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Discovering Lepton Flavour Universality Violating New Physics

Karlsruhe, 16.11.2021

Work supported by FNSNF

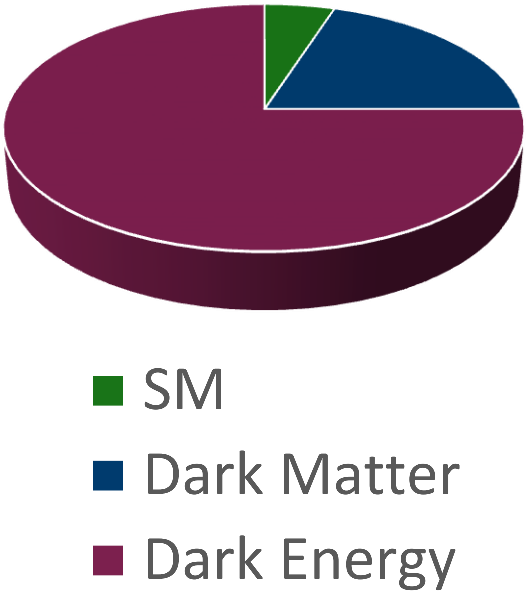
Outline

- Introduction
- Status of the Flavour anomalies
  - $b \to s\mu\mu$
  - $b \to c\tau\nu$
  - a_μ
  - $\tau \to \mu\nu\nu$
  - 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

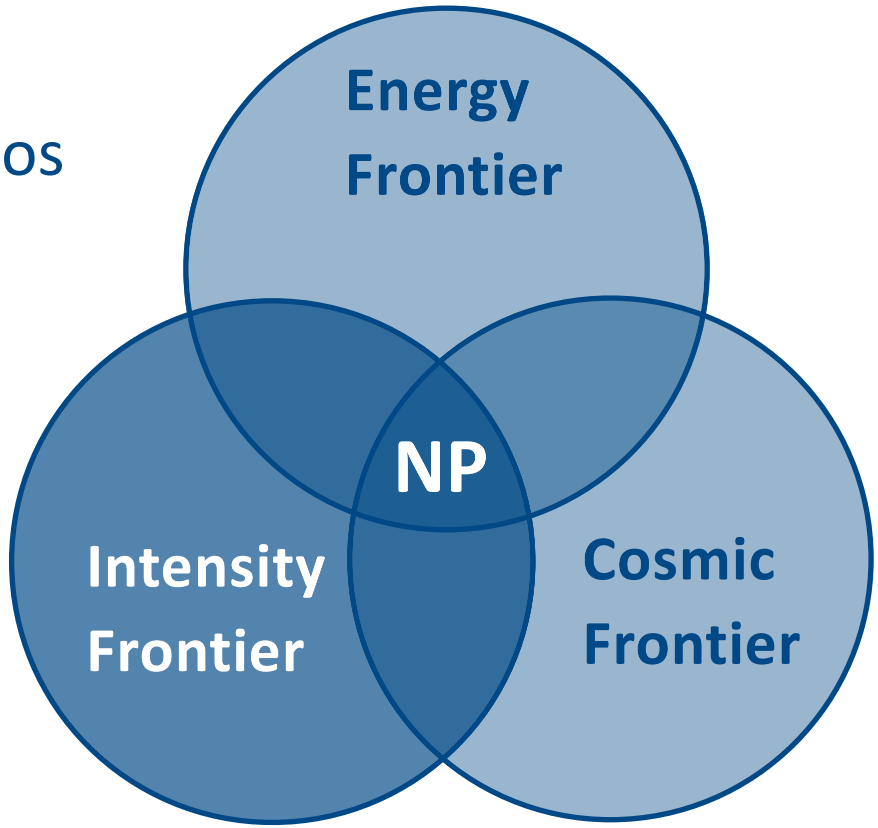
- Dark Matter existence established at cosmological scales
  - New weakly interacting particles
- Neutrinos not exactly massless
  - Right-handed (sterile) neutrinos
- Matter anti-matter asymmetry
  - Additional CP violating interactions



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

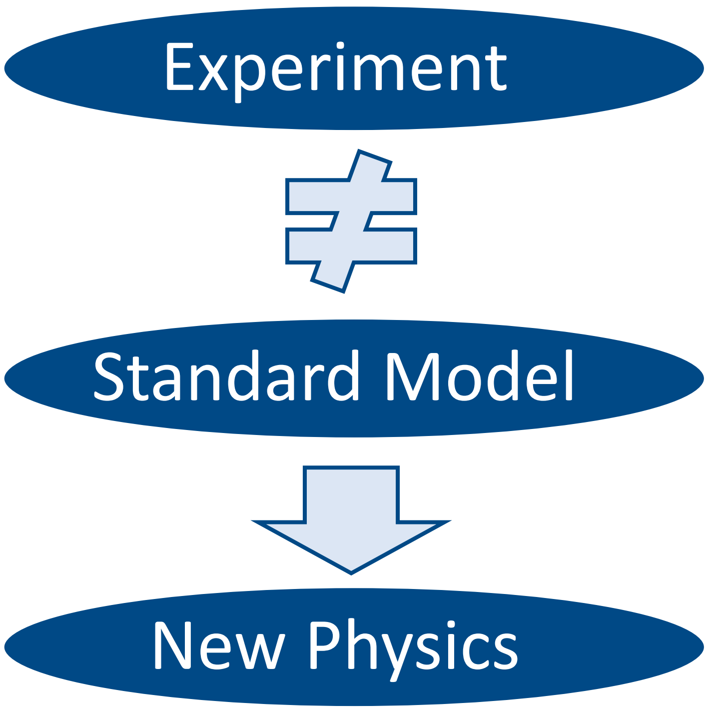
Discovering New Physics

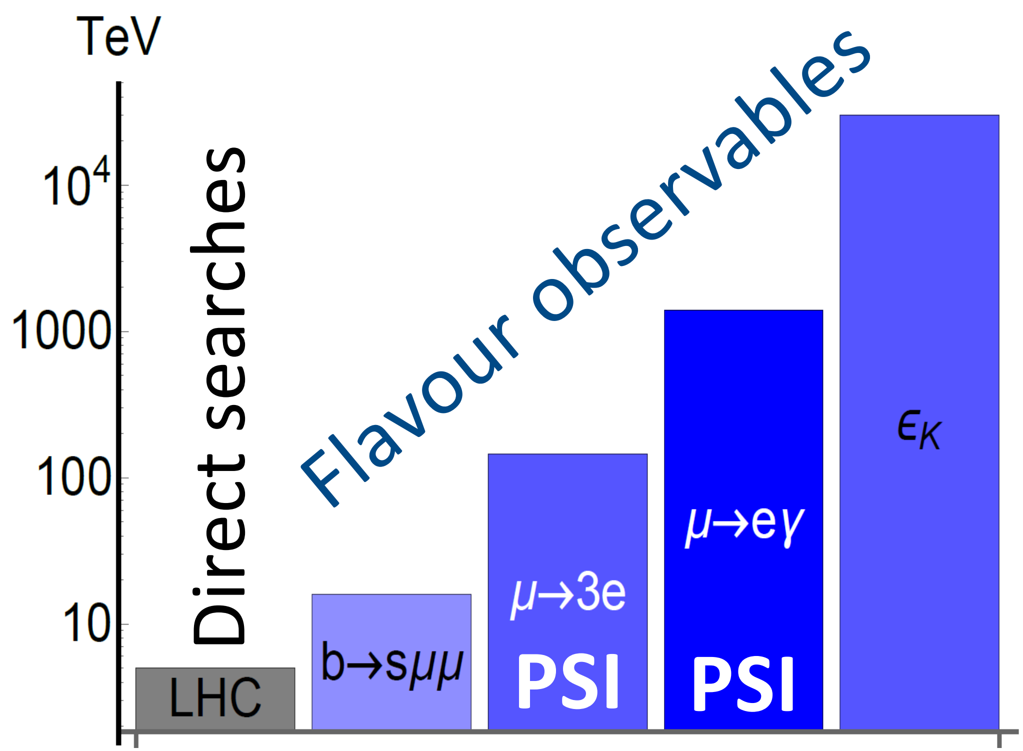
- Cosmic Frontier
  - Cosmic rays and neutrinos
  - Dark Matter
  - Dark Energy
- Energy Frontier
  - LHC
  - Future colliders
- Intensity Frontier
  - Flavour
  - Neutrino-less double-β decay
  - Test of fundamental symmetries
  - Proton decay



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



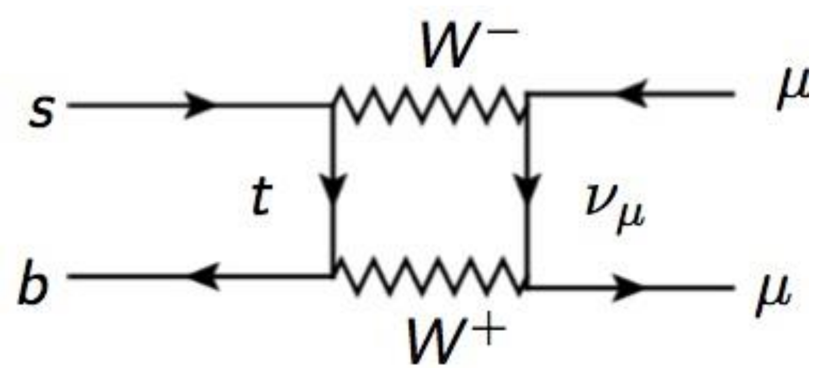


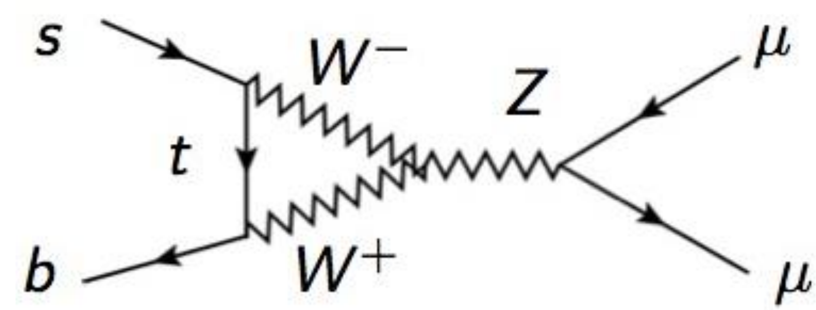
Flavour observables can be sensitive to higher energy scales than collider searches

Overview on the Flavour anomalies

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

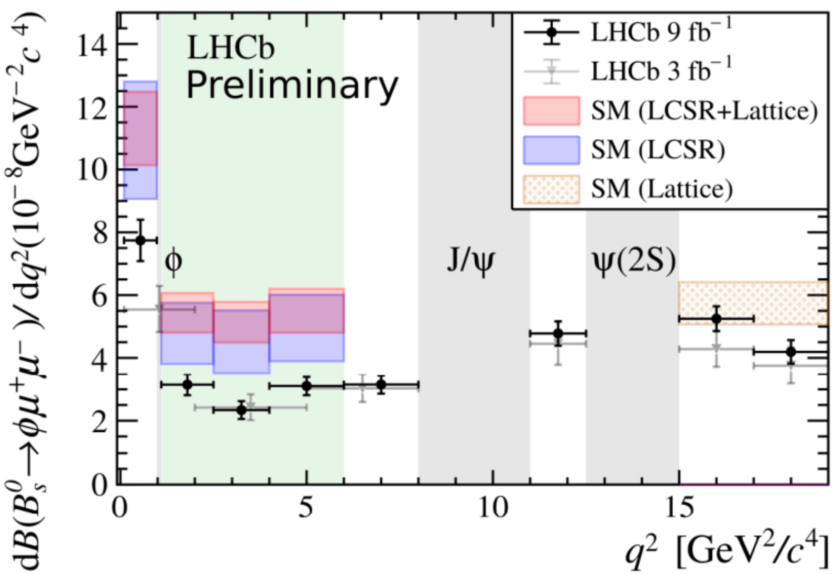


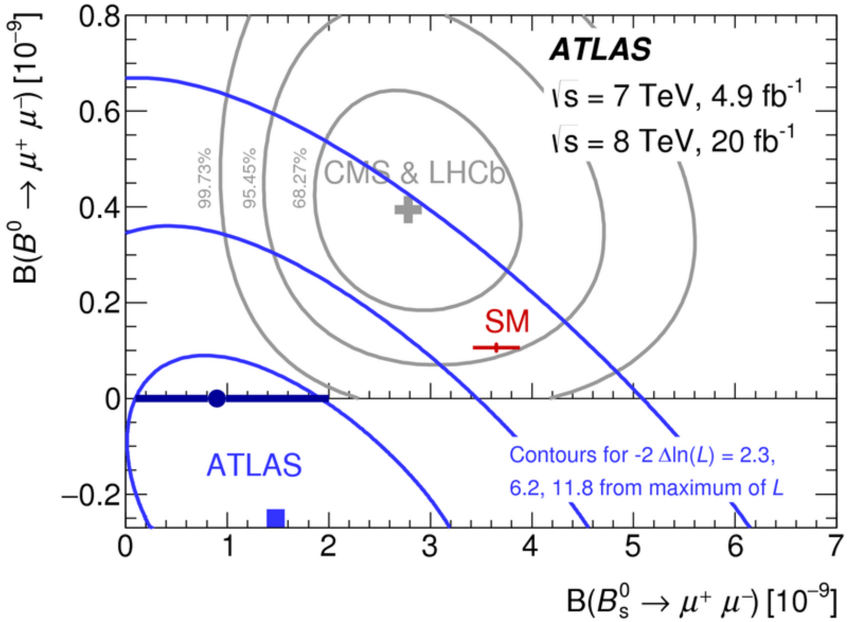


Suppressed in the SM and very sensitive to NP

$B_s \to \mu\mu$ and $B_s \to \phi\mu\mu$

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



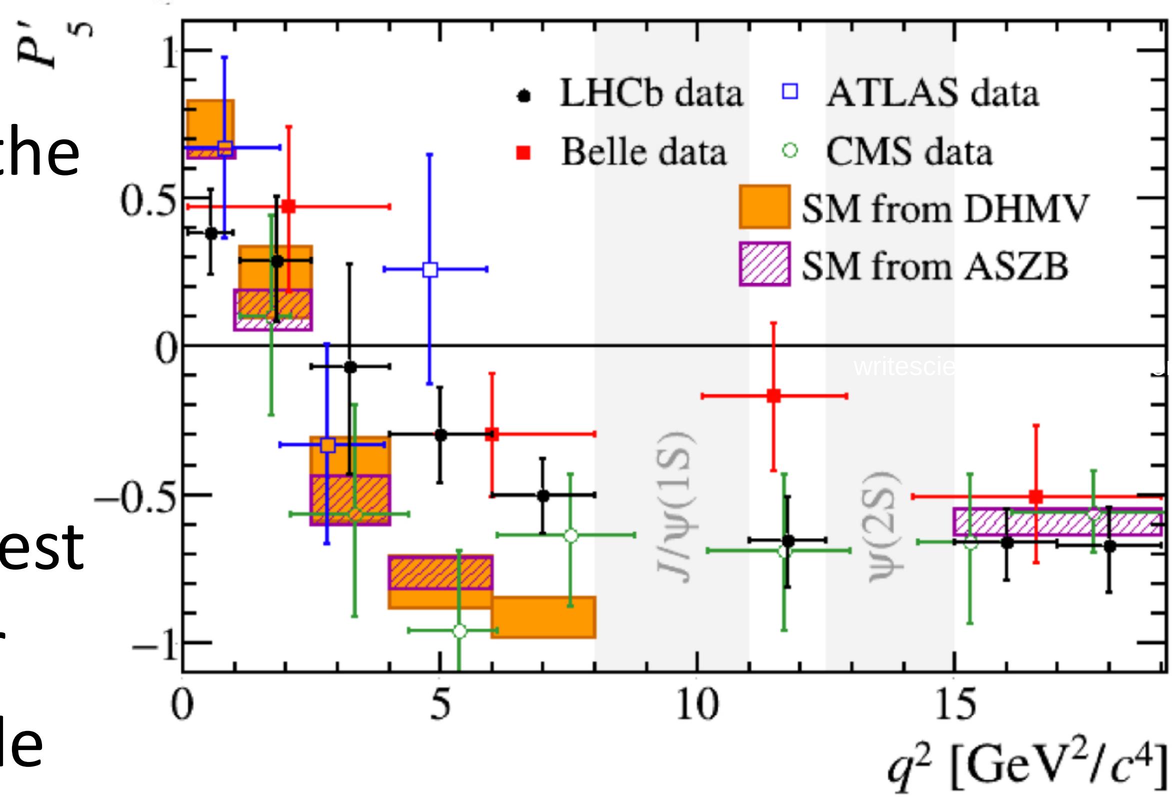


- $B_s \to \phi\mu\mu$ has a higher Br, but knowledge of the form-factor needed

Br's ≈ 20% below SM expectations

The P_5' Anomaly

- P_5´ angular observables in B→K*μμ 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

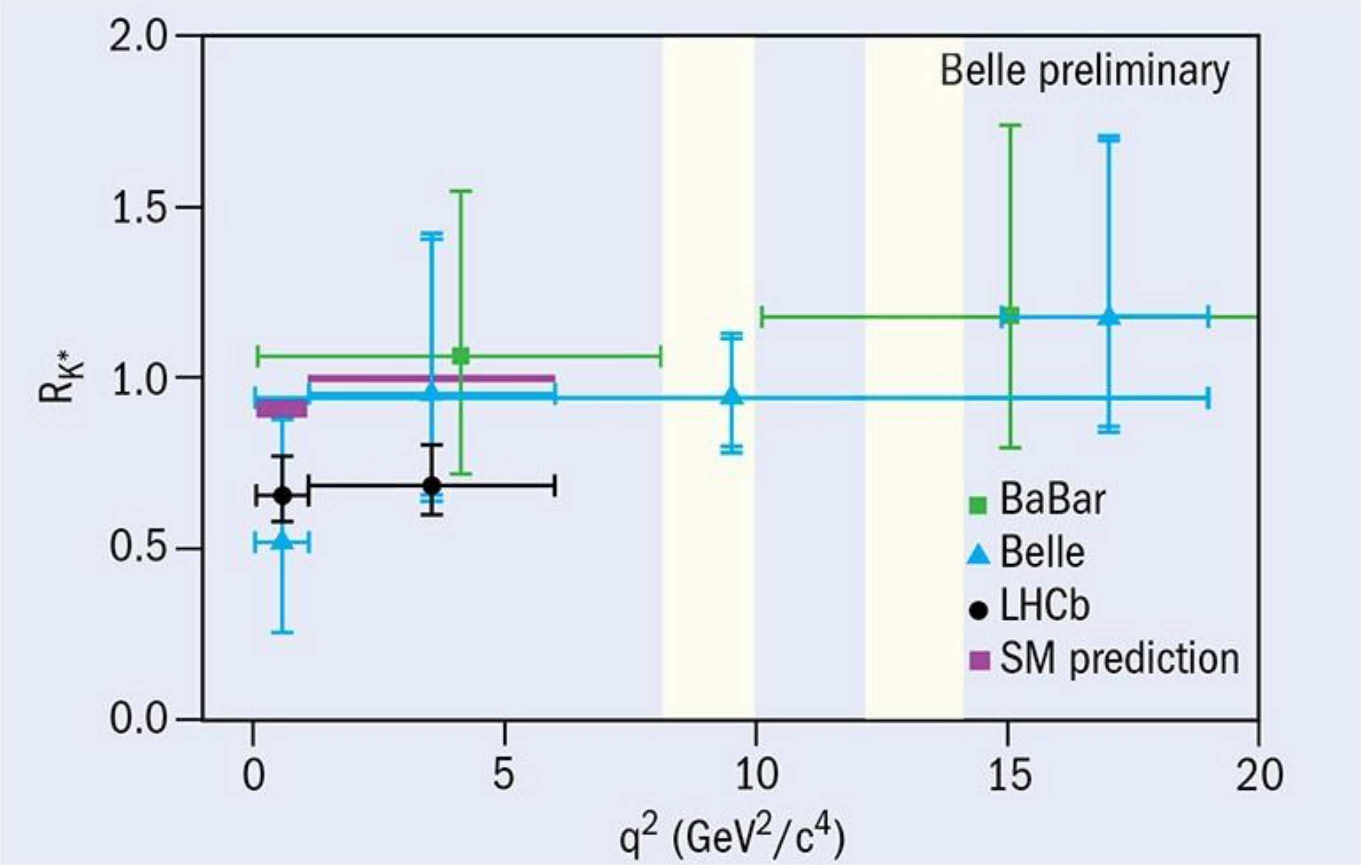


>3σ deviation from the SM prediction

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

Universität Zürich[UZH]

- Theoretically absolutely clean observable (in the SM)

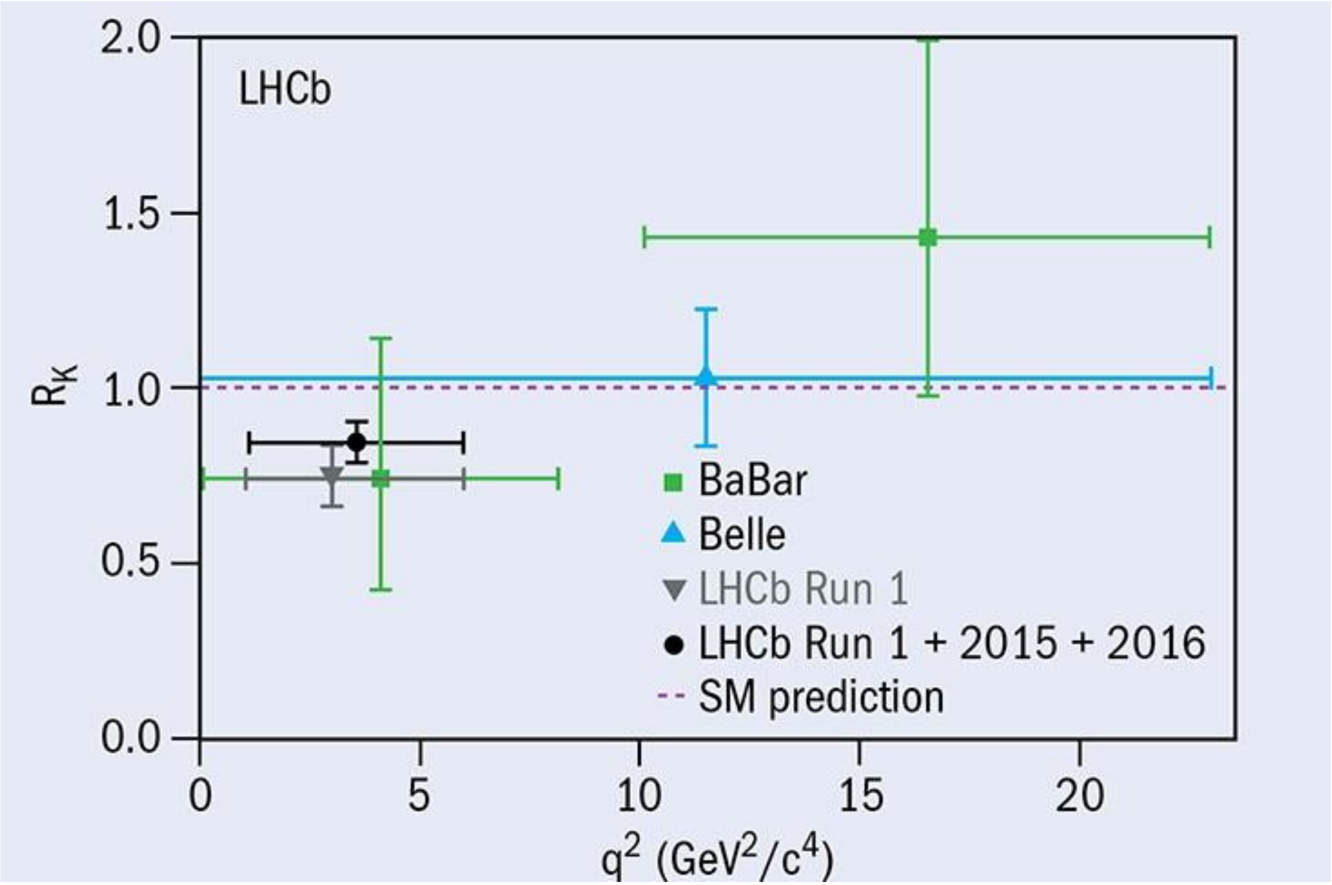


Lepton Flavour Violation in B decays?

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

Universität Zürich[UZH]

- Theoretically absolutely clean observable (in the SM)

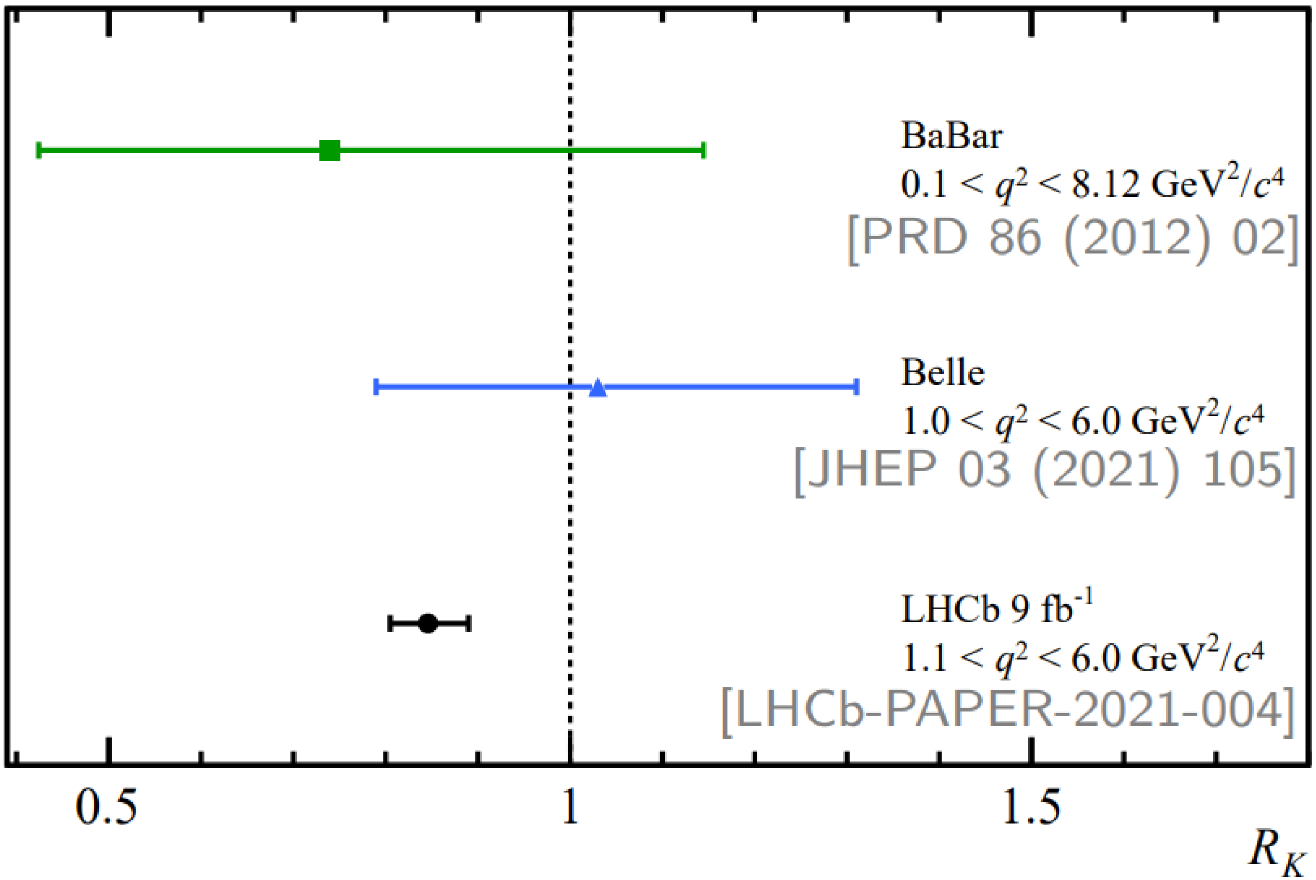


Lepton Flavour Violation in B decays?

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

Universität Zürich[UZH]

- Theoretically absolutely clean observable (in the SM)



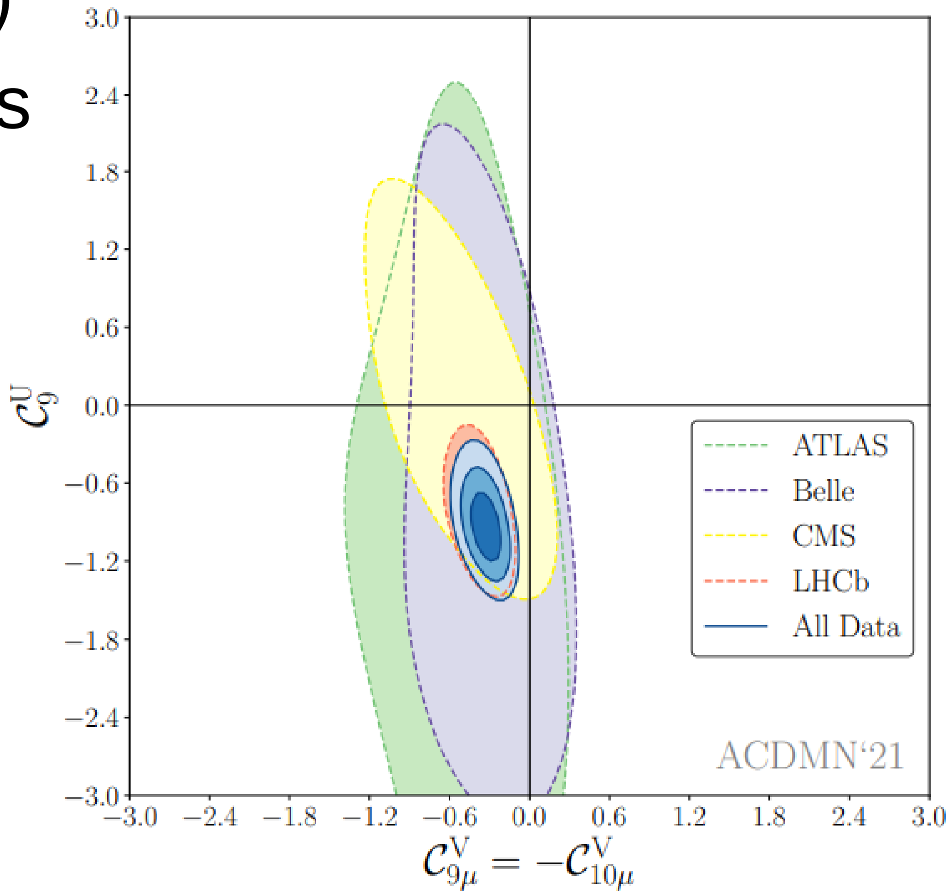
Lepton Flavour Violation in B decays?

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

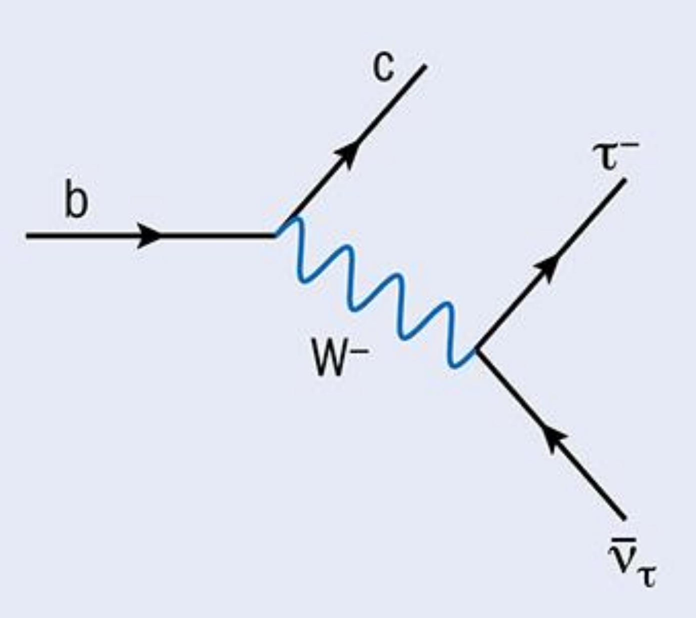
$$O_9 = \bar{s}\gamma^\mu P_L b \bar{\ell}\gamma_\mu \ell$$

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



Fit is >7 σ better than the SM

b→cτν Transitions

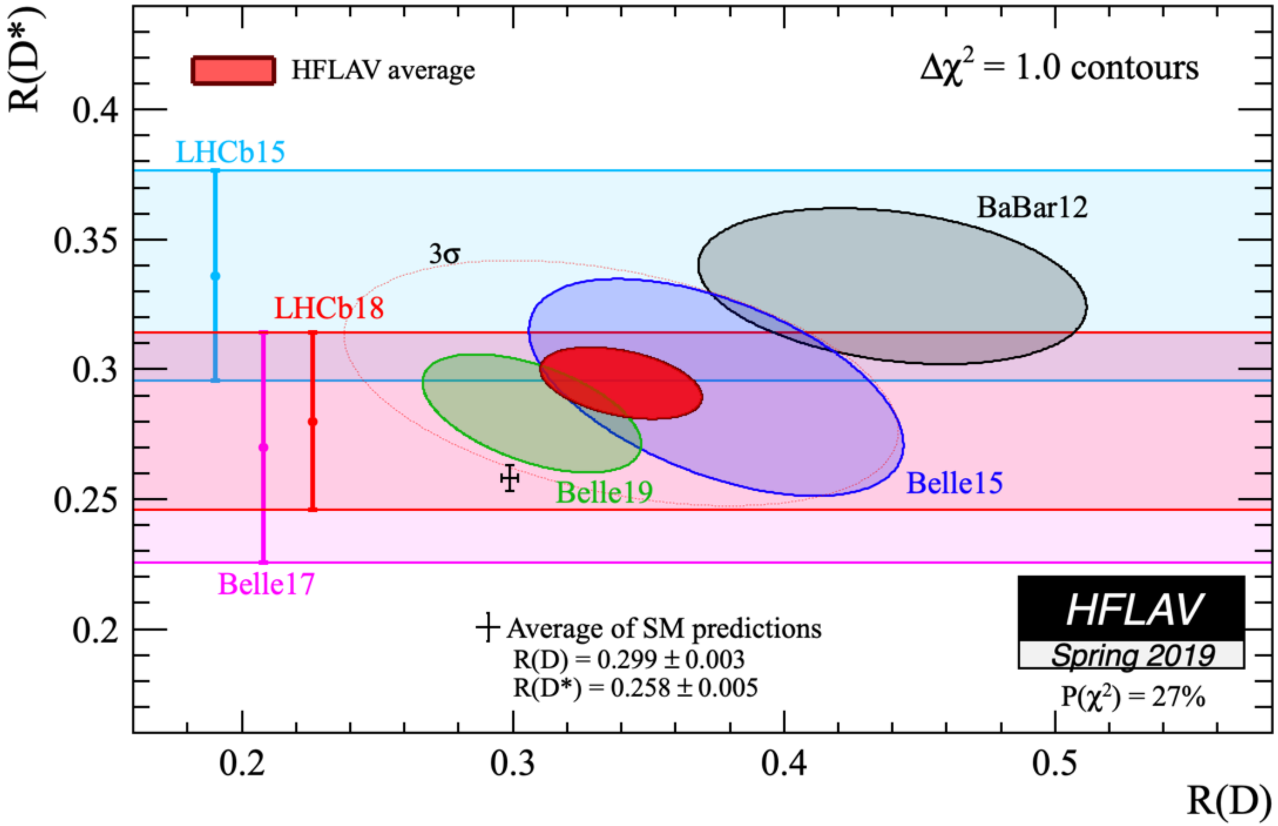


- B→Dτν, B →D*τν, $\Lambda_b \to \Lambda_c \tau\nu$
- Tree-level decays
  in the SM
- Form factors needed
- With light leptons (μ, e)
  used to determine the CKM elements
- CKM fit works very well, i.e. tree-level in
  agreement with ΔF=2 processes

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

$b \to c\tau\nu$ Measurements

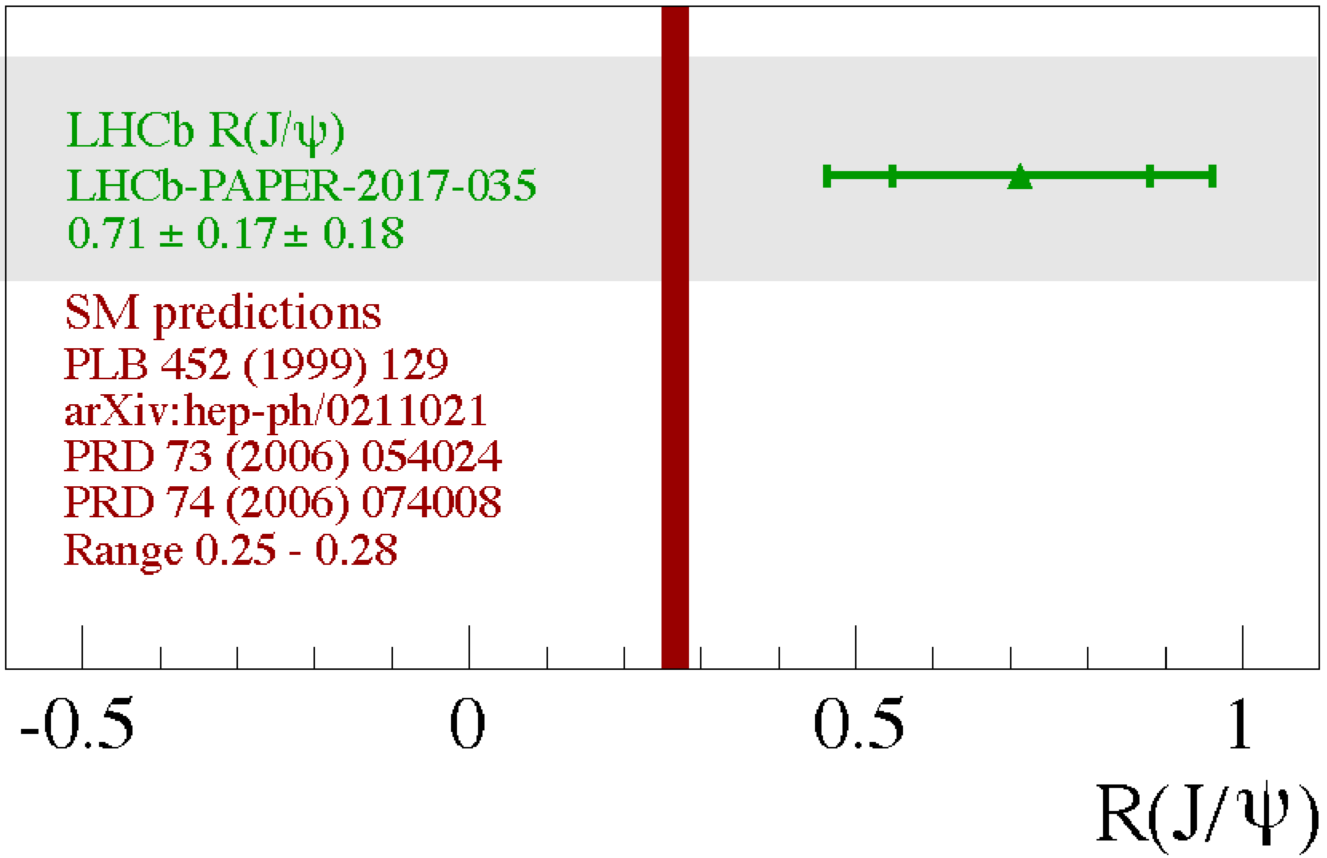
$$R\left(D^{(*)}\right) = B \to D^{(*)}\tau\nu / B \to D^{(*)}\ell\nu$$



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

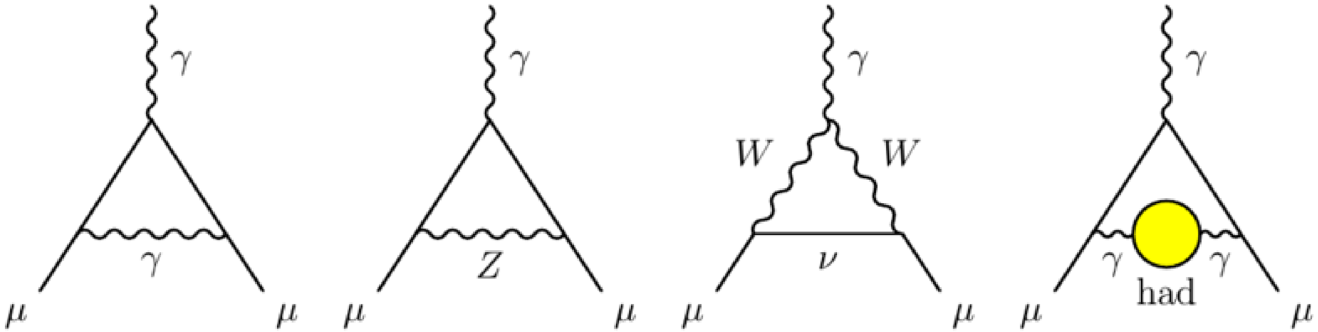
b→cτν Measurements

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



Supports R(D) & R(D*)

Muon Anomalous Magnetic Moment



- Theory prediction challenging (hadronic effects)

$$\Delta a_\mu = (251 \pm 49) \times 10^{-11}$$ 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 $m_\mu \to 0$ ⇨ **measure of LFUV**

4.2σ deviation from the SM prediction

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

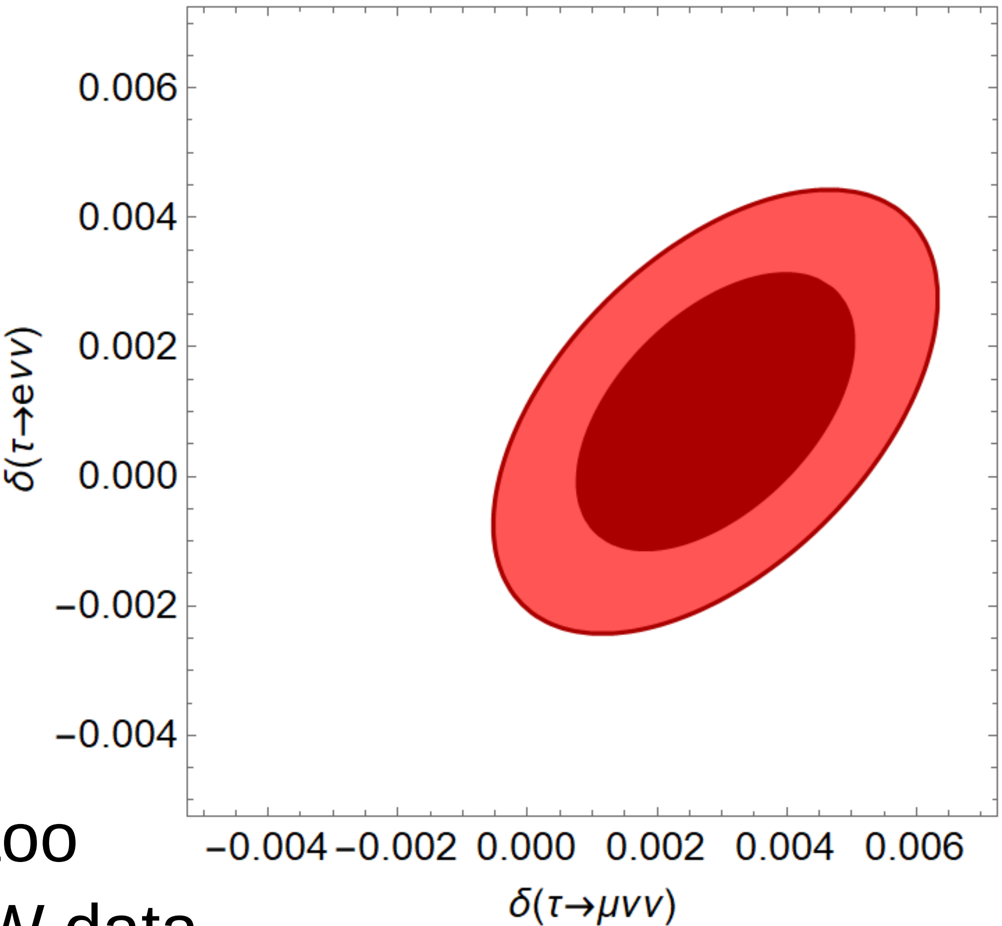
- Ratios of leptonic tau decays

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

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

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

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

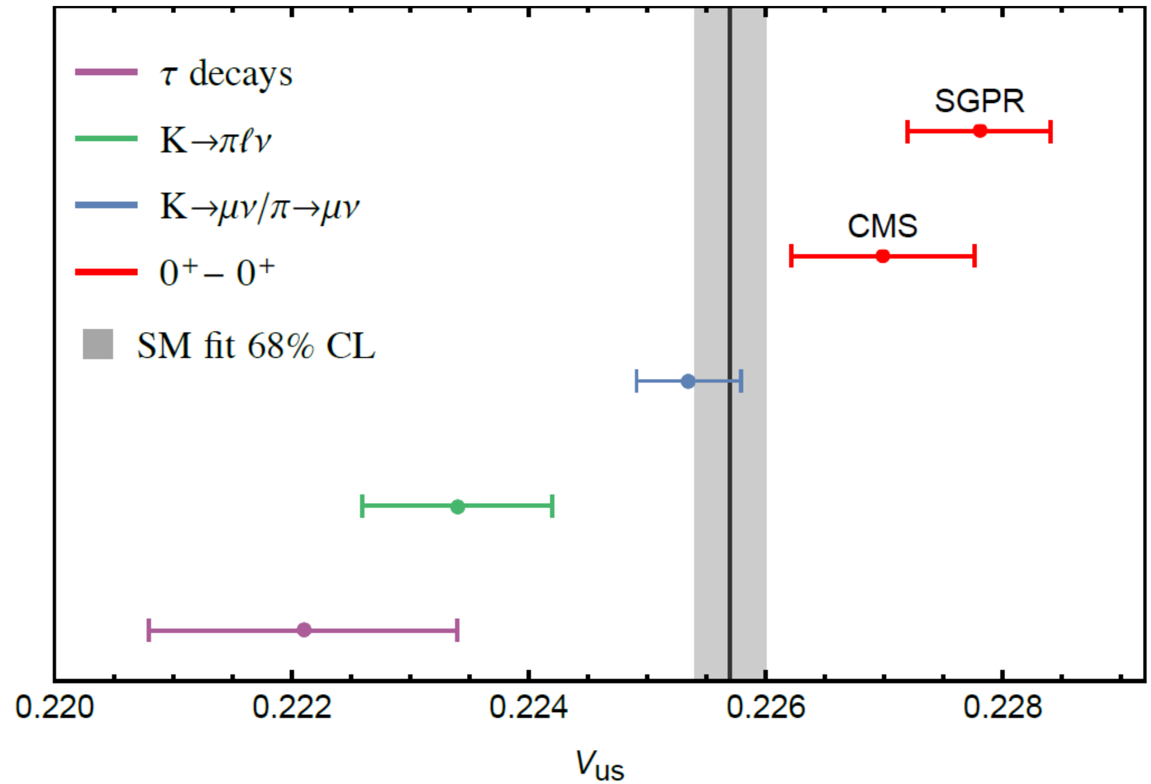


- NP in muon decay too constrained from EW data

≈2σ hint for LFUV in tau decays

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



CMS, SGPR: radiative corrections

$$\left|V_{ud}^{2}\right|+\left|V_{us}^{2}\right|+\left|V_{ub}^{2}\right|=0.9985\pm0.0005\,(\mathrm{PDG})$$

≈3σ hint for LFUV in the charged current

CAA and LFUV

- Assume modified Wℓν couplings

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

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

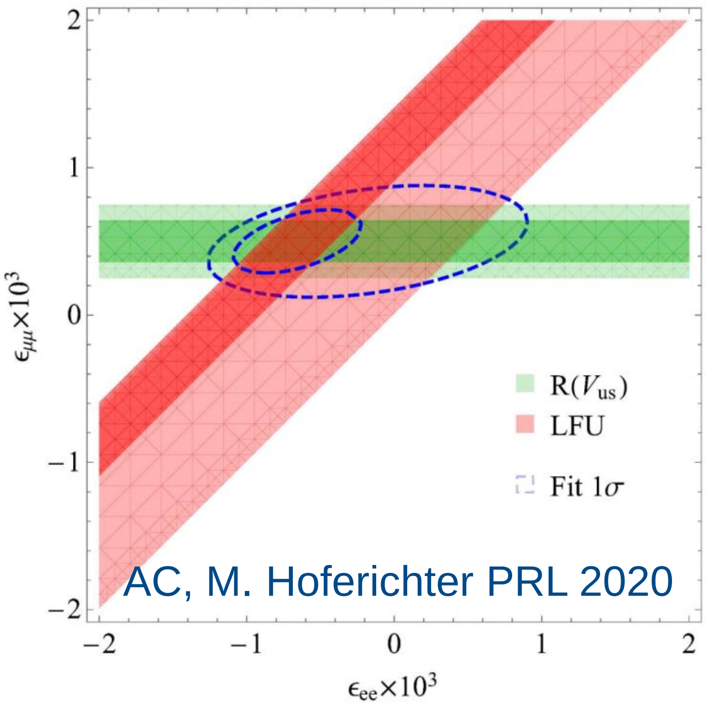
$$1/\tau_\beta \sim \left|V_{ud}\left(1+\varepsilon_{ee}\right)\right|^2 G_F^2$$

- 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

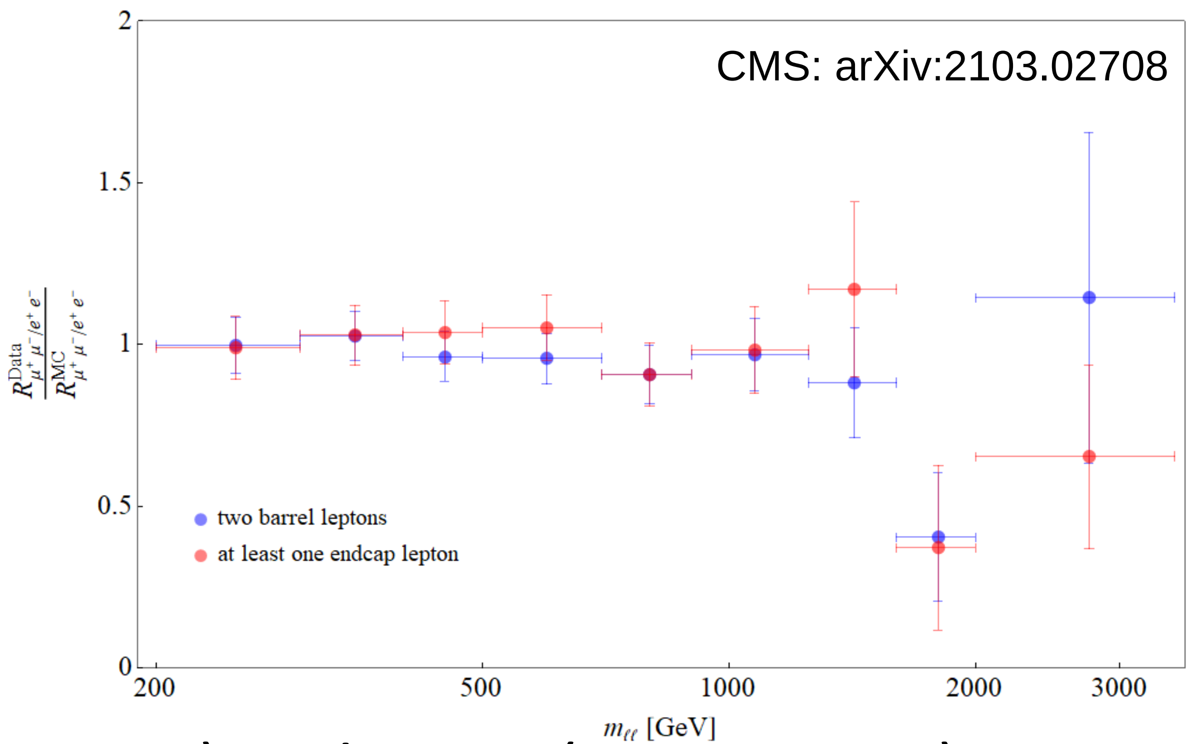
$$\frac{V_{us}^{K_{\mu 2}}}{V_{us}^{\beta}} \equiv \frac{V_{us}^{K_{\mu 2}}}{\sqrt{1-\left(V_{ud}^{\beta}\right)^2 - \left|V_{ub}\right|^2}} \approx 1 - \left(\frac{V_{ud}}{V_{us}}\right)^2 \varepsilon_{\mu\mu}$$



The CAA can be interpreted as a sign of LFUV

Non-Resonant Di-Leptons

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

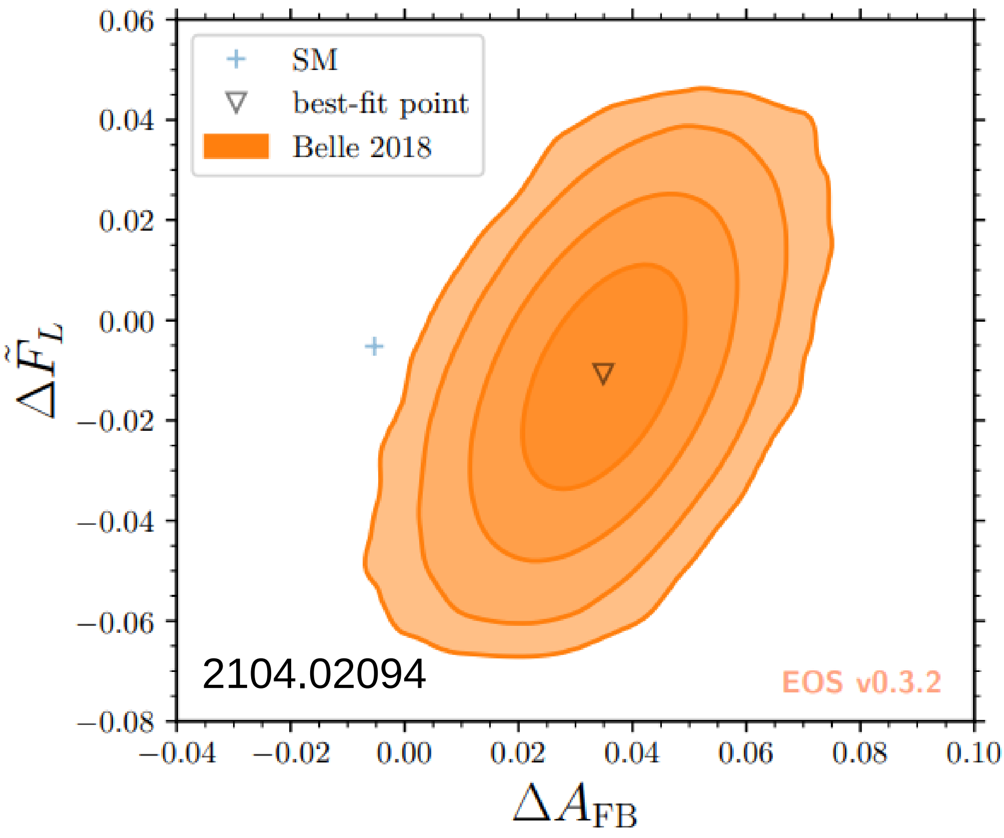


- Also ATLAS (2006.12946) and HERA (1902.03048) observe slightly more electrons than expected.
- No excess in muon data

≈3σ hint for LFUV

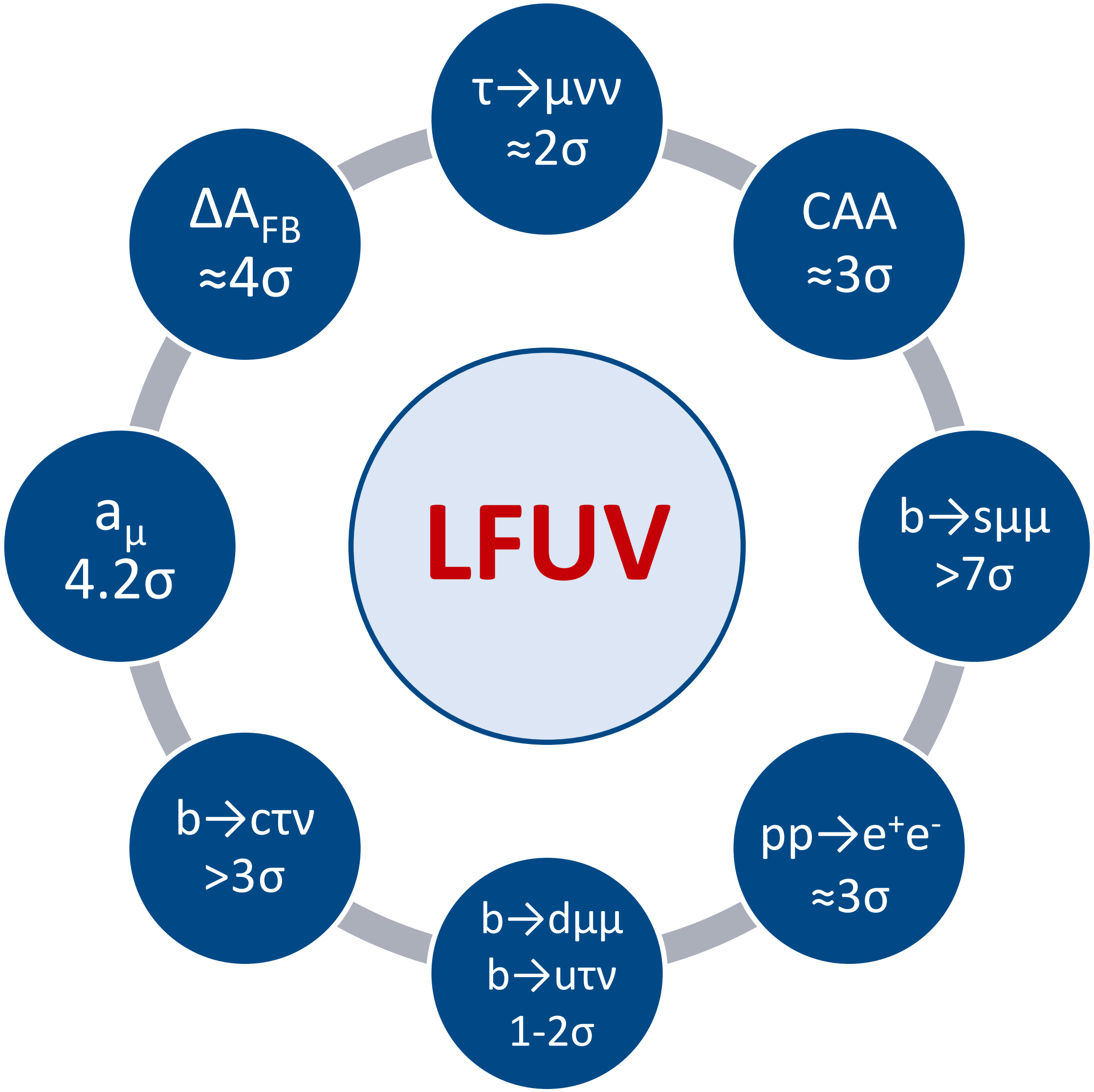
ΔA_{FB} in b→cμν

- $\Delta A_{FB} = A_{FB}\left(b \to c\mu\nu\right) - A_{FB}\left(b \to ce\nu\right)$
- 4σ deviation found by 2104.02094 based on BELLE data 1809.03290
- Scalar and/or tensor operators required for an angular asymmetry
- g-2 and b→sμμ motivate new physics related to muons



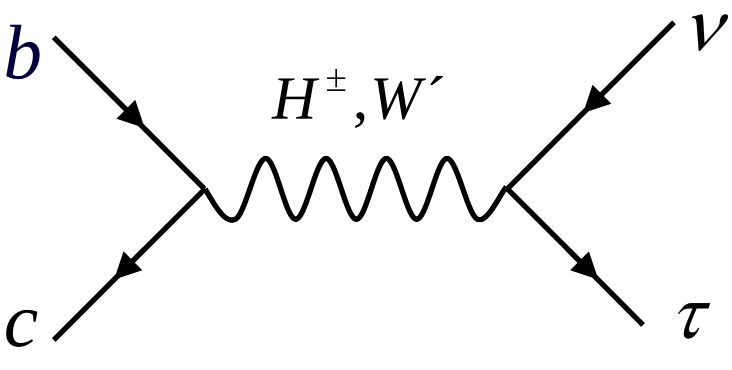
Hint for scalar/tensor NP in b→cμν

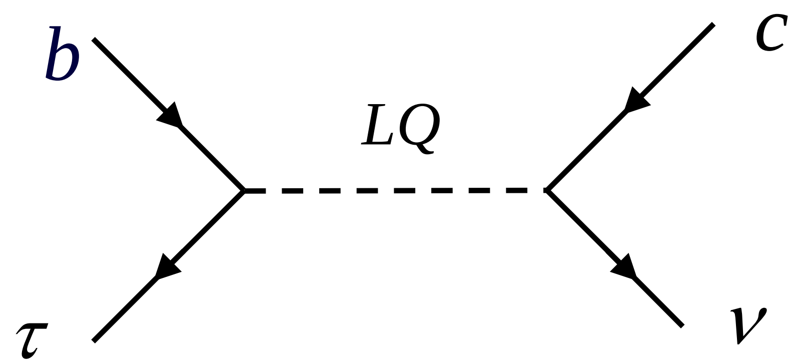
Flavour Anomalies



New Physics Explanations of the Anomalies

R(D) & R(D*)



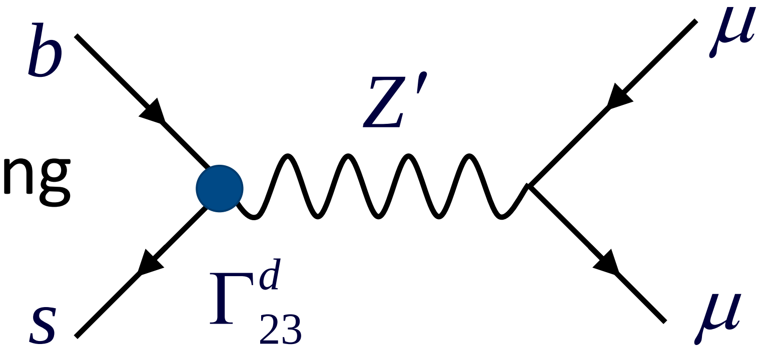


- Charged scalars: Problems with distributions and B_c lifetime A. Celis, M. Jung, X. Q. Li, A. Pich, PLB 2017 R. Alonso, B. Grinstein, J. Martin Camalich, PRL 2017
- W': Strong constraints from direct LHC searches
  D. Buttazzo, A. Greljo, G. Isidori, D. Marzocca, JHEP 2017
- Leptoquark: Strong signals in qq→ττ searches
  CMS, 1809.05558; ATLAS, 1902.08103

Explanation difficult but possible with Leptoquarks

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

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



Γ_{23}^{d}

- 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

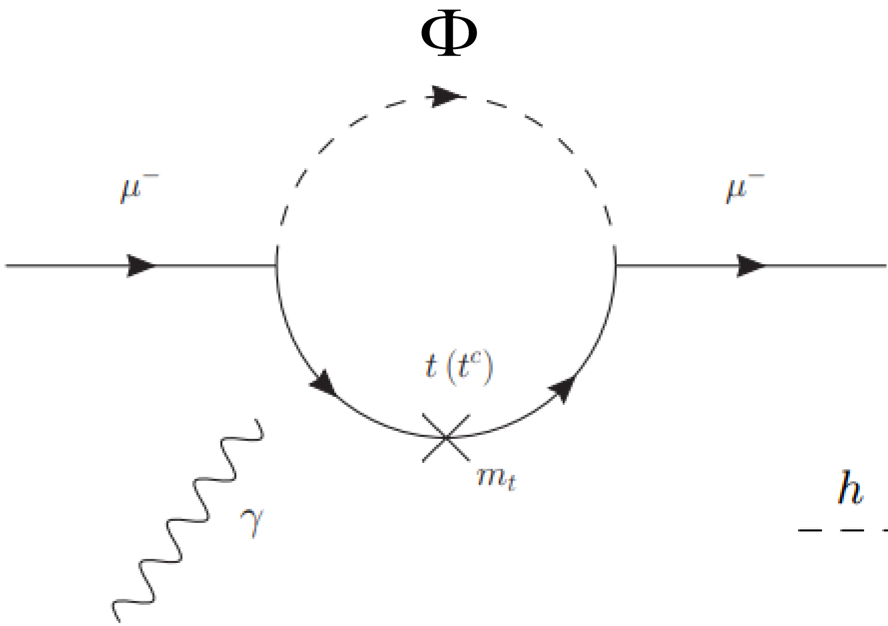
a_μ explanations

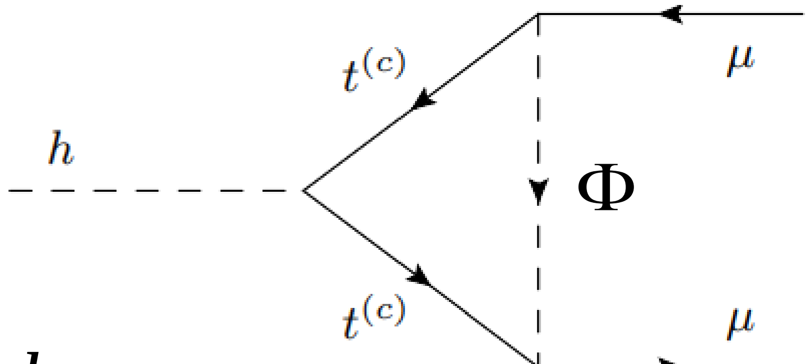
- MSSM
  - tan(ß) enhanced slepton loops
- Scalars
  - Light scalars with enhanced muon couplings
- Z’
  - Very light with τμ couplings (m_τ enhancement)
- New scalars and fermions
  - κ/Y_μ
- Leptoquarks
  - m_t enhanced effects

Chiral enhancement or very light particles

Leptoquarks in a_μ

- Chirally enhanced effects via top-loops



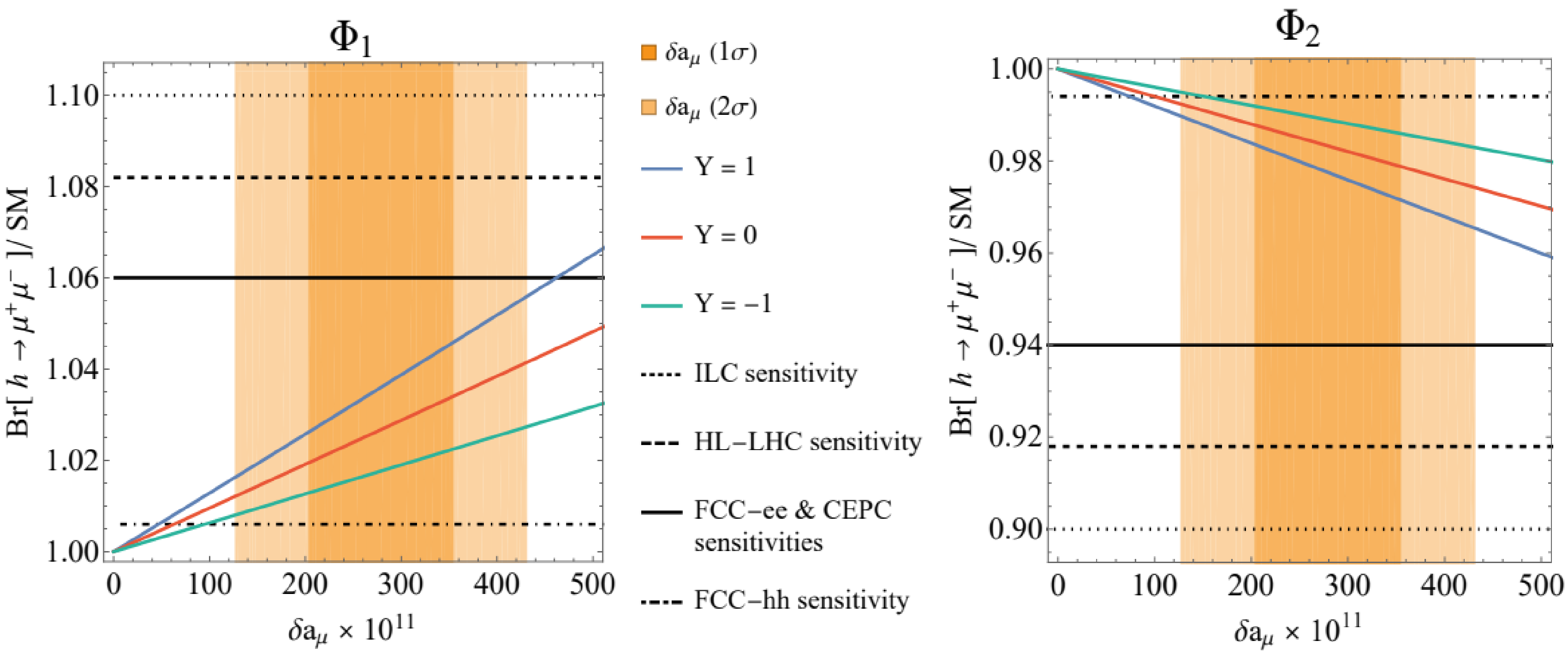


- m_t/m_μ enhanced effect $h \to \mu\mu$
- m_t^2/m_Z^2 enhanced effect in $Z \to \mu\mu$

Correlations with h→μμ and Z→μμ

a_μ vs h→μμ

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

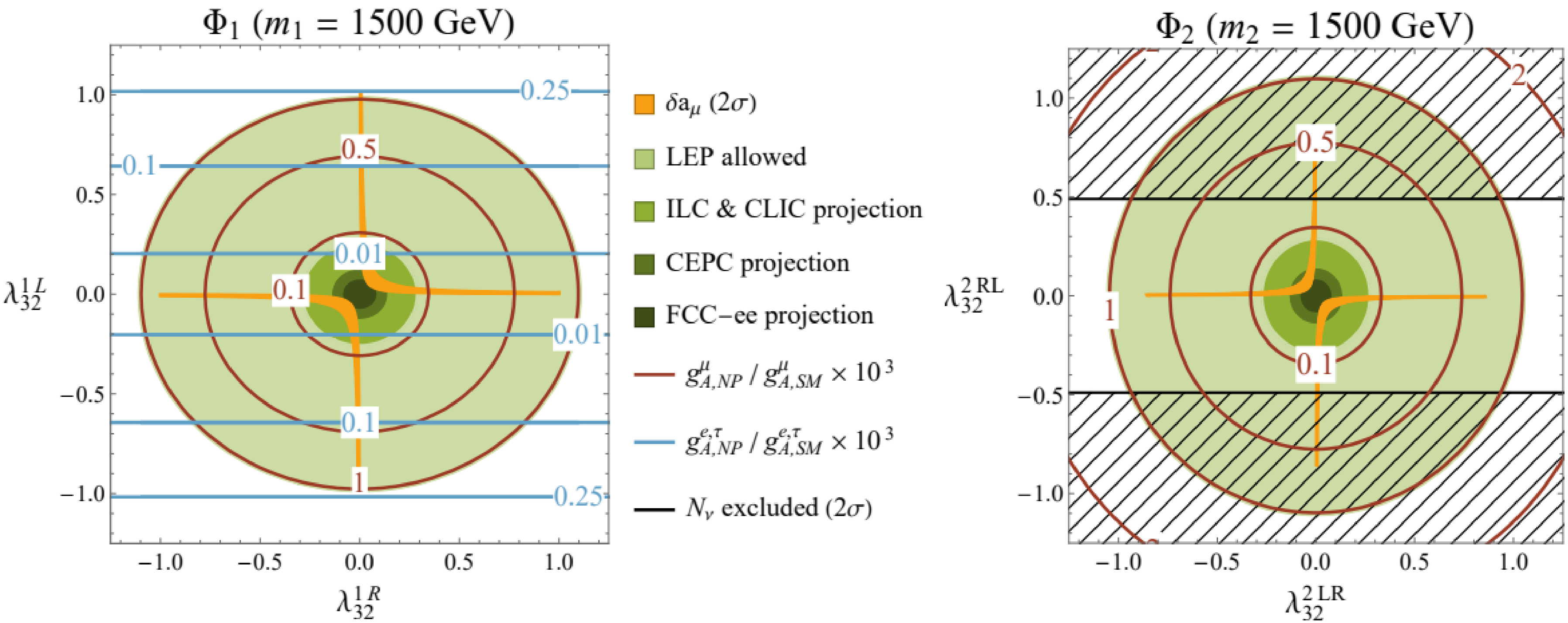


A.C., D. Mueller, F. Saturnino, 2008.02643

h→μμ at future colliders

a_μ vs $Z \to \mu\mu$

- 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→μμ at future colliders

Cabibbo Angle Anomaly and EW Fit

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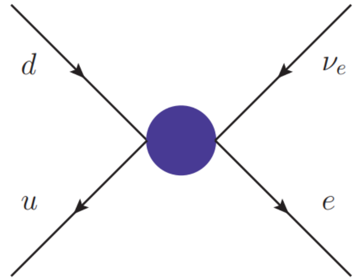
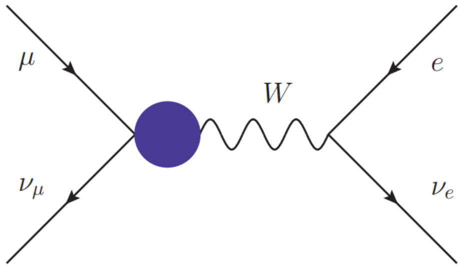
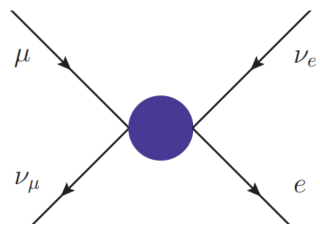
- LQs
- W‘



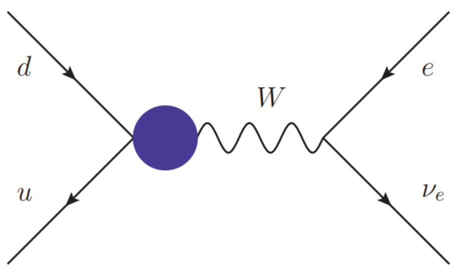
- W-W‘ mixing
- Vector-like leptons

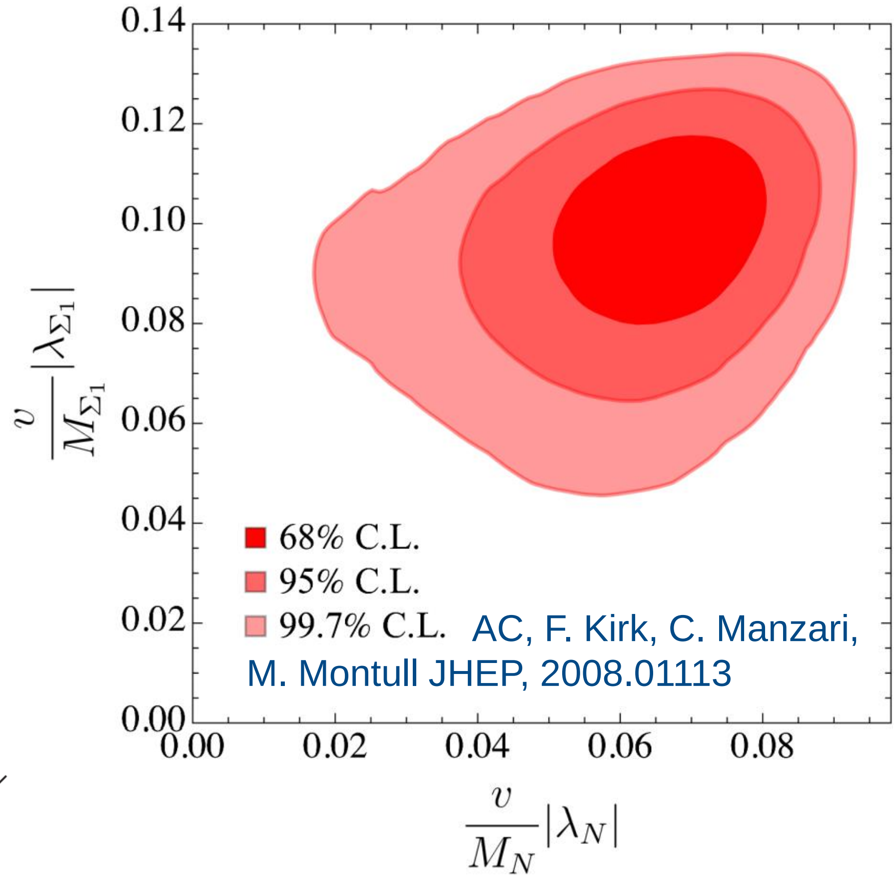


- Z‘
- Singly charged scalar



- Vector-like quarks



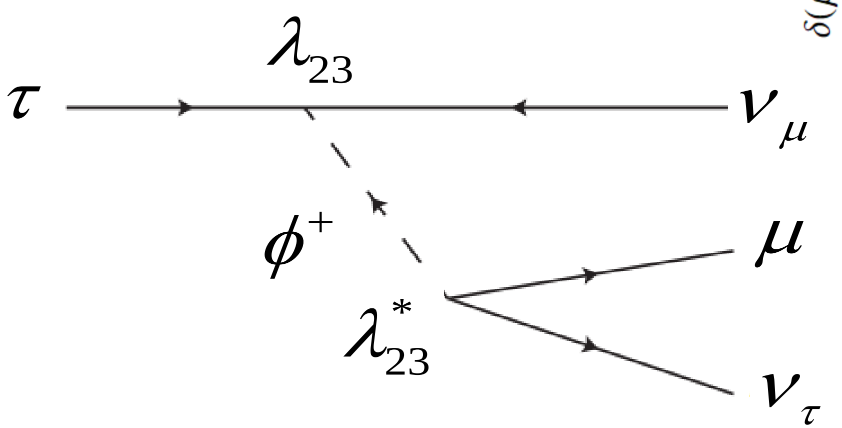


AC, F. Kirk, C. Manzari, M. Montull JHEP, 2008.01113

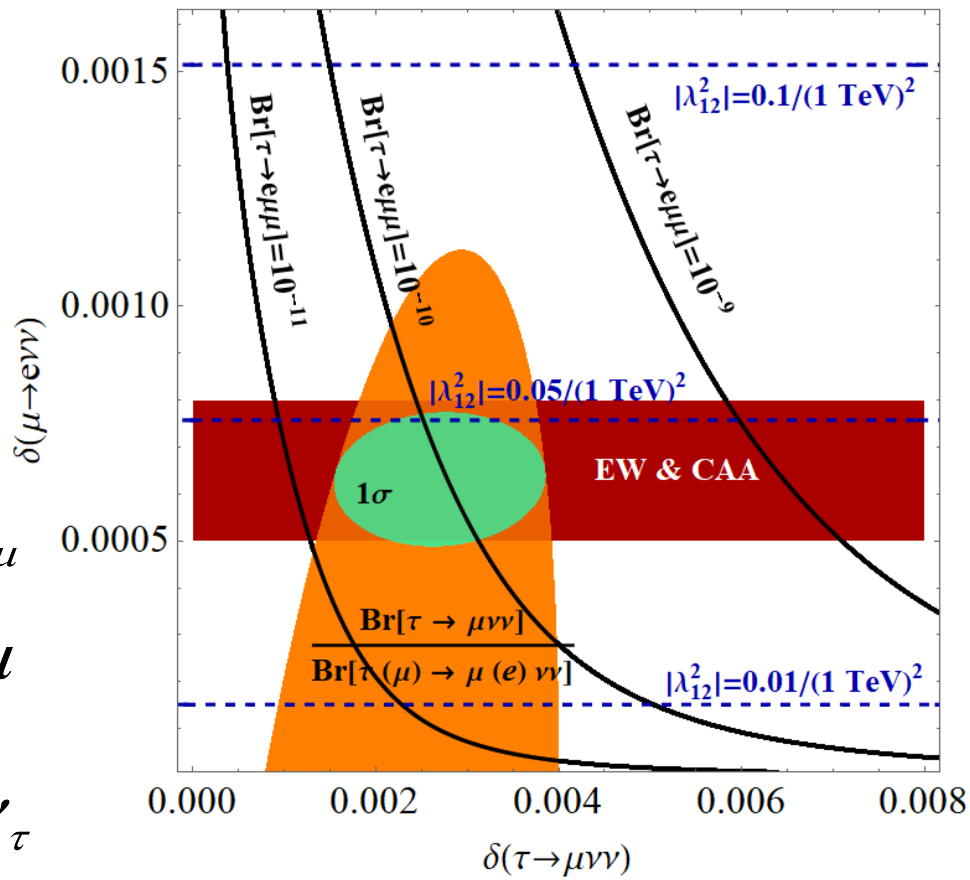
>5σ improvement over SM hypothesis with VLLs

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

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



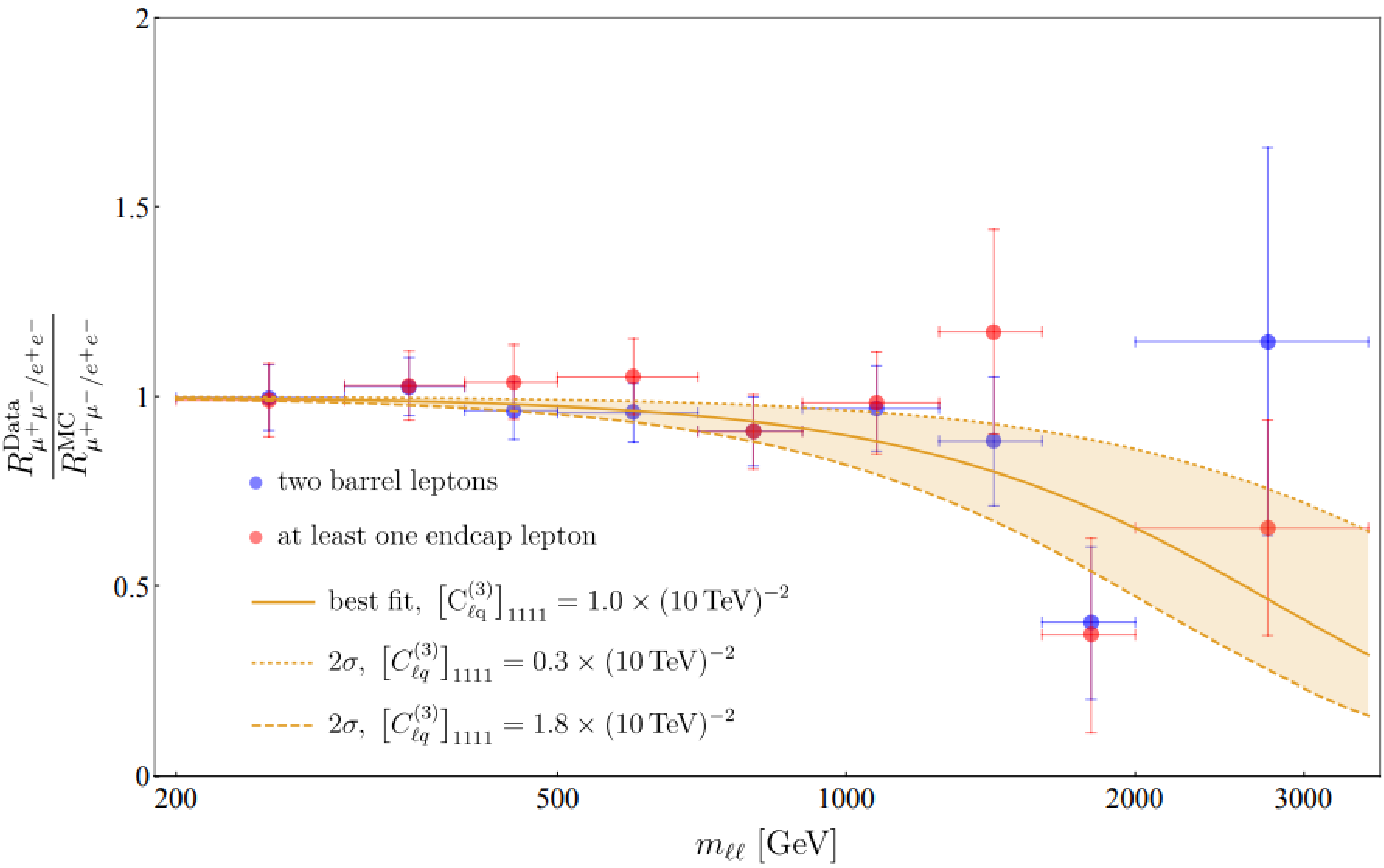
Singly charged scalar



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

4σ hint for modified neutrino couplings

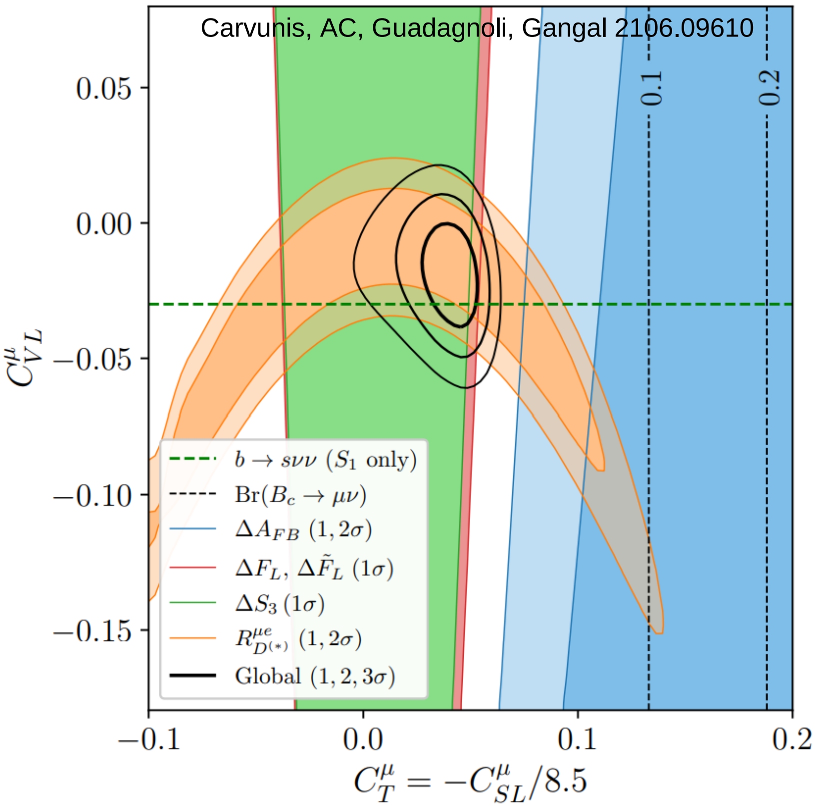
Non-Resonant Di-Leptons

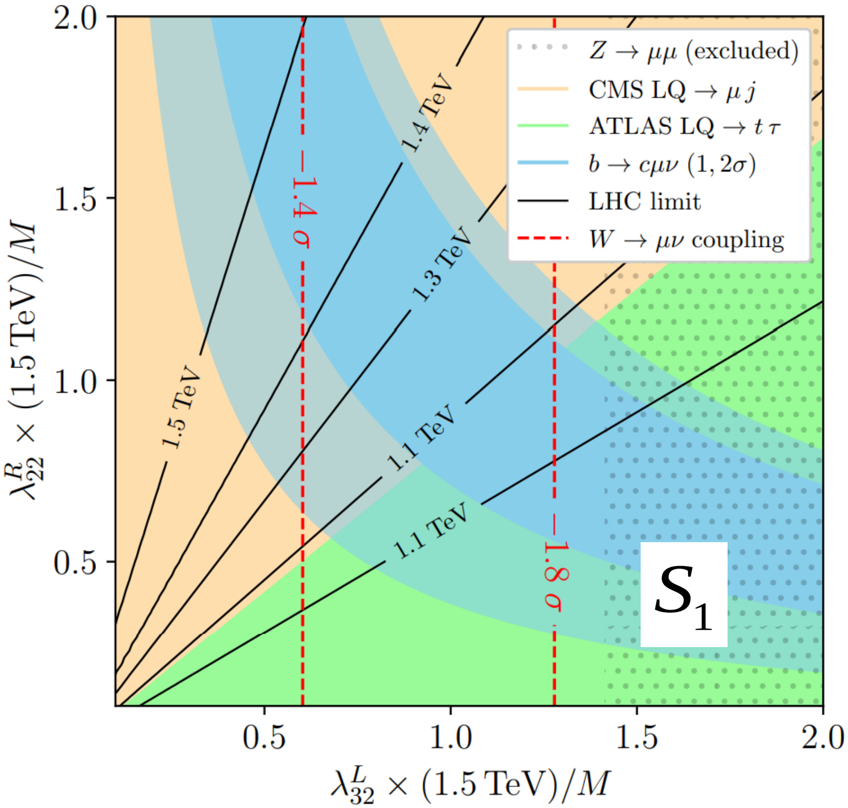


Constructive heavy NP in electrons

ΔA_{FB}

- Right-handed vector operators LFU
- Good fit requires the tensor operator ⇨ **scalar LQ**





Hint for scalar leptoquarks

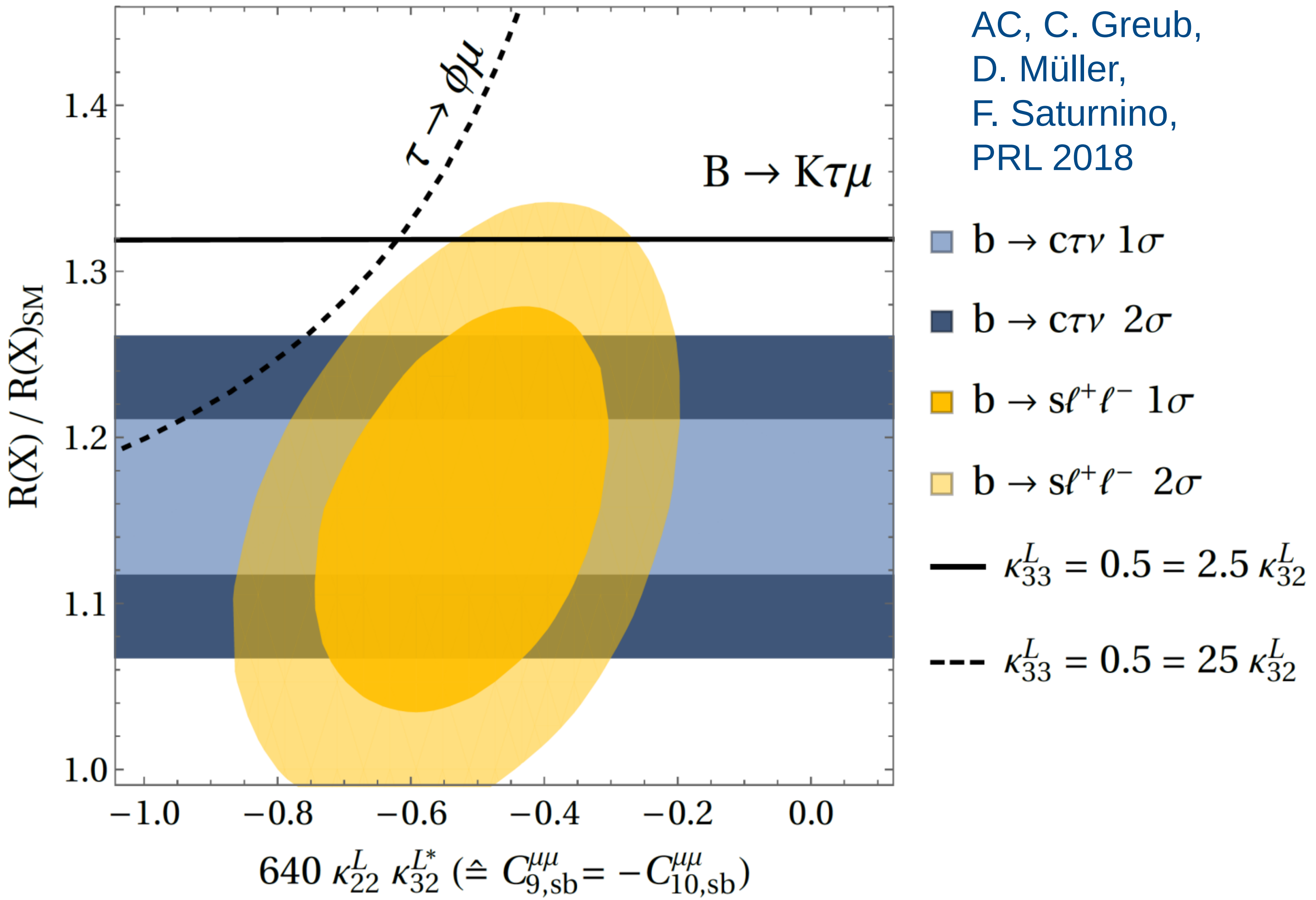
Simultaneous Explanations

Vector Leptoquark SU(2) Singlet

- Left-handed effect in $b \to s\mu\mu$
- Left-handed vector current in R(D) and R(D*)
- No effect in $b \to s\nu\nu$
- No proton decay
- Contained within the Pati-Salam model
- Massive vector bosons
  - Non-renormalizable without Higgs mechanism
  - Pati Salam not possible at the Tev scale because of $K_L \to \mu e$ and $K \to \pi\mu e$

Good solution, but difficult UV completion

Perfect agreement with data



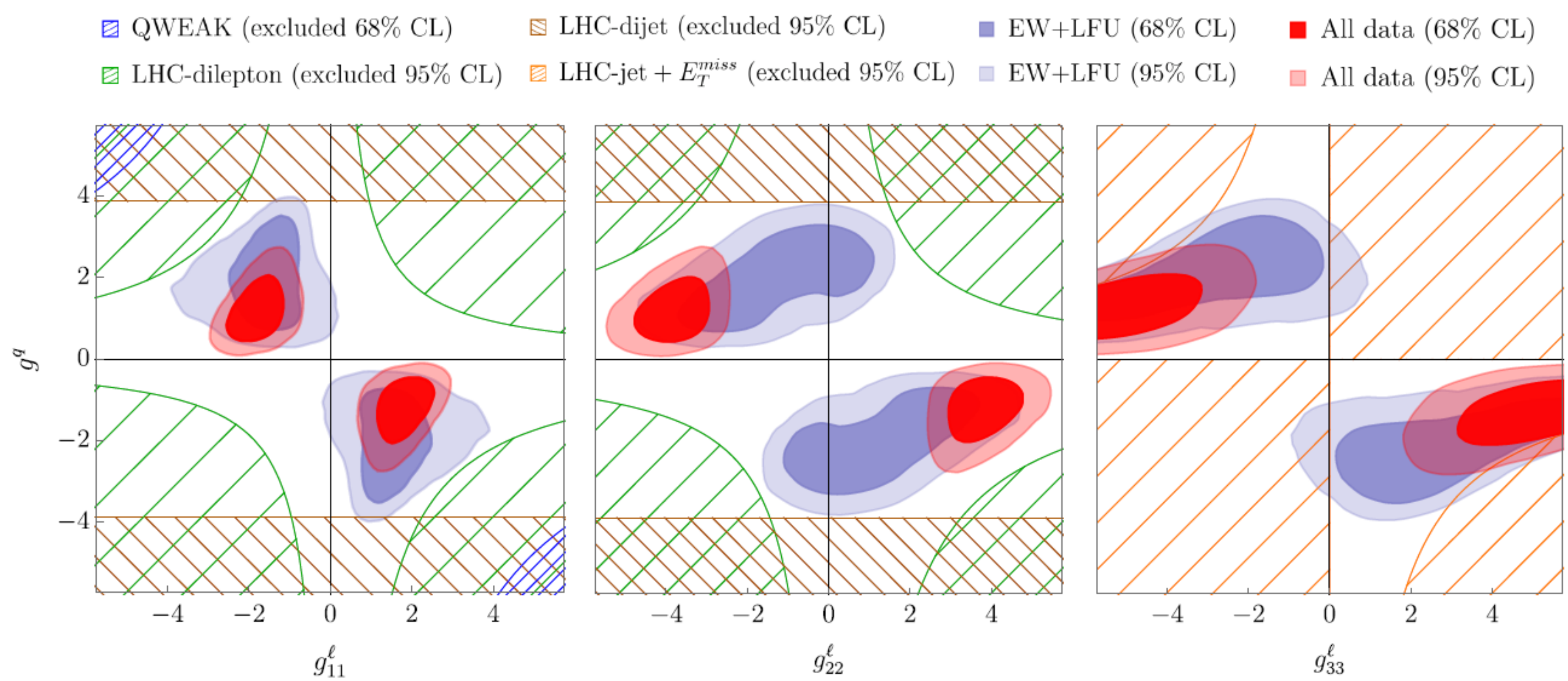
AC, C. Greub,
D. Müller,
F. Saturnino,
PRL 2018

Pati-Salam LQ can explain the flavour anomalies

Vector Triplet Explanation of CAA and $b \to s\mu\mu$

W' Explanation of CAA

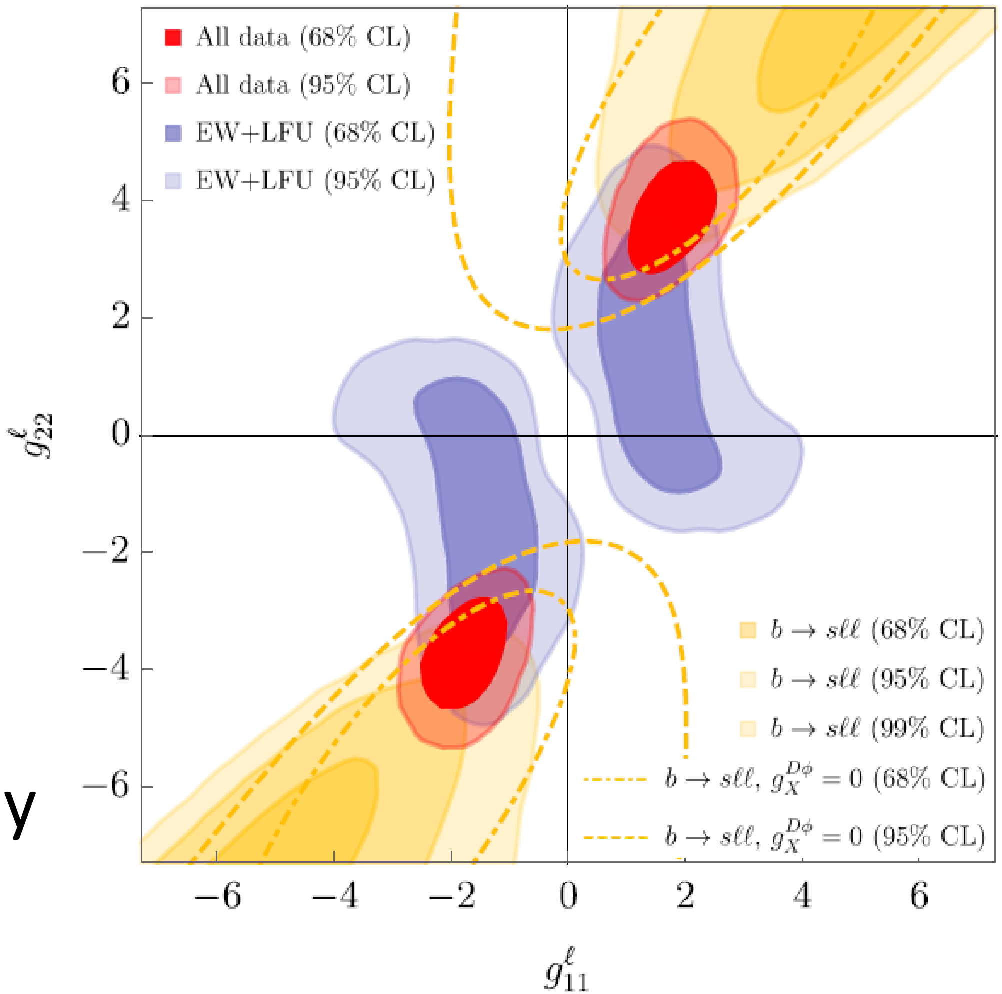
- W' effects in LFU and EW observables
- Z' effects in LHC di-jet and di-lepton tail searches



$R(V_{us})$ 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

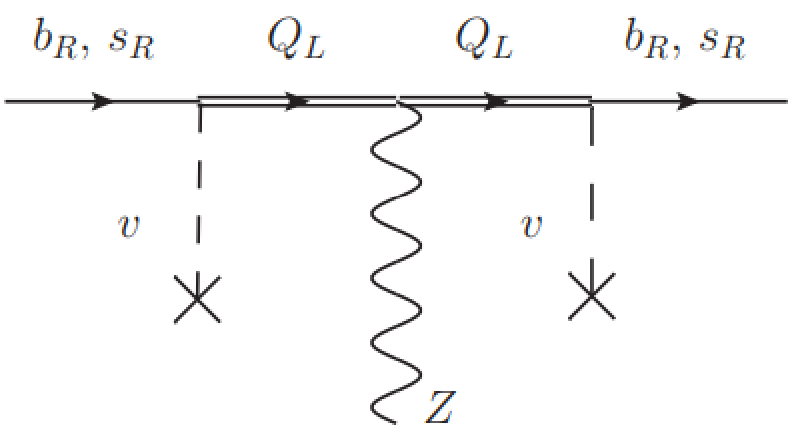
CAA, $\tau \to \mu\nu\nu$,

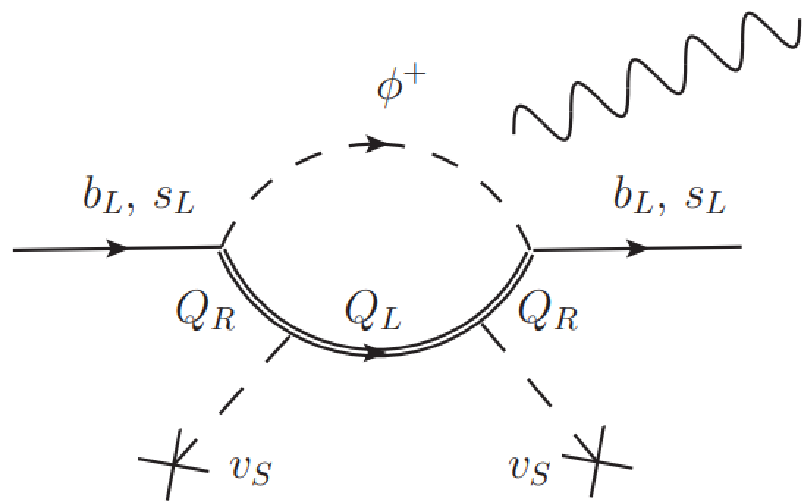
$Z \to bb$

and $b \to s\mu\mu$

Model

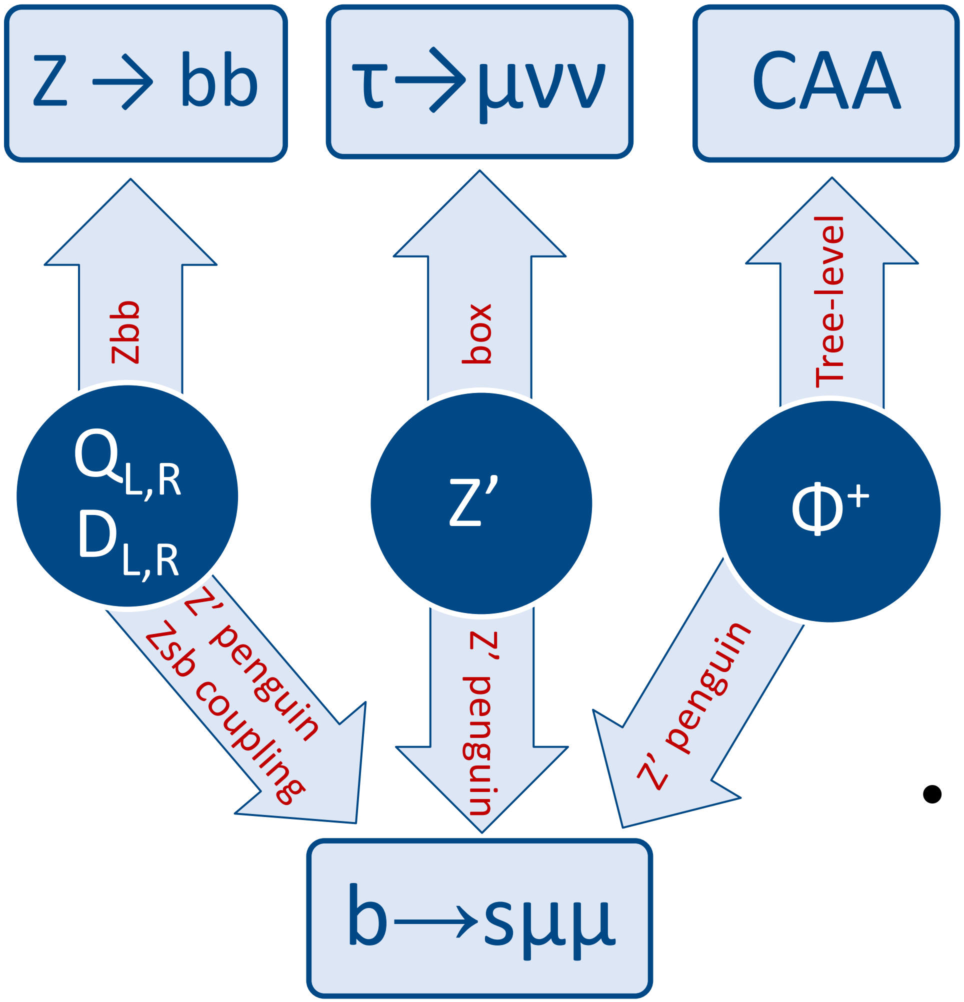
	q_L	d_R	u_R	H	ℓ_L	e_R	Q_L	Q_R	D_L	D_R	ϕ^+	S
$SU(3)_c$	3	3	3	1	1	1	3	3	3	3	1	1
$SU(2)_L$	2	1	1	2	2	1	2	2	1	1	1	1
$U(1)_Y$	$\frac{1}{6}$	$\frac{-1}{3}$	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{-1}{2}$	-1	$\frac{-5}{6}$	$\frac{-5}{6}$	$\frac{-1}{3}$	$\frac{-1}{3}$	1	0
$U(1)'$	0	0	0	0	$(0, 1, -1)$		0	1	1	0	-1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

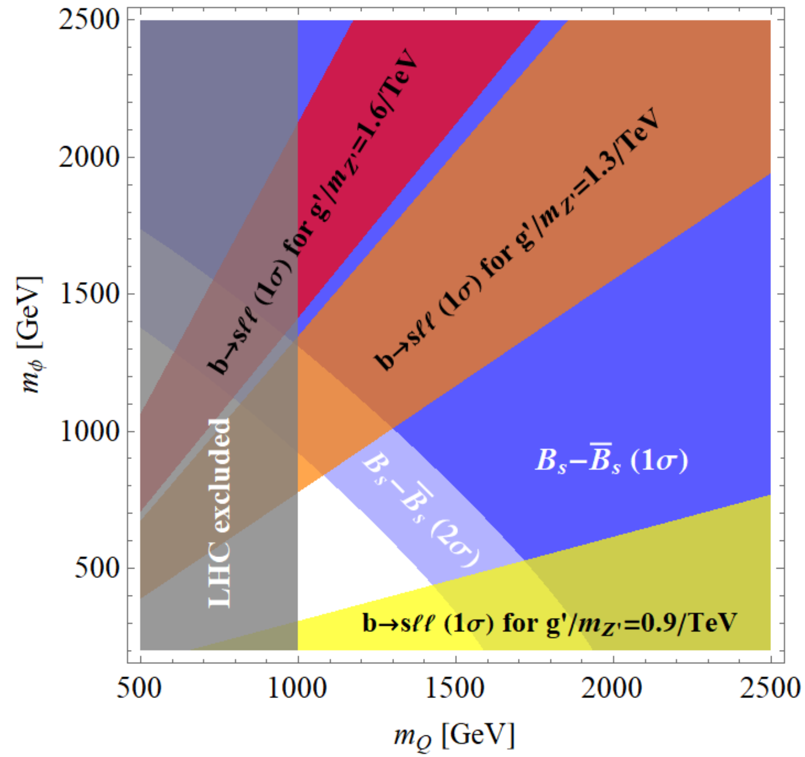




Tree effect in Zbb and loop in Z’sb

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

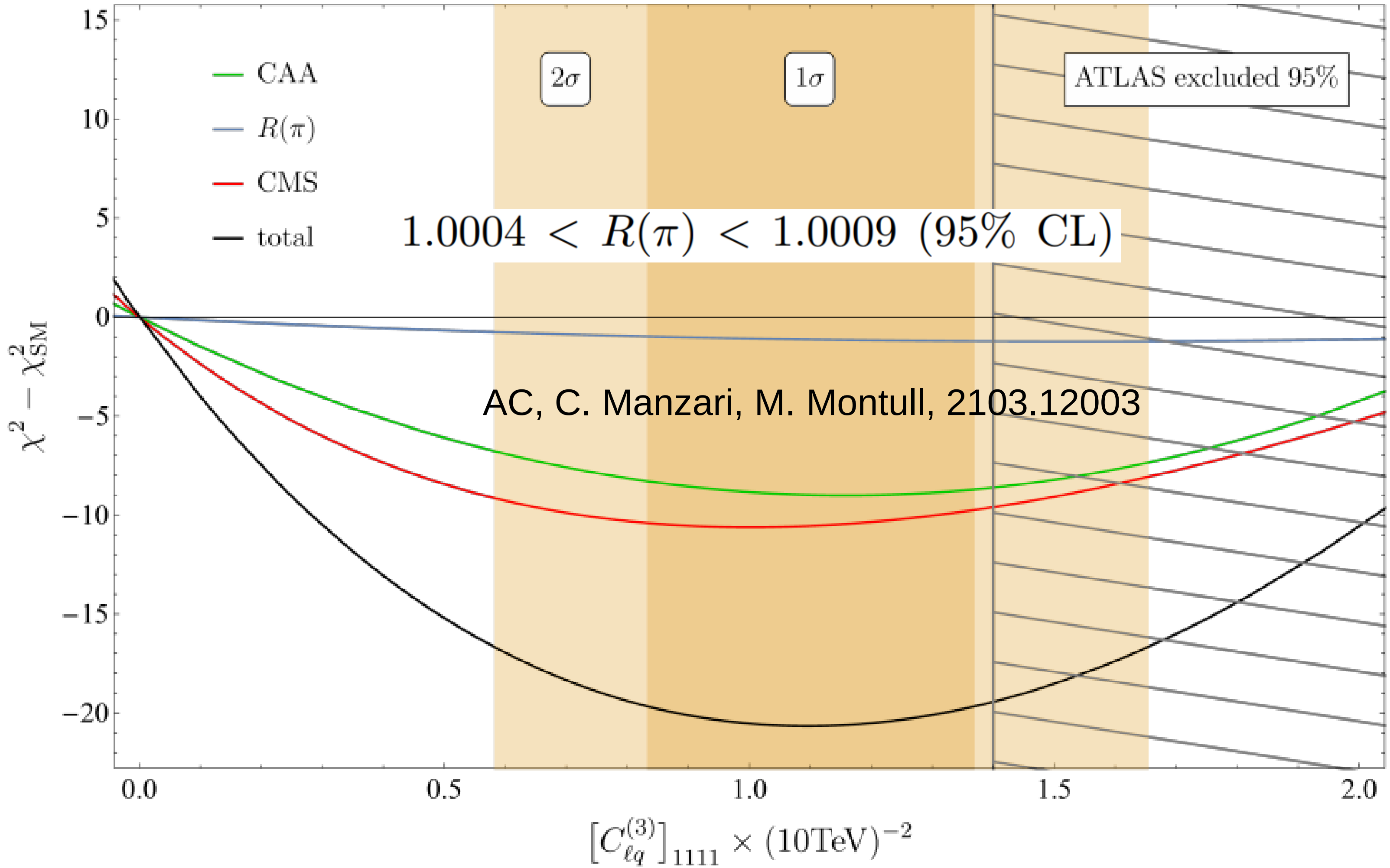




- Z' penguin + modified Zsb coupling give very good fit to b→sll data

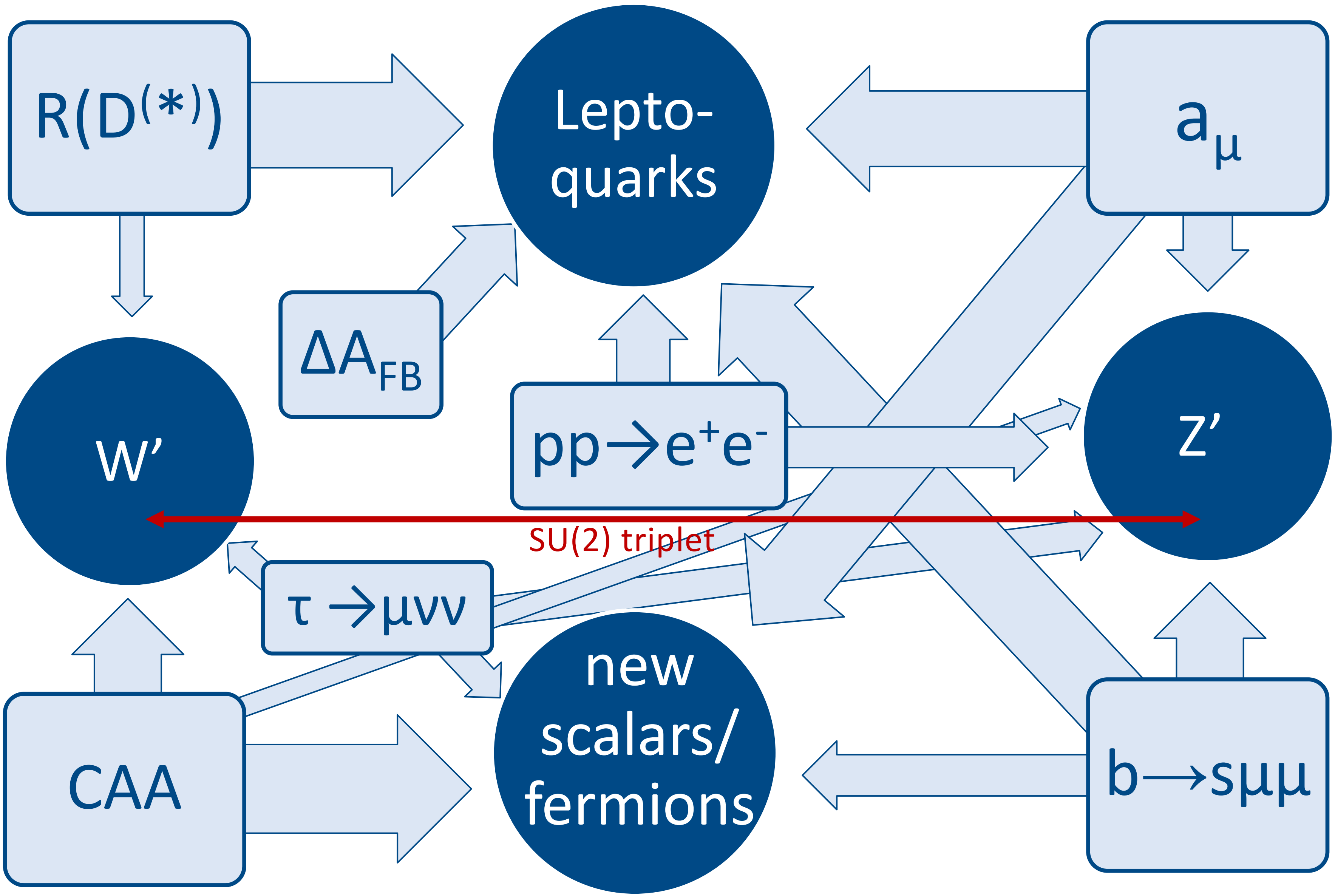
Simple model provides combined explanation

CAA and Non-Resonant Di-Leptons



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

Conclusions



Outlook: Physics at Future Colliders

- Flavour Anomalies require NP at the TeV scale

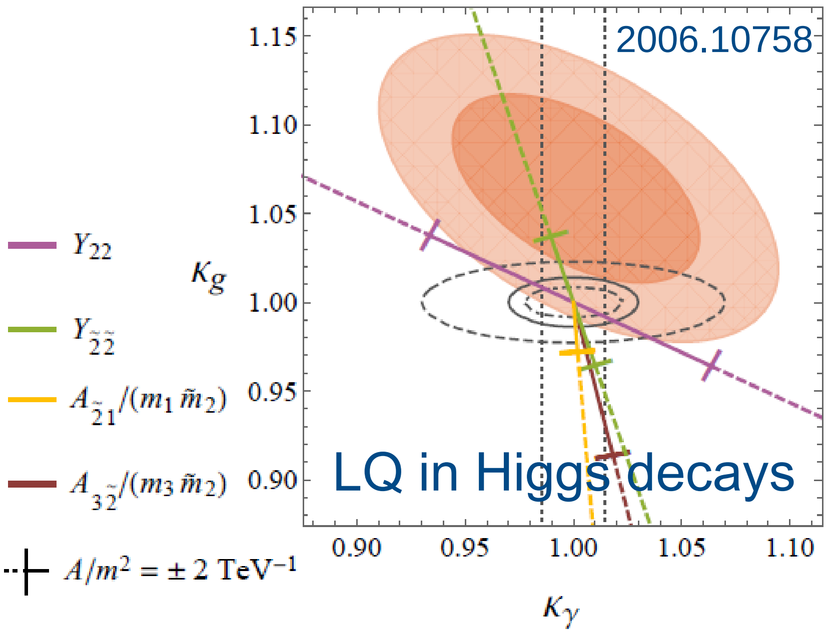
  ⇨ Direct Searches at HL-LHC, HE-LHC, FCC-pp

- This new particles in general also affect EW precision observables

  ⇨ Z decays at CLIC and FCC-ee

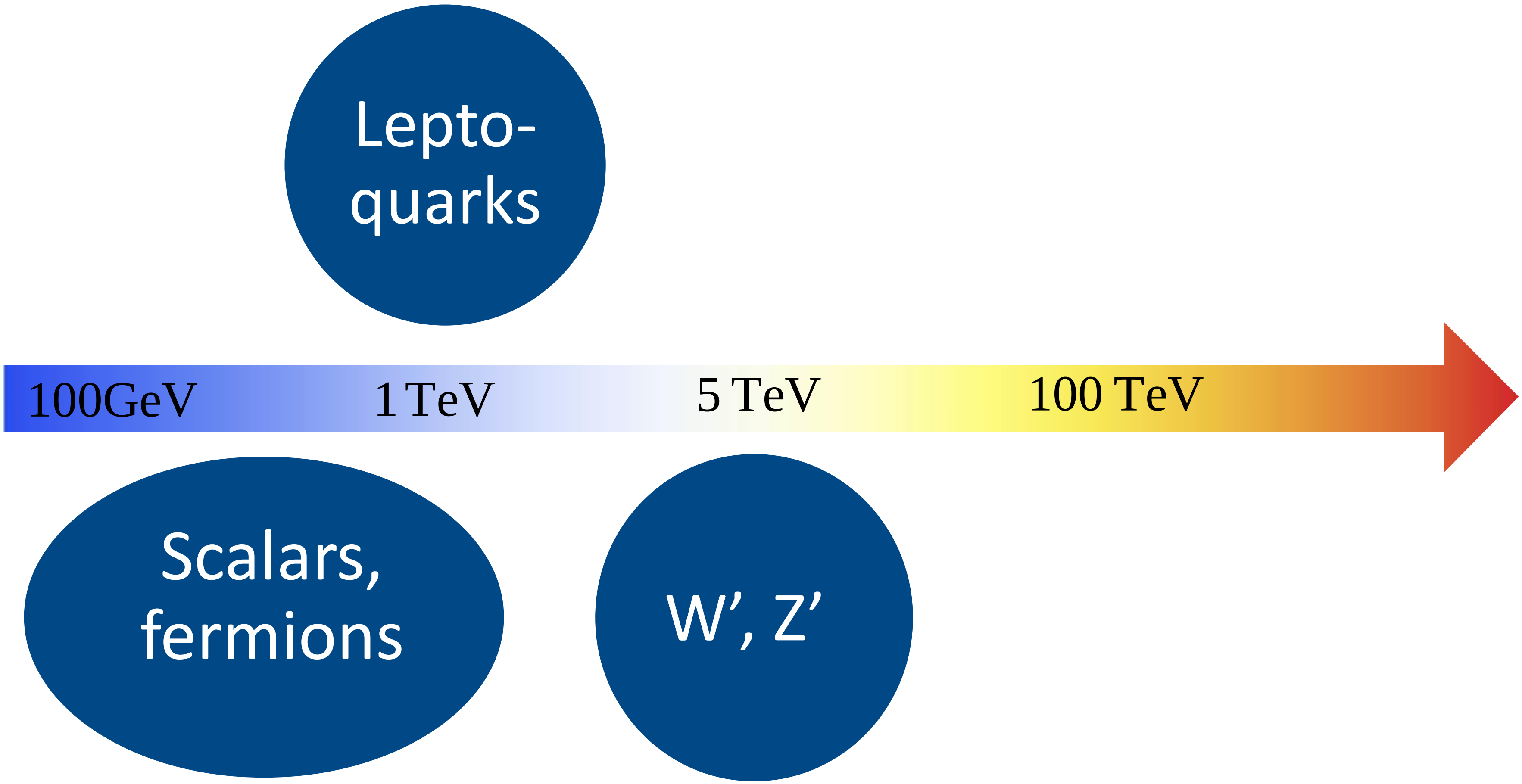
- Flavour is directly linked to the Higgs boson

  ⇨ CLIC, FCC



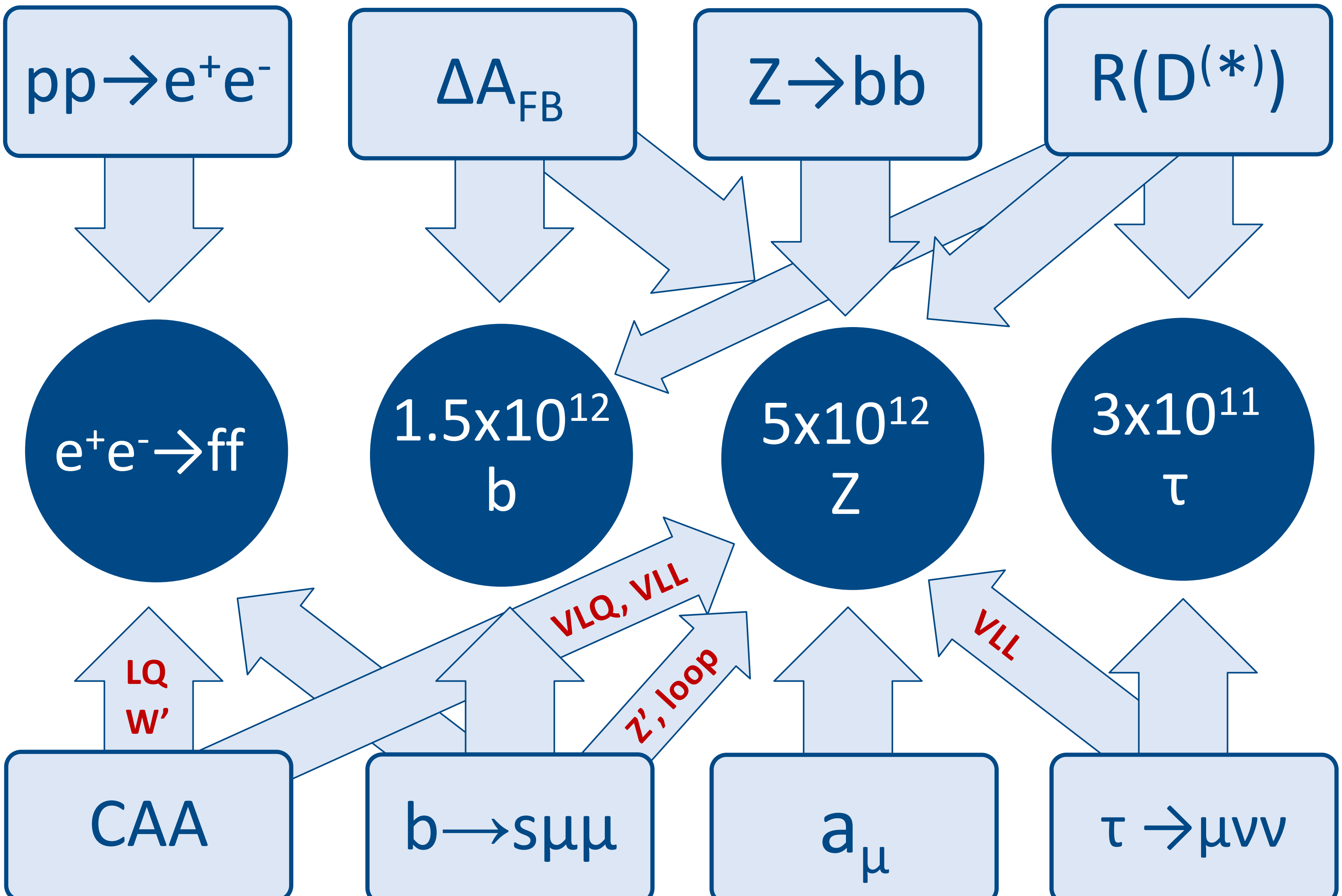
Flavour Anomalies (if confirmed) strengthen the physics case for future colliders significantly

LHC bounds and future prospects



FCC-hh reach six times higher

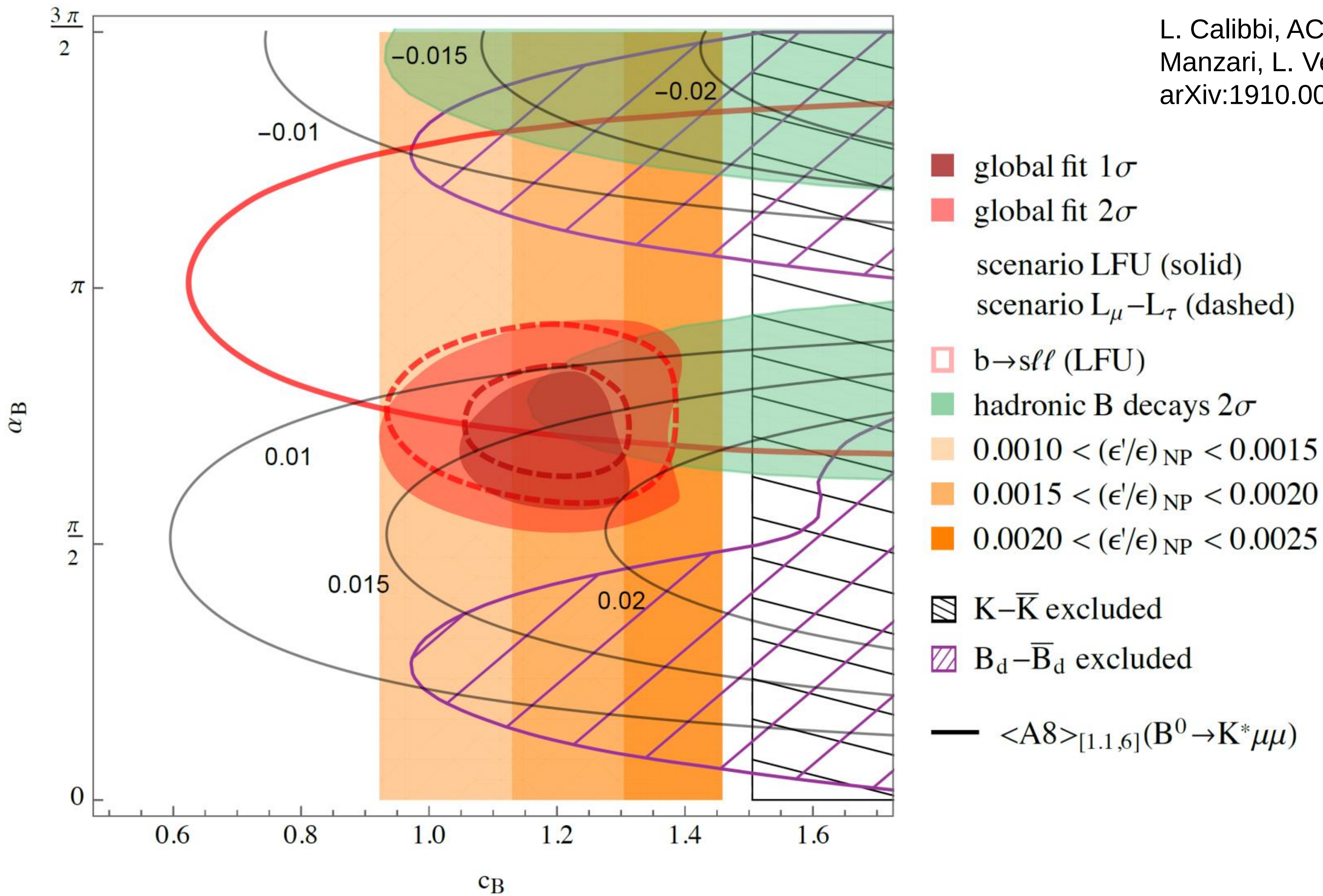
Implications for FCC-ee



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

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

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

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

Universität Zürich[UZH]

- 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

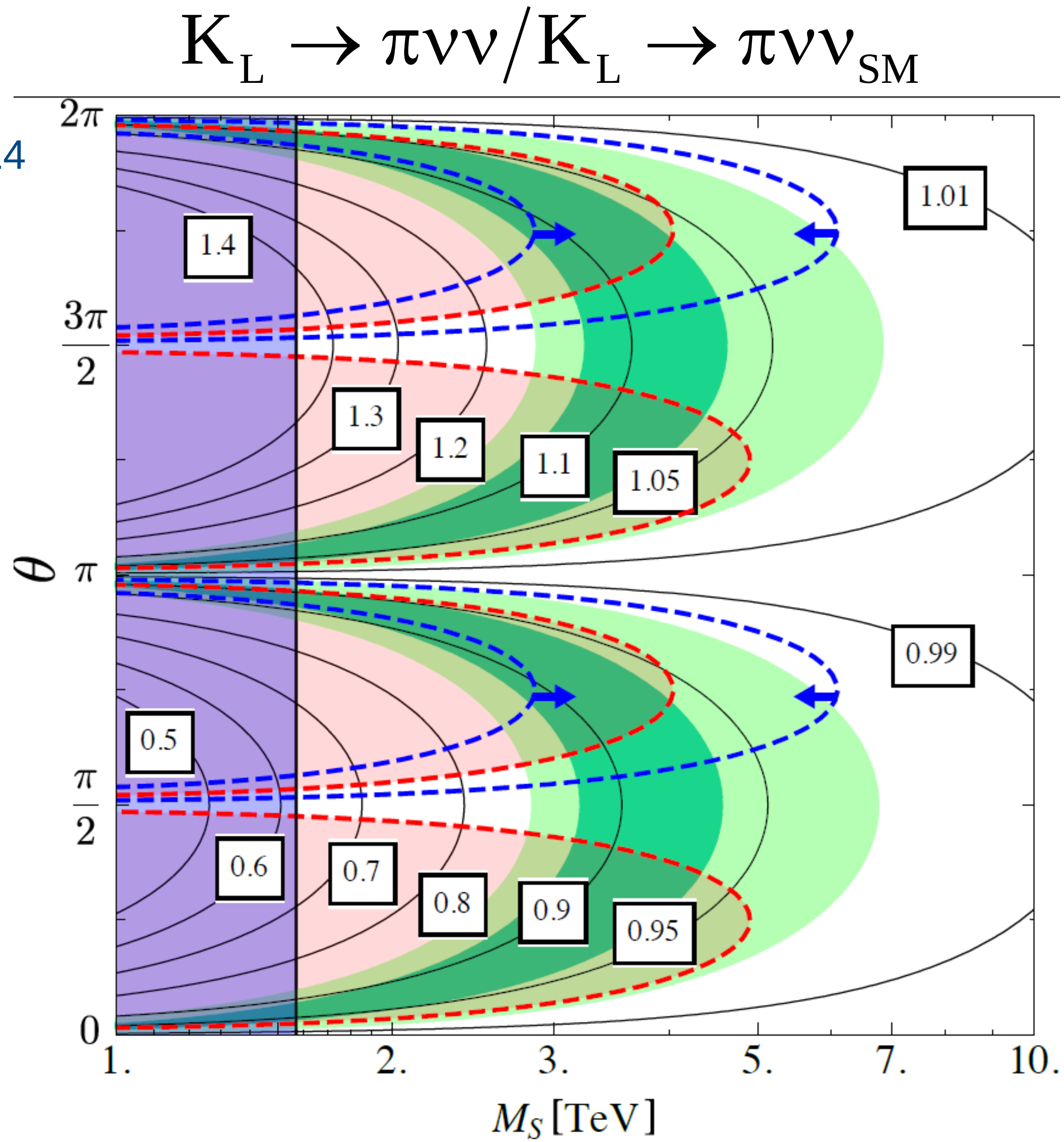
V. Cirigliano, et al. arXiv:1612.03914

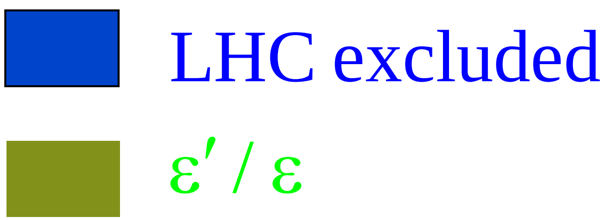
- Z' (also for ΔA_{CP})

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

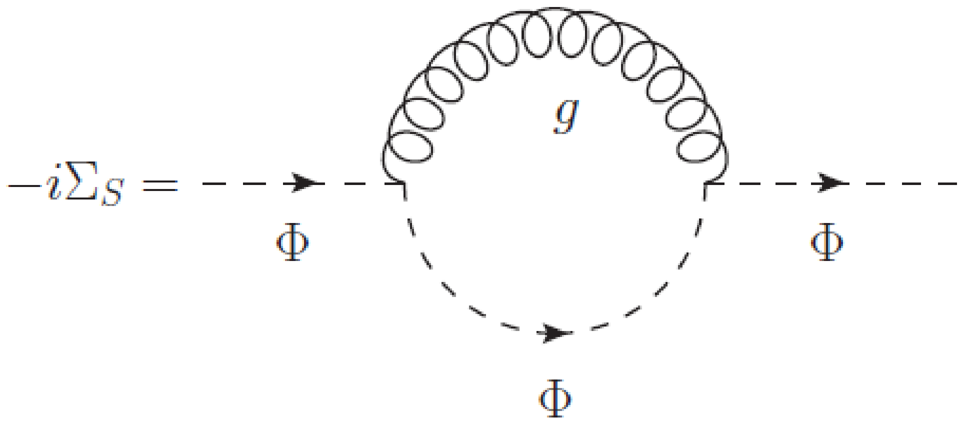
- MSSM

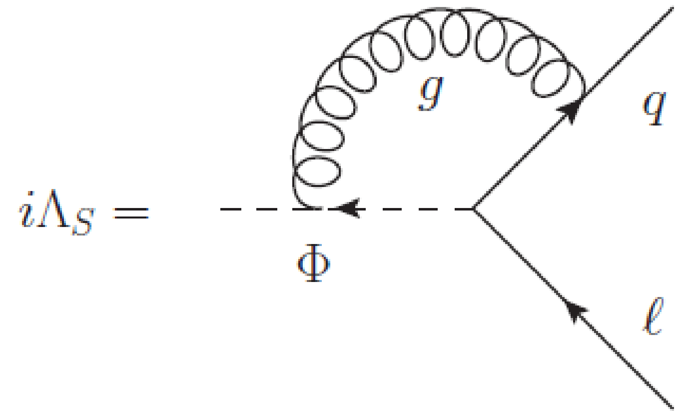
T. Kitahara, U. Nierste, P. Tremper, arXiv:1604.07400
M. Endo, et al. arXiv:1608.01444
A. Crivellin, G. D'Ambrosio, T. Kitahara and U. Nierste, arXiv:1703.05786

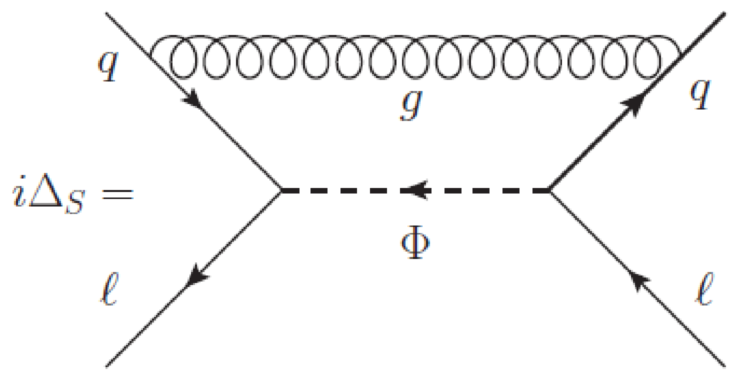


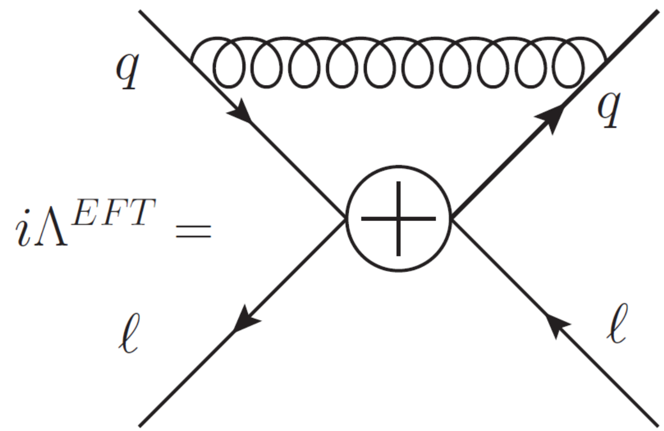


QCD corrections to the Matching



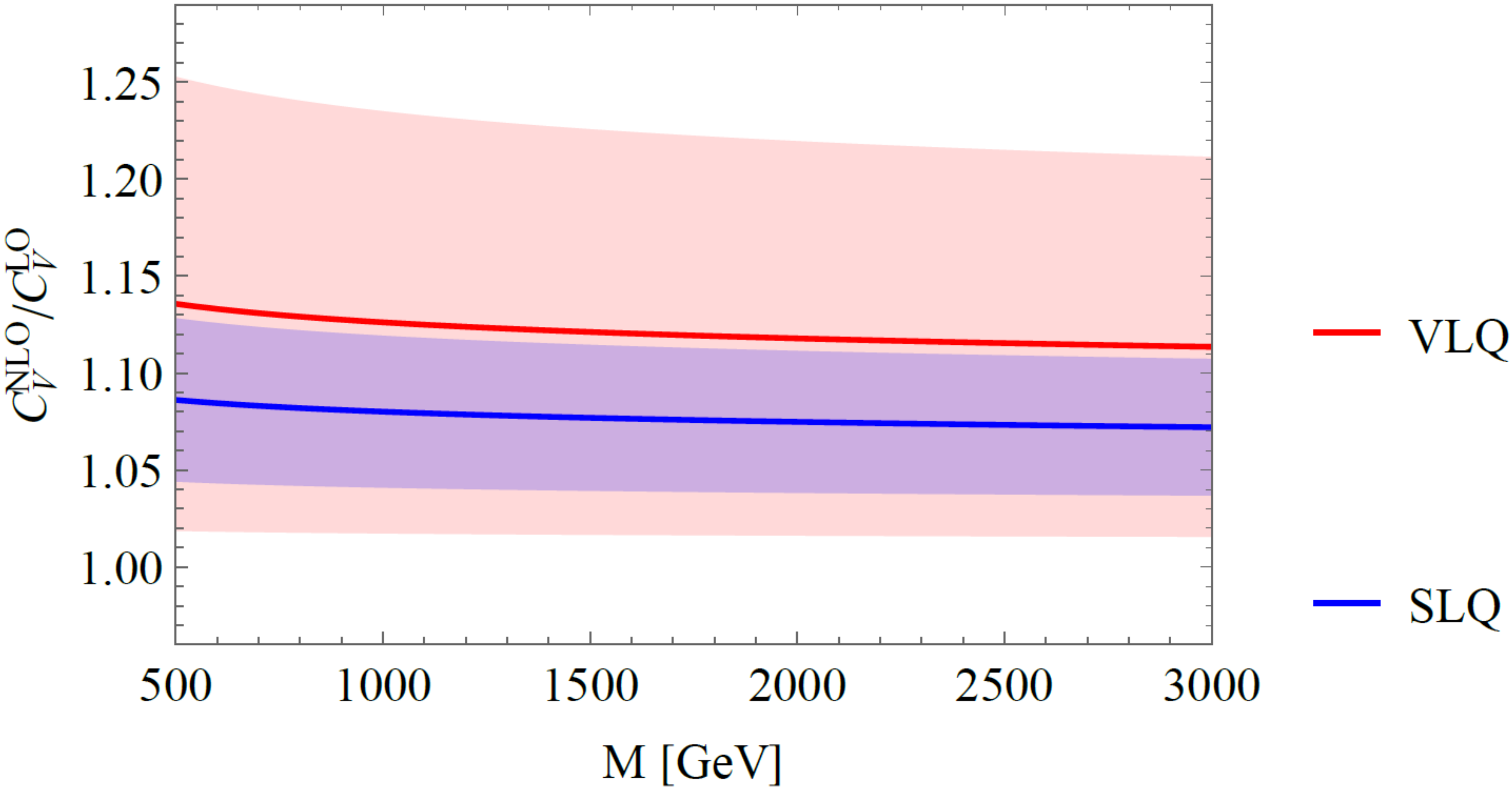






- Perform matching
- Correct for 4-dimensional Fierz identities

Results



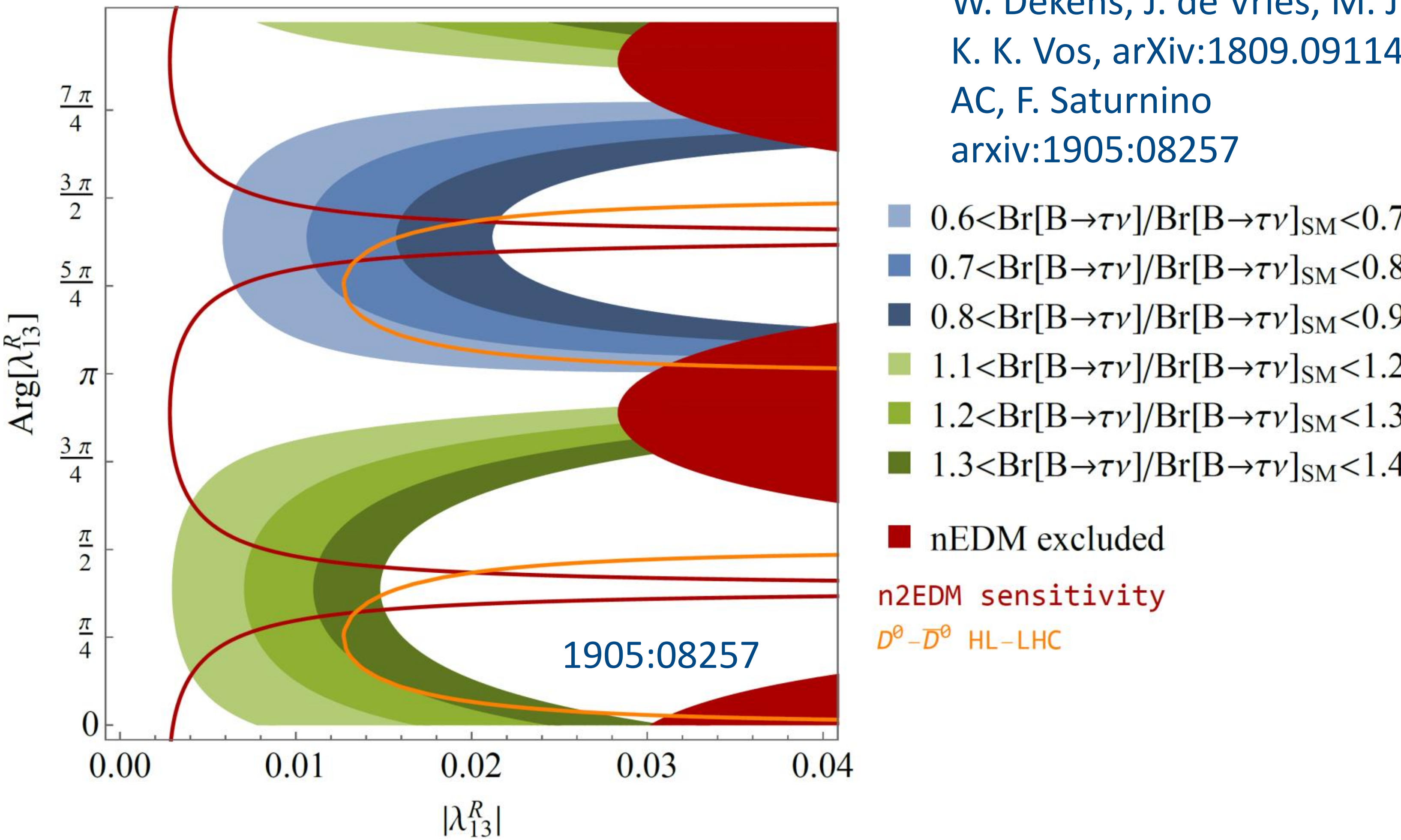
J. Aebischer, AC, C. Greub, 1811.08907

Slightly weaker LHC constraints

Correlations the neutron EDM with S1

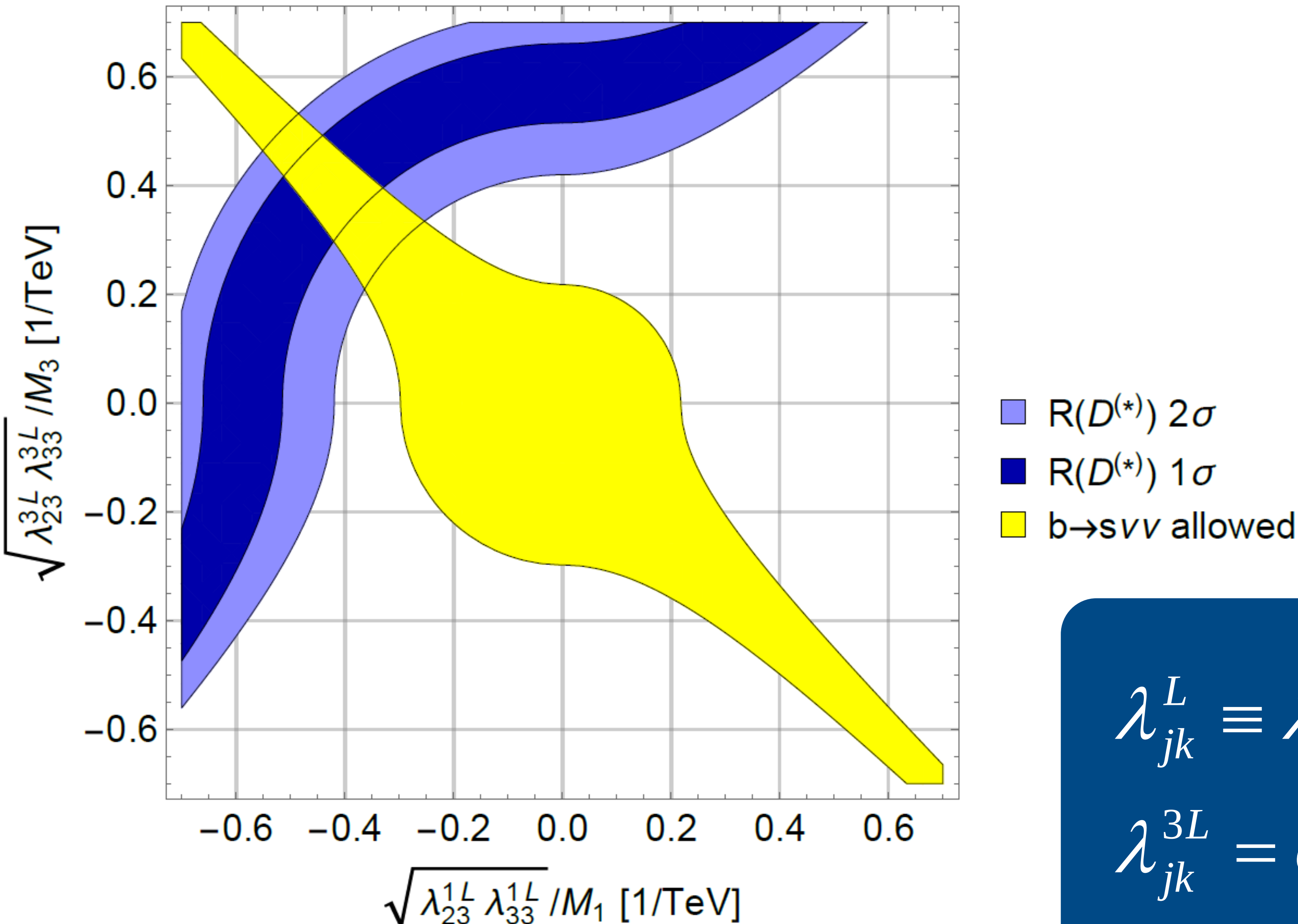
PAUL SCHERRER INSTITUT PSI

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

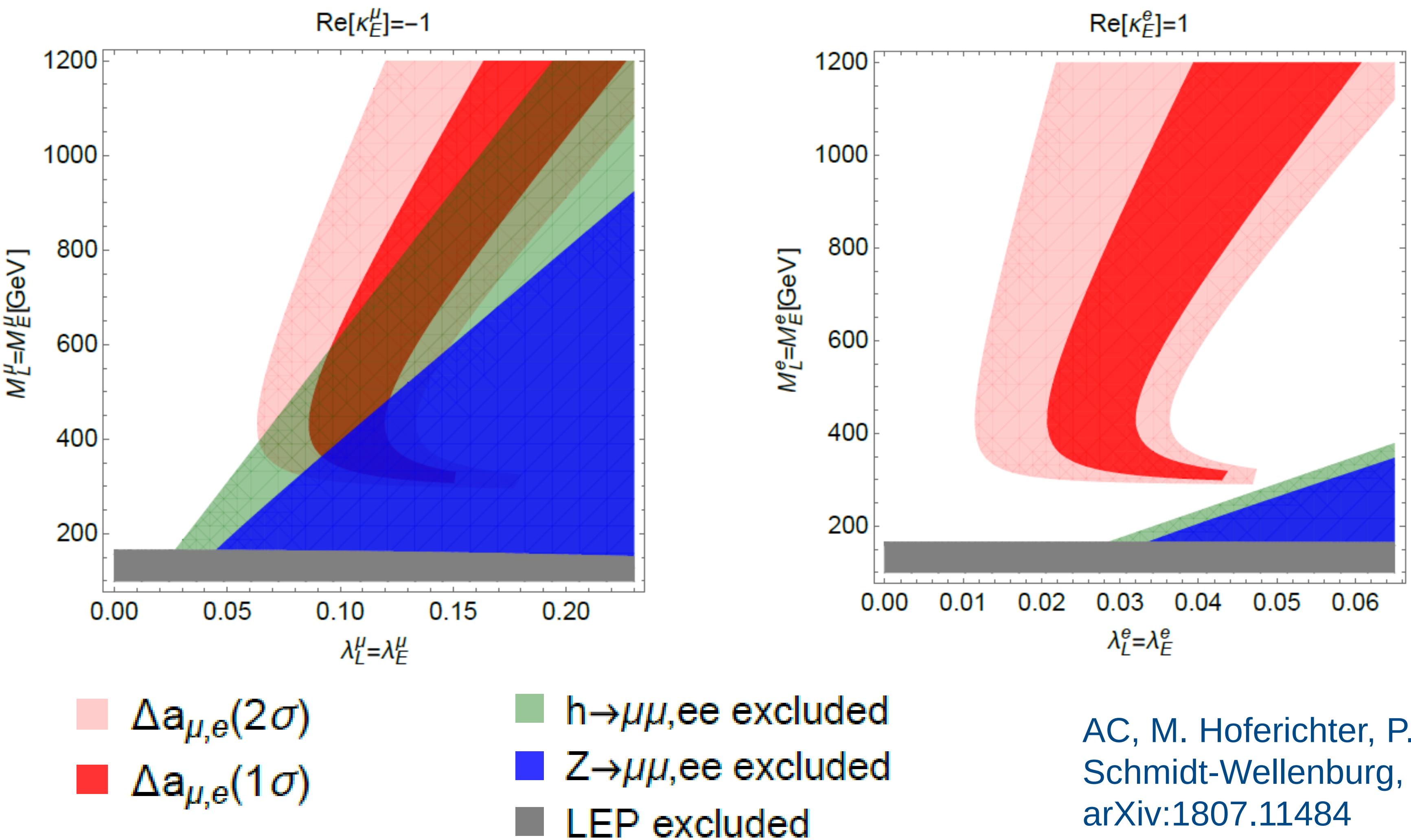
R(D(*)), b→sνν with 2 Scalar LQs



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

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

Model with new vector-like leptons

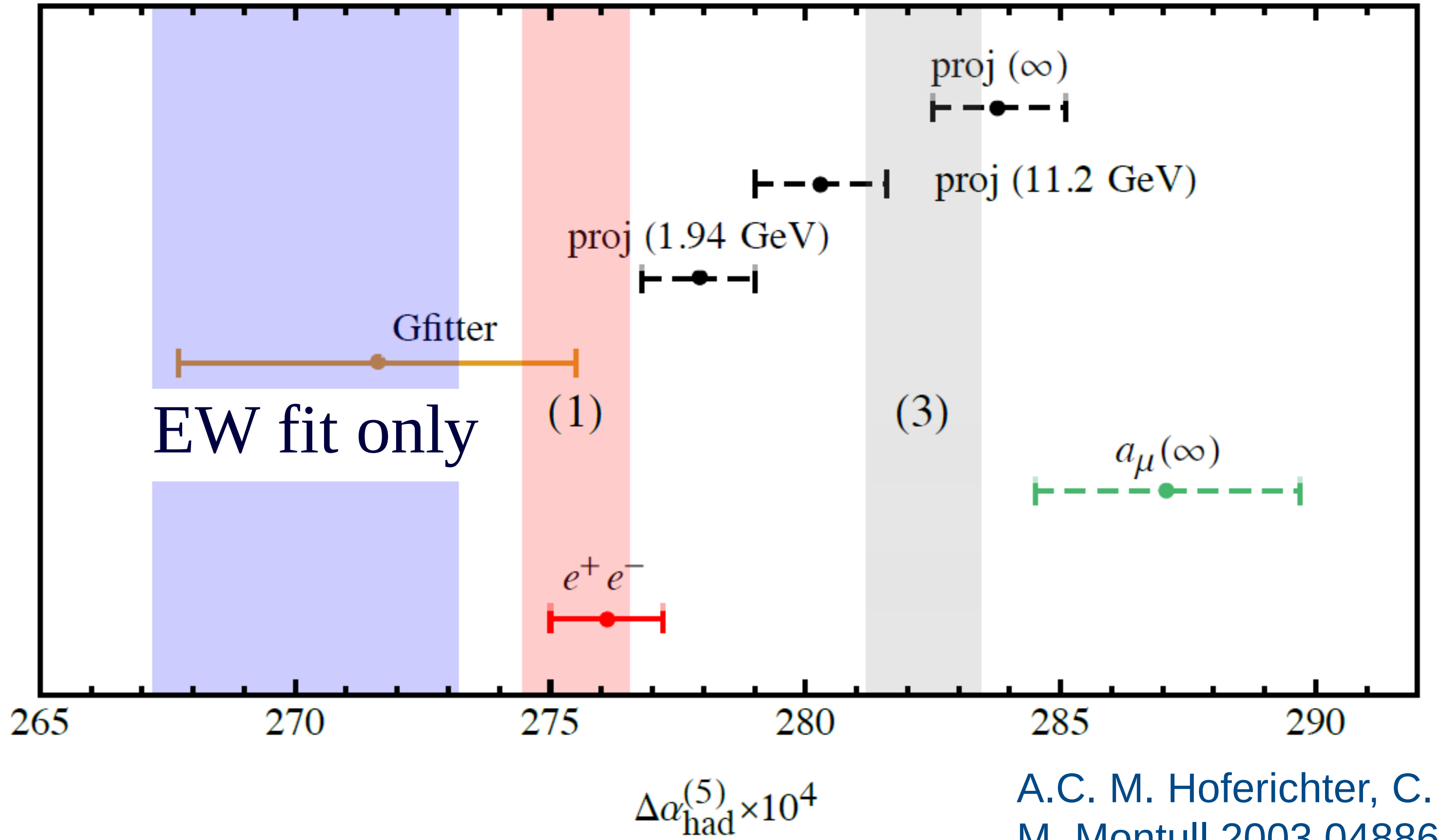


AC, M. Hoferichter, P. Schmidt-Wellenburg, arXiv:1807.11484

Works for a_e but tension with a_μ

Hadronic Vacuum Polarization

- New BMWc lattice QCD result

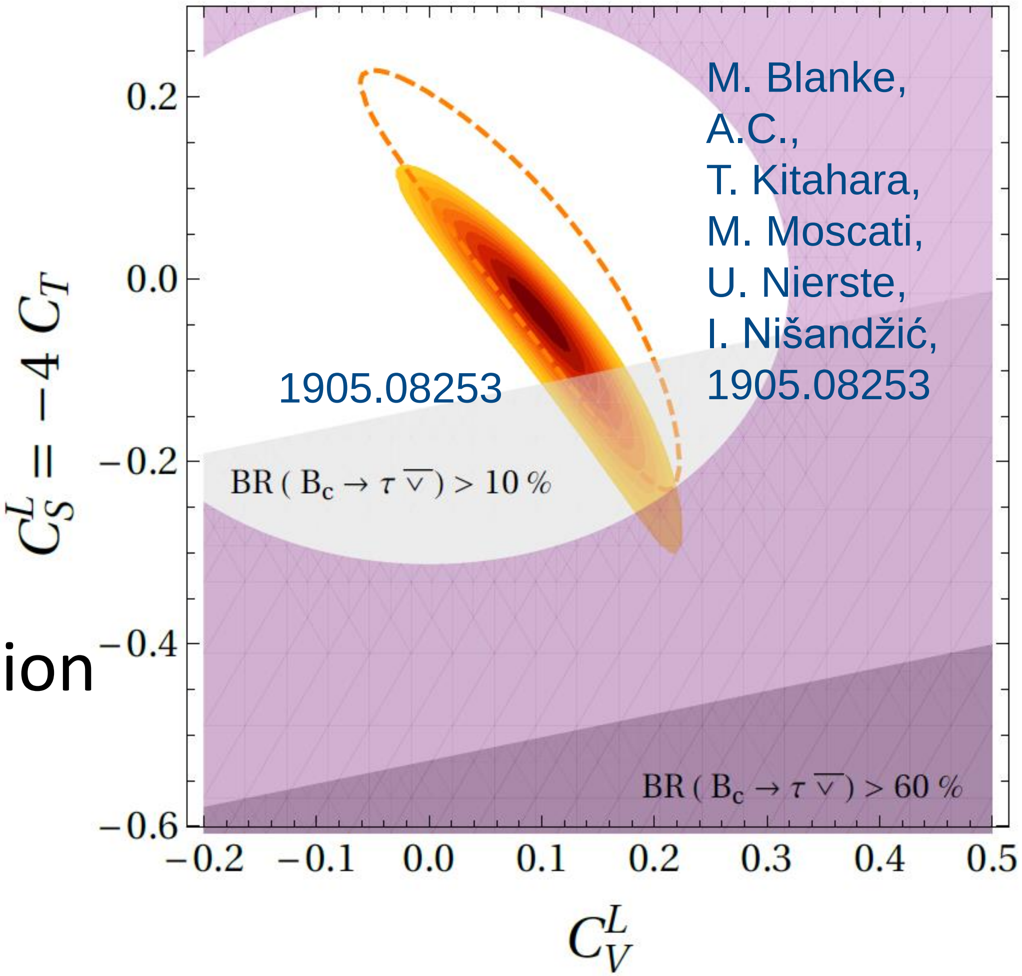


A.C. M. Hoferichter, C. Manzari, M. Montull 2003.04886

Up to 4σ tension in EW fit

b→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



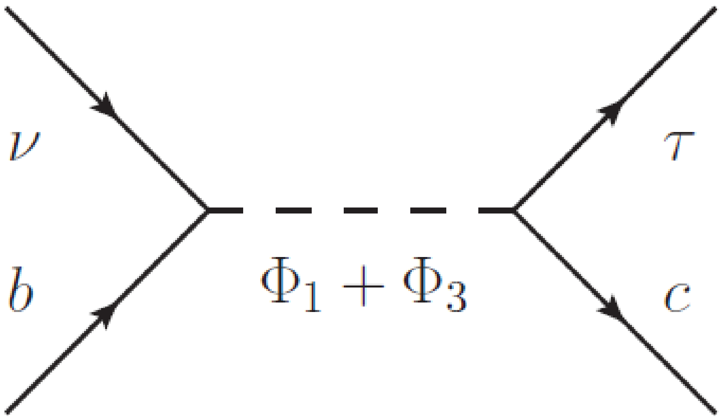
Global fit give up to 4σ preference for NP

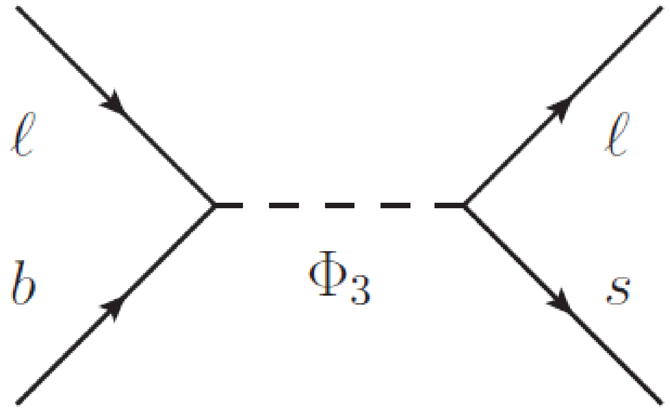
Scalar Leptoquarks

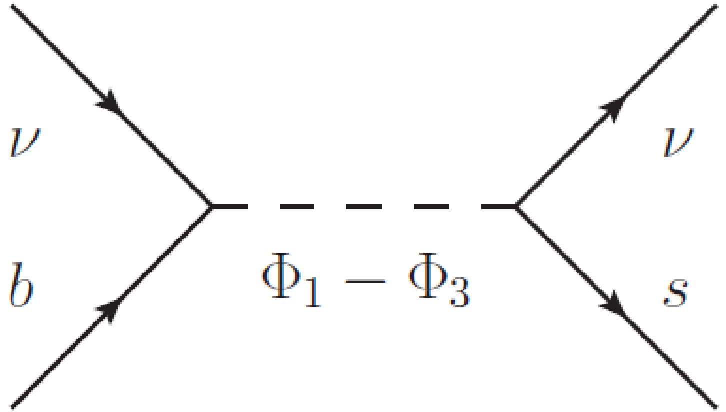
Two Scalar Leptoquarks

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

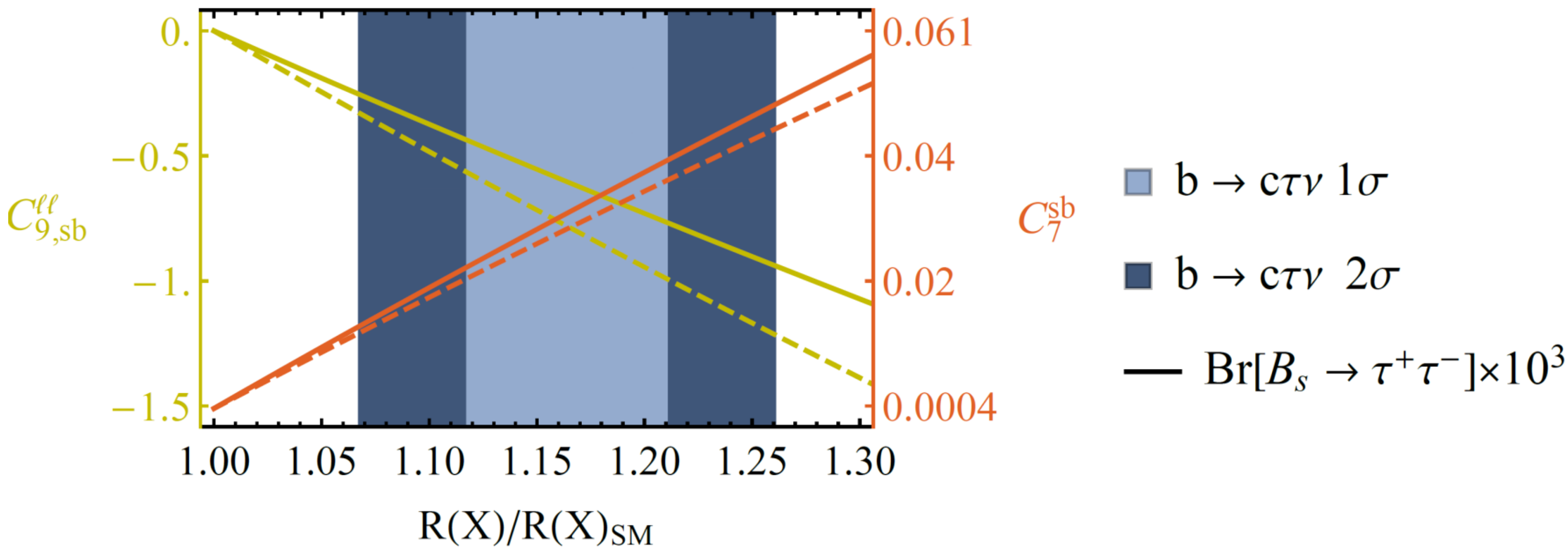
	$C_9^{\mu\mu} = -C_{10}^{\mu\mu}$	$C_9^{\ell\ell}$	$\frac{R(D)}{R(D)_{\text{SM}}}$	$\frac{R(D^*)}{R(D^*)_{\text{SM}}}$	$\frac{B_s\to\tau\tau}{B_s\to\tau\tau\|_{\text{SM}}}$	$\tau\to\mu\gamma$ $\times 10^8$	δa_μ $\times 10^{11}$	$\tilde{V}_{cb}^e/\tilde{V}_{cb}^\mu - 1$ $\times 10^6$	$Z\to\tau\mu$ $\times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

	$C_{SL}^{\tau\tau} = -4C_{TL}^{\tau\tau}$	$C_{VL}^{\tau\tau}$	$R_{\nu\bar{\nu}}^{K^{(*)}}$	$\frac{\Delta m_{B_s}^{\text{NP}}}{\Delta m_{B_s}^{\text{SM}}}$	$B\to K\tau\mu$ $\times 10^5$	$\tau\to\phi\mu$ $\times 10^8$	$\tau\to\mu ee$ $\times 10^{11}$	$\|\Lambda_{33}^{\text{LQ}}(0)\|$ $\times 10^5$	$\frac{\Delta_{33}^L(m_Z^2)}{\Lambda_{\text{SM}}^{L\ell}} \times 10^{-5}$
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→cτν requires large bτ and sτ couplings (follows from SU(2) invariance)

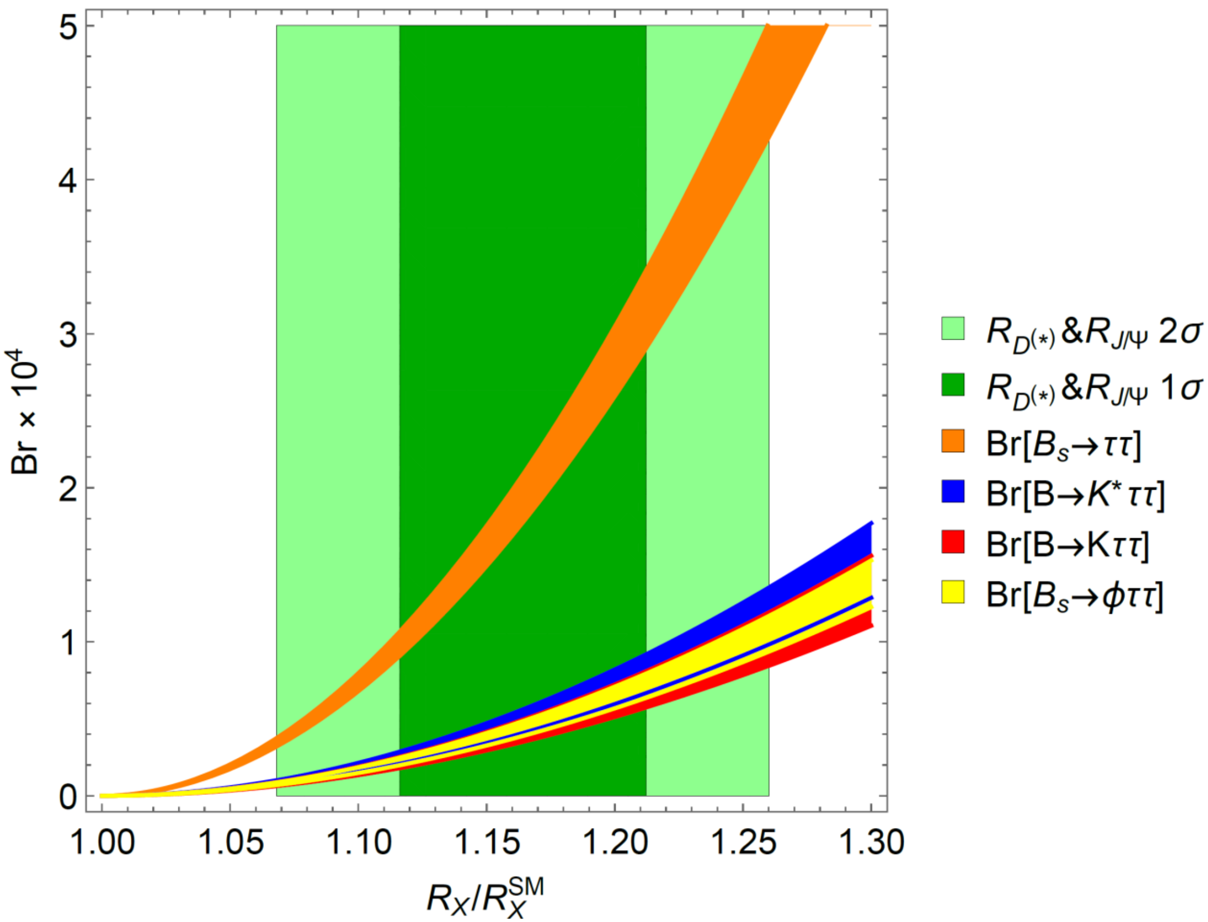


AC, C. Greub, D. Müller, F. Saturnino, PRL 2018

Large loop effects in b→sμμ

R(D$^{(*)}$) and b→sττ

- Large couplings to the second generation



b→sττ

very strongly enhanced

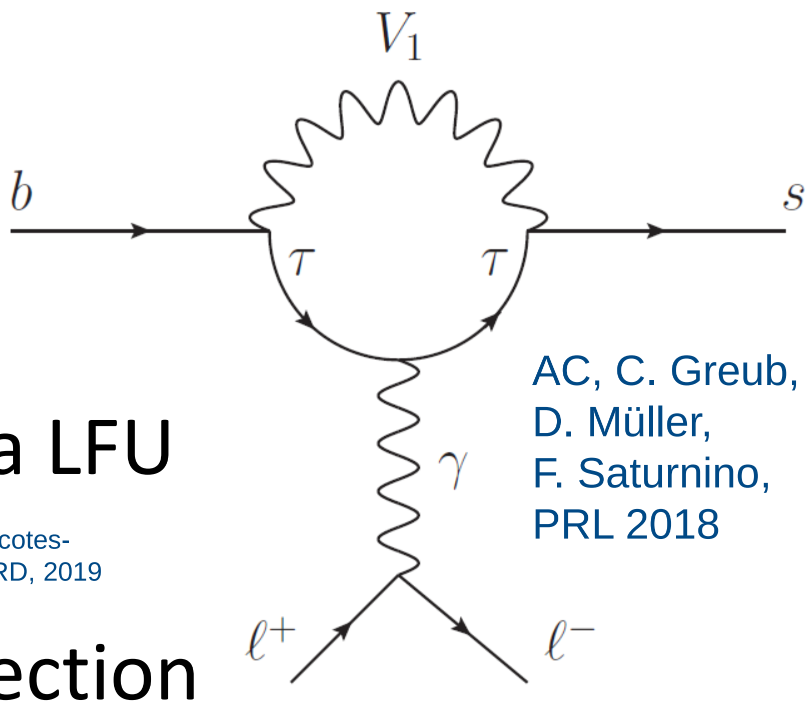
B. Capdevila, AC, S. Descotes-Genon, L. Hofer and J. Matias, PRL.120.181802

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

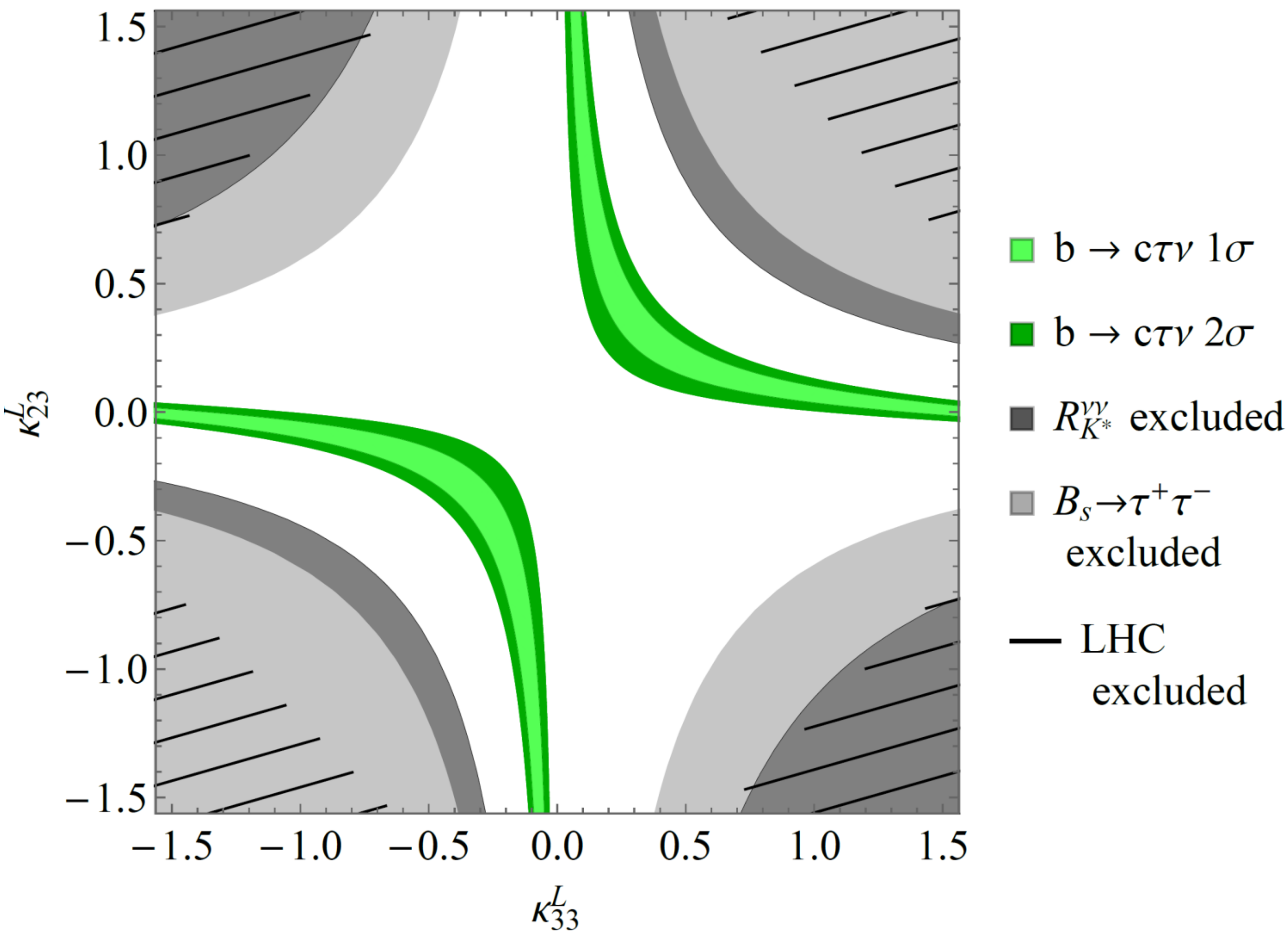
- Effect goes in the right direction



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

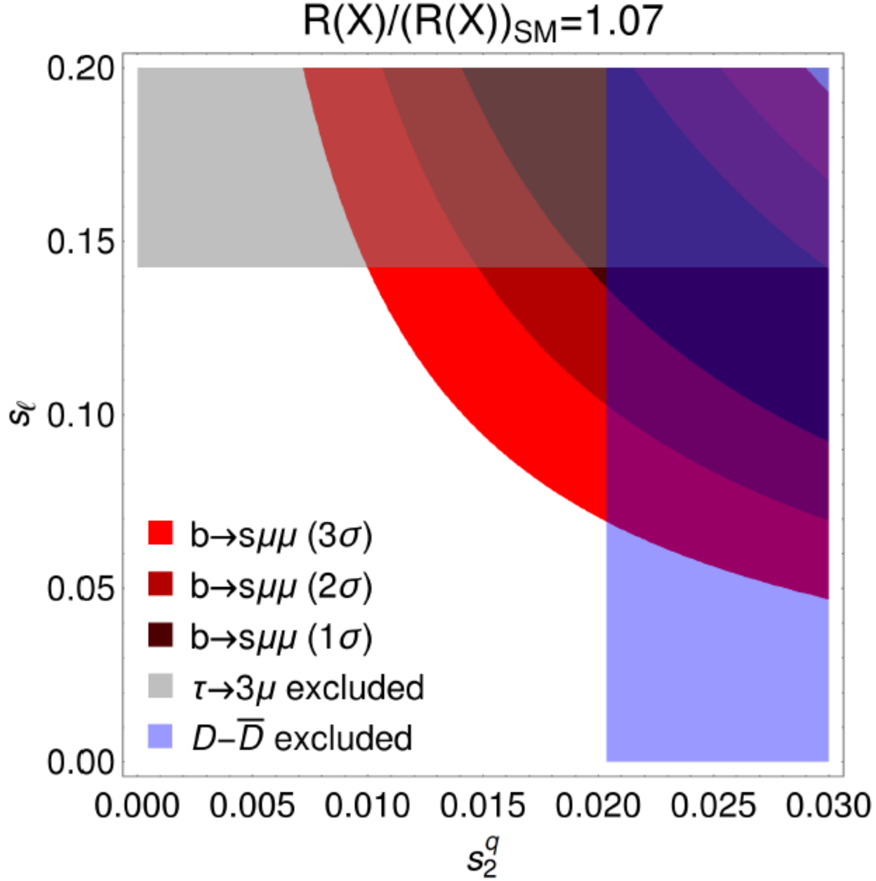
  J. Heeck, D. Teresi, arXiv:1808.07492
- SU(8) might even explain ε'/ε

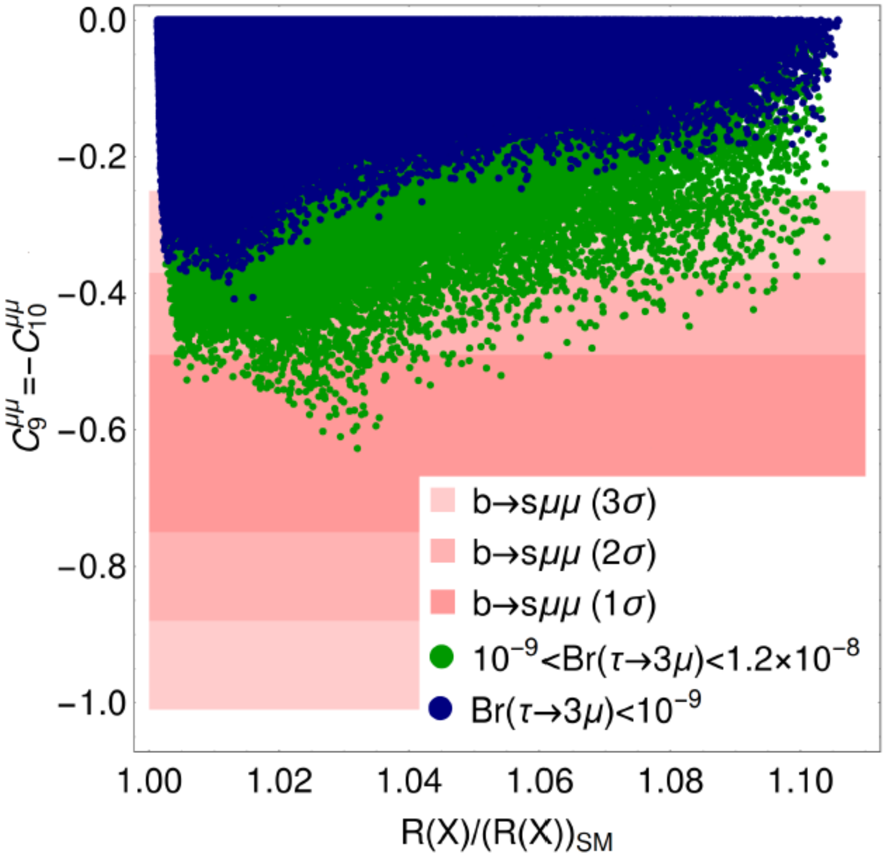
  S. Matsuzaki, K. Nishiwaki and K. Yamamoto, arXiv:1806.02312
- $SU(4)\times SU(2)_L\times SU(2)_R$ in RS background

  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