Flavor for Susy and Susy for Flavor

Oscar Vives

SUSY2023

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C Hagedorn, M.L. López-Ibáñez, M.J Perez, M. Rahat and O.V., arXiv:2107.xxxx

D. Das, M.L. López-Ibáñez, M.J. Perez and O.V., Phys. Rev. D **95**, 035001 (2017)

M.L. López-Ibáñez, A. Melis, M.J. Perez and O.V., JHEP 11 (2017), 162

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Flavour in Standard Model

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

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

Only masses and CKM mixings, V_{CKM}, observable...

But... $\Longrightarrow$ a) what is the origin of the Yukawa structures??

b) why is there a CP-violating phase in CKM??

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b) why is there a CP-violating phase in CKM??

New flavour observables needed !!

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.

$$\Rightarrow \quad \textbf{Severe FCNC problem !!!}$$

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

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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

$$\Rightarrow \quad \textbf{Impossible reproduce masses, mixings}$$
$$\textbf{and CP observables !!!}$$

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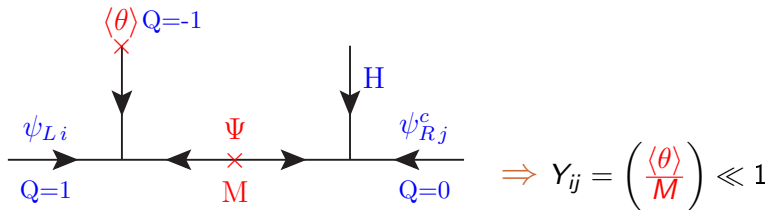
$$\Rightarrow Y_{ij} = \left(\frac{\langle \theta \rangle}{M} \right) \ll 1$$

- 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.

- Nonuniversality in soft terms proportional to symm. breaking.

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$$\Downarrow$$

We can <u>relate</u> the structure in **Yukawa matrices** to the nonuniversality in **Soft Breaking masses** !!!

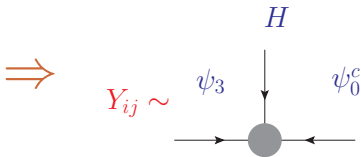New information on flavor if Yukawa matrices and soft terms **not simultaneously diagonalizable.**

Froggatt-Nielsen effective theory

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

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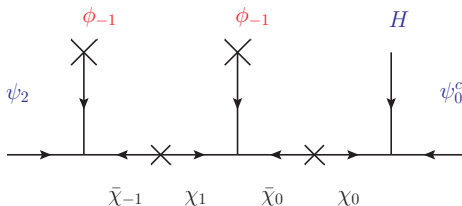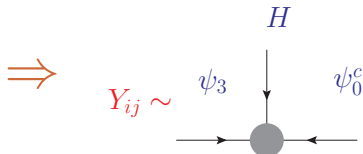
- Even with flavour universal SUSY breaking, $F_x = m_0$, non-universal corrections to trilinear couplings.
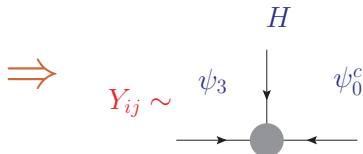
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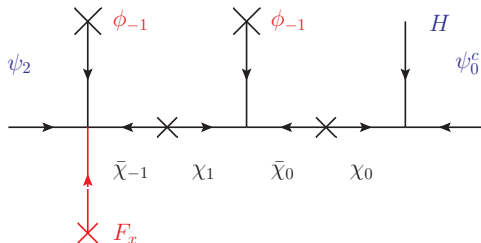

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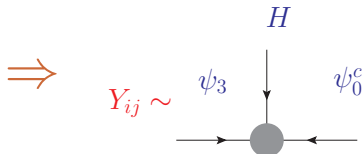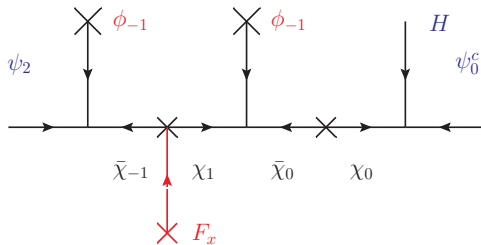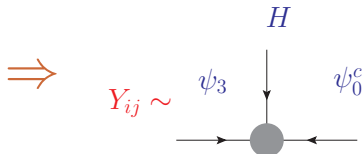- Yukawa couplings in W_{eff} after integration of heavy states.

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H

$\psi_3 \qquad \psi_0^c$

- Even with flavour universal SUSY breaking, $F_x = m_0$, non-universal corrections to trilinear couplings.

H

$Y_{ij}^A \sim \qquad \psi_3 \qquad \psi_0^c \qquad \qquad = 5\, m_0\, Y_{ij}$
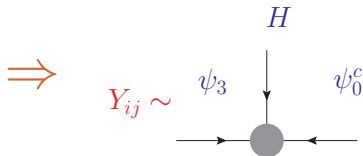
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$$\left(m_{\tilde{\psi}}^2\right)_{ij} = n \; m_0^2 \times \left(\frac{\theta_i \theta_j^\dagger}{M^2}\right)$$

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

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

Field	ℓ, ν	ℓ^c, ν^c	$H_{u,d}$	Σ	ϕ_{123}	ϕ_1	$\bar{\phi}_3$	$\bar{\phi}_{23}$	$\bar{\phi}_{123}$
$\Delta(27)$	**3**	**3**	**1**	**1**	**3**	**3**	$\bar{3}$	$\bar{3}$	$\bar{3}$
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

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

- Higgs couplings, $\frac{v_3}{\Lambda} \simeq \sqrt{y_\tau}$, $\frac{v_{23}}{\Lambda} \simeq \sqrt{y_\tau} \varepsilon$, $\frac{v_{123}}{\Lambda} \simeq \sqrt{y_\tau} \varepsilon^2$:
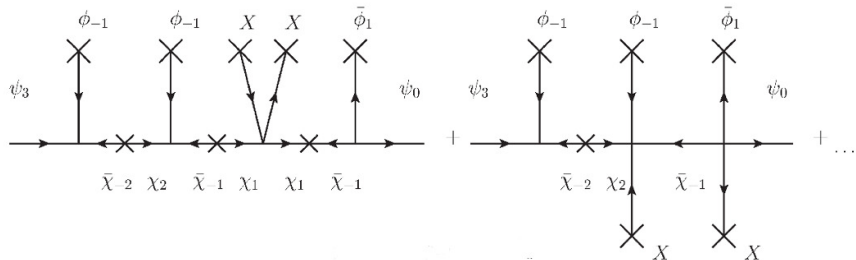
$$Y_\ell \sim y_\tau \begin{pmatrix} \varepsilon^8 & -\varepsilon^3 & \varepsilon^3 \\ -\varepsilon^3 & 3\,\varepsilon^2 & -3\varepsilon^2 \\ \varepsilon^3 & -3\,\varepsilon^2 & 1 \end{pmatrix}, \; A_\ell \sim y_\tau \, a_0 \begin{pmatrix} 13\,\varepsilon^8 & -5\,\varepsilon^3 & 5\,\varepsilon^3 \\ -5\,\varepsilon^3 & 21\,\varepsilon^2 & -21\,\varepsilon^2 \\ 5\,\varepsilon^3 & -21\,\varepsilon^2 & 5 \end{pmatrix}$$

- Soft mass matrices,

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

- After canonical normalization and SCKM basis:

$$
m^2_{\ell,R} \sim m^2_0
\begin{pmatrix}
1 & -9y_\tau\,\varepsilon^3 & 9y_\tau\,\varepsilon^3 \\
-9y_\tau\,\varepsilon^3 & 1 + y_\tau\varepsilon^2 & 2y_\tau\,\varepsilon^2 \\
9y_\tau\,\varepsilon^3 & 2\,y_\tau\,\varepsilon^2 & 1 + y_\tau
\end{pmatrix}
$$

Lepton Flavour Violation

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$$\mathrm{tg}\beta = 20 \ , \ v_{123}/M_a \sim \sqrt{y_{3,a} \, \varepsilon_a}$$
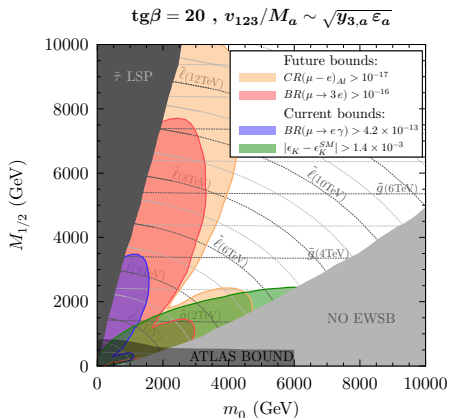
Present bounds on $\mu \to e\gamma$, $\mu \to 3e$, and ε_K, gray rectangle LHC.

- **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.

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Is **SUSY** still useful in flavor ??

Vacuum Alignment in Non-SUSY potentials

- Very particular flavon alignment required to reproduce masses and mixings.

- For triplet representations (see $\Delta(27)$ example):

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

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- In particular, all quartics $|(\phi_i, \phi_j)|^2$ are always allowed by any symmetry, irrespective of the charges of (ϕ_i, ϕ_j).

$\Rightarrow$ We have to eliminate some of this quartics arbitrarily assuming some couplings small or zero.

SUSY Vacuum alignment

Scalar potential derived from **Superpotential**, W.

$$V_{\mathrm{SUSY}} = \sum_n F_n F_n^\dagger = \sum_n \left(\partial_n W\right)\left(\partial_n W\right)^\dagger$$

W : cubic function of superfields singlet under all symmetries.

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$\Rightarrow$ Alignment from vanishing of, driving field, F-terms

Non-SUSY Vacuum alignment

SUSY-broken scalar potential:

$$V = V_{\mathrm{SUSY}} + V_{\mathrm{soft}} = \sum_n F_n F_n^\dagger + m^2 \sum_j \phi_j^* \phi_j$$

where F-terms: $F_n = M\phi_k + f(\phi_i, \phi_j)$, with $f(\phi_i, \phi_j)$, second order pol. in ϕ.

In the SUSY limit $F_n|_{v_s} = 0$, $\Rightarrow$ $f(\phi_l, \phi_n)|_{v_s} = -M\,\phi_k|_{v_s}$

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- Isolated SUSY minimum (no flat directions).

- Arbitrary $m^2 \ll M^2$ ($\zeta \simeq 1$), flavor symmetric.

The full potential at the minimum:

$$V(\phi|_V) = \sum_n F_n F_n^\dagger\Big|_V + m^2 \sum_j \phi_j^* \phi_j\Big|_V$$

and the **F-terms**:

$$F_n|_V = \zeta\, M\, \phi_k|_{V_S} + \zeta^2\, f(\phi_i, \phi_j)|_{V_S} = \zeta\, (1-\zeta)\, M\, \phi_k|_{V_S}$$

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Extremizing respect ζ:

$$\frac{\partial V(\zeta)}{\partial \zeta} = 0 \quad \Rightarrow \quad (1 - 3\,\zeta + 2\,\zeta^2)\, M^2 + m^2 = 0$$

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$$\zeta \approx \tfrac{1}{2} + \tfrac{m^2}{M^2} \quad \text{and} \quad \zeta \approx 1 - \tfrac{m^2}{M^2}$$

Minimum at $\quad V\left(\zeta \approx 1 - \tfrac{m^2}{M^2}\right) \approx m^2 \sum_k \phi_k\, \phi_k^\star|_{V_S}$

Example: Two orthogonal flavons in A_4

$$
\begin{aligned}
W_s \;=\; & \lambda_a \left[(\phi_a \phi_a)_1 - x_a^2 \right] \Phi_a^0 \;+\; \lambda_b \left[(\phi_b \phi_b)_1 - x_b^2 \right] \Phi_b^0 \\
& +\; \lambda_c \, (\phi_a \phi_b)_1 \, \Phi_c^0 \;+\; \lambda_d \, (\phi_a \phi_a)_3 \, \Phi_d^0 \;+\; \lambda_e \, (\phi_b \phi_b)_3 \, \Phi_e^0 .
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$$

Vanishing of the Driving fields, Φ_n^0, F-terms:

$$
\frac{\partial W}{\partial \Phi_{a,b}^0} = \lambda_{a,b} \left[(\phi_{a,b} \phi_{a,b})_1 - x_{a,b}^2 \right] = 0,
$$

$$
\frac{\partial W}{\partial \Phi_c^0} = \lambda_c (\phi_a \phi_b)_1 = 0,
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$$
\frac{\partial W}{\partial \Phi_{d,e_i}^0} = \lambda_{d,e} \phi_{a,b_{i+1}} \phi_{a,b_{i+2}} = 0.
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$$W_s = \lambda_a \left[(\phi_a \phi_a)_1 - x_a^2 \right] \Phi_a^0 + \lambda_b \left[(\phi_b \phi_b)_1 - x_b^2 \right] \Phi_b^0$$
$$+ \lambda_c (\phi_a \phi_b)_1 \Phi_c^0 + \lambda_d (\phi_a \phi_a)_3 \Phi_d^0 + \lambda_e (\phi_b \phi_b)_3 \Phi_e^0.$$

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Can we <u>preserve</u> this alignment in non-SUSY models??

SUSY broken at high scales

Non-SUSY at low energies. Scalar potential from Supersymmetry, plus soft-breaking terms.

$$V = V_S + \mu_a^2 (\phi_a \phi_a^*)_1 = \sum_n F_n F_n^\dagger + \mu_a^2 (\phi_a \phi_a^*)_1$$

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$$V = V_S + \mu_a^2 (\phi_a \phi_a^*)_1 = \sum_n F_n F_n^\dagger + \mu_a^2 (\phi_a \phi_a^*)_1$$

We require that SUSY-breaking preserves the supersymmetric alignment, $v|_V = \zeta \ v|_{V_S}$

$$F_{a^0, b^0} = \lambda_{a,b} \left[\zeta^2 \left. (\phi_{a,b} \phi_{a,b}) \right|_{V_S} - x_{a,b}^2 \right] = \lambda_{a,b} \ x_{a,b}^2 \left(\zeta^2 - 1 \right)$$

SUSY broken at high scales

Non-SUSY at low energies. Scalar potential from Supersymmetry, plus soft-breaking terms.

$$V = V_S + \mu_a^2 \left(\phi_a \phi_a^*\right)_\mathbf{1} = \sum_n F_n F_n^\dagger + \mu_a^2 \left(\phi_a \phi_a^*\right)_\mathbf{1}$$

We require that SUSY-breaking preserves the supersymmetric alignment, $v|_V = \zeta \ v|_{V_S}$

$$F_{a^0, b^0} = \lambda_{a,b} \left[\zeta^2 \left(\phi_{a,b} \phi_{a,b}\right)|_{V_S} - x_{a,b}^2 \right] = \lambda_{a,b} \, x_{a,b}^2 \left(\zeta^2 - 1\right)$$

Then, the scalar potential at the minimum,

$$V = \lambda_a^2 \, x_a^4 \, (1 - \zeta^2)^2 + \lambda_b^2 \, x_b^4 \, (1 - \zeta^2)^2 + \zeta^2 \mu_a^2 x_a^2 + \zeta^2 \mu_b^2 x_b^2.$$

If we minimize the full potential as a function of ζ,

$$\frac{\partial V}{\partial \zeta} \;=\; 4\,\zeta\,(1-\zeta^2)\left(\lambda_a^2\,x_a^4 \;+\; \lambda_b^2\,x_b^4\right) + 2\,\zeta\,\mu_a^2\,x_a^2 \;+\; 2\,\zeta\,\mu_b^2\,x_b^2 \;=\; 0\,.$$

$$\Rightarrow \;\; \zeta^2 \;=\; 1 - \frac{\mu_a^2\,x_a^2 \;+\; \mu_b^2\,x_b^2}{\left(\lambda_a^2\,x_a^4 \;+\; \lambda_b^2\,x_b^4\right)}\,.$$

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BUT soft masses arbitrary, we impose universal rescaling,

$$\frac{\mu_a^2}{\lambda_a^2 x_a^2} \;=\; \frac{\mu_b^2}{\lambda_b^2 x_b^2}\,,$$

and then,

$$\zeta^2 \;=\; 1 - \frac{\mu_a^2}{\lambda_a^2\,x^2} \;=\; 1 - \frac{\mu_b^2}{\lambda_b^2\,y^2}\,.$$

$\Longrightarrow$ SUSY alignment maintained exactly!!
for invariant soft-breaking masses.

$\implies$ SUSY alignment maintained exactly!!
for invariant soft-breaking masses.

even for non-invariant soft-breaking:

$$V = V_S + \mu^2_{kj}\phi^*_k\phi_j = \mu^2_{kj}\ \phi^{a*}_k\phi^a_j + M^2_a\ \phi^{a*}_i\phi^a_i + V_4\,.$$

$\Rightarrow$ <u>SUSY alignment maintained exactly!!</u>
<u>for invariant soft-breaking masses.</u>

even for non-invariant soft-breaking:

$$V = V_S + \mu_{kj}^2 \phi_k^* \phi_j = \mu_{kj}^2 \ \phi_k^{a\,*} \phi_j^a + M_a^2 \ \phi_i^{a\,*} \phi_i^a + V_4 \,.$$

as before,

$$\frac{\partial V}{\partial \phi_i^*} = M_a^2 \phi_i + \mu_{ij}^2 \ \phi_j + \frac{\partial V_4}{\partial \phi_i^*} = 0 \,.$$

$$\mu_{ij}^2 \ \phi_j \big|_V = -(1 - \zeta^2) \ M_a^2 \ \phi_i \big|_V \,,$$

$\implies$ <u>SUSY alignment maintained exactly!!</u>
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as before,

$$\frac{\partial V}{\partial \phi^*_i} = M^2_a\phi_i + \mu^2_{ij}\ \phi_j + \frac{\partial V_4}{\partial \phi^*_i} = 0\,.$$

$$\mu^2_{ij}\ \phi_j\big|_V = -(1 - \zeta^2)\ M^2_a\ \phi_i\big|_V\,,$$

Still preserve vacuum alignment iif the SUSY VEV
is eigenvector of SUSY soft-breaking matrix.

Conclusions

- New flavour structures will provide valuable information on the origin of flavour

- In SUSY, non-universality always present in soft-breaking terms.

- Large reach of flavour observables in realistic flavour models, beyond LHC.

- Even if SUSY not present at low energies, nice properties help in flavor sector.

- Supersymmetric Vacuum alignment can be preserved in softly-broken models.

Conclusions

• New flavour structures will provide valuable information on the origin of flavour

• In SUSY, non-universality always present in soft-breaking terms.

• Large reach of flavour observables in realistic flavour models, beyond LHC.

• Even if SUSY not present at low energies, nice properties help in flavor sector.

• Supersymmetric Vacuum alignment can be preserved in softly-broken models.

Flavor needs **SUSY** and SUSY needs **flavor**

Backup

Mediator Superpotential

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

Mediator Superpotential

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

Diagrams in components