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Anomalies in Particle Physics

PASCOS 2022, Heidelber, 29.07.2022

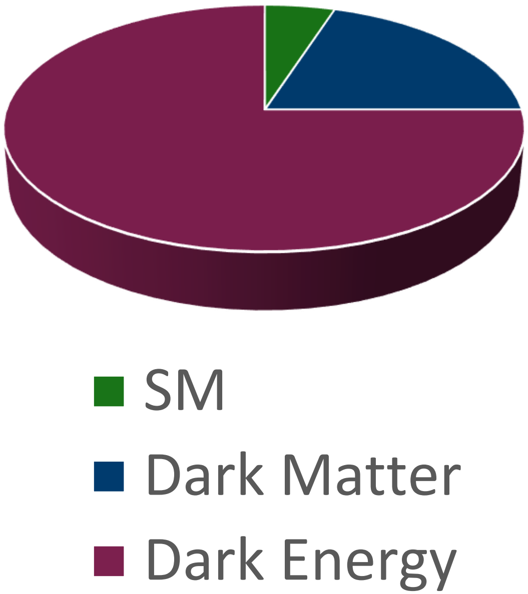
Work supported by FNSNF

Outline

- Introduction
- Status of the anomalies
  - $b \to s\mu\mu$
  - $b \to c\tau\nu$
  - a_μ
  - Cabibbo Angle Anomaly
  - Non-resonant di-leptons
  - EW fit: W mass and $Z \to bb$
- Explanations of the Flavour anomalies
- Common Explanations
- Conclusions

Physics Beyond the Standard Model

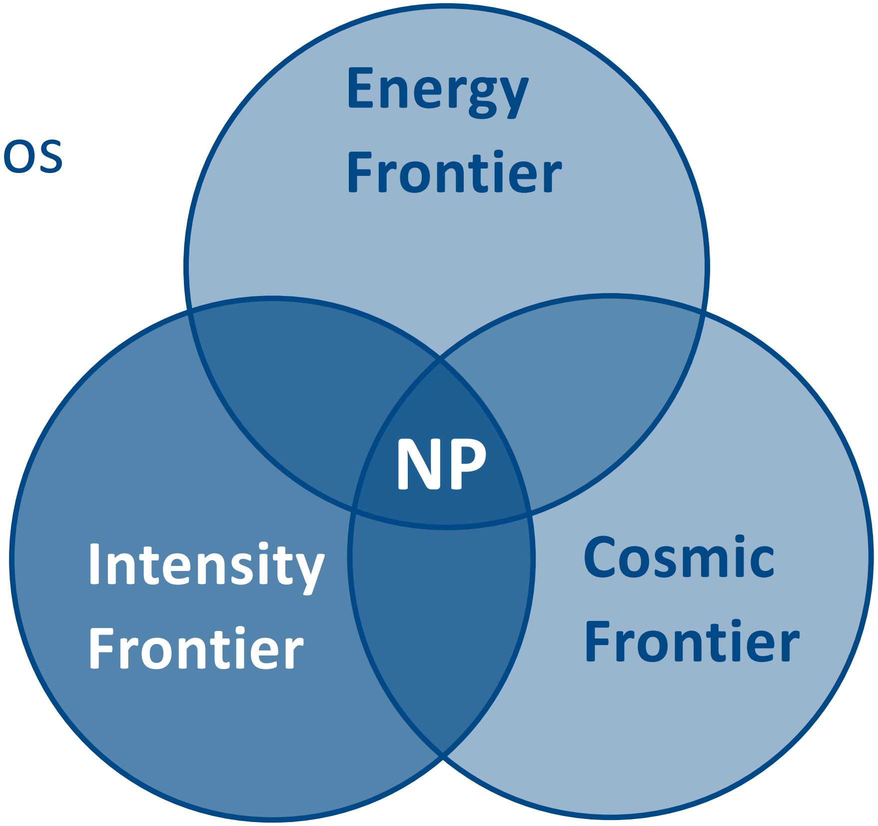
- Dark Matter existence established at cosmological scales
  - New weakly interacting particles
- Neutrinos not exactly massless
  - Right-handed (sterile) neutrinos
- Matter anti-matter asymmetry
  - Additional CP violating interactions



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

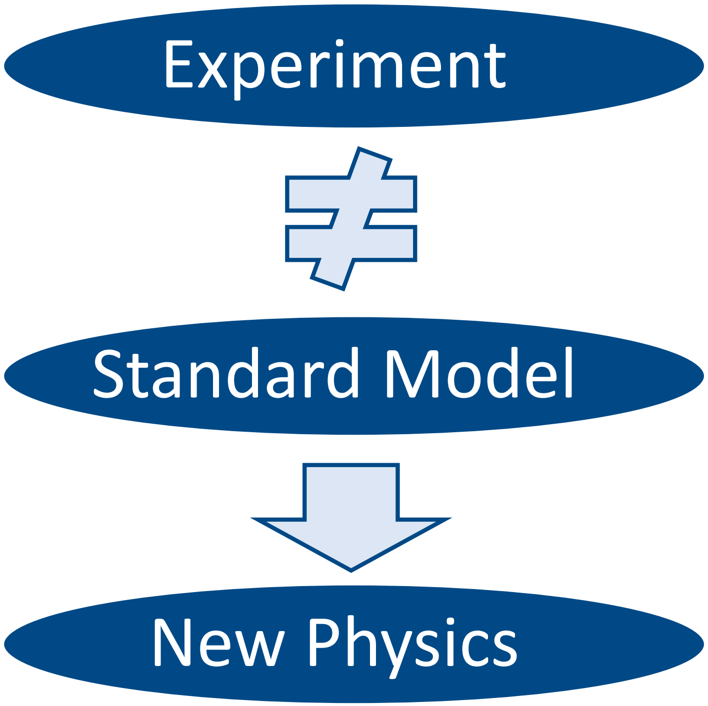
Discovering New Physics

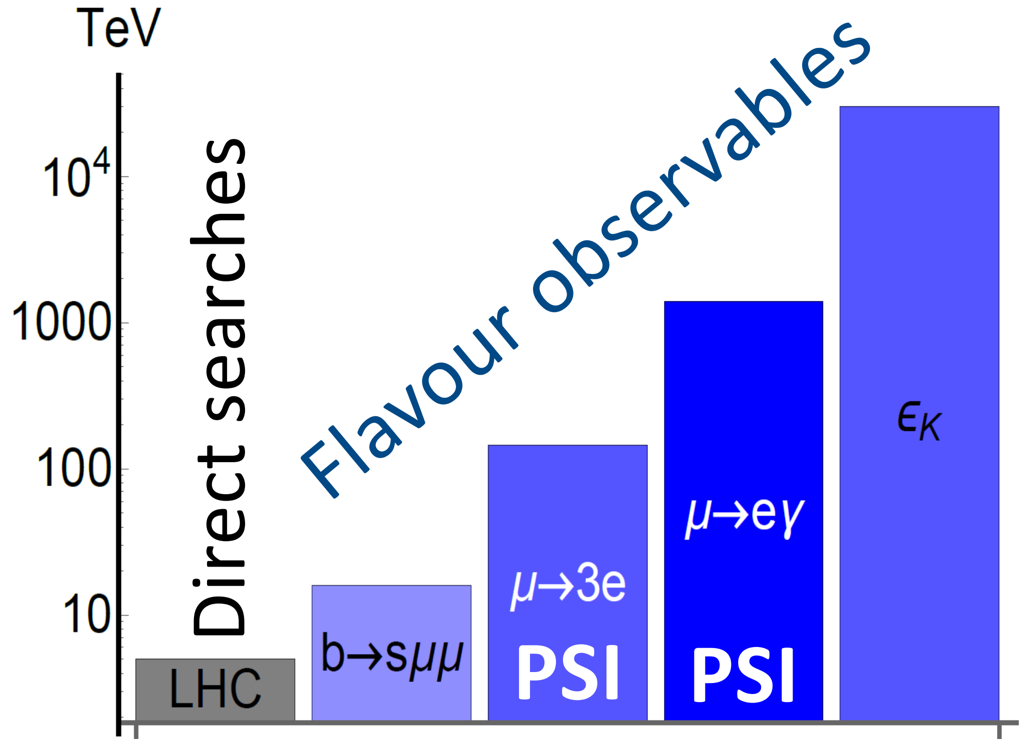
- Cosmic Frontier
  - Cosmic rays and neutrinos
  - Dark Matter
  - Dark Energy
- Energy Frontier
  - LHC
  - Future colliders
- Intensity Frontier
  - Flavour
  - Neutrino-less double-β decay
  - Test of fundamental symmetries
  - Proton decay



Indirect Searches for New Physics

- Perfrom high-statistics measurements to search for the quantum effects of new particles





Flavour observables can be sensitive to higher energy scales than collider searches

LFUV in b→sℓ+ℓ-

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

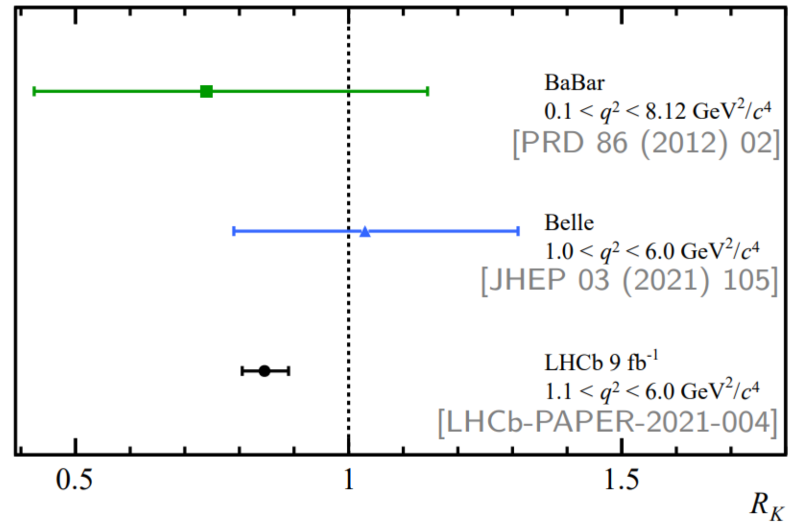
$$R(K^*) = \frac{B \to K^*\mu^+\mu^-}{B \to K^*e^+e^-}$$

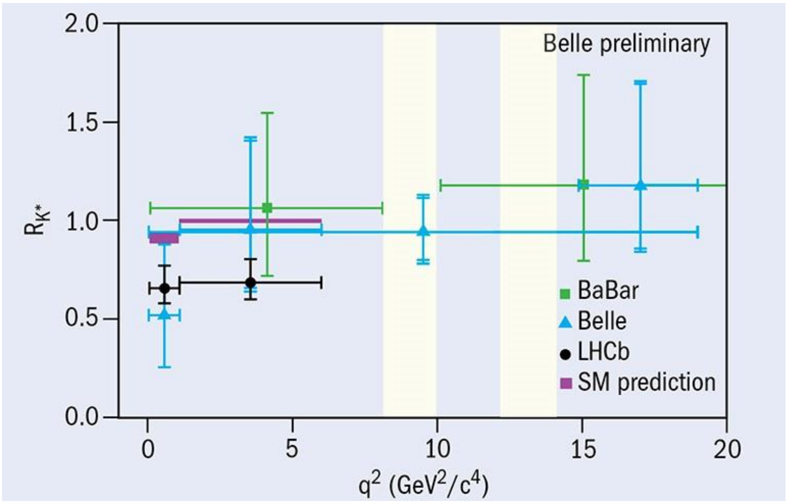
- Muon and electron masses can be neglected

⇨ **Clean prediction**

- Supported by

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

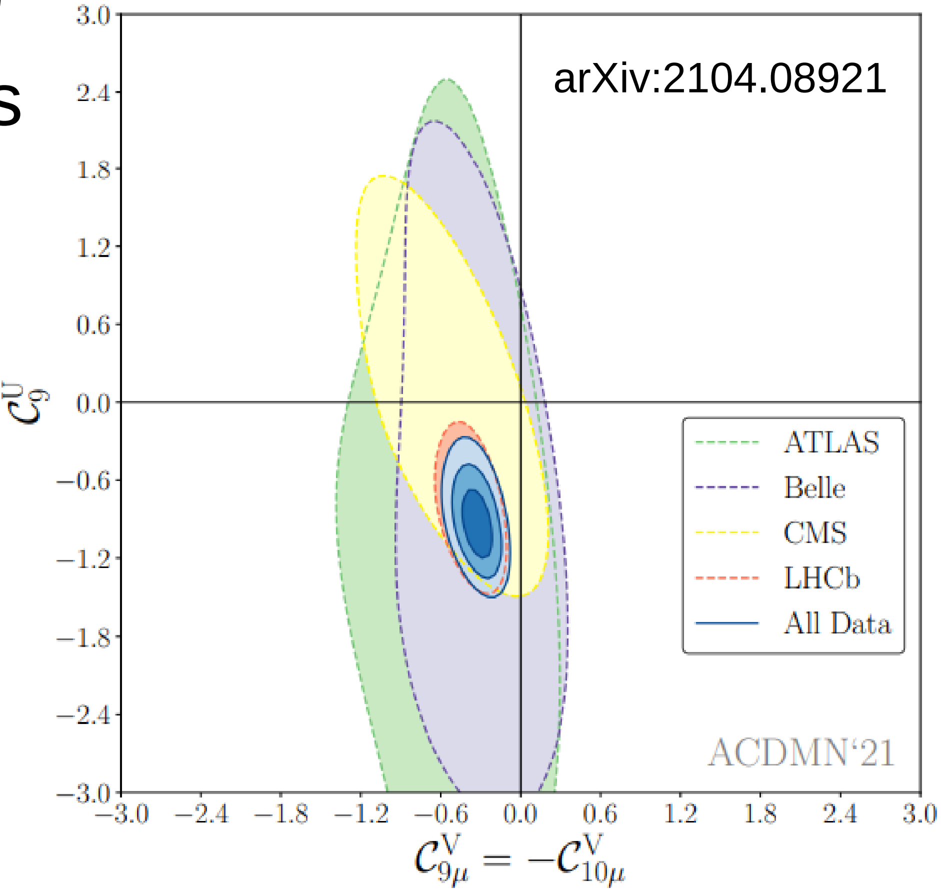




LFUV in B decays >4σ

Global Fit to $b \to s\mu^+\mu^-$ Data

- Perform global model independent fit to include all observables (≈180)
- Several NP hypothesis give a good fit to data significantly preferred over the SM hypothesis



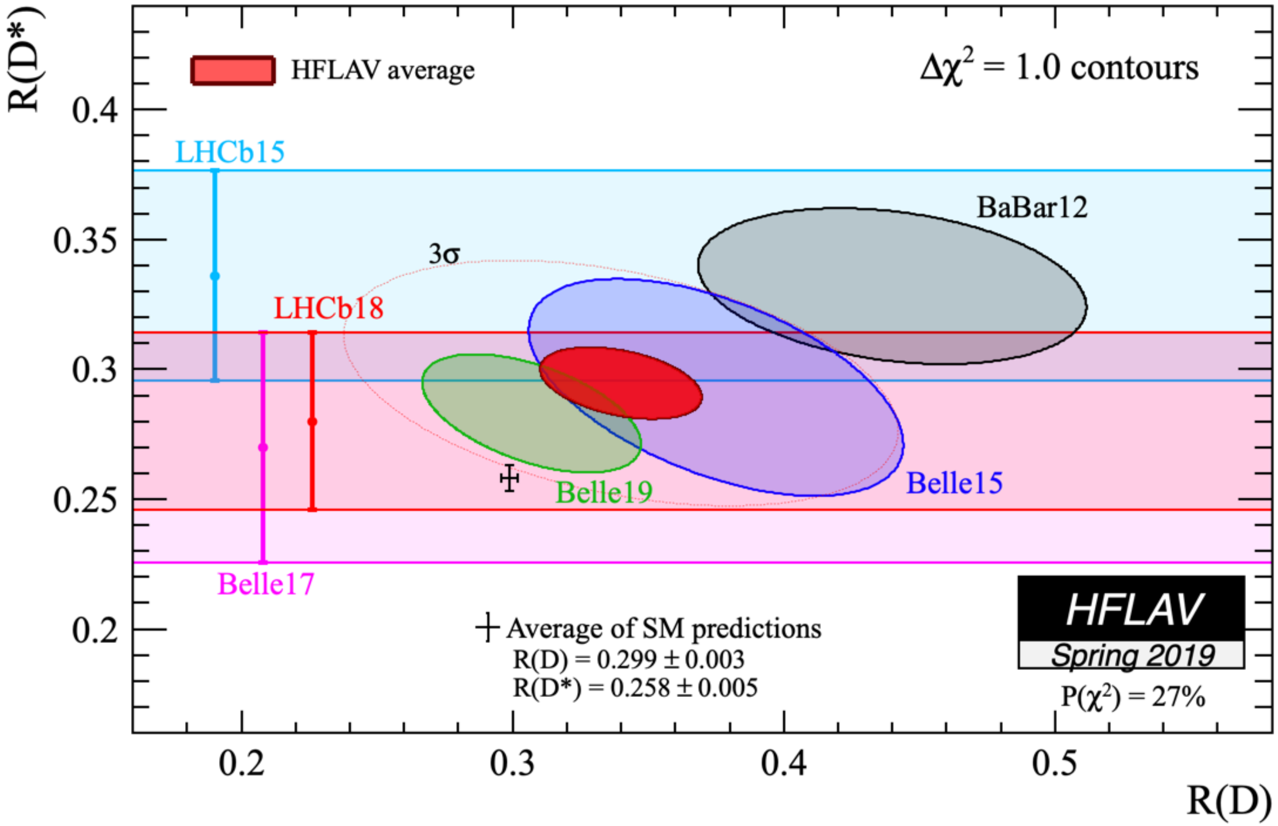
$$O_9 = \bar{s}\gamma^{\mu} P_L b \,\bar{l}\gamma_{\mu} l$$

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

Fit is >7 σ better than the SM

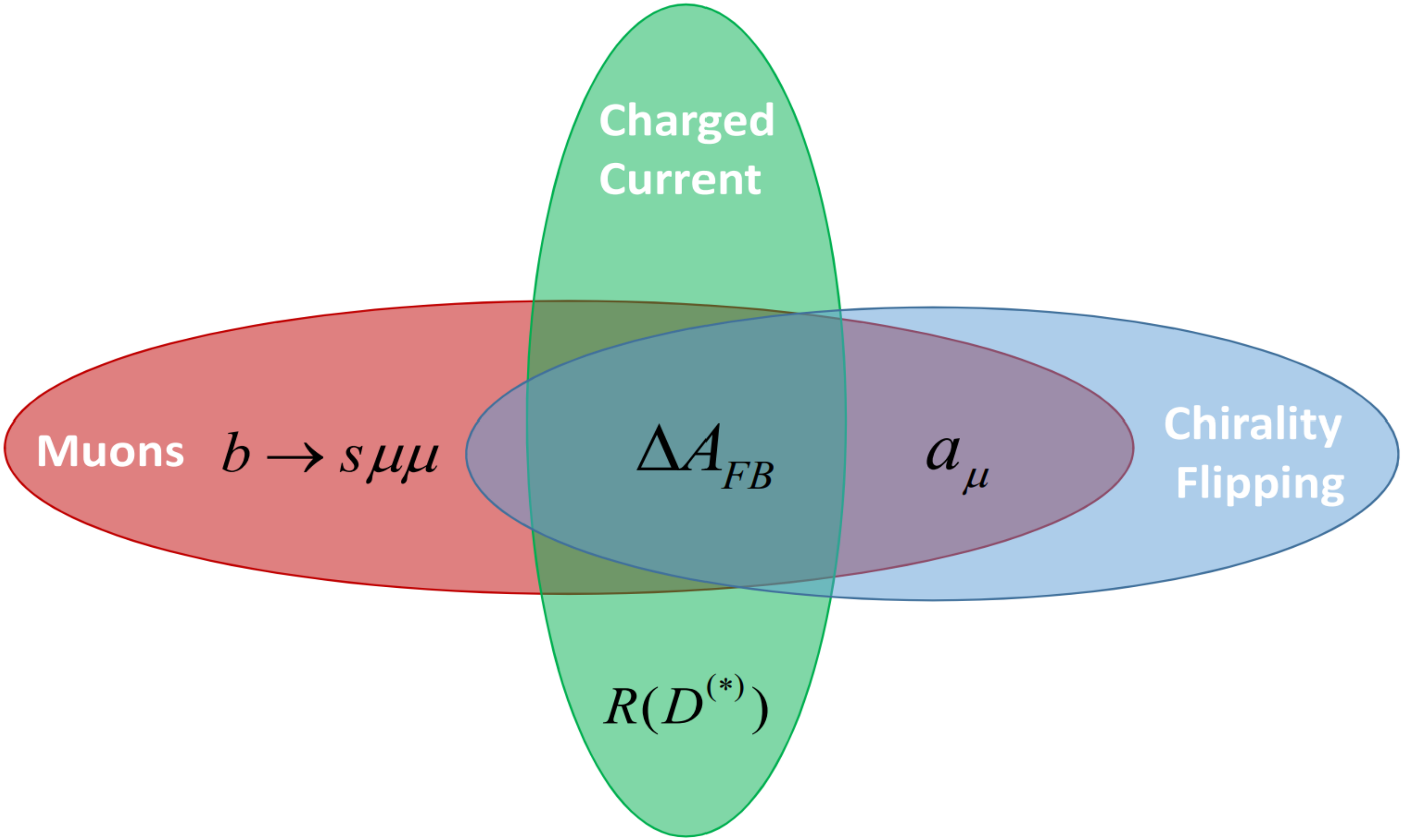
b→cτν

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



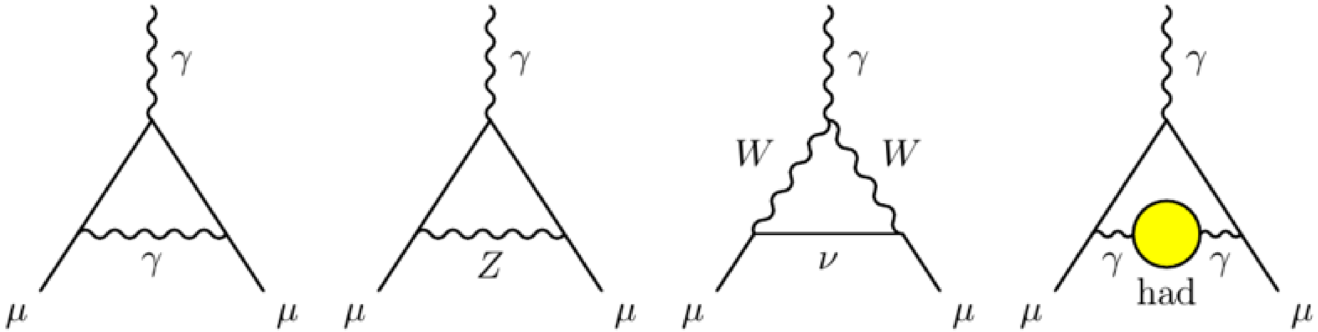
All measurements above the SM prediction
O(10%) constructive effect at 3σ preferred

ΔA_{FB} in B→D*lν



Hint for scalar/tensor NP in b→cμν

Muon Anomalous Magnetic Moment



- Theory prediction challenging (hadronic effects)

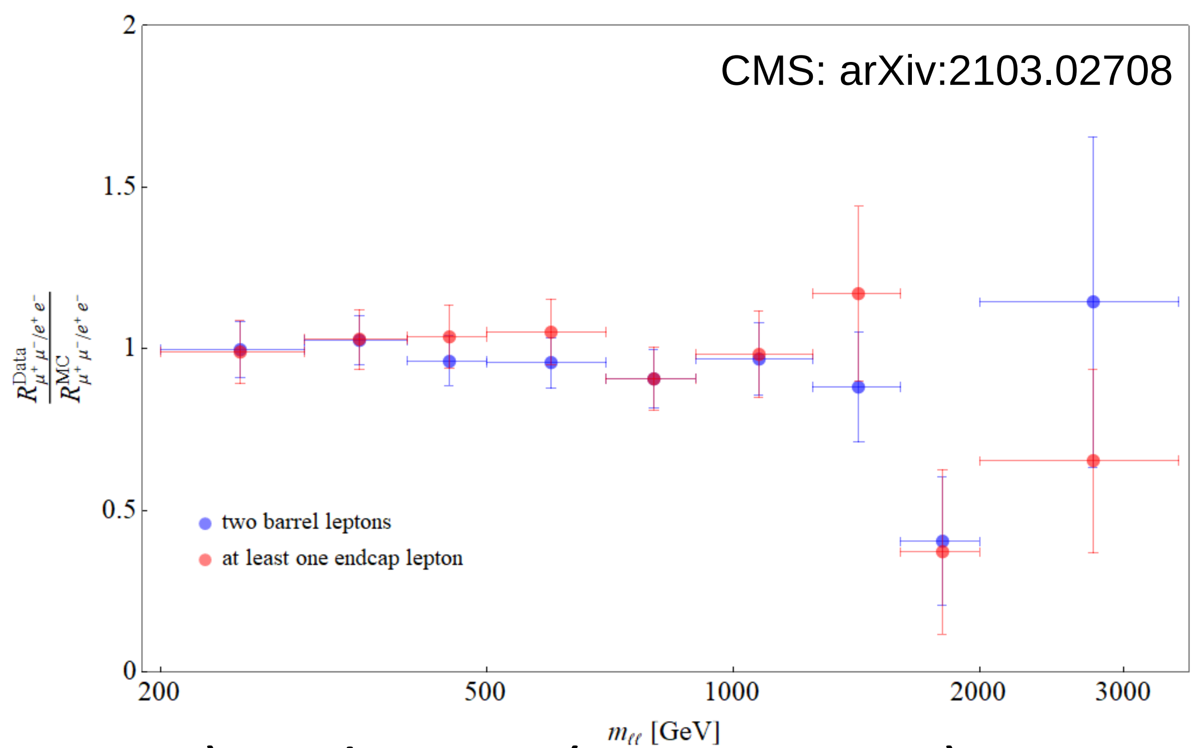
$$\Delta a_\mu = (251 \pm 49) \times 10^{-11}$$ T. Aoyama et al., arXiv:2006.04822

- Need NP of the order of the SM EW contribution
- Chiral enhancement necessary for heavy NP
- Soon more experimental results from Fermilab
- Vanishes for $m_\mu \rightarrow 0$ ⇨ **measure of LFUV**

4.2σ deviation from the SM prediction

Non-Resonant Di-Leptons

- Excess in di-electrons at m_{ee}>1800GeV
- Observed: 44 events
- Expected 29.2 ± 3.6 events



- Also ATLAS (2006.12946) and HERA (1902.03048) observe slightly more electrons than expected.
- No excess in muon data

≈3σ hint for LFUV

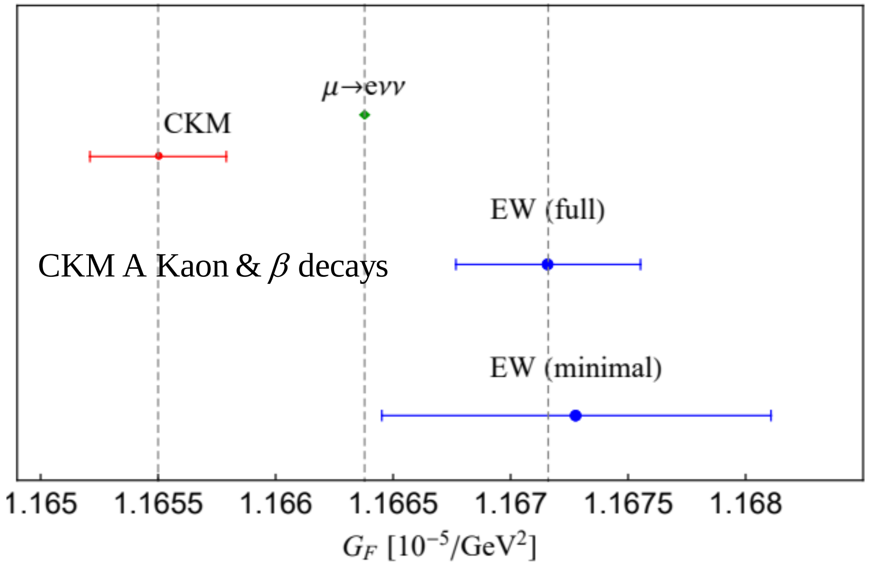
Cabibbo Angle Anomaly (CAA)

- Deficit in first row and first column CKM unitarity

$$|V_{ud}^2|+|V_{us}^2|+|V_{ub}^2|=0.9985\pm0.0005$$
$$|V_{ud}^2|+|V_{cd}^2|+|V_{td}^2|=0.9970\pm0.0018$$

(PDG)

AC, Hoferichter, Manzari, PRL 127 (2021)

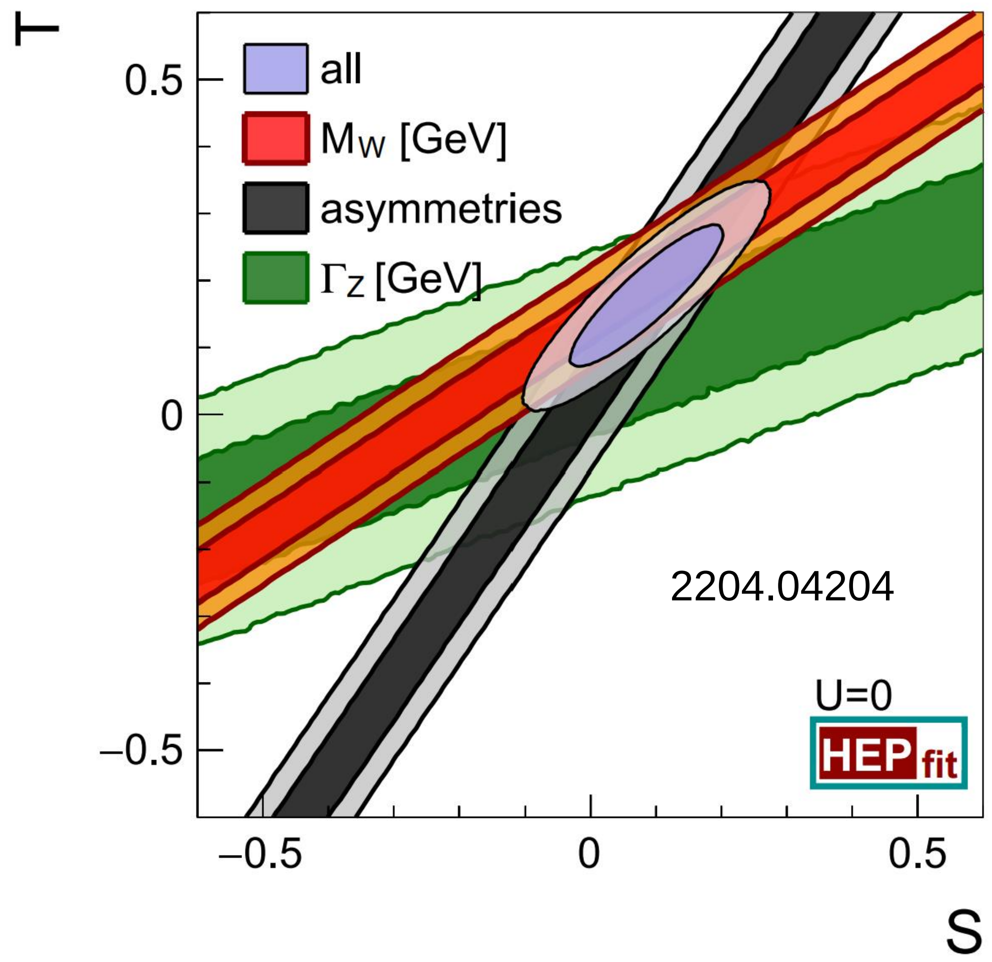


- NP in the determination of V_{ud} from beta decays needed
- Can be interpreted as
  - NP in beta decays
  - NP in the Fermi constant
  - LFUV (modified Wμν coupling)

3σ tension, can be interpreted as LFUV

EW fit: W mass and Z→bb,

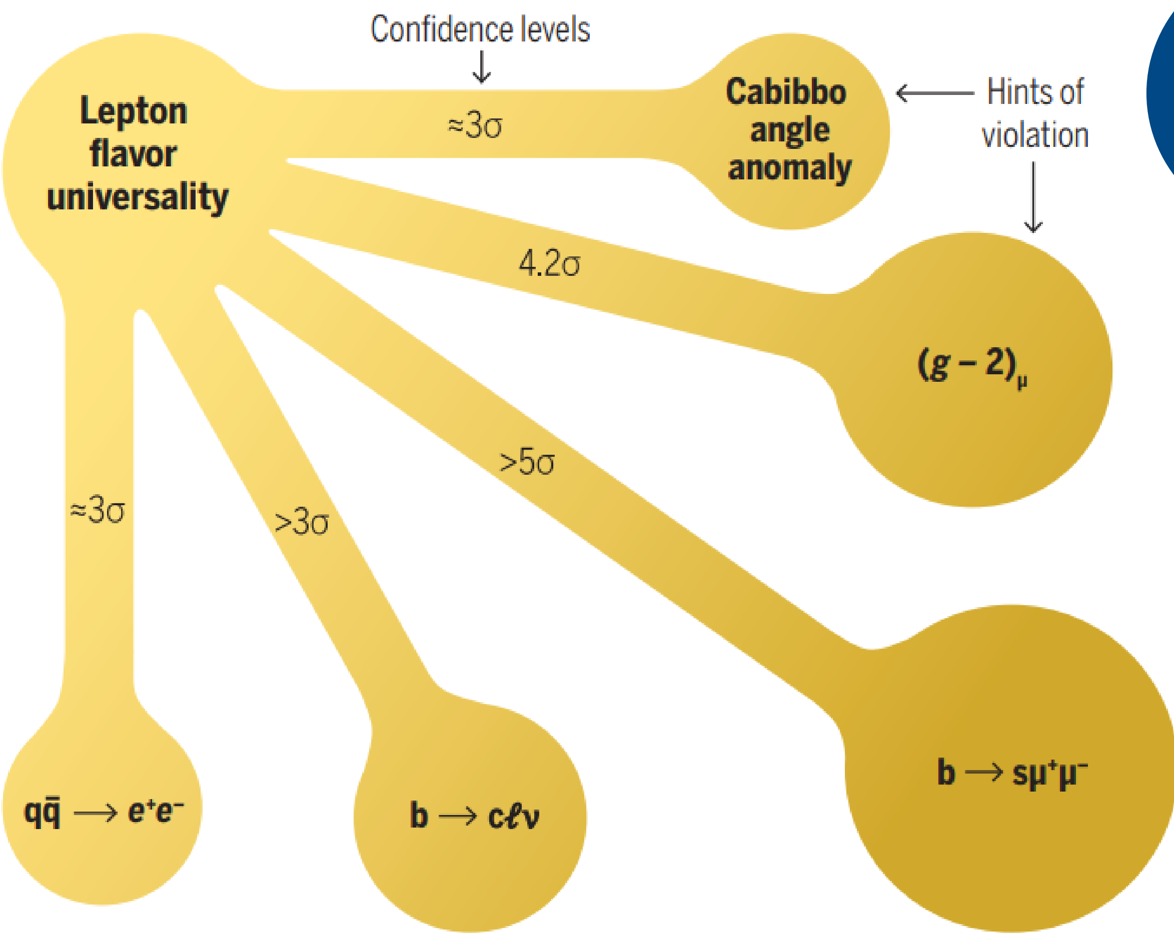
- 3.7 σ tension in the W mass using a conservative error combination
- 2 σ tension in Z→bb from LEP



Related to LFUV?

Hints for New Physics

- LFUV AC, M. Hoferichter, Science 374 (2021)



- EW observables

m_W ≈3-4σ

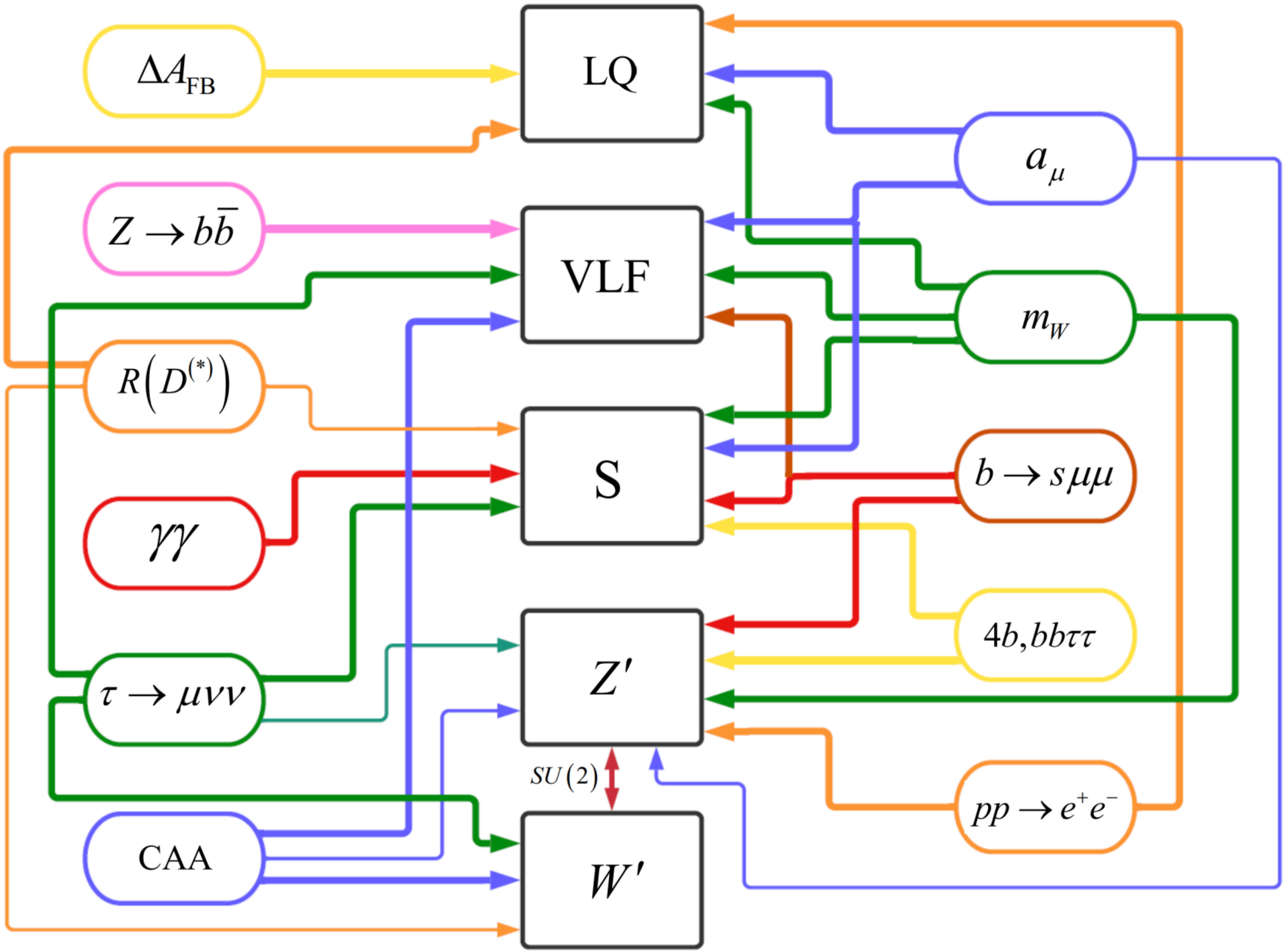
$Z \longrightarrow bb$

- Direct searches

γγ
ττ

4b
bbττ

Expanations



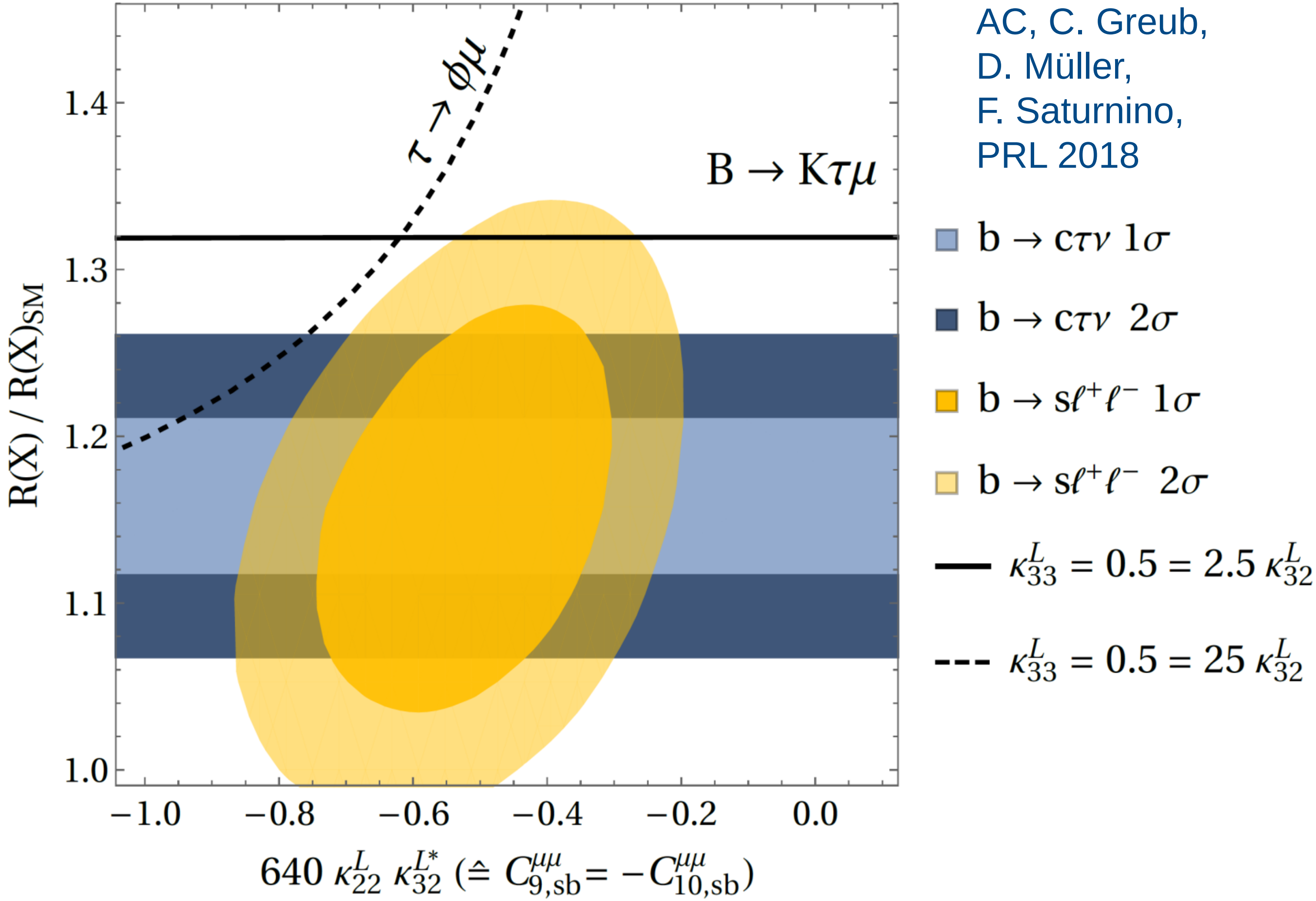
Simultaneous Explanations

Vector Leptoquark SU(2) Singlet

- Left-handed effect in $b \rightarrow s\mu\mu$
- Left-handed vector current in R(D) and R(D*)
- No effect in $b \rightarrow s\nu\nu$
- 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 $K_L \rightarrow \mu e$ and $K \rightarrow \pi\mu e$

Good solution, but difficult UV completion

Perfect agreement with data



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

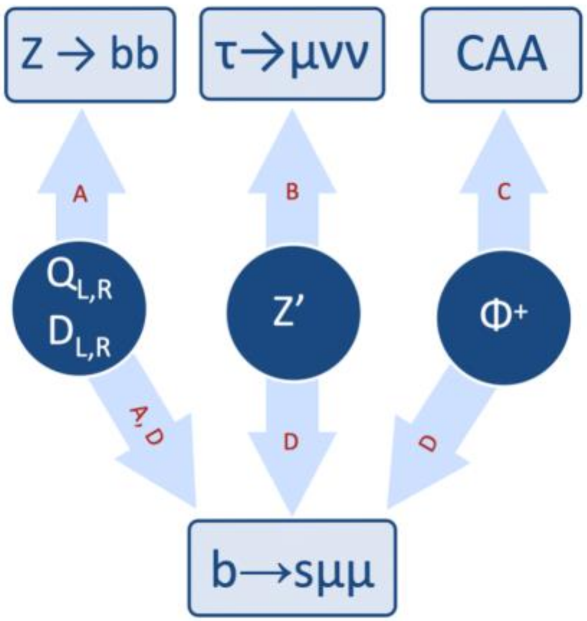
Pati-Salam LQ can explain the flavour anomalies

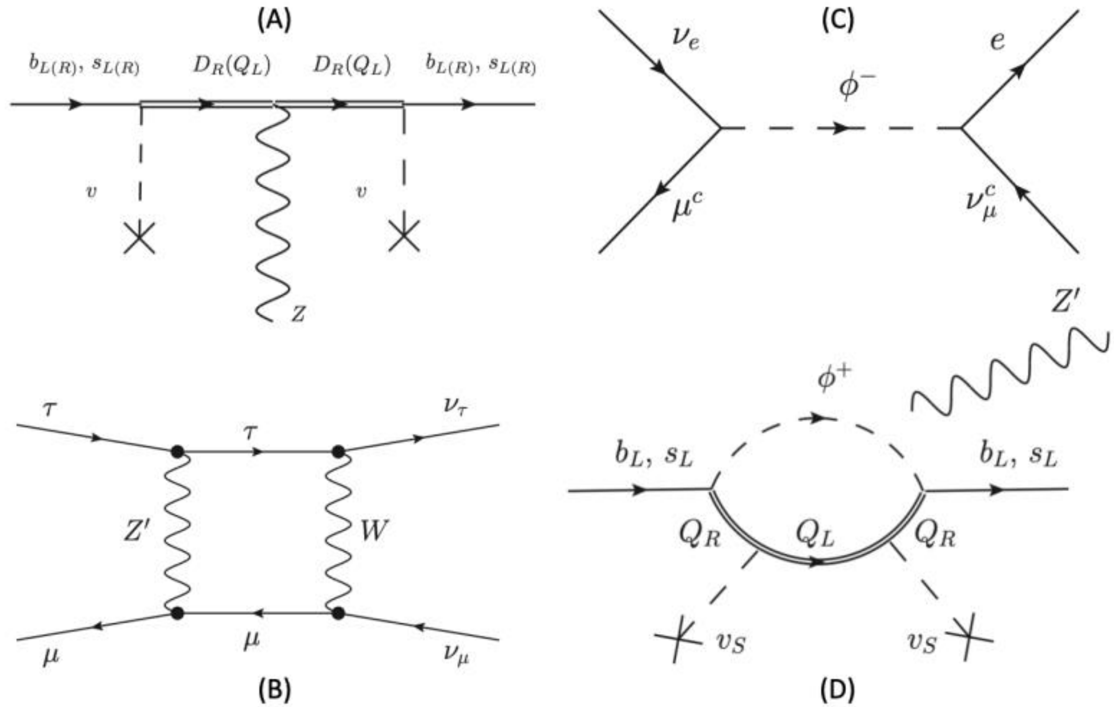
Model for b→sℓℓ, CAA, Z→bb & τ → μνν

- L_μ-L_τ model with vector-like quarks

	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

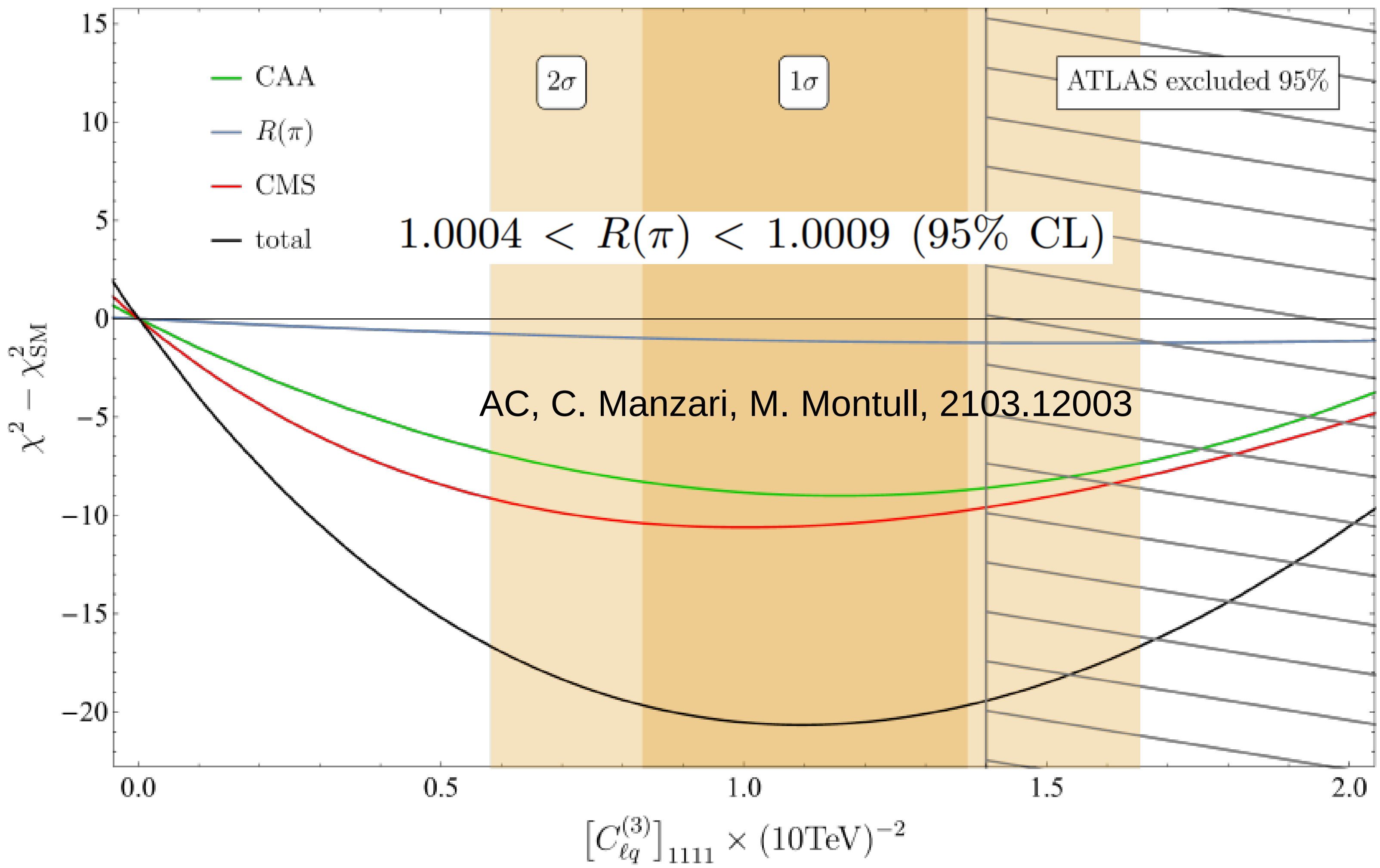
AC, C.A. Manzari et al.
PRL 127 2021





Simple model provides combined explanation

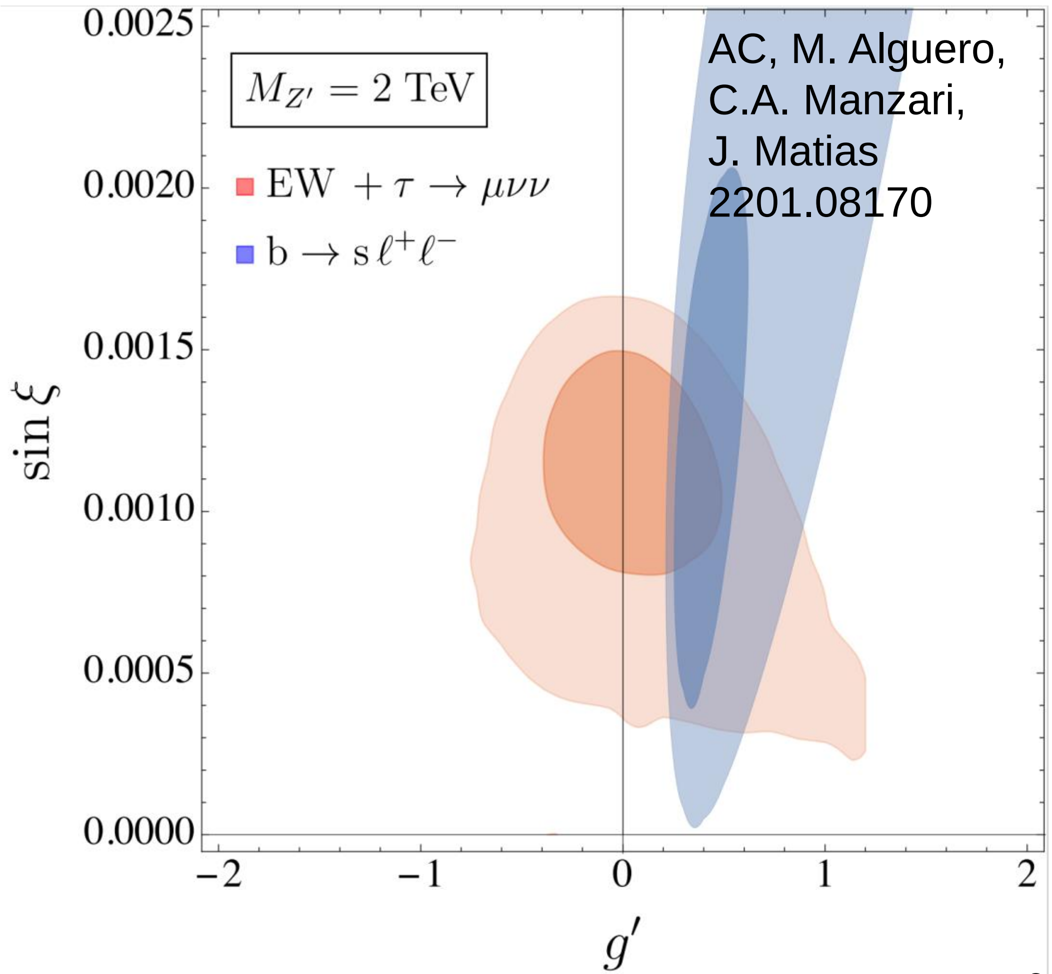
CAA and Non-Resonant Di-Leptons



4.5σ better than SM, prediction for R(π)

b→sℓℓ, W mass and Z' mixing

- Z-Z' mixing can leads to a shift in the predictions of the W mass and can explain the tension in the EW fit ⇨ LFU effect in b→sℓℓ



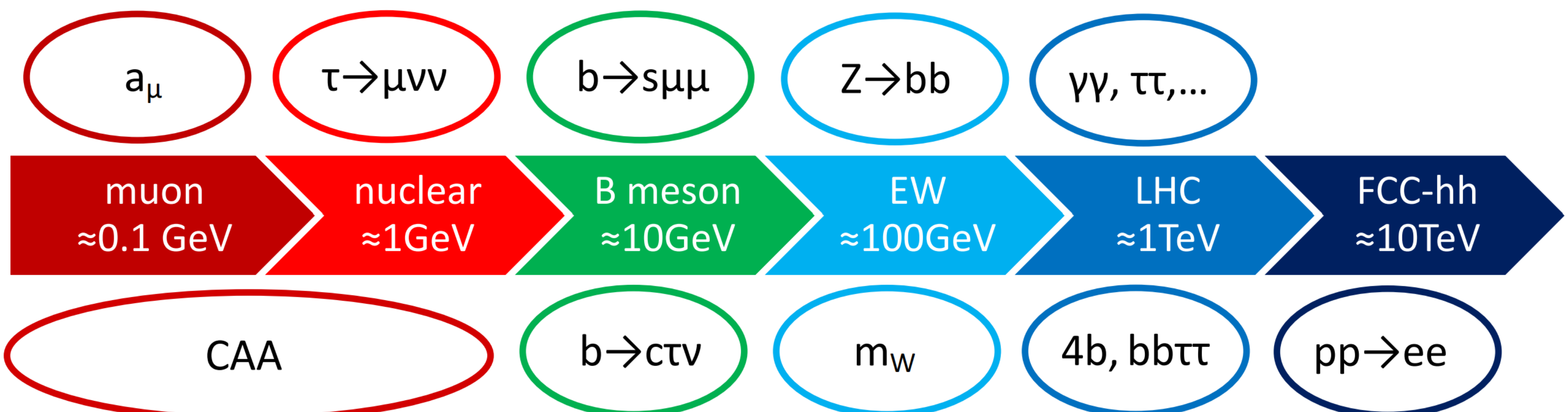
Interesting correlations between b→sℓℓ and the EW fit

8

Conclusions

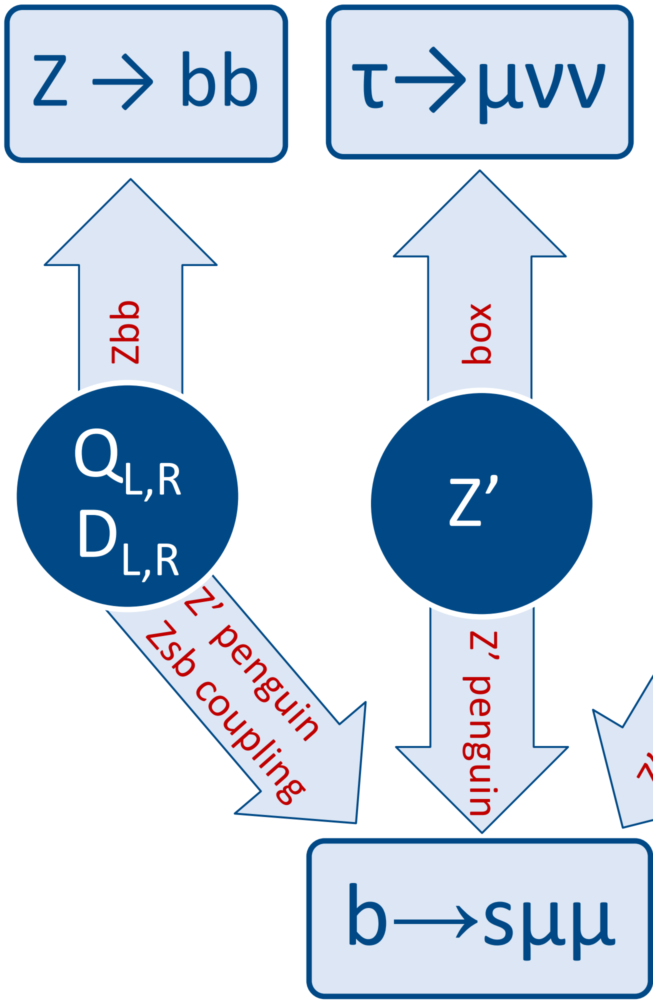
- Many intriguing anomalies emerged in the last years:
  - LFUV
  - EW observables
  - Direct LHC searches

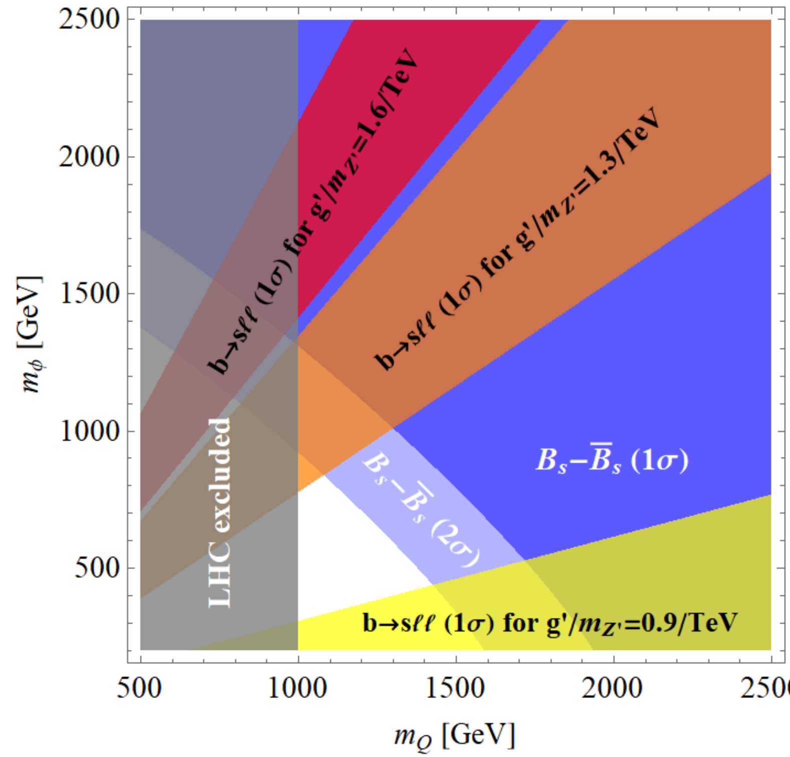
The Standard Model is crumbling



Backup

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

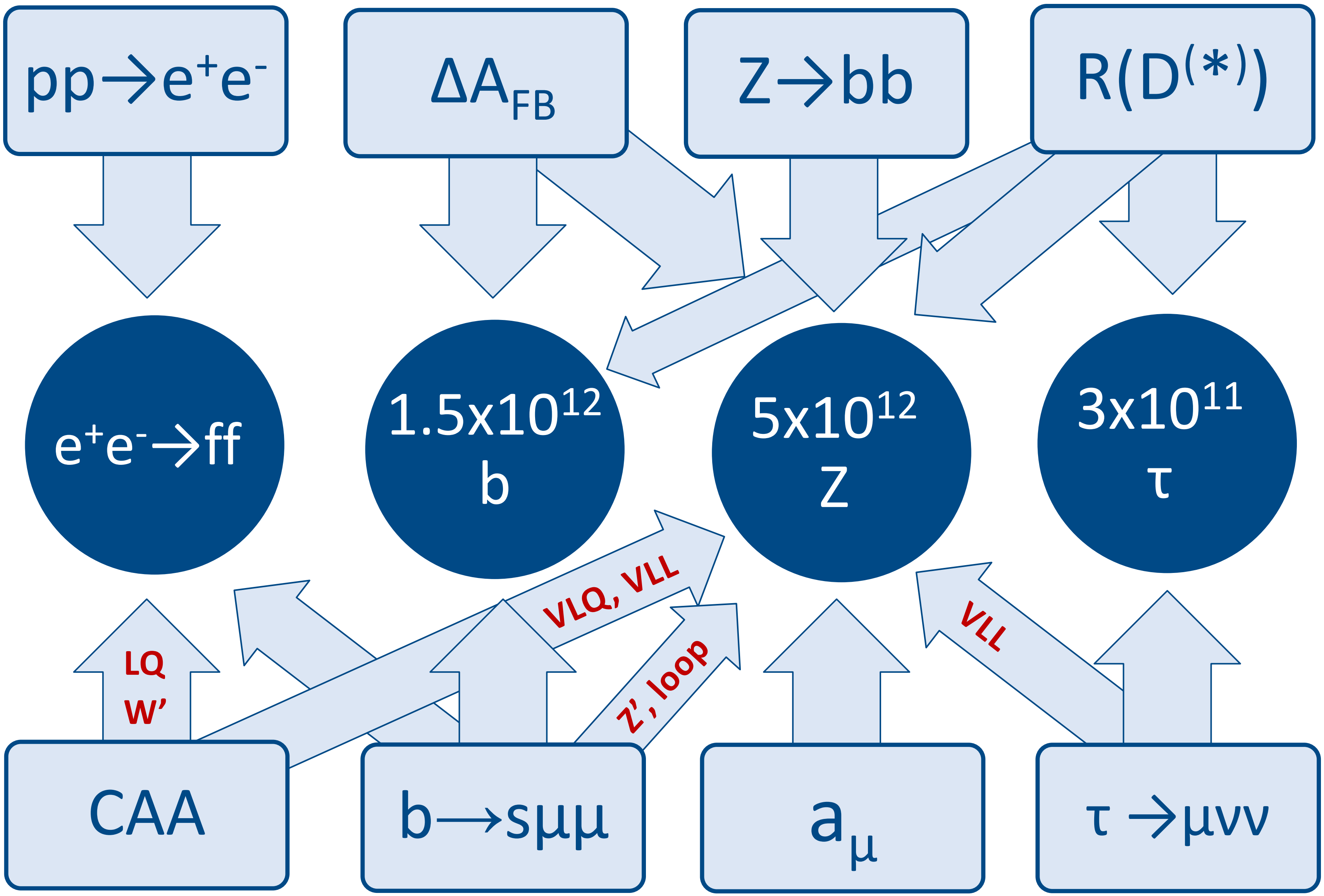




- Z' penguin + modified Zsb coupling give very good fit to b→sll data

Simple model provides combined explanation

Implications for FCC-ee



Outlook: Physics at Future Colliders

- Flavour Anomalies require NP at the TeV scale

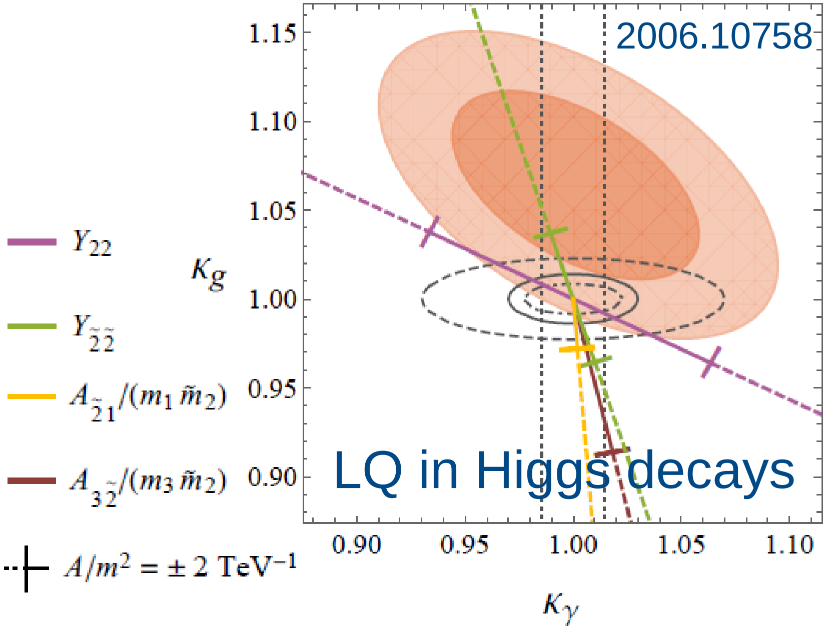
  ⇨ Direct Searches at HL-LHC, HE-LHC, FCC-pp

- This new particles in general also affect EW precision observables

  ⇨ Z decays at CLIC and FCC-ee

- Flavour is directly linked to the Higgs boson

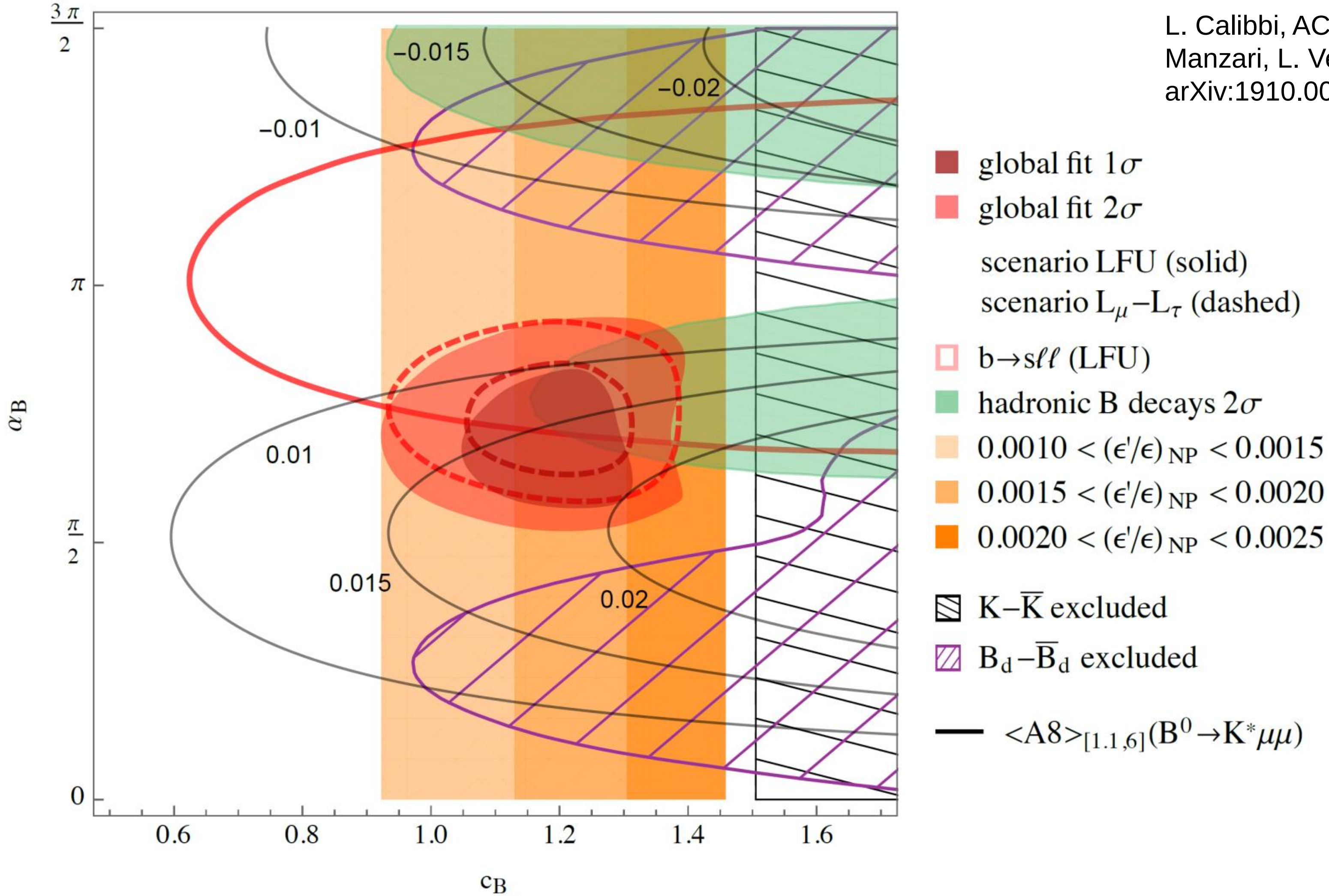
  ⇨ CLIC, FCC



Flavour Anomalies (if confirmed) strengthen the physics case for future colliders significantly

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

$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}, \qquad \eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)}$$

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

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

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

Measurement ≈3σ above the SM prediction

Hadronic B decays

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

- Longstanding B→πK Puzzle

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

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

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

- More observables like

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

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

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

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

CP and isospin violation needed

Similar picture in D decays

Global fit to data: 2-3σ

ε‘/ ε explanations

- W_R coupling

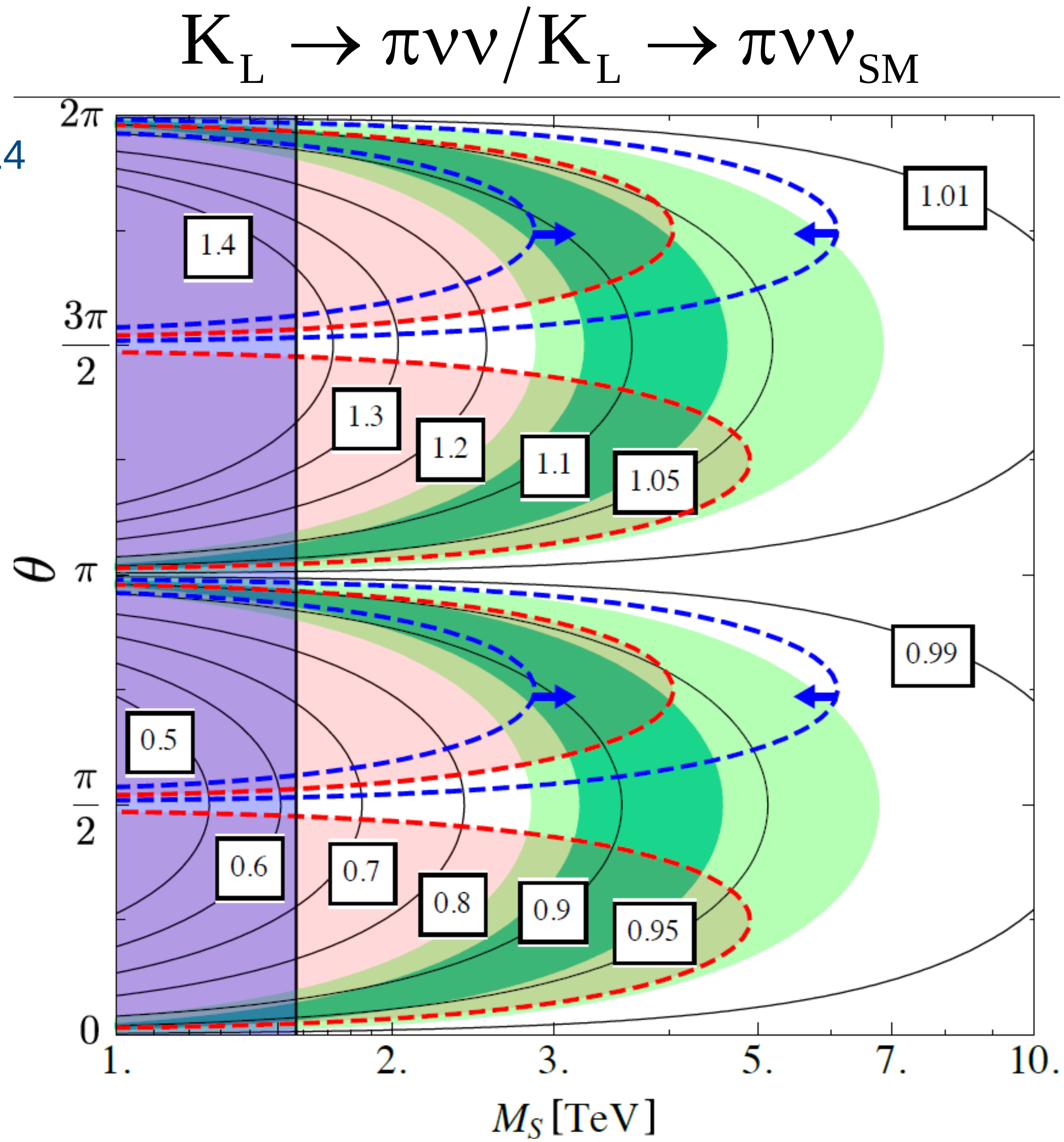
V. Cirigliano, et al. arXiv:1612.03914

- Z' (also for ΔA_{CP})

A. Buras, et al. arXiv:1507.08672
A. Buras and F. De Fazio, arXiv:1512.02869

- MSSM

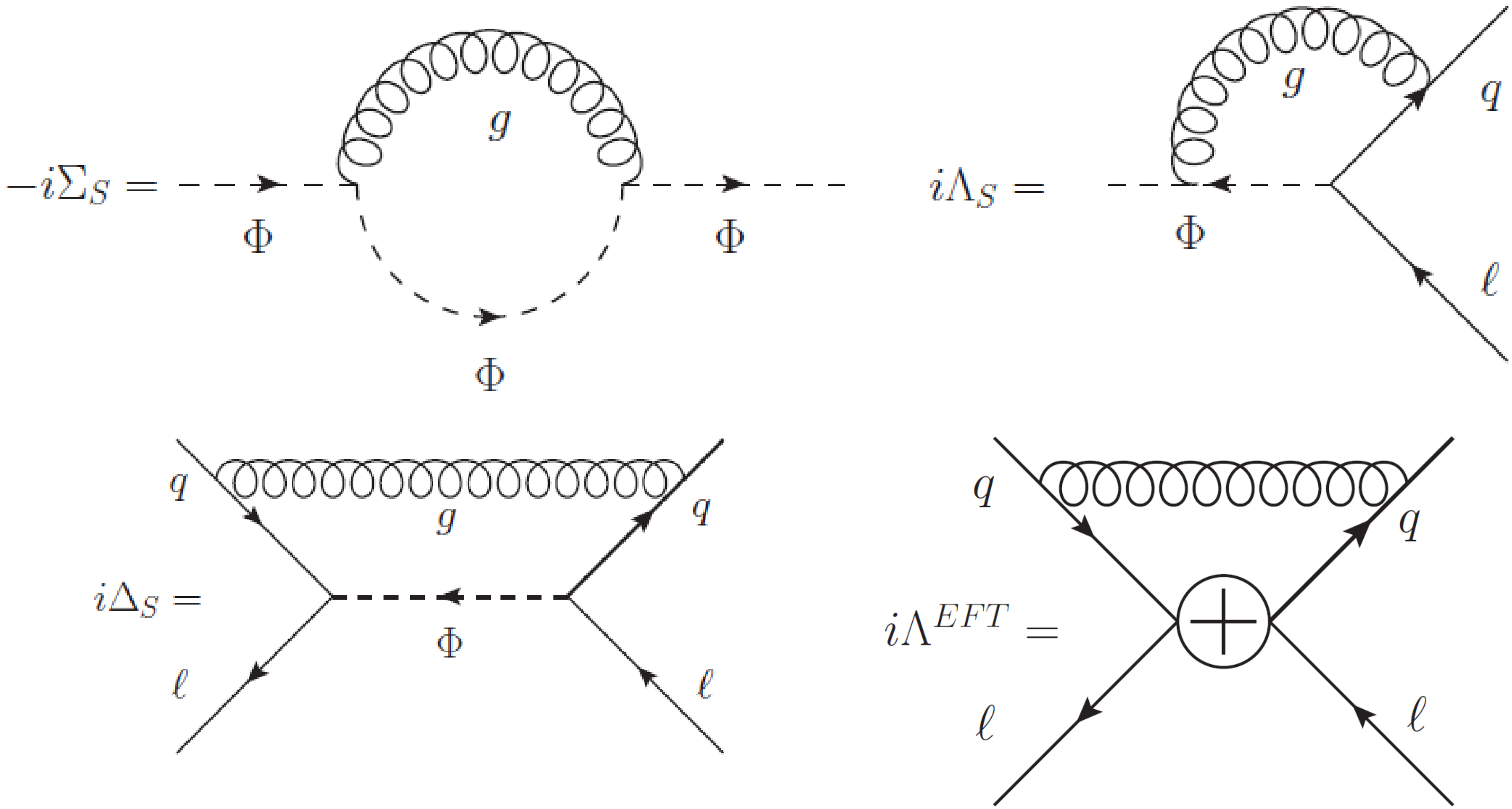
T. Kitahara, U. Nierste, P. Tremper, arXiv:1604.07400
M. Endo, et al. arXiv:1608.01444
A. Crivellin, G. D'Ambrosio, T. Kitahara and U. Nierste, arXiv:1703.05786



LHC excluded

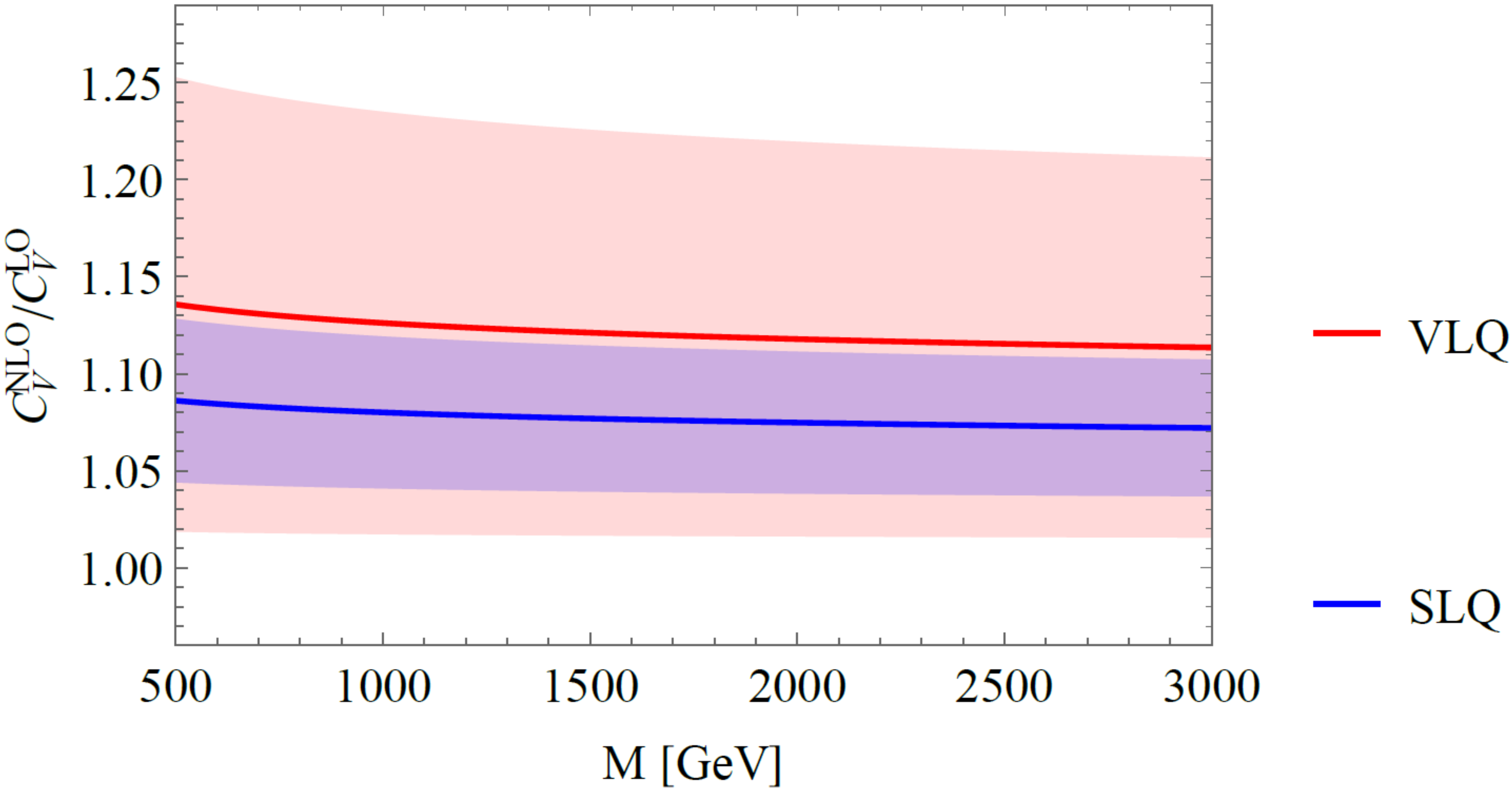
ε′ / ε

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

Correlations the neutron EDM with S1

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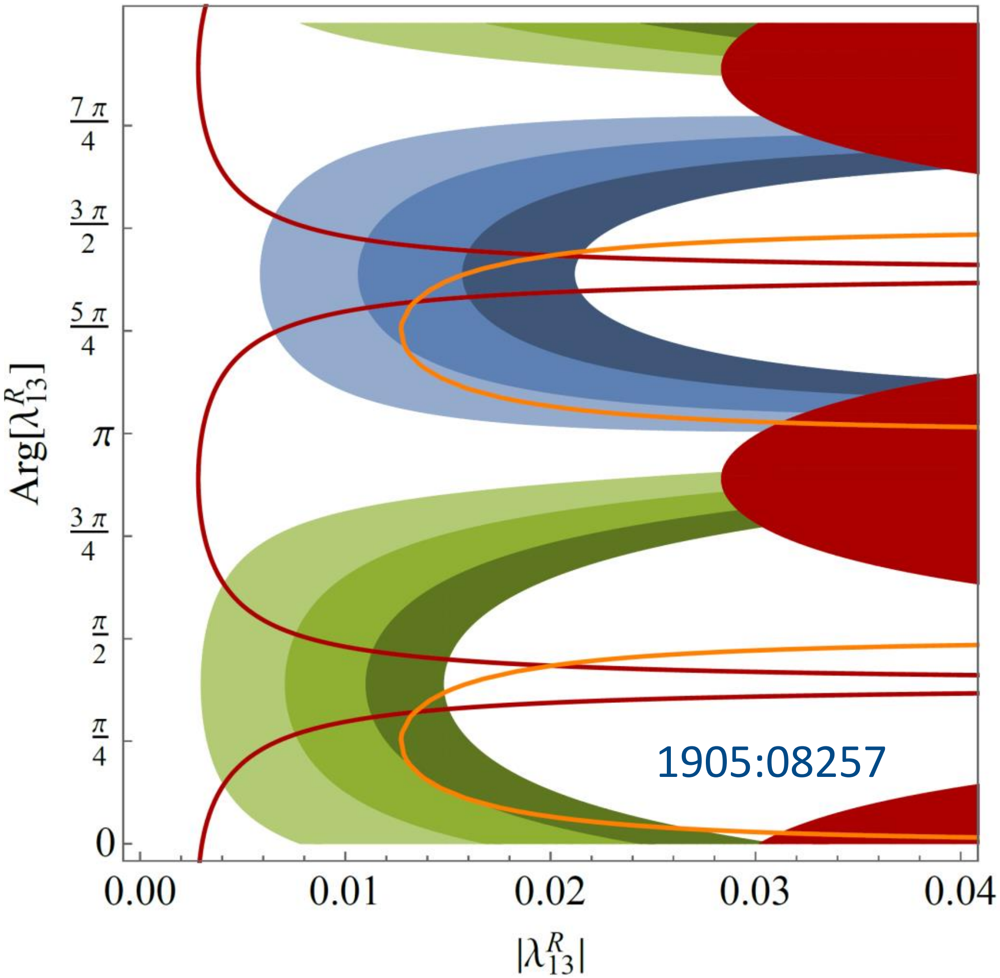

W. Dekens, J. de Vries, M. Jung, K. K. Vos, arXiv:1809.09114
AC, F. Saturnino arxiv:1905:08257

- $0.6 < Br[B\to\tau\nu]/Br[B\to\tau\nu]_{SM} < 0.7$
- $0.7 < Br[B\to\tau\nu]/Br[B\to\tau\nu]_{SM} < 0.8$
- $0.8 < Br[B\to\tau\nu]/Br[B\to\tau\nu]_{SM} < 0.9$
- $1.1 < Br[B\to\tau\nu]/Br[B\to\tau\nu]_{SM} < 1.2$
- $1.2 < Br[B\to\tau\nu]/Br[B\to\tau\nu]_{SM} < 1.3$
- $1.3 < Br[B\to\tau\nu]/Br[B\to\tau\nu]_{SM} < 1.4$
- nEDM excluded

n2EDM sensitivity
$D^0-\bar{D}^0$ HL-LHC

Effect in B predicts measurable nEDM effect

R(D$^{(*)}$), b→sνν with 2 Scalar LQs

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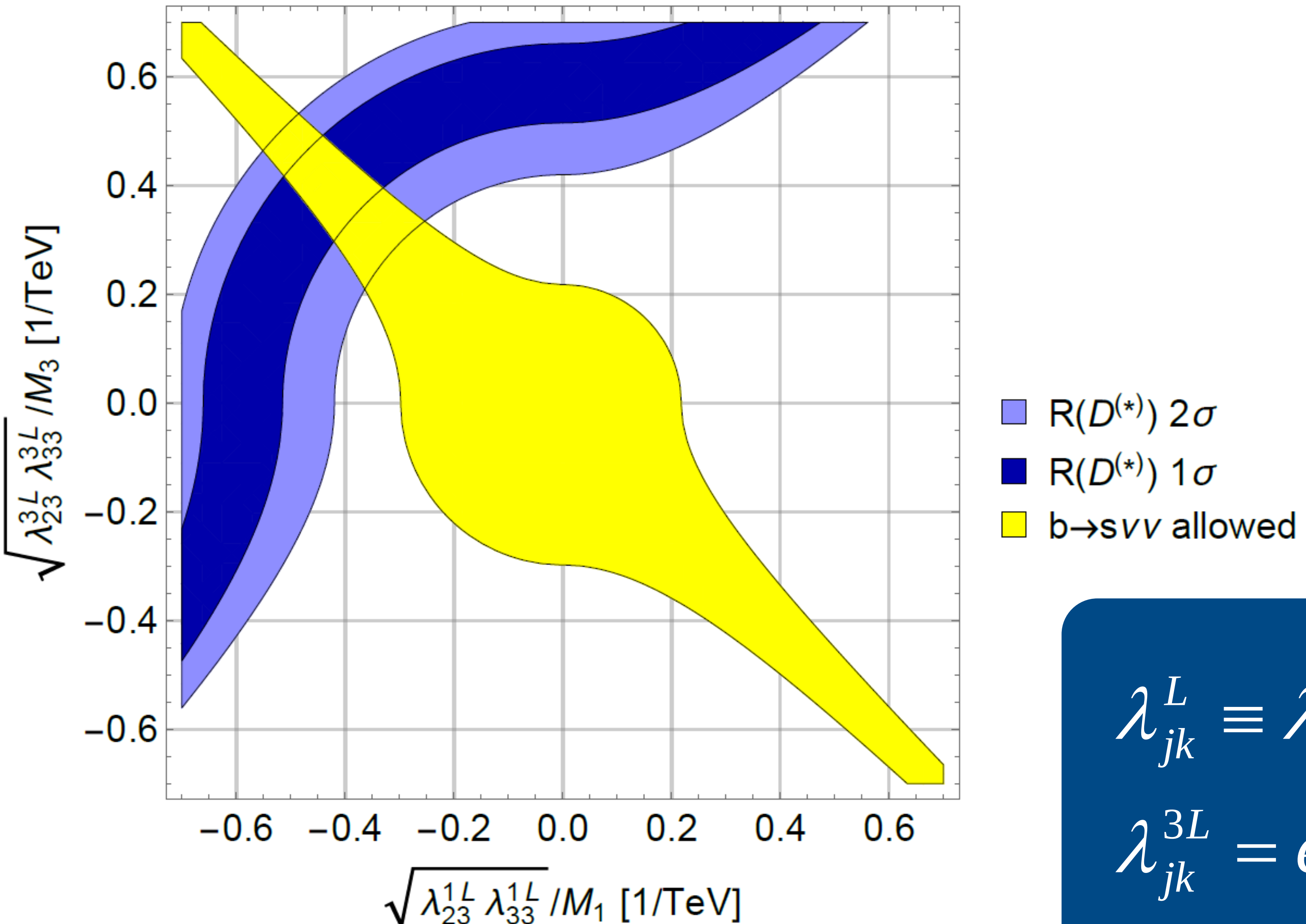
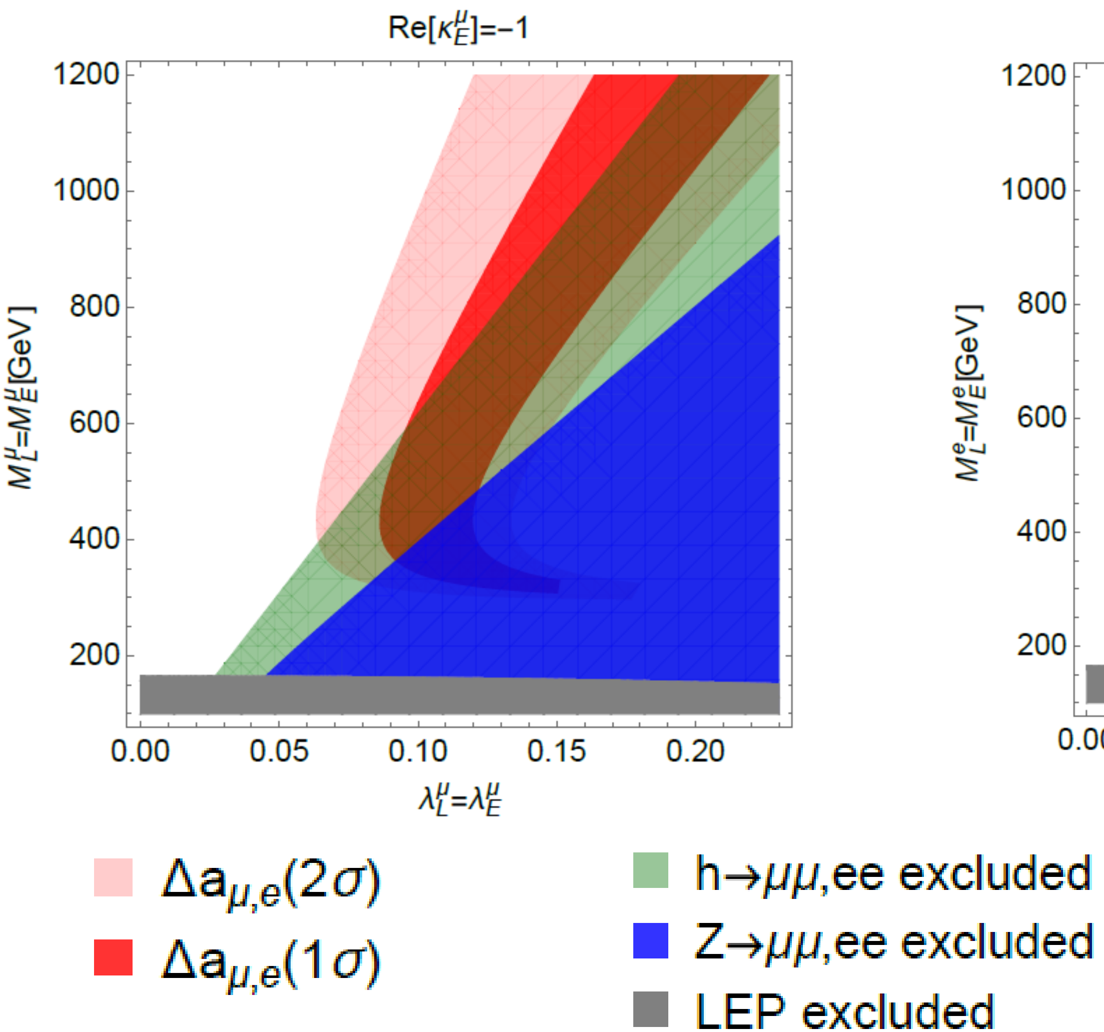


$$\lambda_{jk}^{L} \equiv \lambda_{jk}^{1L}$$

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

Model with new vector-like leptons

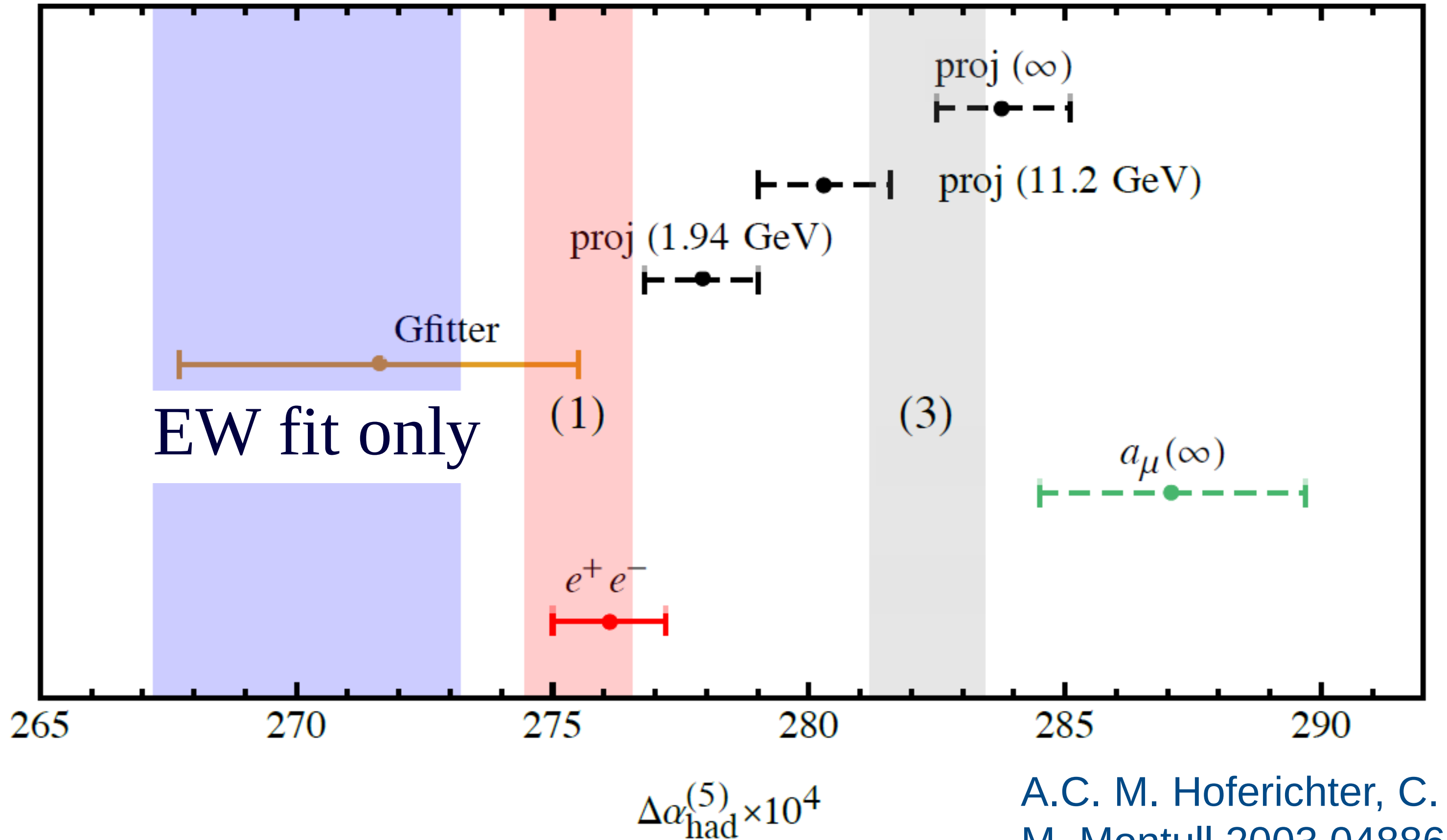


AC, M. Hoferichter, P. Schmidt-Wellenburg, arXiv:1807.11484

Works for a_e but tension with a_μ

Hadronic Vacuum Polarization

- New BMWc lattice QCD result

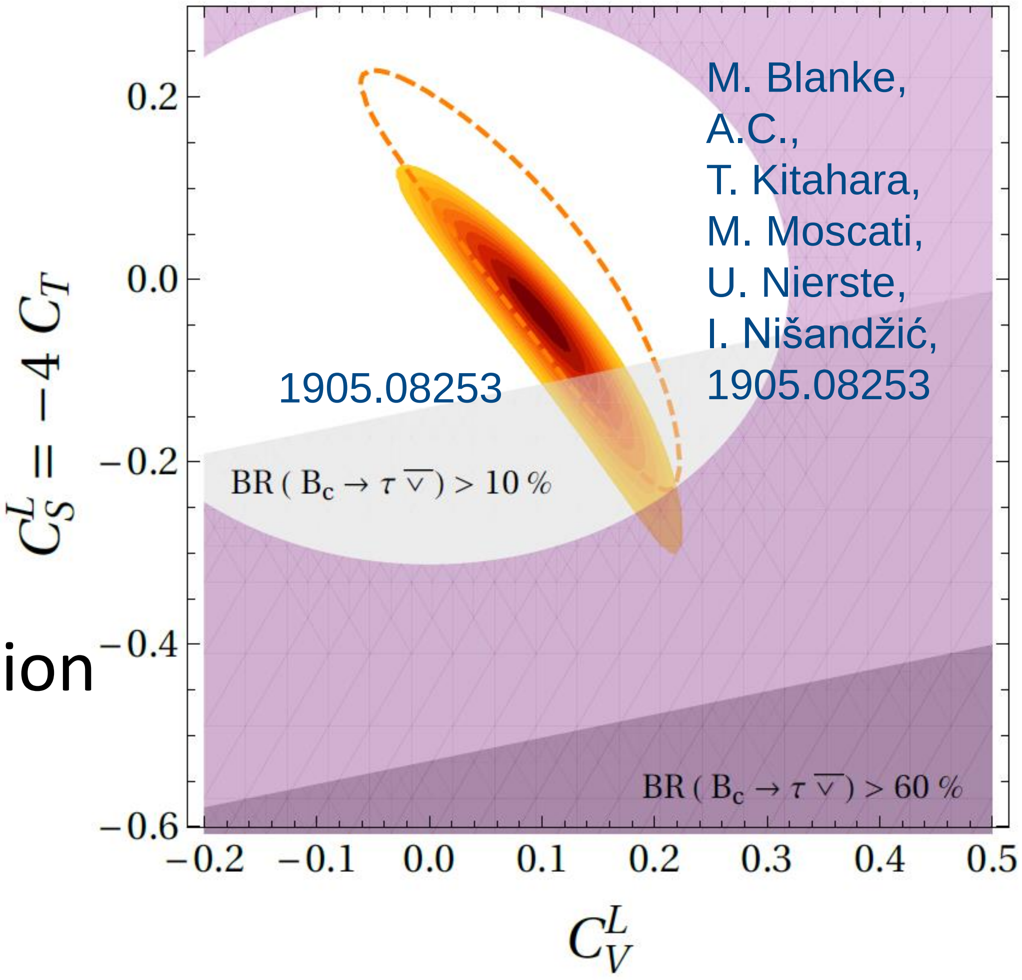


A.C. M. Hoferichter, C. Manzari, M. Montull 2003.04886

Up to 4σ tension in EW fit

$b \to c\tau\nu$ 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



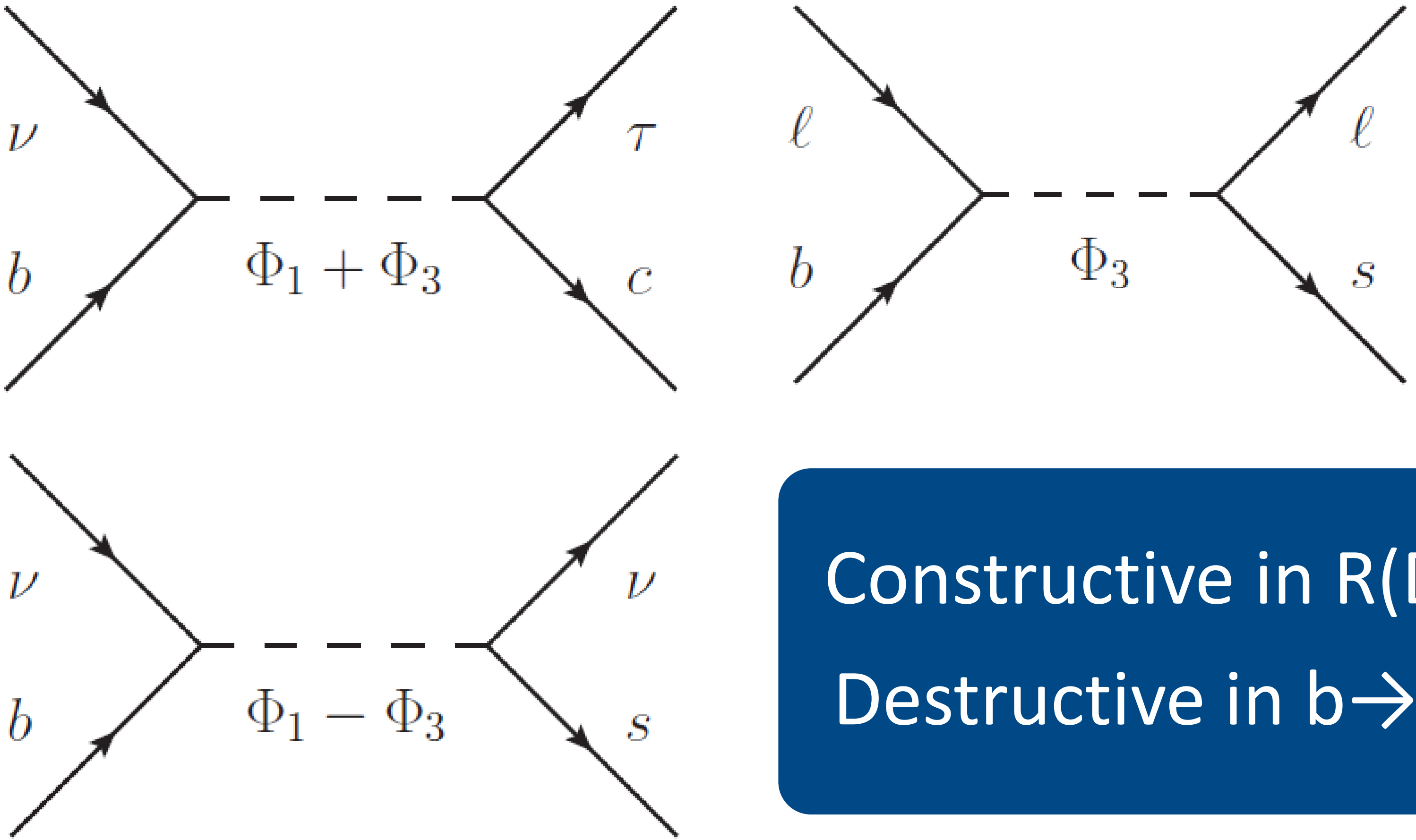
Global fit give up to 4σ preference for NP

Scalar Leptoquarks

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→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

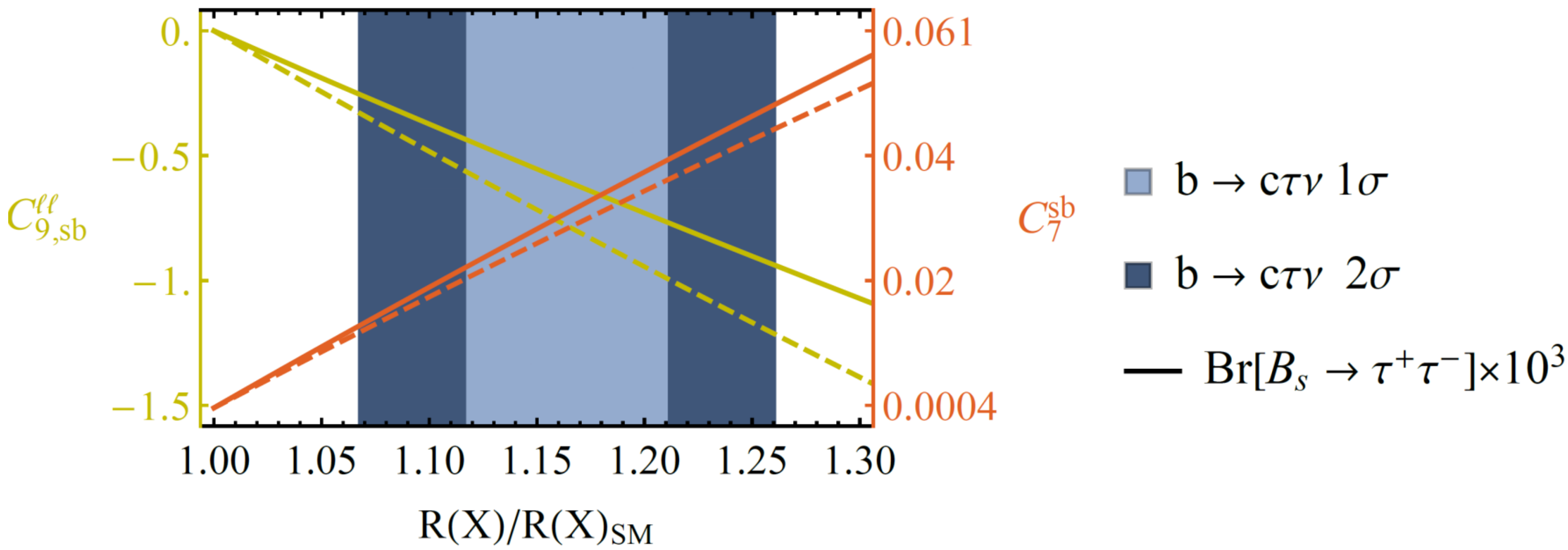
	$C_9^{\mu\mu}=-C_{10}^{\mu\mu}$	$C_9^{\ell\ell}$	$\frac{R(D)}{R(D)_{\rm SM}}$	$\frac{R(D^*)}{R(D^*)_{\rm SM}}$	$\frac{B_s\to\tau\tau}{B_s\to\tau\tau\vert_{\rm SM}}$	$\tau\to\mu\gamma$ $\times 10^8$	δa_μ $\times 10^{11}$	$\tilde{V}_{cb}^e/\tilde{V}_{cb}^\mu-1$ $\times 10^6$	$Z\to\tau\mu$ $\times 10^{10}$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

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

Important Loop-Effects

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

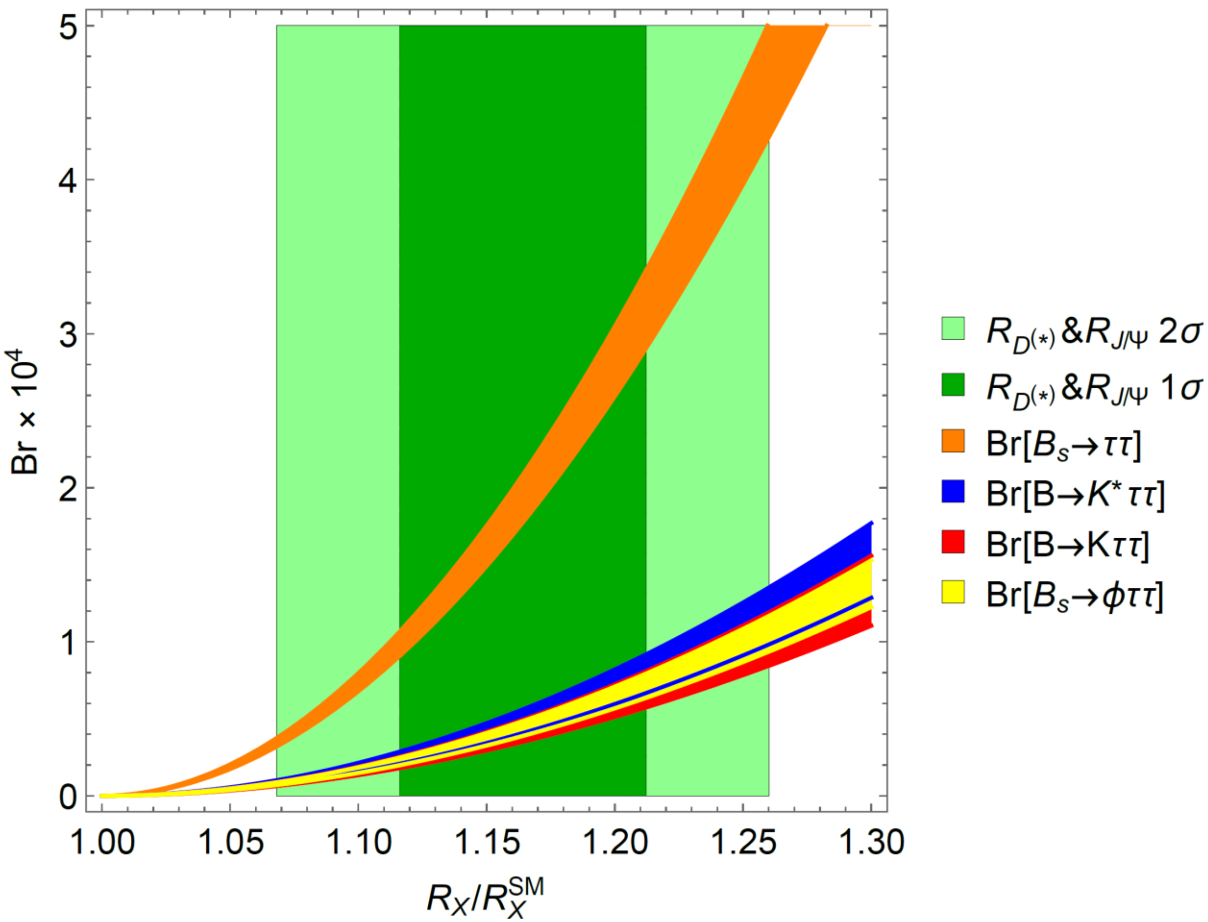


AC, C. Greub, D. Müller, F. Saturnino, PRL 2018

Large loop effects in b→sμμ

R(D$^{(*)}$) and b→sττ

- Large couplings to the second generation



b→sττ very strongly enhanced

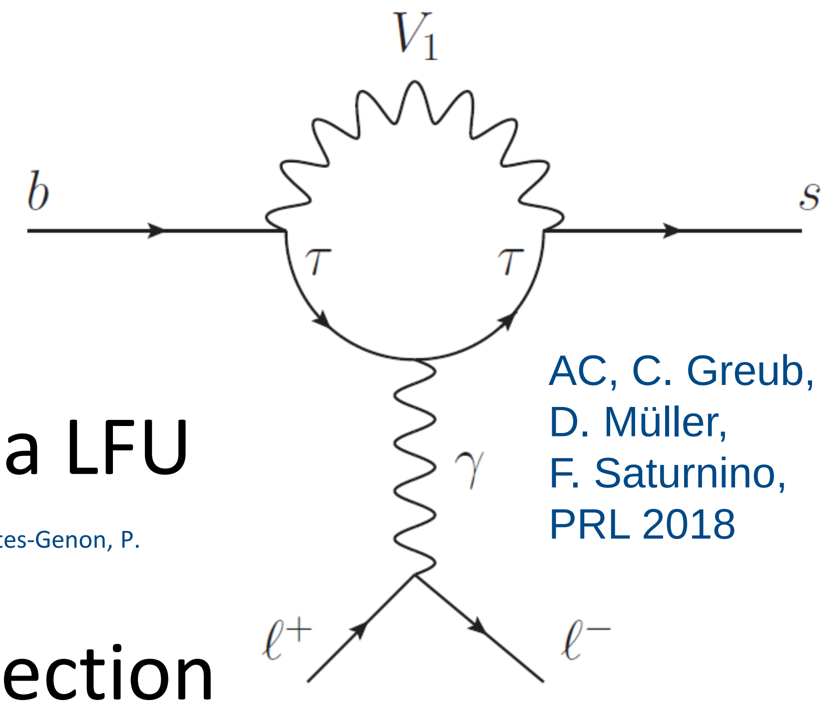
B. Capdevila, AC, S. Descotes-Genon, L. Hofer and J. Matias, PRL.120.181802

Important Loop-Effects

- Explanation of b→cτν requires large LQ-bτ and LQ-c-ν_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

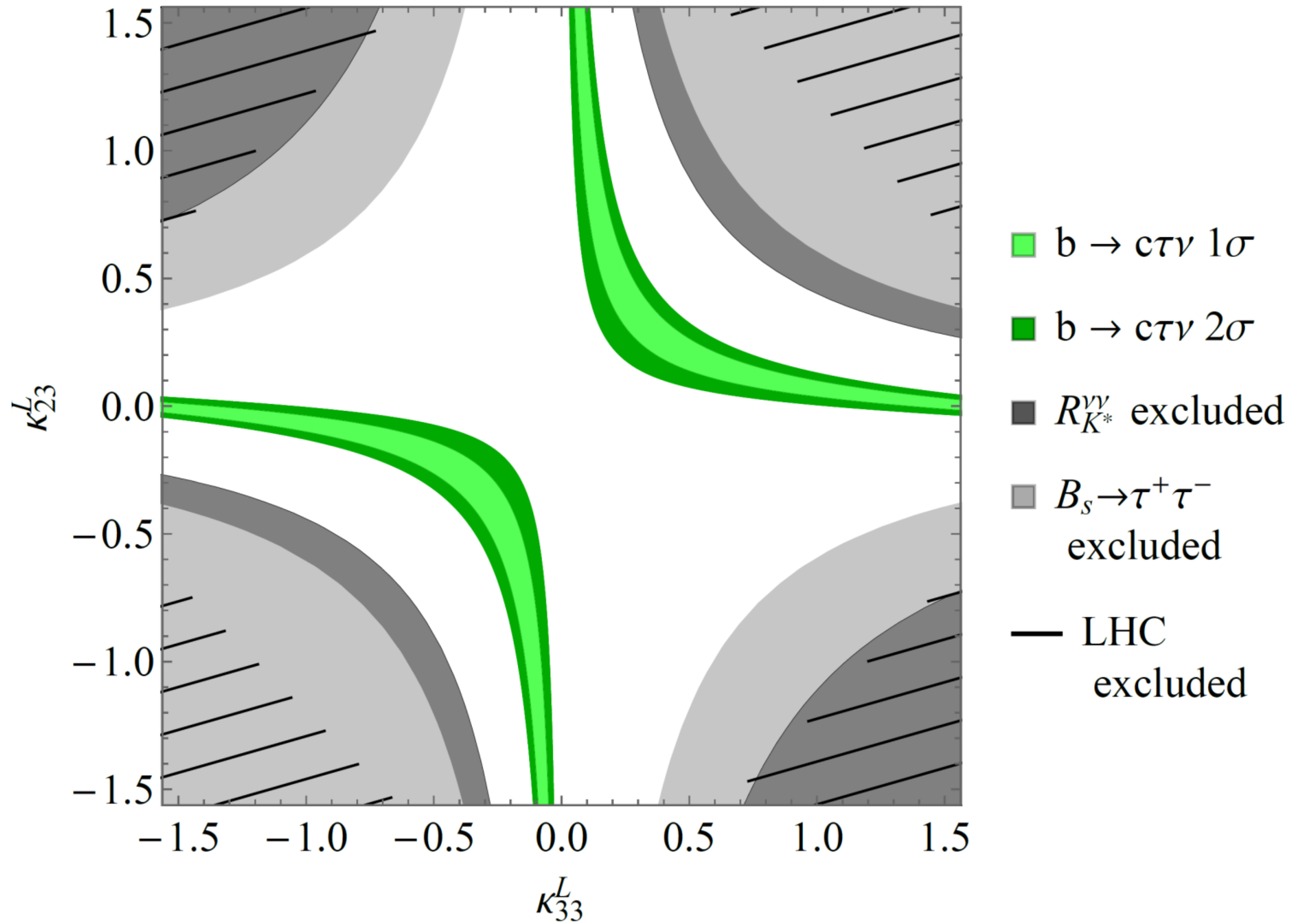
- Effect goes in the right direction



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

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

Vector LQ Phenomenology



Compatible with constraints for generic couplings

Possible UV completions

- $SU(4)\times SU(3)'\times SU(2)_L\times U(1)_Y$ + 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
- $SU(4)\times SU(2)_L\times SU(2)_R$ including scalar LQs and light right-handed neutrinos

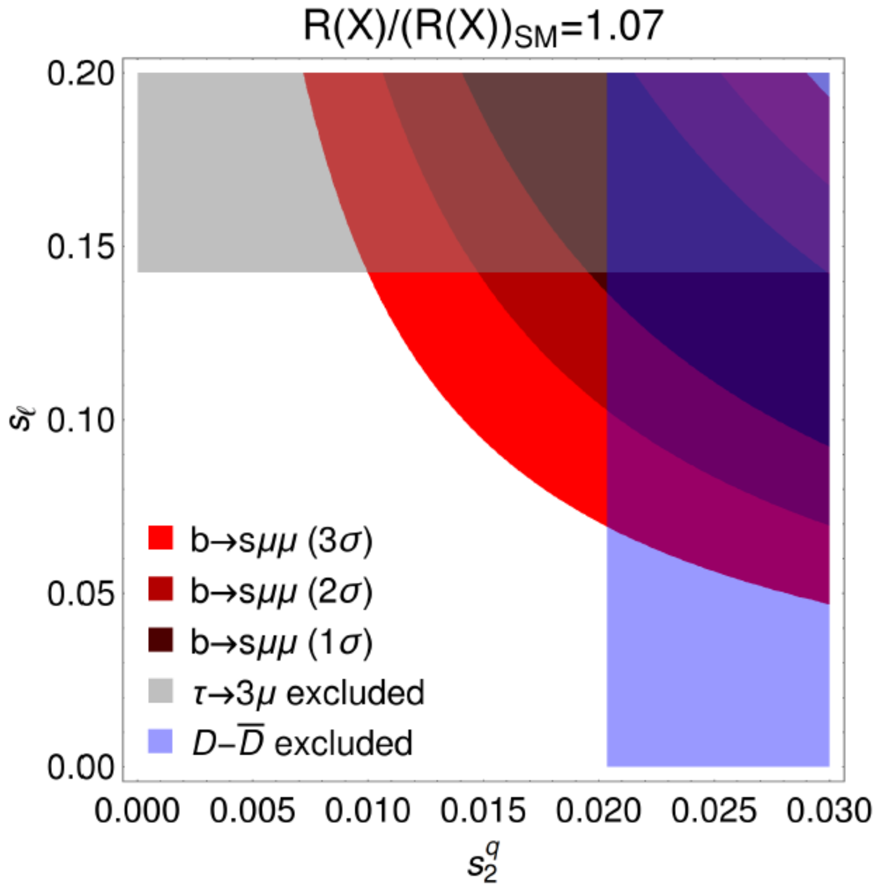
  J. Heeck, D. Teresi, arXiv:1808.07492
- SU(8) might even explain ε'/ε

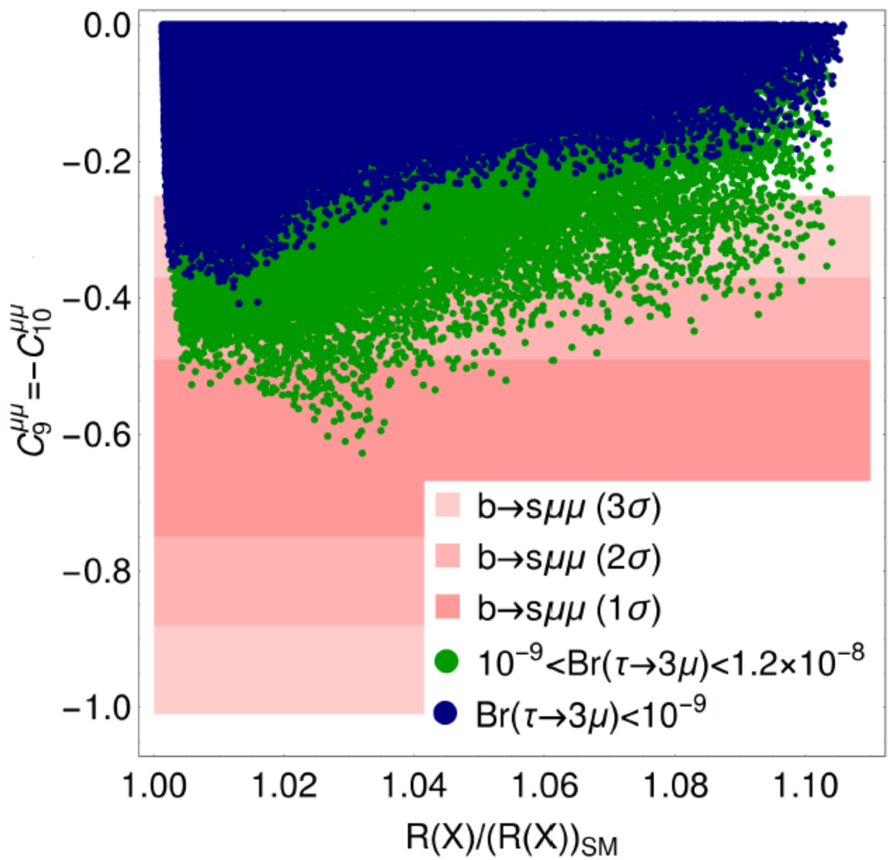
  S. Matsuzaki, K. Nishiwaki and K. Yamamoto, arXiv:1806.02312
- $SU(4)\times SU(2)_L\times SU(2)_R$ in RS background

  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

Model well motivated + limited but sizable effect

$\tau \to \mu\nu\nu$

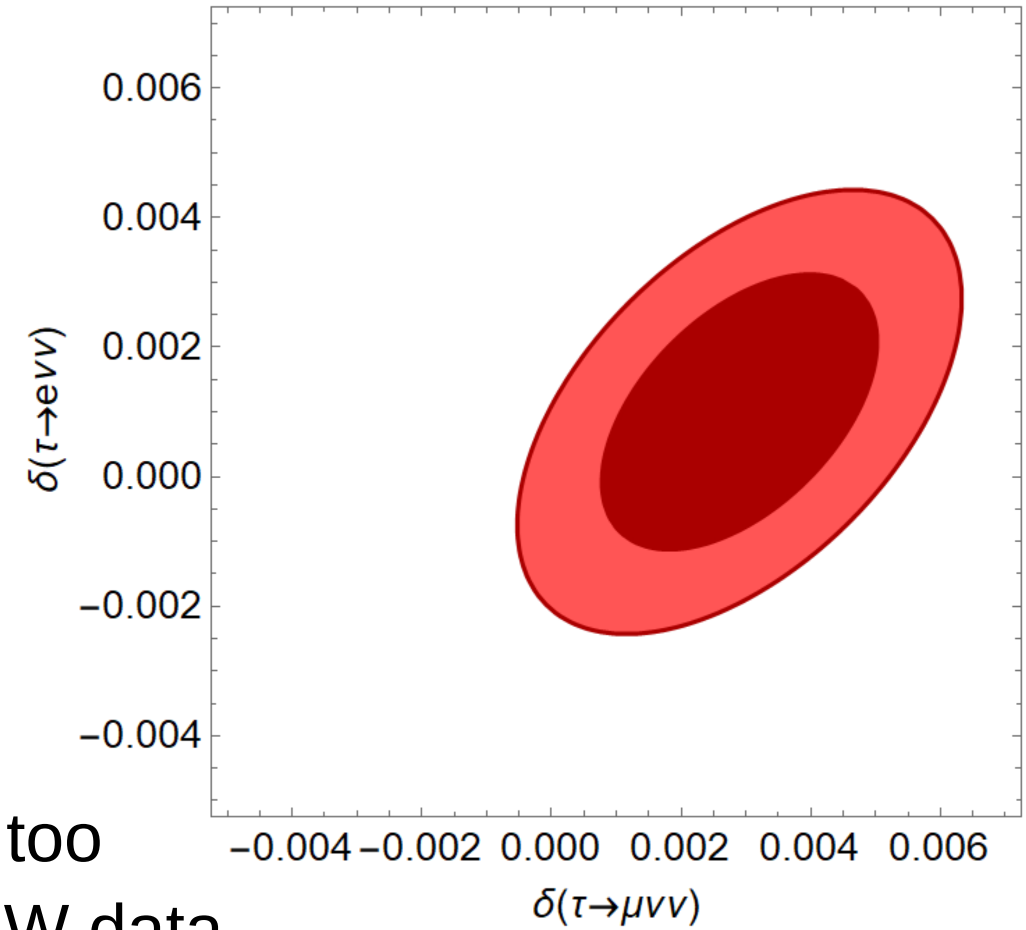
- Ratios of leptonic tau decays

$$\frac{A_{EXP}(\tau \to \mu\nu\bar{\nu})}{A_{SM}(\mu \to e\nu\bar{\nu})} = 1.0029 \pm 0.0014$$

$$\frac{A_{EXP}(\tau \to \mu\nu\bar{\nu})}{A_{SM}(\tau \to e\nu\bar{\nu})} = 1.0018 \pm 0.0014$$

$$\frac{A_{EXP}(\tau \to e\nu\bar{\nu})}{A_{SM}(\mu \to e\nu\bar{\nu})} = 1.0010 \pm 0.0014$$

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

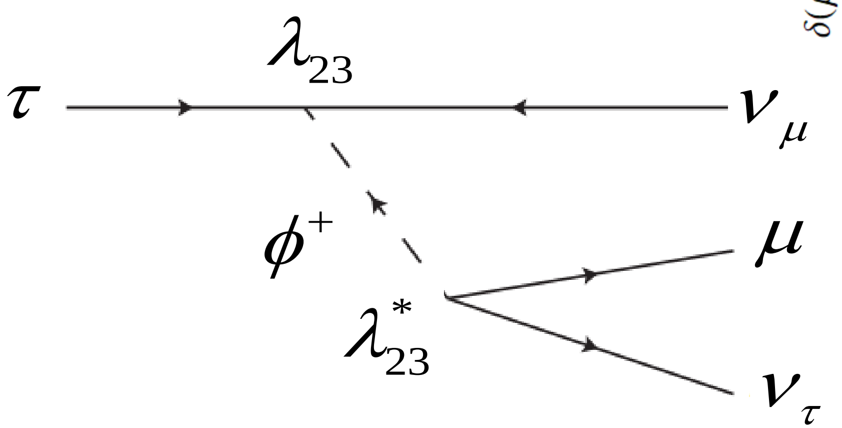


- NP in muon decay too constrained from EW data

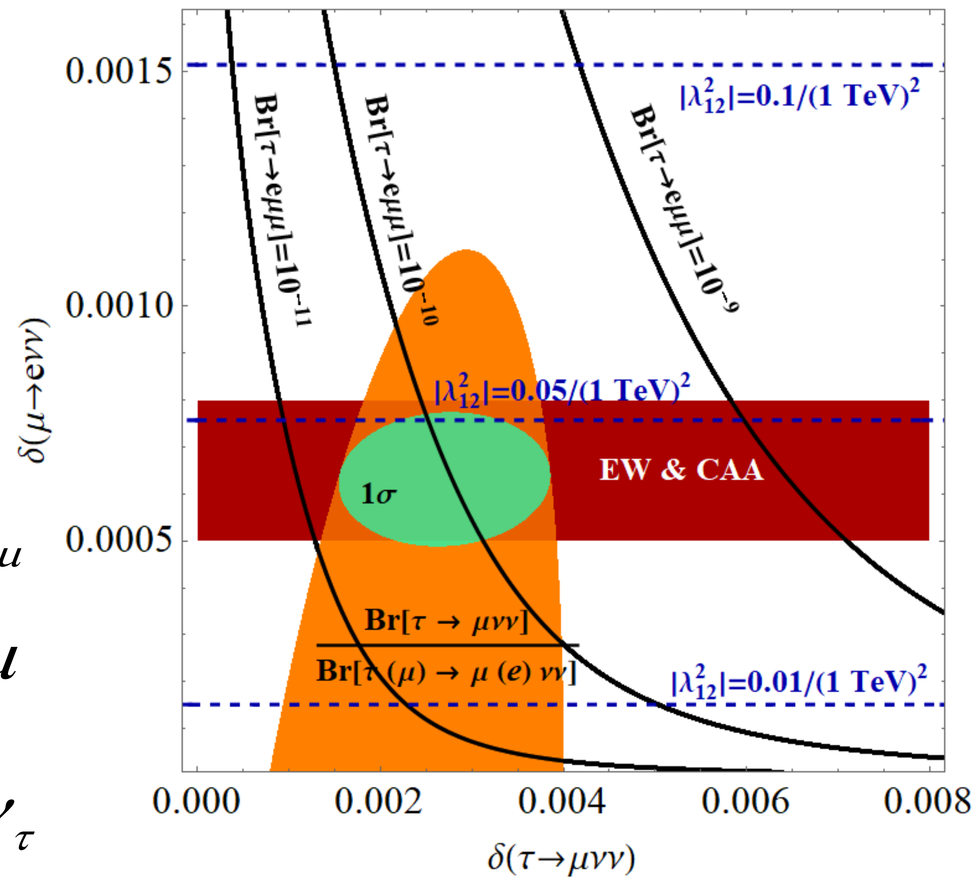
≈2σ hint for LFUV in tau decays

$\tau \to \mu\nu\nu$

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



Singly charged scalar

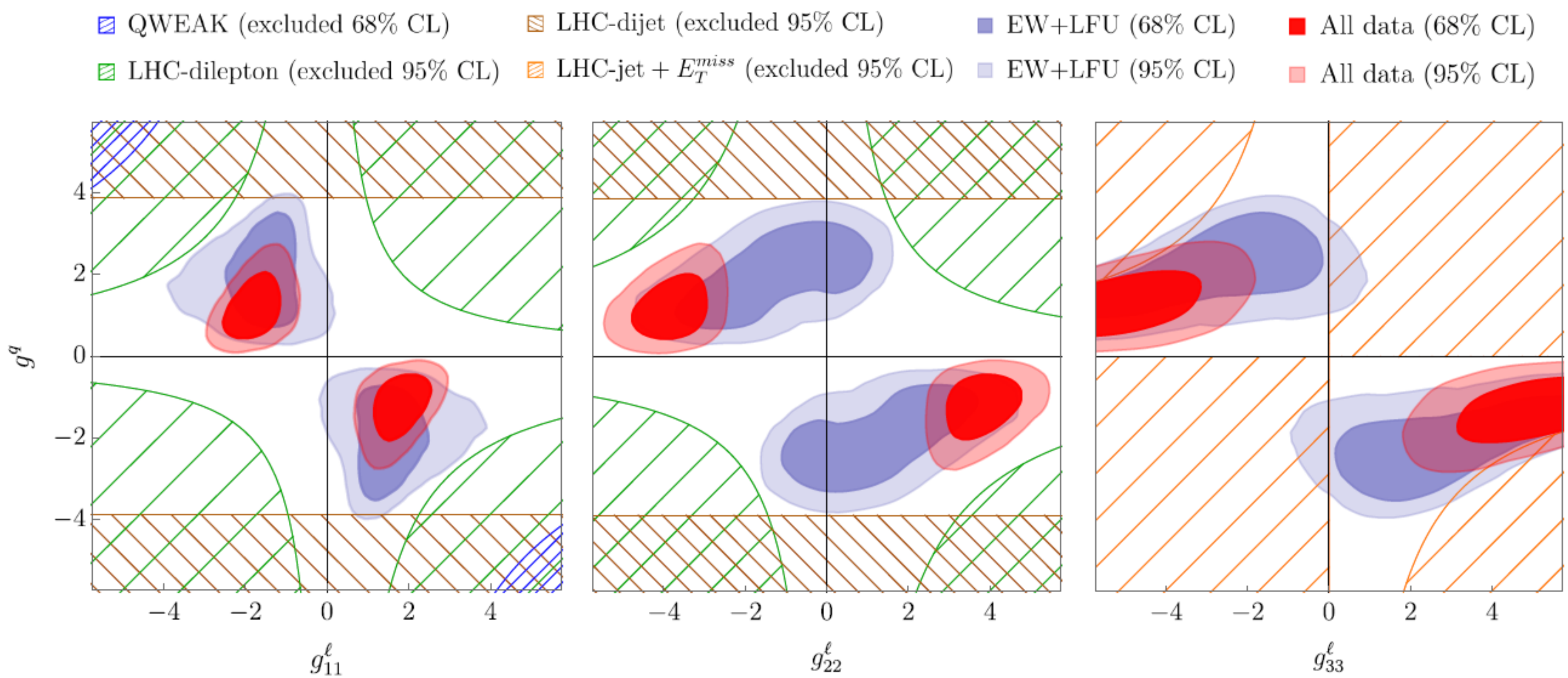


A.C., F. Kirk, C. Manzari, L. Panizzi, arXiv:2012.09845

4σ hint for modified neutrino couplings

W' Explanation of CAA

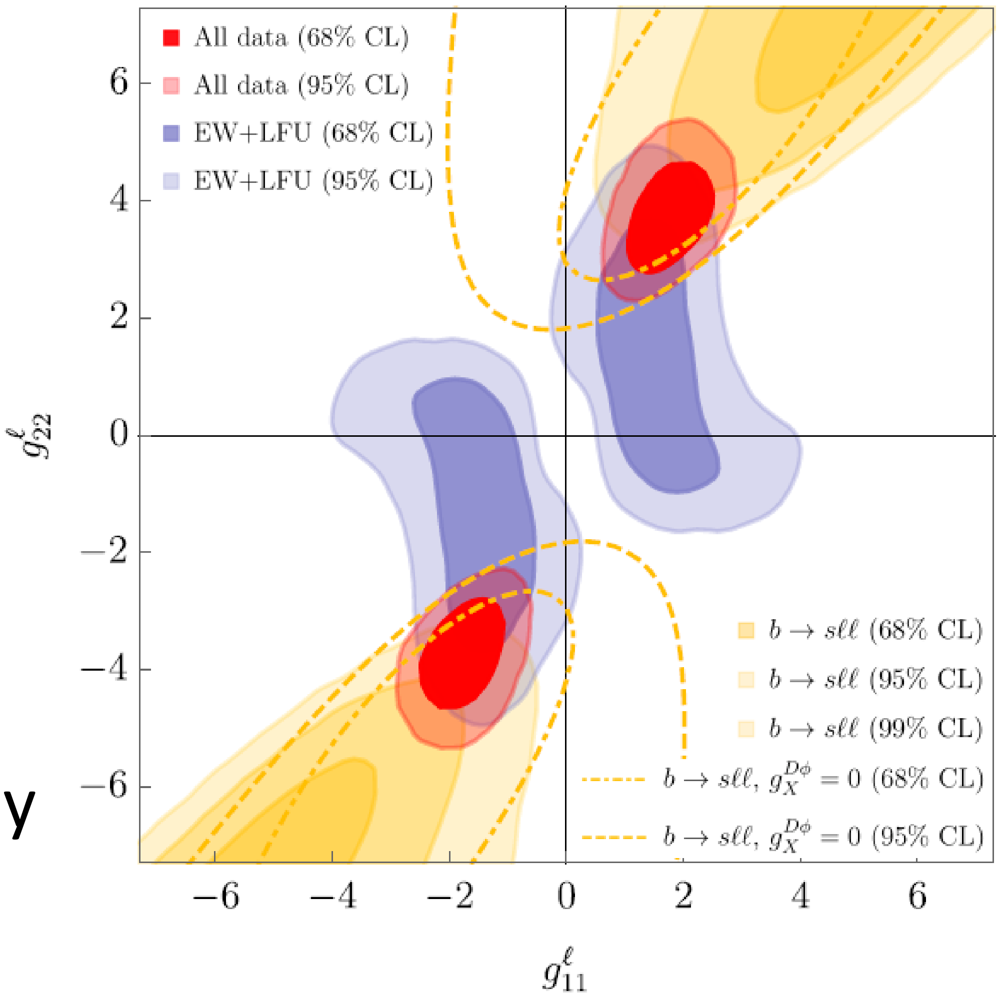
- W' effects in LFU and EW observables
- Z' effects in LHC di-jet and di-lepton tail searches



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

Vector Triplet in $R(V_{us})$ & b→sll

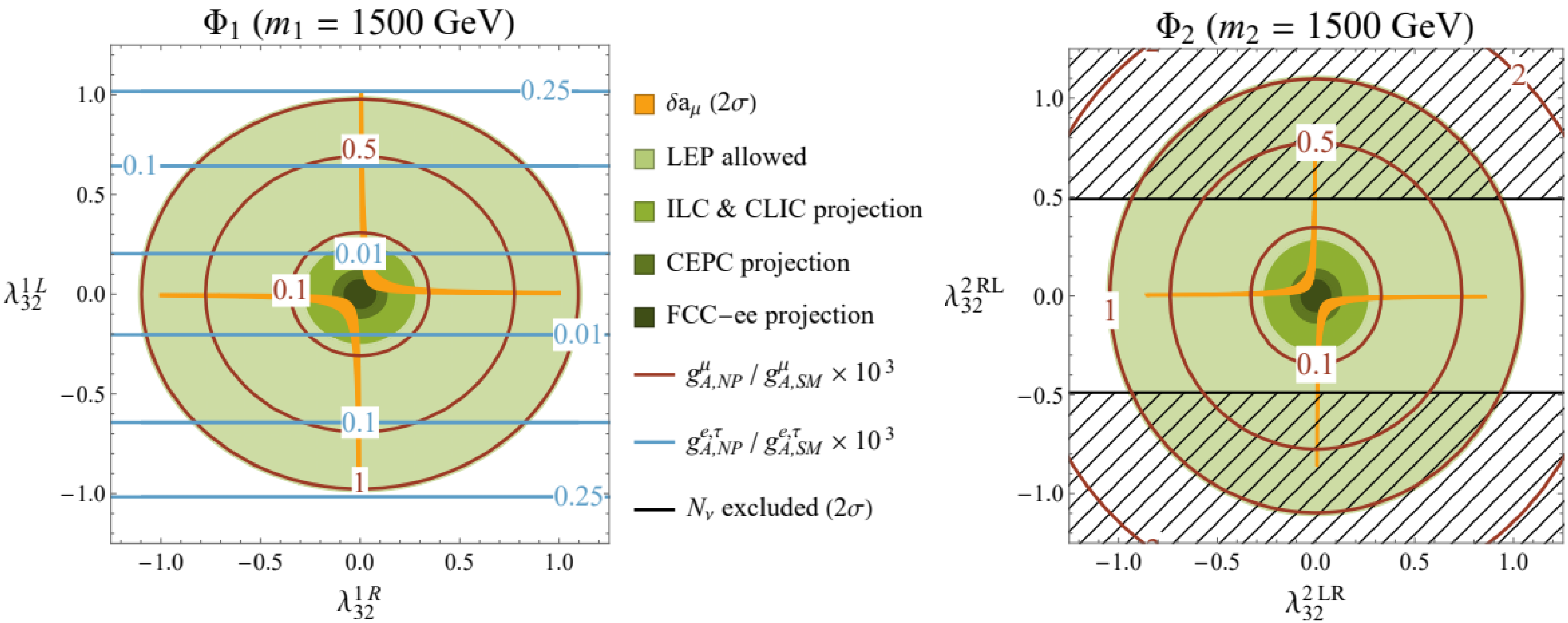
- Region preferred by EW fit overlaps with b→sll region
- Correlations between e.g. π→μν/π→eν and $R(K^{(*)})$ are predicted
- Global fit significantly improved



Common explanation possible

a_μ vs Z→μμ

- Chirally enhanced effects via top-loops



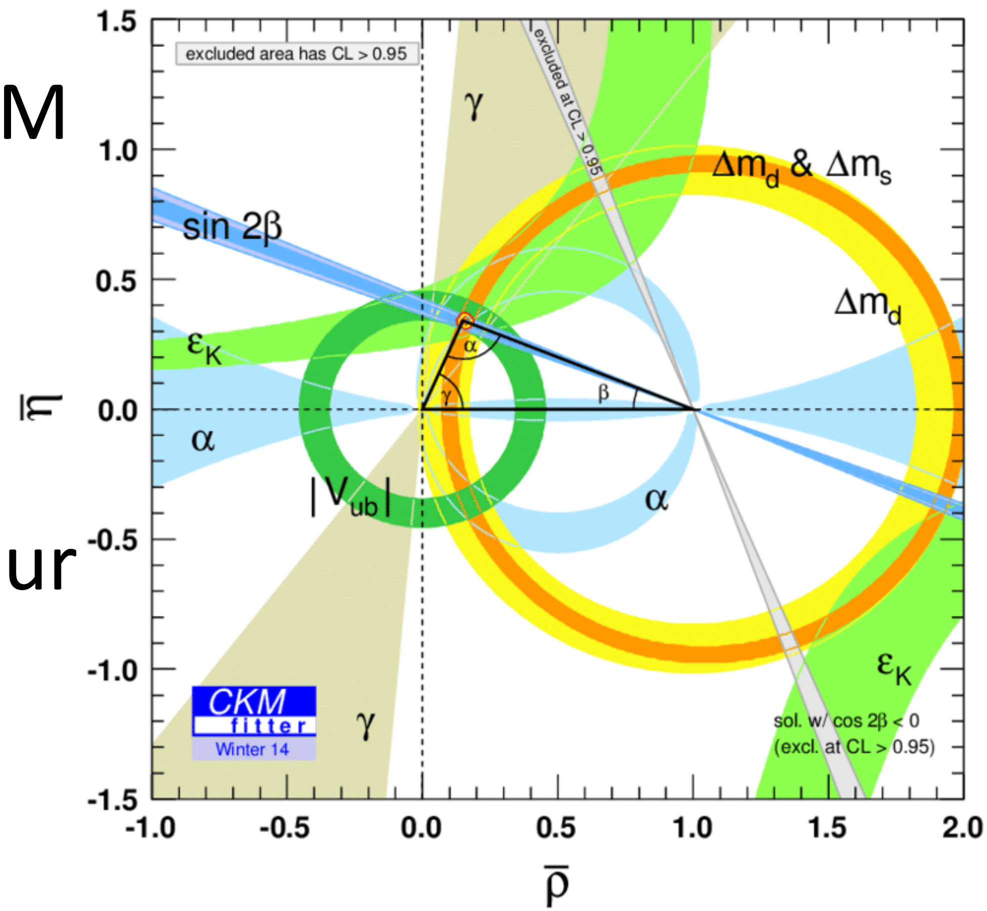
$\lambda_\mu^{L,R}$ Left-, right-handed muon-top coupling

E. Leskow, A.C., G. D'Ambrosio, D. Müller 1612.06858
A.C, C. Greub, D. Müller, F.Saturnino, 2010.06593

Z→μμ at future colliders

Global Fit to the CKM Matrix

- Tree-level determinations of CKM elements (with light leptons) agree with ΔF=2 processes
- Picture of CKM Flavour violation established, but sub leading NP possible



Still room for New Physics effects of O(10%)