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Theory Group of the Laboratory for Particle Physics

Overview of the Flavour Anomalies

Vienna, 08.01.2020

Outline

- Introduction
- Status of the Flavour anomalies
  - $b \to s\mu\mu$
  - $b \to c\tau\nu$
  - a_μ & a_e
- Explanations of the Flavour anomalies
- Common Explanations
  - Vector Leptoquark
  - Scalar Leptoquarks
  - Z´ models
- Conclusions

Physics Beyond the Standard Model

- 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?

Finding New Physics with Flavour

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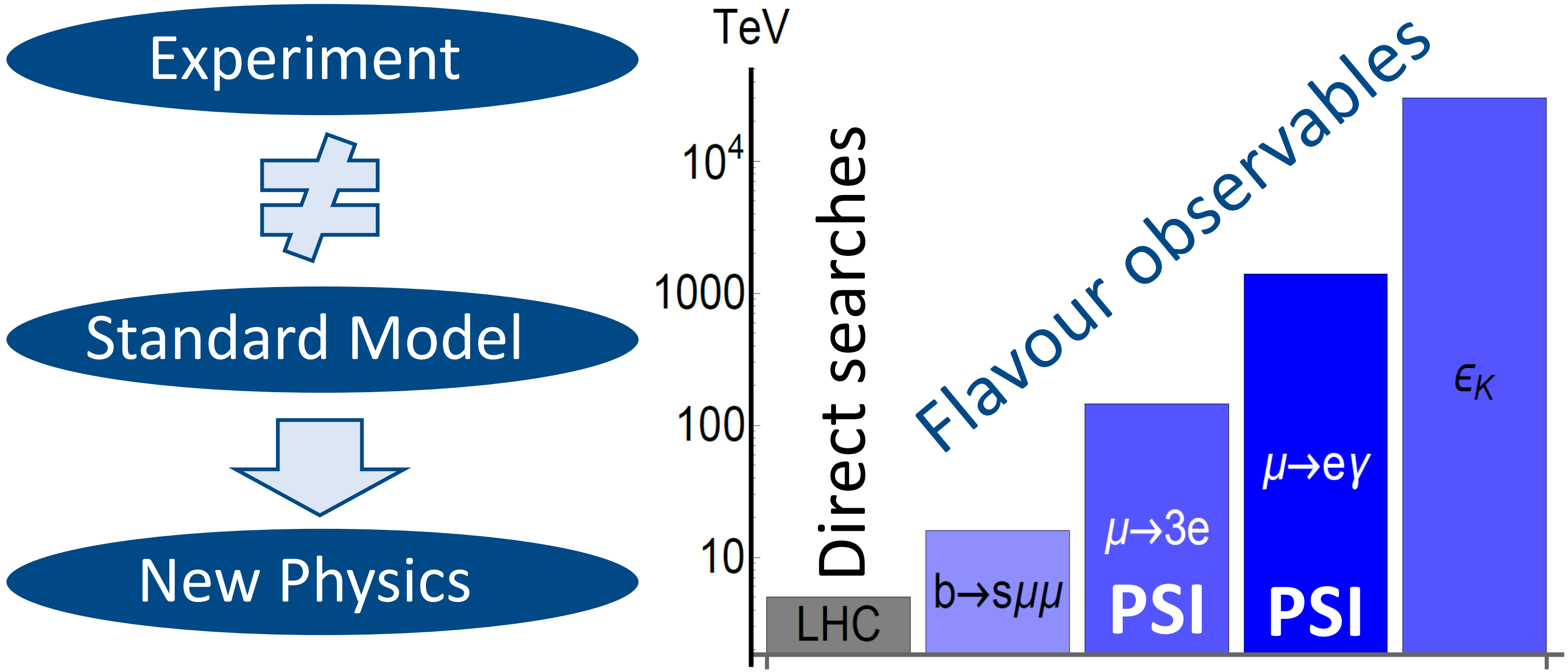
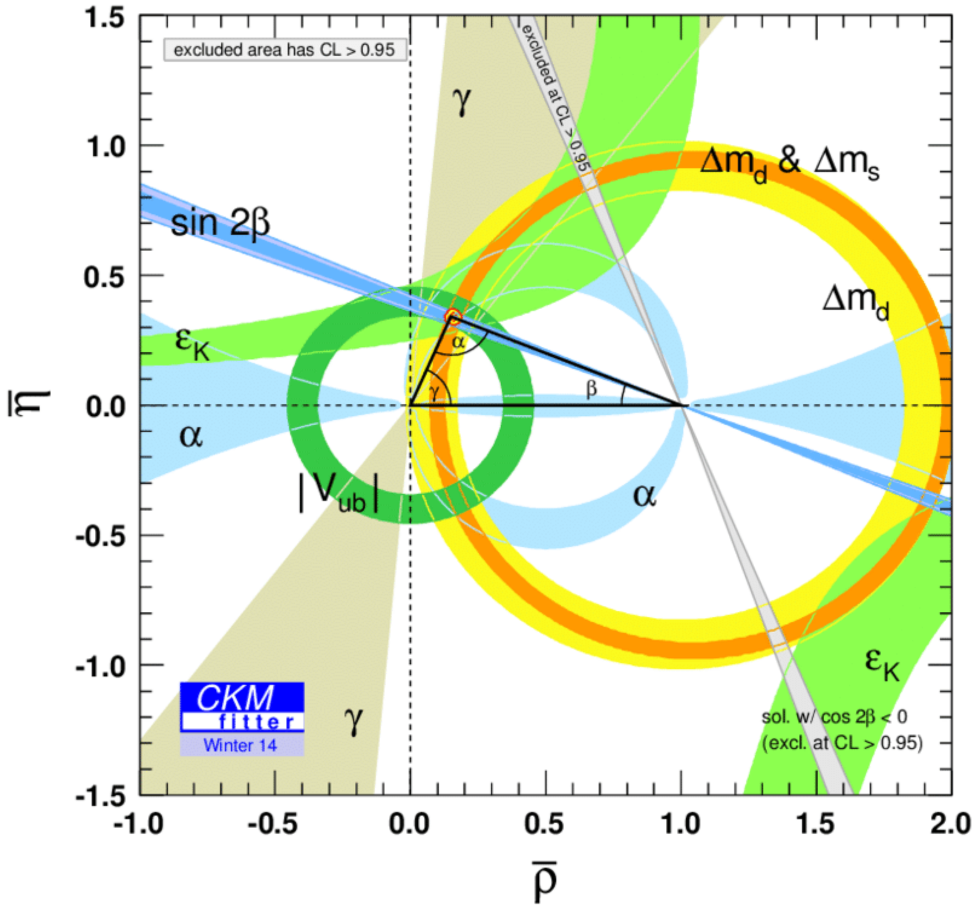
- At colliders one produces many (up to 10^{14}) heavy quarks or leptons and measures their decays into light flavours



Flavour observables are sensitive to higher energy scales than collider searches

Global Fit to the CKM Matrix

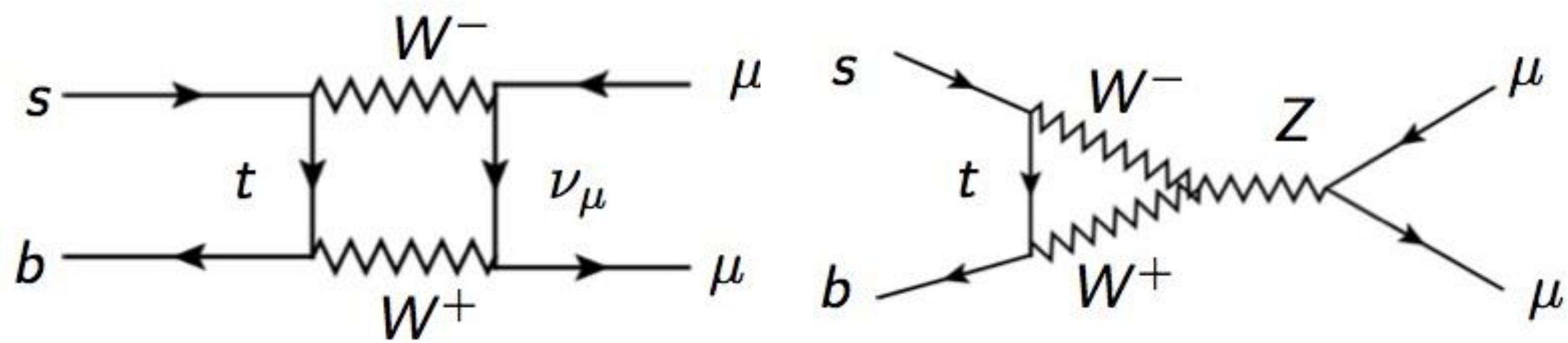


Picture of CKM Flavour violation established

Overview on the Flavour anomalies

$b \rightarrow s\mu^+\mu^-$ Processes

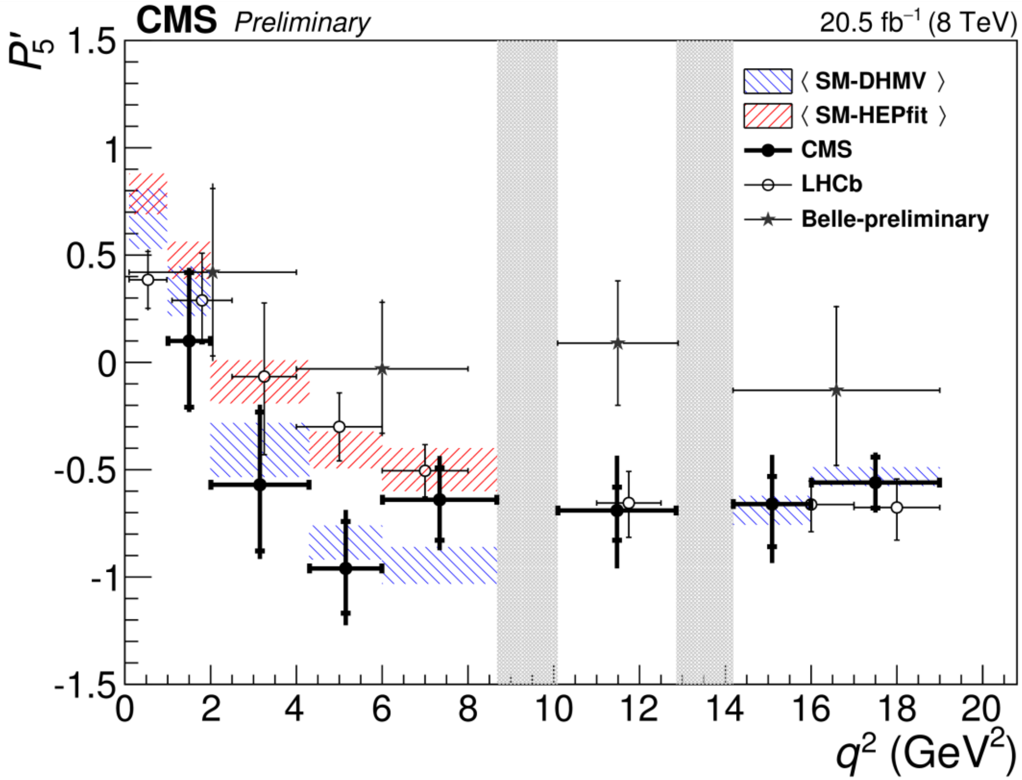
- Flavour Changing Neutral Current (FCNC)
- In the SM it is suppressed by
  - The CKM elements $V_{cb} \approx 0.04$
  - Electroweak scale
  - Loop-factor



Suppressed and very sensitive to New Physics

P_5', $B_s \to \mu\mu$ and $B_s \to \phi\mu\mu$

- P_5': angular observables in $B \to K^*\mu\mu \approx 3\sigma$



- $B_s \to \mu\mu$ and $B_s \to \varphi\mu\mu$ Br 20% to low; $\approx 2\sigma$ each

Hadronic uncertainties or NP?

$R(K^{(*)}) = B \rightarrow K^{(*)}\mu^+\mu^- / B \rightarrow K^{(*)}e^+e^-$

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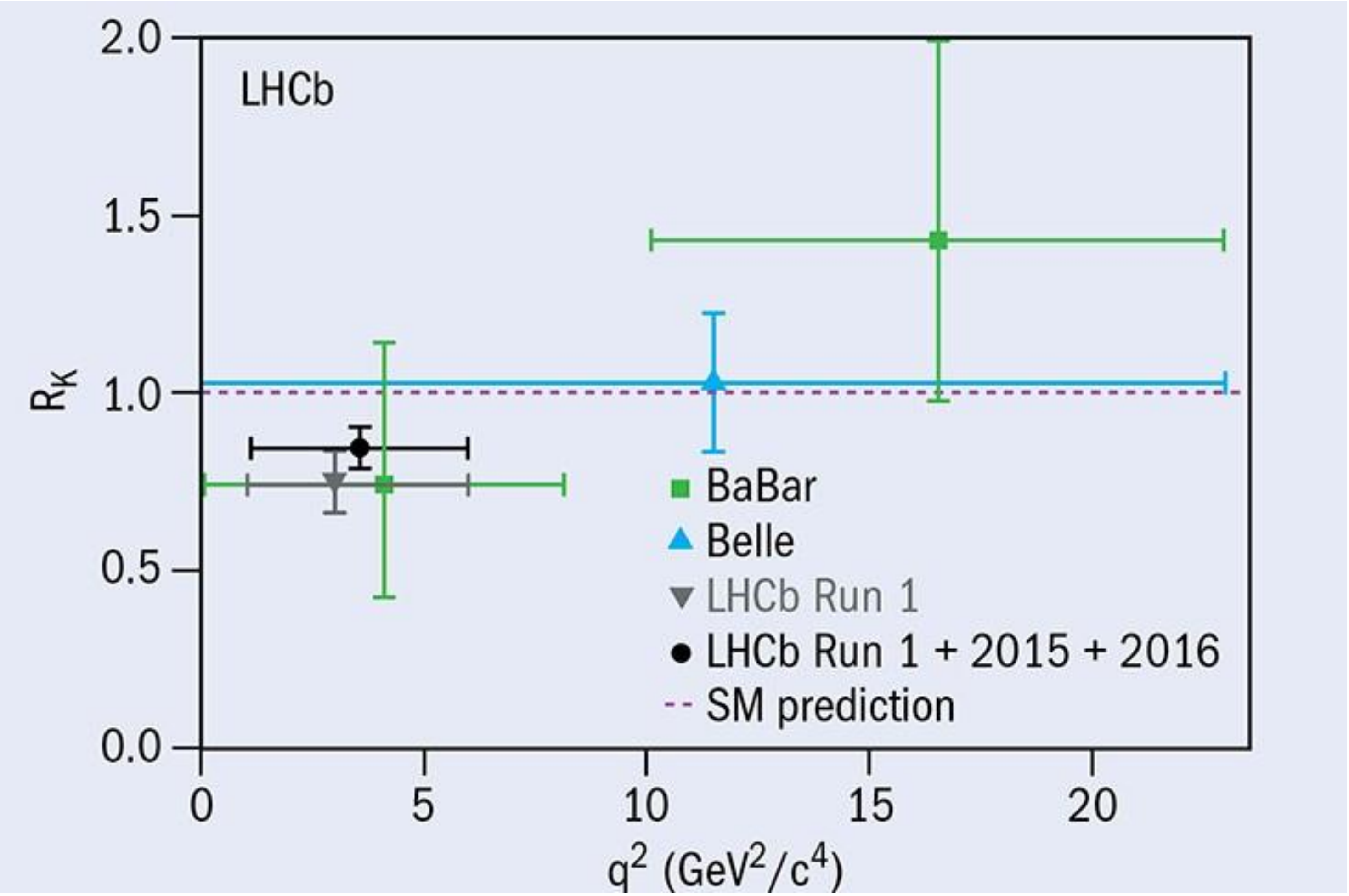
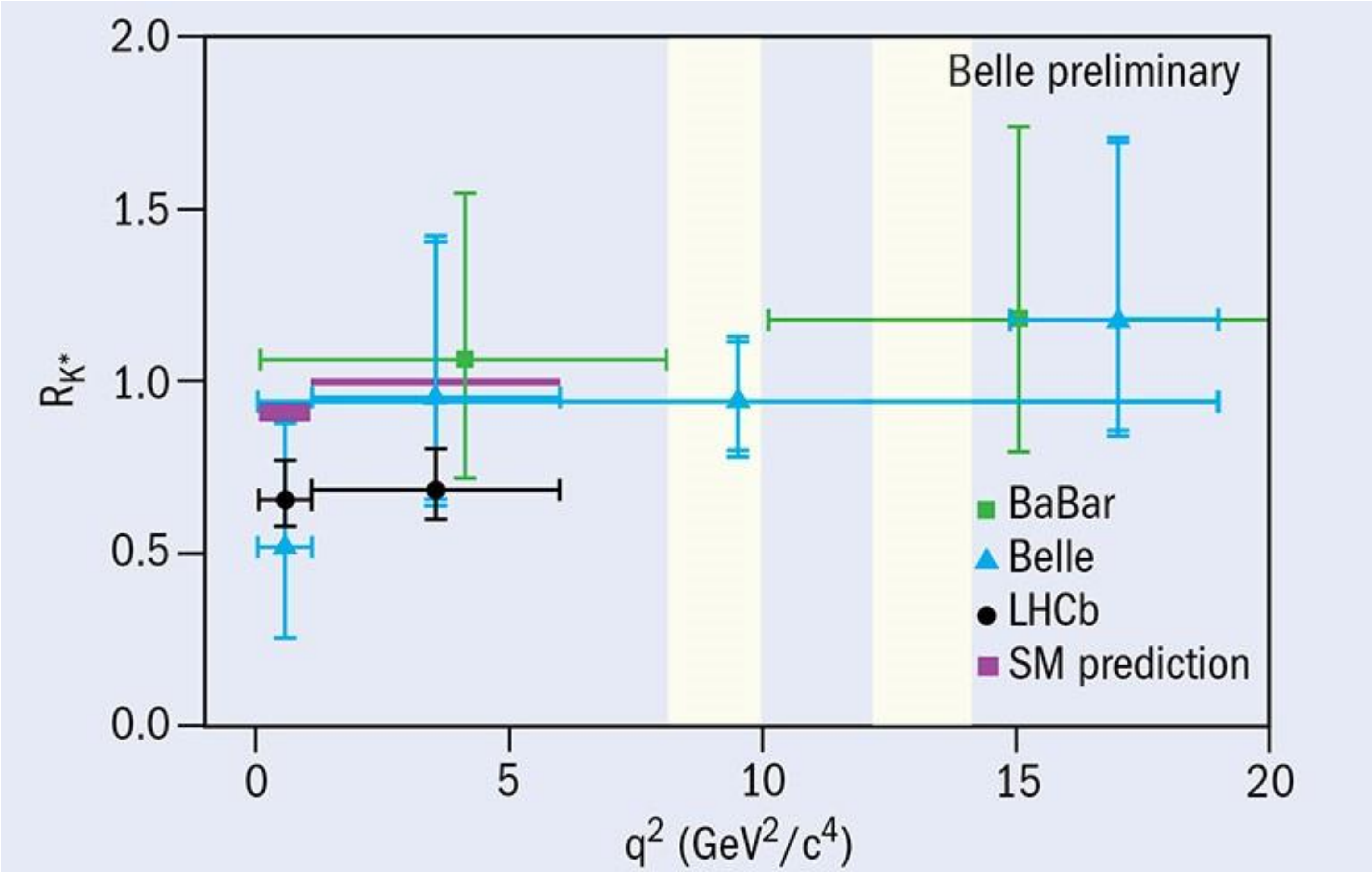


Lepton Flavour Violation in B decays?

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



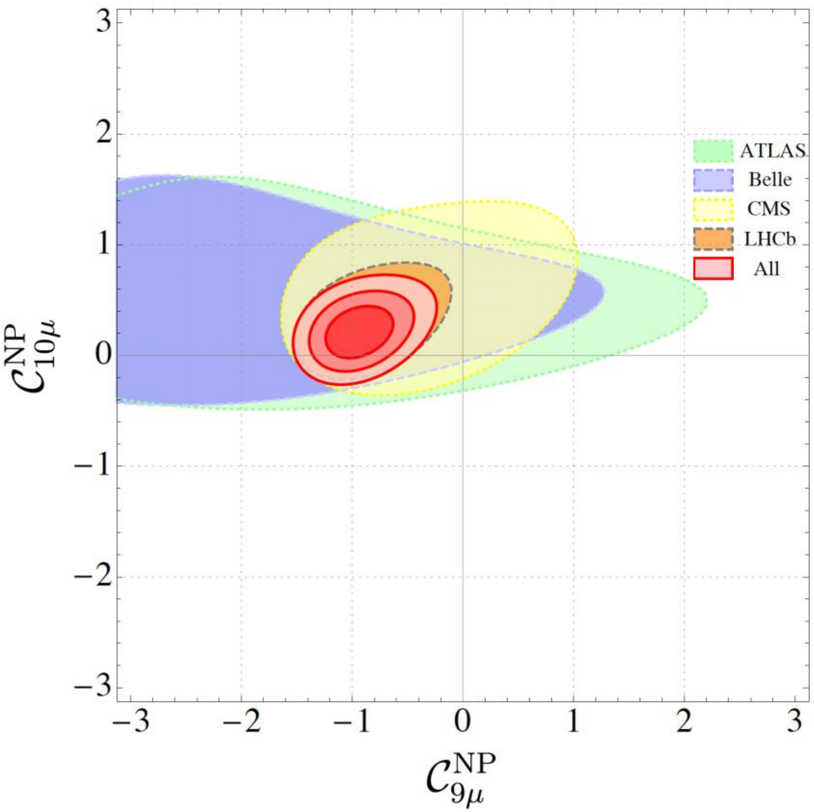
Lepton Flavour Violation in B decays?

Global fit to $b \to s\mu^+\mu^-$ data

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

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

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

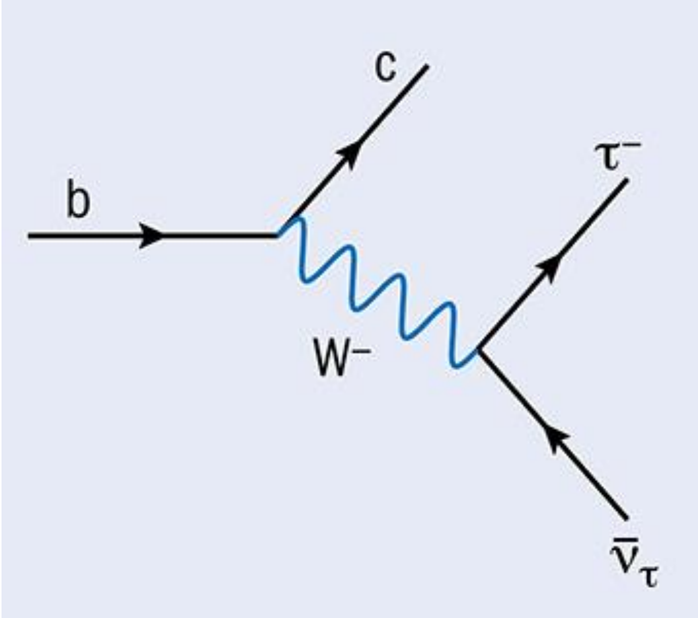


M. Alguero, B. Capdevila, AC, S. Descotes-Genon, P. Masjuan J. Matias and J. Virto, arXiv:1903.09578 [hep-ph].

Fit is 5-6 σ better than the SM

b→clν Transistions

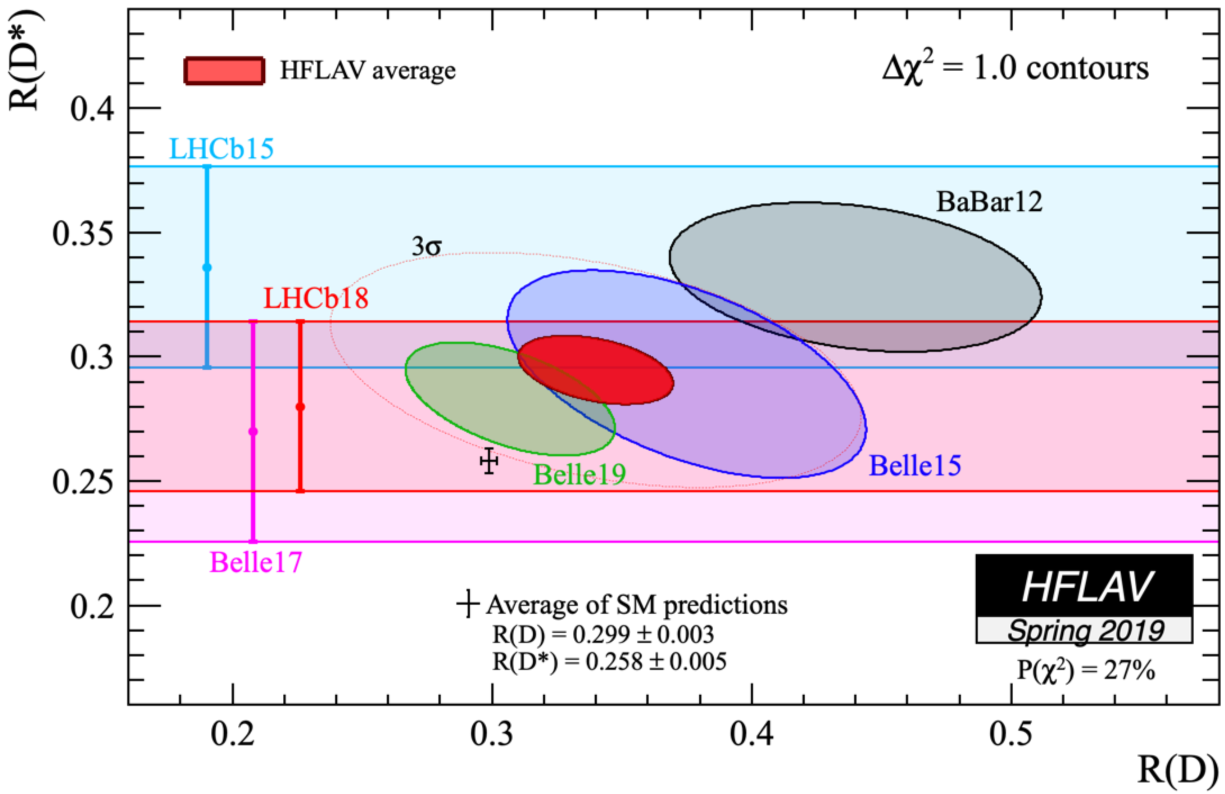
- B→Dlν, B →D*lnu, $\Lambda_b \to \Lambda_c l\nu$
- Tree-level decays in the SM
- Form factors needed
- With light leptons (l=μ, e) used to determine the CKM elements
- CKM fit works very well, i.e. tree-level in agreement with ΔF=2 processes



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

b→cτν Measurements

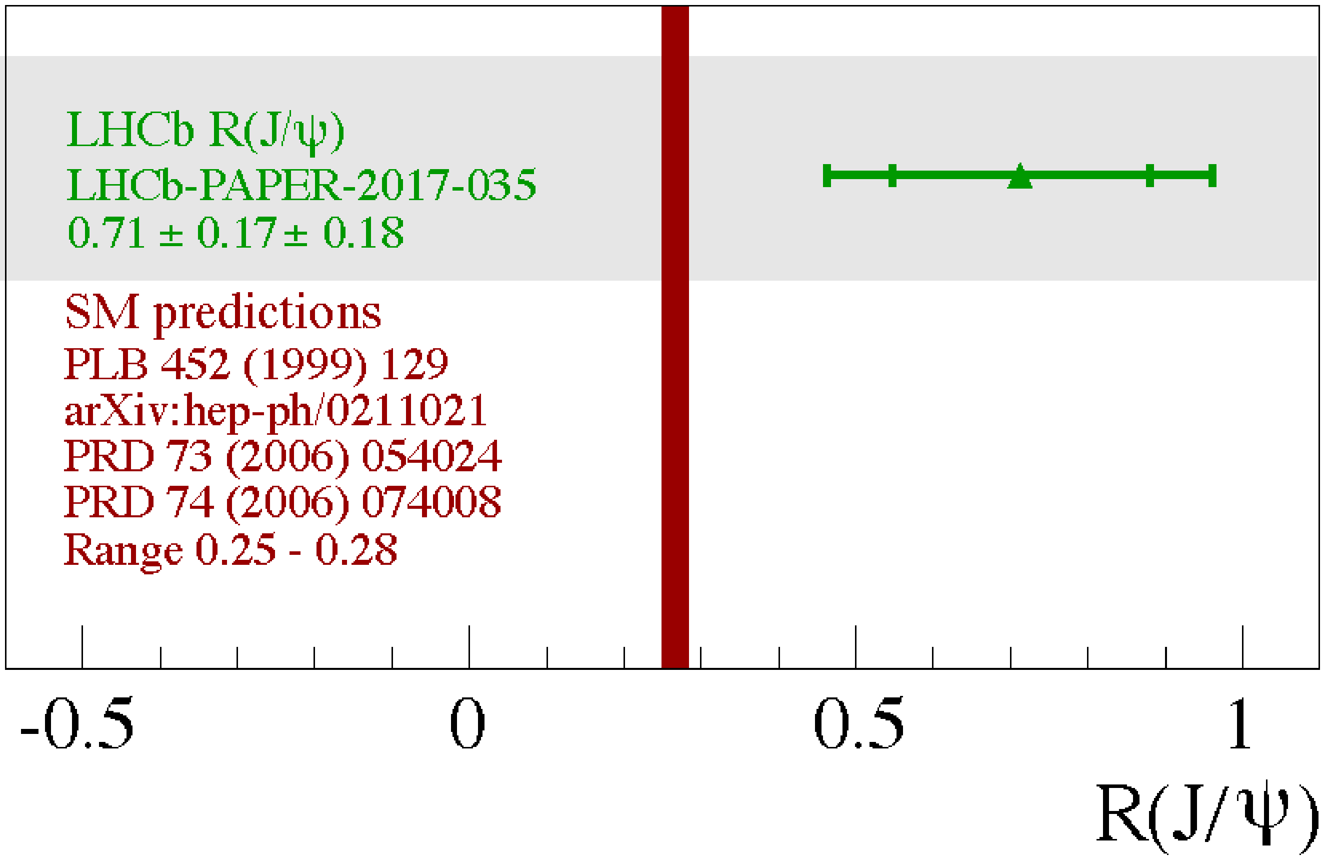
$$R\left(D^{(*)}\right) = B \rightarrow D^{(*)}\tau\nu / B \rightarrow D^{(*)}\ell\nu$$



All measurements above the SM prediction
>3σ deviation

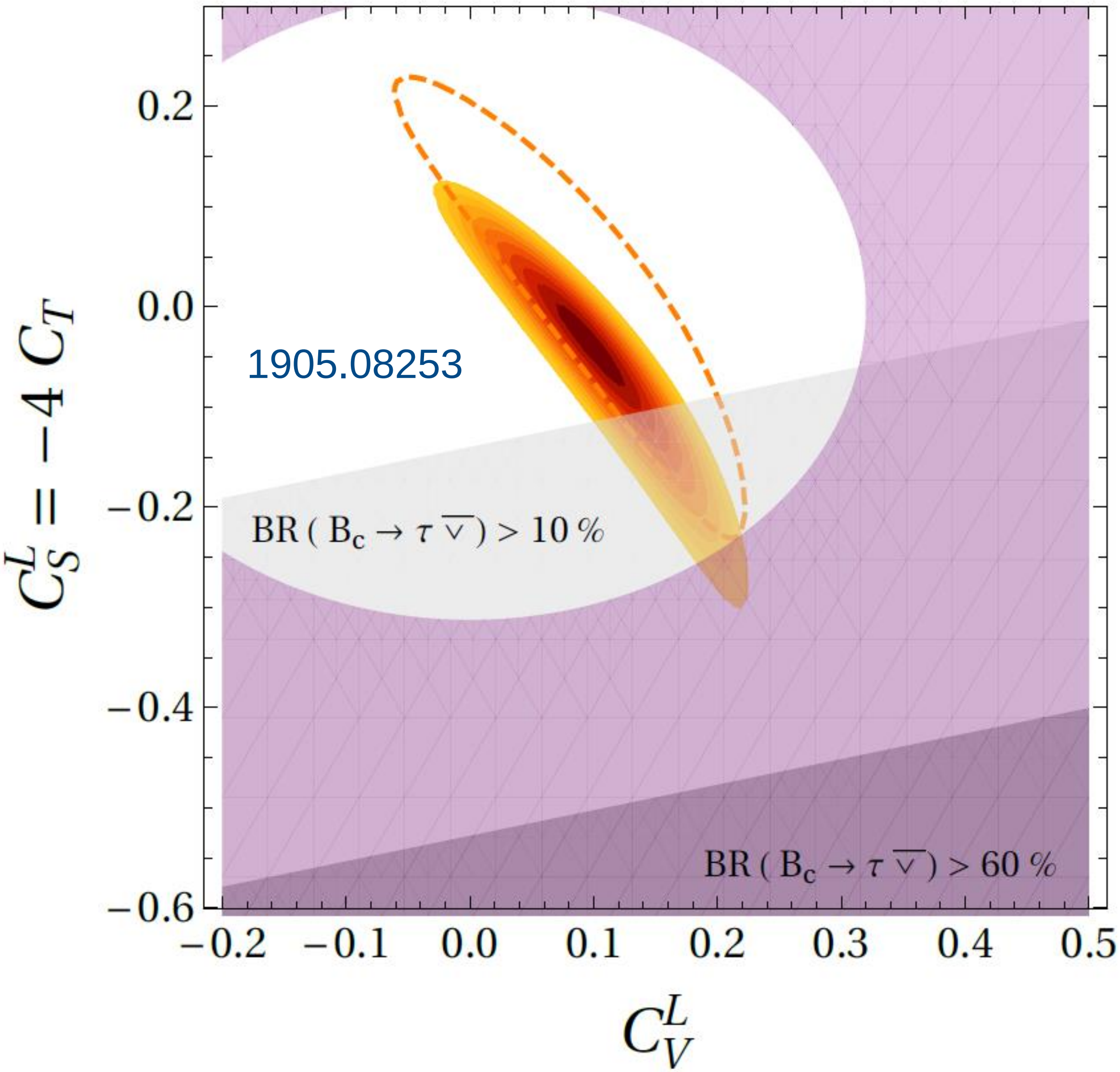
b→cτν Measurements

$$R\left(J/\Psi\right) = B_c \to J/\Psi\, \tau\nu / B_c \to J/\Psi\, l\, \nu$$



Supports R(D) & R(D*)

b→cτν Global Fit



Left-handed vector current needed

M. Blanke, A.C., T. Kitahara, M. Moscati, U. Nierste, I. Nišandžić, 1905.08253

Muon Anomalous Magnetic Moment

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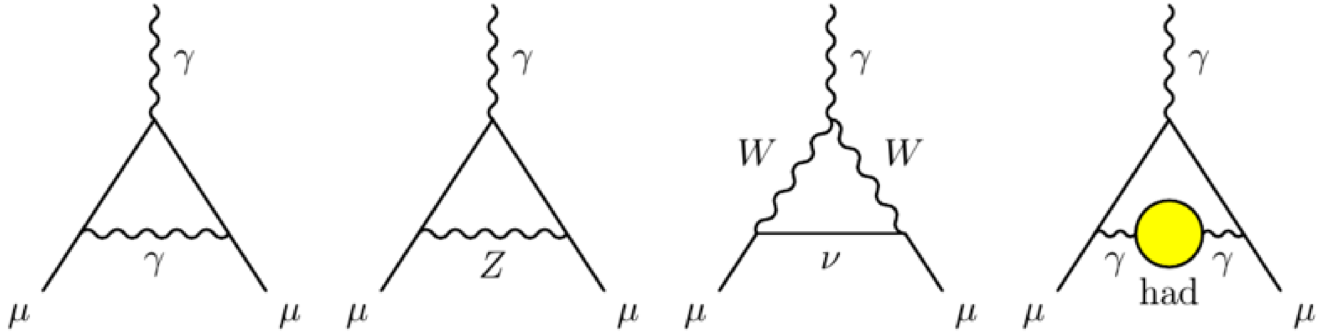
- Single measurement from BNL
- Theory prediction sound but challenging because of hadronic effects.

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

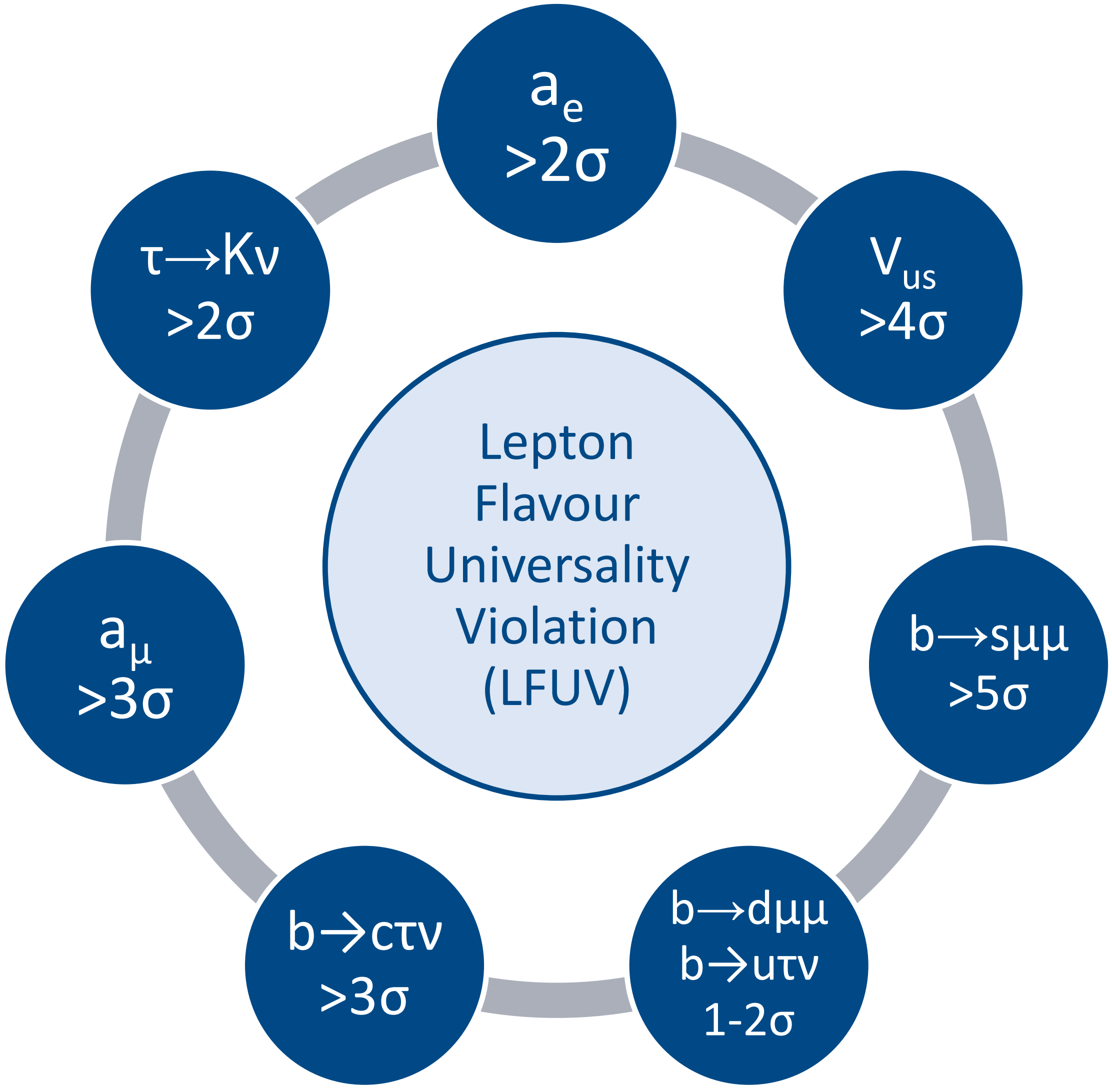
- Soon new experimental results



- Small tension in Δa_e with opposite sign

3σ deviation (order of SM-EW contribution)

Hints for New Physics



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Extensions of the Standard Model to account for the flavour anomalies

R(D) & R(D*)

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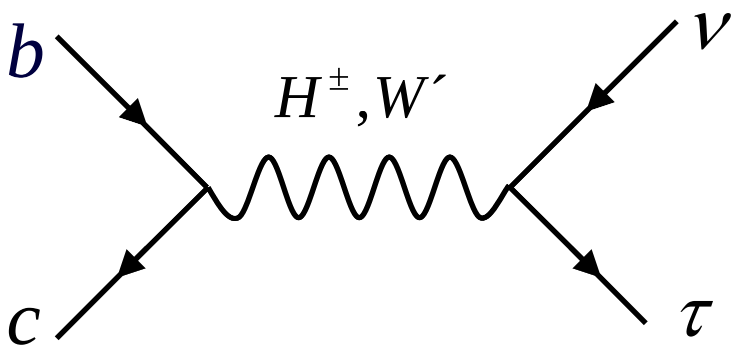
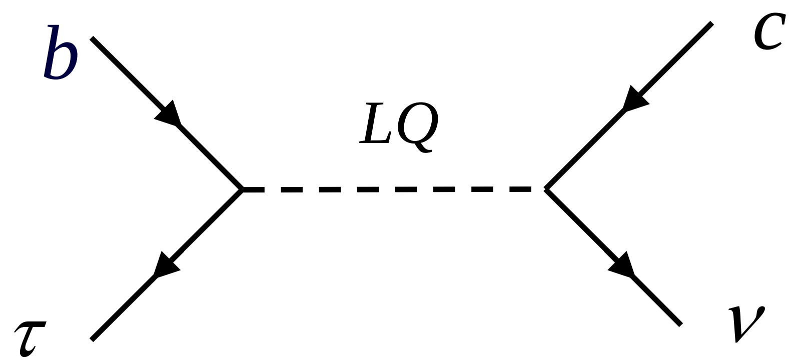


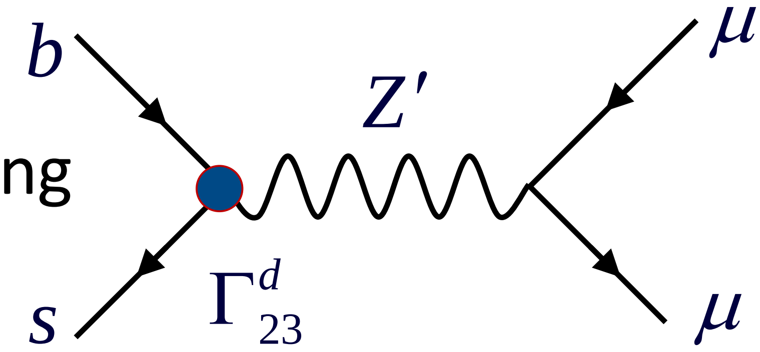


- Charged scalars: Problems with distributions and B_c lifetime
- W’: Strong constraints from direct LHC searches
- Leptoquark: Strong signals in qq→ττ searches

Explanation difficult but possible with Leptoquarks

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

- Z' W. Altmannshofer, S. Gori, M. Pospelov and I. Yavin 1403.1269, ….
  - Necessary effects in B_s mixing
  - Collider constraints



- Loop contributions
  - Scalars and vector-like ferions
  - 2HDM A.C., D. Müller and C. Wiegand, 1903.10440
  - R_2 Leptoquark D. Bečirević and O. Sumensari, 1704.05835
  - Z' coupling to tops J. Kamenik, Y. Soreq and J. Zupan, 1704.06005
- Leptoquarks G. Hiller and M. Schmaltz arXiv:1408.1627
  D. Bečirević, S. Fajfer and N. Košnik,1503.09024, ….

Small effect needed; many possibilities

a_μ explanations

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- MSSM
  - tan(ß) enhanced slepton loops
- Scalars
  - Light scalars with enhanced muon couplings
- Z’
  - Very light with τμ couplings (m_τ enhancement)
- Leptoquarks
  - m_t enhaned effects

Chiral enhancement or very light particles

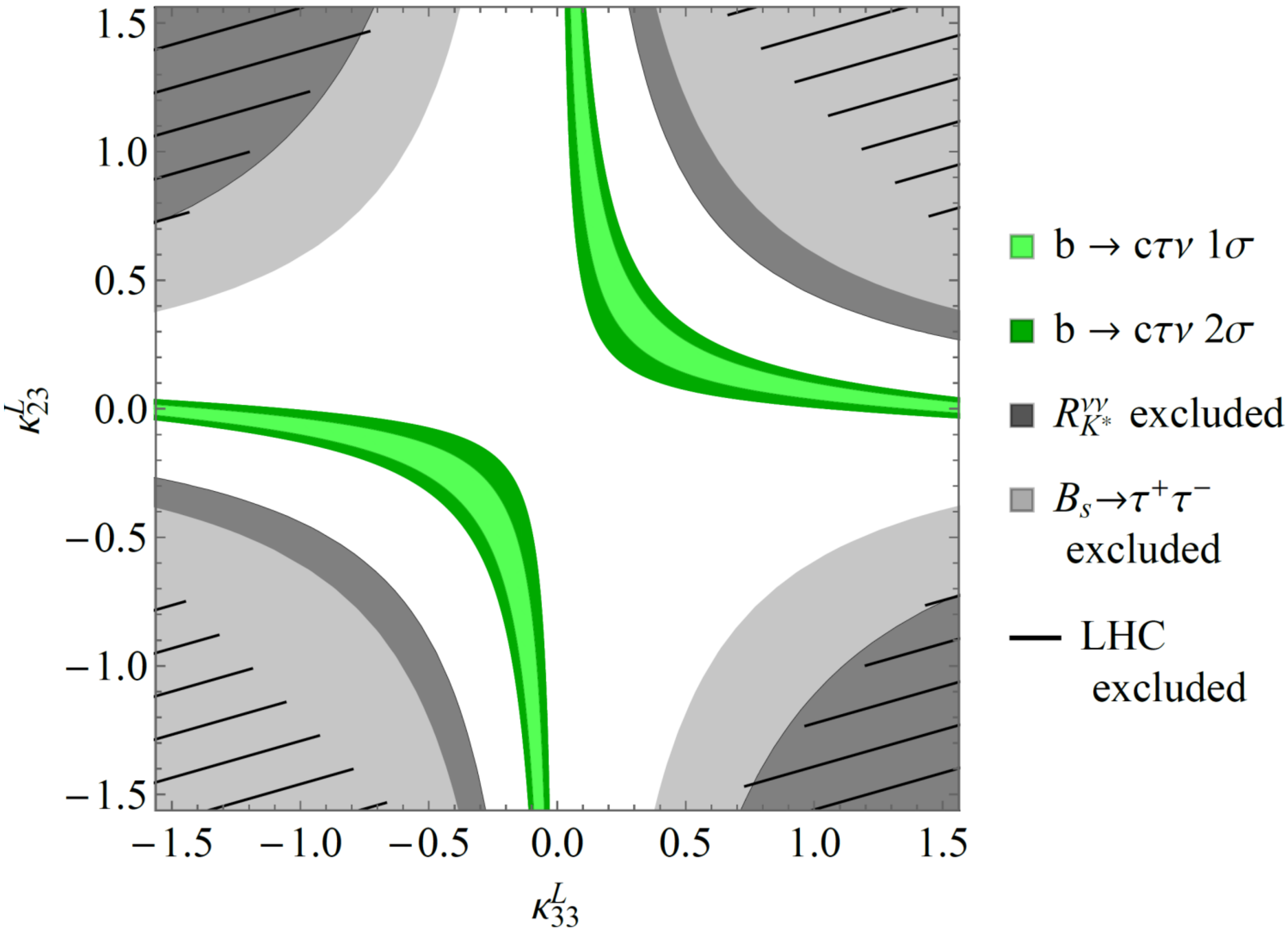
Simultaneous Explanation with the Pati-Salam Leptoquark

Vector Leptoquark SU(2) Singlet

- Left-handed 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

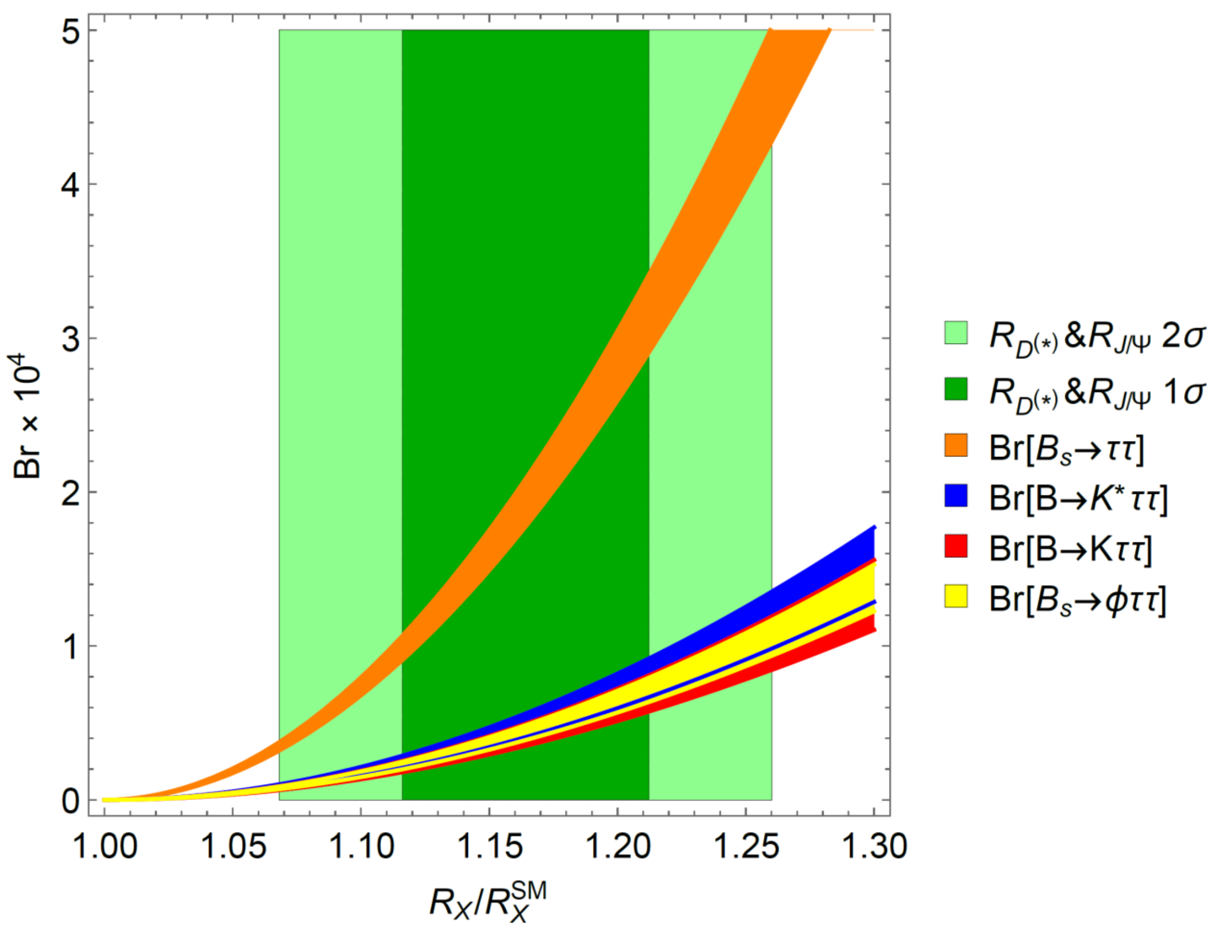
Vector LQ Phenomenology



Compatible with constraints for generic couplings

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

- Large couplings to the second generation



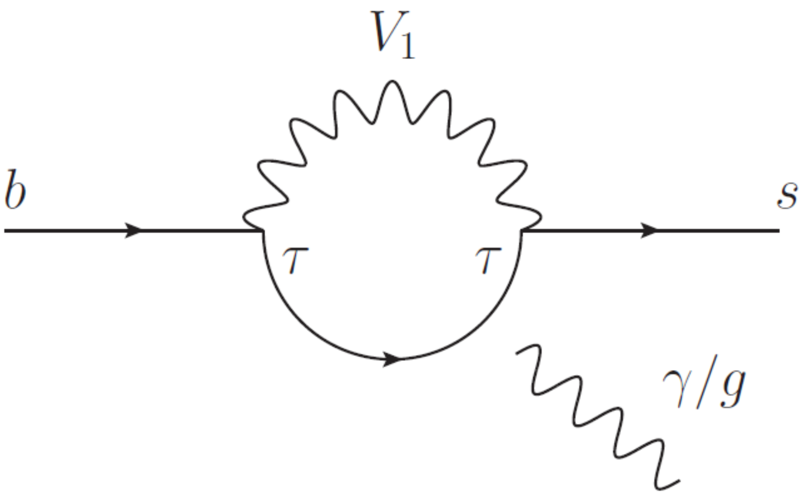
$b \to s\tau\tau$

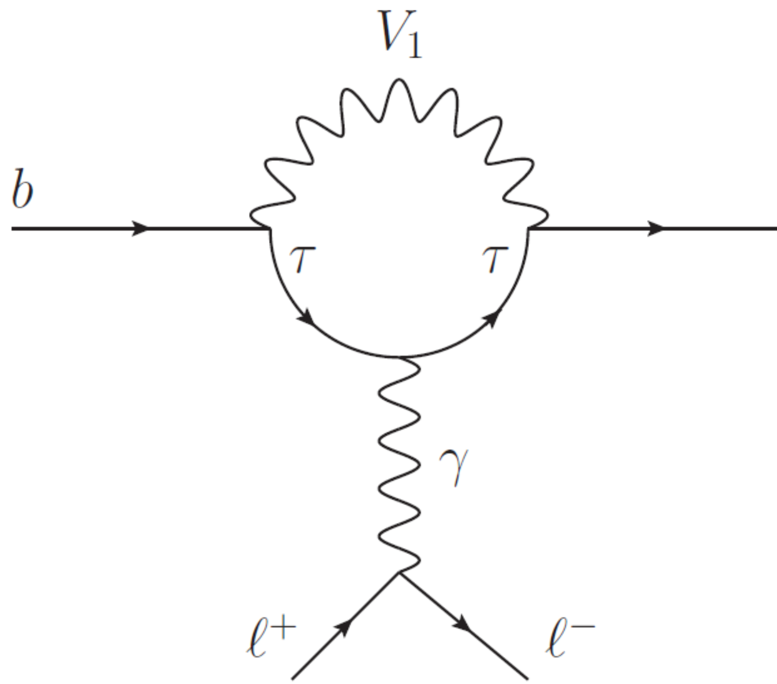
very strongly enhanced

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

Important Loop-Effects

- Explanation of b→cτν requires large bτ and sτ couplings (follows from SU(2) invariance)





AC, C. Greub, D. Müller, F. Saturnino, PRL 2018

Large loop effects in b→sμμ

Important Loop-Effects

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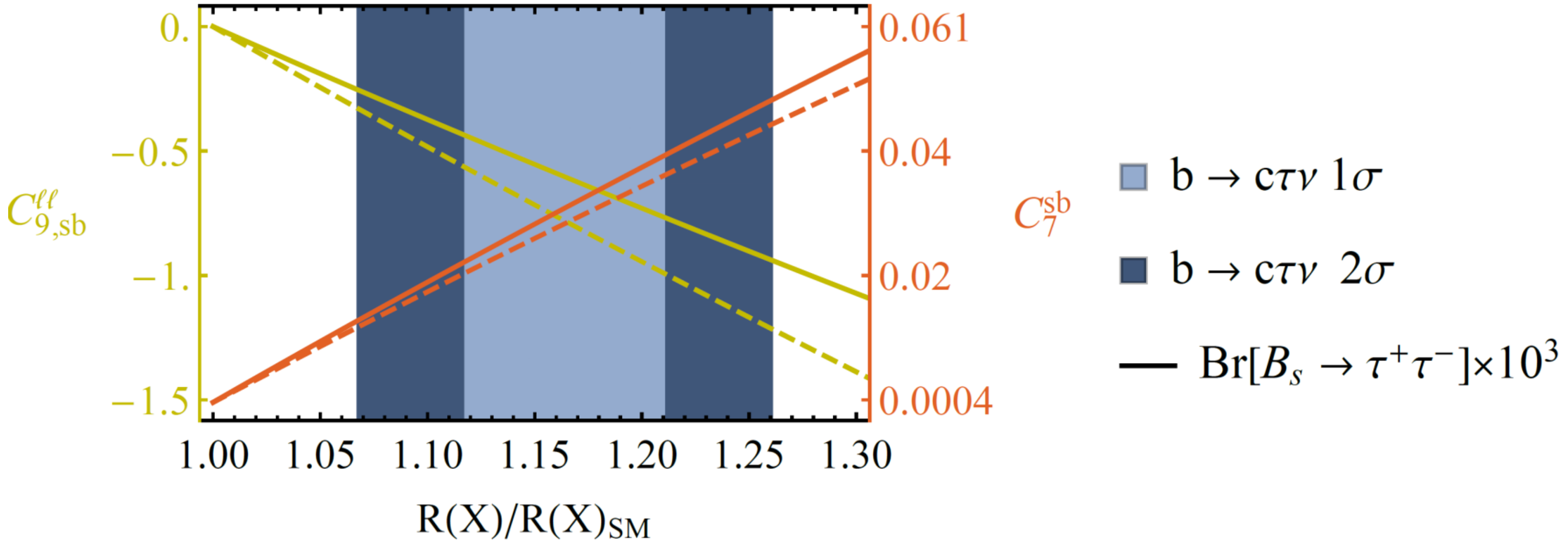
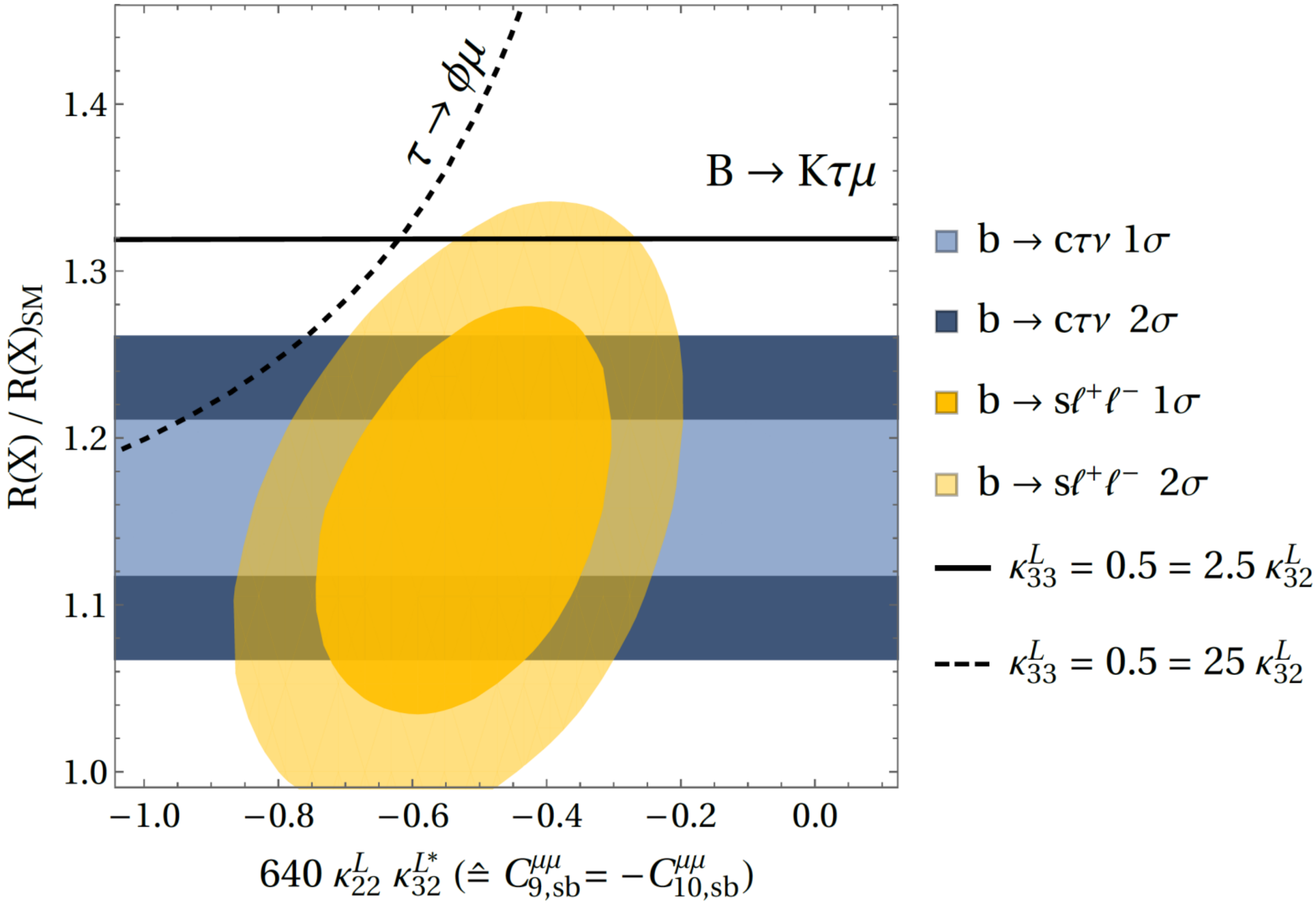
- Explanation of b→cτν requires large bτ and sτ couplings (follows from SU(2) invariance)



AC, C. Greub, D. Müller,
F. Saturnino, PRL 2018

Large loop effects in b→sμμ

Perfect agreement with data



Pati-Salam LQ can explain the flavour anomalies

Possible UV completions

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- $SU(4)\times SU(3)'\times SU(2)_L\times U(1)_Y$ + Vector-like fermions

  L. Di Luzio, A. Greljo, M. Nardecchia, arXiv:1708.08450
- $SU(4)\times U(2)_L\times SU(2)_R$ + Vector-like fermions

  L. Calibbi, AC, T. Li, arXiv:1709.00692
- $SU(4)\times SU(4)\times SU(4)$

  M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, arXiv:1712.01368
- $SU(4)\times U(2)_L\times SU(2)_R$ including scalar LQs and light right-handed neutrinos

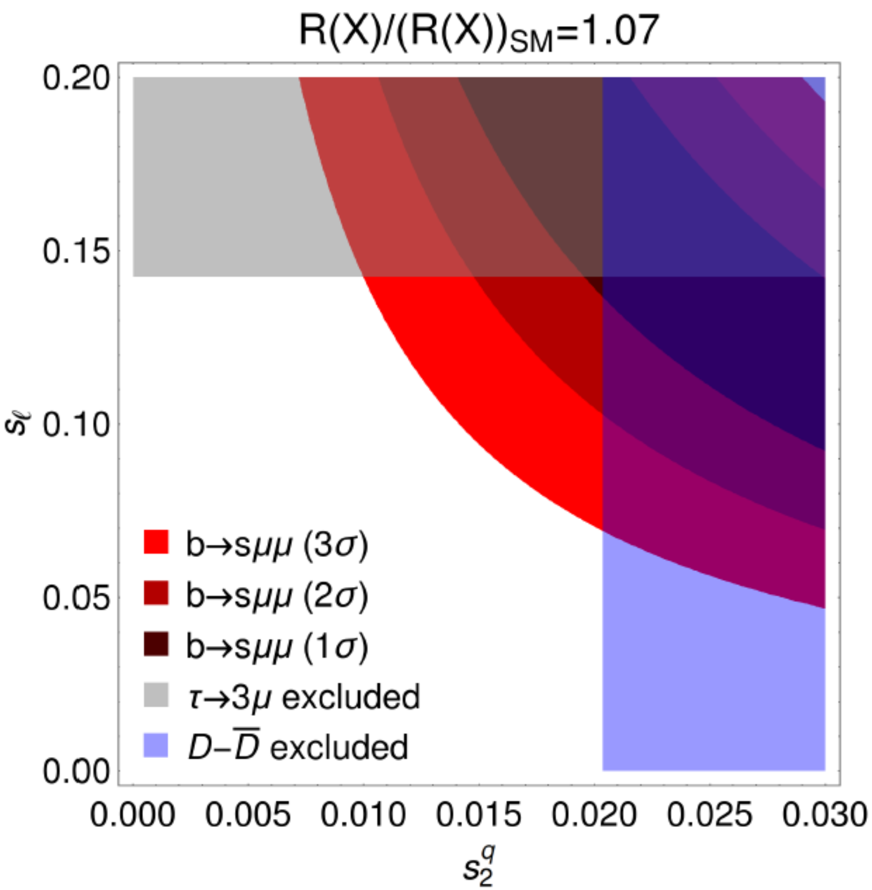
  J. Heeck, D. Teresi, arXiv:1808.07492
- SU(8) might even explain ε'/ε

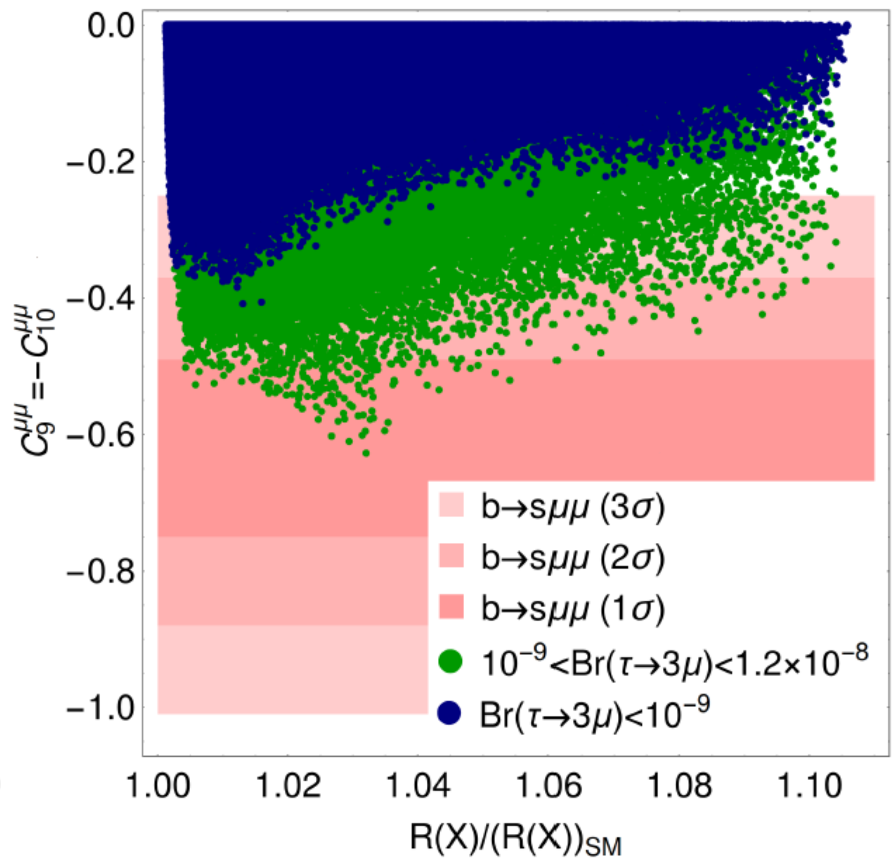
  S. Matsuzaki, K. Nishiwaki and K. Yamamoto, arXiv:1806.02312
- $SU(4)\times U(2)\times SU(2)_R$ in RS background

  M. Blanke, AC, arXiv:1801.07256

Good solution, but challenging UV completion

Pati-Salam RS Phenomenology





$M = 3\,\mathrm{TeV}$, $s_2^\ell = 0.2$, $s_3^\ell = 1/\sqrt{2}$ and $s_3^q = \sqrt{3}/2$

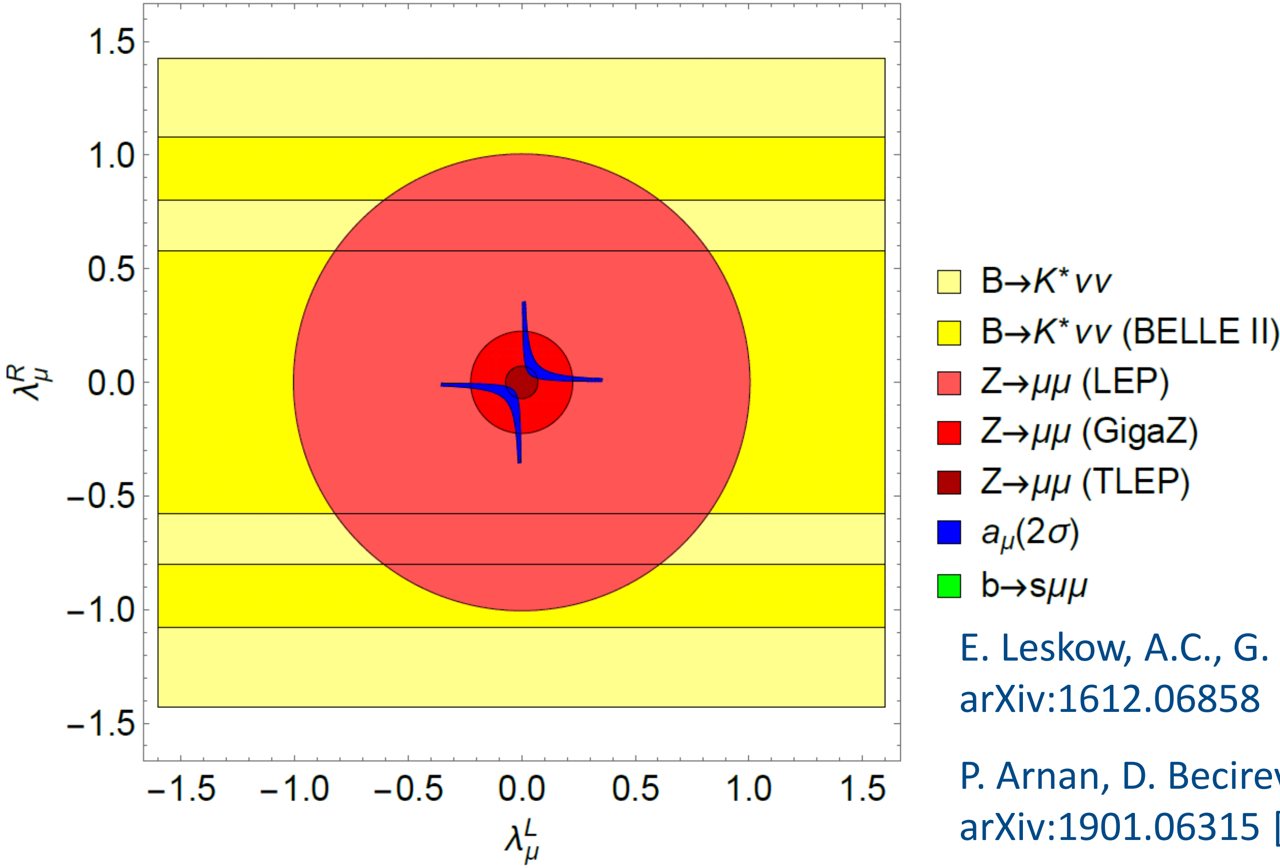
M. Blanke, AC, PRL 2018

Modell well motivated + limited but sizable effect

Scalar Leptoquarks

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

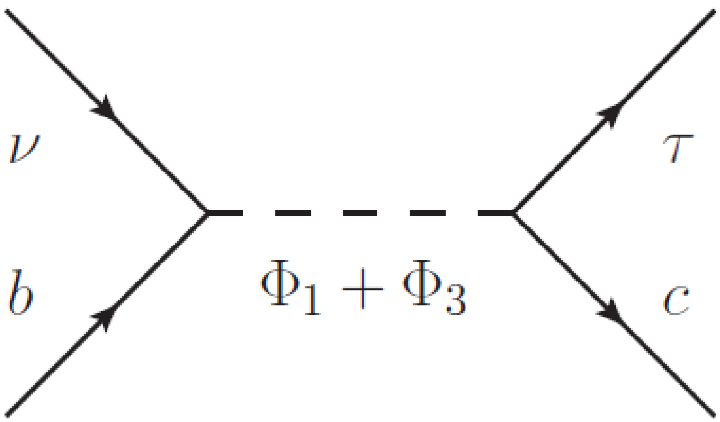
P. Arnan, D. Becirevic, F. Mescia, O. Sumensari, arXiv:1901.06315 [hep-ph]

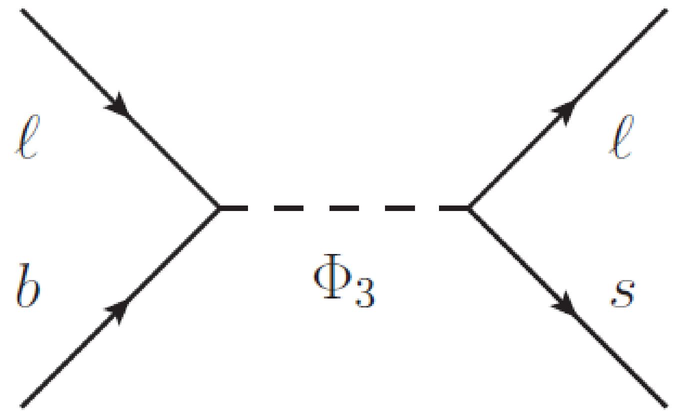
Z→μμ at future colliders

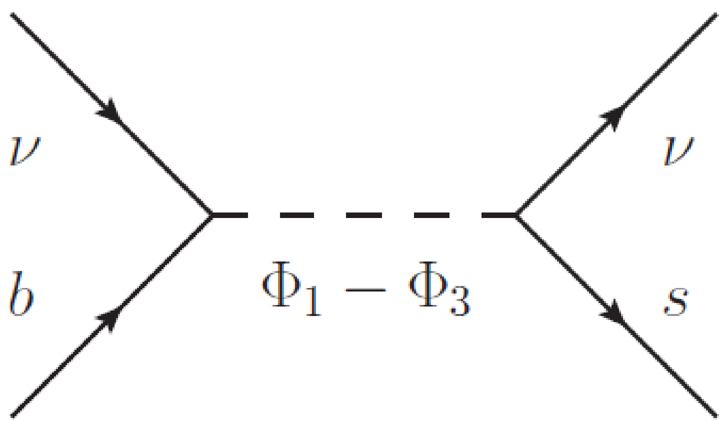
Two Scalar Leptoquarks

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

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



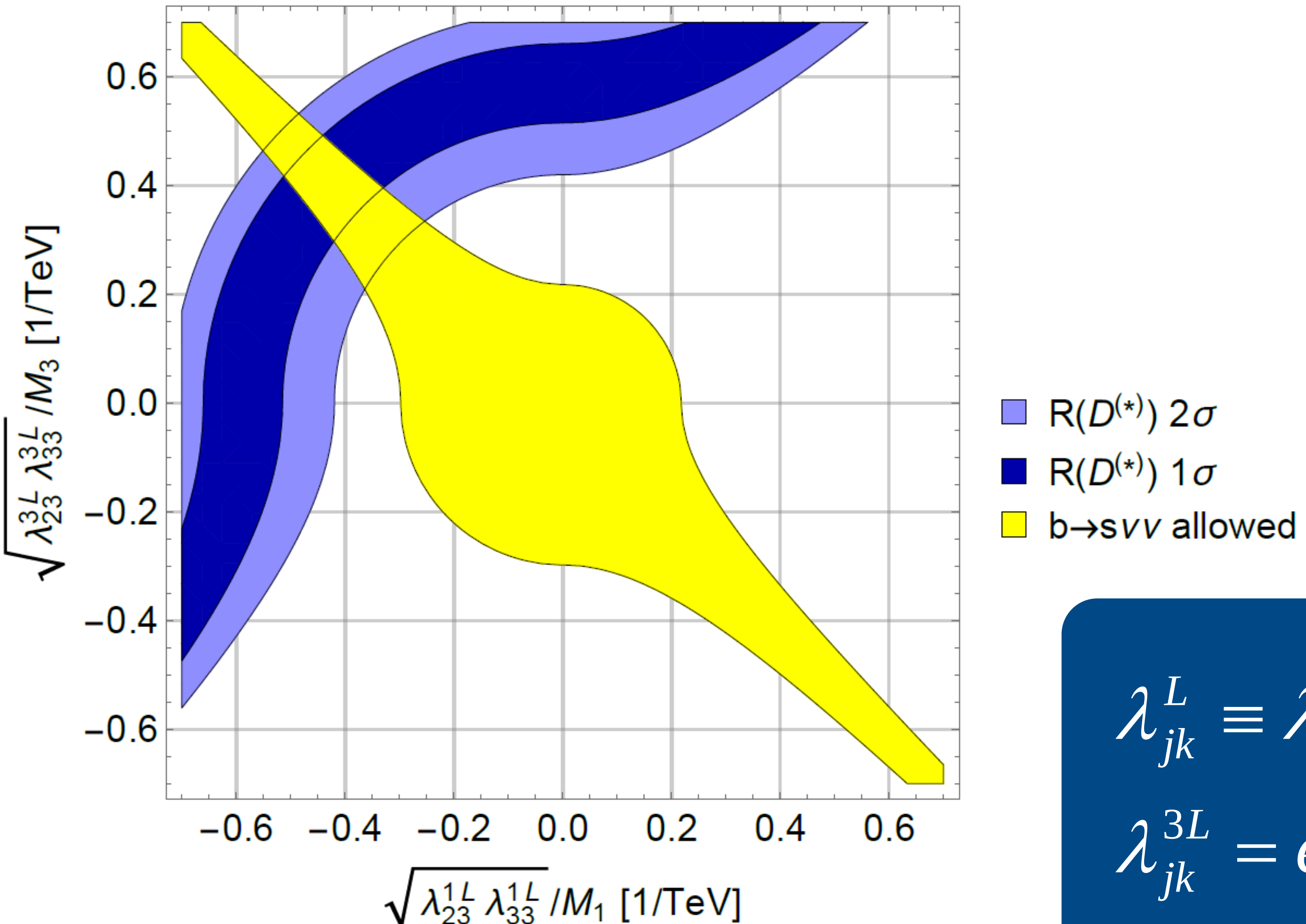




Constructive in $R(D^{(*)})$

Destructive in $b \to s\mu\mu$

R(D$^{(*)}$), b→sνν with 2 Scalar LQs



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

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

$R(D^{(*)})$, $b\to sll$ and a_μ

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- 4 benchmark points

AC, D. Mueller, F. Saturnino
arxiv:1912.04224

	κ_{22}	κ_{32}	κ_{23}	κ_{33}	λ_{22}	λ_{32}	λ_{23}	λ_{33}	$\hat{\lambda}_{32}$	$\hat{\lambda}_{23}$
● p_1	-0.019	-0.059	0.58	-0.11	-0.0082	-0.016	-1.46	-0.064	-0.19	1.34
● p_2	-0.017	-0.070	-1.23	0.066	0.0078	-0.055	1.36	0.052	-0.053	-1.47
● p_3	0.0080	0.081	1.18	-0.073	-0.0017	0.16	-0.76	-0.068	0.023	1.23
● p_4	-0.0032	-0.21	0.44	-0.20	0.014	-0.10	-1.38	-0.068	-0.032	0.57

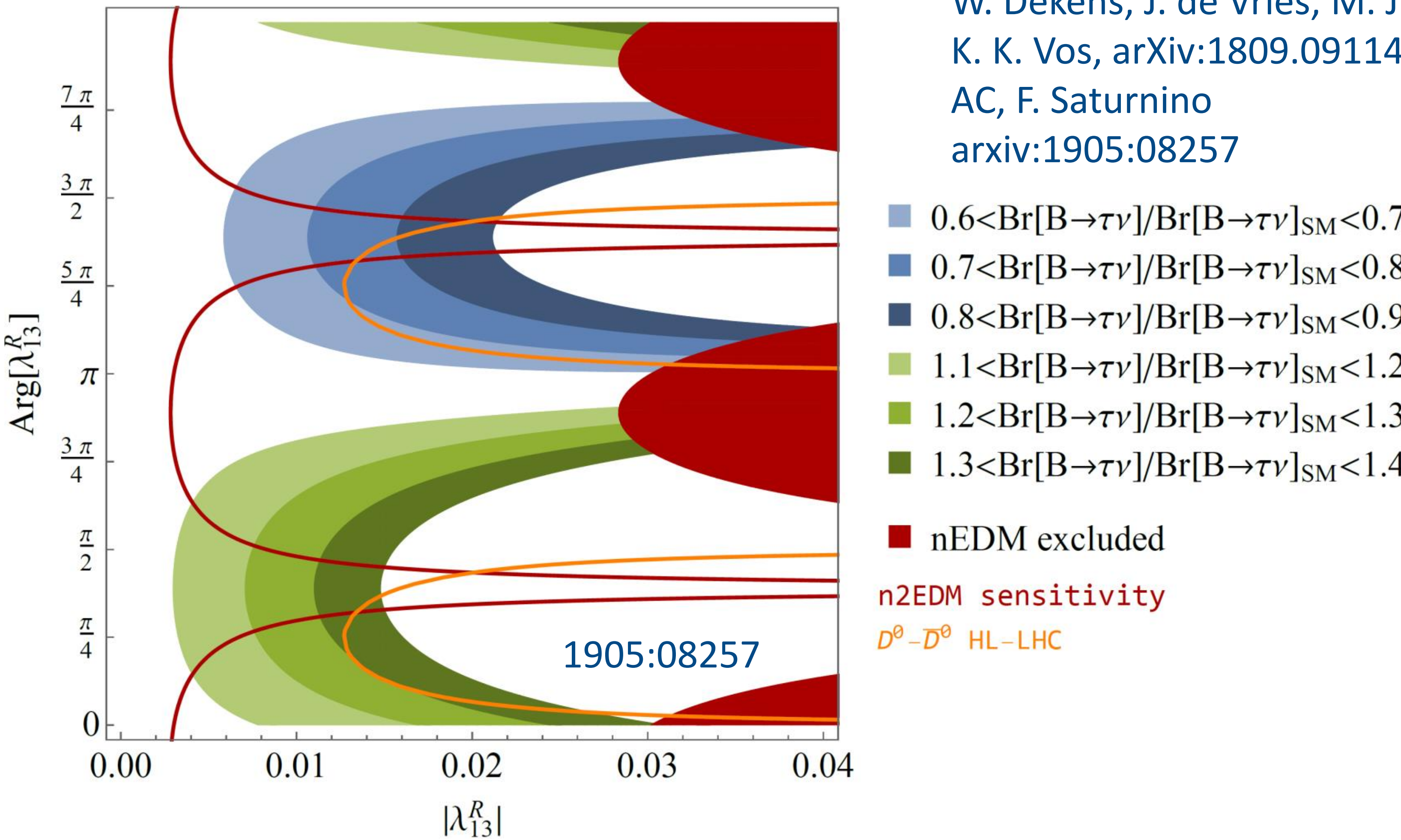
	$C_9^{\mu\mu} = -C_{10}^{\mu\mu}$	$C_9^{\ell\ell}$	$\frac{R(D)}{R(D)_{\rm SM}}$	$\frac{R(D^*)}{R(D^*)_{\rm SM}}$	$\frac{B_s\to\tau\tau}{B_s\to\tau\tau\vert_{\rm SM}}$	$\tau\to\mu\gamma$ $\times10^8$	δa_μ $\times10^{11}$	$\tilde{V}_{cb}^e/\tilde{V}_{cb}^\mu-1$ $\times10^6$	$Z\to\tau\mu$ $\times10^{10}$
● p_1	-0.52	-0.21	1.15	1.10	59.88	4.35	207	291	0.117
● p_2	-0.56	-0.28	1.14	1.10	99.76	0.766	199	448	2.38
● p_3	-0.31	-0.31	1.14	1.09	112.5	3.62	255	17	0.129
● p_4	-0.31	-0.31	1.13	1.11	112.5	0.734	230	934	45.6

	$C_{SL}^{\tau\tau} = -4C_{TL}^{\tau\tau}$	$C_{VL}^{\tau\tau}$	$R_{\nu\bar\nu}^{K^{(*)}}$	$\frac{\Delta m_{B_s}^{\rm NP}}{\Delta m_{B_s}^{\rm SM}}$	$B\to K\tau\mu$ $\times10^5$	$\tau\to\phi\mu$ $\times10^8$	$\tau\to\mu ee$ $\times10^{11}$	$\vert\Lambda_{33}^{\rm LQ}(0)\vert$ $\times10^5$	$\frac{\Delta_{33}^L(m_Z^2)}{\Lambda_{\rm SM}^{L\ell}}\times10^{-5}$
● p_1	0.023	0.040	2.33	0.1	0.512	1.27	44.94	1.11	-3.64
● p_2	0.020	0.040	0.87	0.16	3.32	4.73	7.783	0.90	-3.02
● p_3	0.023	0.037	1.08	0.19	4.07	1.00	37.89	0.89	-3.51
● p_4	0.010	0.047	2.43	0.18	3.69	0.0021	18.60	3.12	-10.04

Common explanation possible

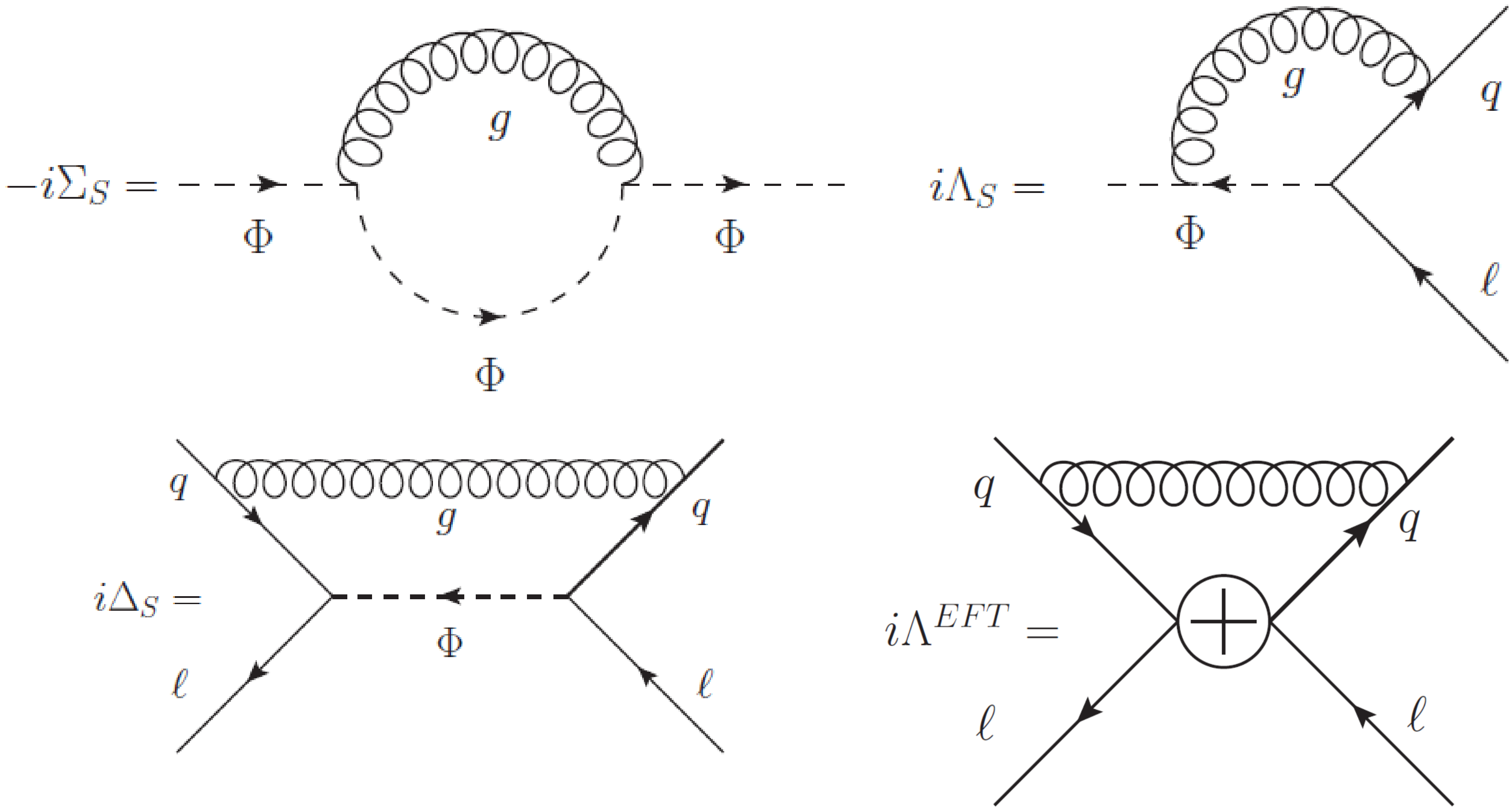
Correlations the neutron EDM with S1

W. Dekens, J. de Vries, M. Jung, K. K. Vos, arXiv:1809.09114
AC, F. Saturnino arxiv:1905:08257



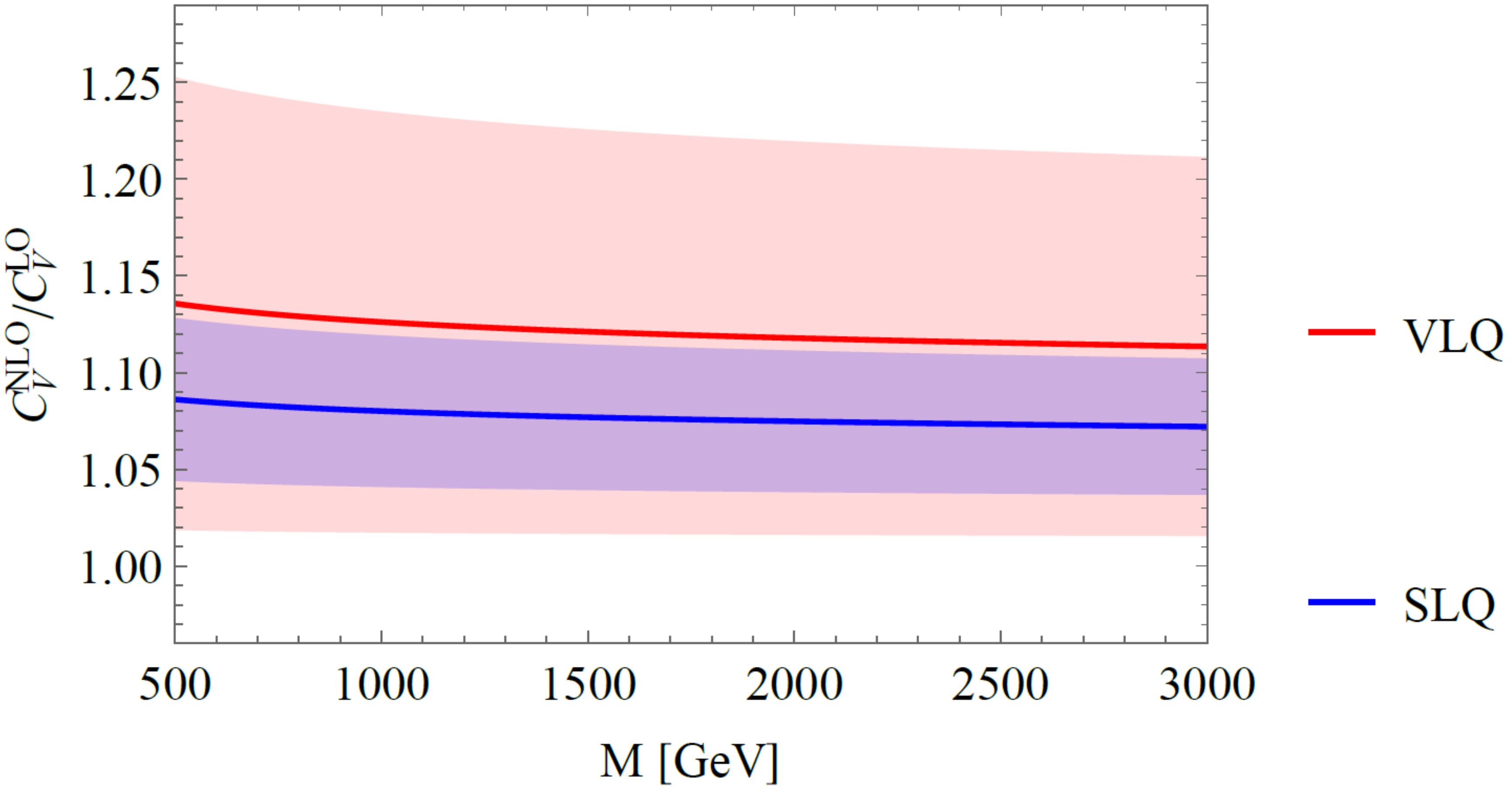
Effect in B predicts measurable nEDM effect

QCD corrections to the Matching



- Perform matching
- Correct for 4-dimensional Fierz identities

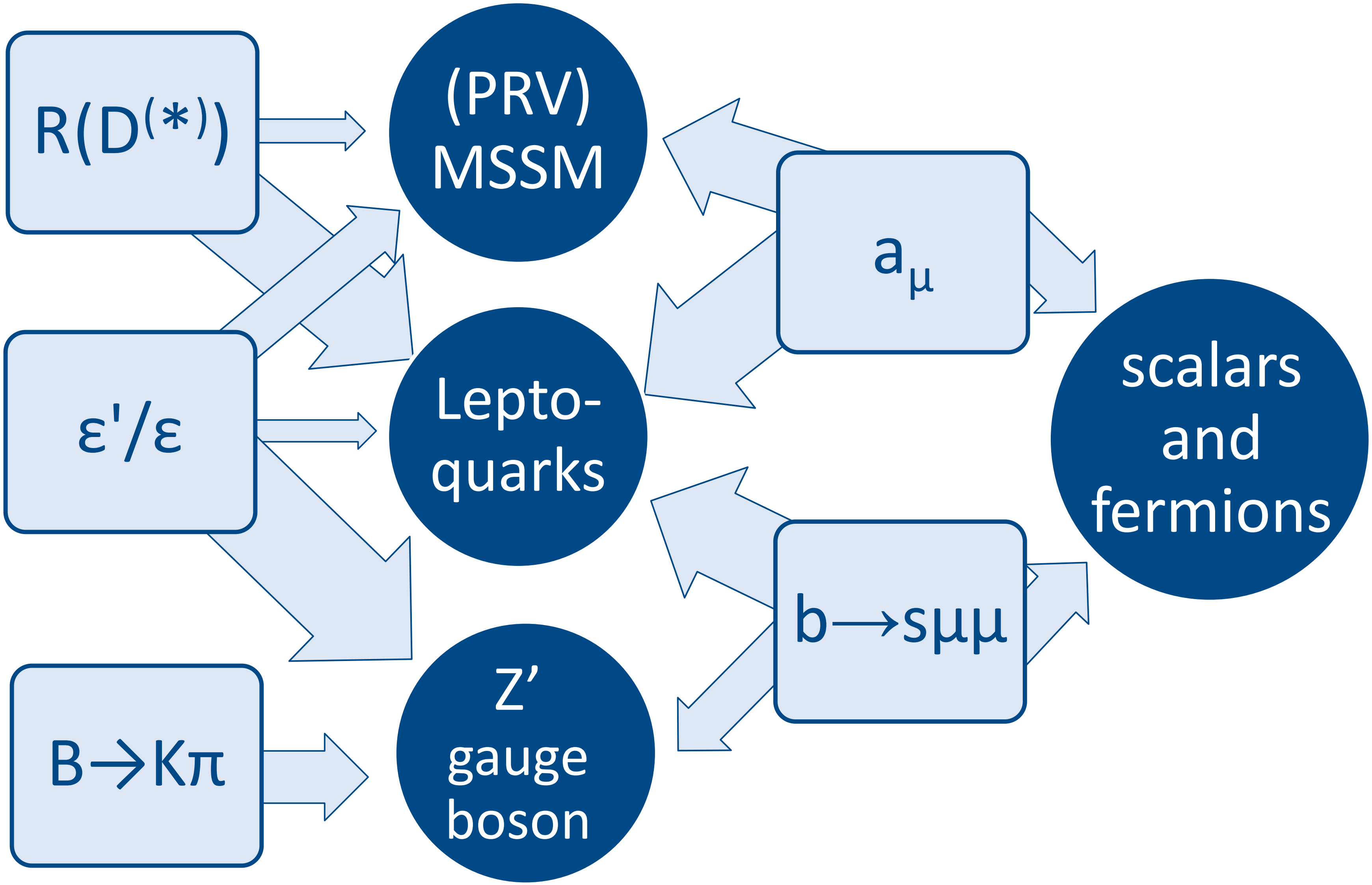
Results



J. Aebischer, AC, C. Greub, 1811.08907

Slightly weaker LHC constraints

Conclusions



Outlook

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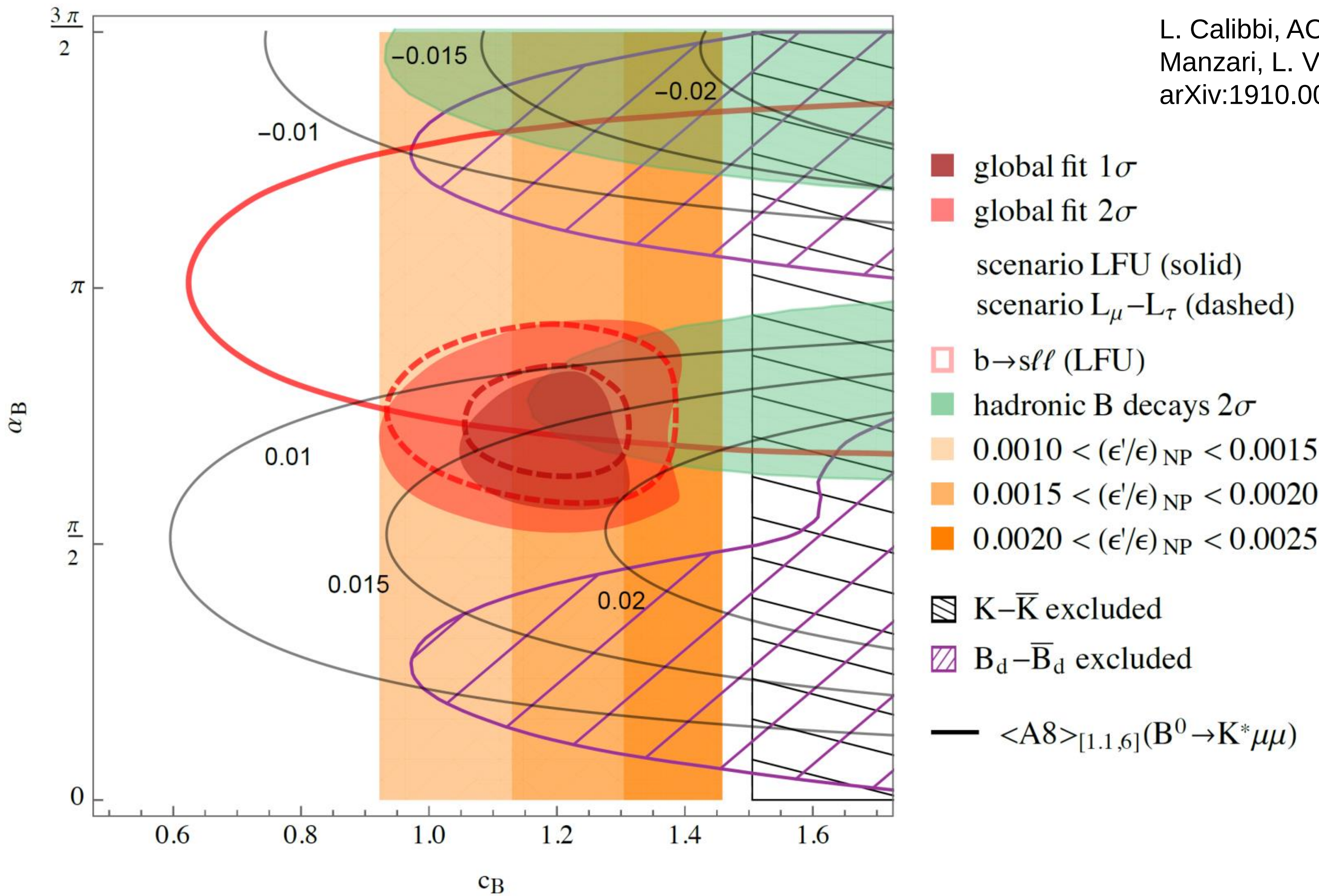
- P5' → $b \to d\mu\mu$
- R(D) & R(D*) → $b \to s\tau\tau$
- R(K) & R(K*) → $\mu \to e\gamma$, $\mu \to eee$
- a_μ → $Z \to \mu\mu$, d_μ, $\mu \to e\gamma$
- R(D), R(D*) & a_μ → $\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$
- R(D), R(D*) & $b \to s\mu\mu$ → $b \to s\tau\mu$, $\tau \to \phi\mu$

Interesting experimental prospects

Z' in $b \to s\mu\mu$, ε'/ε and hadronic B decays

Z' model with U(2) flavour



L. Calibbi, AC, F. Kirk, C. A. Manzari, L. Vernazza. arXiv:1910.00014

Common explanation possible

CP violation in Kaon decays: ε‘/ ε

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- ε: indirect CP violation in Kaon decays
  - K_L and K_S are not CP eigenstates due to mixing
- ε': direct CP violation in Kaon decays

$$\eta_{00} = \frac{A(K_\mathrm{L} \to \pi^0\pi^0)}{A(K_\mathrm{S} \to \pi^0\pi^0)}, \qquad \eta_{+-} = \frac{A(K_\mathrm{L} \to \pi^+\pi^-)}{A(K_\mathrm{S} \to \pi^+\pi^-)}$$

$$\eta_{00} = \varepsilon - \frac{2\varepsilon'}{1-\sqrt{\omega}} \simeq \varepsilon - 2\varepsilon', \qquad \eta_{+-} = \varepsilon + \frac{\varepsilon'}{1+\omega/\sqrt{2}} \simeq \varepsilon + \varepsilon'$$

$$(\varepsilon'/\varepsilon)_\mathrm{SM} = (1.9 \pm 4.5) \times 10^{-4}$$ Buras et al.

$$(\varepsilon'/\varepsilon)_\mathrm{exp} = (16.6 \pm 2.3) \times 10^{-4}$$

Measurement ≈3σ above the SM prediction

Hadronic B decays

L. Hofer, D. Scherer, L. Vernazza,
arXiv:1011.6319 [hep-ph]

- Longstanding B→πK Puzzle

$$\Delta A_{CP}^{-} \equiv A_{CP}\left(B^{-} \to \pi^{0} K^{-}\right) - A_{CP}\left(\bar{B}^{0} \to \pi^{+} K^{-}\right)$$

$$\Delta A_{CP}^{-}|_{exp} = \left(12.4 \pm 2.1\right)\%$$

$$\Delta A_{CP}^{-}|_{SM} = \left(1.8^{+4.1}_{-3.2}\right)\%$$

- More observables like

$$A_{CP}[B_s \to K^{+}K^{-}]_{exp} = \left(-20.0 \pm 6.0 \pm 2.0\right)\%$$

$$A_{CP}[B_s \to K^{+}K^{-}]_{SM} = \left(-5.9^{+26.6}_{-5.1}\right)\%$$

$$\mathrm{Br}[B_s \to \phi\rho^{0}]_{exp} = \left(2.7 \pm 0.7 \pm 0.2 \pm 0.2\right) \times 10^{-7}$$

$$\mathrm{Br}[B_s \to \phi\rho^{0}]_{SM} = \left(5.3^{+1.8}_{-1.3}\right) \times 10^{-7}$$

CP and isospin violation needed

Similar picture in D decays

Global fit to data: 2-3σ

ε'/ ε explanations

- W_R coupling

V. Cirigliano, et al. arXiv:1612.03914

- Z' (also for ΔA_{CP})

A. Buras, et al. arXiv:1507.08672
A. Buras and 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

ε' / ε