Charged scalars confronting neutrino mass and muon g-2 anomaly

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Is the SM the complete picture?

- No compelling evidence of new physics from the energy frontier (LEP, Tevatron, LHC) so far.
- Other experimental observations necessiate new physics.

  1) *Muon anomaly*: A $3.6\,\sigma$ discrepancy between SM prediction and experimental data gives

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 288(63)(48) \times 10^{-11} \ .$$

  2) *Neutrino mass*: Impossible to generate non-zero neutrino masses within the SM alone $\longrightarrow$ Seesaw mechanism!

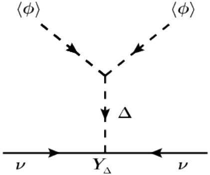
- Our motive: To search for a common framework to accomodate the two aforementioned issues.

A Type-II seesaw solution?

- Features a scalar triplet $\Delta(1,3,2)$ with mass scale M_Δ

$$\Delta = \begin{pmatrix} \frac{H^+}{\sqrt{2}} & \delta^{++} \\ \frac{1}{\sqrt{2}}(v_\Delta + \delta_0 + i\delta_1) & -\frac{H^+}{\sqrt{2}} \end{pmatrix},$$

$$\mathcal{L} \supset -\mu\phi^T(i\sigma_2)\Delta^\dagger\phi - y^{ij}_\Delta\,\overline{L^c_i}\,(i\sigma_2)\Delta L_j$$



- Majorana neutrino mass $m^{ij}_\nu = \sqrt{2}Y^{ij}_\Delta v_\Delta \simeq \mu Y^{ij}_\Delta \frac{v^2}{M^2_\Delta}$

A Type-II seesaw solution?

- Leptophillic $H^+, \ \delta^{++} \Rightarrow$ Additional contributions to Δa_μ
- The contribution turns out to be negative. (JHEP03(2010)044)
- $\Delta a_\mu = \Delta a_\mu^{\text{singly charged}} + \Delta a_\mu^{\text{doubly charged}}$
$$= -\frac{(m_\nu^2)^{\mu\mu}}{96\pi^2}\frac{m_\mu^2}{v_\Delta^2 m_{H^+}^2} - \frac{(m_\nu^2)^{\mu\mu}}{12\pi^2}\frac{m_\mu^2}{v_\Delta^2 m_{H^{++}}^2}$$
- Opt for non-minimal framework

Proposal: Type II + more charged scalars

- We augment the Higgs Triplet model with the charged scalars $k^{++}, k_e^+, k_\mu^+, k_\tau^+$.
- A $\mathbb{Z}_3$ symmetry is introduced.

Field	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$\mathbb{Z}_3$
ϕ	$(\mathbf{1}, \mathbf{2}, 1/2)$	1
L_e, L_μ, L_τ	$(\mathbf{1}, \mathbf{2}, -1/2)$	$1, \omega, \omega^2$
e_R, μ_R, τ_R	$(\mathbf{1}, \mathbf{1}, -1)$	$1, \omega, \omega^2$
Δ	$(\mathbf{1}, \mathbf{3}, 1)$	1
k^{++}	$(\mathbf{1}, \mathbf{1}, 2)$	1
k_e^+, k_μ^+, k_τ^+	$(\mathbf{1}, \mathbf{1}, 1)$	$1, \omega, \omega^2$

Proposal: Type II + more charged scalars

- The scalar potential $V = V_2 + V_3 + V_4$ ($\alpha = e, \mu, \tau$):

$$
\begin{aligned}
V_2 &= \mu_\phi^2(\phi^\dagger\phi) + M_\Delta^2 \mathrm{Tr}(\Delta^\dagger\Delta) + m_k^2|k^{++}|^2 + M_{\alpha\beta}^2 k_\alpha^+ k_\beta^-, \\
V_3 &= \mu_1\, \phi^T(i\sigma_2)\Delta^\dagger\phi + \mu_2\, \mathrm{Tr}\big(\Delta^\dagger\Delta^\dagger\big)k^{++} + \mu_{\alpha\beta}\, k_\alpha^+ k_\beta^+ k^{--} + \mathrm{H.c.} \\
V_4 &= \lambda(\phi^\dagger\phi)^2 + \lambda_1\phi^\dagger\phi\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_2[\mathrm{Tr}(\Delta^\dagger\Delta)]^2 + \lambda_3\mathrm{Tr}[(\Delta^\dagger\Delta)^2] + \lambda_4\phi^\dagger\Delta\Delta^\dagger\phi \\
&\quad +\lambda_5\phi^\dagger\phi|k^{++}|^2 + \lambda_6\mathrm{Tr}(\Delta^\dagger\Delta)|k^{++}|^2 + \lambda_7\big(\tilde{\phi}^\dagger\Delta\phi k^{--} + \mathrm{H.c.}\big) + \lambda_8|k^{++}|^4 \\
&\quad +\lambda_9\phi^\dagger\phi k_\alpha^+ k_\alpha^- + \lambda_{10}\mathrm{Tr}(\Delta^\dagger\Delta)k_\alpha^+ k_\alpha^- + \lambda_{11}k_\alpha^+ k_\alpha^- k^{++}k^{--} \\
&\quad +\lambda_{12}\phi^\dagger\Delta^\dagger\phi k_e^+ + \lambda_{13}k_\alpha^+ k_\alpha^- k_\beta^+ k_\beta^-.
\end{aligned}
$$

- We choose a diagonal $M_{\alpha\beta}$. *Soft* $\mathbb{Z}_3$ violation retained in through off-diagonal entries of $\mu_{\alpha\beta}$
- Seesaw-like Yukawa interactions get flavor-restricted + New terms:

$$
\mathcal{L}_\mathrm{Y} = -y_\Delta^{ee}\,\overline{L_e^c}\,(i\sigma_2)\Delta L_e - y_S^{ee}\,\overline{e_R^c}\,e_R k^{++} - 2\,y_\Delta^{\mu\tau}\,\overline{L_\mu^c}\,i\sigma_2\Delta L_\tau - 2y_S^{\mu\tau}\,\overline{\mu_R^c}\,\tau_R k^{++} - \sum_{\alpha=e,\mu,\tau} y_A^\alpha\,\epsilon^{\alpha\beta\gamma}\,\overline{L_\beta^c}\,i\sigma_2 L_\gamma k_\alpha^+ + \mathrm{H.c}
$$

$\delta^{++} - k^{++}$ mixing

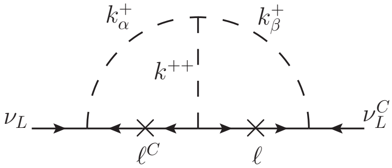
- $\lambda_7\left(\tilde{\phi}^\dagger \Delta \phi k^{--} + \text{H.c.}\right) \xrightarrow{\text{EWSB}}$ Mixing between δ^{++} and k^{++}

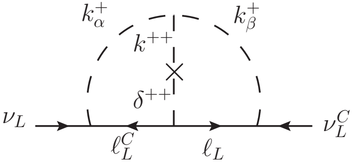
$$\begin{aligned} \delta^{++} &= c_\theta H_1^{++} + s_\theta H_2^{++} \\ k^{++} &= -s_\theta H_1^{++} + c_\theta H_2^{++} \end{aligned}$$

- We choose a real λ_7
- No mixing amongst $(H^+, k_e^+, k_\mu^+, k_\tau^+)$ in the $\lambda_{12} \to 0$ limit and for a diagonal $M_{\alpha\beta}$

Radiative contributions to ν-mass

- $\mathbb{Z}_3$ symmetry $\Rightarrow$ Δ contributes to the ee and $\mu\tau$ elements of m_ν
- Two-loop contributions arise:





- $\mathbb{Z}_3$ breaking $\mu_{\alpha\beta}$ enter these amplitudes.
- Diagram on the left is similar to what is seen in the Zee-Babu model.
- Diagram on the right an artefact of $\delta^{++} - k^{++}$ mixing.

Chirality flip and Δa_μ

- Δ and k^{++} can couple to leptons of specific chiralities only

$$\mathcal{L}_{\mathrm{Y}} \supset -2\, y_\Delta^{\mu\tau}\, \overline{L_\mu^c}\, i\sigma_2 \Delta L_\tau - 2\, y_S^{\mu\tau}\, \overline{\mu_R^c}\, \tau_R k^{++} + \mathrm{H.c}$$

- The mass eigenstates couple to mixed chiralities

$$\mathcal{L}_Y \supset \sum_i \overline{\ell_\alpha^c}(y_{iL}^{\alpha\beta} P_L + y_{iR}^{\alpha\beta} P_R)\ell_\beta\, H_i^{++} + \mathrm{H.c.}$$

where,

$$\begin{aligned} y_{1L}^{\alpha\beta} &= y_\Delta^{\alpha\beta} c_\theta, \\ y_{1R}^{\alpha\beta} &= y_S^{\alpha\beta} s_\theta\ , \\ y_{2L}^{\alpha\beta} &= y_\Delta^{\alpha\beta} s_\theta\ , \\ y_{2R}^{\alpha\beta} &= -y_S^{\alpha\beta} c_\theta\ . \end{aligned}$$

Chirality flip and Δa_μ

- $\Delta a_\mu^{\text{singly charged}} \simeq -\frac{m_\mu^2 (y_\Delta^{\mu\tau})^2}{48\pi^2 M_{H^+}^2} - \frac{m_\mu^2 (y_A^e)^2}{48\pi^2 (M_e^+)^2} - \frac{m_\mu^2 (y_A^\tau)^2}{48\pi^2 (M_\tau^+)^2}$

- $\theta \neq 0 \Rightarrow$ Chirality flipping effect in the 1-loop diagrams for muon g-2

$$\mathcal{L}_{\rm Y} \supset -2\, y_\Delta^{\mu\tau}\, \overline{L_\mu^c}\, i\sigma_2 \Delta L_\tau - 2\, y_S^{\mu\tau}\, \overline{\mu_R^c}\, \tau_R k^{++} + \text{H.c}$$

- For $M_2^{++} = M_1^{++} + \Delta M$ the chirality flipping contribution is

$$\Delta a_\mu^{\text{doubly charged}} \simeq \frac{y_\Delta^{\mu\tau} y_S^{\mu\tau}}{16\pi^2} \frac{m_\mu m_\tau}{(M_1^{++})^3} \Delta M s_\theta c_\theta \log \frac{m_\tau^2}{(M_1^{++})^2} \ .$$

- Size of the chirality flip is $\sim O(m_\tau/m_\mu) \Rightarrow \Delta a_\mu > 0$

LFV

- $\mathbb{Z}_3$ symmetry $\longrightarrow H^{++}_{1,2}$ couple only to ee and $\mu\tau$ bilinears
  $\longrightarrow k_e^+$ couples to $\mu\nu_\tau$; k_μ^+ to $\tau\nu_e$; k_τ^+ to $e\nu_\mu$
  $\Downarrow$
  (1) Only $\tau \to \bar{\mu}ee$ has non-zero rates among the $l_i \to \bar{l}_j l_k l_l$ LFV processes

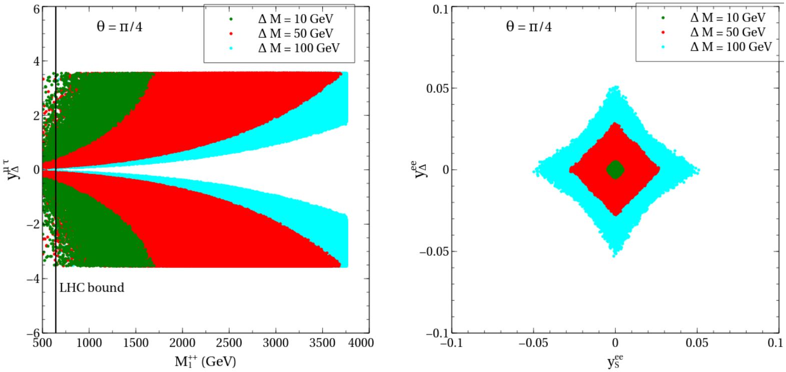
  (2) $l_i \to l_j\gamma$ also absent

- We choose the following parameters:
  $(v_\Delta, M_{H^+}, M_i^{++}, M_\alpha^+, y_A^\alpha, y_\Delta^{ee}, y_S^{ee}, y_\Delta^{\mu\tau}, y_S^{\mu\tau}, \theta)$ as independent.

- *Constraints*
  (a) $12 \times 10^{-10} \leq \Delta a_\mu \leq 44 \times 10^{-10}$ (2σ range)
  (b) $BR_{\tau\to\bar{\mu}ee} < 8.4 \times 10^{-9}$ (most recent limit)
  (c) $\lambda_7 = 2\, s_\theta\, c_\theta \left[(M_2^{++})^2 - (M_1^{++})^2\right]/v^2$ remains perturbative, *i.e.*, $|\lambda_7| \leq 4\pi$

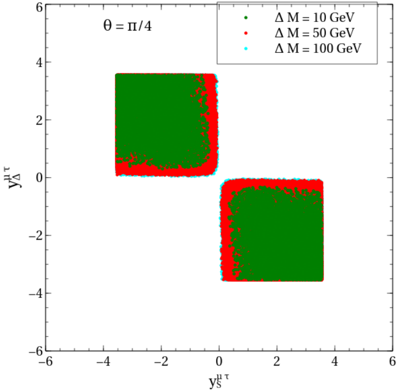
Parameter scans

- $M_{H^+} = M_1^{++},\ M_\alpha^+ \simeq 800$ GeV, $v_\Delta = 10^{-15}$ GeV
- $y_\Delta^{\mu\tau}$ is free from the $m_\nu^{\mu\tau}$ constraint.



Parameter scans

- Parameter space most relaxed for maximal mixing ($\theta = \frac{\pi}{4}$)



Chirality flip and ν-mass

- $m_\nu = \text{Tree}_{\text{Type-II}} + \text{Loop}_{\text{ZB}} + \text{Loop}_{\delta^{++}-k^{++}}$

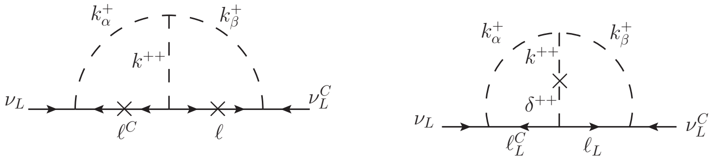
$$
\begin{aligned}
m_\nu^{\alpha\beta} = {} & \sqrt{2} y_\Delta^{\alpha\beta} v_\Delta \\
& -16 \sum_{\alpha'\beta'\alpha''\beta''} \mu_{\alpha''\beta''} y_A^{\alpha''} \epsilon^{\alpha\alpha'\alpha''} y_A^{\beta''} \epsilon^{\beta\beta'\beta''} \Big\{ y_S^{\alpha'\beta'} \Big[s_\theta^2 I_{k1}^{\alpha''\beta''\alpha'\beta'} + c_\theta^2 I_{k2}^{\alpha''\beta''\alpha'\beta'} \Big] \\
& \qquad + y_\Delta^{\alpha'\beta'} s_\theta c_\theta \Big[- I_{\Delta 1}^{\alpha''\beta''\alpha'\beta'} + I_{\Delta 2}^{\alpha''\beta''\alpha'\beta'} \Big] \Big\},
\end{aligned}
$$

$$
I_k(m_1, m_2, m, m_c, m_d) = \int \frac{d^d p_E}{(2\pi)^d} \frac{d^d q_E}{(2\pi)^d} \frac{m_c m_d}{(p_E^2 + m_1^2)(p_E^2 + m_c^2)(q_E^2 + m_2^2)(q_E^2 + m_d^2)((p_E + q_E)^2 + m^2)}
$$

$$
I_\Delta(m_1, m_2, m, m_c, m_d) = -\int \frac{d^d p_E}{(2\pi)^d} \frac{d^d q_E}{(2\pi)^d} \frac{p_E . q_E}{(p_E^2 + m_1^2)(p_E^2 + m_c^2)(q_E^2 + m_2^2)(q_E^2 + m_d^2)((p_E + q_E)^2 + m^2)}
$$

$m_{1,2} \to M_\alpha^+$, $m \to M_{1,2}^{++}$, $m_{c,d} \to$ lepton mass

Chirality flip and ν-mass



- $\mu_{\alpha\beta}$ do not enter into muon g-2 and LFV amplitudes.
  $\Downarrow$
- Can be tuned to fit the ν-oscillation data
- I_Δ integrand has a different momentum structure.
- $\text{Loop}_{\delta^{++}-k^{++}} \sim (m^2_{\text{scalar}}/m^2_{\text{lepton}})\ \text{Loop}_{\text{ZB}}$
- $\theta \neq 0$ causes the new 2-loop amplitude to be dominant.
  $\Downarrow$
- $\mu_{\alpha\beta} << $ Trilinear parameter in the Zee-Babu model

Conclusions

- $\delta^{++} - k^{++}$ mixing $\Rightarrow$ Chirality flip leading to a possible explanation of the muon anomaly

  $\Rightarrow$ A two-loop amplitude different from the Zee-Babu.

- EDMs do not arise at one-loop.
- Possible LHC signal: $pp \longrightarrow \gamma^*(Z^*) \longrightarrow H_1^{++} H_2^{--} \longrightarrow \mu^+ \mu^- \tau \bar{\tau}$

Thank you
for your attention

$$\Delta a_\mu^{\Delta^+} = -\frac{m_\mu^2}{8\pi^2(1+2v_\Delta^2/v_\phi^2)}(y_\Delta^{\mu\tau})^2\int_0^1 dx\frac{x(1-x)}{M_{H^+}^2 - m_\mu^2(1-x)}\ ,$$

$$\Delta a_\mu^{k^+} = -\frac{m_\mu^2}{16\pi^2}\sum_{\alpha=e,\tau}(y_A^\alpha)^2\int_0^1 dx\frac{x(1-x)}{(M_\alpha^+)^2 - m_\mu^2(1-x)},$$

$$\Delta a_\mu^{H_i^{++}} = -\frac{m_\mu^2}{4\pi^2}\int_0^1 dx\ x^2\frac{[(y_{iL}^{\mu\tau})^2+(y_{iR}^{\mu\tau})^2](1-x)+2\,y_{iL}^{\mu\tau}y_{iR}^{\mu\tau}(m_\tau/m_\mu)}{m_\mu^2x^2+(m_\tau^2-m_\mu^2)x+(M_i^{++})^2(1-x)}$$
$$-\frac{m_\mu^2}{2\pi^2}\int_0^1 dx\ x(1-x)\frac{[(y_{iL}^{\mu\tau})^2+(y_{iR}^{\mu\tau})^2]x+2\,y_{iL}^{\mu\tau}y_{iR}^{\mu\tau}(m_\tau/m_\mu)}{m_\mu^2x^2+((M_i^{++})^2-m_\mu^2)x+m_\tau^2(1-x)},$$

$$\frac{\mathrm{BR}_{\tau\to\bar{\mu}ee}}{\mathrm{BR}_{\tau\to\mu\nu\nu}} = \frac{1}{4G_F^2}\Big\{\big(|y_S^{\tau\mu}|^2|y_\Delta^{ee}|^2+|y_\Delta^{\tau\mu}|^2|y_S^{ee}|^2\big)s_\theta^2c_\theta^2\Big(\frac{1}{(M_1^{++})^2}-\frac{1}{(M_2^{++})^2}\Big)^2$$
$$+|y_S^{\tau\mu}|^2|y_S^{ee}|^2\Big(\frac{s_\theta^2}{(M_1^{++})^2}+\frac{c_\theta^2}{(M_2^{++})^2}\Big)^2$$
$$+|y_\Delta^{\tau\mu}|^2|y_\Delta^{ee}|^2\Big(\frac{c_\theta^2}{(M_1^{++})^2}+\frac{s_\theta^2}{(M_2^{++})^2}\Big)^2\Big\}\ ,$$

$$(m_1|m_2|m) = \int d^d p_E d^d q_E \; \frac{1}{(p_E^2+m_1^2)(q_E^2+m_2^2)((p_E+q_E)^2+m^2)} \,,$$
$$(2m_1|m_2|m) = \int d^d p_E d^d q_E \; \frac{1}{(p_E^2+m_1^2)^2(q_E^2+m_2^2)((p_E+q_E)^2+m^2)}$$

$$I_\Delta(m_1,m_2,m,m_c,m_d) = -\int \frac{d^d p_E}{(2\pi)^d}\frac{d^d q_E}{(2\pi)^d}\frac{p_E.q_E}{(p_E^2+m_1^2)(p_E^2+m_c^2)(q_E^2+m_2^2)(q_E^2+m_d^2)((p_E+q_E)^2+m^2)}$$

We define

$$\begin{aligned} D_1 &= p_E^2+m_1^2 \\ D_2 &= q_E^2+m_2^2 \\ D_c &= p_E^2+m_c^2 \\ D_d &= q_E^2+m_d^2 \\ D &= (p_E+q_E)^2+m^2 \end{aligned}$$

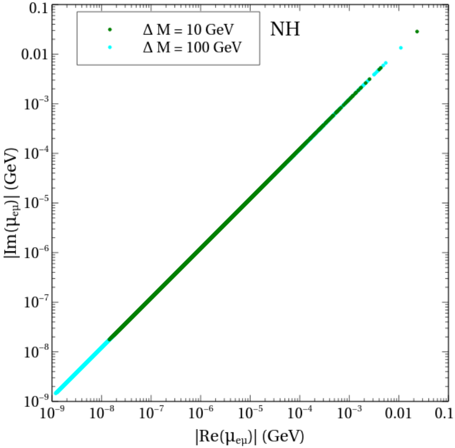
and

$$I_\Delta(m_1,m_2,m,m_c,m_d) = -\frac{1}{2}\int \frac{d^d p_E}{(2\pi)^d}\frac{d^d q_E}{(2\pi)^d}\left[\frac{(D-m^2-D_1+m_1^2-D_2+m_2^2)}{D_1 D_c D_2 D_d D}\right]$$

$$
\begin{aligned}
I_\Delta(m_1, m_2, m, m_c, m_d) = & -\frac{1}{2}\int \frac{d^d p_E}{(2\pi)^d}\frac{d^d q_E}{(2\pi)^d}\left[\frac{1}{D_1 D_c D_2 D_d}\right] \\
& -\frac{1}{2}\frac{1}{(2\pi)^8}\frac{1}{(m_2^2 - m_d^2)}\Big[(m_c|m_2|m) - (m_c|m_d|m)\Big] \\
& -\frac{1}{2}\frac{1}{(2\pi)^8}\frac{1}{(m_1^2 - m_c^2)}\Big[(m_1|m_d|m) - (m_c|m_d|m)\Big] \\
& -\frac{1}{2}\frac{1}{(2\pi)^8}\frac{(m_1^2 + m_2^2 - m^2)}{(m_1^2 - m_c^2)(m_2^2 - m_d^2)}\Big[(m_1|m_2|m) - (m_1|m_d|m) \\
& -(m_c|m_2|m) + (m_c|m_d|m)\Big]
\end{aligned}
$$

$$
\begin{aligned}
= & -\frac{1}{2}\int \frac{d^d p_E}{(2\pi)^d}\frac{d^d q_E}{(2\pi)^d}\left[\frac{1}{D_1 D_c D_2 D_d}\right] \\
& -\frac{1}{2}\frac{1}{(2\pi)^8}\frac{1}{(m_1^2 - m_c^2)(m_2^2 - m_d^2)}\Big[(m_1^2 + m_2^2 - m^2)(m_1|m_2|m) \\
& +(m^2 - m_2^2 - m_c^2)(m_c|m_2|m) + (m^2 - m_1^2 - m_d^2)(m_1|m_d|m) \\
& +(m_c^2 + m_d^2 - m^2)(m_c|m_d|m)\Big]
\end{aligned}
$$

$$
\begin{aligned}
&= -\frac{1}{2}\int \frac{d^d p_E}{(2\pi)^d}\frac{d^d q_E}{(2\pi)^d}\left[\frac{1}{D_1 D_c D_2 D_d}\right] - \frac{1}{2}\frac{1}{(3-d)}\frac{1}{(2\pi)^8}\frac{1}{(m_1^2-m_c^2)(m_2^2-m_d^2)} \\
&\Bigg[(m_1^2+m_2^2-m^2)\Big(m_1^2(2m_1|m_2|m)+m_2^2(2m_2|m_1|m)+m^2(2m|m_1|m_2)\Big) \\
&+(m^2-m_2^2-m_c^2)\Big(m_c^2(2m_c|m_2|m)+m_2^2(2m_2|m_c|m)+m^2(2m|m_c|m_2)\Big) \\
&+(m^2-m_1^2-m_d^2)\Big(m_1^2(2m_1|m_d|m)+m_d^2(2m_d|m_1|m)+m^2(2m|m_1|m_d)\Big) \\
&+(m_c^2+m_d^2-m^2) \\
&\Big(m_c^2(2m_c|m_d|m)+m_d^2(2m_d|m_c|m)+m^2(2m|m_c|m_d)\Big)\Bigg] \qquad \text{(A.18c)}
\end{aligned}
$$



Δ M = 10 GeV
Δ M = 100 GeV
NH
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$|\mathrm{Im}(\mu_{e\mu})|$ (GeV)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 0.01 0.1
$|\mathrm{Re}(\mu_{e\mu})|$ (GeV)