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Finding New Physics with PIONEER

PIONEER collaboration meeting, 07.10.2022

Work supported by FNSNF

Outline

- Introduction
- Anomalies
  - LFUV
  - Cabibbo Angle Anomaly
  - Non-resonant di-leptons
  - W mass and EW fit
- Explanations
- Implications for PIONEER
- Conclusions

PIONEER Goals

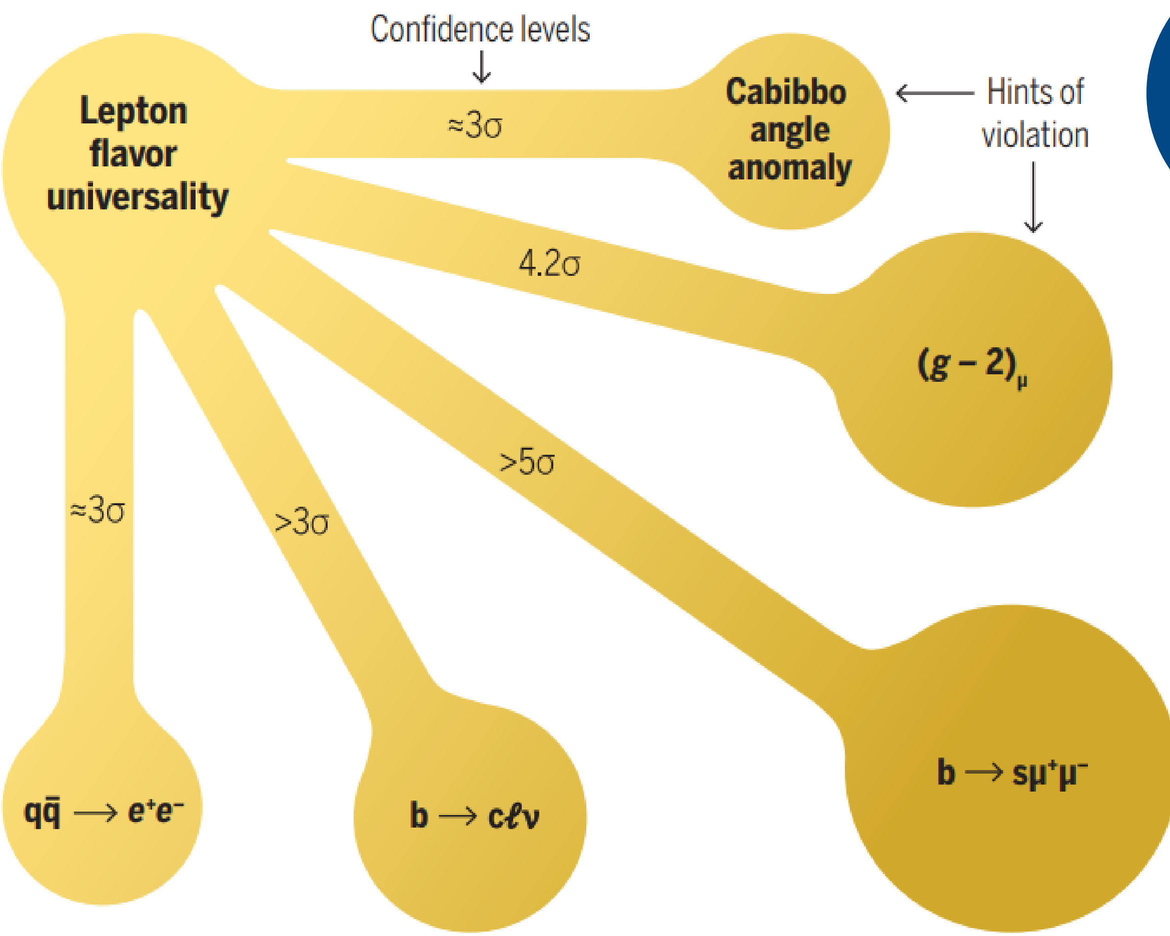
- Improve
  - $R(\pi)=\pi\to\mu\nu/\pi\to e\nu$
  - Pion beta decay $\pi^+\to \pi^0 e\nu$

  by an order of magnitude compare to current limits
- Provide most precise test of
  - μ/e universality
  - CKM unitarity

What is the impact of these measurements?
Which New Physics can be found?

Hints for New Physics

- LFUV AC, M. Hoferichter, Science 374 (2021)



- EW observables

m_W ≈3-4σ

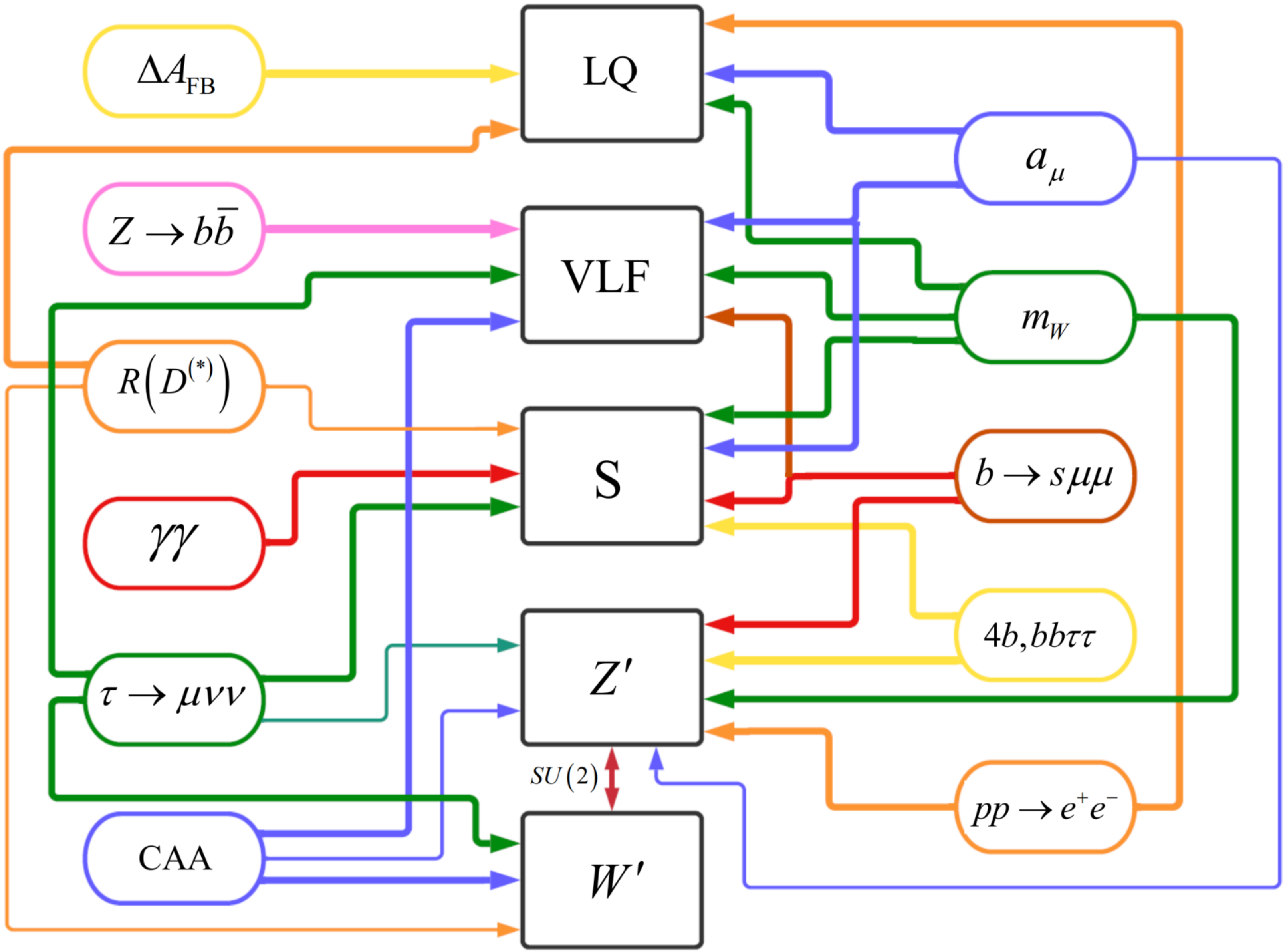
Z→bb

- Direct searches

γγ
ττ

bbγγ
WW
jj(jj)

Expanations

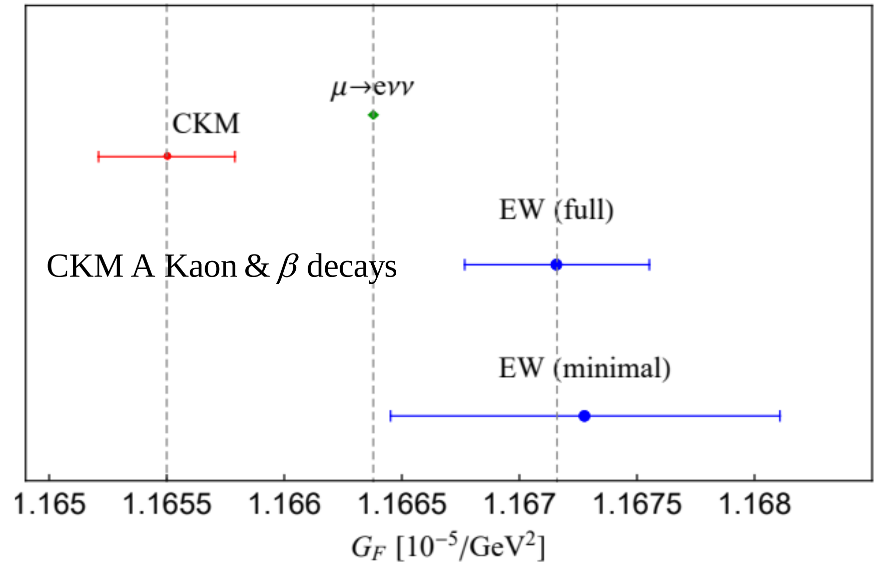


Cabibbo Angle Anomaly (CAA) talk of Martin

- Deficit in first row and first column CKM unitarity

$$\left|V_{ud}^2\right| + \left|V_{us}^2\right| + \left|V_{ub}^2\right| = 0.9985 \pm 0.0005$$
$$\left|V_{ud}^2\right| + \left|V_{cd}^2\right| + \left|V_{td}^2\right| = 0.9970 \pm 0.0018$$
$$(\text{PDG})$$

AC, Hoferichter, Manzari, PRL 127 (2021)

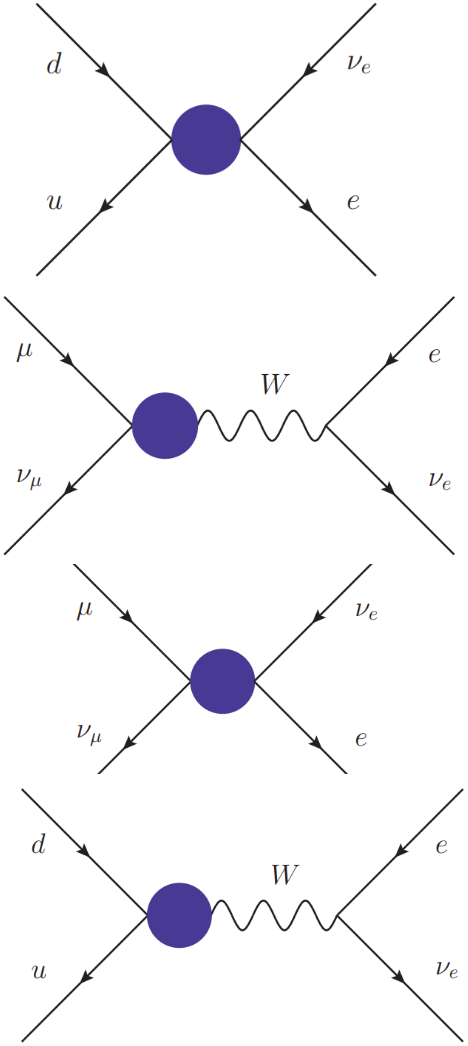


- NP in the determination of V_{ud} from beta decays needed
- Can be interpreted as
  - NP in beta decays
  - NP in the Fermi constant
  - LFUV (modified Wμν coupling)

3σ tension, can be interpreted as LFUV

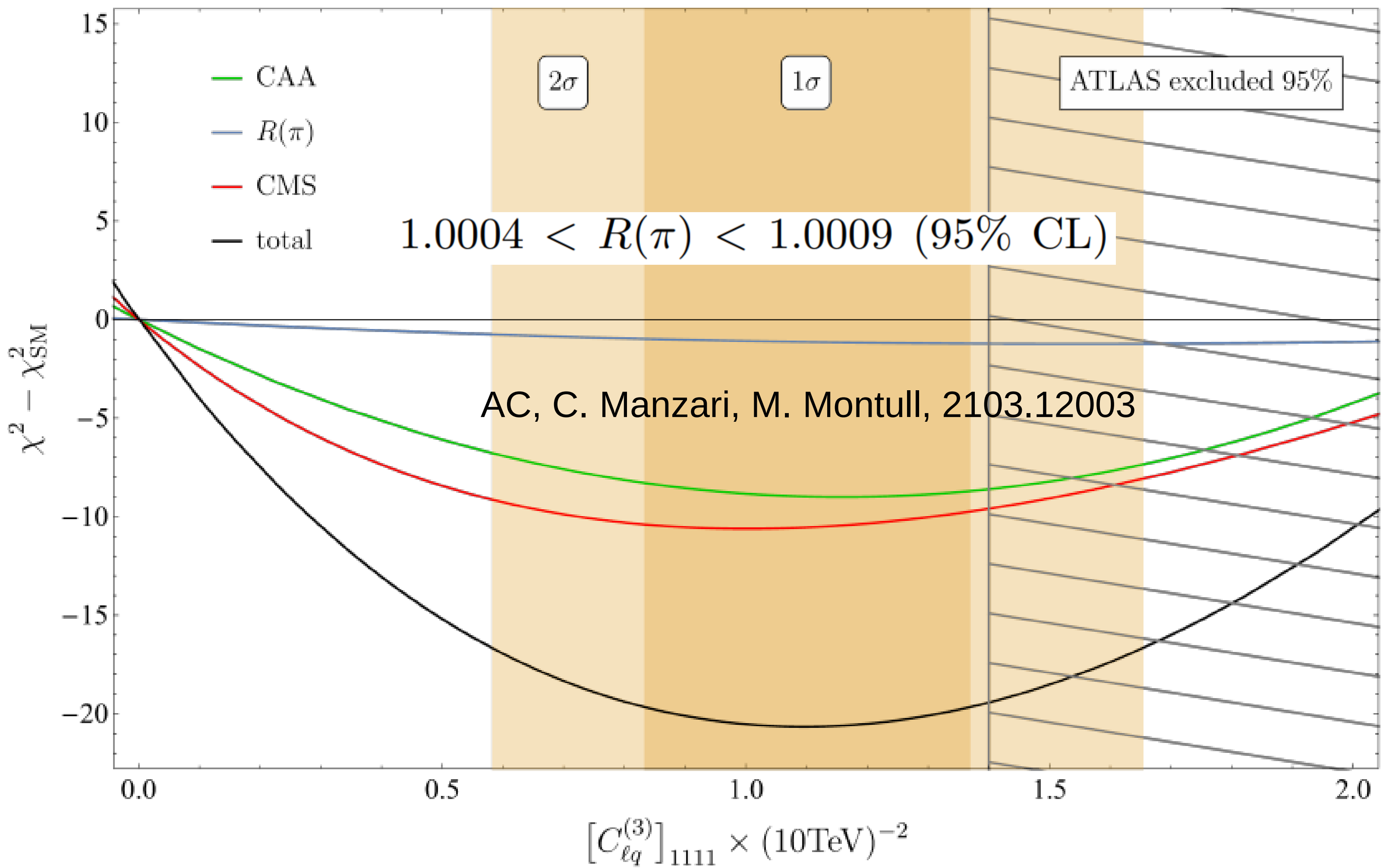
Cabibbo Angle Anomaly and EW Fit

- 4fermion effect in beta decays
  - LQs
  - W‘
- Modifed W coupling in muon decay
  - W-W‘ mixing
  - Vector-like leptons
- 4 fermion effect in muon decay
  - Z‘
  - Singly charged scalar
- Modified Wud coupling
  - Vector-like quarks



>5σ improvement over SM hypothesis with VLLs

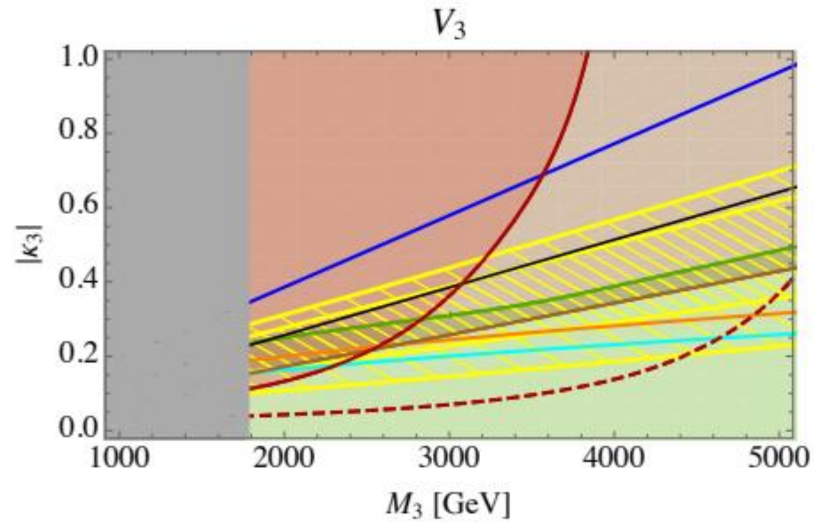
CAA and Non-Resonant Di-Leptons

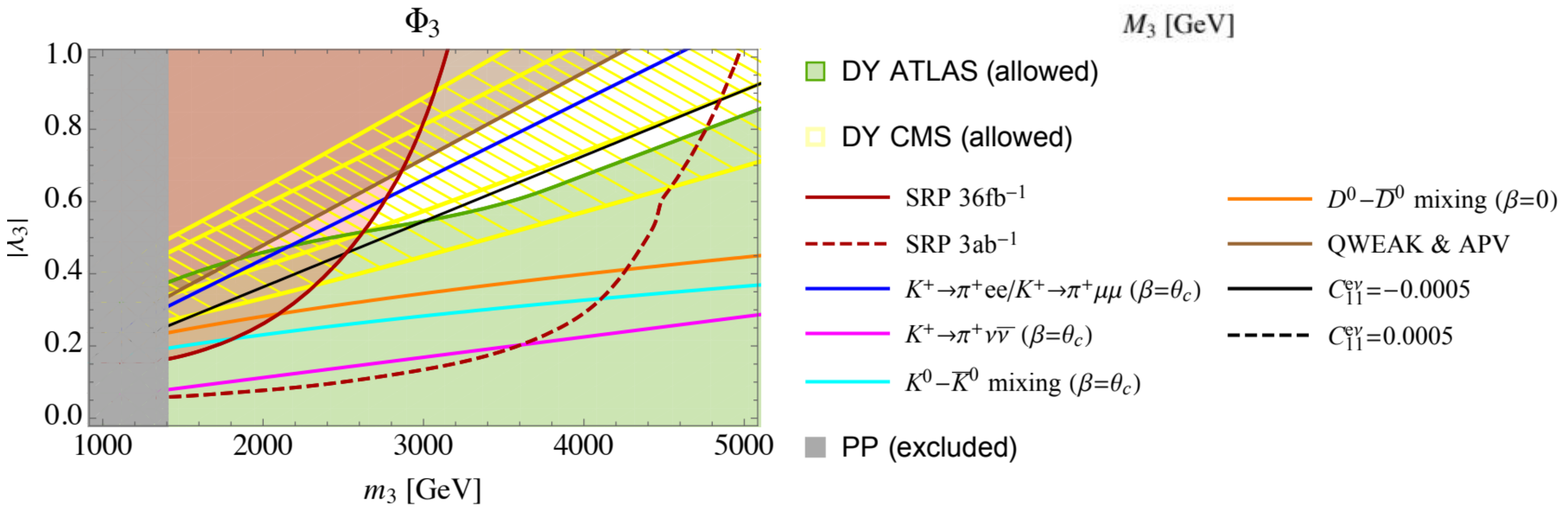


4.5σ better than SM, prediction for R(π)

Leptoquarks

- 10 representations
- Effect in R(π) and beta decays





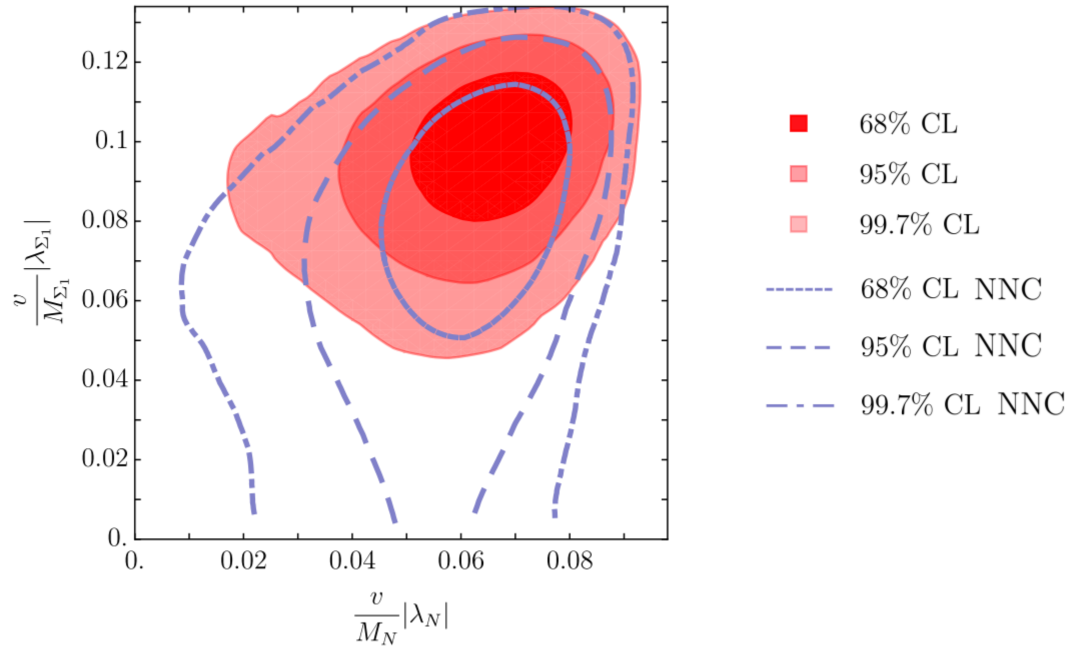
Simple model provides combined explanation

Vector-like leptons

PAUL SCHERRER INSTITUT PSI

- 5 represenations of which 3 generate modified Wlν couplings
- Bounds from EW precision observables

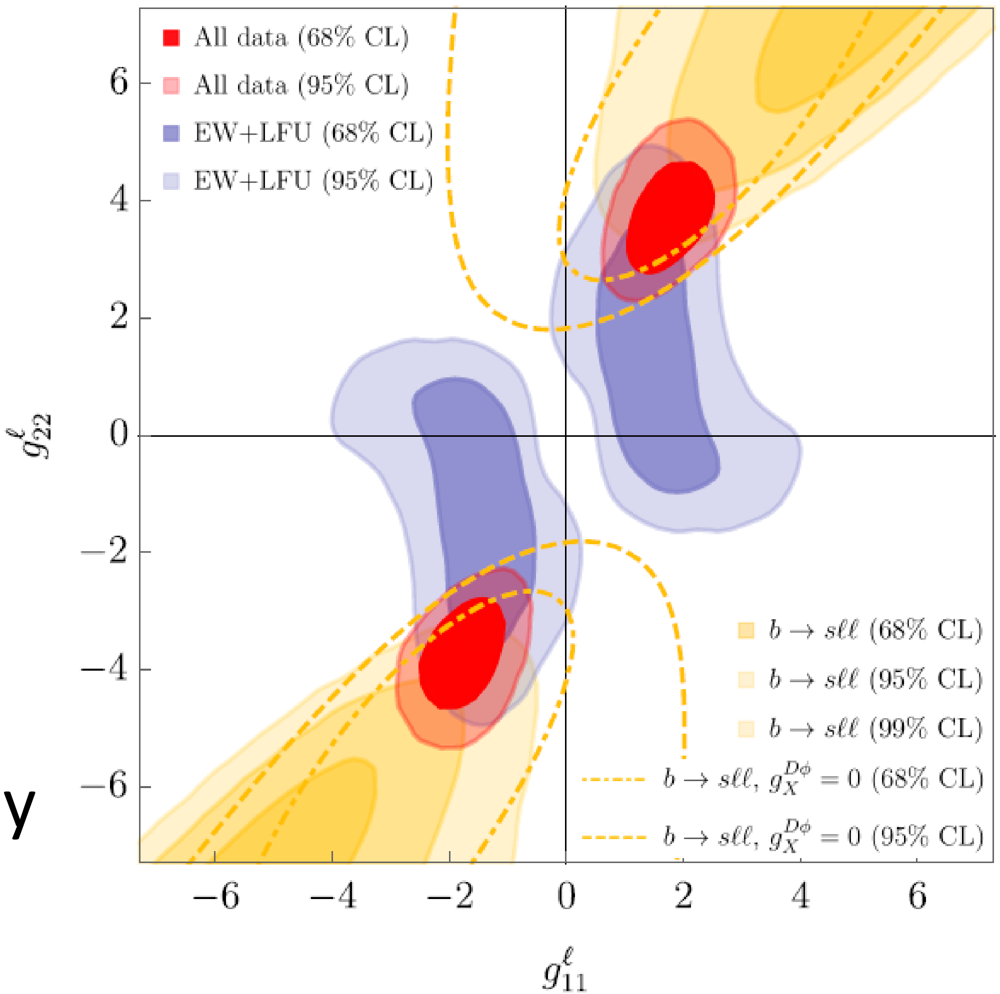
Effect in R(π), R(K) and LFUV in τ decays



Observable	Measurement	SM Posterior	NP Posterior	Pull
M_W [GeV]	80.379(12)	80.363(4)	80.369(6)	0.56
$R\left[\frac{K\to\mu\nu}{K\to e\nu}\right]$	0.9978 ± 0.0020	1	1.00168(39)	−0.80
$R\left[\frac{\pi\to\mu\nu}{\pi\to e\nu}\right]$	1.0010 ± 0.0009	1	1.00168(39)	0.42
$R\left[\frac{\tau\to\mu\nu\bar{\nu}}{\tau\to e\nu\bar{\nu}}\right]$	1.0018 ± 0.0014	1	1.00168(39)	1.2
$\lvert V_{us}^{K_{\mu3}}\rvert$	0.22345(67)	0.22573(35)	0.22519(39)	0.77
$\lvert V_{ud}^{\beta}\rvert$	0.97365(15)	0.97419(8)	0.97378(13)	2.52

W' 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

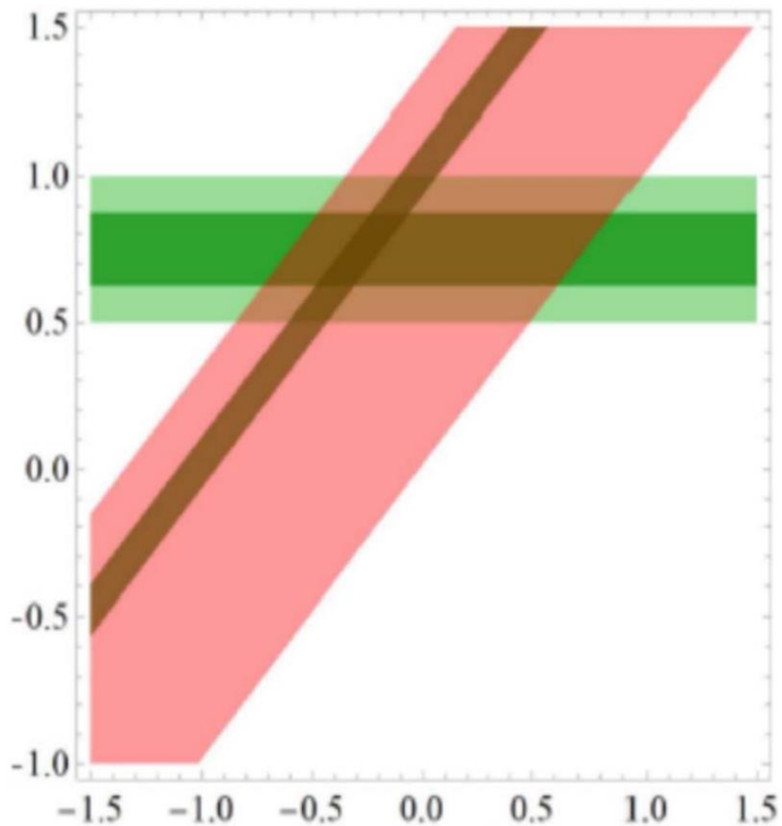


Common explanation possible

Impact of PIONEER

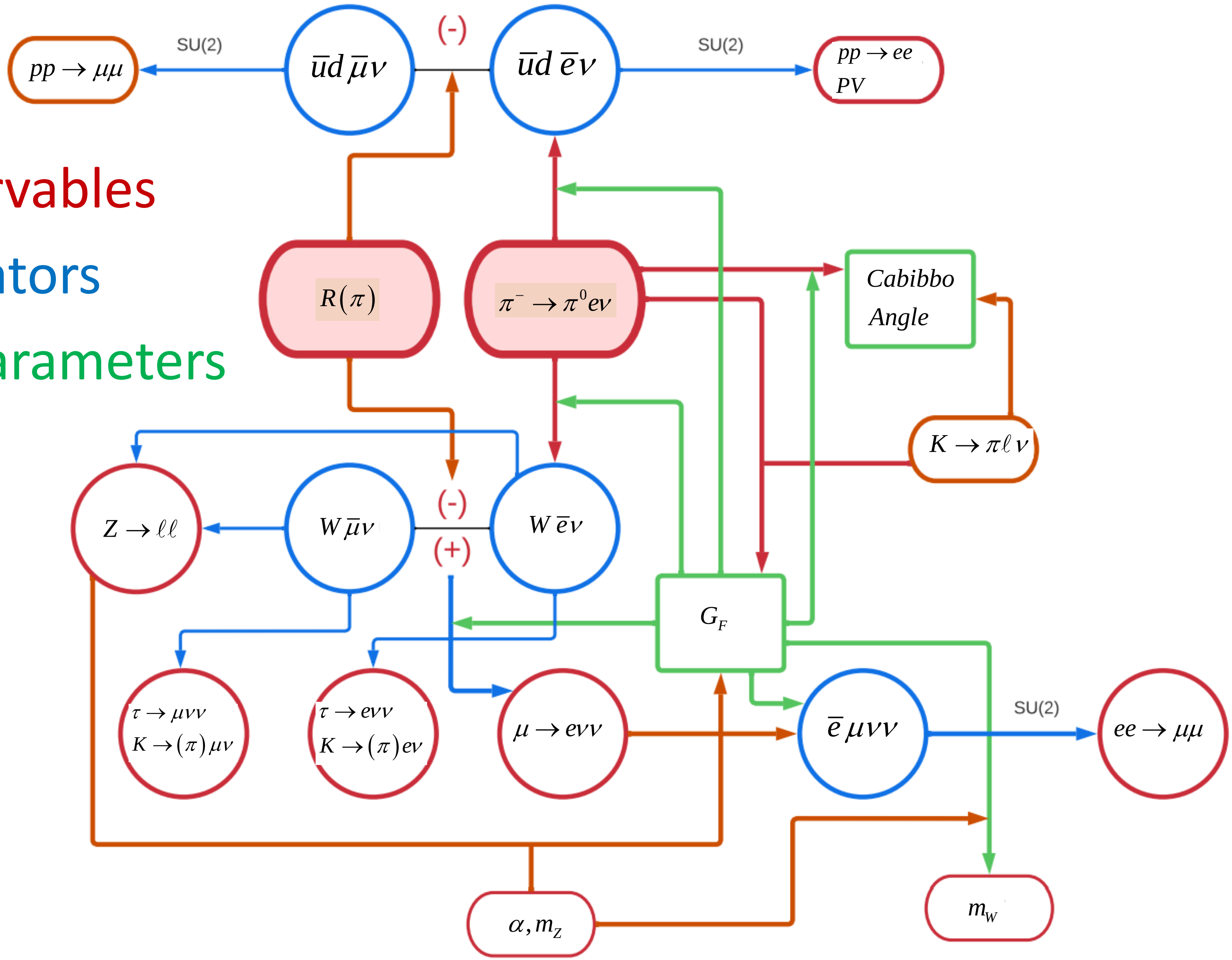
- Test μ-e LFUV with unprecedented precision
- Measure V_{ud} in theoretically clean pion beta decay
- Test of New Physics model
  - Leptoquarks
  - Vector-like leptons
  - W` bosons
  - Vector-like quarks
  - Light new physics

    talks of Asaf and Robert



Impact of PIONEER II

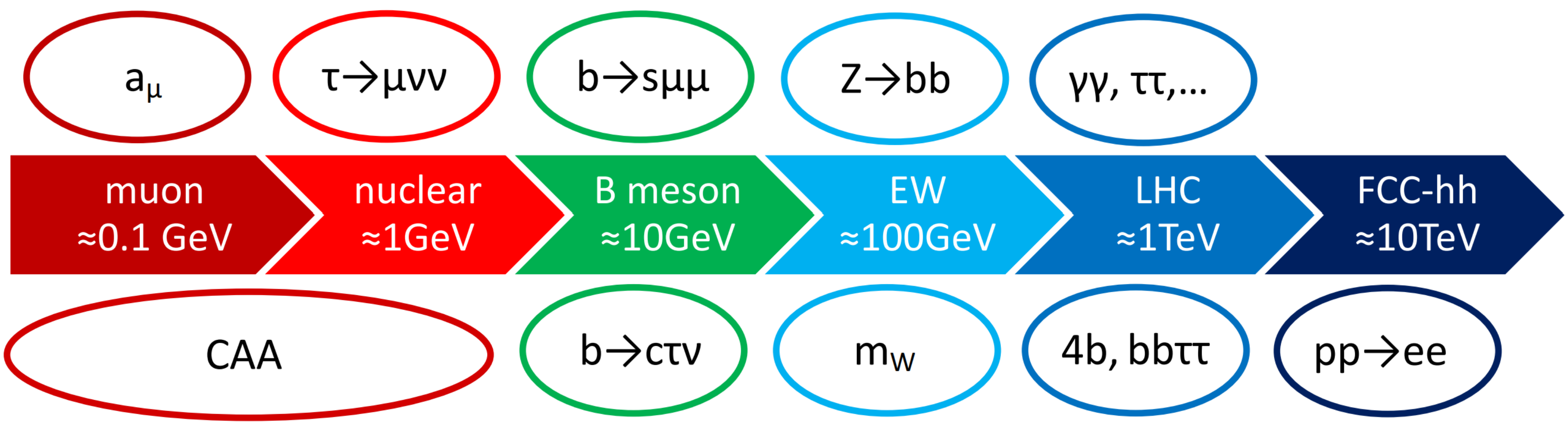
- Observables
- Operators
- SM Parameters



Conclusions

- Many intriguing anomalies emerged in the last years:
  - LFUV
  - EW observables
  - Direct LHC searches

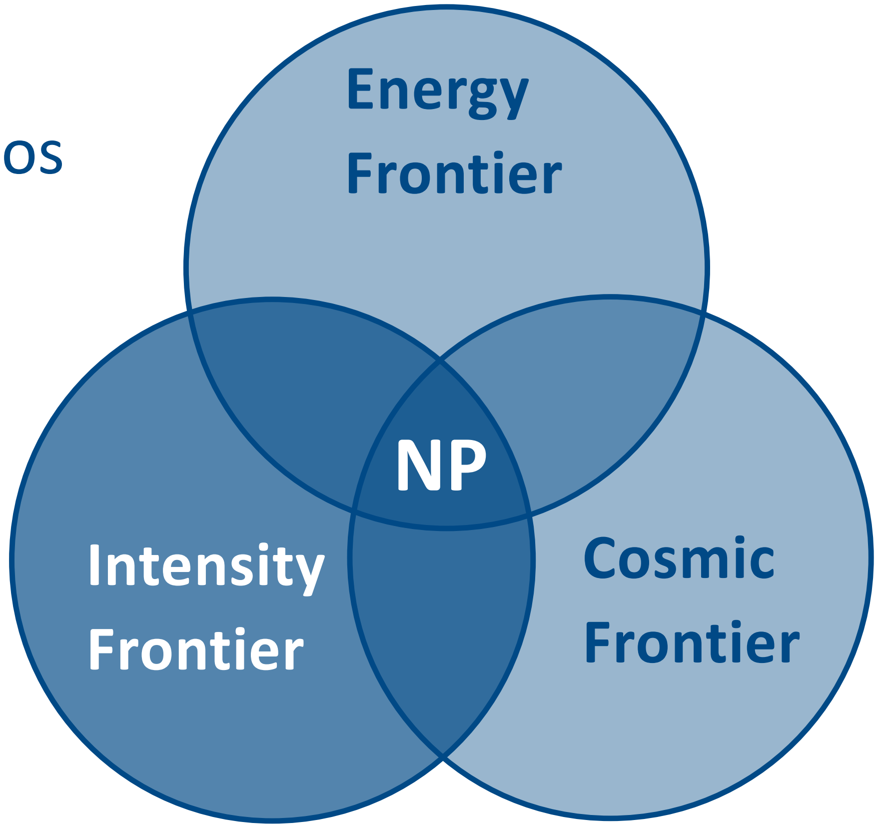
The Standard Model is crumbling; PIONEER can contribute to its fall



Backup

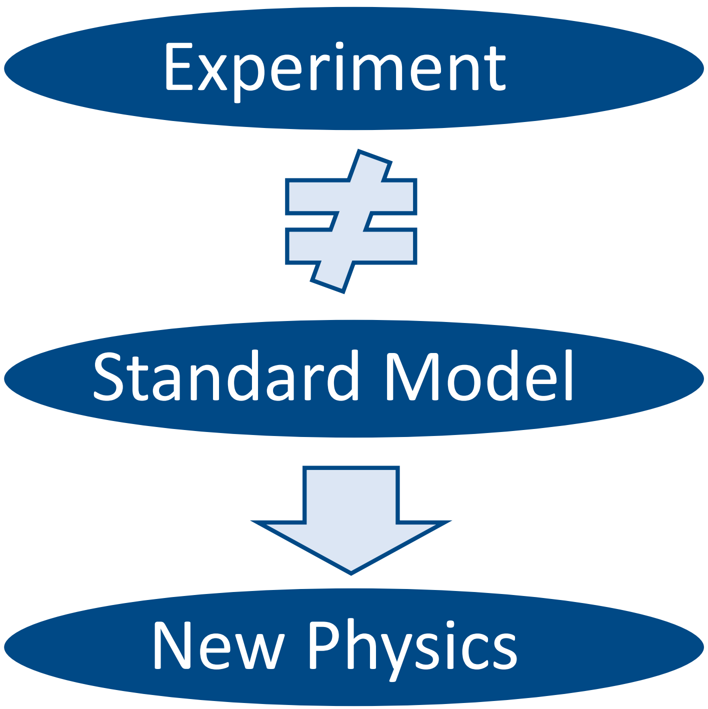
Discovering New Physics

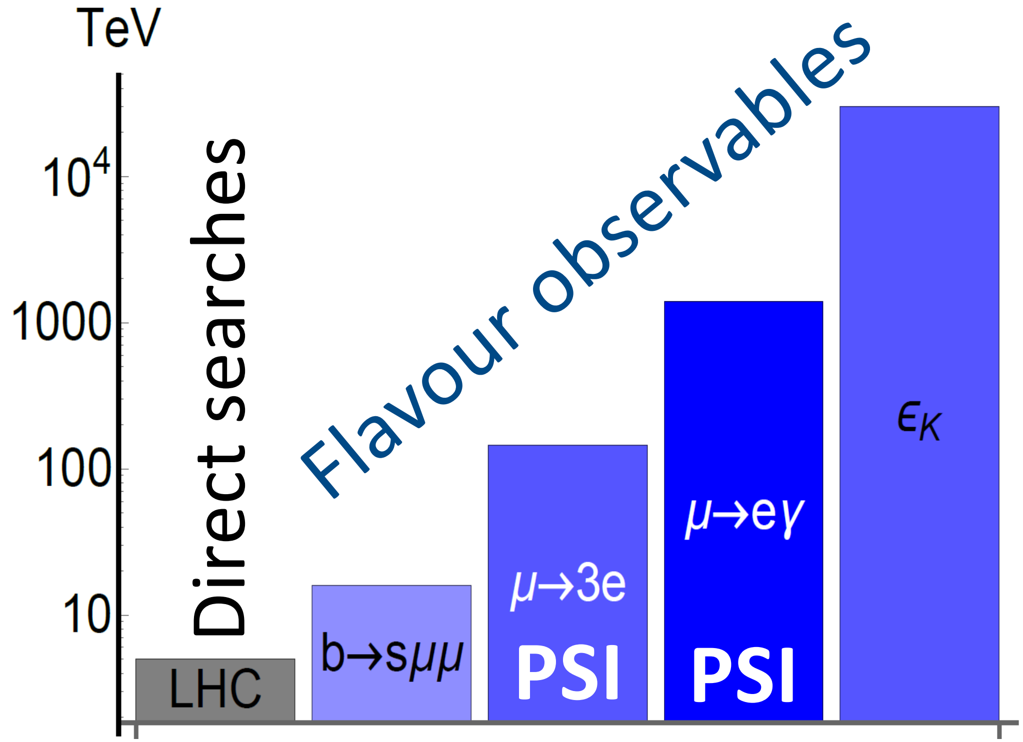
- Cosmic Frontier
  - Cosmic rays and neutrinos
  - Dark Matter
  - Dark Energy
- Energy Frontier
  - LHC
  - Future colliders
- Intensity Frontier
  - Flavour
  - Neutrino-less double-β decay
  - Test of fundamental symmetries
  - Proton decay



Indirect Searches for New Physics

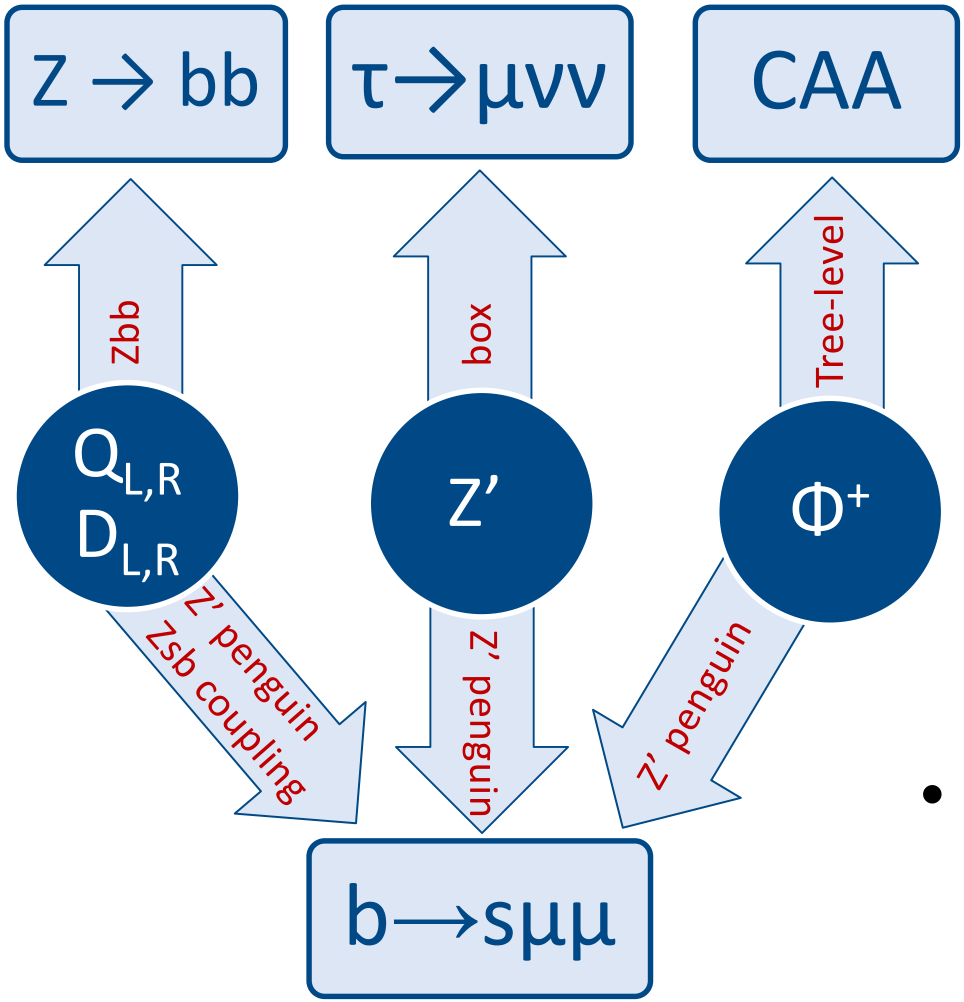
- Perfrom high-statistics measurements to search for the quantum effects of new particles

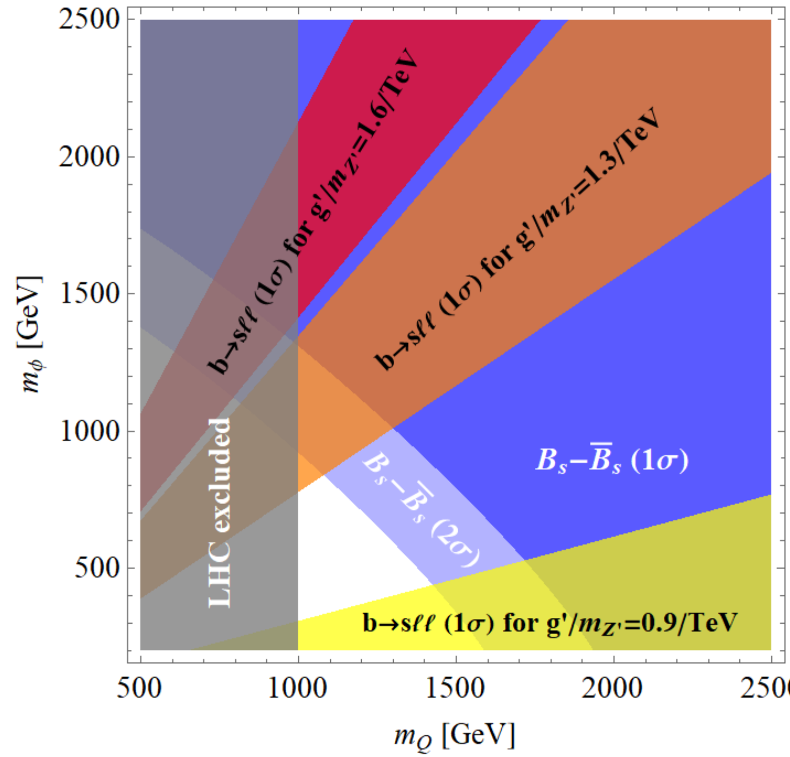




Flavour observables can be sensitive to higher energy scales than collider searches

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

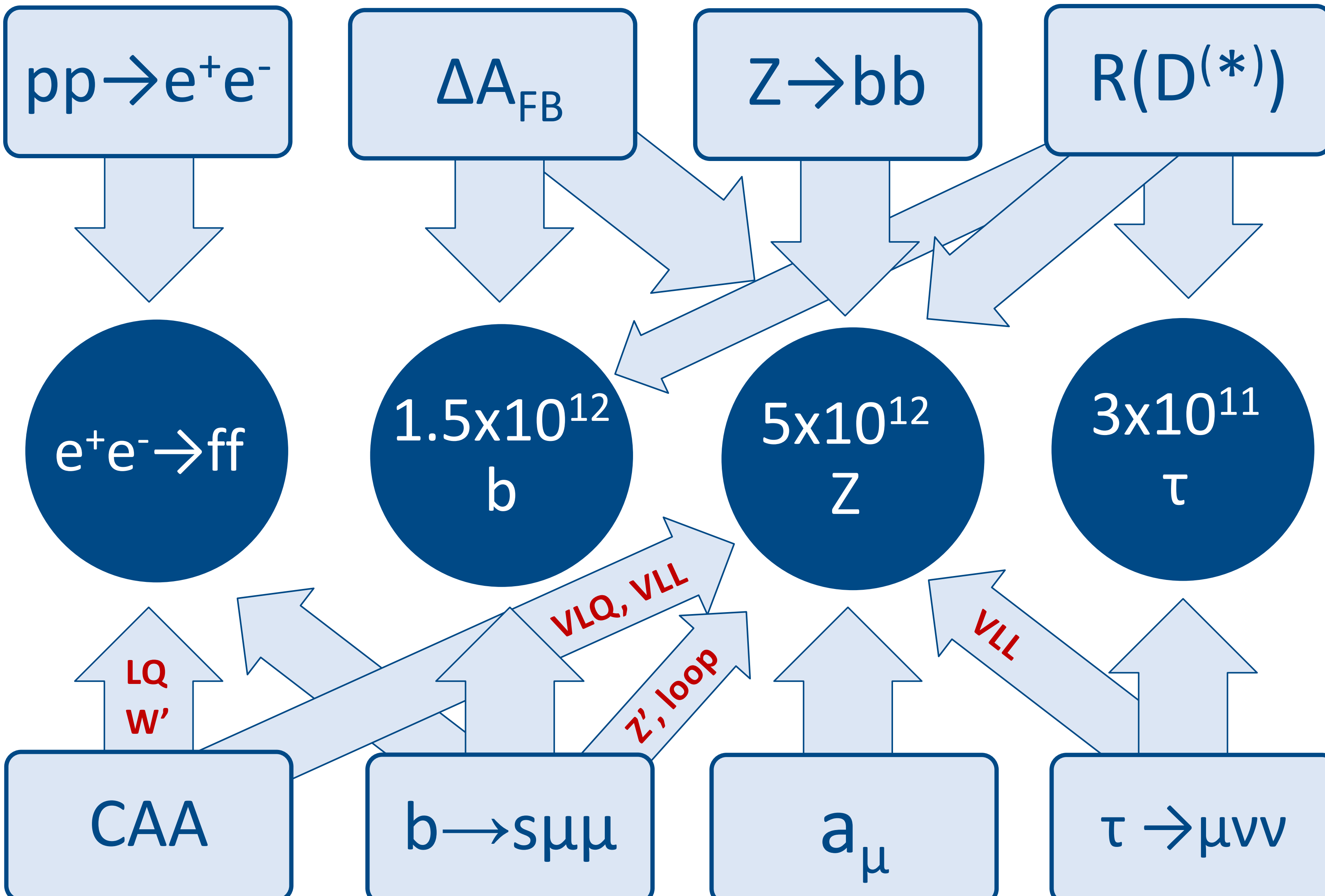




- Z’ penguin + modified Zsb coupling give very good fit to b→sll data

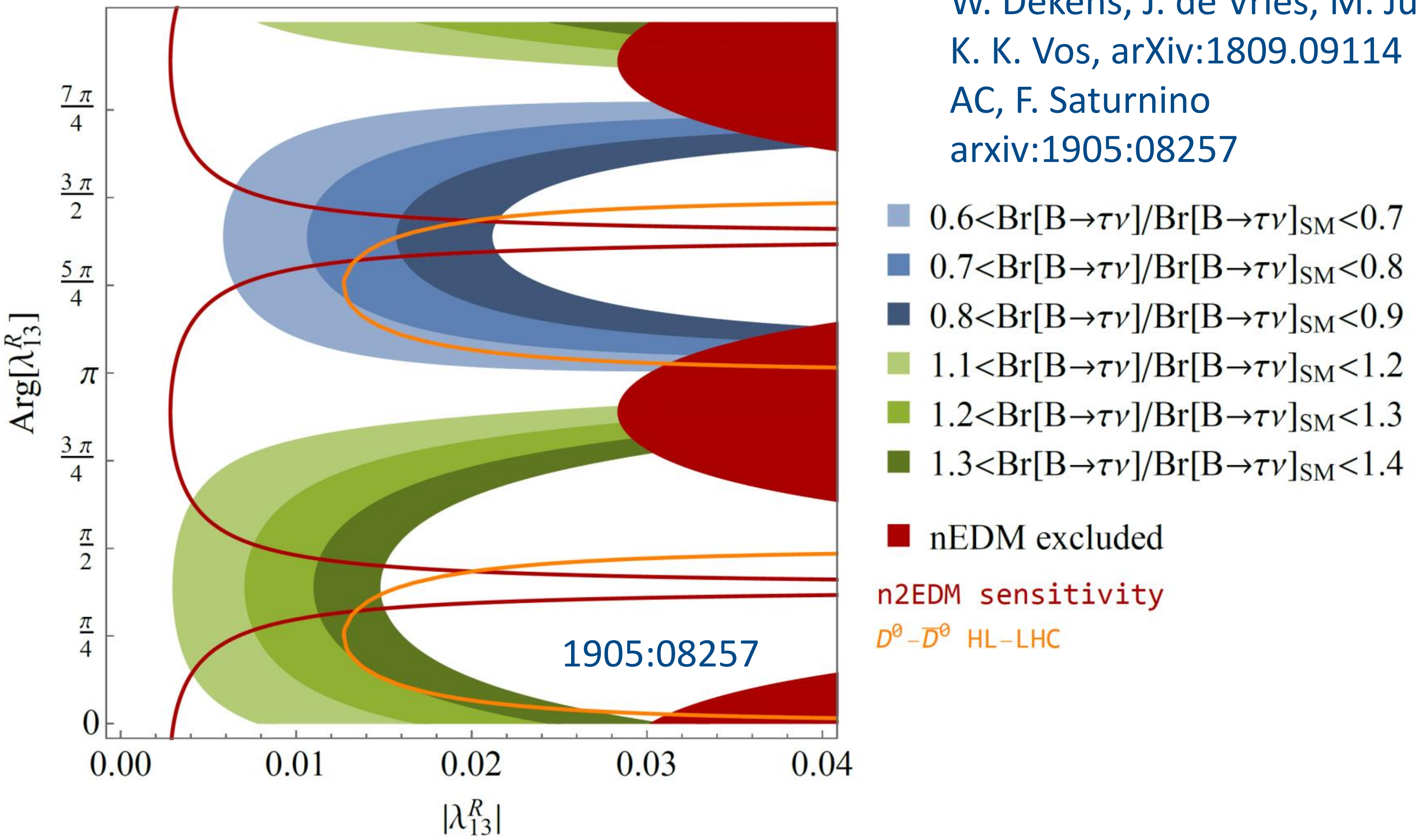
Simple model provides combined explanation

Implications for FCC-ee



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

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

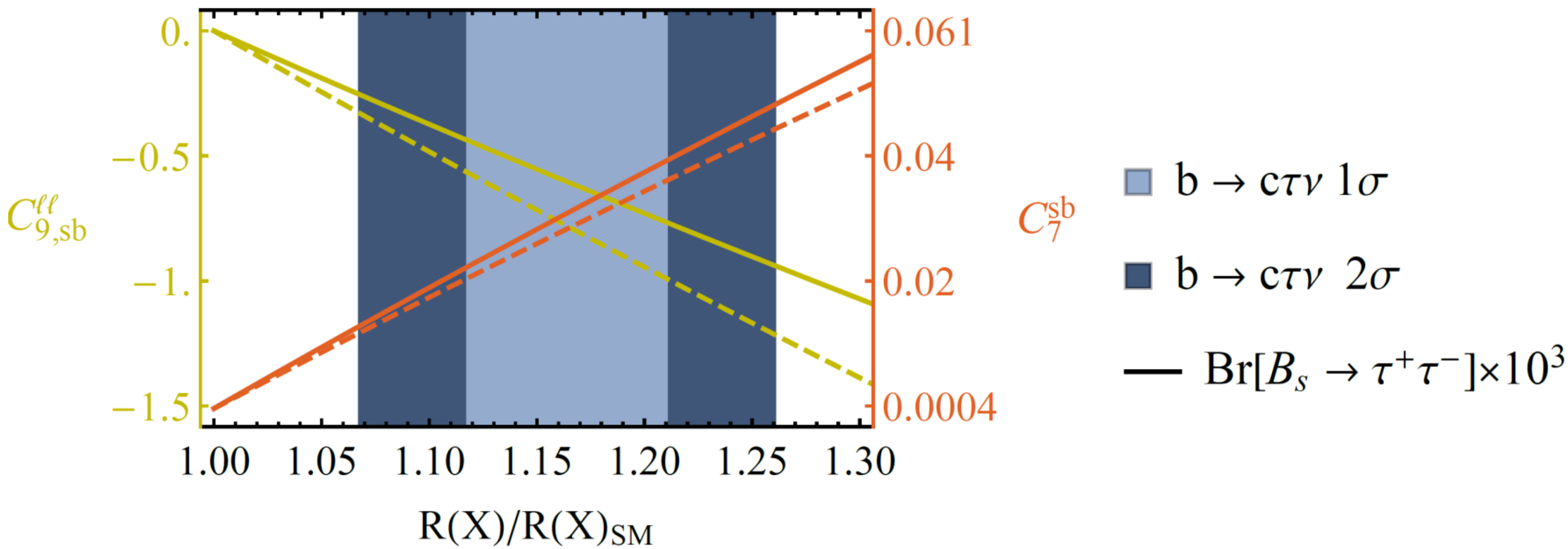
	$C_9^{\mu\mu} = -C_{10}^{\mu\mu}$	$C_9^{\ell\ell}$	$\frac{R(D)}{R(D)_{\rm SM}}$	$\frac{R(D^*)}{R(D^*)_{\rm SM}}$	$\frac{B_s \to \tau\tau}{B_s \to \tau\tau\rvert_{\rm SM}}$	$\tau \to \mu\gamma$ $\times 10^8$	δa_μ $\times 10^{11}$	$\tilde{V}_{cb}^e/\tilde{V}_{cb}^\mu - 1$ $\times 10^6$	$Z \to \tau\mu$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

	$C_{SL}^{\tau\tau} = -4C_{TL}^{\tau\tau}$	$C_{VL}^{\tau\tau}$	$R_{\nu\bar{\nu}}^{K^{(*)}}$	$\frac{\Delta m_{B_s}^{\rm NP}}{\Delta m_{B_s}^{\rm SM}}$	$B \to K\tau\mu$ $\times 10^5$	$\tau \to \phi\mu$ $\times 10^8$	$\tau \to \mu ee$ $\times 10^{11}$	$\lvert\Lambda_{33}^{\rm LQ}(0)\rvert$ $\times 10^5$	$\frac{\Delta_{33}^L(m_Z^2)}{\Lambda_{\rm SM}^{L\ell}} \times 10^{-5}$
● 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)

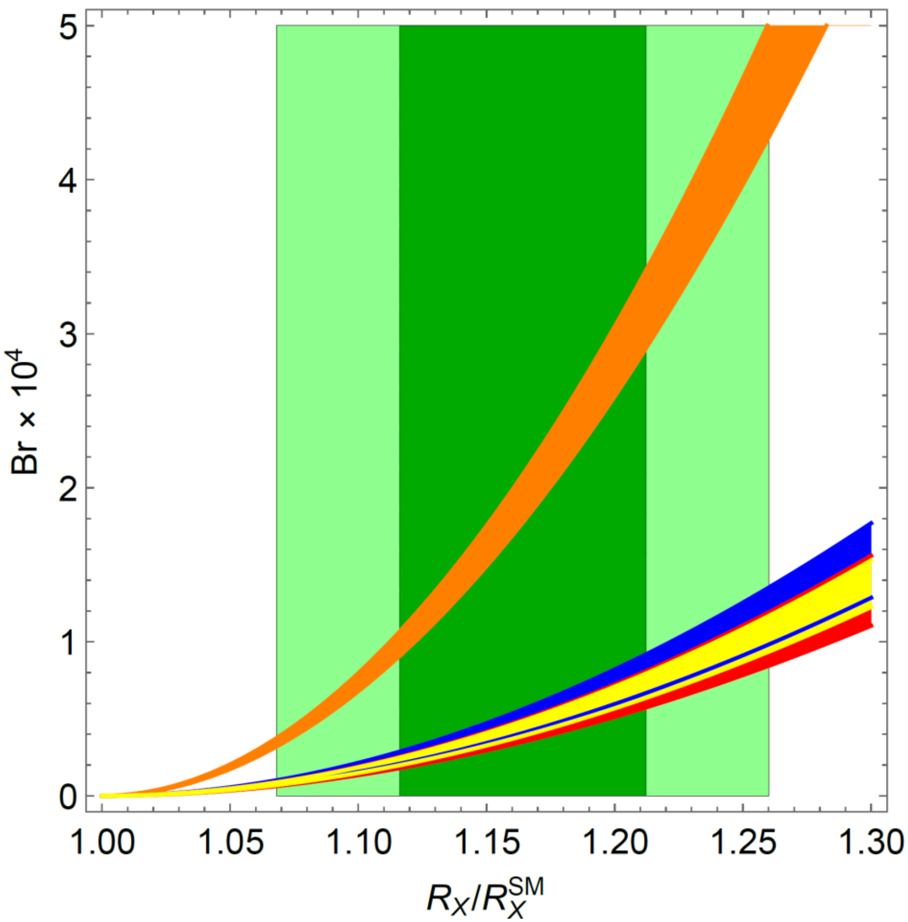


AC, C. Greub, D. Müller, F. Saturnino, PRL 2018

Large loop effects in b→sμμ

R(D$^{(*)}$) and b→sττ

- Large couplings to the second generation



b→sττ very strongly enhanced

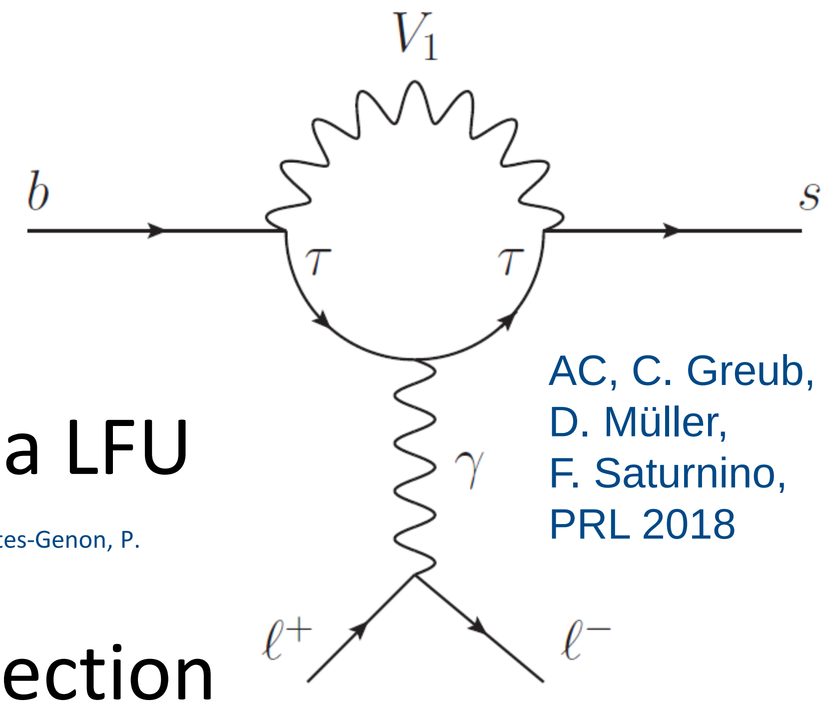
B. Capdevila, AC, S. Descotes-Genon, L. Hofer and J. Matias, PRL.120.181802

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

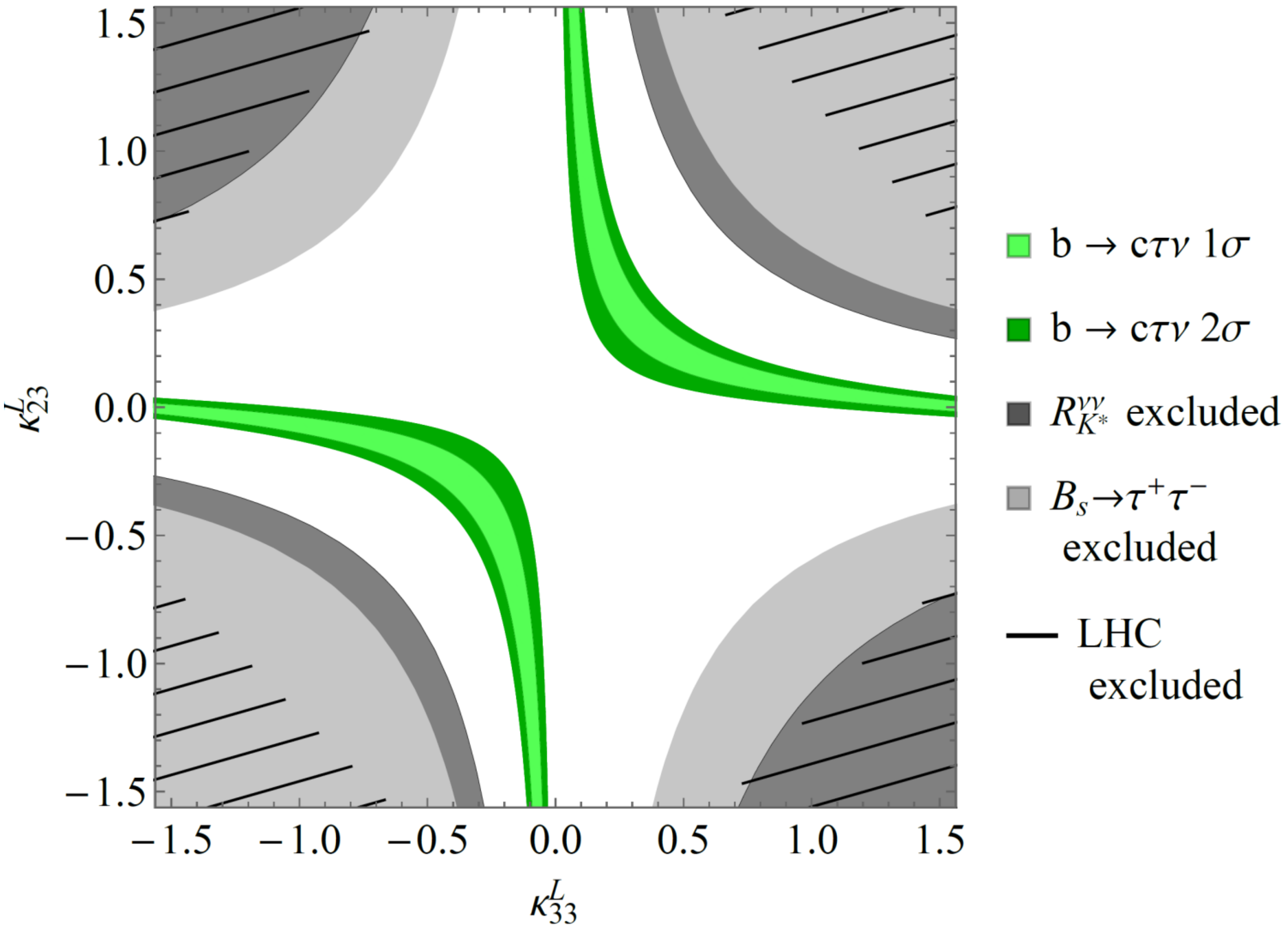
- Effect goes in the right direction



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

τ→μνν

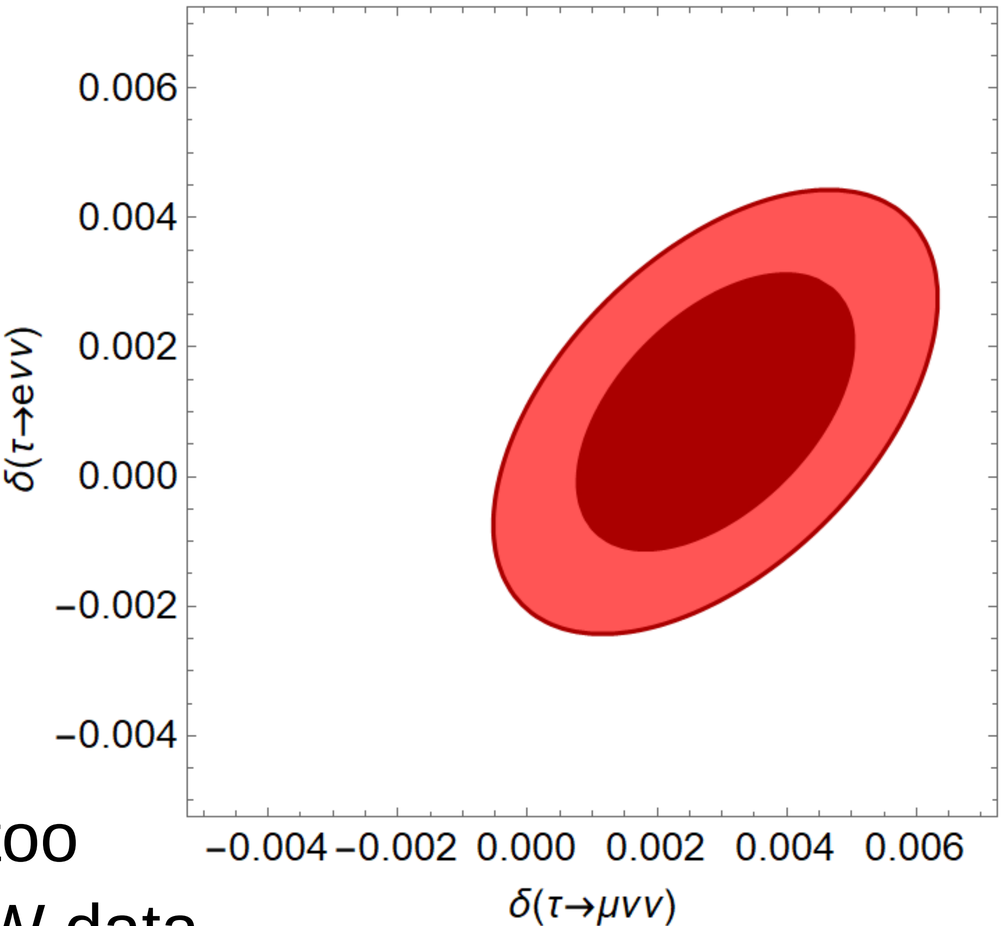
- Ratios of leptonic tau decays

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

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

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

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

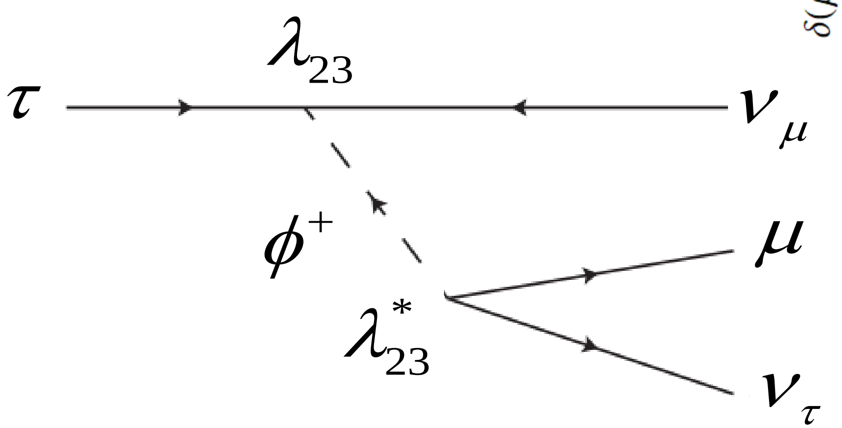


- NP in muon decay too constrained from EW data

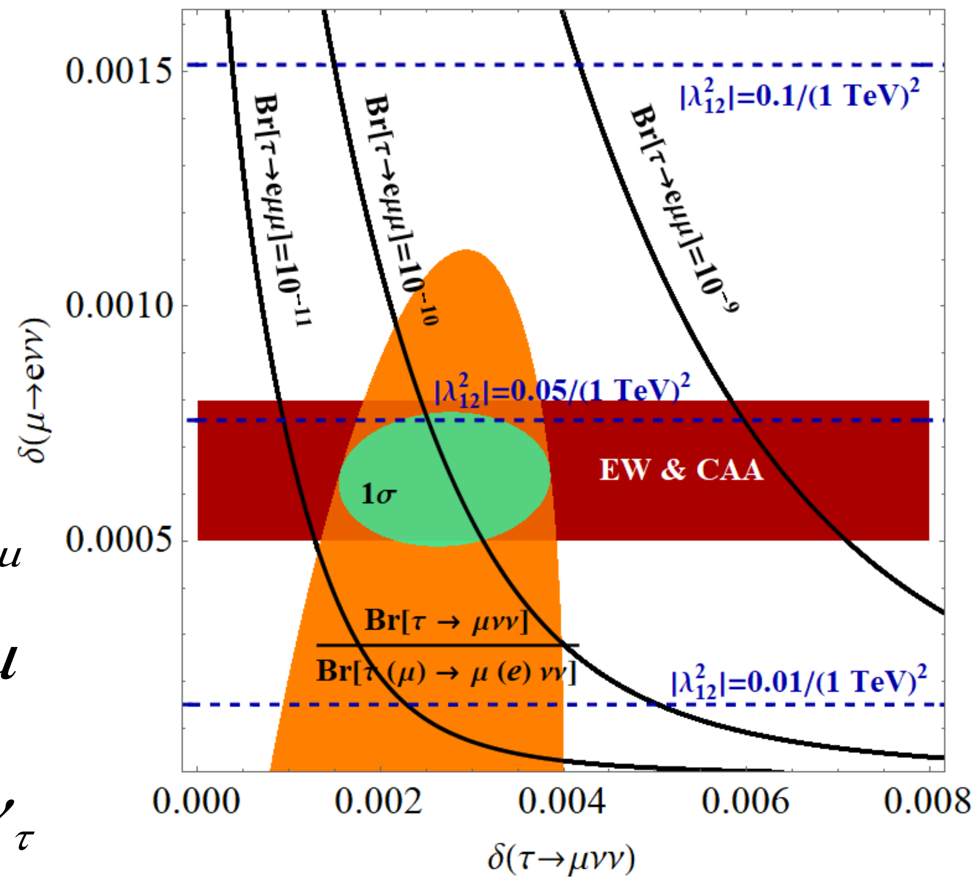
≈2σ hint for LFUV in tau decays

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

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



Singly charged scalar

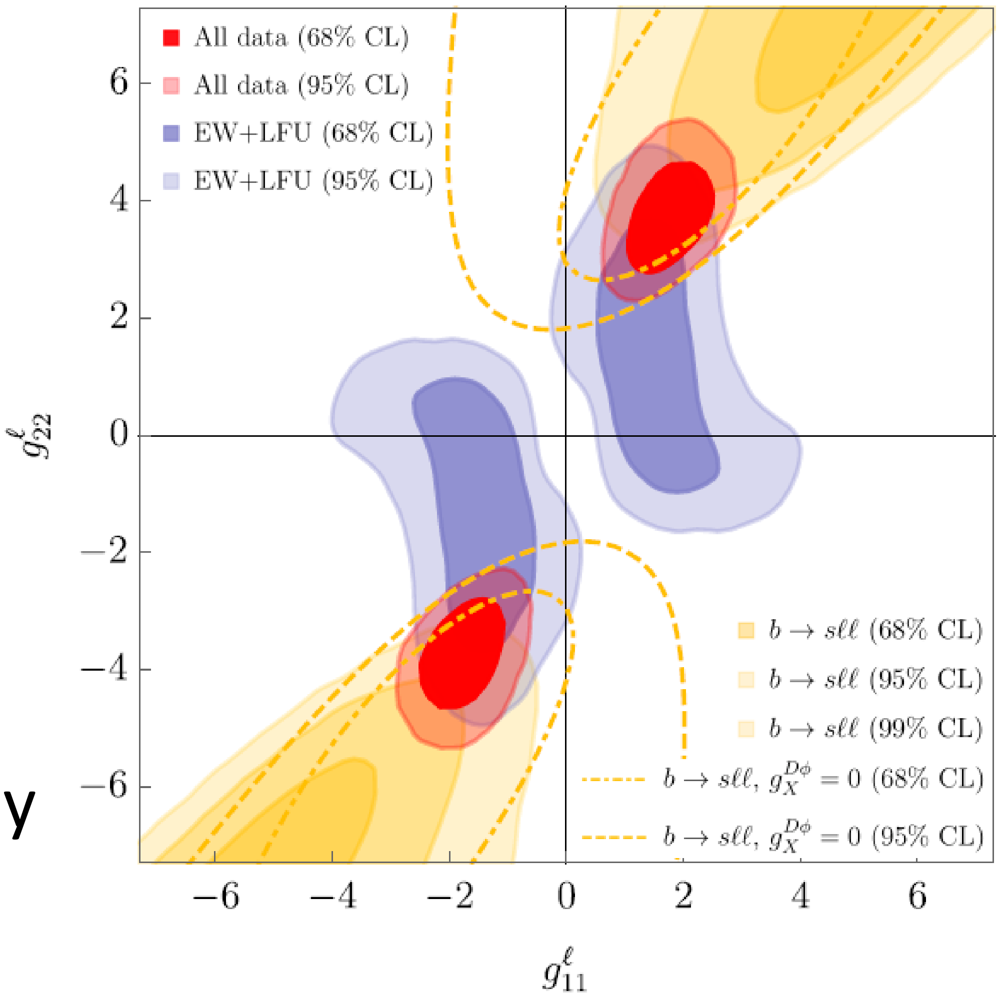


A.C., F. Kirk, C. Manzari, L. Panizzi, arXiv:2012.09845

4σ hint for modified neutrino couplings

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