Predictions for Bs Mixing Phase in Susy Flavor Models

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From the Planck Scale to the ElectroWeak Scale

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Outline

- The observable $S_{\psi\varphi}$: a tension of the Standard Model? ⟶ a hint for New Physics?
- Go beyond the Standard Model ⟶ Susy
  - Flavor Blind MSSM
  - General Minimal Flavor Violation framework
  - MSSM with a generic flavor structure in the soft sector
- Flavor Models:
  - An abelian $U(1)_{F1} \times U(1)_{F2}$ flavor model can address the problem
  - What about the non abelian?

Looking for the "right" model...

"CP Violation in $b \to s$ Transitions within Supersymmetric Theories"
W. Altmannshofer, A. J. Buras, S. Gori, P. Paradisi, D. Straub
in preparation

Signal of New Physics in Bs Mixing Phase?

- **Definition of $S_{\psi\varphi}$:** $S_{\psi\phi}\sin(\Delta M_s t) + C_{\psi\phi}\cos(\Delta M_s t) \equiv \frac{\Gamma(\bar{B}_s^0(t)\to\psi\phi) - \Gamma(B_s^0(t)\to\psi\phi)}{\Gamma(\bar{B}_s^0(t)\to\psi\phi) + \Gamma(B_s^0(t)\to\psi\phi)}$

$$S_{\psi\phi} = \sin(2|\beta_s| - 2\phi_{B_s})$$

SM contribution: $|\beta_s| \sim 0.02$

NP contribution

but soon LHCb...

$S_{\psi\varphi}$ is predicted very small in the SM; much below the current experimental sensitivity

- **CDF and D0:** $|\beta_s| - \phi_{B_s} = 0.57^{+0.24}_{-0.30}\,(stat)\;{}^{+0.07}_{-0.02}\,(syst) \qquad 68\%\ C.L.$ → **~ 2σ of deviation**

arXiv: 0802.2255
arXiv: 0712.2397

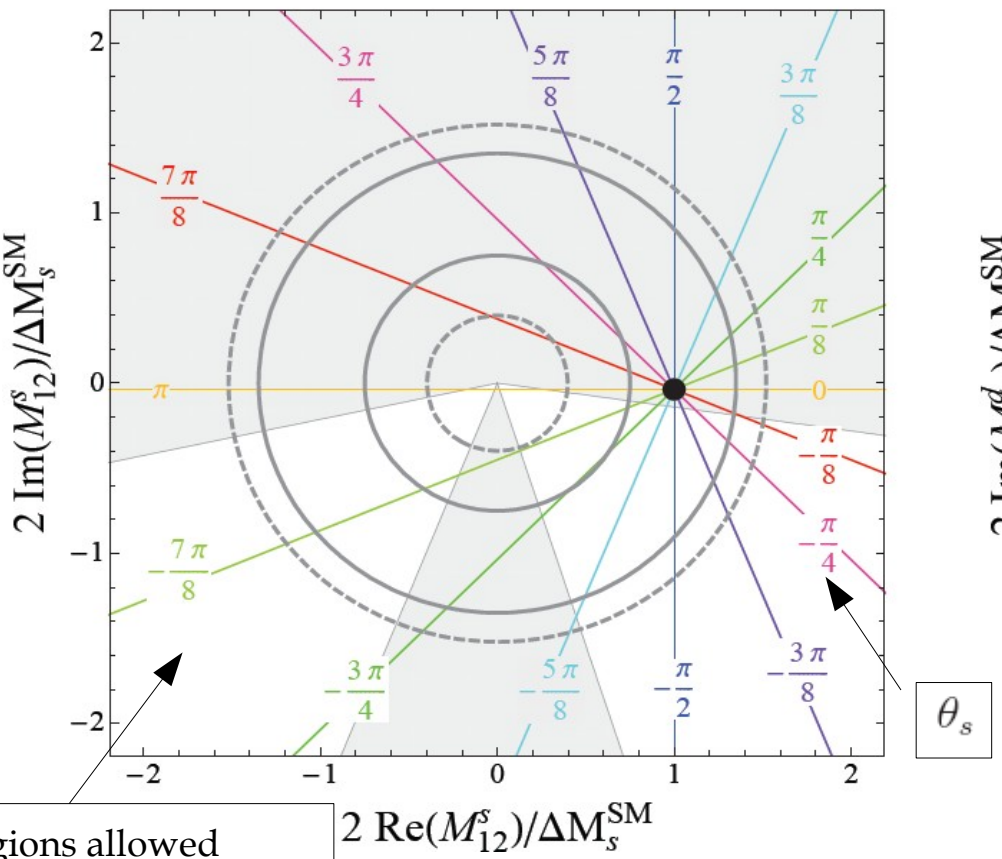
- **Another interesting observable:** $A_{SL}^s \equiv \frac{\Gamma(\bar{B}_s^0\to l^+X) - \Gamma(B_s^0\to l^-X)}{\Gamma(\bar{B}_s^0\to l^+X) + \Gamma(B_s^0\to l^-X)}$

Large room for new physics

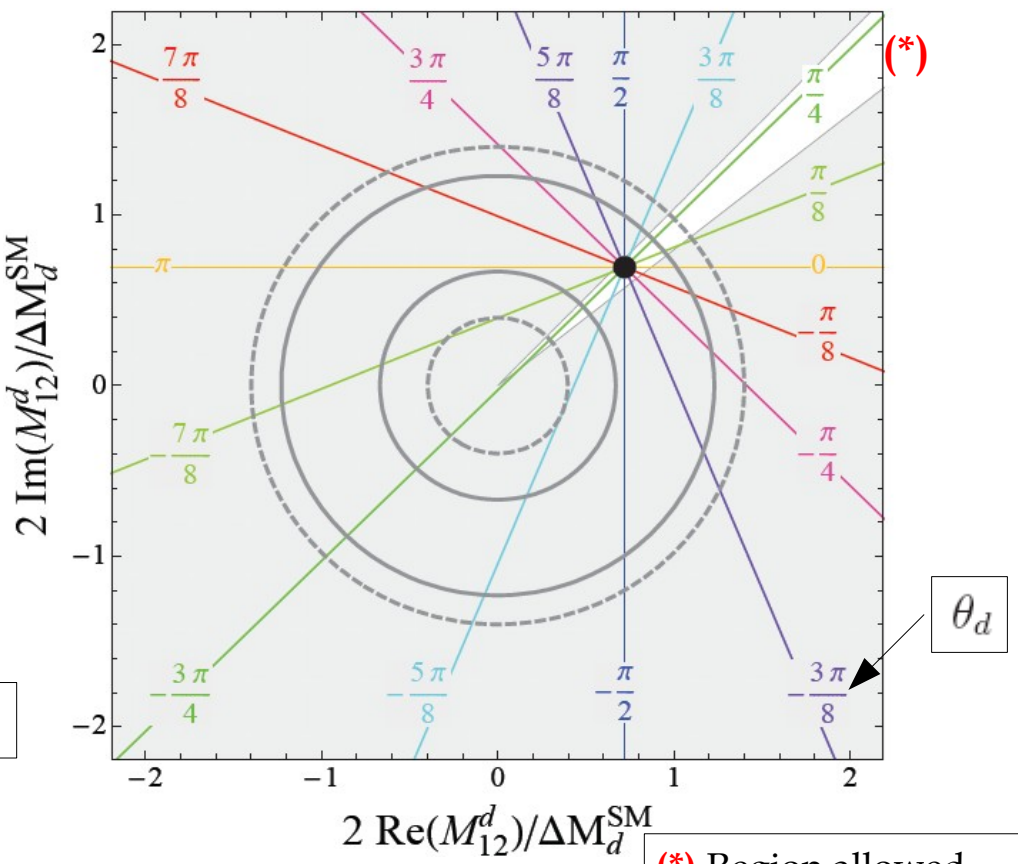
If new physics: $A_{SL}^s = -\left|Re\left(\frac{\Gamma_{12}^s}{M_{12}^s}\right)^{SM}\right|\frac{\Delta M_s^{SM}}{\Delta M_s}S_{\psi\phi}$

- small in the SM
- small contribution of NP in $S_{\psi\varphi}$ would generate large contribution of NP in A^s_{SL}

Comparison between Bs and Bd System



Regions allowed by $S_{\psi\varphi}$ (UT fit), 95% C.L.



(*) Region allowed by $S_{\psi Ks}$ (HFAG), 95% C.L.

Angles defined by

$$\begin{cases} M_{12}^s = \left|(M_{12}^s)^{SM}\right| e^{2i\beta_s} + \left|(M_{12}^s)^{NP}\right| e^{i\theta_s} \\ M_{12}^d = \left|(M_{12}^d)^{SM}\right| e^{2i\beta} + \left|(M_{12}^d)^{NP}\right| e^{i\theta_d} \end{cases}$$

Large room for additional CP violation in Bs system but not in Bd system

Going Beyond the Standard Model

Natural way to introduce new CP violating phases:
go beyond the SM

SUSY ?

The MSSM has many free parameters that can provide such phases:

- Squark masses: m_Q, m_U, m_D
- Trilinear couplings: A_U, A_D
- Higgsino mass: μ
- Gaugino masses: M_1, M_2, M_3

$$M_f^2 = \begin{pmatrix} (M_f^2)_{LL} & (M_f^2)_{LR} \\ * & (M_f^2)_{RR} \end{pmatrix}$$

$$= \begin{pmatrix} (m_f^2)_{LL} + Y_f Y_f^\dagger v_{u,d}^2 + D_{LL}^f & A_f v_{u,d} - \mu Y_f v_{d,u} \\ * & (m_f^2)_{RR} + Y_f^\dagger Y_f v_{u,d}^2 + D_{RR}^f \end{pmatrix}$$

Convenient parametrization through mass insertions:

$$\begin{cases} (\delta_{LL}^f)_{ij} = \dfrac{((M_f^2)_{LL})_{ij}}{\langle (M_f^2)_{LL} \rangle}, \quad (\delta_{LR}^f)_{ij} = \dfrac{((M_f^2)_{LR})_{ij}}{\langle (M_f^2)_{LR} \rangle} \\ (\delta_{RR}^f)_{ij} = \dfrac{((M_f^2)_{RR})_{ij}}{\langle (M_f^2)_{RR} \rangle} \end{cases}$$

(in the Super CKM basis)

The Simplest Approaches

- **Flavor Blind MSSM (FBMSSM):**

Assumptions:

- Universal squark masses
- Hierarchical and flavor diagonal trilinear couplings
- Possibility to have flavor conserving but CP violating phases

no flavor off-diagonal deltas

Minimal Assumptions

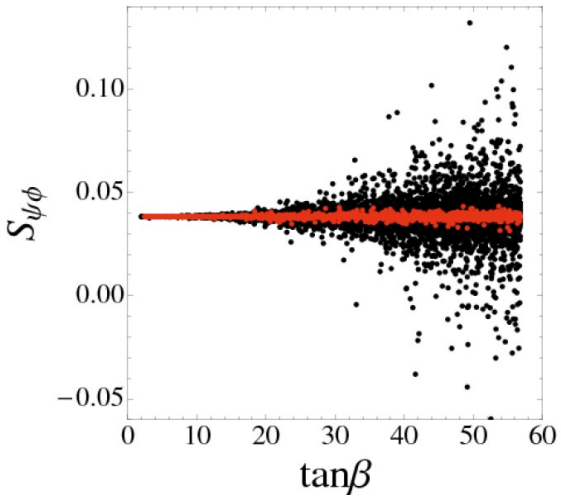
→ Dominant CP violating effects are generated by the phase of μA_t

Altmannshofer, Buras, Paradisi '08

Result:

- Not big effects in Bs mixing phase

$b \to s\gamma$ constraint



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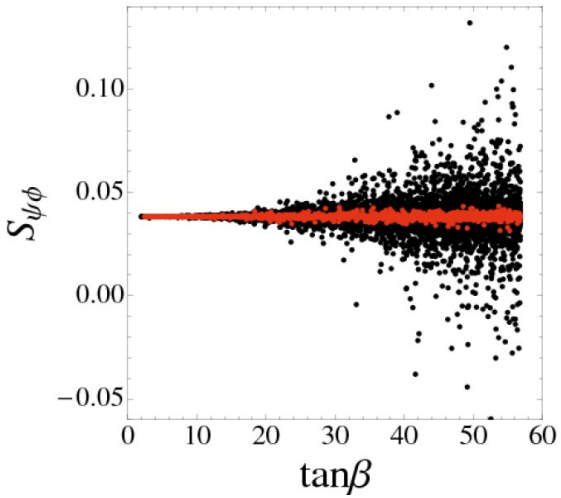

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- **General Minimal Flavor Violation (MFV) framework:** D' Ambrosio, Giudice, Isidori, Strumia '02

Assumpions:
- Putting to zero the Yukawas the symmetry of the lagrangian is $U(3)^5$
- Only Yukawas violate flavor

$$m_Q^2 = m_0^2(1 + b_1 Y_u^\dagger Y_u + b_2 Y_d^\dagger Y_d + c_1 Y_u^\dagger Y_u Y_d^\dagger Y_d + c_1^* Y_d^\dagger Y_d Y_u^\dagger Y_u)$$

c_1 complex parameter

Analogous expansions for m_U, m_D, A_U, A_D Colangelo, Nikolidakis, Smith '08

Result: what do we expect?

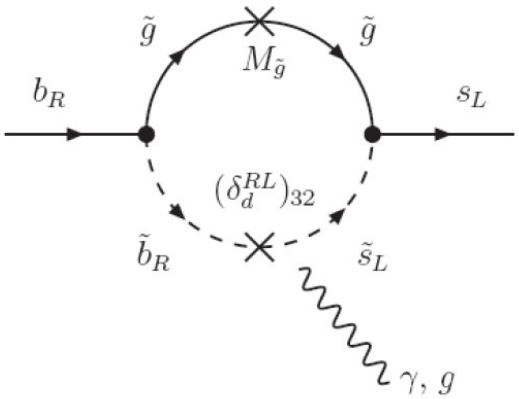
A more General Question...

In a General MSSM how Large can be the Effects in $S_{\psi\varphi}$?

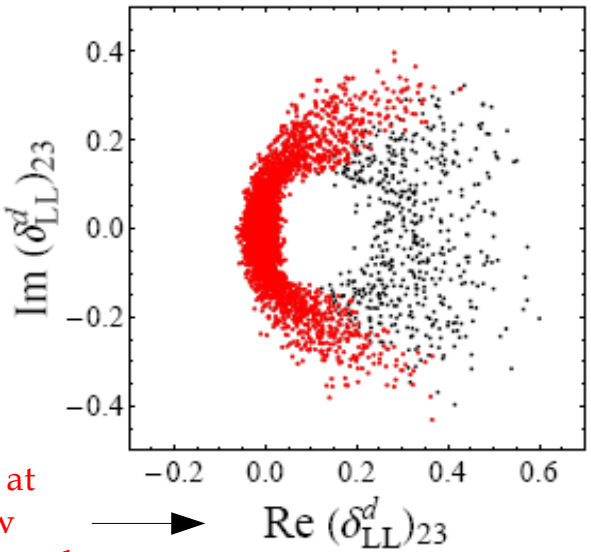
- The soft squark masses m_Q, m_U, m_D and the trilinear couplings A_U, A_D can contain additional flavor structures beyond the CKM matrix.
- Such structures lead to flavor off-diagonal entries in the squark masses.

Complex mass insertions lead to
flavor and CP violating gluino interactions
that will generate the dominant contributions to FCNCs

Example for $b \to s\gamma$

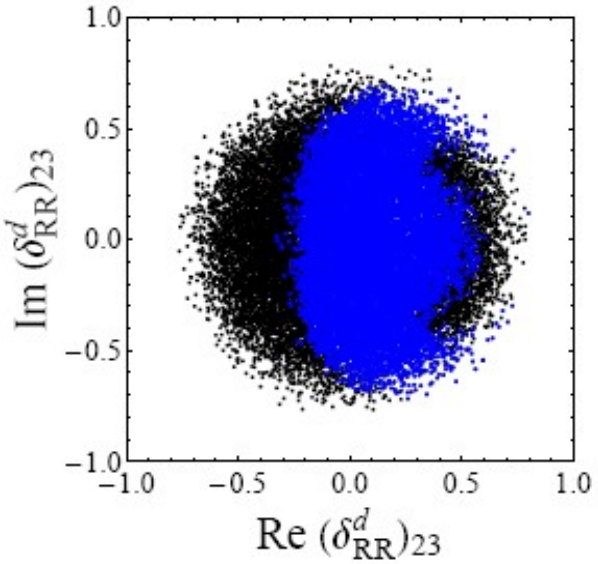


Which are the Allowed Mass Insertions?

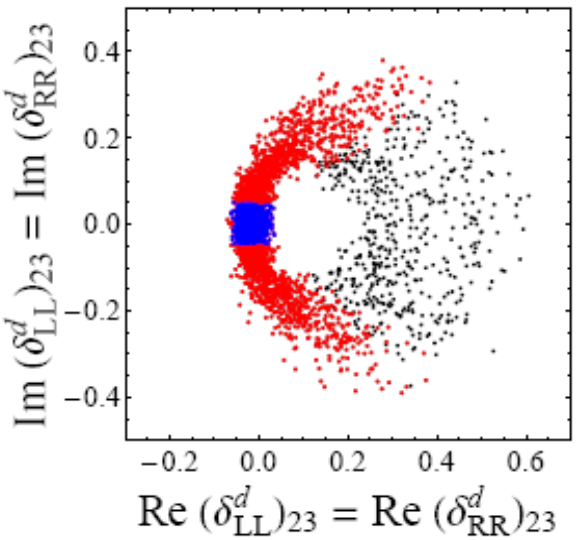


Deltas at the low energy scale →

- Only $(\delta^d_{LL})_{32}$ is on



- Only $(\delta^d_{RR})_{32}$ is on



- $(\delta^d_{LL})_{32}$ and $(\delta^d_{RR})_{32}$ are simultaneously on and fixed at a common value

Fixed parameters:

Msugra spectrum;

$\tan\beta \in [5, 15]$;

$A_0 = 0$;

$\mu > 0$;

$m_0 \in [0, 300]\, GeV$;

$m_{\frac{1}{2}} \in [0, 200]\, GeV$;

Constraints imposed (at 2σ C.L.):

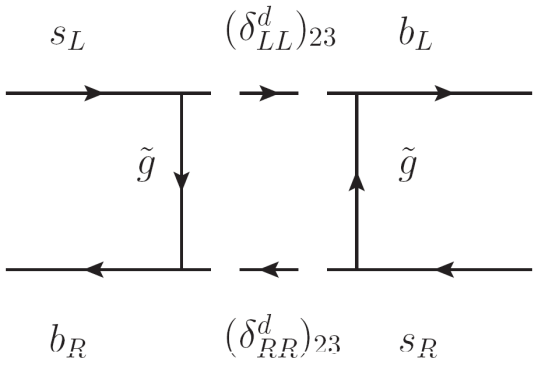
$b \to s\gamma$

$b \to s l^+ l^-$

ΔM_s

Something more about $S_{\psi\varphi}$

Example of contribution:



OPE

$$\mathcal{H}_{eff} = \sum_{i=1}^{5} C_i Q_i + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i \ + \text{h.c.}$$

$$Q_1 = (\bar{s}^i \gamma_\mu P_L \, b^i)\,(\bar{s}^j \gamma^\mu P_L \, b^j)$$

only operator in the SM

$$Q_2 = (\bar{s}^i P_L \, b^i)\,(\bar{s}^j P_L \, b^j)$$

$$Q_3 = (\bar{s}^i P_L \, b^j)\,(\bar{s}^j P_L \, b^i)$$

$$Q_4 = (\bar{s}^i P_L \, b^i)\,(\bar{s}^j P_R \, b^j)$$

$$Q_5 = (\bar{s}^i P_L \, b^j)\,(\bar{s}^j P_R \, b^i)$$

Tilde operators are obtained with the exchange $L \leftrightarrow R$

$$C_1 \propto ((\delta^d_{LL})_{32})^2$$

$$C_2 \propto ((\delta^d_{LR})_{32})^2$$

$$C_3 \propto ((\delta^d_{LR})_{32})^2$$

$$C_4 \propto (\delta^d_{LL})_{32}(\delta^d_{RR})_{32} + A_4 (\delta^d_{LR})_{32}(\delta^d_{RL})_{32}$$

$$C_5 \propto (\delta^d_{LL})_{32}(\delta^d_{RR})_{32} + A_5 (\delta^d_{LR})_{32}(\delta^d_{RL})_{32}$$

numbers

The operators Q_4 and Q_5 are strongly RGE enhanced

Tilde Wilson coeffecients are obtained with the exchange $L \leftrightarrow R$

...An Answer to the more General Question

$b \to s\gamma$ strongly constraints the LR and RL mass insertions, because the corresponding contributions to the amplitude are helicity enhanced

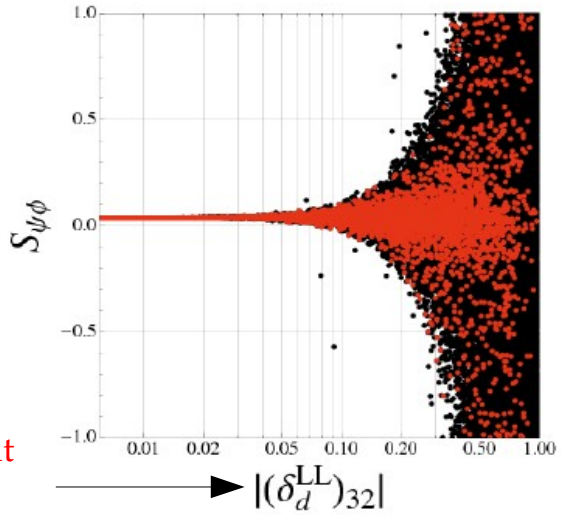
→ **No large effects in $S_{\psi\varphi}$ can be generated by LR and RL Mass Insertions**

...An Answer to the more General Question

$b \to s\gamma$ strongly constraints the LR and RL mass insertions, because the corresponding contributions to the amplitude are helicity enhanced

→ **No large effects in $S_{\psi\varphi}$ can be generated by LR and RL Mass Insertions**

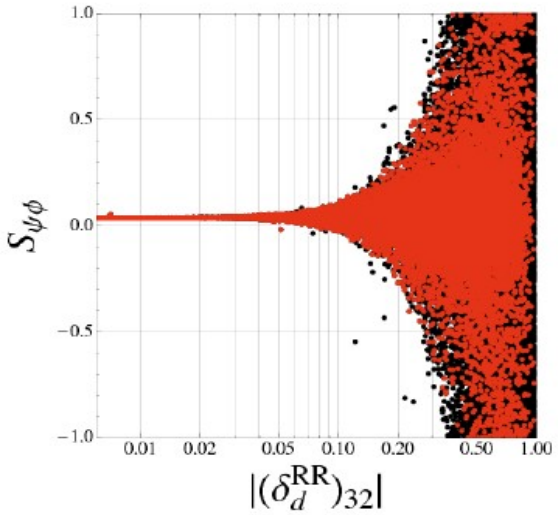
In a General MSSM how Large can be the Effects in $S_{\psi\varphi}$?



Deltas at the low energy scale →

A quite large $(\delta^d_{LL})_{32}$ is required

MFV stays in this group → not suitable for our scope



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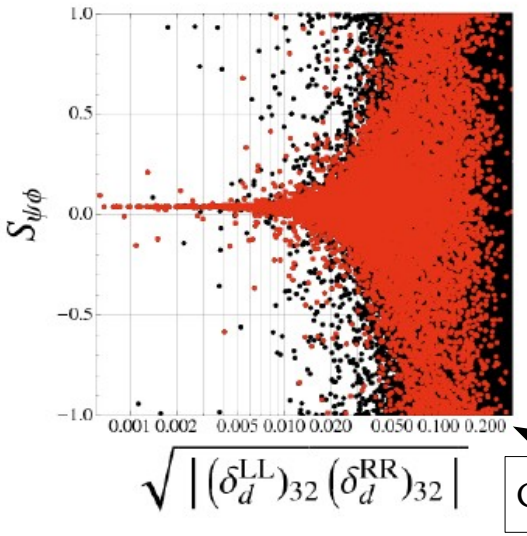

Perfect framework for our scope

Which concrete Flavor Models predict such a pattern?

Both $(\delta^d_{LL})_{32}$ and $(\delta^d_{RR})_{32}$ have to be present

BUT

$(\delta^d_{LL})_{32}$ are always automatically generated through the renormalization group running

→ look for models that have sizeable $(\delta^d_{RR})_{32}$

Flavor Models

Fermion and sfermion mass matrices originate from a common symmetry principle

- Basic ideas:
  - Lagrangian at high energy is symmetric under a flavor symmetry
  - Symmetry is broken by VEVs of one or more flavons
  - Fermion and sfermions mass matrices are functions of $\left(\frac{\langle\phi_i\rangle}{M}\right)^{n_j}$

Fixed	Achieved
Flavor symmetry G_F	Hierarchies between masses of fermions
Charges of SM fields	Structures in the mass matrices of sfermions (deltas)
Breaking mechanism for G_F	Alleviate Susy-Flavor problem

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- What about G_F?
  - Contained in the symmetry of the SM lagrangian without Yukawas: $U(3)^5$
  - Two possibilities:
    - Abelian: $U(1)_F$; $U(1)_{F1} \times U(1)_{F2}$ (Froggatt, Nielsen '78; Nir, Seiberg '93; Dudas, Grojean, Pokorski, Savoy '96;....)
    - Non Abelian: U(2); SU(3) (Barbieri, Dvali, Hall '95; King, Ross '01;....)

Predicting Large Right Handed Currents...

- Examples of possible suitable models:
  - Abelian:
    - Nir, Seiberg '93 (hep-ph/9304307) → Nir, Raz '02 (hep-ph/0206064)
    - Agashe, Carone '03 (hep-ph/0304229)
  - Non Abelian:
    - Barbieri, Hall, Romanino '97 (hep-ph/9702315)
    - Carone, Hall, Moroi '97 (hep-ph/9705383)

- More concretely:

Agashe, Carone '03 (hep-ph/0304229)

$U(1)_{F1} \times U(1)_{F2}$ flavor model

↓

Approximate allignment

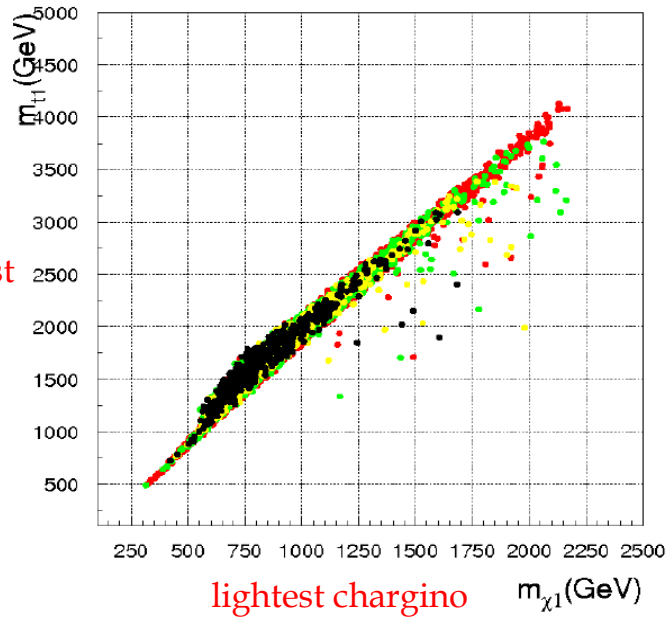
$$\delta^d_{LL} \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & \lambda_c^2 \\ 0 & \lambda_c^2 & 1 \end{pmatrix}, \quad \delta^d_{RR} \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$$

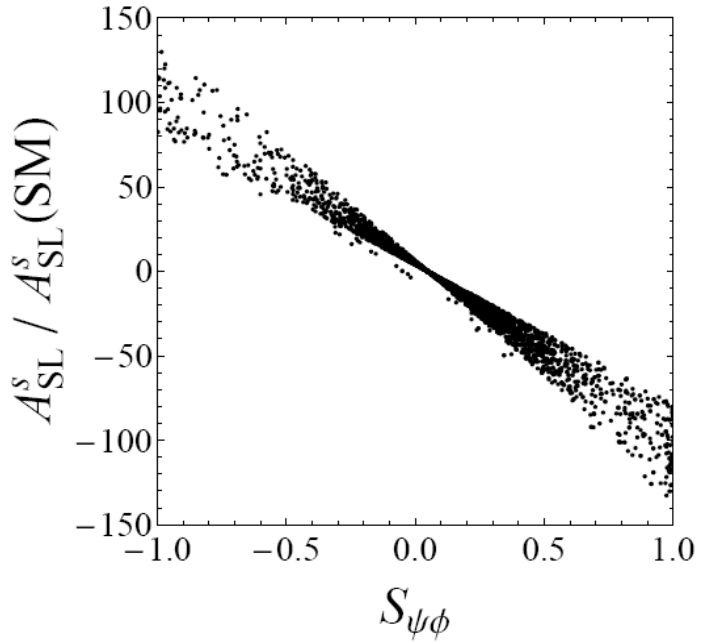
$$(*)\,(\delta^u_{LL})_{12} \sim \lambda_c \left(\frac{m_1^2}{m_2^2} - 1 \right), \quad \delta^{u,d}_{LR} \text{ very small}$$

b-d transitions highly suppressed
d-s transitions highly suppressed
b-s transitions enhanced

- Which phenomenology do we expect in this model?
  - **Large effects in B_s mixing (in particular $S_{\psi\varphi}$ for complex deltas)**
  - (*) In general large effects in $D^0 - \bar{D}^0$ mixing
  - Small effects in B_d and Kaon mixing

Numerical Analysis





- Even for quite heavy masses (2 TeV for the chargino) large contribtutions to $S_{\psi\varphi}$
- For very light masses strong constraint coming from $b \to s\gamma$ and $D^0 - \bar{D}^0$ mixing

- It's possible to obtain $S_{\psi\varphi}$ in the entire range;
- Model independent correlation between semileptonic asymmetry A^s_{SL} and the Bs mixing phase $S_{\psi\varphi}$ (Ligeti, Papucci, Perez '06)

Values for $S_{\psi\varphi}$

$S_{\psi\phi} \in [0.1; 0.2]$

$S_{\psi\phi} \in [0.2; 0.4]$

$S_{\psi\phi} \in [0.4; 0.6]$

$S_{\psi\phi} > 0.6$

Fixed parameters

$\tan\beta \in [5, 15]$;

$A_0 = 0$;

$\mu > 0$;

$m_0 \in [0; 3]\, TeV$;

$m_{\frac{1}{2}} \in [0.1; 2]\, TeV$;

$Arg\left((\delta^d_{RR})_{23}\right) \in [0.2\pi]$

$$m^2_Q \sim \begin{pmatrix} 4m_0^2 & * & * \\ * & m_0^2 & * \\ * & * & m_0^2 \end{pmatrix}$$

Conclusions

- $S_{\psi\varphi}$: a very interesting observable; one of the **tensions** of the Standard Model?

  → **Experimental hint for large deviation from the SM prediction**

How to get large new physics effects?

- **Go beyond the Standard Model:**
  - Flavor Blind MSSM → not possible
  - General Minimal Flavor Violation framework → not possible
  - Which kind of model is suitable?

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- **Flavor Models:**
  - $U(1)_{F1} \times U(1)_{F2}$ flavor model → it works for our scope
    - Testable patterns of flavor violation within this framework
  - Outlook: can also non abelian flavor models generate large effects in $S_{\psi\varphi}$?
    - How to distinguish them from the abelian ones?
    - Which are the correlations with the other flavor transitions?

What comes next