Explaining the Cabibbo Angle Anomaly

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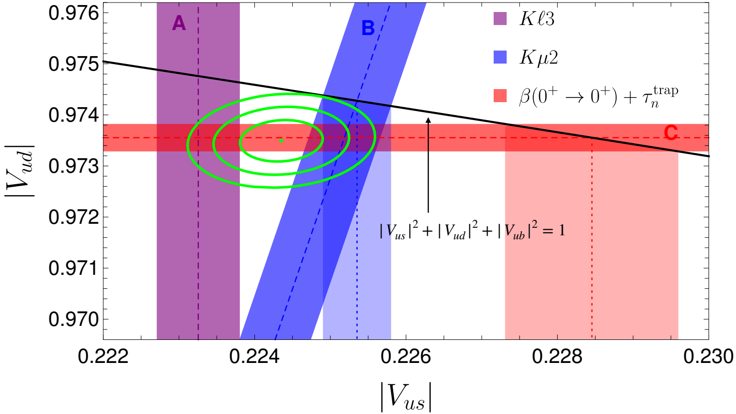
Outline

- The Cabibbo Angle Anomaly
- SMEFT analysis
- Simplified Models
- Conclusions and prospects

The Cabibbo Angle Anomaly I



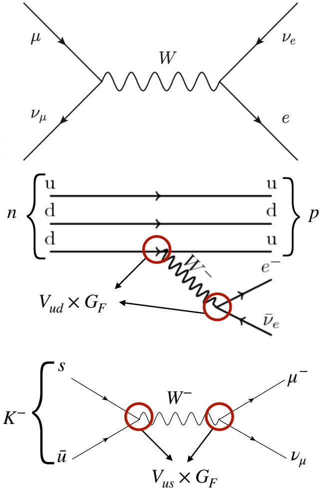
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(5)$$

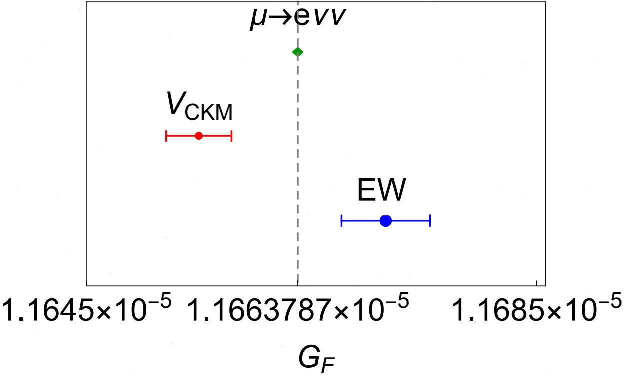
$$\frac{|V_{ud}|^2}{|V_{us}|^2} \approx 20$$

$$|V_{ud}|^2(1-\epsilon)^2 + |V_{us}|^2 + |V_{ub}|^2$$

Note that a deviation from unitarity is also observed in the first column of the CKM matrix $|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 0.9970(18)$, *strengthening the idea of NP related to* V_{ud}

The Cabibbo Angle Anomaly II





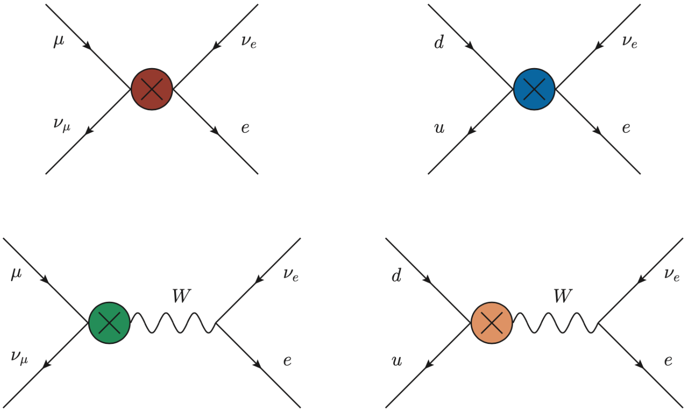
$$G_F^{\mu} = 1.1663787(6) \times 10^{-5}\text{GeV}^{-2}$$

$$G_F^{\text{CKM}} = 1.16550(29) \times 10^{-5}\,\text{GeV}^{-2}$$

SMEFT analysis

BSM explanations can be grouped into 4 classes using an EFT approach with gauge-invariant dimension 6 operators (2102.02825 Crivellin, Hoferichter, C.A.M.)

- four-fermion operators in $\mu \to e\nu\nu$;
- four-fermion operators in $u \to de\nu$;
- modified W-u-d couplings;
- modified W-ℓ-ν couplings.



4-fermion operators in $\mu \to e\nu\nu$

The only viable mechanism to modify the extraction of G_F proceeds via a modification of the SM operator

$$Q_{\ell\ell}^{2112} = \left(\bar{\ell}_2 \gamma^\mu \ell_1\right)\left(\bar{\ell}_1 \gamma^\mu \ell_2\right)$$

To brings data into agreement within 1σ we need

$$C_{\ell\ell}^{2112} = -1.4 \times 10^{-3} G_F$$

Constraints: G_F enters in the computation of EW precision observables
Within the reach of future e^+e^- colliders

4-fermion operators in $u \to de\nu$

We need constructive interference with the SM in β decays. The only possibility is

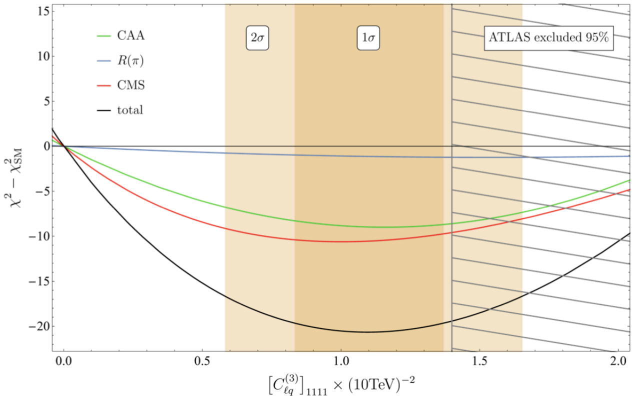
$$Q_{\ell q}^{(3)1111} = (\bar{\ell}_1 \gamma^\mu \tau^I \ell_1)(\bar{q}_1 \gamma^\mu \tau^I q_1)$$

The CAA at 1σ prefers

$$C_{\ell q}^{(3)1111} = \frac{1.22(4)}{(10\text{TeV})^2}$$

CMS $\equiv R_{\frac{e^+e^-}{\mu^+\mu^-}}$ di-lepton searches

$$R_\pi \equiv \frac{\pi \to \mu\nu}{\pi \to e\nu}$$



W-u-d couplings

Here the goal is to modify the extraction of V_{us} and V_{ud} on the quark side. Two solutions are possible

$$Q_{\phi ud}^{ij} = \tilde{\phi} i D_\mu \phi \bar{u}_i \gamma^\mu d_j$$

Generates right-handed W–quark couplings. In addition, a right-handed $W - u - s$ coupling could also account for the difference between $K_{\ell 2}$ and $K\ell 3$ decays

$$Q_{\phi q}^{(3)ij} = \phi^\dagger i \overleftrightarrow{D}_\mu^I \phi \bar{q}_i \gamma^\mu \tau^I q_j$$

Due to $SU(2)_L$ invariance, in general effects in $\Delta F = 2$ processes as well as in Z decays are generated.

W-ℓ-ν couplings

Only one operator generates W-ℓ-ν couplings at tree level

$$Q_{\phi\ell}^{(3)ij} = \phi^\dagger \overleftrightarrow{D}^I_\mu \phi \bar{\ell}_i \gamma^\mu \tau^I \ell_i \, .$$

$C_{\phi\ell}^{(3)11}$ affects β decays and the G_F in the same way $\implies$ no effect on CAA!
$C_{\phi\ell}^{(3)22}$ only enters in muon decay. CAA points to $C_{\phi\ell}^{(3)22} > 0$.

Constraints: EW precision Observables, Tests of Lepton Flavour Universality

Model Building

2 Mechanisms to solve the Cabibbo Angle Anomaly:

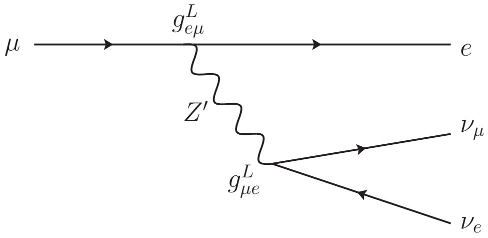
- new physics in G_F:
  - **Singly Charged Scalar Singlet** (2010.14504 Crivellin, M., Algueró, Matias)
  - **Vector-like Leptons** (2008.01113 Crivellin, Kirk, C.A.M., Montull)
  - **Vector Boson Triplet** (2005.13542 Capdevila, Crivellin, C.A.M., Montull)
- new physics in β decay:
  - **Vector Boson Singlet** (2104.07680 Buras, Crivellin, Kirk, C.A.M., Montull)
  - **Vector-like Quarks** (2001.02853 Cheung, Keung, Lu, Tseng)
  - **Vector-like Leptons** (2008.01113 Crivellin, Kirk, C.A.M., Montull)
  - **Vector Boson Triplet** (2005.13542 Capdevila, Crivellin, C.A.M., Montull)

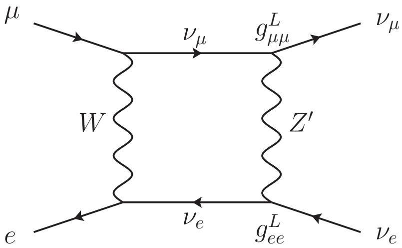
Vector Boson Singlet: Z'

- Constraints: $\mu \to e\gamma$, $\mu \to e$ conversion, EW data, LEP 4-electron bounds

LFU scenario ×

LFUV scenario $\implies$ can alleviate CAA (2104.07680)





Vector-like Quarks I

- 7 possible Vector-like Quarks representations under $SU(3)_C \times SU(2)_L \times U(1)_Y$

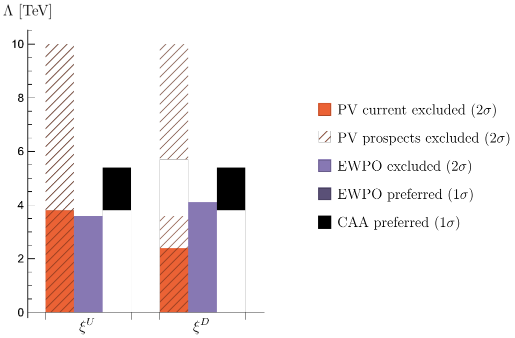
Only 3 of them can generate

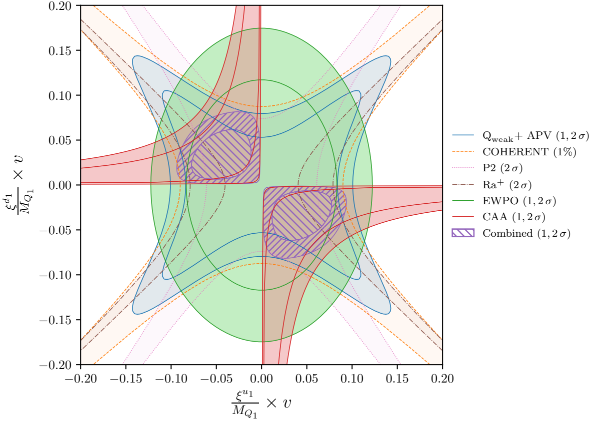
$$C_{\phi q}^{(3)11} < 0 \quad \text{or} \quad C_{\phi ud}^{11} < 0$$

U, D and Q_1 coupling to up- and down-quarks

	$SU(3)$	$SU(2)_L$	$U(1)_Y$
U	3	1	2/3
D	3	1	−1/3
Q_1	3	2	1/6
Q_5	3	2	−5/6
Q_7	3	2	7/6
T_1	3	3	−1/3
T_2	3	3	2/3

Vector-like Quarks II





Regions preferred by the CAA and excluded by EWPO and PV experiments (for couplings fixed to unity on the left).

Vector-like Leptons

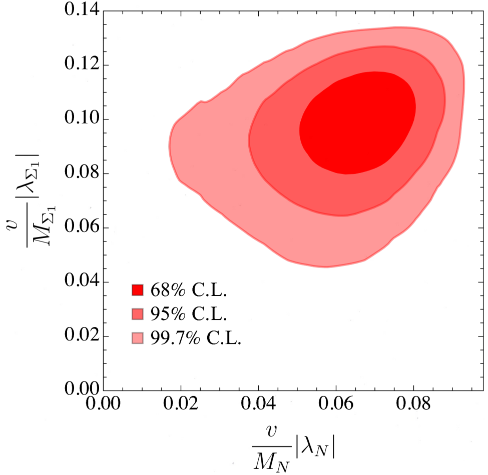
There are 6 possible representations under $U(1)_Y \times SU(2)_L$ generating different patterns of $Q^3_{\phi\ell}$ and $Q^1_{\phi\ell}$. These operators modify W and Z boson couplings

↓

EW precision observables and tests of LFU (π, K, τ decays) have to be considered.

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
ℓ	1	2	-1/2
e	1	1	-1
ϕ	1	2	1/2
N	1	1	0
E	1	1	-1
$\Delta_1 = (\Delta_1^0, \Delta_1^-)$	1	2	-1/2
$\Delta_3 = (\Delta_3^-, \Delta_3^{--})$	1	2	-3/2
$\Sigma_0 = (\Sigma_0^+, \Sigma_0^0, \Sigma_0^-)$	1	3	0
$\Sigma_1 = (\Sigma_1^0, \Sigma_1^-, \Sigma_1^{--})$	1	3	-1

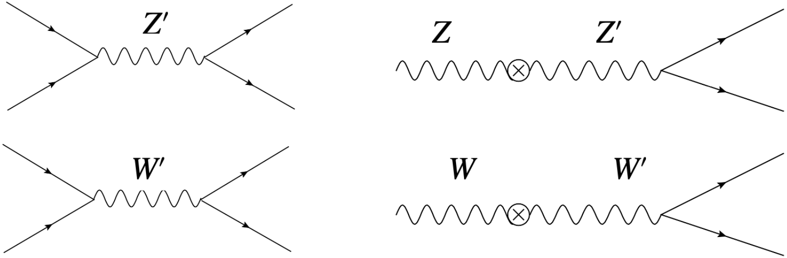
Vector-like Leptons



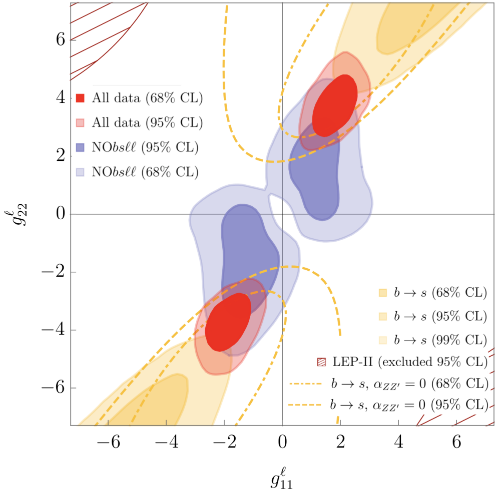
- each representation alone does not improve the fit w.r.t the SM
- there is a **minimal model strongly improving the agreement with data** made of a singlet N coupling with electrons and a triplet Σ_1 coupling with muons! (2008.01113)

Vector Boson Triplet

- $SU(2)_L$ triplet of heavy vector bosons with zero hypercharge: W', Z'
- the W' generates $Q_{\ell\ell}^{2112}$ at tree level and $Q_{\phi\ell}^{(3)}$, $Q_{\phi\ell}^{(1)}$ via $W - W'$ mixing
- **The Z' allows for interesting connections with $b \to s\ell\ell$**



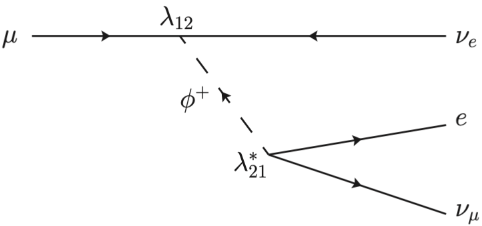
Vector Boson Triplet



- several observables need to be included: CAA, EW data, LFU tests, LHC bounds, parity violation experiments, $b \to s\ell\ell$ and $B_s - \bar{B}_s$
- The global fit improves the agreement with $b \to s\ell\ell$ data by $\approx 5\sigma$ compared to the SM, and solve the CAA. (2005.13542)

The Singly Charged Scalar Singlet

- $SU(2)_L \times SU(3)_C$ singlet with hypercharge $+1$
- can only couple off-diagonally to leptons $\implies$ generates $Q_{\ell\ell}^{2112}$



$$C_{\phi\ell}^{2112} \propto \frac{|\lambda_{12}|^2}{M^2} \overset{!}{>} 0$$

EW Fit + CAA

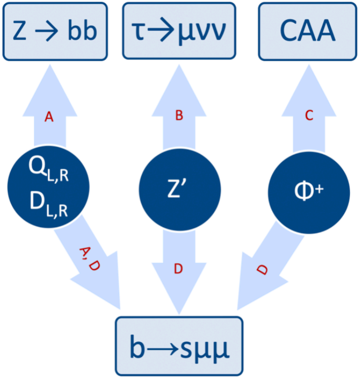
$$|\lambda_{12}|^2 = (0.043 \pm 0.010)\frac{m_{\phi^+}^2}{\text{TeV}^2}$$

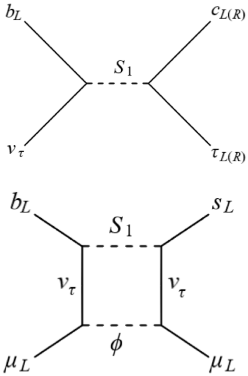
The Singly Charged Scalar Singlet

- it allows very interesting correlations with other observables

$b \to s\ell\ell + Z \to \bar{b}b + \tau \to \mu\nu\nu$ (2010.14504)

$b \to s\ell\ell + (g-2)_\mu$ (2104.05730)

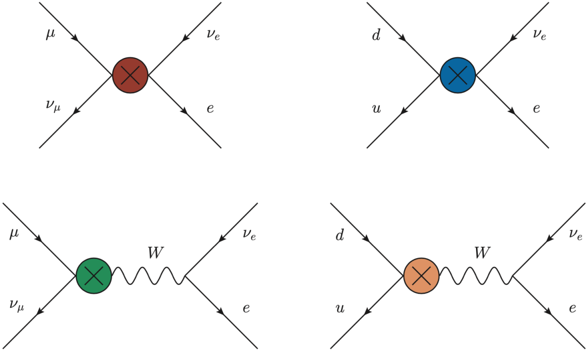




Conclusions

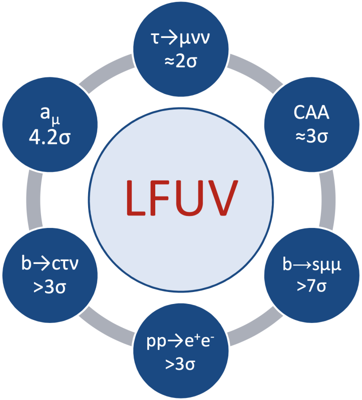
- The Cabibbo Angle Anomaly is a deviation from unitarity observed in the 1^{st} row and column of the CKM matrix at the 3σ level

- If this tension is due to NP, there are only 4 SMEFT operators at the dim-6 level which can explain it



- The NP simplified models able to appropriately generate these operators are: VLQs, VLLs, a Z', a Vector Boson Triplet and a Singly Charged Scalar Singlet
- Interesting model-dependent correlations with other anomalies arise!

- It is worth to look at the CAA as a hint of LFUV!



Backup

Future Prospects

- Improvements in the determination of CKM unitarity:
  a. advances in nuclear-structure and EW radiative corrections treatment
  b. experimental developments in the determination from neutron decay, $K_{\ell 3}$ and complementary constraint on $|V_{ud}|/|V_{us}|$ via pion β decay
  c. improved measurements of $|V_{cd}|$ from D decays to bring the precision of the first column CKM unitarity competitive
- Improvement in a second G_F determination from the EW fit: Belle-II, FCC-ee, ILC, CEPC, or CLIC (m_t and m_W)