

Andreas Crivellin

CERN Theory Division, Leave of absence from PSI & UZH

Discovering Lepton Flavour Universality Violating New Physics

HiDDeN virtual institute, Madrid, 27.04.2021 (remote)



Work supported by

FNSNF

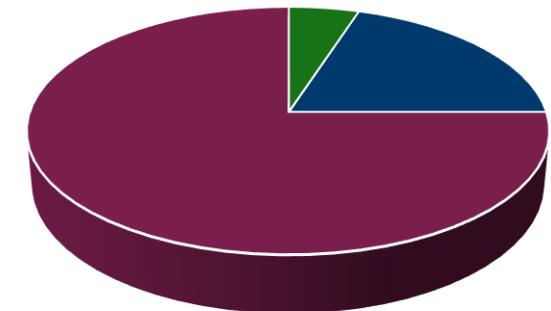
Outline

- Introduction
- Status of the Flavour anomalies
 - $b \rightarrow s \mu \mu$
 - $b \rightarrow c \tau \nu$
 - a_μ
 - $\tau \rightarrow \mu \nu \nu$
 - Cabibbo Angle Anomaly
 - Non-resonant di-leptons
- Explanations of the Flavour anomalies
- Common Explanations
 - Leptoquarks
 - Vector like fermions
- Conclusions

Introduction

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

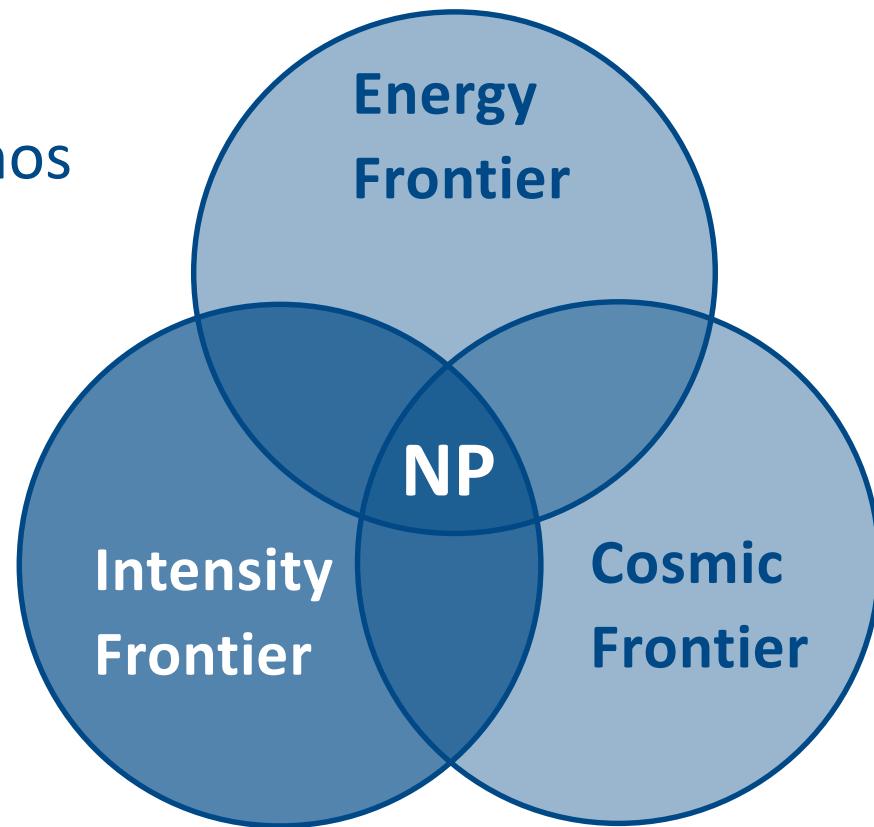


- SM
- Dark Matter
- Dark Energy

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

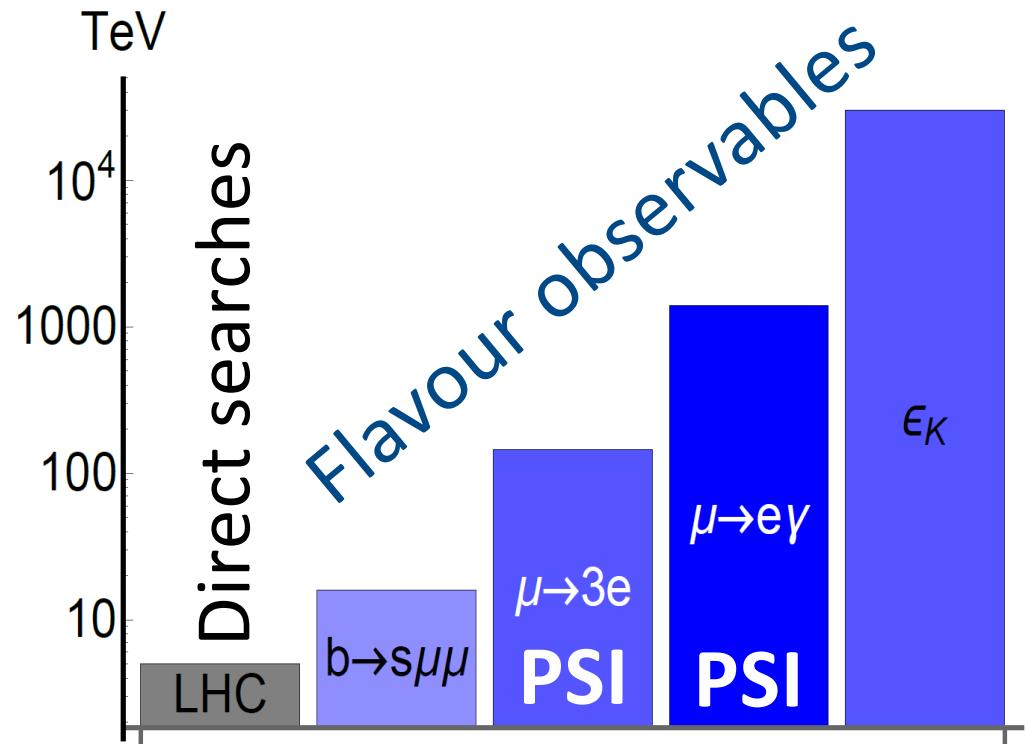
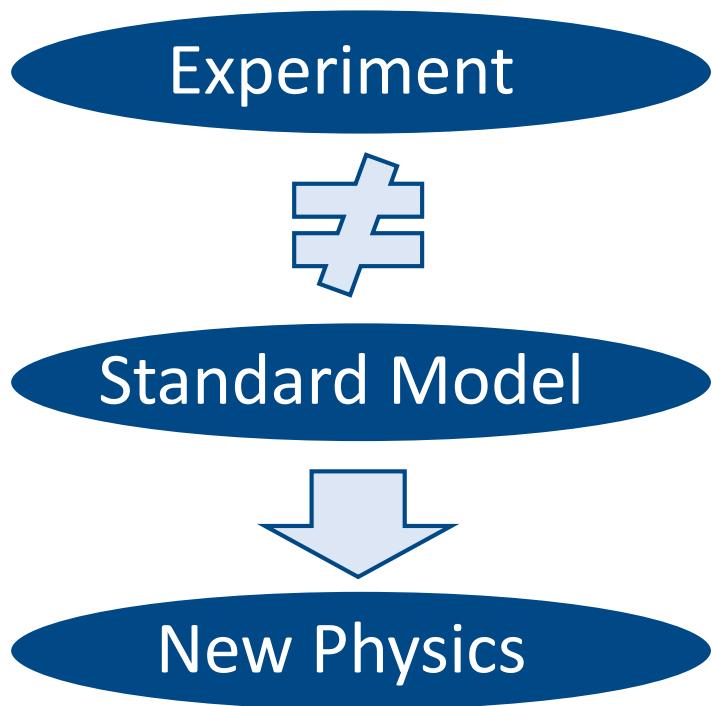
Discovering New Physics

- 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



Finding New Physics with Flavour

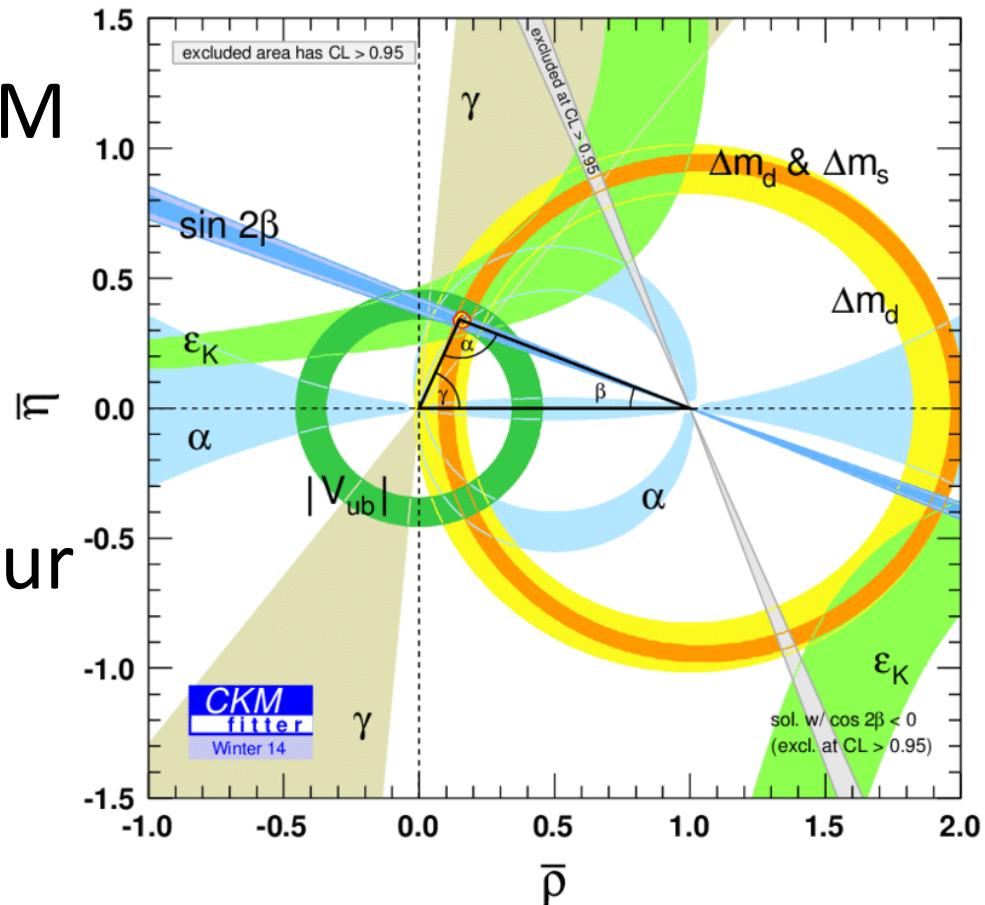
- At colliders one produces many (up to 10^{14}) heavy quarks or leptons and measures their decays into light flavours



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

Global Fit to the CKM Matrix

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

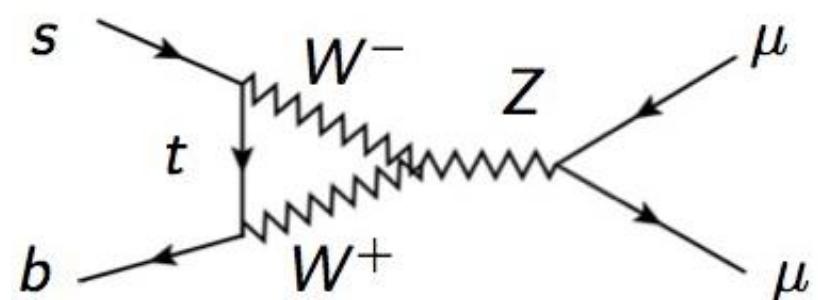
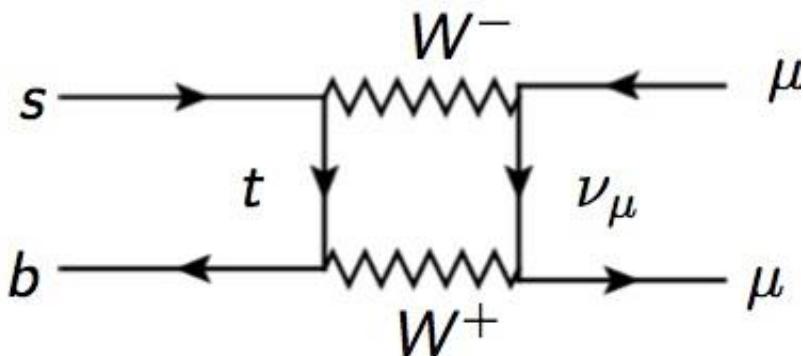


Still room for New Physics effects of $O(10\%)$

Overview on the Flavour anomalies

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

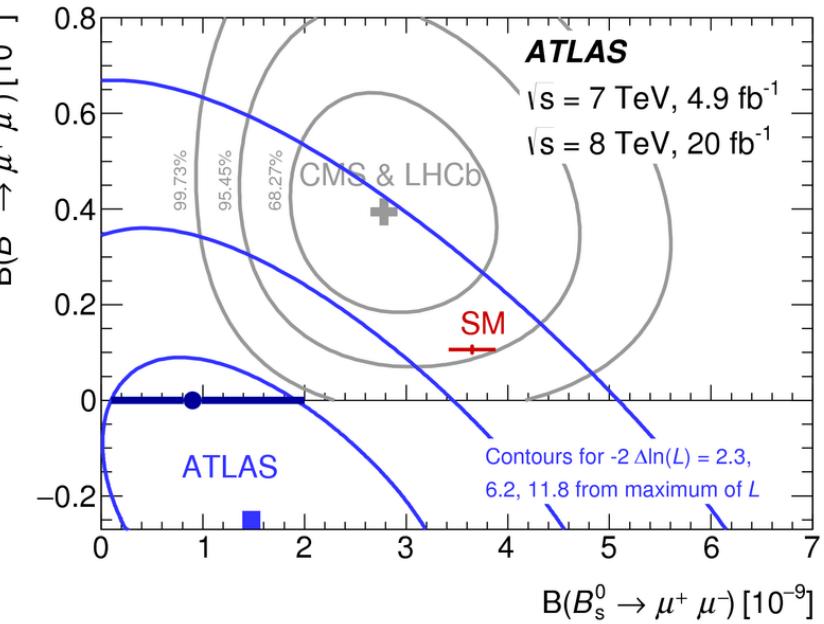
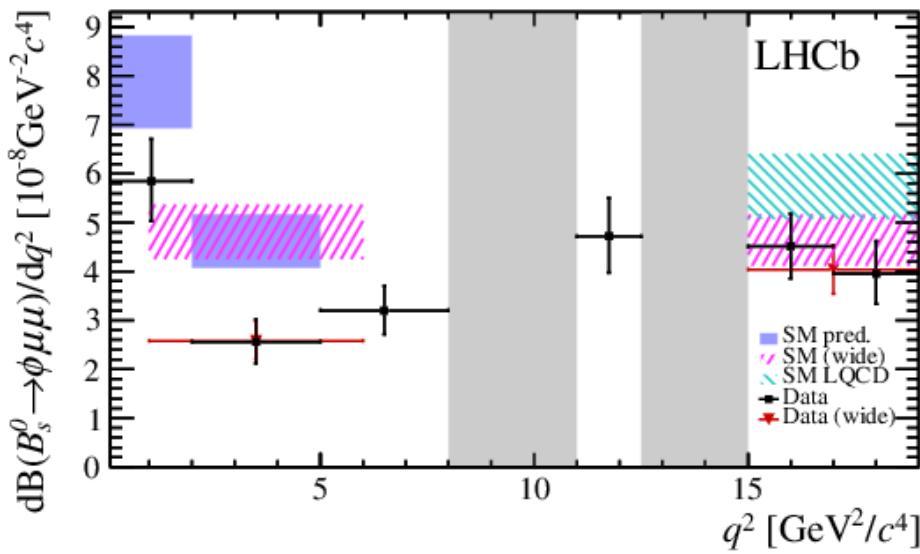
- Flavour Changing Neutral Current (FCNC)
- In the SM it is suppressed by
 - The CKM elements $V_{cb} \approx 0.04$
 - Electroweak scale
 - Loop-factor
- Wilson coefficients precisely known Bobeth et al. PRD, 2013



Suppressed in the SM and very sensitive to NP

$B_s \rightarrow \mu\mu$ and $B_s \rightarrow \phi\mu\mu$

- $B_s \rightarrow \mu\mu$ theoretically clean but chirality suppressed and therefore statistically limited

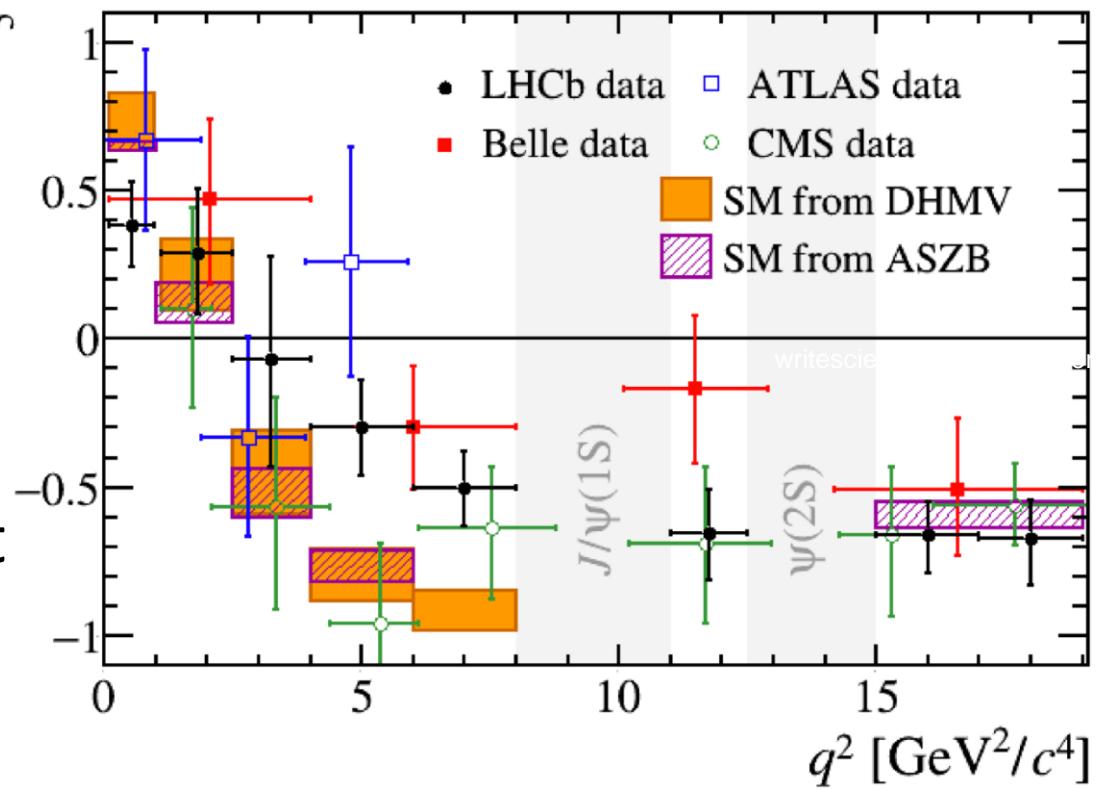


- $B_s \rightarrow \phi\mu\mu$ has a higher Br, but knowledge of the form-factor needed

Br's $\approx 20\%$ below SM expectations

The P_5' Anomaly

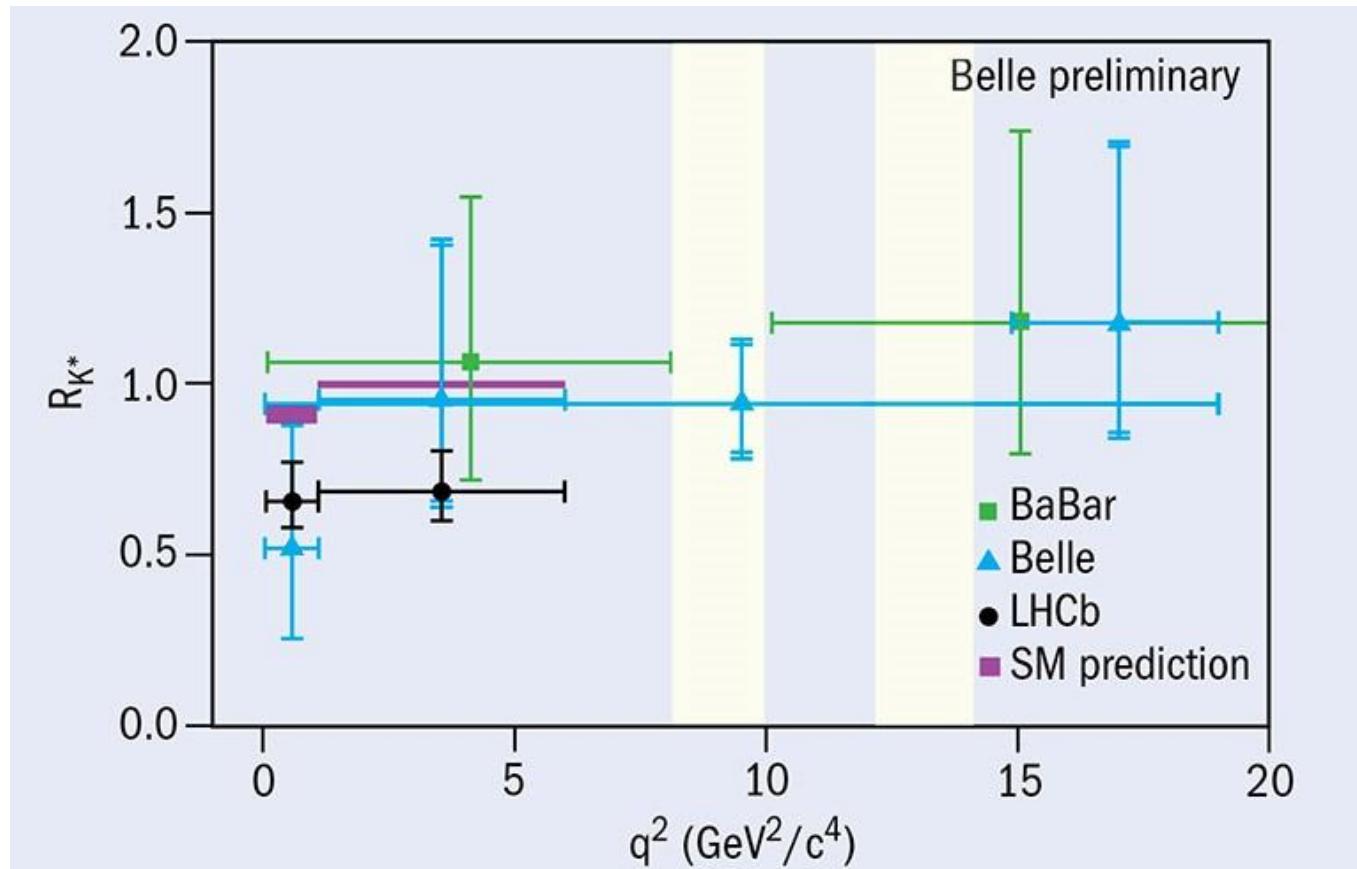
- P_5' angular observables in $B \rightarrow K^* \mu\mu$ S. Descotes-Genon, T. Hurth, J. Matias, J. Virto, JHEP 2013
- Constructed in such a way that the form factor dependence is minimized
- Confirmed by latest LHCb analysis for the charged mode



>3 σ deviation from the SM prediction

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

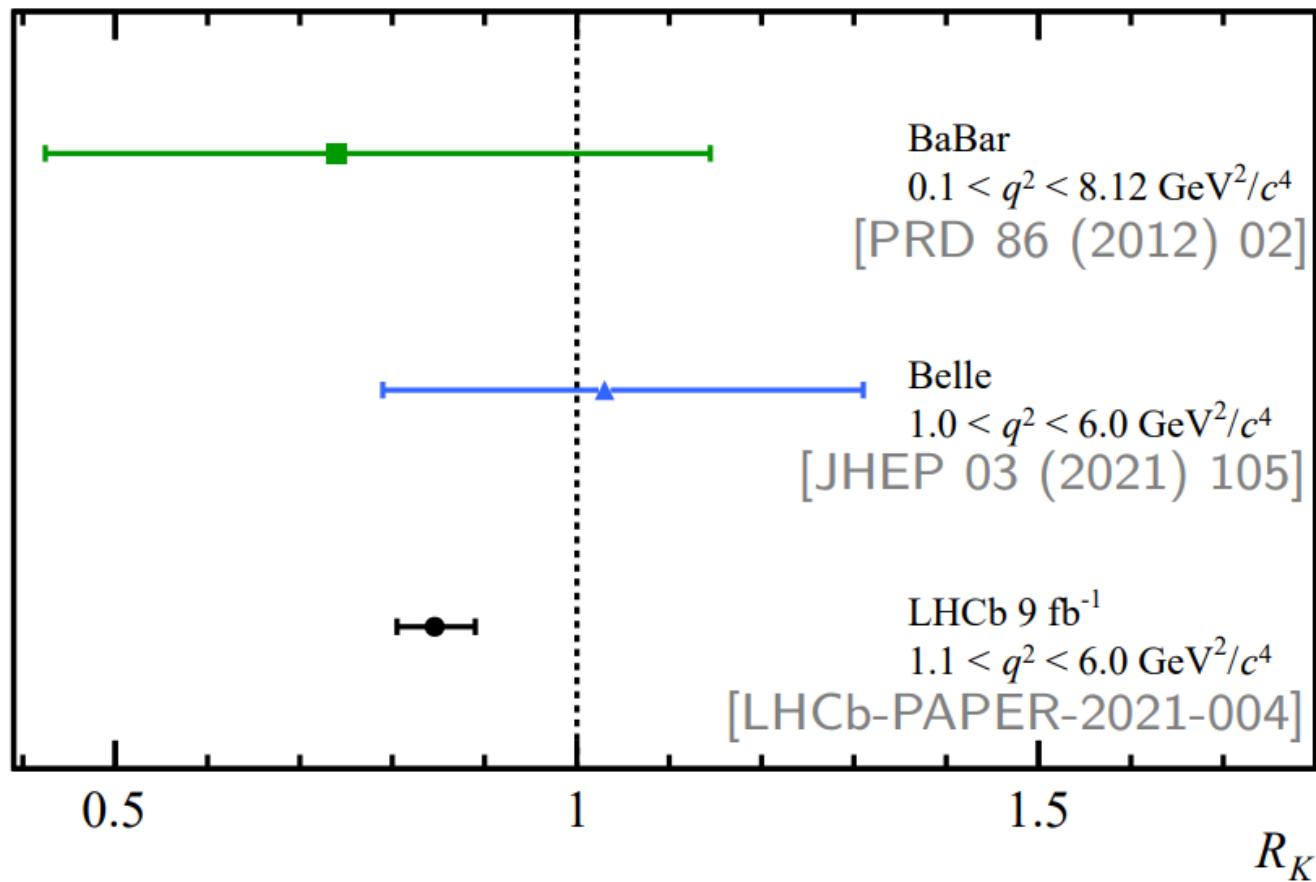
- Theoretically absolutely clean observable (in the SM)



Lepton Flavour Violation in B decays?

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

- Theoretically absolutely clean observable (in the SM)



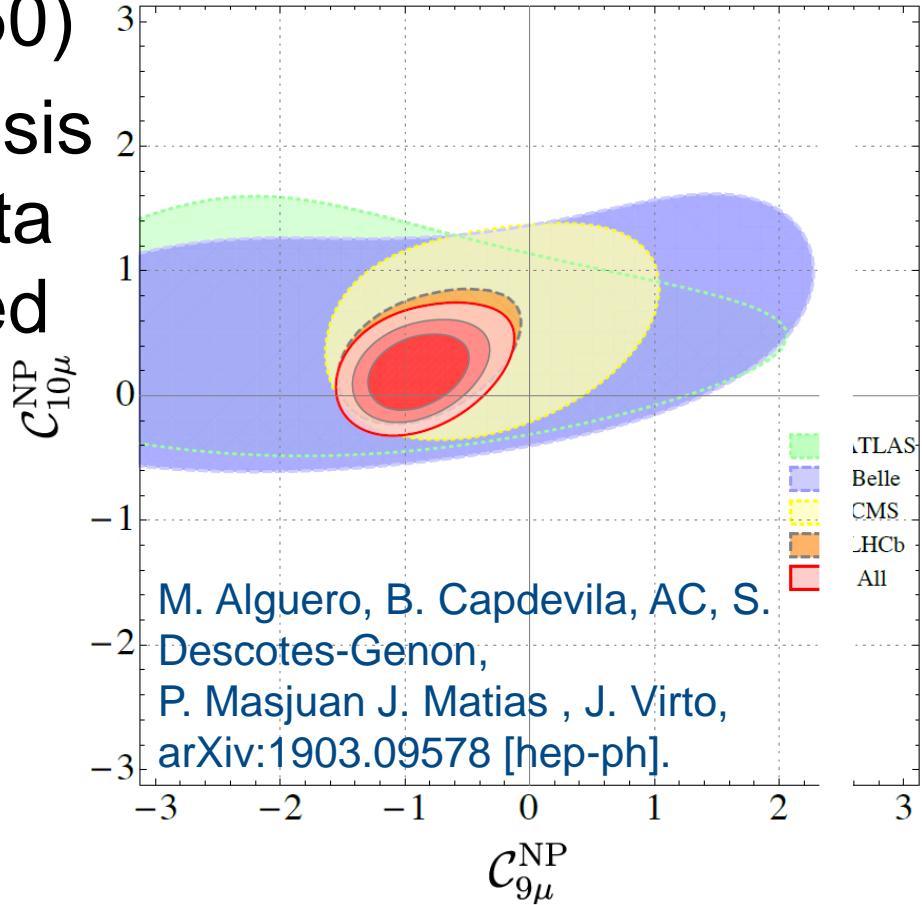
Lepton Flavour Violation in B decays?

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

- Perform global model independent fit to include all observables (≈ 150)
- Several NP hypothesis give a good fit to data significantly preferred over the SM hypothesis

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

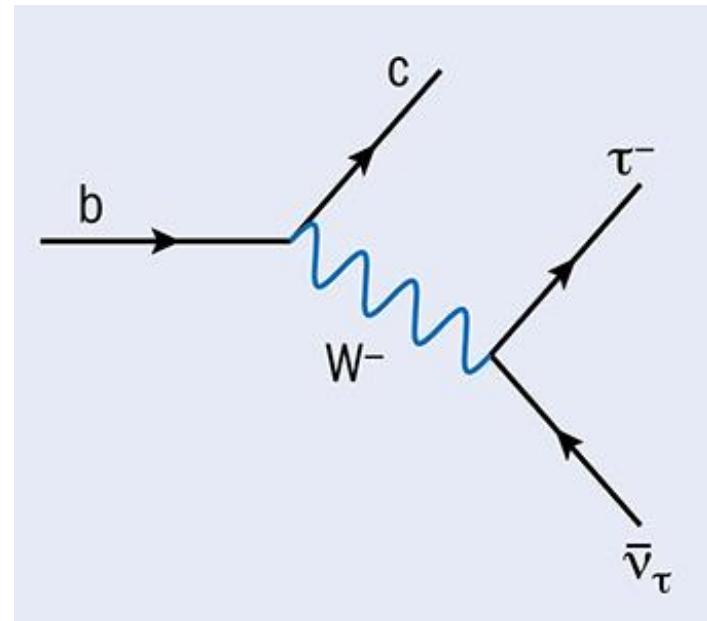
$$O_{10} = \bar{s} \gamma^\mu P_L b \bar{\ell} \gamma_\mu \gamma^5 \ell$$



Fit is 5-6 σ better than the SM

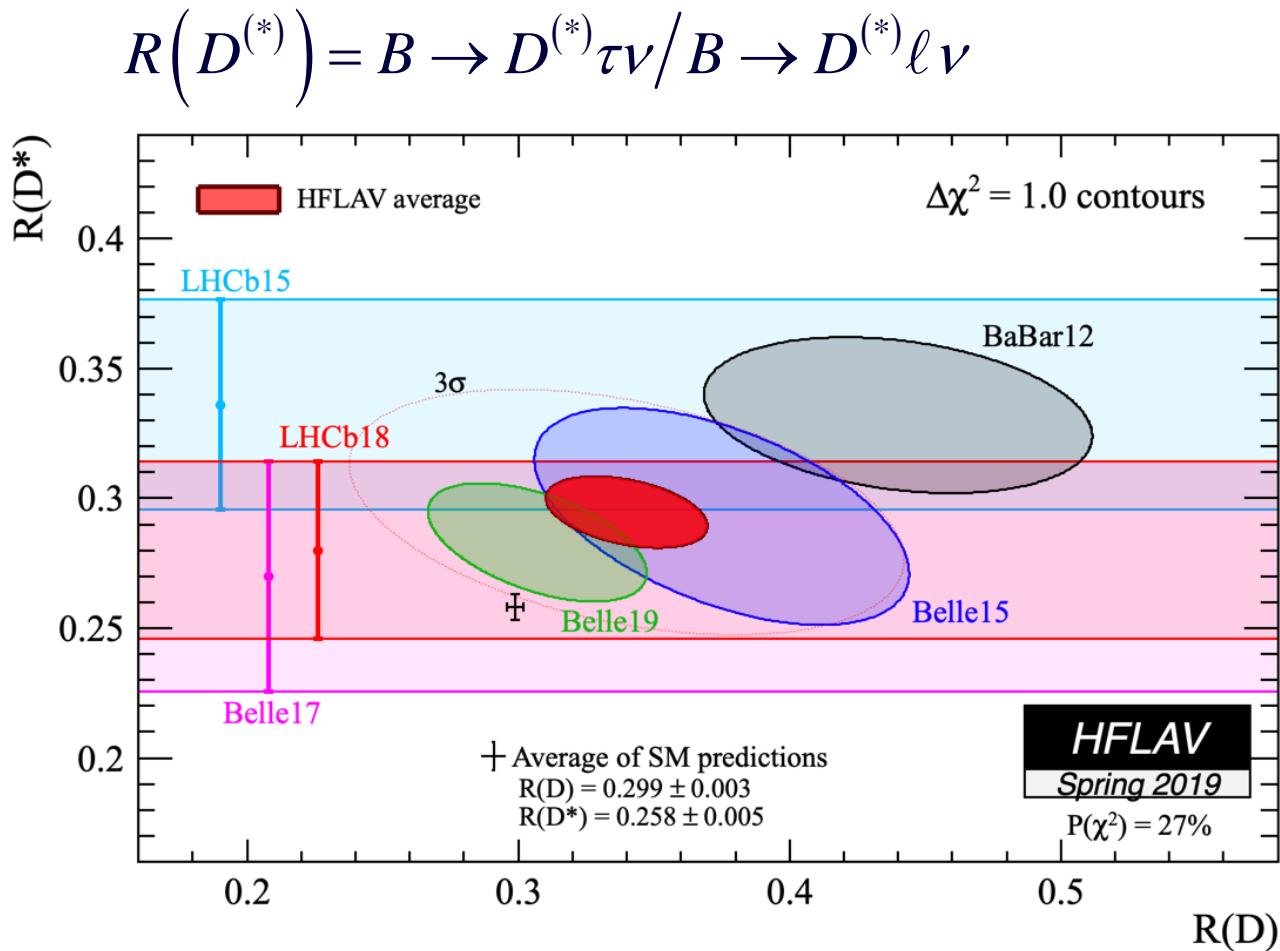
$b \rightarrow c \tau \bar{\nu}_\tau$ Transitions

- $B \rightarrow D \tau \bar{\nu}_\tau$, $B \rightarrow D^* \tau \bar{\nu}_\tau$, $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$
- 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 $\Delta F=2$ processes



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

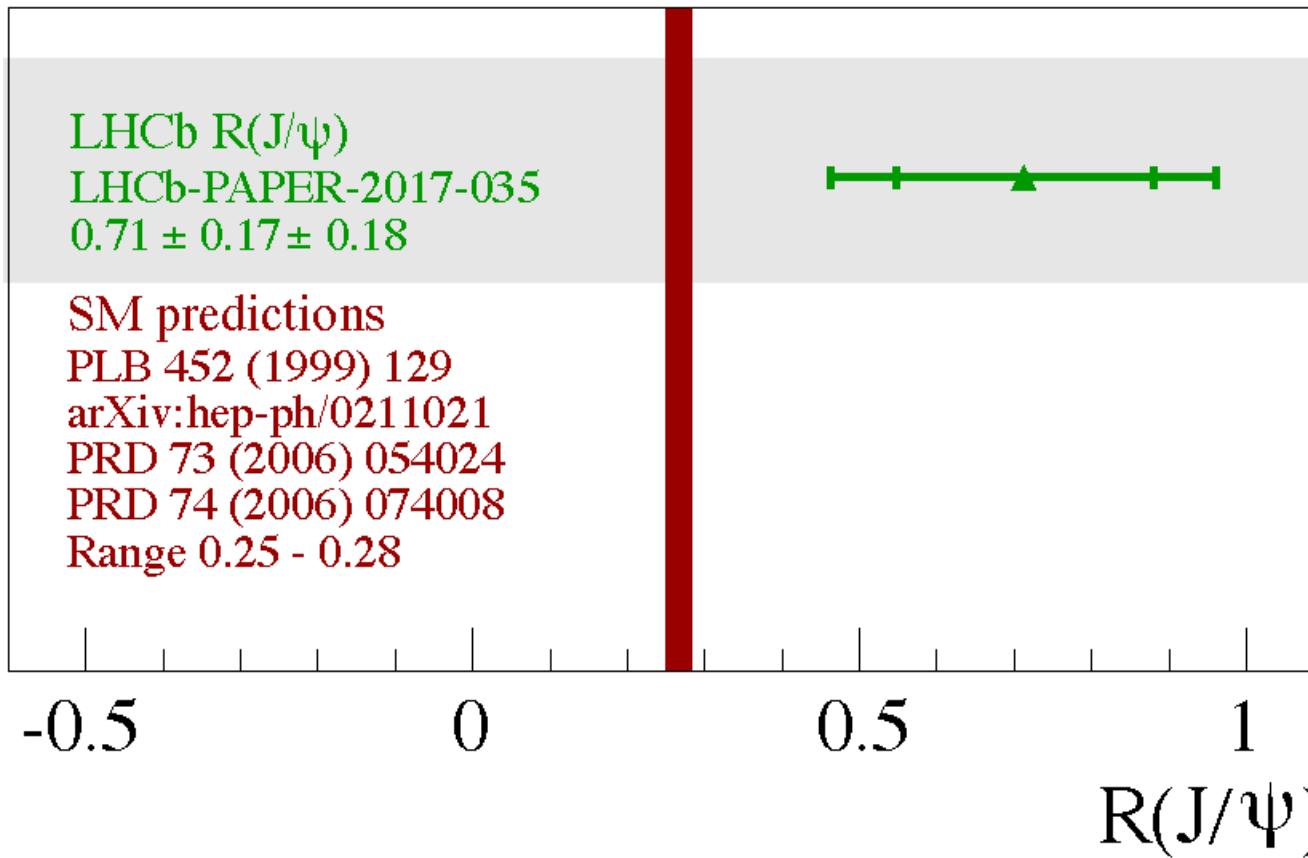
$b \rightarrow c\tau\nu$ Measurements



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

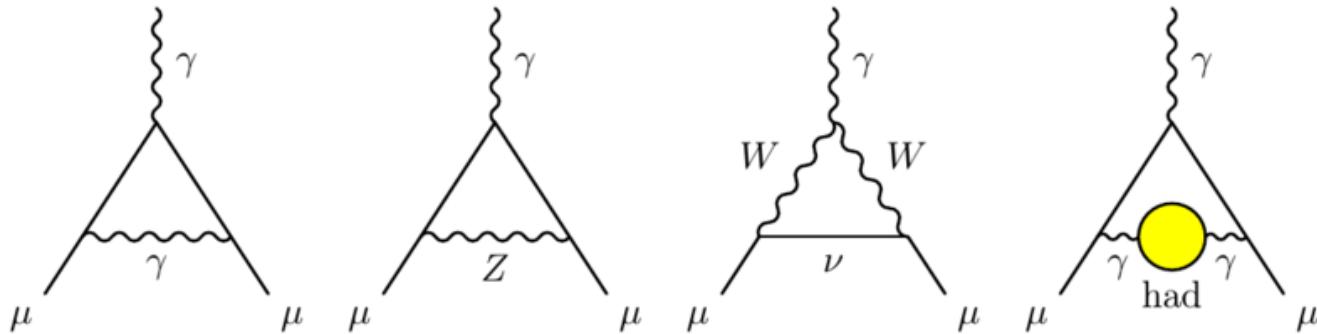
$b \rightarrow c\tau\nu$ Measurements

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



Supports $R(D)$ & $R(D^*)$

Muon Anomalous Magnetic Moment



- Theory prediction challenging (hadronic effects)

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

- 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**

3.7 σ deviation from the SM prediction

$\tau \rightarrow \mu \nu \bar{\nu}$

- Ratios of leptonic tau decays

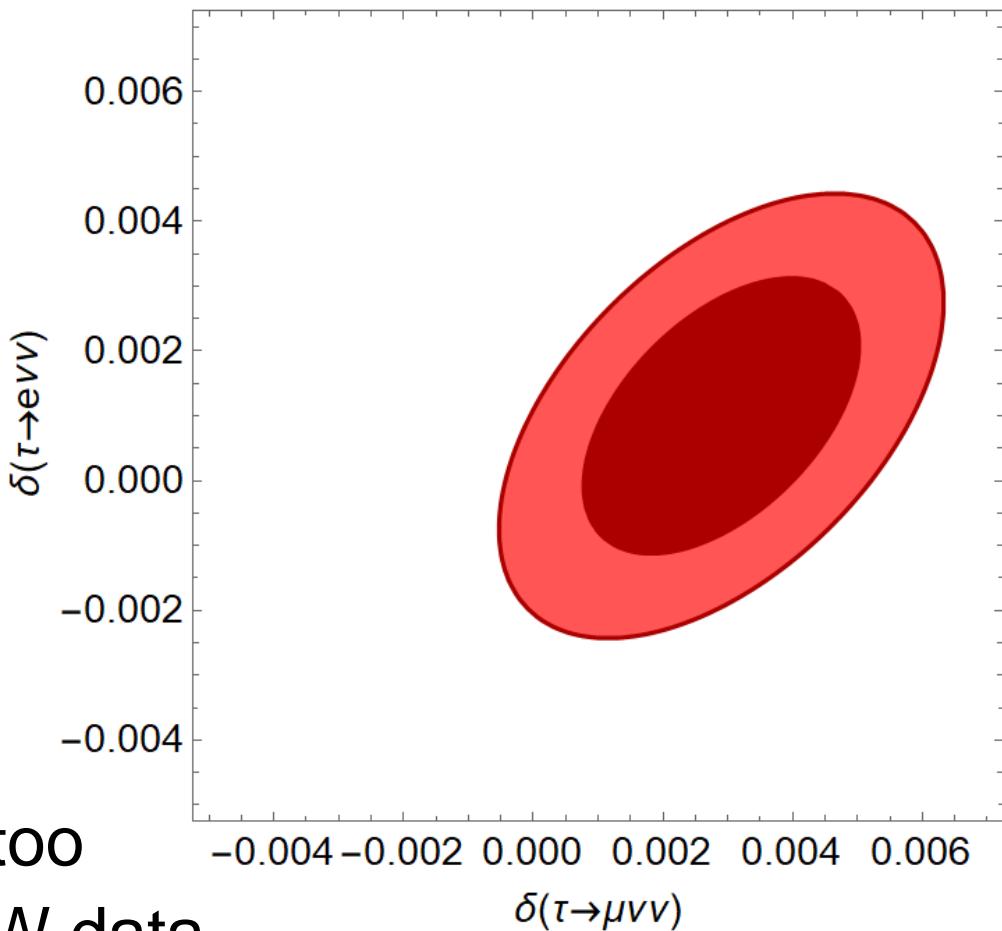
$$\frac{\mathcal{A}_{\text{EXP}}(\tau \rightarrow \mu \nu \bar{\nu})}{\mathcal{A}_{\text{SM}}(\mu \rightarrow e \nu \bar{\nu})} = 1.0029 \pm 0.0014$$

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

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

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

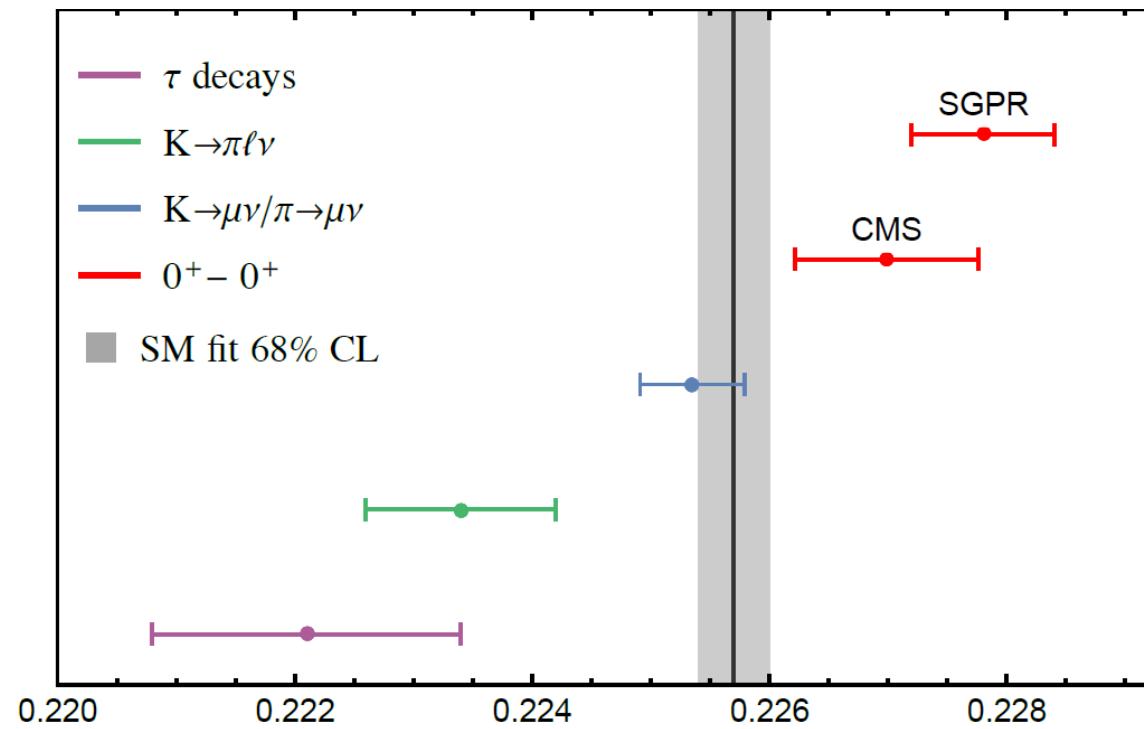
- NP in muon decay too constrained from EW data



≈2σ hint for LFUV in tau decays

Cabibbo Angle Anomaly

- V_{ud} from super-allowed beta decays
- V_{us} from Kaon and tau decays
- Disagreement leads to a (apparent) violation of CKM unitarity V_{us}



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

CMS, SGPR:
radiative corrections

≈ 3σ hint for LFUV in the charged current

CAA and LFUV

- Assume modified $W\ell v$ couplings

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

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

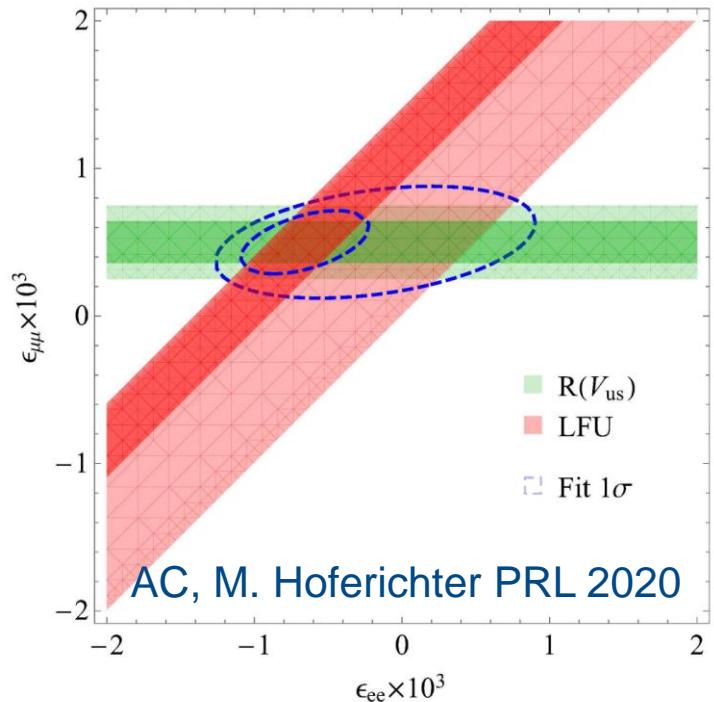
$$1/\tau_\beta \sim |V_{ud}(1 + \varepsilon_{ee})|^2 G_F^2$$

- Fermi constant determined from muon decay

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

- Dependence on ε_{ee} cancels

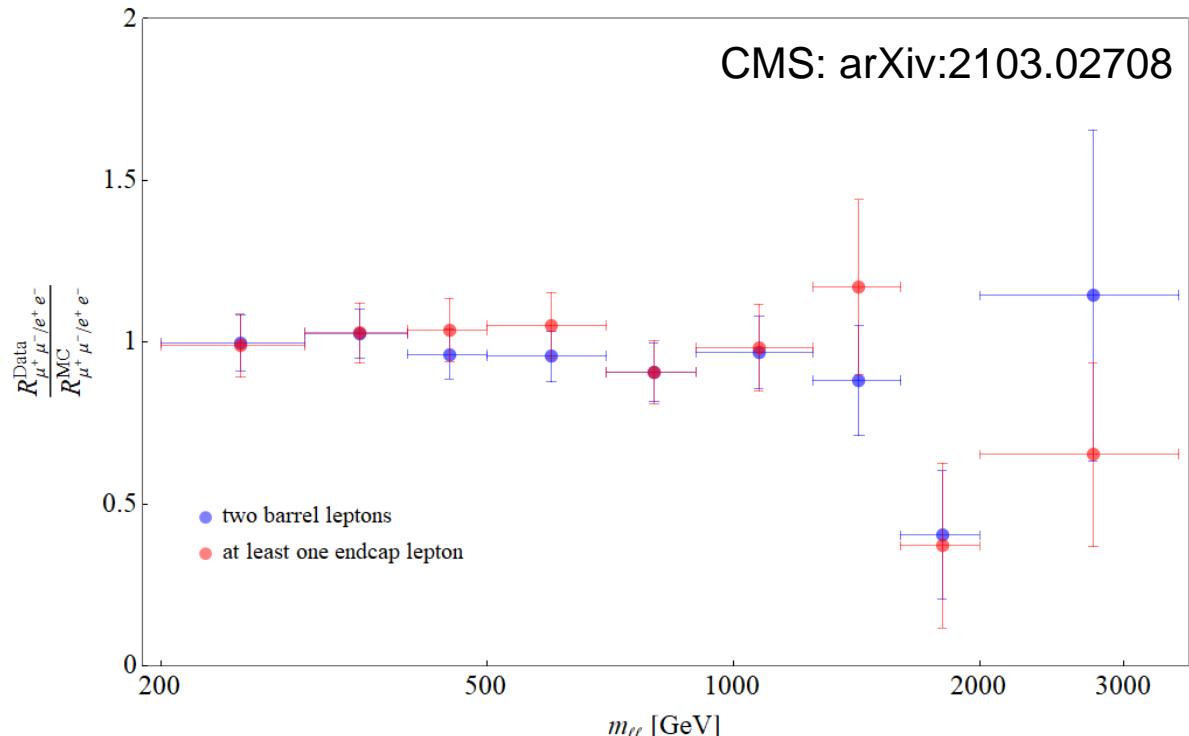
$$R(V_{us}) \equiv \frac{V_{us}^{K_{\mu 2}}}{V_{us}^\beta} \equiv \frac{V_{us}^{K_{\mu 2}}}{\sqrt{1 - (V_{ud}^\beta)^2 - |V_{ub}|^2}} \approx 1 - \left(\frac{V_{ud}}{V_{us}} \right)^2 \varepsilon_{\mu\mu}$$



The CAA can be interpreted as a sign of LFUV

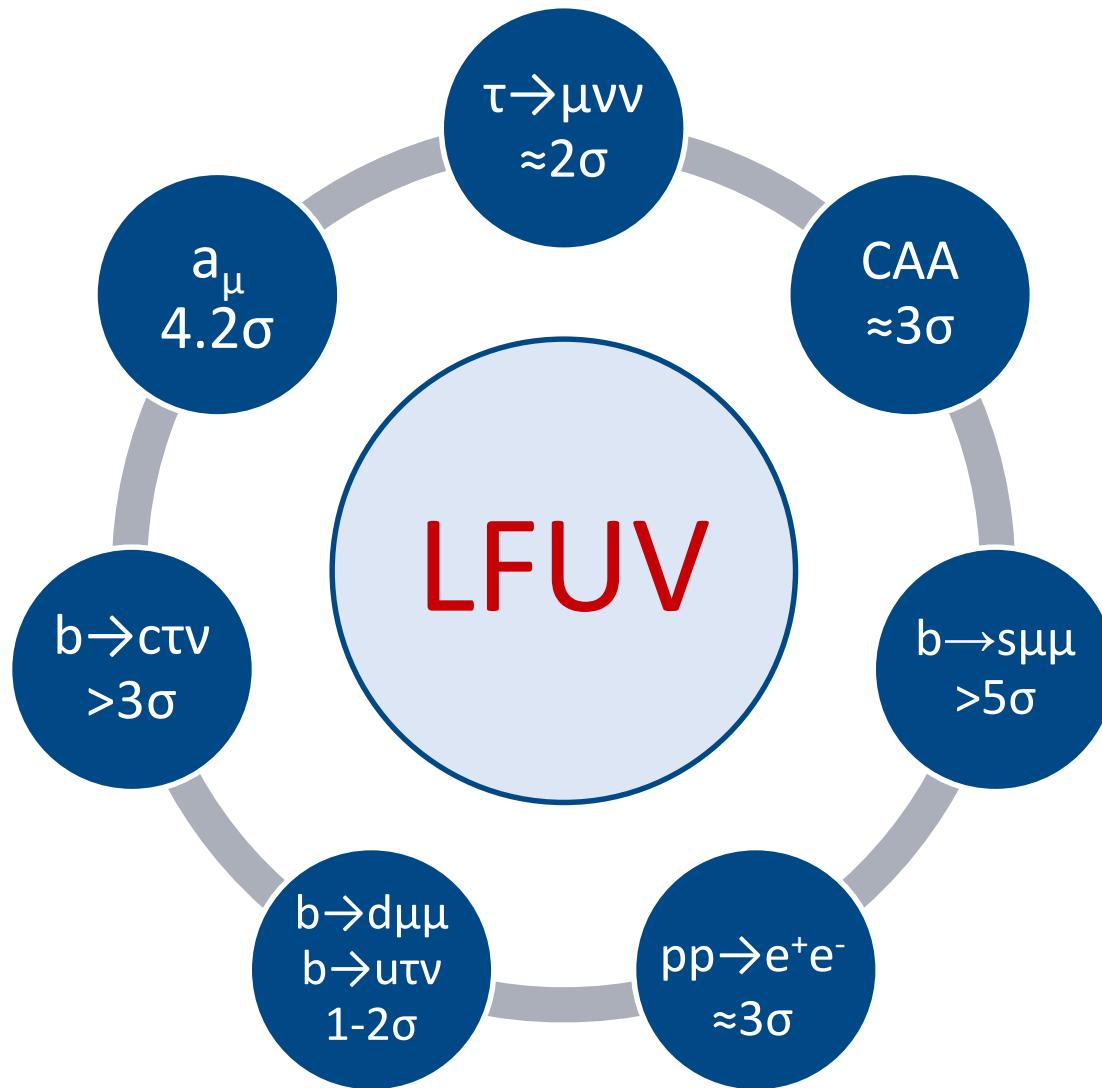
Non-Resonant Di-Leptons

- Excess in di-electrons at $m_{ee} > 1800\text{GeV}$
- 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



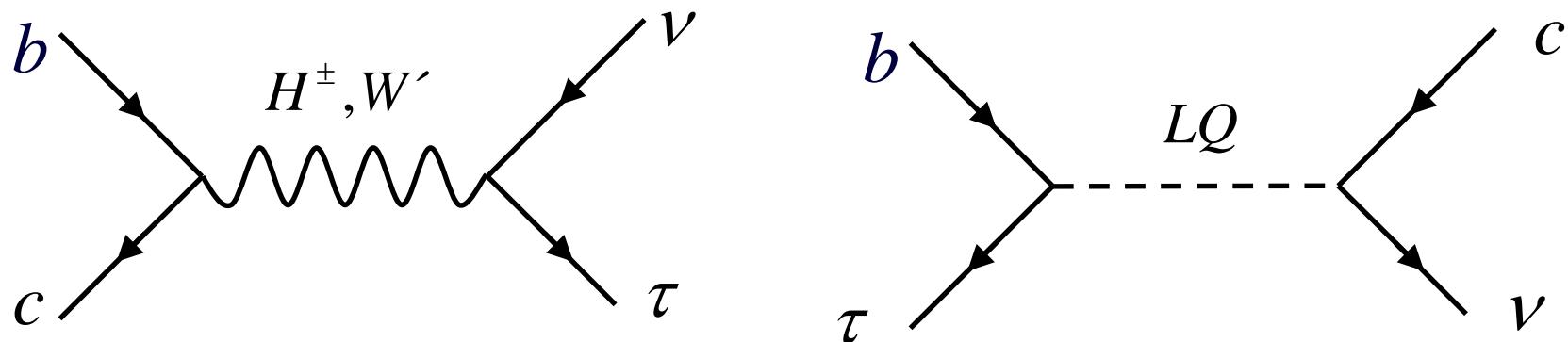
≈ 3σ hint for LFUV

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 $qq \rightarrow \tau\tau$ searches
CMS, 1809.05558; ATLAS, 1902.08103

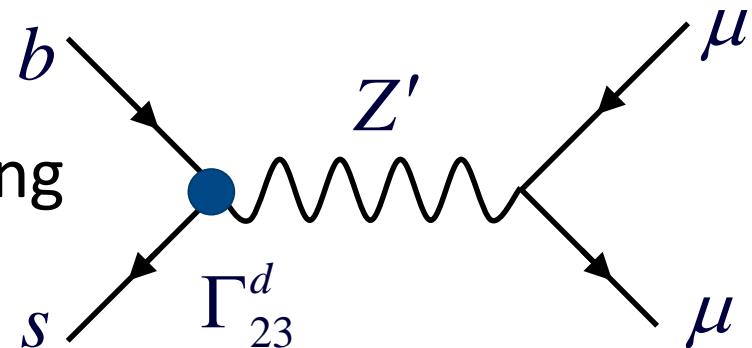
Explanation difficult but possible with Leptoquarks

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

B. Gripaios, M. Nardecchia,
S. A. Renner, JHEP 2016

- 2HDM A.C., D. Müller and C. Wiegand, 1903.10440

- R_2 Leptoquark D. Bećirević 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. Bećirević, S. Fajfer and N. Košnik, 1503.09024,

Small effect needed; many possibilities

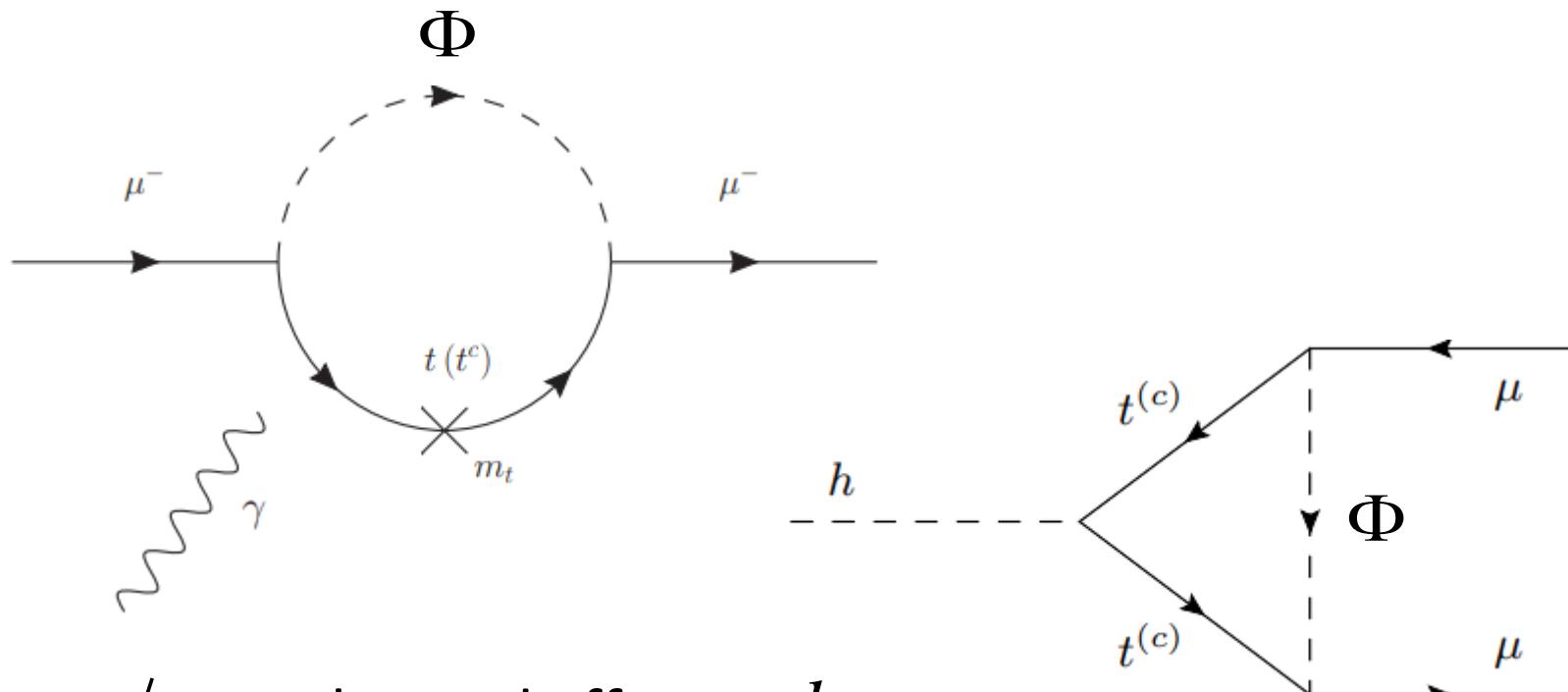
a_μ & a_e explanations

- MSSM
 - $\tan(\beta)$ enhanced slepton loops
- Scalars
 - Light scalars with enhanced muon couplings
- Z'
 - Very light with $\tau\mu$ couplings (m_τ enhancement)
- New scalars and fermions
 - κ/Y_μ
- Leptoquarks
 - m_t enhanced effects

Chiral enhancement or very light particles

Leptoquarks in a_μ

- Chirally enhanced effects via top-loops

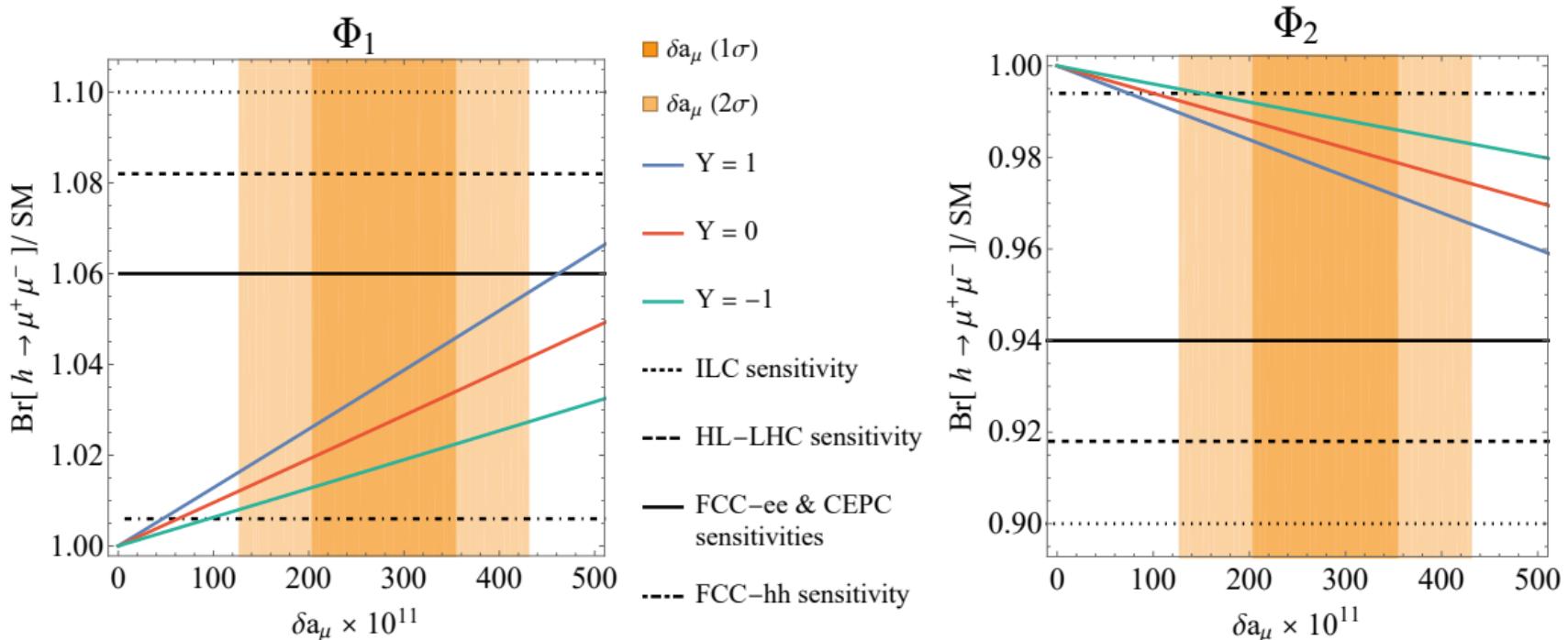


- m_t/m_μ enhanced effect $h \rightarrow \mu\mu$
- m_t^2/m_Z^2 enhanced effect in $Z \rightarrow \mu\mu$

Correlations with $h \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$

a_μ vs $h \rightarrow \mu\mu$

- Chirally enhanced effects via top-loops
- Same coupling structure → direct correlation

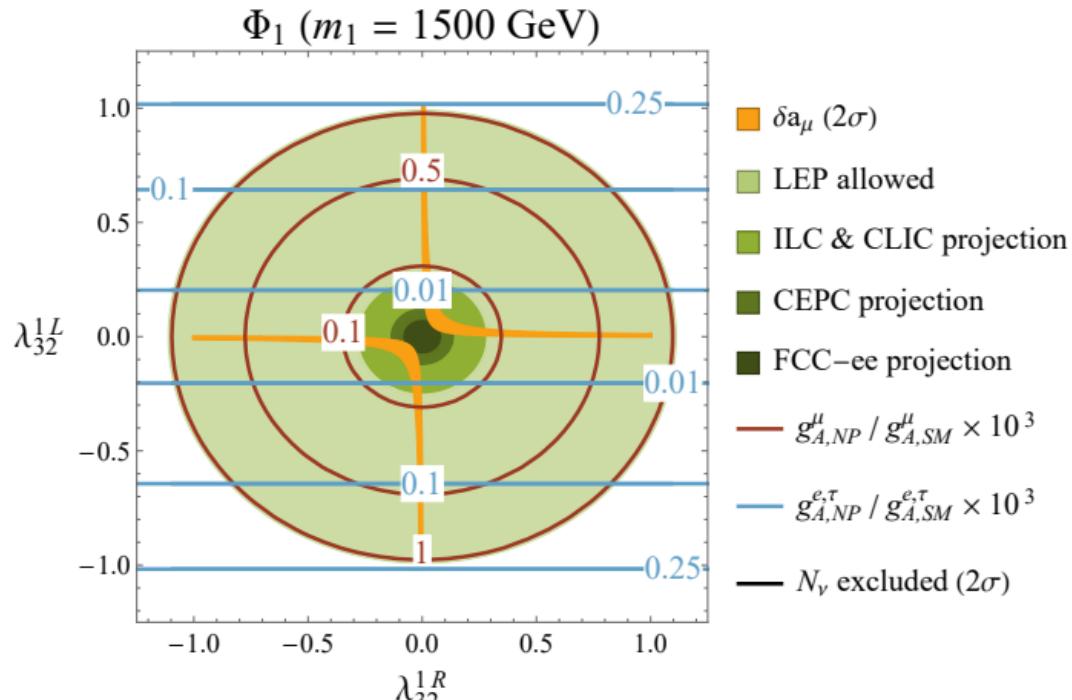


A.C., D. Mueller, F. Saturnino, 2008.02643

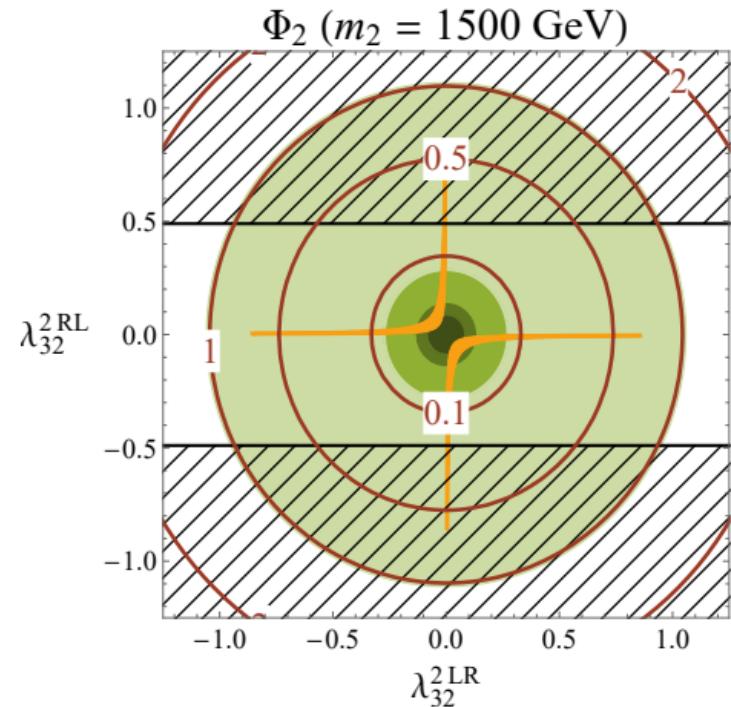
$h \rightarrow \mu\mu$ at future colliders

a_μ vs $Z \rightarrow \mu\mu$

■ Chirally enhanced effects via top-loops



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

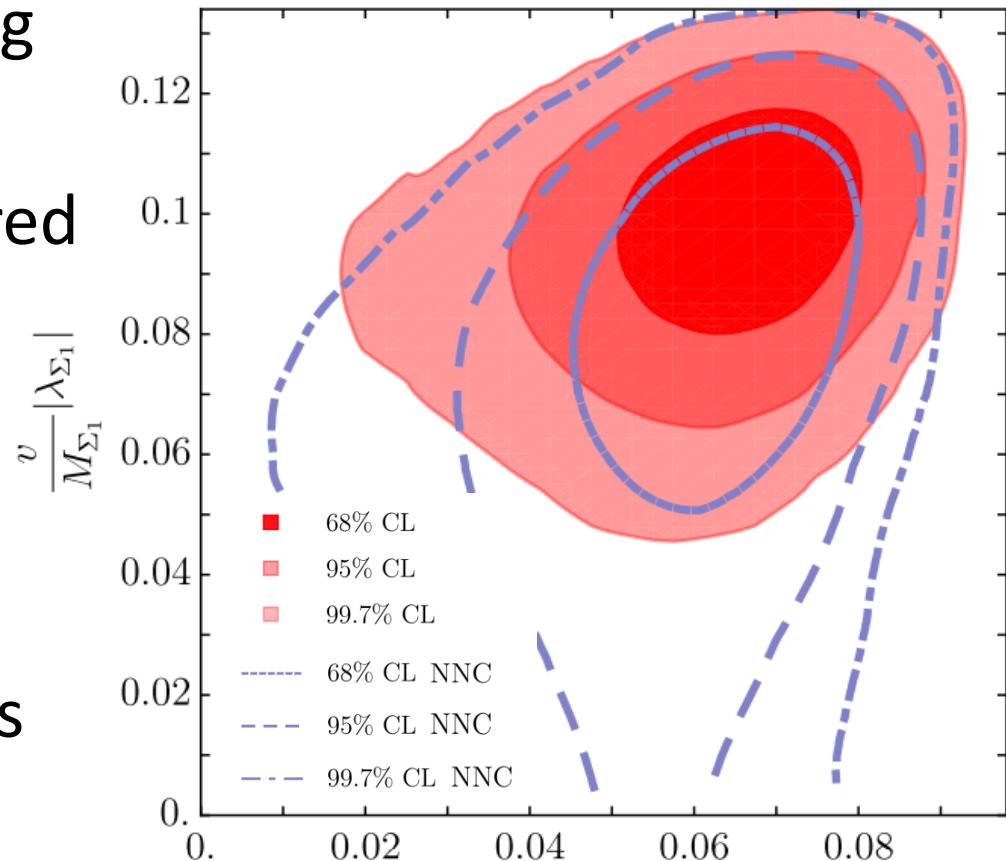


E. Leskow, A.C., G. D'Ambrosio,
D. Müller 1612.06858
A.C, C. Greub, D. Müller, F.Saturnino,
2010.06593

$Z \rightarrow \mu\mu$ at future colliders

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

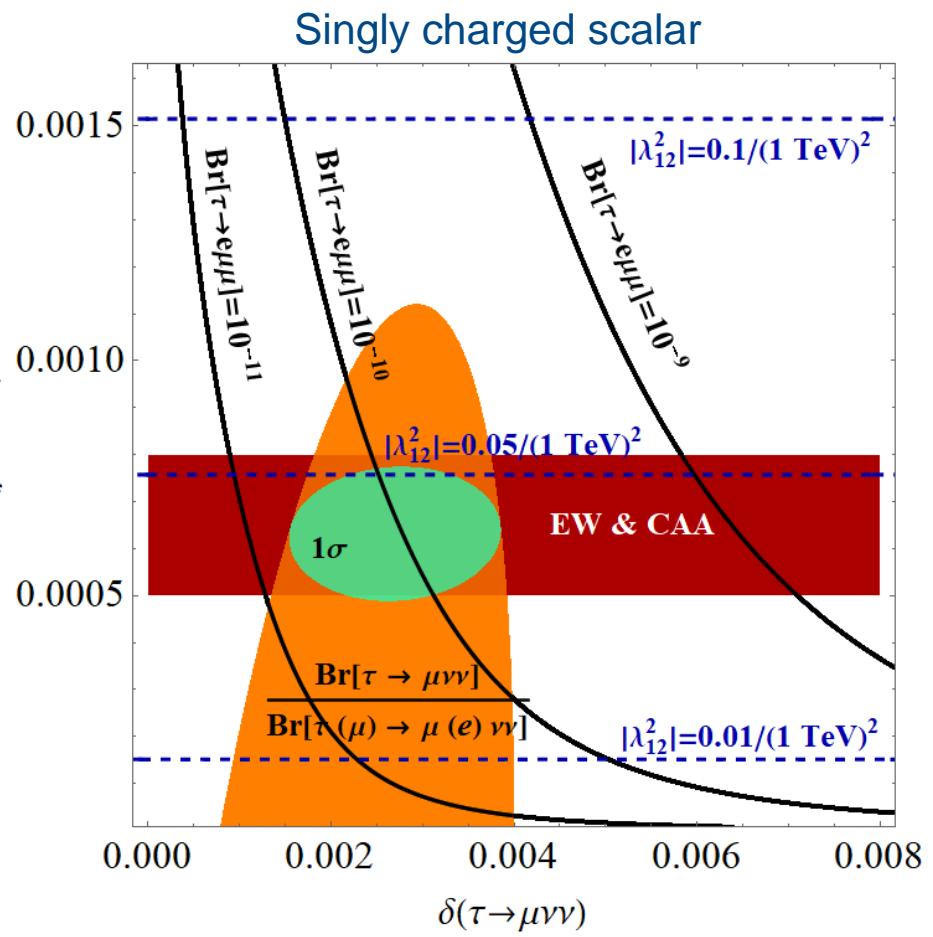
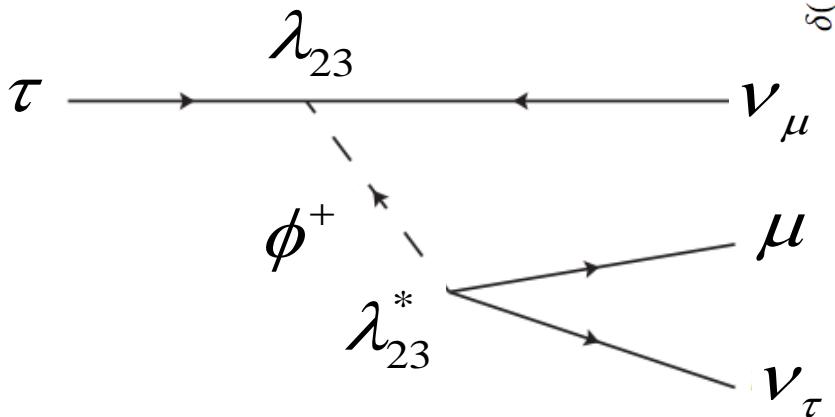


AC, F. Kirk, C. Manzari,
M. Montull JHEP, 2008.01113 $\frac{v}{M_N} |\lambda_N|$

>5 σ improvement over SM hypothesis

$\tau \rightarrow \mu \nu \nu$

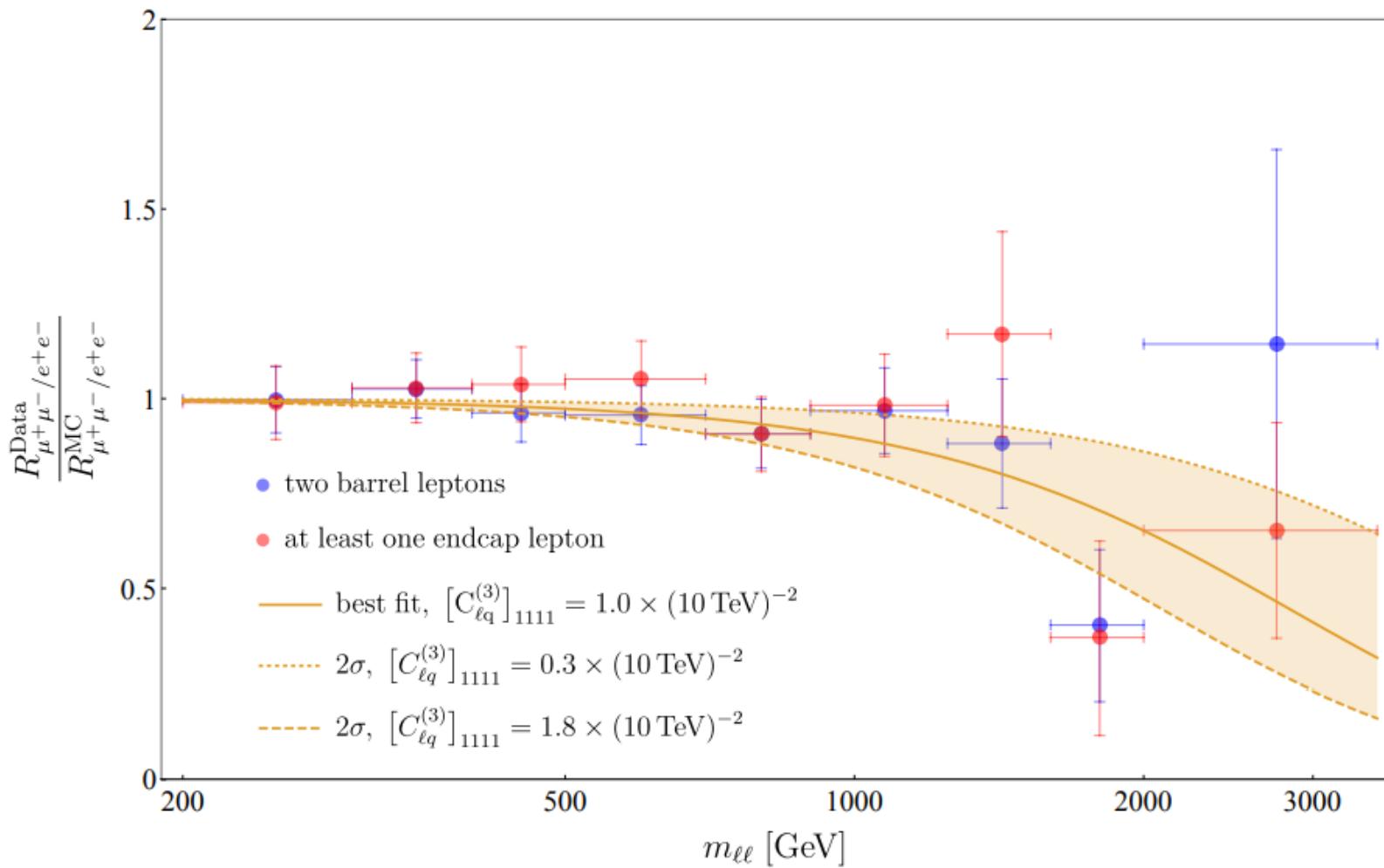
- L_μ - L_τ Z' (box diagrams)
- LFV violating Z'
- Modified Wlv couplings
- W'
- Singly charged scalar



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

4 σ hint for modified neutrino couplings

Non-Resonant Di-Leptons



Constructive heavy NP in electrons

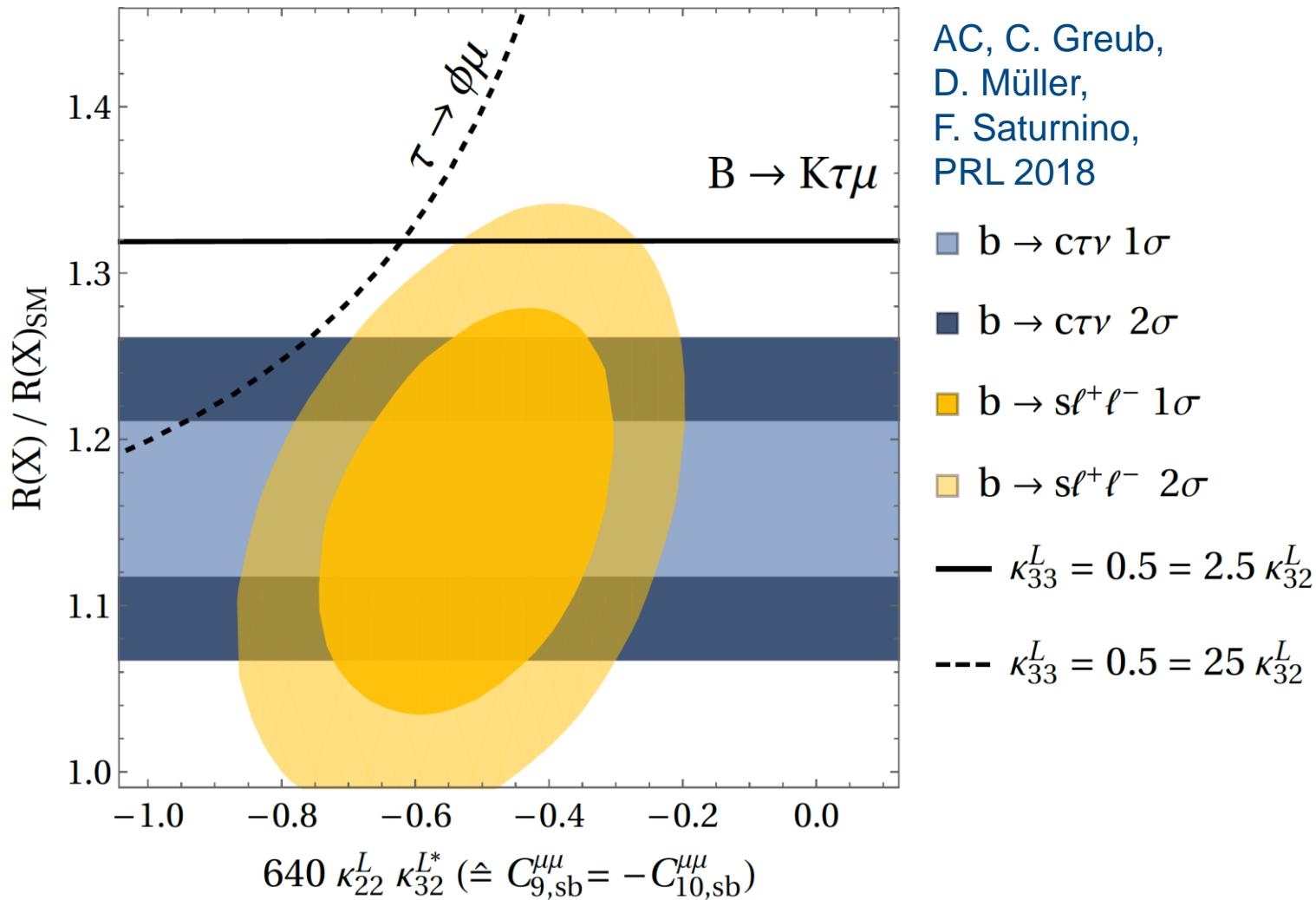
Simultaneous Explanations

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 $b \rightarrow svv$
- 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

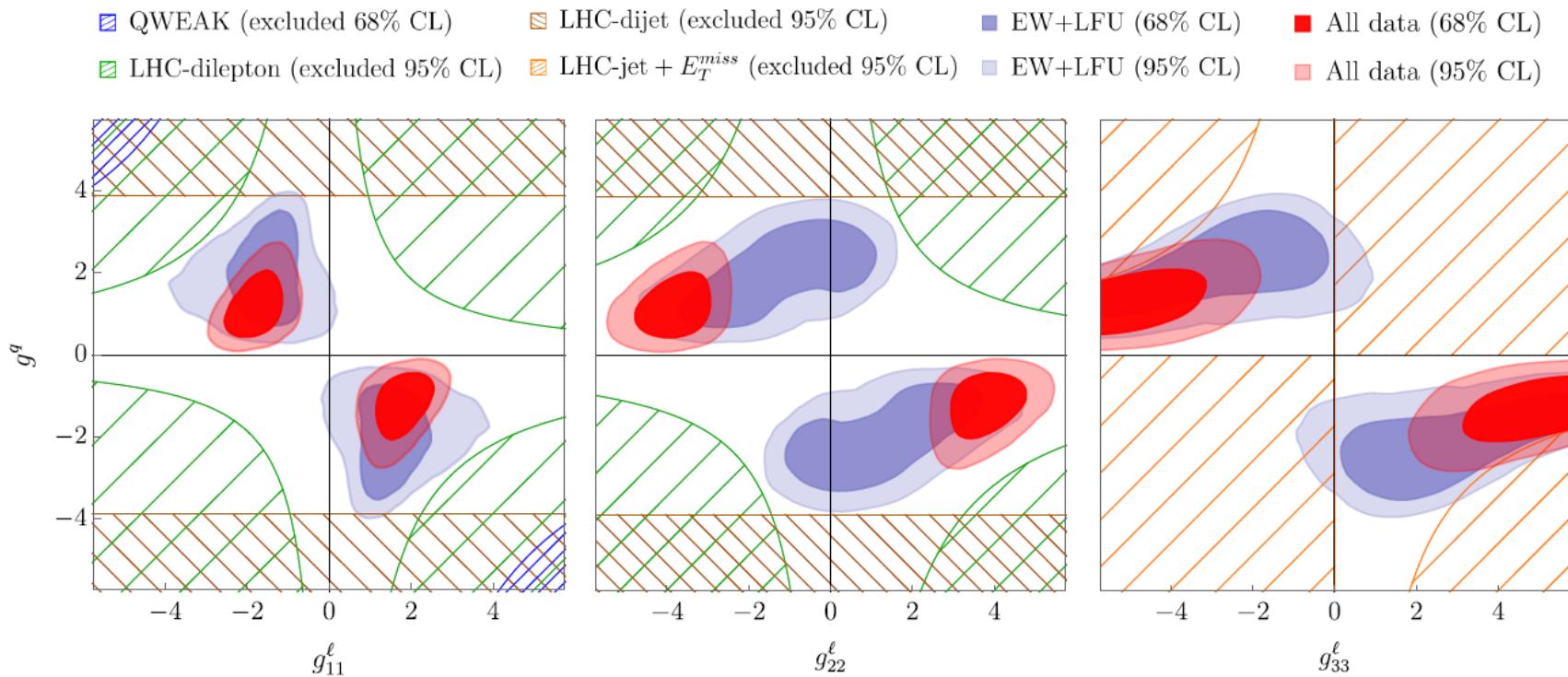


Pati-Salam LQ can explain the flavour anomalies

Vector Triplet Explanation of $R(V_{us})$ and $b \rightarrow s\mu\mu$

W' Explanation of $R(V_{us})$

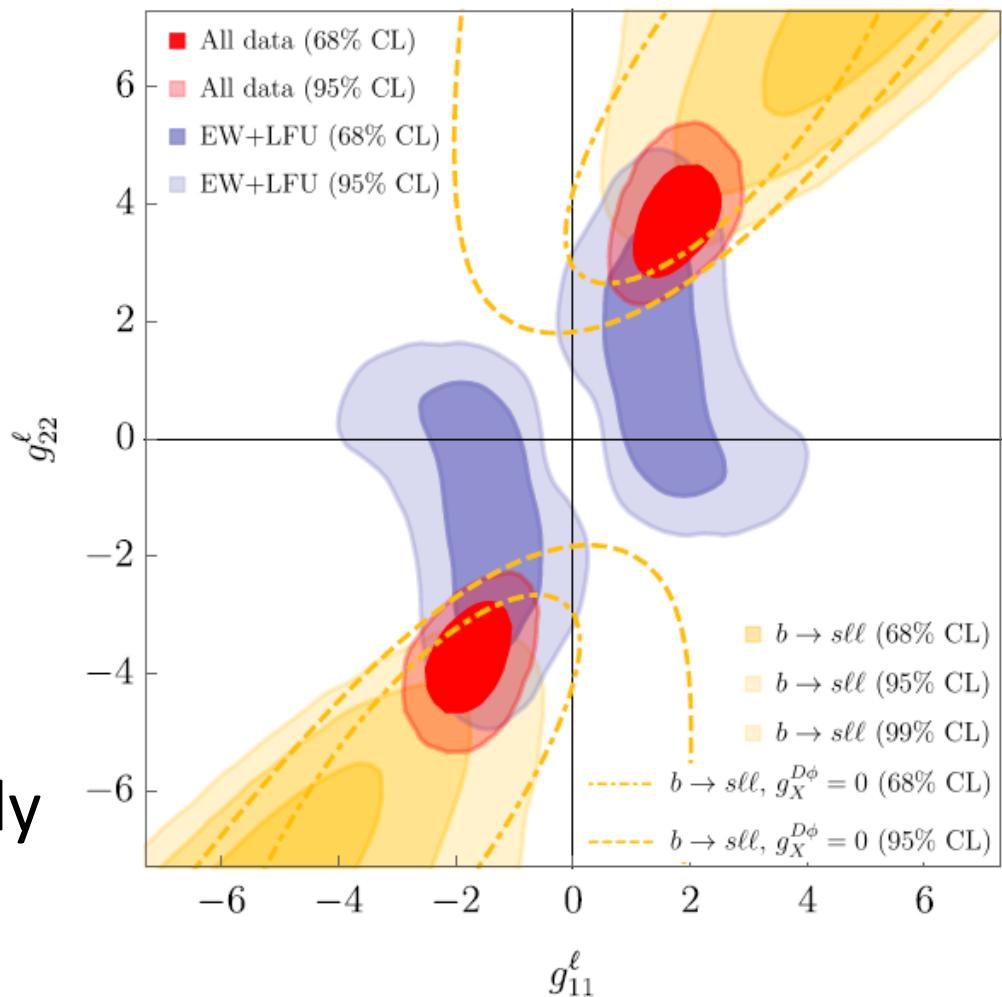
- W' effects in LFU and EW observables
- Z' effects in LHC di-jet and di-lepton tail searches



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

Vector Triplet in $R(V_{us})$ & $b \rightarrow sll$

- Region preferred by EW fit overlaps with $b \rightarrow sll$ region
- Correlations between e.g. $\pi \rightarrow \mu\nu/\pi \rightarrow e\nu$ and $R(K^{(*)})$ are predicted
- Global fit significantly improved

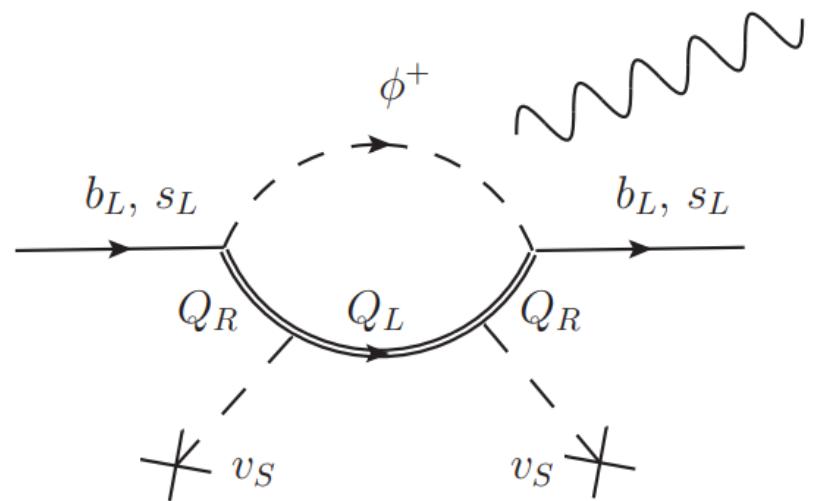
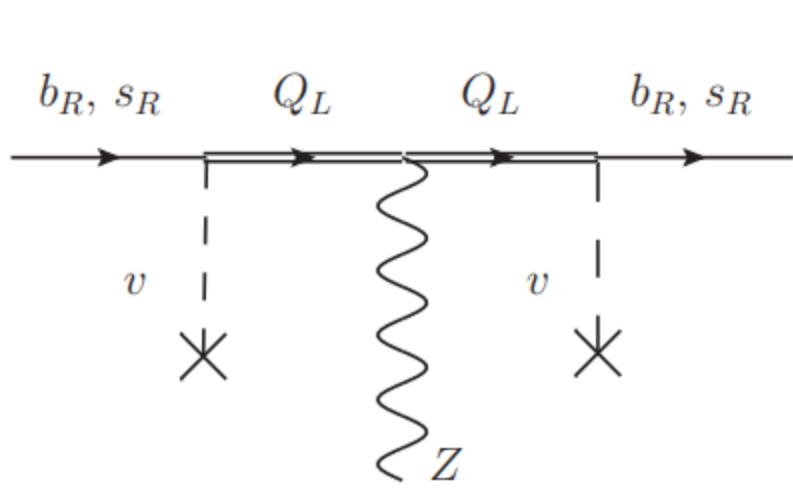


Common explanation possible

$R(V_{us})$, $\tau \rightarrow \mu \nu \bar{\nu}$,
 $Z \rightarrow b\bar{b}$
and $b \rightarrow s \mu \bar{\mu}$

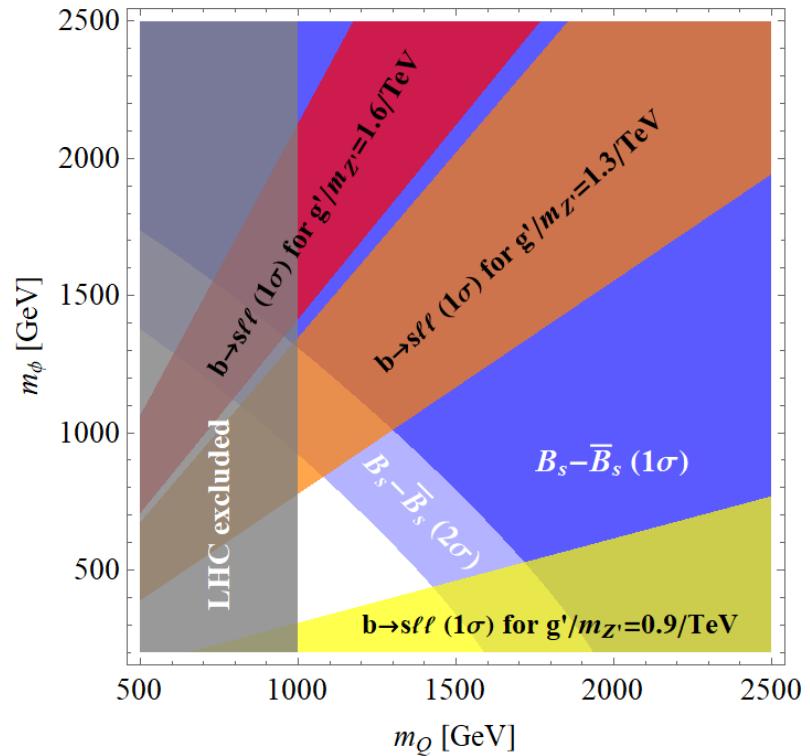
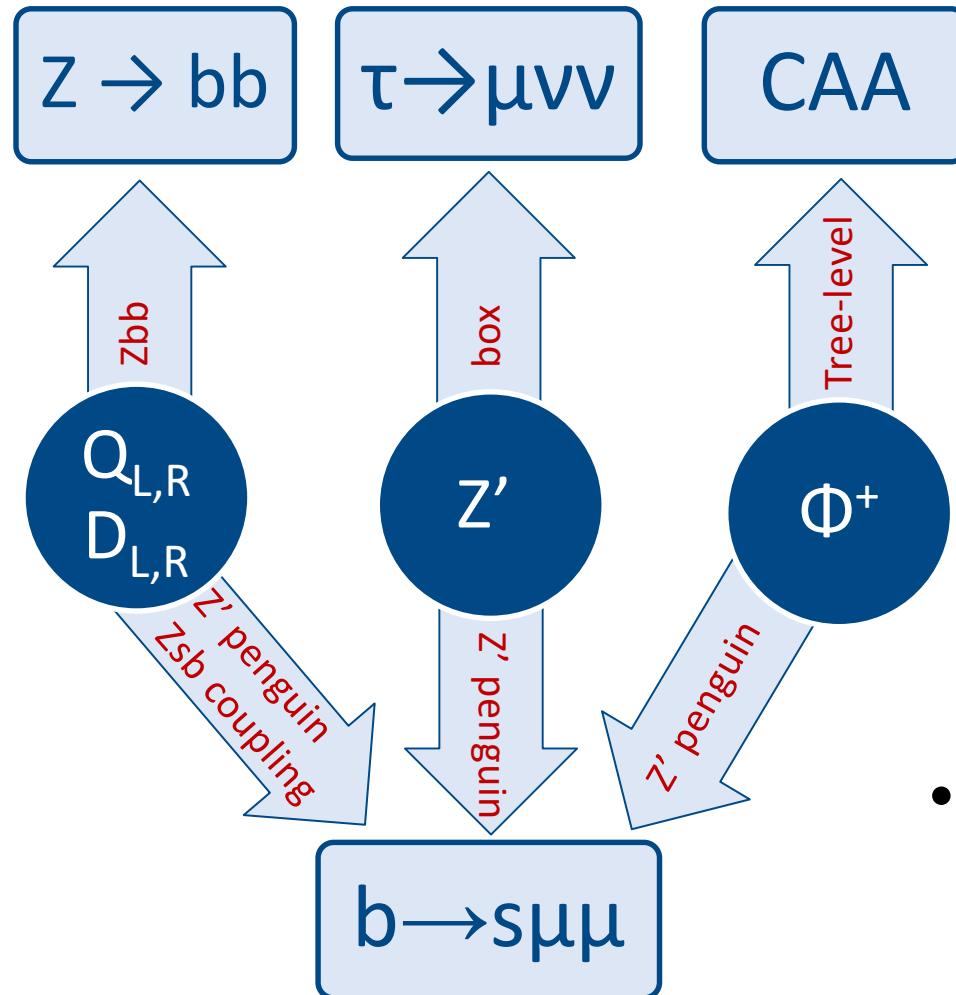
Model

	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 $Z'sb$

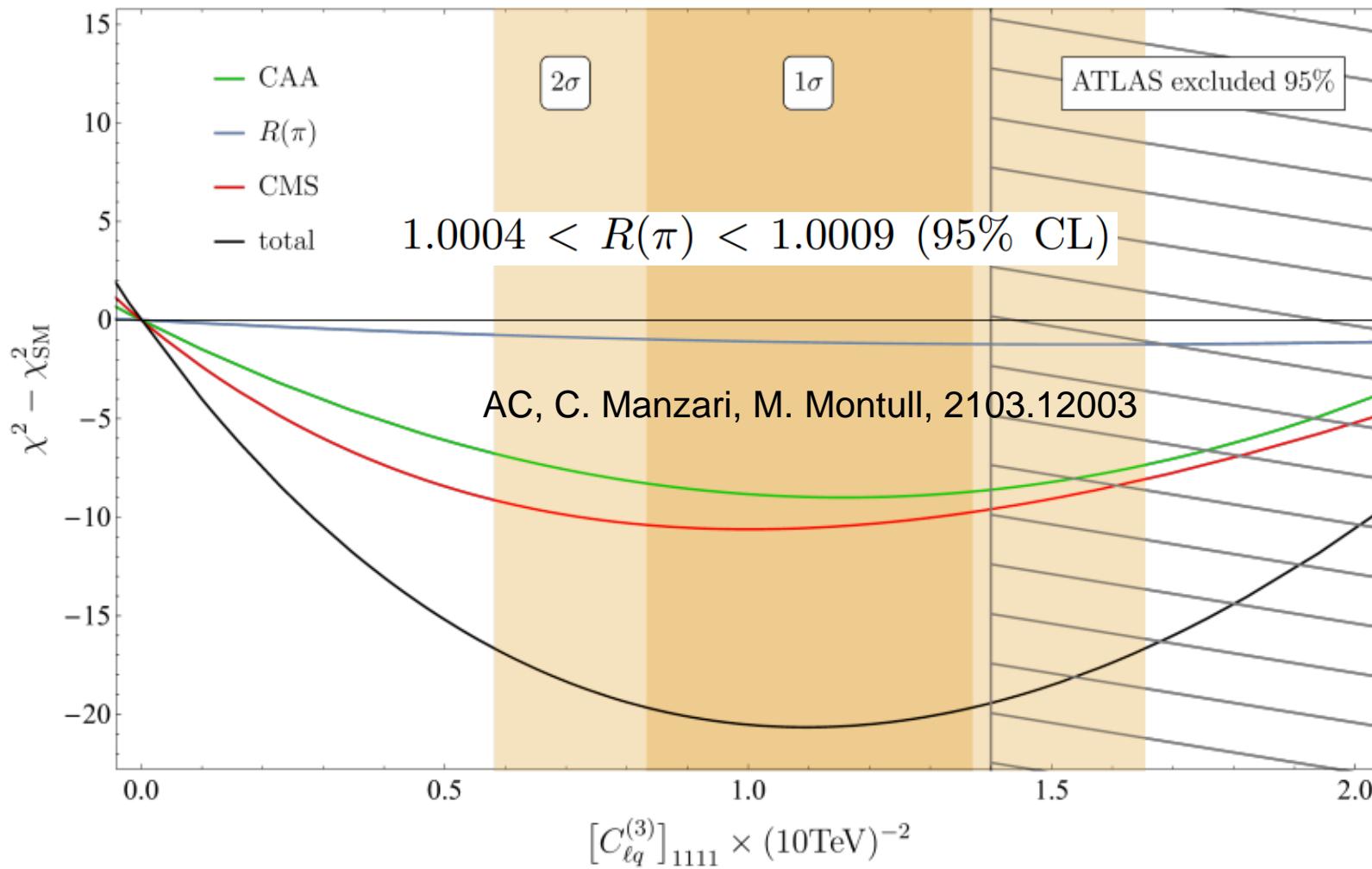
Model for $b \rightarrow s\ell\ell$, CAA, $Z \rightarrow bb$ and $\tau \rightarrow \mu\nu\nu$



- Z' penguin + modified Z_{sb} coupling give very good fit to $b \rightarrow s\ell\ell$ data

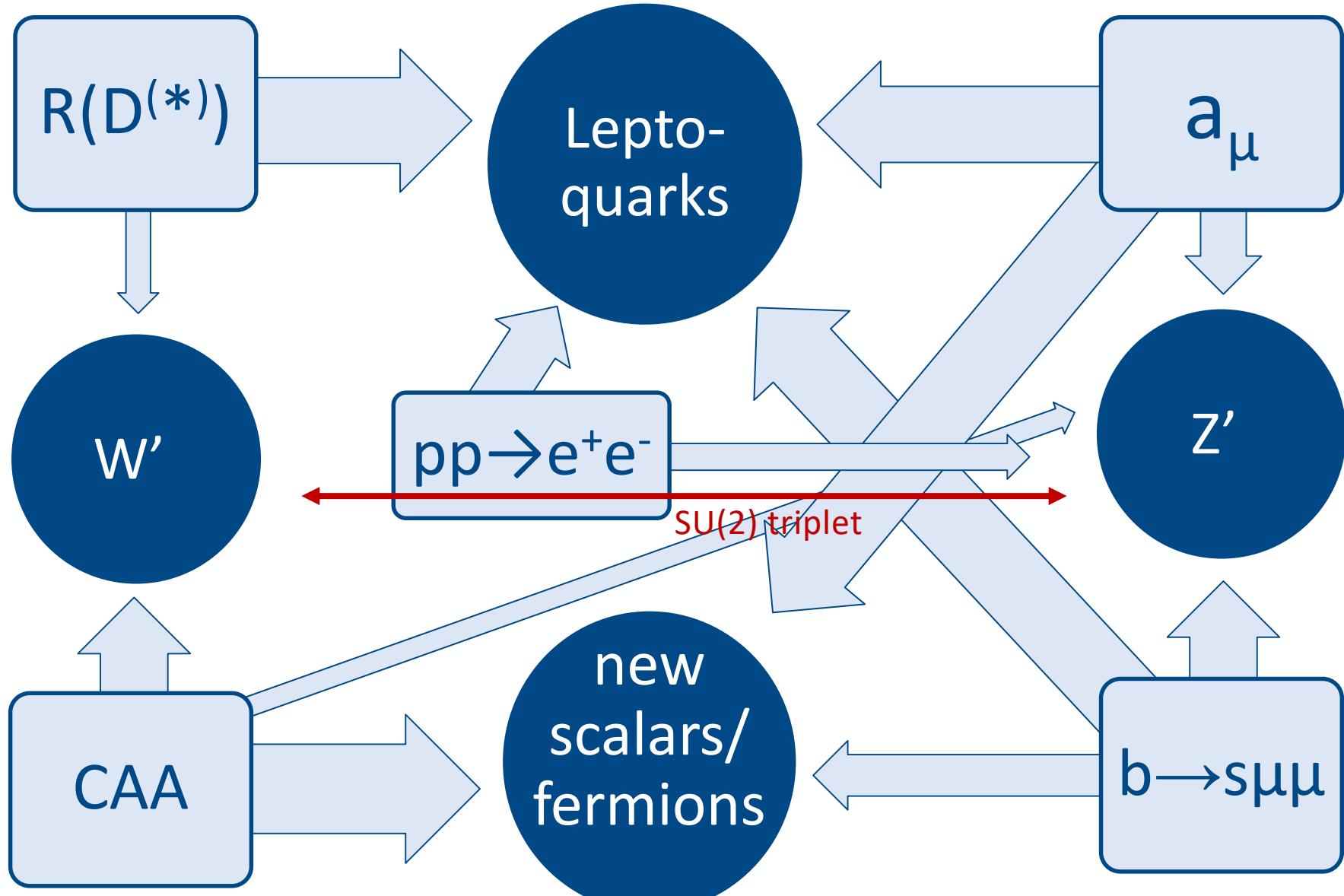
Simple model provides combined explanation

CAA and Non-Resonant Di-Leptons



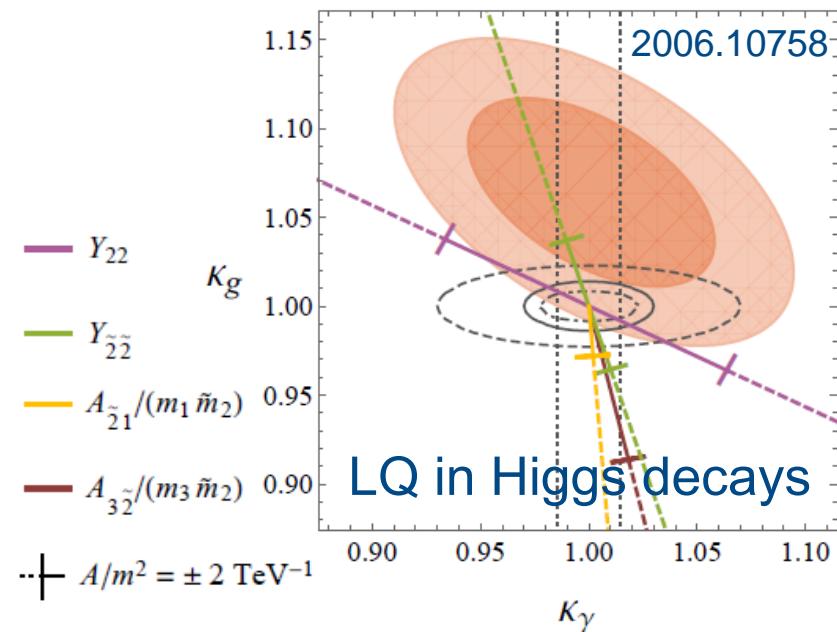
4.5 σ better than SM, prediction for $R(\pi)$

Conclusions



Outlook: Physics at Future Colliders

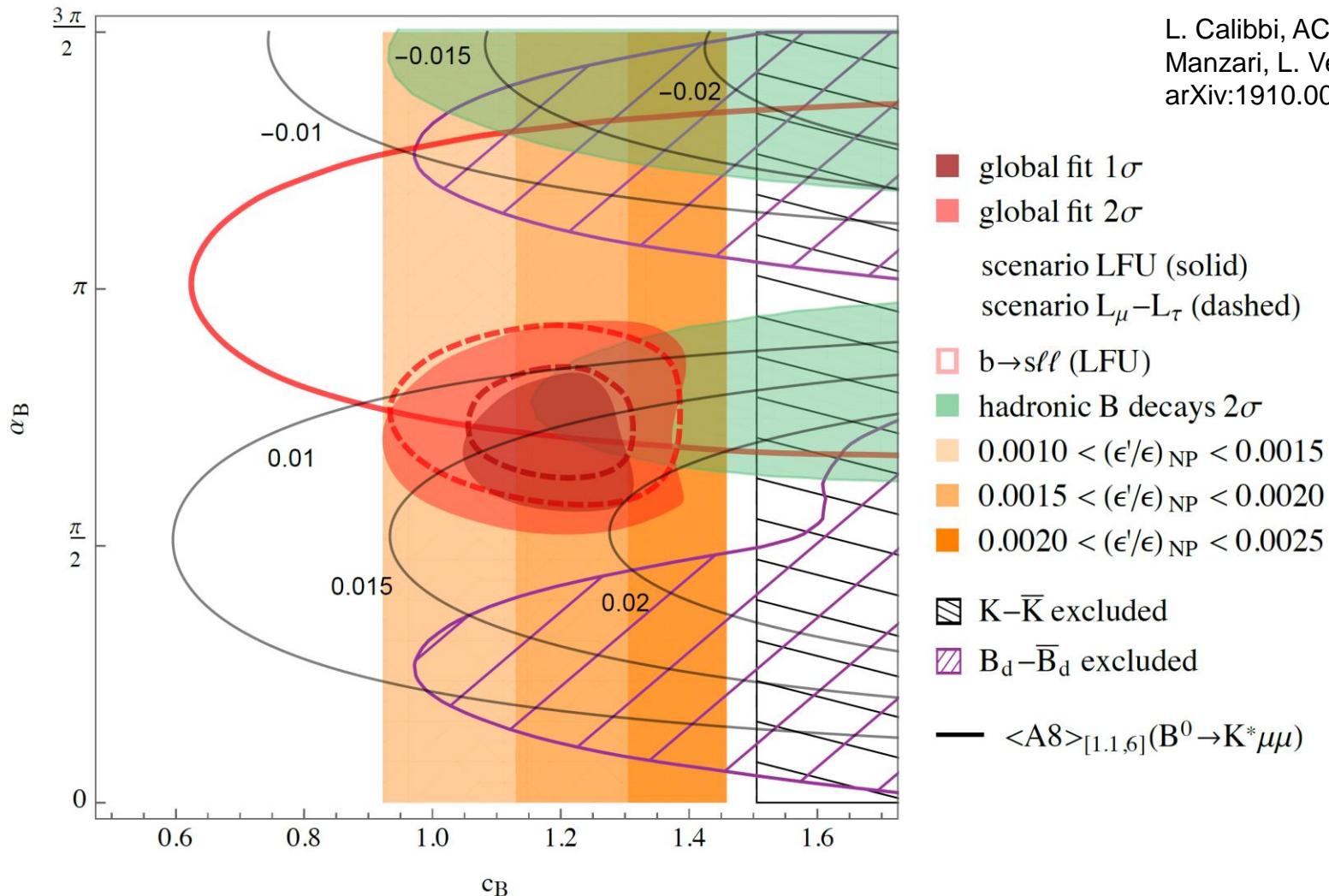
- Flavour Anomalies require NP at the TeV scale
→ Direct Searches at HL-LHC, HE-LHC, FCC-pp
- This new particles in general also affect EW precision observables
→ Z decays at CLIC and FCC-ee
- Flavour is directly linked to the Higgs boson
→ CLIC, FCC



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

Backup

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

- 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

$$\eta_{00} = \frac{A(K_L \rightarrow \pi^0 \pi^0)}{A(K_S \rightarrow \pi^0 \pi^0)}, \quad \eta_{+-} = \frac{A(K_L \rightarrow \pi^+ \pi^-)}{A(K_S \rightarrow \pi^+ \pi^-)}$$
$$\eta_{00} = \varepsilon - \frac{2\varepsilon'}{1 - \sqrt{\omega}} \simeq \varepsilon - 2\varepsilon', \quad \eta_{+-} = \varepsilon + \frac{\varepsilon'}{1 + \omega/\sqrt{2}} \simeq \varepsilon + \varepsilon'$$

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

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

Measurement $\approx 3\sigma$ above the SM prediction

Hadronic B decays

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



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Zürich^{UZH}

- Longstanding $B \rightarrow \pi K$ Puzzle

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

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

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

- More observables like

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

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

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

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

CP and
isospin
violation
needed

Similar
picture
in D decays

Global fit to data: $2-3\sigma$

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

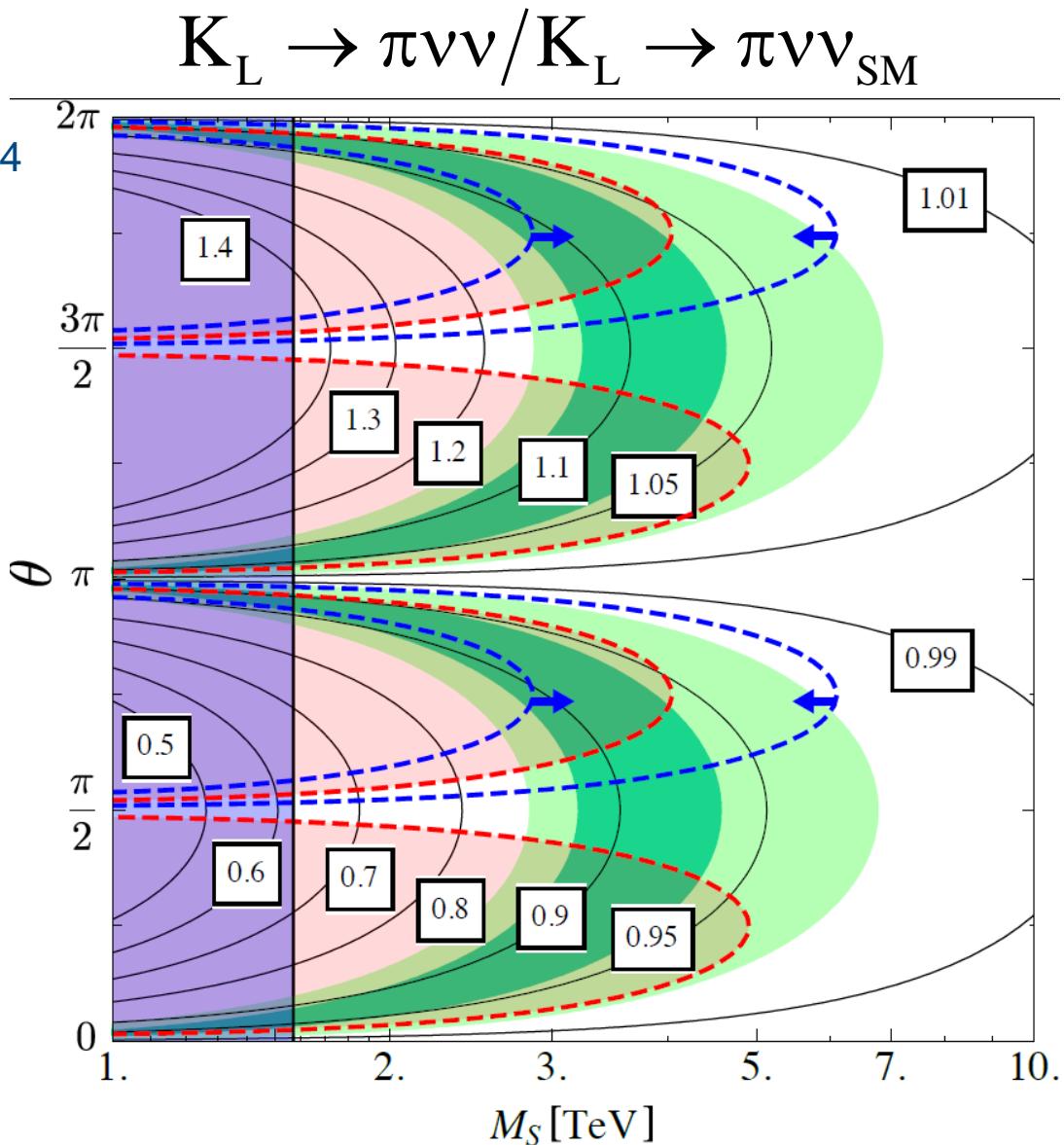
A. Buras and F. De Fazio,
arXiv:1512.02869

- MSSM

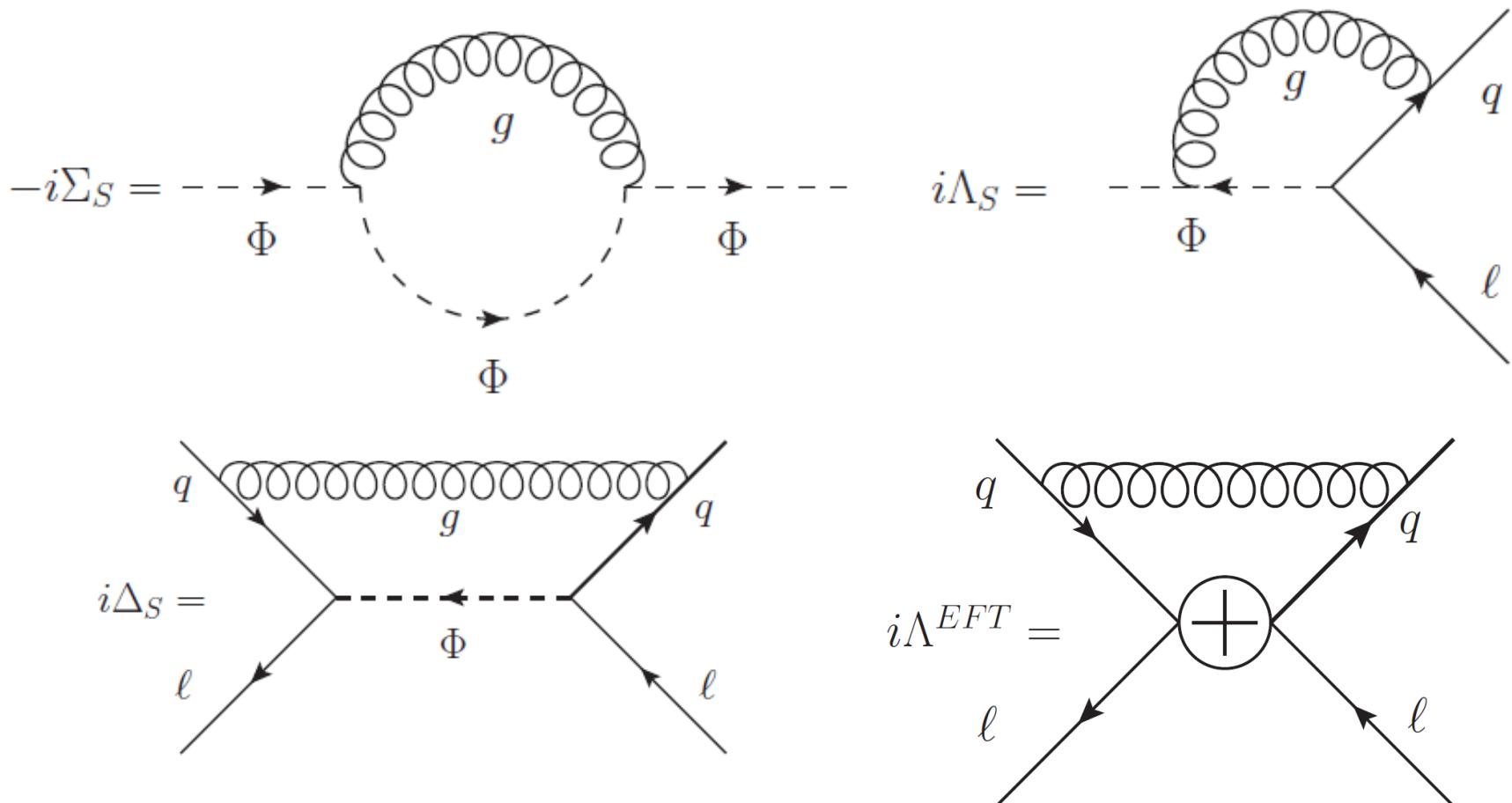
T. Kitahara, U. Nierste,
P. Tremper, arXiv:1604.07400
M. Endo, et al. arXiv:1608.01444
A. Crivellin, G. D'Ambrosio,
T. Kitahara and U. Nierste,
arXiv:1703.05786

 LHC excluded

 ε'/ε

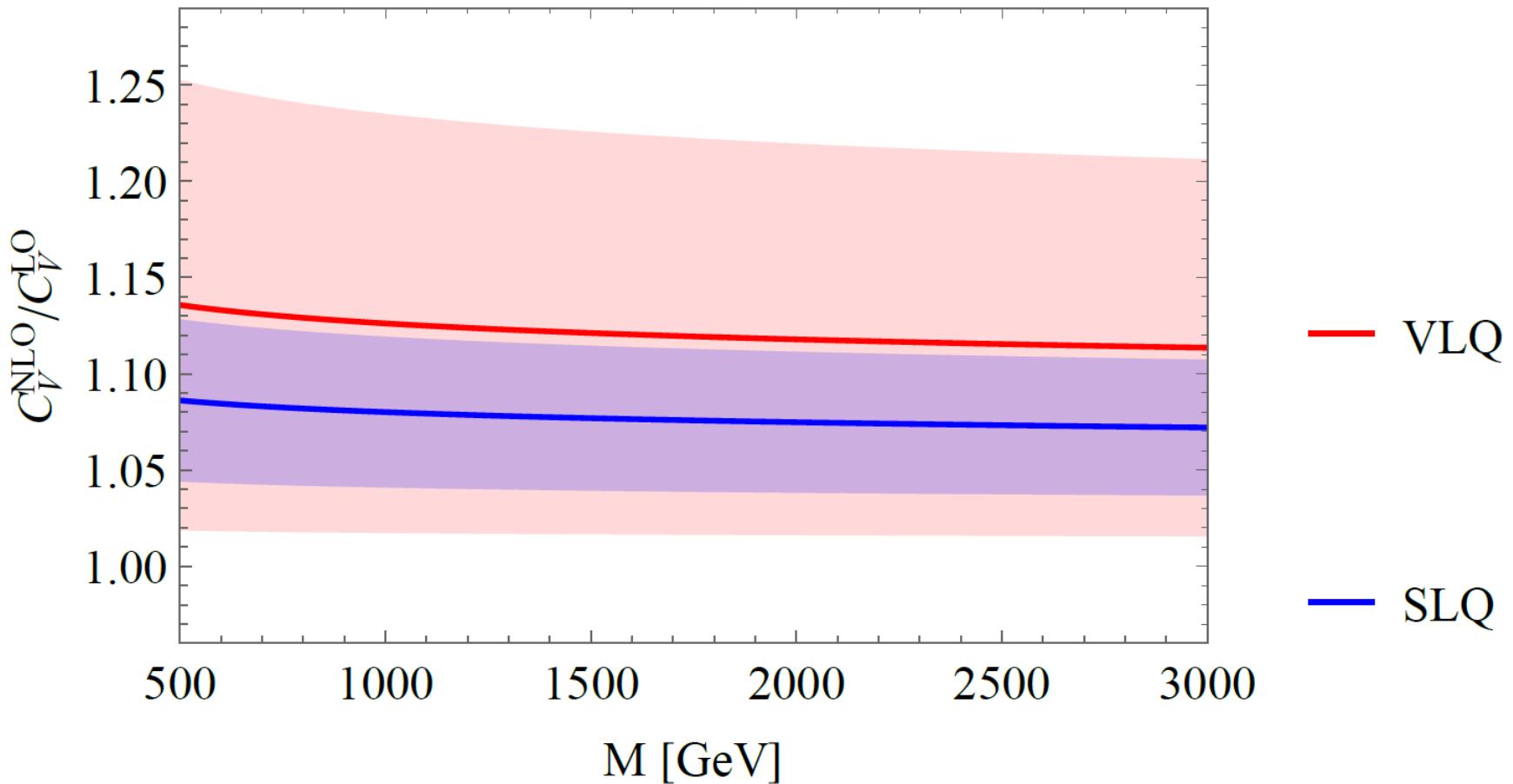


QCD corrections to the Matching



- Perform matching
- Correct for 4-dimensional Fierz identities

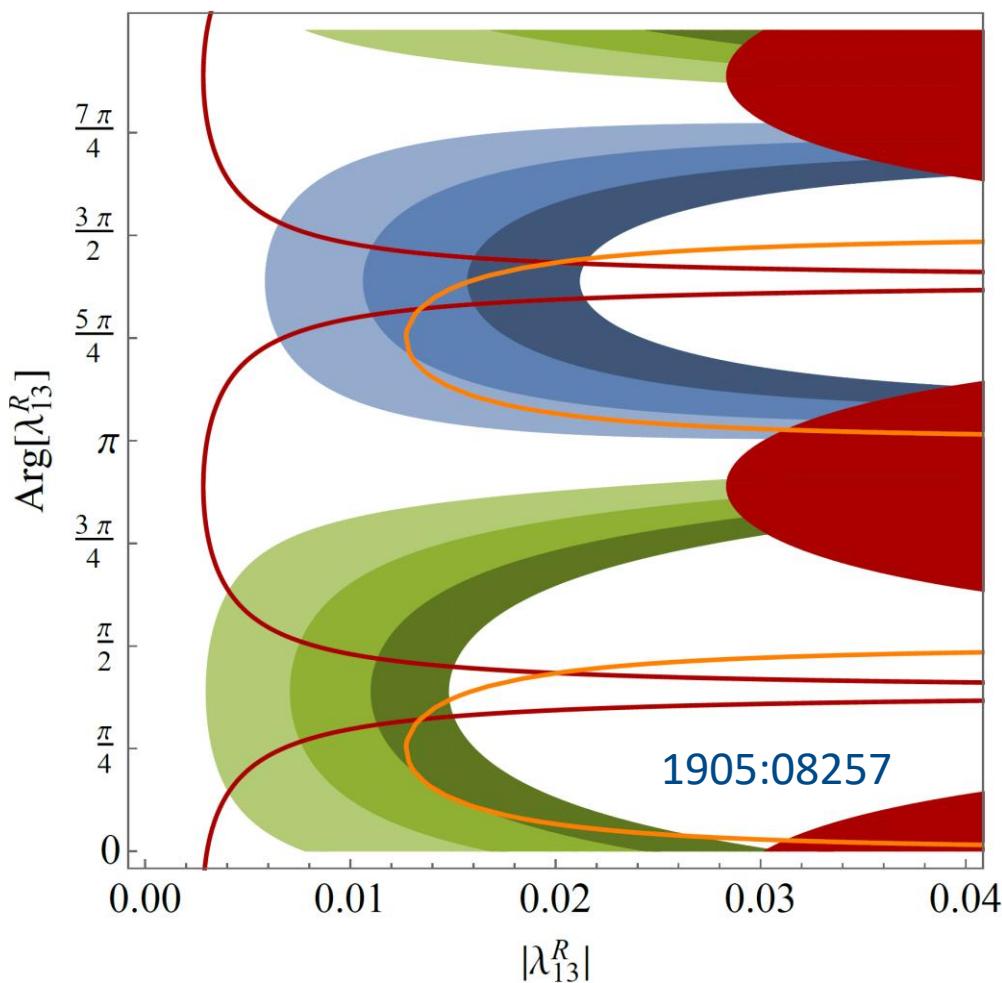
Results



J. Aebischer, AC, C. Greub, 1811.08907

Slightly weaker LHC constraints

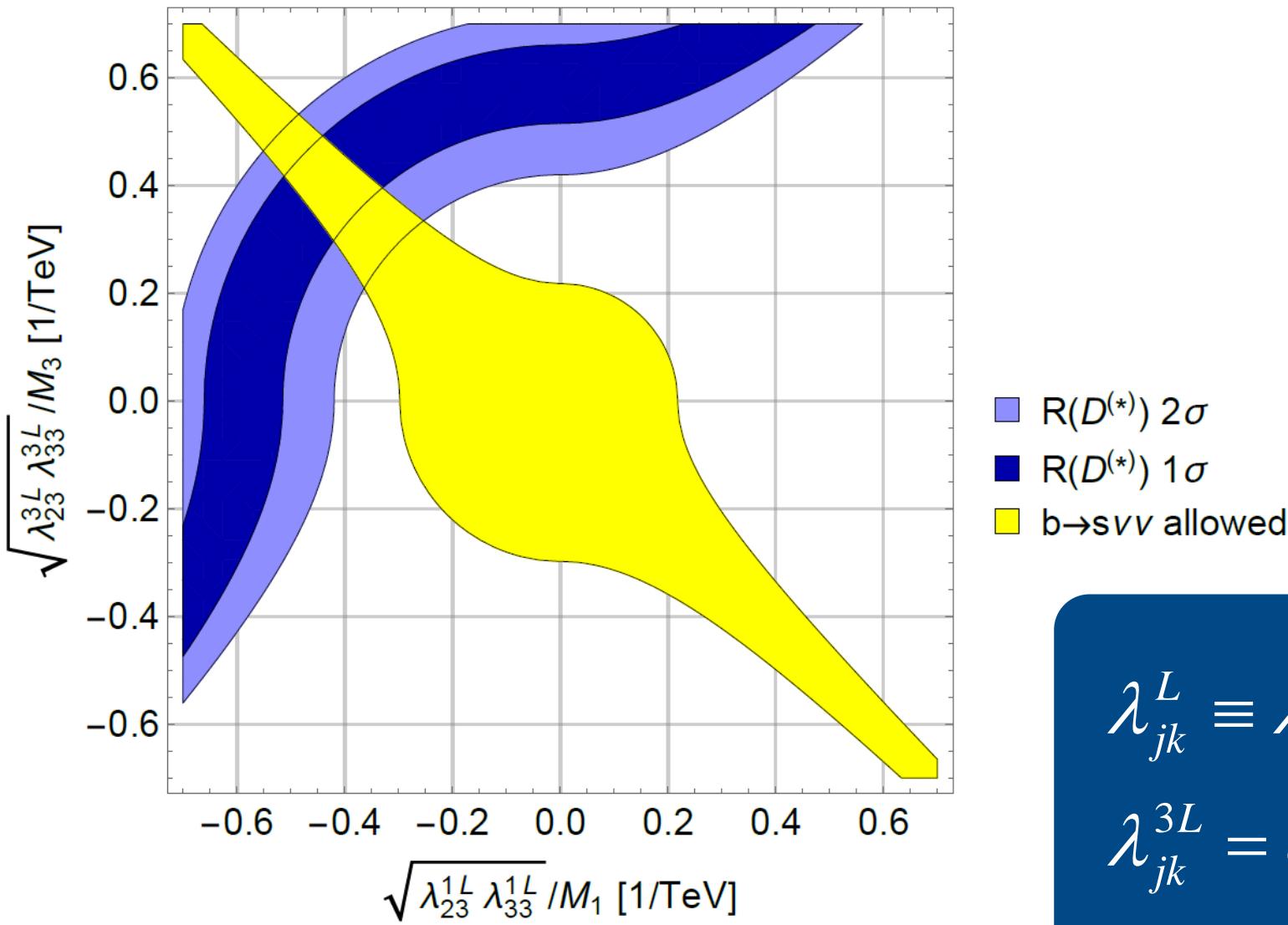
Correlations the neutron EDM with S1



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

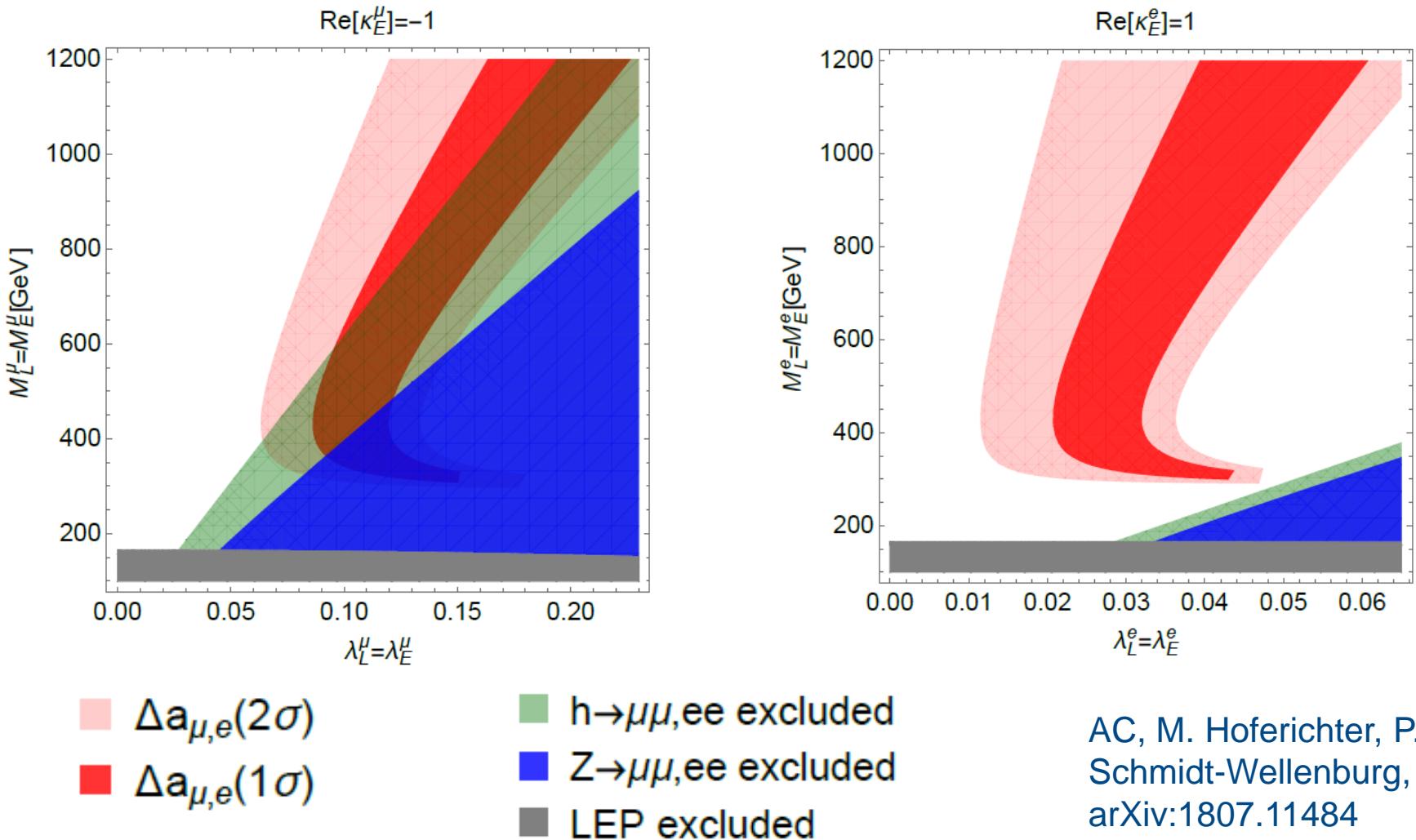
$R(D^{(*)})$, $b \rightarrow svv$ with 2 Scalar LQs



■ $R(D^{(*)}) 2\sigma$
■ $R(D^{(*)}) 1\sigma$
■ $b \rightarrow svv$ allowed

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

Model with new vector-like leptons

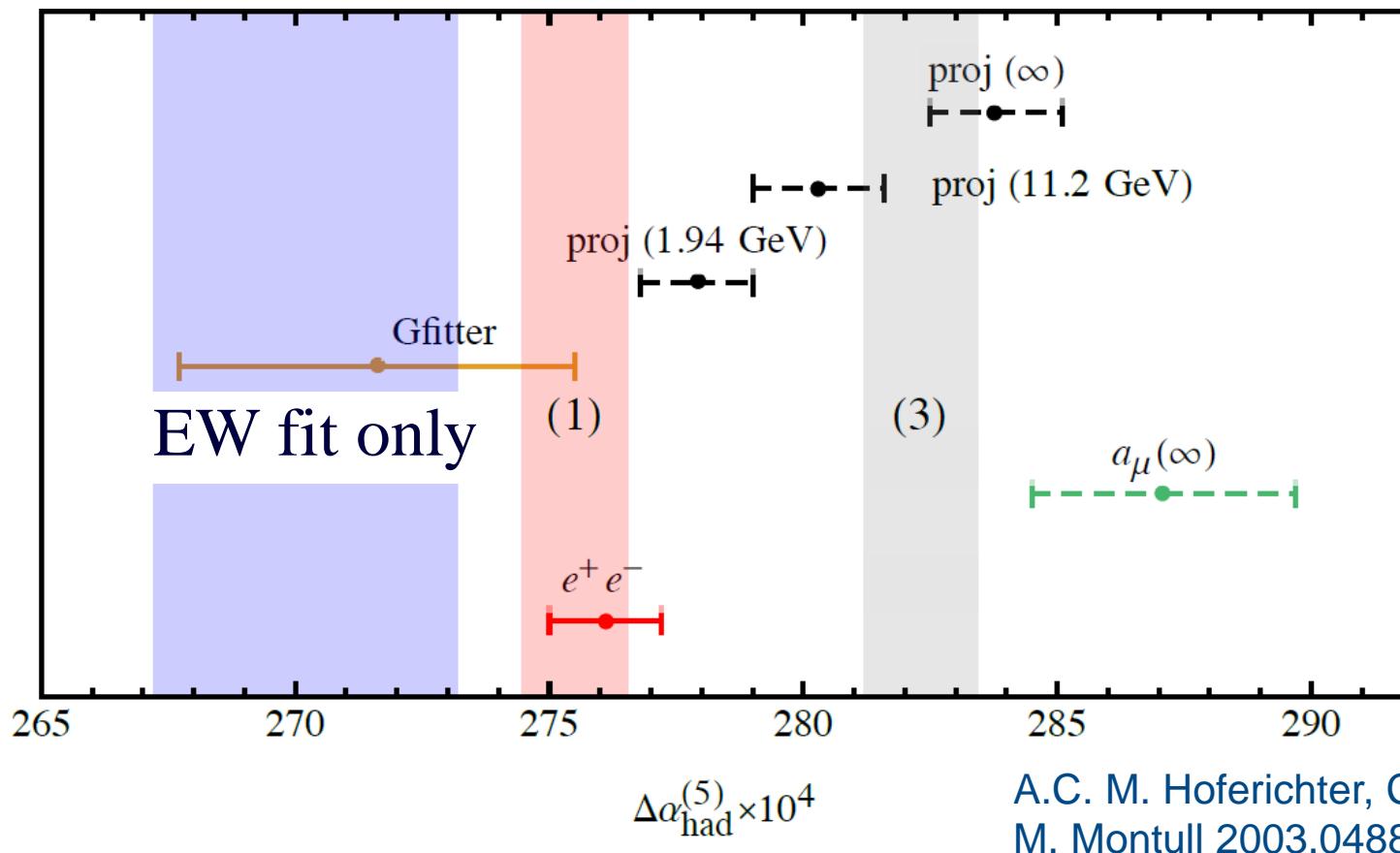


AC, M. Hoferichter, P.
Schmidt-Wellenburg,
arXiv:1807.11484

Works for a_e but tension with a_μ

Hadronic Vacuum Polarization

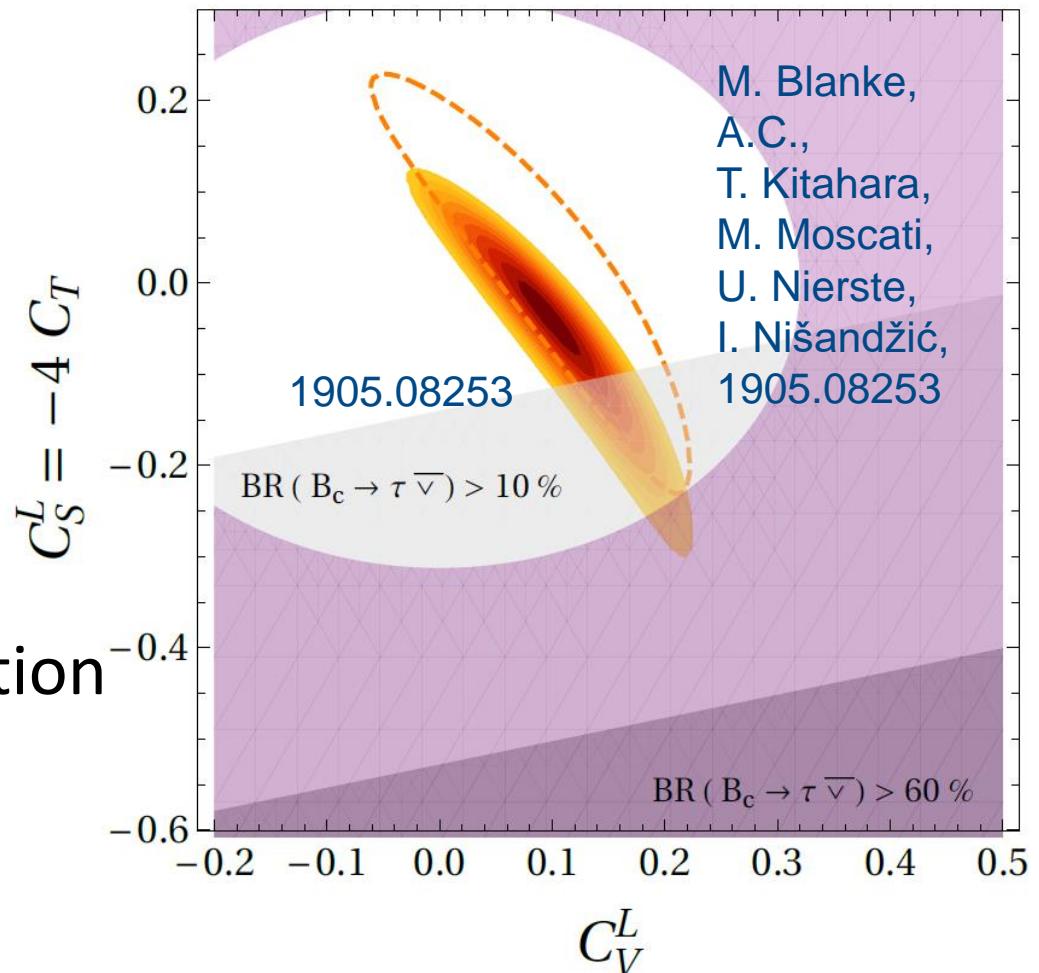
- New BMWc lattice QCD result



Up to 4σ tension in EW fit

$b \rightarrow c\tau\nu$ Global Fit

- Pure scalar-tensor explanations in tension with the B_c lifetime
- Pure left-handed vector, i.e. contribution to the SM operator gives good fit



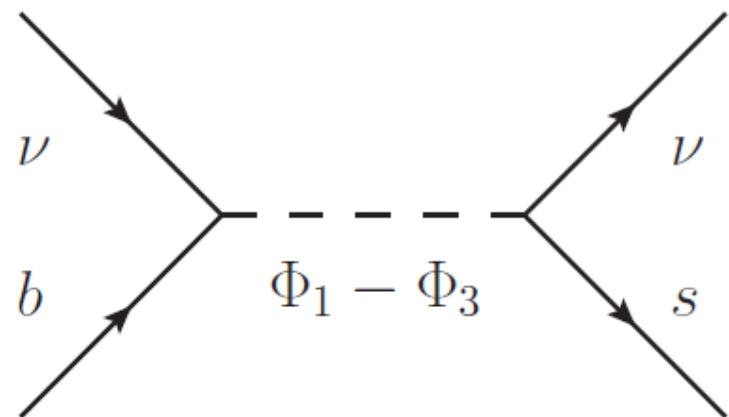
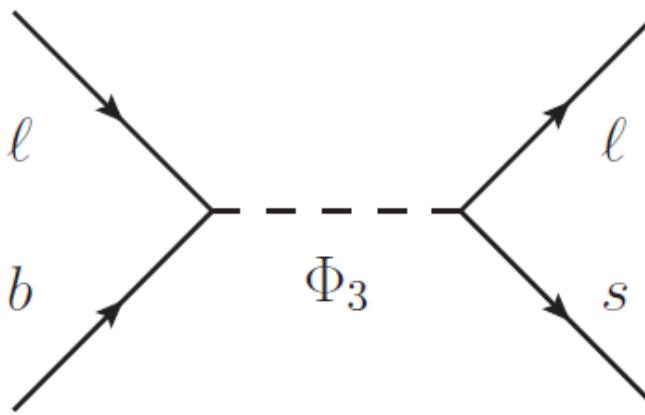
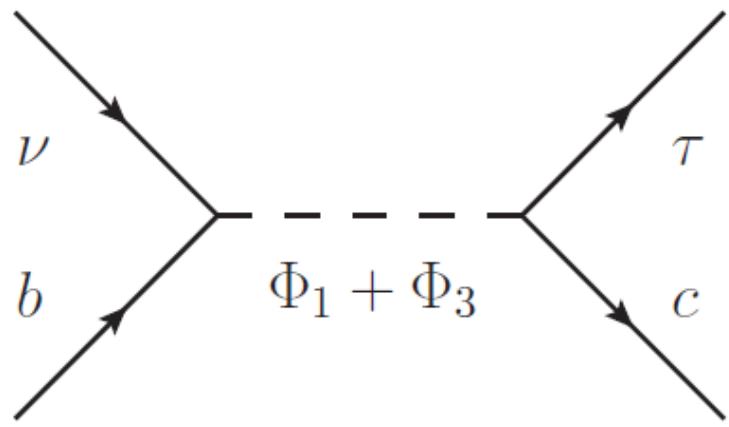
Global fit give up to 4σ preference for NP

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 $b \rightarrow s \mu \mu$

R(D^(*)), b→sll and a_μ

■ 4 benchmark points

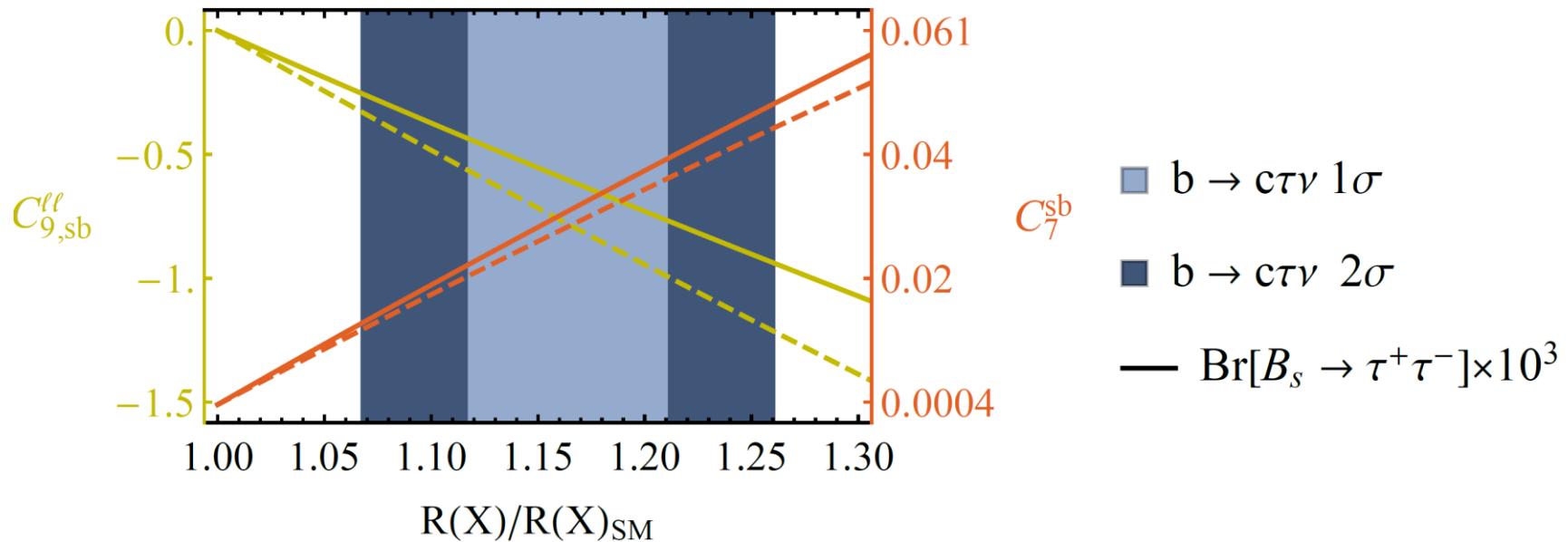
AC, D. Mueller, F. Saturnino
arxiv:1912.04224

	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
	$C_9^{\mu\mu} = -C_{10}^{\mu\mu}$	$C_9^{\ell\ell}$	$\frac{R(D)}{R(D)_{\text{SM}}}$	$\frac{R(D^*)}{R(D^*)_{\text{SM}}}$	$\frac{B_s \rightarrow \tau\tau}{B_s \rightarrow \tau\tau _{\text{SM}}}$	$\tau \rightarrow \mu\gamma$ $\times 10^8$	δa_μ $\times 10^{11}$	$\tilde{V}_{cb}^e/\tilde{V}_{cb}^\mu - 1$ $\times 10^6$	$Z \rightarrow \tau\mu$ $\times 10^{10}$	
● 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	
	$C_{SL}^{\tau\tau} = -4C_{TL}^{\tau\tau}$	$C_{VL}^{\tau\tau}$	$R_{\nu\nu}^{K(*)}$	$\frac{\Delta m_{B_s}^{\text{NP}}}{\Delta m_{B_s}^{\text{SM}}}$	$B \rightarrow K\tau\mu$ $\times 10^5$	$\tau \rightarrow \phi\mu$ $\times 10^8$	$\tau \rightarrow \mu ee$ $\times 10^{11}$	$ \Lambda_{33}^{\text{LQ}}(0) $ $\times 10^5$	$\frac{\Delta_{33}^L(m_Z^2)}{\Lambda_{\text{SM}}^{L\ell} \times 10^{-5}}$	
● 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 $b \rightarrow c\tau\nu$ requires large $b\tau$ and $s\tau$ couplings (follows from SU(2) invariance)

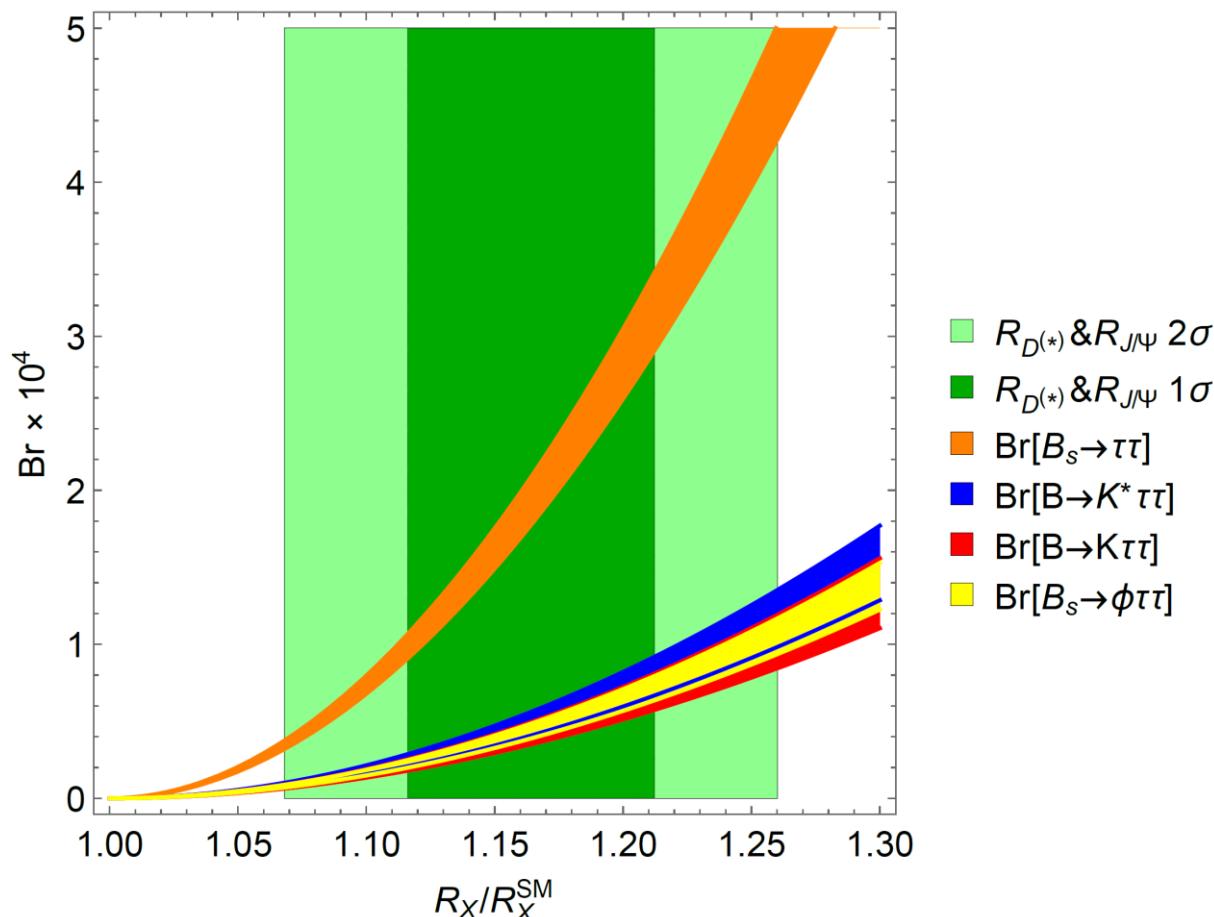


AC, C. Greub, D. Müller,
F. Saturnino, PRL 2018

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

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

- Large couplings to the second generation



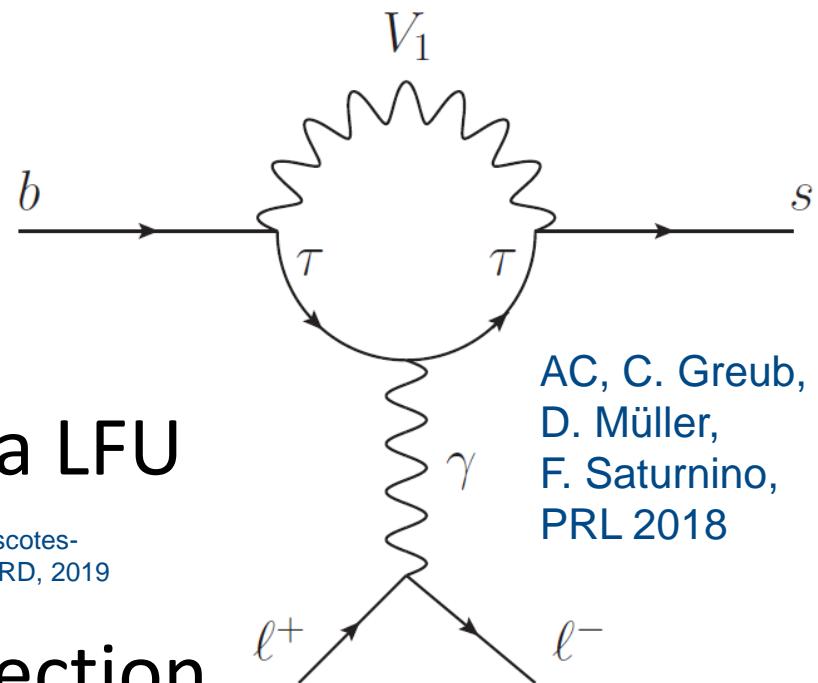
$b \rightarrow s\tau\tau$
very
strongly
enhanced

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

Important Loop-Effects

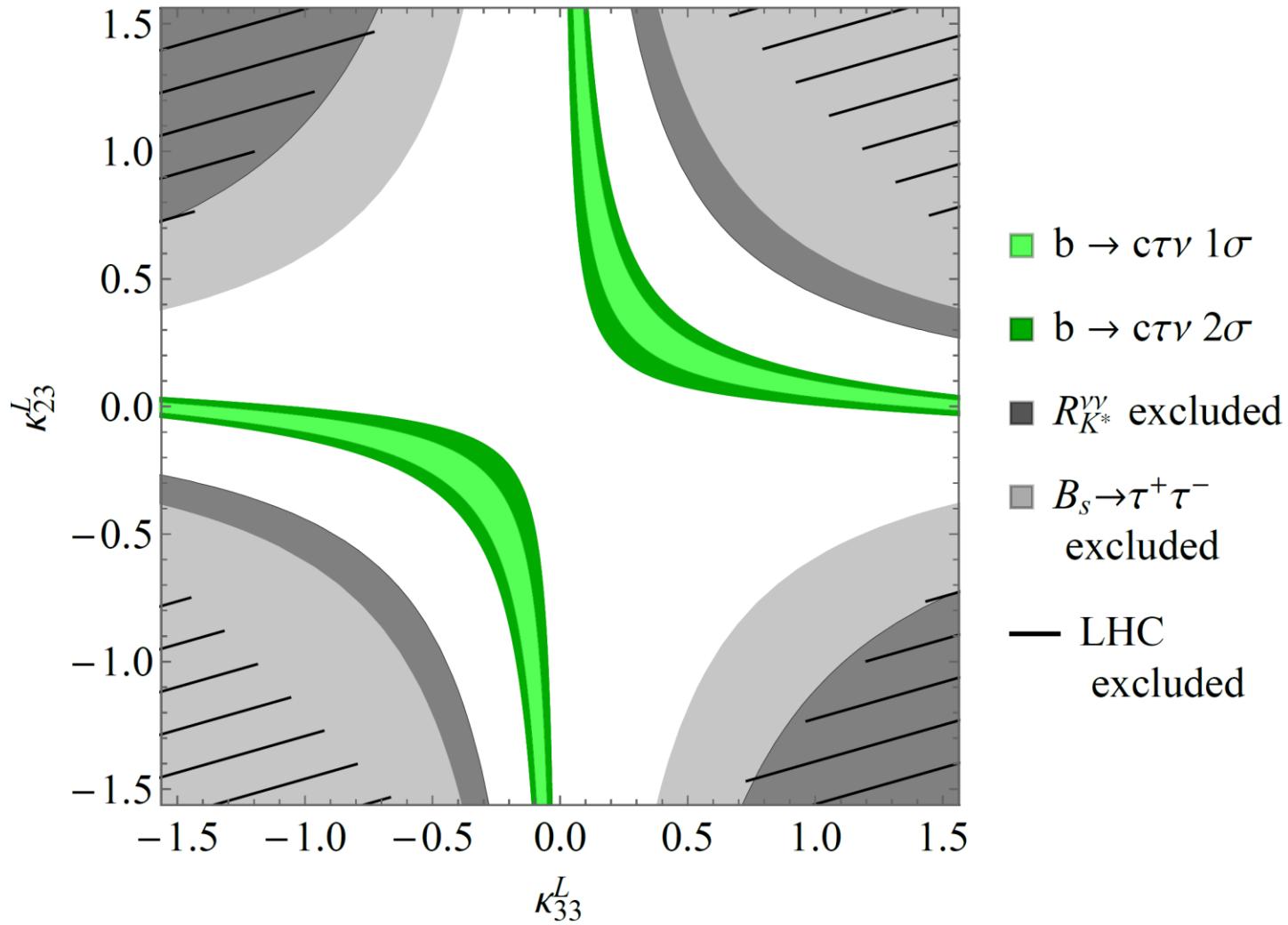
- Explanation of $b \rightarrow c\tau\nu$ requires large LQ- $b\tau$ and LQ- $c-\nu_\tau$ couplings
- Via SU(2) invariance this leads to large effects in $b \rightarrow s\tau\tau$ processes
- Closing the tau-loop gives a LFU effect in $b \rightarrow sll$
- Effect goes in the right direction

M. Algueró, B. Capdevila, S. Descotes-Genon, P. Masjuan, J. Matias, PRD, 2019



Explanation of $b \rightarrow c\tau\nu$ leads to
loop effects in $b \rightarrow s\mu\mu$

Vector LQ Phenomenology



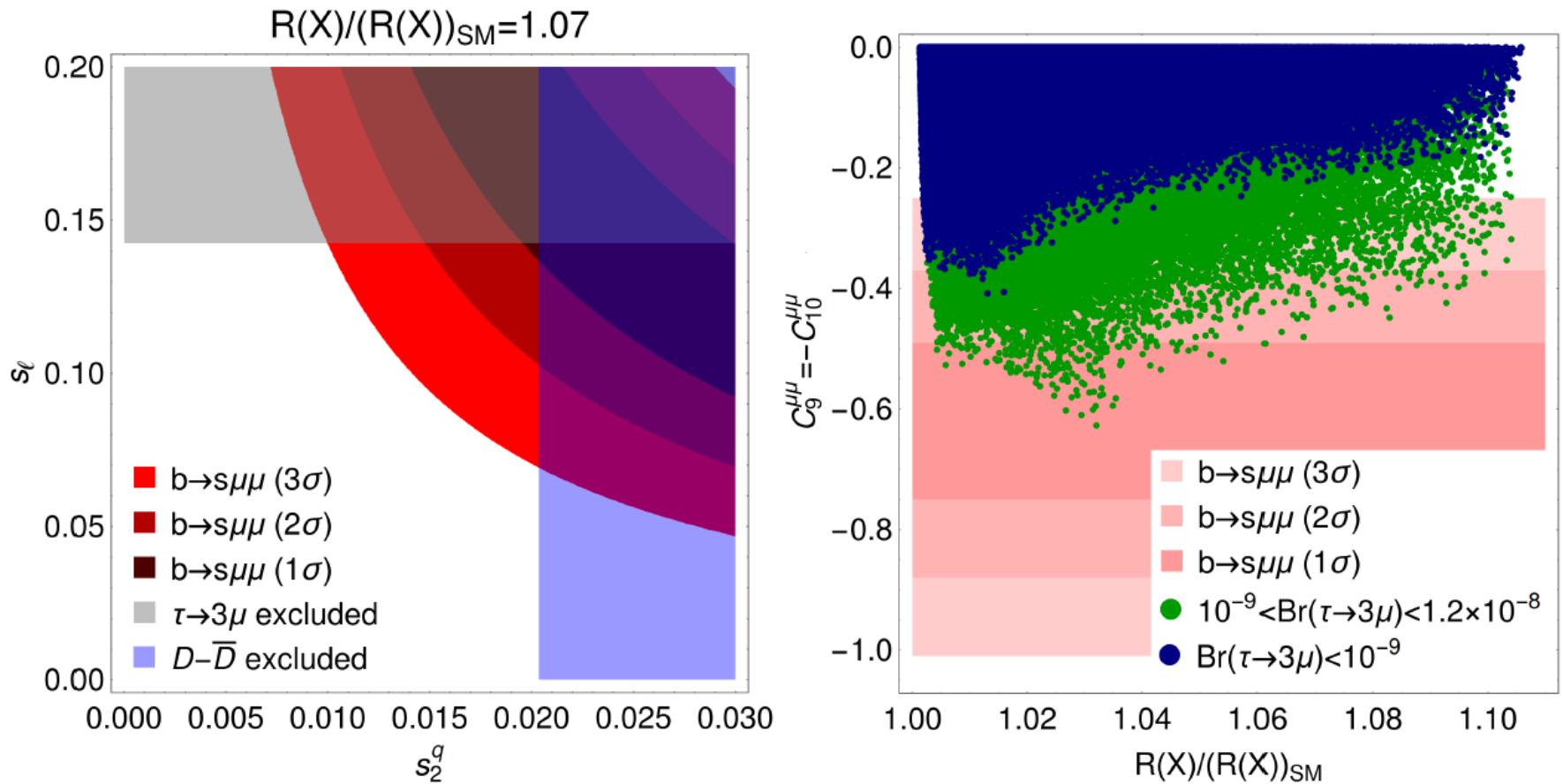
Compatible with constraints for generic couplings

Possible UV completions

- $SU(4) \times SU(3)' \times SU(2)_L \times U(1)_Y + \text{Vector-like fermions}$
L. Di Luzio, A. Greljo, M. Nardecchia, arXiv:1708.08450
- $SU(4) \times U(2)_L \times SU(2)_R + \text{Vector-like fermions}$
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. Blanke, AC, PRL 2018

Model well motivated + limited but sizable effect