Title: Deconstructing a Natural and Flavorful Supersymmetric Standard Model

Date: Apr 21, 2011 01:00 PM

URL: http://pirsa.org/11040079

Abstract: Using the framework of deconstruction, we construct simple, weakly-coupled supersymmetric models that explain the Standard Model flavor hierarchy and produce a flavorful soft spectrum compatible with precision limits. Electroweak symmetry breaking is fully natural/ the mu-term is dynamically generated with no B mu-problem and the Higgs mass is easily raised above LEP limits without reliance on large radiative corrections. These models possess the distinctive spectrum of superpartners characteristic of 'effective supersymmetry': the third generation superpartners tend to be light, while the rest of the scalars are heavy.

# Outline

1. Motivation: What Do We Expect from SUSY?
2. From gauge mediation to EW scale quivers
3. Vector-like Higgses
4. Chiral Higgses
5. Conclusions

# Supersymmetry

## Why SUSY can be useful?

Motivated BSM candidate: addresses the gauge hierarchy problem, improves gauge coupling unification (compared to the SM), can accommodate viable DM candidate...

# Supersymmetry

**Why SUSY can be useful?**

Motivated BSM candidate: addresses the gauge hierarchy problem, improves gauge coupling unification (compared to the SM), can accommodate viable DM candidate...

What do we know already about SUSY (if it is there)?

- (nearly) flavor blind

# Supersymmetry

**Why SUSY can be useful?**

Motivated BSM candidate: addresses the gauge hierarchy problem, improves gauge coupling unification (compared to the SM), can accommodate viable DM candidate...

What do we know already about SUSY (if it is there)?

- (nearly) flavor blind
- does not have big CP-phases

# Supersymmetry

**Why SUSY can be useful?**

Motivated BSM candidate: addresses the gauge hierarchy problem, improves gauge coupling unification (compared to the SM), can accommodate viable DM candidate...

What do we know already about SUSY (if it is there)?

- (nearly) flavor blind
- does not have big CP-phases
- either non-minimal, or suffers from some mild degree of fine-tuning

# More requirements from the EW-scale SUSY

## The MSSM coincidence problem

In order to have a viable SUSY-model at the EW scale within the current experimental bounds one should require $\mu \sim m_{soft}$. The $\mu$-term is a-priori perfectly supersymmetric: $W = \mu H_u H_d$. It is unclear why should it coincide with the soft mass scale.

# More requirements from the EW-scale SUSY

## The MSSM coincidence problem

In order to have a viable SUSY-model at the EW scale within the current experimental bounds one should require $\mu \sim m_{soft}$. The $\mu$-term is a-priori perfectly supersymmetric: $W = \mu H_u H_d$. It is unclear why should it coincide with the soft mass scale.

There are more points one can add to the requirements list: improved unification, DM candidate... We will also try to address the flavor puzzle of the SM.

# More requirements from the EW-scale SUSY

## The MSSM coincidence problem

In order to have a viable SUSY-model at the EW scale within the current experimental bounds one should require $\mu \sim m_{soft}$. The $\mu$-term is a-priori perfectly supersymmetric: $W = \mu H_u H_d$. It is unclear why should it coincide with the soft mass scale.

There are more points one can add to the requirements list: improved unification, DM candidate... We will also try to address the flavor puzzle of the SM.

## The SM flavor puzzle

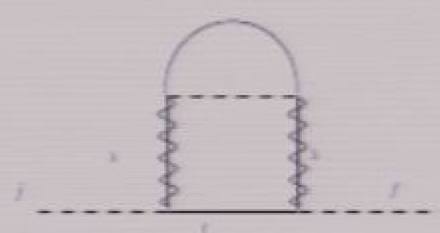
The SM flavor structure – possible hint for the NP. E.g. the ratios between the quark masses: $\frac{m_c}{m_t} \sim \frac{m_s}{m_b} \sim 10^{-2}$, the hierarchical structure of the CKM matrix. These small numbers are technically natural, but it is plausible that they can be addressed in the framework of EW scale SUSY.

# Gauge mediation

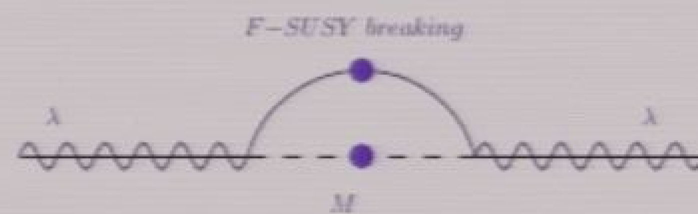
Main motivation: a flavor blind mediation mechanism. Natural solution – gauge interactions. Minimal gauge mediation:

$$W = X\varphi\tilde{\varphi}, \qquad \langle X \rangle = M + F\theta^2$$

Scalar masses (one of many diagrams)



Gaugino masses

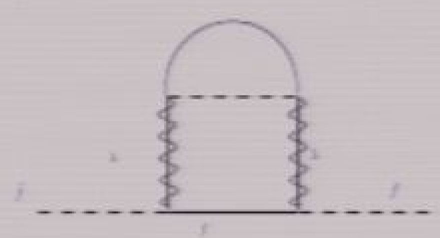


# Gauge mediation

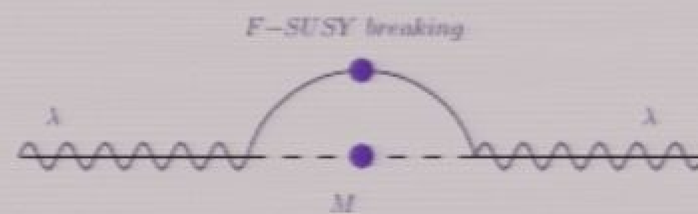
Main motivation: a flavor blind mediation mechanism. Natural solution – gauge interactions. Minimal gauge mediation:

$$W = X\varphi\tilde{\varphi}, \qquad \langle X \rangle = M + F\theta^2$$

Scalar masses (one of many diagrams)



Gaugino masses




Assuming small SUSY-breaking, namely $F \ll M^2$

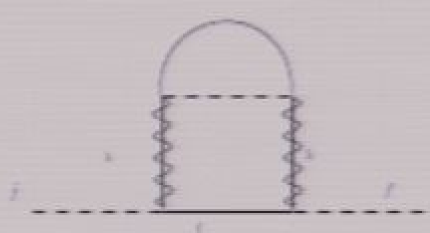
$$m_{\tilde{f}}^2 \propto \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2 \qquad m_\lambda \propto \frac{\alpha}{4\pi}\frac{F}{M}$$

# Gauge mediation

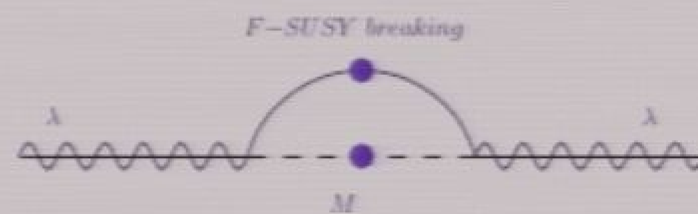
Main motivation: a flavor blind mediation mechanism. Natural solution – gauge interactions. Minimal gauge mediation:

$$W = X\varphi\tilde{\varphi}, \qquad \langle X \rangle = M + F\theta^2$$

Scalar masses (one of many diagrams)



Gaugino masses




Assuming small SUSY-breaking, namely $F \ll M^2$

$$m_{\tilde{f}}^2 \propto \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2 \qquad m_\lambda \propto \frac{\alpha}{4\pi}\frac{F}{M}$$

- naturally no sources of flavor violation
- $m_\lambda \sim m_{\tilde{f}}$ – natural outcome of minimal gauge mediation

# Disadvantages of Gauge Mediation

- In gauge mediation $m_{soft} \propto g^2$ and therefore squarks are much heavier than sleptons. This exacerbates the little hierarchy problem (TeV-scale stops)

# Disadvantages of Gauge Mediation

- In gauge mediation $m_{soft} \propto g^2$ and therefore squarks are much heavier than sleptons. This exacerbates the little hierarchy problem (TeV-scale stops)
- Very often in dynamical models one gets

$$m_\lambda \propto \frac{F^3}{M^5}$$

The hierarchy problem then is even more annoying

# Disadvantages of Gauge Mediation

- In gauge mediation $m_{soft} \propto g^2$ and therefore squarks are much heavier than sleptons. This exacerbates the little hierarchy problem (TeV-scale stops)
- Very often in dynamical models one gets

$$m_\lambda \propto \frac{F^3}{M^5}$$

  The hierarchy problem then is even more annoying
- $\mu/B\mu$ problem. Typically is $\mu$ and $B\mu$ are produced dynamically one gets $B\mu \gg \mu^2$ (Dvali, Giudice, Pomarol; 1996). It is hard to find an appealing dynamical solution to the $\mu$ problem in gauge mediation.

# Deconstruction

**Main idea of deconstruction** *Arkani-Hamed, Cohen, Georgi (2001)*

Extra-dimensional effects *dynamically* emerge from a calculable, 4D theory. In the ideal case the theory is simple and UV free. In deconstructed models the extra-dimension is "latticed"; the gauge group is enlarged to contain two, or more SM-like gauge groups.

# Disadvantages of Gauge Mediation

- In gauge mediation $m_{soft} \propto g^2$ and therefore squarks are much heavier than sleptons. This exacerbates the little hierarchy problem (TeV-scale stops)
- Very often in dynamical models one gets

$$m_\lambda \propto \frac{F^3}{M^5}$$

  The hierarchy problem then is even more annoying
- $\mu/B\mu$ problem. Typically is $\mu$ and $B\mu$ are produced dynamically one gets $B\mu \gg \mu^2$ (Dvali, Giudice, Pomarol; 1996). It is hard to find an appealing dynamical solution to the $\mu$ problem in gauge mediation.

# Deconstruction

**Main idea of deconstruction** *Arkani-Hamed, Cohen, Georgi (2001)*

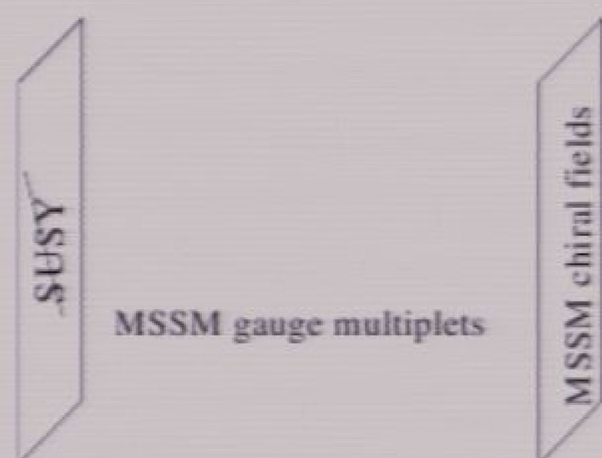
Extra-dimensional effects *dynamically* emerge from a calculable, 4D theory. In the ideal case the theory is simple and UV free. In deconstructed models the extra-dimension is "latticed"; the gauge group is enlarged to contain two, or more SM-like gauge groups.

# Deconstruction

**Main idea of deconstruction** *Arkani-Hamed, Cohen, Georgi (2001)*

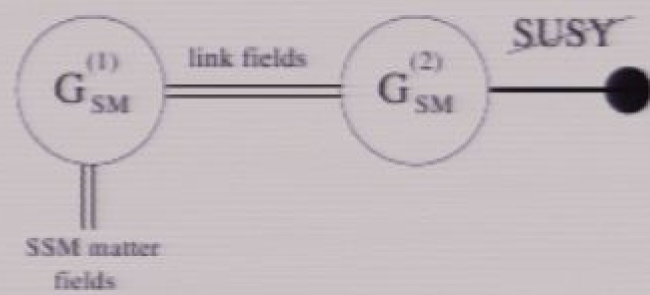
Extra-dimensional effects *dynamically* emerge from a calculable, 4D theory. In the ideal case the theory is simple and UV free. In deconstructed models the extra-dimension is "latticed"; the gauge group is enlarged to contain two, or more SM-like gauge groups.

Example: gaugino mediation



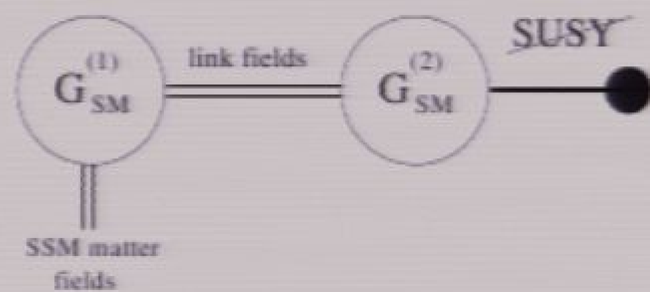
# Deconstructed Gaugino Mediation

One can reproduce effects of gaugino mediation (scalar mass suppression) in a two-site model:



# Deconstructed Gaugino Mediation

One can reproduce effects of gaugino mediation (scalar mass suppression) in a two-site model:




Three scale model:

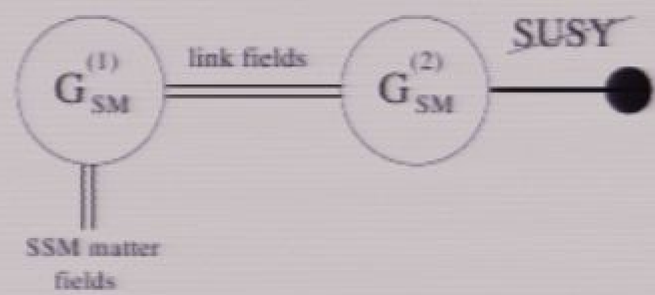
- $M$ - messenger mass scale
- $\sqrt{F}$ - SUSY-breaking scale
- $v$ - scale of link fields VEVs, two gauge groups are broken to the diagonal.

# Two regimes of two-site model

In what sense does this two-site model "mimic" 5D gaugino mediation?

# Deconstructed Gaugino Mediation

One can reproduce effects of gaugino mediation (scalar mass suppression) in a two-site model:




Three scale model:

- $M$ - messenger mass scale
- $\sqrt{F}$ - SUSY-breaking scale
- $v$ - scale of link fields VEVs, two gauge groups are broken to the diagonal.

# Two regimes of two-site model

In what sense does this two-site model "mimic" 5D gaugino mediation?

# Two regimes of two-site model

In what sense does this two-site model "mimic" 5D gaugino mediation?

**$v \ll M$**

- gaugino mass $m_\lambda \sim \frac{\alpha_2}{4\pi}\frac{F}{M}$
- above the scale $v$ scalars get masses at 4 loops
- below the scale $v$: $m_{\tilde{f}}^2 \sim \left(\frac{\alpha_1}{4\pi}\right)^2 \left(\frac{v}{M}\right)^2 \left(\frac{F}{M}\right)^2$

**$v \gg M$**

- the gauge group is broken to the diagonal at the scale $v$
- gaugino get mass $m_\lambda \sim \frac{\alpha_d}{4\pi}\frac{F}{M}$
- scalars are not screened $m_{\tilde{f}}^2 \sim \left(\frac{\alpha_d}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$

# Two regimes of two-site model

In what sense does this two-site model "mimic" 5D gaugino mediation?

**$v \ll M$**

- gaugino mass $m_\lambda \sim \frac{\alpha_2}{4\pi}\frac{F}{M}$
- above the scale $v$ scalars get masses at 4 loops
- below the scale $v$: $m_{\tilde{f}}^2 \sim \left(\frac{\alpha_1}{4\pi}\right)^2 \left(\frac{v}{M}\right)^2 \left(\frac{F}{M}\right)^2$

**$v \gg M$**

- the gauge group is broken to the diagonal at the scale $v$
- gaugino get mass $m_\lambda \sim \frac{\alpha_d}{4\pi}\frac{F}{M}$
- scalars are not screened $m_{\tilde{f}}^2 \sim \left(\frac{\alpha_d}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$

For $v \ll M$ we get scalar screening, namely the dominant contributions to the scalar masses will come from running and non-decoupling effects (e.g. non-decoupling 3-loop contribution). In this sense it is very similar to the 5D gaugino mediation.

# Advantages and open questions of the two-site quiver.

This two site model is a particular example of highly non-minimal gauge-mediation scenario. What are the advantages of this scenario compared to the minimal gauge mediation?

# Advantages and open questions of the two-site quiver.

This two site model is a particular example of highly non-minimal gauge-mediation scenario. What are the advantages of this scenario compared to the minimal gauge mediation?

- Since it is still gauge mediation, it is perfectly flavor blind.

# Advantages and open questions of the two-site quiver.

This two site model is a particular example of highly non-minimal gauge-mediation scenario. What are the advantages of this scenario compared to the minimal gauge mediation?

- Since it is still gauge mediation, it is perfectly flavor blind.
- Scalar mass suppression can compensate for the gaugino mass suppression. The resulting spectrum can even have sleptons lighter than the EW gauginos.

# Advantages and open questions of the two-site quiver.

This two site model is a particular example of highly non-minimal gauge-mediation scenario. What are the advantages of this scenario compared to the minimal gauge mediation?

- Since it is still gauge mediation, it is perfectly flavor blind.
- Scalar mass suppression can compensate for the gaugino mass suppression. The resulting spectrum can even have sleptons lighter than the EW gauginos.
- Naturally corrects the Higgs quartic coupling (the D-terms of $Z'$, $W'$). This corrections are numerically small, but one can hope that this can be improved in modified models.

# Advantages and open questions of the two-site quiver.

This two site model is a particular example of highly non-minimal gauge-mediation scenario. What are the advantages of this scenario compared to the minimal gauge mediation?

- Since it is still gauge mediation, it is perfectly flavor blind.
- Scalar mass suppression can compensate for the gaugino mass suppression. The resulting spectrum can even have sleptons lighter than the EW gauginos.
- Naturally corrects the Higgs quartic coupling (the D-terms of $Z'$, $W'$). This corrections are numerically small, but one can hope that this can be improved in modified models.

What is still difficult to achieve?

- No built-in solution to the $\mu$ (or $\mu/B\mu$) problem
- We still face the little hierarchy problem

# Modified two-site model

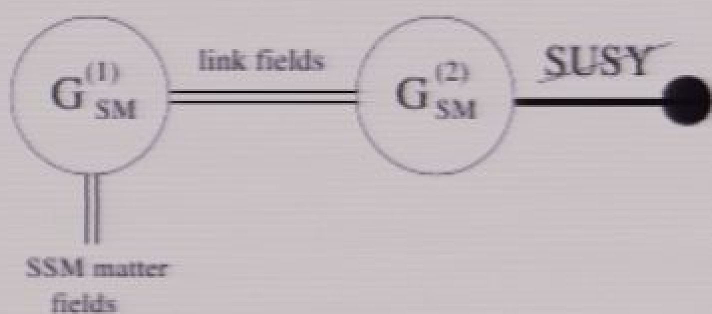
**How can we explain the smallness of quark masses?**

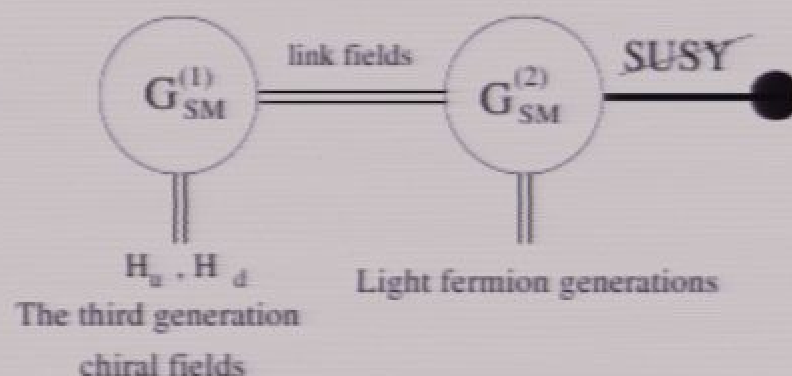
Simple solution: not all the scalars are charged under the LH SM. We can charge some of the fields under the RH group. If this is the case, some of the Yukawa couplings are forbidden at the renormalizable level.

# Modified two-site model

**How can we explain the smallness of quark masses?**

Simple solution: not all the scalars are charged under the LH SM. We can charge some of the fields under the RH group. If this is the case, some of the Yukawa couplings are forbidden at the renormalizable level.




As we will see this framework also helps us to address the $\mu$-problem

# On the origin of the two-site model

## UV completion of the two-site model

The two-site model gaugino mediation can naturally emerge from massive SQCD with two different mass scales *(D.Green, AK, Z. Komargodski)*. If the two-site model indeed emerges from the dynamical model than:

- It is very easy to get suppressed gaugino masses $m_\lambda \propto F^3$.
- If the gaugino masses are suppressed, low-scale mediation regime is strongly favored.

# On the origin of the two-site model

## UV completion of the two-site model

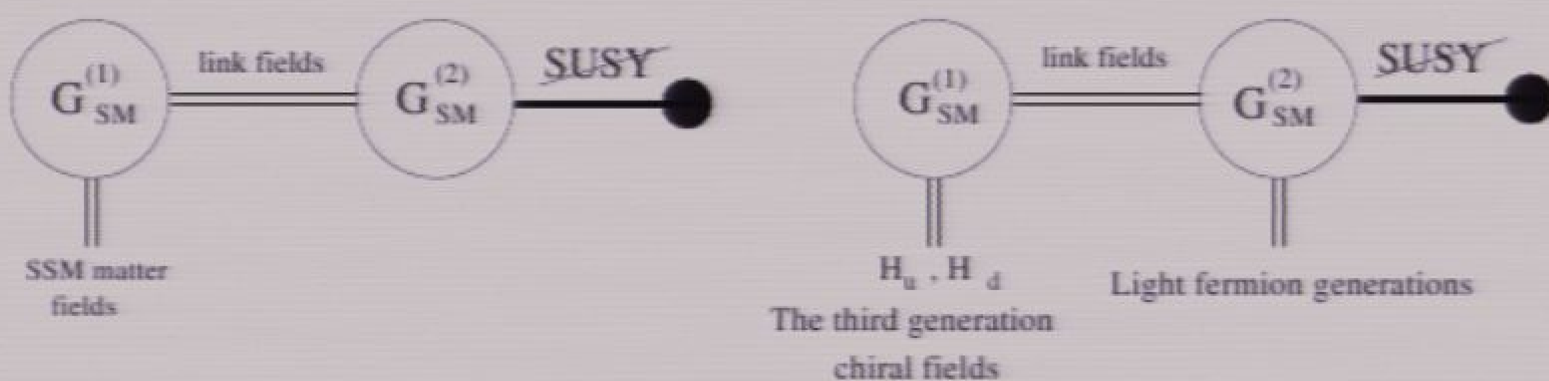
The two-site model gaugino mediation can naturally emerge from massive SQCD with two different mass scales *(D.Green, AK, Z. Komargodski)*. If the two-site model indeed emerges from the dynamical model than:

- It is very easy to get suppressed gaugino masses $m_\lambda \propto F^3$.
- If the gaugino masses are suppressed, low-scale mediation regime is strongly favored.

We will have in mind this dynamical model as a motivation for our further model-building, but remain agnostic about precise nature of the UV completion. Models which explain both the SM flavor puzzle and the $\mu$-problem also favor the low-scale regime. A simple UV completion is unable to produce all the couplings we need for these our models, but they can be produced in more sophisticated UV completions.

# First look on the model

In this model we just move the light generations (quarks and leptons) to the RH site. The tree level $\mu$-term is forbidden. Note that only the third generation tree level Yukawas are allowed by gauge invariance.



# On the origin of the two-site model

## UV completion of the two-site model

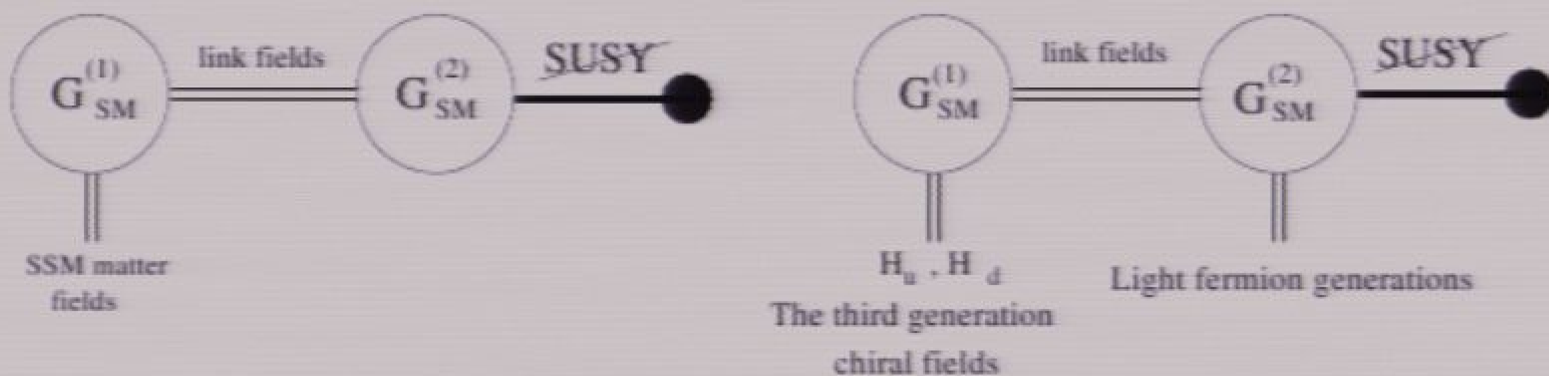
The two-site model gaugino mediation can naturally emerge from massive SQCD with two different mass scales *(D.Green, AK, Z. Komargodski)*. If the two-site model indeed emerges from the dynamical model than:

- It is very easy to get suppressed gaugino masses $m_\lambda \propto F^3$.
- If the gaugino masses are suppressed, low-scale mediation regime is strongly favored.

We will have in mind this dynamical model as a motivation for our further model-building, but remain agnostic about precise nature of the UV completion. Models which explain both the SM flavor puzzle and the $\mu$-problem also favor the low-scale regime. A simple UV completion is unable to produce all the couplings we need for these our models, but they can be produced in more sophisticated UV completions.

# First look on the model

In this model we just move the light generations (quarks and leptons) to the RH site. The tree level $\mu$-term is forbidden. Note that only the third generation tree level Yukawas are allowed by gauge invariance.



# The $\mu$-term and flavor

## The $\mu$-term

We can write down a following operator which would produce an effective $\mu$-term: $\Delta W \sim \frac{\chi\tilde{\chi}H_u H_d}{M_*}$. A leading contribution to the $B\mu$ comes from a wino loop: $B\mu \sim \frac{\alpha_2}{2\pi}\mu m_{\tilde{W}} \ln\left(\frac{\chi}{m_{\tilde{W}}}\right)$. We naturally get $B\mu < \mu^2$.

# The $\mu$-term and flavor

## The $\mu$-term

We can write down a following operator which would produce an effective $\mu$-term: $\Delta W \sim \frac{\chi\tilde{\chi}H_u H_d}{M_*}$. A leading contribution to the $B\mu$ comes from a wino loop: $B\mu \sim \frac{\alpha_2}{2\pi}\mu m_{\tilde{W}} \ln\left(\frac{\chi}{m_{\tilde{W}}}\right)$. We naturally get $B\mu < \mu^2$.

## Light generations Yukawas

If we allow non-renormalizable terms in the superpotential, these Yukawas can come from dimension 4 and dimension 5 operators with insertions of the link fields. We will also assume that these operators are formed at scale $M_*$, e.g.: $\Delta W \sim \frac{H_u \tilde{\chi} Q_2 \bar{u}_2}{M_*}$ Since we have a two-site model, we will be able only to explain the smallness of the second generation compared to the third. One more small number should be put by hand.

# The $\mu$-term and flavor

## The $\mu$-term

We can write down a following operator which would produce an effective $\mu$-term: $\Delta W \sim \frac{\chi\tilde{\chi}H_uH_d}{M_*}$. A leading contribution to the $B\mu$ comes from a wino loop: $B\mu \sim \frac{\alpha_2}{2\pi}\mu m_{\tilde{W}} \ln\left(\frac{\chi}{m_{\tilde{W}}}\right)$. We naturally get $B\mu < \mu^2$.

# The $\mu$-term and flavor

## The $\mu$-term

We can write down a following operator which would produce an effective $\mu$-term: $\Delta W \sim \frac{\chi\tilde{\chi}H_u H_d}{M_*}$. A leading contribution to the $B\mu$ comes from a wino loop: $B\mu \sim \frac{\alpha_2}{2\pi}\mu m_{\tilde{W}} \ln\left(\frac{\chi}{m_{\tilde{W}}}\right)$. We naturally get $B\mu < \mu^2$.

## Light generations Yukawas

If we allow non-renormalizable terms in the superpotential, these Yukawas can come from dimension 4 and dimension 5 operators with insertions of the link fields. We will also assume that these operators are formed at scale $M_*$, e.g.: $\Delta W \sim \frac{H_u \tilde{\chi} Q_2 \bar{u}_2}{M_*}$ Since we have a two-site model, we will be able only to explain the smallness of the second generation compared to the third. One more small number should be put by hand.

# Flavor structure

Define a small number $\epsilon \equiv \frac{\chi}{M_*}$. Yukawa matrices in the flavor basis:

**Up-type sector**

$$Y_u \sim \sin\beta \begin{pmatrix} \epsilon & \epsilon & \epsilon^2 \\ \epsilon & \epsilon & \epsilon^2 \\ \epsilon^2 & \epsilon^2 & 1 \end{pmatrix}$$

**Down type sector**

$$Y_d \sim \cos\beta \begin{pmatrix} \epsilon & \epsilon & \epsilon^2 \\ \epsilon & \epsilon & \epsilon^2 \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

# Flavor structure

Define a small number $\epsilon \equiv \frac{\chi}{M_*}$. Yukawa matrices in the flavor basis:

**Up-type sector**

$$Y_u \sim \sin\beta \begin{pmatrix} \epsilon & \epsilon & \epsilon^2 \\ \epsilon & \epsilon & \epsilon^2 \\ \epsilon^2 & \epsilon^2 & 1 \end{pmatrix}$$

**Down type sector**

$$Y_d \sim \cos\beta \begin{pmatrix} \epsilon & \epsilon & \epsilon^2 \\ \epsilon & \epsilon & \epsilon^2 \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

It is then natural to choose $\epsilon \sim \frac{m_c}{m_t} \lesssim 10^{-2}$. The CKM matrix is:

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

# Soft masses structure

## Soft masses

The light flavors get regular soft masses$^2$ from gauge mediation: $m^2_{GM}$. The heavy flavors get masses$^2$ from gaugino mediation – loop suppressed $m^2_{\tilde{g}M}$. These masses are diagonal in flavor basis, but we should rotate them into the fermion mass basis.

# Soft masses structure

## Soft masses

The light flavors get regular soft masses$^2$ from gauge mediation: $m^2_{GM}$. The heavy flavors get masses$^2$ from gaugino mediation – loop suppressed $m^2_{\tilde{g}M}$. These masses are diagonal in flavor basis, but we should rotate them into the fermion mass basis.

The soft masses in the fermion mass basis:

$$m^2_{\tilde{Q}} \sim \begin{pmatrix} m^2_{GM} & 0 & \epsilon^2 m^2_{GM} \\ 0 & m^2_{GM} & \epsilon^2 m^2_{GM} \\ \epsilon^2 m^2_{GM} & \epsilon^2 m^2_{GM} & m^2_{\tilde{g}M} \end{pmatrix},$$

$$m^2_{\bar{\tilde{u}}} \sim \begin{pmatrix} m^2_{GM} & 0 & \epsilon^2 m^2_{GM} \\ 0 & m^2_{GM} & \epsilon^2 m^2_{GM} \\ \epsilon^2 m^2_{GM} & \epsilon^2 m^2_{GM} & m^2_{\tilde{g}M} \end{pmatrix}, \quad m^2_{\bar{\tilde{d}}} \sim \begin{pmatrix} m^2_{GM} & 0 & \epsilon m^2_{GM} \\ 0 & m^2_{GM} & \epsilon m^2_{GM} \\ \epsilon m^2_{GM} & \epsilon m^2_{GM} & m^2_{\tilde{g}M} \end{pmatrix}$$

# Phenomenology, flavor constraints

**Spectrum - "more minimal SUSY"**

Since the third generation scalars get their masses at 3-loop, they are significantly lighter than the first and the second generation scalars. Only $\tilde{t}, \tilde{b}, \tilde{\tau}$ (and gauginos) are accessible at the LHC.

# Phenomenology, flavor constraints

## Spectrum - "more minimal SUSY"

Since the third generation scalars get their masses at 3-loop, they are significantly lighter than the first and the second generation scalars. Only $\tilde{t}, \tilde{b}, \tilde{\tau}$ (and gauginos) are accessible at the LHC.

## Flavor constraints

There are three different sources for FCNC:

- Conventional diagrams due to non-diagonal squark masses
- Box diagrams with the link fields – suppressed by $\left(\frac{v}{M_*}\right)^4$, virtually unimportant
- Tree-level FCNCs mediated by $Z'$ – well within the bounds for $M_{Z'} \sim 10$ TeV

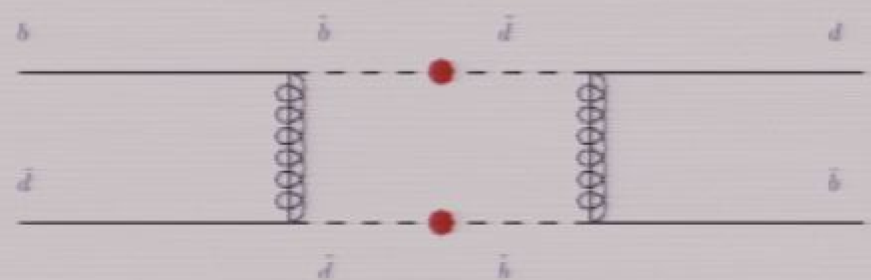
# Squark-mediated FCNC

Usually the most stringent constraints come from $K-\bar{K}$ and $\mu \to e\gamma$. In our model $\mu \to e\gamma$ is suppressed (magnetic transition, heavy sfermions). We will have the most stringent constraints from $K-\bar{K}$. We also find a new contribution to $B-\bar{B}$, but it does not yield the strongest bound.

# Squark-mediated FCNC

Usually the most stringent constraints come from $K-\bar{K}$ and $\mu \to e\gamma$. In our model $\mu \to e\gamma$ is suppressed (magnetic transition, heavy sfermions). We will have the most stringent constraints from $K-\bar{K}$. We also find a new contribution to $B-\bar{B}$, but it does not yield the strongest bound.

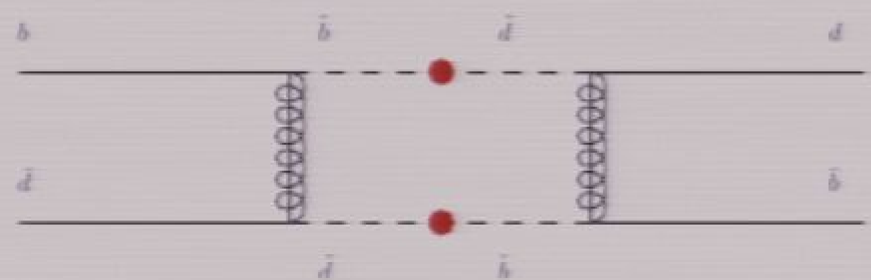
New contribution to $B-\bar{B}$



# Squark-mediated FCNC

Usually the most stringent constraints come from $K-\bar{K}$ and $\mu \to e\gamma$. In our model $\mu \to e\gamma$ is suppressed (magnetic transition, heavy sfermions). We will have the most stringent constraints from $K-\bar{K}$. We also find a new contribution to $B-\bar{B}$, but it does not yield the strongest bound.

New contribution to $B-\bar{B}$

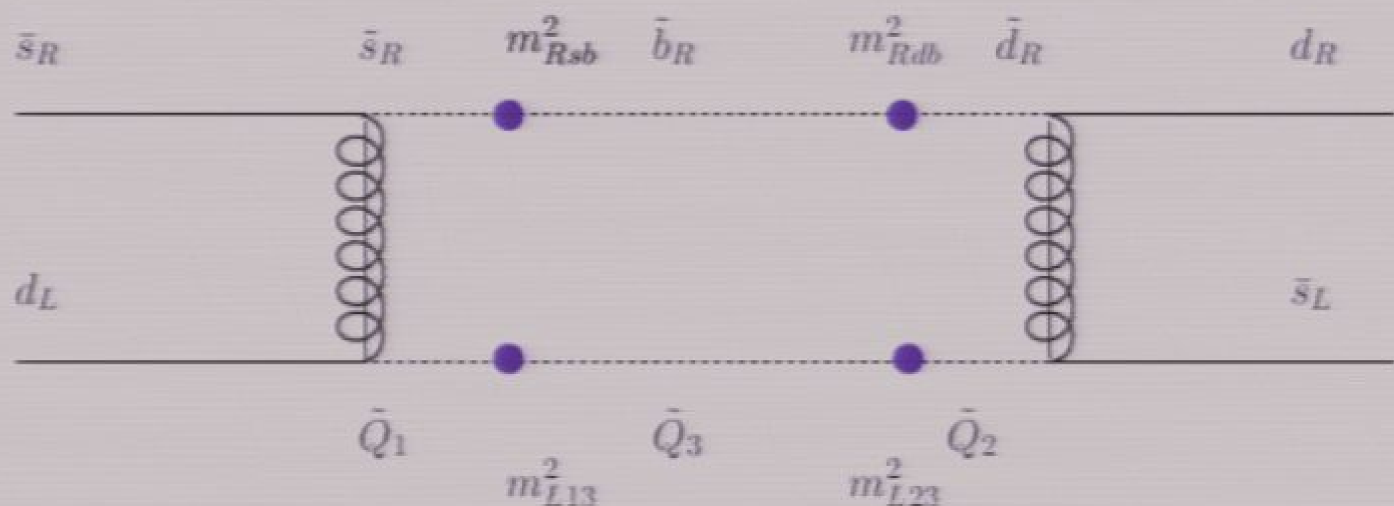


## $B-\bar{B}$

The leading contribution $\epsilon^2$ comes from operator $(\bar{b}_R\gamma^\mu d_R)^2$ - relatively weakly constrained. The most interesting constraint comes from $(\bar{b}_R d_L)(\bar{b}_L d_R)$, predicted to be of order $\epsilon^3 \sim 10^{-6}$.

# The bottleneck - $K - \bar{K}$

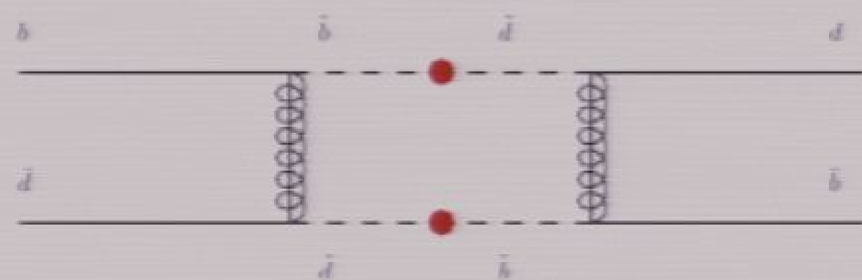
We have an extremely stringent constraint on an operator $(\bar{s}_R d_L)(\bar{s}_L d_R)$. The contribution comes from a diagram with two insertions:



# Squark-mediated FCNC

Usually the most stringent constraints come from $K-\bar{K}$ and $\mu \to e\gamma$. In our model $\mu \to e\gamma$ is suppressed (magnetic transition, heavy sfermions). We will have the most stringent constraints from $K-\bar{K}$. We also find a new contribution to $B-\bar{B}$, but it does not yield the strongest bound.

New contribution to $B-\bar{B}$

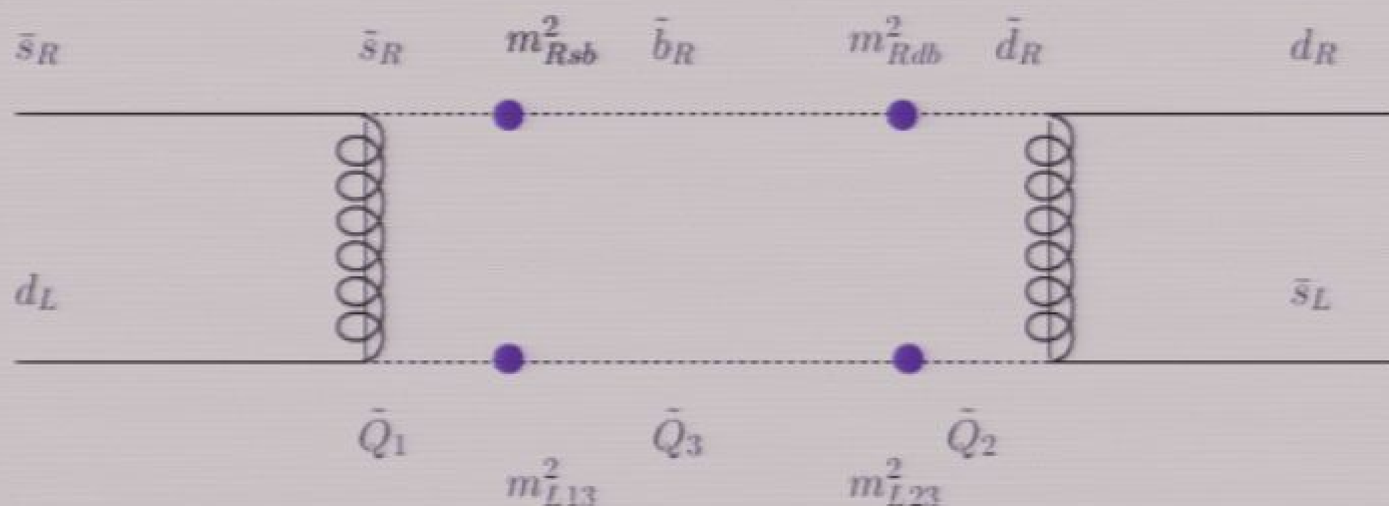


## $B-\bar{B}$

The leading contribution $\epsilon^2$ comes from operator $(\bar{b}_R\gamma^\mu d_R)^2$ - relatively weakly constrained. The most interesting constraint comes from $(\bar{b}_R d_L)(\bar{b}_L d_R)$, predicted to be of order $\epsilon^3 \sim 10^{-6}$.

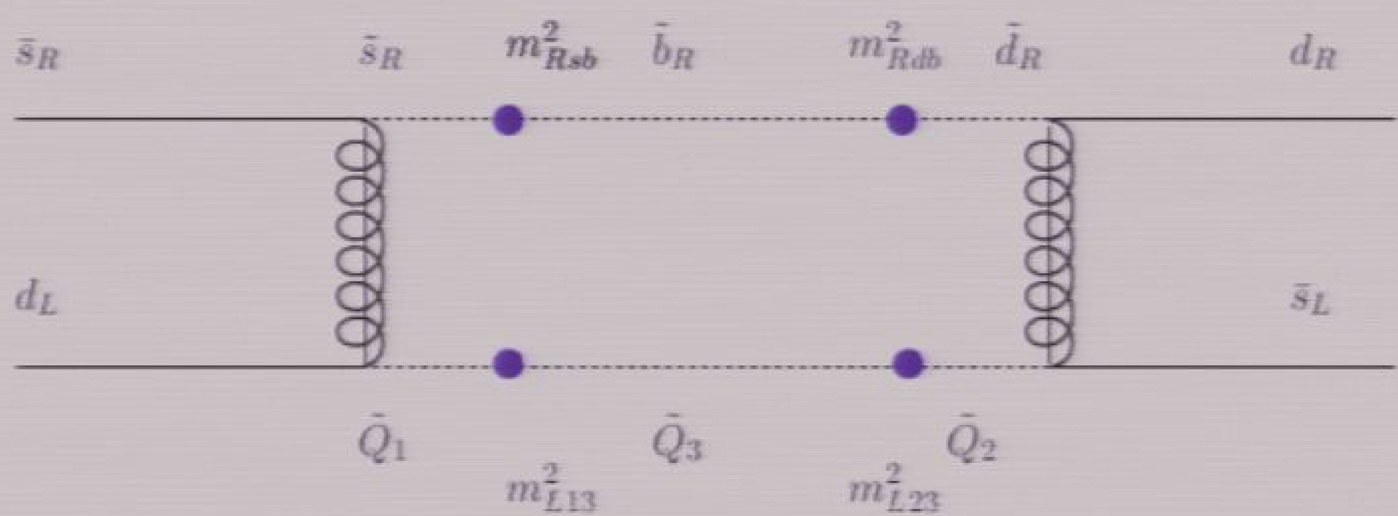
# The bottleneck - $K - \bar{K}$

We have an extremely stringent constraint on an operator $(\bar{s}_R d_L)(\bar{s}_L d_R)$. The contribution comes from a diagram with two insertions:



# The bottleneck - $K - \bar{K}$

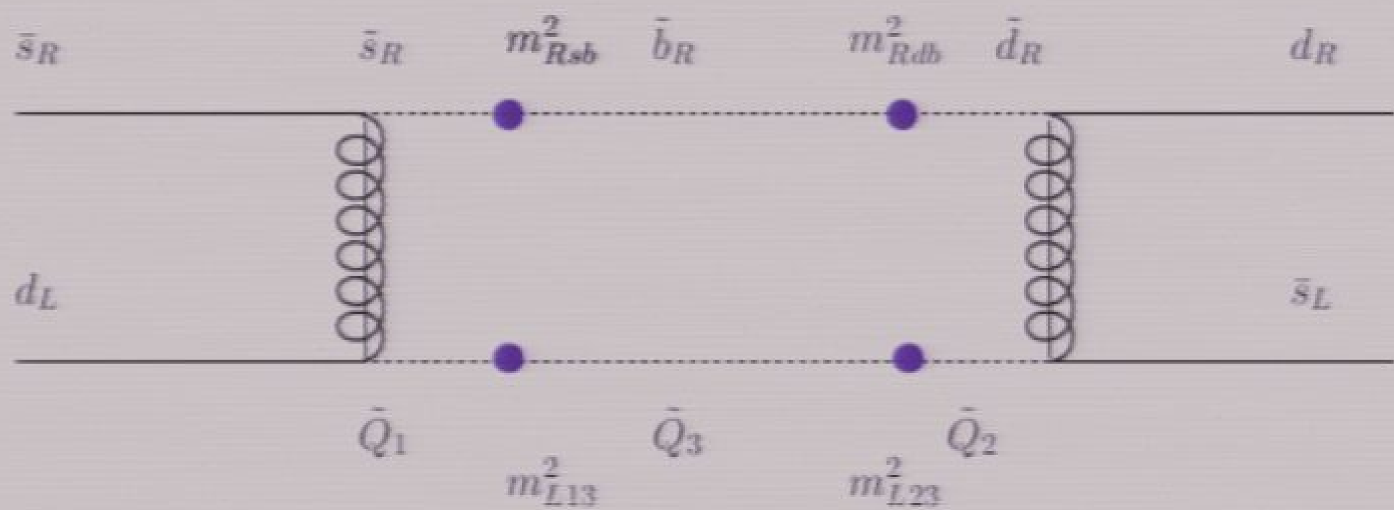
We have an extremely stringent constraint on an operator $(\bar{s}_R d_L)(\bar{s}_L d_R)$.
The contribution comes from a diagram with two insertions:




- We have stringent bounds even if the contribution is real

# The bottleneck - $K - \bar{K}$

We have an extremely stringent constraint on an operator $(\bar{s}_R d_L)(\bar{s}_L d_R)$. The contribution comes from a diagram with two insertions:




- We have stringent bounds even if the contribution is real
- If we have $\mathcal{O}(1)$ phase, we violate the SM bounds by 2 orders of magnitude. We are forced to assume at this point that the phase in RH sector is almost aligned with the phase in the LH sector.

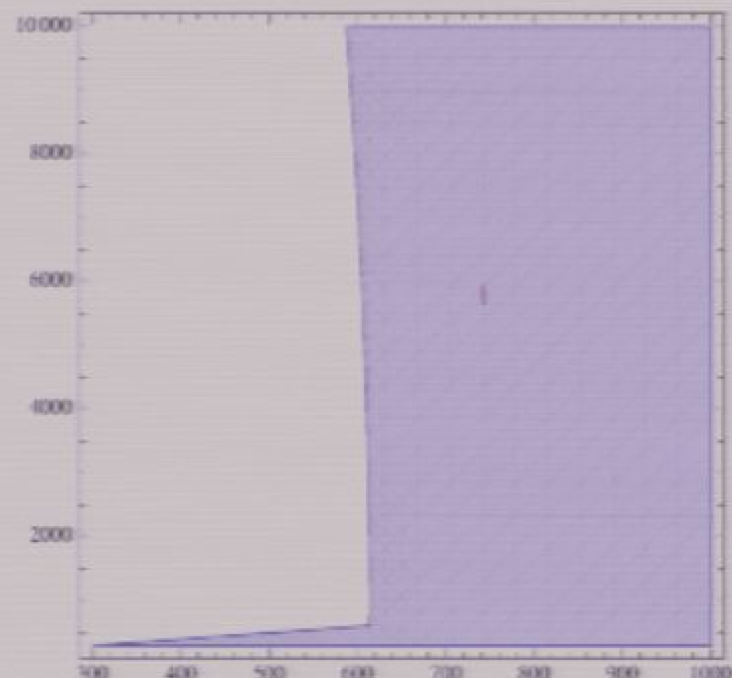
# $K - \bar{K}$ constraints

The contribution scales as $V_{us} V_{ub} \times \epsilon \sim 10^{-6}$.

# $K - \bar{K}$ constraints

The contribution scales as $V_{us} V_{ub} \times \epsilon \sim 10^{-6}$.

Illustrative example: $m_{\tilde{g}} = 1$ TeV, $\epsilon = 10^{-2}$, $\tan\beta = 20$:



# The little hierarchy problem

Two allow both $\tilde{t}$s to be light (say of order 500 GeV) one should introduce additional contributions to the Higgs quartic. In our model these contributions are naturally present: D-terms of the $Z', W'$:

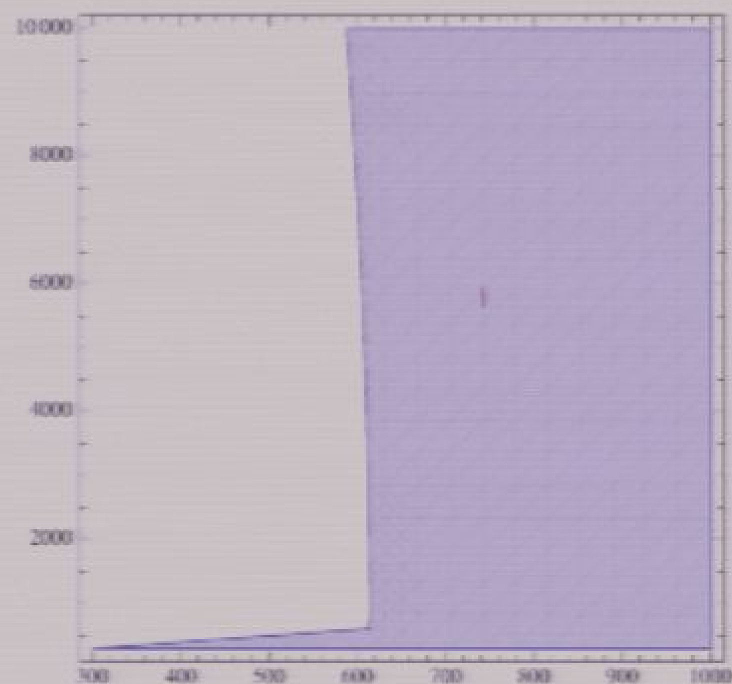
$$\delta V = \frac{g^2\Delta}{8}\left|H_u^\dagger\sigma^a H_u + H_d^\dagger\sigma^a H_d\right|^2 + \frac{3g'^2\Delta'}{40}\left|H_u^\dagger H_u - H_d^\dagger H_d\right|^2$$

$$\Delta = \frac{g_1^2}{g_2^2}\frac{2\tilde{m}_\chi^2}{M_2^2 + 2\tilde{m}_\chi^2}\,.$$

# $K - \bar{K}$ constraints

The contribution scales as $V_{us} V_{ub} \times \epsilon \sim 10^{-6}$.

Illustrative example: $m_{\tilde{g}} = 1$ TeV, $\epsilon = 10^{-2}$, $\tan\beta = 20$:




- The shaded region is allowed by $\Delta m_K$ constraints
- With maximal phase, the pink region is allowed by $\epsilon_K$
- Need $m_{\tilde{b}} > 600$ GeV

# The little hierarchy problem

Two allow both $\tilde{t}$s to be light (say of order 500 GeV) one should introduce additional contributions to the Higgs quartic. In our model these contributions are naturally present: D-terms of the $Z', W'$:

$$\delta V = \frac{g^2\Delta}{8}\left|H_u^\dagger\sigma^a H_u + H_d^\dagger\sigma^a H_d\right|^2 + \frac{3g'^2\Delta'}{40}\left|H_u^\dagger H_u - H_d^\dagger H_d\right|^2$$

$$\Delta = \frac{g_1^2}{g_2^2}\frac{2\tilde{m}_\chi^2}{M_2^2 + 2\tilde{m}_\chi^2}\,.$$

# The little hierarchy problem

Two allow both $\tilde{t}$s to be light (say of order 500 GeV) one should introduce additional contributions to the Higgs quartic. In our model these contributions are naturally present: D-terms of the $Z', W'$:

$$\delta V = \frac{g^2\Delta}{8}\left|H_u^\dagger\sigma^a H_u + H_d^\dagger\sigma^a H_d\right|^2 + \frac{3g'^2\Delta'}{40}\left|H_u^\dagger H_u - H_d^\dagger H_d\right|^2$$

$$\Delta = \frac{g_1^2}{g_2^2}\frac{2\tilde{m}_\chi^2}{M_2^2 + 2\tilde{m}_\chi^2} .$$

## New D-term corrections

In pure gaugino mediation this correction is tiny, since one chooses $g_1 \ll g_2$ to ameliorate the Landau pole problem. But in our model we moved most of the SM matter to the second sector, so it is natural to choose $g_1 \sim g_2$ such that these corrections are substantial.

# The little hierarchy problem

Two allow both $\tilde{t}$s to be light (say of order 500 GeV) one should introduce additional contributions to the Higgs quartic. In our model these contributions are naturally present: D-terms of the $Z', W'$:

$$\delta V = \frac{g^2\Delta}{8}\left|H_u^\dagger\sigma^a H_u + H_d^\dagger\sigma^a H_d\right|^2 + \frac{3g'^2\Delta'}{40}\left|H_u^\dagger H_u - H_d^\dagger H_d\right|^2$$

$$\Delta = \frac{g_1^2}{g_2^2}\frac{2\tilde{m}_\chi^2}{M_2^2 + 2\tilde{m}_\chi^2} \, .$$

## New D-term corrections

In pure gaugino mediation this correction is tiny, since one chooses $g_1 \ll g_2$ to ameliorate the Landau pole problem. But in our model we moved most of the SM matter to the second sector, so it is natural to choose $g_1 \sim g_2$ such that these corrections are substantial.

# Layout

Try now a different idea: let the $\mu$ -term be forbidden by gauge invariance. Charge $H_d$ under the second gauge group. Can we find an anomaly-free configuration?

# The little hierarchy problem

Two allow both $\tilde{t}$s to be light (say of order 500 GeV) one should introduce additional contributions to the Higgs quartic. In our model these contributions are naturally present: D-terms of the $Z', W'$:

$$\delta V = \frac{g^2 \Delta}{8} \left| H_u^\dagger \sigma^a H_u + H_d^\dagger \sigma^a H_d \right|^2 + \frac{3 g'^2 \Delta'}{40} \left| H_u^\dagger H_u - H_d^\dagger H_d \right|^2$$

$$\Delta = \frac{g_1^2}{g_2^2} \frac{2\tilde{m}_\chi^2}{M_2^2 + 2\tilde{m}_\chi^2} \,.$$

## New D-term corrections

In pure gaugino mediation this correction is tiny, since one chooses $g_1 \ll g_2$ to ameliorate the Landau pole problem. But in our model we moved most of the SM matter to the second sector, so it is natural to choose $g_1 \sim g_2$ such that these corrections are substantial.

# Layout

Try now a different idea: let the $\mu$ -term be forbidden by gauge invariance. Charge $H_d$ under the second gauge group. Can we find an anomaly-free configuration?

# Layout

Try now a different idea: let the $\mu$ -term be forbidden by gauge invariance. Charge $H_d$ under the second gauge group. Can we find an anomaly-free configuration?

Charge all the fields on the third generation under and $L_2$ under $G^{(1)}$, let all the rest fields be charged under $G^{(2)}$. This configuration is anomaly free.

# Layout

Try now a different idea: let the $\mu$ -term be forbidden by gauge invariance. Charge $H_d$ under the second gauge group. Can we find an anomaly-free configuration?

Charge all the fields on the third generation under and $L_2$ under $G^{(1)}$, let all the rest fields be charged under $G^{(2)}$. This configuration is anomaly free.

The $\mu$-term is formed from an operator

$$W \sim \chi H_u H_d$$

# Soft masses structure

## Soft masses

The light flavors get regular soft masses$^2$ from gauge mediation: $m^2_{GM}$. The heavy flavors get masses$^2$ from gaugino mediation – loop suppressed $m^2_{\tilde{g}M}$. These masses are diagonal in flavor basis, but we should rotate them into the fermion mass basis.

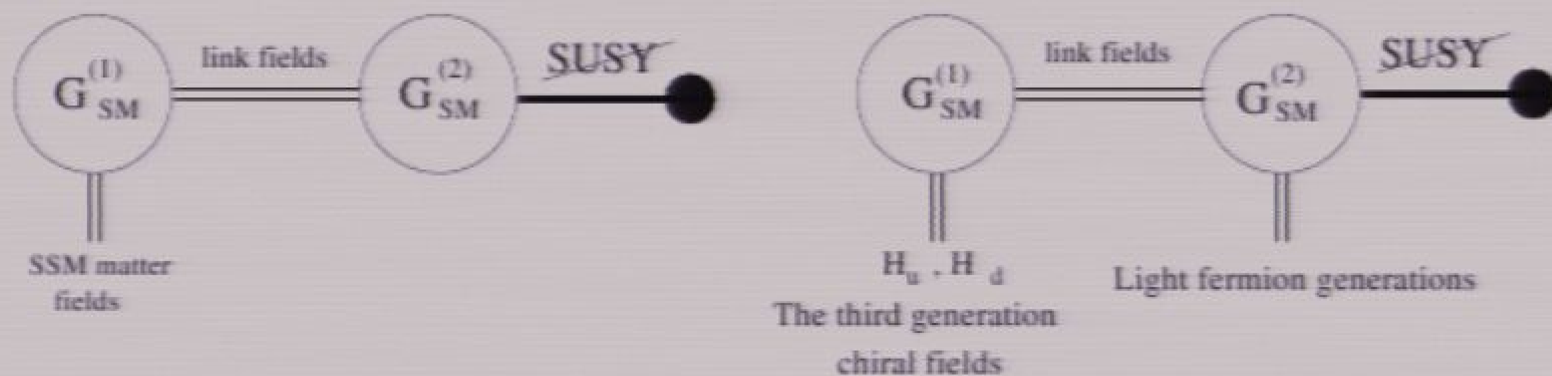
The soft masses in the fermion mass basis:

$$m^2_{\tilde{Q}} \sim \begin{pmatrix} m^2_{GM} & 0 & \epsilon^2 m^2_{GM} \\ 0 & m^2_{GM} & \epsilon^2 m^2_{GM} \\ \epsilon^2 m^2_{GM} & \epsilon^2 m^2_{GM} & m^2_{\tilde{g}M} \end{pmatrix},$$

$$m^2_{\tilde{\bar{u}}} \sim \begin{pmatrix} m^2_{GM} & 0 & \epsilon^2 m^2_{GM} \\ 0 & m^2_{GM} & \epsilon^2 m^2_{GM} \\ \epsilon^2 m^2_{GM} & \epsilon^2 m^2_{GM} & m^2_{\tilde{g}M} \end{pmatrix}, \quad m^2_{\tilde{\bar{d}}} \sim \begin{pmatrix} m^2_{GM} & 0 & \epsilon m^2_{GM} \\ 0 & m^2_{GM} & \epsilon m^2_{GM} \\ \epsilon m^2_{GM} & \epsilon m^2_{GM} & m^2_{\tilde{g}M} \end{pmatrix}$$

# First look on the model

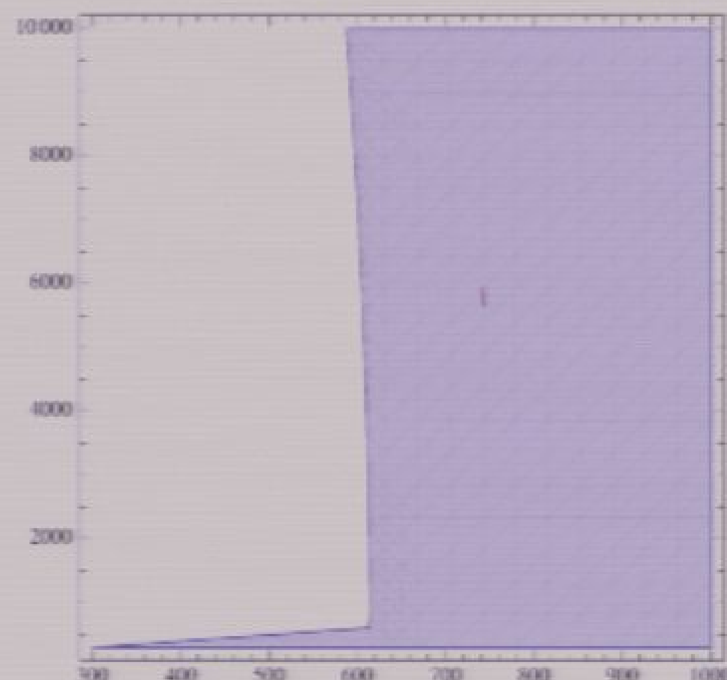
In this model we just move the light generations (quarks and leptons) to the RH site. The tree level $\mu$-term is forbidden. Note that only the third generation tree level Yukawas are allowed by gauge invariance.



# $K - \bar{K}$ constraints

The contribution scales as $V_{us} V_{ub} \times \epsilon \sim 10^{-6}$.

Illustrative example: $m_{\tilde{g}} = 1$ TeV, $\epsilon = 10^{-2}$, $\tan\beta = 20$:




- The shaded region is allowed by $\Delta m_K$ constraints
- With maximal phase, the pink region is allowed by $\epsilon_K$
- Need $m_{\tilde{b}} > 600$ GeV

# Flavor structure

Up-type Yukawa texture is similar to the vector-like Higgses model:

$$Y_u = \begin{pmatrix} \epsilon & \epsilon & \epsilon^2 \\ \epsilon & \epsilon & \epsilon^2 \\ \epsilon^2 & \epsilon^2 & 1 \end{pmatrix}$$

# Layout

Try now a different idea: let the $\mu$ -term be forbidden by gauge invariance. Charge $H_d$ under the second gauge group. Can we find an anomaly-free configuration?

Charge all the fields on the third generation under and $L_2$ under $G^{(1)}$, let all the rest fields be charged under $G^{(2)}$. This configuration is anomaly free.

The $\mu$-term is formed from an operator

$$W \sim \chi H_u H_d$$

# Flavor structure

Up-type Yukawa texture is similar to the vector-like Higgses model:

$$Y_u = \begin{pmatrix} \epsilon & \epsilon & \epsilon^2 \\ \epsilon & \epsilon & \epsilon^2 \\ \epsilon^2 & \epsilon^2 & 1 \end{pmatrix}$$

# Flavor structure

Up-type Yukawa texture is similar to the vector-like Higgses model:

$$Y_u = \begin{pmatrix} \epsilon & \epsilon & \epsilon^2 \\ \epsilon & \epsilon & \epsilon^2 \\ \epsilon^2 & \epsilon^2 & 1 \end{pmatrix}$$

Down-type Yukawas are very different, since we can now write down a tree-level Yukawa for the light generations:

$$Y_d = \begin{pmatrix} 1 & 1 & \epsilon' \\ 1 & 1 & \epsilon' \\ \epsilon'^2 & \epsilon'^2 & \epsilon' \end{pmatrix}$$

Naively we would expect that this immediately predicts an untenable CKM matrix and drop this model

# An uplifted region of SUSY

What $\tan\beta$ should we expect in this model?

# An uplifted region of SUSY

What $\tan\beta$ should we expect in this model?

**$\tan\beta \gg 1$** *Dobrescu, Fox, 2010*

Since we placed $H_u$ and $H_d$ on different nodes, we find that $|m^2_{H_u}| \ll m^2_{H_d}$ the $B\mu$ is small (we get it from gaugino loops. In this limit it can be estimated from $B\mu \tan\beta \approx m^2_{H_d}$. We easily get $\tan\beta \sim \mathcal{O}(10^4)$.

# Flavor structure

Up-type Yukawa texture is similar to the vector-like Higgses model:

$$Y_u = \begin{pmatrix} \epsilon & \epsilon & \epsilon^2 \\ \epsilon & \epsilon & \epsilon^2 \\ \epsilon^2 & \epsilon^2 & 1 \end{pmatrix}$$

Down-type Yukawas are very different, since we can now write down a tree-level Yukawa for the light generations:

$$Y_d = \begin{pmatrix} 1 & 1 & \epsilon' \\ 1 & 1 & \epsilon' \\ \epsilon'^2 & \epsilon'^2 & \epsilon' \end{pmatrix}$$

Naively we would expect that this immediately predicts an untenable CKM matrix and drop this model

# An uplifted region of SUSY

What $\tan\beta$ should we expect in this model?

**$\tan\beta \gg 1$** *Dobrescu, Fox, 2010*

Since we placed $H_u$ and $H_d$ on different nodes, we find that $|m^2_{H_u}| \ll m^2_{H_d}$ the $B\mu$ is small (we get it from gaugino loops. In this limit it can be estimated from $B\mu \tan\beta \approx m^2_{H_d}$. We easily get $\tan\beta \sim \mathcal{O}(10^4)$.

In this region of parameter space the masses of the down-type quarks are largely determined by one-loop induced couplings to $H_u^\dagger$.

$Y_d$ does not directly determine the CKM matrix structure

# Down-type masses

The couplings to $H_u^\dagger$ are formed at one-loop and they are sensitive to the scalar spectrum. However in this model we also have "more-minimal SUSY", so these loops are small for the light generations, but big for the third generations. After we take the leading order masses of the down-type quarks we find:

$$M_d \simeq v \begin{pmatrix} \cos\beta & \cos\beta & \epsilon' \cos\beta \\ \cos\beta & \cos\beta & \epsilon' \cos\beta \\ \epsilon'^2 \cos\beta & \epsilon'^2 \cos\beta & \frac{\alpha_3}{4\pi}\epsilon' \end{pmatrix}$$

# Down-type masses

The couplings to $H_u^\dagger$ are formed at one-loop and they are sensitive to the scalar spectrum. However in this model we also have "more-minimal SUSY", so these loops are small for the light generations, but big for the third generations. After we take the leading order masses of the down-type quarks we find:

$$M_d \simeq v \begin{pmatrix} \cos\beta & \cos\beta & \epsilon' \cos\beta \\ \cos\beta & \cos\beta & \epsilon' \cos\beta \\ \epsilon'^2 \cos\beta & \epsilon'^2 \cos\beta & \frac{\alpha_3}{4\pi}\epsilon' \end{pmatrix}$$

We find a "hybrid down-type mass matrix": the bottom-mass is controlled by a coupling to $H_u^\dagger$, while all other masses are dominated by couplings to $H_d$.

# Down-type masses

The couplings to $H_u^\dagger$ are formed at one-loop and they are sensitive to the scalar spectrum. However in this model we also have "more-minimal SUSY", so these loops are small for the light generations, but big for the third generations. After we take the leading order masses of the down-type quarks we find:

$$M_d \simeq v \begin{pmatrix} \cos\beta & \cos\beta & \epsilon' \cos\beta \\ \cos\beta & \cos\beta & \epsilon' \cos\beta \\ \epsilon'^2 \cos\beta & \epsilon'^2 \cos\beta & \frac{\alpha_3}{4\pi}\epsilon' \end{pmatrix}$$

We find a "hybrid down-type mass matrix": the bottom-mass is controlled by a coupling to $H_u^\dagger$, while all other masses are dominated by couplings to $H_d$.

# CKM and the bottom mass

If we assume suppressed gaugino masses it is easy to get a tenable CKM matrix. One finds that the rotations in the down-type sector are smaller than in the up-type sector and therefore the CKM matrix is just

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

# CKM and the bottom mass

If we assume suppressed gaugino masses it is easy to get a tenable CKM matrix. One finds that the rotations in the down-type sector are smaller than in the up-type sector and therefore the CKM matrix is just

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

## The b-quark mass

One finds that an accurate estimate for the b-quark mass is $m_b \approx v \frac{2\alpha_3}{3\pi} \frac{\mu}{m_{\tilde{Q}_3}} \epsilon'$. This can give viable values only for $\epsilon' \sim \mathcal{O}(1)$.
Unfortunately the b-mass is an unresolved issue of this model

# CKM and the bottom mass

If we assume suppressed gaugino masses it is easy to get a tenable CKM matrix. One finds that the rotations in the down-type sector are smaller than in the up-type sector and therefore the CKM matrix is just

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

## The b-quark mass

One finds that an accurate estimate for the b-quark mass is $m_b \approx v \frac{2\alpha_3}{3\pi} \frac{\mu}{m_{\tilde{Q}_3}} \epsilon'$. This can give viable values only for $\epsilon' \sim \mathcal{O}(1)$.
Unfortunately the b-mass is an unresolved issue of this model

# Conclusions and Outlook

We presented models which:

- solve a $\mu/B\mu$ problem of SUSY
- (partially) explain the SM flavor structure
- satisfy precision flavor constraints
- ameliorate the little hierarchy problem

# Conclusions and Outlook

We presented models which:

- solve a $\mu/B\mu$ problem of SUSY
- (partially) explain the SM flavor structure
- satisfy precision flavor constraints
- ameliorate the little hierarchy problem

Among important open questions of these models:

- embedding neutrino masses and mixings into this scenario
- b-quark mass problem chiral-Higgses model

# Conclusions and Outlook

We presented models which:

- solve a $\mu/B\mu$ problem of SUSY
- (partially) explain the SM flavor structure
- satisfy precision flavor constraints
- ameliorate the little hierarchy problem

Among important open questions of these models:

- embedding neutrino masses and mixings into this scenario
- b-quark mass problem chiral-Higgses model

# CKM and the bottom mass

If we assume suppressed gaugino masses it is easy to get a tenable CKM matrix. One finds that the rotations in the down-type sector are smaller than in the up-type sector and therefore the CKM matrix is just

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

## The b-quark mass

One finds that an accurate estimate for the b-quark mass is $m_b \approx v \frac{2\alpha_3}{3\pi} \frac{\mu}{m_{\tilde{Q}_3}} \epsilon'$. This can give viable values only for $\epsilon' \sim \mathcal{O}(1)$.
Unfortunately the b-mass is an unresolved issue of this model

# CKM and the bottom mass

If we assume suppressed gaugino masses it is easy to get a tenable CKM matrix. One finds that the rotations in the down-type sector are smaller than in the up-type sector and therefore the CKM matrix is just

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

# Down-type masses

The couplings to $H_u^\dagger$ are formed at one-loop and they are sensitive to the scalar spectrum. However in this model we also have "more-minimal SUSY", so these loops are small for the light generations, but big for the third generations. After we take the leading order masses of the down-type quarks we find:

$$M_d \simeq v \begin{pmatrix} \cos\beta & \cos\beta & \epsilon' \cos\beta \\ \cos\beta & \cos\beta & \epsilon' \cos\beta \\ \epsilon'^2 \cos\beta & \epsilon'^2 \cos\beta & \frac{\alpha_3}{4\pi}\epsilon' \end{pmatrix}$$

We find a "hybrid down-type mass matrix": the bottom-mass is controlled by a coupling to $H_u^\dagger$, while all other masses are dominated by couplings to $H_d$.

# Down-type masses

The couplings to $H_u^\dagger$ are formed at one-loop and they are sensitive to the scalar spectrum. However in this model we also have "more-minimal SUSY", so these loops are small for the light generations, but big for the third generations. After we take the leading order masses of the down-type quarks we find:

$$M_d \simeq v \begin{pmatrix} \cos\beta & \cos\beta & \epsilon' \cos\beta \\ \cos\beta & \cos\beta & \epsilon' \cos\beta \\ \epsilon'^2 \cos\beta & \epsilon'^2 \cos\beta & \frac{\alpha_3}{4\pi}\epsilon' \end{pmatrix}$$

We find a "hybrid down-type mass matrix": the bottom-mass is controlled by a coupling to $H_u^\dagger$, while all other masses are dominated by couplings to $H_d$.