Flavor in SUSY after LHC

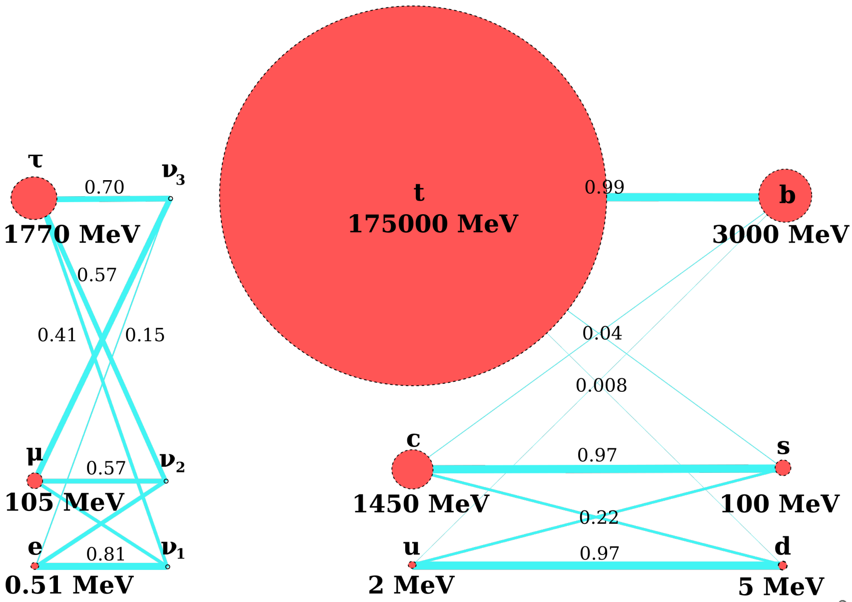
Oscar Vives

workshop on the Standard Model and Beyond

Corfu, 2-10/09/2017

D. Das, M.L. López-Ibáñez, M.J. Perez and O.V., Phys. Rev. D **95**, *no. 3, 035001 (2017), arXiv:1607.06827*

M.L. López-Ibáñez, A. Melis, M.J. Perez and O.V., arXiv:1709.xxxx


τ
1770 MeV
ν3
0.70
0.57
0.41
0.15
μ
105 MeV
ν2
0.57
e
0.51 MeV
ν1
0.81
t
175000 MeV
0.99
b
3000 MeV
0.04
0.008
c
1450 MeV
0.97
s
100 MeV
0.22
u
2 MeV
0.97
d
5 MeV

Standard Model

All Observed *Flavour transitions* can be accomodated in Yukawa couplings:

$$\mathcal{L}_Y \quad = \quad H \; \bar{Q}_i \; Y^d_{ij} \; d_j \quad + \quad H^* \; \bar{Q}_i \; Y^u_{ij} \; u_j$$

Only masses and CKM mixings, $V_{\rm CKM}$, observable...

But... $\Rightarrow$ a) what is the origin of the Yukawa structures??
b) why is there a CP-violating phase in CKM??

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New Physics

New flavour structures generically present $\Rightarrow$ measure of new observables provides new information on flavour origin...

SUSY Flavour (and CP) problems

Soft masses fixed by $m_{3/2}$. $O(m_{3/2})$ elements in soft matrices.

$\Rightarrow$ **Severe FCNC problem !!!**

CP broken, we can expect all complex paramaters have $O(1)$ phases. $\Rightarrow$ **Too large EDMs !!!**

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SM Flavour and CP

Fermion masses fixed by M_W. If $O(1)$ elements in Yukawa matrices and $O(1)$ phases

$\Rightarrow$ **Impossible reproduce masses, mixings and CP observables !!!**

Flavour symmetries in SUSY

- Very different elements in Yukawa matrices: $y_t \simeq 1$, $y_u \simeq 10^{-5}$
- Expect couplings in a "fundamental" theory $\mathcal{O}(1)$
- Small couplings generated as function of small vevs or loops.
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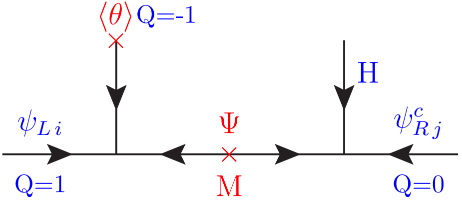

$$\Rightarrow Y_{ij} = \left(\frac{\langle\theta\rangle}{M}\right) \ll 1$$

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- Yukawa couplings forbidden by symmetry, generated only after Spontaneous Symmetry Breaking.

- Unbroken symmetry applies both to fermion and sfermions.

- Diagonal soft masses allowed by symmetry.

- Nonuniversality in soft terms proportional to symm. breaking.

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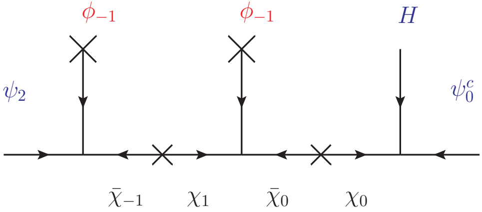
⇓

We can relate the structure in Yukawa matrices to the nonuniversality in Soft Breaking masses !!!

Froggatt-Nielsen effective theory

- Yukawa couplings in $W_{\rm eff}$ after integration of heavy states.



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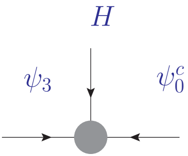

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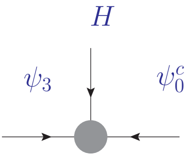

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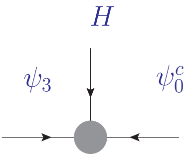

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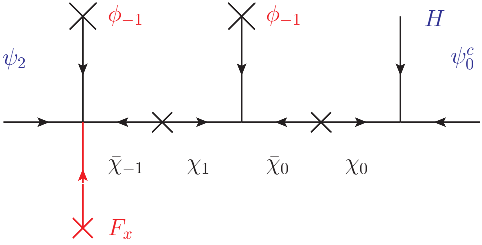

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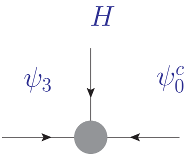

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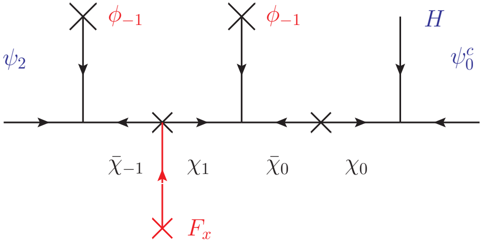

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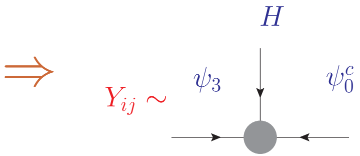

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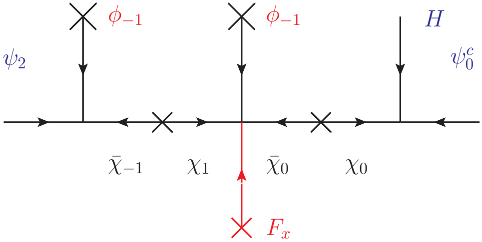

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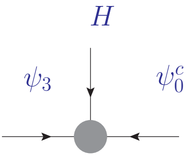

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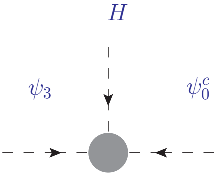
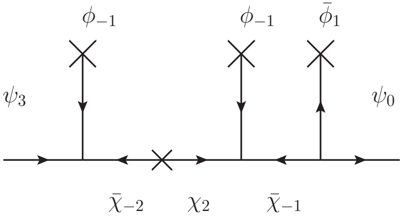
$Y_{ij}^A \sim$



$= 5\ m_0\ Y_{ij}$

- Similar with corrections to kinetic terms and soft masses.



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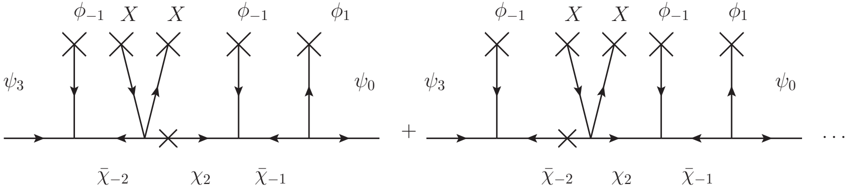

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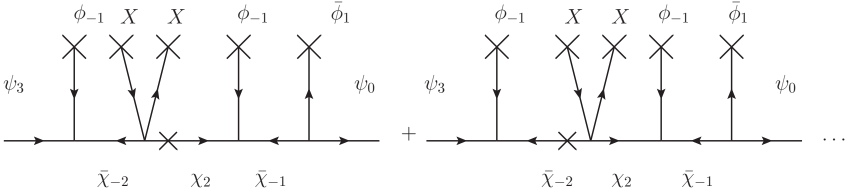

$$\Downarrow$$

$$\left(m^2_{\tilde{\psi}}\right)_{ij} = n \; m_0^2 \times \left(\frac{\theta_i \theta_j^\dagger}{M^2}\right)$$

Abelian Flavour symmetry

- "Simple" Abelian model with charges

$$Q_1 \sim 3, \quad Q_2 \sim 2, \quad Q_3 \sim 0, \quad d_1^c \sim 1, \quad d_2^c \sim 0, \quad d_3^c \sim 0,$$
$$u_1^c \sim 3, \quad u_2^c \sim 2, \quad u_3^c \sim 0, \quad \phi_1 \sim -1 \quad \text{with} \quad \frac{\langle\phi_1\rangle}{M} = \lambda_c$$

- Yukawa couplings proportional to: $Y_{ij} = \left(\langle\phi_1\rangle/M\right)^{(q_1^i + q_1^j)}$

$$M^d = \langle H_1 \rangle \begin{pmatrix} \lambda^4 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda & 1 & 1 \end{pmatrix}, \quad M^u = \langle H_2 \rangle \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}.$$

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- Trilinear couplings::

$$Y_d^A = \begin{pmatrix} 9\lambda^4 & 7\lambda^3 & 7\lambda^3 \\ 7\lambda^3 & 5\lambda^2 & 5\lambda^2 \\ 3\lambda & 1 & 1 \end{pmatrix}, \quad Y_u^A = \begin{pmatrix} 13\lambda^6 & 11\lambda^5 & 7\lambda^3 \\ 11\lambda^5 & 9\lambda^4 & 5\lambda^2 \\ 7\lambda^3 & 5\lambda^2 & 1 \end{pmatrix}.$$

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$\Longrightarrow$ **In SCKM basis trilinear couplings not diagonalized, preserve the structure of Yukawas in flavour basis!!!**

- Soft mass coupling $\phi_i^\dagger \phi_i$ invariant under all symmetries
  $\Rightarrow$ flavour diagonal soft masses allowed by flavour symmetry

- Diagonal masses equal with single F_x as required by phenomenology

- After symmetry breaking offdiagonal entries proportional to flavon vevs, $M_{ij}^2 = m_0^2 \left(\langle\phi_1\rangle/M\right)^{|q_1^i - q_1^j|}$

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$$M^2_{\tilde{Q}} \sim M^2_{\tilde{U}_R} \sim M^2_{\tilde{D}_R} \sim m_0^2 \begin{pmatrix} 1 & 6\,\lambda^3 & 6\,\lambda^3 \\ 6\,\lambda^3 & 1 & \lambda^2 \\ 6\,\lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

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Flavour Observables

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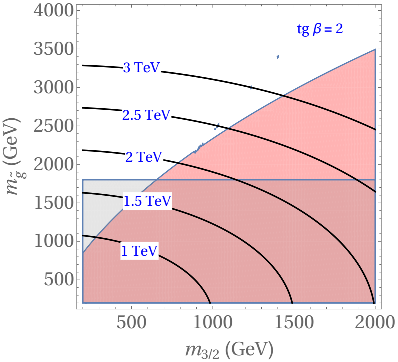

Red area excuded by K–$\overline{K}$, gray rectangle LHC direct searches, black lines average squark masses.

Discrete Non-Abelian symmetries: A4

- A4, Z_4, $U(1)_R$ charges for leptons:

Field	ν^c	l	e^c	μ^c	τ^c	h_d	h_u	φ_T	ξ'	φ_S	ξ
A_4	**3**	**3**	**1**	**1**	**1**	**1**	**1**	**3**	**1'**	**3**	**1**
Z_4	-1	i	1	i	-1	1	i	i	i	1	1
$U(1)_R$	1	1	1	1	1	0	0	0	0	0	0

with $\langle\varphi_T\rangle = (0, v_T, 0)$, $\langle\xi\rangle = u$, $\langle\varphi_S\rangle = v_S \times (1,1,1)$, $\langle\xi\rangle = u'$

- Dirac and Majorana masses, $\frac{v_T}{\lambda} \sim \frac{u}{\Lambda} = \varepsilon, \frac{v_S}{\Lambda} \sim \frac{u'}{\Lambda} = \varepsilon'$:

$$Y_D^\nu \sim y_\nu \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \quad M_{\nu_R} \sim \begin{pmatrix} M' + 2bv_S & -bv_S & -bv_S \\ -bv_S & 2bv_S & M' - bv_S \\ -bv_S & M' - bv_S & 2bv_S \end{pmatrix}$$

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$$\varepsilon = 0.06,\ \varepsilon' = 0.03,\ \tan\beta = 5, \qquad U_{PMNS} = \begin{pmatrix} 0.83 & -0.53 & 0.15 \\ -0-31 & -0.71 & -0.62 \\ -0.44 & -0.47 & 0.77 \end{pmatrix}$$

- Charged-lepton-Higgs matrices:

$$Y_l \sim \varepsilon \begin{pmatrix} \varepsilon^2 & \varepsilon^2\varepsilon' & \varepsilon^2\varepsilon' \\ \varepsilon\varepsilon' & \varepsilon & \varepsilon\varepsilon' \\ \varepsilon' & \varepsilon' & 1 \end{pmatrix}, \quad Y_l^A \sim m_{3/2}\,\varepsilon \begin{pmatrix} 7\varepsilon^2 & 9\varepsilon^2\varepsilon' & 9\varepsilon^2\varepsilon' \\ 7\varepsilon\varepsilon' & 5\varepsilon & 7\varepsilon\varepsilon' \\ 5\varepsilon' & 5\varepsilon' & 3 \end{pmatrix}$$

- Soft mass matrices,

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$$M^2_{\tilde{l}_R} \sim m^2_{3/2} \begin{pmatrix} 1+2(\varepsilon^2+\varepsilon'^{\,2}) & 2\varepsilon'^2 & 2\varepsilon'^2 \\ 2\varepsilon'^2 & 1+2(\varepsilon^2+\varepsilon'^{\,2}) & 2\varepsilon'^2 \\ 2\varepsilon'^2 & 2\varepsilon'^2 & 1+2(\varepsilon^2+\varepsilon'^{\,2}) \end{pmatrix}$$

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- After canonical normalization and SCKM basis:

$$M^2_{\tilde{l}_L} \sim m^2_{3/2} \begin{pmatrix} 1 & -0.006 & 0.005 \\ -0.006 & 1 & -0.006 \\ 0.005 & -0.006 & 1 \end{pmatrix}$$

Lepton Flavour Violation

- $\mu \to e\gamma$ and $\mu \to 3e$ very sensitive even with heavy sfermions

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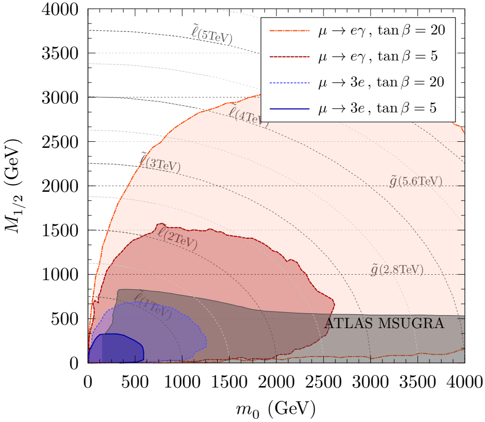

Present bounds on $\mu \to e\gamma$ and $\mu \to 3e$, gray rectangle LHC direct searches.

Conclusions

- Flavour symmetries solve the CP and flavour problems both in New Physics (SUSY) and in the SM.
- New flavour structures will provide valuable information on the origin of flavour
- In SUSY, non-universality always present in soft-breaking terms.
- Flavour structures of soft masses and trilinears remember structures in flavour basis.
- Large reach of flavour observables in realistic flavour models, beyond LHC.
- Lepton Flavour Violation and Kaon sector very sensitive to SUSY flavour structures.

Backup 1

Mediator Superpotential

$$W \supset g \sum_{q_i} \left(\psi_{q_i}\bar{\chi}_{-q_i+1}\phi \;+\; \chi_{q_i}\bar{\chi}_{-q_i+1}\phi \;+\; \chi_{q_i-1}\bar{\chi}_{-q_i}\bar{\phi} \;+\; \bar{\chi}_{-q_i}\psi^c_{r,q_i}H\right)$$
$$+\; M\sum_{q_i}\chi_{q_i}\bar{\chi}_{-q_i} \;+\; M\phi\bar{\phi} \;+\; \dots$$

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Diagrams in components