# A Complete Vector-like 4th Family Model for Muon Anomalies

in preparation

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with

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# Outline

1. <u>Introduction</u>

2. Vector-Like 4$^{th}$ Family with Vector-Like U(1)'

3. Phenomenology

4. Conclusion

# Muon Anomalies

➤ Muon $g - 2$

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 2.68\,(63)(43) \times 10^{-9} \quad \sim 3.5\,\sigma$$
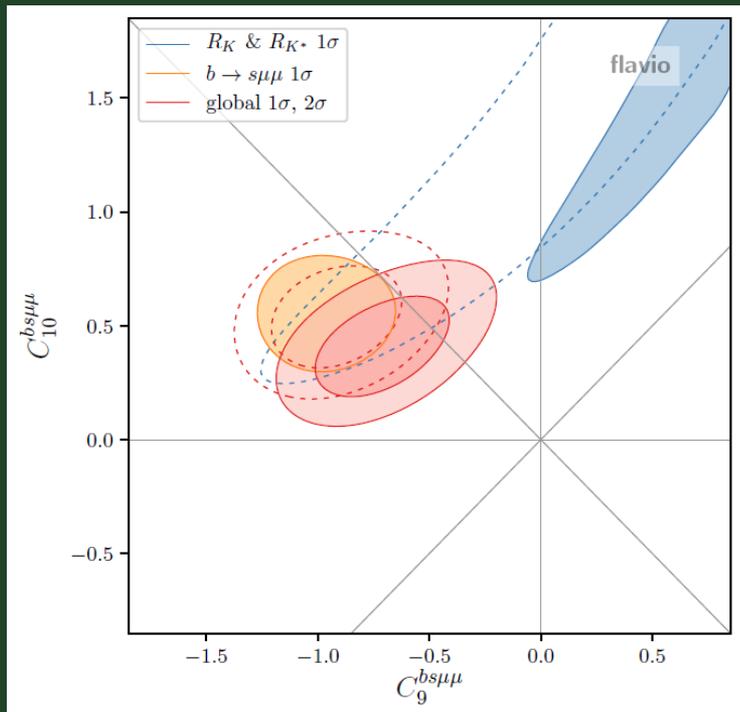
➤ Muon Anomalies for $b \to s\,\mu^+\mu^-$ Processes

- angular observables in $B \to K^*\mu^+\mu^-$      $\sim 3.4\,\sigma$ @LHCb, Belle, ALTAS, CMS

- Lepton Non-Universality $R_{K^{(*)}}$      $\sim 2.5\,\sigma$ below @LHCb, Babar

- branching ratio of $B_s \to \phi\,\mu^+\mu^-$      $\sim 3.5\,\sigma$ below @LHCb

- e.t.c.

# $b \rightarrow s\,\mu^+\mu^-$ Anomalies

➢ These anomalies are understood by

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \sum_{j=9,10} \left(C_j\,\mathcal{O}_j + C_j'\,\mathcal{O}_j'\right) + h.c.$$

$$\mathcal{O}_9^{(')\mu} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)(\bar{\mu}\gamma^\mu \mu) \quad \mathcal{O}_{10}^{(')\mu} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$



➢ global analysis
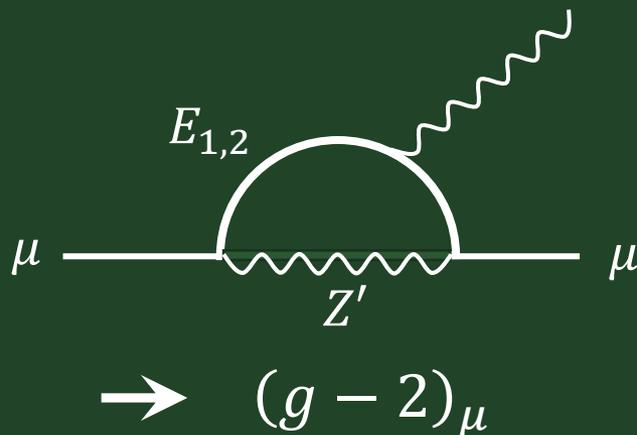
$$(C_9^{NP}, C_{10}) \sim (-0.7, 0.4) \quad \Delta\chi \sim 6.5$$

$$(C_9^{NP}, C_{10}) \sim (-0.5, 0.5) \quad \Delta\chi \sim 6.5$$

$$(C_9^{NP}, C_9') \sim (-1.0, 0.5) \quad \Delta\chi \sim 6.3$$

J. Aebischer, W.Altmannshofer, et.al
1903.10434

# VL-fermion + $U(1)'$

simultaneous explanation for muon anomalies

➢ $U(1)'$ + VL-leptons                    + VL-qaurks



$\rightarrow$    $(g-2)_\mu$              $\rightarrow$    $C_9^{NP}, C_{10}, C_9'$

➢ Models

- $U(1)_{L_\mu - L_\tau}$ + VL-lepton + VL-quark      W.Altmannshofer et.al 1604.08221

- $U(1)_{3-4}$ + VL 4th family          S. Raby, A.Trautner 1712.09360

- ... Allanach, Queiroz et.al 1511.07447, Megias, Quiros et.al 1701.05072

# Outline

# Our Model

➢ Complete Vector-Like 4ᵗʰ Family + $U(1)'$

| | $Q_L$ | $\overline{U}_R$ | $\overline{D}_R$ | $L_L$ | $\overline{E}_R$ | $\overline{N}_R$ | $\overline{Q}_R$ | $U_L$ | $D_L$ | $\overline{L}_R$ | $E_L$ | $N_L$ | $\phi$ | $\Phi$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SU(3)_C$ | 3 | $\overline{3}$ | $\overline{3}$ | 1 | 1 | 1 | $\overline{3}$ | 3 | 3 | 1 | 1 | 1 | 1 | 1 |
| $SU(2)_L$ | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 1 |
| $U(1)_Y$ | $\frac{1}{3}$ | $-\frac{4}{3}$ | $\frac{2}{3}$ | $-1$ | 2 | 0 | $-\frac{1}{3}$ | $\frac{4}{3}$ | $-\frac{2}{3}$ | 1 | $-2$ | 0 | 0 | 0 |
| $U(1)'$ | -1 | +1 | +1 | -1 | +1 | +1 | +1 | -1 | -1 | +1 | -1 | -1 | 0 | -1 |

Vector-Like (VL)-fermions        $\langle\phi\rangle\sim\langle\Phi\rangle\sim\mathrm{TeV}$

- Only the VL-family have $U(1)'$ charge

- All $Z'$- SM particle couplings appear in mass basis

- Unwanted new physics contributions may be evaded

- $U(1)'$ charge is compatible with Pati-Salam gauge group

# Mass Matrix and Couplings

➢ Yukawa interactions and mass matrix

$$-\mathcal{L}_{\text{Yukawa}} = \overline{e}_{R_i}\, Y_e^{ij}\, l_{L_j}\, H + \lambda_e \overline{E}_R L_L H - \lambda'_e \overline{L}_R \widetilde{H} E_L$$

$$+ \lambda_V^L \phi\, \overline{L}_R L_L - \lambda_V^E \phi\, \overline{E}_R E_R + \lambda_i^L \Phi \overline{L}_R l_{L_i} - \lambda_i^E \Phi^* \overline{e}_{R_i} E_L$$

$$\overline{\widehat{E}}_R M_e \widehat{E}_L = \begin{pmatrix} \overline{e}_{R_i} & \overline{E}_R & \overline{E'_R} \end{pmatrix} \begin{pmatrix} Y_e^{ij} H & 0 & \lambda_i^L \Phi \\ 0 & \lambda_e H & \lambda_V^E \phi \\ \lambda_j^L \Phi & \lambda_V^L \phi & \lambda'_e H \end{pmatrix} \begin{pmatrix} e_{L_j} \\ E'_L \\ E_L \end{pmatrix}$$

* similar for neutrino/quark

➢ $Z'$-coupling in mass basis : $U_R^{e\dagger} M_e U_L^e = \text{diag}\left(m_e, m_\mu, m_\tau, m_{E_1}, m_{E_2}\right)$

$$g_{e_L}^{Z\prime} = g' U_L^{e\dagger} \begin{pmatrix} 0_{3\times3} & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} U_L^e \qquad g_{e_R}^{Z\prime} = g' U_R^{e\dagger} \begin{pmatrix} 0_{3\times3} & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} U_R^e$$

rotation matrices determine $Z'$-couplings to the SM families

# Towards Grand Unification

➢ UV-completion of model

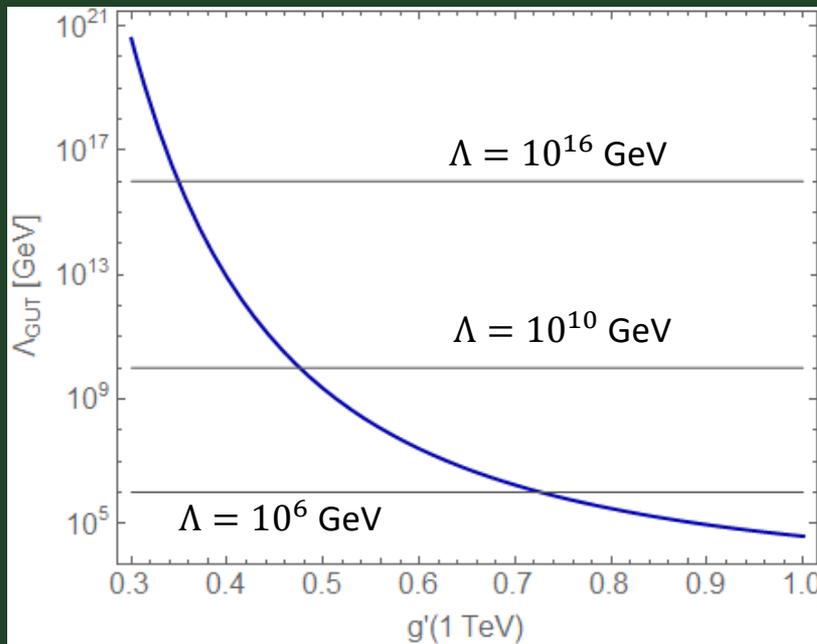- extra VL-family, extra U(1)' often appear in GUT/string model
  0409098, 0606187, 0708.2691, 1211.4317

- Complete family may be easily embedded into GUT models

➢ Gauge coupling constant running



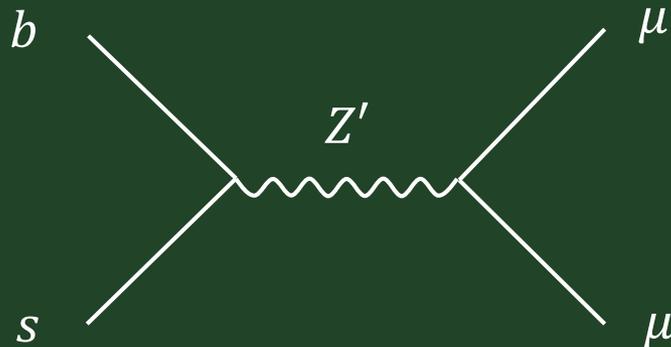$$\frac{d\,g'}{d\,\ln\mu} = \frac{65}{3} \cdot \frac{g'^3}{16\pi^2}$$

- Landau pole easily appear

- $g' \lesssim 1/3$ for $\Lambda \sim 10^{16}$ GeV

- $g' \lesssim 1/2$ for $\Lambda \sim 10^{10}$ GeV

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3. <u>Phenomenology</u>

4. Conclusion

# Quark Sector

➤ $b \rightarrow s\mu^+\mu^-$ anomalies



$$C_9^{NP} \sim -0.64 \times \left(\frac{1 \text{ TeV}}{m_{Z'}}\right)^2 \left(\frac{g_{\mu\mu}^V \cdot g_{bs}^L}{0.001}\right)$$

$$g_{bs}^{Z'} \sim g'\left[U_d^\dagger\right]_{bD_i}[U_d]_{D_i s}$$

$$g_{\mu\mu}^{Z'} \sim g'\left[U_e^\dagger\right]_{\mu E_i}[U_e]_{E_i \mu}$$

rotation matrices determine $Z'$-couplings to the SM families

➤ CKM matrix and SM-boson couplings

$$5 \times 5 \text{ "CKM" matrix} \quad V_{CKM} = U_u^\dagger \begin{pmatrix} 1_{3\times3} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} U_d$$

- CKM matrix is NOT unitary

- Unitarity recovers as $v_H/v_\Phi \rightarrow 0$, Z/h-boson couplings as well

# $\chi^2$-Fitting

➤ **65 parameters**

  2 mass parameters $m_{Z'}$, $v_\phi$, 59 couplings, 4 phases in Yukawa

  ⬇

➤ **98 observables**

- SM fermion mass, $V_{CKM}$

- SM lepton/boson/top decays

- LFV decays

- Meson mixing, rare B/K decays

- $\Delta a_\mu$

- $C_9^{NP}$, $C_{10}$, $C'_{9,10}$

⬇

Minimizing $\quad \chi^2 = \sum_{i=1}^{98} \frac{\left(x_i - x_i^0\right)^2}{\sigma_i^2}$

$x_i$ model prediction

$x_i^0$: exp. value/SM value

$\sigma_i$: uncertainty

# Best Fitted Points

| Observables | BestFit I $g' < 1/2$ | BestFit II $g' < 1/3$ | Data/Remark |
|---|---|---|---|
| $\chi^2/\text{d.o.f}$ | 0.698 | 0.707 | $N_{obs} = 98, N_{inp} = 65$ |
| $g'$ | 0.499 | 0.333 | |
| $m_{Z'}, m_\chi$ [GeV] | $500, 448$ | $442, 445$ | $\chi$ is $U(1)'$ Higgs |
| $\Delta a_\mu$ | $2.58 \times 10^{-9}$ | $2.71 \times 10^{-9}$ | $2.68(76) \times 10^{-9}$ |
| $(\text{Re}C_9^\mu, \text{Re}C_{10}^\mu)$ | $(-0.55, 0.51)$ | $(-0.63, 0.42)$ | |
| $\Delta M_d, \Delta M_s$ [ps$^{-1}$] | $0.602, 19.6$ | $0.606, 19.7$ | $0.507(81), 17.8(2.5)$ |
| $m_{E_1}, m_{N_1}$ [GeV] | $(452, 588)$ | $(507, 704)$ | $\gtrsim 500$ |
| $m_{U_1}, m_{D_1}$ [GeV] | $(2484, 1906)$ | $(1936, 3406)$ | $\gtrsim 1000$ |

The other observables are fitted as pull $< 2\,\sigma$

$$m_{Z'}, m_\chi, m_{E_1} \sim 500 \text{ GeV}$$

# Dimuon $Z'$ Search at LHC

$$\sigma_{fid}(pp \to Z' \to \mu^+\mu^-) = 1.18 \text{ (I)}, 1.68 \text{ (II) [fb]}$$

MadGraph5
FeynRules

**Fiducial region**

$p_T(l) > 30 \text{ [GeV]}$
$|\eta(l)| < 2.5$
$m_{ll} > m_{Z'} - 2\Gamma_{Z'}$

# VL-lepton mass



$m_{Z'} < 600$ GeV, $m_{E_1} < 500$ GeV for $\Delta a_\mu \sim 2.68 \times 10^{-9}$

# Summary

- SM extension via complete Vector-Like 4$^{\text{th}}$ family and $U(1)'$

- All $Z'$ couplings to SM particles are controlled by mixing

- The muon anomalies can be explained

- Consistent with current limits from LHC, variety of new signals

work in progress…

Thank you for attention

Backup

# $Z'$ mass and $U(1)'$ coupling



best point (I) can be excluded if sensitivity will be improved double

# VL-quark mass



$(C_9^{NP}, C_{10}) \sim (-0.55, 0.55)$ kept even for heavy VL-quark

## Mass and Decays at best(I)

| particle | mass [GeV] | width [GeV] | decay I | Br | decay II | Br |
|----------|-----------|-------------|---------|-----|----------|-----|
| $Z'$ | 500.0 | 1.90 | $\mu\mu$ | 49.6% | $\nu\nu$ | 49.5 % |
| $\chi$ | 447.8 | $1.9 \times 10^{-4}$ | $tt$ | 99.8% | $\mu\mu$ | 0.06 % |
| $\sigma$ | 3292 | 0.028 | $E_1 E_1$ | 27.0% | $D_2 t$ | 15.2 % |
| $E_1$ | 451.6 | $3.8 \times 10^{-5}$ | $\chi\mu$ | 95.4 % | $h\mu$ | 3.8% |
| $N_1$ | 588.0 | 2.37 | $W E_1$ | 94.3 % | $Z'\nu$ | 2.95% |
| $E_2$ | 647.9 | 3.01 | $Z\mu$ | 74.2 % | $h\mu$ | 18.6% |
| $N_2$ | 3164 | 8.95 | $W E_2$ | 39.0 % | $h N_1$ | 25.0 % |
| $D_1$ | 1907 | 0.016 | $Z'b$ | 51.5 % | $\chi b$ | 46.6 % |
| $D_2$ | 2485 | 6.66 | $Z'b$ | 46.8 % | $\chi b$ | 44.1% |
| $U_1$ | 2485 | 6.66 | $Z't$ | 46.9% | $\chi t$ | 44.1 % |
| $U_2$ | 11742 | 0.081 | $W D_2$ | 44.8 % | $h U_1$ | 22.4 % |

# Mass and Decays at best(II)

| particle | mass [GeV] | width [GeV] | decay I | Br | decay II | Br |
|---|---|---|---|---|---|---|
| $Z'$ | 442.0 | 0.35 | $\mu\mu$ | 50.7% | $\nu\nu$ | 48.6 % |
| $\chi$ | 445.0 | $1.9 \times 10^{-4}$ | $tt$ | 98.9% | $tc$ | 0.96 % |
| $\sigma$ | 1421 | $6.4 \times 10^{-3}$ | $E_1 E_1$ | 30.6% | $N_1 \nu$ | 30.2 % |
| $E_1$ | 507.4 | 0.020 | $Z'\mu$ | 73.1 % | $\chi\mu$ | 26.7 % |
| $N_1$ | 703.6 | 4.34 | $W E_1$ | 88.5 % | $Z'\nu$ | 7.43% |
| $E_2$ | 746.2 | 4.64 | $Z E_1$ | 57.9 % | $h E_1$ | 30.2% |
| $N_2$ | 23150 | 0.76 | $W E_2$ | 44.4 % | $Z N_1$ | 24.9 % |
| $U_1$ | 1936 | $6.3 \times 10^{-4}$ | $Z't$ | 29.6 % | $\chi t$ | 24.1 % |
| $D_1$ | 3406 | 13.3 | $Z'b$ | 46.2 % | $\chi b$ | 44.7% |
| $U_2$ | 3406 | 13.3 | $Z't$ | 46.5% | $\chi t$ | 45.0 % |
| $D_2$ | 13053 | 0.085 | $W D_2$ | 44.4 % | $h D_1$ | 22.4 % |

# $B - Z'$ mixing

$$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$



VL-family

$$\epsilon \sim \frac{g_Y g'}{6\pi^2} \text{Log}\left(\frac{M_E^2}{M_L^2} \cdot \frac{M_Q^2 M_D^2}{M_U^4}\right)$$

$$\sim 0.005 \text{ (I)}, 0.009 \text{ (II)}$$

# $(g-2)_\mu$ and $U(1)'$ charge

➢ Contribution to $\Delta a_\mu$



$$\Delta a_\mu \sim 1.3 \times 10^{-9} \sum_{k=1,2} \left(\frac{g_L^k g_R^k}{10^{-3}}\right)\left(\frac{m_{E_k}}{1\text{ TeV}}\right)\left(\frac{1\text{ TeV}}{m_{Z'}}\right)^2$$

both left and right interactions are necessary

$$\left(\overline{\mu}_R \quad \overline{E}_R \quad \overline{E'}_R\right) \begin{pmatrix} m_\mu & 0 & \lambda_i^E \Phi \\ 0 & \lambda_e H & \lambda_V^E \phi \\ \lambda_j^L \Phi & \lambda_V^L \phi & \boxed{\lambda'_e H} \end{pmatrix} \begin{pmatrix} \mu_L \\ E'_L \\ E_L \end{pmatrix}$$

VL-lepton/Higgs couplings

$$\lambda_e \overline{E}_R L_L H - \lambda'_e \overline{L}_R \widetilde{H} E_L$$

are mandatory

$\lambda_e = 0.$

# $(g-2)_\mu$ and $U(1)'$ charge

➤ To write $\lambda_e \overline{E}_R L_L H - \lambda'_e \overline{L}_R \widetilde{H} E_L$

|  | $Q_L$ | $\overline{U}_R$ | $\overline{D}_R$ | $L_L$ | $\overline{E}_R$ | $\overline{N}_R$ | $\overline{Q}_R$ | $U_L$ | $D_L$ | $\overline{L}_R$ | $E_L$ | $N_L$ | $\phi$ | $\Phi$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SU(3)_C$ | 3 | $\overline{3}$ | $\overline{3}$ | 1 | 1 | 1 | $\overline{3}$ | 3 | 3 | 1 | 1 | 1 | 1 | 1 |
| $SU(2)_L$ | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 1 |
| $U(1)_Y$ | $\frac{1}{2}$ | $-\frac{4}{3}$ | $\frac{2}{3}$ | $-1$ | 2 | 0 | $-\frac{1}{2}$ | $\frac{4}{3}$ | $-\frac{2}{3}$ | 1 | $-2$ | 0 | 0 | 0 |
| $U(1)'$ | -1 | +1 | +1 | -1 | +1 | +1 | +1 | -1 | -1 | +1 | -1 | -1 | 0 | -1 |

✓ cannot be like below

| $U(1)'$ | -1 | -1 | -1 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | -1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

➤ $SU(5)$ vs Pati-Salam $G_{\mathrm{PS}} = SU(4) \times SU(2) \times SU(2)$

$\times$ $(L_L, \overline{D}_R) \in \overline{5}$,      $(Q_L, \overline{U}_R, \overline{E}_R) \in 10$      in $SU(5)$

○ $(Q_L \quad L_L) \in (4, 2, 1)$, $\begin{pmatrix} \overline{D}_R & \overline{E}_R \\ \overline{U}_R & \overline{N}_R \end{pmatrix} \in (\overline{4}, 1, 2)$   in Pati-Salam

# CKM matrix

➢ CKM from independent measurement

$$|V_{CKM}| = \begin{pmatrix} 0.9742 & 0.2243 & 0.00394 \\ 0.218 & 0.997 & 0.04228 \\ 0.0081 & 0.0394 & 1.019 \end{pmatrix}_{PDG}$$

➢ CKM global fit (assuming unitarity)

$$|V_{CKM}| = \begin{pmatrix} 0.97446 & 0.22452 & 0.00365 \\ 0.22438 & 0.97359 & 0.04214 \\ 0.00896 & 0.04133 & 0.999105 \end{pmatrix}_{PDG}$$

➢ Our best-fit point CLL

$$|V_{CKM}| = \begin{pmatrix} 0.9745 & 0.2245 & 0.00362 \\ 0.2244 & 0.9736 & 0.04168 \\ 0.00886 & 0.0410 & 0.9991 \end{pmatrix}$$

- tried to fit indep. result

- well fitted to global fit

- CP-phases are also fitted

# Neutrino Mass

➢ Majorana mass for $\nu_{R_{1,2,3}}$, $M_R \sim 10^{14}$ GeV

$$M_{Dirac} = \begin{pmatrix} Y_\nu^{ij}H & 0_i & \lambda_i^N\Phi \\ 0_j & \lambda_\nu H & \lambda_V^N\phi \\ \lambda_j^L\Phi & \lambda_V^L\phi & \lambda_\nu'H \end{pmatrix} \xrightarrow{U_L} \tilde{M}_{Dirac} = \begin{pmatrix} \tilde{Y}_\nu^{ij}H & \tilde{\lambda}^N_{\ i}H & \lambda_i^N\Phi \\ 0_j & 0 & \lambda_V^N\phi \\ 0 & \tilde{M}_L & \tilde{m}_5 \end{pmatrix}$$

Majorana mass

$$M_{10\times10} = \begin{pmatrix} M_R & 0 & 0 & \tilde{Y}_\nu^{ij}H & \tilde{\lambda}^N_{\ i}H & \lambda_i^N\Phi \\ 0 & 0 & 0 & 0_j & 0 & \lambda_V^N\phi \\ 0 & 0 & 0 & 0 & \tilde{M}_L & \tilde{m}_5 \\ \tilde{Y}_\nu^{ij}H & 0_i & 0 & 0_{3\times3} & 0 & 0 \\ \tilde{\lambda}^N_{\ i}H & 0 & \tilde{M}_L & 0 & 0 & 0 \\ \lambda_i^{N^T}\Phi & \lambda_V^N\phi & \tilde{m}_5 & 0 & 0 & 0 \end{pmatrix}$$

decoupled by $M_R$

Dirac neutrino $\sim$ TeV

SM neutrino $\sim v_H^2/M_R$

# Full list of observables best(1)-1/5

| name | value | data | Unc. | pull |
|------|-------|------|------|------|
| $m_e(m_Z)$ [GeV] | $4.866 \times 10^{-4}$ | $4.866 \times 10^{-4}$ | $4.866 \times 10^{-8}$ | 0.000 |
| $m_\mu(m_Z)$ [GeV] | 0.103 | 0.103 | $1.027 \times 10^{-5}$ | 0.001 |
| $m_\tau(m_Z)$ [GeV] | 1.75 | 1.75 | $1.746 \times 10^{-4}$ | 0.001 |
| $\mathrm{Br}\,(\mu \to e\nu\bar{\nu})$ | 1.000 | 1.000 | $1.000 \times 10^{-4}$ | 0.000 |
| $\mathrm{Br}\,(\mu^- \to e^- e^+ e^-)$ | 0.000 | 0.000 | $7.803 \times 10^{-13}$ | 0.000 |
| $\mathrm{Br}\,(\mu \to e\gamma)$ | $5.684 \times 10^{-18}$ | 0.000 | $3.277 \times 10^{-13}$ | 0.000 |
| $\mathrm{Br}\,(\tau \to e\nu\bar{\nu})$ | 0.179 | 0.179 | $1.785 \times 10^{-5}$ | 0.000 |
| $\mathrm{Br}\,(\tau \to \mu\nu\bar{\nu})$ | 0.174 | 0.174 | $1.736 \times 10^{-5}$ | 0.000 |
| $\mathrm{Br}\,(\tau^- \to e^- e^+ e^-)$ | 0.000 | 0.000 | $2.107 \times 10^{-8}$ | 0.000 |
| $\mathrm{Br}\,(\tau^- \to e^- \mu^+ e^-)$ | 0.000 | 0.000 | $1.170 \times 10^{-8}$ | 0.000 |
| $\mathrm{Br}\,(\tau^- \to \mu^- e^+ \mu^-)$ | 0.000 | 0.000 | $1.327 \times 10^{-8}$ | 0.000 |
| $\mathrm{Br}\,(\tau^- \to \mu^- \mu^+ \mu^-)$ | 0.000 | 0.000 | $1.639 \times 10^{-8}$ | 0.000 |
| $\mathrm{Br}\,(\tau^- \to e^- \mu^+ \mu^-)$ | 0.000 | 0.000 | $2.107 \times 10^{-8}$ | 0.000 |
| $\mathrm{Br}\,(\tau^- \to \mu^- e^+ e^-)$ | 0.000 | 0.000 | $1.405 \times 10^{-8}$ | 0.000 |
| $\mathrm{Br}\,(\tau \to e\gamma)$ | 0.000 | 0.000 | $2.575 \times 10^{-8}$ | 0.000 |
| $\mathrm{Br}\,(\tau \to \mu\gamma)$ | 0.000 | 0.000 | $3.433 \times 10^{-8}$ | 0.000 |
| $\Delta a_e$ | 0.000 | $-8.700 \times 10^{-13}$ | $3.600 \times 10^{-13}$ | 2.417 |
| $\Delta a_\mu$ | $2.666 \times 10^{-9}$ | $2.680 \times 10^{-9}$ | $7.600 \times 10^{-10}$ | 0.019 |

# Full list of observables best(1)-2/5

| name | value | data | Unc. | pull |
|---|---|---|---|---|
| $\mathrm{Br}\left(W^+ \to e^+\nu\right)$ | 0.109 | 0.109 | $1.086\times10^{-4}$ | 0.000 |
| $\mathrm{Br}\left(W^+ \to \mu^+\nu\right)$ | 0.109 | 0.109 | $1.086\times10^{-4}$ | 0.000 |
| $\mathrm{Br}\left(W^+ \to \tau^+\nu\right)$ | 0.109 | 0.109 | $1.085\times10^{-4}$ | 0.000 |
| $\mathrm{Br}\left(W \to \mathrm{had}\right)$ | 0.652 | 0.666 | 0.0253 | 0.550 |
| $\mathrm{Br}\left(W^+ \to c\bar{s}\right)$ | 0.309 | 0.324 | 0.0324 | 0.463 |
| $\mathrm{Br}\left(Z \to e^+e^-\right)$ | 0.0333 | 0.0333 | $6.216\times10^{-5}$ | 0.000 |
| $\mathrm{Br}\left(Z \to \mu^+\mu^+\right)$ | 0.0333 | 0.0333 | $6.216\times10^{-5}$ | 0.000 |
| $\mathrm{Br}\left(Z \to \tau^+\tau^+\right)$ | 0.0333 | 0.0333 | $6.203\times10^{-5}$ | 0.000 |
| $\mathrm{Br}\left(Z \to \mathrm{had}\right)$ | 0.676 | 0.677 | 0.0254 | 0.014 |
| $\mathrm{Br}\left(Z \to u\bar{u} + c\bar{c}\right)/2$ | 0.116 | 0.116 | $4.349\times10^{-3}$ | 0.000 |
| $\mathrm{Br}\left(Z \to d\bar{d} + s\bar{s} + b\bar{b}\right)/3$ | 0.148 | 0.148 | $5.574\times10^{-3}$ | 0.000 |
| $\mathrm{Br}\left(Z \to c\bar{c}\right)$ | 0.116 | 0.116 | $4.348\times10^{-3}$ | 0.000 |
| $\mathrm{Br}\left(Z \to b\bar{b}\right)$ | 0.148 | 0.148 | $5.559\times10^{-3}$ | 0.000 |
| $\mathrm{Br}\left(Z \to e^+\mu^-\right)$ | 0.000 | 0.000 | $4.560\times10^{-7}$ | 0.000 |
| $\mathrm{Br}\left(Z \to e^+\tau^-\right)$ | 0.000 | 0.000 | $5.958\times10^{-6}$ | 0.000 |
| $\mathrm{Br}\left(Z \to \mu^+\tau^-\right)$ | 0.000 | 0.000 | $7.295\times10^{-6}$ | 0.000 |
| $A_e$ | 0.147 | 0.147 | $1.468\times10^{-3}$ | 0.000 |
| $A_\mu$ | 0.147 | 0.147 | 0.0147 | 0.000 |
| $A_\tau$ | 0.147 | 0.147 | $1.468\times10^{-3}$ | 0.000 |
| $A_s$ | 0.941 | 0.941 | 0.0941 | 0.000 |
| $A_c$ | 0.695 | 0.695 | $6.949\times10^{-3}$ | 0.000 |
| $A_b$ | 0.941 | 0.941 | $9.406\times10^{-3}$ | 0.000 |
| $\mu_{\mu\mu}$ | 0.977 | 0.000 | 1.30 | 0.751 |
| $\mu_{\tau\tau}$ | 0.981 | 1.12 | 0.230 | 0.606 |
| $\mu_{bb}$ | 0.842 | 0.950 | 0.220 | 0.491 |
| $\mu_{\gamma\gamma}$ | 1.00 | 1.16 | 0.180 | 0.862 |
| $\mathrm{Br}\left(h \to e^+e^-\right)$ | $4.779\times10^{-9}$ | 0.000 | $1.155\times10^{-3}$ | 0.000 |
| $\mathrm{Br}\left(h \to e^+\mu^-\right)$ | 0.000 | 0.000 | $2.128\times10^{-4}$ | 0.000 |
| $\mathrm{Br}\left(h \to e^+\tau^-\right)$ | 0.000 | 0.000 | $4.195\times10^{-3}$ | 0.000 |
| $\mathrm{Br}\left(h \to \mu^+\tau^-\right)$ | 0.000 | 0.000 | $8.694\times10^{-3}$ | 0.000 |

# Full list of observables best(1)-3/5

| name | value | data | Unc. | pull |
|---|---|---|---|---|
| $m_u(m_Z)$ [GeV] | $1.329 \times 10^{-3}$ | $1.288 \times 10^{-3}$ | $3.917 \times 10^{-4}$ | 0.104 |
| $m_c(m_Z)$ [GeV] | 0.627 | 0.627 | 0.0192 | 0.000 |
| $m_t(m_Z)$ [GeV] | $1.717 \times 10^{+2}$ | $1.717 \times 10^{+2}$ | 1.51 | 0.037 |
| $m_d(m_Z)$ [GeV] | $2.755 \times 10^{-3}$ | $2.751 \times 10^{-3}$ | $2.873 \times 10^{-4}$ | 0.013 |
| $m_s(m_Z)$ [GeV] | 0.0543 | 0.0543 | $2.873 \times 10^{-3}$ | 0.008 |
| $m_b(m_Z)$ [GeV] | 2.85 | 2.85 | 0.0261 | 0.021 |
| $|V_{ud}|$ | 0.974 | 0.974 | $2.100 \times 10^{-4}$ | 1.262 |
| $|V_{us}|$ | 0.225 | 0.224 | $5.000 \times 10^{-4}$ | 0.420 |
| $|V_{ub}|$ | $3.594 \times 10^{-3}$ | $3.940 \times 10^{-3}$ | $3.600 \times 10^{-4}$ | 0.961 |
| $|V_{cd}|$ | 0.224 | 0.218 | $4.000 \times 10^{-3}$ | 1.592 |
| $|V_{cs}|$ | 0.974 | 0.997 | 0.0170 | 1.375 |
| $|V_{cb}|$ | 0.0415 | 0.0422 | $8.000 \times 10^{-4}$ | 0.873 |
| $|V_{td}|$ | $8.777 \times 10^{-3}$ | $8.100 \times 10^{-3}$ | $5.000 \times 10^{-4}$ | 1.353 |
| $|V_{ts}|$ | 0.0407 | 0.0394 | $2.300 \times 10^{-3}$ | 0.575 |
| $|V_{tb}|$ | 0.999 | 1.02 | 0.0250 | 0.795 |
| $\alpha$ | 1.53 | 1.47 | 0.0969 | 0.578 |
| $\sin 2\beta$ | 0.697 | 0.691 | 0.0170 | 0.325 |
| $\gamma$ | 1.23 | 1.28 | 0.0812 | 0.706 |

# Full list of observables best(1)-4/5

| name | value | data | Unc. | pull |
|------|-------|------|------|------|
| $\Delta M_K \ [\mathrm{ps}^{-1}]$ | $4.605 \times 10^{-3}$ | $5.293 \times 10^{-3}$ | $2.170 \times 10^{-3}$ | 0.317 |
| $\epsilon_K$ | $2.230 \times 10^{-3}$ | $2.228 \times 10^{-3}$ | $2.070 \times 10^{-4}$ | 0.008 |
| $\Delta M_{B_d} \ [\mathrm{ps}^{-1}]$ | 0.591 | 0.506 | 0.0810 | 1.041 |
| $S_{\psi K_s}$ | 0.696 | 0.695 | 0.0190 | 0.036 |
| $\Delta M_{B_s} \ [\mathrm{ps}^{-1}]$ | 19.3 | 17.8 | 2.49 | 0.628 |
| $S_{\psi \phi}$ | 0.0374 | 0.0210 | 0.0310 | 0.528 |
| $\left| x_{12}^D \right|$ | $2.009 \times 10^{-7}$ | 0.000 | $5.000 \times 10^{-3}$ | 0.000 |
| $R_K^{\nu\nu}$ | 1.16 | 1.00 | 3.35 | 0.048 |
| $R_{K^*}^{\nu\nu}$ | 1.16 | 1.00 | 3.43 | 0.046 |
| $R_{B_d \to \mu\mu}$ | 1.04 | 1.51 | 1.42 | 0.327 |
| $R_{B_s \to \mu\mu}$ | 0.786 | 0.750 | 0.157 | 0.229 |
| $\Gamma_t$ | 1.49 | 1.41 | 0.170 | 0.485 |
| $\mathrm{Br}\,(t \to Zq)$ | 0.000 | 0.000 | $3.040 \times 10^{-4}$ | 0.000 |
| $\mathrm{Br}\,(t \to Zu)$ | 0.000 | 0.000 | $1.459 \times 10^{-3}$ | 0.000 |
| $\mathrm{Br}\,(t \to Zc)$ | $3.519 \times 10^{-18}$ | 0.000 | $1.338 \times 10^{-3}$ | 0.000 |

# Full list of observables best(1)-5/5

| name | value | data | Unc. | pull |
|------|-------|------|------|------|
| $\mathrm{Re}C_9^e$ | $-1.689 \times 10^{-15}$ | 0.000 | 0.100 | 0.000 |
| $\mathrm{Im}C_9^e$ | $6.359 \times 10^{-18}$ | 0.000 | 0.100 | 0.000 |
| $\mathrm{Re}C_{10}^e$ | $1.625 \times 10^{-15}$ | 0.000 | 0.100 | 0.000 |
| $\mathrm{Im}C_{10}^e$ | $-6.121 \times 10^{-18}$ | 0.000 | 0.100 | 0.000 |
| $\mathrm{Re}C_9'^e$ | $-1.819 \times 10^{-17}$ | 0.000 | 0.100 | 0.000 |
| $\mathrm{Im}C_9'^e$ | $3.530 \times 10^{-19}$ | 0.000 | 0.100 | 0.000 |
| $\mathrm{Re}C_{10}'^e$ | $1.751 \times 10^{-17}$ | 0.000 | 0.100 | 0.000 |
| $\mathrm{Im}C_{10}'^e$ | $-3.397 \times 10^{-19}$ | 0.000 | 0.100 | 0.000 |
| $\mathrm{Re}C_9^\mu$ | $-0.553$ | $-0.530$ | 0.0800 | 0.288 |
| $\mathrm{Im}C_9^\mu$ | $2.083 \times 10^{-3}$ | 0.000 | 0.100 | 0.021 |
| $\mathrm{Re}C_{10}^\mu$ | 0.512 | 0.530 | 0.0800 | 0.227 |
| $\mathrm{Im}C_{10}^\mu$ | $-1.928 \times 10^{-3}$ | 0.000 | 0.100 | 0.019 |
| $\mathrm{Re}C_9'^\mu$ | $-5.958 \times 10^{-3}$ | 0.000 | 0.100 | 0.060 |
| $\mathrm{Im}C_9'^\mu$ | $1.156 \times 10^{-4}$ | 0.000 | 0.100 | 0.001 |
| $\mathrm{Re}C_{10}'^\mu$ | $5.514 \times 10^{-3}$ | 0.000 | 0.100 | 0.055 |
| $\mathrm{Im}C_{10}'^\mu$ | $-1.070 \times 10^{-4}$ | 0.000 | 0.100 | 0.001 |
| $\mathrm{Br}\left(B \to K\tau^+\tau^-\right)$ | $1.200 \times 10^{-7}$ | 0.000 | $1.757 \times 10^{-3}$ | 0.000 |