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# Lepton Flavour Universality Violation and B Meson Decays

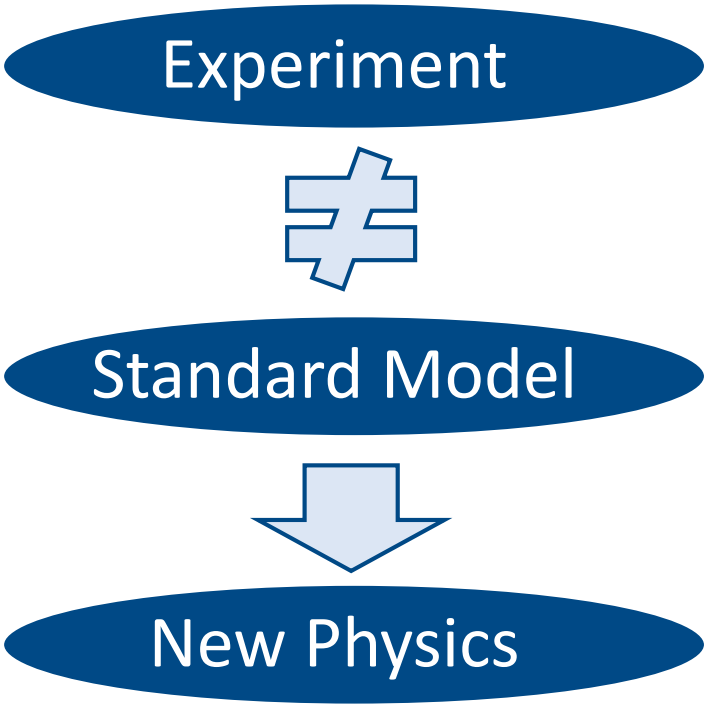
**Karlsruhe, 07.09.2018**

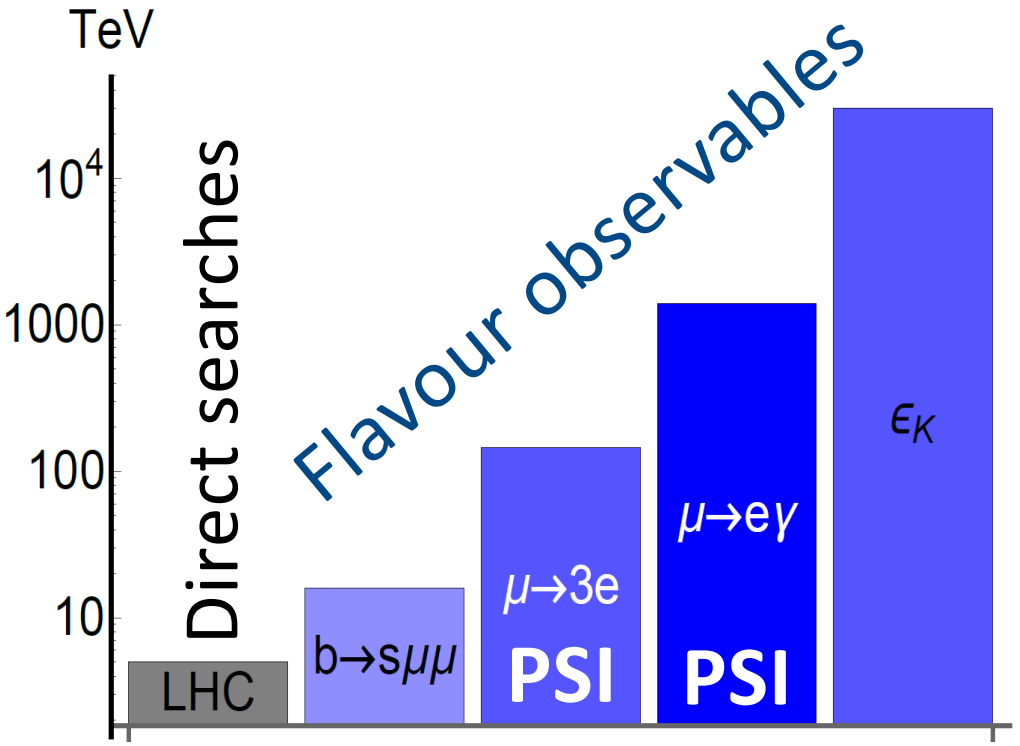
# Outline

- Introduction: Searching for NP with Flavour
- Flavour anomalies
  - $b \to s\mu^+\mu^-$
  - $b \to c\tau\nu$
  - $a_\mu$ (anomalous magnetic moment of the muon)
- New Physics explanations for the anomalies
  - Z', W'
  - Leptoquarks
- The Pati-Salam leptoquark
- Conclusions

# 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**

Tages-Anzeiger

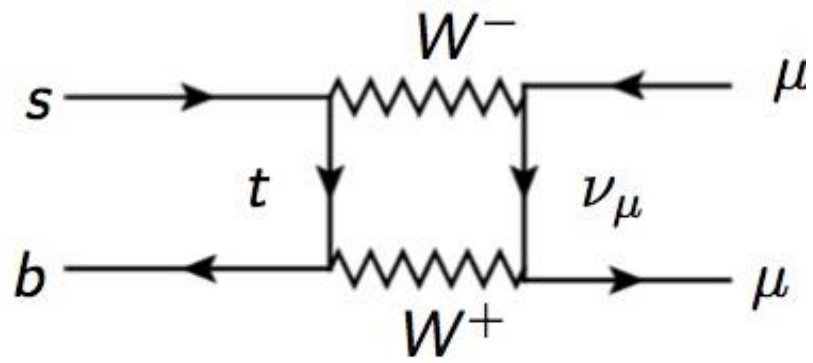
# Spuren einer neuen Kraft

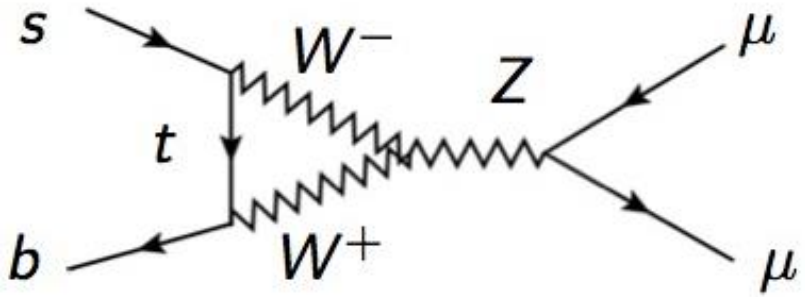
Ein Experiment am Cern liefert Hinweise darauf, dass das bisherige Standardmodell der Teilchenphysik nicht ausreicht, um das Universum zu erklären.

**Gigantische Zahlen**
Unvorstellbare Leistung am Cern

# $b \to s\mu^+\mu^-$

- Flavour Changing Neutral Current (FCNC)
- In the SM it is suppressed by
  - The CKM elements $V_{cb} \approx 0.04$
  - Electroweak scale $m_t^2 / m_W^4$
  - Loop-factor $1/(16\pi^2)$



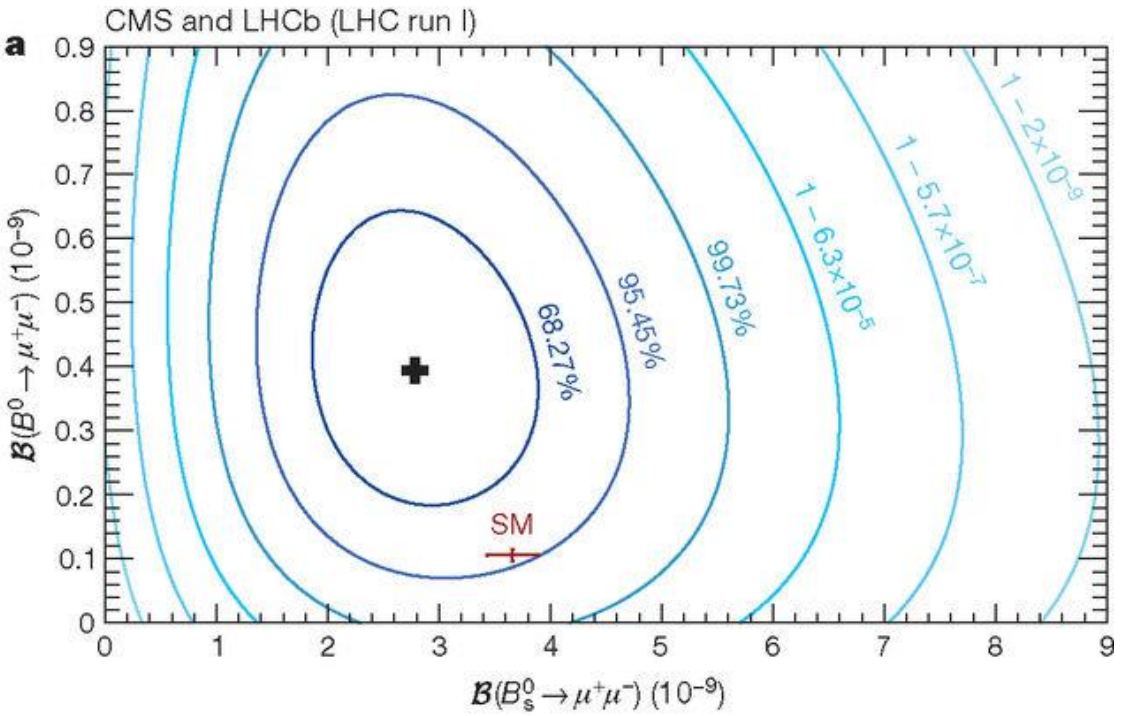




**Suppressed and very sensitive to New Physics**

# $B_q \to \mu^+\mu^-$

$$\mathcal{B}(B_q \to \ell^+\ell^-) = \left|V_{tb}V_{tq}^*\right|^2 G_F^4 m_W^4 \frac{m_{B_q}^3 f_{B_q}^2}{8\pi^5 \Gamma_{B_q}} \sqrt{1 - \frac{4m_\ell^2}{m_{B_q}^2}} \left|C_{10}^2\right|$$

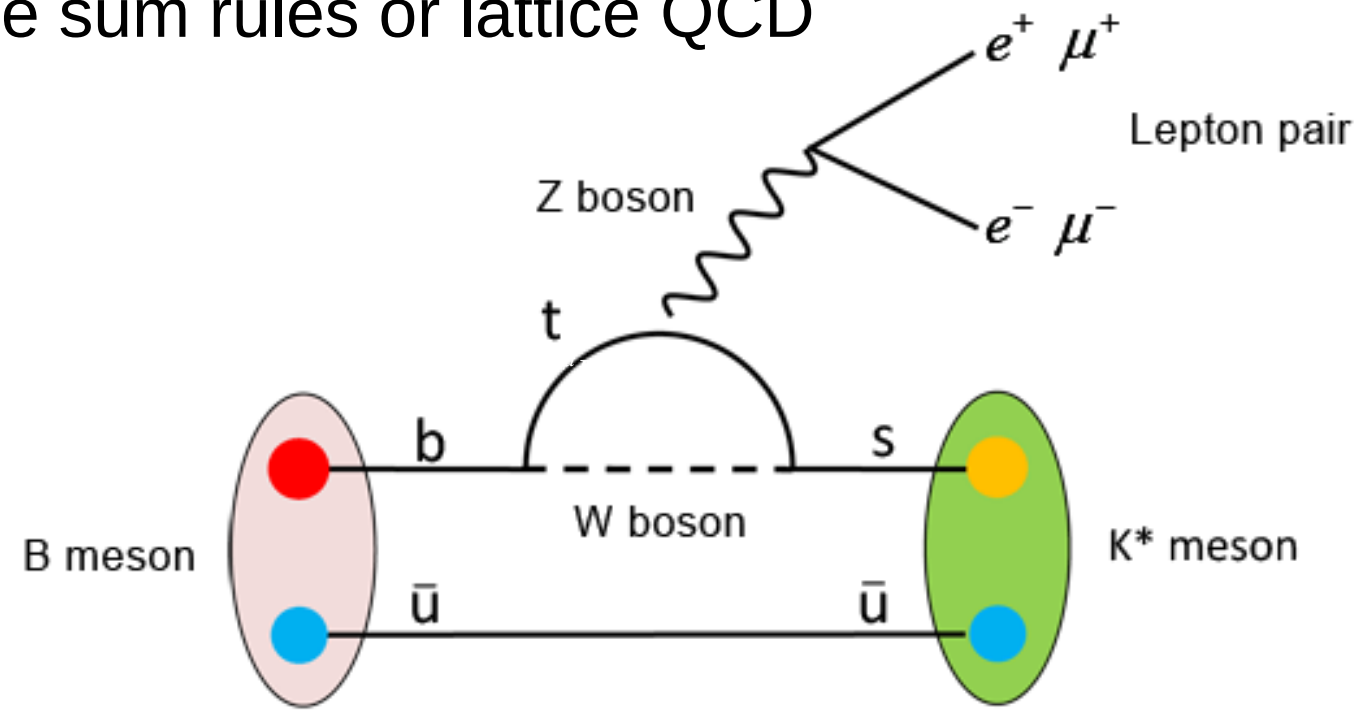
- Theoretically clean
- Chirality suppressed by the muon mass
- Low branching ratio, error dominated by statistics




**Measurement below but compatible with the SM**

# $B \to K^* \mu^+ \mu^-$, $B \to K \mu^+ \mu^-$ & $B_s \to \phi \mu^+ \mu^-$

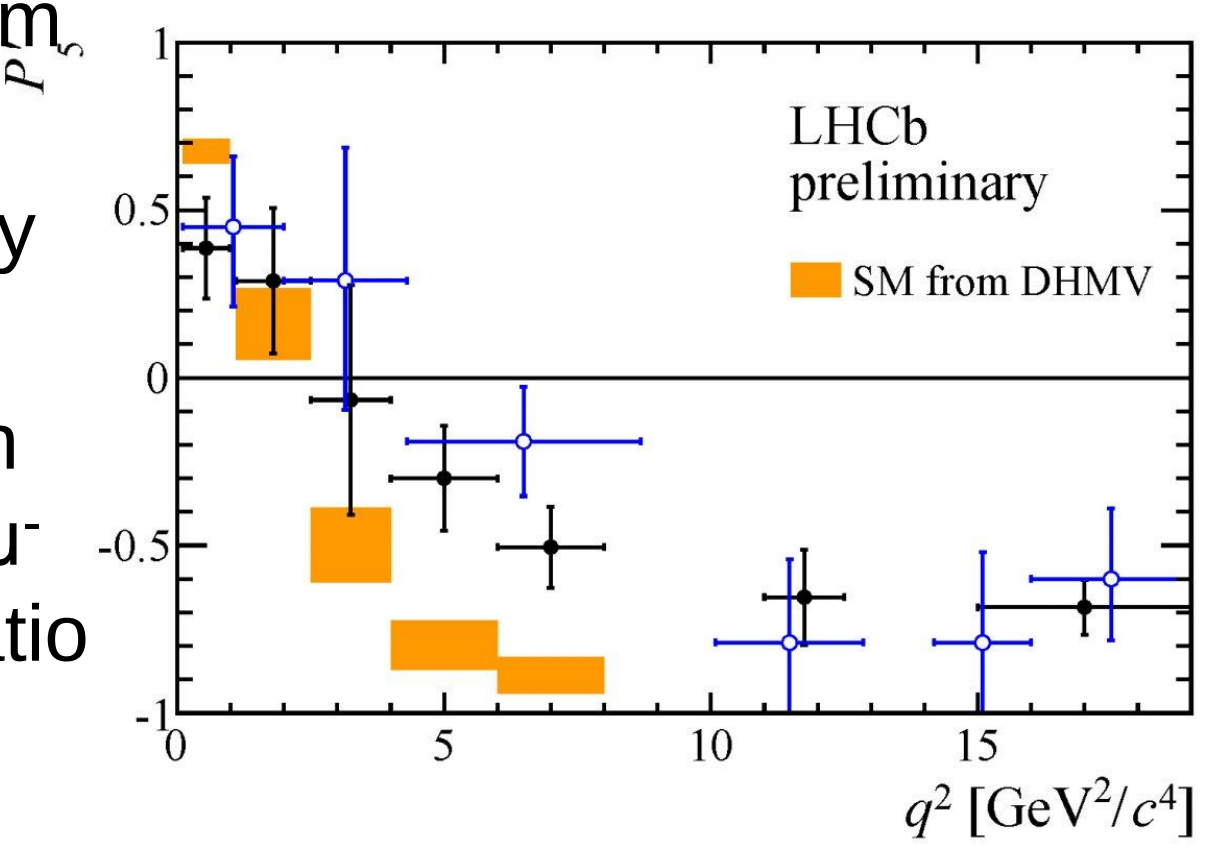
- Semi-leptonic decays depend on form-factors
  - Non-perturbative quantities calculated with light-cone sum rules or lattice QCD




**Right choice of observables can reduce the hadronic uncertainties**

# $P_5'$ 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?

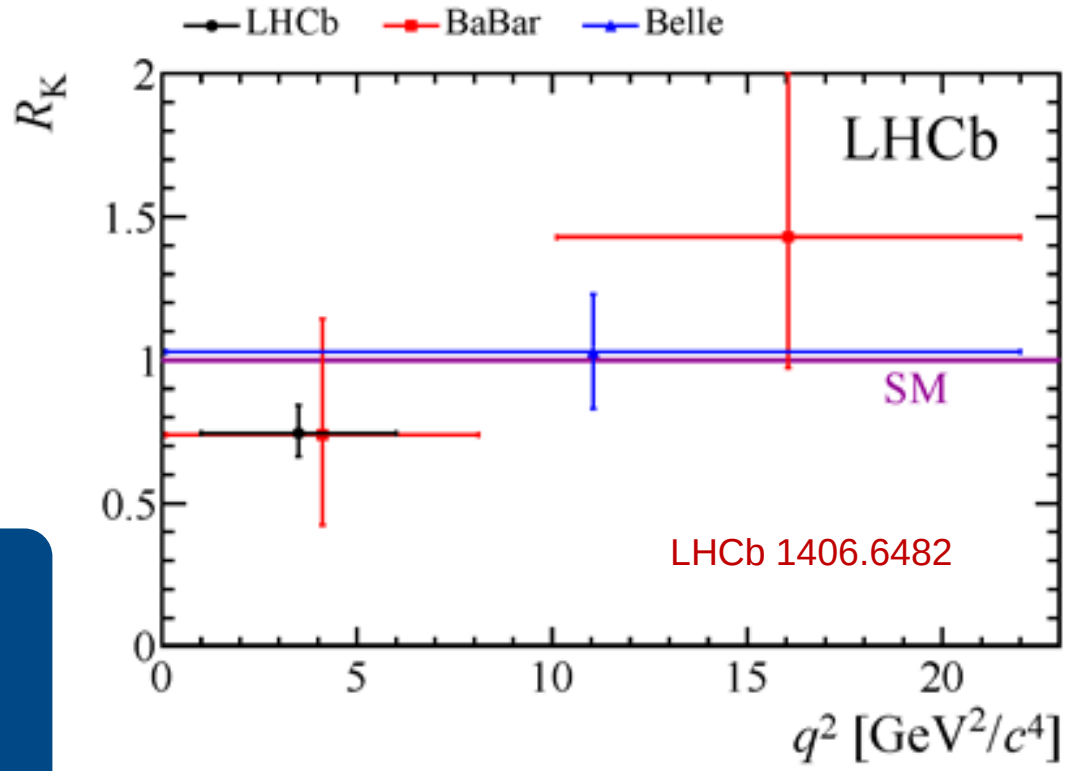
# $R(K) = B \to K\mu^+\mu^-/B \to Ke^+e^-$

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

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

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

**Lepton Flavour Violation in B decays?**

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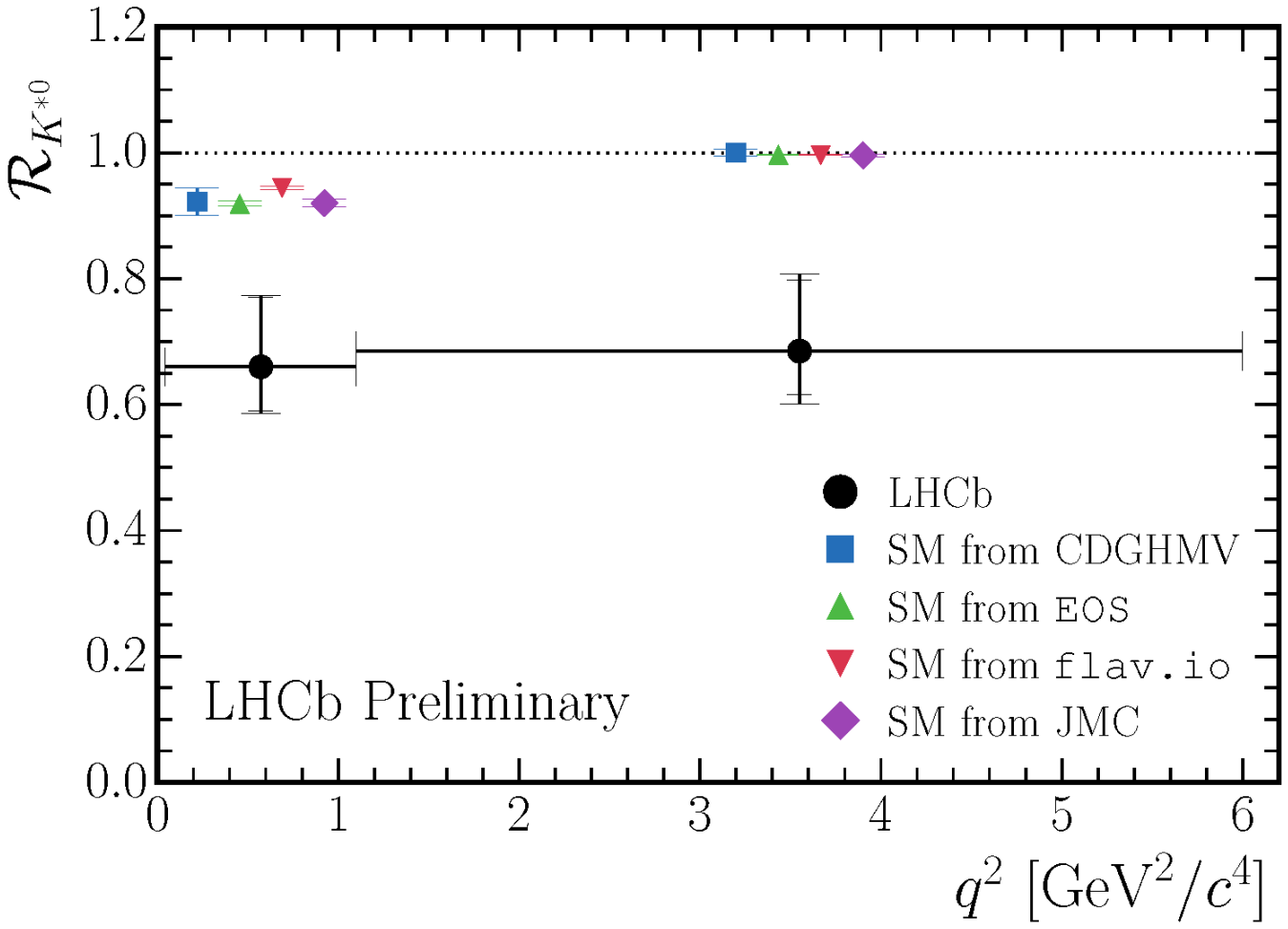
# $R(K^*) = B \to K^* \mu^+ \mu^- / B \to K^* e^+ e^-$

- 2.2-2.4 σ in two bins

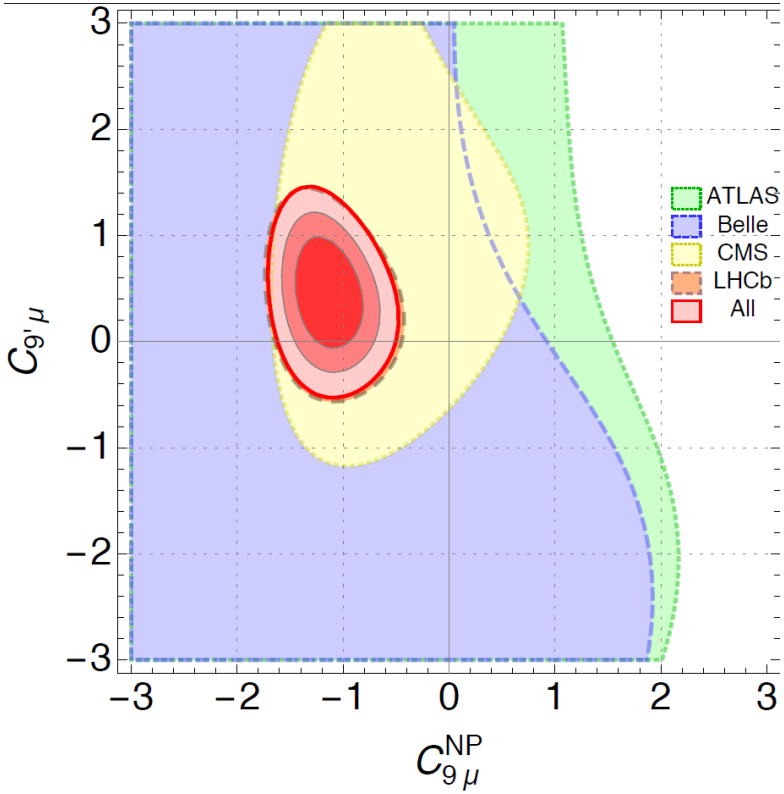


# Global fit to b→sμ⁺μ⁻ data

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

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

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

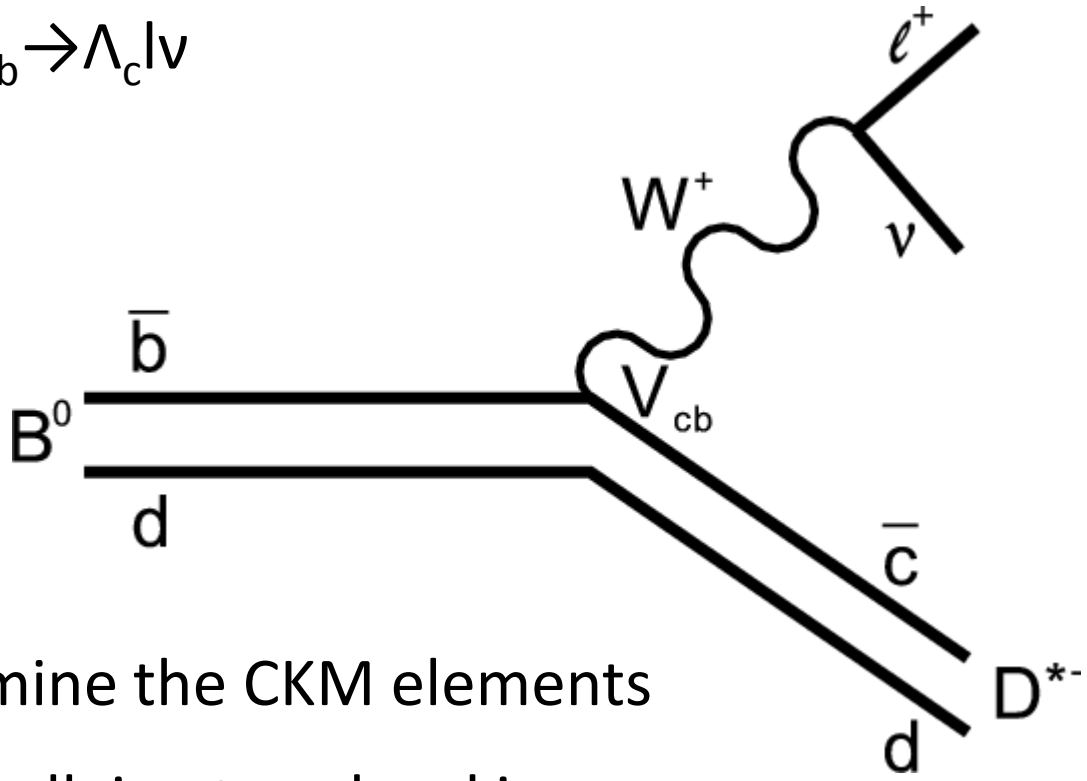



B. Capdevila, AC, S. Descotes-Genon, J. Matias and J. Virto, arXiv:1704.05340 [hep-ph].

**Fit is 5-6 σ better than the SM**

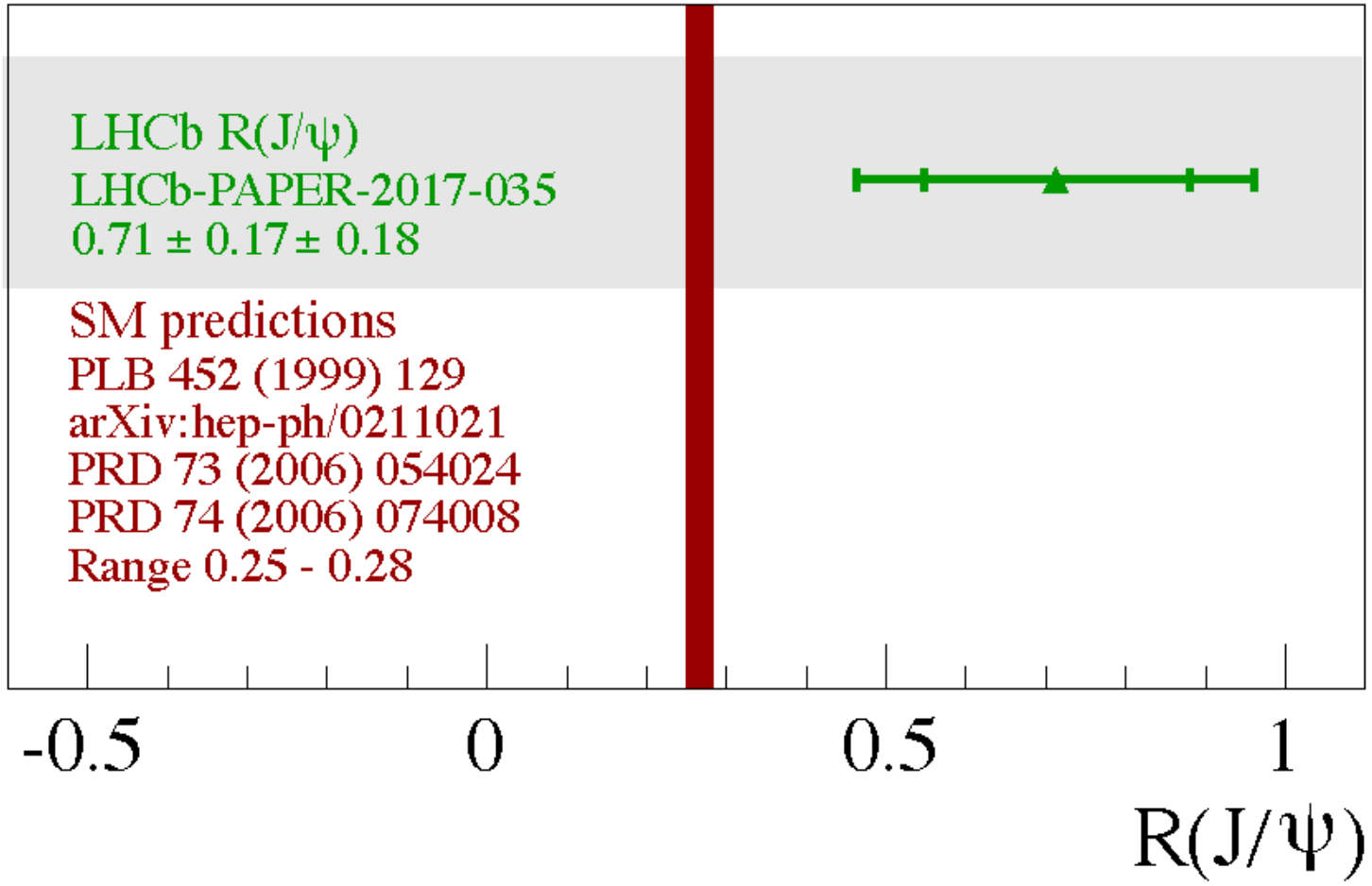
# b→clν processes

- B→Dlν, B →D*lnu, $\Lambda_b \rightarrow \Lambda_c l\nu$
- Tree-level decays in the SM
- Form factors needed
- With light leptons (l=μe) used to determine the CKM elements
- CKM fit works very well, i.e. tree-level in agreement with ΔF=2 processes




**Largest B branching ratios, used to determine the CKM elements, usually assumed to be free of NP**

# b→cτν processes



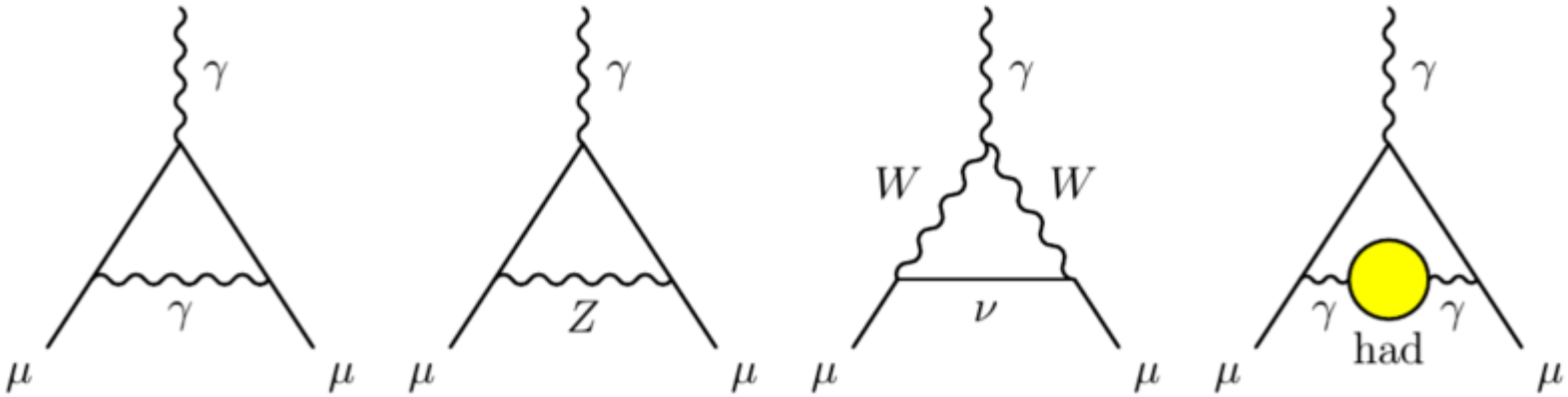

All measurements above the SM prediction
4σ deviation

# Muon Anomalous Magnetic Moment

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

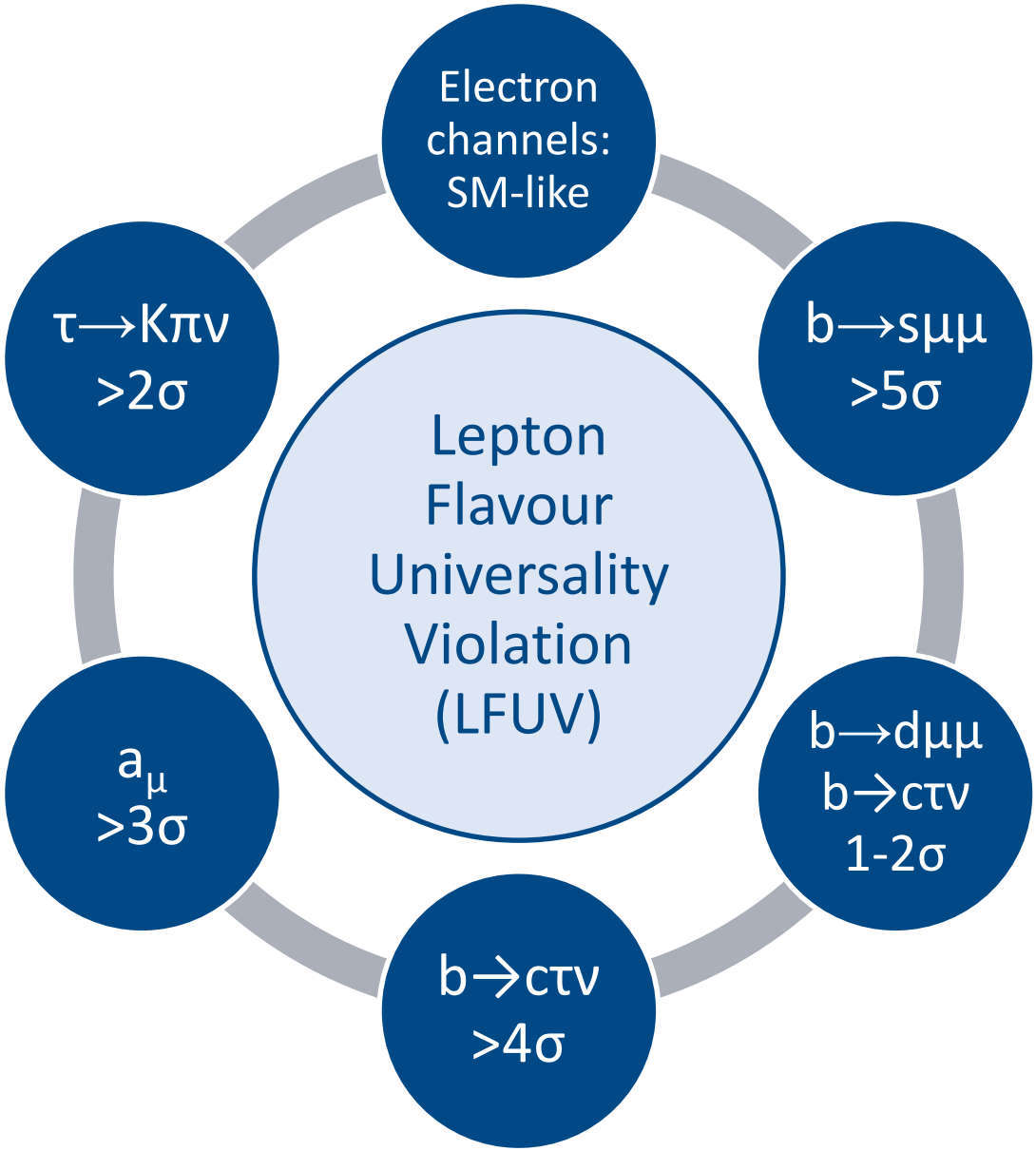
$$\Delta a_\mu = \left(236 \pm 87\right) \times 10^{-11}$$

- Soon new experimental results from Fermilab




3σ deviation (order of SM-EW contribution)

# Hints for New Physics

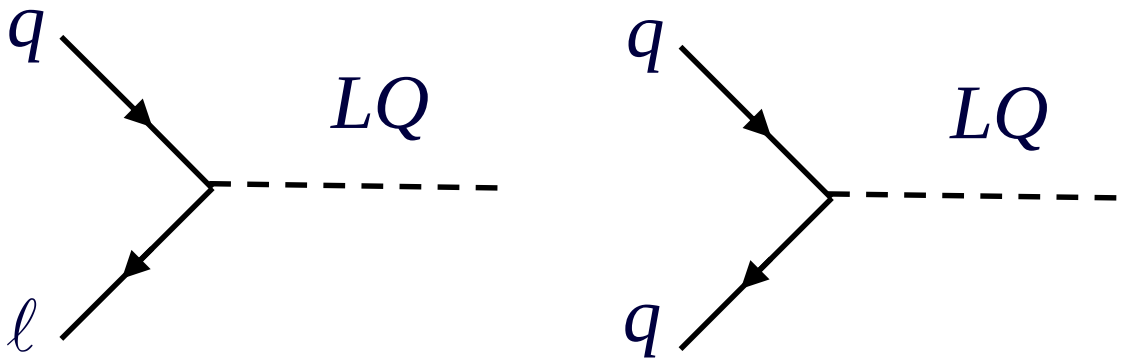



Probability for statistical fluctuation < 0.0001%

# Extensions of the Standard Model to account for the flavour anomalies

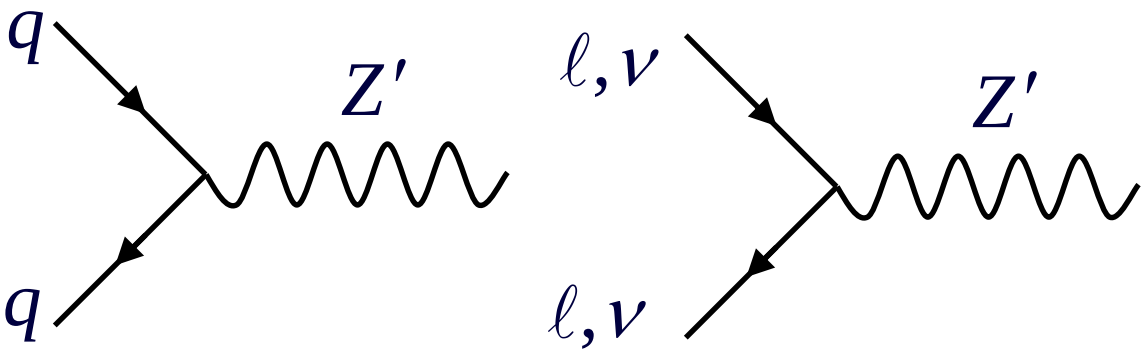
# Leptoquarks

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

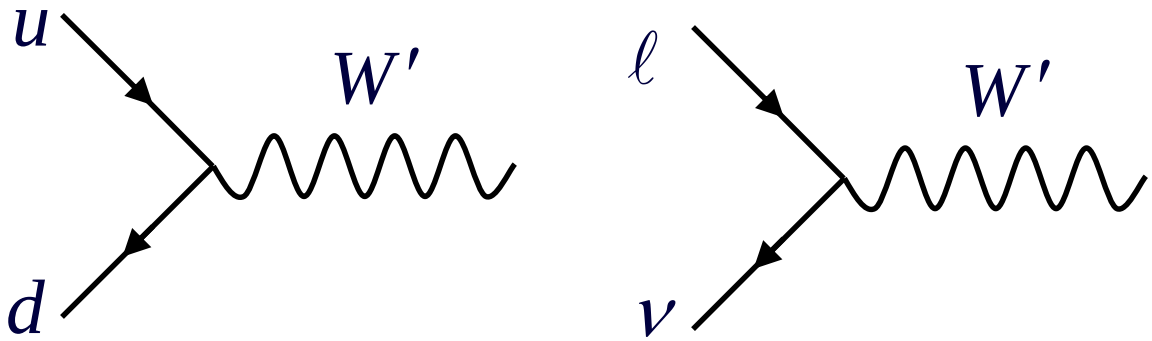


# Z' and W'

- Z': neutral heavy gauge boson



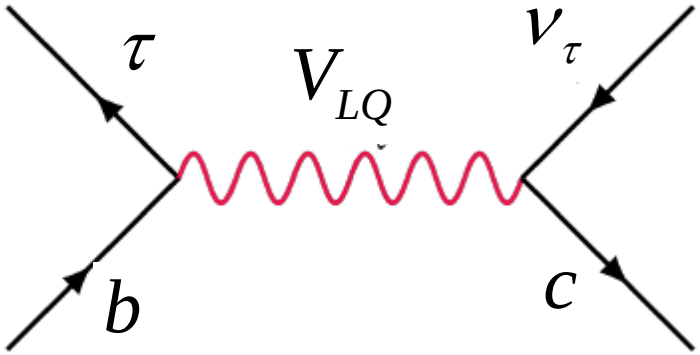

- W': charged heavy gauge boson




New heavy gauge bosons

# R(D) & R(D*)

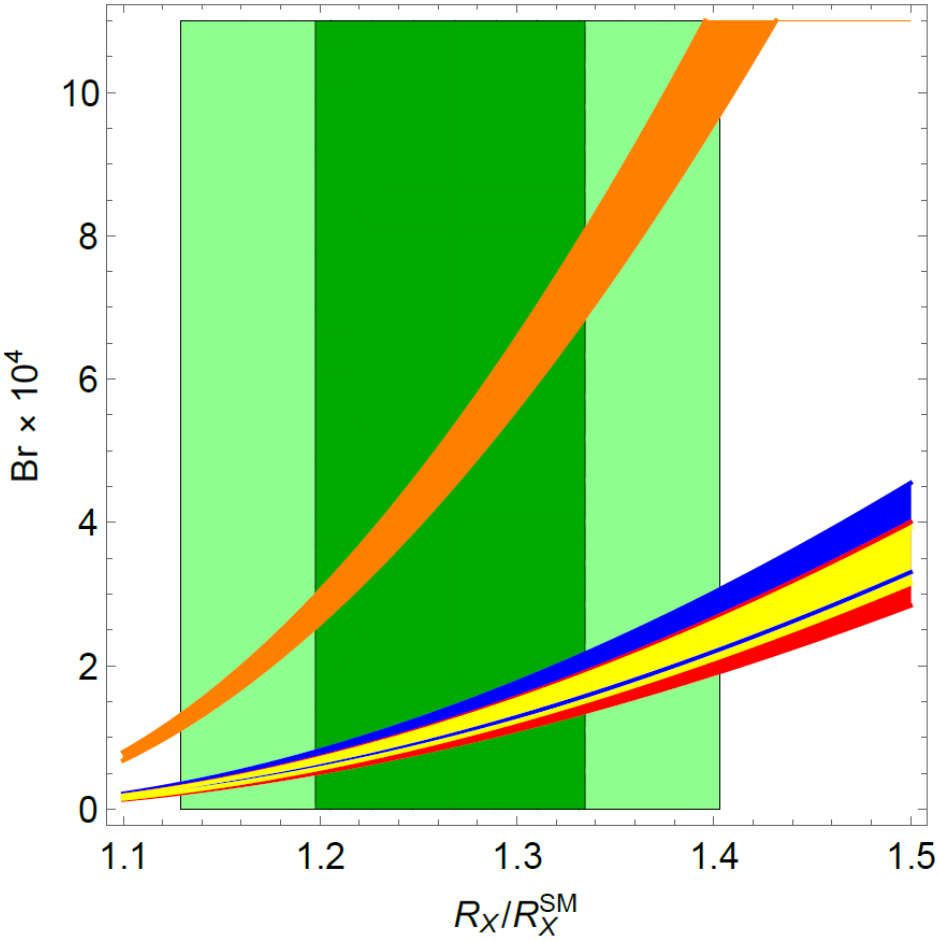
- Charged scalars
  - Problems with $q^2$ distributions and $B_c$ lifetime
- W's
  - Strong constraints from direct LHC searches
  - Can work with right-handed neutrinos
- Leptoquarks
  - Strong signals in qq→ττ searches




**Explanation difficult but possible**

# R(D(*)) and b→sττ (model-independent)

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

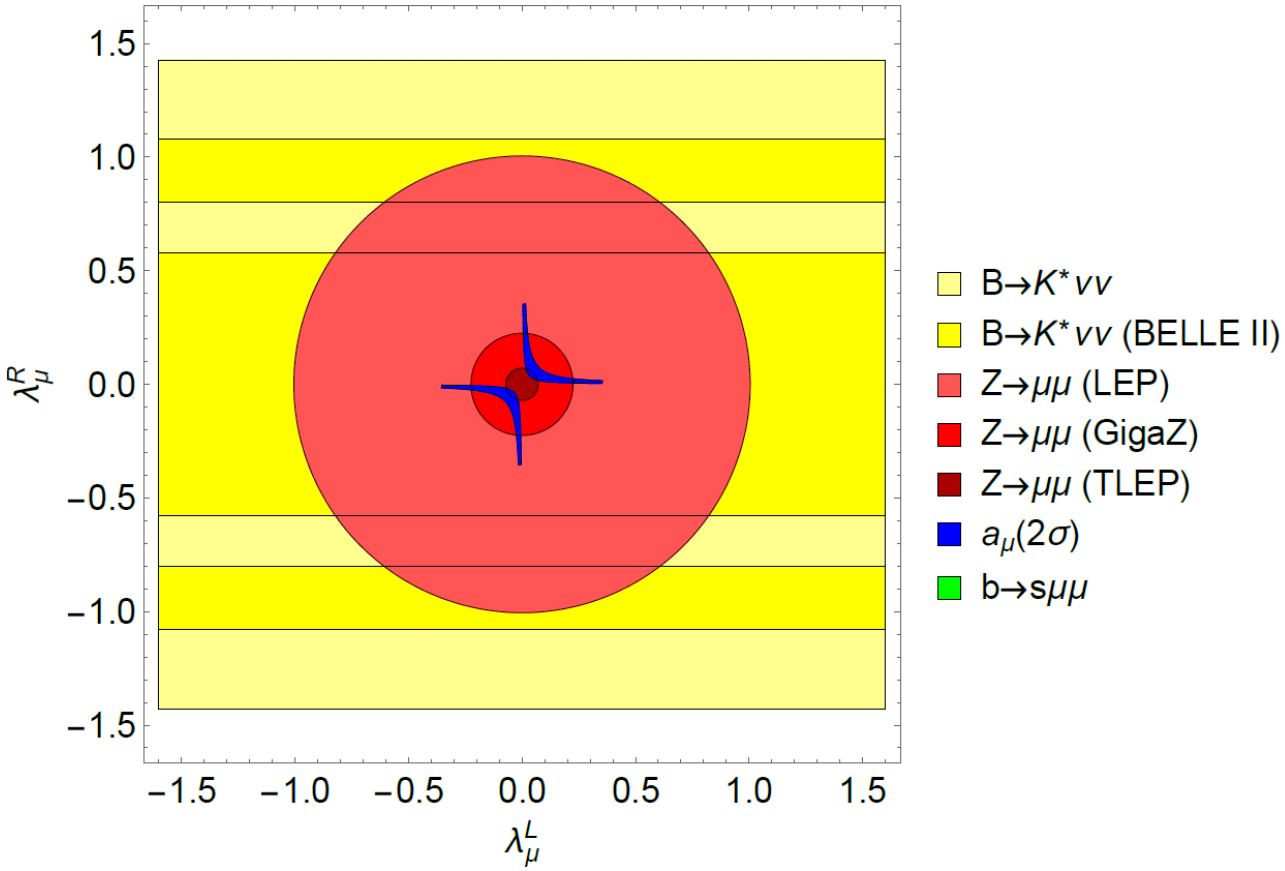



b→sττ very strongly enhanced

B. Capdevila, A.C., S. Descotes-Genon, L. Hofer and J. Matias, PRL.120.181802

# Leptoquarks in $a_\mu$

- 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**

# $b \to s\mu^+\mu^-$: Z' and Leptoquarks

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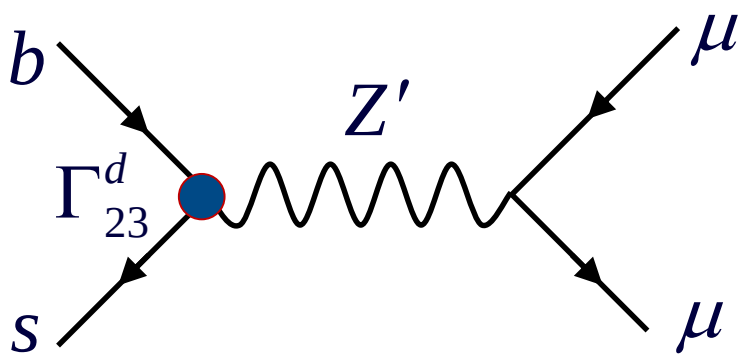
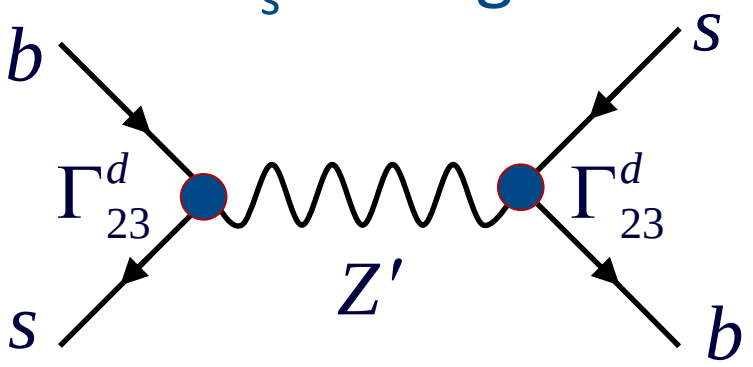
## $b \to s\mu\mu$

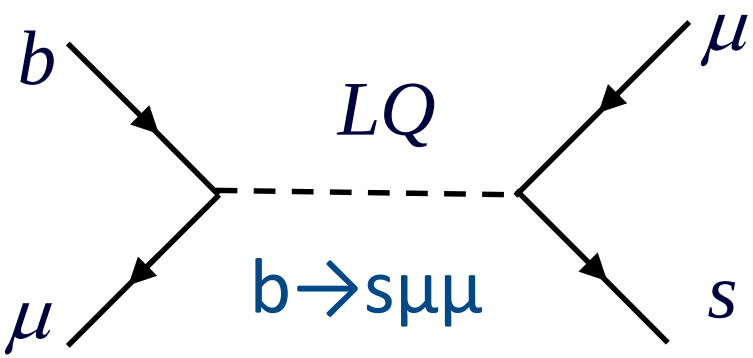



$$C_9^{\mu\mu} \propto \Gamma_{23}^{dL}\, g'^2 / m_{Z'}^2$$

## $B_s$ mixing




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




**Z' affects $B_s$ mixing**

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# Simultaneous Explanation with the Pati-Salam Leptoquark

# Vector Leptoquark SU(2) Singlet

- Left-handed 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**

# Important Loop-Effects

A.C., C. Greub,
D. Müller, F. Saturnino,
arXiv:1807.02068

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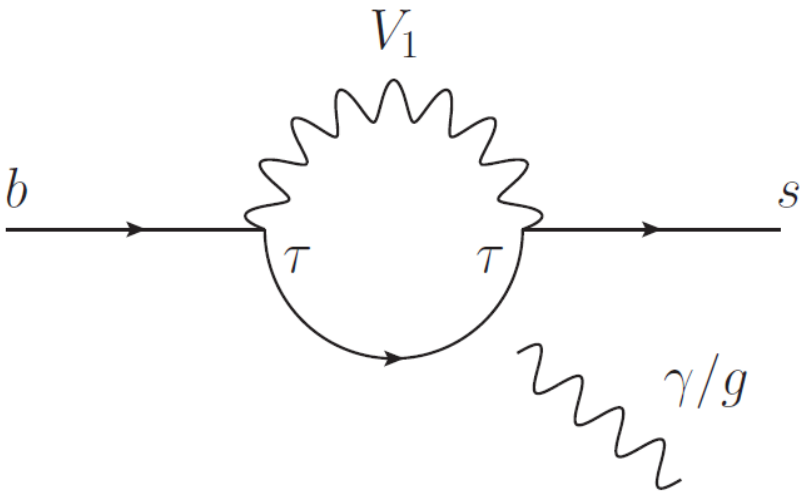
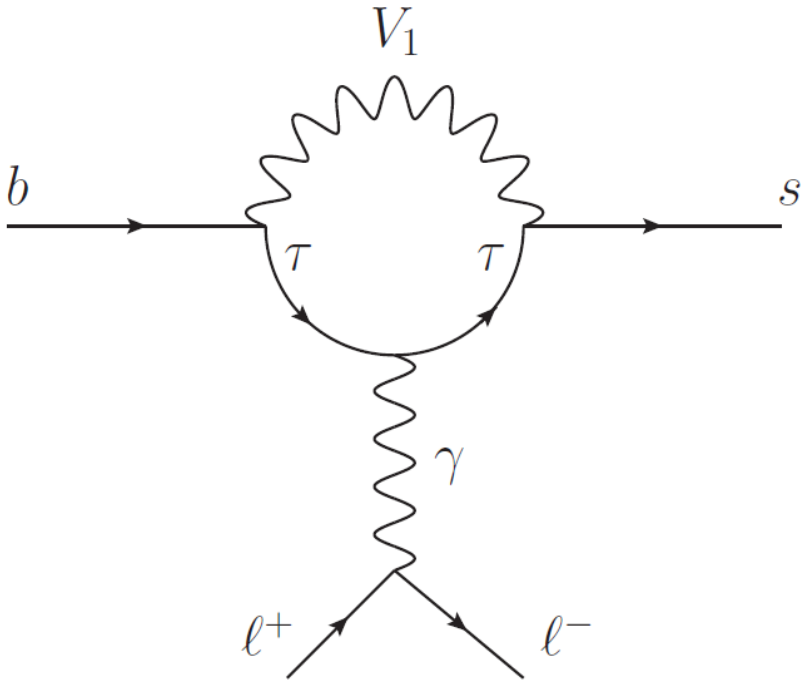
- Explanation of $b \to c\tau\nu$ requires large $b\tau$ and $s\tau$ couplings (follows from SU(2) invariance)




Large loop effects in $b \to s\mu\mu$

# Important Loop-Effects

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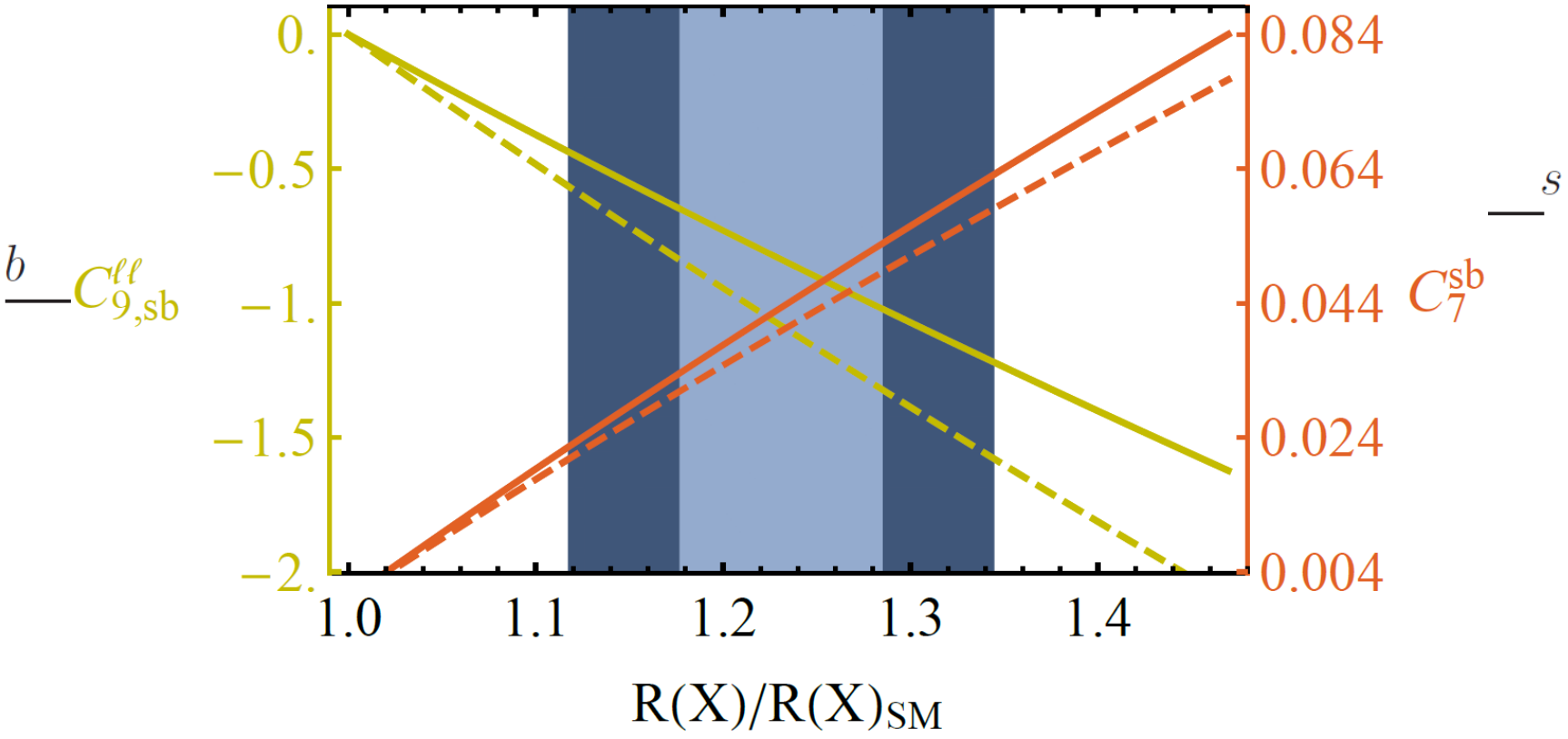
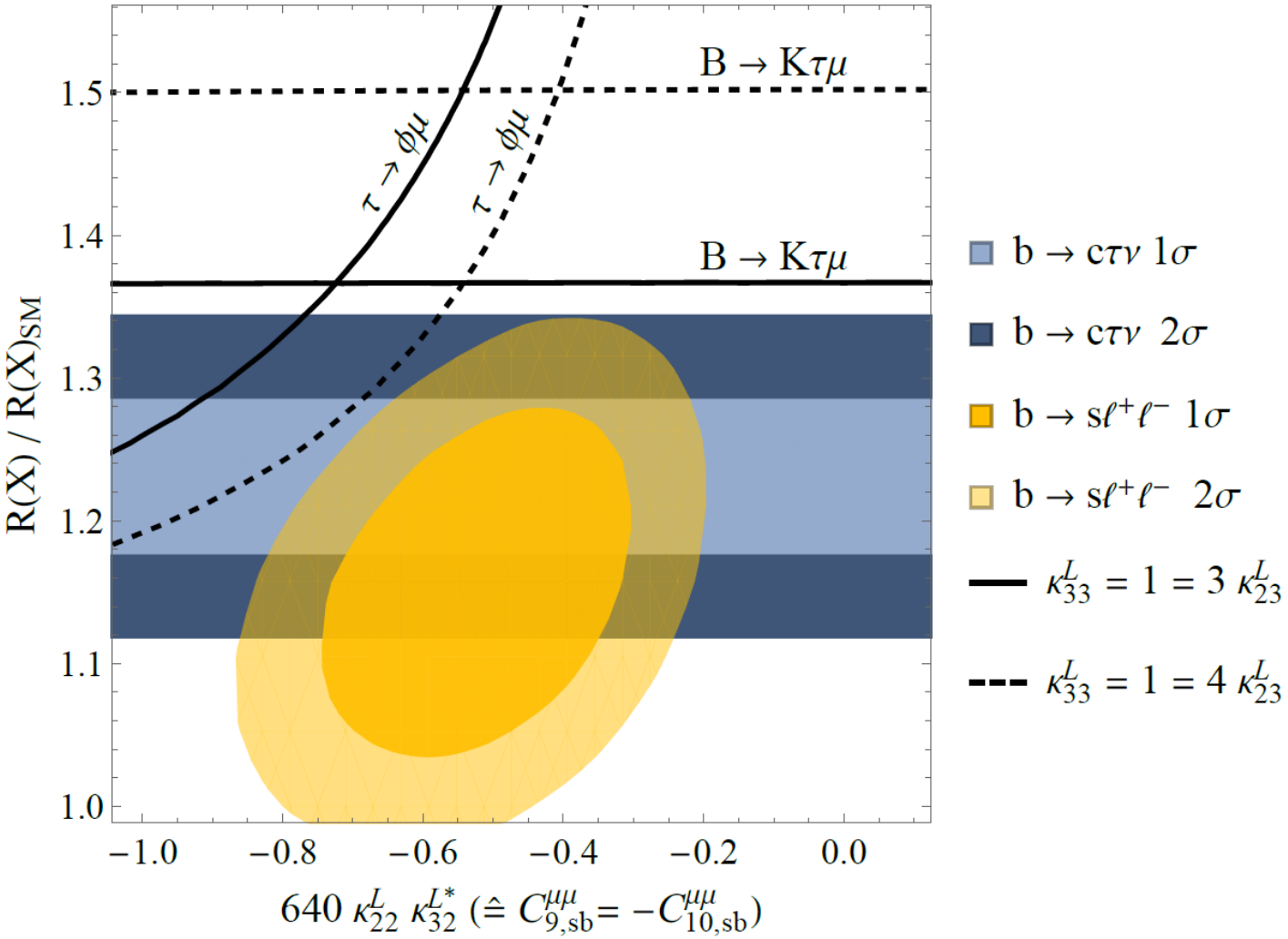


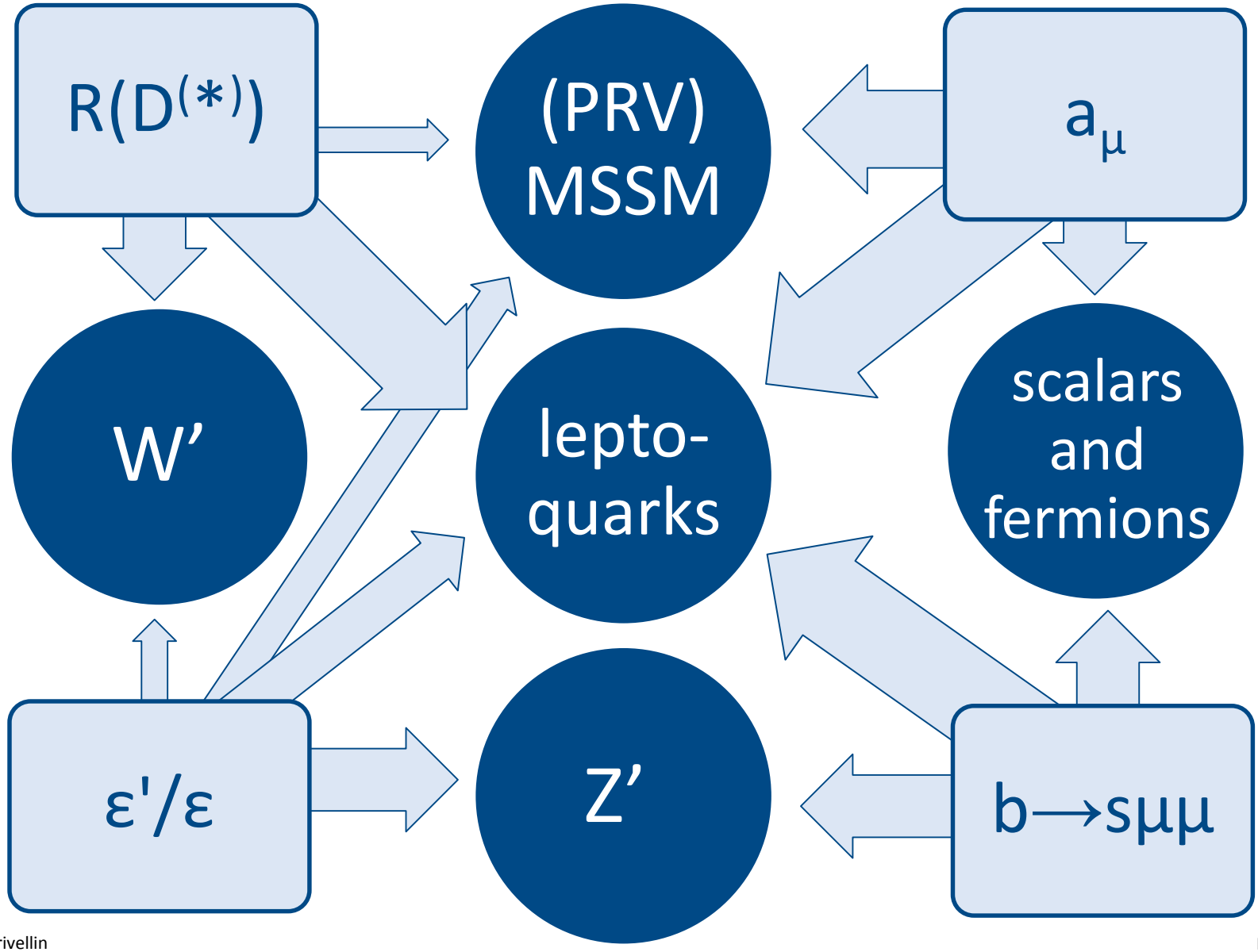

Large loop effects in b→sμμ

# Perfect agreement with data

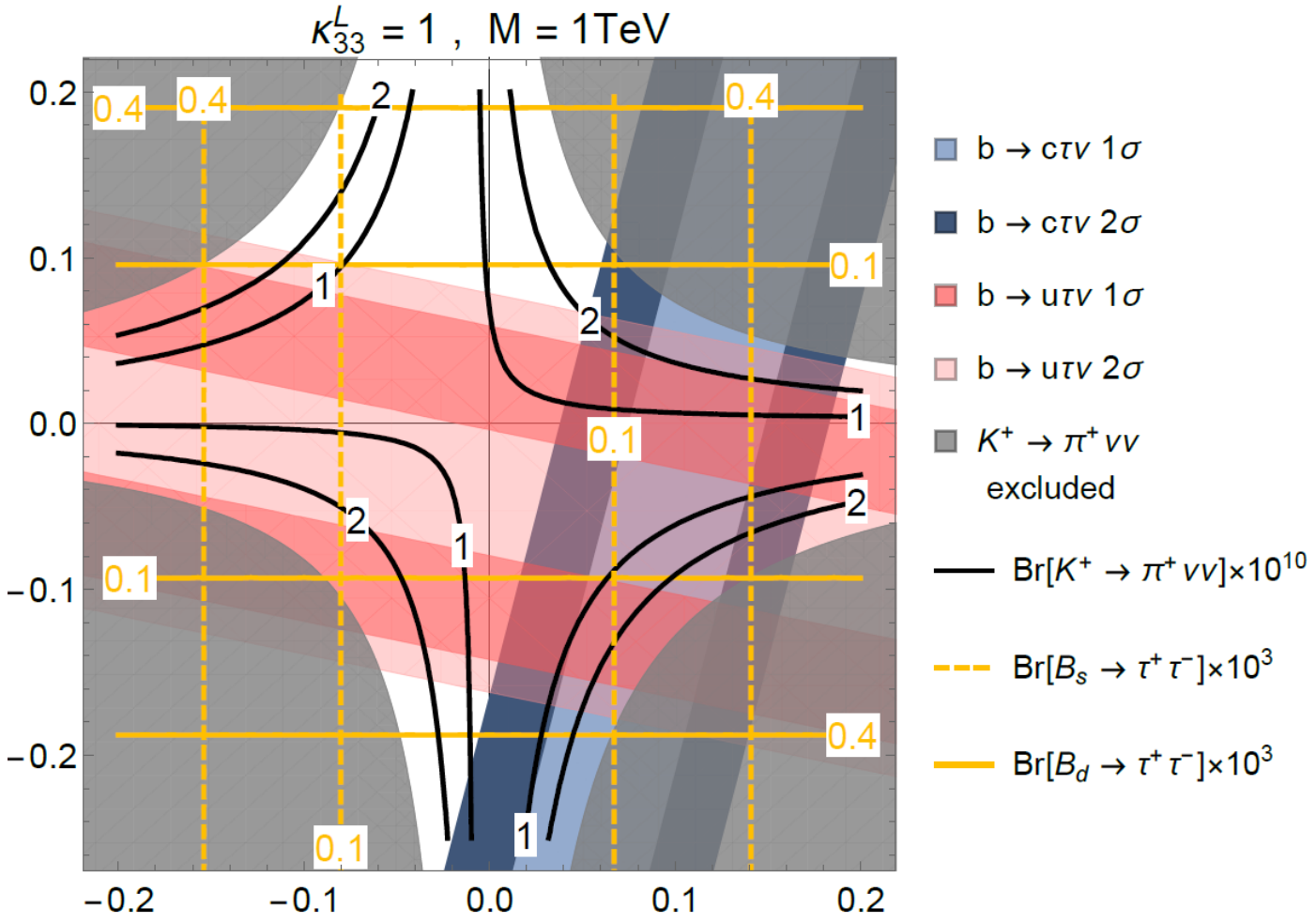



**Pati-Salam LQ can explain the flavour anomalies**

# Conclusions



# Vector LQ Phenomenology




Many correlations

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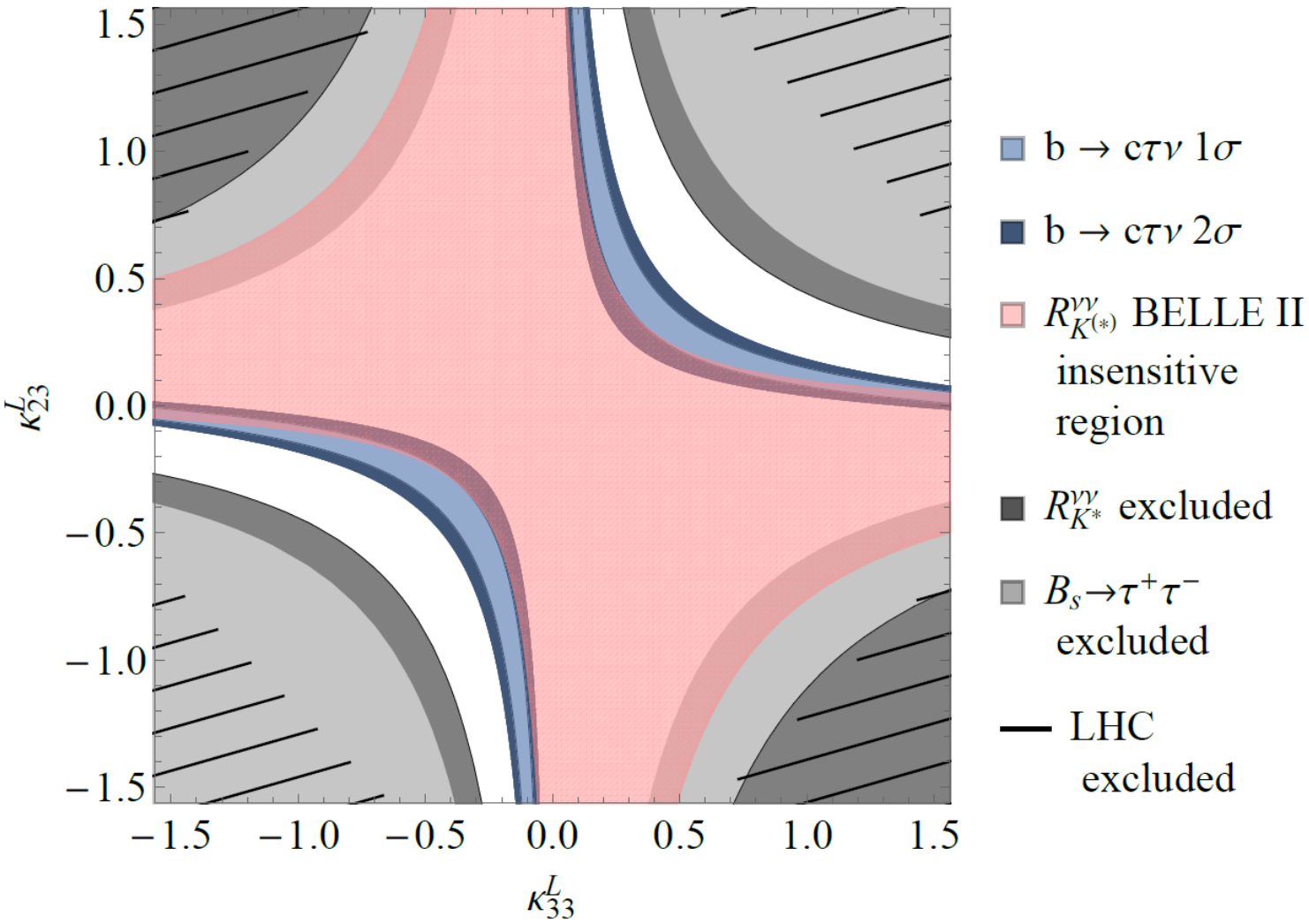


Many correlations

# Two Scalar Leptoquarks

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

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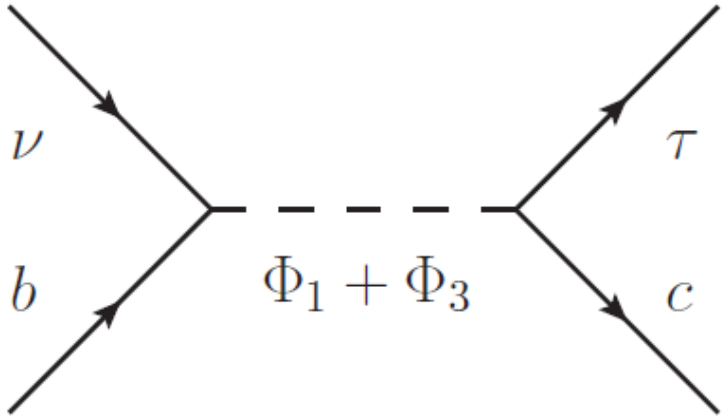
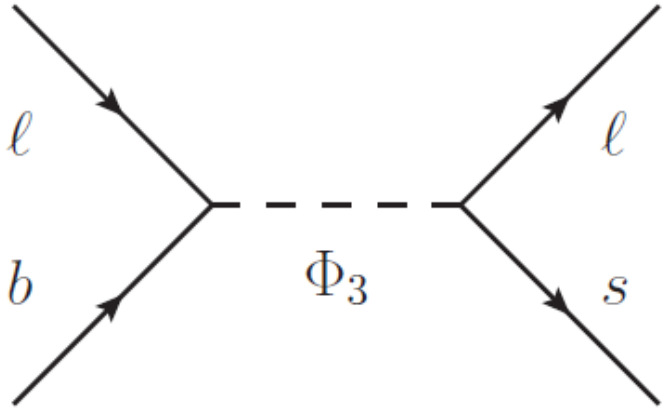
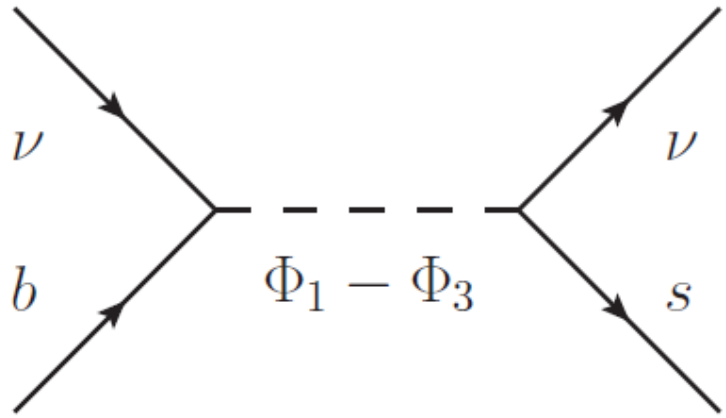
- $\Phi_1$ scalar leptoquark singlet with Y=-2/3
- $\Phi_3$ scalar leptoquark triplet with Y=-2/3




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

Destructive in b→sμμ