

# Flavor in SUSY after LHC

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COST workshop on Higgs and Flavour Physics  
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*D. Das, M.L. López-Ibáñez, M.J. Perez and O.V., Phys. Rev. D 95, no. 3, 035001 (2017), 1607.06827*

*M.L. López-Ibáñez, A. Melis, M.J. Perez and O.V., JHEP 1711 (2017) 162, 1710.02593*

*I. de Medeiros Varzielas, M. L. López-Ibáñez, A. Melis and O.V., JHEP 1809 (2018) 047, 1807.00860*

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## Flavour in Standard Model

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

$$\mathcal{L}_Y = H \bar{Q}_i Y_{ij}^d d_j + H^* \bar{Q}_i Y_{ij}^u u_j$$

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

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## SUSY Flavour (and CP) problems

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

⇒ **Severe FCNC problem !!!**

CP broken, we can expect all complex parameters have  $O(1)$  phases.

⇒ **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

⇒ **Impossible reproduce masses, mixings and CP observables !!!**

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



- 
- Flavour symmetry explains masses and mixings in Yukawas.
  - 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.
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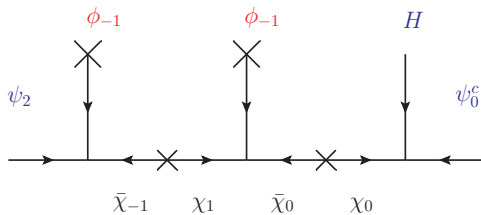


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New information on flavor if Yukawa matrices and soft terms not simultaneously diagonalizable.

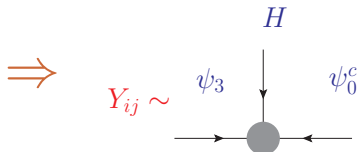
## Froggatt-Nielsen effective theory

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



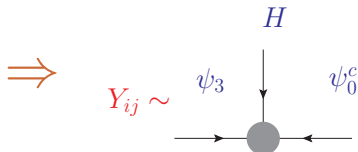
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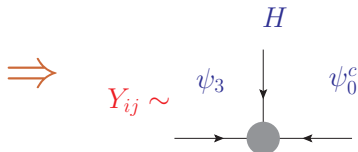
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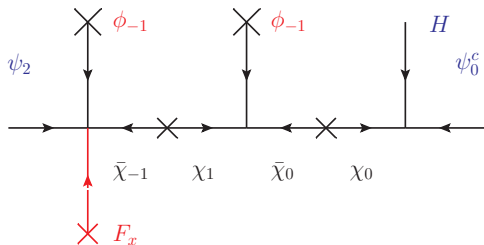
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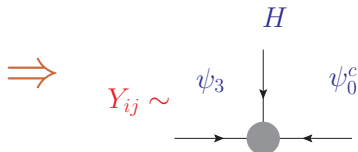


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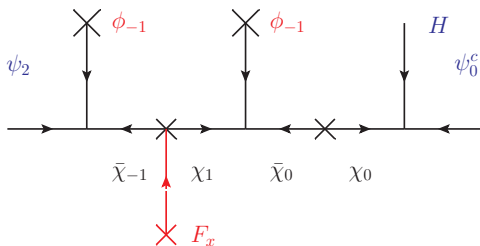


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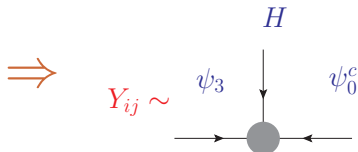
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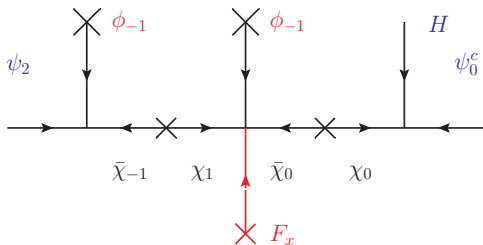


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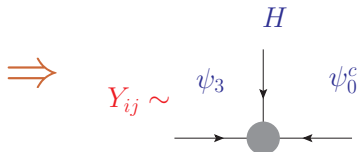


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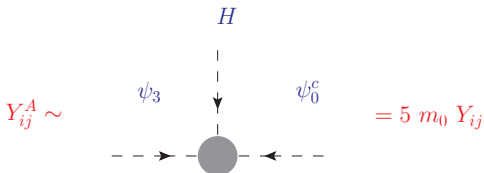


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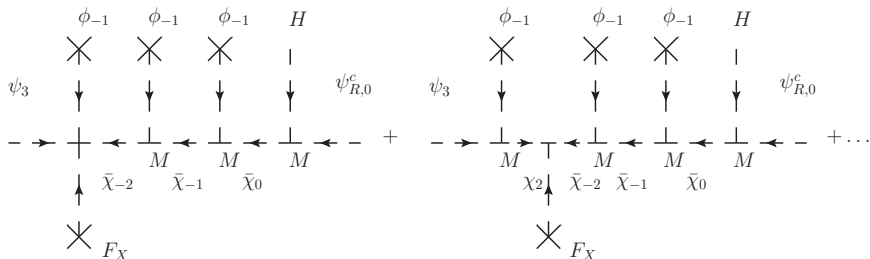
## Mediator Superpotential

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

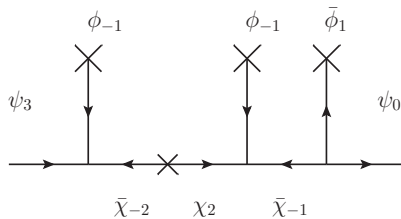
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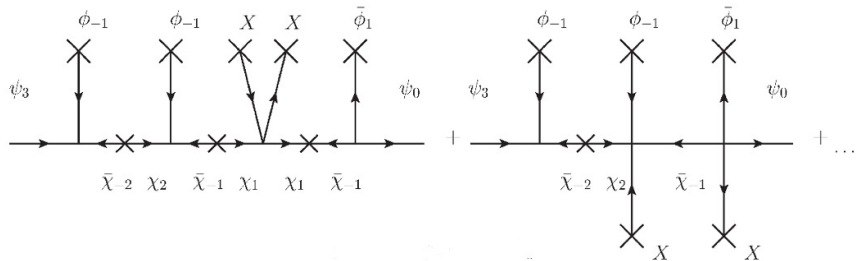
## Diagrams in components



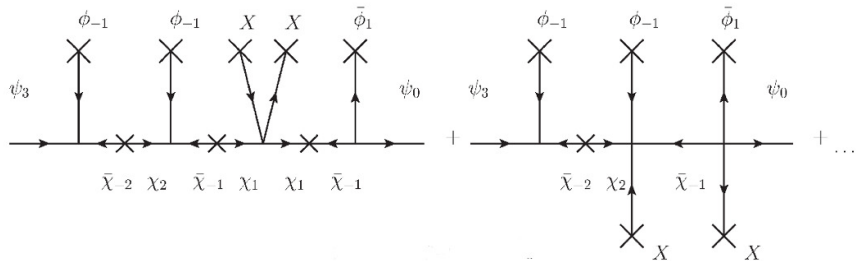
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$$\left(m_{\tilde{\psi}}^2\right)_{ij} = n m_0^2 \times \left(\frac{\theta_i \theta_j^\dagger}{M^2}\right)$$

## Abelian Flavour symmetry

- “Simple” Abelian model with charges

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

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

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



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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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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,  $M_{ij}^2 = m_0^2 (\langle \phi_1 \rangle / M)^{|q_i^i - q_i^j|}$

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

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- After canonical normalization:

$$M_Q^2 \sim M_{U_R}^2 \sim M_{D_R}^2 \sim m_0^2 \begin{pmatrix} 1 & 4\lambda^3 & 4\lambda^3 \\ 4\lambda^3 & 1 & \frac{3}{2}\lambda^4 \\ 4\lambda^3 & \frac{3}{2}\lambda^4 & 1 \end{pmatrix}$$

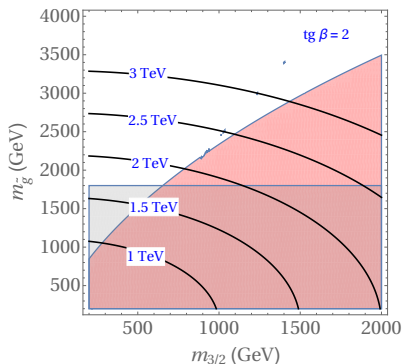
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## Flavour Observables

- $K-\bar{K}$  and  $B-\bar{B}$  mixing most sensitive observables

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Red area excluded by  $K-\bar{K}$ , gray rectangle LHC direct searches, black lines average squark masses.

## Discrete Non-Abelian symmetries: $\Delta(27)$

- $\Delta(27)$ ,  $Z_2$ ,  $U(1)_{FN}$ ,  $U(1)_R$ , charges for leptons:

Field	$\ell, \nu$	$\ell^c, \nu^c$	$H_{u,d}$	$\Sigma$	$\phi_{123}$	$\phi_1$	$\bar{\phi}_3$	$\bar{\phi}_{23}$	$\bar{\phi}_{123}$
$\Delta(27)$	<b>3</b>	<b>3</b>	<b>1</b>	<b>1</b>	<b>3</b>	<b>3</b>	<b><math>\bar{3}</math></b>	<b><math>\bar{3}</math></b>	<b><math>\bar{3}</math></b>
$Z_2$	1	1	1	1	1	-1	-1	-1	-1
$U(1)_{FN}$	0	0	0	2	-1	-4	0	-1	1
$U(1)_R$	1	1	0	0	0	0	0	0	0

$$\langle \bar{\phi}_3 \rangle = v_3 (0, 0, 1), \quad \langle \bar{\phi}_{23} \rangle = v_{23} (0, -1, 1), \quad \langle \bar{\phi}_{123} \rangle = v_{123} (1, 1, 1)$$

- Higgs couplings,  $\frac{v_3}{\Lambda} \simeq \sqrt{y_\tau}$ ,  $\frac{v_{23}}{\Lambda} \simeq \sqrt{y_\tau \epsilon}$ ,  $\frac{v_{123}}{\Lambda} \simeq \sqrt{y_\tau \epsilon^2}$ :

$$Y_\ell \sim y_\tau \begin{pmatrix} \epsilon^8 & -\epsilon^3 & \epsilon^3 \\ -\epsilon^3 & 3\epsilon^2 & -3\epsilon^2 \\ \epsilon^3 & -3\epsilon^2 & 1 \end{pmatrix}, \quad A_\ell \sim y_\tau a_0 \begin{pmatrix} 13\epsilon^8 & -5\epsilon^3 & 5\epsilon^3 \\ -5\epsilon^3 & 21\epsilon^2 & -21\epsilon^2 \\ 5\epsilon^3 & -21\epsilon^2 & 5 \end{pmatrix}$$



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$$m_{\ell,R}^2 \sim m_0^2 \begin{pmatrix} 1 + 2 y_\tau \varepsilon^4 & -12 y_\tau \varepsilon^3 & 12 y_\tau \varepsilon^3 \\ -12 y_\tau \varepsilon^3 & 1 + 2 y_\tau \varepsilon^2 & -2 y_\tau \varepsilon^2 \\ 12 y_\tau \varepsilon^3 & -2 y_\tau \varepsilon^2 & 1 + 2 y_\tau \end{pmatrix}$$

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- After canonical normalization and SCKM basis:

$$m_{\ell,R}^2 \sim m_0^2 \begin{pmatrix} 1 & -9 y_\tau \varepsilon^3 & 9 y_\tau \varepsilon^3 \\ -9 y_\tau \varepsilon^3 & 1 + y_\tau \varepsilon^2 & 2 y_\tau \varepsilon^2 \\ 9 y_\tau \varepsilon^3 & 2 y_\tau \varepsilon^2 & 1 + y_\tau \end{pmatrix}$$

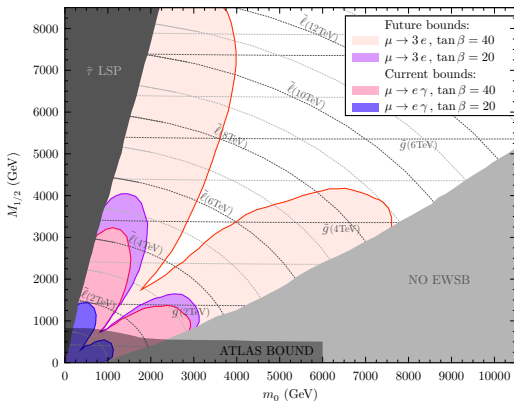
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## Lepton Flavour Violation

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

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

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## 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.