Searching for Lepton Flavour (Universality) Violation and Collider Signals from a Singly-Charged Scalar Singlet

Fiona Kirk
based on arXiv:2012.09845 with Andreas Crivellin, Claudio Andrea Manzari and Luca Panizzi

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The Cabibbo Angle Anomaly (CAA)

The Cabibbo angle can be determined from

- $V_{ud}$ from superallowed $\beta$-decays ($0^+ \rightarrow 0^+$-transitions)

  \[ V_{ud} \rightarrow n \rightarrow W^- \rightarrow e \rightarrow \nu_e \]

- $V_{us}$ from $\tau$-decays & from $K$-decays

  \[ V_{us} \rightarrow \nu_\tau \rightarrow W^- \rightarrow \bar{u} \rightarrow K^- \rightarrow \bar{\nu} \rightarrow \pi^0 \]

- $V_{cd}$ from $D \rightarrow \mu\nu$
The Cabibbo Angle Anomaly: Determination of $V_{us}$

\[
|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \Rightarrow V_{us} \sim \sqrt{1 - V_{ud}^2} \quad (V_{ub} \approx 0.0037 \sim 0)
\]

$3 \sigma$ tension (https://pdg.lbl.gov/2020/reviews/rpp2020-rev-vud-vus.pdf)
New Physics Interpretations of the CAA arXiv: 2008.03261

• Direct contributions to $\beta$-decays

• Modified $W_{ud}$-coupling

• Modified $W_{\ell\nu}$-coupling

• Direct contributions to $\mu$-decays
  ⇒ Modified Fermi constant, $G_F$

$$\delta(\mu \to e\bar{\nu}\nu) = \frac{A_{NP}(\mu \to e\bar{\nu}\nu)}{A_{SM}(\mu \to e\bar{\nu}\nu)}$$

⇒ $G_F = G_F^{SM} \left(1 + \delta(\mu \to e\bar{\nu}\nu)\right)$
Resolution of the Cabibbo Angle Anomaly

\[ |V_{ud}|^2 (1 - \delta(\mu \rightarrow e\bar{\nu}\nu))^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(5) \]
Lepton Flavour Universality Violation in $\tau$ decays

$$\frac{A(\tau \rightarrow \mu \bar{\nu} \nu)}{A(\mu \rightarrow e \bar{\nu} \nu)} \bigg|_{\text{EXP}} = 1.0029(14)$$

$$\frac{A(\tau \rightarrow \mu \bar{\nu} \nu)}{A(\tau \rightarrow e \bar{\nu} \nu)} \bigg|_{\text{EXP}} = 1.0018(14)$$

$$\frac{A(\tau \rightarrow e \bar{\nu} \nu)}{A(\mu \rightarrow e \bar{\nu} \nu)} \bigg|_{\text{EXP}} = 1.0010(14)$$

$$\delta(\tau \rightarrow \mu \bar{\nu} \nu) = \frac{A_{NP}(\tau \rightarrow \mu \bar{\nu} \nu)}{A_{SM}(\tau \rightarrow \mu \bar{\nu} \nu)}$$

$$\delta(\tau \rightarrow e \bar{\nu} \nu) = \frac{A_{NP}(\tau \rightarrow e \bar{\nu} \nu)}{A_{SM}(\tau \rightarrow e \bar{\nu} \nu)}$$

Plot for $\delta(\mu \rightarrow e \bar{\nu} \nu) = 0$
The Singly Charged Scalar $\phi^+$

|               | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ | New singly charged scalar |
|---------------|-----------|-----------|----------|---------------------------|
| $\phi^+$      | 1         | 1         | 1        |                           |

$\Rightarrow$ no couplings to quarks, right-handed leptons

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \left( \frac{\lambda_{ij}}{2} \bar{L}_{a,i} \varepsilon_{ab} L_{b,j} \Phi^+ + \text{h.c.} \right)$$

Here

- $a, b$: $SU(2)_L$ indices
- $i, j$: flavour indices

$\varepsilon_{ab} = i \sigma_2 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$

$\Rightarrow$ couplings $\lambda_{ij}$ antisymmetric in flavour

$\Rightarrow$ automatically lepton flavour (universality) violating

Only 4 new parameters: $\lambda_{12}, \lambda_{13}, \lambda_{23}$ and $m_\Phi$
LFV via $\phi^+$: $\ell \rightarrow \ell'\bar{\nu}\nu$

Effect is necessarily constructive:

$$\delta(\mu \rightarrow e\bar{\nu}\nu) = \frac{A_{NP}(\mu \rightarrow e\bar{\nu}\nu)}{A_{SM}(\mu \rightarrow e\bar{\nu}\nu)} = + \left| \frac{\lambda_{12}}{g_2^2} \right|^2 \frac{m_W^2}{m^2_{\phi}} \overset{\text{fit}}{=} 0.00065(15)$$

$$\delta(\tau \rightarrow \mu\bar{\nu}\nu) = \frac{A_{NP}(\tau \rightarrow \mu\bar{\nu}\nu)}{A_{SM}(\tau \rightarrow \mu\bar{\nu}\nu)} = + \left| \frac{\lambda_{23}}{g_2^2} \right|^2 \frac{m_W^2}{m^2_{\phi}} \approx 0.0019$$
More Lepton Flavour Violation via $\phi^+$

Strong constraints from $\mu \rightarrow e\gamma$, $\mu \rightarrow e$ conversion

$\Rightarrow \lambda_{13} \approx 0$ is a useful hypothesis
LHC Searches

$\phi^+$: same quantum numbers as right-handed sleptons

**Drell-Yan Pair Production**

of $\phi^+$, with final state $e^+e^-$ or $\mu^+\mu^-$ & missing transverse energy

\[
\begin{align*}
\text{Br}(\phi^+ \rightarrow e^+\nu) + \text{Br}(\phi^+ \rightarrow \mu^+\nu) & \geq \frac{1}{2} \\
\end{align*}
\]

Recast of ATLAS searches for sleptons with 139/fb data, arXiv:1908.08215 [hep-ex]

Dashed lines: projected exclusion reach for an integrated luminosity of 3/ab at HL-LHC
Scenario with $\lambda_{13} = 0$
(constraints from $\mu \rightarrow e\gamma$, $\mu \rightarrow e$ conv.)

Best fit region for

- EW data & the Cabibbo angle anomaly
- $\tau \rightarrow \mu\bar{\nu}\nu / \tau(\mu) \rightarrow e\bar{\nu}\nu$

... suggests

- $\text{Br}(\tau \rightarrow e\mu\mu) \sim 10^{-10} \frac{m_\phi^4}{(5\text{ TeV})^4}$
- $10^{-11} \lesssim \text{Br}(\tau \rightarrow e\gamma) \lesssim 5 \times 10^{-11}$
- $|\lambda_{12}|^2 \sim \frac{0.05}{(1\text{ TeV})^2}$ (→ mono photon)
Conclusions

The Singly Charged Singlet Scalar $\phi^+$

- can couple to
  - left-handed leptons only
  - only in a flavour off-diag. way ($\lambda_{ij}, i \neq j$)

- is very predictive
  - only 4 free parameters: $\lambda_{12}, \lambda_{13}, \lambda_{23} & m_\phi$
  - can be searched for in low-energy experiments & at colliders

- can explain
  - the Cabibbo Angle Anomaly
  - LFUV in $\tau \rightarrow \mu \bar{\nu} \nu / \tau \rightarrow e \bar{\nu} \nu$

- predicts
  - $\text{Br}(\tau \rightarrow e \mu \mu) \sim 10^{-10} \frac{m_\phi^4}{(5 \text{ TeV})^4}$
  - $10^{-11} \lesssim \text{Br}(\tau \rightarrow e \gamma) \lesssim 5 \times 10^{-11}$
  - $|\lambda_{12}|^2 \sim \frac{0.05}{(1 \text{ TeV})^2} \rightarrow \text{mono photon searches at future } e^+ e^- \text{ colliders}$
Thank you for your Attention