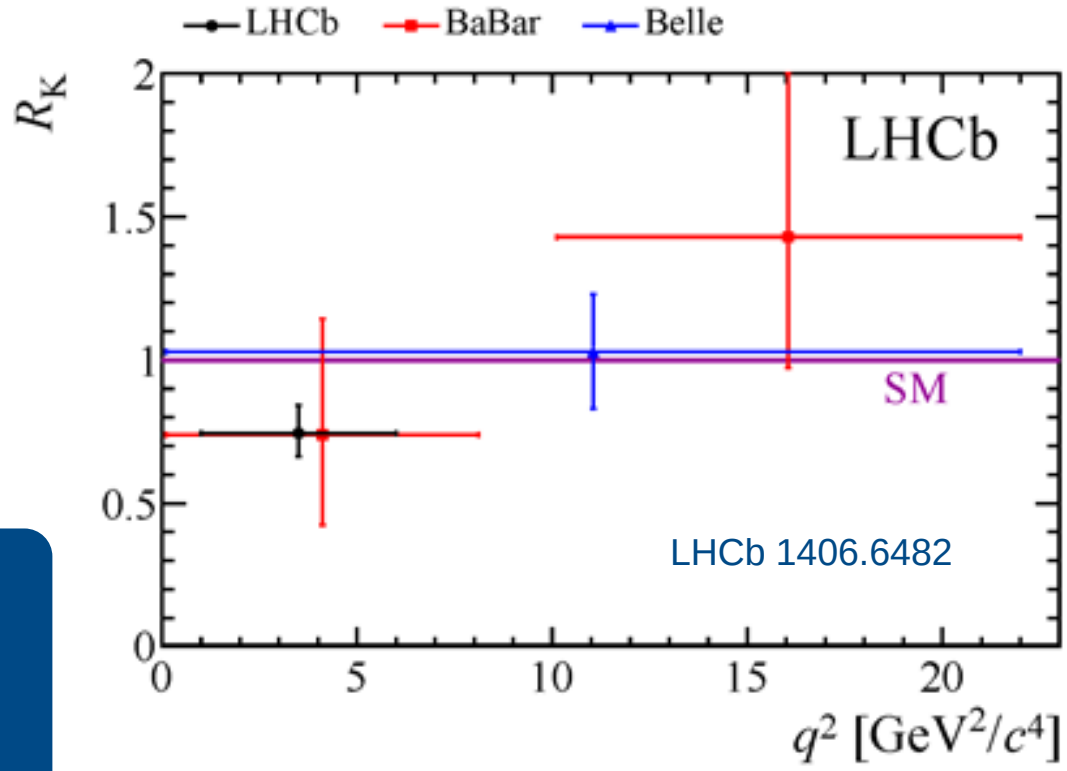
R(K) = B→Kμμ/B→Kee

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

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

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

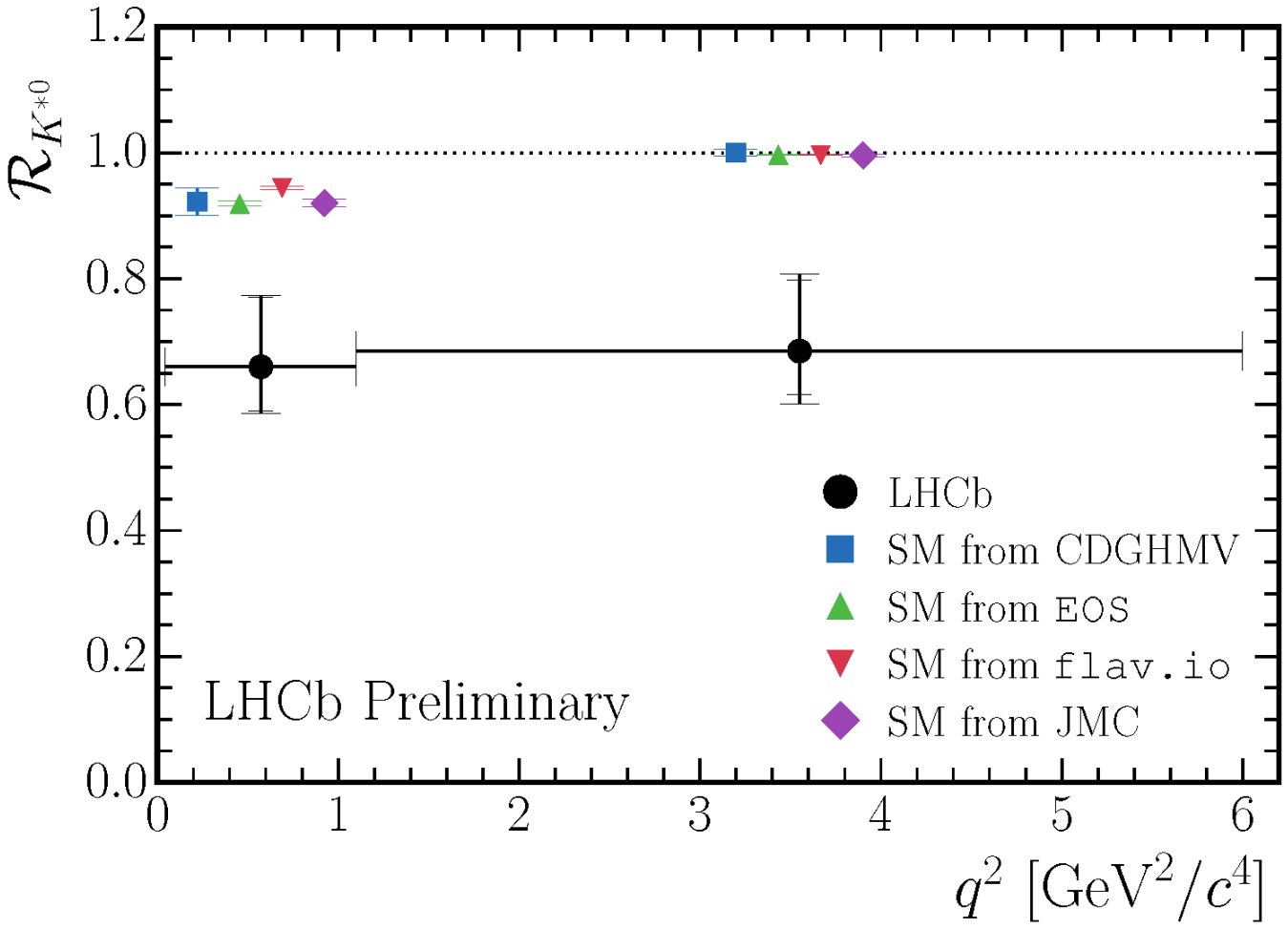
$$R_K^{\mathrm{exp}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$



Lepton Flavour Violation in B decays?

R(K*) = B→K*μμ/B→K*ee

- 2.2-2.4 σ in two bins

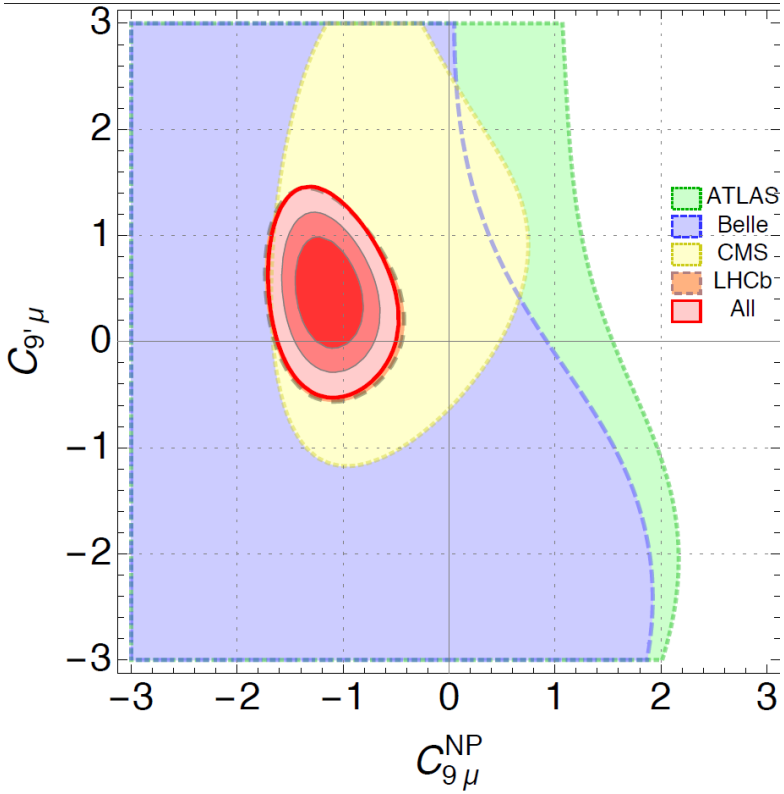


Global fit to b→sμμ data

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

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

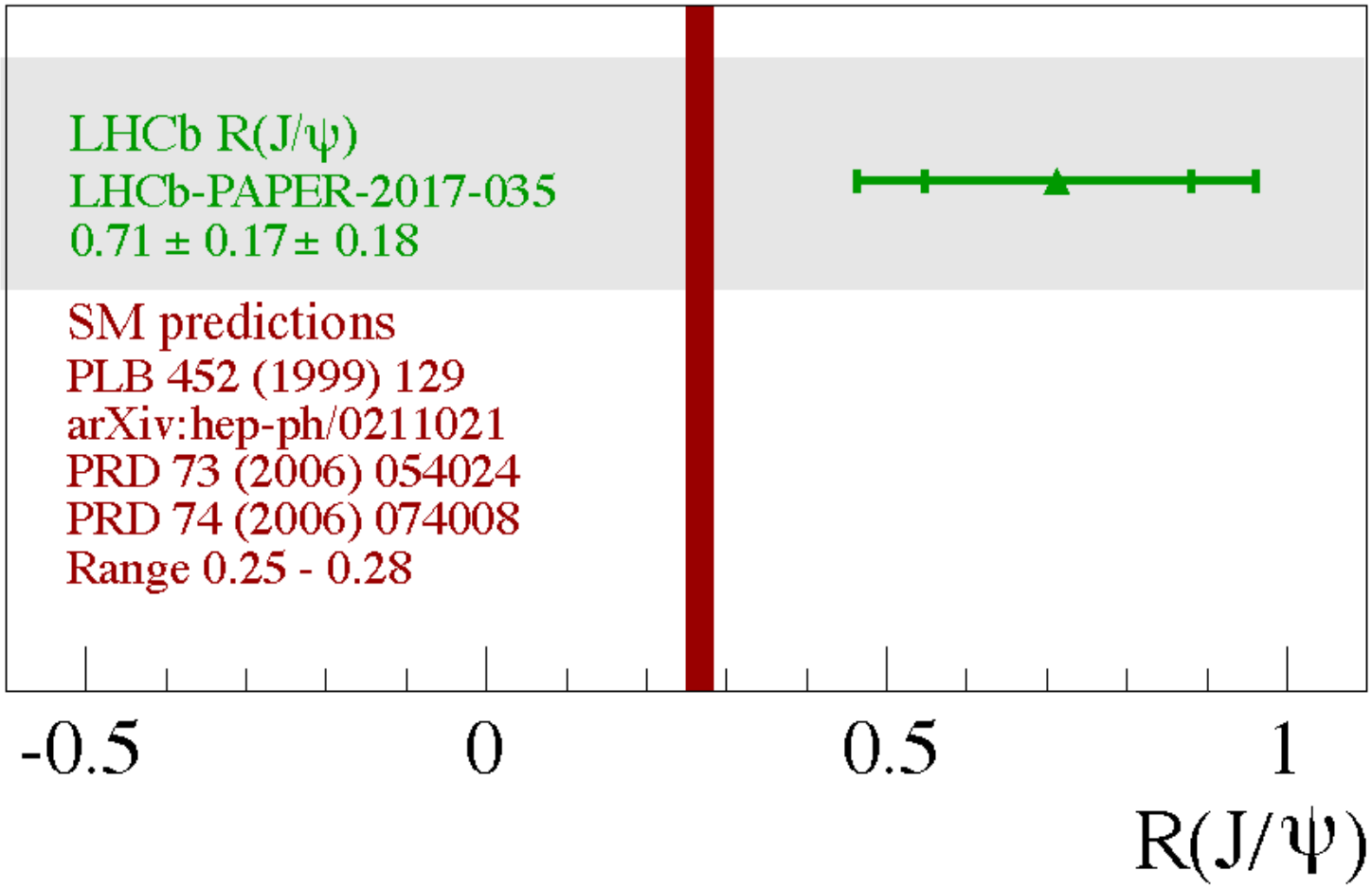
$$O_{10} = \bar{s}\gamma^\mu P_L b \bar{l}\gamma_\mu \gamma^5 l$$



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

Fit is 5-6 σ better than the SM

b→cτν processes



All measurements above the SM prediction
≈4σ deviation

Muon Anomalous Magnetic Moment

- Single measurement from BNL
- Theory prediction sound but challenging because of hadronic effects.

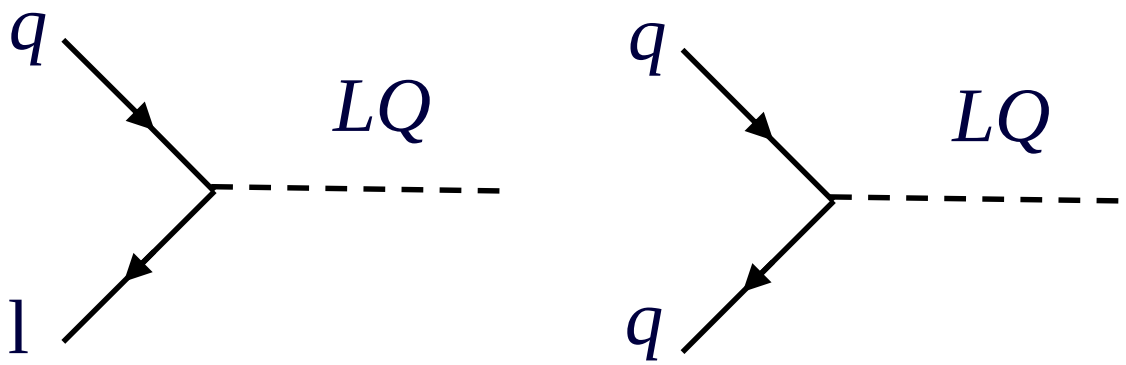
$$\Delta a_\mu = \left(236 \pm 87\right) \times 10^{-11}$$

- Soon new experimental results from Fermilab

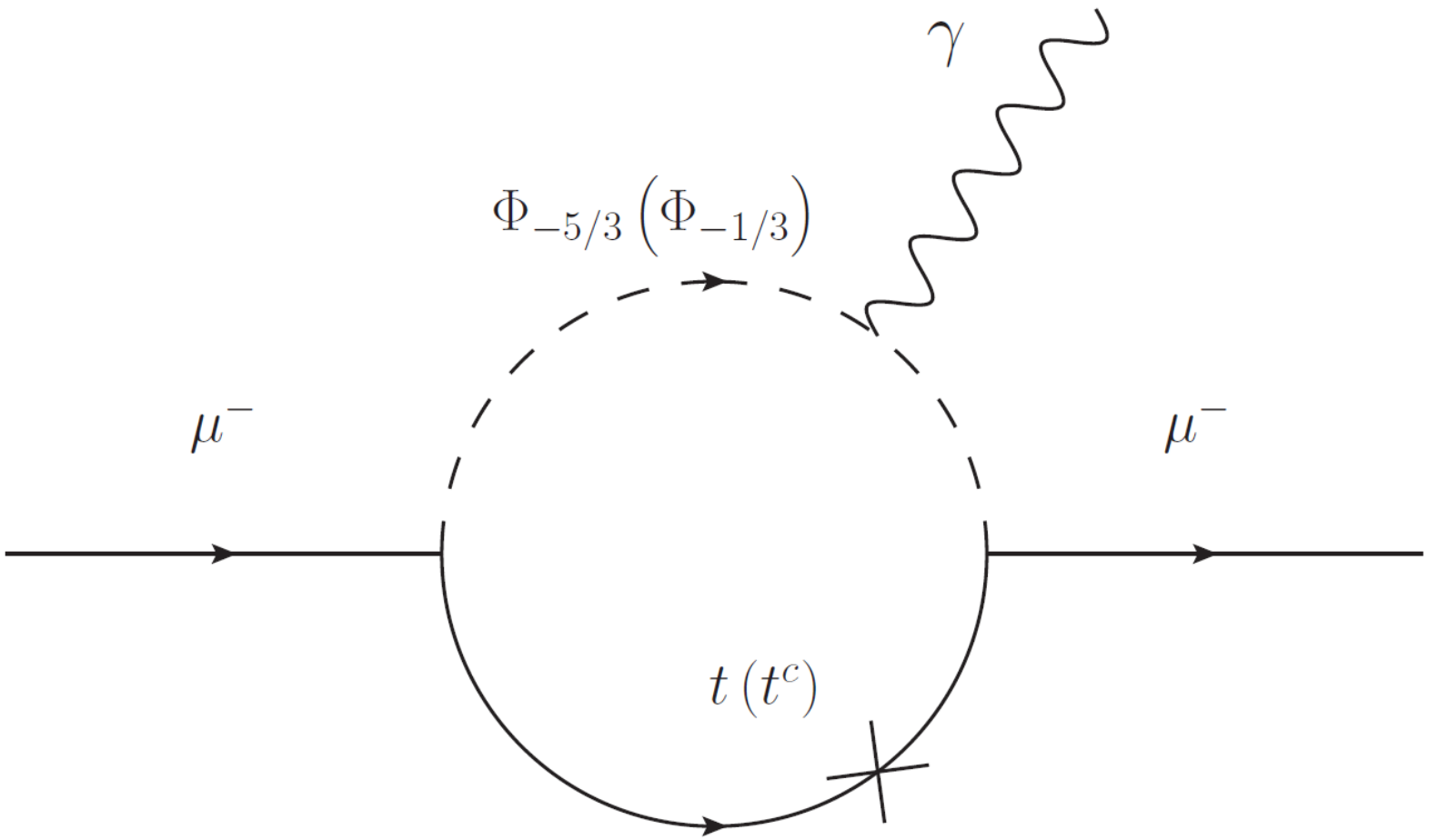
3 σ deviation (order of SM-EW contribution)

Leptoquarks

- Scalars or Vectors
- 5 gauge representations each which are invariant under the SM gauge group
- Couple quarks to leptons
- Maybe also quarks to quarks
  - Proton decay
- Are present in Grand Unified Theories



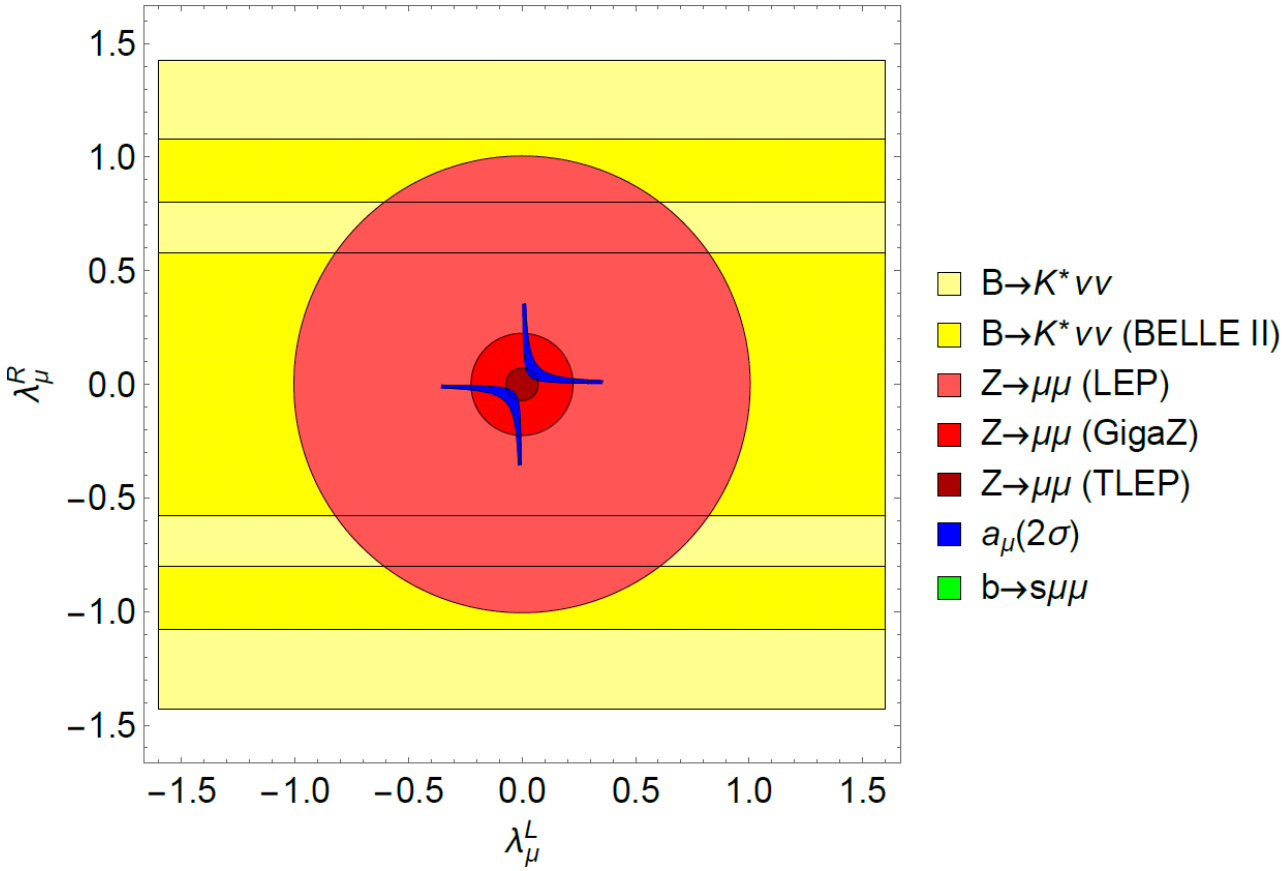
a_μ: Leptoquarks



m_t/m_μ enhancement

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

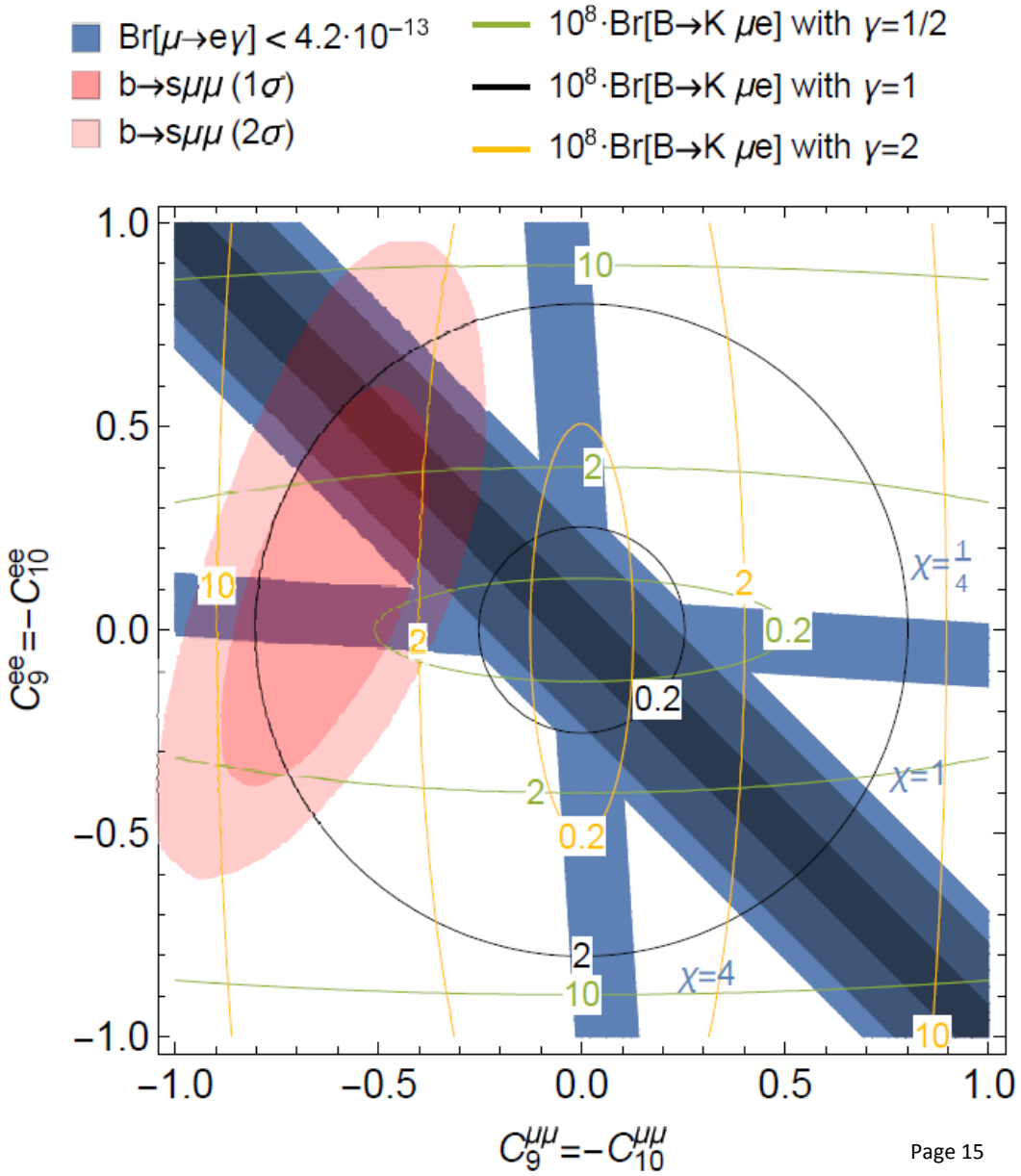
Z→μμ at future colliders

R(K), R(K*) and μ→eγ with LQs

- Three LQs give a good fit
  - Scalar triplet
  - Vector singlet
  - Vector triplet

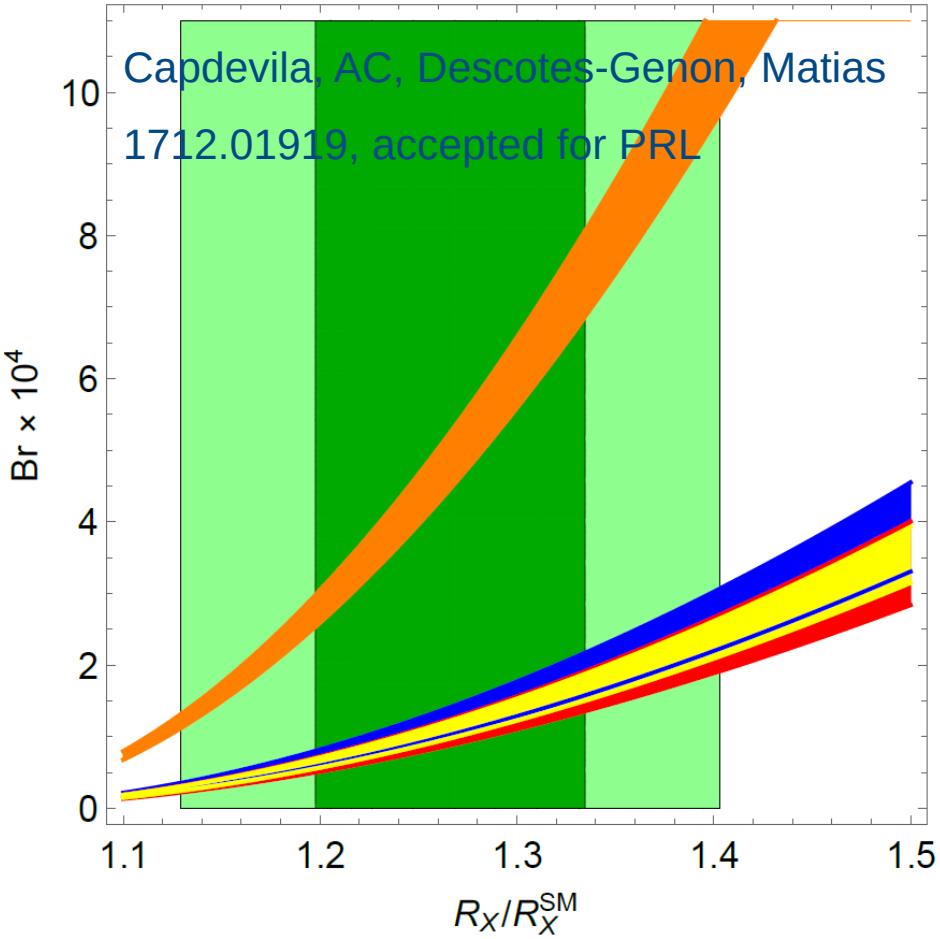
b→sμμ
& b→see
generate
μ→eγ

AC, D. Mueller, A. Signer, Y. Ulrich,
arXiv:1706.08511



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

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



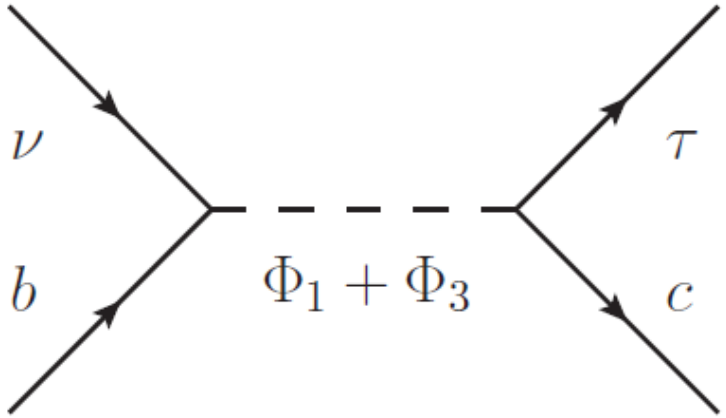
$b\to s\tau\tau$ very strongly enhanced

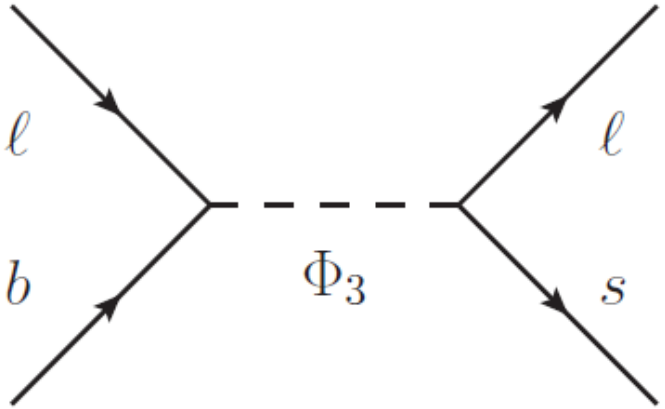
See also R. Alonso, B. Grinstein and J. Martin Camalich, 1505.05164

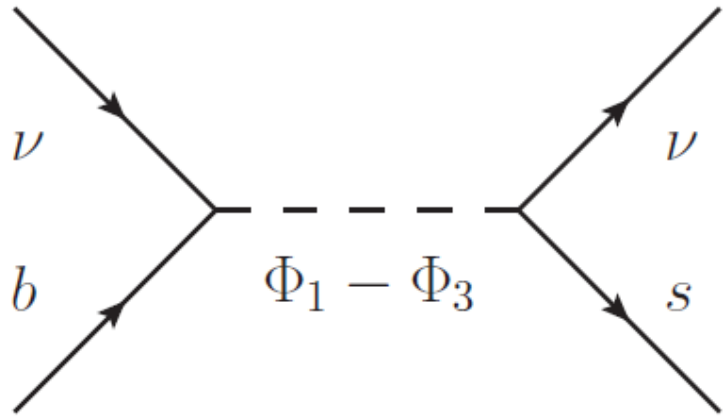
Two Scalar Leptoquarks for b→cτν

- Φ_1 scalar leptoquark singlet with Y=-2/3
- Φ_3 scalar leptoquark triplet with Y=-2/3

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



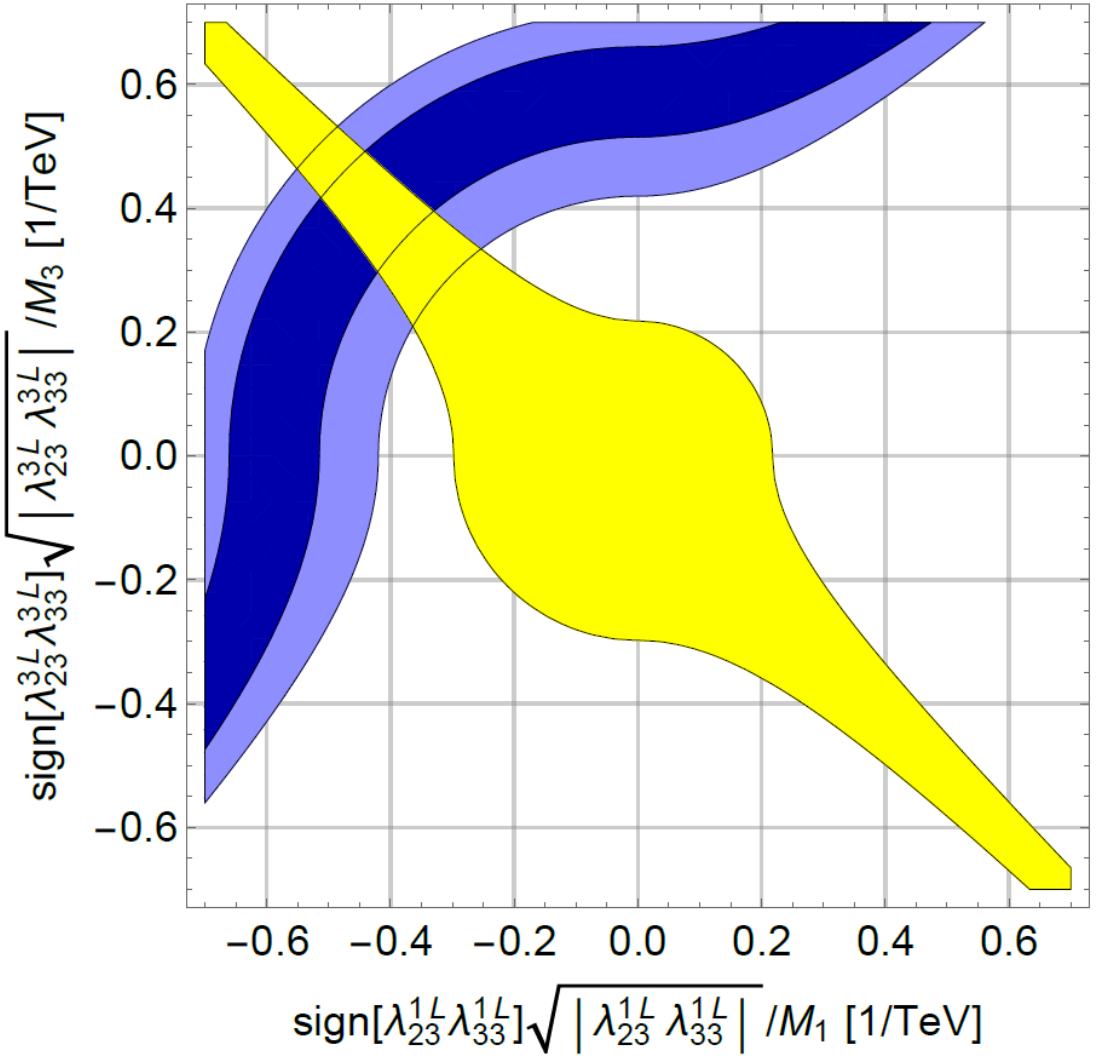




Constructive in R(D$^{(*)}$)

Destructive in b→svv

R(D$^{(*)}$), b→svv with 2 Scalar LQs

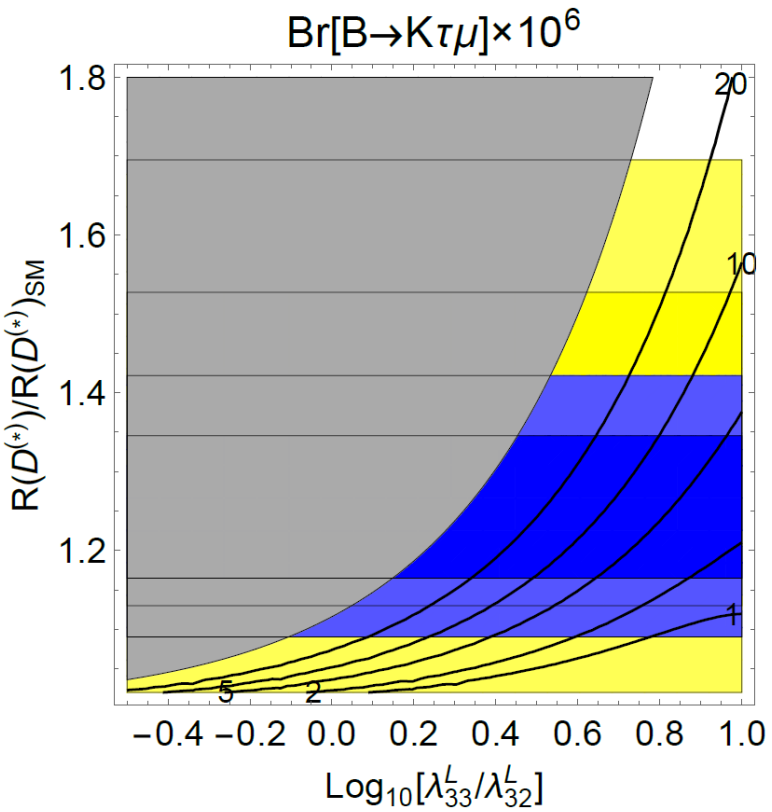


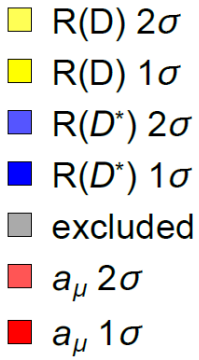
$$\lambda_{jk}^{L} \equiv \lambda_{jk}^{1L}$$

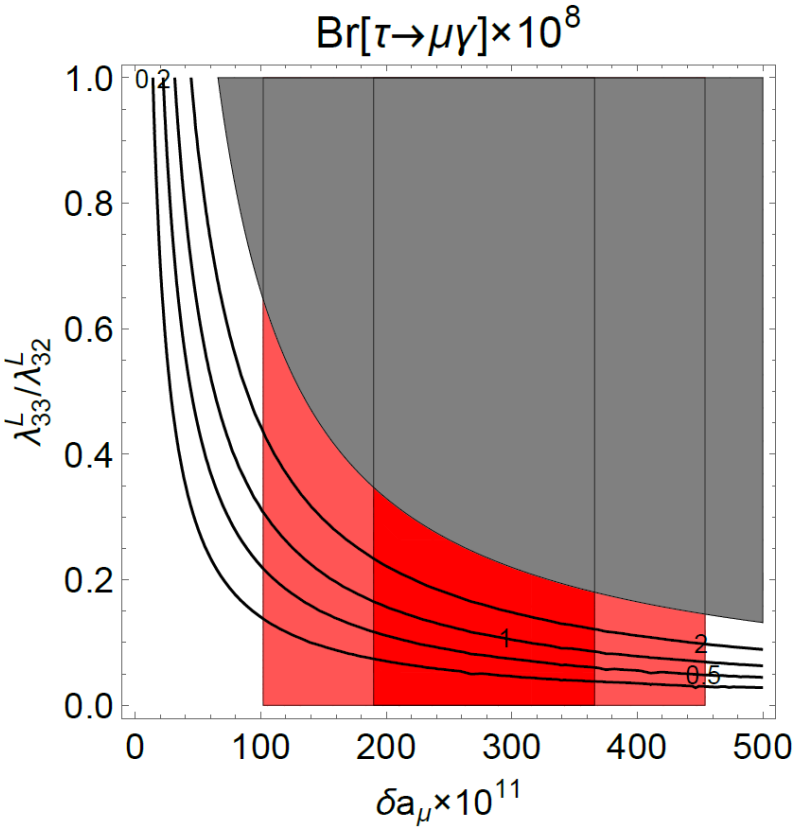
$$\lambda_{jk}^{3L} = e^{i\pi j}\lambda_{jk}^{L}$$

$R(D^{(*)})$, $b\to s\mu\mu$ and a_μ with 2 scalar LQs

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







2 out of 3 can be explained

Vector Leptoquark SU(2) Singlet

- $C_9 = -C_{10}$ effect in $b \to s\mu\mu$
- Left handed vector current in R(D) and R(D*)
- No effect in $b \to s\nu\nu$
- 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 $K_L \to \mu e$ and $K \to \pi \mu e$

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

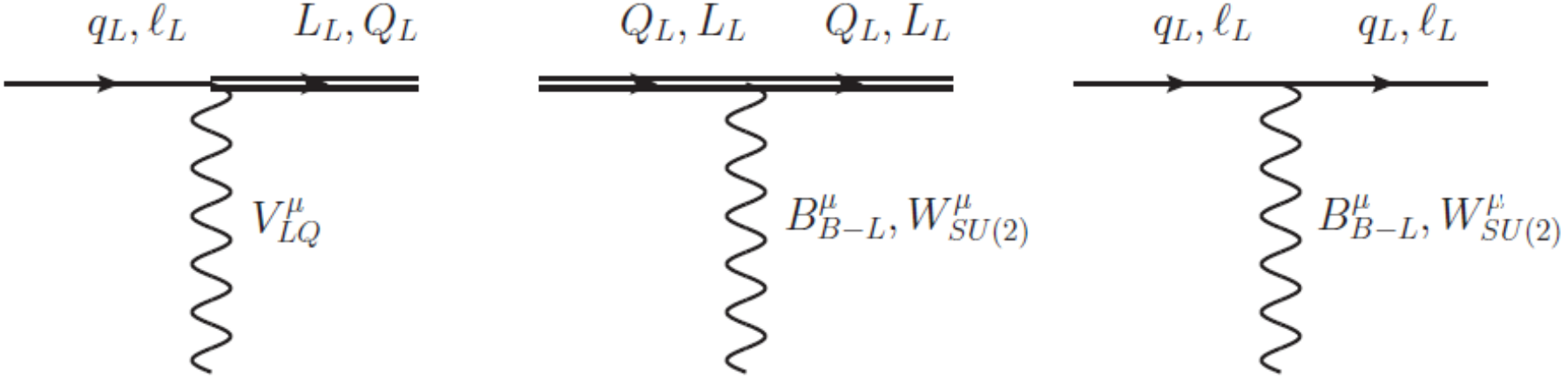
L. Calibbi, AC and T. Li,
A model of vector leptoquarks in view of the B-physics anomalies
arXiv:1709.00692

Pati-Salam + vector-like fermions

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

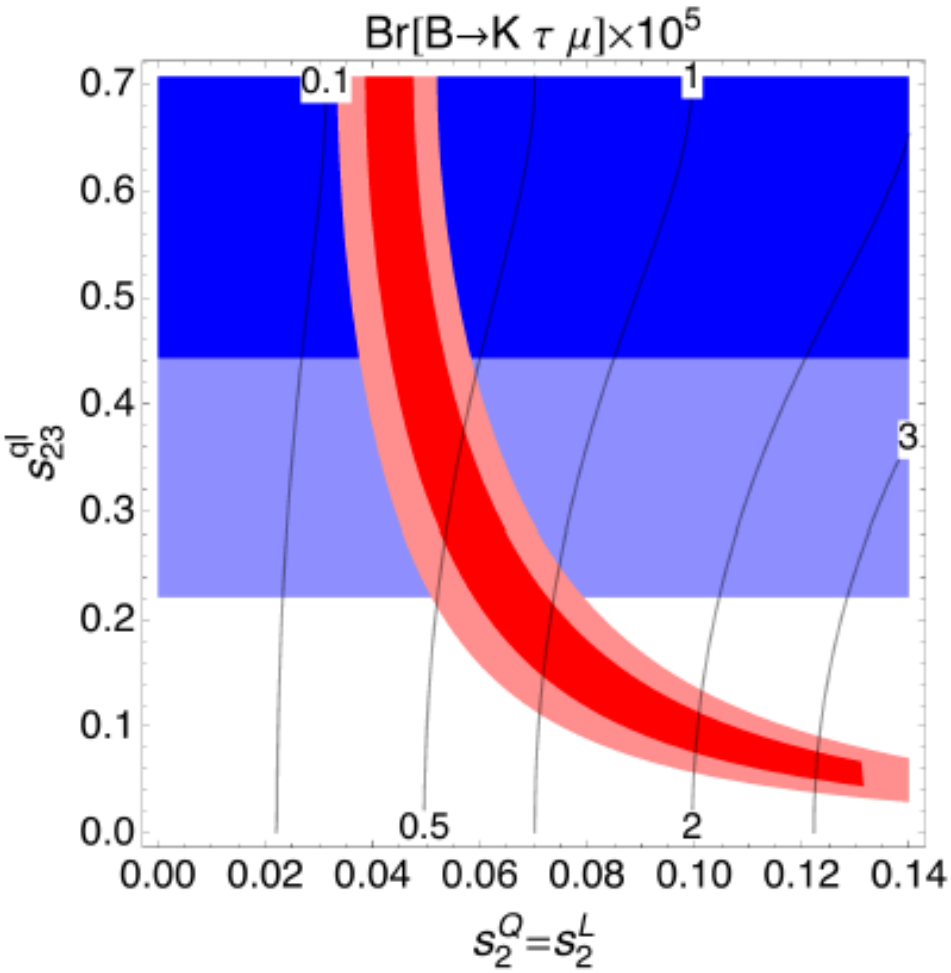
$$L \supset -\left(m^Q_{ij}\bar{q}_{iL} + M^Q_{ij}\bar{Q}_{iL}\right)Q'_{jR} - \left(M^L_{ij}\bar{L}_{iL} + m^L_{ij}\bar{\mathrm{l}}_{iL}\right)L'_{jR}$$

- 3 light generation (SM fermions)
- 3 heavy generation (vector like)



Only the LQ couples flavour violating

R(D$^{(*)}$) and b→sμμ



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

$$M = 1.5\,TeV$$

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

- R(D$^{(*)}$) 2σ
- R(D$^{(*)}$) 1σ
- $C_9^{\mu\mu} = -C_{10}^{\mu\mu}$ 2σ
- $C_9^{\mu\mu} = -C_{10}^{\mu\mu}$ 1σ

LHCb bounds require additional heavy neutral fermions

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

Pati-Salam + Randall-Sundrum

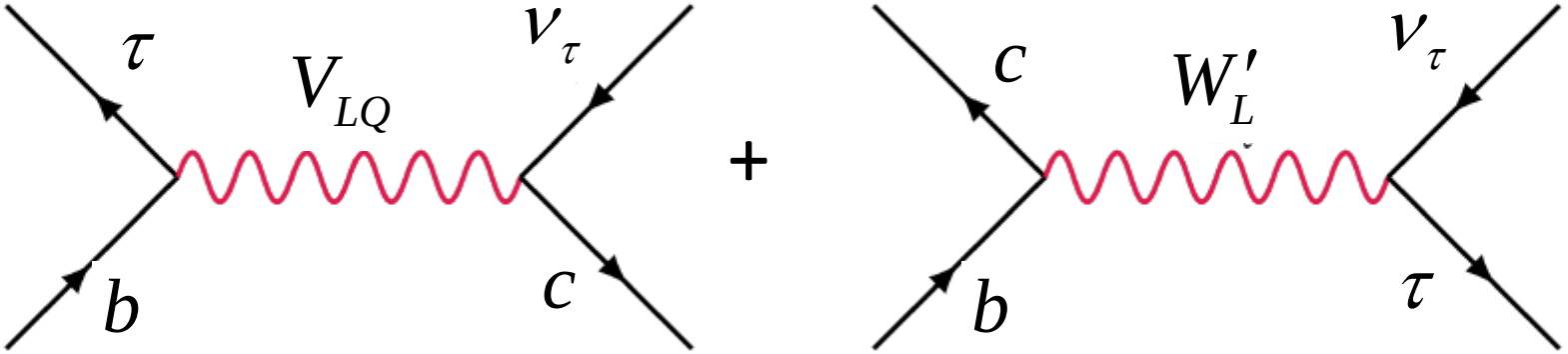
M. Blanke, AC, arXiv:1801.07256

- $SU(4) \otimes SU(2)_L \otimes SU(2)_R$ broken to the SM via boundary conditions on a compact extra dimension
- Zero modes: SM fermions
- KK modes: Vector-like fermions and massive gauge bosons
- No zero mode for the Leptoquark
- Flavour alignment to the down-sector

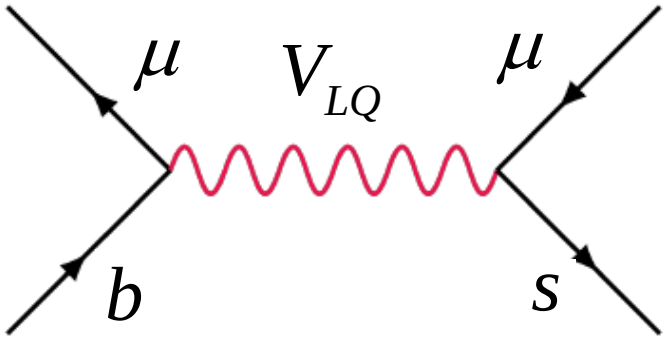
PS + RS naturally accounts for a vector LQ + VLFs

Flavour effects

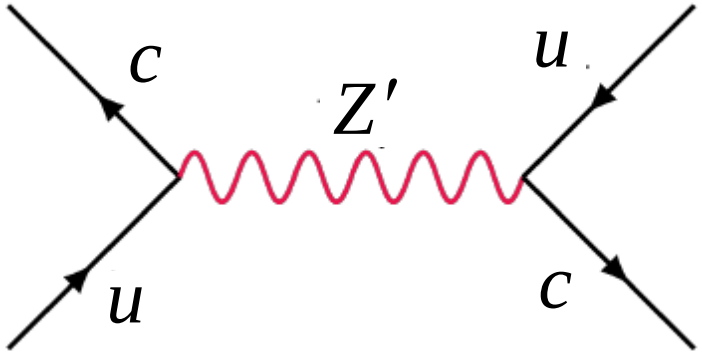
- b→cτν



- b→sμμ

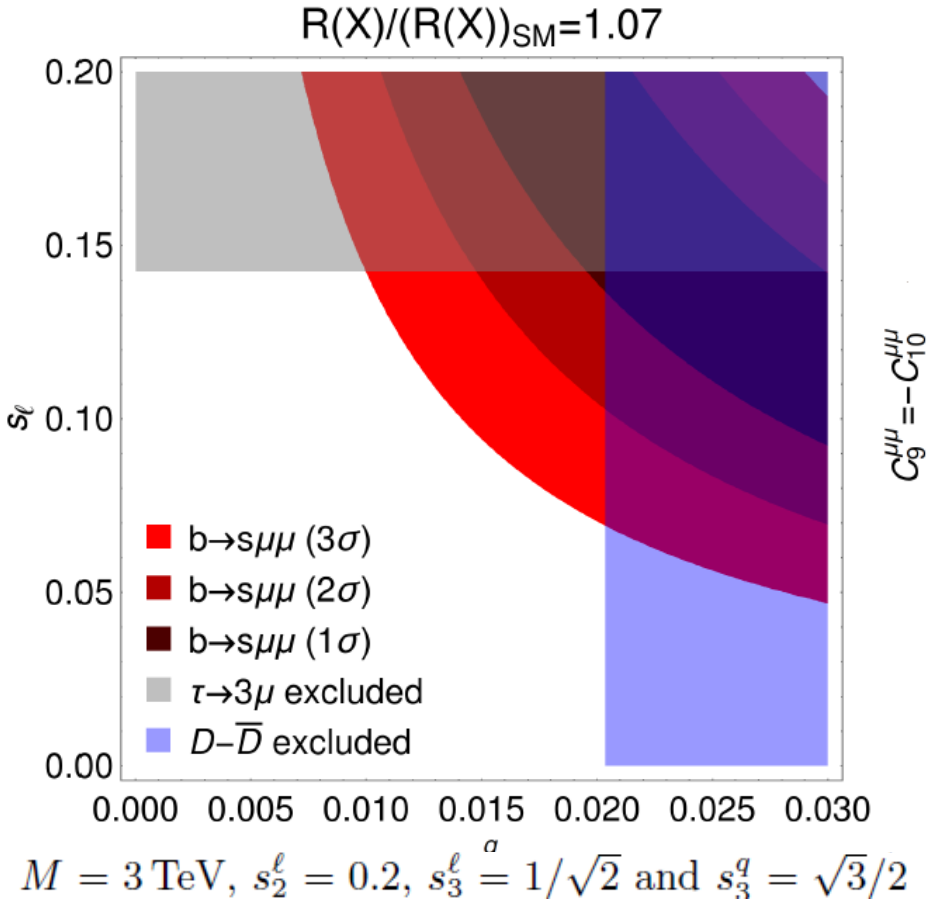


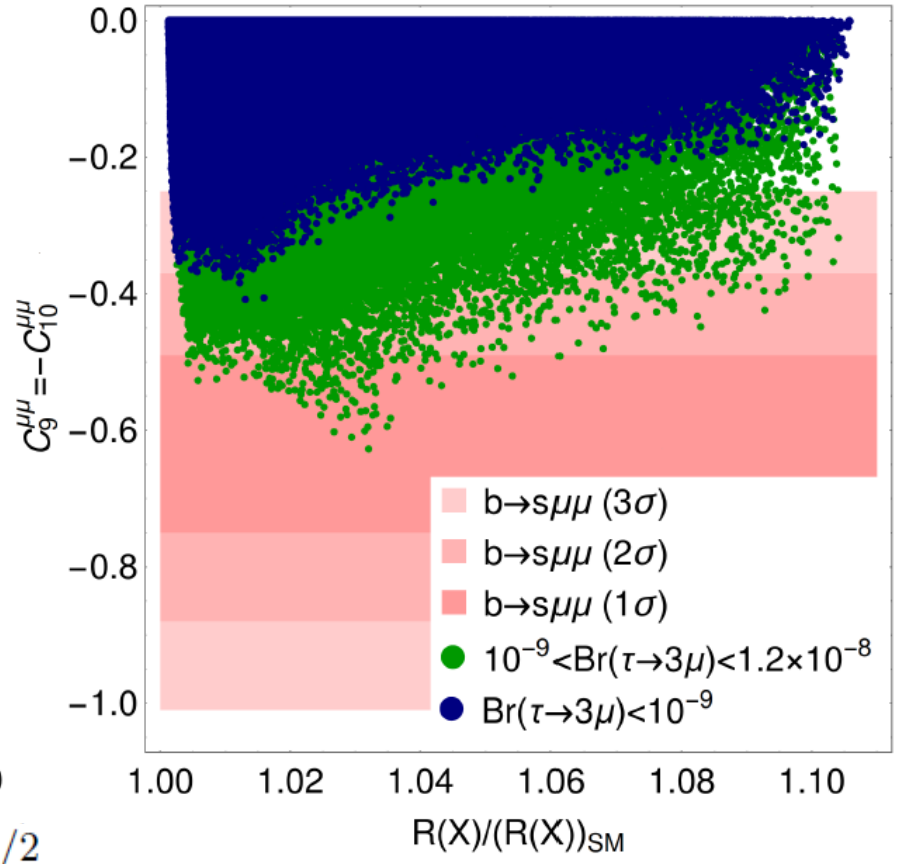
- τ → μμμ & D mixing



D mixing τ→μμμ and cannot be avoided

PS+RS Phenomenology





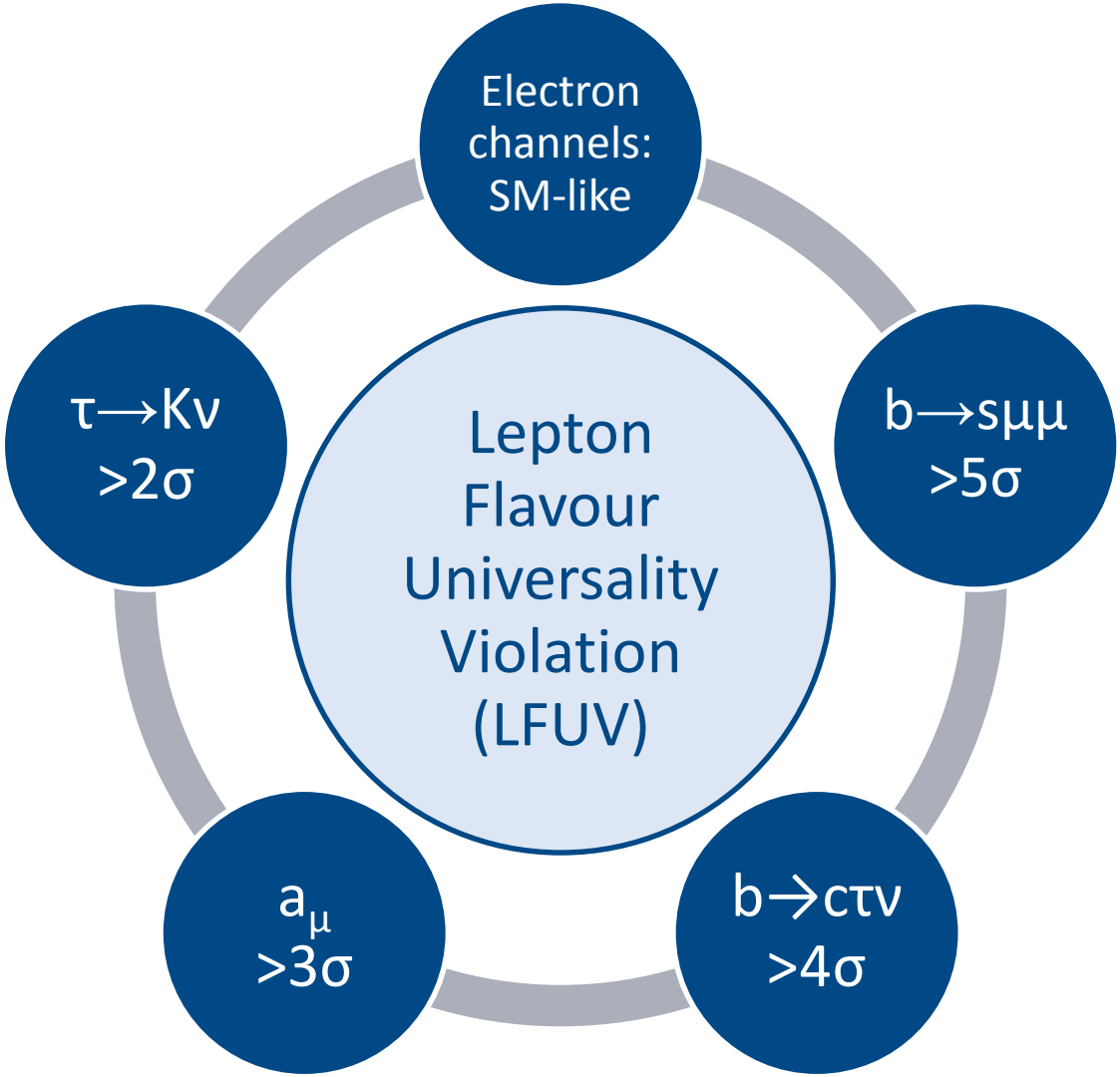
Modell well motivated + limited but sizable effect

Outlook

- 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*) & $b \to s\mu\mu$ → $b \to s\tau\mu$

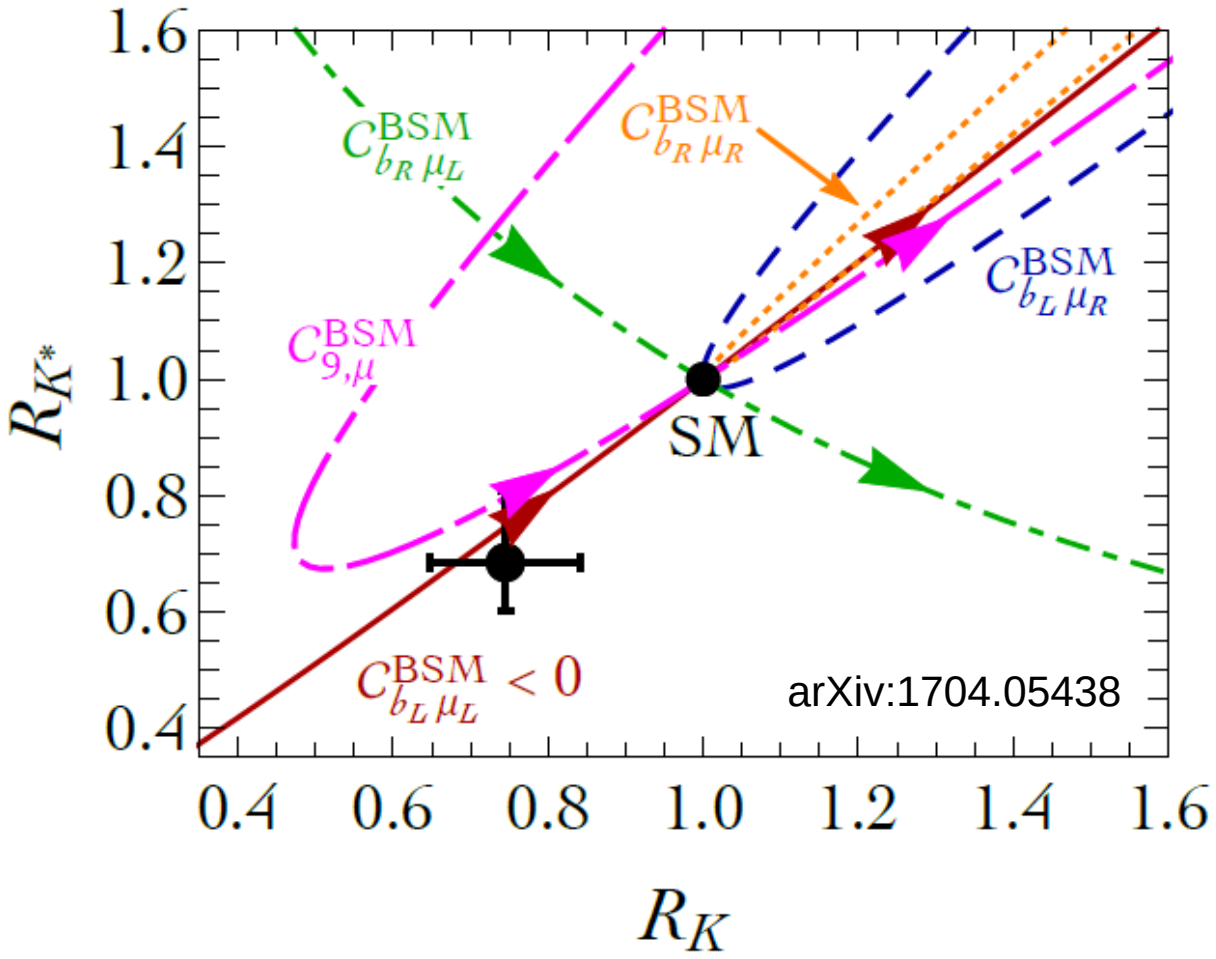
Interesting experimental prospects

Conclusions



Leptoquarks provide a very promising solution to the flavour anomalies

R(K) & R(K*)



Combined ≈4 σ evidence for LFUV