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New Physics Models

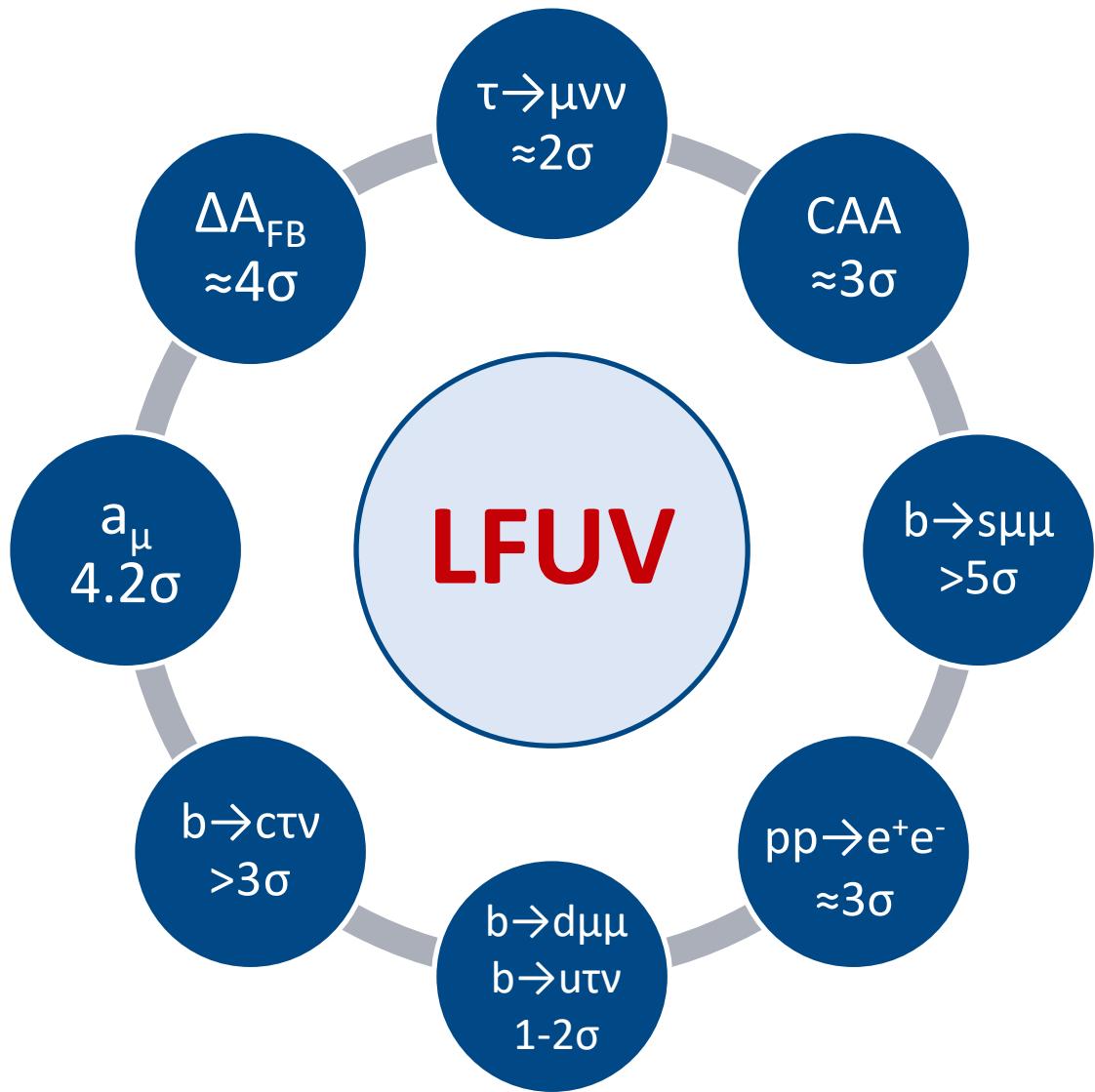
LIO international conference on Future colliders and the origin of
mass 21-25 June 2021



Outline

- Introduction:
Anomalies pointing towards Lepton Flavour Universality Violation
- Explaining the Flavour Anomalies
- Prospects for future colliders

Flavour Anomalies



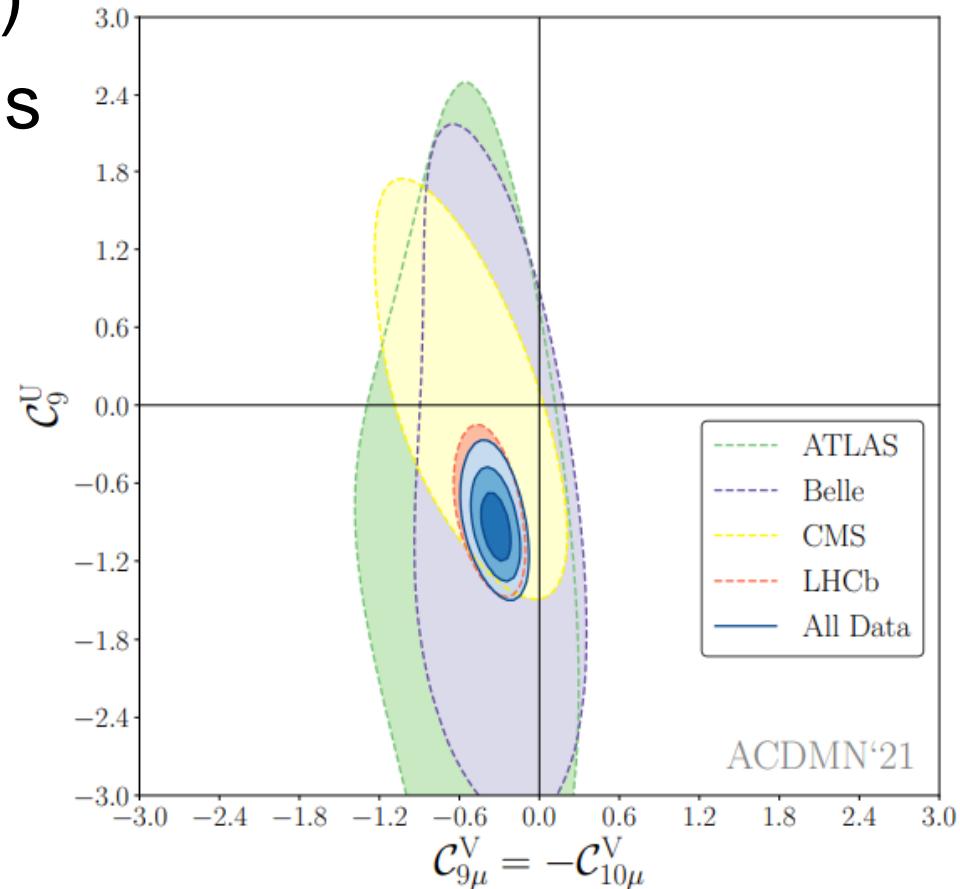
Global Fit to $b \rightarrow s\mu^+\mu^-$ Data

See talk of Nazila

- 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

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

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

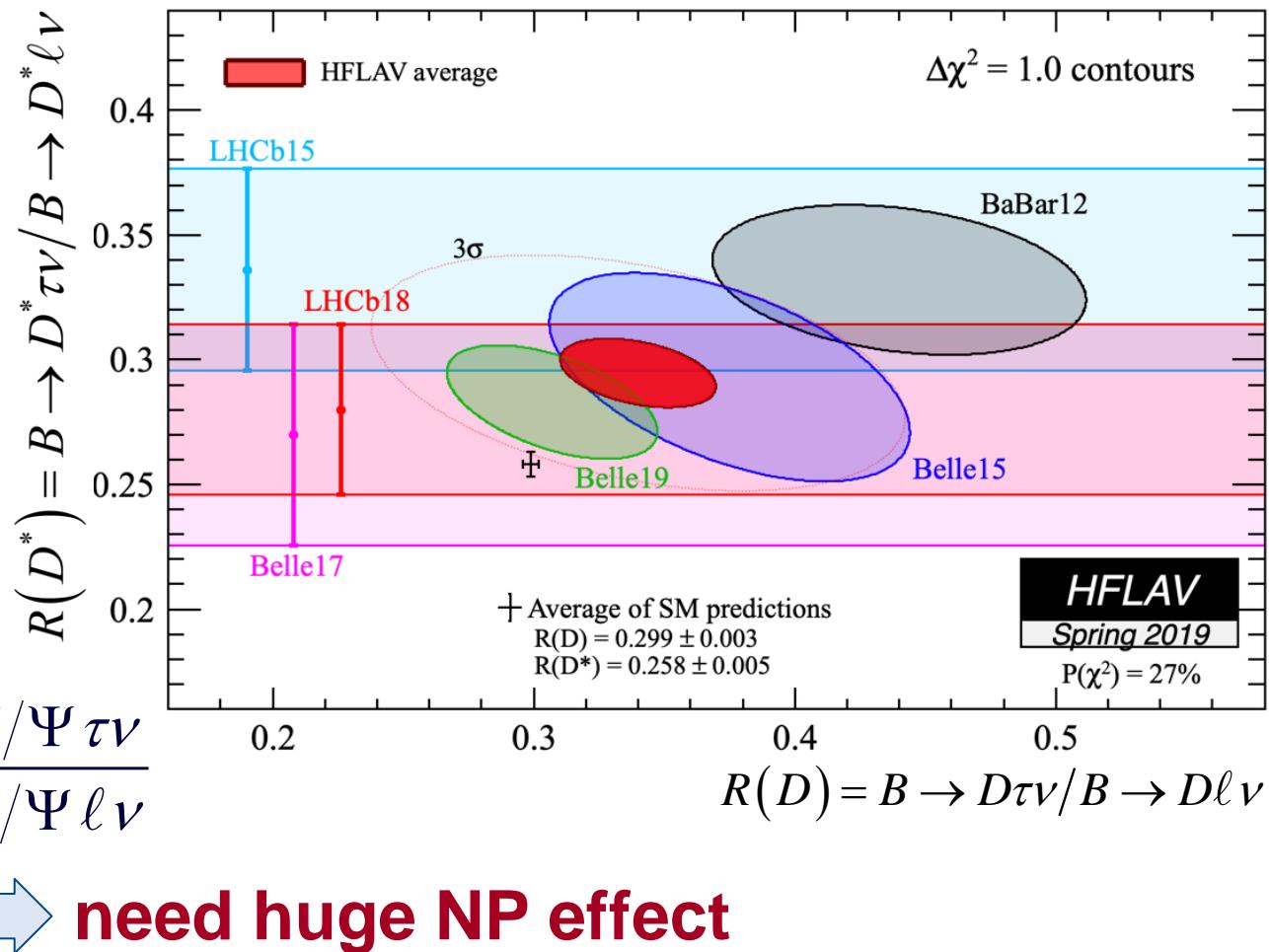


Fit is $>7 \sigma$ better than the SM

b \rightarrow c $\tau\nu$ Transitions

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

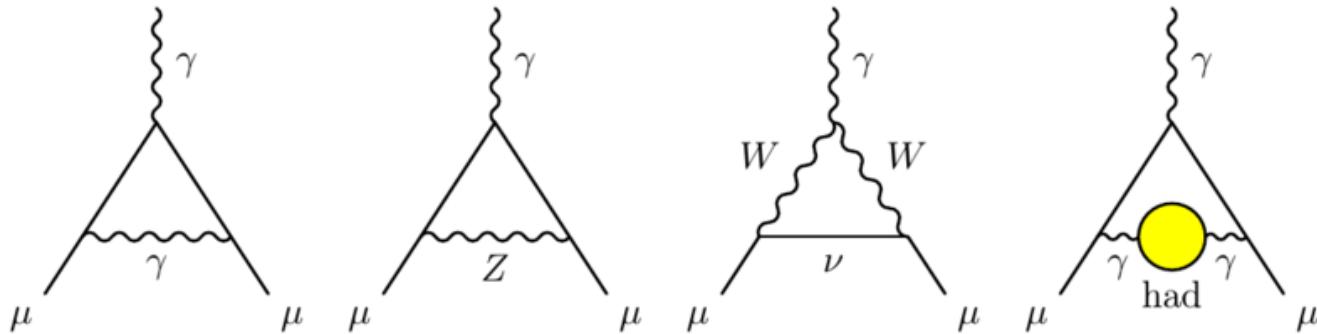
$$R(J/\Psi) = \frac{B_c \rightarrow J/\Psi \tau\nu}{B_c \rightarrow J/\Psi \ell\nu}$$



- Tree-level **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 $m_\mu \rightarrow 0$ **measure of LFUV**

4.2 σ deviation from the SM prediction

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

- Ratios of leptonic tau decays

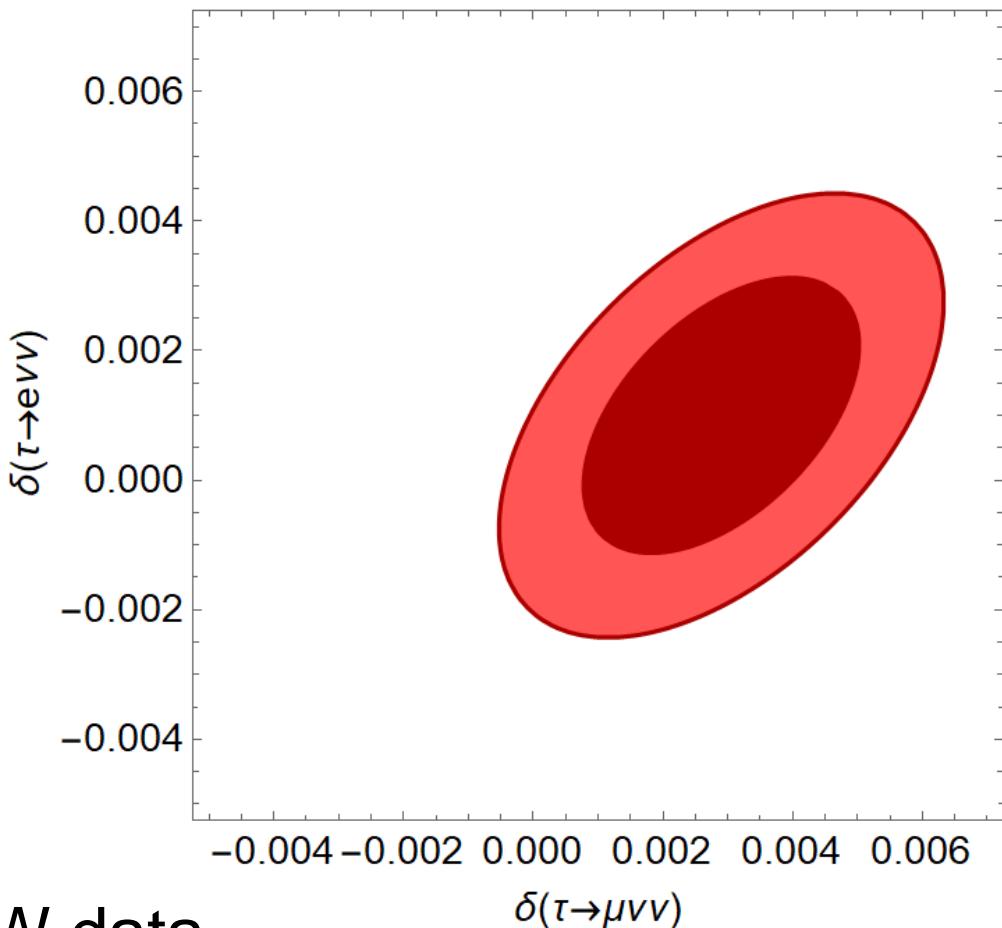
$$\frac{\mathcal{A}_{\text{EXP}}(\tau \rightarrow \mu \nu \bar{\nu})}{\mathcal{A}_{\text{SM}}(\mu \rightarrow e \nu \bar{\nu})} = 1.0029 \pm 0.0014$$

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

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

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

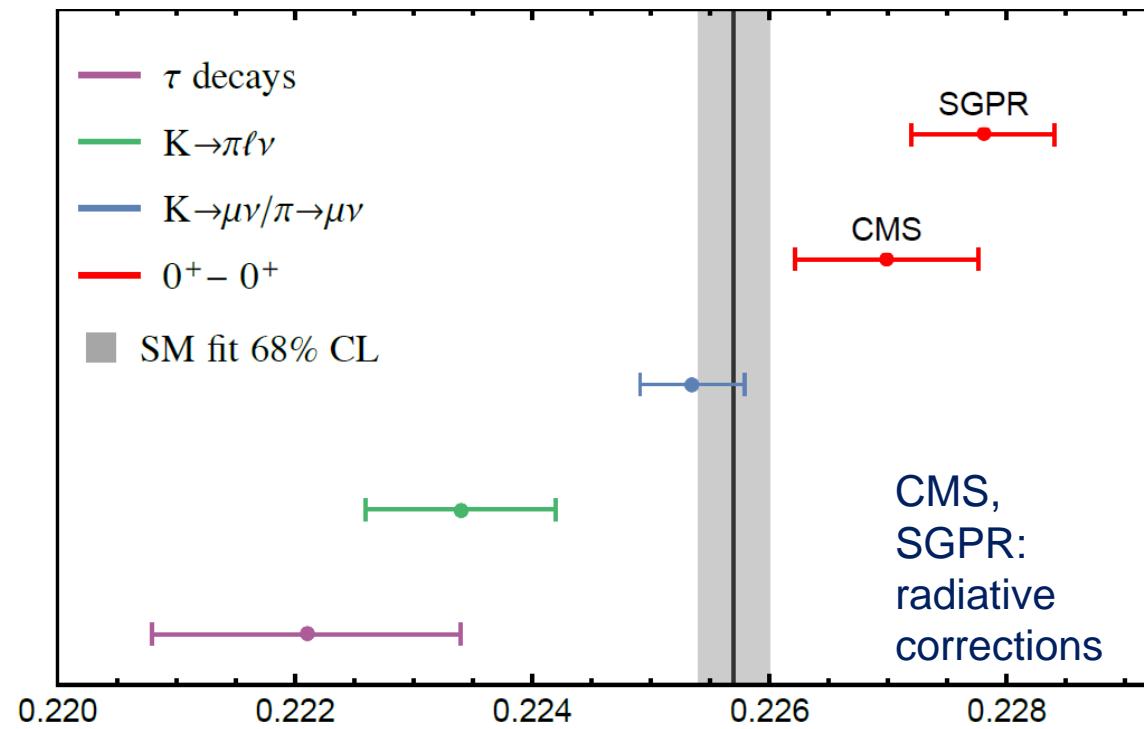
- NP in muon decay constrained from EW data



≈2σ 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 $W\ell v$ couplings

$$L = i g_2 / \sqrt{2} \nu_f \gamma^\mu P_L 1_i W_\mu (\delta_{fi} + \varepsilon_{fi})$$

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

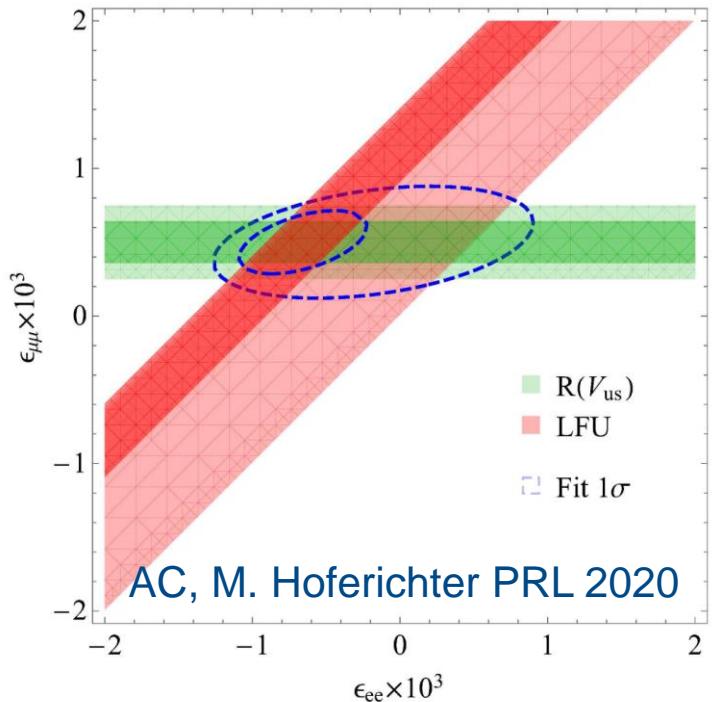
$$1/\tau_\beta \sim |V_{ud}(1 + \varepsilon_{ee})|^2 G_F^2$$

- Fermi constant determined from muon decay

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

- Dependence on ε_{ee} cancels

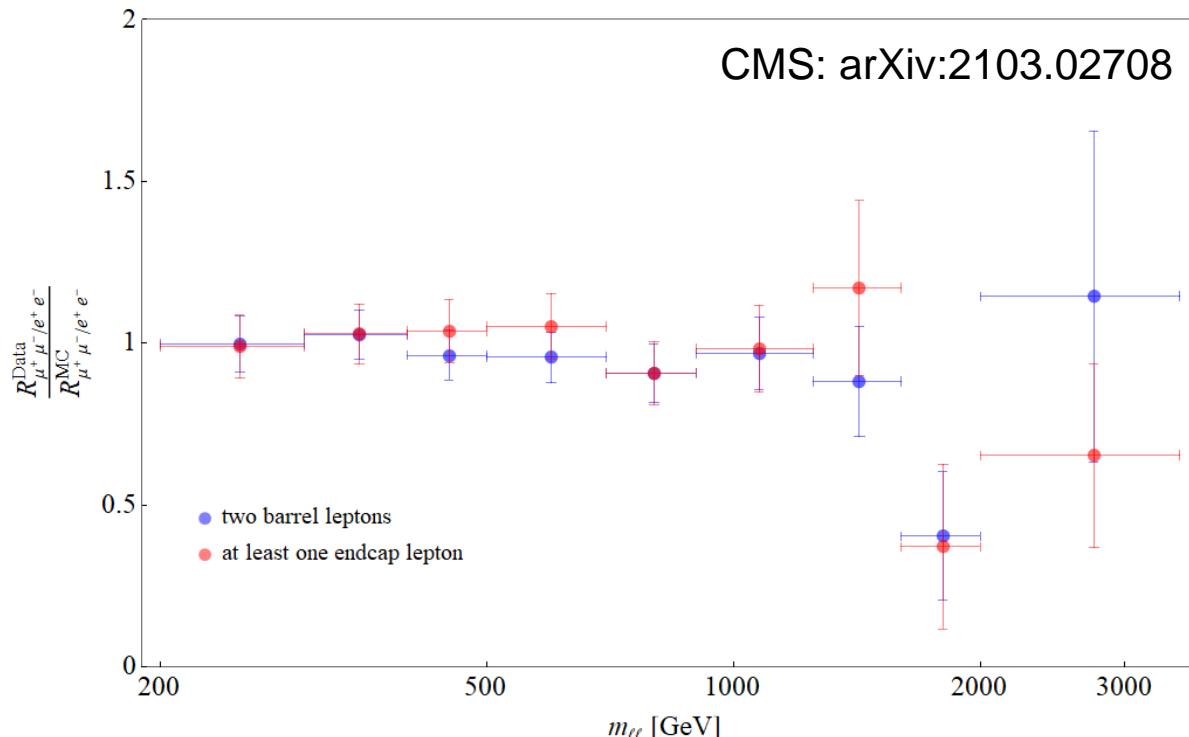
$$R(V_{us}) \equiv \frac{V_{us}^{K_{\mu 2}}}{V_{us}^\beta} \equiv \frac{V_{us}^{K_{\mu 2}}}{\sqrt{1 - (V_{ud}^\beta)^2 - |V_{ub}|^2}} \approx 1 - \left(\frac{V_{ud}}{V_{us}} \right)^2 \varepsilon_{\mu\mu}$$



The CAA can be interpreted as a sign of LFUV

Non-Resonant Di-Leptons

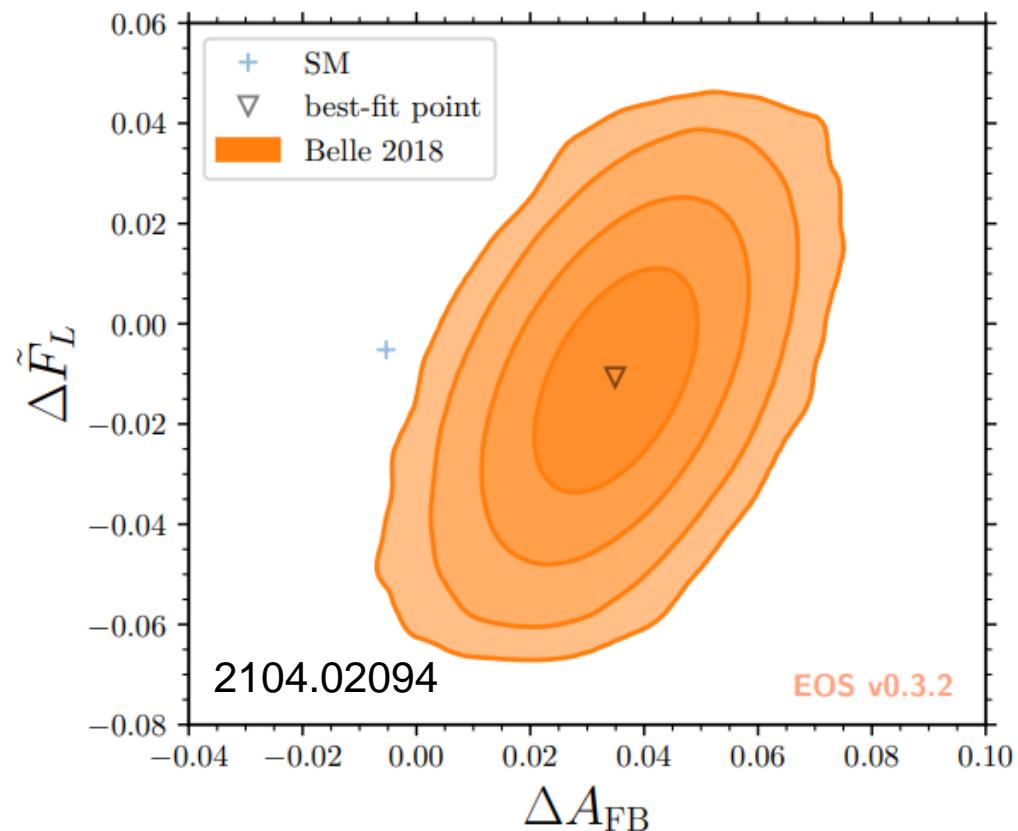
- Excess in di-electrons at $m_{ee} > 1800\text{GeV}$
- Observed: 44 events
- Expected 29.2 ± 3.6 events
- Also ATLAS (2006.12946) and HERA (1902.03048) observe slightly more electrons than expected.
- No excess in muon data



≈ 3σ hint for LFUV

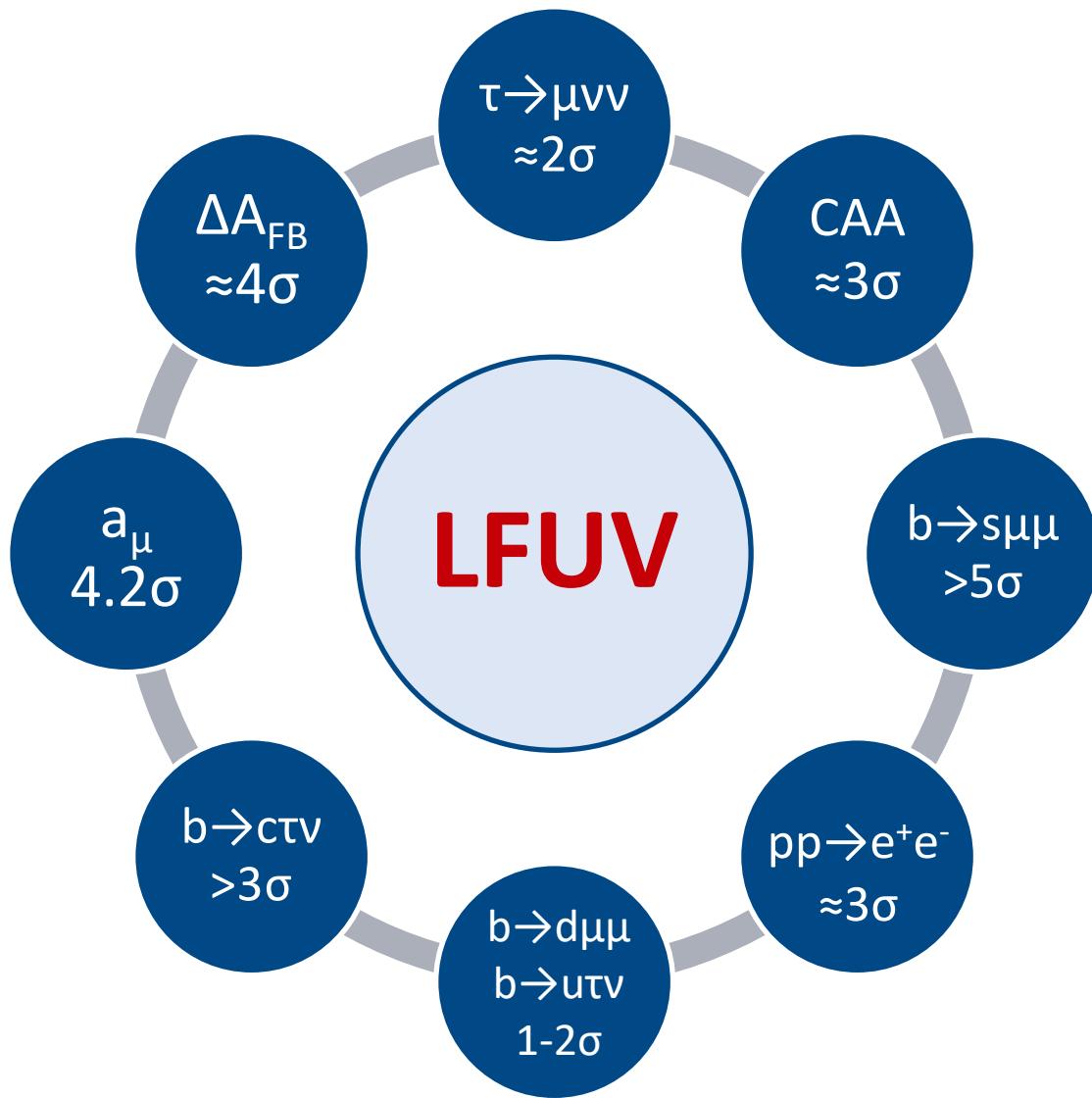
ΔA_{FB} in $b \rightarrow c\mu\nu$

- $\Delta A_{FB} = A_{FB}(b \rightarrow c\mu\nu) - A_{FB}(b \rightarrow cev)$
- 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



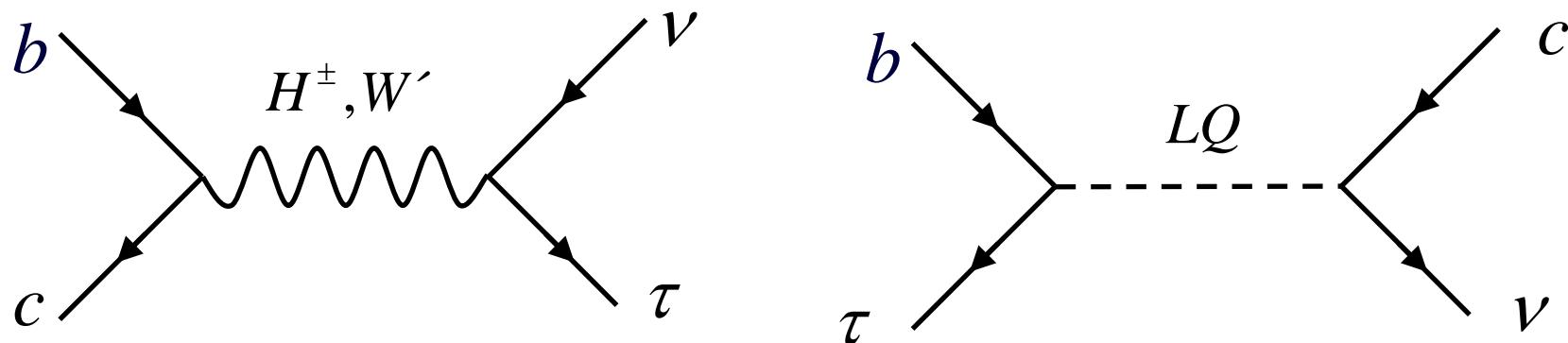
Hint for scalar/tensor NP in $b \rightarrow c\mu\nu$

Accumulated Evidence for LFUV



New Physics Explanations of the Anomalies

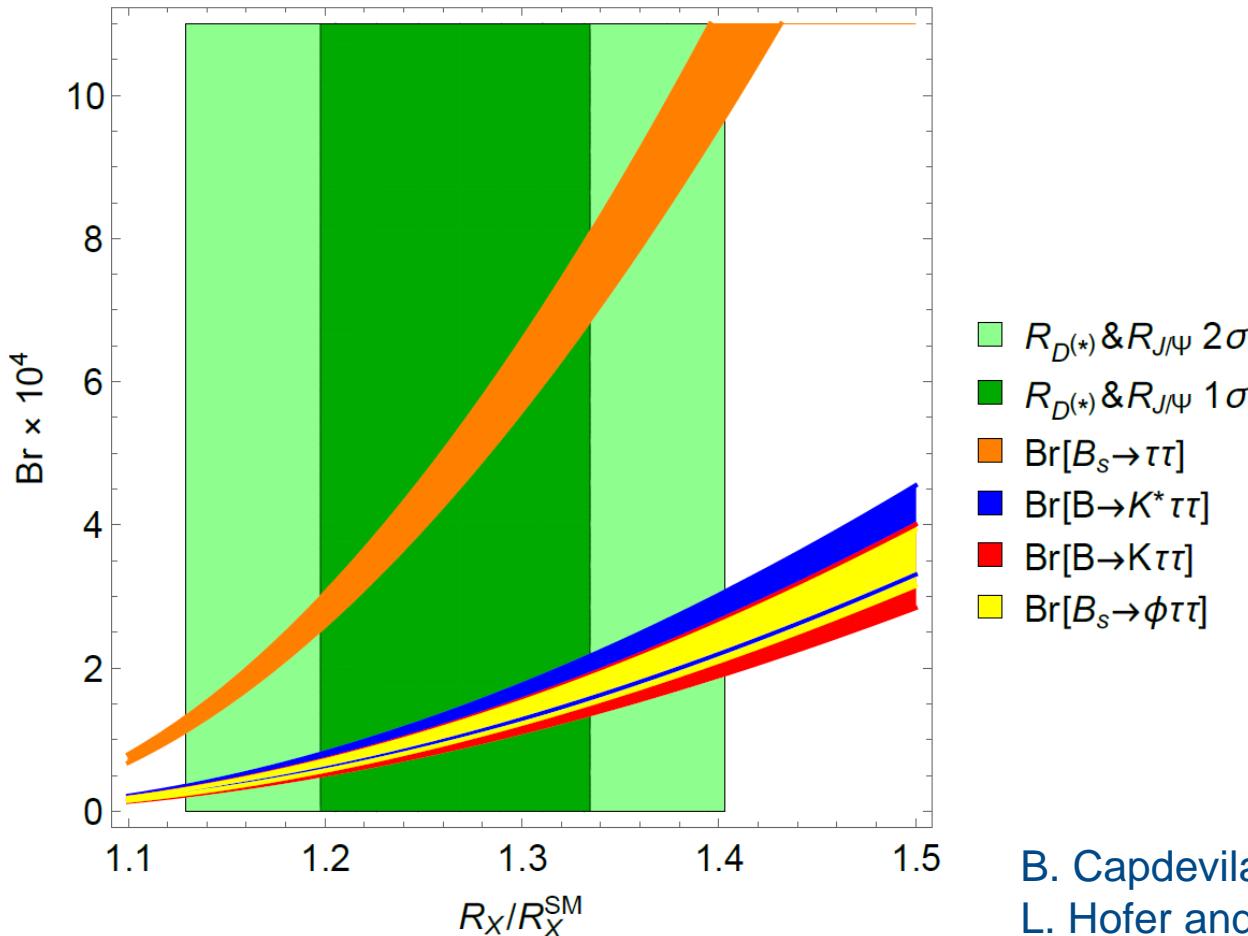
$R(D)$ & $R(D^*)$



- 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
- Cancelation in $b \rightarrow s\tau\tau$ needed: $C^{(1)}=C^{(3)}$



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

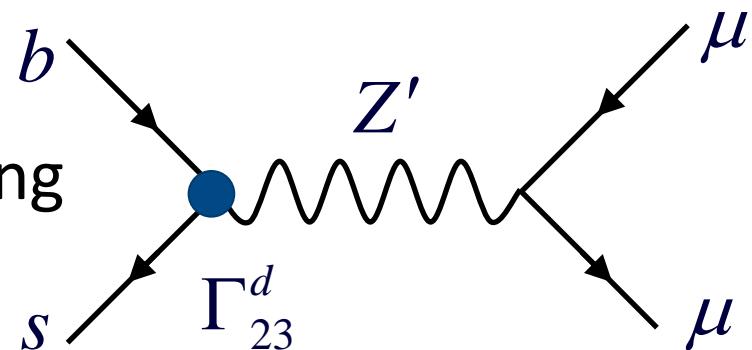
B. Capdevila, A.C., S. Descotes-Genon,
L. Hofer and J. Matias, PRL.120.181802

$b \rightarrow s \mu^+ \mu^-$ 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. Bećirević and O. Sumensari, 1704.05835

- Z' coupling to tops J. Kamenik, Y. Soreq and J. Zupan, 1704.06005

■ Leptoquarks

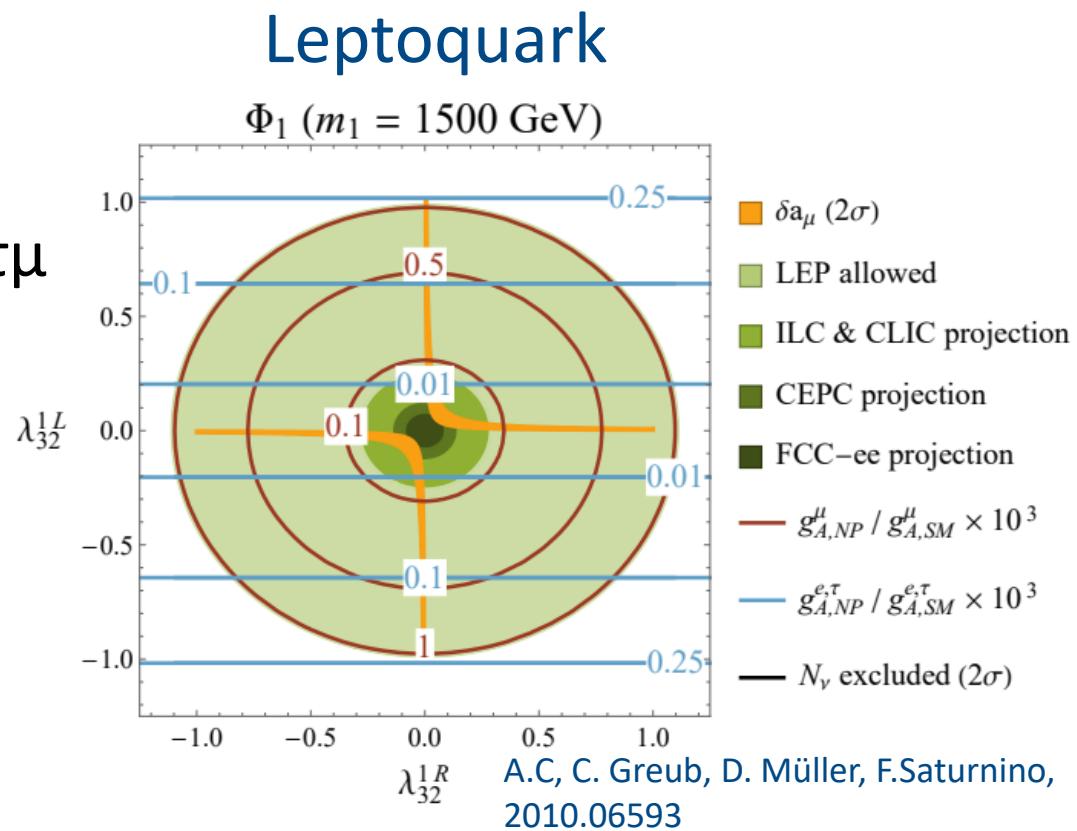
G. Hiller and M. Schmaltz, 1408.1627

D. Bećirević, S. Fajfer and N. Košnik, 1503.09024,

Small effect needed; many possibilities

a_μ explanations

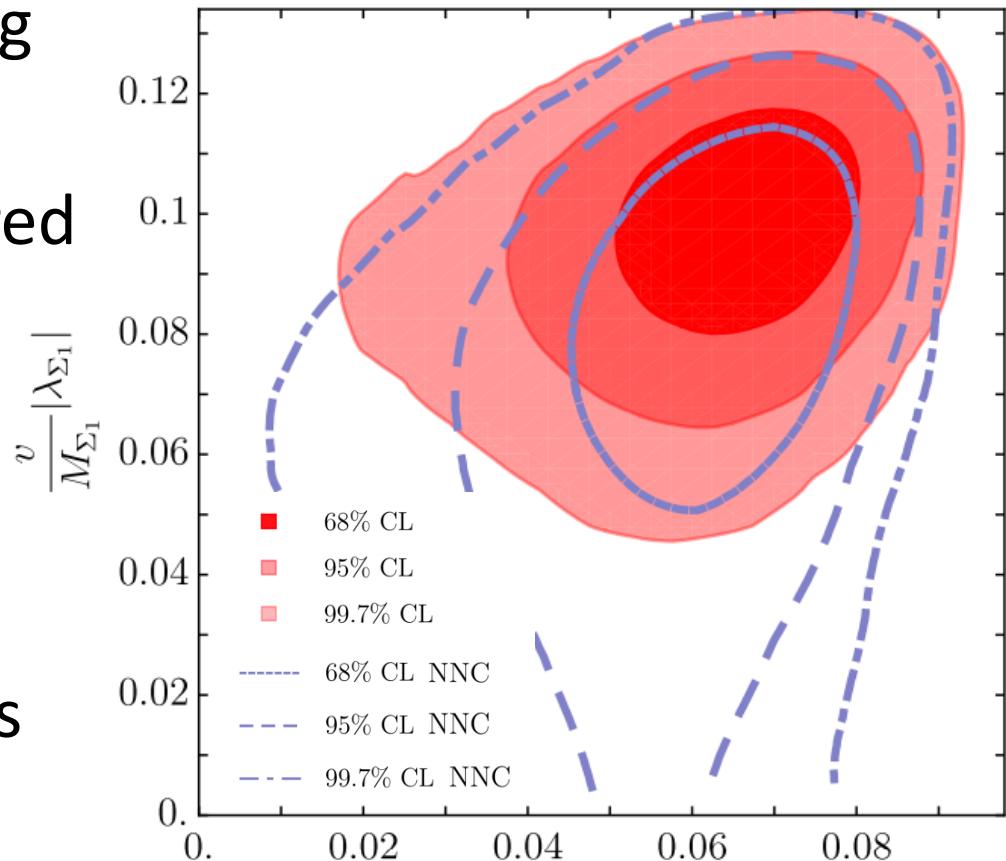
- MSSM $\tan(\beta)$ enhanced slepton loops
- (light) Scalars with enhanced muon couplings
- Z' : Very light or with $\tau\mu$ couplings (m_τ enhancement)
- New scalars and fermions κ/Y_μ
- Leptoquarks m_t enhanced effects



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

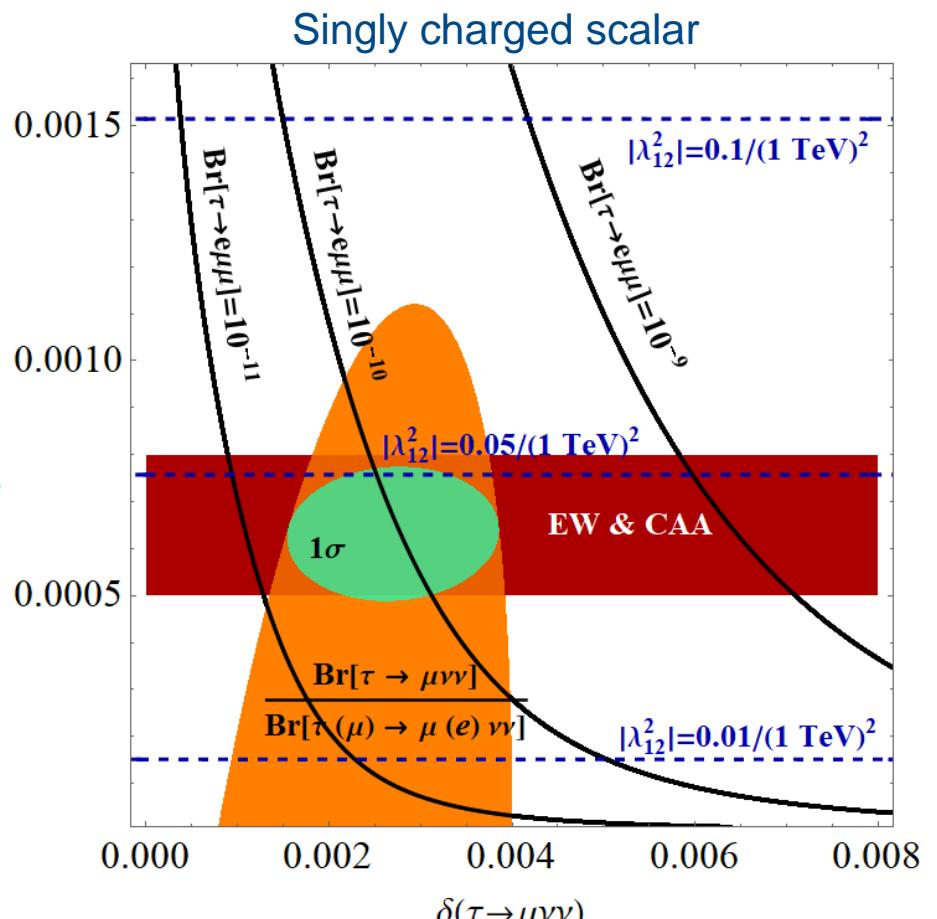
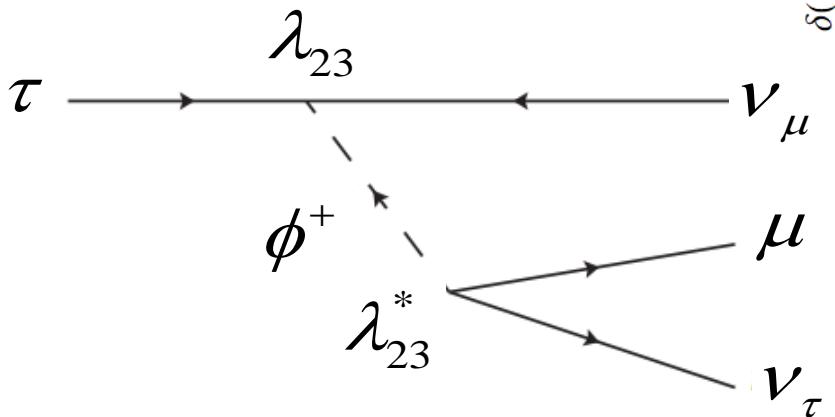


AC, F. Kirk, C. Manzari,
M. Montull JHEP, 2008.01113 $\frac{v}{M_N} |\lambda_N|$

>5 σ improvement over SM hypothesis

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

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

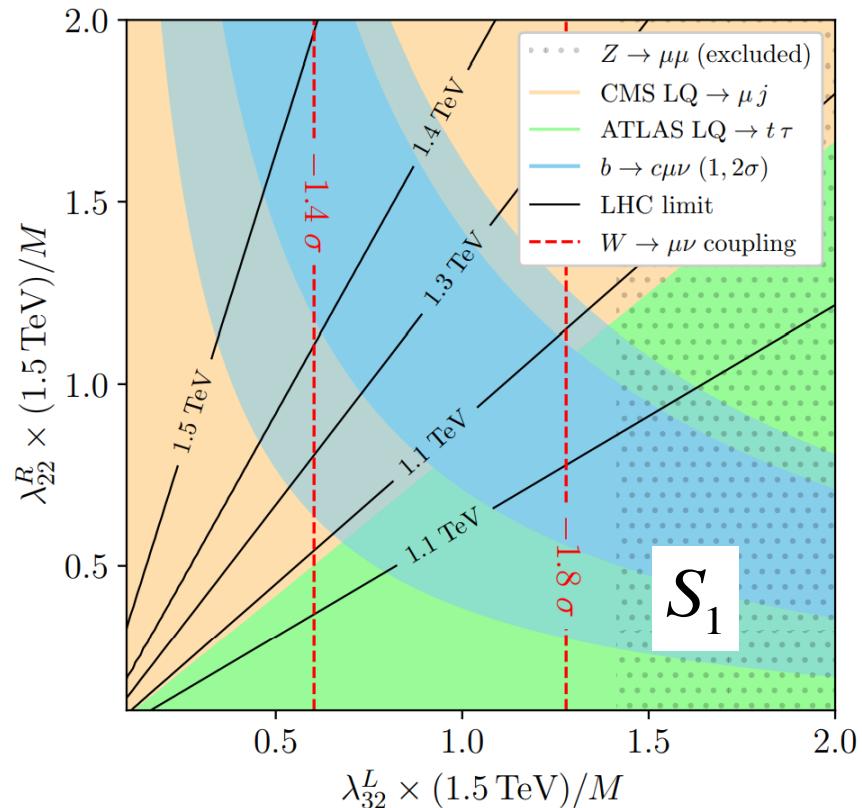
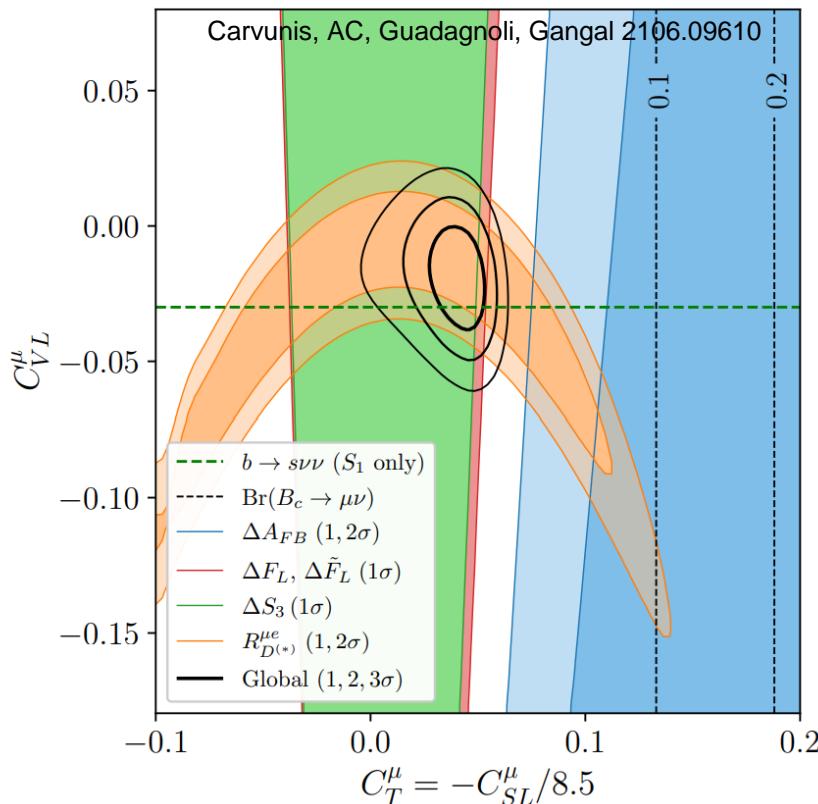


A.C., F. Kirk, C. Manzari, L. Panizzi, arXiv:2012.09845

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

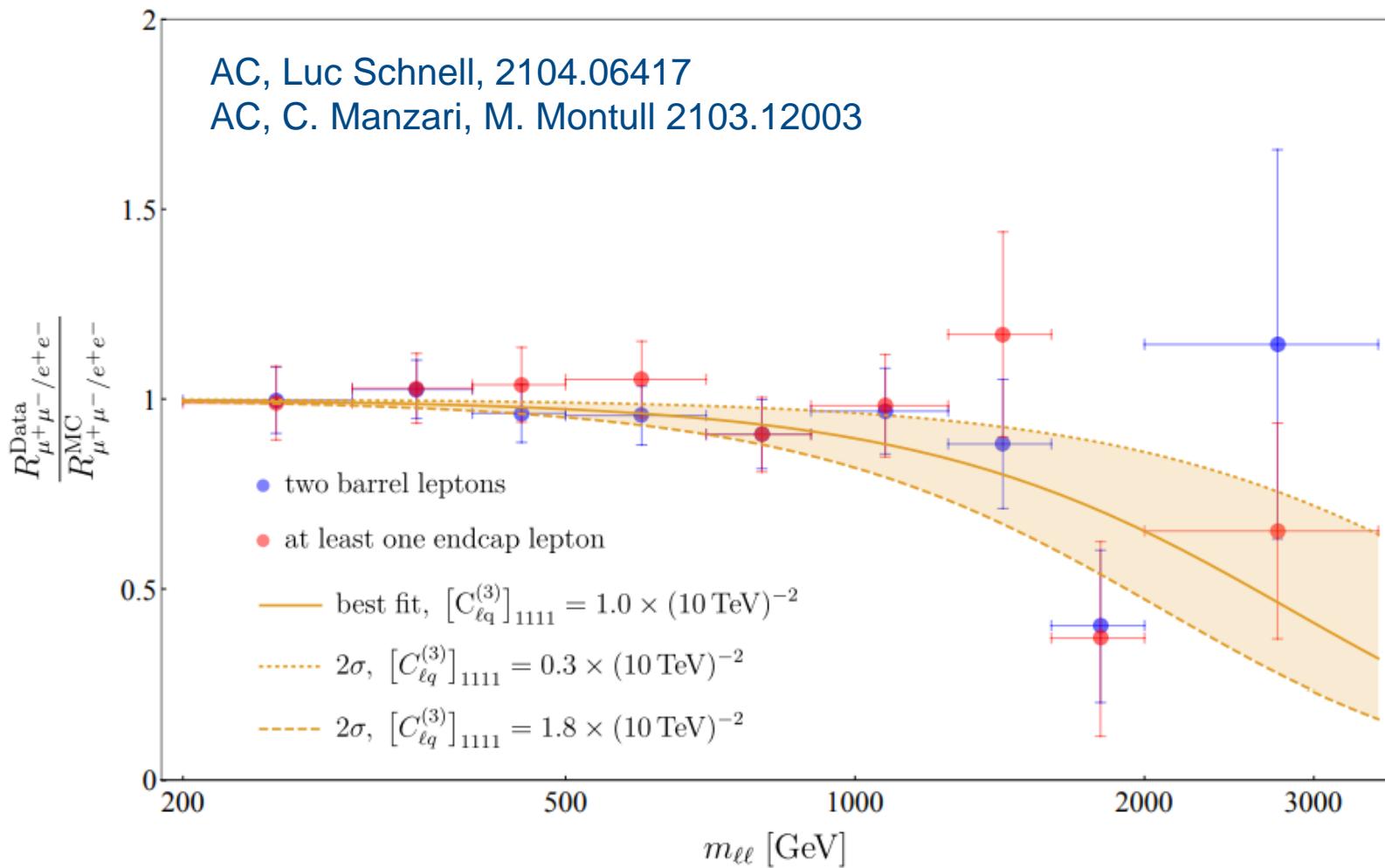
ΔA_{FB}

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



Hint for scalar leptoquarks

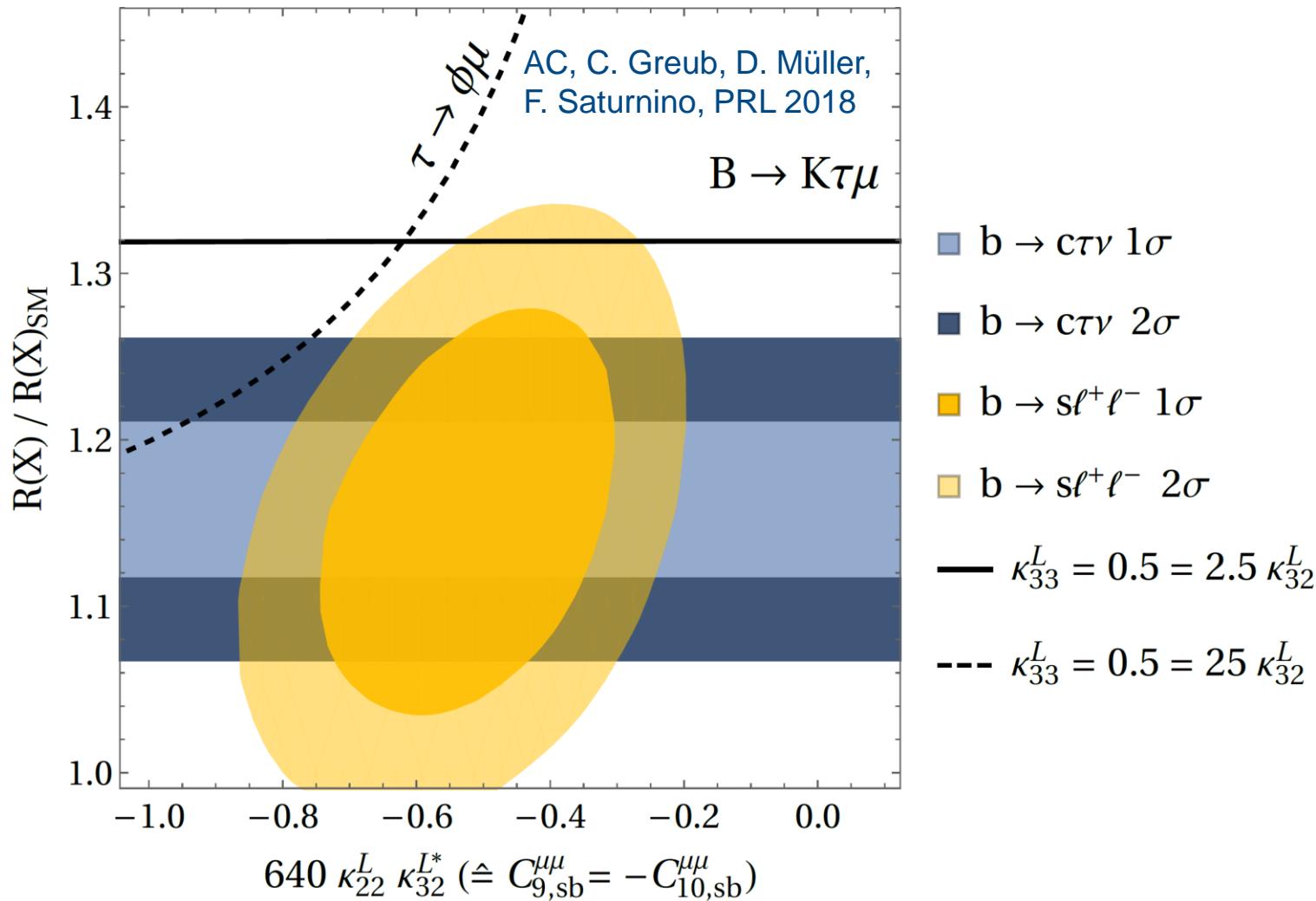
Non-Resonant Di-Leptons



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

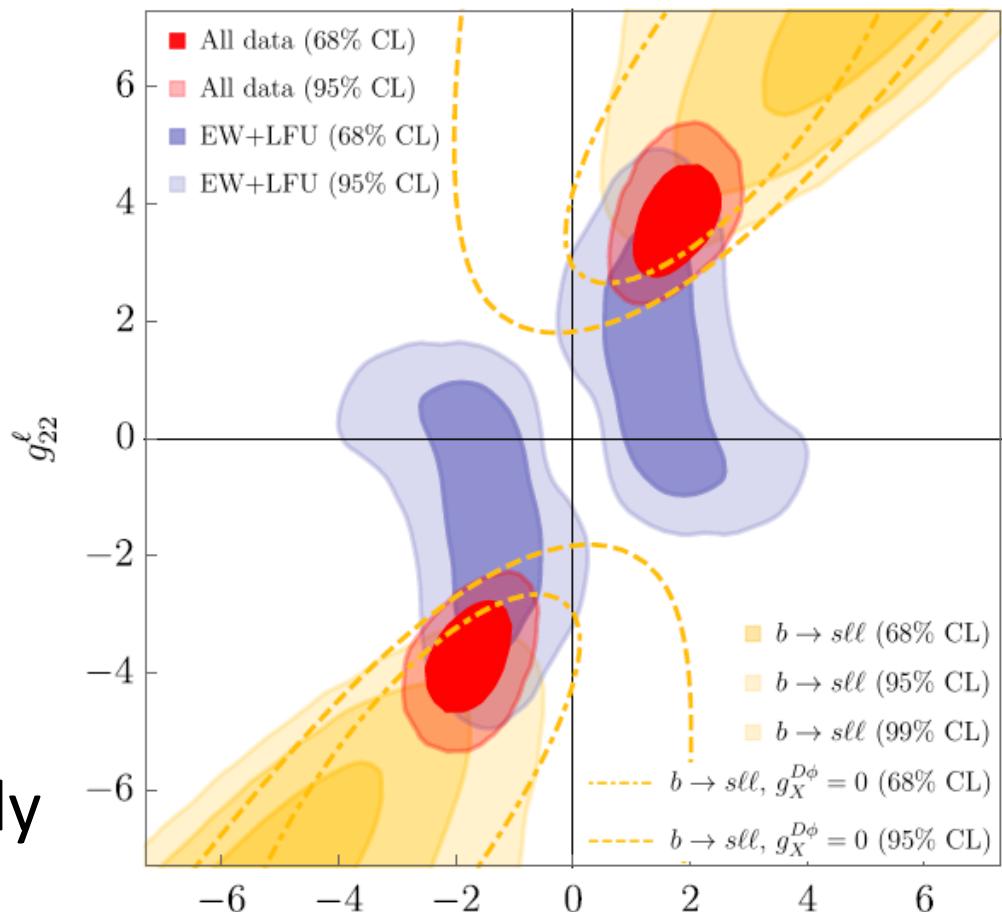
AC, D. Mueller, F. Saturnino
arxiv:1912.04224

	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
	$C_9^{\mu\mu} = -C_{10}^{\mu\mu}$	$C_9^{\ell\ell}$	$\frac{R(D)}{R(D)_{\text{SM}}}$	$\frac{R(D^*)}{R(D^*)_{\text{SM}}}$	$\frac{B_s \rightarrow \tau\tau}{B_s \rightarrow \tau\tau _{\text{SM}}}$	$\tau \rightarrow \mu\gamma$ $\times 10^8$	δa_μ $\times 10^{11}$	$\tilde{V}_{cb}^e/\tilde{V}_{cb}^\mu - 1$ $\times 10^6$	$Z \rightarrow \tau\mu$ $\times 10^{10}$	
● p_1	-0.52	-0.21	1.15	1.10	59.88	4.35	207	291	0.117	
● p_2	-0.56	-0.28	1.14	1.10	99.76	0.766	199	448	2.38	
● p_3	-0.31	-0.31	1.14	1.09	112.5	3.62	255	17	0.129	
● p_4	-0.31	-0.31	1.13	1.11	112.5	0.734	230	934	45.6	
	$C_{SL}^{\tau\tau} = -4C_{TL}^{\tau\tau}$	$C_{VL}^{\tau\tau}$	$R_{\nu\nu}^{K(*)}$	$\frac{\Delta m_{B_s}^{\text{NP}}}{\Delta m_{B_s}^{\text{SM}}}$	$B \rightarrow K\tau\mu$ $\times 10^5$	$\tau \rightarrow \phi\mu$ $\times 10^8$	$\tau \rightarrow \mu ee$ $\times 10^{11}$	$ \Lambda_{33}^{\text{LQ}}(0) $ $\times 10^5$	$\frac{\Delta_{33}^L(m_Z^2)}{\Lambda_{\text{SM}}^{L\ell} \times 10^{-5}}$	
● p_1	0.023	0.040	2.33	0.1	0.512	1.27	44.94	1.11	-3.64	
● p_2	0.020	0.040	0.87	0.16	3.32	4.73	7.783	0.90	-3.02	
● p_3	0.023	0.037	1.08	0.19	4.07	1.00	37.89	0.89	-3.51	
● p_4	0.010	0.047	2.43	0.18	3.69	0.0021	18.60	3.12	-10.04	

Common explanation possible

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

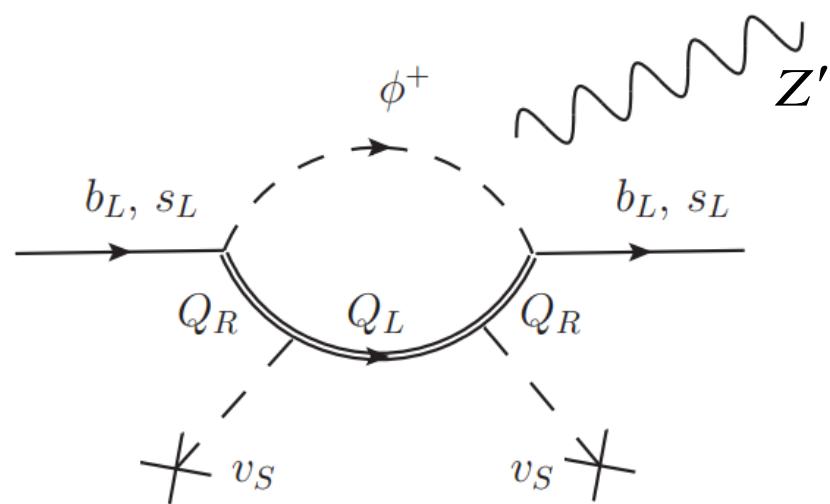
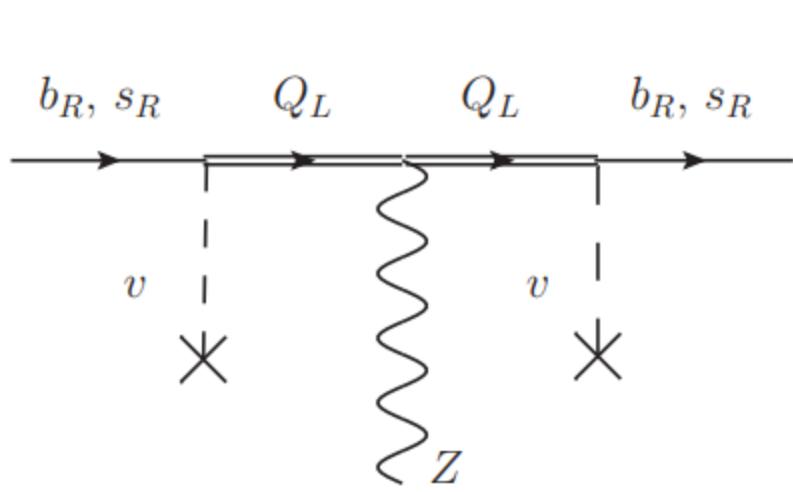


B. Capdevilla, AC, C. Manzari,
M. Montull, PRD 2020

Common explanation possible

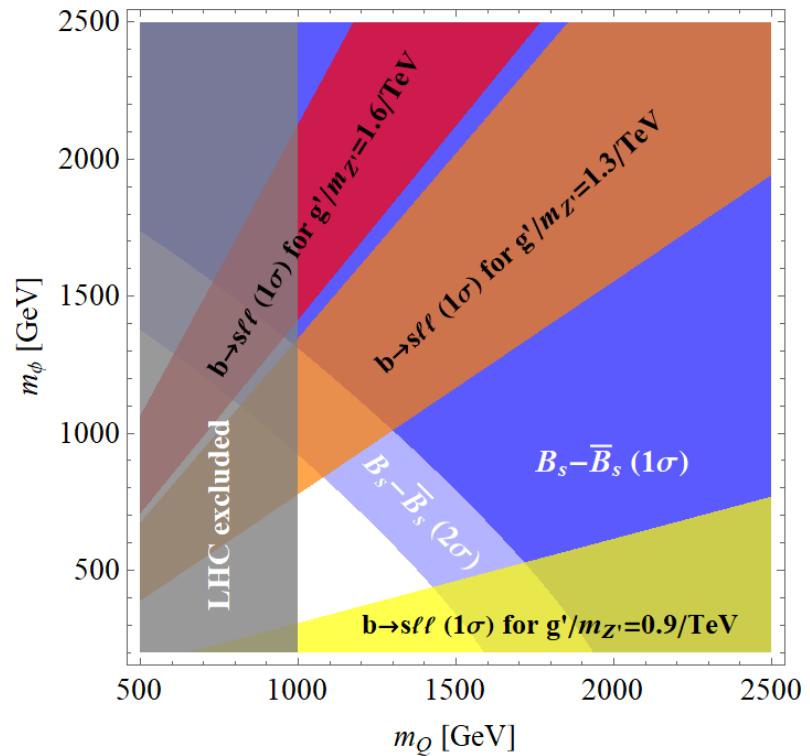
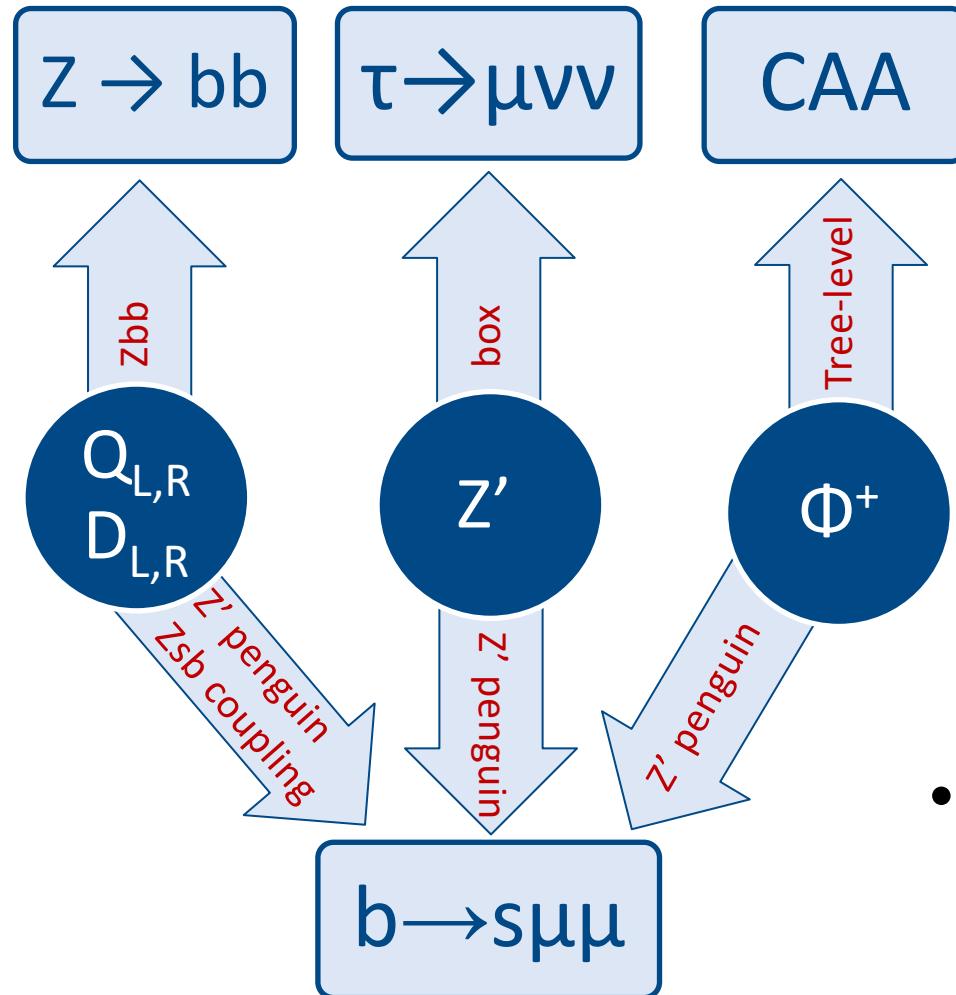
Model for $b \rightarrow s\ell\bar{\ell}$, CAA, $Z \rightarrow bb$ and $\tau \rightarrow \mu\nu\nu$

	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	1	1	0	-1	-1



Tree effect in Zbb and loop in $Z'sb$

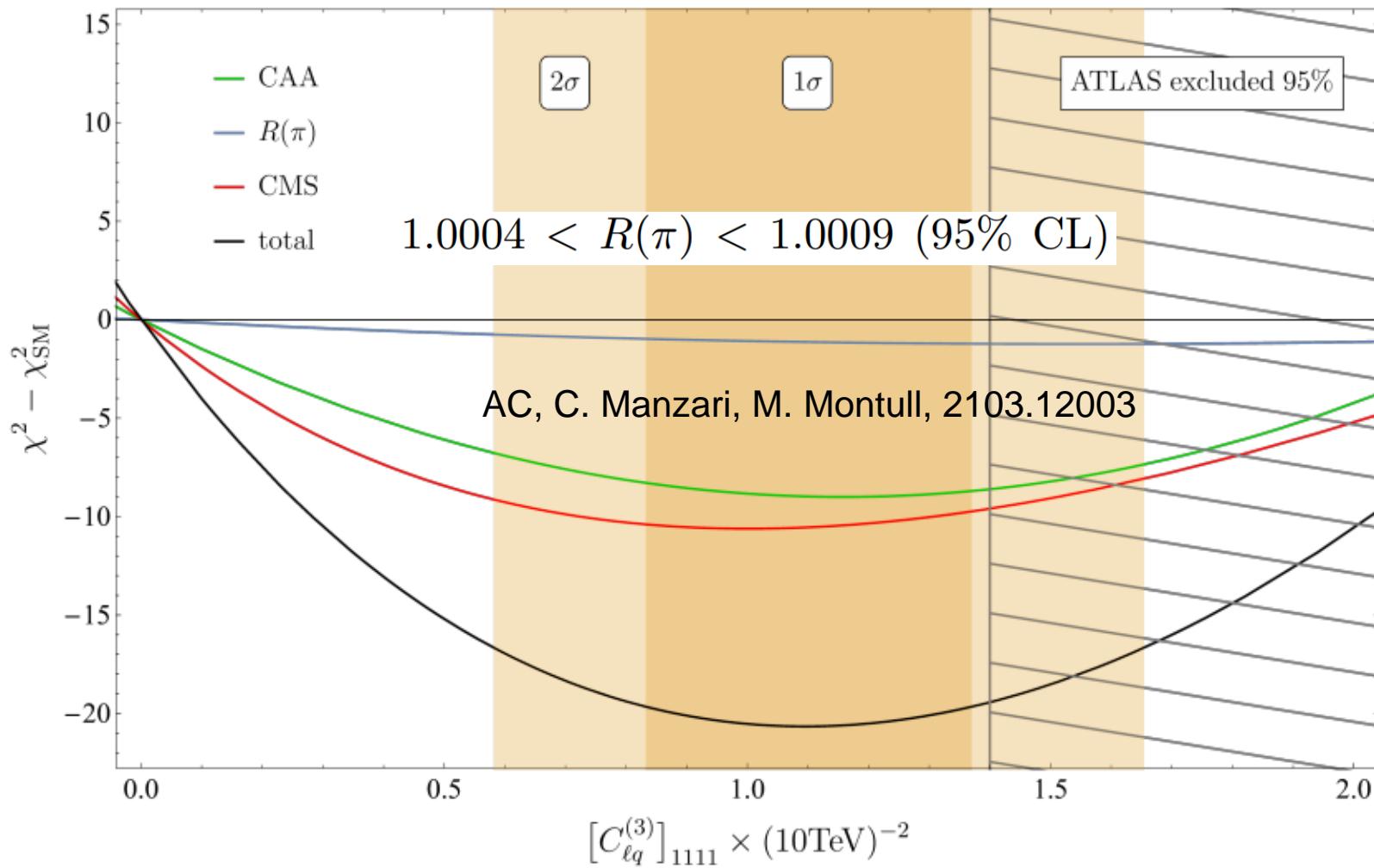
Model for $b \rightarrow s\ell\ell$, CAA, $Z \rightarrow bb$ and $\tau \rightarrow \mu\nu\nu$



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

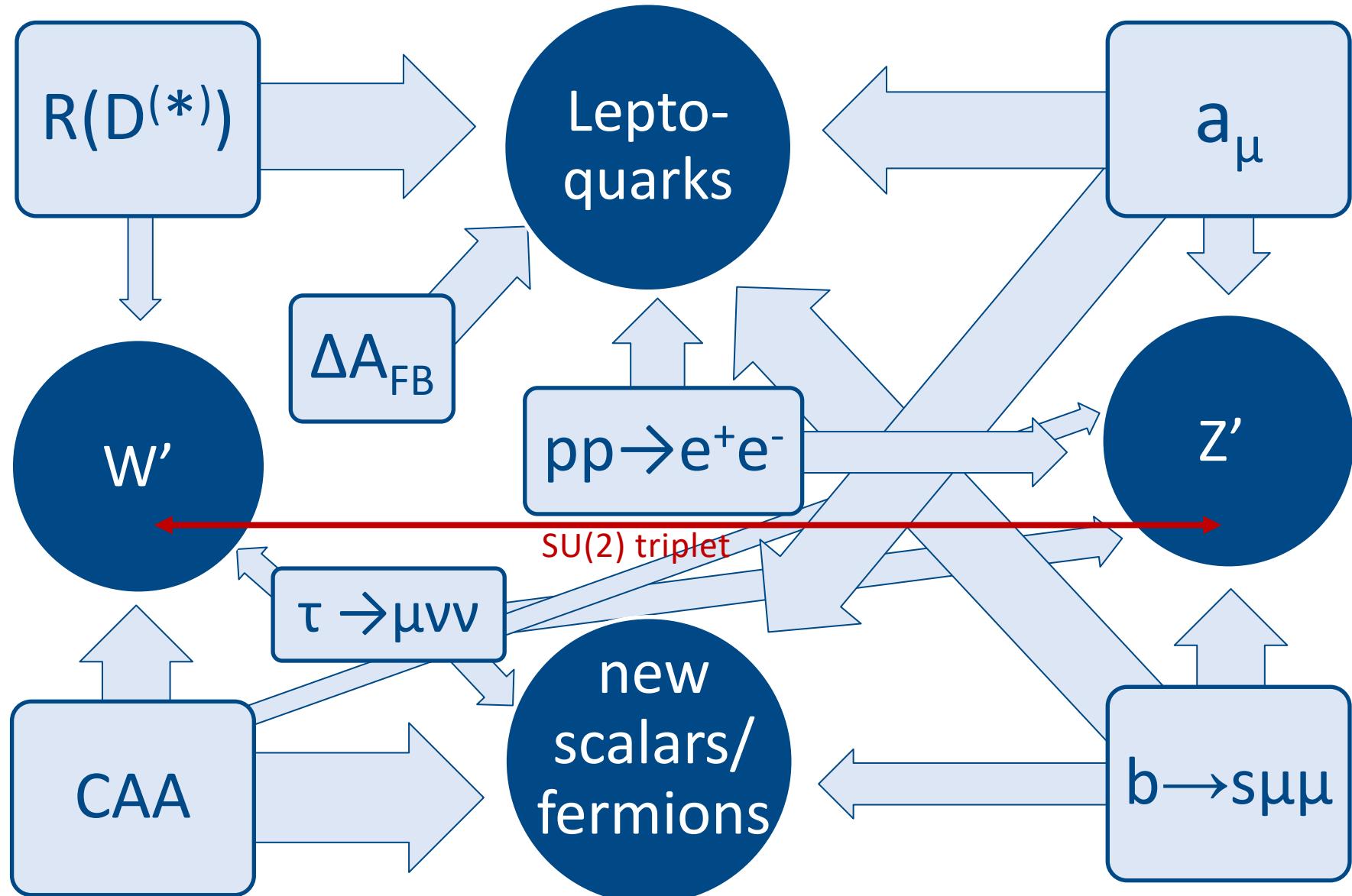
Simple model provides combined explanation

CAA and Non-Resonant Di-Leptons

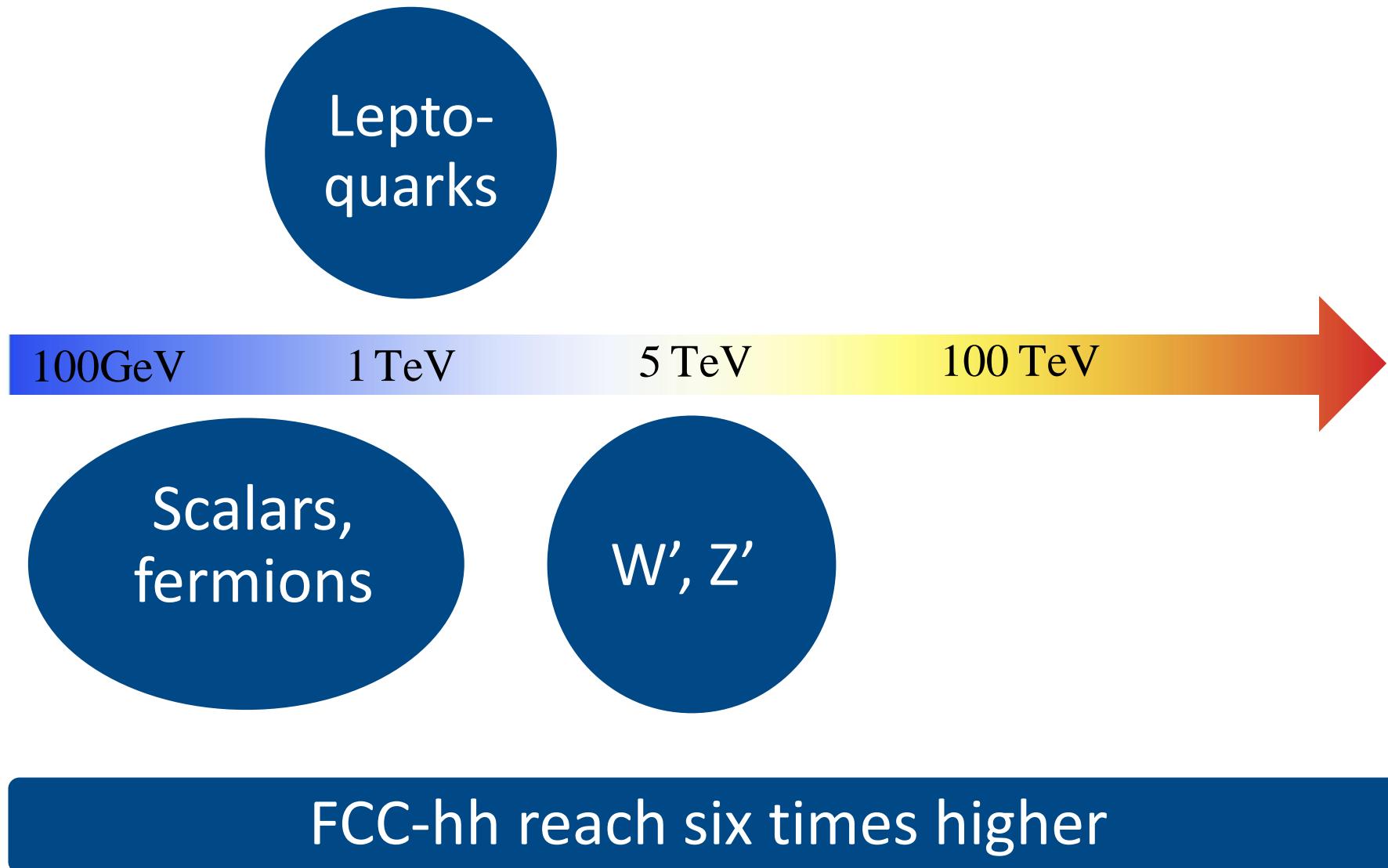


4.5 σ better than SM, prediction for $R(\pi)$

Conclusions



LHC bounds and future prospects



Implications for FCC-ee

