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WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

Andreas Crivellin

Theory Group of the Laboratory for Particle Physics, PSI &
University of Zurich

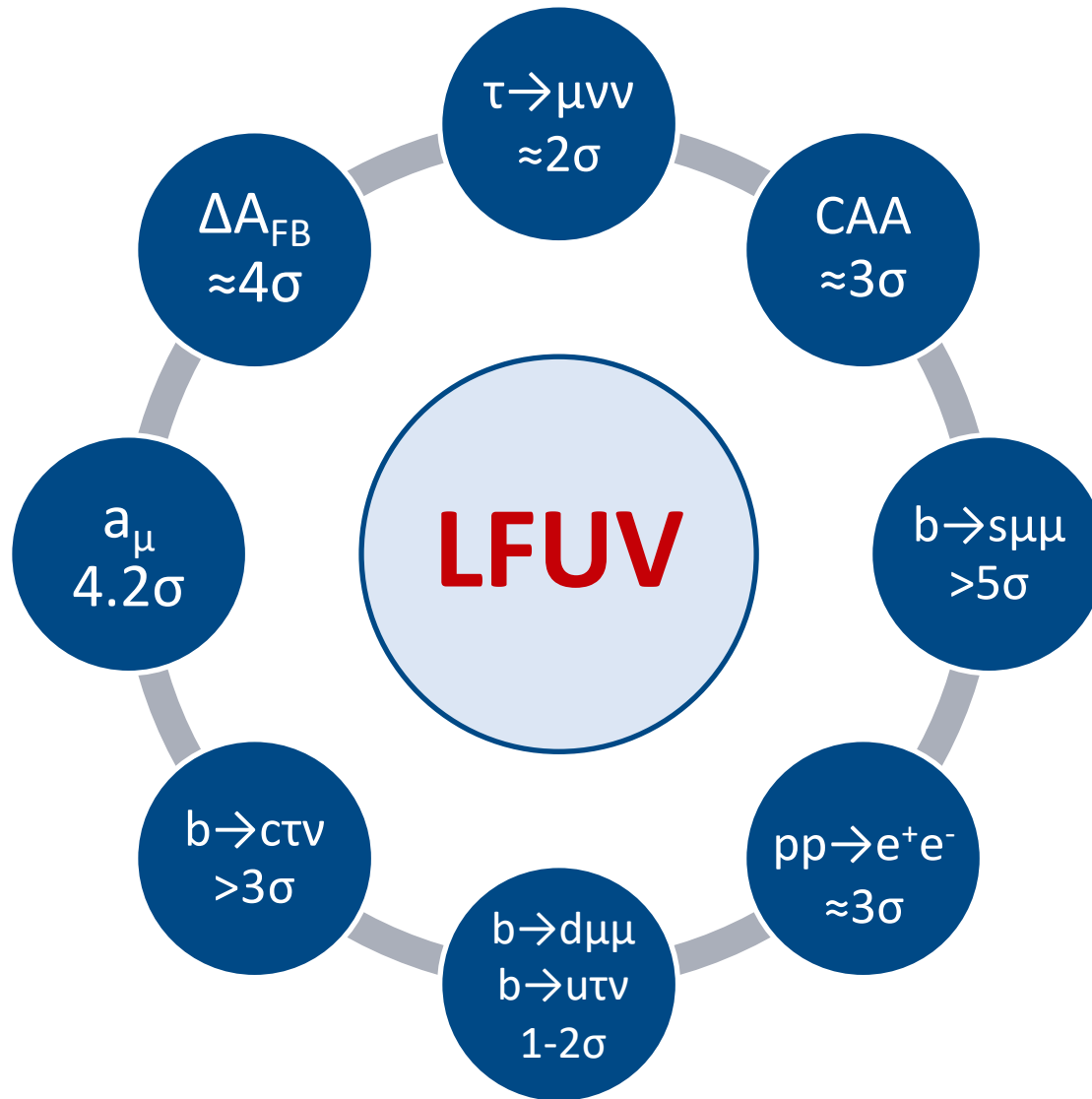
New Physics Models

Mini-workshop on missing particle signatures and new physics at
Belle II and LHCb, 5-6 July 2021

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
 - ΔA_{FB}
- Explanations of the Flavour anomalies
- Common Explanations
- Conclusions

Flavour Anomalies



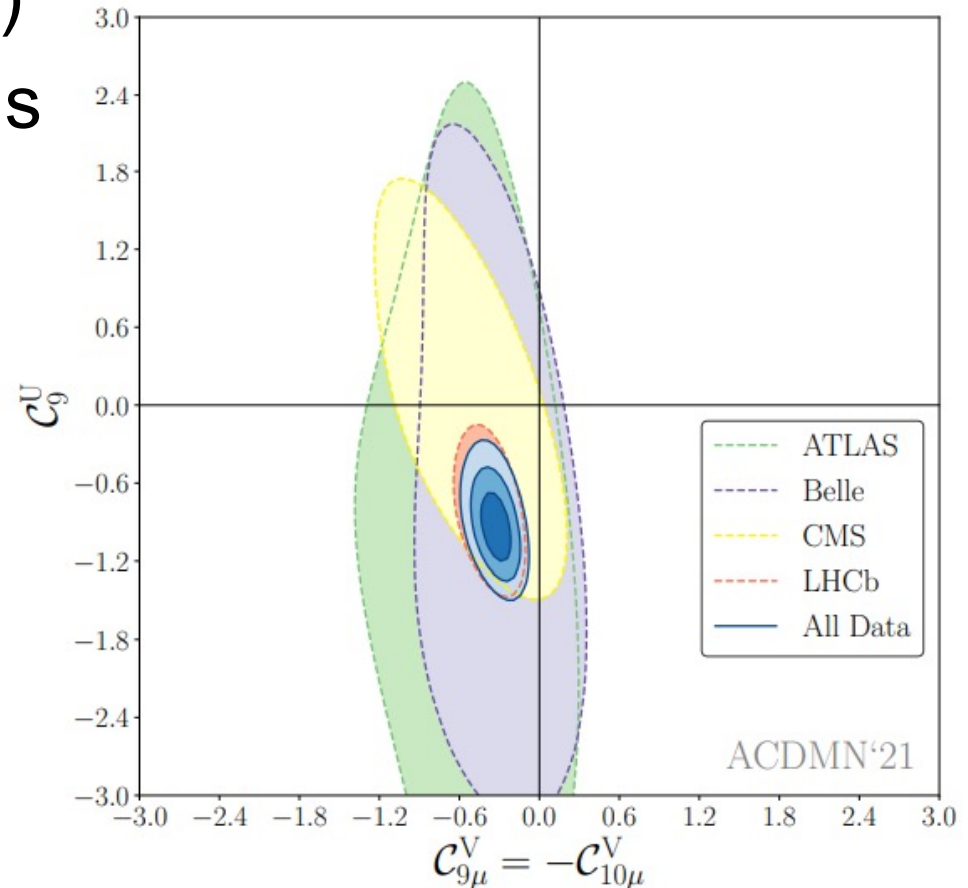
Global Fit to $b \rightarrow s \mu^+ \mu^-$ Data

See talk of Peter Stangel

- 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

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

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



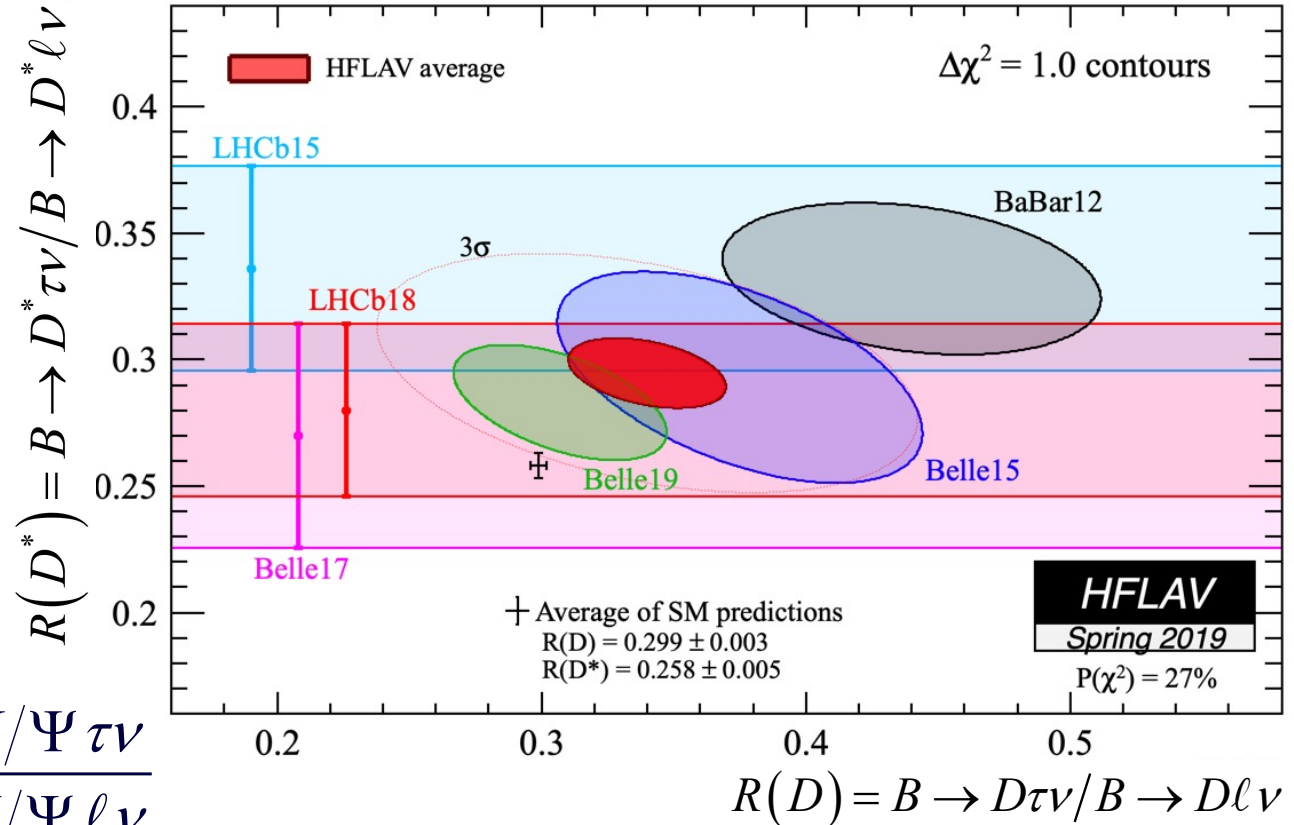
Fit is $>7 \sigma$ better than the SM

$b \rightarrow c \tau \nu$ Transitions

See talk of Zoltan Ligeti

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

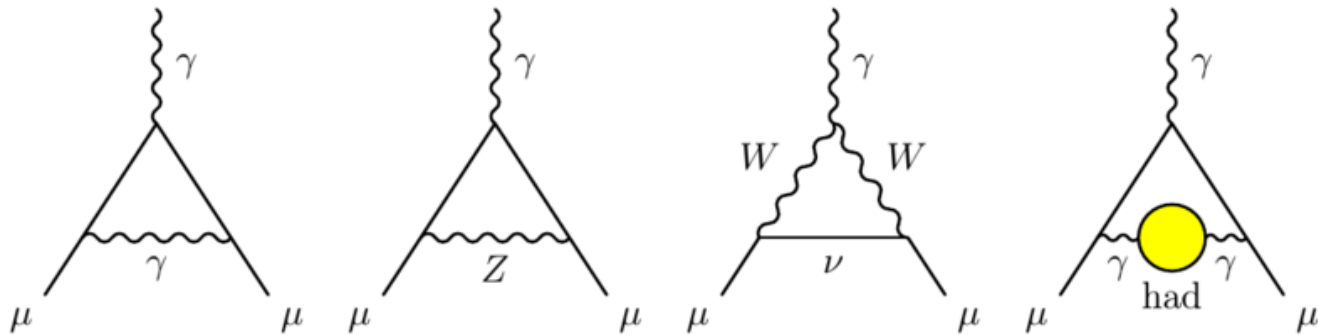
$$R(J/\Psi) = \frac{B_c \rightarrow J/\Psi \tau \nu}{B_c \rightarrow J/\Psi \ell \nu}$$



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

O(10%) constructive preferred effect at 3 σ

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 new experimental results from Fermilab
- Vanishes for $m_\mu \rightarrow 0$ \Rightarrow **measure of LFUV**

4.2 σ deviation from the SM prediction

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

- Ratios of leptonic tau decays

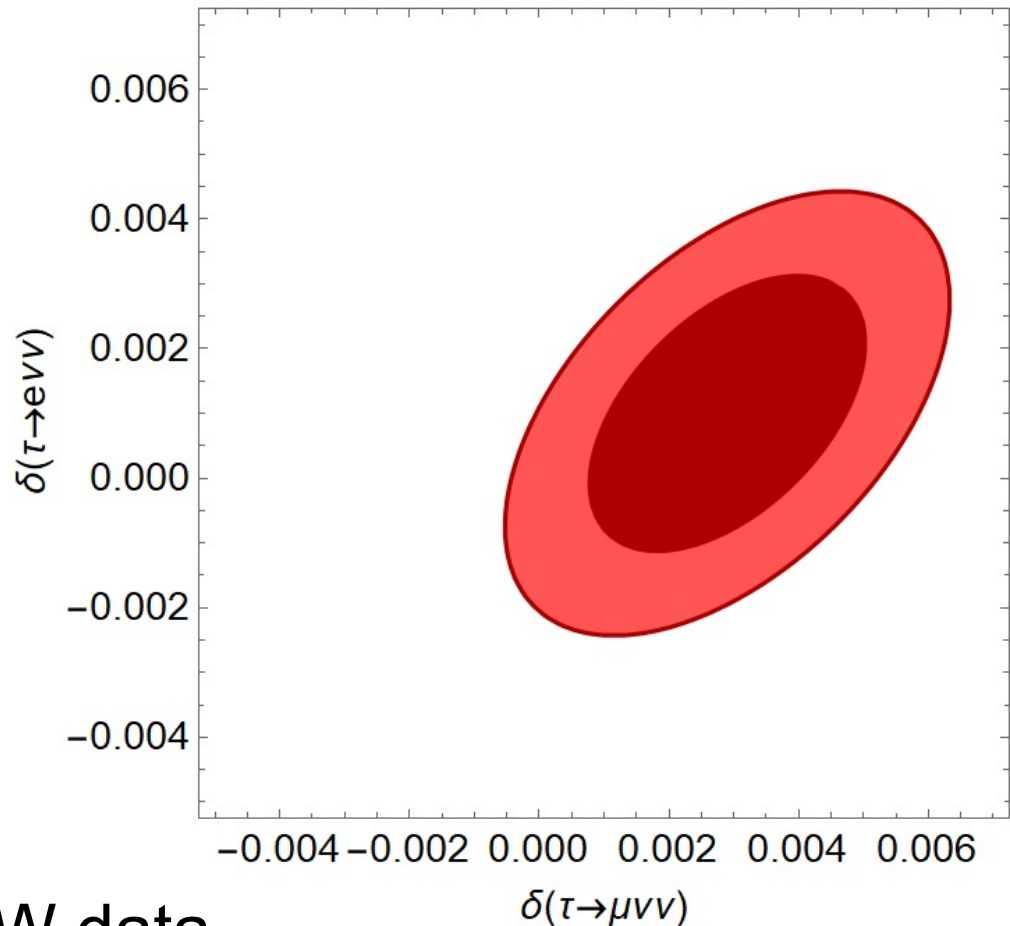
$$\frac{\mathcal{A}_{\text{EXP}}(\tau \rightarrow \mu \nu \bar{\nu})}{\mathcal{A}_{\text{SM}}(\mu \rightarrow e \nu \bar{\nu})} = 1.0029 \pm 0.0014$$

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

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

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

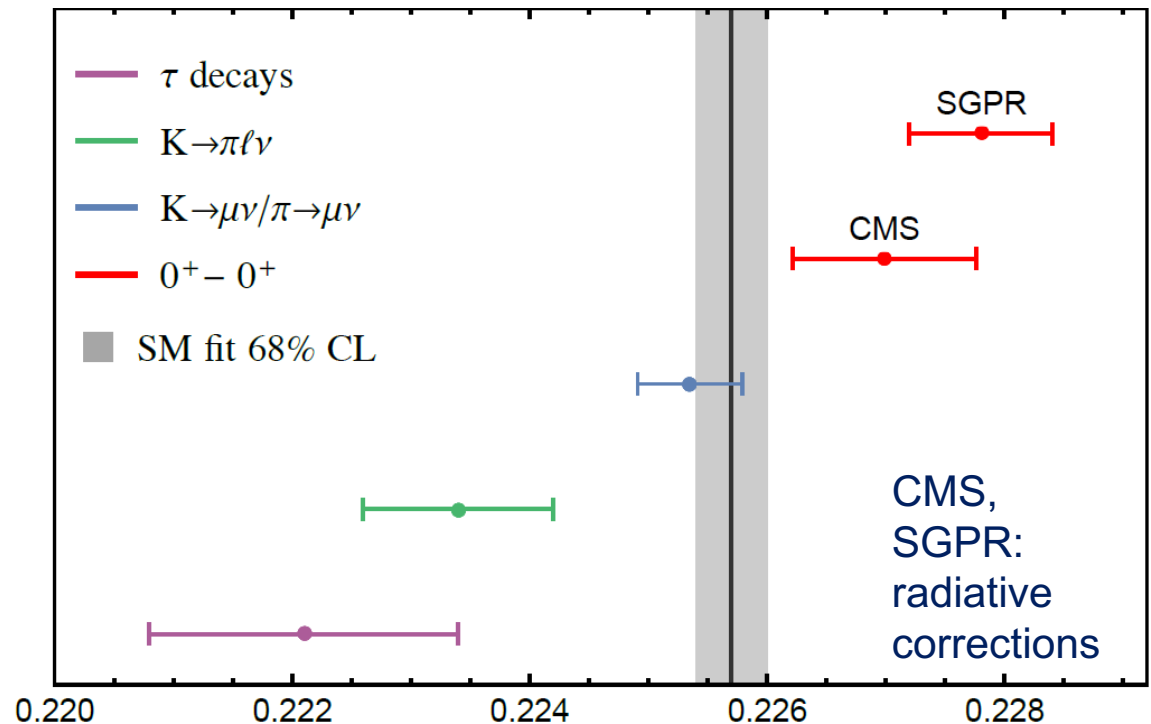
- NP in muon decay constrained from EW data



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

Cabibbo Angle Anomaly (CAA)

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



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

3 σ tension

CAA and LFUV

- Assume modified $W\ell\nu$ couplings

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

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

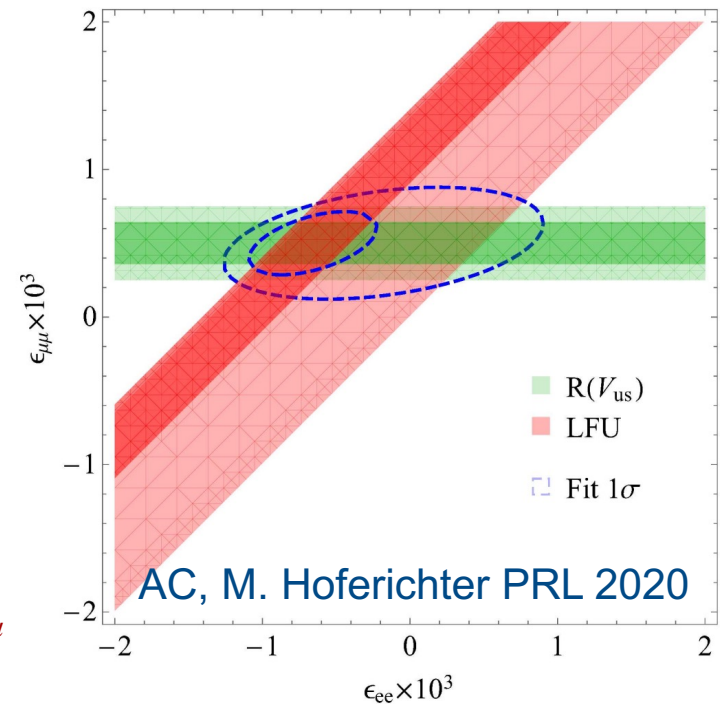
$$1 / \tau_\beta \sim |V_{ud} (1 + \epsilon_{ee})|^2 G_F^2$$

- Fermi constant determined from muon decay

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

- Dependence on ϵ_{ee} cancels

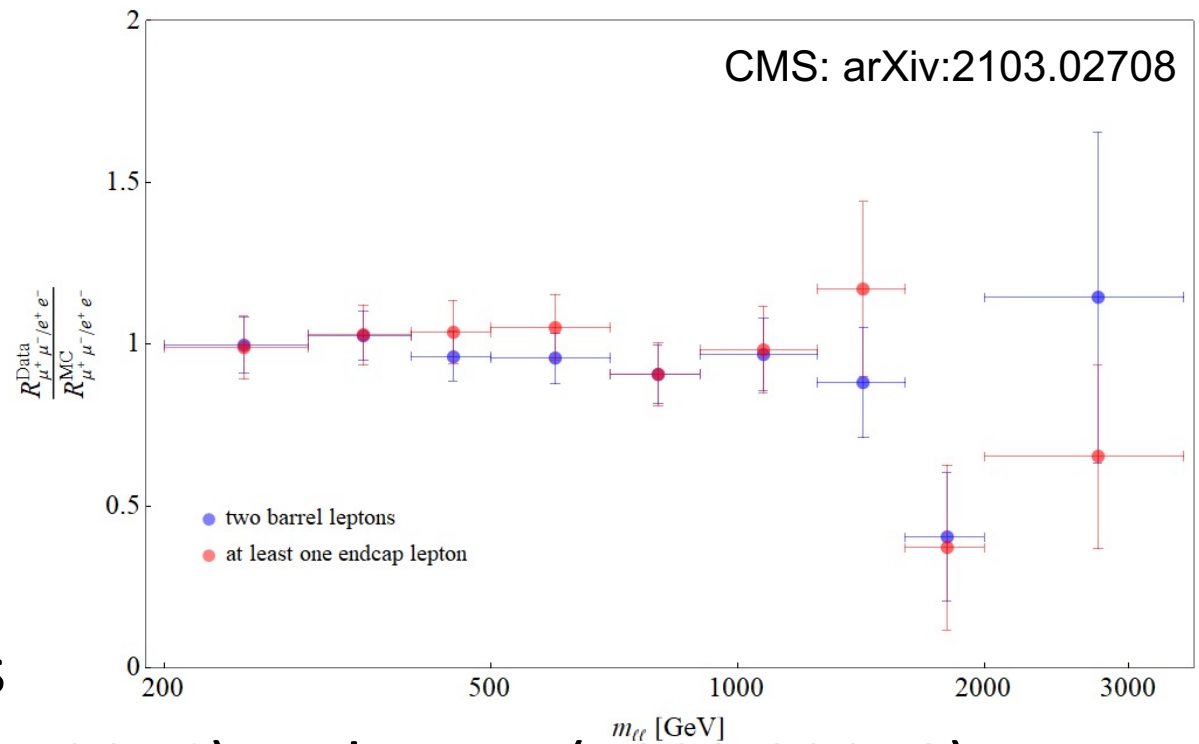
$$R(V_{us}) \equiv \frac{V_{us}^{K_{\mu 2}}}{V_{us}^\beta} \equiv \frac{V_{us}^{K_{\mu 2}}}{\sqrt{1 - (V_{ud}^\beta)^2 - |V_{ub}|^2}} \approx 1 - \left(\frac{V_{ud}}{V_{us}} \right)^2 \epsilon_{\mu\mu}$$



The CAA can be interpreted as a sign of LFUV

Non-Resonant Di-Leptons

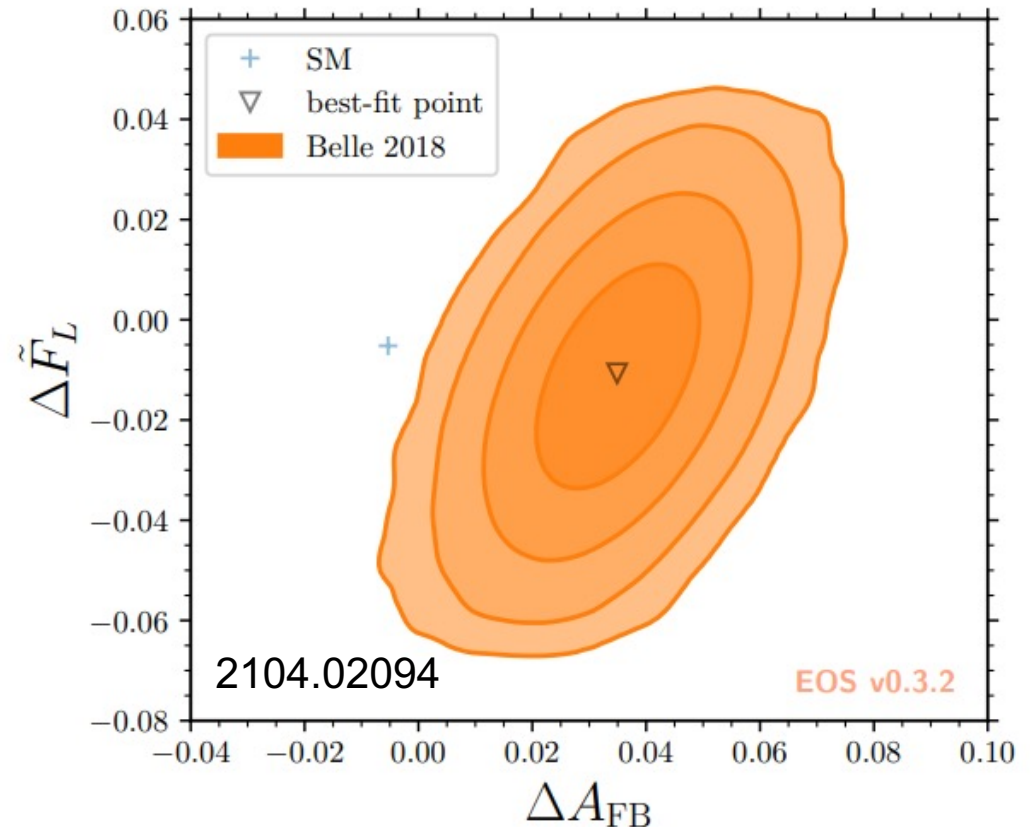
- Excess in di-electrons at $m_{ee} > 1800 \text{ GeV}$
- Observed: 44 events
- Expected 29.2 ± 3.6 events
- Also ATLAS (2006.12946) and HERA (1902.03048) observe slightly more electrons than expected.
- No excess in muon data



$\approx 3\sigma$ hint for LFUV

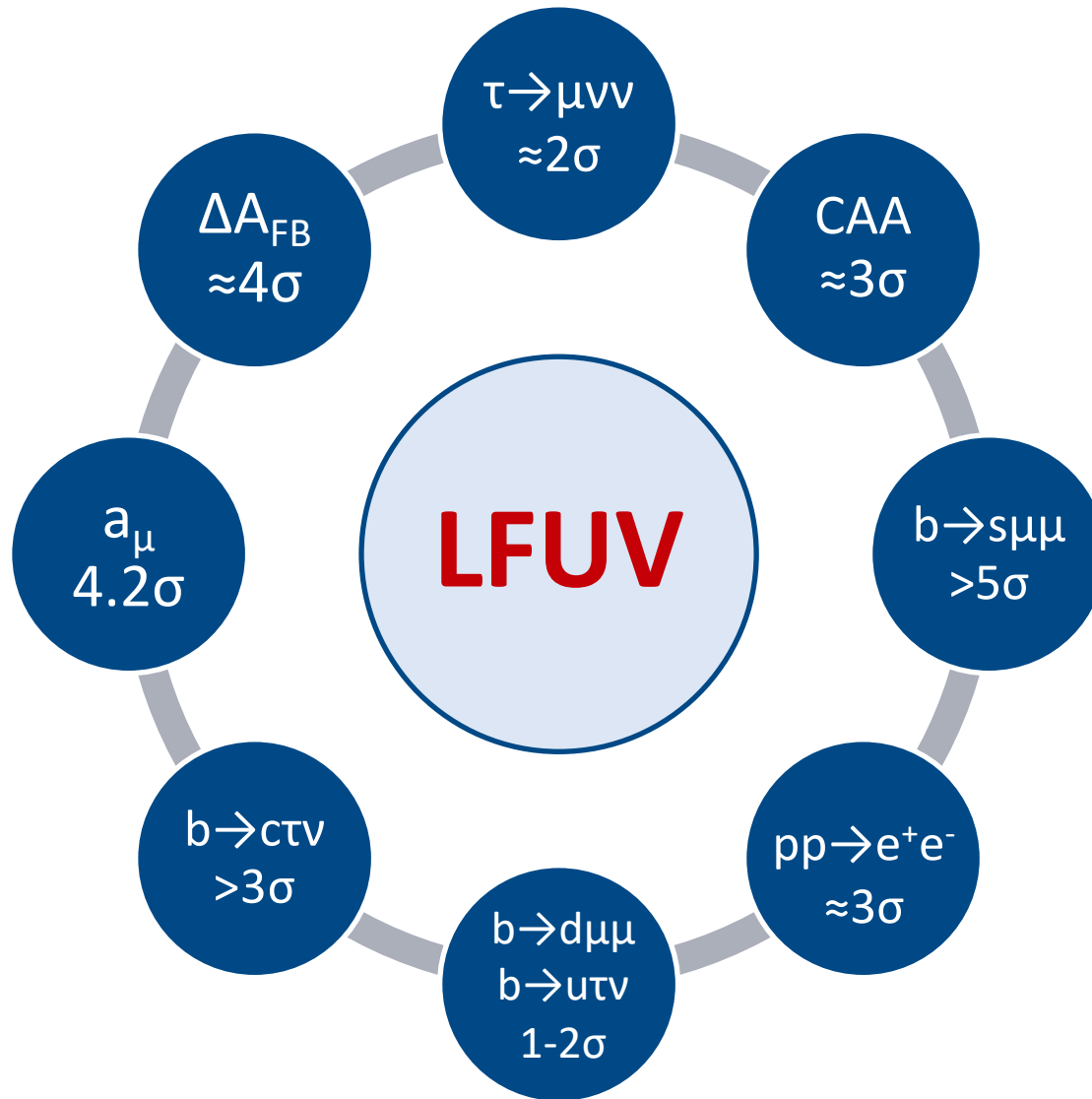
ΔA_{FB} in $b \rightarrow c \mu \nu$

- $\Delta A_{FB} = A_{FB}(b \rightarrow c \mu \nu) - A_{FB}(b \rightarrow c e \nu)$
- 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 $b \rightarrow s \mu \mu$ motivate new physics related to muons



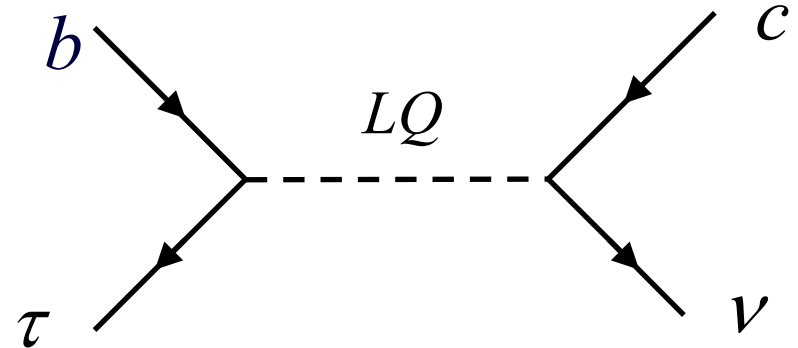
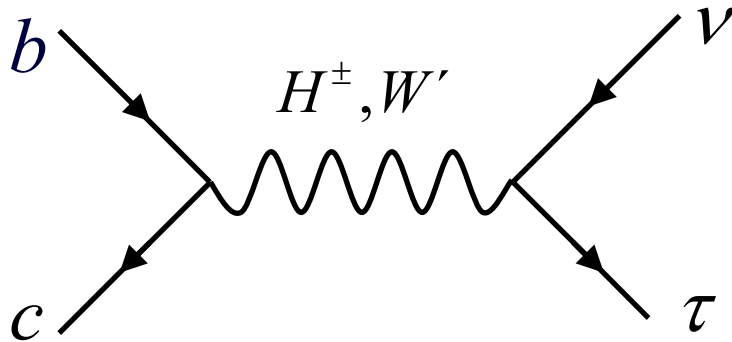
Hint for scalar/tensor NP in $b \rightarrow c \mu \nu$

Accumulated Evidence for LFUV



New Physics
Explanations of the
Anomalies

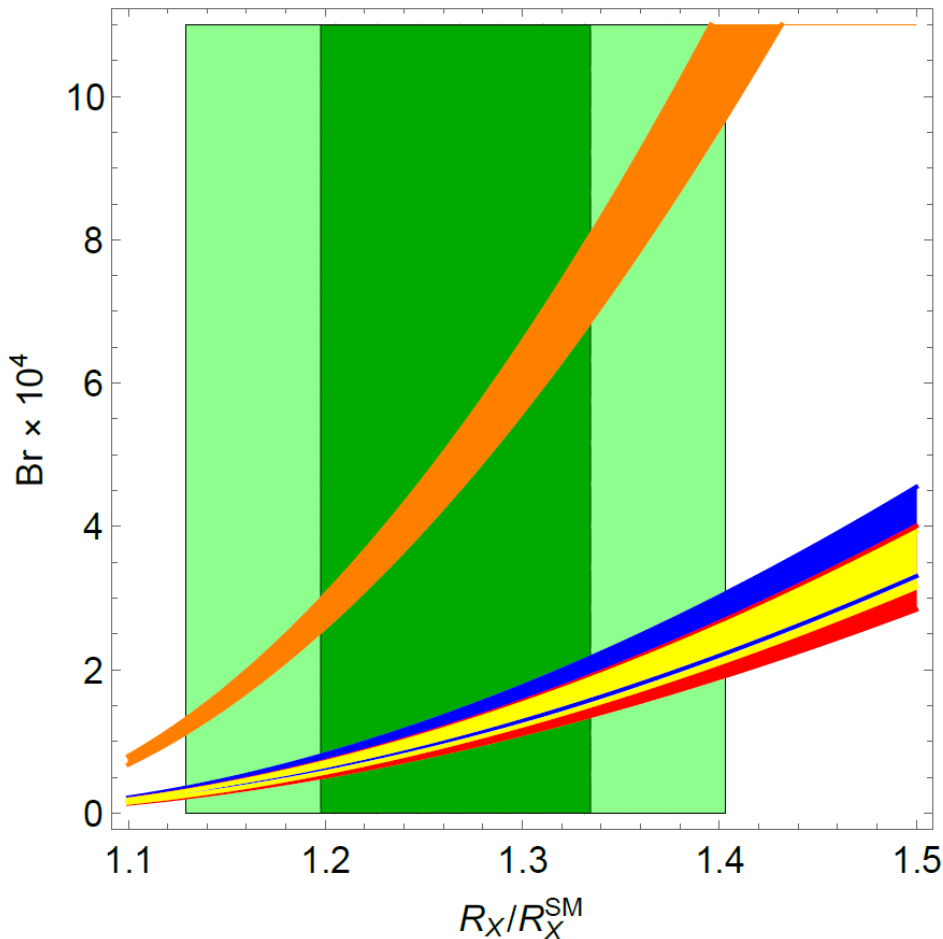
R(D) & R(D*)



- 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

- Large couplings to the second generation
- Cancellation in $b \rightarrow svv$ needed: $C^{(1)}=C^{(3)}$



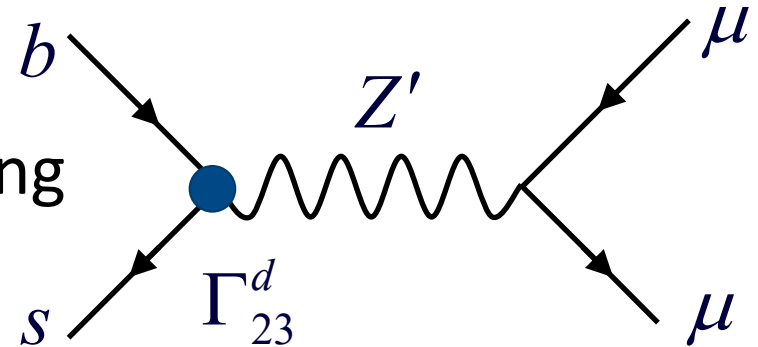
see talk of Jacopo Cerasoli

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

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

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

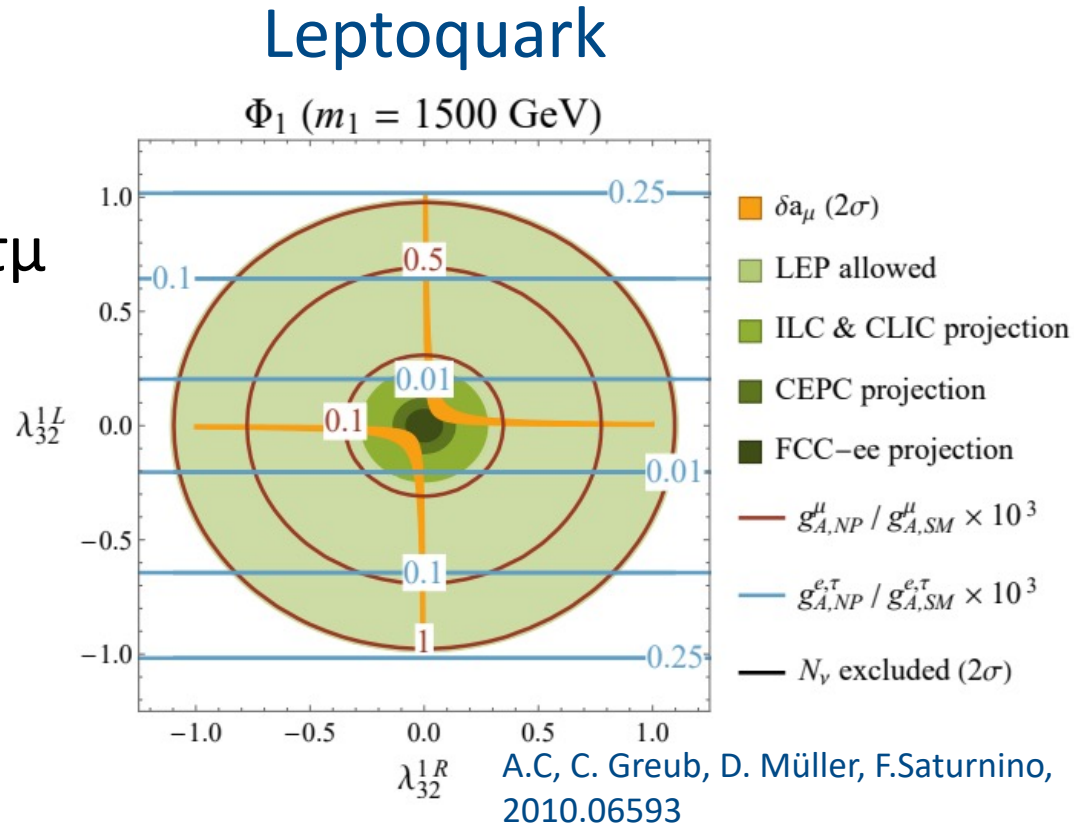
- Z' W. Altmannshofer, S. Gori, M. Pospelov and I. Yavin 1403.1269,
 - Necessary effects in B_s mixing
 - Collider constraints
- Loop contributions
 - Scalars and vector-like fermions B. Gripaios, M. Nardecchia, S. A. Renner, JHEP 2016
 - 2HDM A.C., D. Müller and C. Wiegand, 1903.10440
 - R_2 Leptoquark D. 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

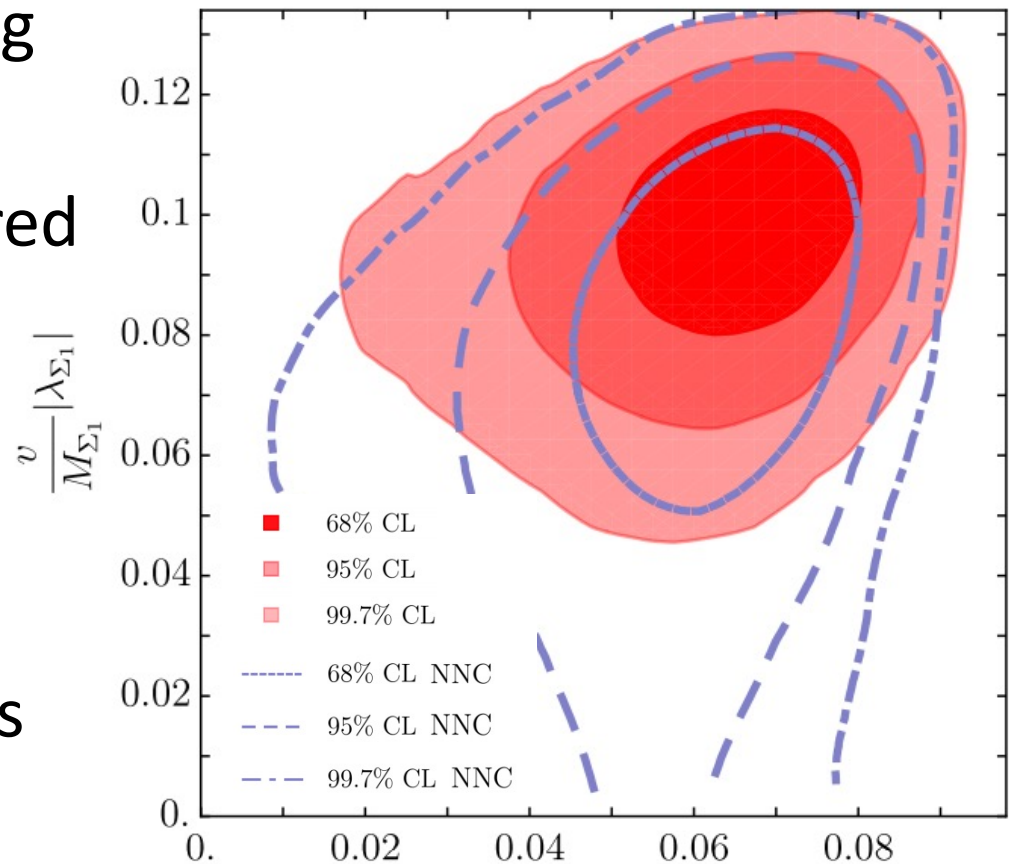
- MSSM $\tan(\beta)$ enhanced slepton loops
- (light) Scalars with enhanced muon couplings
- Z' : Very light or with $\tau\mu$ couplings (m_τ enhancement)
- New scalars and fermions κ/Y_μ
- Leptoquarks m_t enhanced effects



Chiral enhancement or very light particles

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

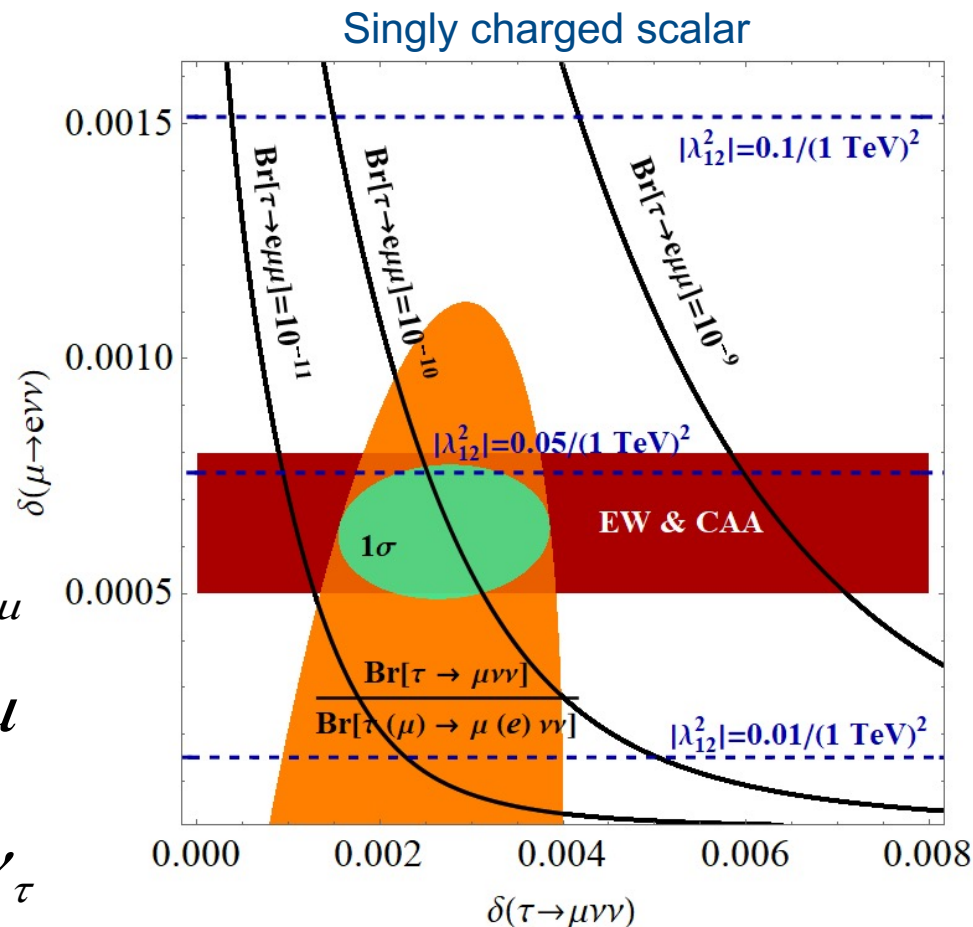
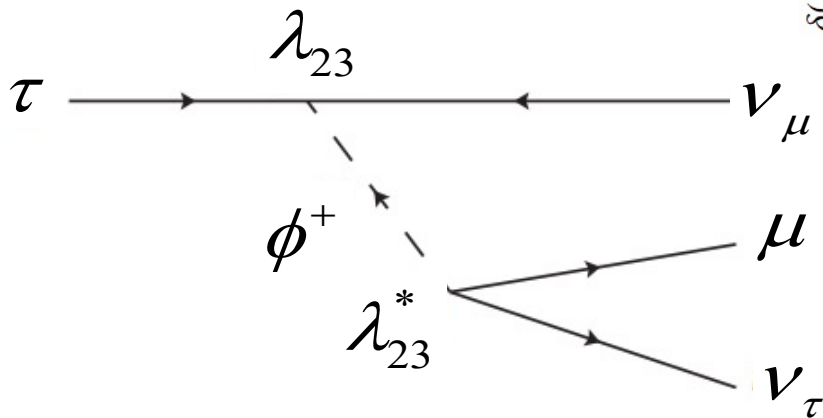


AC, F. Kirk, C. Manzari,
M. Montull JHEP, 2008.01113 $\frac{v}{M_N} |\lambda_N|$

>5 σ improvement over SM hypothesis

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

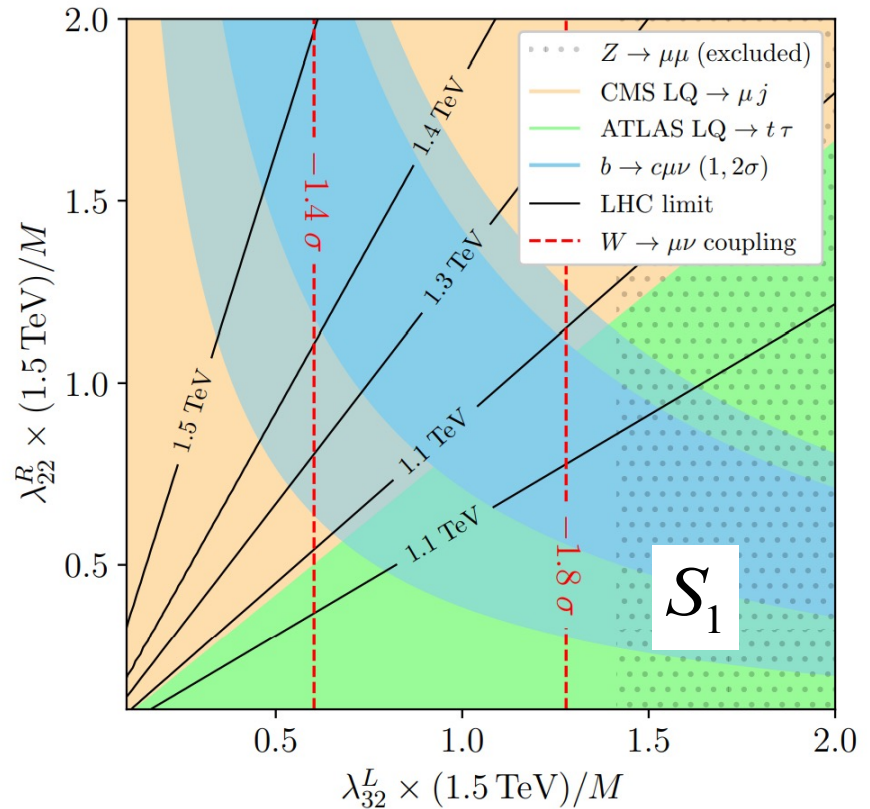
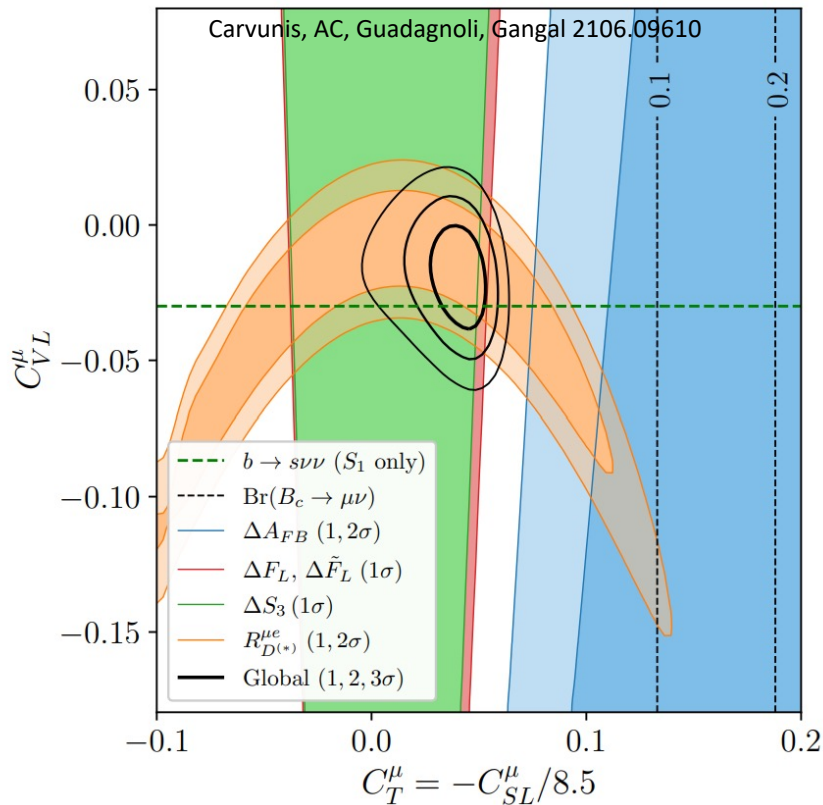
- L_μ - L_τ Z' (box diagrams)
- LFV violating Z'
- Modified $W\ell\nu$ couplings
- W'
- Singly charged scalar



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

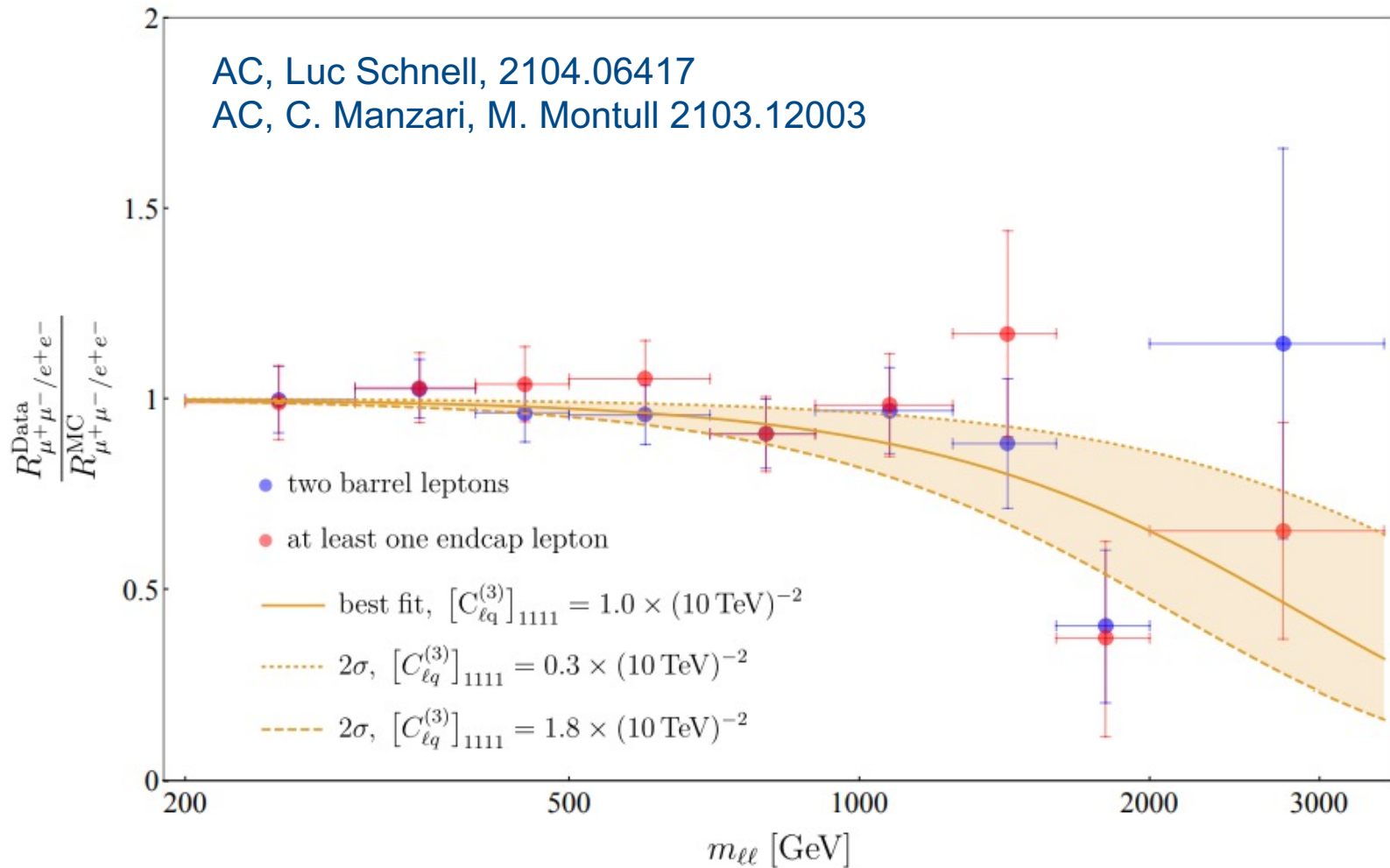
Scenarios can be distinguished by $\pi \rightarrow \mu \nu / \pi \rightarrow e \nu$

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



Hint for scalar leptoquarks

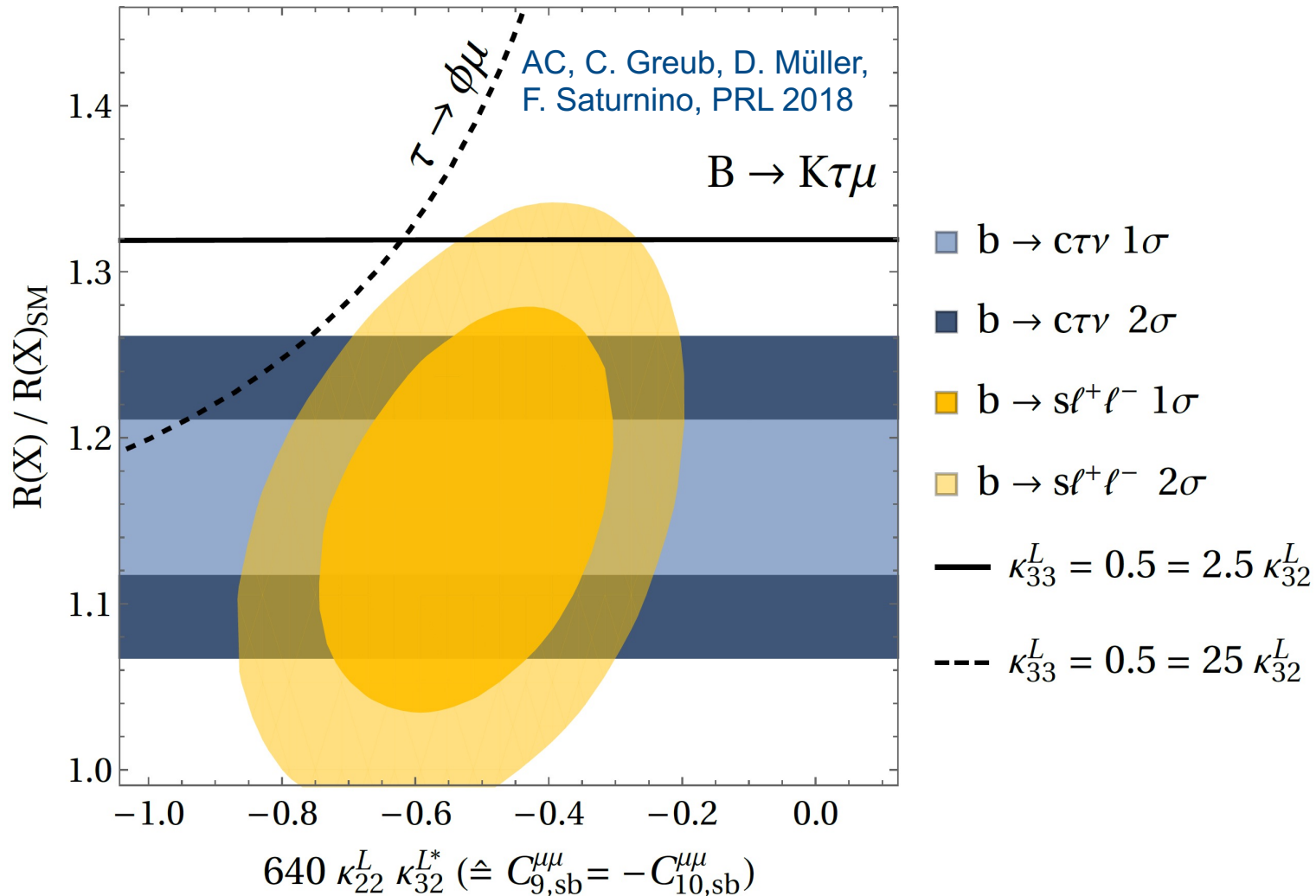
Non-Resonant Di-Leptons



Constructive heavy NP in electrons (e.g. LQs)

Common explanations

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



Pati-Salam LQ can explain the flavour anomalies

S1-S3 LQ model: $R(D^{(*)})$, $b \rightarrow sll$ and a_μ

■ 4 benchmark points

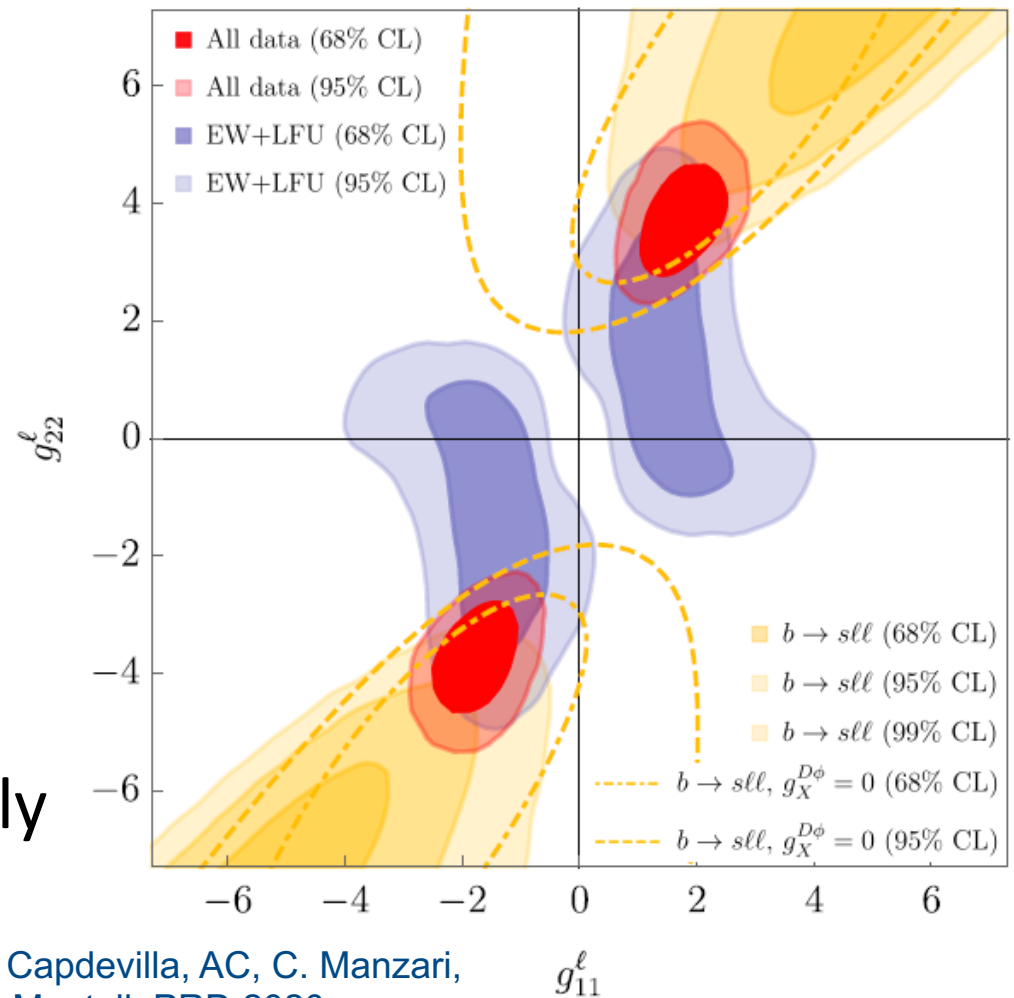
AC, D. Mueller, F. Saturnino
arxiv:1912.04224

	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
	$C_9^{\mu\mu} = -C_{10}^{\mu\mu}$	$C_9^{\ell\ell}$	$\frac{R(D)}{R(D)_{SM}}$	$\frac{R(D^*)}{R(D^*)_{SM}}$	$\frac{B_s \rightarrow \tau\tau}{B_s \rightarrow \tau\tau _{SM}}$	$\tau \rightarrow \mu\gamma$ $\times 10^8$	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	
	$C_{SL}^{\tau\tau} = -4C_{TL}^{\tau\tau}$	$C_{VL}^{\tau\tau}$	$R_{\nu\nu}^{K^{(*)}}$	$\frac{\Delta m_{B_s}^{NP}}{\Delta m_{B_s}^{SM}}$	$B \rightarrow K\tau\mu$ $\times 10^5$	$\tau \rightarrow \phi\mu$ $\times 10^8$	$\tau \rightarrow \mu ee$ $\times 10^{11}$	$ \Lambda_{33}^{LQ}(0) $ $\times 10^5$	$\frac{\Delta_{33}^L(m_Z^2)}{\Lambda_{SM}^{LL} \times 10^{-5}}$	
● 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

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

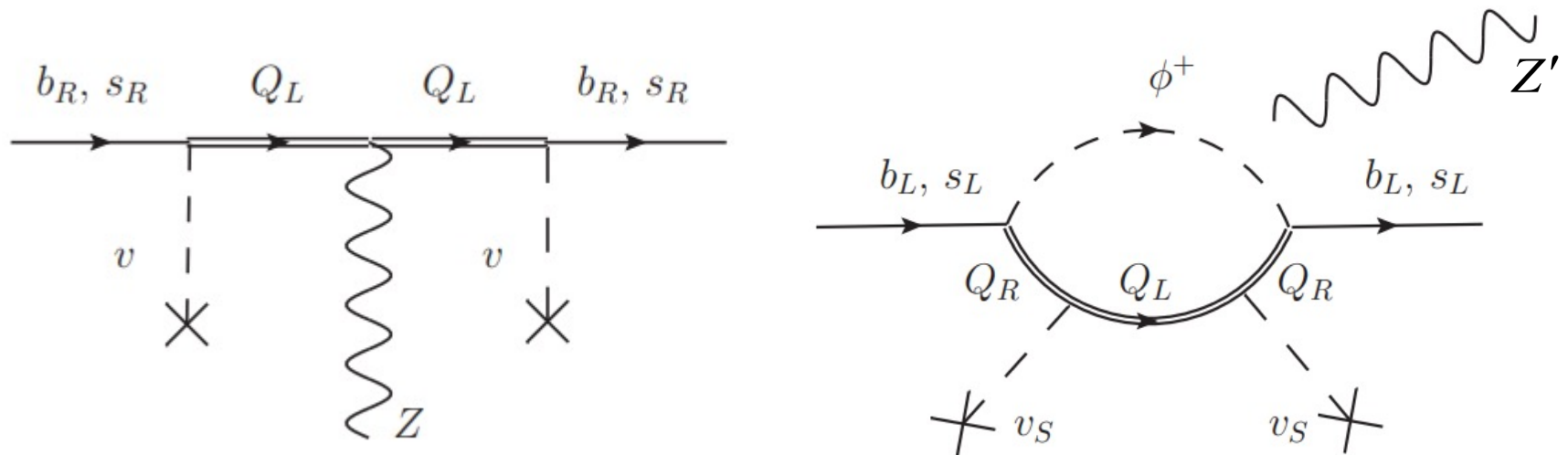


B. Capdevilla, AC, C. Manzari,
M. Montull, PRD 2020

Common explanation possible

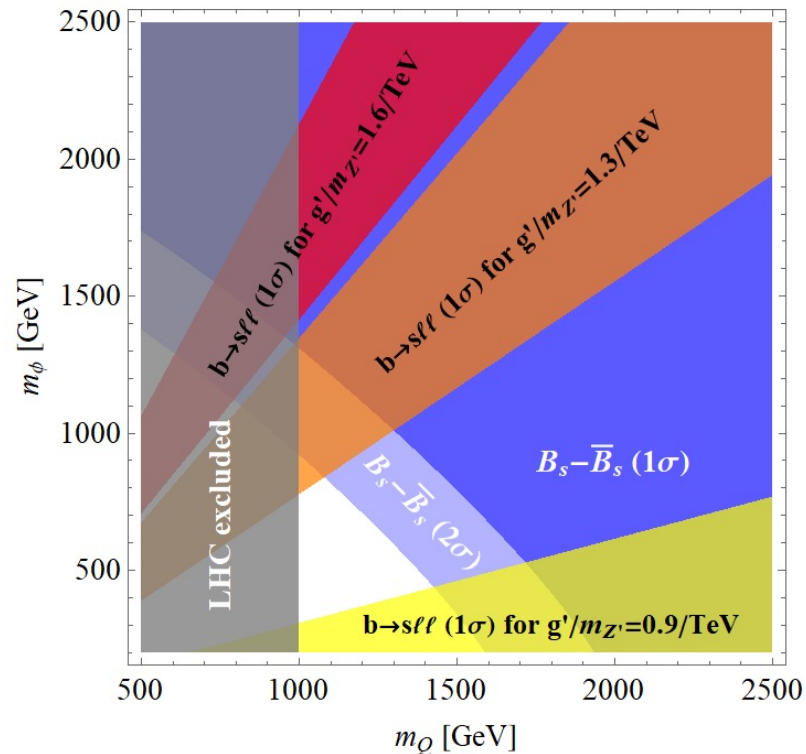
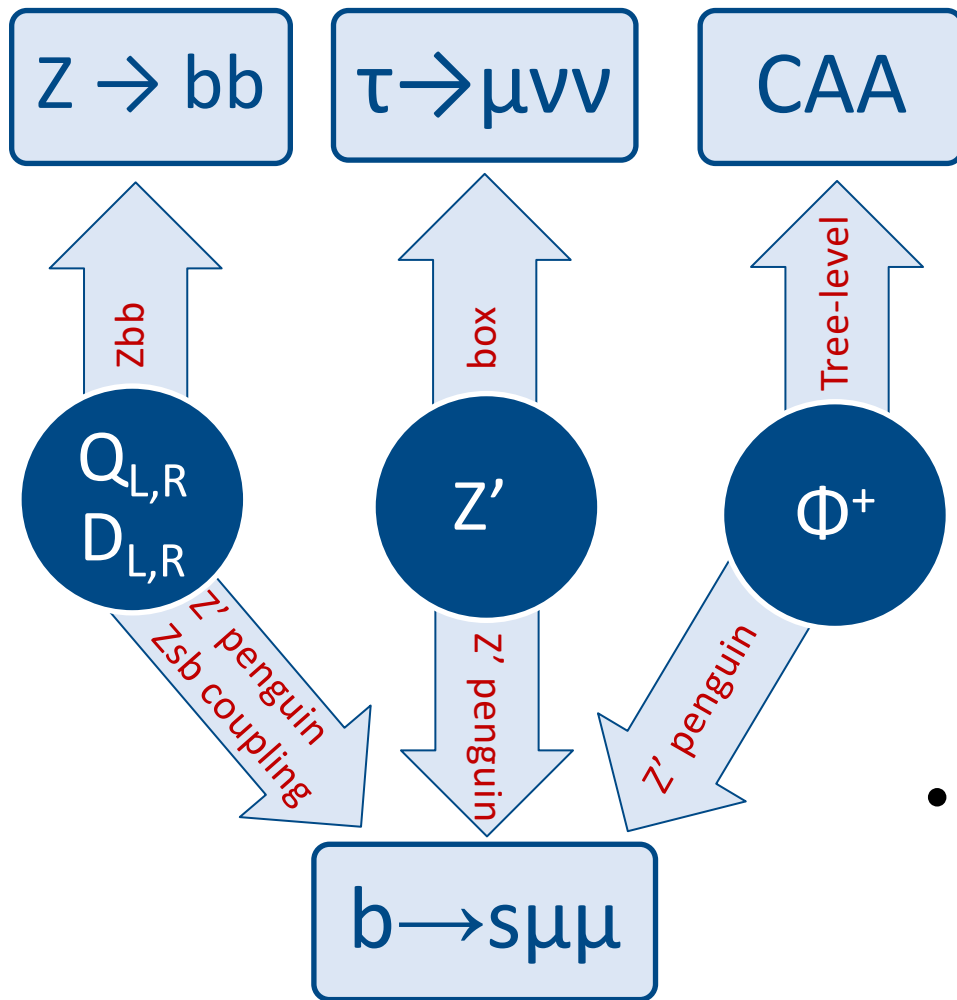
Model for $b \rightarrow s \ell \ell$, CAA, $Z \rightarrow b \bar{b}$ and $\tau \rightarrow \mu \nu$

	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 $Z' s \bar{b}$

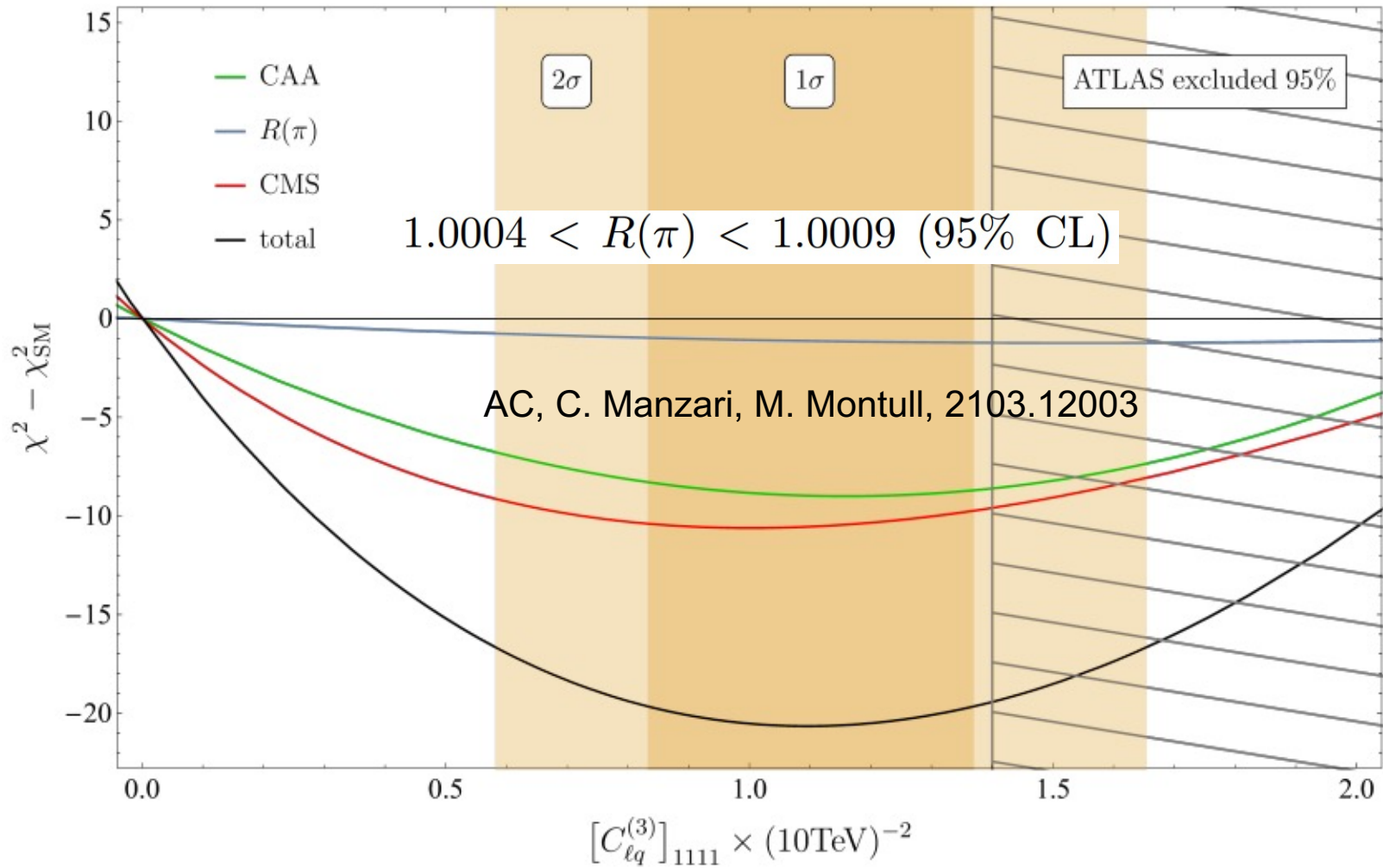
Model for $b \rightarrow s \ell \ell$, CAA, $Z \rightarrow bb$ and $\tau \rightarrow \mu \nu \nu$



- Z' penguin + modified 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

