Andreas Crivellin

CERN Theory Division, Leave of absence from PSI & UZH

Lepton Flavour Universality Violating Anomalies

Unveiling hidden Physics Beyond the Standard Model at the LHC

01.03.2021 (remote)

Outline

- Introduction
- Hints for Lepton Flavour Universality Violation
  - ➢ Semi-leptonic B decays
  - ➢ Anomalous magnetic moment of the muon
  - ➢ Tau decays
  - ➢ Cabibbo Angle Anomaly
- Explanations of the Anomalies
- Common explanations
- Conclusions

Introduction

Discovering New Physics

- Cosmic Frontier
  - Cosmic rays and neutrinos
  - Dark Matter
  - Dark Energy
- Energy Frontier
  - LHC
  - Future colliders
- Intensity Frontier
  - **Flavour**
  - Neutrino-less double-β decay
 - Test of fundamental symmetries
  - Proton decay
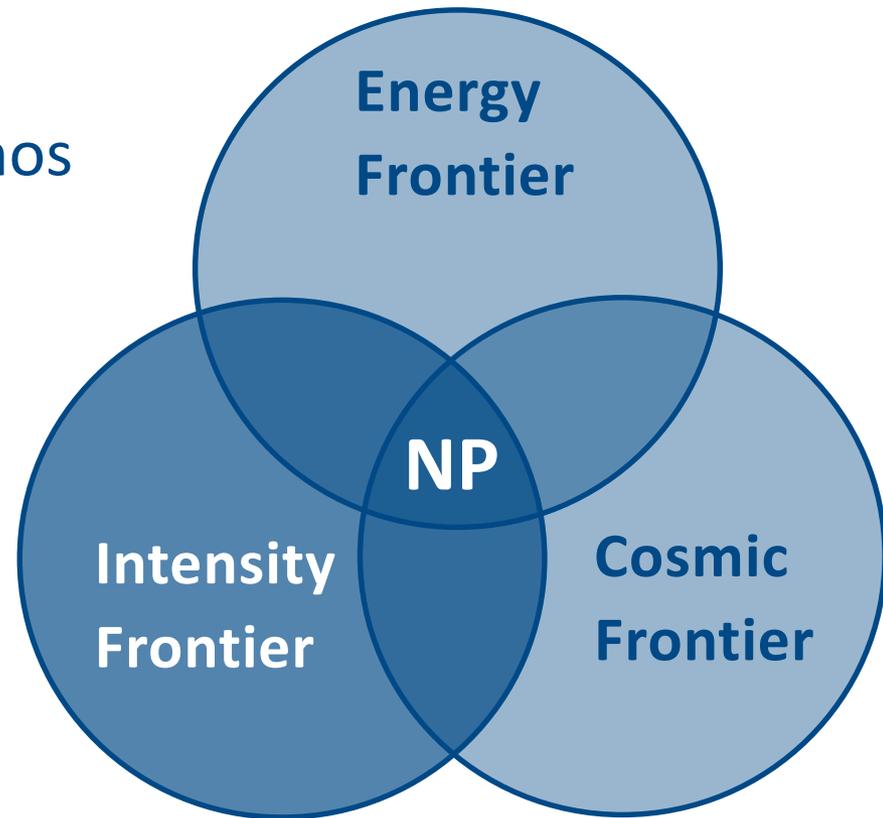
Lepton Flavour (Universality) Violation

In the Standard Model:

- Lepton Flavour is conserved

  (for vanishing neutrino masses)

  ➢ Excellent approximation: branching ratios

    smaller than 10^{-45}

  ⟹ Any observation proves **new physics**

- Gauge Interactions are Lepton Flavour Universal
- Only Higgs Yukawa distinguish flavors

  ⟹ Very small effect (except for phase space)

LFUV is an excellent probe of the SM

Hints for LFUV
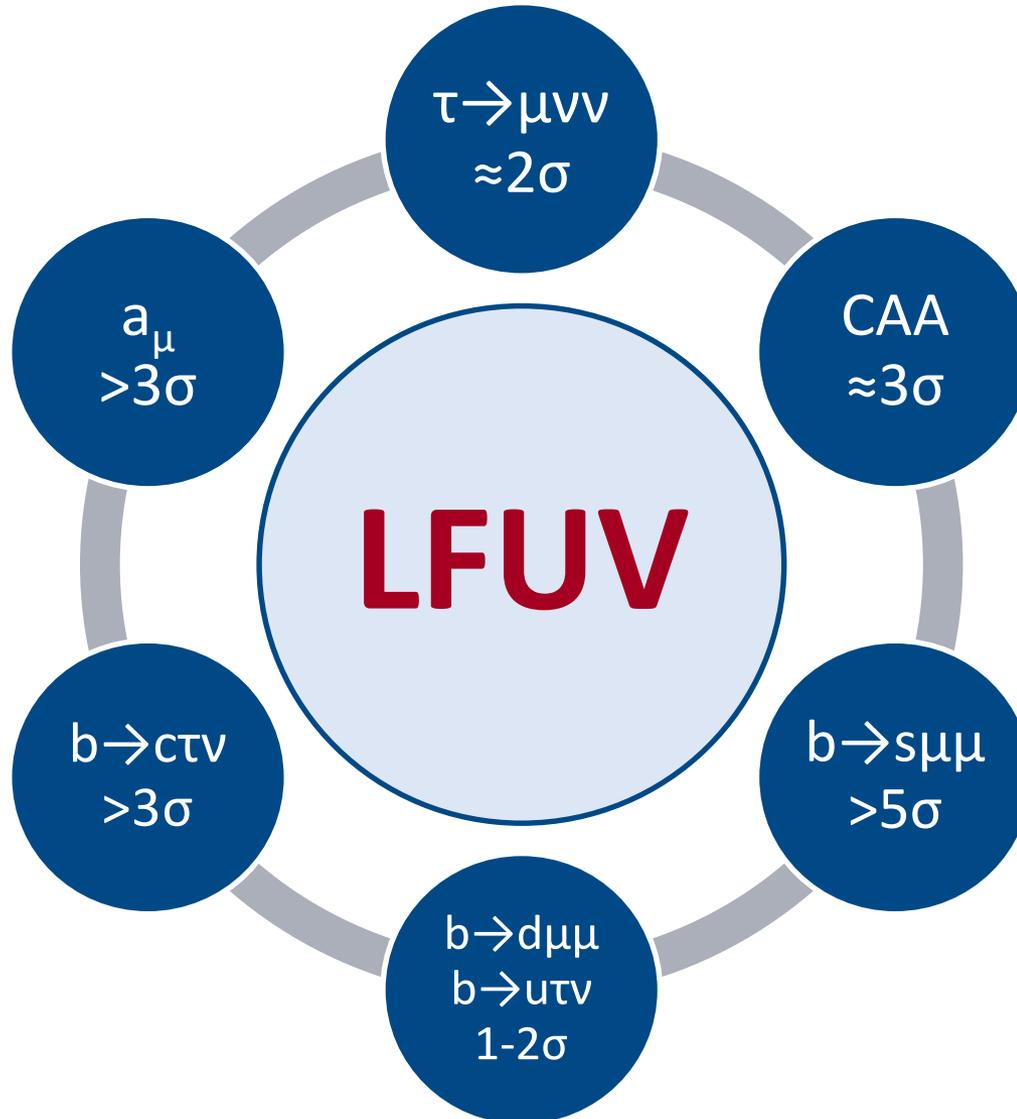
Overview on hints for Lepton Flavour Universality Violation
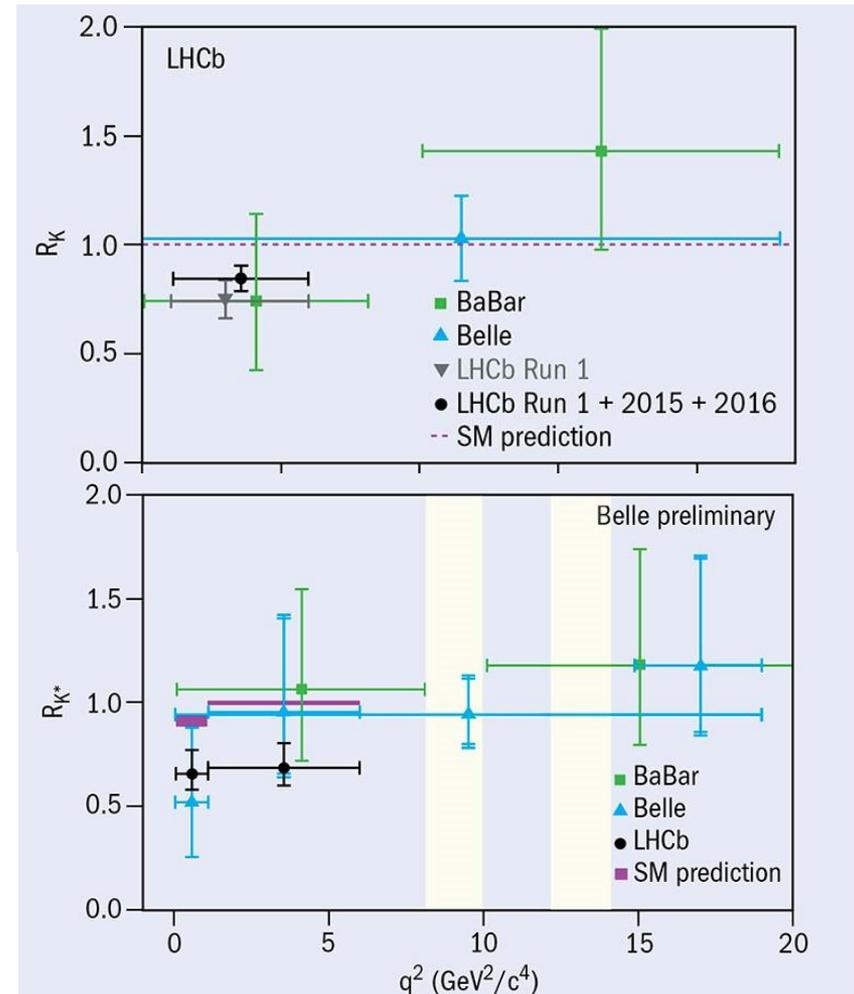
LFUV in b→sℓ⁺ ℓ⁻

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

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

- Muon and electron masses can be neglected

  ⟹ **Clean prediction**

- Supported by

$$\frac{\Lambda_b \to Kp\mu^+\mu^-}{\Lambda_b \to Kpe^+e^-} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

LFUV in B decays >4σ

Global Fit to b→sμ⁺μ⁻ Data

- Hint for LFUV are accompanied by deviations in measurements with muons include

  ➤ $\mathrm{Br}\left[B_s \to \mu^+ \mu^- \right] \approx 2\sigma$

  ➤ $\mathrm{Br}\left[B_s \to \phi\mu^+ \mu^- \right] \approx 2\sigma$

  ➤ $P_5'\left[B \to K^* \mu^+ \mu^- \right] > 4\sigma$

- Fit to all observables (≈150) provides several preferred patterns

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

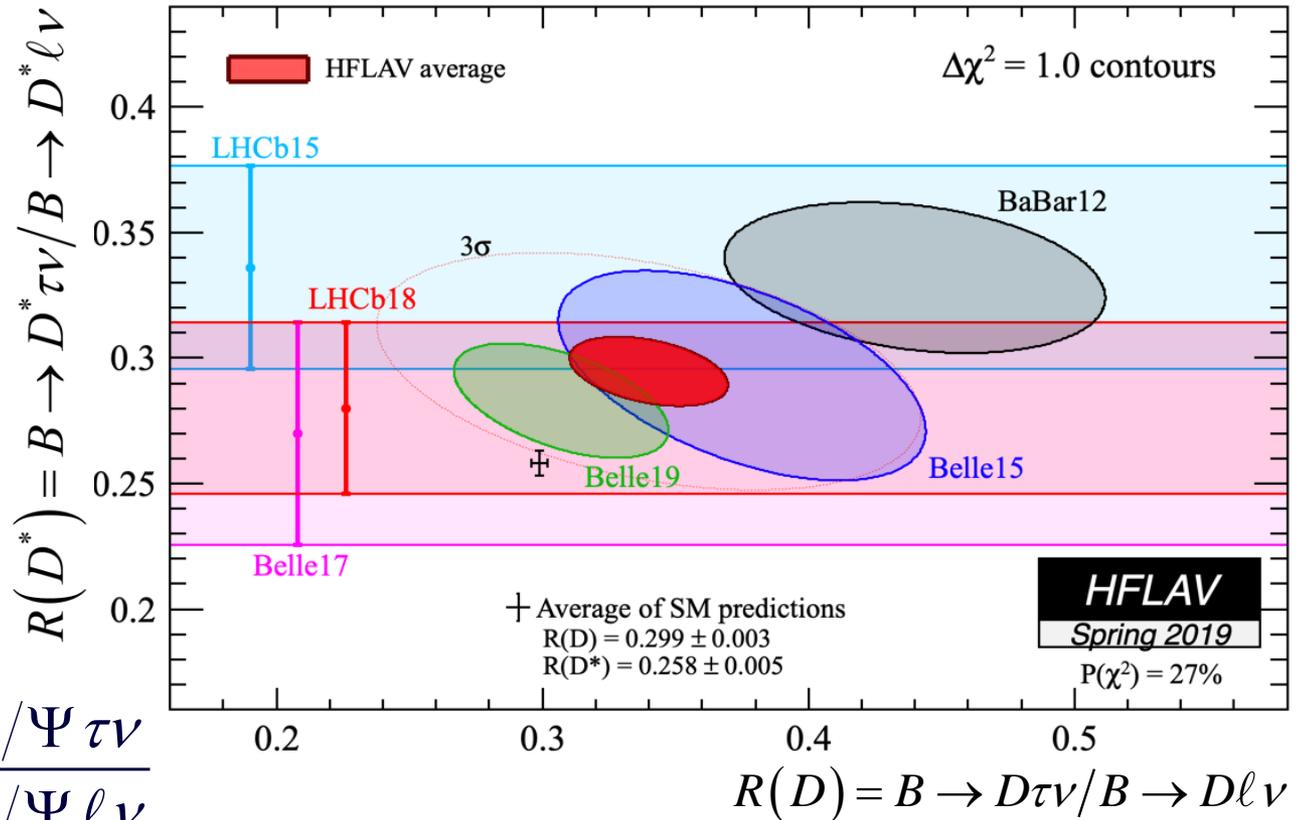 $$O_{10} = \bar{s}\gamma^\mu P_L b \,\bar{\ell}\gamma_\mu \gamma^5 \ell$$

arXiv:1903.09578 [hep-ph].

Legend:
- ATLAS
- Belle
- CMS
- LHCb
- All

Axis labels: $\mathcal{C}_{10\mu}^{\mathrm{NP}}$ (vertical), $\mathcal{C}_{9\mu}^{\mathrm{NP}}$ (horizontal)
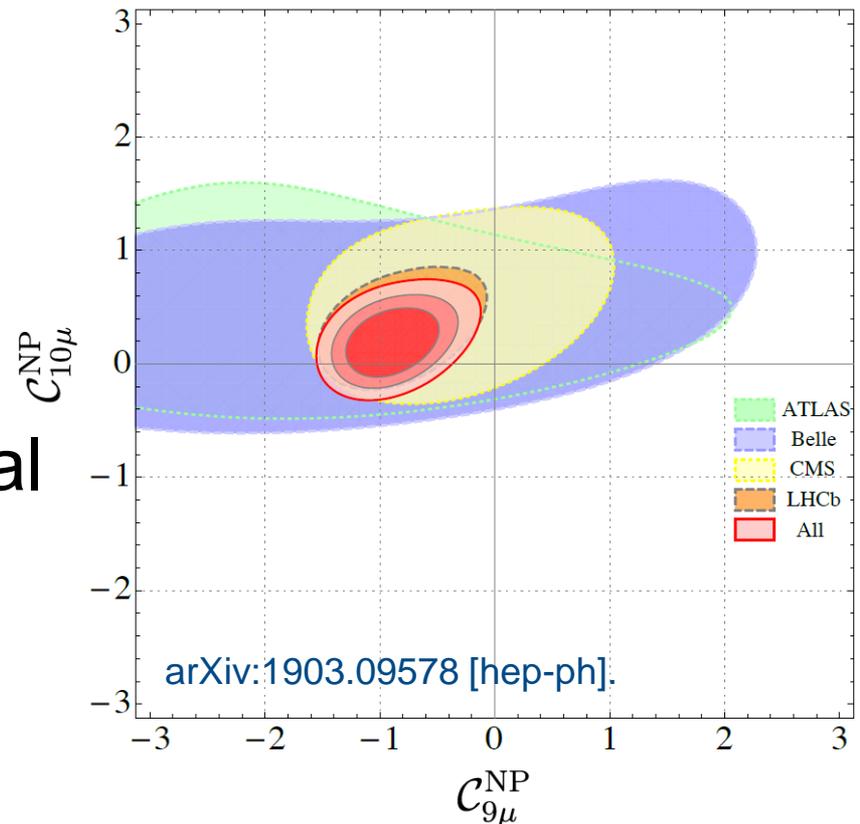
New Physics Fit is 5-6 σ better than the SM

b→cτν Transitions

- LFU test of the charged current
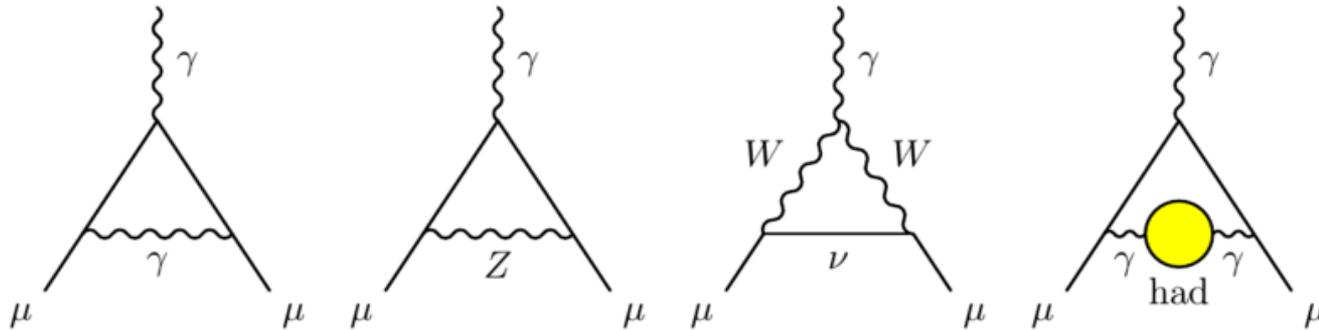
- Tau mode consistently enhanced

- Supported by

$$R(J/\Psi) = \frac{B_c \to J/\Psi\,\tau\nu}{B_c \to J/\Psi\,\ell\nu}$$

In figure:
- HFLAV average
- $\Delta\chi^2 = 1.0$ contours
- LHCb15
- BaBar12
- 3σ
- LHCb18
- Belle19
- Belle15
- Belle17
- Average of SM predictions
  R(D) = 0.299 ± 0.003
  R(D*) = 0.258 ± 0.005
- HFLAV Spring 2019 P(χ^2) = 27%
- $R(D^*) = B \to D^*\tau\nu / B \to D^*\ell\nu$
- $R(D) = B \to D\tau\nu / B \to D\ell\nu$

- Tree-level ⟹ **need huge NP effect**

O(10%) constructive preferred effect at 3σ

Muon Anomalous Magnetic Moment

- Theory prediction challenging (hadronic effects)

$$\Delta a_{\mu} = \left(279 \pm 76\right) \times 10^{-11}$$ T. Aoyama et al., arXiv:2006.04822

- Need NP of the order of the SM EW contribution

- Chiral enhancement necessary for heavy NP

- Soon new experimental results from Fermilab

- Vanishes for $m_{\mu} \to 0$ ⟹ **measure of LFUV**

3.7σ deviation from the SM prediction
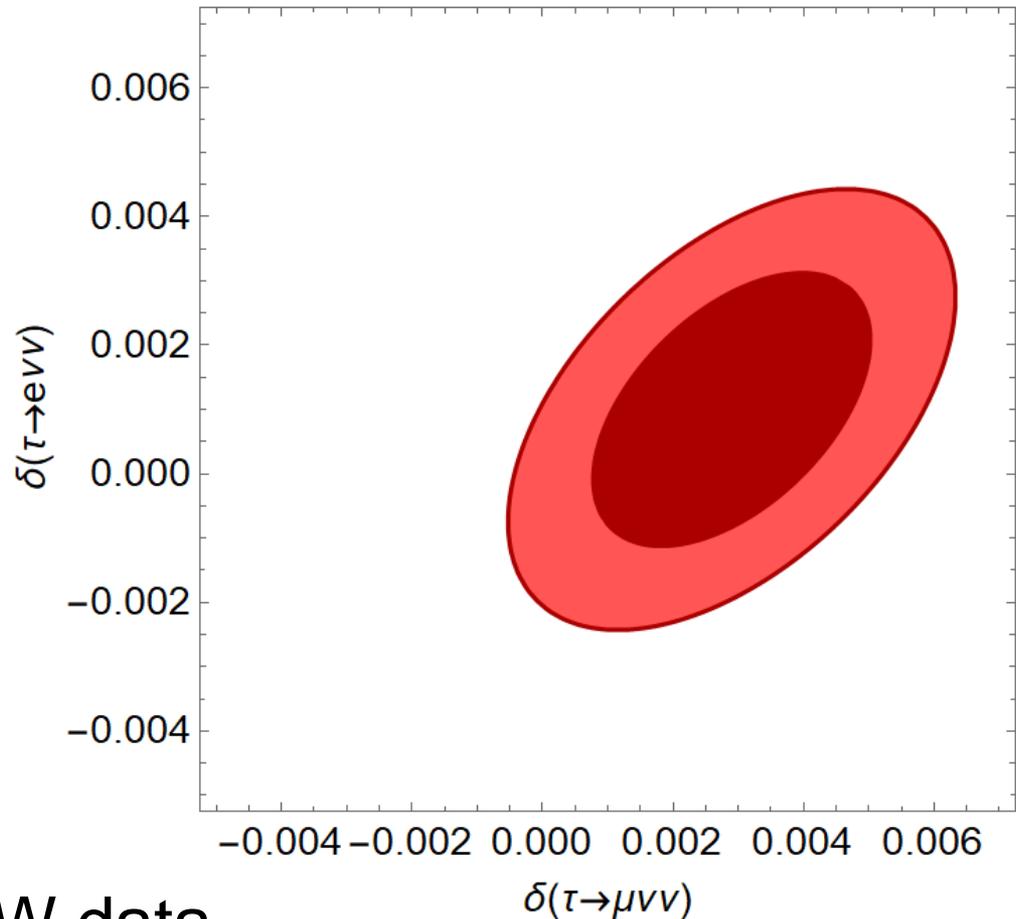
τ→μνν and τ→eνν

- ## Ratios of leptonic tau decays

$$\frac{\mathcal{A}_{\mathrm{EXP}}(\tau \to \mu \nu \bar{\nu})}{\mathcal{A}_{\mathrm{SM}}(\mu \to e \nu \bar{\nu})} = 1.0029 \pm 0.0014$$

$$\frac{\mathcal{A}_{\mathrm{EXP}}(\tau \to \mu \nu \bar{\nu})}{\mathcal{A}_{\mathrm{SM}}(\tau \to e \nu \bar{\nu})} = 1.0018 \pm 0.0014$$

$$\frac{\mathcal{A}_{\mathrm{EXP}}(\tau \to e \nu \bar{\nu})}{\mathcal{A}_{\mathrm{SM}}(\mu \to e \nu \bar{\nu})} = 1.0010 \pm 0.0014$$

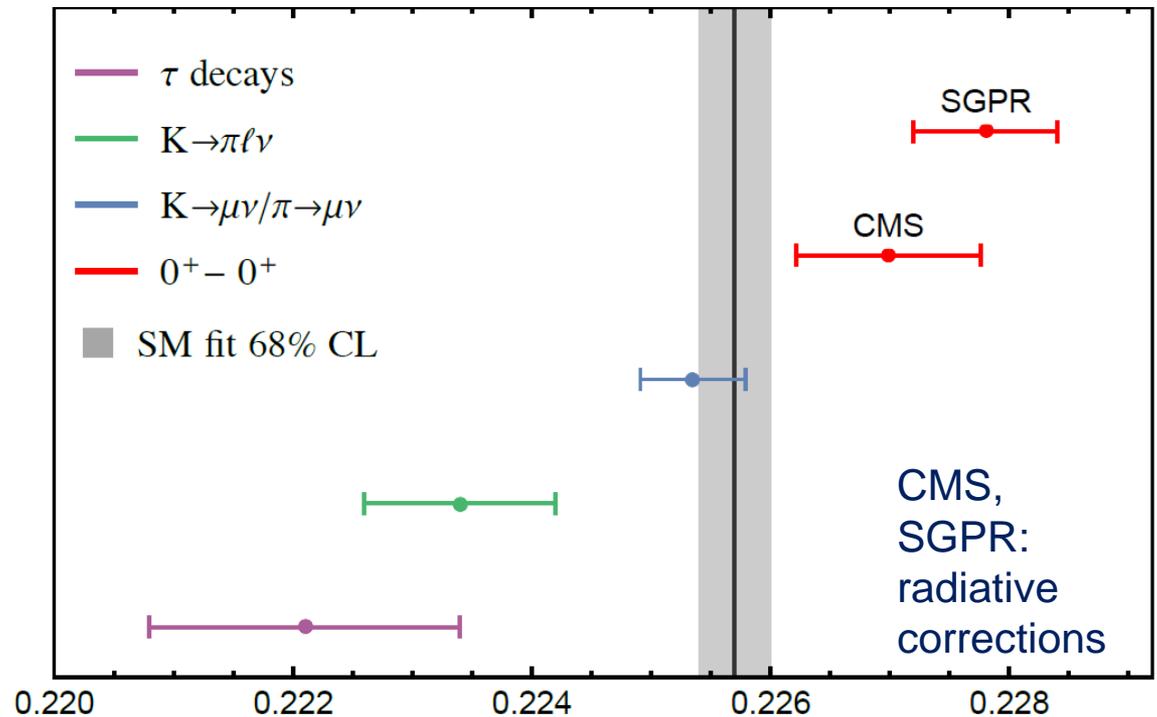$$\rho = \begin{pmatrix} 1.00 & 0.49 & 0.51 \\ 0.49 & 1.00 & -0.49 \\ 0.51 & -0.49 & 1.00 \end{pmatrix}$$

- ## NP in muon decay constrained from EW data

≈2σ hint for LFUV in tau decays

Cabibbo Angle Anomaly (CAA)

- V_{ud} from super-allowed beta decays

- V_{us} from Kaon and tau decays

- Disagreement leads to a (apparent) violation of CKM unitarity

$$\left|V_{ud}^2\right| + \left|V_{us}^2\right| + \left|V_{ub}^2\right| = 0.9985 \pm 0.0005 \, (\text{PDG})$$

3σ tension

CAA and LFUV

- Assume modified Wℓν couplings

$$L = i\, g_2 \big/ \sqrt{2}\, \nu_f \gamma^\mu P_L \ell_i W_\mu \left(\delta_{fi} + \varepsilon_{fi} \right)$$

- V_{ud} from beta decays depends on Fermi constant

$$1/\tau_\beta \sim \left| V_{ud} \left(1 + \varepsilon_{ee} \right) \right|^2 G_F^2$$

- Fermi constant determined from muon decay

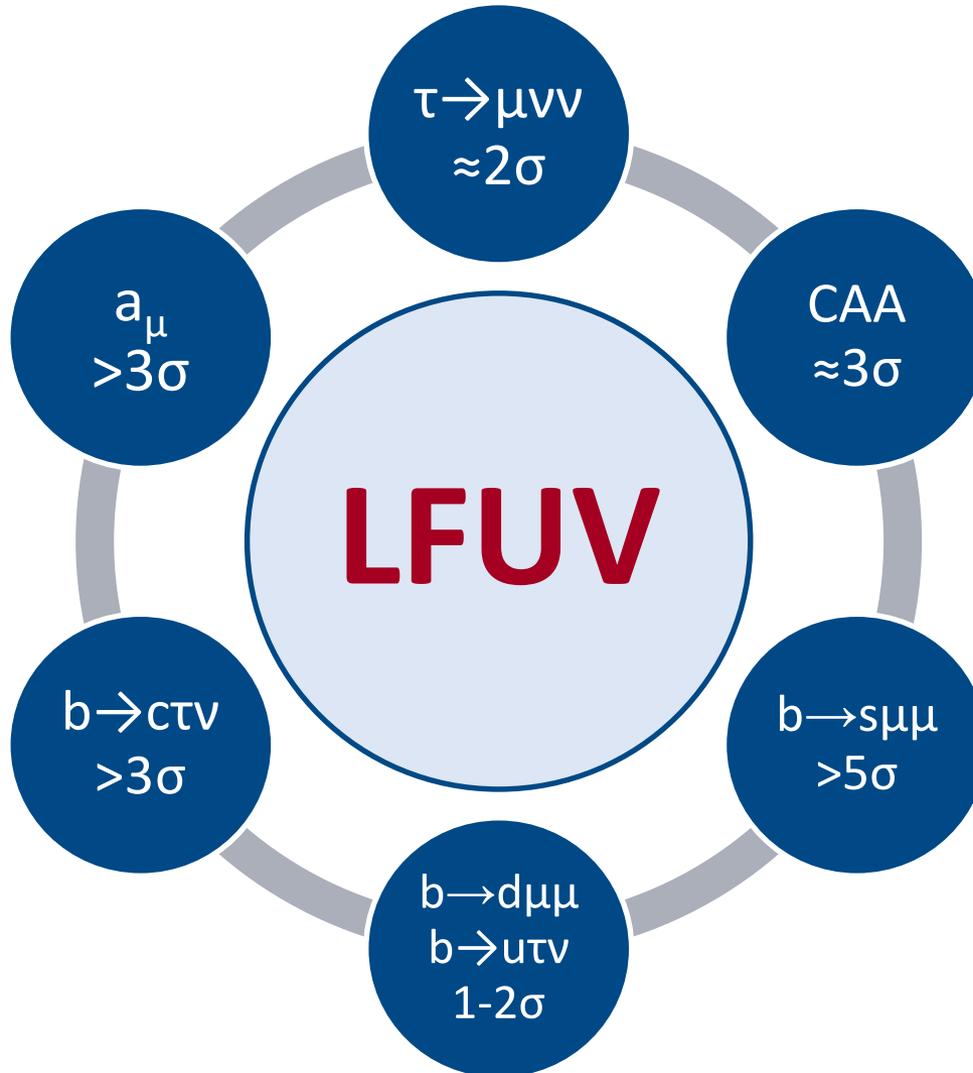$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} (1 + \Delta q)\left(1 + \varepsilon_{ee} + \varepsilon_{\mu\mu} \right)^2$$

- Dependence on ε_{ee} cancels

$$R(V_{us}) \equiv \frac{V_{us}^{K_{\mu 2}}}{V_{us}^\beta} \equiv \frac{V_{us}^{K_{\mu 2}}}{\sqrt{1 - \left(V_{ud}^\beta \right)^2 - \left| V_{ub} \right|^2}} \approx 1 - \left(\frac{V_{ud}}{V_{us}} \right)^2 \varepsilon_{\mu\mu}$$

AC, M. Hoferichter PRL 2020

- $R(V_{us})$
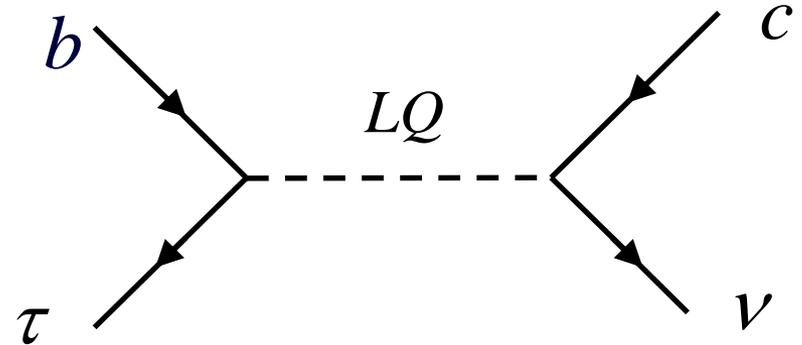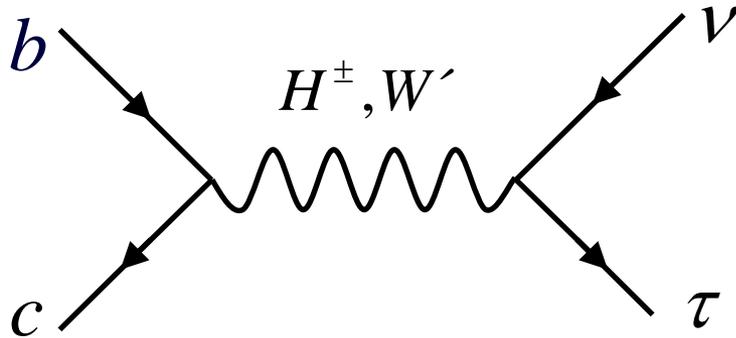- LFU
- Fit 1σ
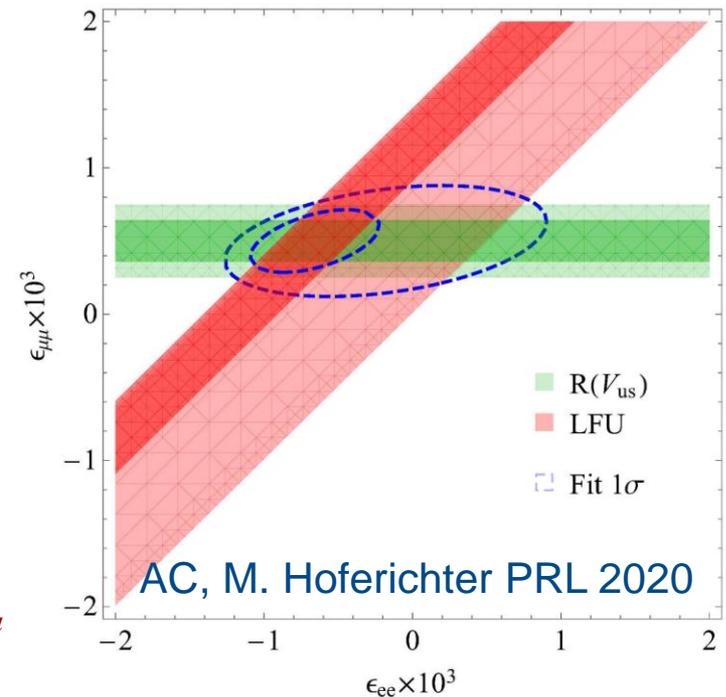
The CAA can be interpreted as a sign of LFUV

Hints for New Physics

# New Physics Explanations of the Anomalies

R(D) & R(D*)

- Charged scalars: Problems with distributions and B_c lifetime
  A. Celis, M. Jung, X. Q. Li, A. Pich, PLB 2017
  R. Alonso, B. Grinstein, J. Martin Camalich, PRL 2017

- W': Strong constraints from direct LHC searches
  D. Buttazzo, A. Greljo, G. Isidori, D. Marzocca, JHEP 2017

- Leptoquark: Strong signals in qq→ττ searches
  CMS, 1809.05558; ATLAS, 1902.08103

Explanation difficult but possible with Leptoquarks

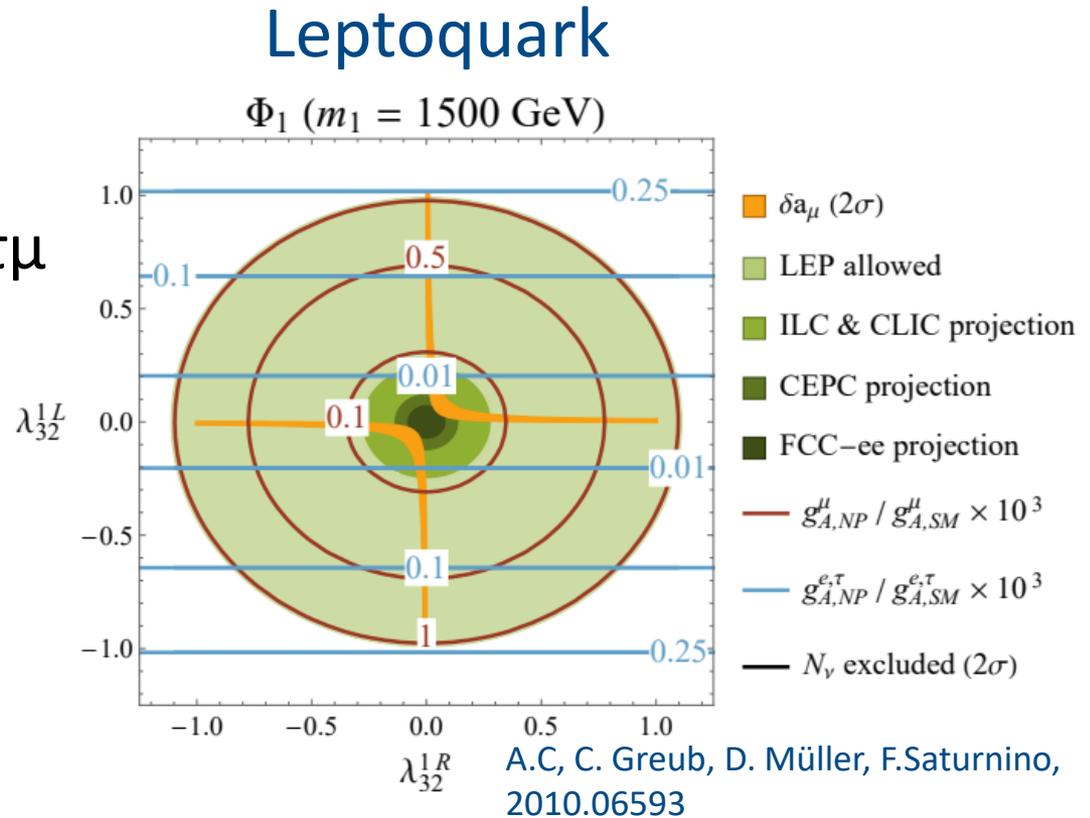# b→sµ⁺µ⁻ explanations

- **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 fermions B. Gripaios, M. Nardecchia, S. A. Renner, JHEP 2016
  - ## 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, 1408.1627
  D. Bečirević, S. Fajfer and N. Košnik,1503.09024, ….
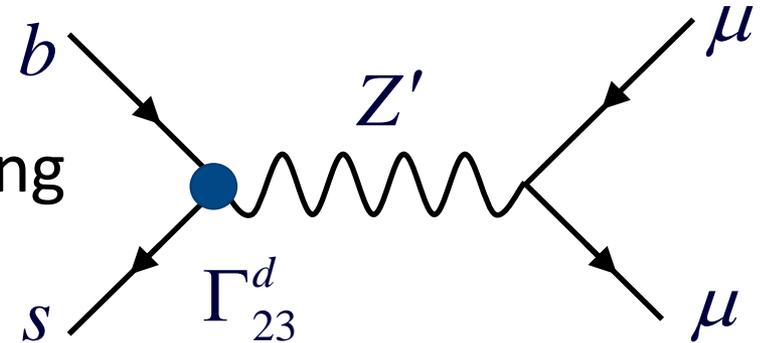
Small effect needed; many possibilities

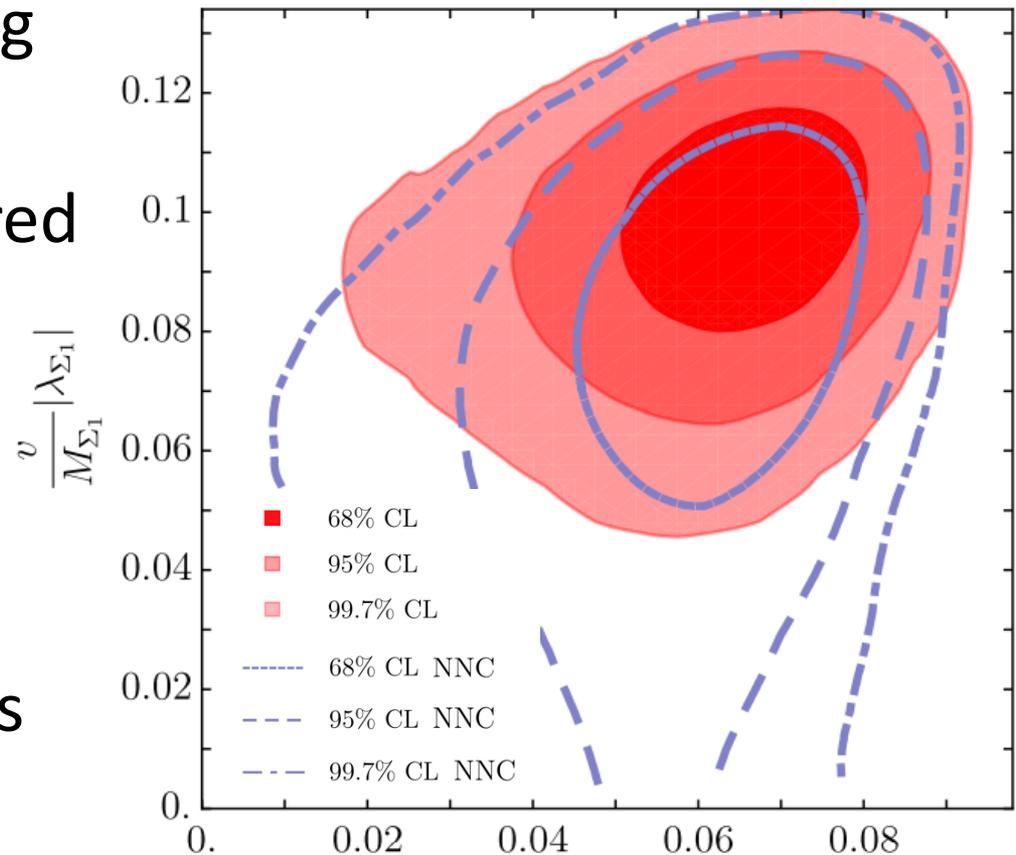# a$_\mu$ explanations

- MSSM tan(ß) enhanced slepton loops

- (light) Scalars with enhanced muon couplings

- Z': Very light or with τμ couplings (m$_\tau$ enhancement)

- New scalars and fermions κ/Y$_\mu$

- Leptoquarks m$_t$ enhanced effects

Leptoquark

Φ_1 ($m_1 = 1500$ GeV)

Legend:
- δa_μ (2σ)
- LEP allowed
- ILC & CLIC projection
- CEPC projection
- FCC−ee projection
- $g^\mu_{A,NP} / g^\mu_{A,SM} \times 10^3$
- $g^{e,\tau}_{A,NP} / g^{e,\tau}_{A,SM} \times 10^3$
- N_ν excluded (2σ)

A.C, C. Greub, D. Müller, F.Saturnino, 2010.06593

Chiral enhancement or very light particles

Cabibbo Angle Anomaly and EW Fit

- Modified W_{ud} coupling
- Tree-level effects in beta decays disfavoured by LHC searches
- W-W' mixing
- Vector-like leptons
  - $SU(2)_L$ singlet N coupling to electrons
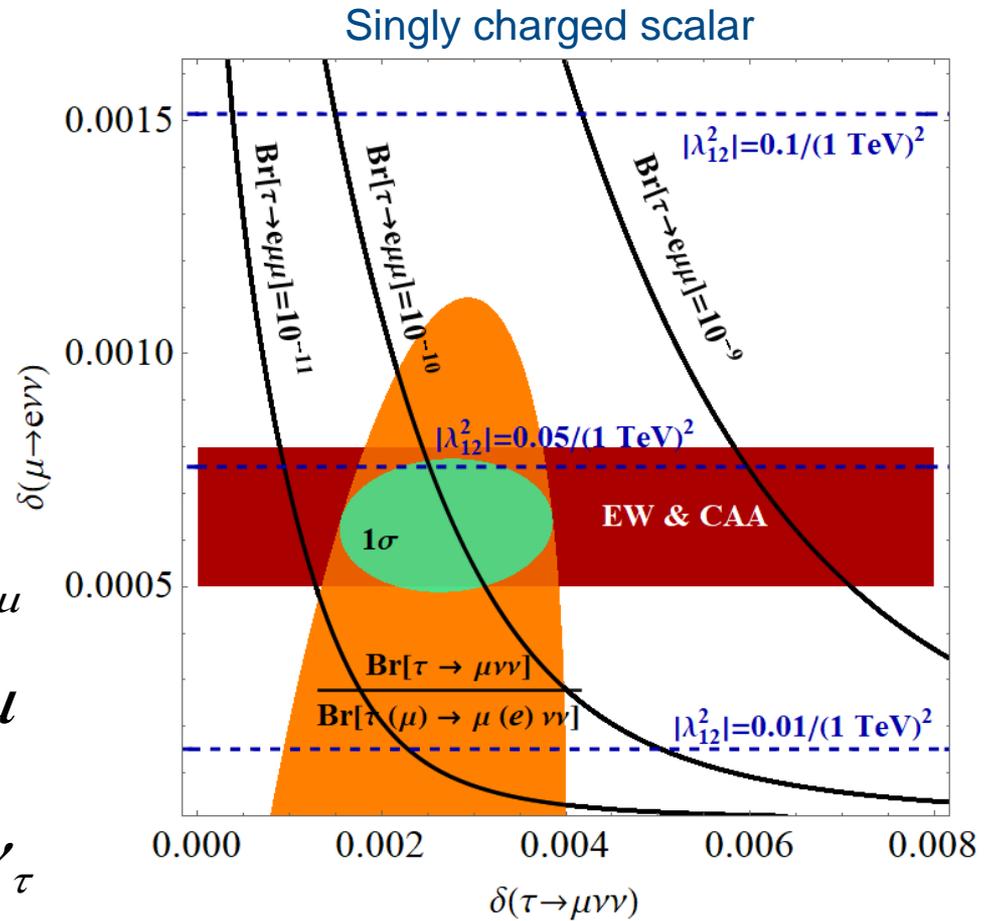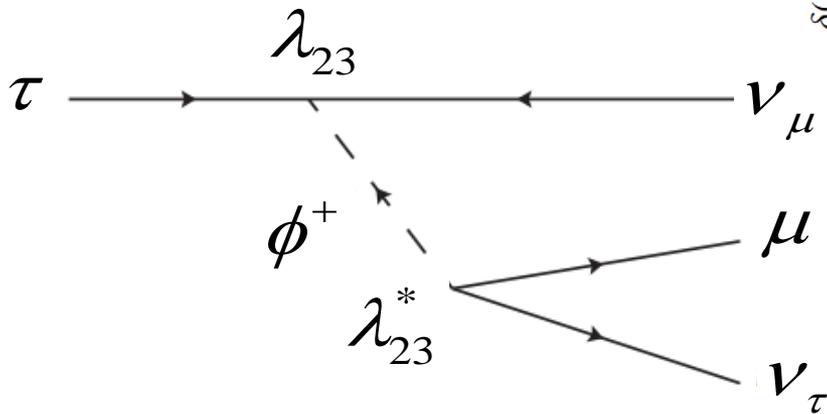 - $SU(2)_L$ triplet Σ coupling to muon

Legend:
- 68% CL
- 95% CL
- 99.7% CL
- 68% CL NNC
- 95% CL NNC
- 99.7% CL NNC

Axes: vertical $\frac{v}{M_{\Sigma_1}}|\lambda_{\Sigma_1}|$, horizontal $\frac{v}{M_N}|\lambda_N|$

AC, F. Kirk, C. Manzari, M. Montull JHEP, 2008.01113

>5σ improvement over SM hypothesis

τ→μνν

- L_μ-L_τ Z' (box diagrams)
- LFV violating Z'
- Modified Wℓν couplings
- W'
- Singly charged scalar

A.C., F. Kirk, C. Manzari, L. Panizzi, arXiv:2012.09845

Scenarios can be distinguished by π→μν/ π→eν

Simultaneous Explanations

b→sℓℓ and b→cτν with a Vector Leptoquark

AC, C. Greub, D. Müller, F. Saturnino, PRL 2018
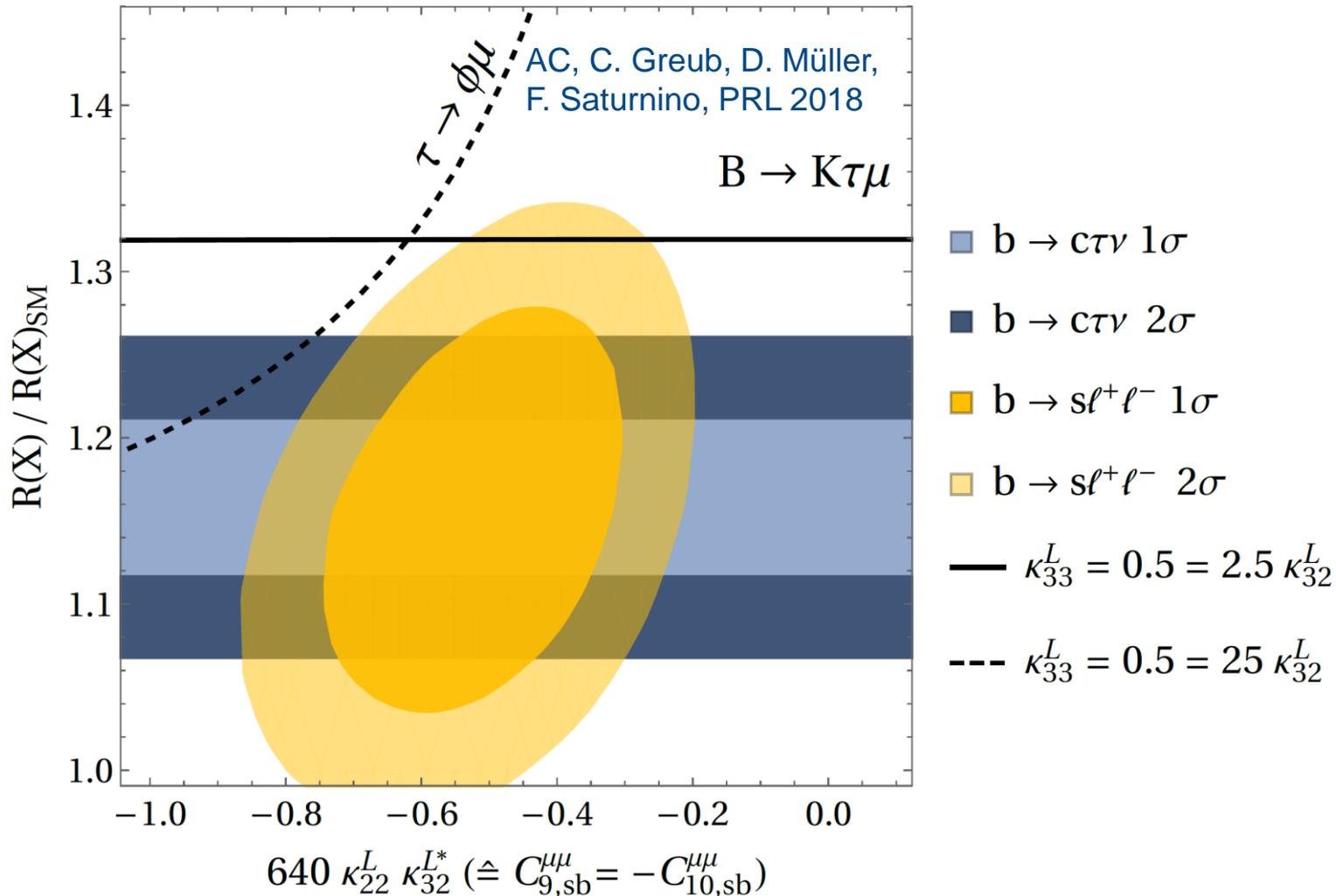
Pati-Salam LQ can explain the flavour anomalies

Vector Triplet in the CAA & b→sℓℓ

- Region from EW fit overlaps with b→sℓℓ region

- Correlations between e.g. $\pi \to \mu\nu / \pi \to e\nu$ and $R(K^{(*)})$ are predicted
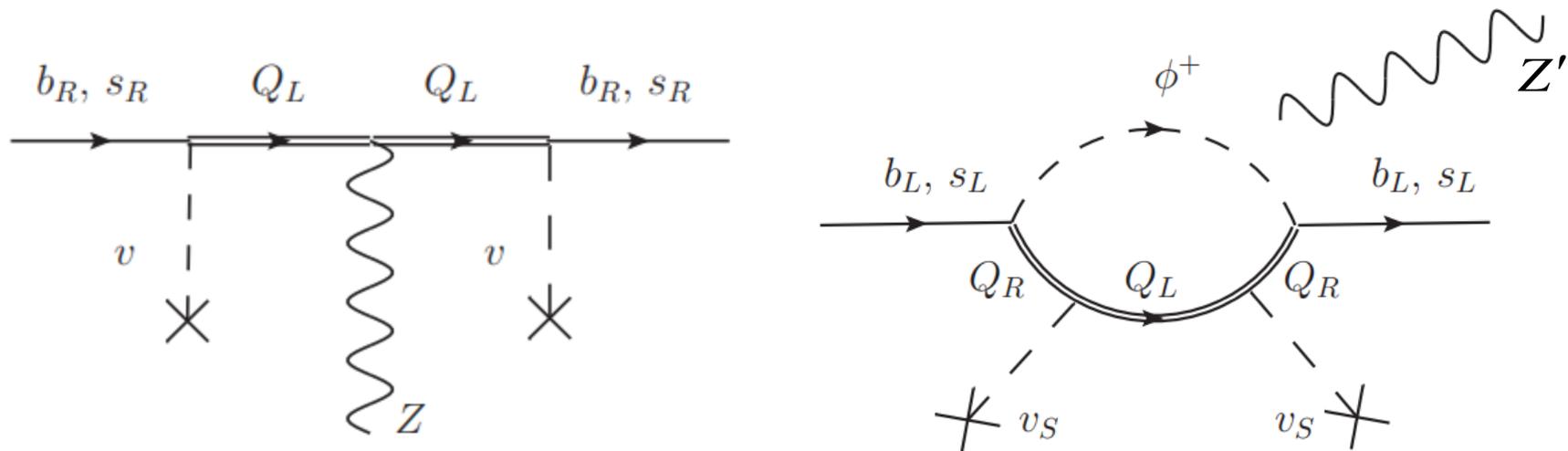
- Global fit significantly improved
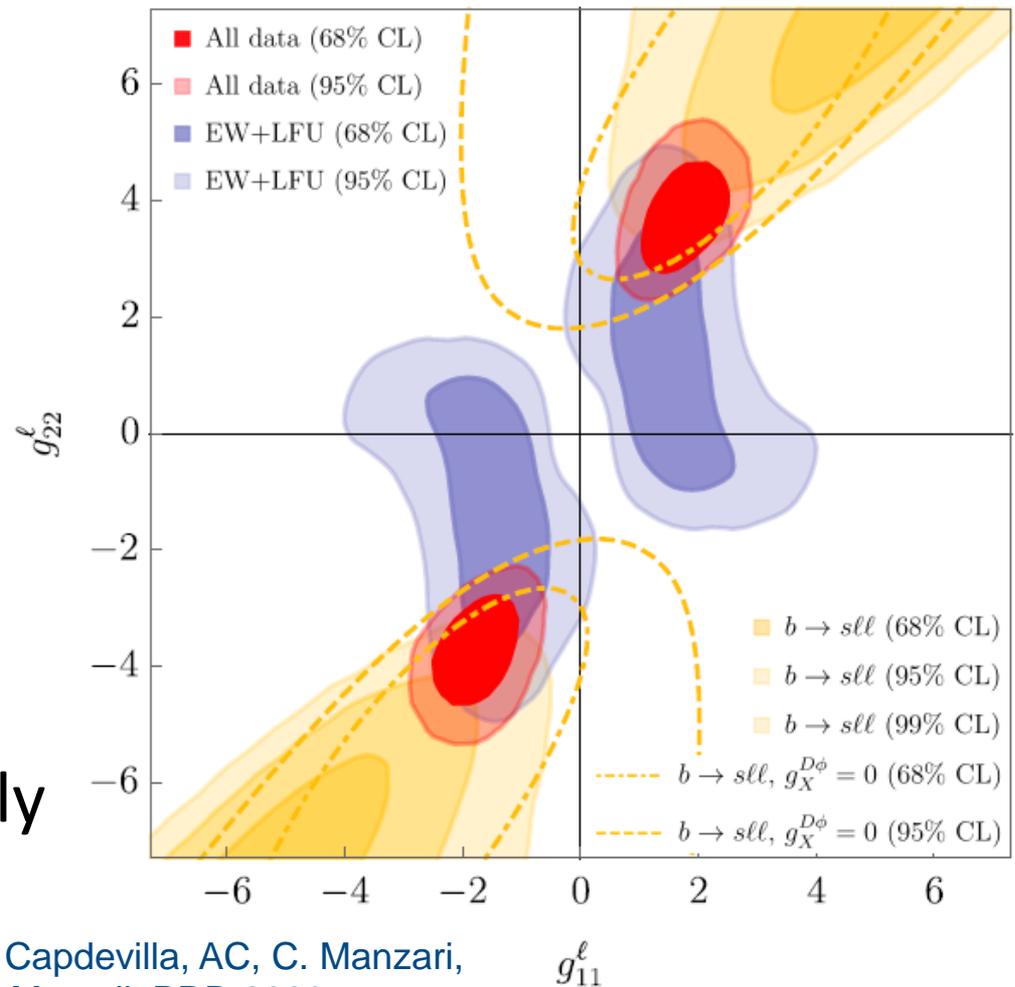
B. Capdevilla, AC, C. Manzari,
M. Montull, PRD 2020
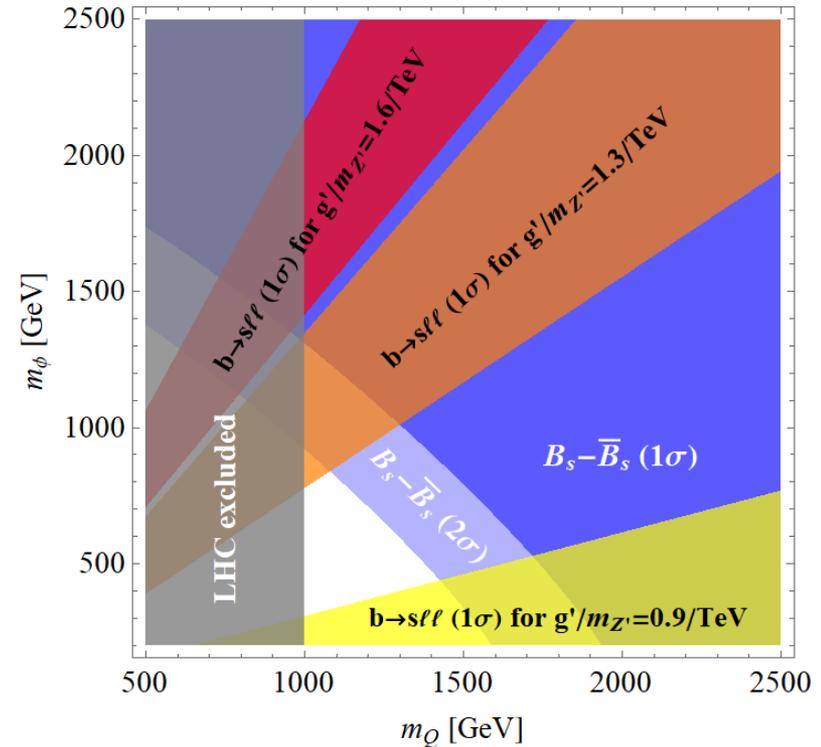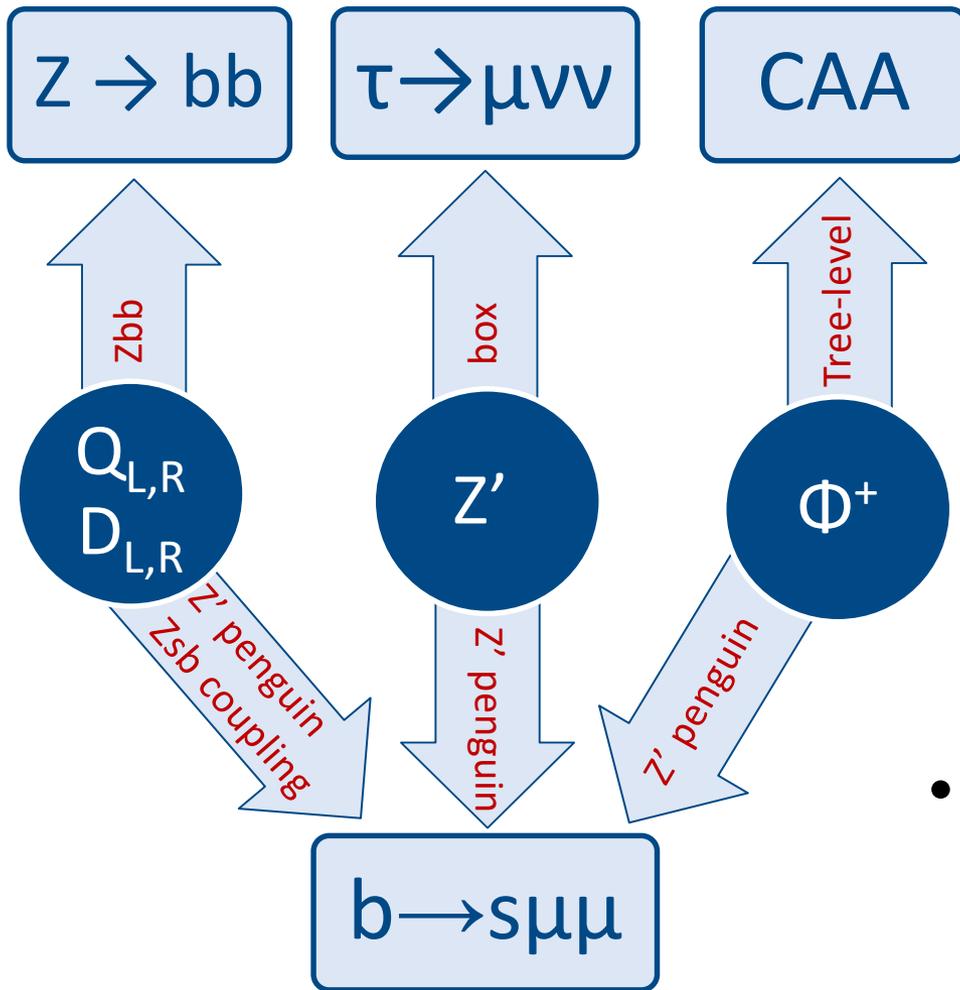
Common explanation possible

Model for b→sℓℓ, CAA, Z→bb and τ → μνν

	q_L	d_R	u_R	H	ℓ_L	e_R	Q_L	Q_R	D_L	D_R	ϕ^+	S
$SU(3)_c$	3	3	3	1	1	1	3	3	3	3	1	1
$SU(2)_L$	2	1	1	2	2	1	2	2	1	1	1	1
$U(1)_Y$	$\frac{1}{6}$	$\frac{-1}{3}$	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{-1}{2}$	-1	$\frac{-5}{6}$	$\frac{-5}{6}$	$\frac{-1}{3}$	$\frac{-1}{3}$	1	0
$U(1)'$	0	0	0	0	$(0, 1, -1)$		0	1	1	0	-1	-1

Tree effect in Zbb and loop in Z'sb

Model for b→sℓℓ, CAA, Z→bb and τ → μνν

- Z' penguin + modified Zsb coupling give very good fit to b→sll data

Simple model provides combined explanation

Conclusions
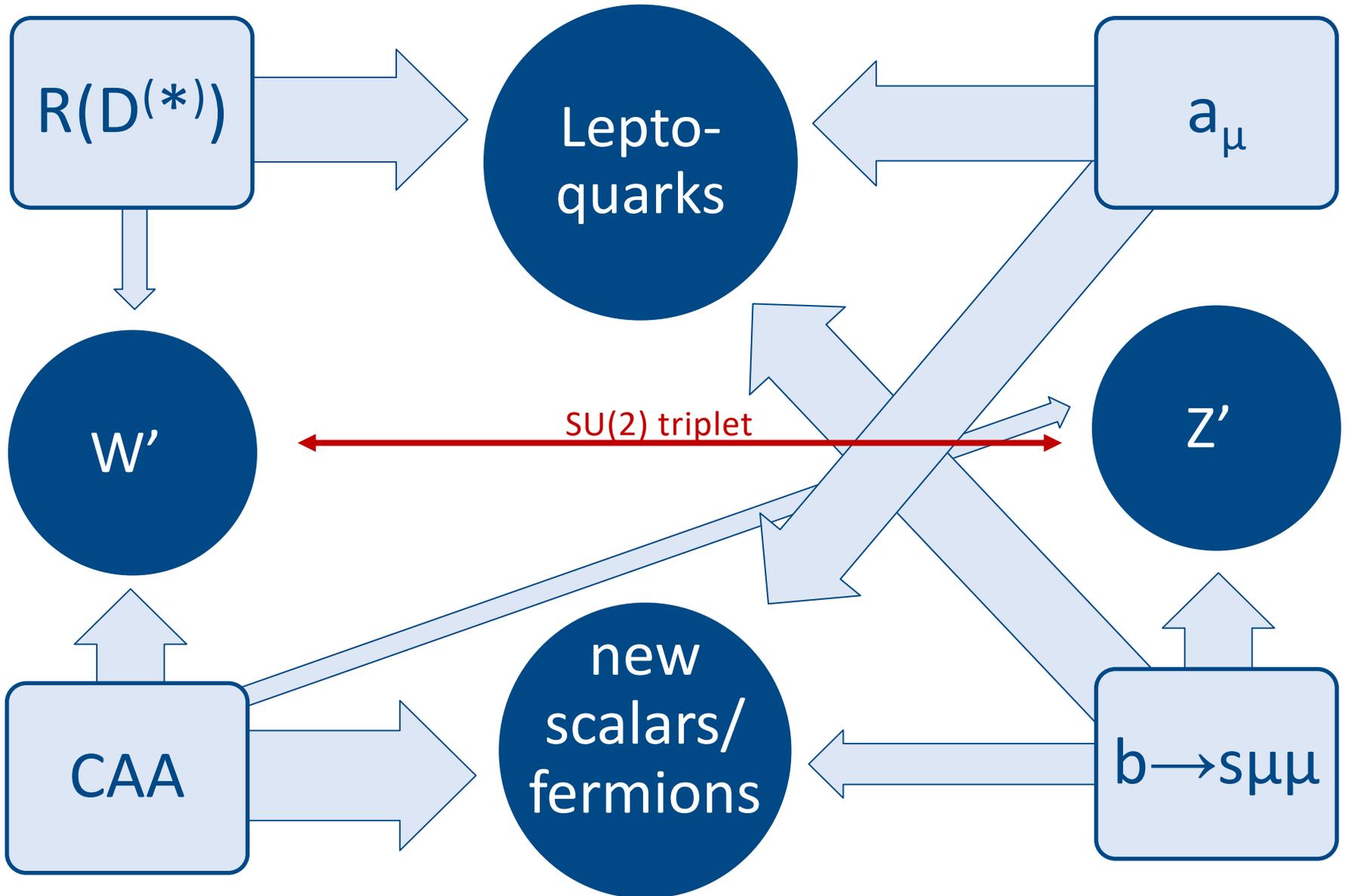
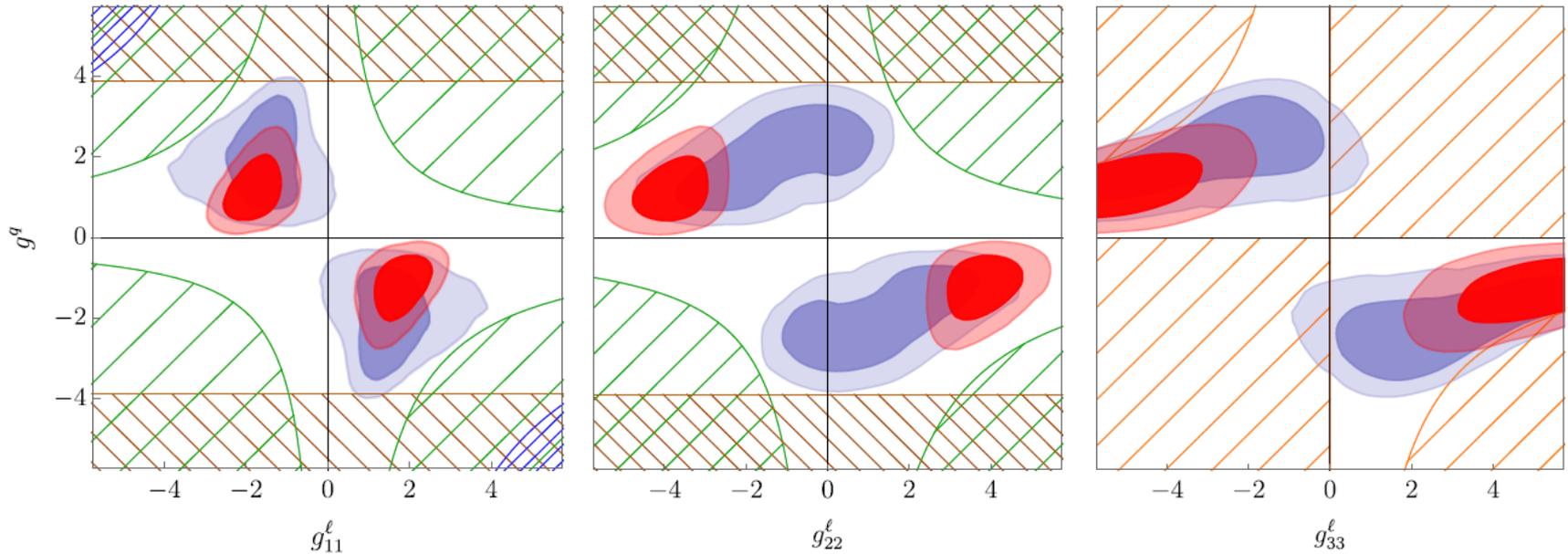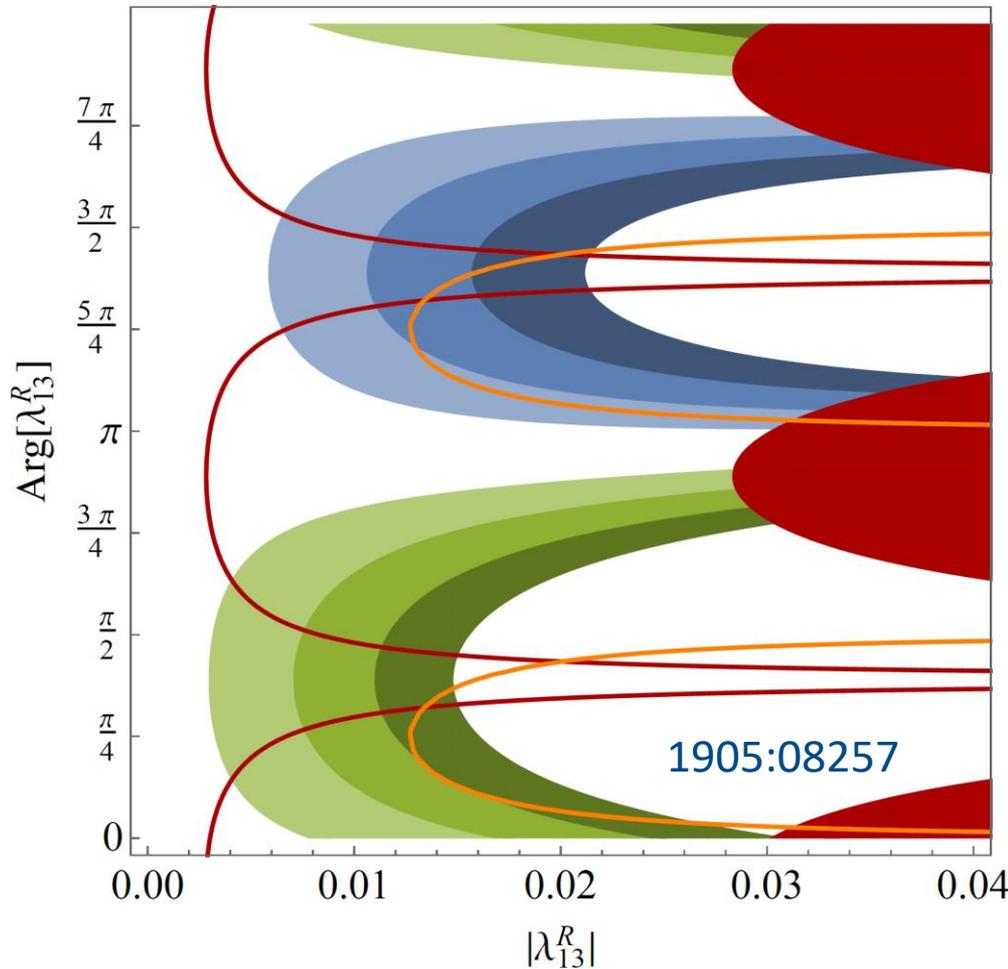# Backup

W' Explanation of R(V$_{us}$)

- W' effects in LFU and EW observables

- Z' effects in LHC di-jet and di-lepton tail searches

R(V$_{us}$) can be explained by a left-handed W'

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

$0.6 < \mathrm{Br}[B \to \tau\nu]/\mathrm{Br}[B \to \tau\nu]_{\mathrm{SM}} < 0.7$

$0.7 < \mathrm{Br}[B \to \tau\nu]/\mathrm{Br}[B \to \tau\nu]_{\mathrm{SM}} < 0.8$

$0.8 < \mathrm{Br}[B \to \tau\nu]/\mathrm{Br}[B \to \tau\nu]_{\mathrm{SM}} < 0.9$

$1.1 < \mathrm{Br}[B \to \tau\nu]/\mathrm{Br}[B \to \tau\nu]_{\mathrm{SM}} < 1.2$

$1.2 < \mathrm{Br}[B \to \tau\nu]/\mathrm{Br}[B \to \tau\nu]_{\mathrm{SM}} < 1.3$

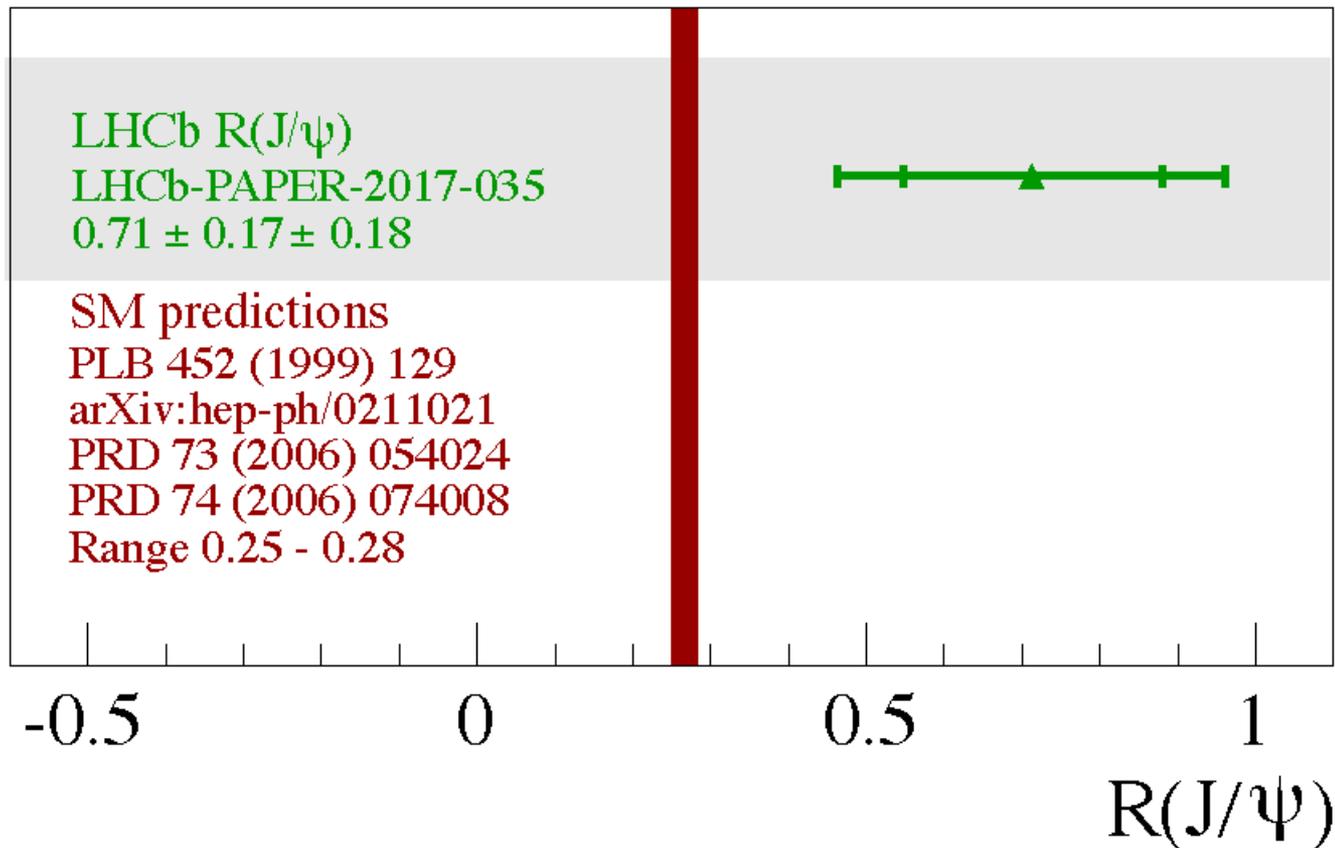$1.3 < \mathrm{Br}[B \to \tau\nu]/\mathrm{Br}[B \to \tau\nu]_{\mathrm{SM}} < 1.4$

nEDM excluded

n2EDM sensitivity

$D^0 - \bar{D}^0$ HL-LHC

1905:08257

Effect in B predicts measurable nEDM effect

b→cτν Measurements

$$R(J/\Psi) = B_c \rightarrow J/\Psi\,\tau\nu\,/\,B_c \rightarrow J/\Psi\,\ell\,\nu$$

LHCb R(J/ψ)
LHCb-PAPER-2017-035
0.71 ± 0.17 ± 0.18

SM predictions
PLB 452 (1999) 129
arXiv:hep-ph/0211021
PRD 73 (2006) 054024
PRD 74 (2006) 074008
Range 0.25 - 0.28

R(J/ψ)

Supports R(D) & R(D*)

R(D$^{(*)}$), b→sνν with 2 Scalar LQs
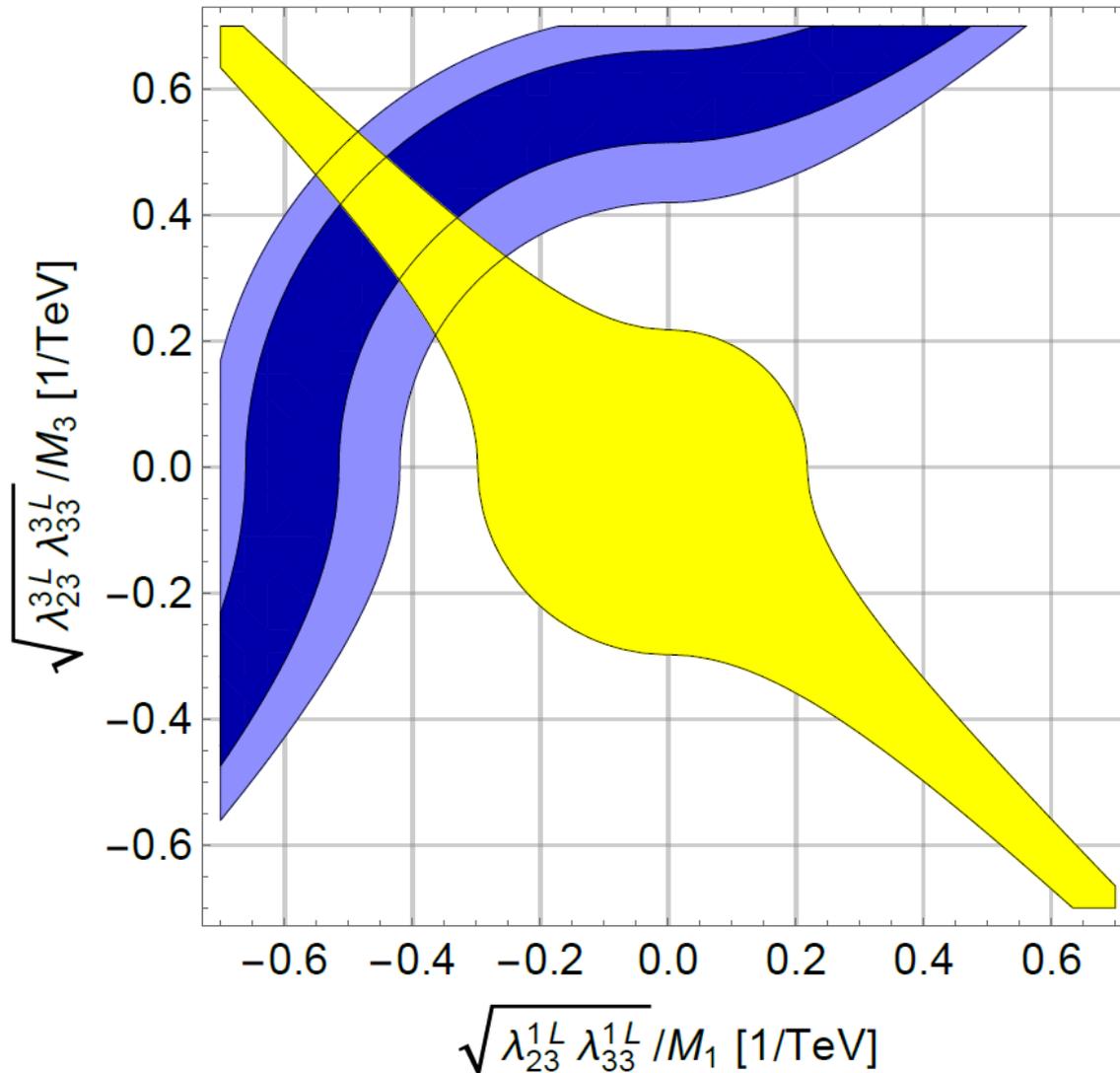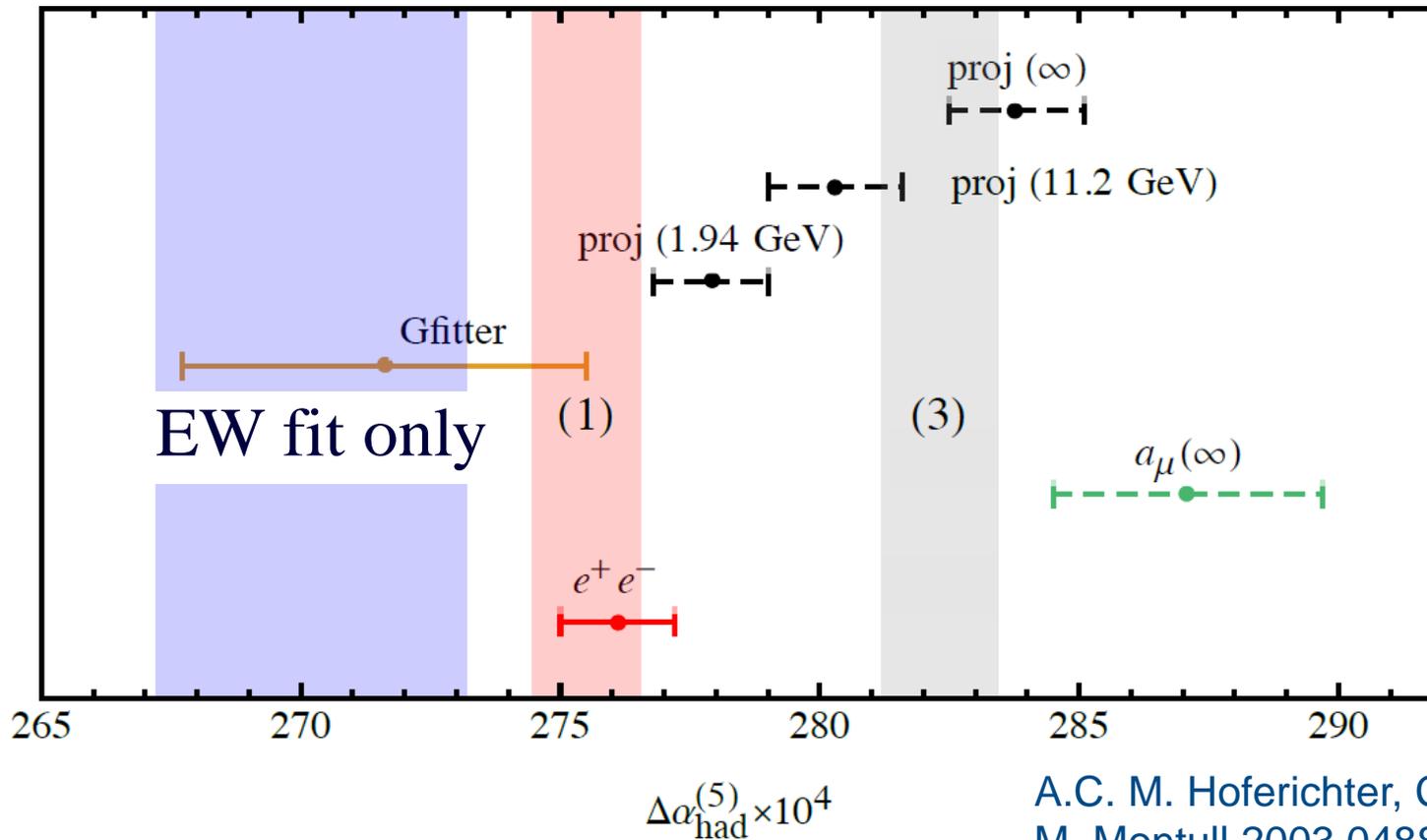

R(D$^{(*)}$) 2σ
R(D$^{(*)}$) 1σ
b→sνν allowed

$$\lambda_{jk}^{L} \equiv \lambda_{jk}^{1L}$$
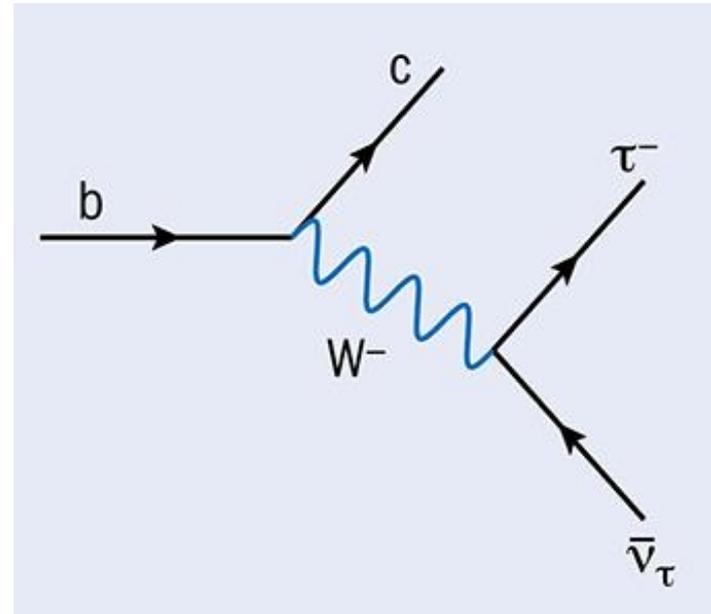$$\lambda_{jk}^{3L} = e^{i\pi j} \lambda_{jk}^{L}$$

Hadronic Vacuum Polarization

- New BMWc lattice QCD result

$\Delta\alpha_{had}^{(5)}\times 10^4$

A.C. M. Hoferichter, C. Manzari, M. Montull 2003.04886

Up to 4σ tension in EW fit

b→cτν Transitions

- B→Dτν, B →D*τν, Λ_b→Λ_cτν

- Tree-level decays in the SM

- Form factors needed

- With light leptons (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 Global Fit

- Pure scalar-tensor explenations in tension with the B_c lifetime

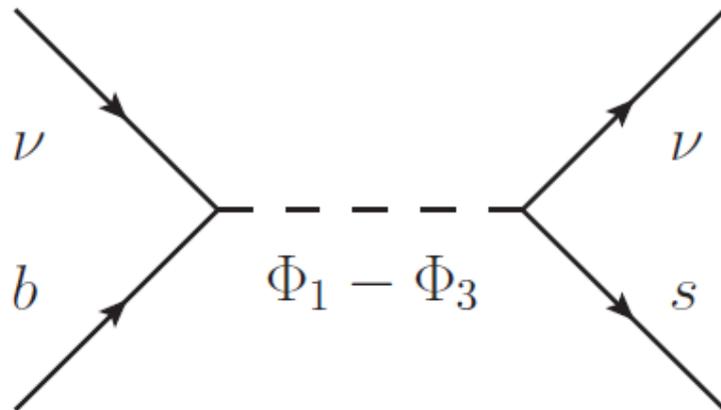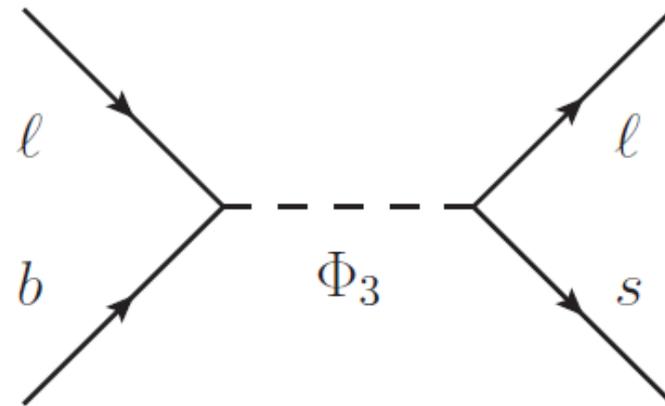- Pure left-handed vector, i.e. contribution to the SM operator gives good fit
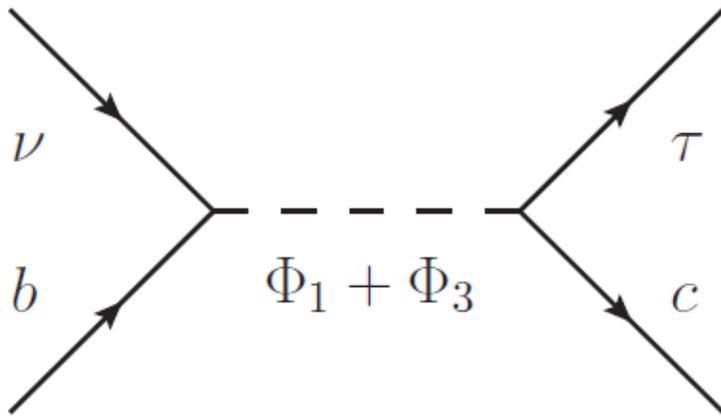

M. Blanke,
A.C.,
T. Kitahara,
M. Moscati,
U. Nierste,
I. Nišandžić,
1905.08253

1905.08253

BR ($B_c \to \tau \bar{\nu}$) > 10 %

BR ($B_c \to \tau \bar{\nu}$) > 60 %

$C_S^L = -4 \, C_T$

C_V^L
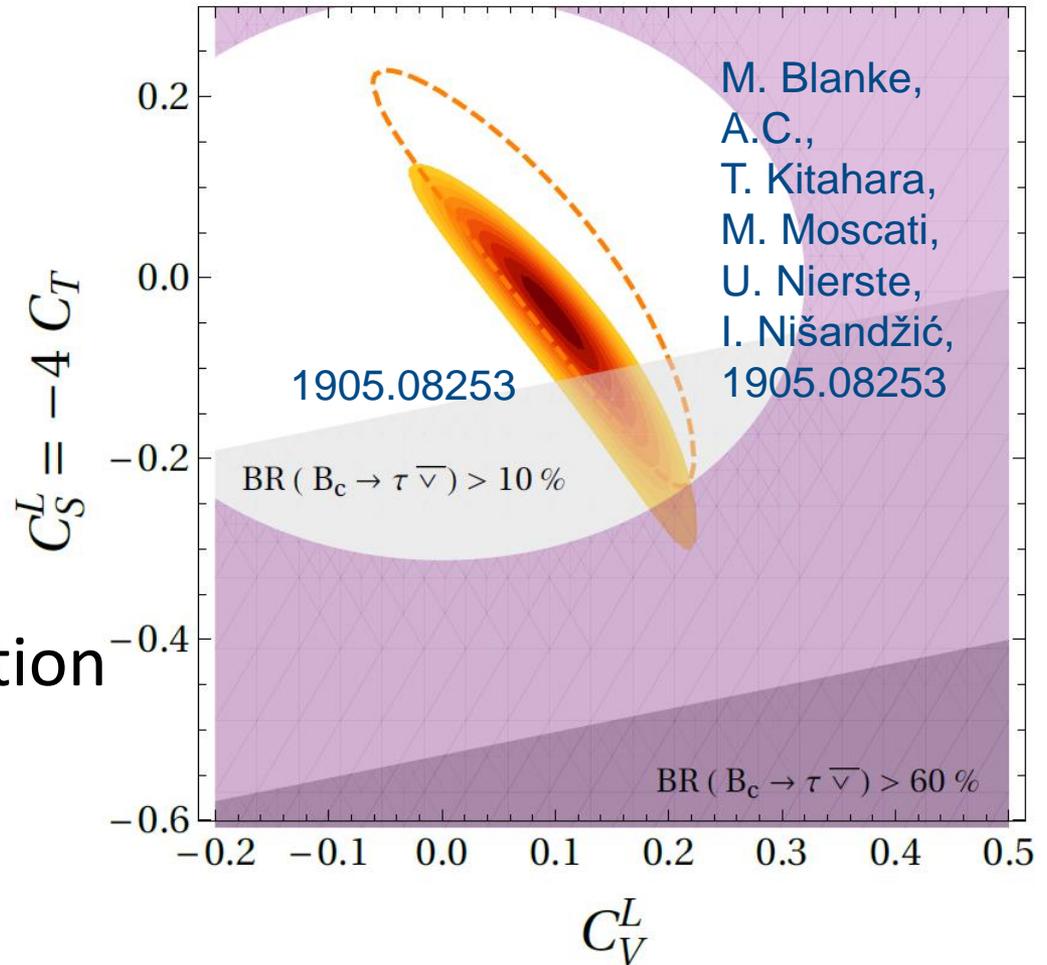
Global fit give up to 4σ preference for NP

Two Scalar Leptoquarks

- 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

$R(D^{(*)})$, $b \to sll$ and a_μ

- ## 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

	$C_9^{\mu\mu} = -C_{10}^{\mu\mu}$	$C_9^{\ell\ell}$	$\dfrac{R(D)}{R(D)_{\rm SM}}$	$\dfrac{R(D^*)}{R(D^*)_{\rm SM}}$	$\dfrac{B_s \to \tau\tau}{B_s \to \tau\tau\big|_{\rm SM}}$	$\tau \to \mu\gamma$ $\times 10^8$	δa_μ $\times 10^{11}$	$\tilde{V}_{cb}^e/\tilde{V}_{cb}^\mu - 1$ $\times 10^6$	$Z \to \tau\mu$ $\times 10^{10}$
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

	$C_{SL}^{\tau\tau} = -4C_{TL}^{\tau\tau}$	$C_{VL}^{\tau\tau}$	$R_{\nu\bar{\nu}}^{K^{(*)}}$	$\dfrac{\Delta m_{B_s}^{\rm NP}}{\Delta m_{B_s}^{\rm SM}}$	$B \to K\tau\mu$ $\times 10^5$	$\tau \to \phi\mu$ $\times 10^8$	$\tau \to \mu ee$ $\times 10^{11}$	$|\Lambda_{33}^{\rm LQ}(0)|$ $\times 10^5$	$\dfrac{\Delta_{33}^L(m_Z^2)}{\Lambda_{\rm SM}^{L\ell}} \times 10^{-5}$
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

Outlook: Physics at Future Colliders

- Flavour Anomalies require NP at the TeV scale

  ⮕ Direct Searches at HL-LHC, HE-LHC, FCC-pp

- This new particles in general also affect EW precision observables

  ⮕ Z decays at CLIC and FCC-ee

2006.10758

Y_{22}

$Y_{\tilde{2}\tilde{2}}$

$A_{\tilde{2}1}/(m_1 \tilde{m}_2)$

$A_{3\tilde{2}}/(m_3 \tilde{m}_2)$

$A/m^2 = \pm 2 \text{ TeV}^{-1}$

κ_g

κ_γ

LQ in Higgs decays

- Flavour is directly linked to the Higgs boson

  ⮕ CLIC, FCC
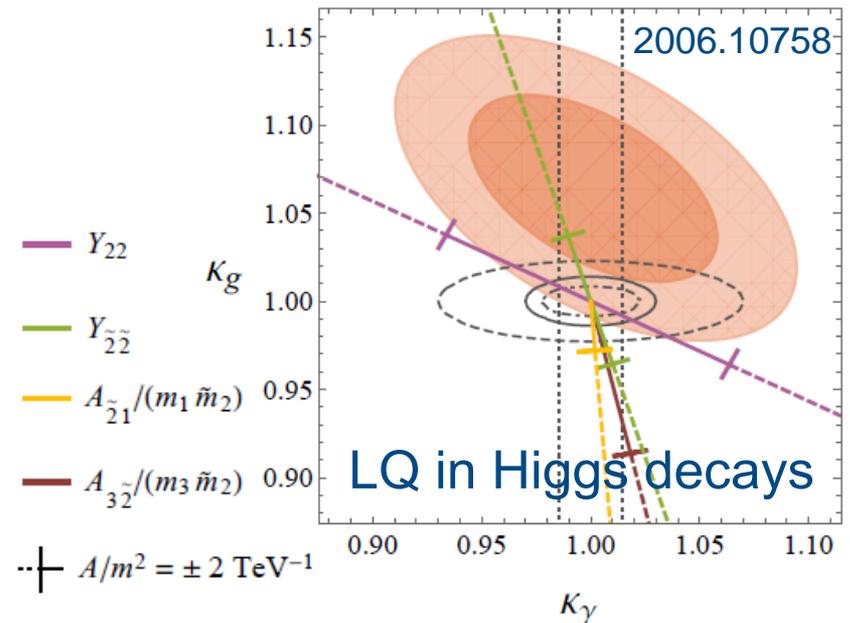
Flavour Anomalies (if confirmed) strengthen the physics case for future colliders significantly

Important Loop-Effects

- Explanation of b→cτν requires large bτ and sτ couplings (follows from SU(2) invariance)
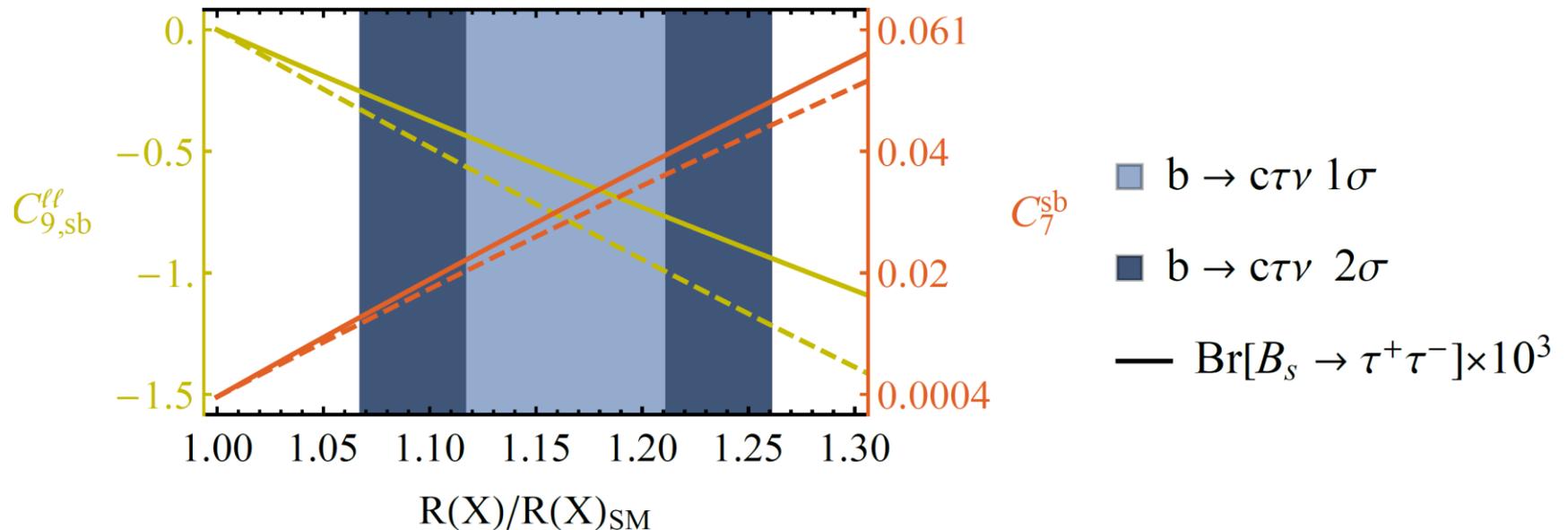
AC, C. Greub, D. Müller, F. Saturnino, PRL 2018

Large loop effects in b→sμμ

R(D$^{(*)}$) and b→sττ

- Large couplings to the second generation

b→sττ
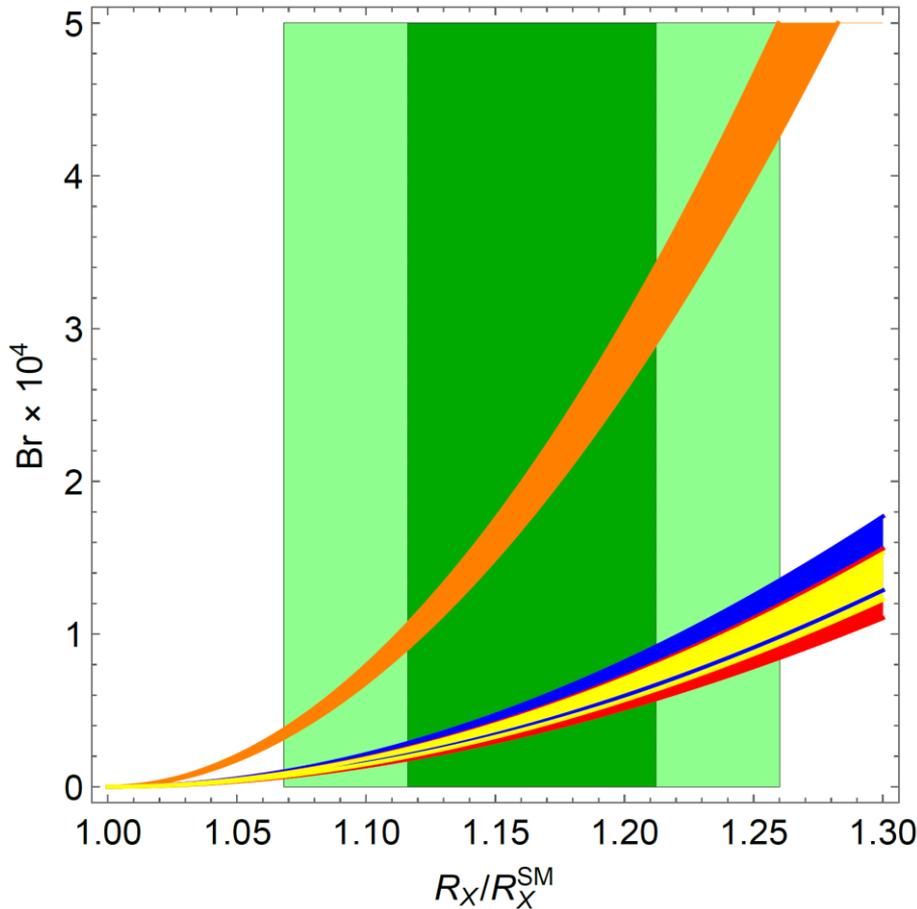
very strongly enhanced

Important Loop-Effects

- Explanation of b→cτv requires large LQ-bτ and LQ-c-v_τ couplings

- Via SU(2) invariance this leads to large effects in b→sττ processes

- Closing the tau-loop gives a LFU effect in b→sll M. Algueró, B. Capdevila, S. Descotes-Genon, P. Masjuan, J. Matias, PRD, 2019

- Effect goes in the right direction
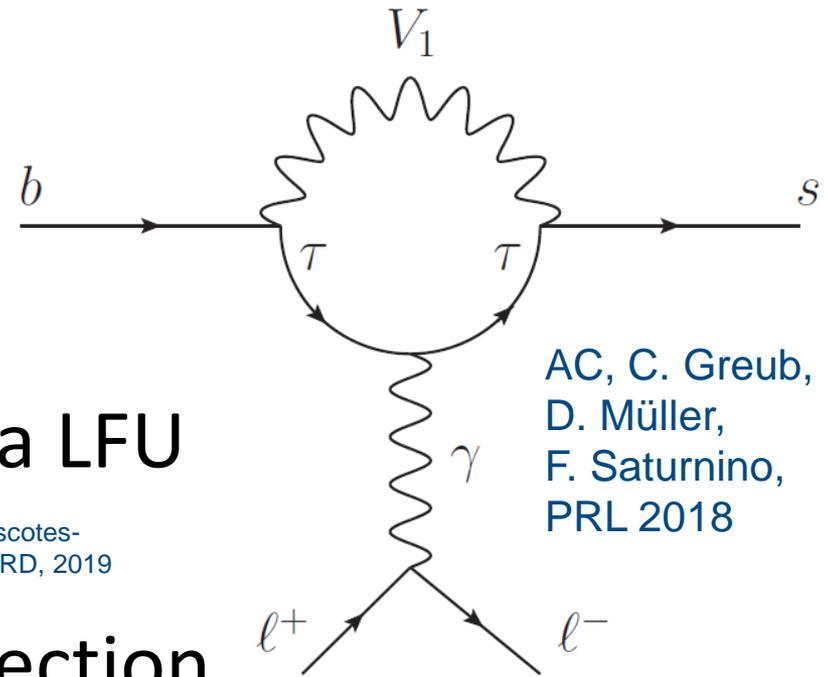
AC, C. Greub, D. Müller, F. Saturnino, PRL 2018

Explanation of b→cτv leads to loop effects in b→sμμ

Vector LQ Phenomenology
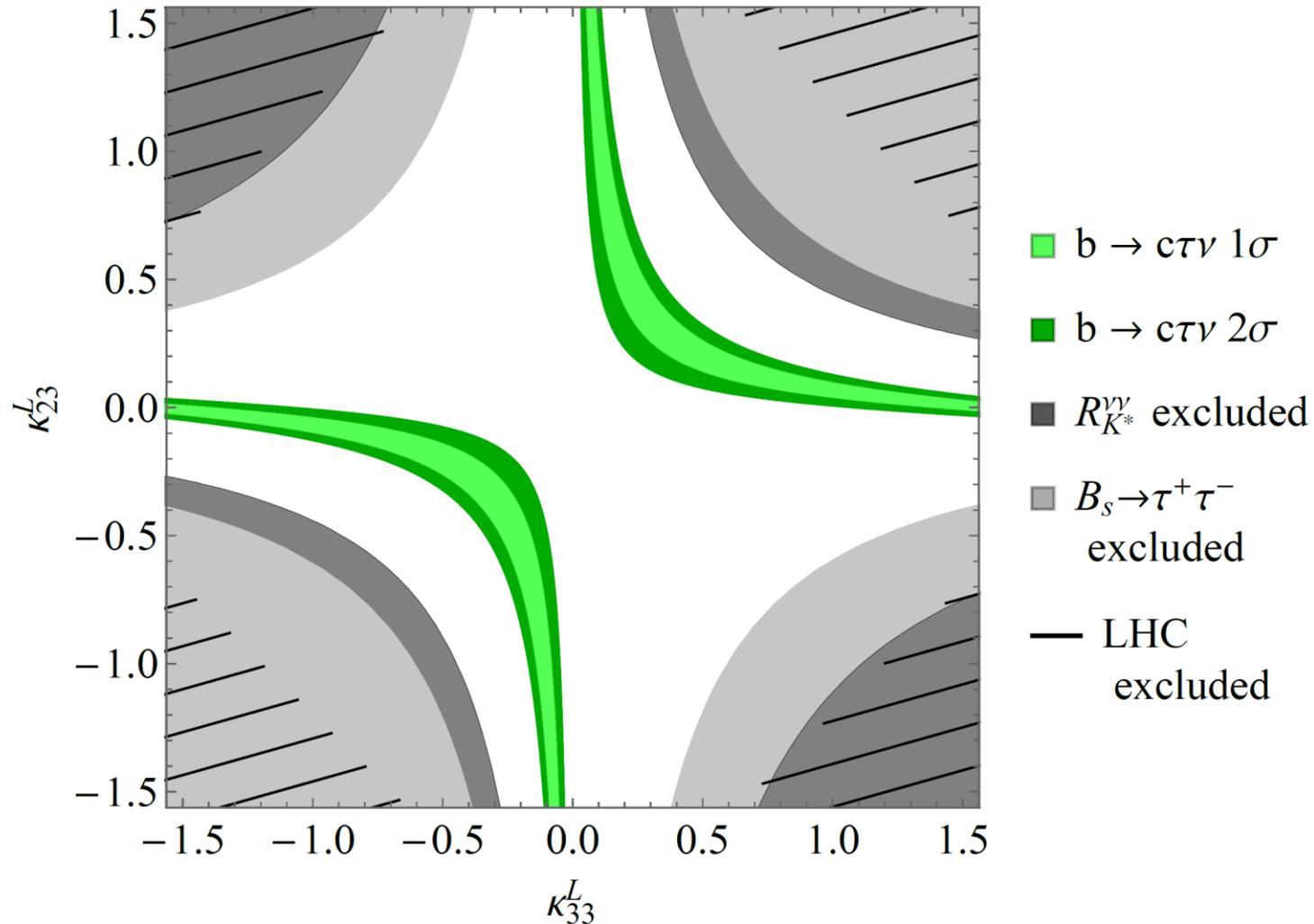
Compatible with constraints for generic couplings

Possible UV completions

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

  L. Di Luzio, A. Greljo, M. Nardecchia, arXiv:1708.08450

- SU(4)×U(2)$_L$×SU(2)$_R$ + Vector-like fermions

  L. Calibbi, AC, T. Li, arXiv:1709.00692

- SU(4)×SU(4)×SU(4)

  M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, arXiv:1712.01368

- SU(4)×U(2)$_L$×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)×U(2)×SU(2)$_R$ in RS background

  M. Blanke, AC, arXiv:1801.07256

Good solution, but challenging UV completion
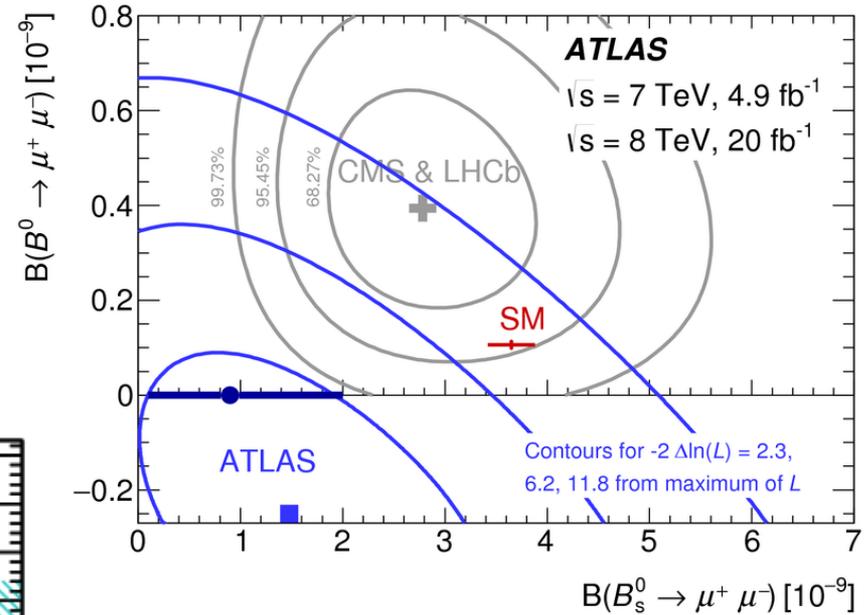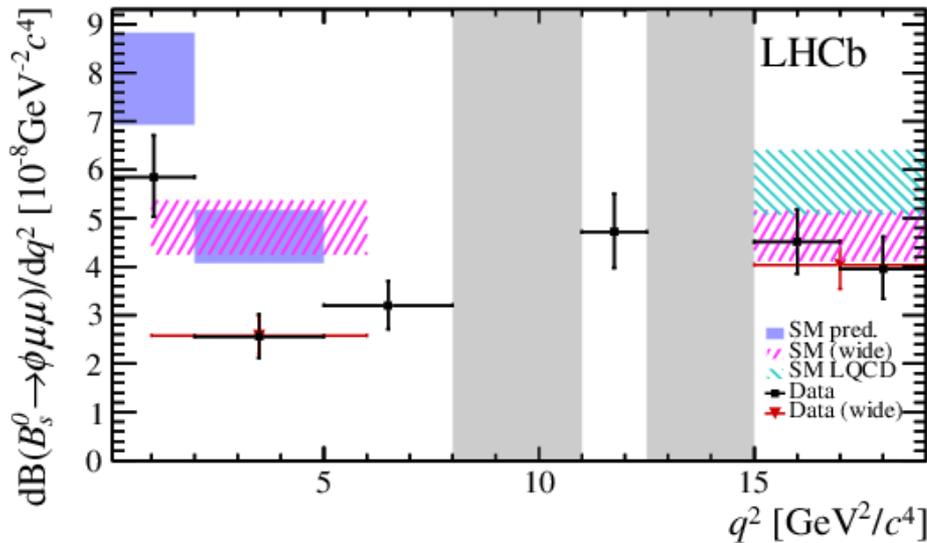
Pati-Salam RS Phenomenology
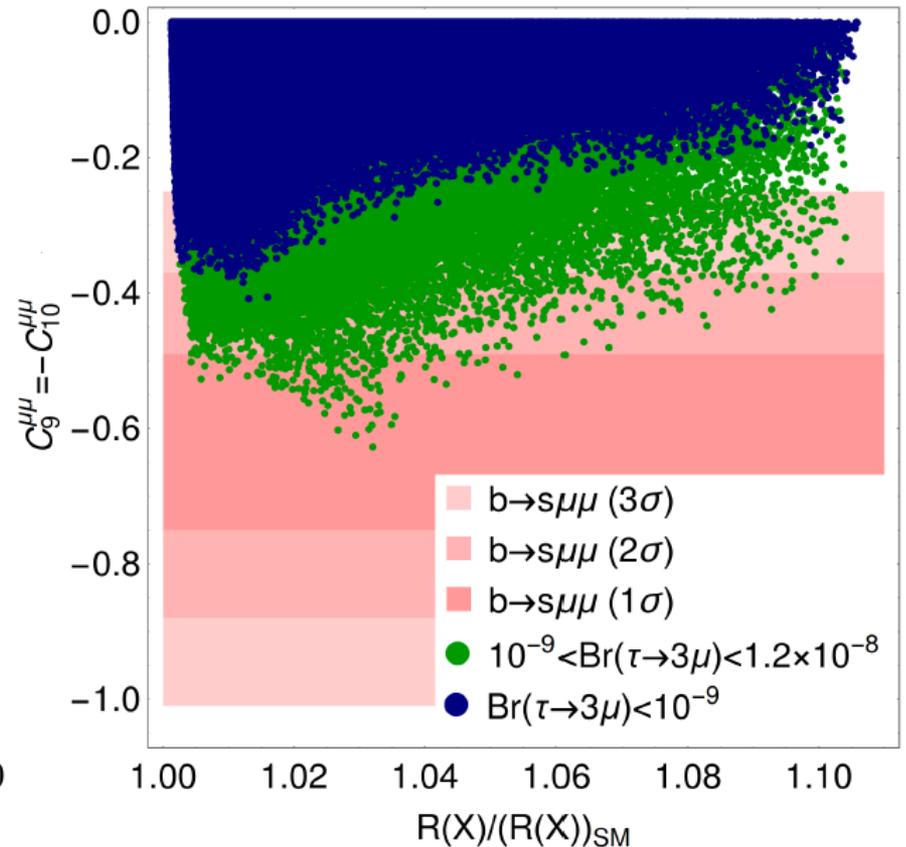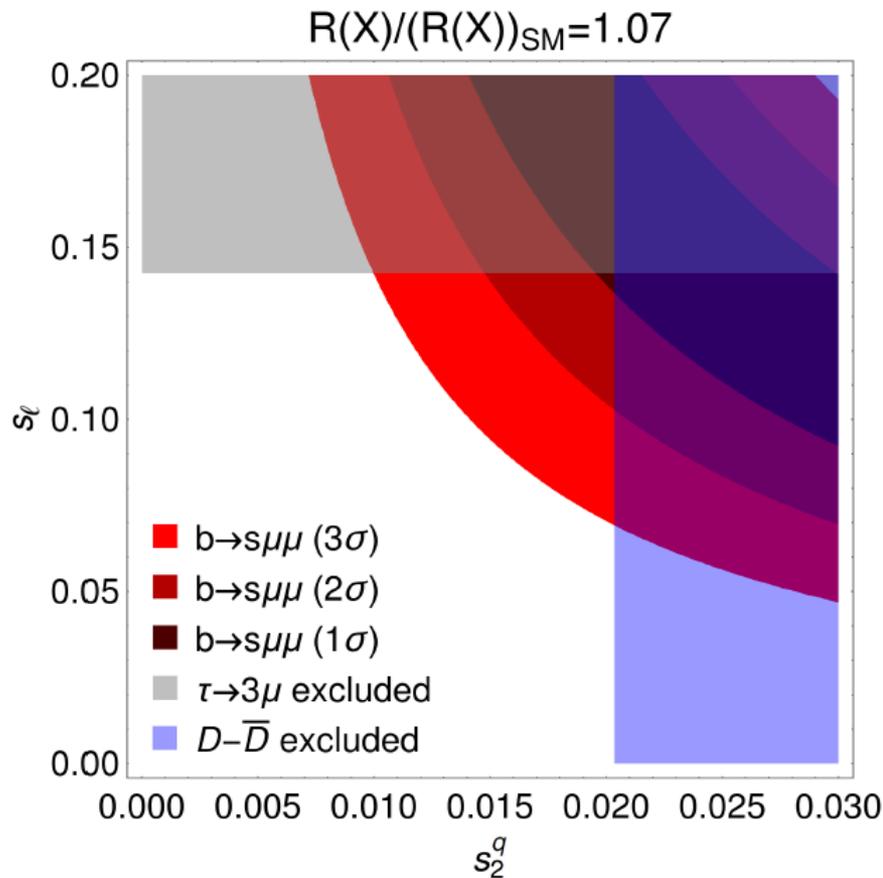
$$M = 3\,\mathrm{TeV},\ s_2^\ell = 0.2,\ s_3^\ell = 1/\sqrt{2}\ \text{and}\ s_3^q = \sqrt{3}/2$$

M. Blanke, AC, PRL 2018

Model well motivated + limited but sizable effect

B$_s$→µµ and B$_s$→ϕµµ

- B$_s$→µµ theoretically clean but chirality suppressed and therefore statistically limited

- B$_s$→ϕµµ has a higher Br, but knowledge of the form-factor needed

Br's ≈ 20% below SM expectations

Leptoquarks in a$_\mu$

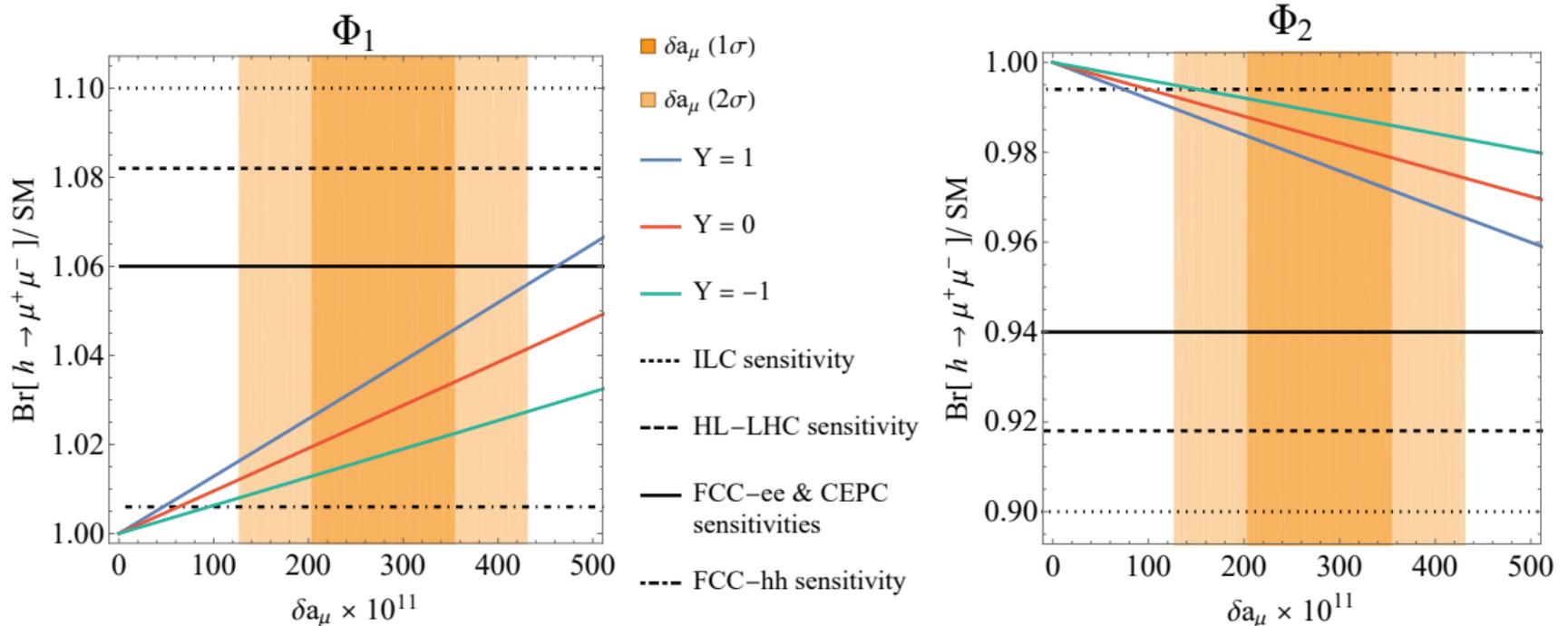- Chirally enhanced effects via top-loops
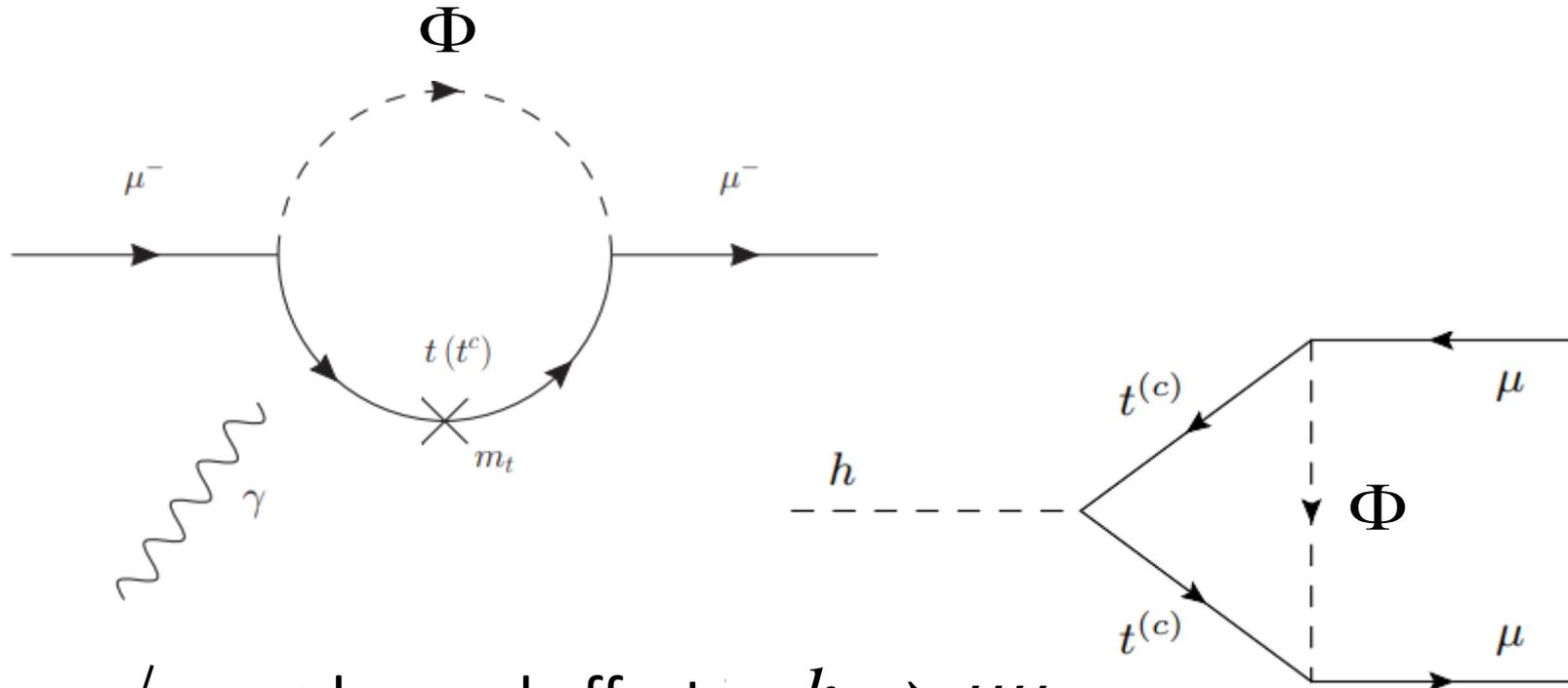
- m_t/m_μ enhanced effect $\quad h \to \mu\mu$
- m_t^2/m_Z^2 enhanced effect in $Z \to \mu\mu$

Correlations with h→μμ and Z→μμ

a_μ vs $h \to \mu\mu$

- Chirally enhanced effects via top-loops

- Same coupling structure $\to$ direct correlation

A.C., D. Mueller, F. Saturnino, 2008.02643
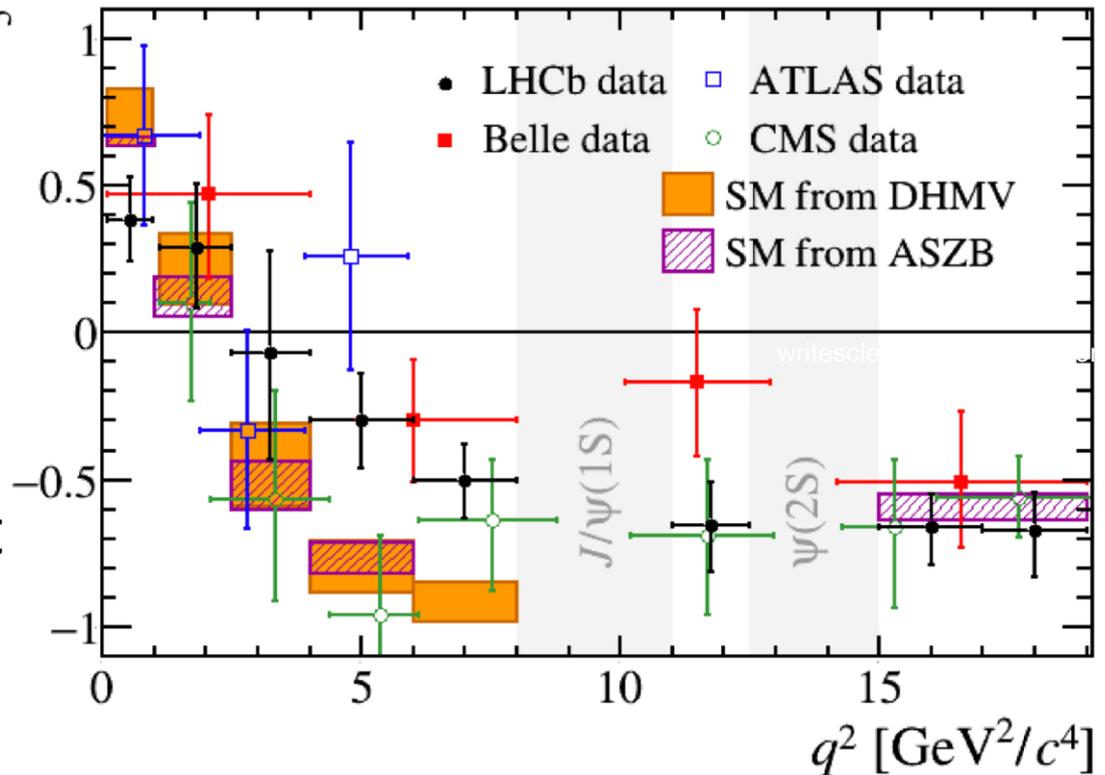
h→μμ at future colliders

The P$_5$' Anomaly

- P$_5$' angular S. Descotes-Genon, T. Hurth, J. Matias, J. Virto, JHEP 2013
  observables in B→K*μμ
- Constructed in such a way that the form factor dependence is minimized
- Confirmed by latest LHCb analysis for the chatged mode

>3σ deviation from the SM prediction

b→sμ⁺μ⁻ 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

- Wilson coefficients precisely known   Bobeth et al. PRD, 2013
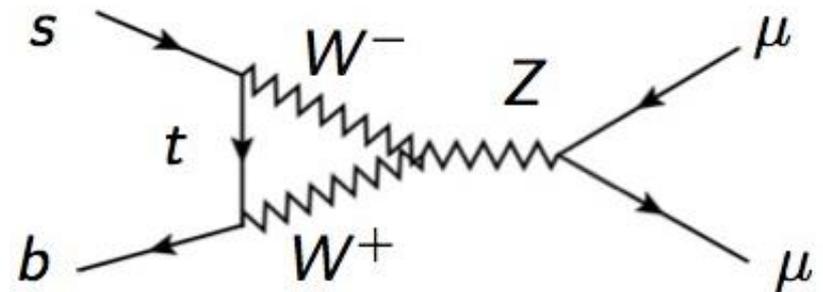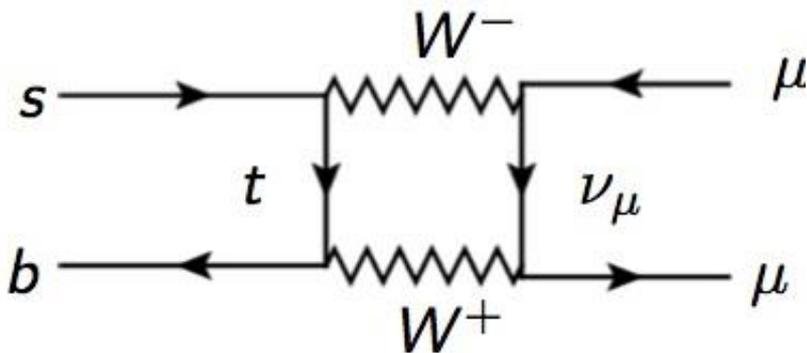
Suppressed in the SM and very sensitive to NP