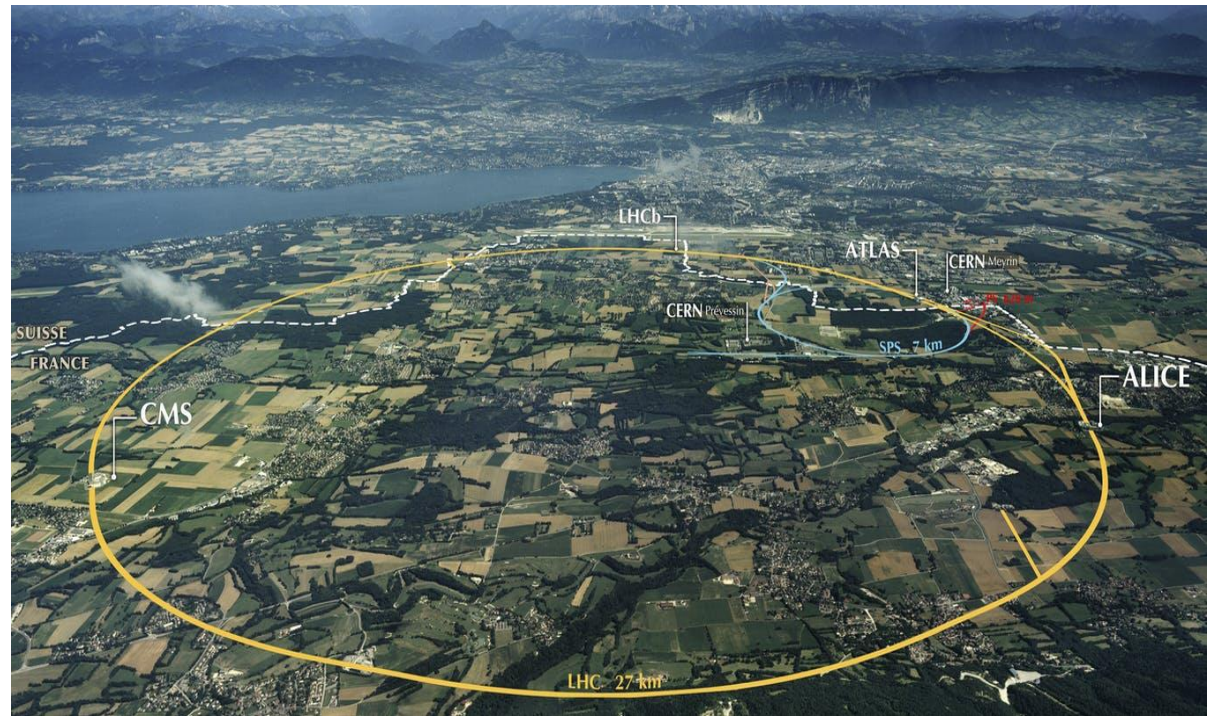


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Andreas Crivellin

CERN Theory Division, PSI & UZH

Heavy Flavours -- Theory

LHCP, Paris, 10.06.2021 (remote)

Work supported by



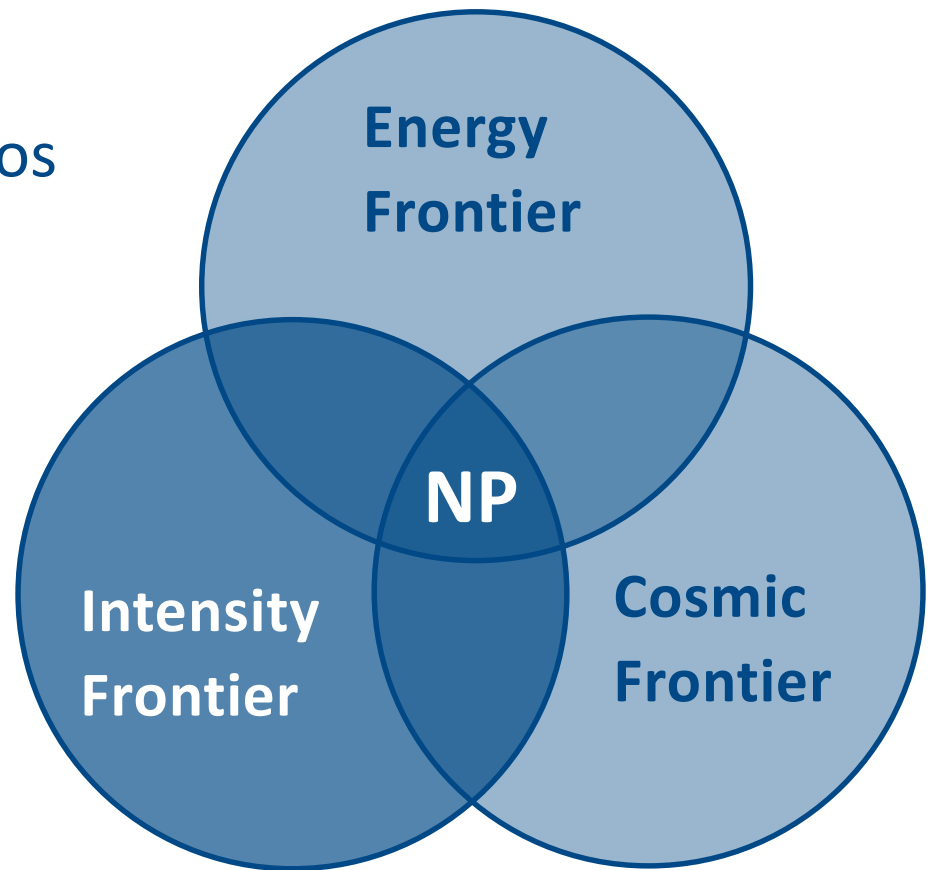
Outline

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

Introduction

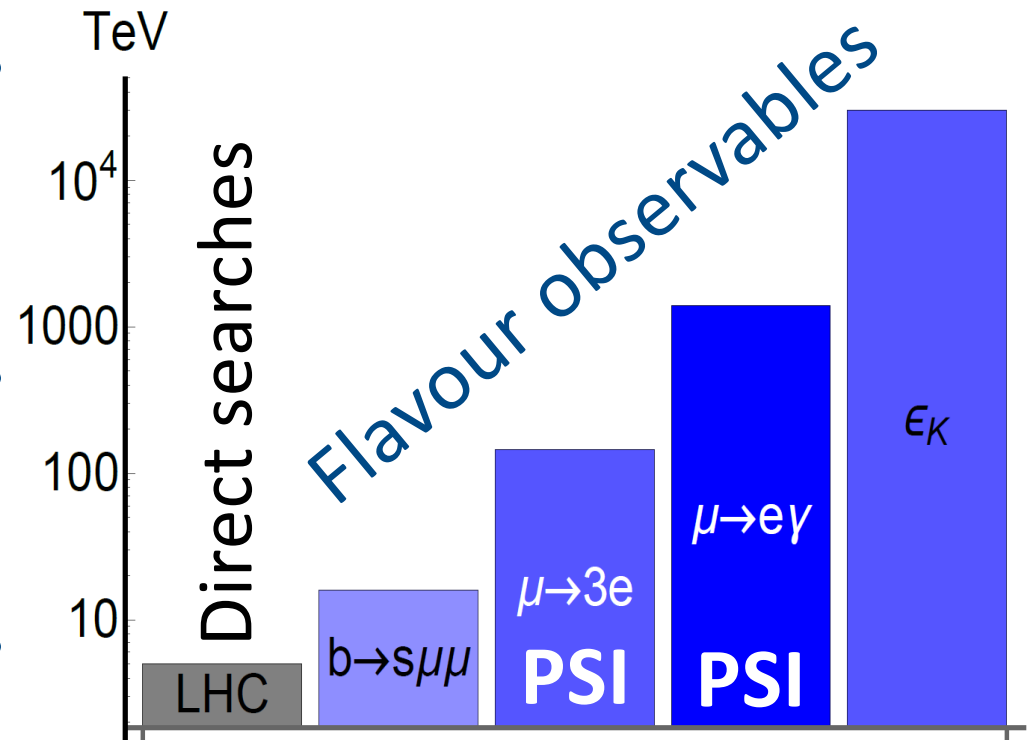
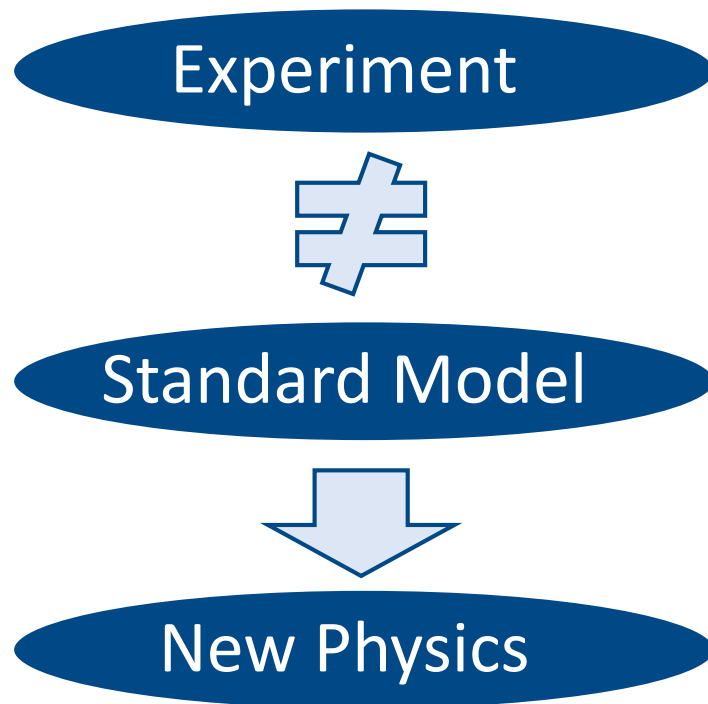
Discovering New Physics

- **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

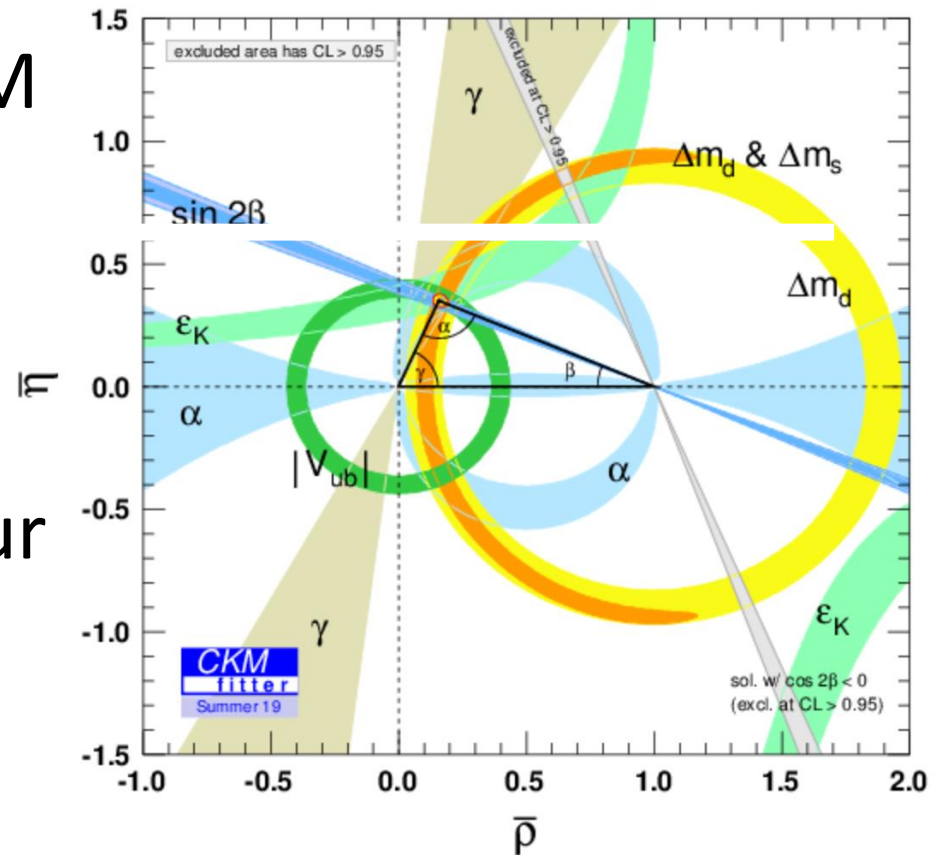
- At colliders one produces many (up to 10^{14}) heavy quarks or leptons and measures their decays into light flavours



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 $b \rightarrow s \ell^+ \ell^-$

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

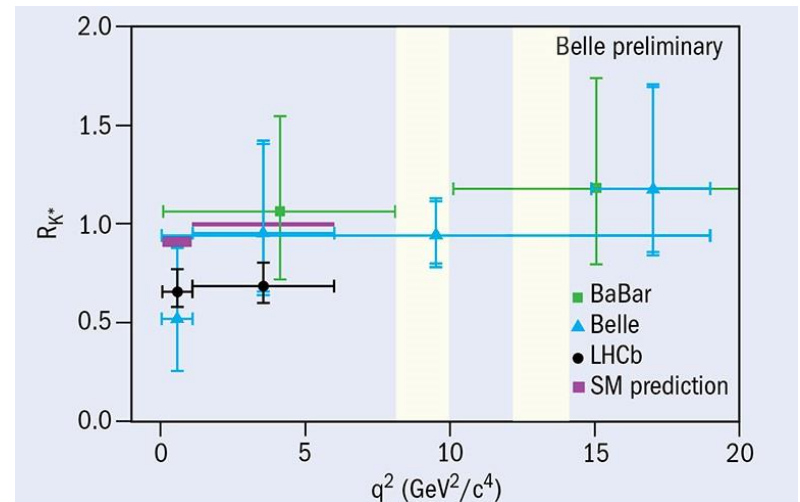
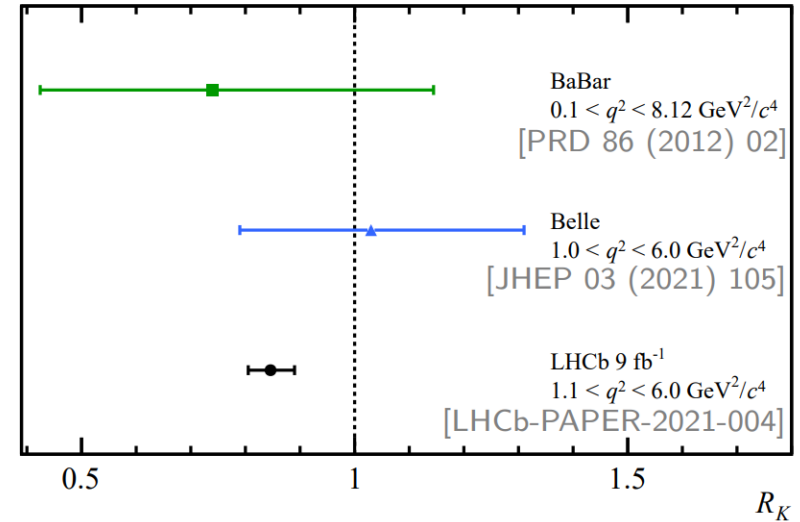
$$R(K^*) = \frac{B \rightarrow K^* \mu^+ \mu^-}{B \rightarrow K^* e^+ e^-}$$

- Muon and electron masses can be neglected

➡ **Clean prediction**

- Supported by

$$\frac{\Lambda_b \rightarrow K \mu^+ \mu^-}{\Lambda_b \rightarrow K e^+ e^-} = 0.86_{-0.11}^{+0.14} \pm 0.05$$



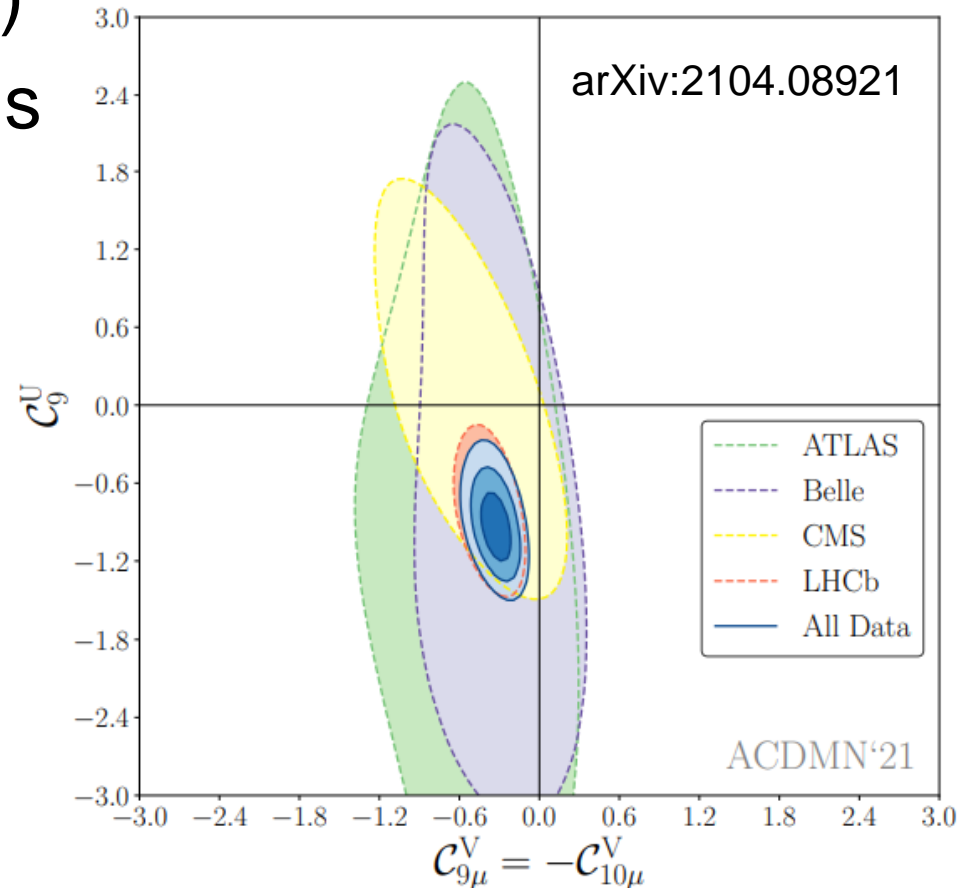
LFUV in B decays $>4\sigma$

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

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

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

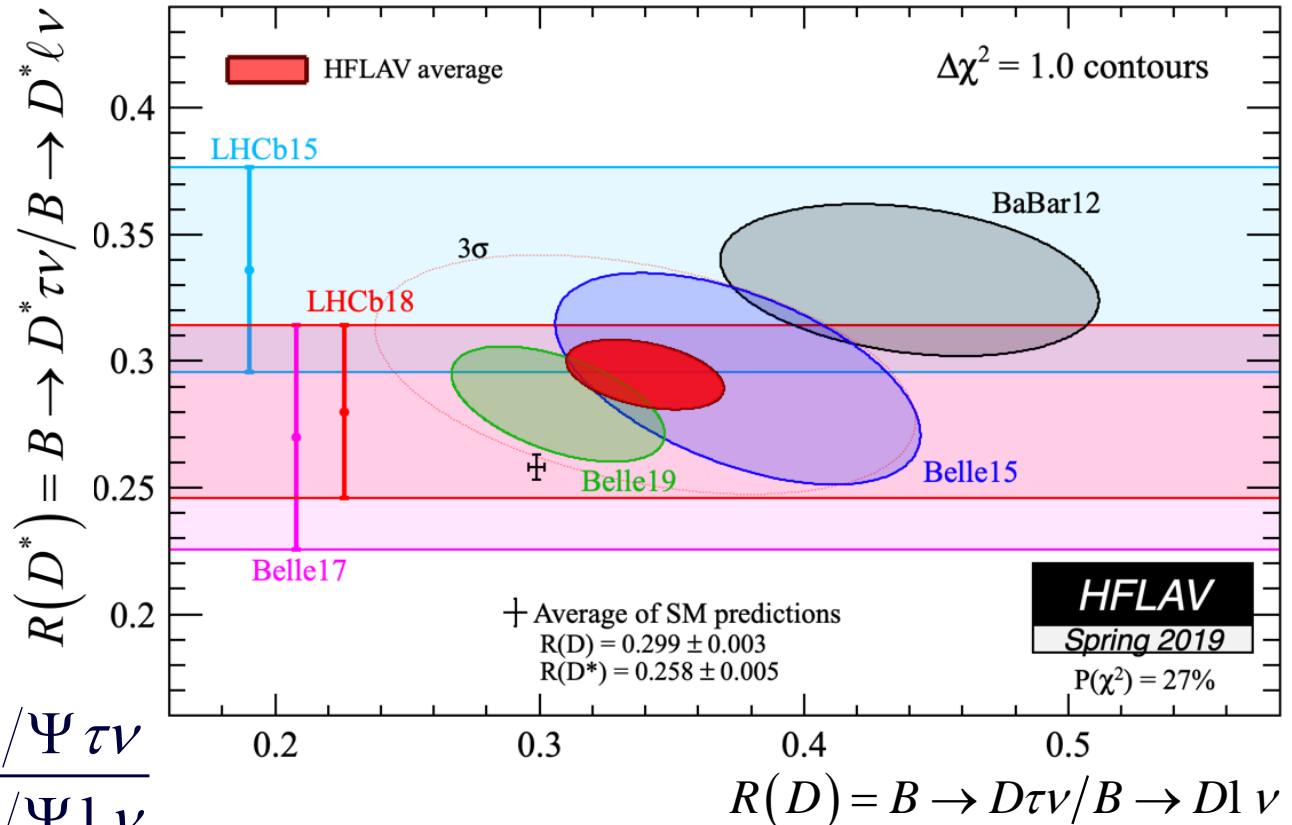


Fit is $>7 \sigma$ better than the SM

$b \rightarrow c \tau \nu$ Transitions

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

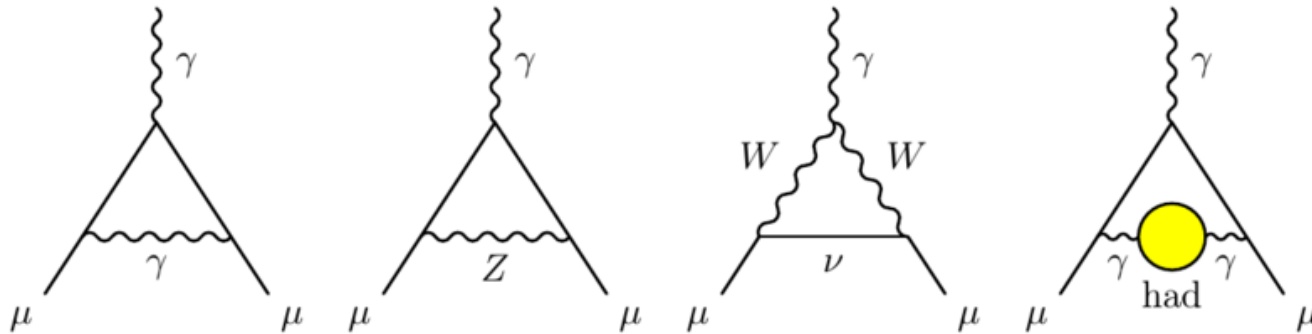
$$R(J/\Psi) = \frac{B_c \rightarrow J/\Psi \tau \nu}{B_c \rightarrow J/\Psi 1 \nu}$$



- Tree-level \Rightarrow **need larger NP effect**

O(10%) constructive preferred effect at 3 σ

Muon Anomalous Magnetic Moment



- Theory prediction intricate (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 $m_\mu \rightarrow 0$ \Rightarrow **measure of LFUV**

4.2 σ deviation from the SM prediction

Cabibbo Angle Anomaly (CAA)

- Deficit in first row and first column CKM unitarity

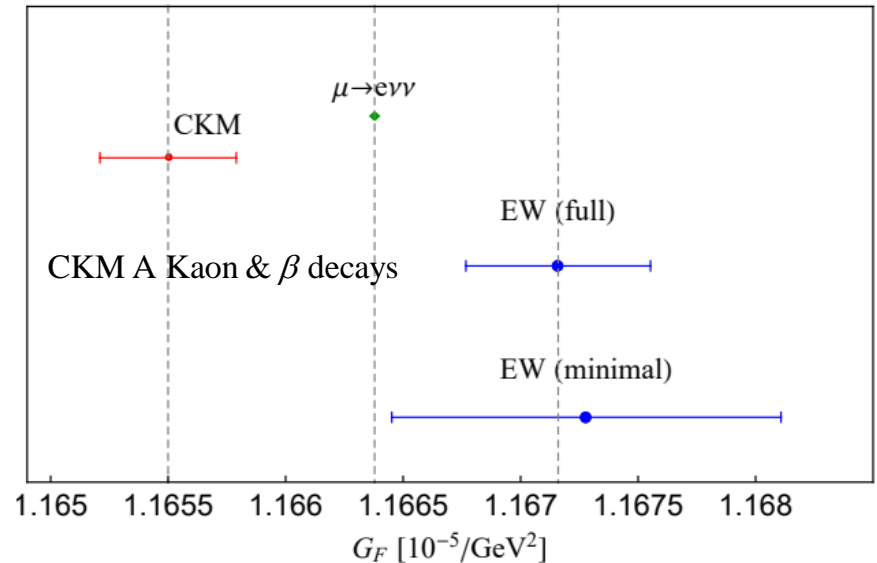
$$|V_{ud}^2| + |V_{us}^2| + |V_{ub}^2| = 0.9985 \pm 0.0005$$

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

(PDG)

AC, Hoferichter, Manzari, 2102.02825

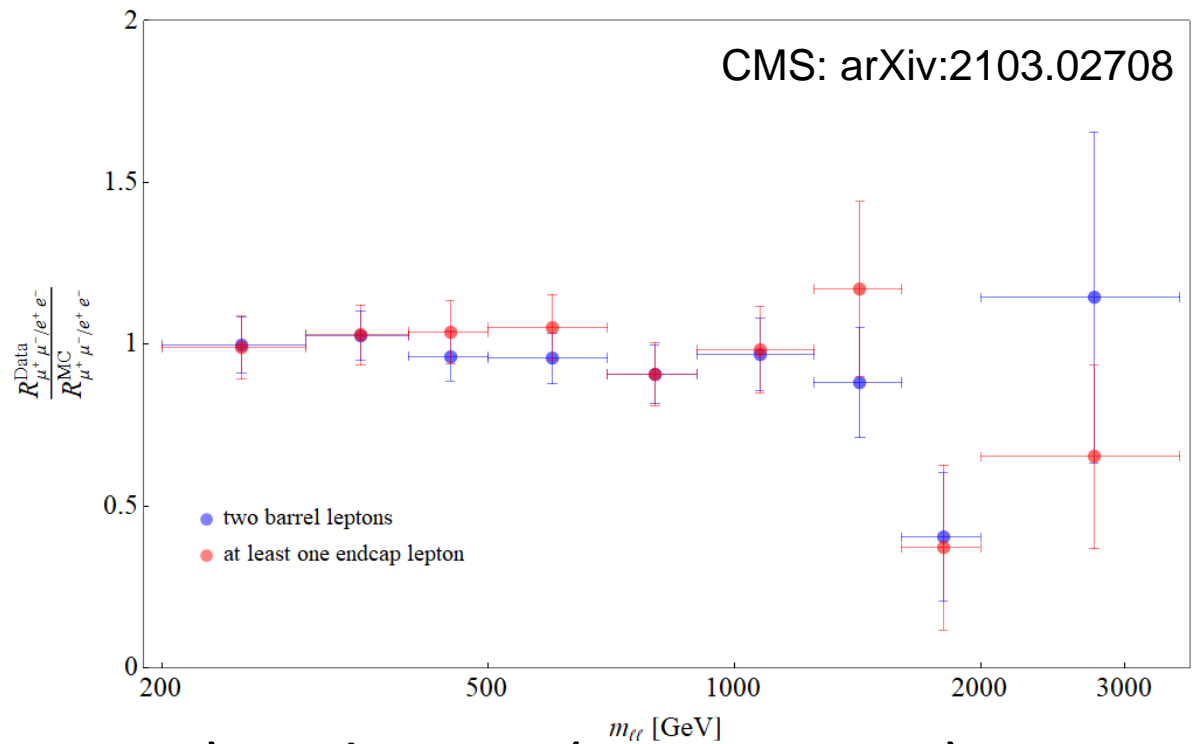
- NP in the determination of V_{ud} from beta decays needed
- Can be interpreted as
 - NP in beta decays
 - NP in the Fermi constant
 - LFUV (modified $W\mu\nu$ coupling)



3σ tension

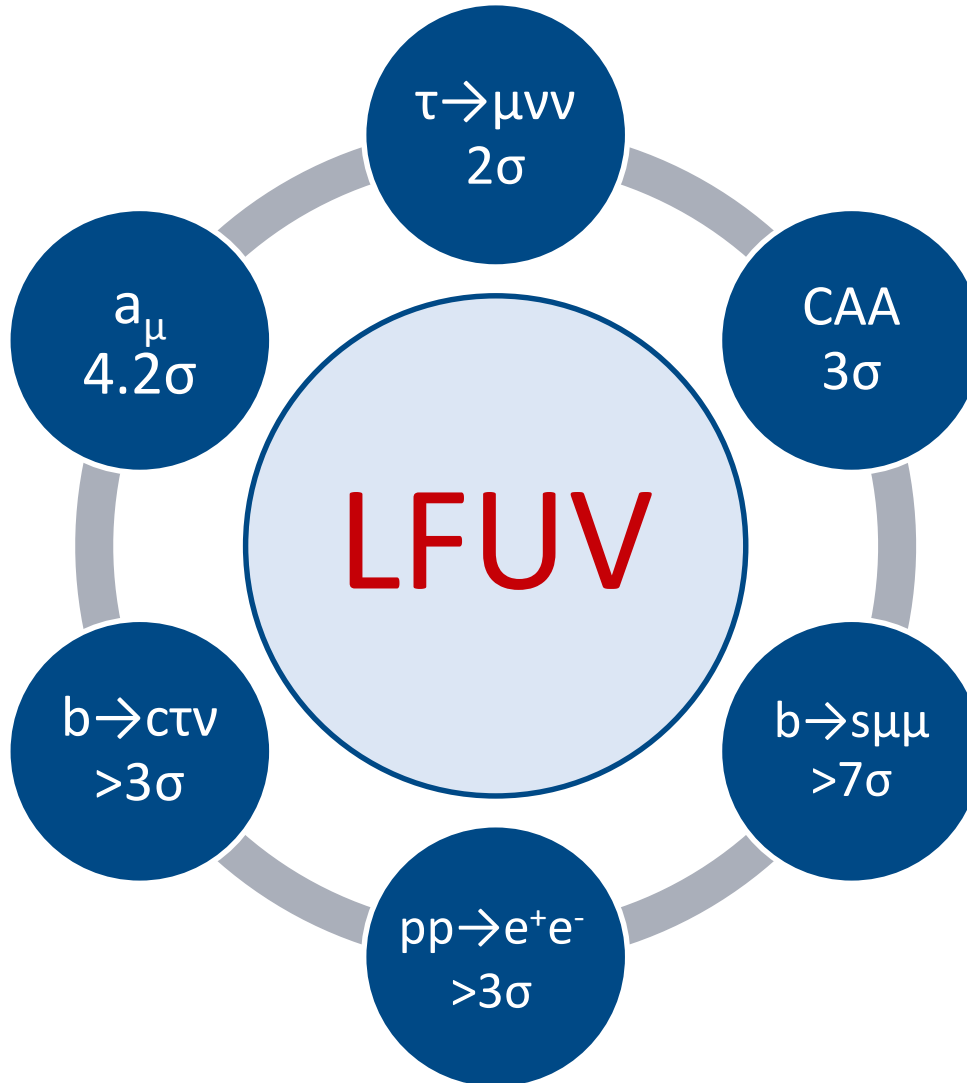
Non-Resonant Di-Leptons

- 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

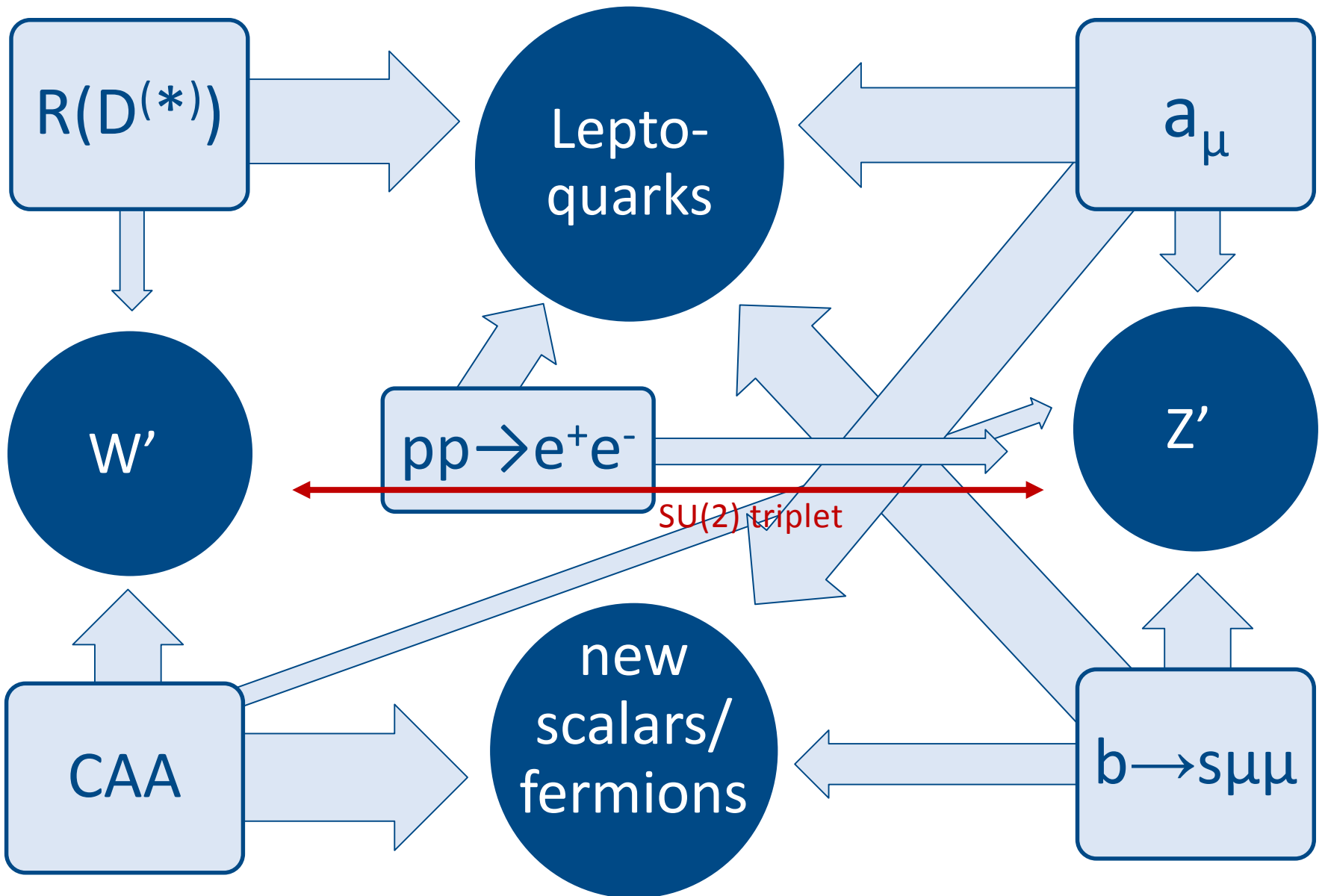


$\approx 3\sigma$ hint for LFUV

Hints for New Physics

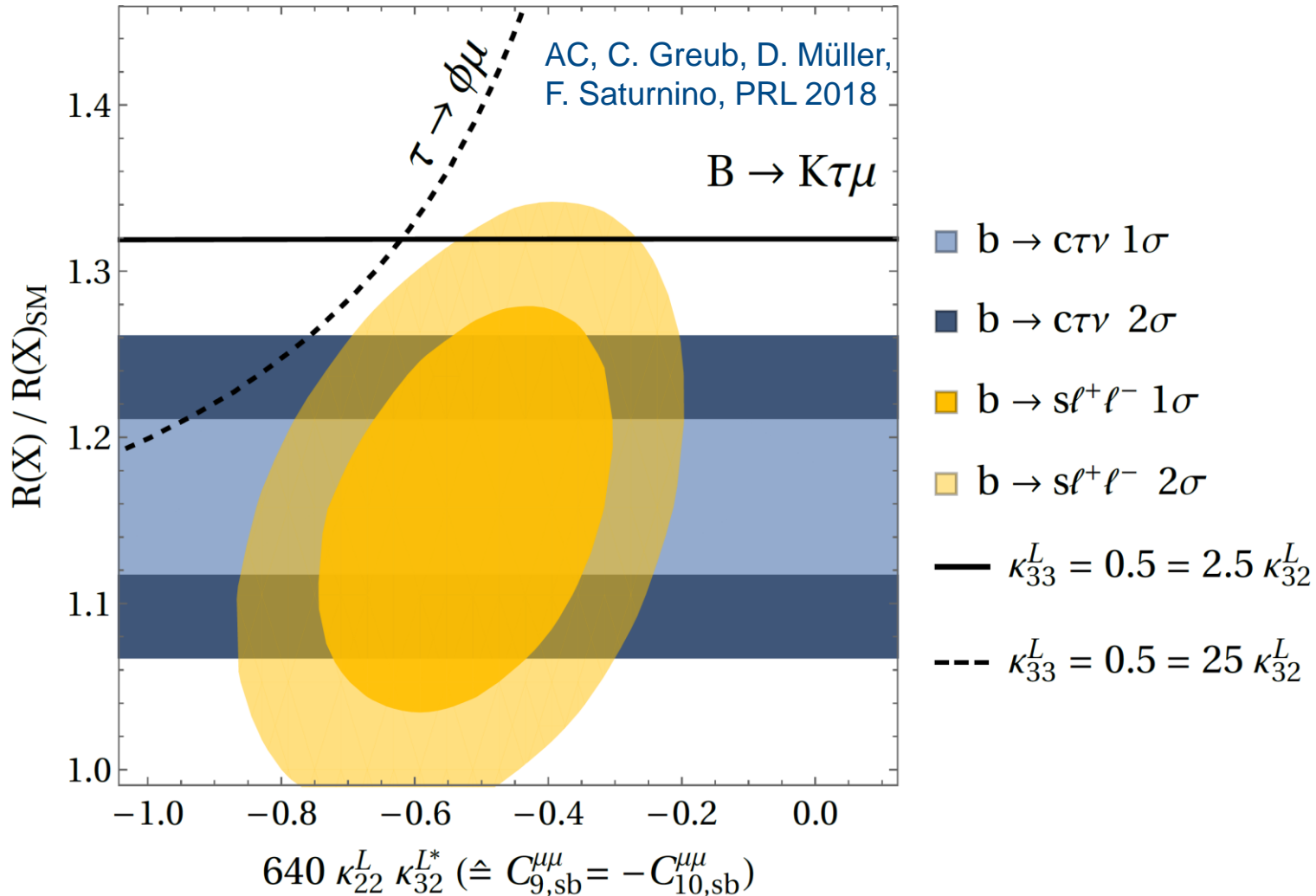


New Physics Explanations



Simultaneous Explanations

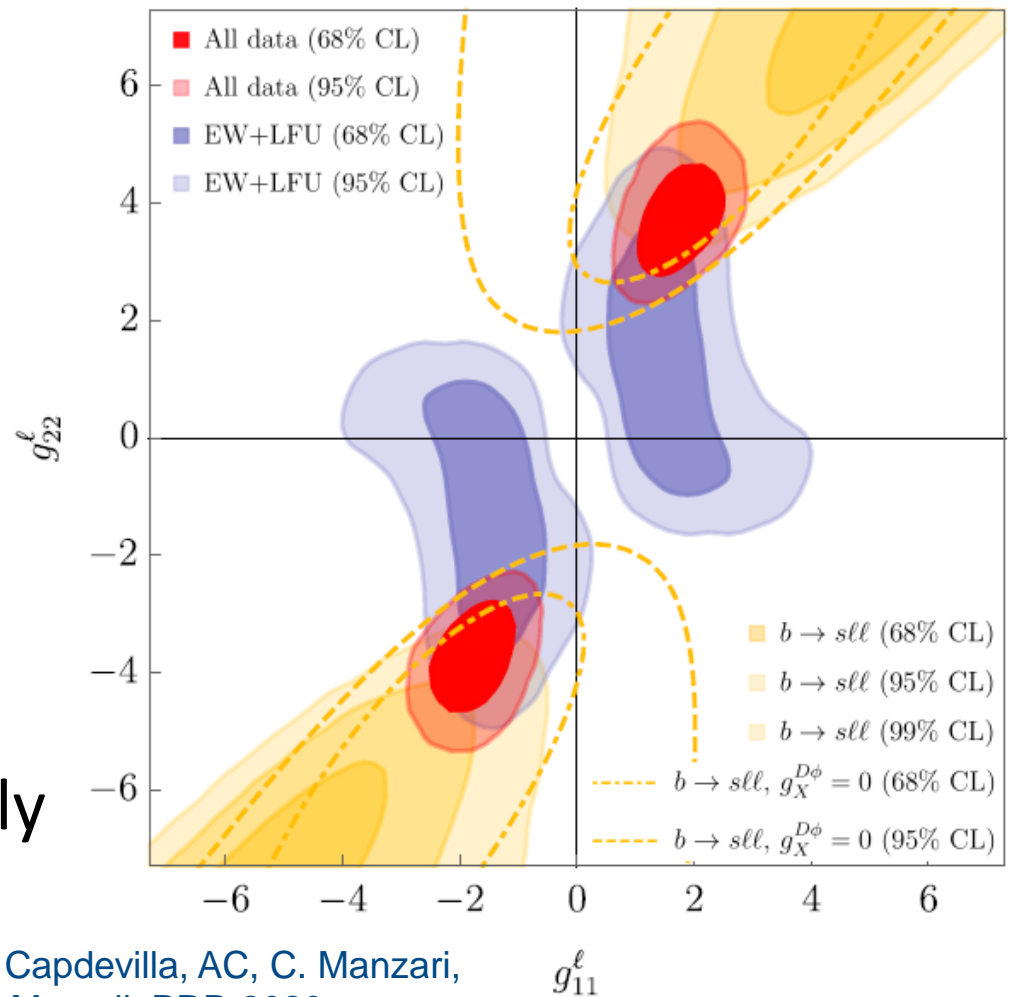
$b \rightarrow s \ell \ell$ and $b \rightarrow c \tau \nu$ with a Vector Leptoquark



Pati-Salam LQ can explain the flavour anomalies

Vector Triplet in the CAA & $b \rightarrow s\ell\ell$

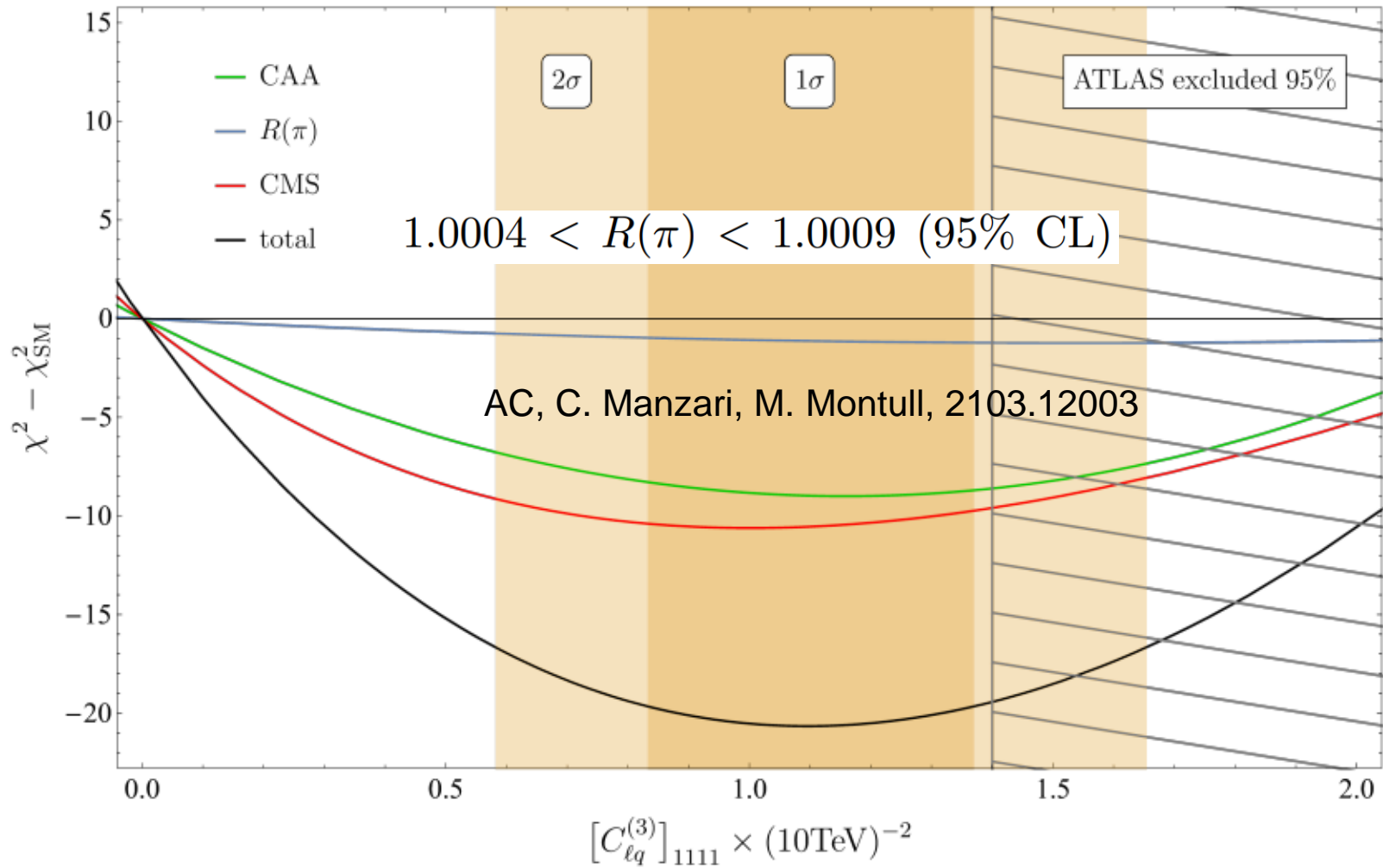
- Region from EW fit overlaps with $b \rightarrow s\ell\ell$ region
- Correlations between e.g. $\pi \rightarrow \mu\nu/\pi \rightarrow e\nu$ and $R(K^{(*)})$ are predicted
- Global fit significantly improved



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

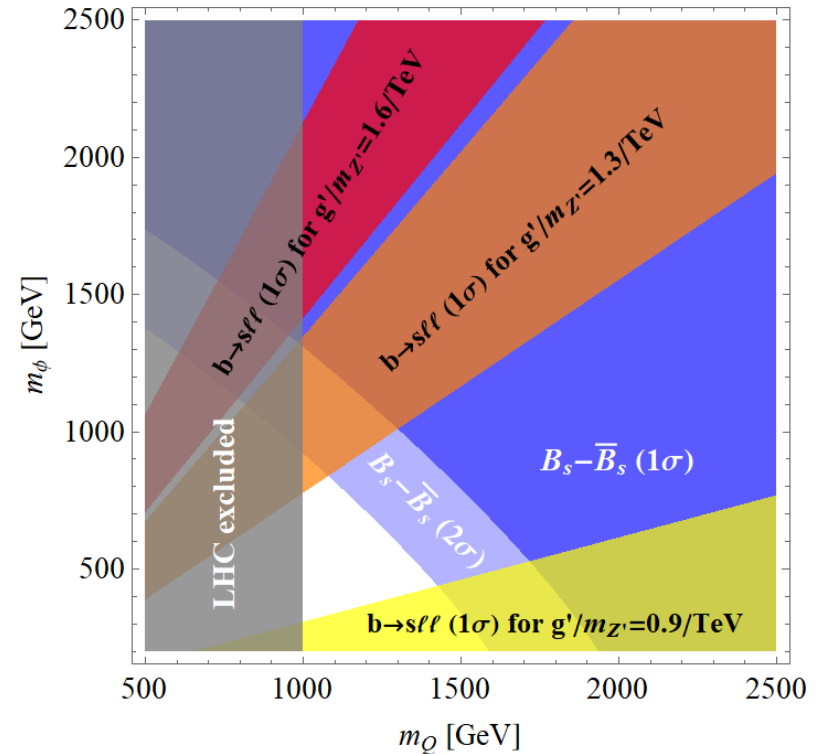
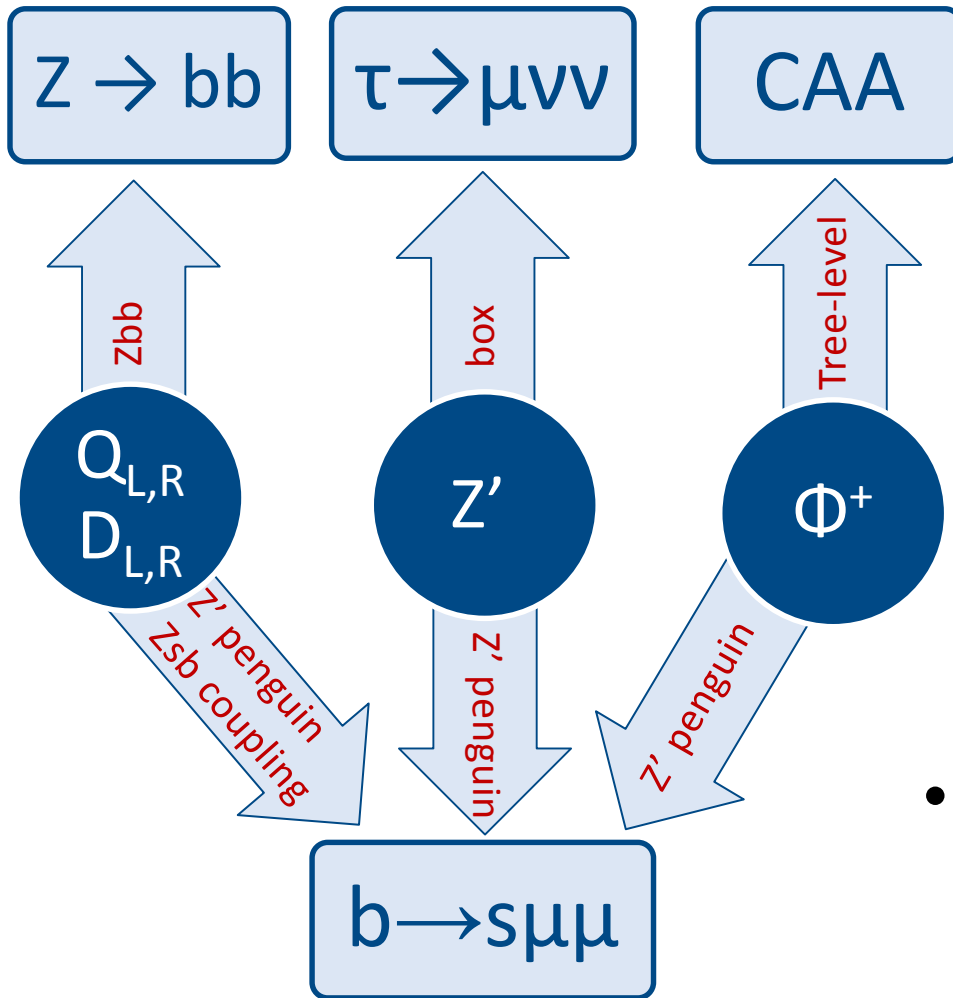
Common explanation possible

CAA and Non-Resonant Di-Leptons



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

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

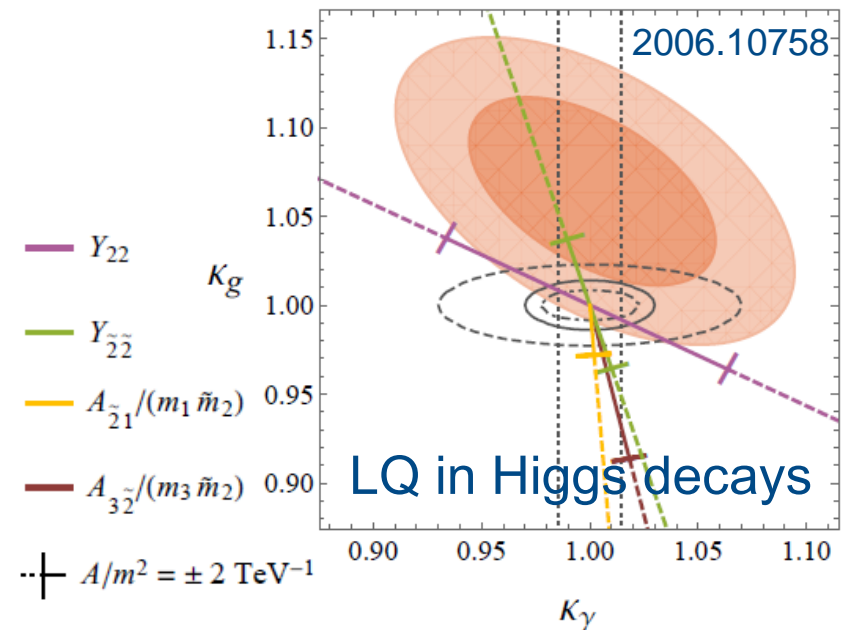


- Z' penguin + modified Zsb coupling give very good fit to $b \rightarrow s \ell \ell$ data

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

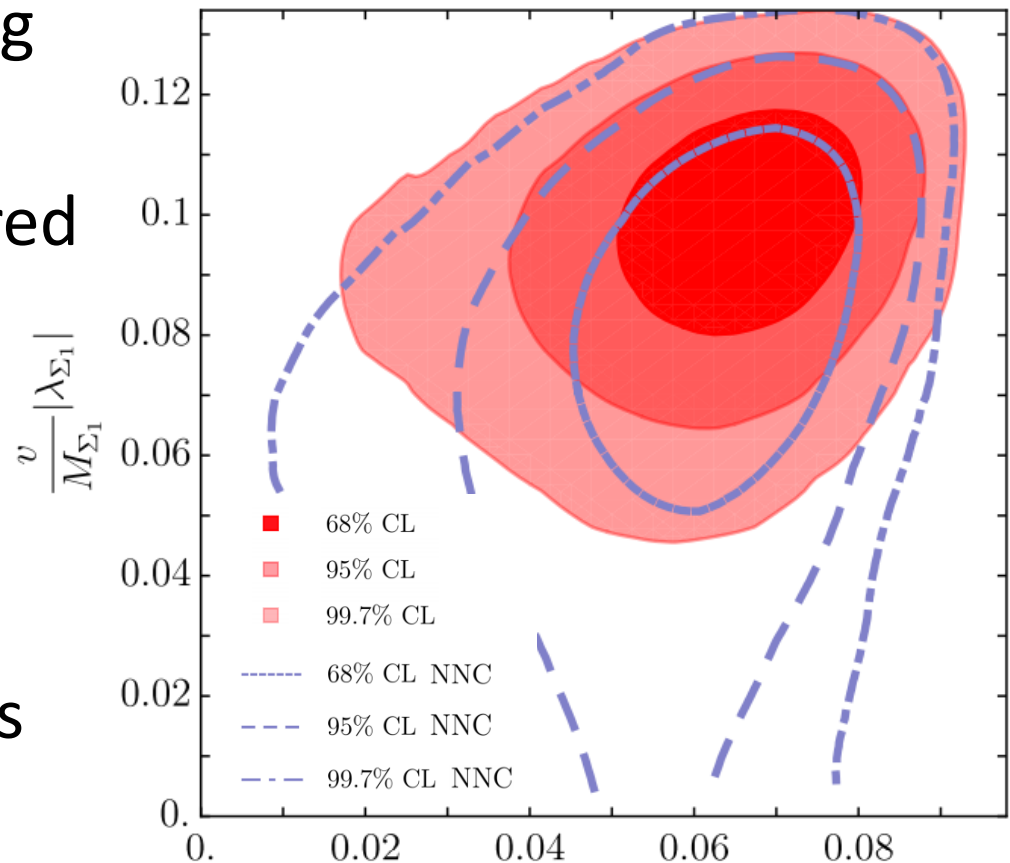


The flavour anomalies strengthen the physics case for future colliders significantly

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

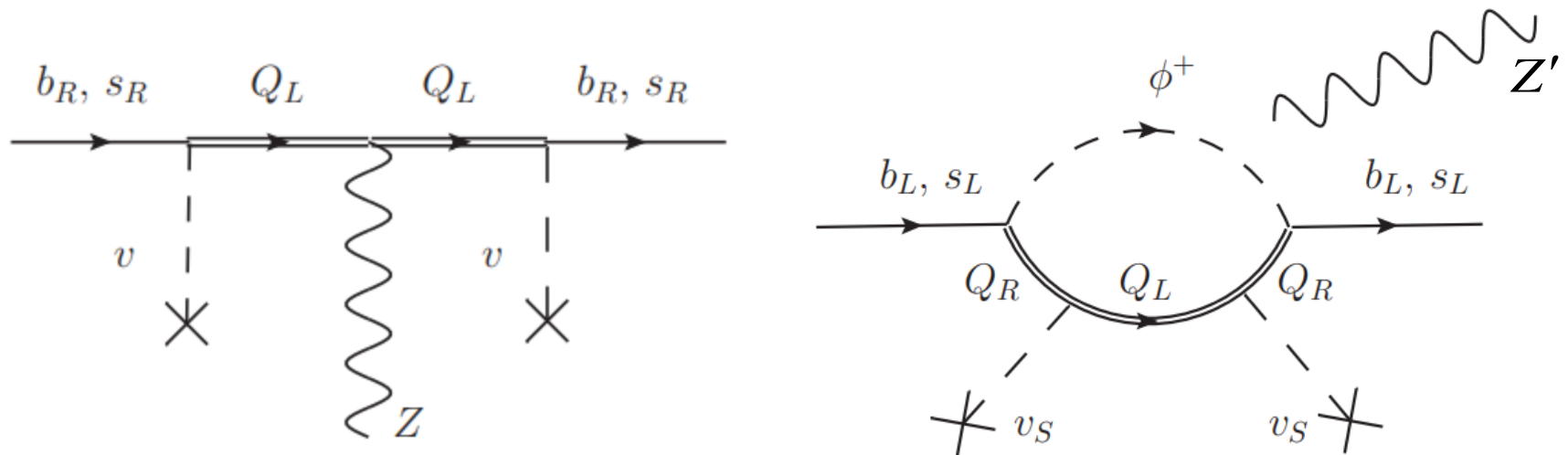


AC, F. Kirk, C. Manzari,
M. Montull JHEP, 2008.01113

>5 σ improvement over SM hypothesis

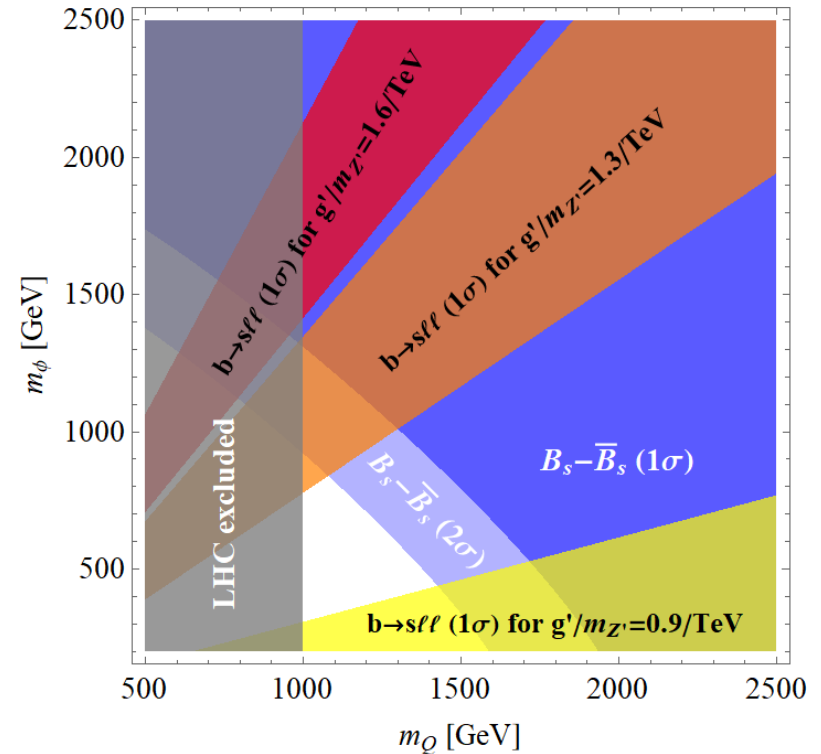
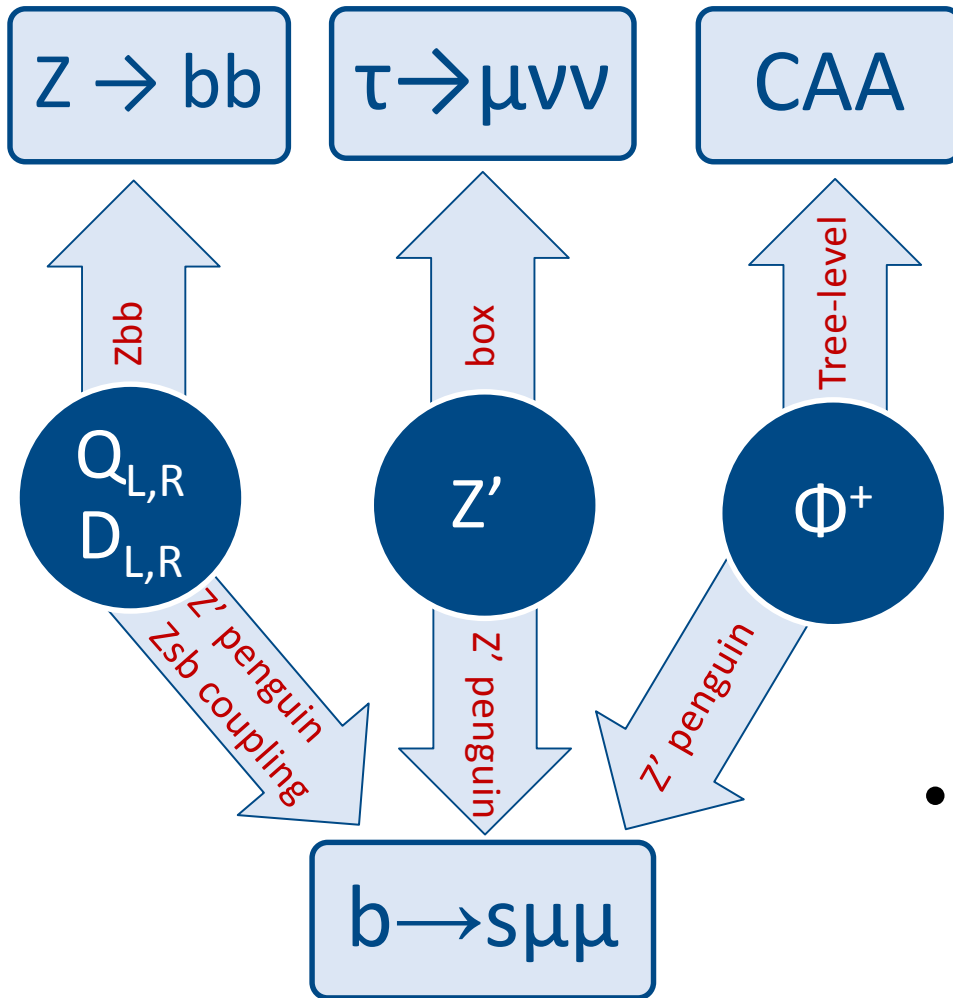
Model for $b \rightarrow s \ell \ell$, CAA, $Z \rightarrow b \bar{b}$ and $\tau \rightarrow \mu \nu$

	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	0	1	1	0	-1	-1



Tree effect in $Z b \bar{b}$ and loop in $Z' s \bar{b}$

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



- Z' penguin + modified Zsb coupling give very good fit to $b \rightarrow s \ell \ell$ data

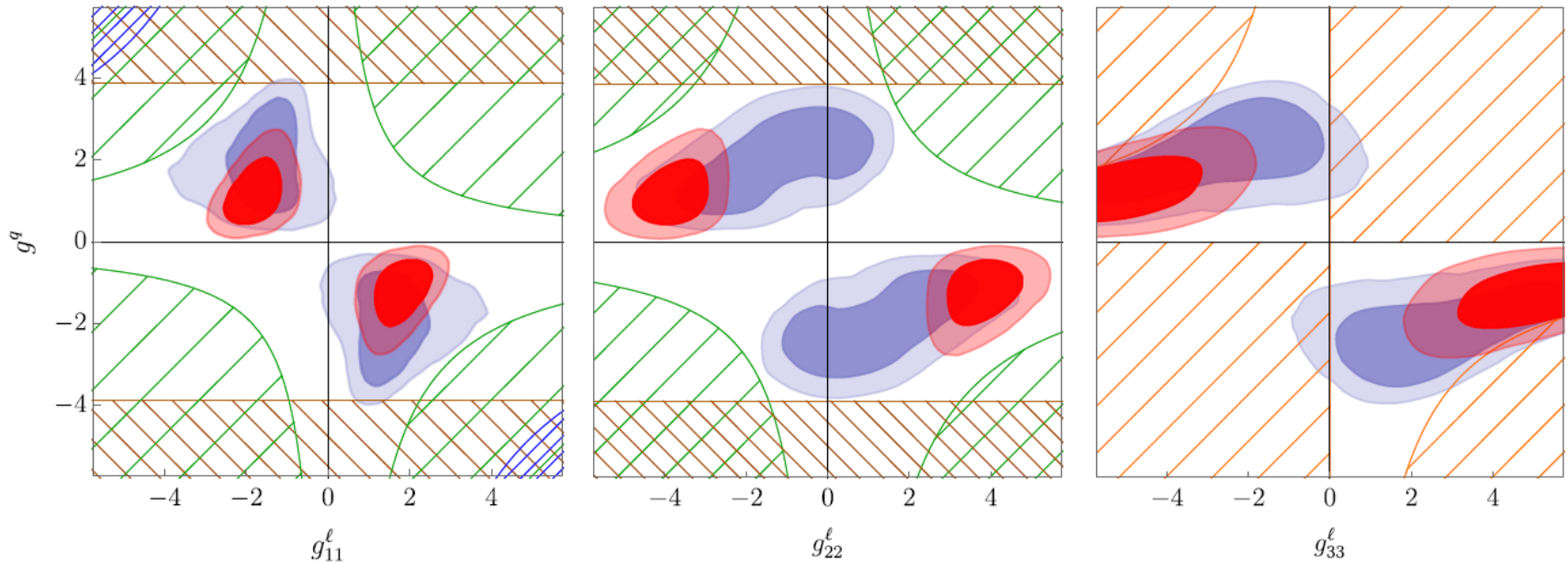
Simple model provides combined explanation

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

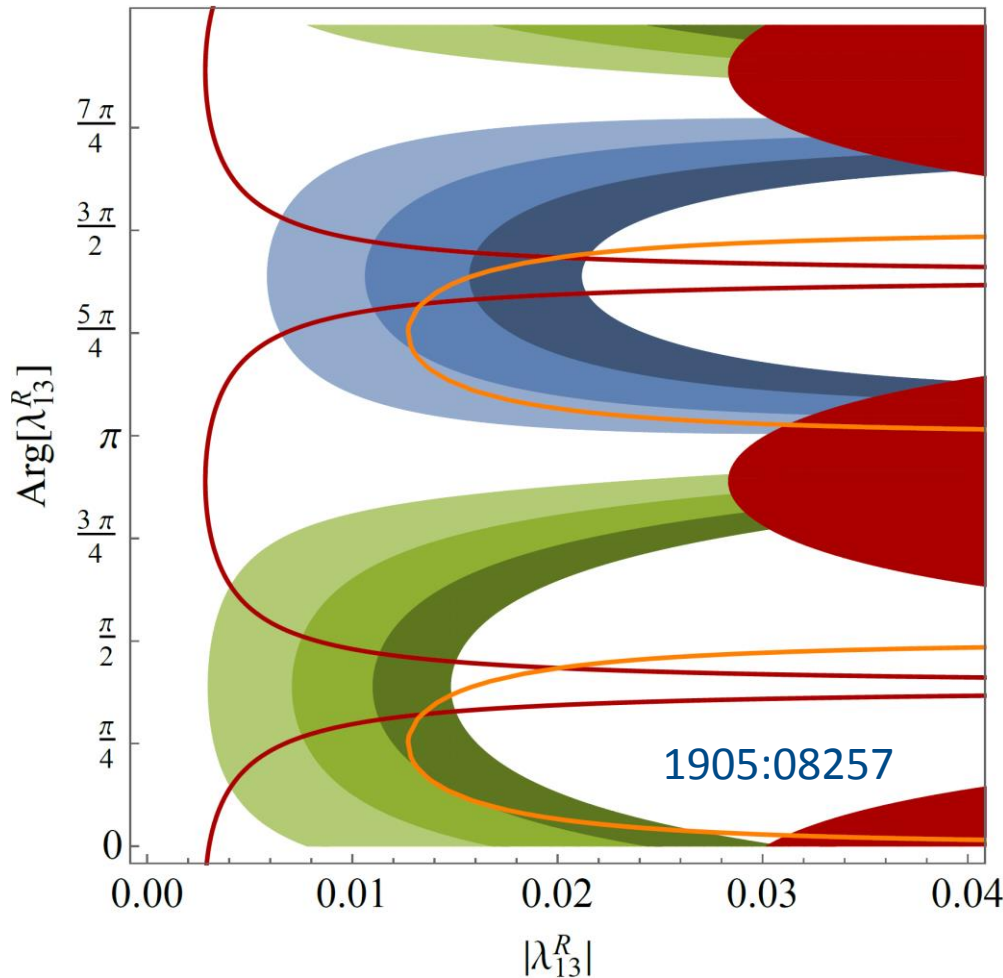
- W' effects in LFU and EW observables
- Z' effects in LHC di-jet and di-lepton tail searches

▨ QWEAK (excluded 68% CL)
 ▨ LHC-dilepton (excluded 95% CL)
 ■ EW+LFU (68% CL)
 ■ All data (68% CL)

▨ LHC-dilepton (excluded 95% CL)
 ▨ LHC-jet + E_T^{miss} (excluded 95% CL)
 ■ EW+LFU (95% CL)
 ■ All data (95% CL)



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



W. Dekens, J. de Vries, M. Jung,
K. K. Vos, arXiv:1809.09114

AC, F. Saturnino

arxiv:1905:08257

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

■ nEDM excluded

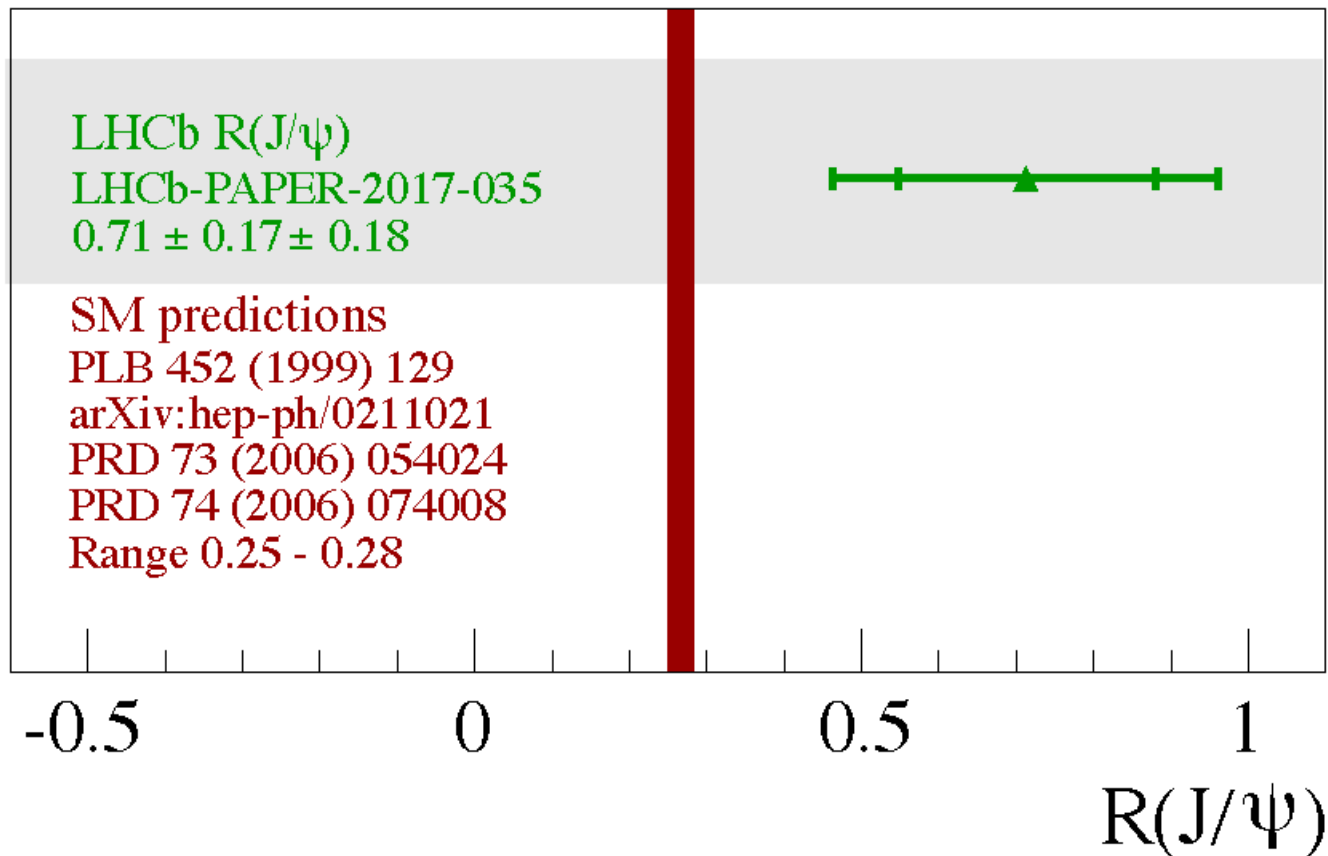
n2EDM sensitivity

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

Effect in B predicts measurable nEDM effect

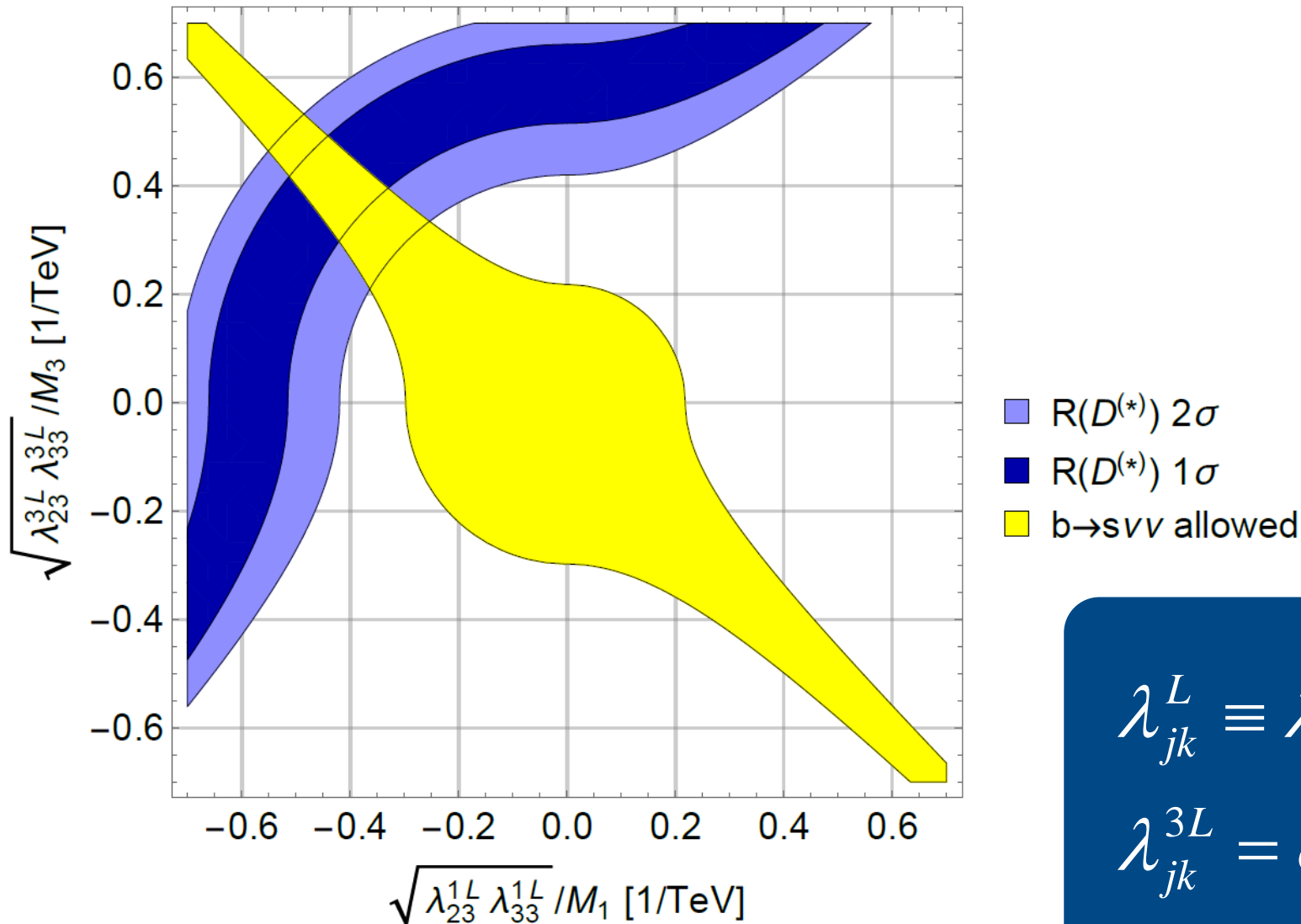
$b \rightarrow c \tau \nu$ Measurements

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



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

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

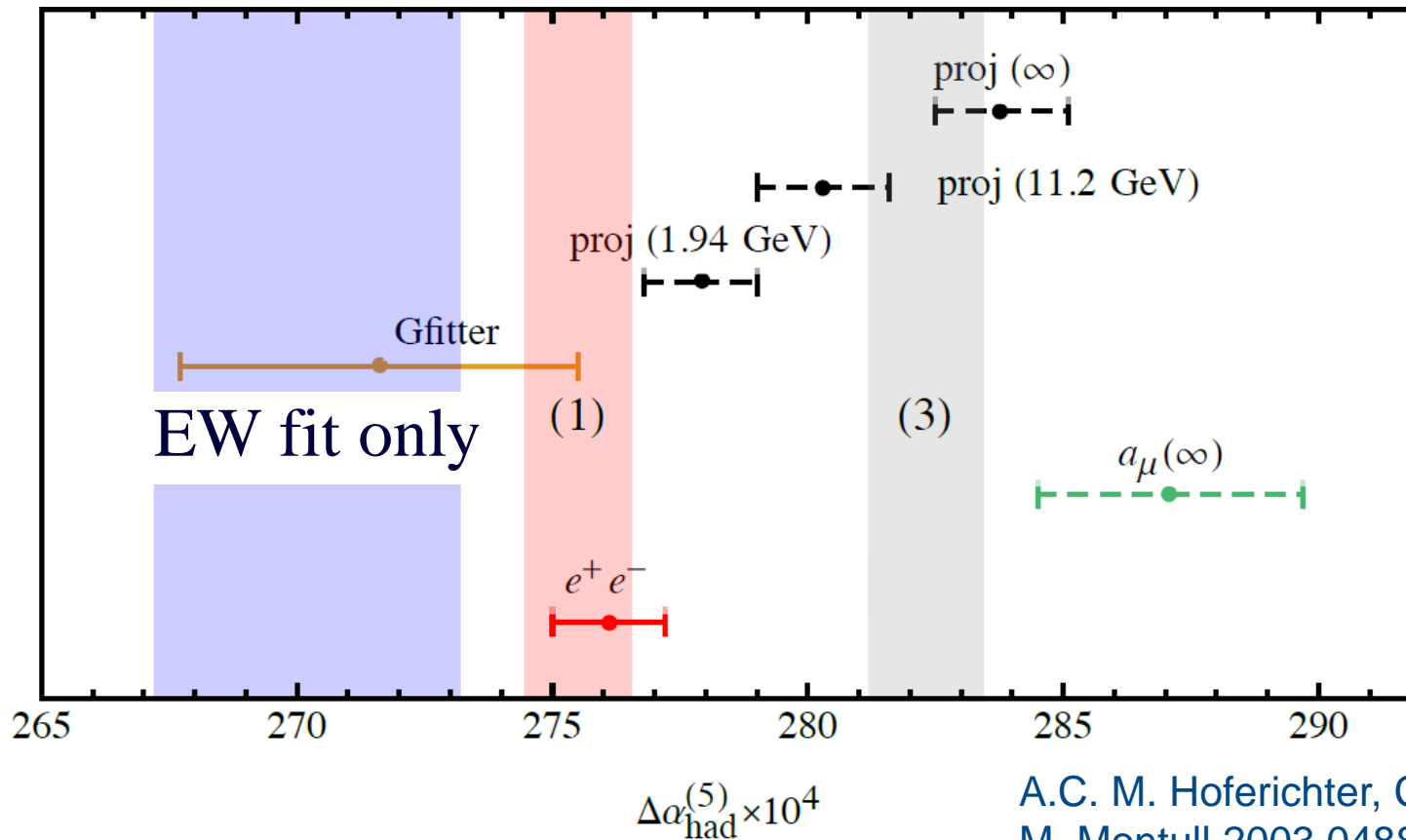


$$\lambda_{jk}^L \equiv \lambda_{jk}^{1L}$$

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

Hadronic Vacuum Polarization

- New BMWc lattice QCD result

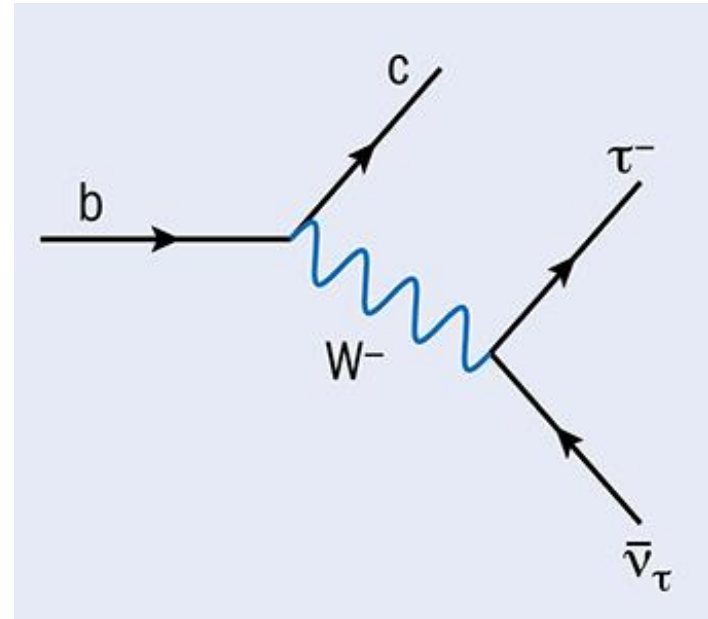


A.C. M. Hoferichter, C. Manzari,
M. Montull 2003.04886

Up to 4σ tension in EW fit

$b \rightarrow c \tau \nu$ Transitions

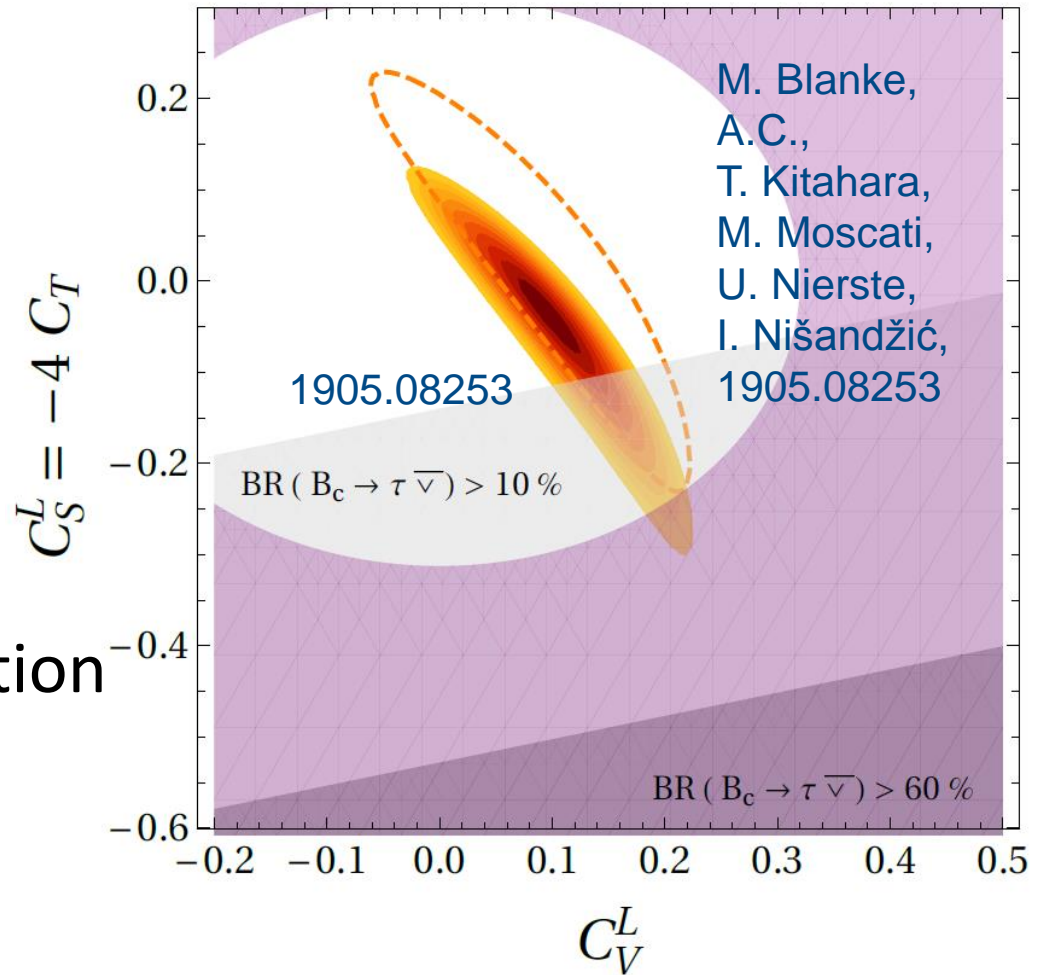
- $B \rightarrow D \tau \nu$, $B \rightarrow D^* \tau \nu$, $\Lambda_b \rightarrow \Lambda_c \tau \nu$
- Tree-level decays in the SM
- Form factors needed
- With light leptons (μ , e) used to determine the CKM elements
- CKM fit works very well, i.e. tree-level in agreement with $\Delta F=2$ processes



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

$b \rightarrow c \tau \nu$ 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



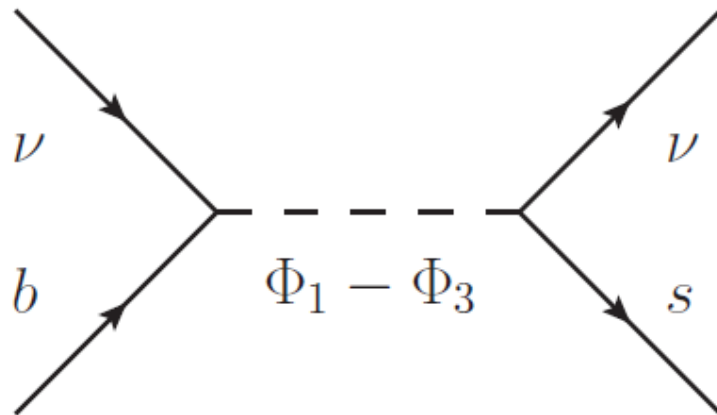
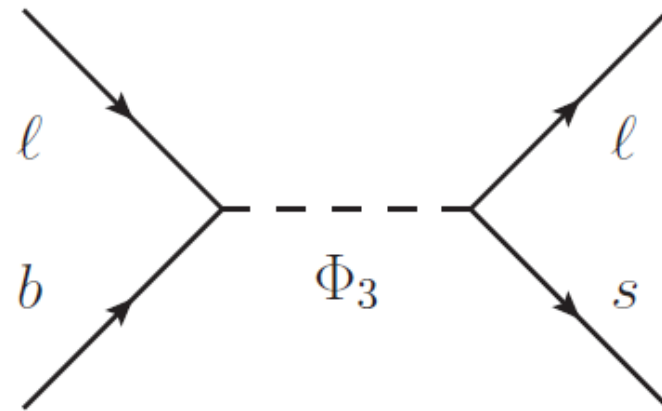
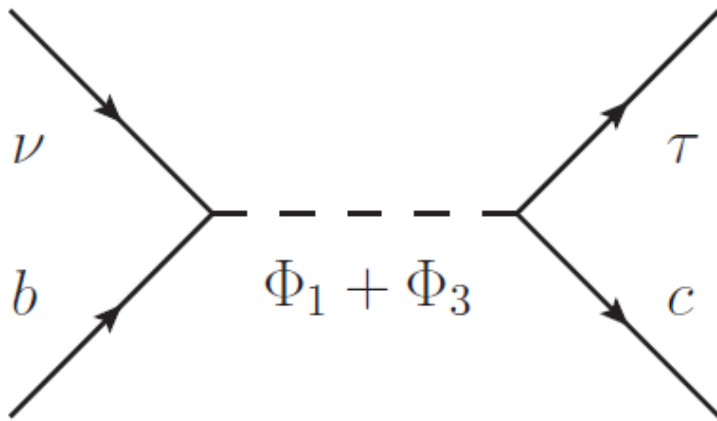
Global fit give up to 4σ preference for NP

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

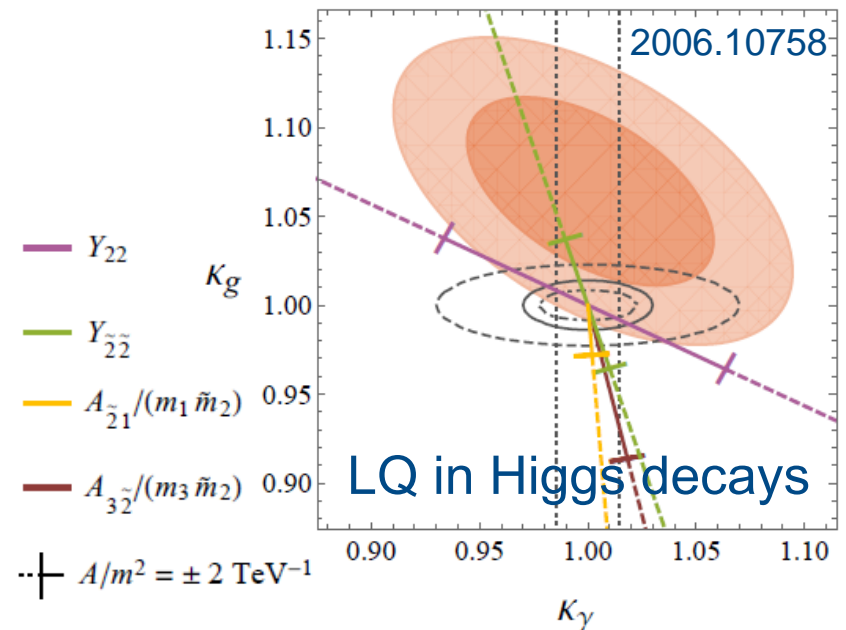
AC, D. Mueller, F. Saturnino
arxiv:1912.04224

	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 $\times 10^{11}$	$V_{cb}^e/V_{cb}^\mu - 1$ $\times 10^6$	$Z \rightarrow \tau\mu$ $\times 10^{10}$	
● 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) $ $\times 10^5$	$\frac{\Delta_{33}^L(m_Z^2)}{\Lambda_{\text{SM}}^{LL} \times 10^{-5}}$	
● p_1	0.023	0.040	2.33	0.1	0.512	1.27	44.94	1.11	-3.64	
● p_2	0.020	0.040	0.87	0.16	3.32	4.73	7.783	0.90	-3.02	
● p_3	0.023	0.037	1.08	0.19	4.07	1.00	37.89	0.89	-3.51	
● p_4	0.010	0.047	2.43	0.18	3.69	0.0021	18.60	3.12	-10.04	

Common explanation possible

Outlook: Physics at Future Colliders

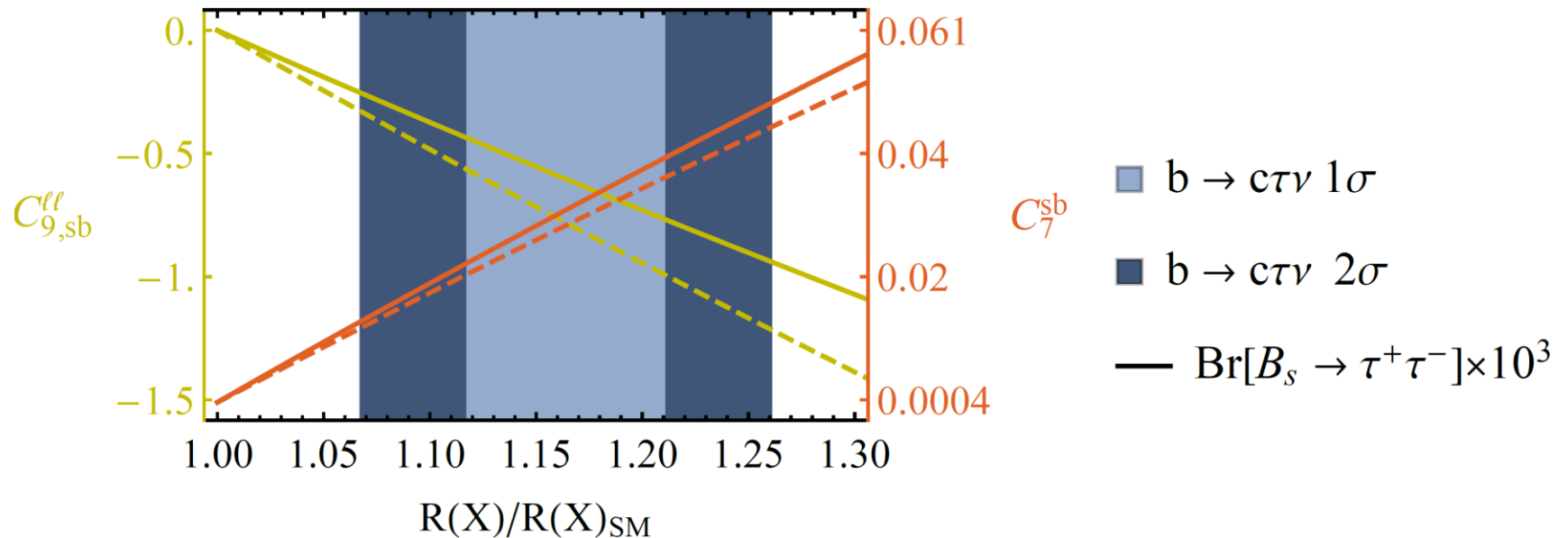
- Flavour Anomalies require NP at the TeV scale
 - ➡ Direct Searches at HL-LHC, HE-LHC, FCC-pp
- This new particles in general also affect EW precision observables
 - ➡ Z decays at CLIC and FCC-ee
- Flavour is directly linked to the Higgs boson
 - ➡ CLIC, FCC



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

Important Loop-Effects

- Explanation of $b \rightarrow c\tau\nu$ requires large $b\tau$ and $s\tau$ couplings (follows from $SU(2)$ invariance)

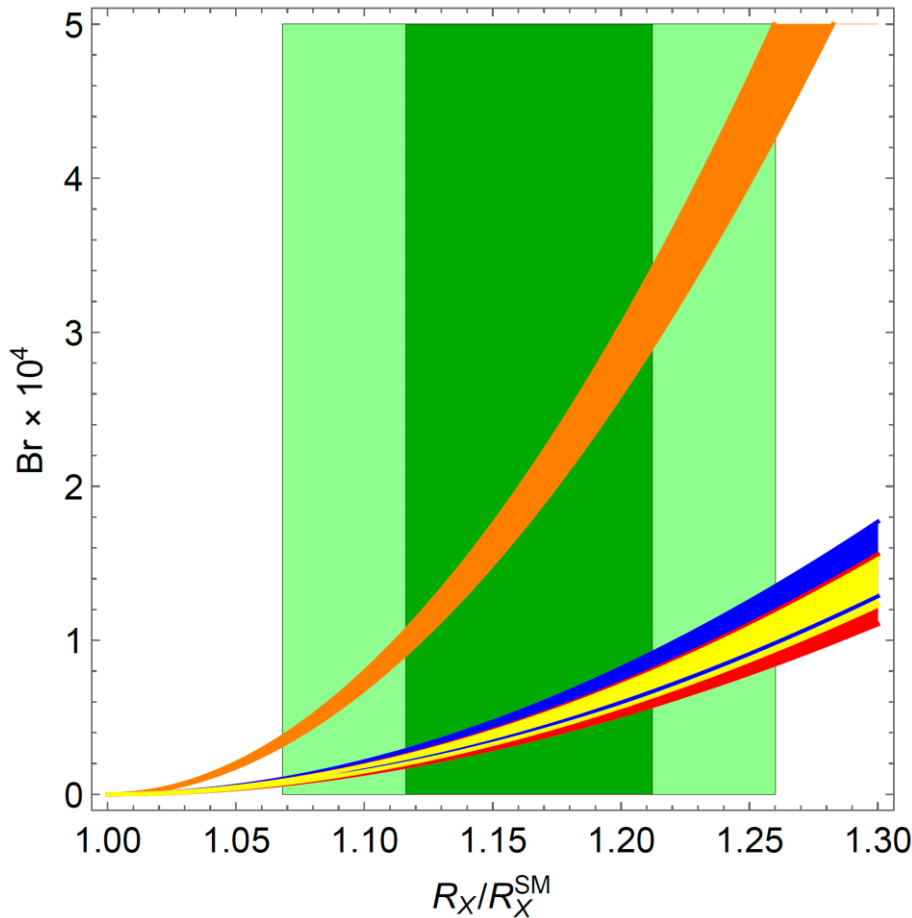


AC, C. Greub, D. Müller,
F. Saturnino, PRL 2018

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

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

- Large couplings to the second generation



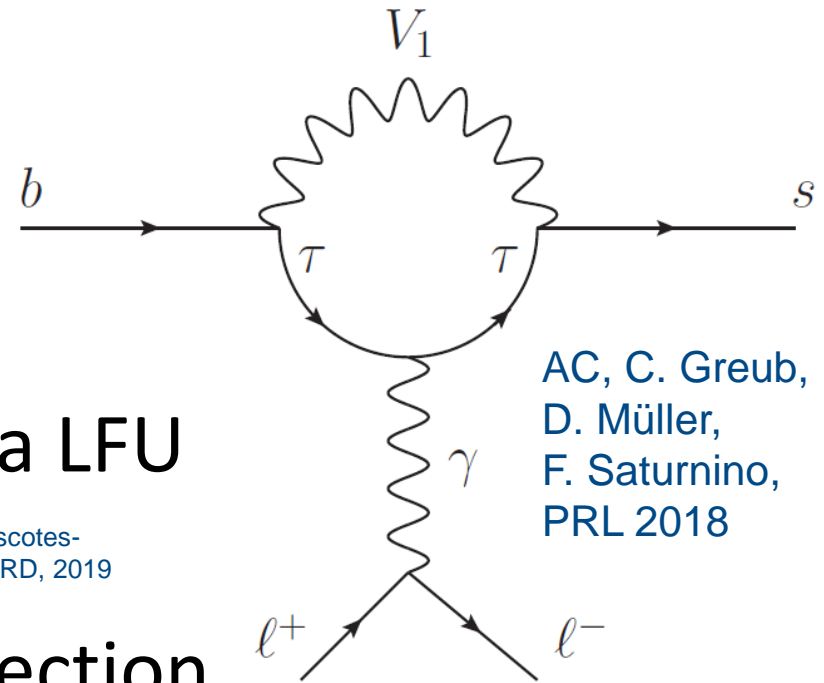
$b \rightarrow s\tau\tau$
very
strongly
enhanced

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

Important Loop-Effects

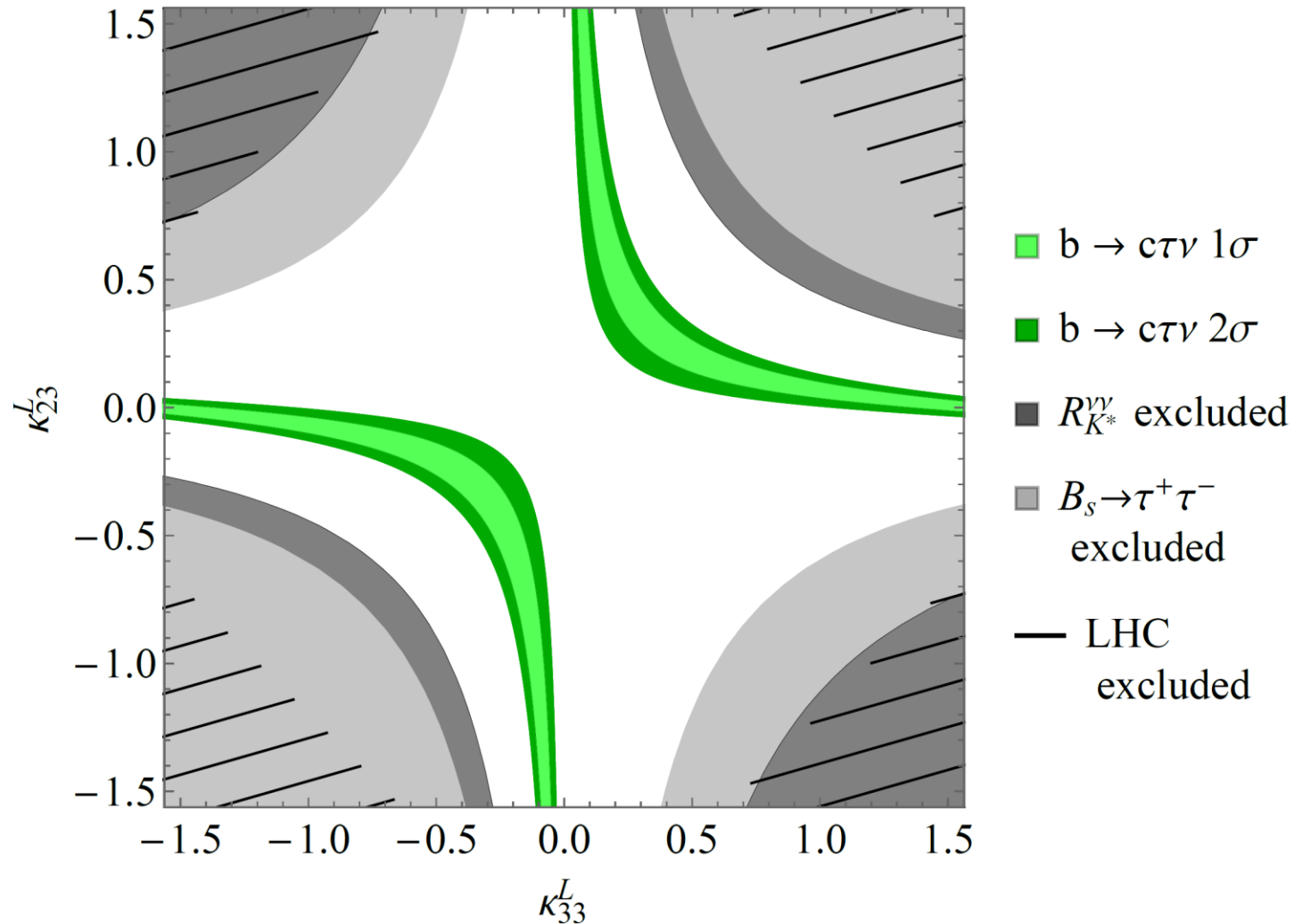
- Explanation of $b \rightarrow c\tau\nu$ requires large LQ- $b\tau$ and LQ- $c-\nu_\tau$ couplings
- Via SU(2) invariance this leads to large effects in $b \rightarrow s\tau\tau$ processes
- Closing the tau-loop gives a LFU effect in $b \rightarrow sll$
- Effect goes in the right direction

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



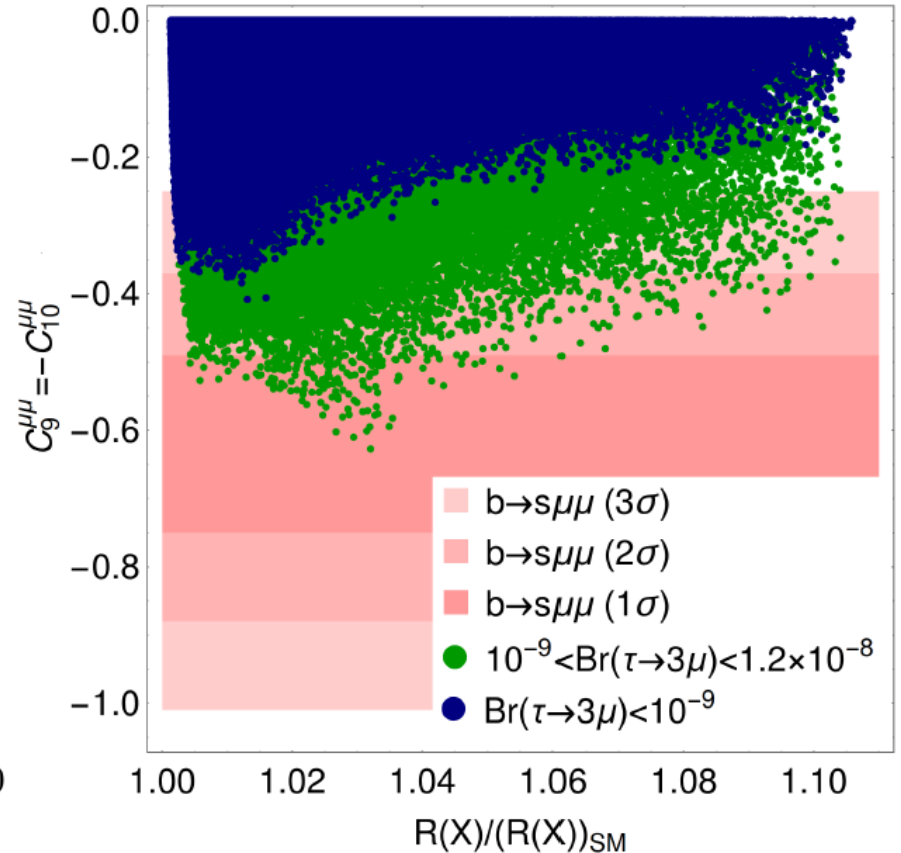
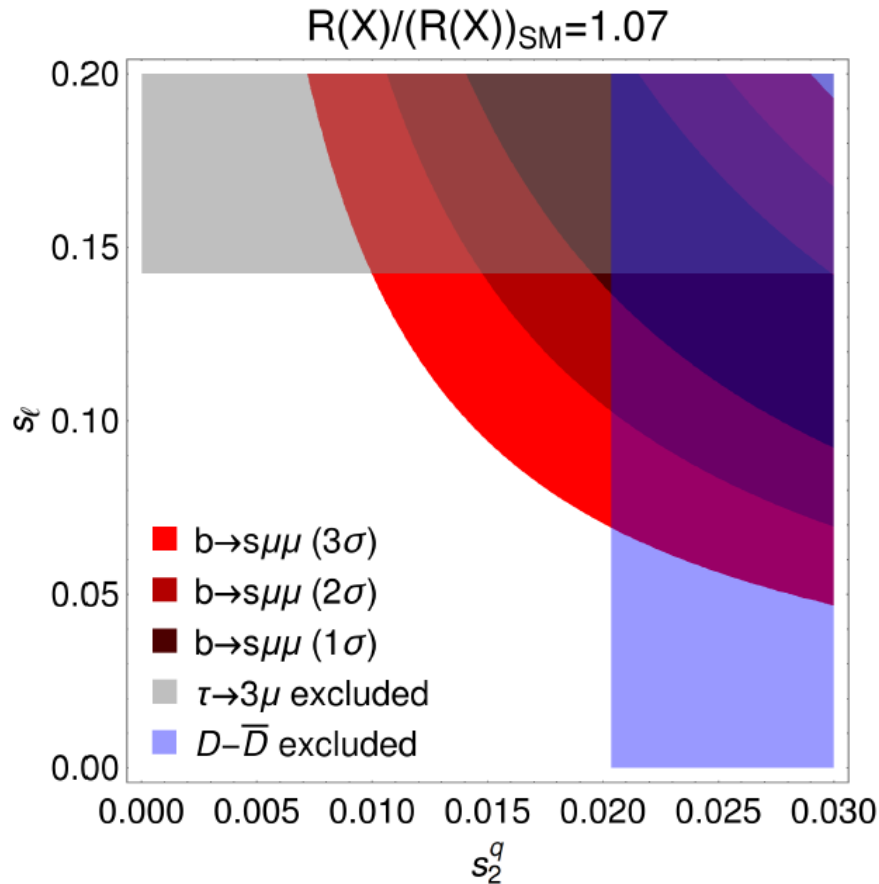
Compatible with constraints for generic couplings

Possible UV completions

- $SU(4) \times SU(3)' \times SU(2)_L \times U(1)_Y$ + 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



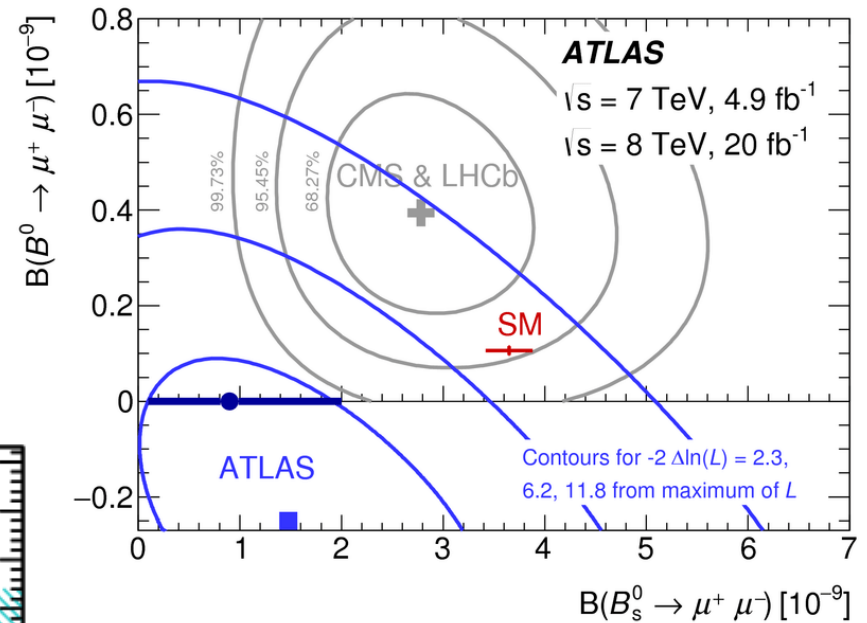
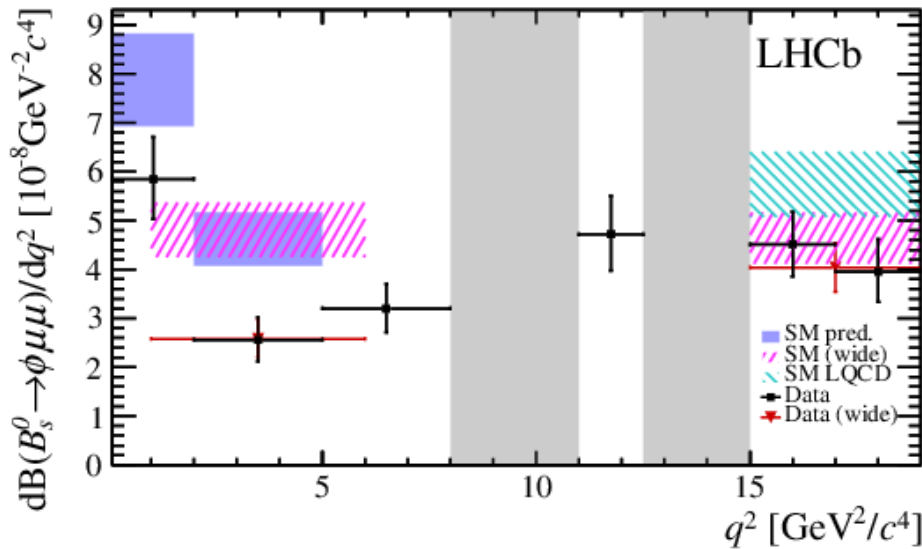
$M = 3 \text{ TeV}, s_2^\ell = 0.2, s_3^\ell = 1/\sqrt{2}$ and $s_3^q = \sqrt{3}/2$

M. Blanke, AC, PRL 2018

Model well motivated + limited but sizable effect

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

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

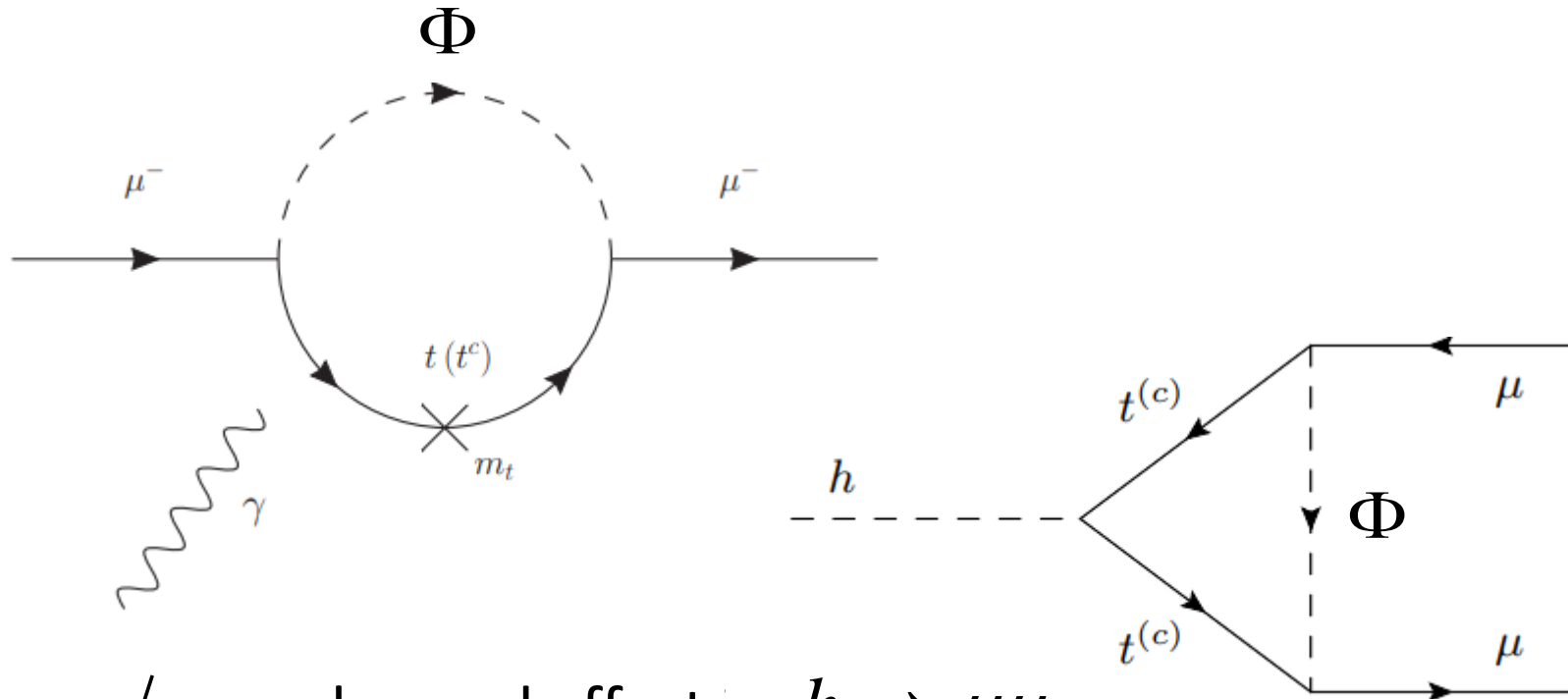


- $B_s \rightarrow \phi\mu\mu$ has a higher Br, but knowledge of the form-factor needed

Br's \approx 20% below SM expectations

Leptoquarks in a_μ

- Chirally enhanced effects via top-loops

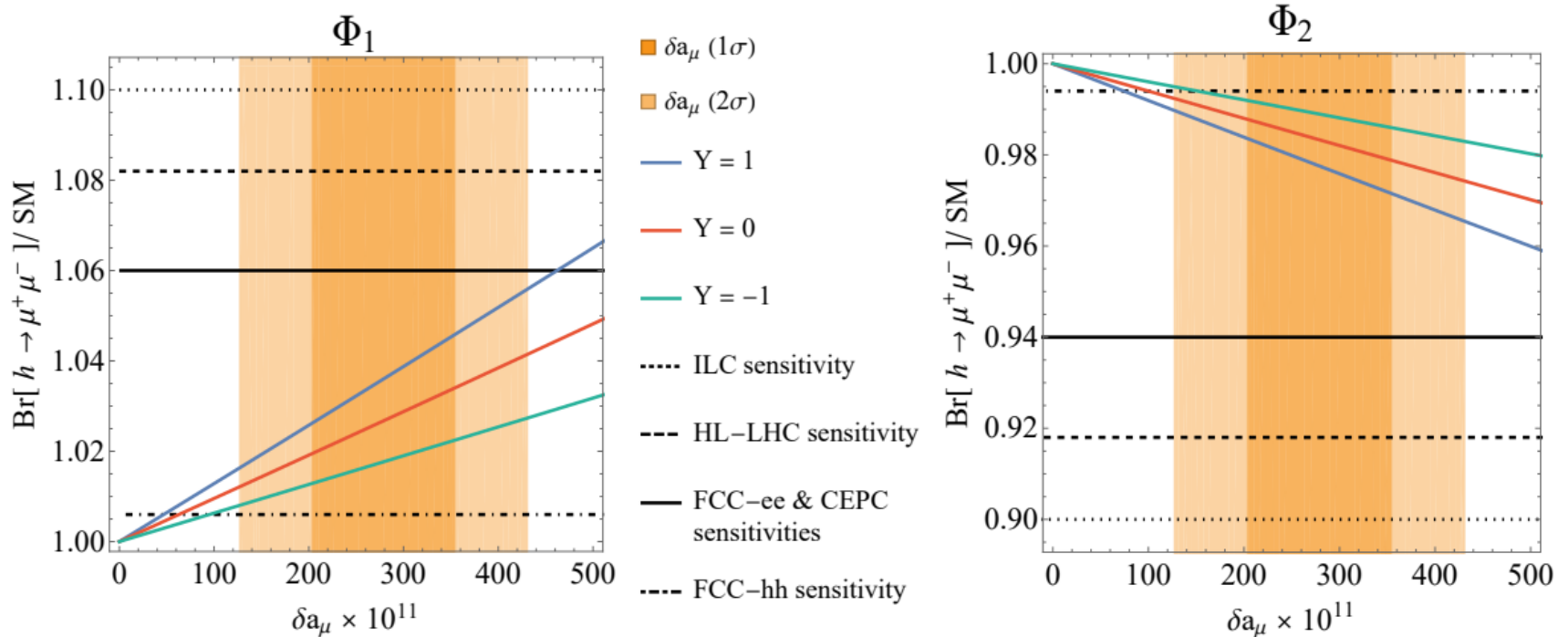


- m_t/m_μ enhanced effect $h \rightarrow \mu\mu$
- m_t^2/m_Z^2 enhanced effect in $Z \rightarrow \mu\mu$

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 \rightarrow direct correlation



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

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

$\tau \rightarrow \mu\nu\nu$ and $\tau \rightarrow e\nu\nu$

- Ratios of leptonic tau decays

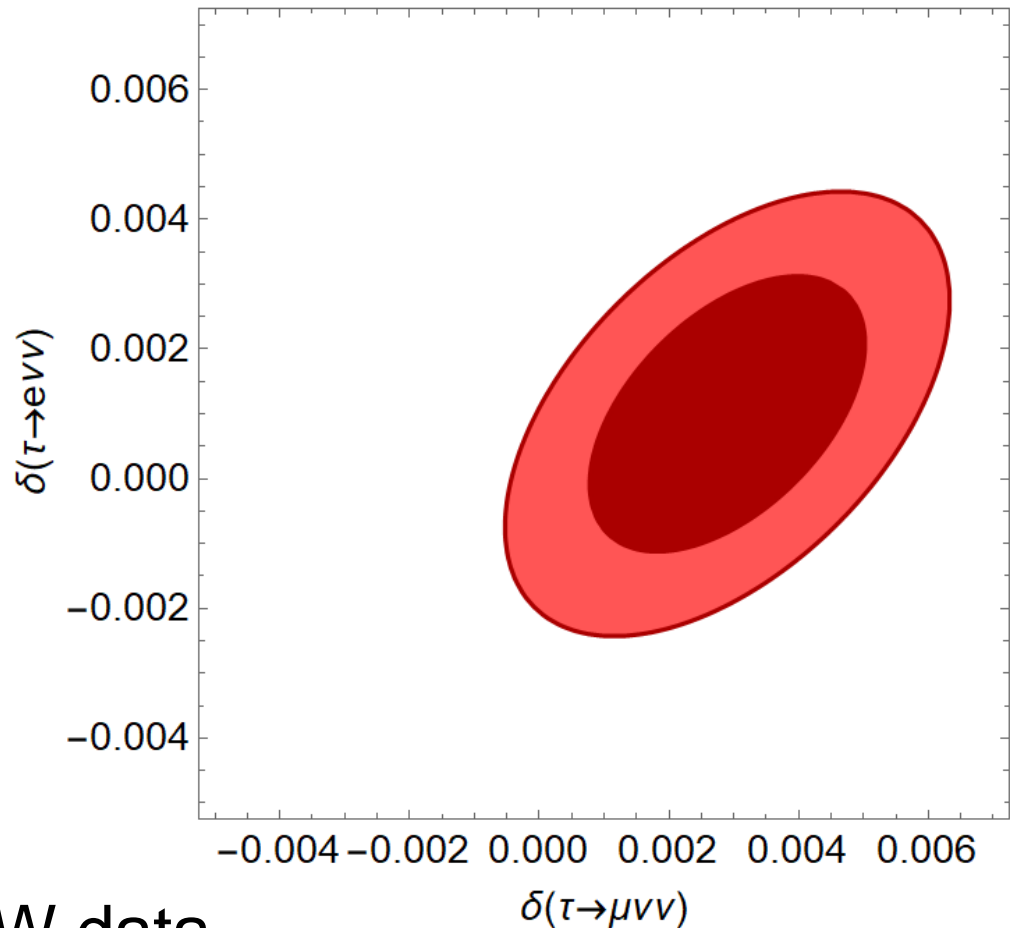
$$\frac{A_{\text{EXP}}(\tau \rightarrow \mu\nu\bar{\nu})}{A_{\text{SM}}(\mu \rightarrow e\nu\bar{\nu})} = 1.0029 \pm 0.0014$$

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

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

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

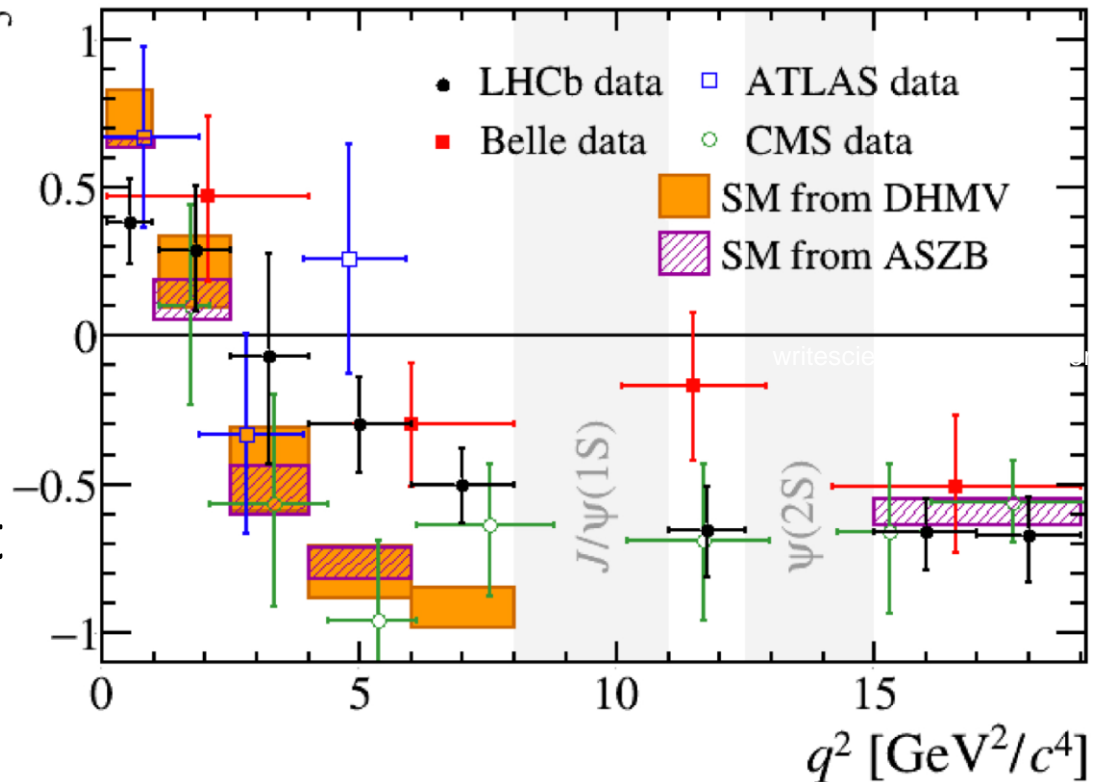
- NP in muon decay constrained from EW data



$\approx 2\sigma$ hint for LFUV in tau decays

The P_5' Anomaly

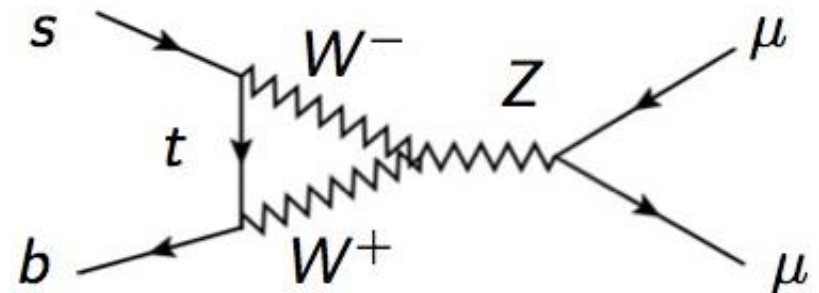
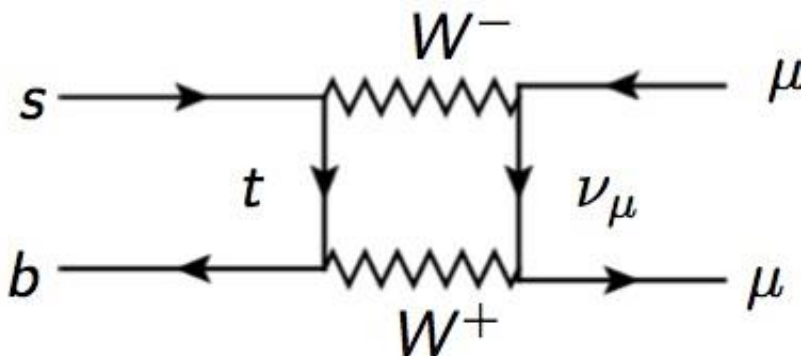
- P_5' angular observables in $B \rightarrow K^* \mu \mu$ S. Descotes-Genon, T. Hurth, J. Matias, J. Virto, JHEP 2013
- Constructed in such a way that the form factor dependence is minimized
- Confirmed by latest LHCb analysis for the charged mode



>3 σ deviation from the SM prediction

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

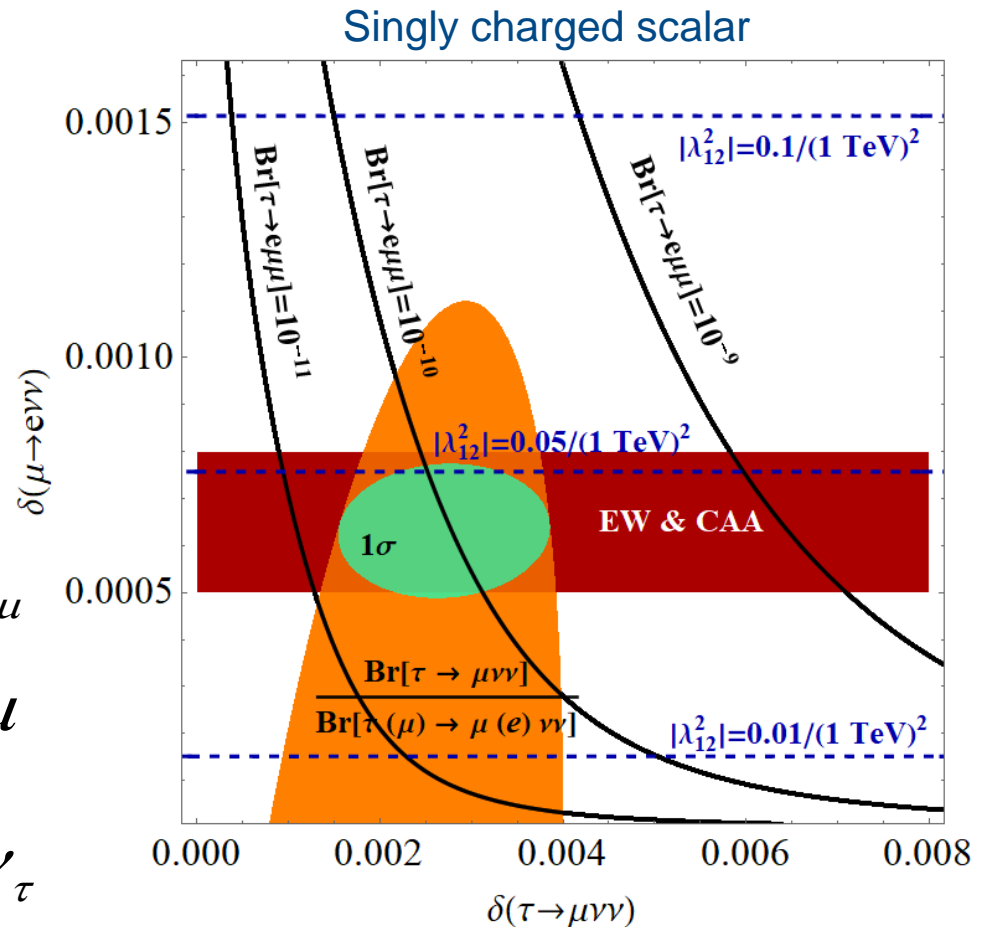
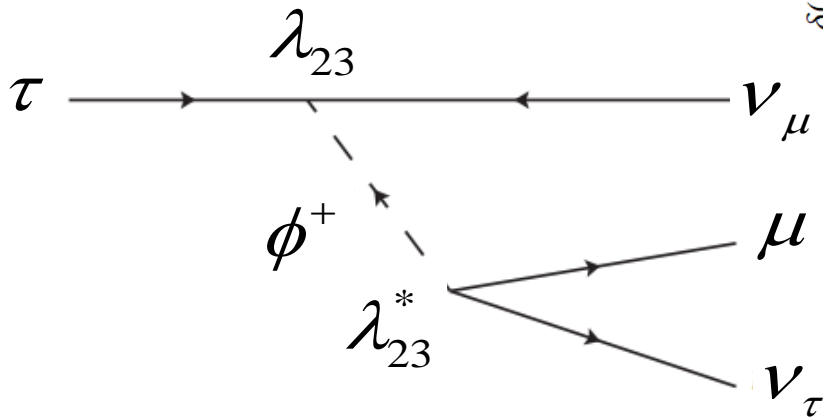
- Flavour Changing Neutral Current (FCNC)
- In the SM it is suppressed by
 - The CKM elements $V_{cb} \approx 0.04$
 - Electroweak scale
 - Loop-factor
- Wilson coefficients precisely known Bobeth et al. PRD, 2013



Suppressed in the SM and very sensitive to NP

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

- L_μ - L_τ Z' (box diagrams)
- LFV violating Z'
- Modified $W\ell\nu$ couplings
- W'
- Singly charged scalar



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

Scenarios can be distinguished by $\pi \rightarrow \mu \nu / \pi \rightarrow e \nu$