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Flavored Gauge Mediation with Discrete Non-Abelian Symmetries

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Based on:

1610.09024	LE, TG
1812.10811	LE, TG, AR
1912.12938	LE, TG, AR

+ work in progress

See also: $\boxed{\text{Talk by Ariel Rock}}$ next!

Main idea:

Generalization of minimal gauge mediation to include Yukawa couplings between messenger + MSSM fields

$\Rightarrow$ "flavored gauge mediation"

$\hookrightarrow$ Higgs + $SU(2)_L$ messenger doublet mixing

- use discrete non-Abelian symmetry to control this mixing in a 3-family scenario
- This symmetry also can play a role as (part of) the family symmetry that yields SM fermion masses + mixings.

Background / Motivation

- Minimal Gauge mediation : elegant framework for ~~SUSY~~ parameters

Dine, Fischler, Srednicki 1981

Dimopolous + Raby 1981, 1983

Dine, Fischler 1982

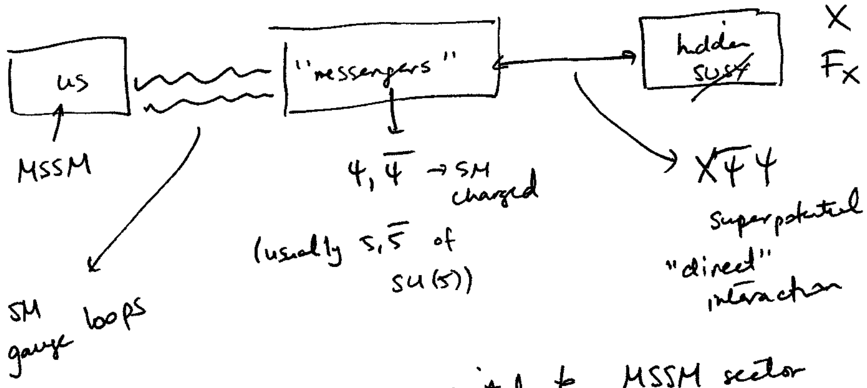
Nappi, Ovrut 1982

Alvarez - Gaume et al 1982

Dine + Nelson 1993

" w/ Shirman 1995

" " w/ Nir 1995



$\Rightarrow$ ~~SUSY~~ in hidden sector mediated to MSSM sector via loops involving messenger fields + SM gauge fields.

Reviews:

- Giudice Rattazzi 1998
- Martin 1997

Advantages

- flavor diagonal
- clean, economical, not UV sensitive

Disadvantage :

Post LHC Higgs measurement in 2012 minimal gauge mediation "disfavored" due to challenges in obtaining 125 GeV Higgs w/o ultraheavy squarks.

(realized before discovery: Draper et al 2011)

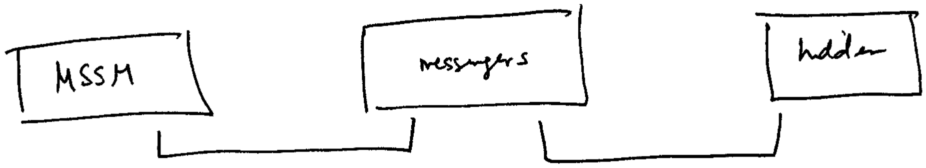
Reason: trilinear ~~SUSY~~ parameters $\tilde{A}_{u,d,e}$ predicted to be 0 at input scale ($M_{messenger}$: masses of $\bar\Phi, \Phi$)

$\Rightarrow$ generally insufficient stop mixing
ultraheavy (10 TeV ish) $SU(3)_c$ - charged superpartners needed to boost m_{h^0}.

$\Rightarrow$ modify minimal gauge mediation to allow for more "direct" interactions b/w MSSM + messengers

Precursors : Chacko, Ponton 2002
Shadmi et al 2011

→ New structure:



$X \bar{\Psi} \Psi$

messenger-~~md~~ MSSM
superpotential interactions

Many explorations!
(starting in 2012)

Chacko-Ponton 2002
Shadmi, Szabo 2011
Evans, Ibe, Yanagida 2011, 2012
Kang et al 2012
Craig et al 2012
Albaid + Babu 2012
Abdullah et al 2012
...

Many possibilities →
see eg Evans + Shih 2013
(1303.0228)

Focus here on particular category of interactions →
"flavored gauge mediation" (FGM)
↳ term coined by Shadmi + collaborators

idea: $SU(2)_L$ doublet messengers mix →
+ MSSM Higgs H_u, H_d

eg $\quad Y_u \, Q \bar{u} H_u \longrightarrow Y_u' \, Q \bar{u} M_u$

↳ messenger doublet

↑ messenger Yukawa coupling

etc.

messenger Yukawas "correct" the minimal gauge mediation predictions
for the MSSM soft mass parameters

- Advantage → can generate sizable stop mixing
  + thus lower needed values of squarks, gluino!

better discovery potential → eg benchmarks for LHC studies:
Ierushalmi, Iwamoto, Lee, Nepomnyashy, Shadmi 2016

- Disadvantage → lose beautiful, automatically flavor diagonal soft terms.

⇒ FCNC constraints must be in the back of our minds as a concern →
though not as automatically constraining as we might think

see eg Calibbi et al 2014
Ierushalmi et al 2016

So we've seen $\boxed{\text{FGM}}$ is an intriguing non-minimal extension of minimal gauge mediation.

Key ingredient: $\boxed{\text{Symmetry}}$ that controls the Higgs-messenger mixing + generation of messenger Yukawas.

→ one canonical choice: $U(1)$ symmetries

ingredient in LHC benchmarks of Ierushalmi et al. + many other studies.

→ Alternative: $\boxed{\text{discrete non-Abelian symmetries}}$

- more constraining! adds to predictivity of theory
- such symmetries are often used in generation of fermion masses → might also find utility here.

Initial (first, to our knowledge) proposal of this type:

$\boxed{S_3'}$ symmetry in a 2-family scenario. $\boxed{\text{Perez, Ramond, Zhang 2012}}$ (PRZ) $\boxed{1209.6071}$

reps: $2, 1, 1'$

$2 \otimes 2 = 2 \oplus 1 \oplus 1'$

PRZ proposal: embed ~~#~~ 2-generations into 2 (doublet) rep of S_3' as well Higgs-messengers in S_3' doublets

$$\mathcal{H}_u^{(2)} = R_u \begin{pmatrix} H_u \\ M_u \end{pmatrix} \qquad \mathcal{H}_d^{(2)} = R_d \begin{pmatrix} H_d \\ M_d \end{pmatrix}$$

Explored Higgs-messenger sector, including coupling to SUSY field X

also S_3' doublet

$$W_H = m\, \mathcal{H}_u^{(2)} \mathcal{H}_d^{(2)} + \lambda X\, \mathcal{H}_u^{(2)} \mathcal{H}_d^{(2)}$$
$$= \mathcal{H}_u^{(2)T}\, \mathbb{M}\, \mathcal{H}_d^{(2)} + \theta^2\, \mathcal{H}_u^{(2)T}\, \mathbb{F}\, \mathcal{H}_d^{(2)}$$

PRZ (continued):

explored field space direction of $\langle \lambda X \rangle = M \underbrace{\begin{pmatrix} \sin\phi \\ \cos\phi \end{pmatrix}}_{\langle X \rangle} + \theta^2 F \underbrace{\begin{pmatrix} \sin\xi \\ \cos\xi \end{pmatrix}}_{\langle F_X \rangle}$

+ found important constraints:

$$[\mathbb{M}, \mathbb{F}] = 0$$ (required for smooth decoupling of heavy messengers after $\cancel{\text{SUSY}}$)

PRZ further explored the generation of MSSM Yukawas in their two-family scenario:

$Y_u \; Q \; u \; H_u \rightarrow \quad 2 \otimes 2 \otimes 2 \quad S_3$

generic relation b/w Y_u + messenger Yukawa Y_u'

if $Y_u \sim \begin{pmatrix} 0 & \\ & 1 \end{pmatrix}$, $\underbrace{\quad Y_u' \sim \begin{pmatrix} 1 & \\ & 0 \end{pmatrix}}_{S_3}$

⇒ Soon after PRZ's paper came out (2013 ish) Todd Garon + I wondered, can we make this work for 3 families?

ie. S_3 as messenger – Higgs symmetry + S_3 as (part of) family symmetry.

Questions: can a fully-fledged 3 generation model work in details? if so, what is the anticipated LHC reach? What are the flavor constraints + can they be satisfied?

Challenges standard lore that flavor symm breaking + $\cancel{\text{SUSY}}$ should <u>not</u> be linked (else risk ruination + despair!)

↑ for good reasons!

Answer: still in progress, taking steps in framework. Ariel will report on the best-motivated + most promising direction. Here: a bit more background + context.

Higgs - Messenger Sector and the μ / B_μ problem

First discussion topic $\rightarrow$ scrutiny of the Higgs-messenger sector in the simplest generalization of PRZ to 3 families suffers from a severe μ / B_μ problem!

To see this:

Take, as in PRZ,

$$\mathcal{H}_u^{(2)} \sim 2 \quad , \quad \mathcal{H}_d^{(2)} \sim 2 , \quad X \sim 2$$

$$W_H = \mathcal{H}_u^{(2)T} (\mathbb{M} + \theta^2 \mathbb{F}) \mathcal{H}_d^{(2)} \qquad \langle \lambda X \rangle = M \begin{pmatrix} \sin\phi \\ \cos\phi \end{pmatrix} + \theta^2 F \begin{pmatrix} \sin\xi \\ \cos\xi \end{pmatrix}$$

$m \mathcal{H}_u^{(2)} \mathcal{H}_d^{(2)} + \lambda X \mathcal{H}_u^{(2)} \mathcal{H}_d^{(2)}$

$$\mathbb{M} = \begin{pmatrix} M \sin\phi & m \\ m & M\cos\phi \end{pmatrix}$$

$$\mathbb{F} = \begin{pmatrix} F\sin\xi & 0 \\ 0 & F\cos\xi \end{pmatrix}$$

Require $[\mathbb{M}, \mathbb{F}] = 0 \quad \Rightarrow \quad \tan\xi = 1$

$$\mathbb{F} \rightarrow F \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

ie commutator relation restricts $\mathbb{F}$ to the identity

$\Rightarrow$ severe problem: both eigenvalues of $\mathbb{F} \sim \mathcal{O}(F)$
but one of them should be identified with $b = B_\mu \mu$.

$\therefore \; B_\mu \gg \mu \quad \rightarrow$ fine-tuning.

Actually it's worse than just a fine-tuning issue
as B_μ + μ <u>cannot</u> here be independently tuned.

Not surprising: in GMSB
long known that the coupling
$X H_u H_d$ gives tree-level μ + b:

$$\mu = \lambda \langle X \rangle , \quad b = B_\mu \mu = \lambda \langle F_X \rangle$$

but $m_{soft} \sim \dfrac{1}{16\pi^2} \dfrac{\langle F_X \rangle}{\langle X \rangle} \rightarrow B_\mu = \dfrac{\langle F_X \rangle}{\langle X \rangle} \sim 16\pi^2 \, m_{soft}$

well known problem!! "μ / B_μ" problem of gauge mediation

Usually the coupling

$$W_H = \lambda X H_u H_d$$ is thus forbidden (eg by some symmetry)

in attempts to solve this μ / B_μ problem.

see eg reviews: Giudice Rattazzi 1998

Polonsky 2001

Problem here:

we need $X \mathcal{H}_u^{(2)} \mathcal{H}_d^{(2)}$ coupling

because we need

$X \bar{\Psi} \Psi$ direct interaction ~~b~~ b/w hidden + messenger fields

to mediate $\cancel{SUSY}$ to MSSM sector!

S_3 symmetry then <u>requires</u> the problematic $X H_u H_d$ term.

So here the μ/B_μ problem is worse than in the usual gauge mediation scenarios

where there is freedom to switch off $X H_u H_d$.

(Note: FGM with $U(1)$ does not have ~~these~~ is problem as can choose $U(1)$ charges judiciously to forbid $X H_u H_d$ term.)

$\boxed{\text{Our "solution"}}$ $\boxed{\text{LE, TG 2016}}$

$\Rightarrow$ extend the Higgs-messenger sector to include additional Higgs-messenger fields, this time in <u>1</u> reps of S_3 -

Higgs-messenger fields:

$$\mathcal{H}_u^{(2)}, \ \mathcal{H}_d^{(2)}, \ \mathcal{H}_u^{(1)}, \ \mathcal{H}_d^{(1)},$$

$$W_H = \lambda X \mathcal{H}_u^{(2)} \mathcal{H}_d^{(2)} + \lambda' \left(X \mathcal{H}_u^{(1)} \mathcal{H}_d^{(2)} + X \mathcal{H}_u^{(2)} \mathcal{H}_d^{(1)} \right)$$
$$+ K M \mathcal{H}_u^{(2)} \mathcal{H}_d^{(2)} + K' M \mathcal{H}_u^{(1)} \mathcal{H}_d^{(1)}$$

$$\rightarrow \mathbb{M} = M \begin{pmatrix} \sin\phi & K & \epsilon' \cos\phi \\ K & \cos\phi & \epsilon' \sin\phi \\ \epsilon' \cos\phi & \epsilon \sin\phi & K' \end{pmatrix} \qquad \mathbb{F} = F \begin{pmatrix} \sin\xi & 0 & \epsilon' \cos\xi \\ 0 & \cos\xi & \epsilon' \sin\xi \\ \epsilon' \cos\xi & \epsilon' \sin\xi & 0 \end{pmatrix}$$

$$[\mathbb{M}, \mathbb{F}] = 0 \quad \Rightarrow \quad K' = K = \frac{\sin(\phi - \xi)}{\cos\xi - \sin\xi} \qquad \xi \neq \pi/4$$

The key next step is the requirement of an eigenvalue hierarchy for both $\mathbb{M}$ + $\mathbb{F}$ (simultaneously diagonalizable)

e-vals of $\mathbb{M}$: $M_1 = \left(\dfrac{\cos(\xi+\phi) - 2\sin(\xi-\phi)}{\cos\xi - \sin\xi} \right) M$ ← make light → "μ"

$$M_{2,3} = \left(\frac{\cos\phi - \sin\phi}{\cos\xi - \sin\xi} \right) \sqrt{1 - \sin\xi\cos\xi}\; M$$

evals of $\mathbb{F}$: $F_1 = F(\cos\xi + \sin\xi)$ ← make light → "b"

$$F_{2,3} = F\sqrt{1 - \sin\xi\cos\xi}$$

note F_1, M_1 evector is "trimaximal" vector $\frac{1}{\sqrt{3}}(1,1,1)$

$\xi \to -\pi/4 + \ldots$ achieves the light eval condition:

but to avoid the problematic relation that $B\mu = \dfrac{b}{\mu} = \dfrac{F}{M}$, need also $\phi \neq \xi$ but "close"

eg: $\xi \to -\pi/4 + \eta$ $\quad \eta \ll 1 \quad \rho \ll 1 \quad \rho/\eta \sim (4\pi)^2$

$\phi \to \xi + \rho$ $\quad$ fine-tuning!

→ But even though we still have to fine-tune to get light μ + $B\mu$, this is great progress from what we had before, which was the wrong prediction for $B\mu/\mu$.

In other words → we can now tune μ + $B\mu$ independently (as is done in many phenomenological models of MSSM soft terms)

we see this then requires

$$\mathcal{H}_u = \begin{pmatrix} \mathcal{H}_u^{(2)} \\ \mathcal{H}_u^{(1)} \end{pmatrix} = R_u \begin{pmatrix} H_u \\ M_{u1} \\ M_{u2} \end{pmatrix} \qquad \mathcal{H}_d = \begin{pmatrix} \mathcal{H}_d^{(2)} \\ \mathcal{H}_d^{(1)} \end{pmatrix} = R_d \begin{pmatrix} H_d \\ M_{d1} \\ M_{d2} \end{pmatrix}$$

$\boxed{\text{2 doublet messenger pairs at minimum}}$ $\quad N_\psi = 2$ model!

MSSM + Messenger Yukawas: S_3' as part of family symmetry

We have seen that a naive 3-family extension of PRZ requires

$$H_u^{(2)}, \; H_u^{(1)} \quad \text{and} \quad H_d^{(2)}, \; H_d^{(1)}$$

upon SUSY̸ we get 2 heavy messenger pairs and one H_u, H_d EW set.

Now consider embeddings of MSSM matter fields into S_3' reps.

1st consideration: top quark Yukawa coupling
want it to be <u>renormalizable</u> superpotential coupling
(else tuning considerations)

can either:
couple it "only" to $H_u^{(1)}$ — LE, TG 2016; LE, TG, AR 2018, 2019
(↳ predominantly)

or couple it also to $H_u^{(2)}$ — LE, TG 2016 + in progress

$H_u^{(1)}$: one (boring but safe) option: MSSM blind wrt S_3'.
then other symmetries required to control MSSM + messenger Yukawas

→ can ~~also~~/instead charge MSSM fields wrt S_3'
+ still have scenarios where $H_u^{(1)}$ coupling dominates.

$H_u^{(2)}$: clearly requires MSSM fields to be nontrivially charged wrt S_3'.

Sta. Let's consider the case where MSSM fields are embedded nontrivially into S_3'.
Since it's such a simple group, not too many options.
Take here $\boxed{2 \oplus 1}$ embeddings for all:

$$Q_2 \sim 2, \quad Q_1 \sim 1 \qquad \bar{u}_2 \sim 2, \; \bar{u}_1 \sim 1 \qquad \bar{d}_2 \sim 2, \; \bar{d}_1 \sim 1$$

+ same for charged leptons (neglect neutrino sector here).

Then, can write renormalizable superpotential couplings as

$$W_u = y_u \left(Q_2 \bar{u}_2 H_u^{(2)} + \beta_1 Q_2 \bar{u}_2 H_u^{(1)} + \beta_2 Q_2 \bar{u}_1 H_u^{(2)} + \beta_3 Q_1 \bar{u}_2 H_u^{(2)} + \beta_4 Q_1 \bar{u}_1 H_u^{(1)} \right)$$

W_u: up-type quarks

(can do same for d's, leptons)

$y_u, \{\beta_i\}$ coefficients unfixed by S_3

From here, and from diagonalization of Higgs-messenger sector, get

MSSM $\nearrow$

$$Y_u = \frac{y_u}{\sqrt{3}} \begin{pmatrix} 1 & \beta_1 & \beta_2 \\ \beta_1 & 1 & \beta_2 \\ \beta_3 & \beta_3 & \beta_4 \end{pmatrix} \qquad (*)$$

$$Y_{u_1}' = y_u \begin{pmatrix} -\left(\frac{1}{2}+\frac{1}{2\sqrt{3}}\right) & \frac{\beta_1}{\sqrt{3}} & \beta_2\left(\frac{1}{2}-\frac{1}{2\sqrt{3}}\right) \\ \beta_1/\sqrt{3} & \frac{1}{2}-\frac{1}{2\sqrt{3}} & -\beta_2\left(\frac{1}{2}+\frac{1}{2\sqrt{3}}\right) \\ \beta_3\left(\frac{1}{2}-\frac{1}{2\sqrt{3}}\right) & -\beta_3\left(\frac{1}{2}+\frac{1}{2\sqrt{3}}\right) & \beta_4/\sqrt{3} \end{pmatrix}$$

Y_{u_1}': messenger 1

$$Y_{u_2}' = y_u \begin{pmatrix} \frac{1}{2}-\frac{1}{2\sqrt{3}} & \frac{\beta_1}{\sqrt{3}} & -\beta_2\left(\frac{1}{2}+\frac{1}{2\sqrt{3}}\right) \\ \beta_1/\sqrt{3} & -\left(\frac{1}{2}+\frac{1}{2\sqrt{3}}\right) & \beta_2\left(\frac{1}{2}-\frac{1}{2\sqrt{3}}\right) \\ \beta_3\left(\frac{1}{2}+\frac{1}{2\sqrt{3}}\right) & \beta_3\left(\frac{1}{2}-\frac{1}{2\sqrt{3}}\right) & \beta_4/\sqrt{3} \end{pmatrix}$$

Y_{u_2}': messenger 2

$\longleftrightarrow$ Same ~~structure~~ up to some permutation of entries

Quite generally:

(*) for <u>arb</u> β_i does <u>not</u> display an eigenvalue hierarchy as needed for SM fermion masses.

But with extra structure (relations among the β_i) we can have categories of solns.

LE, TG, AR 2018, 2019

$\boxed{\text{3 categories:}}$ each with associated characteristic Y_{u_1}', Y_{u_2}' + soft term predictions

$\Longrightarrow H_u^{(1)}$ dominant: β_4 coupling dominates rest. Ariel will describe this one in detail next!

$H_u^{(2)}$ dominant: β_1 coupling dominates rest. (work in progress w/ Eu, Leonard)

$H_u^{(1)} \cdot H_u^{(2)}$ "democratic": "democratic" limit of β_i equal (+ corrections)

LE, TG 2016; with Eu, in progress

Summary statement:

- Several categories of how to achieve fermion mass hierarchy.

  <u>All</u> require structure beyond S_3
  (further layers of model-building)

- current status for each:

  - 1st stage: simplified scenarios with just 3rd generation masses.

    $\Longrightarrow$ messenger Yukawa predictions
    + superpartner mass spectrum.

    Generic result → because <u>2 pairs</u> of messengers are required spectrum heavier than if we ~~could~~ had just 1 pair
    (eg U(1) benchmarks for FGM of Shadmi + collaborators).

    Best case so far:
    $H_u^{(1)}$ dominant scenario → sizable stop mixing
    (next talk)

  - 2nd stage: continue to build on SM flavor structure
    (1st + 2nd generation masses, Cabibbo angle, ...)

    ~~rep 2 2 the~~ $H_u^{(1)}$ dominant scenario
    LE, TG, AR 2019
    (Cabibbo angle generation).

- Final assessment still TBD.
  can ~~we~~ we overlay this framework with enough structure to achieve full 3-generation model,
  and what are the (expected) predictions for FCNC?
  can a fully viable scenario be obtained?

$\boxed{\text{Stay tuned!}}$

(+Thank you!)

Happy to be here for the "virtual" PHENO 2020!