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Heavy Flavours -- Theory

LHCP, Paris, 10.06.2021 (remote)

Work supported by FNSNF

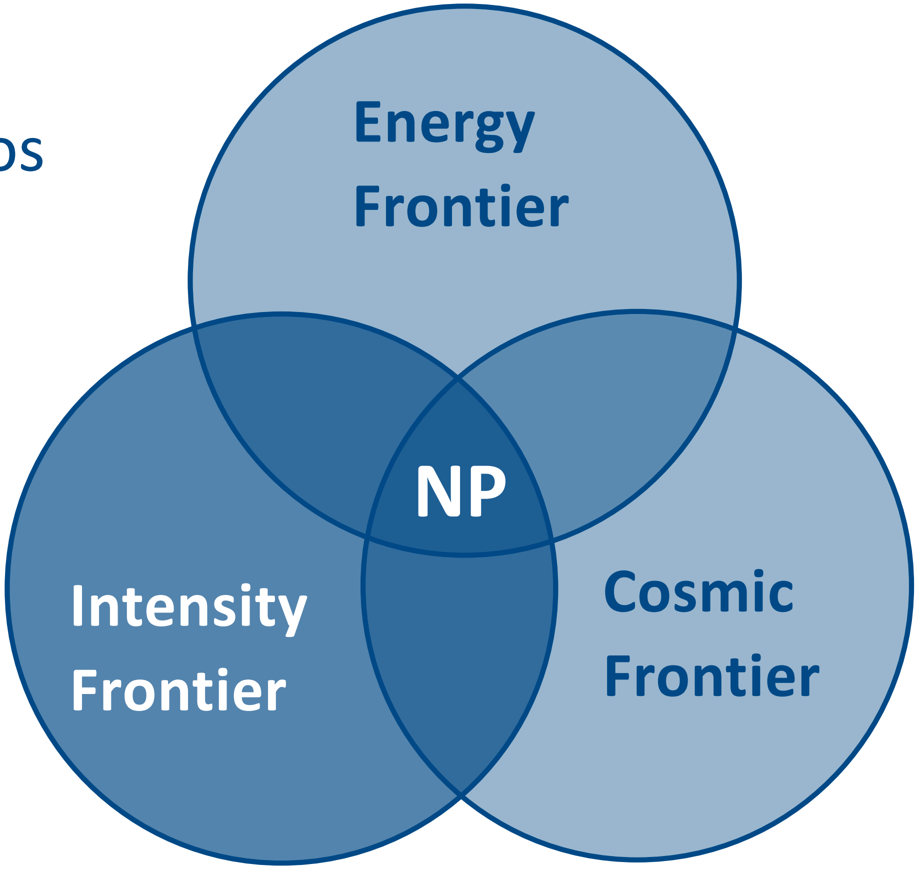
Outline

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

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



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

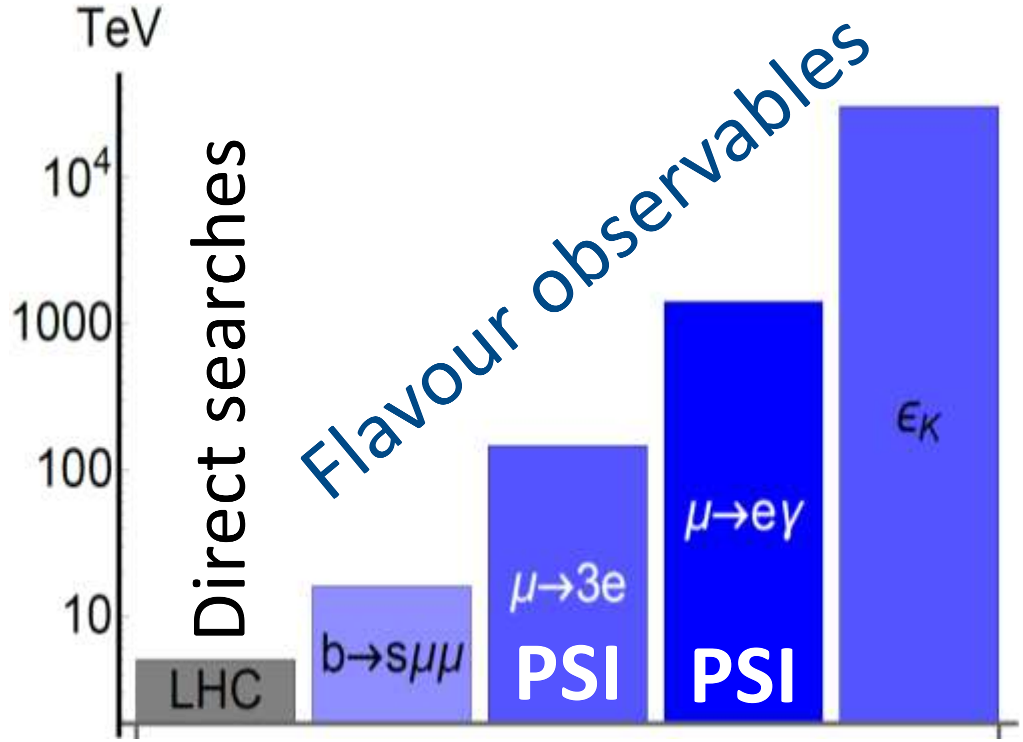
Experiment

≠

Standard Model

↓

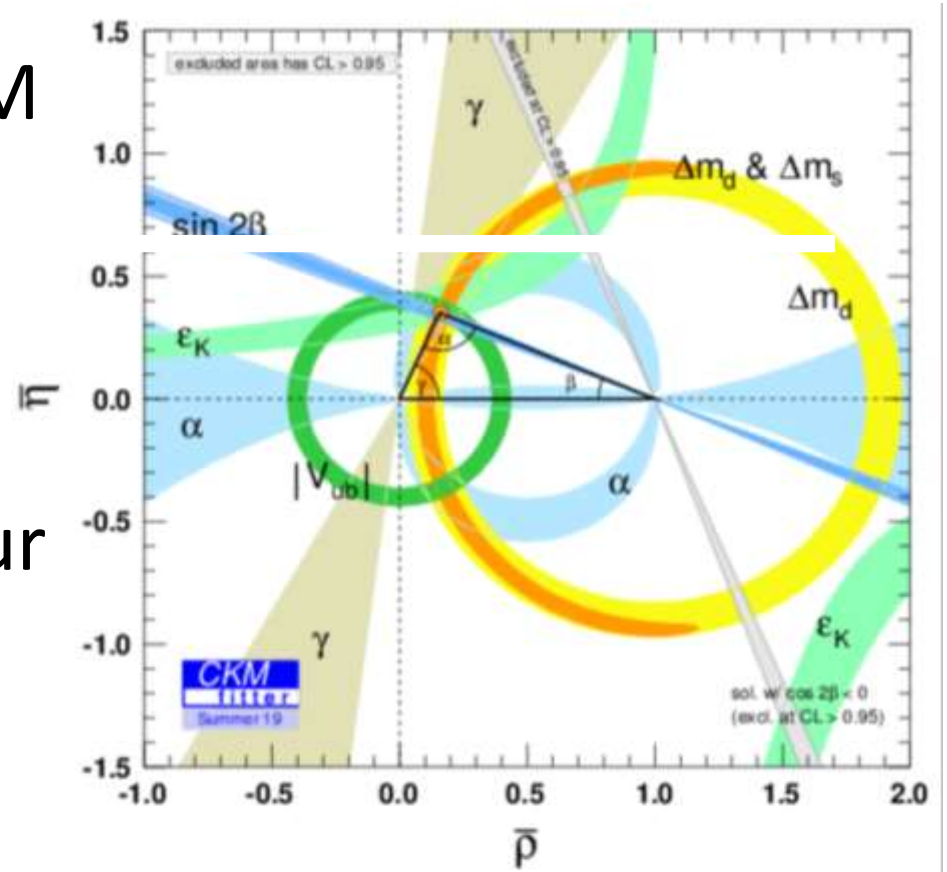
New Physics



Flavour observables probe 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%)

Lepton Flavour (Universality) Violation

In the Standard Model accidental symmetry:

- 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 Yukawa couplings distinguish flavors

⇨ Very small effect (except for phase space)

LFUV is an excellent probe of the SM

Overview on hints for Lepton Flavour Universality Violation

LFUV in b→sℓ⁺ ℓ⁻

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

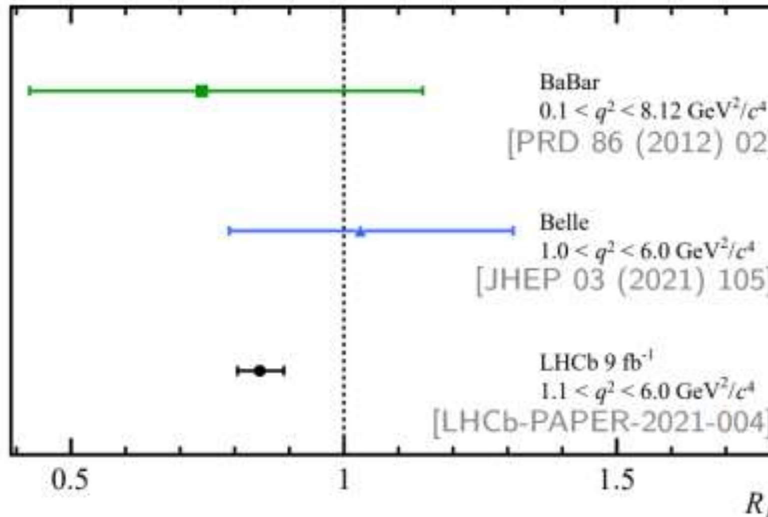
$$R(K^*) = \frac{B \to K^*\mu^+\mu^-}{B \to K^*e^+e^-}$$

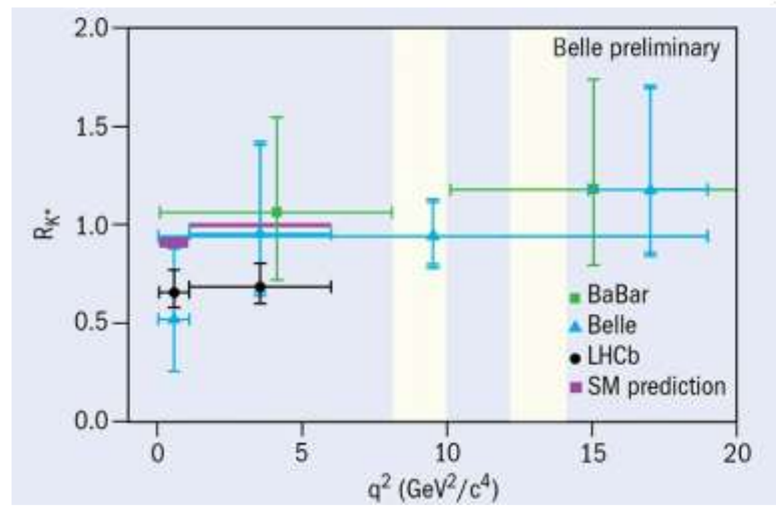
- Muon and electron masses can be neglected

⇨ **Clean prediction**

- Supported by

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





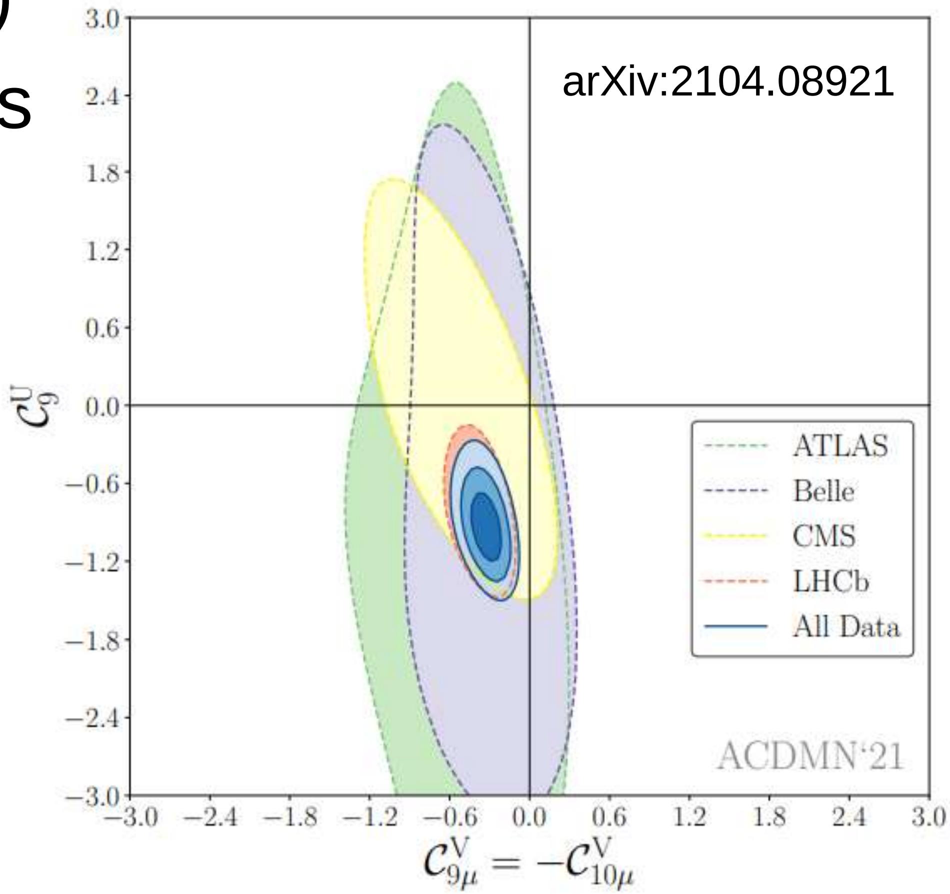
LFUV in B decays >4σ

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

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

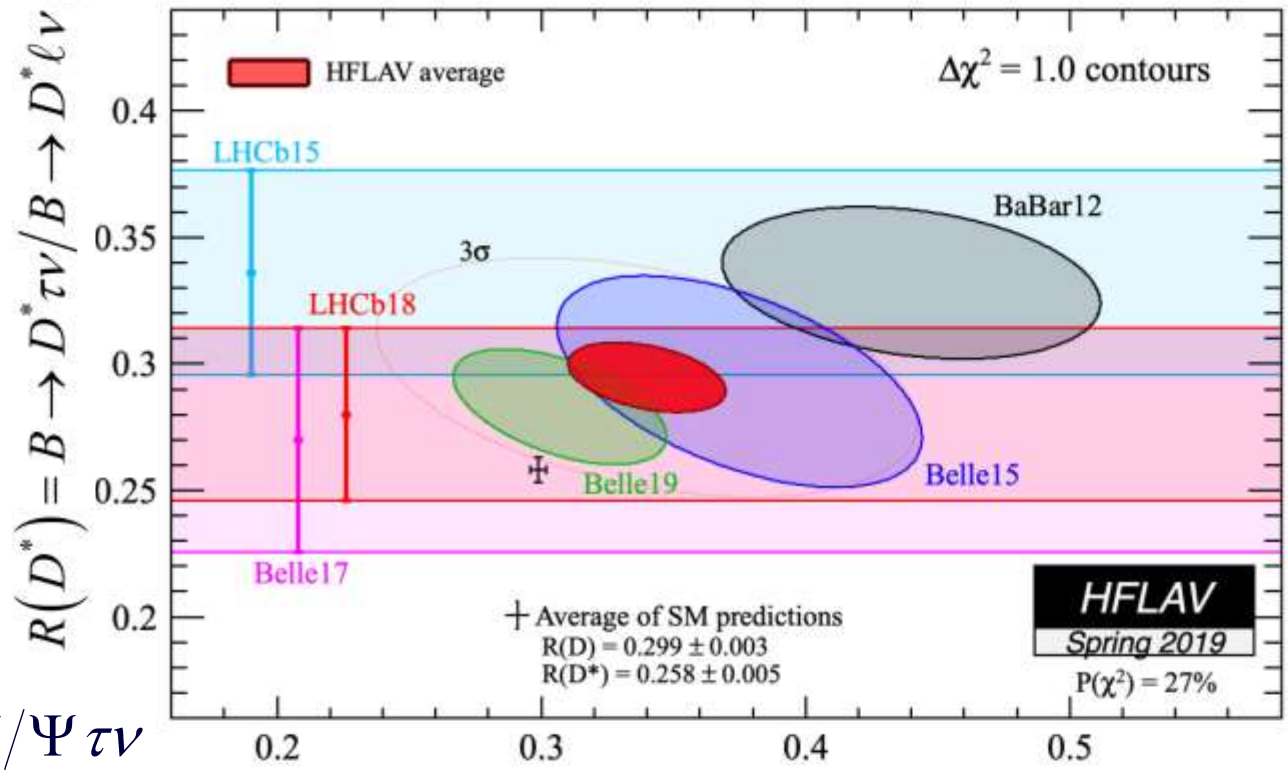
$$O_{10} = \bar{s}\gamma^{\mu} P_L b \bar{l} \gamma_{\mu} \gamma^5 l$$



Fit is >7 σ better than the SM

b→cτν Transitions

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



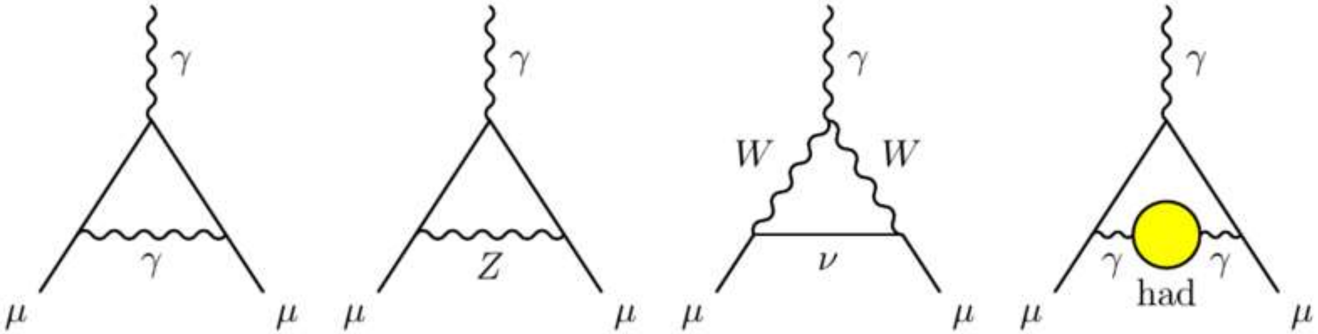
$$R(J/\Psi) = \frac{B_c \to J/\Psi\,\tau\nu}{B_c \to J/\Psi\, l\,\nu}$$

$$R(D) = B \to D\tau\nu / B \to Dl\,\nu$$

- Tree-level ⇨ **need larger NP effect**

O(10%) constructive preferred effect at 3σ

Muon Anomalous Magnetic Moment



- Theory prediction intricate (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

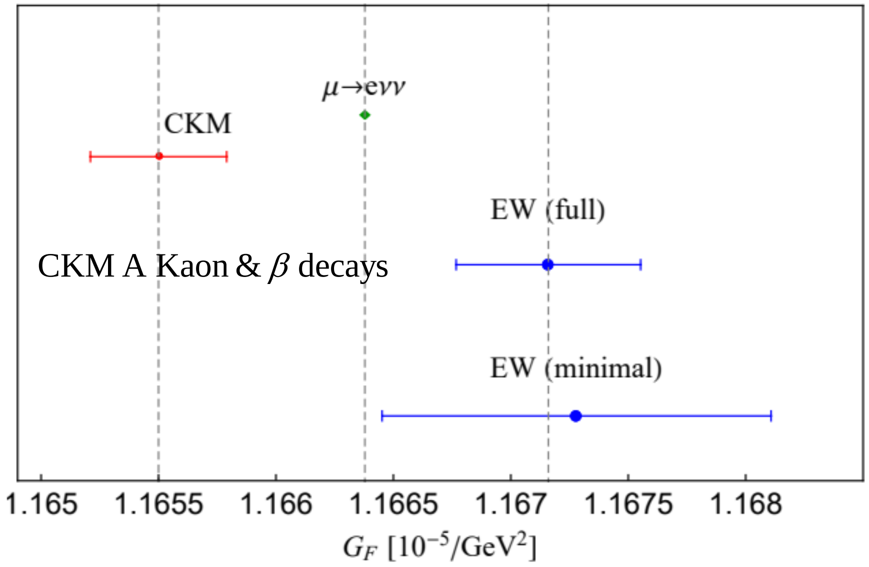
Cabibbo Angle Anomaly (CAA)

- Deficit in first row and first column CKM unitarity

$$|V_{ud}^2| + |V_{us}^2| + |V_{ub}^2| = 0.9985 \pm 0.0005$$
$$|V_{ud}^2| + |V_{cd}^2| + |V_{td}^2| = 0.9970 \pm 0.0018$$

(PDG)

AC, Hoferichter, Manzari, 2102.02825

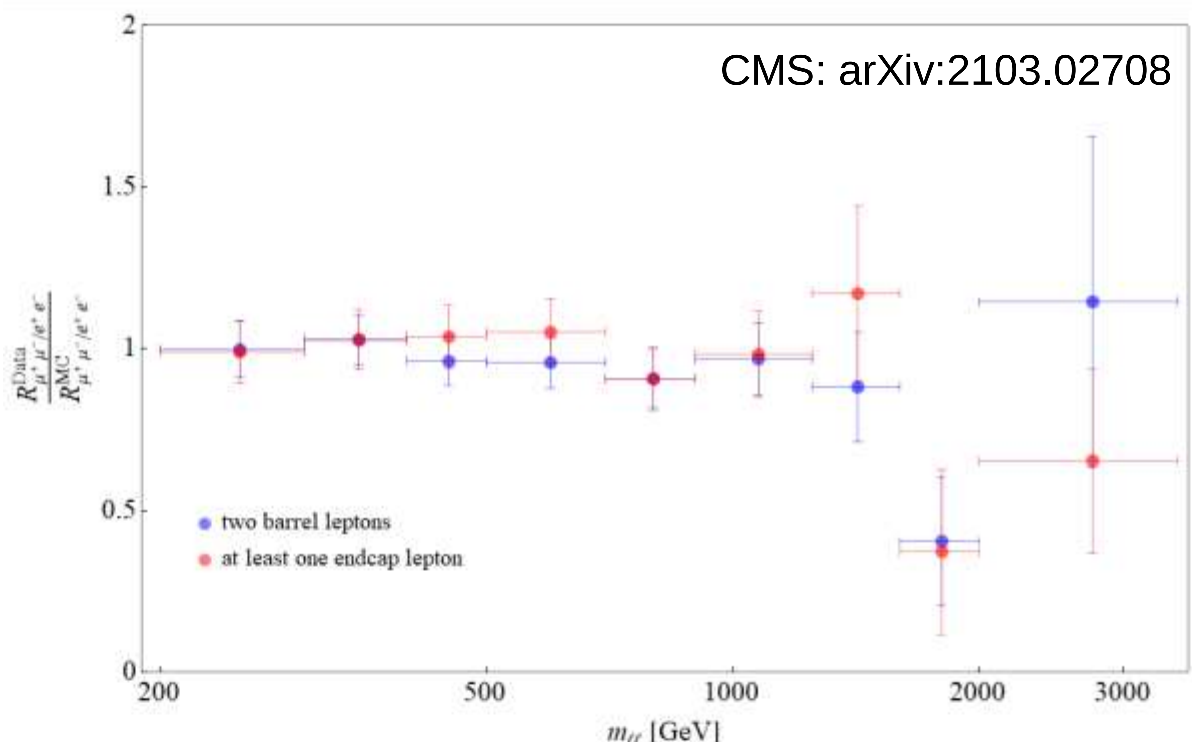


- NP in the determination of V_{ud} from beta decays needed
- Can be interpreted as
  - NP in beta decays
  - NP in the Fermi constant
  - LFUV (modified Wμν coupling)

3σ tension

Non-Resonant Di-Leptons

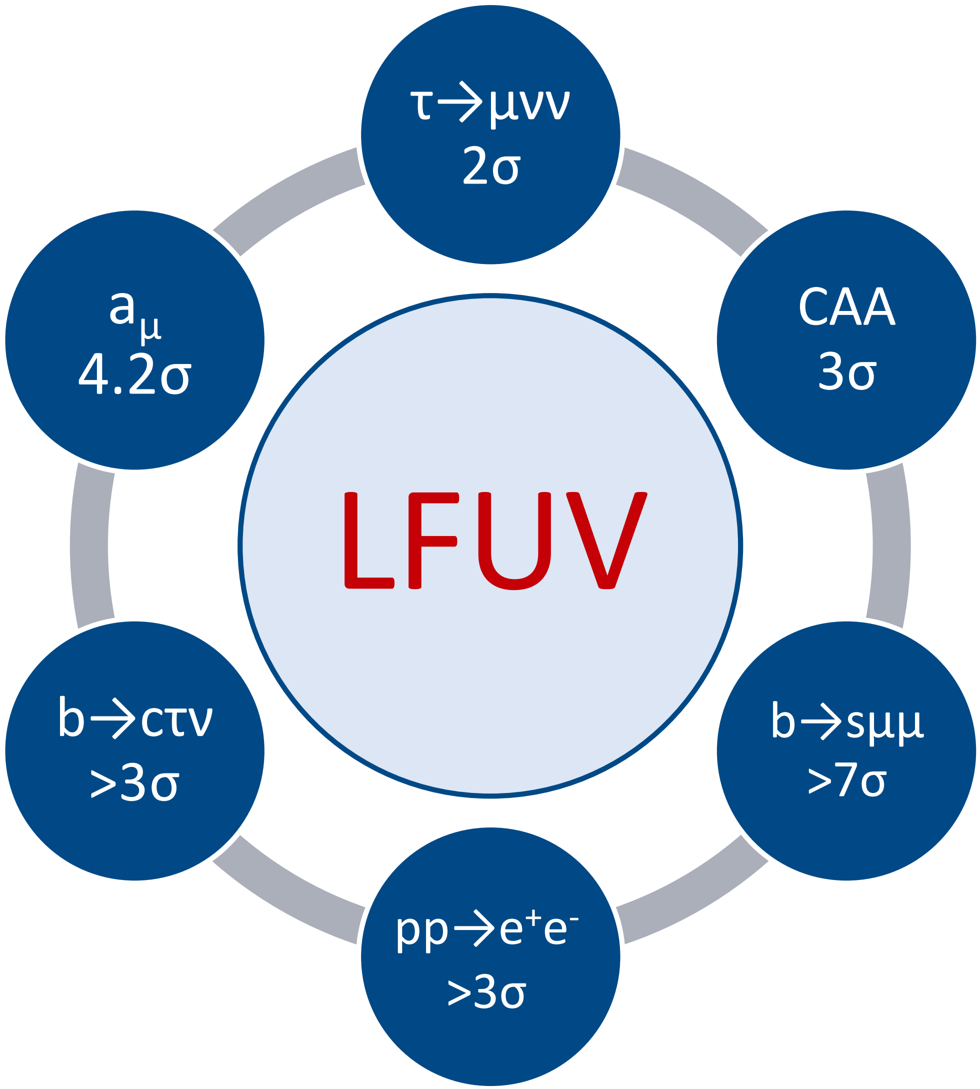
- Excess in di-electrons at m_{ee}>1800GeV
- Observed: 44 events
- Expected 29.2 ± 3.6 events



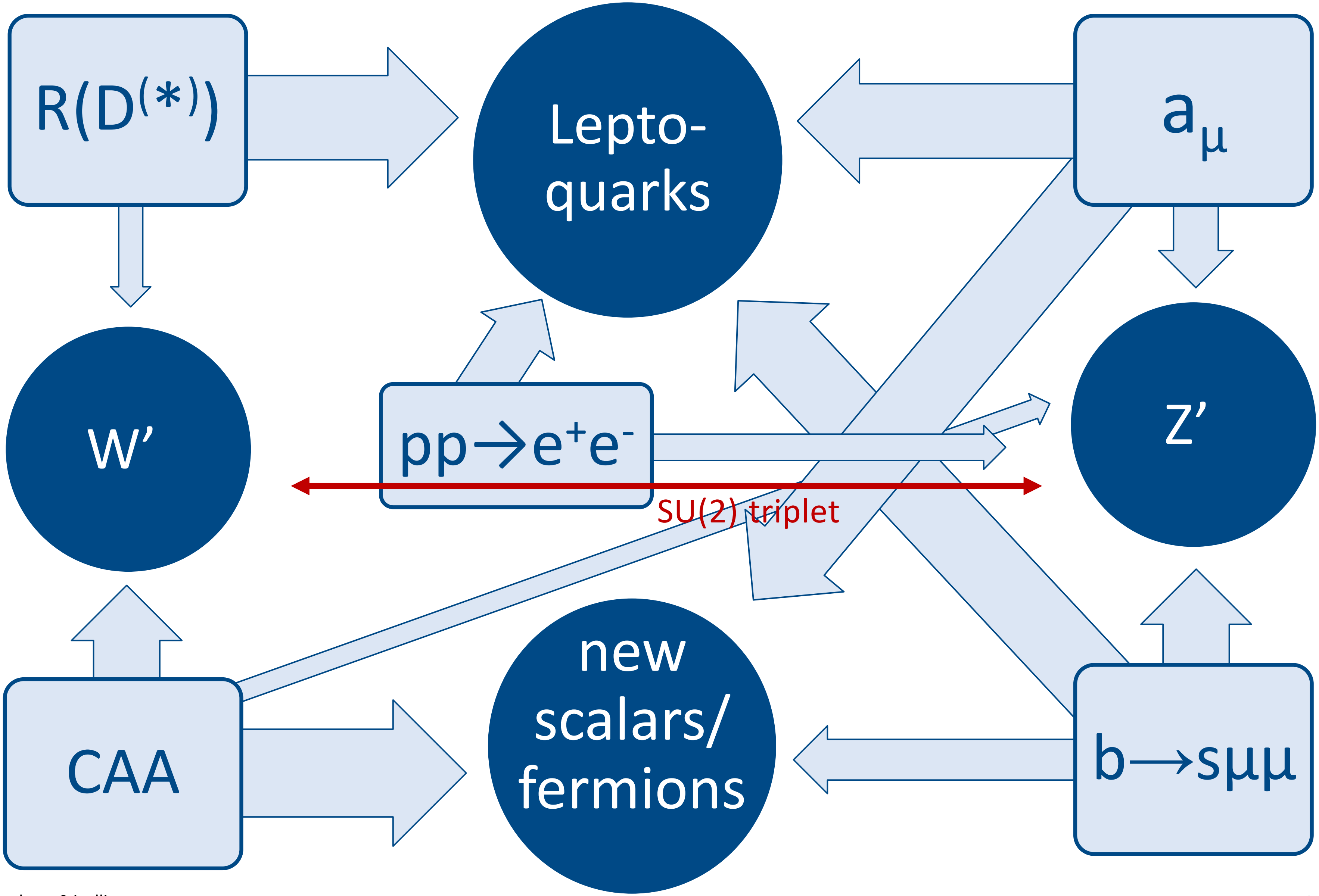
- Also ATLAS (2006.12946) and HERA (1902.03048) observe slightly more electrons than expected.
- No excess in muon data

≈3σ hint for LFUV

Hints for New Physics

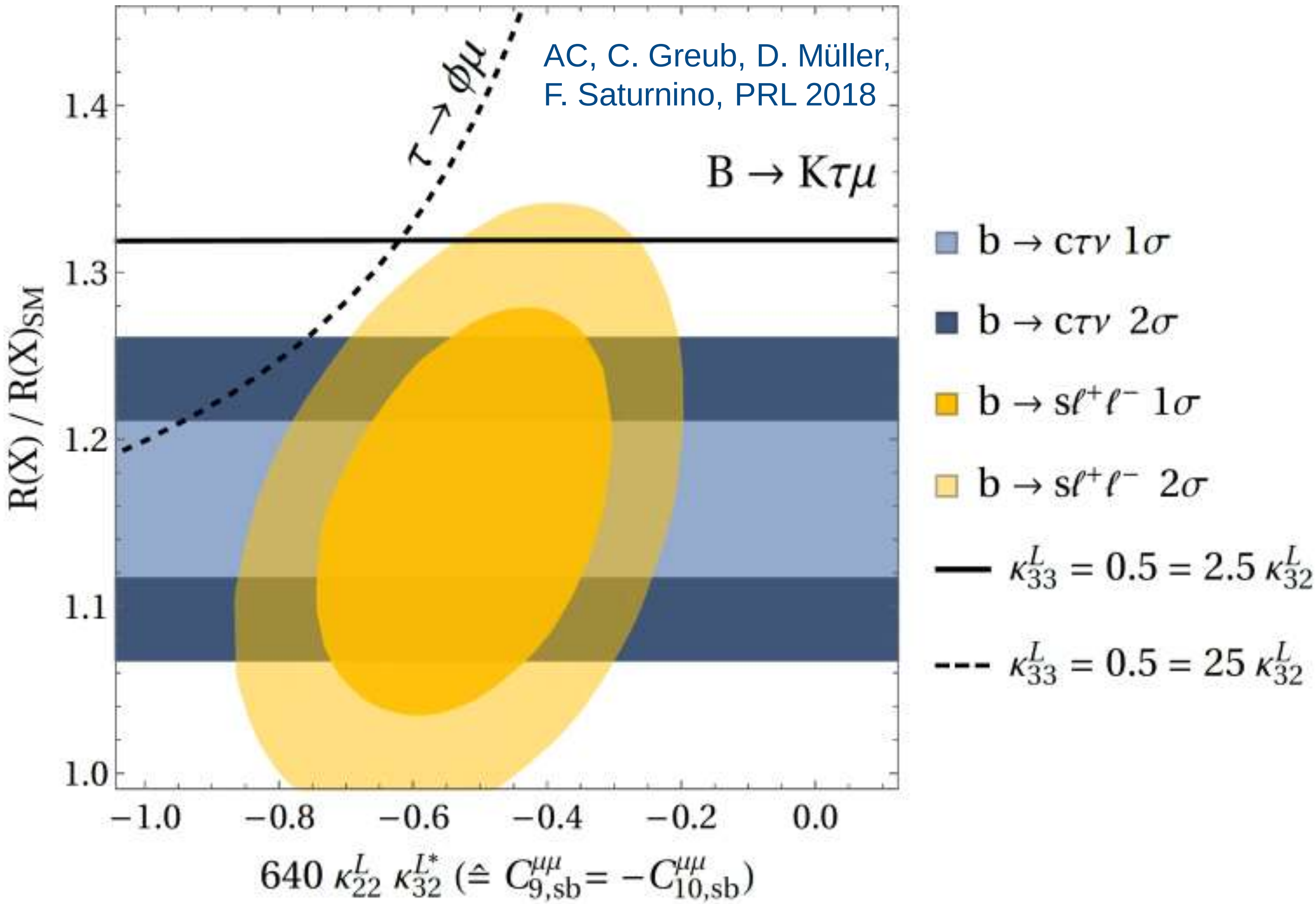


New Physics Explanations



Simultaneous Explanations

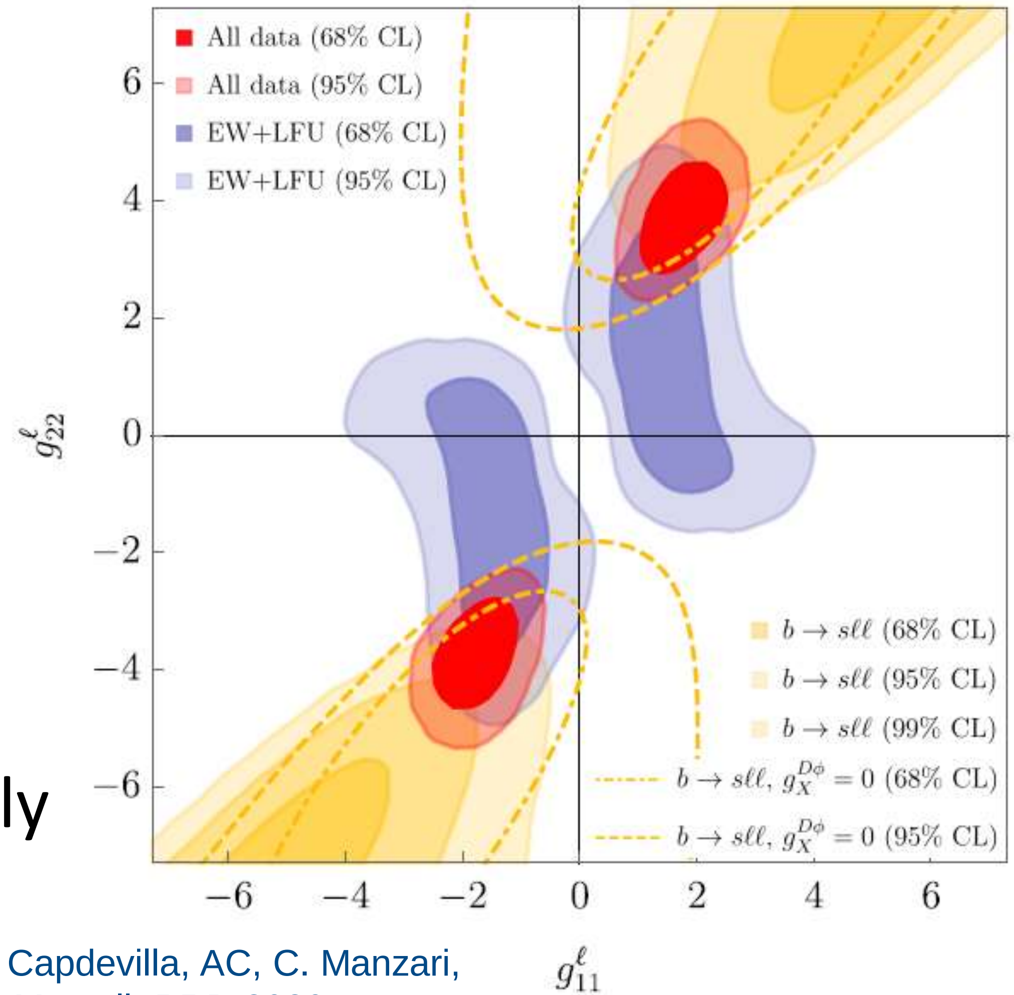
b→sℓℓ and b→cτν with a Vector Leptoquark



Pati-Salam LQ can explain the flavour anomalies

Vector Triplet in the CAA & b→sℓℓ

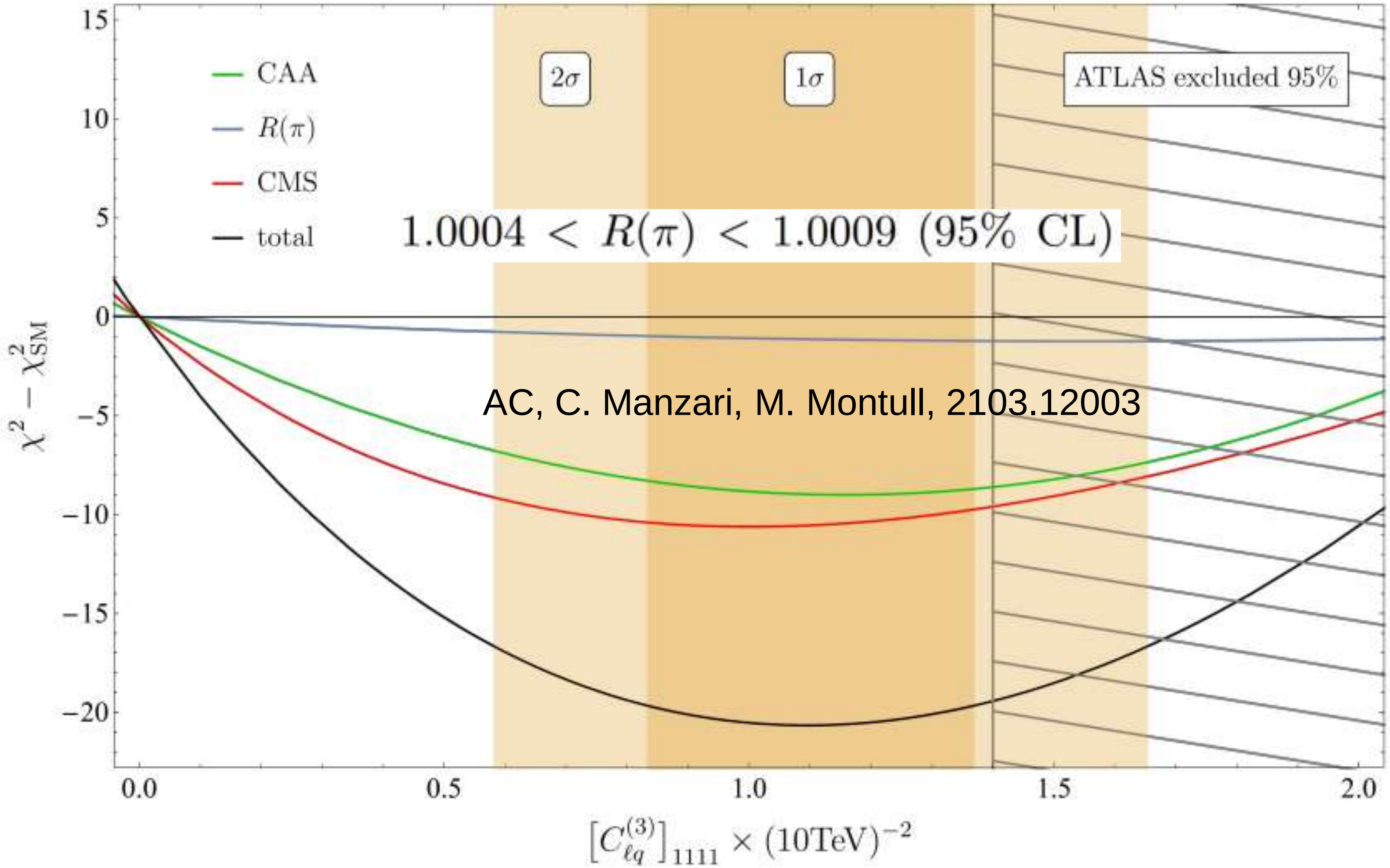
- Region from EW fit overlaps with b→sℓℓ region
- Correlations between e.g. $\pi\to\mu\nu/\pi\to e\nu$ and $R(K^{(*)})$ are predicted
- Global fit significantly improved



B. Capdevilla, AC, C. Manzari, M. Montull, PRD 2020

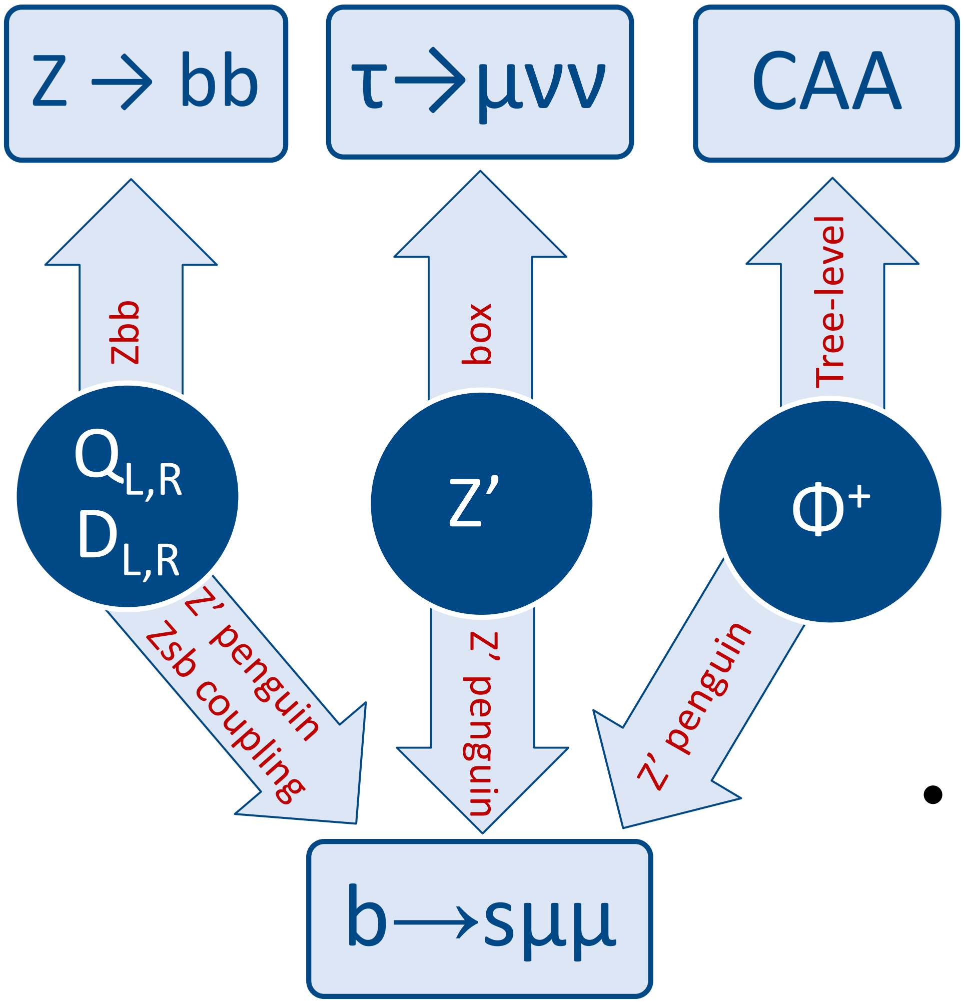
Common explanation possible

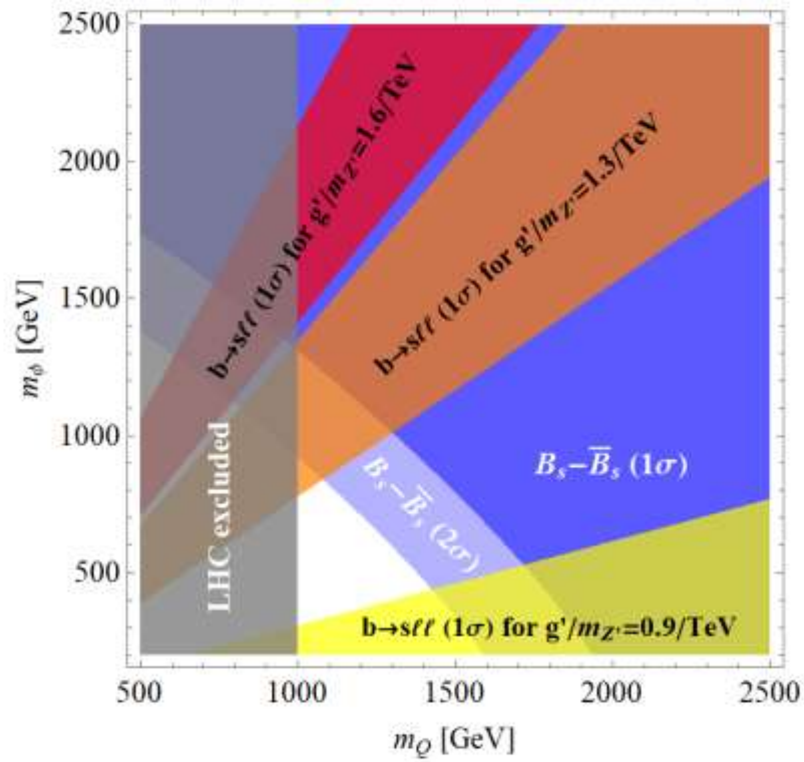
CAA and Non-Resonant Di-Leptons



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

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

Outlook

- Flavour Anomalies require NP at the TeV scale

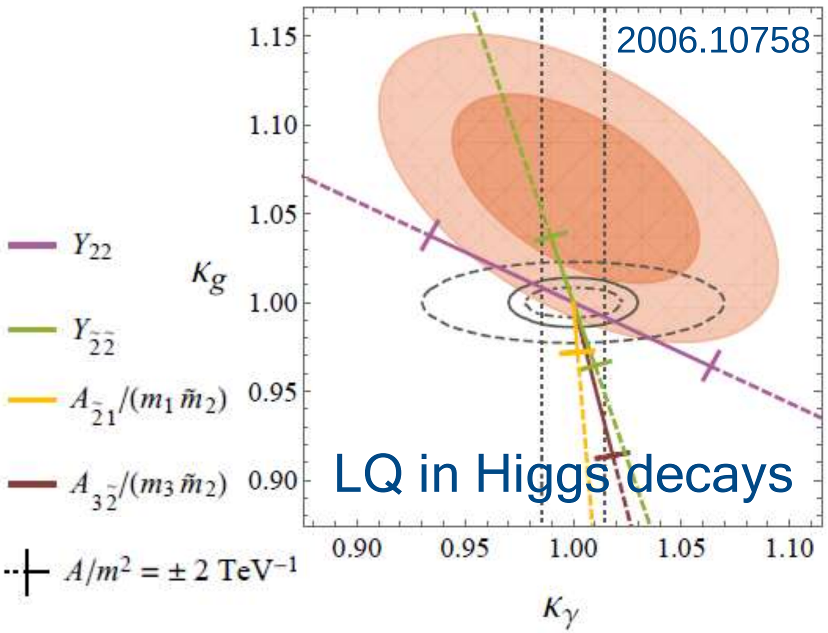
  ⇨ Direct Searches at (HL-) LHC, FCC-pp

- This new particles in general also affect EW precision observables

  ⇨ Z decays at CLIC and FCC-ee, CEPC

- Flavour is directly linked to the Higgs boson

  ⇨ CLIC, FCC

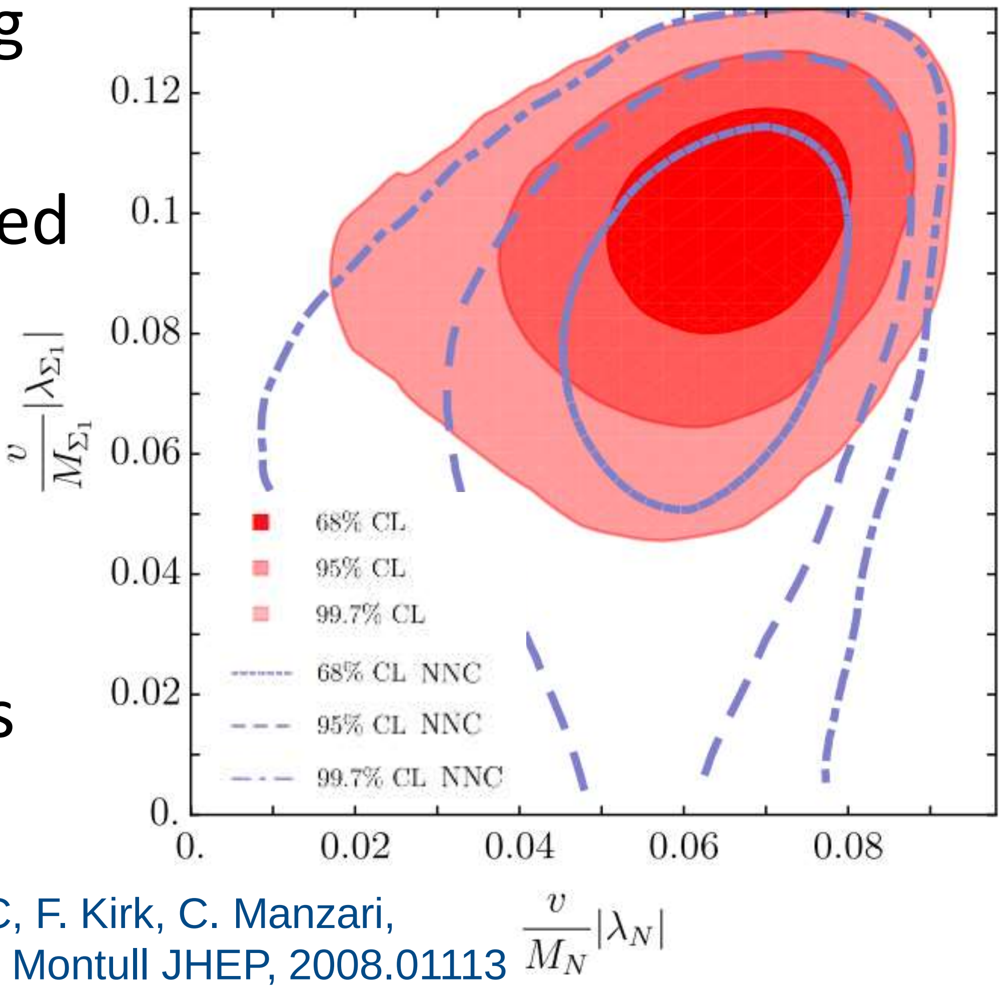


The flavour anomalies strengthen the physics case for future colliders significantly

Backup

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

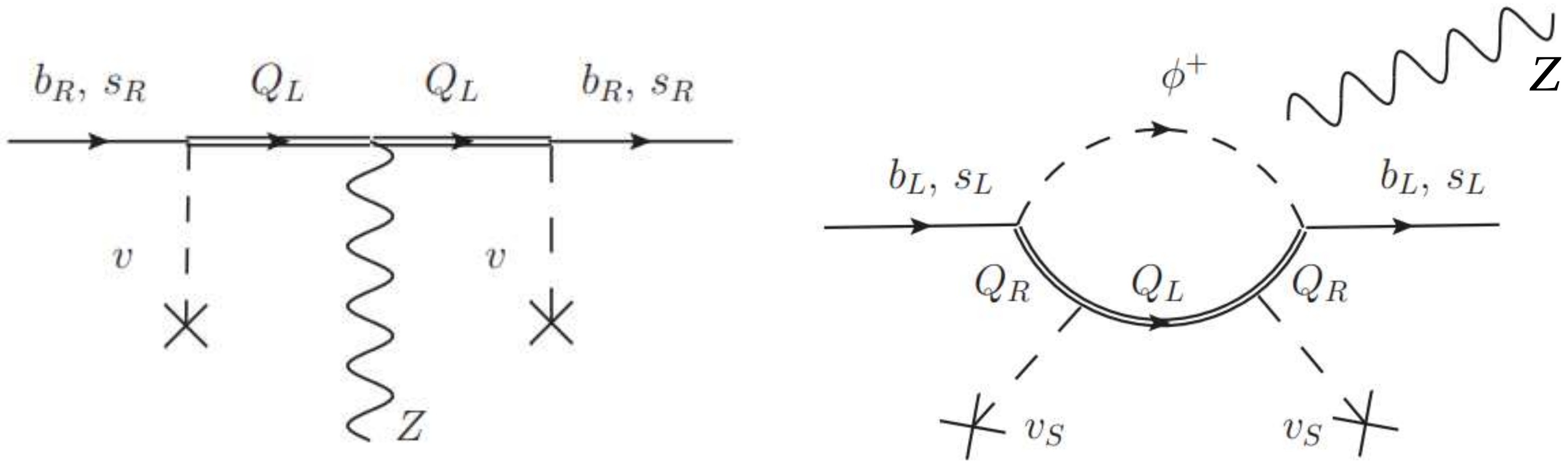


AC, F. Kirk, C. Manzari, M. Montull JHEP, 2008.01113

>5σ improvement over SM hypothesis

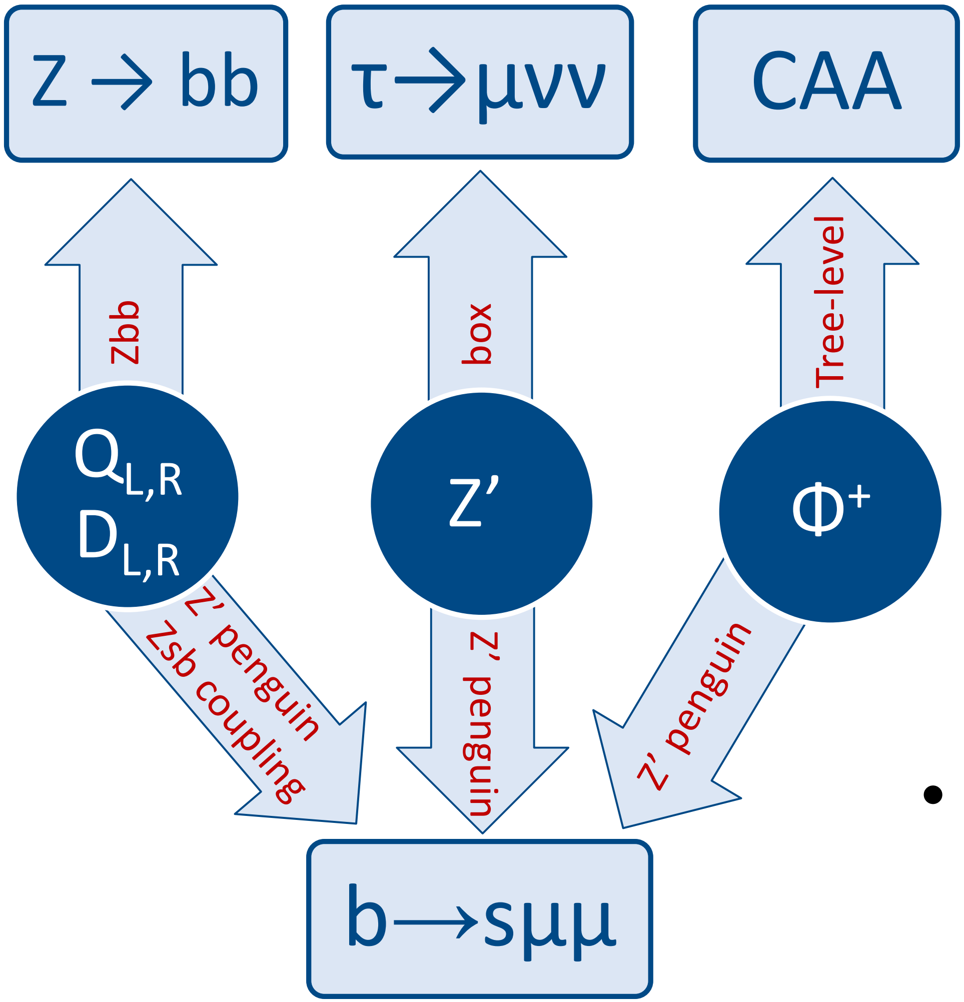
Model for b→sℓℓ, CAA, Z→bb and τ → μνν

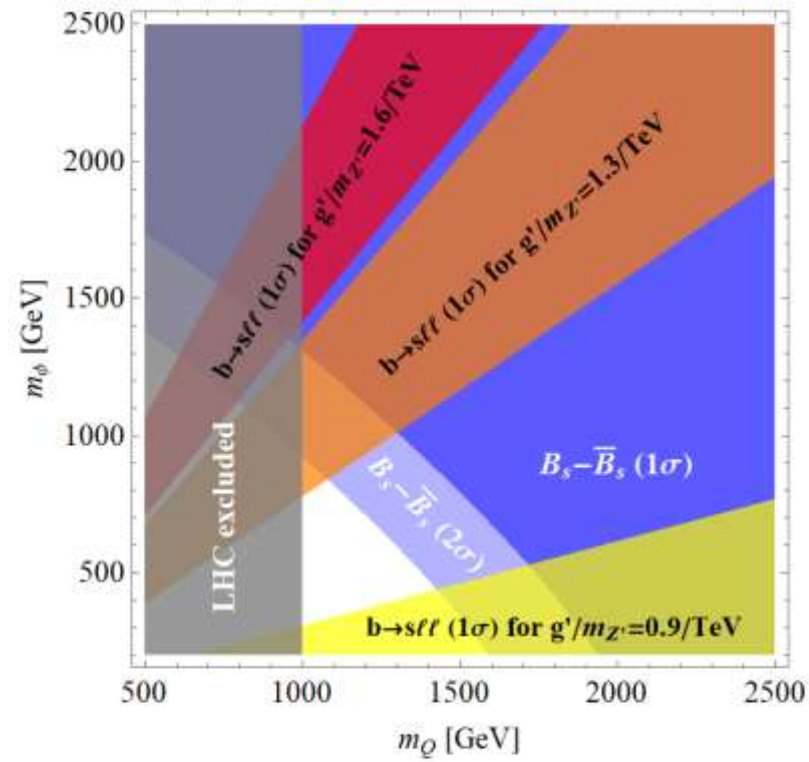
	q_L	d_R	u_R	H	ℓ_L	e_R	Q_L	Q_R	D_L	D_R	ϕ^+	S
$SU(3)_c$	3	3	3	1	1	1	3	3	3	3	1	1
$SU(2)_L$	2	1	1	2	2	1	2	2	1	1	1	1
$U(1)_Y$	$\frac{1}{6}$	$\frac{-1}{3}$	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{-1}{2}$	-1	$\frac{-5}{6}$	$\frac{-5}{6}$	$\frac{-1}{3}$	$\frac{-1}{3}$	1	0
$U(1)'$	0	0	0	0	$(0,1,-1)$		0	1	1	0	-1	-1



Tree effect in Zbb and loop in Z’sb

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



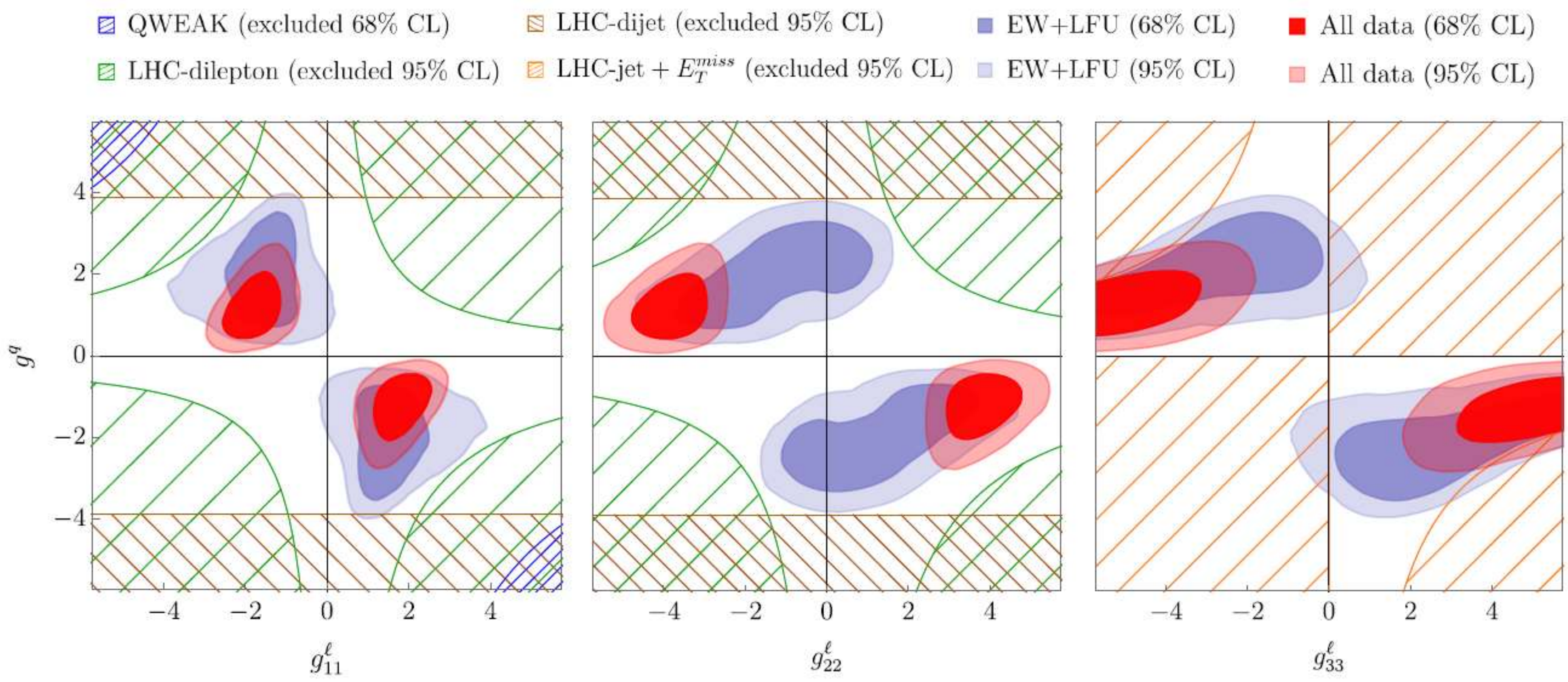


- Z’ penguin + modified Zsb coupling give very good fit to b→sll data

Simple model provides combined explanation

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

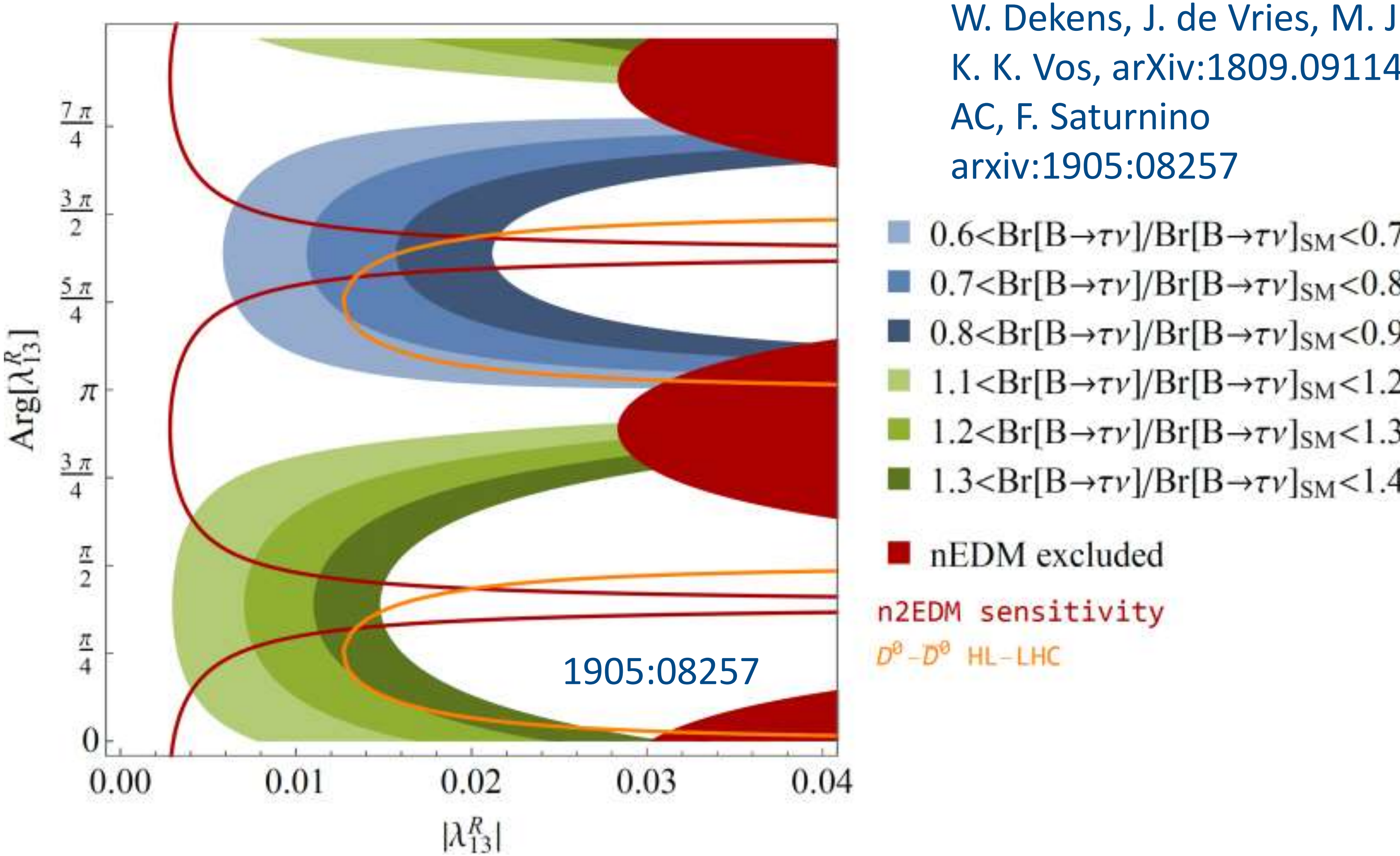
- W' effects in LFU and EW observables
- Z' effects in LHC di-jet and di-lepton tail searches



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

Correlations the neutron EDM with S1

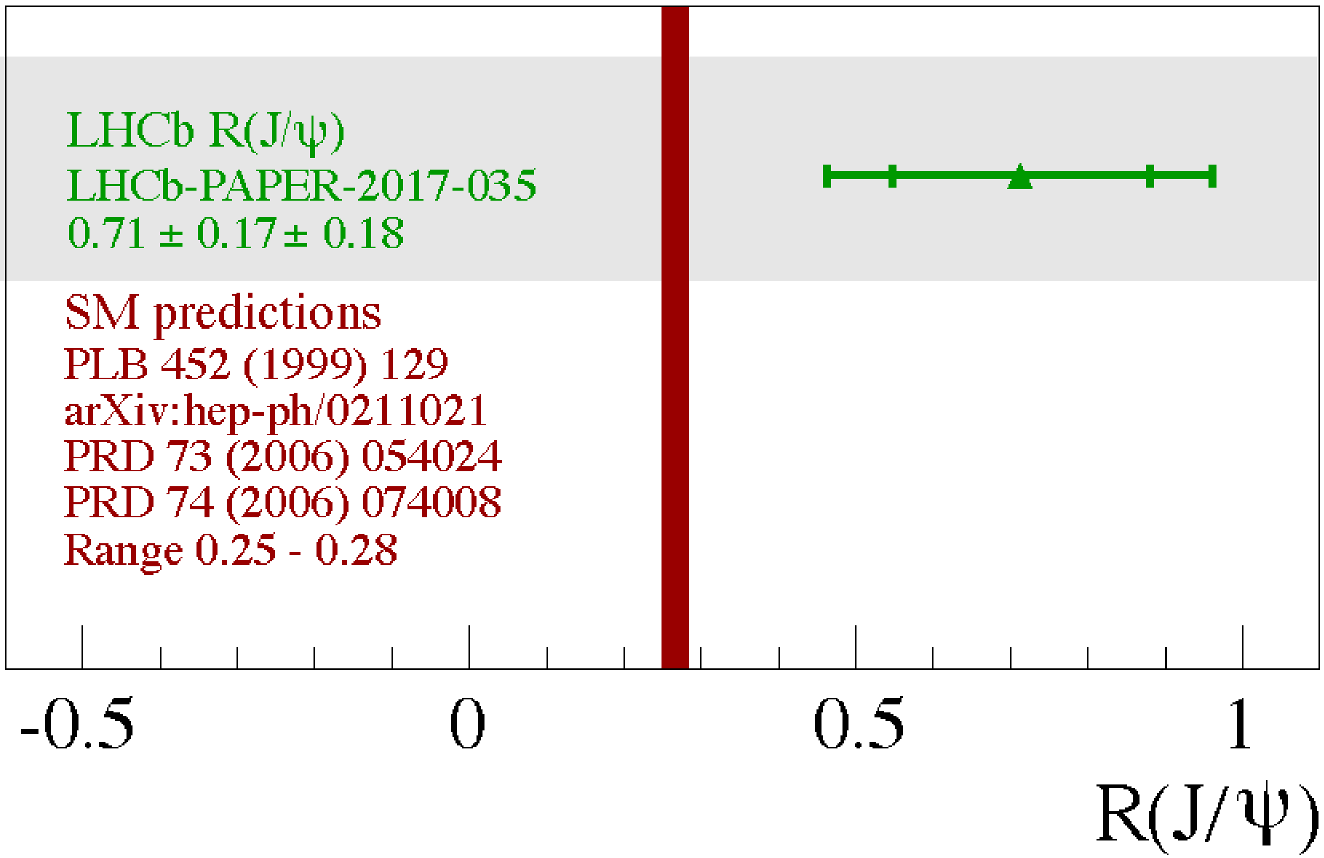
W. Dekens, J. de Vries, M. Jung, K. K. Vos, arXiv:1809.09114
AC, F. Saturnino arxiv:1905:08257



Effect in B predicts measurable nEDM effect

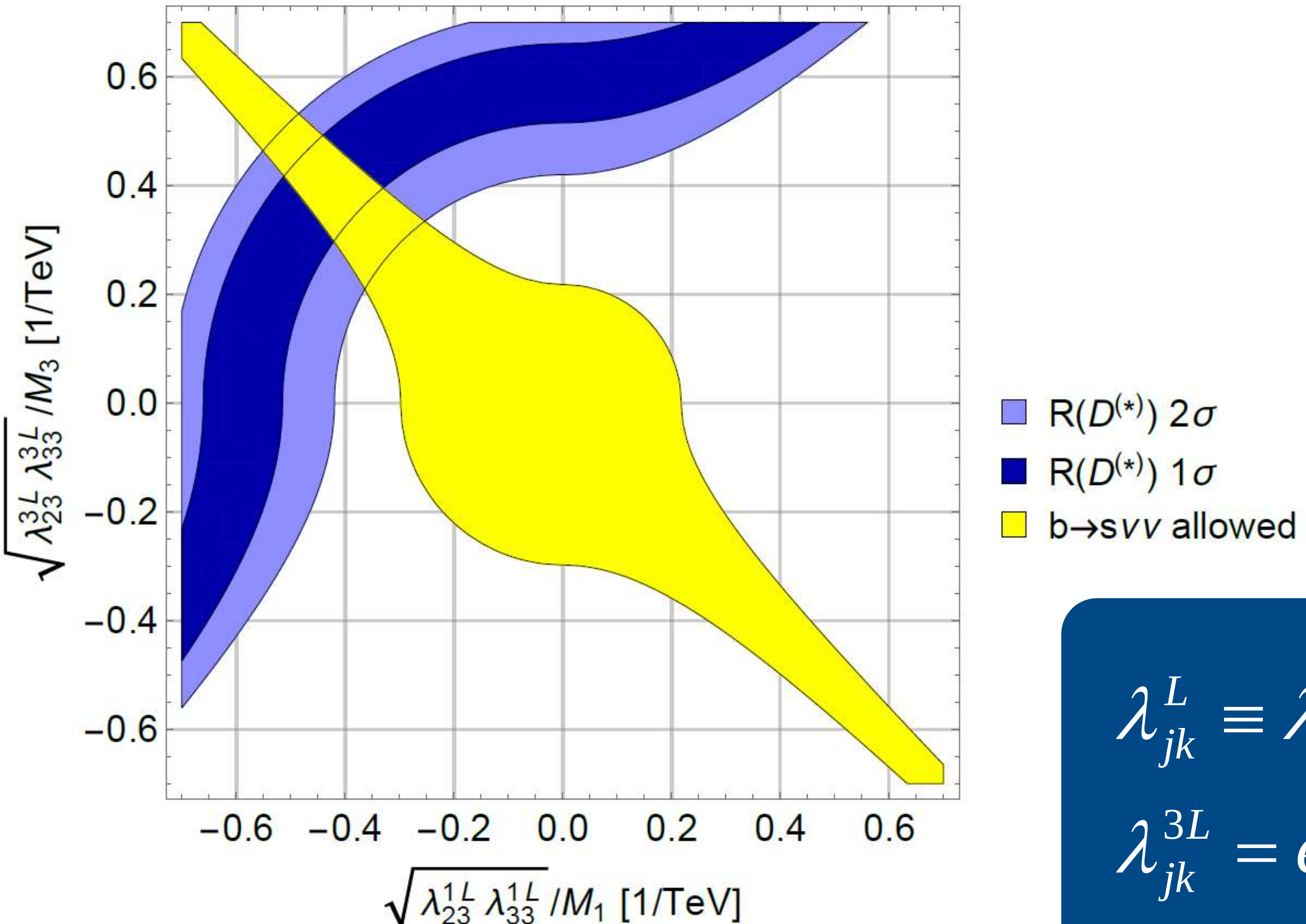
b→cτν Measurements

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



Supports R(D) & R(D*)

$R(D^{(*)})$, $b \to s\nu\nu$ with 2 Scalar LQs

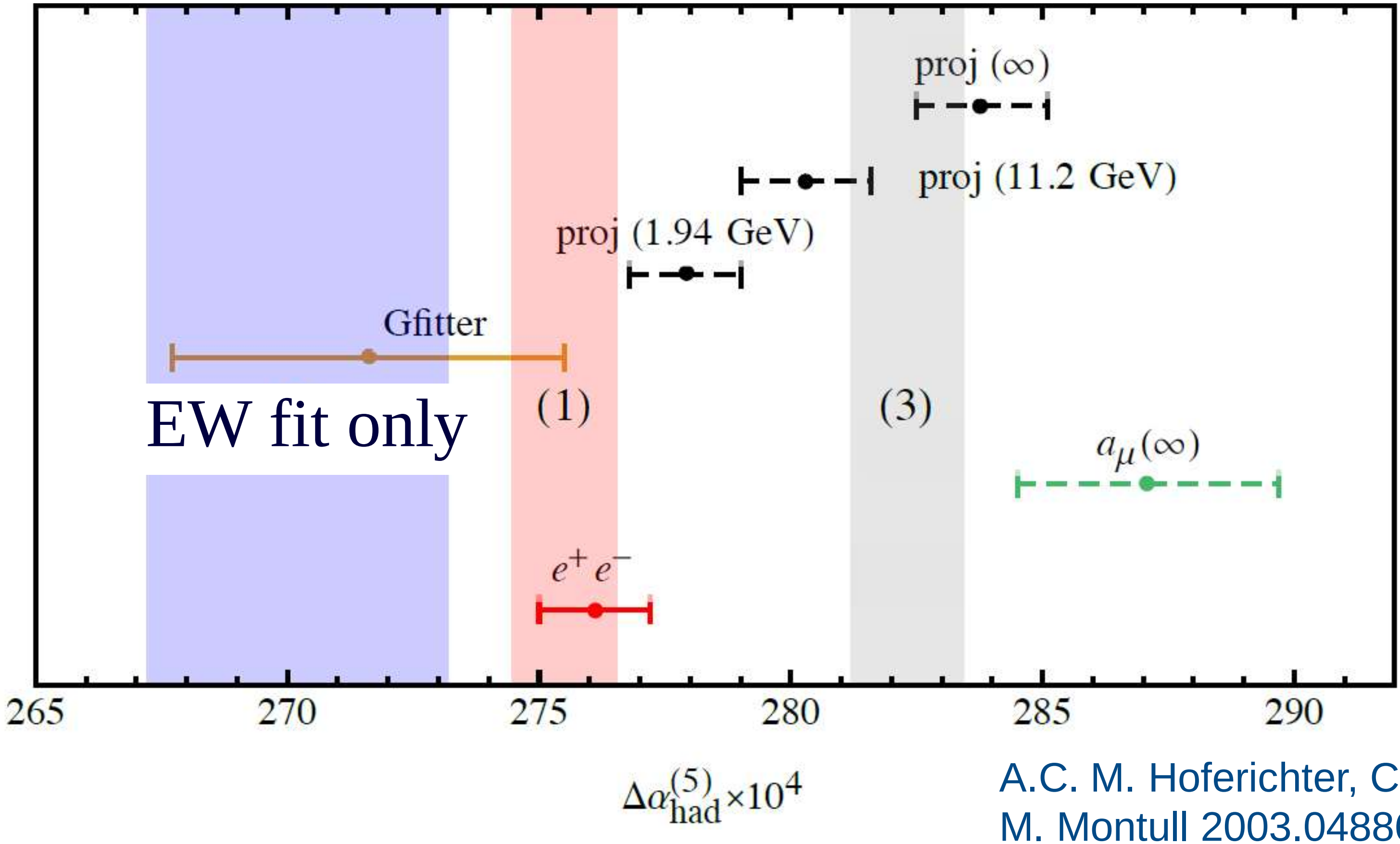


$$\lambda_{jk}^{L} \equiv \lambda_{jk}^{1L}$$

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

Hadronic Vacuum Polarization

- New BMWc lattice QCD result

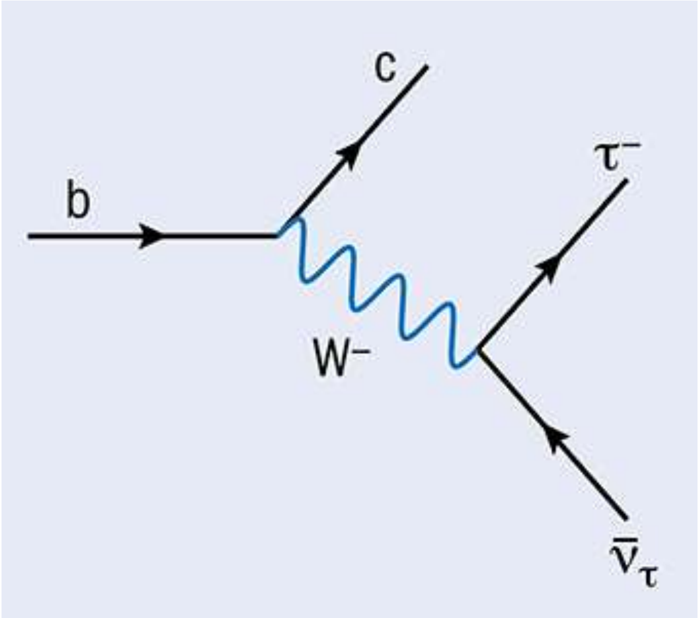


A.C. M. Hoferichter, C. Manzari, M. Montull 2003.04886

Up to 4σ tension in EW fit

$b \to c\tau\nu$ Transitions

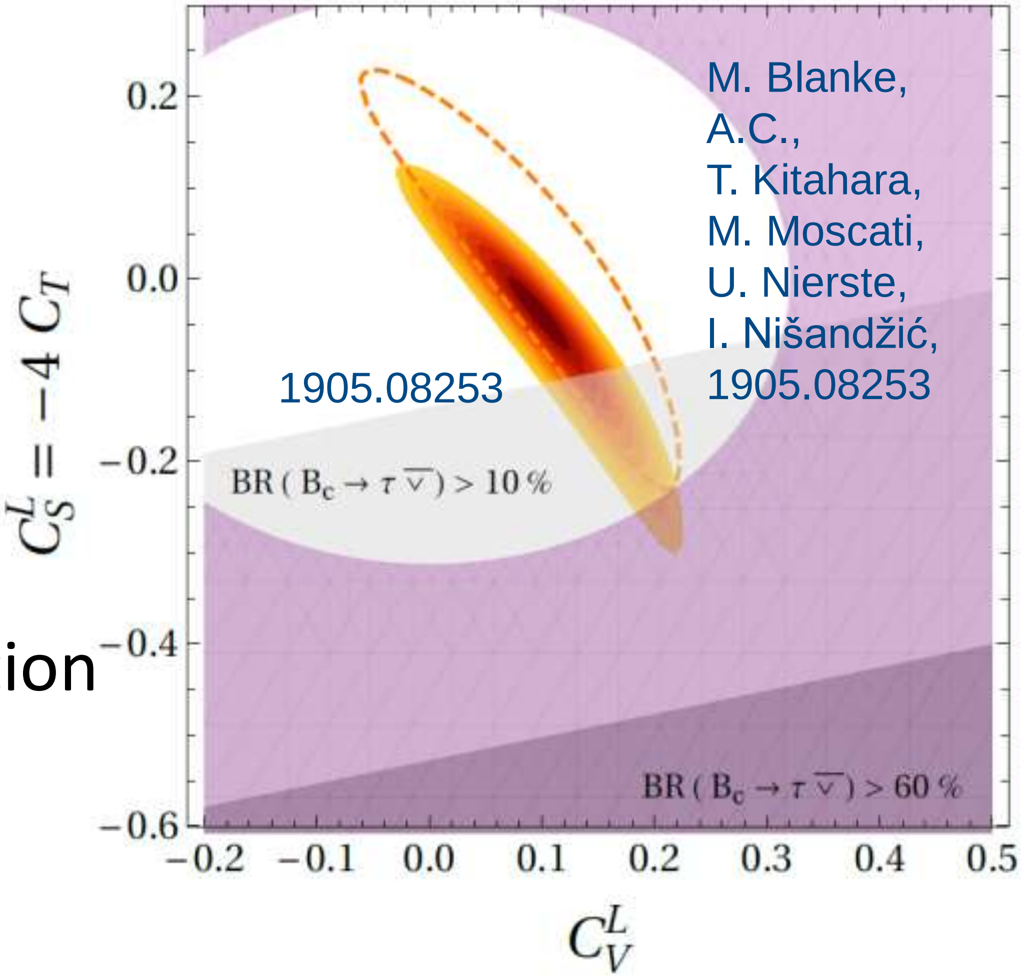
- $B \to D\tau\nu$, $B \to D^*\tau\nu$, $\Lambda_b \to \Lambda_c\tau\nu$
- Tree-level decays in the SM
- Form factors needed
- With light leptons (μ, e) used to determine the CKM elements
- CKM fit works very well, i.e. tree-level in agreement with ΔF=2 processes



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

b→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

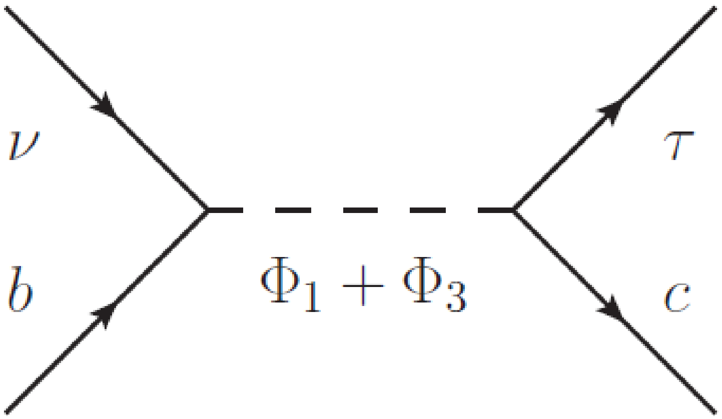


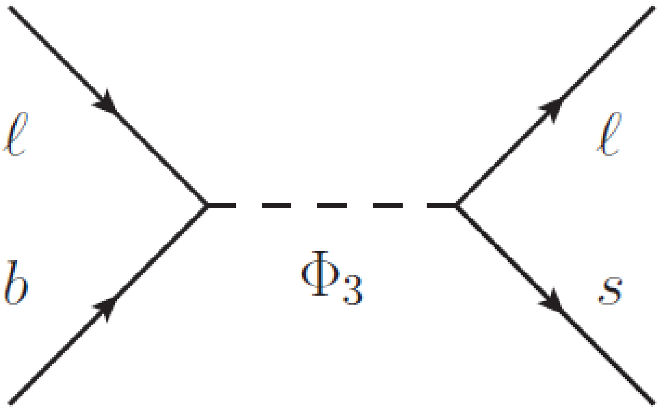
Global fit give up to 4σ preference for NP

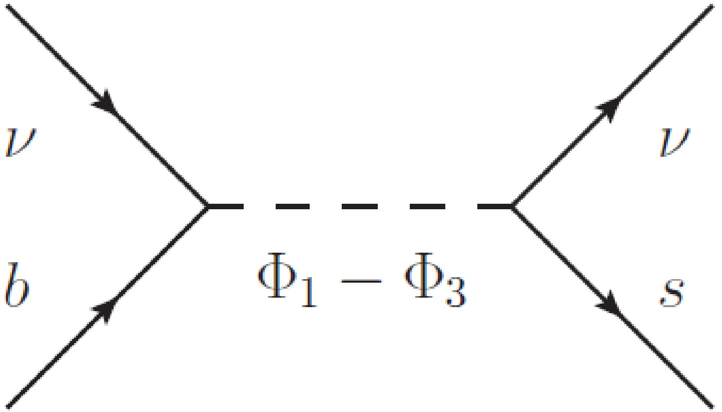
Two Scalar Leptoquarks

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$_\mu$

- 4 benchmark points

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

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

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

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

Common explanation possible

Outlook: Physics at Future Colliders

- Flavour Anomalies require NP at the TeV scale

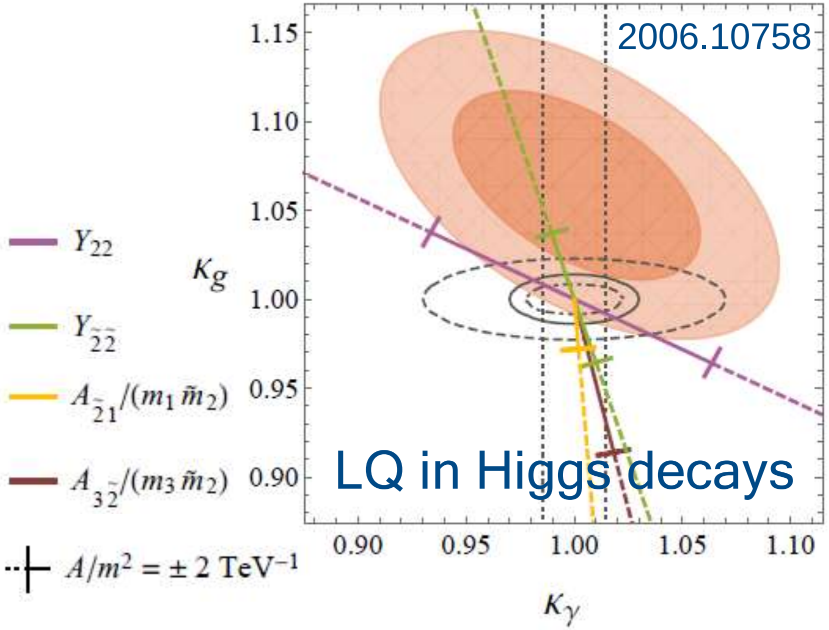
  ⇨ Direct Searches at HL-LHC, HE-LHC, FCC-pp

- 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

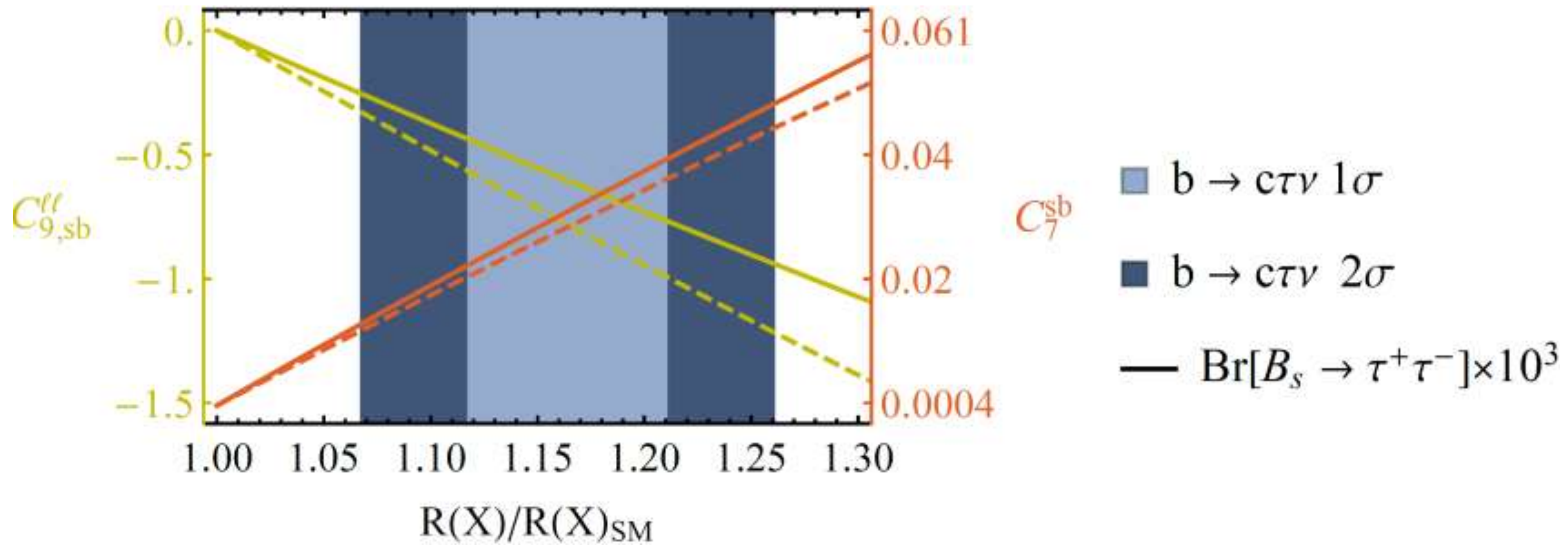
  ⇨ CLIC, FCC



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

Important Loop-Effects

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

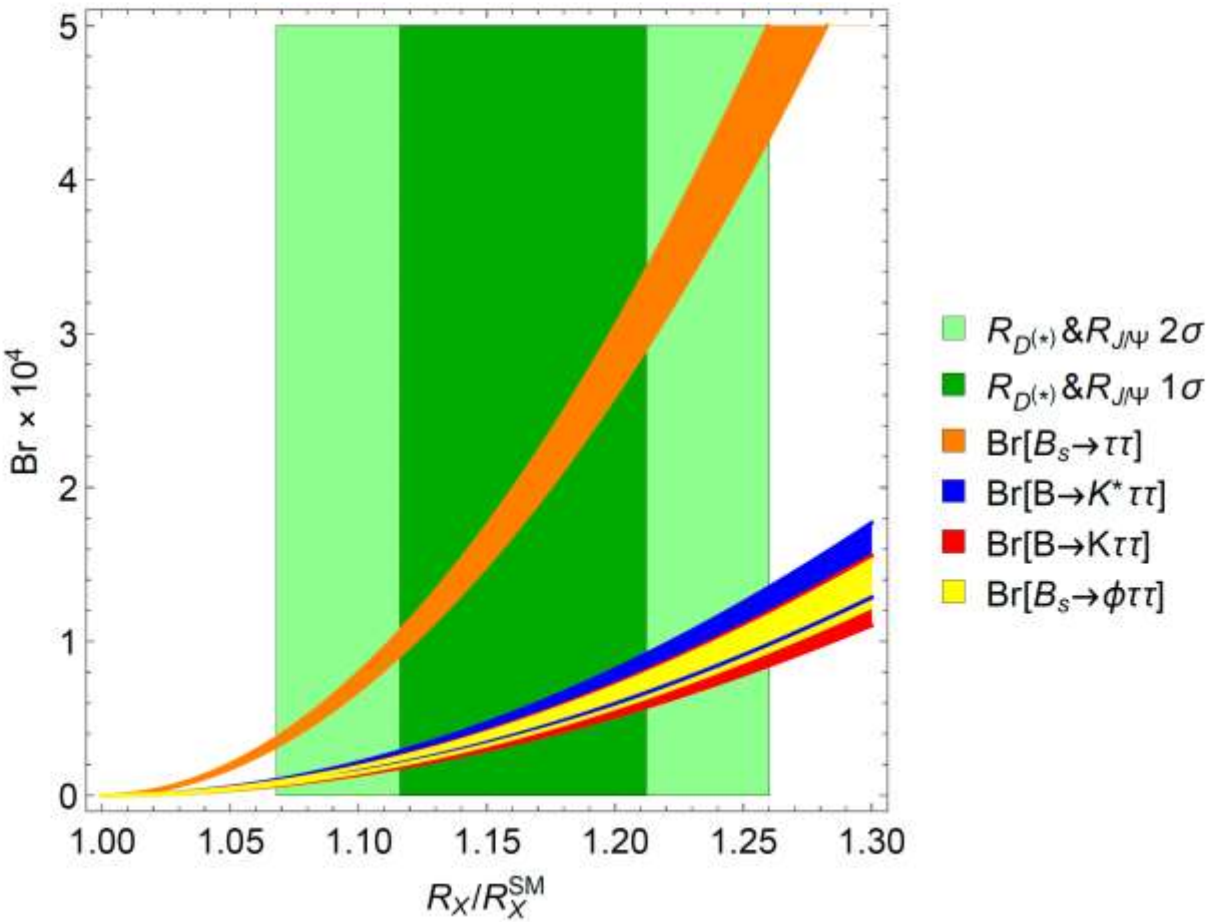


AC, C. Greub, D. Müller, F. Saturnino, PRL 2018

Large loop effects in b→sμμ

R(D$^{(*)}$) and b→sττ

- Large couplings to the second generation



b→sττ
very strongly enhanced

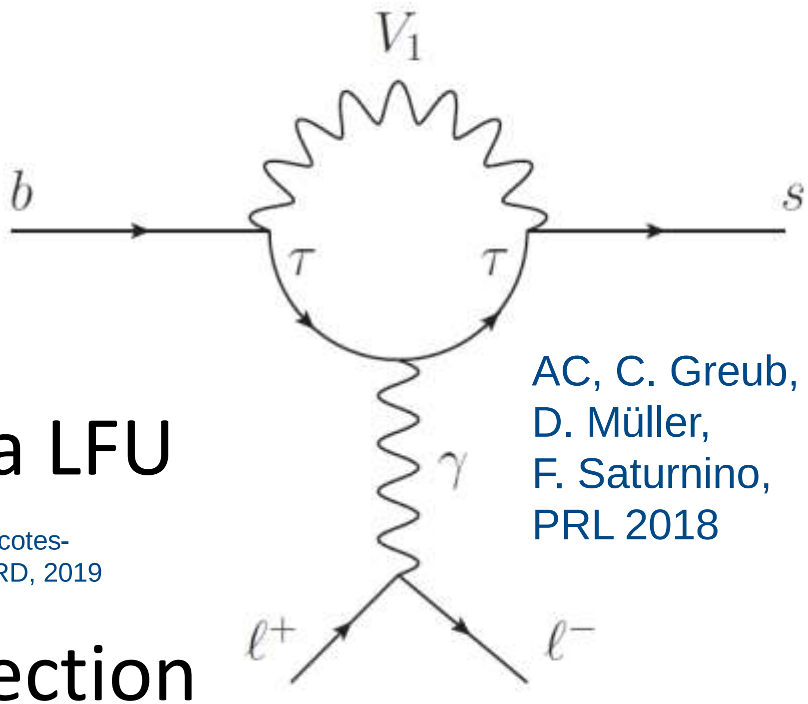
B. Capdevila, AC, S. Descotes-Genon, L. Hofer and J. Matias, PRL.120.181802

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

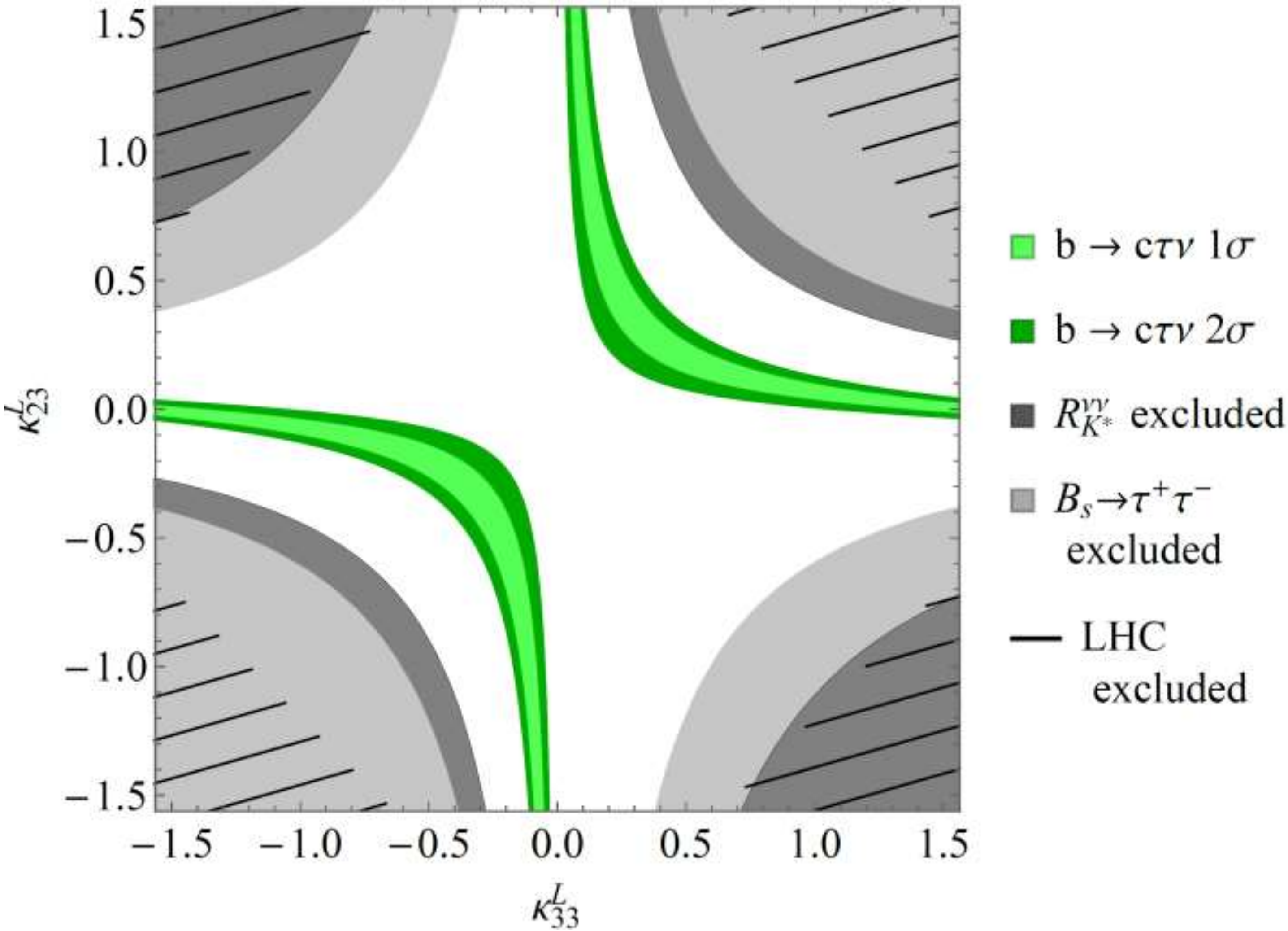
- Effect goes in the right direction



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

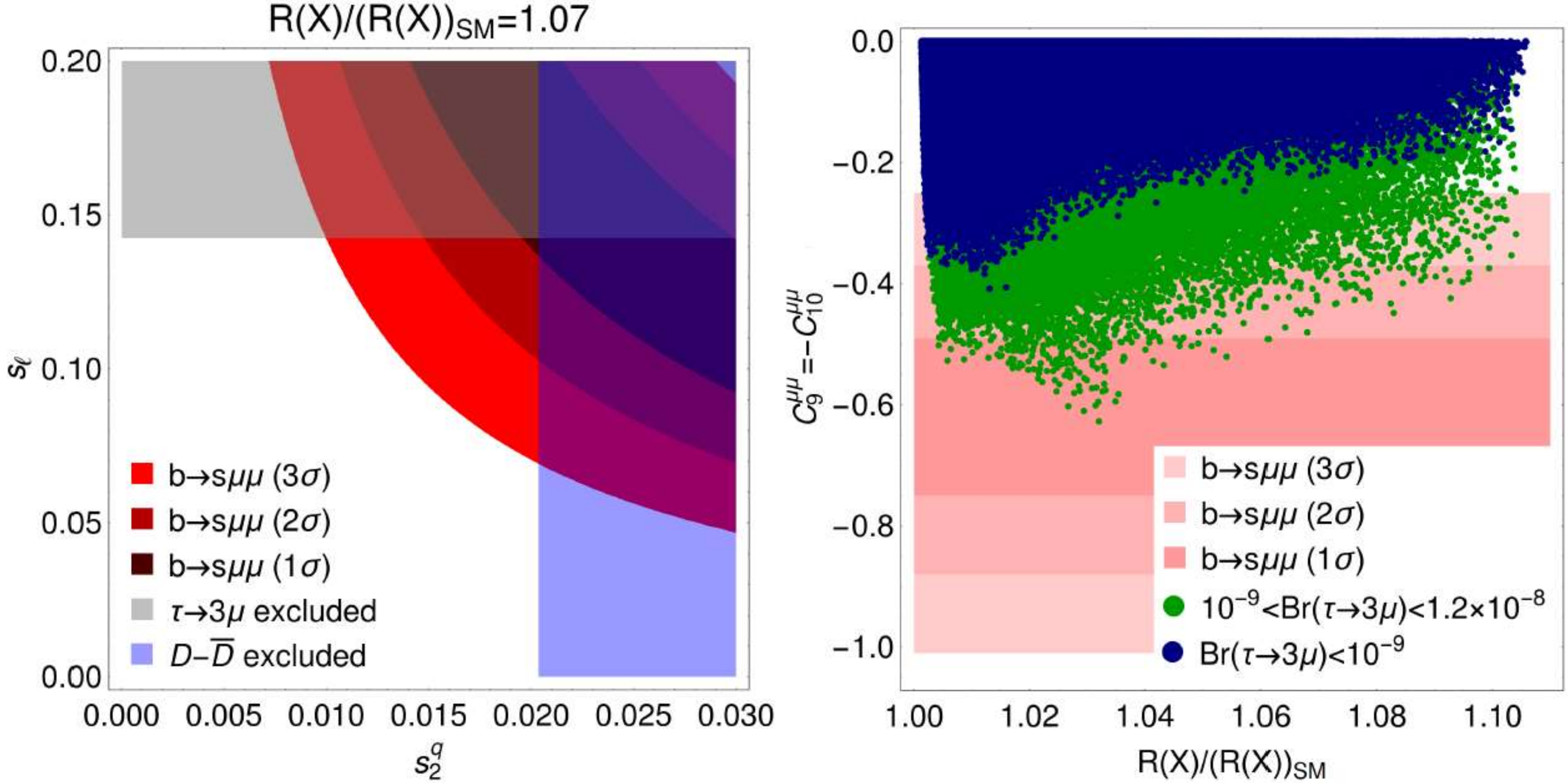
  J. Heeck, D. Teresi, arXiv:1808.07492
- SU(8) might even explain ε'/ε

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

  M. Blanke, AC, arXiv:1801.07256

Good solution, but challenging UV completion

Pati-Salam RS Phenomenology



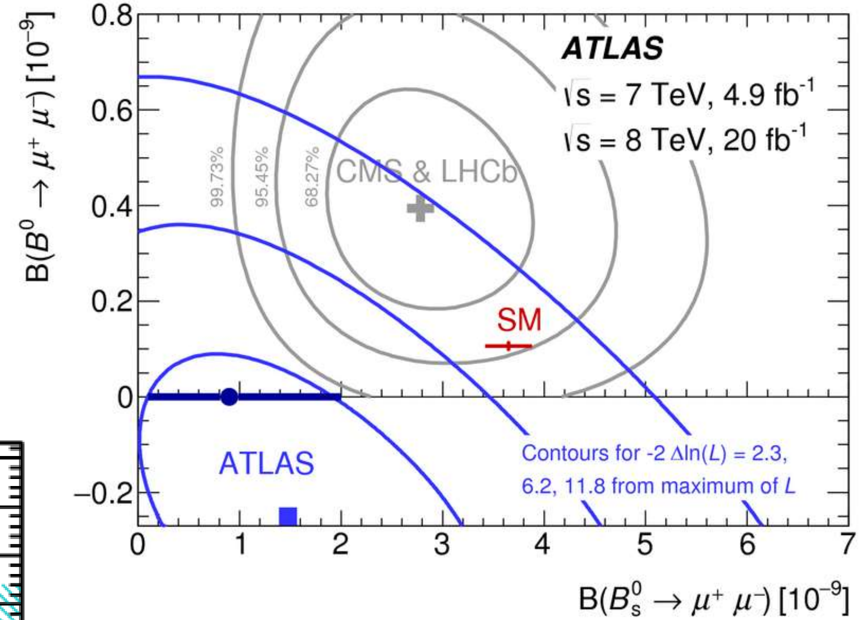
$M = 3\,\mathrm{TeV},\ s_2^\ell = 0.2,\ s_3^\ell = 1/\sqrt{2}$ and $s_3^q = \sqrt{3}/2$

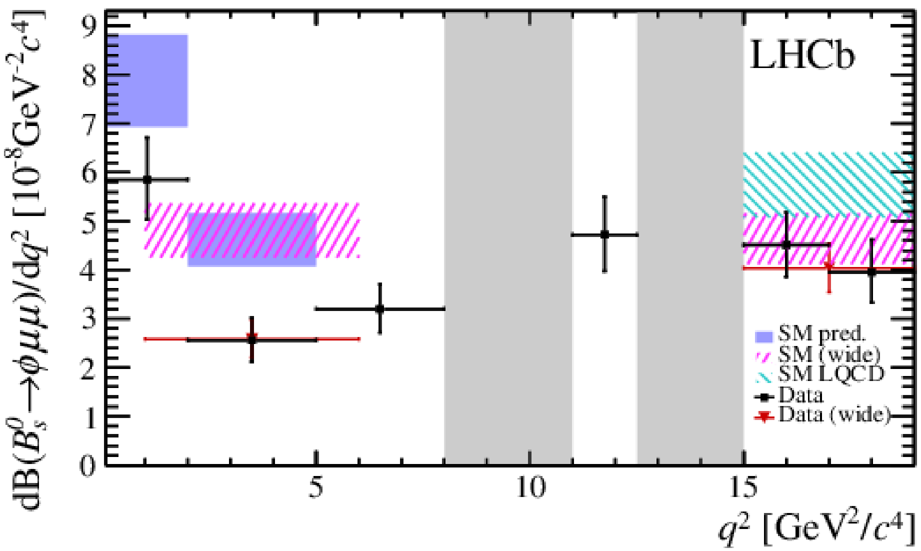
M. Blanke, AC, PRL 2018

Model well motivated + limited but sizable effect

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

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



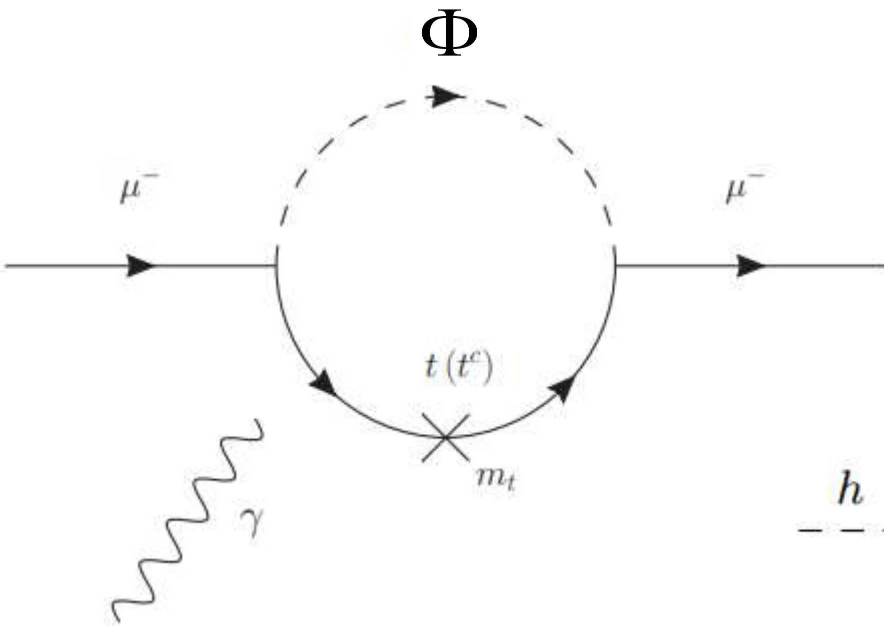


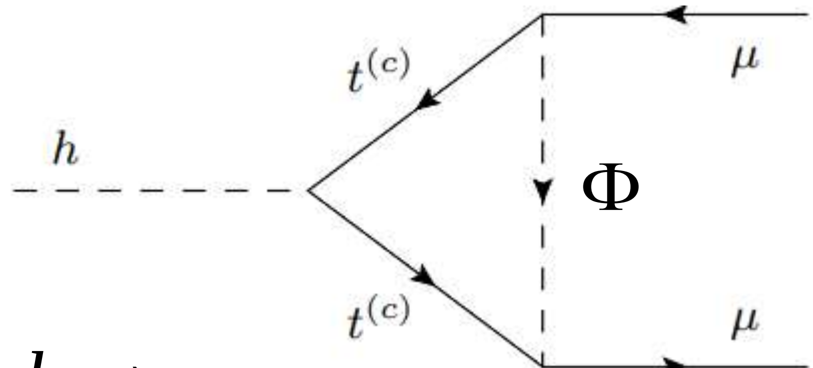
- $B_s \to \phi\mu\mu$ has a higher Br, but knowledge of the form-factor needed

Br's ≈ 20% below SM expectations

Leptoquarks in a_μ

- Chirally enhanced effects via top-loops



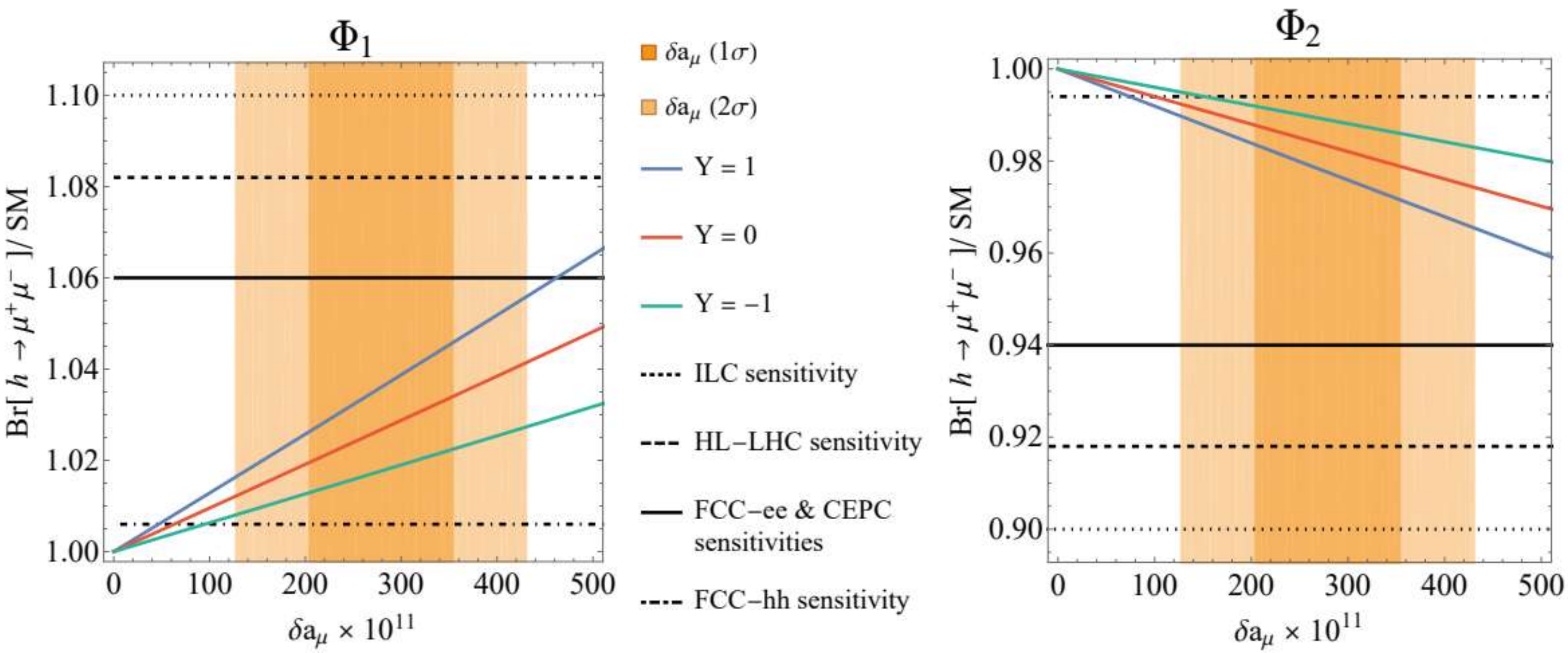


- m_t / m_μ enhanced effect $h \to \mu\mu$
- m_t^2 / m_Z^2 enhanced effect in $Z \to \mu\mu$

Correlations with h→μμ and Z→μμ

a_μ vs $h \to \mu\mu$

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



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

h→μμ at future colliders

τ→μνν and τ→eνν

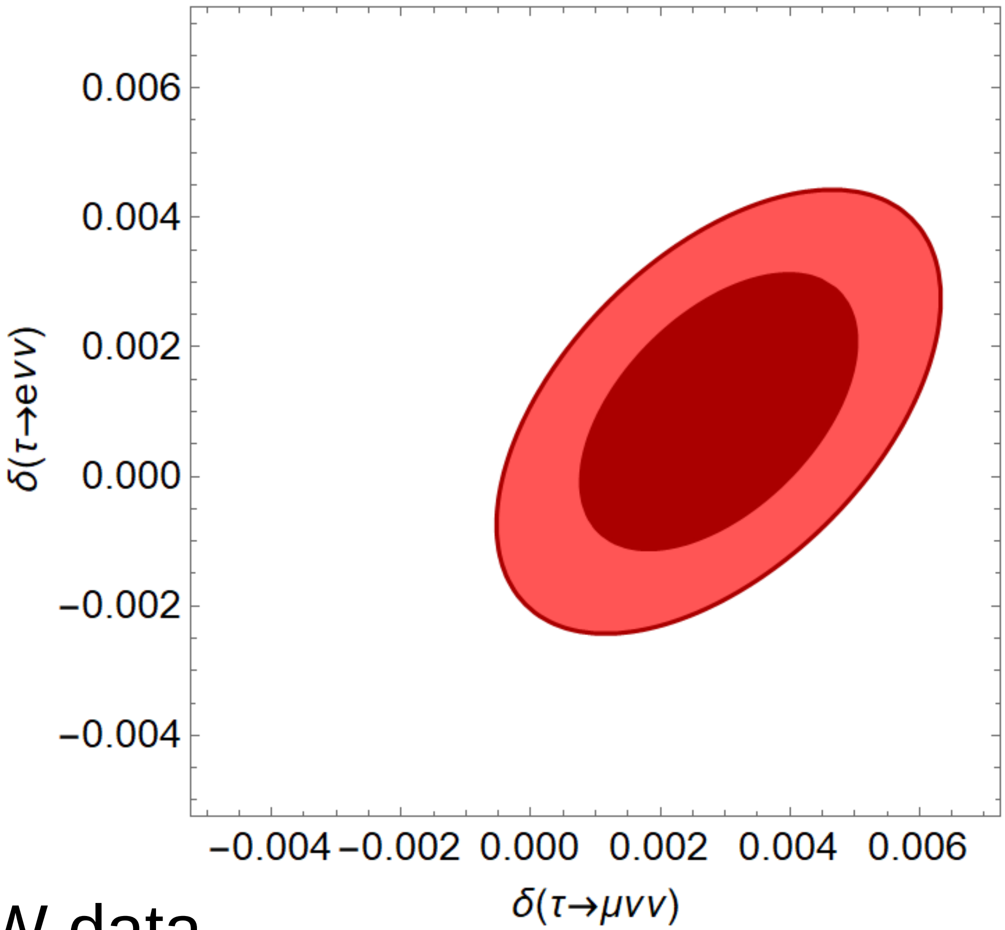
- Ratios of leptonic tau decays

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

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

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

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

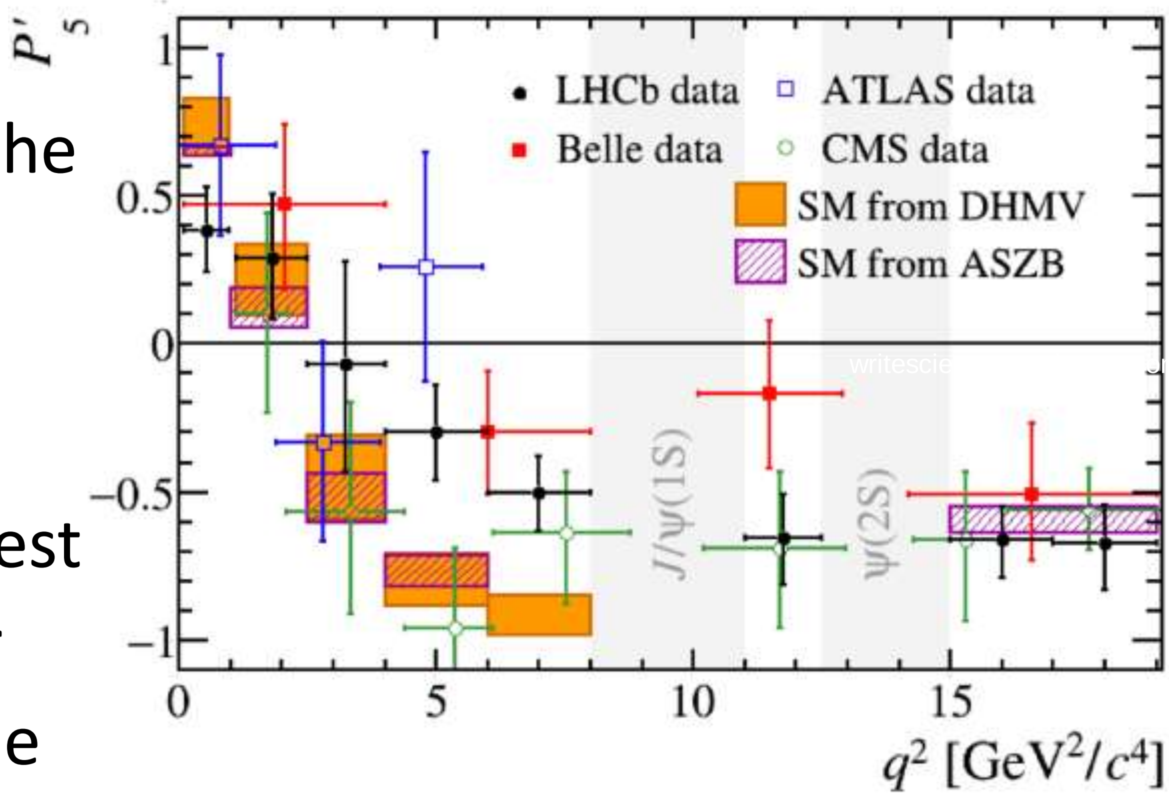


- NP in muon decay constrained from EW data

≈2σ hint for LFUV in tau decays

The P_5' Anomaly

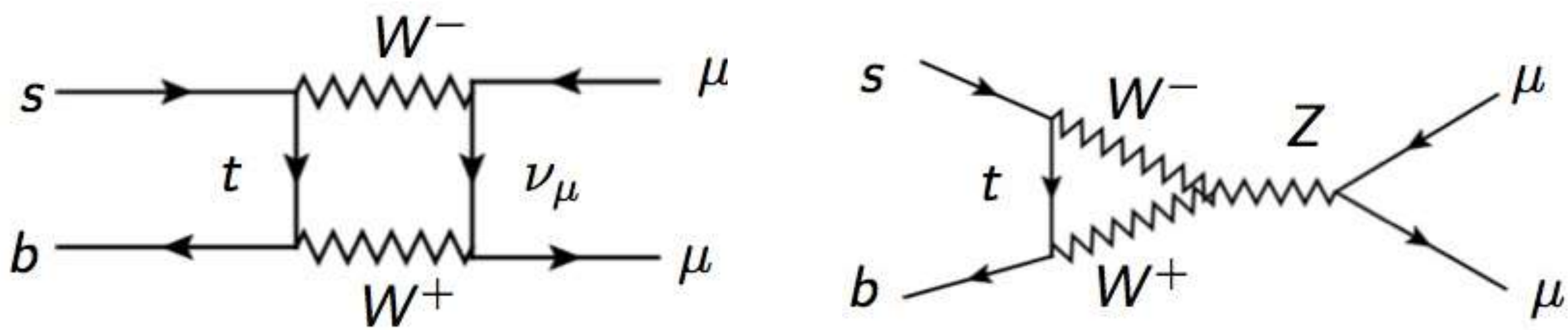
- P_5´ angular observables in $B \rightarrow K^*\mu\mu$ S. Descotes-Genon, T. Hurth, J. Matias, J. Virto, JHEP 2013
- Constructed in such a way that the form factor dependence is minimized
- Confirmed by latest LHCb analysis for the chatged mode



>3σ deviation from the SM prediction

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

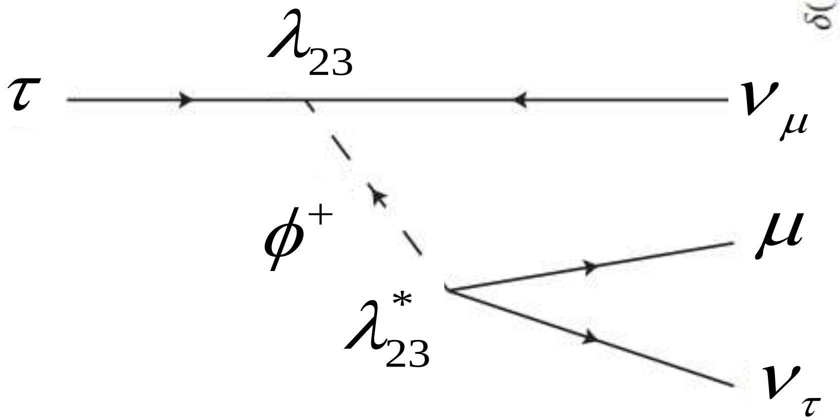
- Flavour Changing Neutral Current (FCNC)
- In the SM it is suppressed by
  - The CKM elements $V_{cb} \approx 0.04$
  - Electroweak scale
  - Loop-factor
- Wilson coefficients precisely known Bobeth et al. PRD, 2013



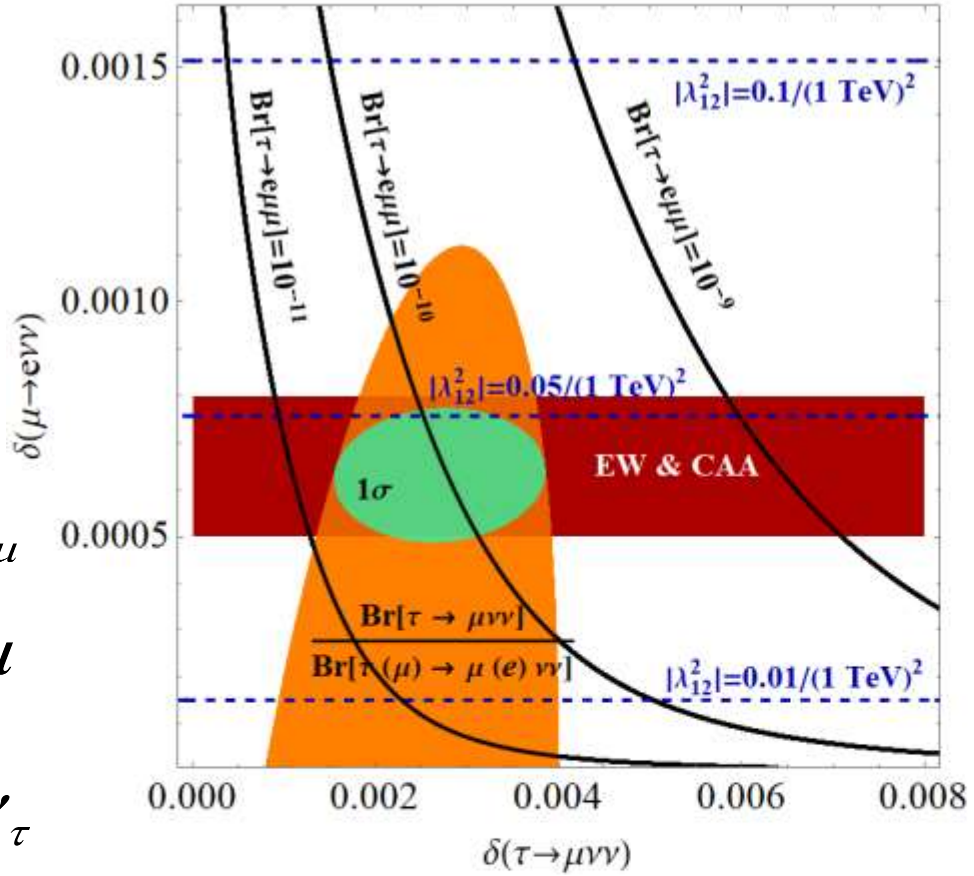
Suppressed in the SM and very sensitive to NP

τ→μνν

- 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

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