PHENO 2020

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: Talk by Ariel Rock next!

$\boxed{\text{Main idea:}}$

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

$\Rightarrow$ "flavored gauge mediation"

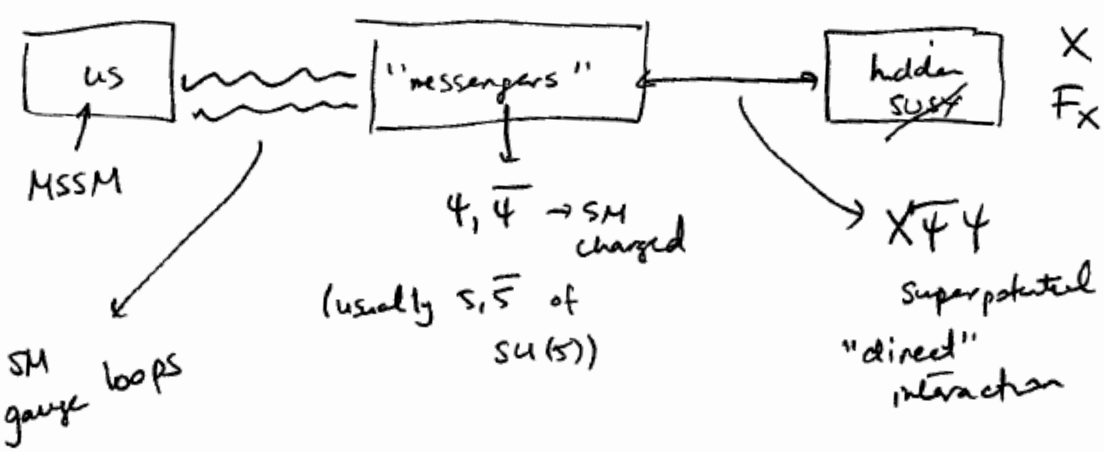
$\hookrightarrow$ Higgs + $SU(2)_L$ messenger doublet mixing

- use <u>discrete</u> non-Abelian symmetry to control this mixing in a <u>3-family</u> scenario

- This symmetry also can play a role as (part of) the <u>family symmetry</u> that yields SM fermion masses + mixings.

Background / Motivation

• Minimal Gauge mediation : elegant framework for $\cancel{\text{SUSY}}$ parameters



Dine, Fischler, Srednicki 1981

Dimopoulos + Raby 1981, 1983

Dine, Fischler 1982

Nappi, Ovrut 1982

Alvarez-Gaume et al 1982

Dine + Nelson 1993

" w/ Shirman 1995

" " w/ Nir 1995

$\Rightarrow$ $\cancel{\text{SUSY}}$ 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 $\cancel{SUSY}$ 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}.

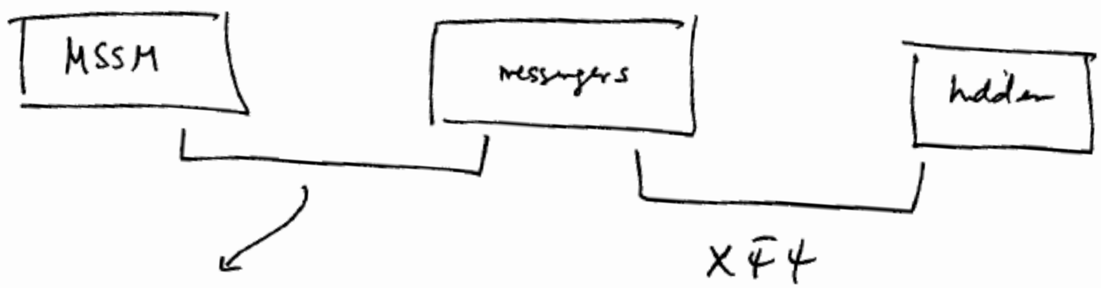
⇒ modify minimal gauge mediation

to allow for more "direct" interactions b/w MSSM + messengers

Precursors: Chacko, Ponton 2002

Shadmi et al 2011

→ New structure:



messenger-~~and~~ MSSM superpotential interactions

Many possibilities →

see eg Evans + Shih 2013 (1303.0228)

Many explorations! (starting in 2012)

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

Focus here on particular category of interactions →

"flavored gauge mediation" (FGM)

↳ term coined by Shadmi + collaborators

idea: $SU(2)_L$ doublet messengers

+ MSSM Higgs H_u, H_d mix $\longrightarrow$

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

etc.

Y_u' ↑ messenger Yukawa coupling

M_u ↳ messenger doublet

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

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

better discovery potential $\longrightarrow$ eg benchmarks for LHC studies:

Ierushalmi, Iwamoto, Lee, Nepomnyashcy, Shadmi 2016

- Disadvantage $\rightarrow$ lose beautiful, automatically flavor diagonal soft terms.

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 $\mathbf{2}$ (doublet) rep of S_3'

Higgs-messengers in S_3' doublets as well

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

Explored Higgs-messenger sector, including coupling to $\cancel{SUSY}$ 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 $\langle \lambda X \rangle = M \begin{pmatrix} \sin\phi \\ \cos\phi \end{pmatrix} + \theta^2 F \begin{pmatrix} \sin\xi \\ \cos\xi \end{pmatrix}$

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad \langle x \rangle \qquad\qquad \langle F_x \rangle$

+ found important constraints:

$$[M, F] = 0$$ (required for smooth decoupling of heavy messengers after 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'

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

$\Rightarrow$ 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

for good reasons!

+ ~~SUSY~~ should <u>not</u> be linked

(else risk ruination + despair!)

Answer: still in progress, taking steps in framework.

Ariel will report on the best-motivated direction. Here: a bit more

+ most promising

background + context.

Higgs - Messenger Sector and the μ / B_μ problem

First discussion topic → 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,

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

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

$$\langle \lambda X \rangle = M \begin{pmatrix} \sin\phi \\ \cos\phi \end{pmatrix} + \theta^2 F \begin{pmatrix} \sin\xi \\ \cos\xi \end{pmatrix}$$

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

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

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

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

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

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 $b = B_\mu \mu$.

$\therefore B_\mu \gg \mu \quad \longrightarrow$ fine-tuning.

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

Not surprising: in GMSB
long known that the coupling

$X H_u H_d$ gives tree-level μ + b:

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

$$\text{but } m_{soft} \sim \frac{1}{16\pi^2} \frac{\langle F_X \rangle}{\langle X \rangle} \longrightarrow B_\mu = \frac{\langle F_X \rangle}{\langle X \rangle} \sim 16\pi^2 m_{soft}$$

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

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 Giudice Rattazzi 1998
reviews: Polonsky 2001

Problem here:

we need $X\, H_u^{(2)} H_d^{(2)}$ coupling

because we need

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

to mediate ~~SUSY~~ to MSSM sector!

S_3 symmetry then requires the problematic $X H_u H_d$ term.

So here the $\mu/B\mu$ 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~~ this problem as

can choose $U(1)$ charges judiciously to forbid $X H_u H_d$ term.)

Our "solution" LE, TG 2016

$\Rightarrow$ extend the Higgs-messenger sector to include additional Higgs-messenger fields, this time in $\underline{1}$ reps of S_3.

Higgs-messenger fields:

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

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

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

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

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

e-vals of $\mathbb{M}$: $$M_1 = \left(\frac{\cos(\xi + \phi) - 2\sin(\xi - \phi)}{\cos\xi - \sin\xi} \right) M \quad \longleftarrow \text{ make light } \rightarrow \text{ "}\mu\text{"}$$

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

evals of $\mathbb{F}$: $$F_1 = F(\cos\xi + \sin\xi) \quad \longleftarrow \text{ make light } \rightarrow \text{ "}b\text{"}$$

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

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

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

but to avoid the problematic relation that

$$B\mu = \frac{b}{\mu} = \frac{F}{M}$$, need <u>also</u> $\phi \neq \xi$

but "close"

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

$\phi \to \xi + \rho$

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 <u>prediction</u> for $B\mu/\mu$.

In other words $\rightarrow$

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

we see this then requires

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

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

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

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

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

upon SU~~SY~~ 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 $\mathcal{H}_u^{(1)}$ LE, TG 2016

(predominantly) LE, TG, AR 2018, 2019

or couple it also to $\mathcal{H}_u^{(2)}$ LE, TG 2016 + in progress

$\mathcal{H}_u^{(1)}$: one (boring but safe) option: MSSM blind wrt S_3'.

then other symmetries required to control MSSM + messenger Yukawas

$\longrightarrow$ can also/instead charge MSSM fields wrt S_3'

+ still have scenarios where $\mathcal{H}_u^{(1)}$ coupling dominates.

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

$\boxed{2 \oplus 1}$ embeddings

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

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

Then, can write renormalizable superpotential couplings as

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

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

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

MSSM

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

↑ messenger 1

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

↑ 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

$\boxed{\text{3 categories:}}$

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

each with associated characteristic Y_{u1}', Y_{u2}' + soft term predictions

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

$\mathcal{H}_u^{(1)} + \mathcal{H}_u^{(2)}$ "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.

  $\underline{\text{All}}$ require structure beyond S_3'
  (further layers of model-building)

- Final assessment still TBD.

can 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?

Stay tuned!

(Thank you!)

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