Gauge mediation with a local flavour

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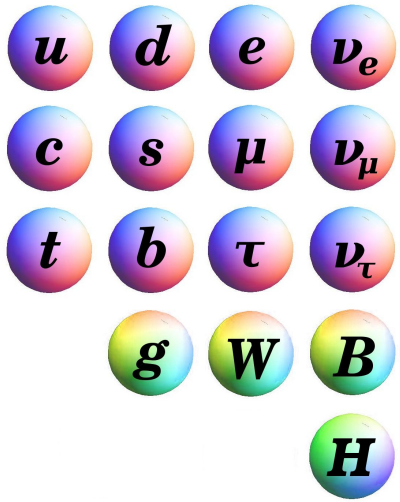
partly based on 1312.0935 (with M. McGarrie, A. Weiler)

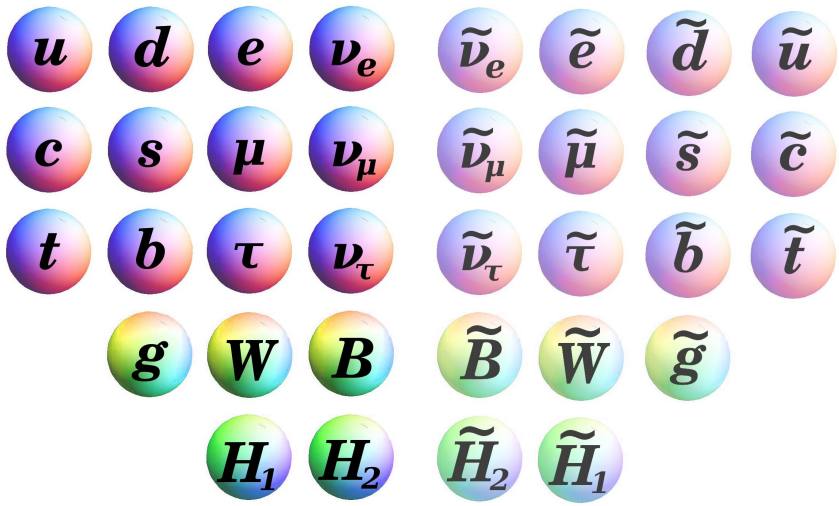
Outline

Review: Messenger gauge mediation

The Standard Model of Elementary Particle Physics



The Minimal Supersymmetric Standard Model



Gauge-mediated supersymmetry breaking

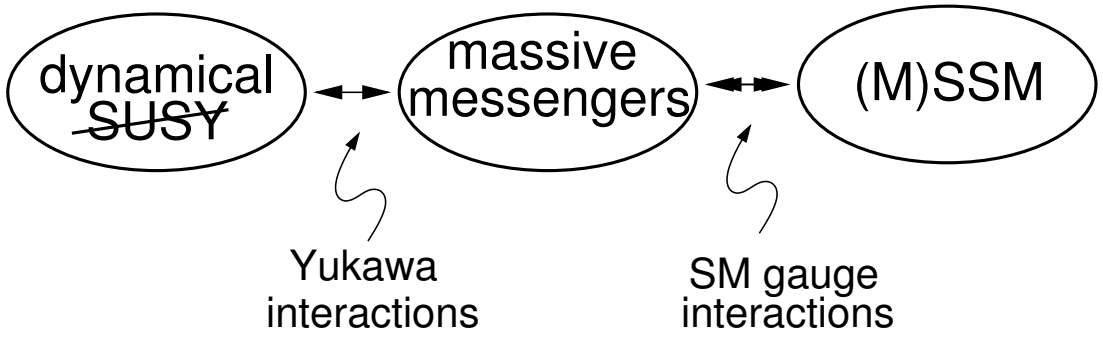
- TeV-scale SUSY has many nice features: hierarchy, unification, DM...
- But most general parameterization of SUSY breaking introduces $\mathcal{O}(100)$ new free parameters even in minimal SUSY Standard Model

$$\begin{aligned}\mathcal{L} = &-\frac{1}{2}\left(M_3\,\tilde{g}\tilde{g} + M_2\,\widetilde{W}\widetilde{W} + M_1\,\widetilde{B}\widetilde{B} + \text{h.c.}\right)\\ &-\left(a_u^{IJ}\,\tilde{u}_I^c\tilde{q}_J H_2 - a_d^{IJ}\,\tilde{d}_I^c\tilde{q}_J H_1 - a_e^{IJ}\,\tilde{e}_I^c\tilde{\ell}_J H_1 + \text{h.c.}\right)\\ &- m^2_{q\,IJ}\,\tilde{q}_I^*\tilde{q}_J - m^2_{\ell\,IJ}\,\tilde{\ell}_I^*\tilde{\ell}_J - m^2_{u\,IJ}\,\tilde{u}_I^{c*}\tilde{u}_J^c - m^2_{d\,IJ}\,\tilde{d}_I^{c*}\tilde{d}_J^c - m^2_{e\,IJ}\,\tilde{e}_I^{c*}\tilde{e}_J^c\\ &- m^2_{H_1}\,|H_1|^2 - m^2_{H_2}|H_2|^2 - \left(m_3^2\,H_2 H_1 + \text{h.c.}\right)\end{aligned}$$

- **How are SUSY breaking terms generated?**

  Supertrace theorem: not by tree-level renormalizable couplings to ~~SUSY~~
  - "Gravity mediation": use non-renormalizable interactions / HD operators
  - "Gauge mediation": use loops

Messenger gauge mediation



Simplest construction: → Dine/Nelson/Nir/Shirman early '90s

$$W = X\Phi\widetilde{\Phi} \qquad \langle X \rangle = M + F\theta^2 \qquad (\Phi, \widetilde{\Phi}) \sim \mathbf{5} \oplus \bar{\mathbf{5}} \text{ of SU(5)} \supset G_{\text{SM}}$$

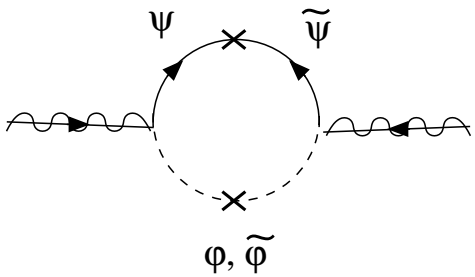
- $X =$ background field: "goldstino superfield"
- $M =$ SUSY mass for scalars and fermions contained in Φ and $\widetilde{\Phi}$
- $F =$ ~~SUSY~~ mass splitting

Minimal messenger gauge mediation

- Messengers $\Phi = \varphi + \sqrt{2}\theta\,\psi + \ldots, \qquad \widetilde{\Phi} = \widetilde{\varphi} + \sqrt{2}\theta\,\widetilde{\psi} + \ldots$

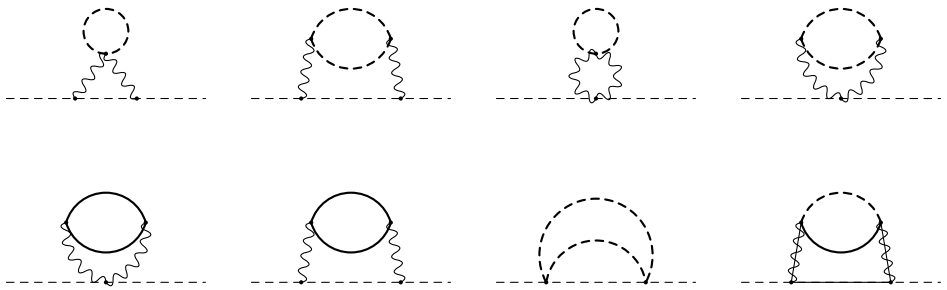
$$\mathcal{L}_{\text{tree}} = -\frac{M}{2}(\psi\widetilde{\psi} + \overline{\psi}\overline{\widetilde{\psi}}) - M^2(|\varphi|^2 + |\widetilde{\varphi}|^2) - F(\varphi\widetilde{\varphi} + \varphi^*\widetilde{\varphi}^*) + \ldots$$

- Gaugino mass induced @ 1 loop:



$$\Rightarrow \quad M_{1/2} = \frac{g^2}{16\pi^2}\frac{F}{M}$$

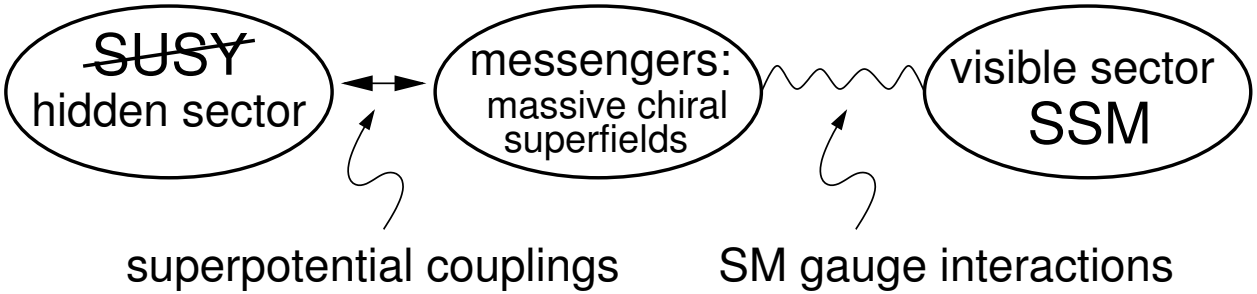
- Scalar soft masses induced @ 2 loops:



$$\Rightarrow \quad m_0^2 \sim \left(\frac{g^2}{16\pi^2}\right)^2 \left|\frac{F}{M}\right|^2$$

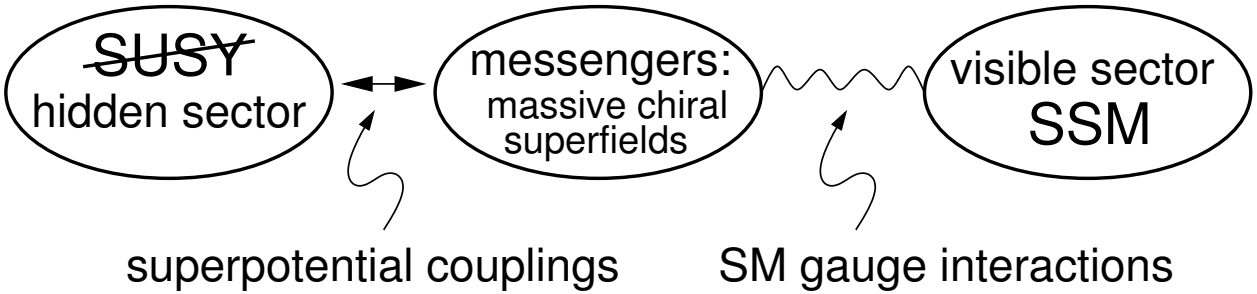
Figure stolen from → Martin '97

Messenger gauge mediation features



- very few parameters: M, F, (# of $\Phi \oplus \widetilde{\Phi}$ pairs)
- completely renormalizable, well controlled model (no reliance on Planck-scale physics)
- predictions independent on dynamical ~~SUSY~~ details (what generates F and M?)
- flavour-blind ~~SUSY~~ soft terms: no FCNC problems

Messenger gauge mediation bugs



- μ/B_μ problem:
  - no higgsino mass μ induced
  - simplest extensions generating μ have too large Higgs mass mixing B_μ
- embedding in dynamical model nontrivial (R-symmetry / $M_{1/2}$ issues)
- trilinear A-terms small $\Rightarrow$ hard to get $m_h = 125$ GeV in MSSM
- no soft mass for singlets: must be extended to work with NMSSM
- flavour-blind ~~SUSY~~ soft terms: generation-independent squark masses

  Cannot have 3rd generation squarks $\lesssim$ 1 TeV
  and 1st two generation squarks above LHC bounds at the same time
  ("natural SUSY" / "effective SUSY" / "inverted hierarchy")

Messenger gauge mediation: Bugs & features

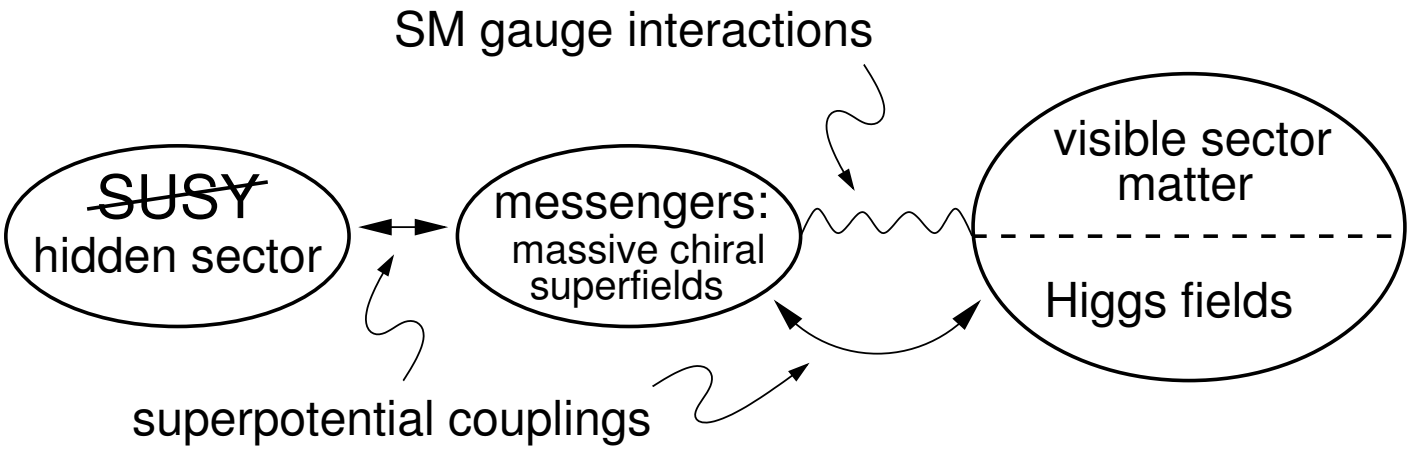
How to fix the bugs (μ/B_μ, A-terms, singlet masses, generation universality) **without ruining the features** (predictivity, calculability, no flavour problem) **?**

- To address Higgs sector problems, need extra couplings to Higgs sector
  $\rightarrow$ next slide
- To address flavour issue, need extra couplings to matter
  $\rightarrow$ rest of this talk

A nonminimal extension: Gauge-Higgs mediation

Allow for superpotential couplings between messengers and Higgs sector

see e.g. model of → Craig/Knapen/Shih '13



- $\mu, B\mu$ ✓
- trilinears ✓
- soft terms for singlets ✓
- flavour ✓ ×

Aim of this talk

Construct a gauge-mediated model with

1. light 3rd generation squarks, heavy and degenerate 1st and 2nd
2. FCNCs under control

Crucial ingredients:

$SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(3)_F$ gauge group

Both chiral + gauge messengers

Gauge-mediated models with light 3rd generation squarks

1. Yukawa-deflected GM / Flavoured GM

→ Chacko/Ponton'02, . . . Shadmi/Szabo '11, Kang et al. '12, Albaid/Babu '12, Abdullah et al. '12, Calibbi/Paradisi/Ziegler '13, Galon/Perez/Shadmi '13. . .

Introduce also matter-messenger couplings in W:
generically large flavour violation
(can be averted with extra flavour symmetries)

Example: → Abdullah/Galon/Shadmi/Shirman '12

$$W = Y_u\, QUH_u + Y_d\, QDH_d + Y'_u\, QU\widetilde{\Phi} + Y'_d\, QD\Psi + X\left(\widetilde{\Phi}\Phi + \widetilde{\Psi}\Psi + \ldots\right)$$

- flavour problems ameliorated if Y_u aligned with Y'_u and Y_d with Y'_d
- tachyonic one-loop contribution to soft masses at order $|Y'_{u,d}|^2 \frac{|F_X|^4}{|X|^6}$
  → Evans/Ibe/Yanagida '12
- for low messenger scales ($F_X \approx X^2$): light 3rd generation squarks

2. Higgsed gauge mediation

Introduce chiral messengers charged under gauged horizontal symmetry

→ Craig/McCullough/Thaler '12

Example:

- Gauge $SU(3)_F$ with $Q, U, D \sim \mathbf{3}$
- Yukawa couplings from supersymmetric $SU(3)_F$ breaking: $\Sigma, \Sigma' \sim \bar{\mathbf{6}}$,

$$W = \frac{\Sigma}{\Lambda} QUH_u + \frac{\Sigma'}{\Lambda} QDH_d, \qquad \frac{\langle \Sigma \rangle}{\Lambda} = Y_u, \quad \frac{\langle \Sigma \rangle'}{\Lambda} = Y_d$$

- $SU(3)_F$ contributes to gauge-mediated soft masses. Largest contribution to first two generations
  Light 3rd generation squarks

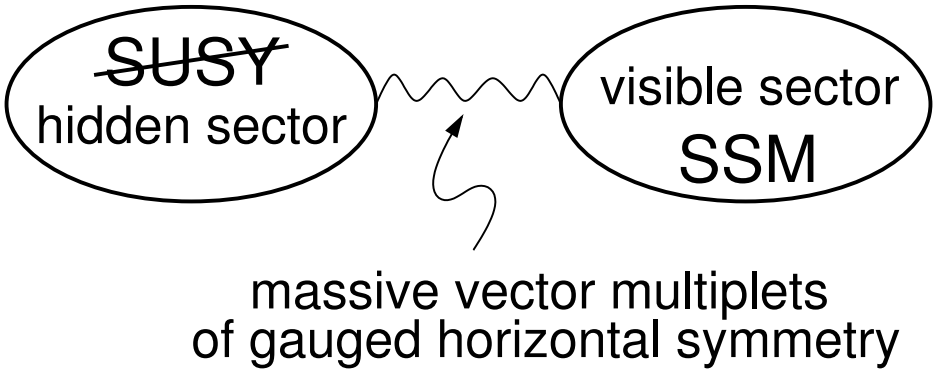
3. This talk: Flavour gauge messengers

Gauge $SU(3)_F$ and break non-supersymmetrically

→ FB/McGarrie/Weiler '13

- Some fields charged under $SU(3)_F$ pick up nonzero F-term VEVs
- Gauge messengers: SUSY breaking mass splittings within massive vector multiplet

Messengers = massive ~~chiral~~ vector superfields



- Negative contributions to squark soft masses.
  Largest for 3rd generation if F-terms aligned with 3rd gen. Yukawas
  Light 3rd generation squarks

Flavour gauge messengers: Model building

Brief history of gauge messengers

- Invented in 1980s GUT model building
  → Witten's inverted hierarchy '81, Dimopoulos/Raby '83, Kaplunovsky '83,...
- More detailed studies in late '90s (product gauge groups broken to SM)
  → Dimopoulos et al. '97, Murayama '97, Giudice/Rattazzi '97,...
- Briefly resurrected in 2000s → Dermisek/Kim/Kim '06
- Again of interest in GGM context → Buican/Komargodski '09,Intriligator/Sudano '10
- Also related: Tree-level GM → Nardecchia/Romanino/Ziegler '09

Never very popular for (GUT-)model building (we'll see why)

Now use idea for gauged flavour symmetry

A simplistic model

SSM Quark superfields $Q, U, D \sim \mathbf{3}$ under $\mathrm{SU}(3)_\mathrm{F}$

Yukawa couplings from $\Sigma, \Sigma' \sim \bar{\mathbf{6}}$, hidden sector: $X \sim \mathbf{3}$

Break $\mathrm{SU}(3)_\mathrm{F} \to \mathrm{SU}(2)_\mathrm{F}$ by

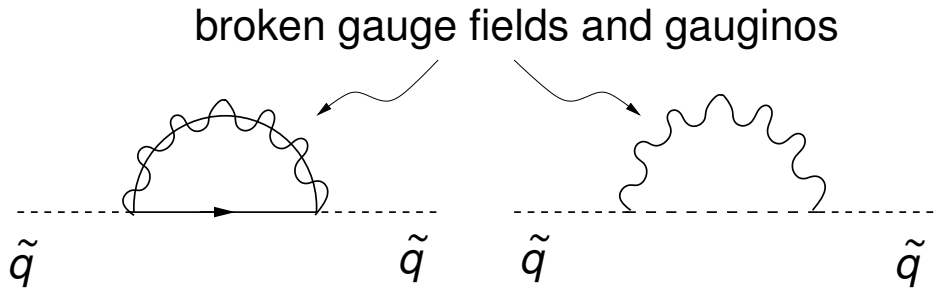
$$\langle X \rangle = \begin{pmatrix} 0 \\ 0 \\ F_X \theta^2 \end{pmatrix}$$

Simultaneously break $\mathrm{SU}(3)_\mathrm{F} \to 0$ by

$$\frac{\langle \Sigma \rangle}{\Lambda} = \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix}, \qquad \frac{\langle \Sigma' \rangle}{\Lambda} = Y_d$$

A simplistic model

- SUSY-breaking X VEV:
  SUSY-breaking mass splittings between gauge fields and gauginos
- Dominant effect: Tachyonic one-loop squark mass^2 → Intriligator/Sudano '10



- Alignment of X with 3rd generation: largest effect for 3rd generation squarks

$$\delta m_Q^2 = \delta m_U^2 = \delta m_D^2 = -\frac{g_F^2}{16\pi^2}\frac{|F_X|^2}{\Sigma_{33}^2}\begin{pmatrix} \frac{13}{24} & 0 & 0 \\ 0 & \frac{13}{24} & 0 \\ 0 & 0 & \frac{7}{6} \end{pmatrix}$$

- One-loop SU(3)$_F$ tachyon comparable with usual 2-loop GM masses if g_F small

A more realistic model

Previously no explanation for alignment of VEVs or for Yukawa hierarchies

Better: Simple O'Raifeartaigh model

$$W = \kappa Y \left(T\widetilde{T} - f^2 \right) + m\widetilde{X}T + mX\widetilde{T}$$

where $X, T = \mathbf{3}$, $\quad \widetilde{X}, \widetilde{T} = \bar{\mathbf{3}}$, $\quad Y =$ singlet

For $\kappa f > m$: Vacuum at $T = (0, 0, v)$, $\quad F_X = m\,T$, $\quad v^2 = f^2 - m^2/\kappa^2$

- Top Yukawa now generated by

$$W = \frac{\widetilde{T}\widetilde{T}}{\Lambda^2} QUH_u$$

  preserving $SU(2)_F$ subgroup
- For full flavour structure need to break also $SU(2)_F$ at lower scale (independently)
- SUSY breaking aligned with $SU(3)_F \to SU(2)_F$ breaking by e.o.m.
- "Small SUSY breaking limit", $F_X < v^2$
- On the wishlist: fully dynamical model

1-loop squark mass from flavour gauge messengers

$$K_{\text{eff}}^{(1\text{-loop})} = \frac{1}{16\pi^2}\,\text{tr}\left(M_V^2 \log\frac{M_V^2}{\Lambda^2}\right)$$
$$= \frac{g_F^2}{16\pi^2}\left(Q_i^\dagger \mathbf{T}^{ab}_{ij} Q_j + U_i^\dagger \mathbf{T}^{ab}_{ij} U_j + D_i^\dagger \mathbf{T}^{ab}_{ij} D_j\right) \times$$
$$\times \log\left(\frac{T_i^\dagger \mathbf{T}_{ij} T_j + X_i^\dagger \mathbf{T}_{ij} X_j + \widetilde{T}_i \mathbf{T}_{ij} \widetilde{T}_j^\dagger + \widetilde{X}_i \mathbf{T}_{ij} \widetilde{X}_j^\dagger}{\Lambda^2}\right)^{ab} + \ldots$$

where $\mathbf{T}^{ab} = \{\mathrm{t}^a, \mathrm{t}^b\}$ (fundamental generators)
and $\langle\widetilde{T}\rangle^\dagger = \langle T\rangle = (0,\, 0,\, v)$; $\quad \langle\widetilde{X}\rangle^\dagger = \langle X\rangle = (0,\, 0,\, F_X\theta^2)$

$$\Rightarrow \qquad \delta m_Q^2 = \delta m_U^2 = \delta m_D^2 = -\frac{g_F^2}{16\pi^2}\frac{|F_X|^2}{v^2}\begin{pmatrix} \frac{7}{6} & 0 & 0 \\ 0 & \frac{7}{6} & 0 \\ 0 & 0 & \frac{8}{3} \end{pmatrix}$$

(More general: $m^2 = -\frac{g_F^2}{16\pi^2}\Delta c_2\ \Lambda^2$ → Intriligator/Sudano '10)

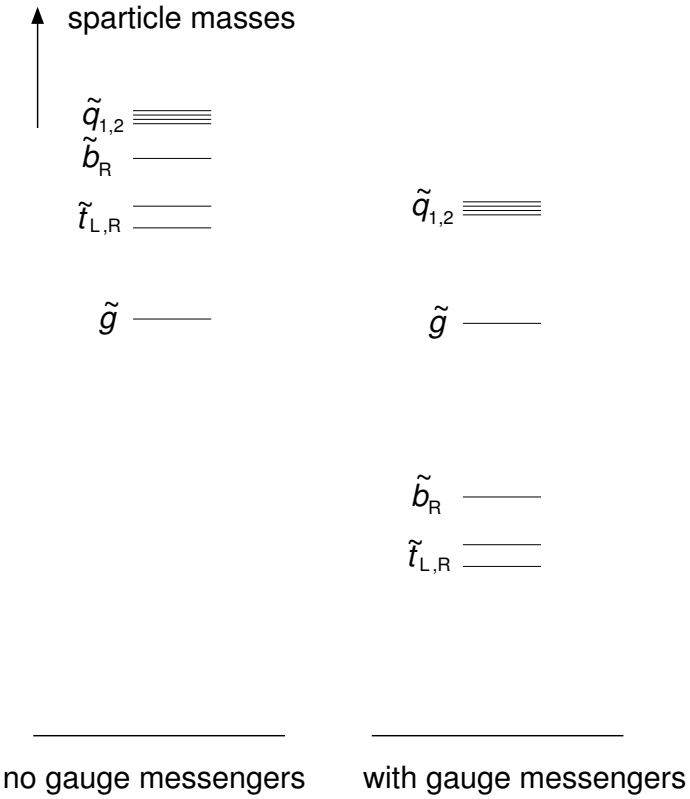
Flavour gauge messengers: Consequences

Effect on the superpartner spectrum

Tachyonic contribution to squark masses from flavour gauge messengers:

$$\delta m^2_{Q,U,D} = -\frac{g_F^2}{16\pi^2} \begin{pmatrix} \frac{7}{6} & 0 & 0 \\ 0 & \frac{7}{6} & 0 \\ 0 & 0 & \frac{8}{3} \end{pmatrix} \frac{F^2}{M^2}$$

- largest for stops and sbottoms
- if one-loop $SU(3)_F$ effects comparable with two-loop $SU(3)_C \times SU(2)_L \times U(1)_Y$ effects:
  - stop and sbottom masses lowered
  - first- and second-generation squark masses slightly lowered
  - rest of spectrum hardly affected



Effect on the superpartner spectrum

- 3rd generation squarks tachyonic at mediation scale, runs positive due to gluino loops

  (cf. also → Dermisek/Kim '06, Dermisek/Kim/Kim '06, Draper et al. '11)
- Can get sub-TeV stops and sbottoms with first-generation squarks above LHC limits
- Can get maximal stop mixing contributions to m_{h^0} in MSSM with moderate or zero A_t at mediation scale

  ↑

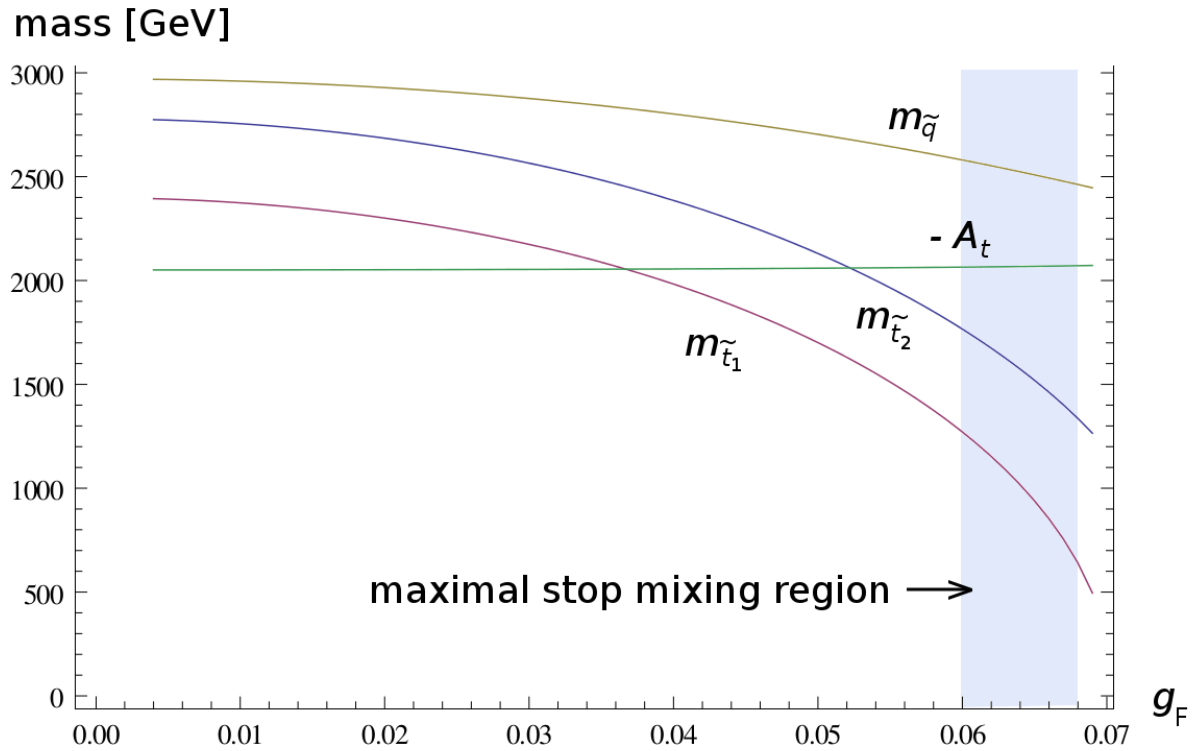
  naive prediction of gauge mediation

  (may not hold if $\mu/B\mu$ generated by Higgs-messenger couplings)
- Can also lift m_{h^0} by extra d.o.f. or non-decoupling effects...
  flavour gauge messengers really just affect the flavour sector

Light stops and lightest Higgs mass in MSSM

Gaugino and matter soft terms: minimal GMSB + flavour gauge messengers
Higgs soft terms: free parameters (gauge-Higgs mediation)

Effect of switching on SU$(3)_F$ gauge coupling:



$\Lambda_{\mathrm{MGM}} = 3 \cdot 10^5$ GeV, $M = 10^7$ GeV, $N_5 = 1$, $A_0 = -2$ TeV, $m^2_{H_u} = m^2_{H_d} = 10^5\ (\mathrm{GeV})^2$, $\tan\beta = 10$

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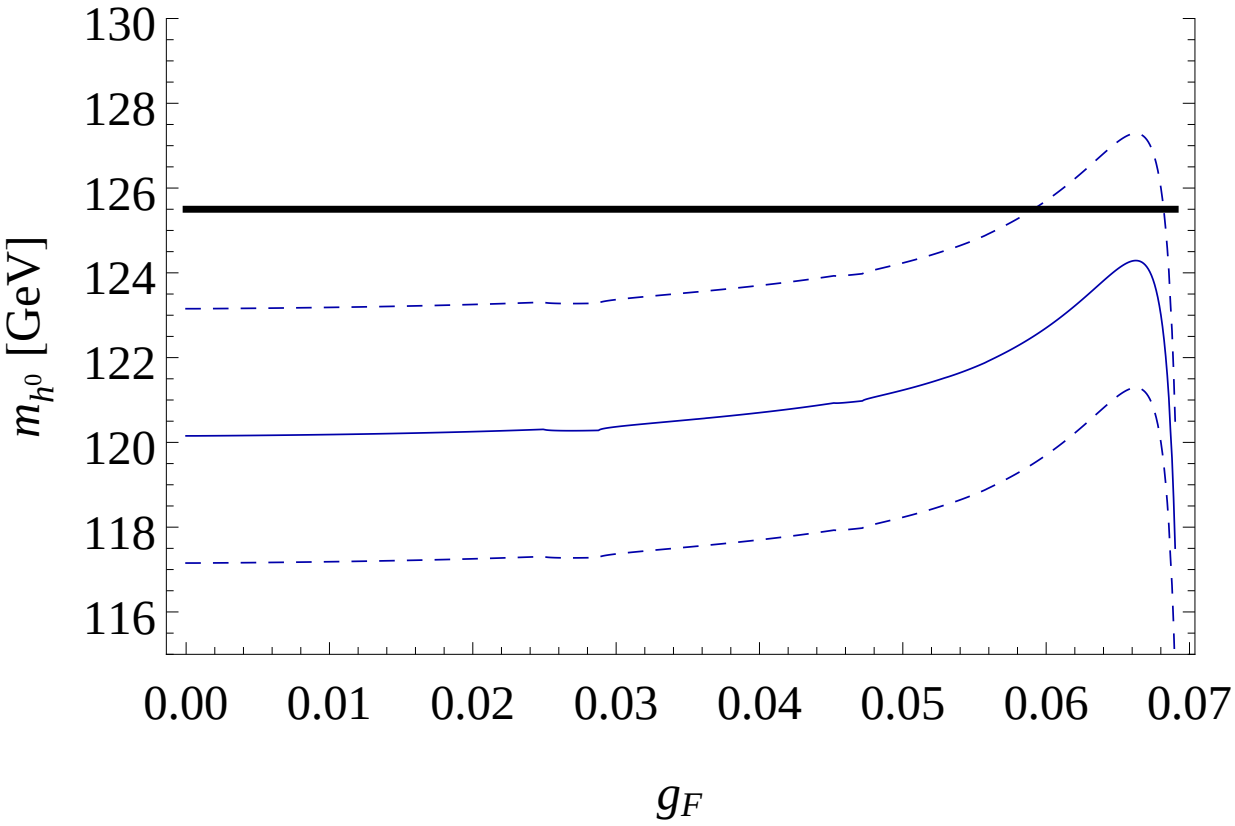

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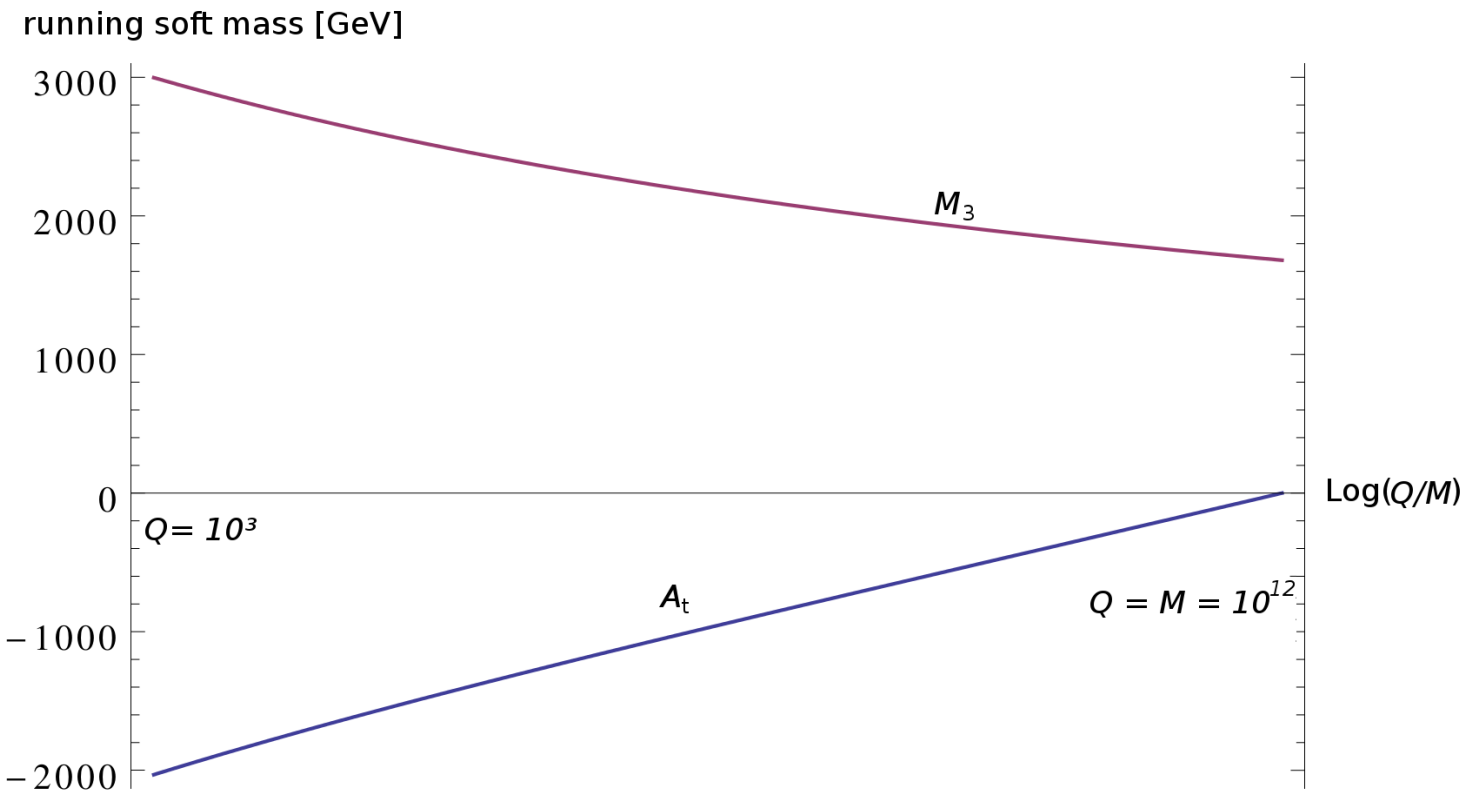
Radiative maximal stop mixing

Example with a high messenger scale ($M = 10^{12}$ GeV), radiatively induced A_t, $m_{h^0} = 124 \pm 3$ GeV:

similar to → Draper/Meade/Reece/Shih '11



Drawback: uncomfortably large gluino mass ≈ 3 TeV

$\Lambda_{\text{MGM}} = 1.5 \cdot 10^5$ GeV, $M = 10^{12}$ GeV, $N_5 = 3$, $A_0 = 0$, $m^2_{H_u} = -1.8 \cdot 10^6\ (\text{GeV})^2$, $m^2_{H_d} = 10^5\ (\text{GeV})^2$, $g_F = 0.15$, $\tan\beta = 10$

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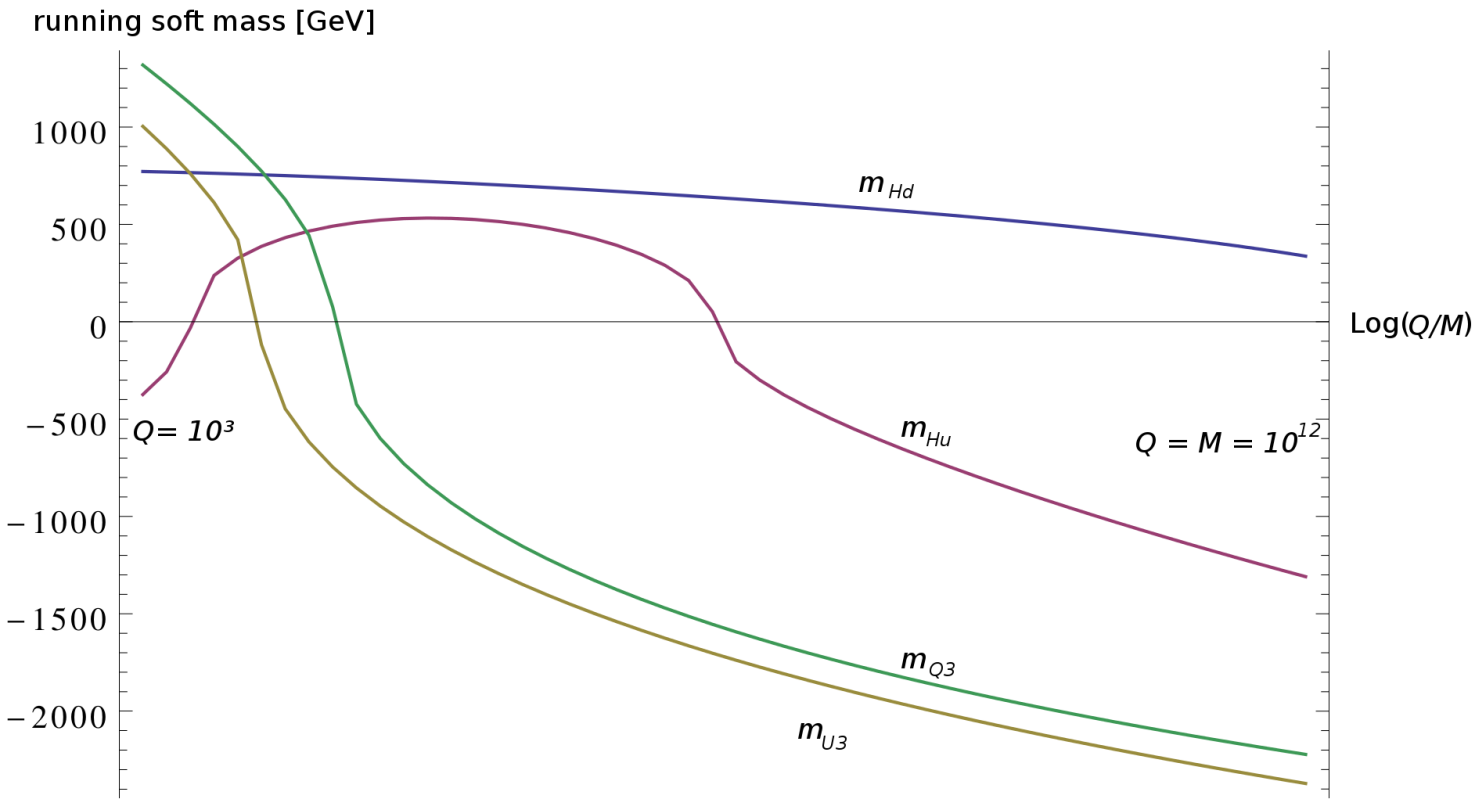

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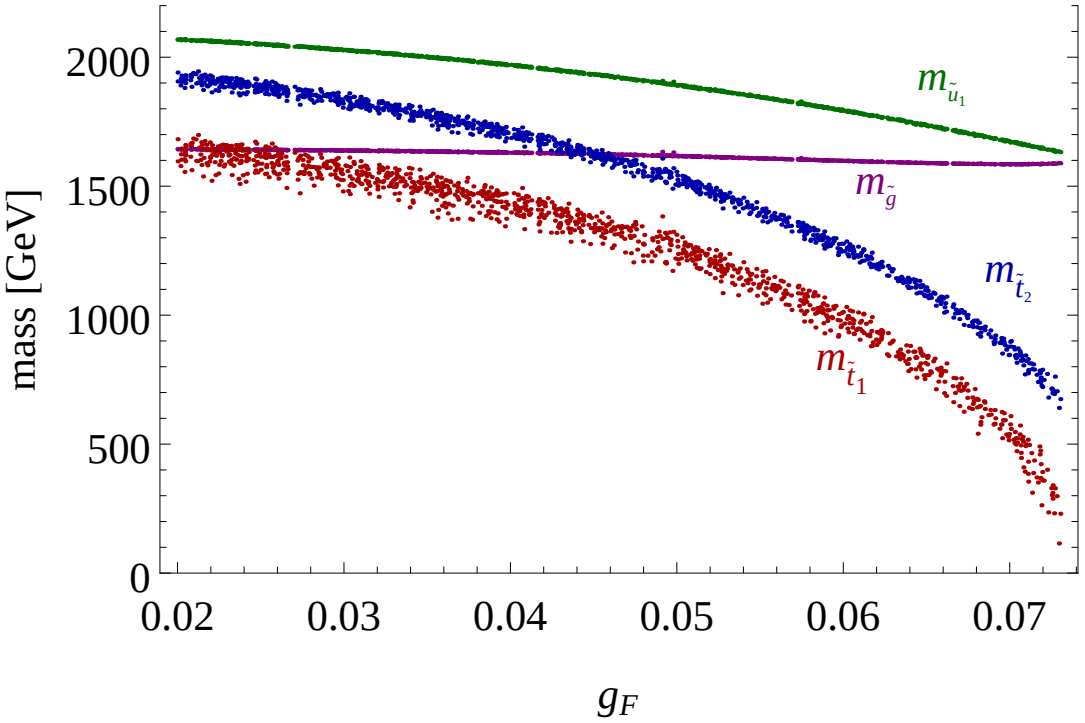
Gauge messengers in NMSSM

Similar picture:



(using `SPheno` → Porod '03 and `SARAH` → Staub '08)

- scan over Higgs sector parameters, requiring $m_{h^0} = 125.5 \pm 3$ GeV
- gauge mediation parameters held fixed

Model building: Flavour symmetry breaking

Non-universal gauge messenger contribution to squark masses is diagonal only in one particular flavour basis

Rotating to SCKM basis $\Rightarrow$ off-diagonal squark masses $\Rightarrow$ FCNCs

Model dependent

Simple example: Break $SU(2)_F \rightarrow 0$ with extra VEVs

$\langle S \rangle = (0, u, w), \qquad \langle \widetilde{S} \rangle^\dagger = e^{i\phi} \langle S \rangle$

Treat all fields as spurions; impose discrete symmetry; take $|w| \sim |u| \ll |v|$

$$W = \frac{\widetilde{T}_i \widetilde{T}_j}{\Lambda^2} Q_i U_j H_u + \frac{\widetilde{S}_i \widetilde{S}_j}{\Lambda^2} Q_i U_j H_u + \ldots + \frac{S_i \widetilde{T}_i S_j \widetilde{T}_j T_k S_l T_n S_q}{\Lambda^8} \epsilon_{klm} \epsilon_{npq} Q_m U_q H_u$$

induces realistic up-type Yukawa matrix if $|w|/|v| \sim |u|/|v| = \epsilon \approx 0.1$

Non-abelian Froggatt-Nielsen model

Down-type Yukawas similar

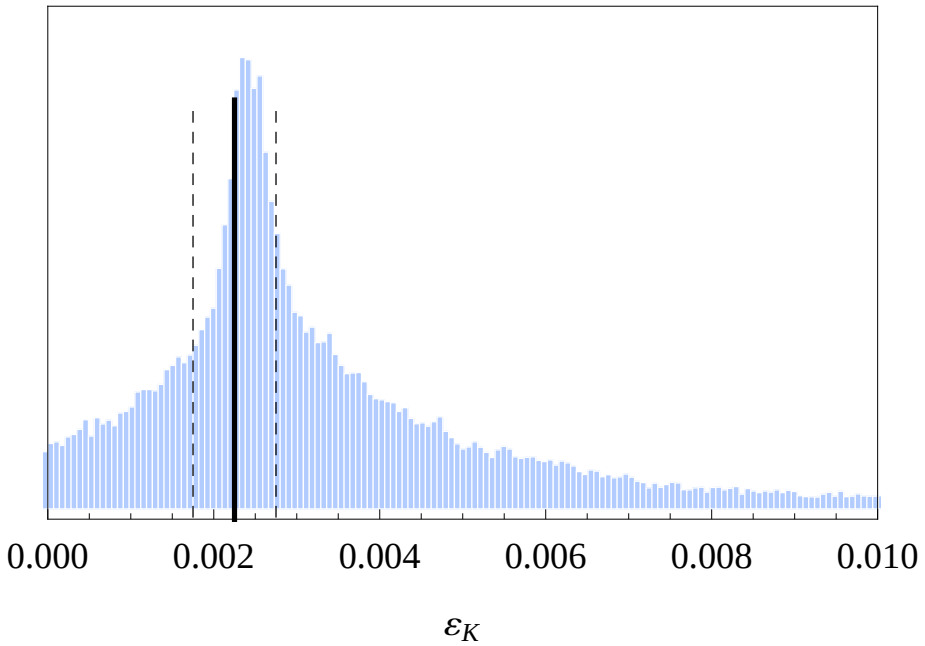
Model building: Flavour symmetry breaking

Mass and CKM hierarchies roughly reproduced, e.g.

$$V_{\text{CKM}} \sim \begin{pmatrix} 1 & \epsilon & \epsilon^2 \\ \epsilon & 1 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$$

although V_{us}, V_{cb} a bit too small

Flavour constraints: mostly from $\Delta F = 2$ observables, especially ϵ_K
Using MCMC scan to sample flavour model parameter space:



On the wishlist: nicer flavour models

Conclusions

Conclusions

- Non-minimal versions of gauge mediation remain an attractive BSM scenario
- Gauge messengers for a gauged flavour symmetry: interesting model-building ingredient
- For $SU(3)_F$ with SUSY breaking aligned with $SU(3)_F \rightarrow SU(2)_F$ breaking in flavour space:
  - large negative contributions to 3rd gen. masses $\Rightarrow$ stops and sbottoms light
  - smaller -ve contributions to 1st/2nd gen. masses $\Rightarrow$ other squarks heavy
- Allows for maximal stop mixing without extremely large A-terms $\Rightarrow$ 125 GeV Higgs in MSSM
- Alignment of VEVs can be realized dynamically
- Large contributions to ϵ_K possible. Model dependent, can be estimated in a given flavour model