Finding the flavon of $\mathcal{Z}_N \times \mathcal{Z}_M$ flavour symmetry

Neelam Singh

Department of Physics, Indian Institute of Technology (BHU), Varanasi

October 16, 2024

17^{th} International Conference on Interconnections between Particle Physics and Cosmology
PPC 2024 : IIT Hyderabad

Based on:

[Eur. Phys. J. C 83, 4, 305 (2023)], G. Abbas, V. Singh, R. Sain and N. Singh

[arXiv:2407.09255 [hep-ph]] (accepted in Phys. Rev. D), G. Abbas, A. K. Alok, N. R. S. Chundawat, N. Khan and N. Singh

Dedicated to the memory of

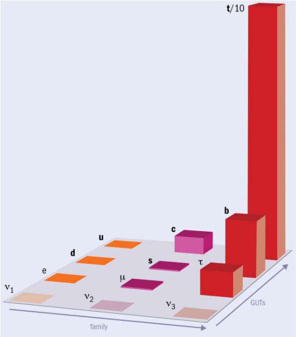
Prof. Ashutosh Kumar Alok

(IIT Jodhpur)

Outlines

1. Flavour problem of the Standard Model (SM)
2. $\mathcal{Z}_N \times \mathcal{Z}_M$ flavour symmetry
3. Constraints on the flavour scale
4. Collider signatures of the flavon
5. Summary

The SM flavour problem



Quark mixing angles: $\theta_{12} = 13.04^o \pm 0.05^o, \theta_{23} = 2.38^o \pm 0.06^o, \theta_{13} = 0.201^o \pm 0.011^o$[1]

Leptonic mixing angles: $\theta_{12} = 33.41^{\circ}{}^{+0.75^\circ}_{-0.72^\circ}, \theta_{23} = 49.1^{\circ}{}^{+1.0^\circ}_{-1.3^\circ}, \theta_{13} = 8.54^{\circ}{}^{+0.11^\circ}_{-0.12^\circ}$[1]

[1] PDG

$\mathcal{Z}_N \times \mathcal{Z}_M$ flavour symmetry

- The Froggatt-Nielsen (FN) mechanism is achieved through an abelian $U(1)$ symmetry by employing a flavon field (χ), which couples with the top quark at tree-level, and the masses of other fermions originate from the higher dimensional non-renormalizable operators of the following form,

$$\begin{aligned} \mathcal{O} &= y\left(\frac{\chi}{\Lambda}\right)^{(\theta_i+\theta_j)} \bar{\psi}\varphi\psi, \\ &= y\epsilon^{(\theta_i+\theta_j)} \bar{\psi}\varphi\psi = Y\bar{\psi}\varphi\psi, \end{aligned}$$

where $\epsilon = \dfrac{\langle \chi \rangle}{\Lambda} < 1$. [2]

- We introduce a framework based on discrete symmetry, $\mathcal{Z}_N \times \mathcal{Z}_M$, imposed on the SM, and employ a gauge singlet flavon field (χ). [3] [4]

[2] Froggatt and Nielsen 1979
[3] Int. J. Mod. Phys. A 34, no.20, 1950104 (2019), G. Abbas
[4] Int. J. Mod. Phys. A 36, 2150090 (2021), G.Abbas

$\mathcal{Z}_N \times \mathcal{Z}_M$ flavour symmetry

- The minimal realization of the $\mathcal{Z}_N \times \mathcal{Z}_M$ flavour symmetry turns out to be $\mathcal{Z}_2 \times \mathcal{Z}_5$. [5]
- Other non-minimal forms are $\mathcal{Z}_2 \times \mathcal{Z}_9$, $\mathcal{Z}_2 \times \mathcal{Z}_{11}$, and $\mathcal{Z}_8 \times \mathcal{Z}_{22}$ [6]that also provide the set-up to achieve FN mechanism.
- The charge-assignment to the SM and flavon fields under these symmetries are,

Fields	$\mathcal{Z}_2$	$\mathcal{Z}_5$
u_R, c_R, t_R	+	ω^2
$d_R, s_R, b_R, e_R, \mu_R, \tau_R$	-	ω
$\nu_{e_R}, \nu_{\mu_R}, \nu_{\tau_R}$	-	ω^3
ψ_L^1	+	ω
ψ_L^2	+	ω^4
ψ_L^3	+	ω^2
χ	-	ω
φ	+	**1**

Fields	$\mathcal{Z}_2$	$\mathcal{Z}_9$
u_R, t_R	+	1
c_R	+	ω^4
$d_R, s_R, b_R, e_R, \mu_R, \tau_R$	-	ω^3
ν_{e_R}, ν_{μ_R}	+	ω^6
ν_{τ_R}	+	ω^7
ψ_L^1	+	ω
ψ_L^2	+	ω^8
ψ_L^3	+	1
χ	-	ω
φ	+	**1**

[5]Eur. Phys. J. C 83, 4, 305 (2023), G. Abbas, V. Singh, R. Sain and N. Singh
[6]Phys.Rev.D 108 (2023) 11, 115035, G. Abbas, R. Adhikari and E. J. Chun

Masses and mixing patterns

- The masses of quarks and charged leptons in terms of the expansion parameter $\epsilon (< 1)$, up to leading-order are, [7]

masses	$\mathcal{Z}_2 \times \mathcal{Z}_5$	$\mathcal{Z}_2 \times \mathcal{Z}_9$
$\{m_t, m_c, m_u\}$	$\simeq \{\lvert y_{33}^u\rvert,\ \lvert y_{22}^u\rvert\epsilon^2,\ \lvert y_{11}^u\rvert\epsilon^4\}v/\sqrt{2}$	$\simeq \{\lvert y_{33}^u\rvert,\ \lvert y_{22}^u\rvert\epsilon^4,\ \lvert y_{11}^u\rvert\epsilon^8\}v/\sqrt{2}$
$\{m_b, m_s, m_d\}$	$\simeq \{\lvert y_{33}^d\rvert\epsilon,\ \lvert y_{22}^d\rvert\epsilon^3\ \lvert y_{11}^d\rvert\epsilon^5\}v/\sqrt{2}$	$\simeq \{\lvert y_{33}^d\rvert\epsilon^3,\ \lvert y_{22}^d\rvert\epsilon^5,\ \lvert y_{11}^d\rvert\epsilon^7\}v/\sqrt{2}$
$\{m_\tau, m_\mu, m_e\}$	$\simeq \{\lvert y_{33}^l\rvert\epsilon,\ \lvert y_{22}^l\rvert\epsilon^3,\ \lvert y_{11}^l\rvert\epsilon^5\}v/\sqrt{2}$	$\simeq \{\lvert y_{33}^l\rvert\epsilon^3,\ \lvert y_{22}^l\rvert\epsilon^5,\ \lvert y_{11}^l\rvert\epsilon^7\}v/\sqrt{2}$

masses	$\mathcal{Z}_2 \times \mathcal{Z}_{11}$	$\mathcal{Z}_8 \times \mathcal{Z}_{22}$
$\{m_t, m_c, m_u\}$	$\simeq \{\lvert y_{33}^u\rvert,\ \lvert y_{22}^u\rvert\epsilon^6,\ \lvert y_{11}^u\rvert\epsilon^{10}\}v/\sqrt{2}$	$\simeq \{\lvert y_{33}^u\rvert\epsilon,\ \lvert y_{22}^u\rvert\epsilon^4,\ \lvert y_{11}^u\rvert\epsilon^8\}v/\sqrt{2}$
$\{m_b, m_s, m_d\}$	$\simeq \{\lvert y_{33}^d\rvert\epsilon^3,\ \lvert y_{22}^d\rvert\epsilon^7,\ \lvert y_{11}^d\rvert\epsilon^9\}v/\sqrt{2}$	$\simeq \{\lvert y_{33}^d\rvert\epsilon^3,\ \lvert y_{22}^d\rvert\epsilon^5,\ \lvert y_{11}^d\rvert\epsilon^7\}v/\sqrt{2}$
$\{m_\tau, m_\mu, m_e\}$	$\simeq \{\lvert y_{33}^l\rvert\epsilon^3,\ \lvert y_{22}^l\rvert\epsilon^7,\ \lvert y_{11}^l\rvert\epsilon^9\}v/\sqrt{2}$	$\simeq \{\lvert y_{33}^l\rvert\epsilon^3,\ \lvert y_{22}^l\rvert\epsilon^5,\ \lvert y_{11}^l\rvert\epsilon^9\}v/\sqrt{2}$

where $\epsilon = 0.1$ for $\mathcal{Z}_2 \times \mathcal{Z}_5$, $\epsilon = 0.23$ for $\mathcal{Z}_2 \times \mathcal{Z}_9$, $\epsilon = 0.28$ for $\mathcal{Z}_2 \times \mathcal{Z}_{11}$, and $\epsilon = 0.23$ for $\mathcal{Z}_8 \times \mathcal{Z}_{22}$ are used to produce the masses and mixing patterns of fermions.

[7] [arXiv:2407.09255 [hep-ph]](accepted in Phys. Rev. D) , G. Abbas, A. K. Alok, N. R. S. Chundawat, N. Khan and N. Singh

Masses and mixing patterns

- The mixing angles of quarks are obtained as,

Quark mixing angles	$\mathcal{Z}_2 \times \mathcal{Z}_5$	$\mathcal{Z}_2 \times \mathcal{Z}_9$
$\sin\theta_{12} \simeq \lvert V_{us}\rvert$	$\simeq \left\lvert \frac{y^d_{12}}{y^d_{22}} - \frac{y^u_{12}}{y^u_{22}} \right\rvert \epsilon^2$	$\simeq \left\lvert \frac{y^d_{12}}{y^d_{22}} - \frac{y^u_{12}}{y^u_{22}} \right\rvert \epsilon^2$
$\sin\theta_{23} \simeq \lvert V_{cb}\rvert$	$\simeq \lvert \frac{y^d_{23}}{y^d_{33}} - \frac{y^u_{23}}{y^u_{33}} \rvert \epsilon^2$	$\simeq \left\lvert \frac{y^d_{23}}{y^d_{33}} \right\rvert \epsilon^2$
$\sin\theta_{13} \simeq \lvert V_{ub}\rvert$	$\simeq \left\lvert \frac{y^d_{13}}{y^d_{33}} - \frac{y^u_{12} y^d_{23}}{y^u_{22} y^d_{33}} - \frac{y^u_{13}}{y^u_{33}} \right\rvert \epsilon^4$	$\simeq \left\lvert \frac{y^d_{13}}{y^d_{33}} - \frac{y^u_{12} y^d_{23}}{y^u_{22} y^d_{33}} \right\rvert \epsilon^4$

Quark mixing angles	$\mathcal{Z}_2 \times \mathcal{Z}_{11}$	$\mathcal{Z}_8 \times \mathcal{Z}_{22}$
$\sin\theta_{12} \simeq \lvert V_{us}\rvert$	$\simeq \left\lvert \frac{y^d_{12}}{y^d_{22}} \right\rvert \epsilon^2$	$\simeq \left\lvert \frac{y^d_{12}}{y^d_{22}} - \frac{y^u_{12}}{y^u_{22}} \right\rvert \epsilon$
$\sin\theta_{23} \simeq \lvert V_{cb}\rvert$	$\simeq \lvert \frac{y^d_{23}}{y^d_{33}} - \frac{y^u_{23}}{y^u_{33}} \rvert \epsilon^4$	$\simeq \lvert \frac{y^d_{23}}{y^d_{33}} - \frac{y^u_{23}}{y^u_{33}} \rvert \epsilon^2$
$\sin\theta_{13} \simeq \lvert V_{ub}\rvert$	$\simeq \left\lvert \frac{y^d_{13}}{y^d_{33}} \right\rvert \epsilon^6$	$\simeq \left\lvert \frac{y^d_{13}}{y^d_{33}} - \frac{y^u_{12} y^d_{23}}{y^u_{22} y^d_{33}} - \frac{y^u_{13}}{y^u_{33}} \right\rvert \epsilon^3$

The scalar potential

- The scalar potential of the model can be written in the following form,

$$-\mathcal{L}_{\text{potential}} = -\mu^2 \varphi^\dagger \varphi + \lambda(\varphi^\dagger \varphi)^2 - \mu_\chi^2 \chi^* \chi + \lambda_\chi (\chi^* \chi)^2 + \lambda_{\varphi\chi}(\chi^* \chi)(\varphi^\dagger \varphi).$$

- The flavon field (χ) can be parametrized by excitations around its VEV,

$$\chi(x) = \frac{f + s(x) + i\, a(x)}{\sqrt{2}}.$$

Softly broken scalar potential

$$V_\rho = \rho\, \chi^2 + \text{H.c.}$$

$$m_s = \sqrt{\mu_\chi - 2\rho} = \sqrt{\lambda_\chi} f \quad \text{and } m_a = \sqrt{2\rho}$$

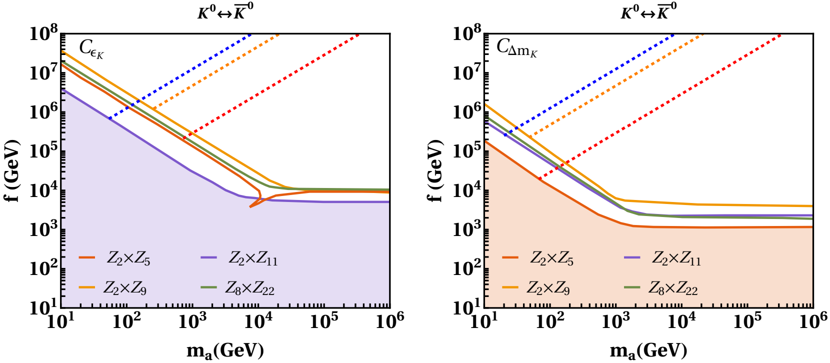
Symmetry conserving scalar potential

$$V_{\tilde{N}} = -\lambda \frac{\chi^{\tilde{N}}}{\Lambda^{\tilde{N}-4}} + \text{H.c.}$$

$$m_a^2 = \frac{1}{8} |\lambda| \tilde{N}^2 \epsilon^{\tilde{N}-4} f^2$$

Quark flavour constraints on the flavour scale

$$C_{\epsilon_K} = \frac{\text{Im}\langle K^0|\mathcal{H}_{\text{eff}}^{\Delta F=2}|\bar{K}^0\rangle}{\text{Im}\langle K^0|\mathcal{H}_{\text{SM}}^{\Delta F=2}|\bar{K}^0\rangle} = 1.12^{+0.27}_{-0.25}\,[8],\quad C_{\Delta m_K} = \frac{\text{Re}\langle K^0|\mathcal{H}_{\text{eff}}^{\Delta F=2}|\bar{K}^0\rangle}{\text{Re}\langle K^0|\mathcal{H}_{\text{SM}}^{\Delta F=2}|\bar{K}^0\rangle} = 0.93^{+1.14}_{-0.42}\,[8]$$



[8]@95% C.L. , M. Bona et al. 2007, [UTFIT]

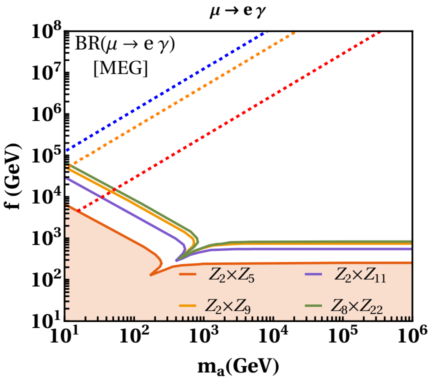
Leptonic flavour constraints

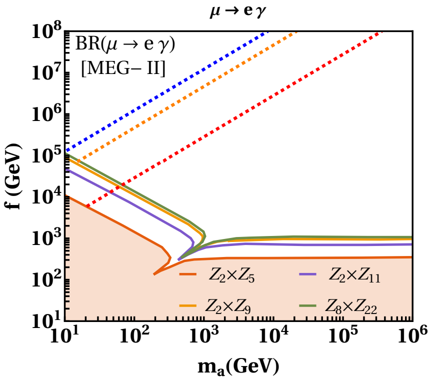
Observables	Current sensitivity	Ref.	Future projection	Ref.
BR$(\mu \to e\gamma)$	$< 4.2 \times 10^{-13}$	MEG	6×10^{-14}	MEG2
BR $(\mu \to e)^{\rm Au}$	$< 7 \times 10^{-13}$	SINDRUM 2	–	–
BR $(\mu \to e)^{\rm Al}$	–	–	3×10^{-15}	COMET Phase-1
BR $(\mu \to e)^{\rm Al}$	–	–	6×10^{-17}	COMET Phase-2
BR $(\mu \to e)^{\rm Al}$	–	–	6×10^{-17}	Mu2e
BR $(\mu \to e)^{\rm Al}$	–	–	3×10^{-18}	Mu2e 2
BR $(\mu \to e)^{\rm Si}$	–	–	2×10^{-14}	DeeMe
BR $(\mu \to e)^{\rm Ti}$			$\sim 10^{-20} - 10^{-18}$	PRISM/PRIME
BR$(\mu \to 3e)$	$< 1.0 \times 10^{-12}$	SINDRUM	$\sim 10^{-16}$	Mu3e

Table: Experimental upper limits on various Leptonic flavour violation (LFV) processes.[9]

[5] Eur. Phys. J. C 83, 4, 305 (2023), G. Abbas, V. Singh, R. Sain, and N. Singh

Leptonic flavour constraints





Collider signatures of the flavon

$$pp \to a \to f_i \bar{f}_j / \gamma\gamma$$

m_a [GeV]	HL-LHC [14 TeV, 3 ab^{-1}] 500	1000	HE-LHC [27 TeV, 15 ab^{-1}] 500	1000	100 TeV, 30 ab^{-1} 500	1000
jet-jet [pb]		$4 \cdot 10^{-2}$		$3 \cdot 10^{-2}$		$4 \cdot 10^{-2}$
$\tau\tau$ [pb]	$7 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	$7 \cdot 10^{-4}$	$5 \cdot 10^{-3}$	$8 \cdot 10^{-4}$
ee, $\mu\mu$ [pb]	$2 \cdot 10^{-4}$	$4 \cdot 10^{-5}$	$1 \cdot 10^{-4}$	$3 \cdot 10^{-5}$	$1 \cdot 10^{-4}$	$3 \cdot 10^{-5}$
μe [pb]	$9 \cdot 10^{-4}$	$7 \cdot 10^{-5}$	$7 \cdot 10^{-4}$	$5 \cdot 10^{-5}$	$1 \cdot 10^{-3}$	$1 \cdot 10^{-4}$
$\mu\tau$ [pb]	$2 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	$1 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	$2 \cdot 10^{-3}$	$3 \cdot 10^{-4}$
$e\tau$ [pb]	$1 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	$8 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	$1 \cdot 10^{-3}$	$3 \cdot 10^{-4}$
$b\bar{b}$ [pb]		$9 \cdot 10^{-3}$		$5 \cdot 10^{-3}$		$7 \cdot 10^{-3}$
$\gamma\gamma$ [pb]	$1 \cdot 10^{-4}$	$2 \cdot 10^{-5}$	$6 \cdot 10^{-5}$	$1 \cdot 10^{-5}$	$7 \cdot 10^{-5}$	$1 \cdot 10^{-5}$
$t\bar{t}$ [pb]	4	$5 \cdot 10^{-2}$	3	$4 \cdot 10^{-2}$	8	0.1

Table: Estimated reach ($\sigma \times BR$) of the future colliders

m_a [GeV]	Benchmark $\mathcal{Z}_2 \times \mathcal{Z}_5$ 500	1000	Benchmark $\mathcal{Z}_2 \times \mathcal{Z}_9$ 500	1000	Benchmark $\mathcal{Z}_2 \times \mathcal{Z}_{11}$ 500	1000	Benchmark $\mathcal{Z}_8 \times \mathcal{Z}_{22}$ 500	1000
jet-jet [pb]		$3.6 \cdot 10^{-2}$		$1.5 \cdot 10^{-6}$		$2.3 \cdot 10^{-7}$		$1.4 \cdot 10^{-3}$
$\tau\tau$ [pb]	$1.2 \cdot 10^{-3}$	$9.2 \cdot 10^{-5}$	$8.0 \cdot 10^{-5}$	$3.4 \cdot 10^{-6}$	$2.9 \cdot 10^{-5}$	$1.6 \cdot 10^{-6}$	$3.4 \cdot 10^{-3}$	$6.1 \cdot 10^{-5}$
$\mu\tau$ [pb]	$1.4 \cdot 10^{-3}$	$1.1 \cdot 10^{-4}$	$2.3 \cdot 10^{-4}$	$9.5 \cdot 10^{-6}$	$3 \cdot 10^{-5}$	$1.7 \cdot 10^{-6}$	$5.8 \cdot 10^{-3}$	$1 \cdot 10^{-4}$
$e\tau$ [pb]	$1.1 \cdot 10^{-3}$	$8.9 \cdot 10^{-5}$	$2.2 \cdot 10^{-4}$	$9.4 \cdot 10^{-6}$	$8.5 \cdot 10^{-5}$	$4.7 \cdot 10^{-6}$	$3.2 \cdot 10^{-4}$	$5.8 \cdot 10^{-6}$
$\mu\mu$ [pb]	$1.1 \cdot 10^{-6}$	$8.3 \cdot 10^{-8}$	$1.7 \cdot 10^{-6}$	$7.3 \cdot 10^{-8}$	$2.2 \cdot 10^{-7}$	$1.2 \cdot 10^{-8}$	$2.9 \cdot 10^{-5}$	$5.3 \cdot 10^{-7}$
ee [pb]	$2.5 \cdot 10^{-10}$	$2 \cdot 10^{-11}$	$3.4 \cdot 10^{-9}$	$1.4 \cdot 10^{-10}$	$6.7 \cdot 10^{-11}$	$3.7 \cdot 10^{-12}$	$1.7 \cdot 10^{-9}$	$3 \cdot 10^{-11}$
$\gamma\gamma$ [pb]	$1.3 \cdot 10^{-7}$	$3.6 \cdot 10^{-9}$	$8.2 \cdot 10^{-10}$	$1.2 \cdot 10^{-11}$	$1.5 \cdot 10^{-10}$	$3 \cdot 10^{-12}$	$6.6 \cdot 10^{-4}$	$1 \cdot 10^{-5}$
$b\bar{b}$ [pb]	$9.8 \cdot 10^{-3}$	$6.3 \cdot 10^{-4}$	$4.7 \cdot 10^{-4}$	$1.9 \cdot 10^{-5}$	$1.2 \cdot 10^{-4}$	$5.7 \cdot 10^{-6}$	$1.9 \cdot 10^{-2}$	$3.2 \cdot 10^{-4}$
$t\bar{t}$ [pb]							4.42	0.12

Table: Benchmark points at 14 TeV, $3ab^{-1}$ HL-LHC

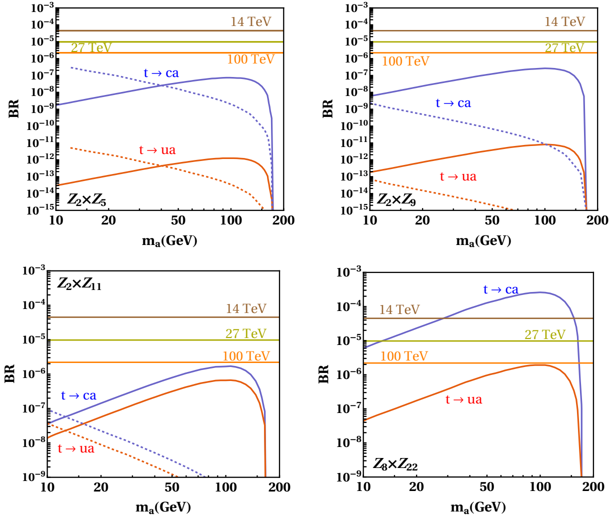
m_a [GeV]	Benchmark $\mathcal{Z}_2 \times \mathcal{Z}_5$ 500	1000	Benchmark $\mathcal{Z}_2 \times \mathcal{Z}_9$ 500	1000	Benchmark $\mathcal{Z}_2 \times \mathcal{Z}_{11}$ 500	1000	Benchmark $\mathcal{Z}_8 \times \mathcal{Z}_{22}$ 500	1000
jet-jet [pb]		**0.133**		$8.2 \cdot 10^{-6}$		$9.4 \cdot 10^{-7}$		$9.8 \cdot 10^{-3}$
$\tau\tau$ [pb]	$2.6 \cdot 10^{-3}$	$2.8 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$	$1.7 \cdot 10^{-5}$	$8 \cdot 10^{-5}$	$5.6 \cdot 10^{-6}$	$1.5 \cdot 10^{-2}$	$4 \cdot 10^{-4}$
$\mu\tau$ [pb]	**$3.2 \cdot 10^{-3}$**	**$3.5 \cdot 10^{-4}$**	$8.3 \cdot 10^{-4}$	$4.8 \cdot 10^{-5}$	$8.4 \cdot 10^{-5}$	$5.8 \cdot 10^{-6}$	**$2.5 \cdot 10^{-2}$**	**$6.8 \cdot 10^{-4}$**
$e\tau$ [pb]	**$2.6 \cdot 10^{-3}$**	**$2.8 \cdot 10^{-4}$**	**$8.2 \cdot 10^{-4}$**	$4.8 \cdot 10^{-5}$	$2.3 \cdot 10^{-4}$	$1.6 \cdot 10^{-5}$	**$1.4 \cdot 10^{-3}$**	$3.8 \cdot 10^{-5}$
$\mu\mu$ [pb]	$2.4 \cdot 10^{-6}$	$2.6 \cdot 10^{-7}$	$6.4 \cdot 10^{-6}$	$3.7 \cdot 10^{-7}$	$6.2 \cdot 10^{-7}$	$4.3 \cdot 10^{-8}$	**$1.3 \cdot 10^{-4}$**	$3.5 \cdot 10^{-6}$
ee [pb]	$5.6 \cdot 10^{-10}$	$6.1 \cdot 10^{-11}$	$1.3 \cdot 10^{-8}$	$7.4 \cdot 10^{-10}$	$1.8 \cdot 10^{-10}$	$1.3 \cdot 10^{-11}$	$7.2 \cdot 10^{-9}$	$1.9 \cdot 10^{-10}$
$\gamma\gamma$ [pb]	$2.9 \cdot 10^{-7}$	$1.1 \cdot 10^{-8}$	$3 \cdot 10^{-9}$	$6.3 \cdot 10^{-11}$	$4.2 \cdot 10^{-10}$	$1.1 \cdot 10^{-11}$	**$2.8 \cdot 10^{-3}$**	**$6.7 \cdot 10^{-5}$**
$b\bar{b}$ [pb]	$2.7 \cdot 10^{-2}$	$2.3 \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$	$1 \cdot 10^{-4}$	$3.8 \cdot 10^{-4}$	$2.3 \cdot 10^{-5}$	$8.8 \cdot 10^{-2}$	$2.2 \cdot 10^{-3}$
$t\bar{t}$ [pb]							**20.46**	**0.83**

Table: Benchmark points at 27 TeV, $15ab^{-1}$ HE-LHC

	Benchmark $\mathcal{Z}_2 \times \mathcal{Z}_5$		Benchmark $\mathcal{Z}_2 \times \mathcal{Z}_9$		Benchmark $\mathcal{Z}_2 \times \mathcal{Z}_{11}$		Benchmark $\mathcal{Z}_8 \times \mathcal{Z}_{22}$	
m_a [GeV]	500	1000	500	1000	500	1000	500	1000
jet-jet [pb]		0.95		$1.1 \cdot 10^{-4}$		$8.1 \cdot 10^{-6}$		0.18
$\tau\tau$ [pb]	$1.1 \cdot 10^{-2}$	$1.4 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$	$1.9 \cdot 10^{-4}$	$4.8 \cdot 10^{-4}$	$3.8 \cdot 10^{-5}$	0.14	$6.2 \cdot 10^{-3}$
$\mu\tau$ [pb]	$1.3 \cdot 10^{-2}$	$1.7 \cdot 10^{-3}$	$6.3 \cdot 10^{-3}$	$5.5 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$3.9 \cdot 10^{-5}$	0.23	$1.0 \cdot 10^{-2}$
$e\tau$ [pb]	$1.1 \cdot 10^{-2}$	$1.4 \cdot 10^{-3}$	$6.2 \cdot 10^{-3}$	$5.4 \cdot 10^{-4}$	$1.3 \cdot 10^{-3}$	$1.1 \cdot 10^{-4}$	$1.3 \cdot 10^{-2}$	$5.9 \cdot 10^{-4}$
$\mu\mu$ [pb]	$9.9 \cdot 10^{-5}$	$1.3 \cdot 10^{-6}$	$4.8 \cdot 10^{-5}$	$4.2 \cdot 10^{-6}$	$3.7 \cdot 10^{-6}$	$2.9 \cdot 10^{-7}$	$1.2 \cdot 10^{-3}$	$5.4 \cdot 10^{-5}$
ee [pb]	$2.4 \cdot 10^{-9}$	$3.0 \cdot 10^{-10}$	$9.6 \cdot 10^{-8}$	$8.4 \cdot 10^{-9}$	$1.1 \cdot 10^{-9}$	$8.8 \cdot 10^{-11}$	$6.9 \cdot 10^{-8}$	$3.0 \cdot 10^{-9}$
$\gamma\gamma$ [pb]	$1.2 \cdot 10^{-6}$	$5.6 \cdot 10^{-8}$	$2.3 \cdot 10^{-8}$	$7.2 \cdot 10^{-10}$	$2.5 \cdot 10^{-9}$	$7.2 \cdot 10^{-11}$	$2.7 \cdot 10^{-2}$	$1 \cdot 10^{-3}$
$b\bar{b}$ [pb]	0.15	$1.7 \cdot 10^{-2}$	$1.7 \cdot 10^{-2}$	$1.3 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	1.03	$4.1 \cdot 10^{-2}$
$t\bar{t}$ [pb]							241.4	15.4

Table: Benchmark points for a 100 TeV, $30ab^{-1}$ hadron collider

Anomalous top decays



Conclusions

- The $\mathcal{Z}_N \times \mathcal{Z}_M$ flavour symmetry in a unique and novel framework that can effectively address the flavour problem of the SM.
- We have investigated the bounds on the flavour scale of the minimal and non-minimal versions of this symmetry using the current as well as the future projected sensitivities of the quark and lepton flavour physics data.
- The HL-LHC will be able to probe the signatures of the flavon of $\mathcal{Z}_2 \times \mathcal{Z}_5$ and the $\mathcal{Z}_8 \times \mathcal{Z}_{22}$ flavour symmetries.
- In addition to the $\mathcal{Z}_2 \times \mathcal{Z}_5$ and the $\mathcal{Z}_8 \times \mathcal{Z}_{22}$, HE-LHC will be sensitive to $\mathcal{Z}_2 \times \mathcal{Z}_9$ flavour symmetry through few specific inclusive signatures.
- The future 100 TeV collider will be decisive to test all of these four $\mathcal{Z}_N \times \mathcal{Z}_M$ flavour symmetries at the experimental frontiers.

Conclusions

- The $\mathcal{Z}_N \times \mathcal{Z}_M$ flavour symmetry in a unique and novel framework that can effectively address the flavour problem of the SM.
- We have investigated the bounds on the flavour scale of the minimal and non-minimal versions of this symmetry using the current as well as the future projected sensitivities of the quark and lepton flavour physics data.
- The HL-LHC will be able to probe the signatures of the flavon of $\mathcal{Z}_2 \times \mathcal{Z}_5$ and the $\mathcal{Z}_8 \times \mathcal{Z}_{22}$ flavour symmetries.
- In addition to the $\mathcal{Z}_2 \times \mathcal{Z}_5$ and the $\mathcal{Z}_8 \times \mathcal{Z}_{22}$, HE-LHC will be sensitive to $\mathcal{Z}_2 \times \mathcal{Z}_9$ flavour symmetry through few specific inclusive signatures.
- The future 100 TeV collider will be decisive to test all of these four $\mathcal{Z}_N \times \mathcal{Z}_M$ flavour symmetries at the experimental frontiers.

Thank you !

Backup slides

The couplings of the scalar and pseudoscalar components of the flavon field are obtained by writing the effective Yukawa couplings in the following form:

$$Y_{ij}^f \varphi = y_{ij}^f \left(\frac{\chi}{\Lambda}\right)^{n_{ij}^f} \left(\frac{v+h}{\sqrt{2}}.\right) \cong y_{ij}^f \epsilon^{n_{ij}^f} \frac{v}{\sqrt{2}} \left[1 + \frac{n_{ij}^f (s+ia)}{f} + \frac{h}{v}\right] = M_f \left[1 + \frac{n_{ij}^f (s+ia)}{f} + \frac{h}{v}\right], \quad (1)$$

The couplings of a field with fermions for minimal $\mathcal{Z}_2 \times \mathcal{Z}_5$ symmetry are given by,

$$y_{af_{iL}f_{jR}}^u \equiv y_{aij}^u = \frac{v}{\sqrt{2}f} \begin{pmatrix} 4y_{11}^u \epsilon^4 & 4y_{12}^u \epsilon^4 & 4y_{13}^u \epsilon^4 \\ 2y_{21}^u \epsilon^2 & 2y_{22}^u \epsilon^2 & 2y_{23}^u \epsilon^2 \\ 0 & 0 & 0 \end{pmatrix}, y_{aij}^d = \frac{v}{\sqrt{2}f} \begin{pmatrix} 5y_{11}^d \epsilon^5 & 5y_{12}^d \epsilon^5 & 5y_{13}^d \epsilon^5 \\ 3y_{21}^d \epsilon^3 & 3y_{22}^d \epsilon^3 & 3y_{23}^d \epsilon^3 \\ y_{31}^d \epsilon & y_{32}^d \epsilon & y_{33}^d \epsilon \end{pmatrix}, \quad (2)$$

$$y_{aij}^\ell = \frac{v}{\sqrt{2}f} \begin{pmatrix} 5y_{11}^\ell \epsilon^5 & 5y_{12}^\ell \epsilon^5 & 5y_{13}^\ell \epsilon^5 \\ 3y_{21}^\ell \epsilon^3 & 3y_{22}^\ell \epsilon^3 & 3y_{23}^\ell \epsilon^3 \\ y_{31}^\ell \epsilon & y_{32}^\ell \epsilon & y_{33}^\ell \epsilon \end{pmatrix}.$$

In the similar way, the couplings of *a* field with fermions for non-minimal $\mathcal{Z}_2 \times \mathcal{Z}_9$ symmetry are given by

$$
\begin{aligned}
y^u_{af_{iL}f_{jR}} &\equiv y^u_{aij} = \frac{v}{\sqrt{2}f}\begin{pmatrix} 8y^u_{11}\epsilon^8 & 6y^u_{12}\epsilon^6 & 8y^u_{13}\epsilon^8 \\ 8y^u_{21}\epsilon^8 & 4y^u_{22}\epsilon^4 & 8y^u_{23}\epsilon^8 \\ 0 & 4y^u_{32}\epsilon^4 & 0 \end{pmatrix}, y^d_{aij} = \frac{v}{\sqrt{2}f}\begin{pmatrix} 7y^d_{11}\epsilon^7 & 7y^d_{12}\epsilon^7 & 7y^d_{13}\epsilon^7 \\ 5y^d_{21}\epsilon^5 & 5y^d_{22}\epsilon^5 & 5y^d_{23}\epsilon^5 \\ 3y^d_{31}\epsilon^3 & 3y^d_{32}\epsilon^3 & 3y^d_{33}\epsilon^3 \end{pmatrix}, \quad (3)\\
y^\ell_{aij} &= \frac{v}{\sqrt{2}f}\begin{pmatrix} 7y^\ell_{11}\epsilon^7 & 7y^\ell_{12}\epsilon^7 & 7y^\ell_{13}\epsilon^7 \\ 5y^\ell_{21}\epsilon^5 & 5y^\ell_{22}\epsilon^5 & 5y^\ell_{23}\epsilon^5 \\ 3y^\ell_{31}\epsilon^3 & 3y^\ell_{32}\epsilon^3 & 3y^\ell_{33}\epsilon^3 \end{pmatrix}.
\end{aligned}
$$

The tree-level contribution to neutral meson mixing due to the flavon exchange gives rise to the following Wilson coefficients,

$$
\begin{aligned}
C_2^{ij} &= -(y_{ji}^*)^2 \left(\frac{1}{m_s^2} - \frac{1}{m_a^2} \right) \\
\tilde{C}_2^{ij} &= -y_{ij}^2 \left(\frac{1}{m_s^2} - \frac{1}{m_a^2} \right) \\
C_4^{ij} &= -\frac{y_{ij} y_{ji}}{2} \left(\frac{1}{m_s^2} + \frac{1}{m_a^2} \right) ,
\end{aligned} \tag{4}
$$