Flavour issues for heavy scalar spectra and a low mass gluino: the g2-MSSM case

K. Kadota, G. Kane, J. Kersten & L. V-S
(CINVESTAV-Mexico) arXiv:1107.3105

DESY Theory Workshop
09/29/2011

PROGRAMME

- Overview of G2-MSSM models
- How can Flavour arise?
- Constraints from Vacuum Stability
- Constraints from Flavour & CP violation
- *Could there be Signals at the LHC?*
- Summary

OVERVIEW OF G2-MSSM MODELS

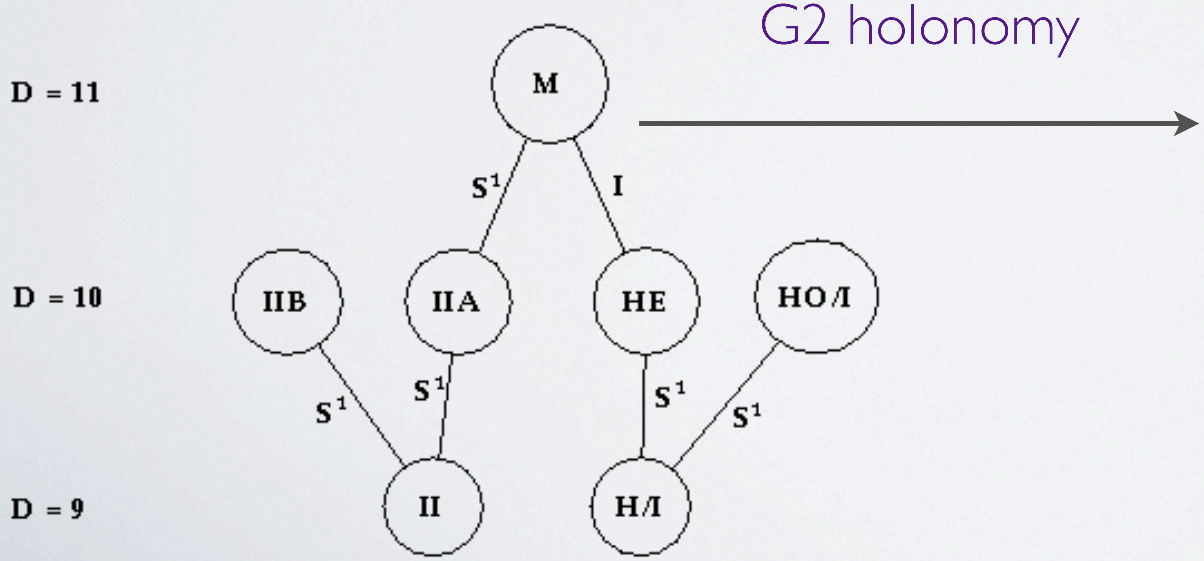
ACHARYA & DENEF, VALANDRO, JHEP 0506 TH/0502060

ACHARYA, BOBKOV, KANE, KUMAR, SHAO PRD 76, TH/0701034

ACHARYA, BOBKOV, KANE, KUMAR, VAMAN PRL 97, TH/0606262

ACHARYA & BOBKOV, 0810.3285...

Compactification with a d=7 manifold with G2 holonomy



D=4 sugra eff. theory with SM content → G2-MSSM

$+\ m_{3/2}$

& moduli

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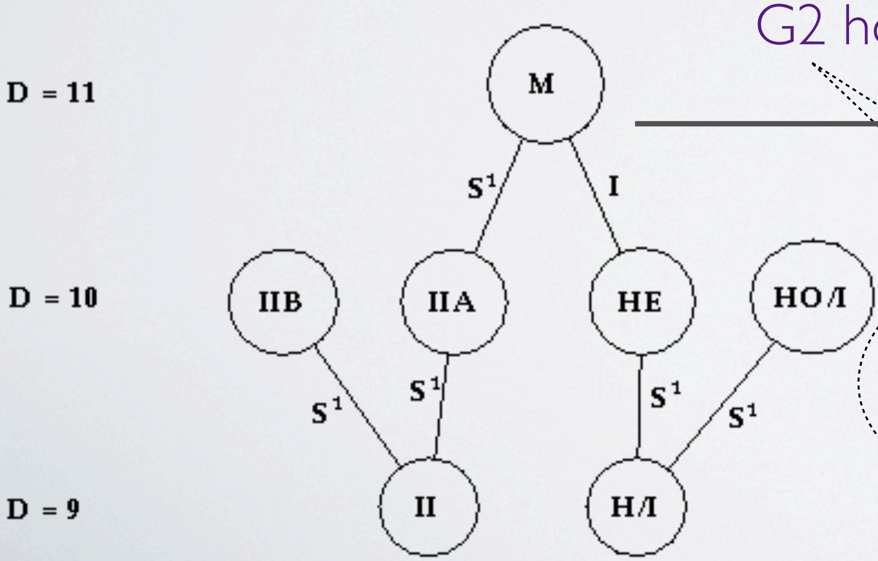

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One of the exceptional Lie groups, proper subgroup of SO(7).

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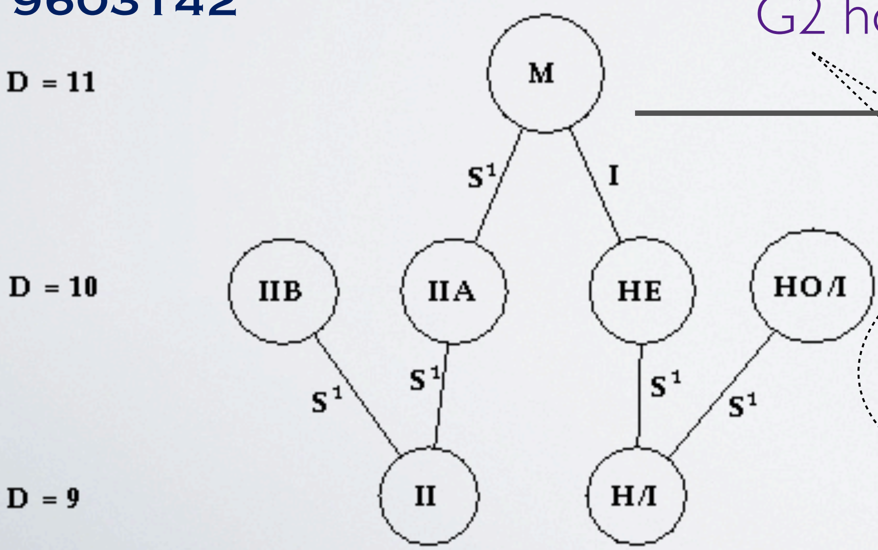
Acharya & bobkov, 0810.3285...

horava, witten 9603142



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D=4 sugra eff. theory with SM content → G2-MSSM

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- Dynamics of the Hidden Sector
  - Generates the hierarchy between M_{Planck} and M_{EW}
  - Supersymmetry breaking also stabilize the moduli, with M ~ $m_{3/2}$ ≳ 20 TeV
- The cosmological moduli solutions are based on:
  - Non-thermal, moduli dominated, pre BBN cosmology is very plausibly "a generic" outcome of string/M theory
  - A non-thermal WIMP miracle occurs for wine-like Dark Matter particles produced when the moduli decay before BBN
  - Wino DM consistent with indirect detection (PAMELA, Fermi)

- Spectra
    - $m_{\tilde{f}} \sim m_{3/2}$
    - $m_{\tilde{g}} \sim O(1\,\mathrm{TeV})$
- despite heavy scalars, there is a light Higgs → EWSB achieved
- while FCNC under control,

BOUNDS ON Y_{IJ}, AND SOFT TERMS CAN BE OBTAINED

HOW CAN FLAVOUR ARISE?

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$$K = \tilde{K}_{F_i^\dagger F_j} F_i^\dagger F_j + \tilde{K}_{f_i^c f_j^{c\dagger}} f_i^c f_j^{c\dagger} + \tilde{K}_{H_f^\dagger H_f} H_f^\dagger H_f + K_{\mathrm{H}}$$

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and the superpotential:

$$\begin{aligned} W = & \; Y_l^{ij} \epsilon_{\alpha\beta} H_d^\alpha E_i^c L_j^\beta - Y_\nu^{ij} \epsilon_{\alpha\beta} H_u^\alpha N_i^c L_j^\beta \\ & + Y_d^{ij} \epsilon_{\alpha\beta} H_d^\alpha D_i^c Q_j^\beta - Y_u^{ij} \epsilon_{\alpha\beta} H_u^\alpha U_i^c Q_j^\beta \\ & + \mu \epsilon_{\alpha\beta} H_u^\alpha H_d^\beta + \frac{1}{2} M_\nu^{ij} N_i^c N_j^c \; , \end{aligned}$$

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... up to Yukawa couplings, but this is even a problem in SM.

- In ST, the Yukawa couplings are given generically by

$$Y^f_{ij} = e^{-V_{ij}}$$

- Where

V_{ij} are parameters related to the moduli of the internal space of the theory

In ST it has been considered that it is just a matter of computation.... while this is done we can constrain the size by phenomenological observations

Kähler metric for matter not fully explored $\Leftrightarrow$ V_{ij} can be phenomenologically constrained (e.g. FCNC)

Once $K_{\rm H}$ and V_{ij} are specified, all mass squared masses and trilinear terms can be computed

M-SUGRA

$$m'^2_{\bar\alpha\beta} = m^2_{3/2}\,\langle \tilde K_{\bar\alpha\beta}\rangle - \left\langle \mathcal{F}^{*\bar m}\left(\partial^*_{\bar m}\partial_n \tilde K_{\bar\alpha\beta} - (\partial^*_{\bar m}\tilde K_{\bar\alpha\gamma})\,\tilde K^{\gamma\bar\delta}\,\partial_n \tilde K_{\bar\delta\beta}\right)\mathcal{F}^n\right\rangle ,$$

$$a'_{\alpha\beta\gamma} = \langle \mathcal{F}^m\rangle\left[\left\langle \frac{\partial_m K_{\rm H}}{M_{\rm P}^2}\right\rangle Y'_{\alpha\beta\gamma} + \frac{\mathcal{N}\partial Y_{\alpha\beta\gamma}}{\partial\langle h_m\rangle}\right]$$
$$- \langle \mathcal{F}^m\rangle\left[\left\langle \tilde K^{\delta\bar\rho}\,(\partial_m \tilde K_{\bar\rho\alpha})\right\rangle Y'_{\delta\beta\gamma} + (\alpha\leftrightarrow\beta) + (\alpha\leftrightarrow\gamma)\right],$$

$$F \to \hat F \equiv V_F^{-1} F \quad , \quad f^c \to \hat f^c \equiv f^c\, V_{f^c}^{-1\dagger} \quad , \quad H_f \to \hat H_f \equiv \tilde K^{\frac{1}{2}}_{H_f^\dagger H_f}\, H_f \, ,$$

$$V_F^\dagger \tilde K_{F^\dagger F} V_F = \mathbb{1}\, , \quad V_{f^c}^\dagger \tilde K_{f^c f^{c\dagger}} V_{f^c} = \mathbb{1}$$

MFV at MPlanck

$$m'^2_{\tilde F^\dagger \tilde F} = m_0^2\ \mathbb{1}$$
$$m'^2_{\tilde f^c \tilde f^{c\dagger}} = m_0^2\ \mathbb{1}$$

$$(a^f)_{ij} = A^f\, Y^f_{ij}$$

Trilinear couplings proportional to Yukawa couplings

In Family Symmetries

$$
\begin{aligned}
m'^2_{\bar{\alpha}\beta} &= m^2_{3/2}\,\langle \tilde{K}_{\bar{\alpha}\beta}\rangle - \left\langle \mathcal{F}^{*\bar{m}} \left(\partial^*_{\bar{m}} \partial_n \tilde{K}_{\bar{\alpha}\beta} - (\partial^*_{\bar{m}} \tilde{K}_{\bar{\alpha}\gamma})\, \tilde{K}^{\gamma\bar{\delta}}\, \partial_n \tilde{K}_{\bar{\delta}\beta} \right) \mathcal{F}^n \right\rangle , \\
a'_{\alpha\beta\gamma} &= \langle \mathcal{F}^m \rangle \left[\left\langle \frac{\partial_m K_{\mathrm{H}}}{M_{\mathrm{P}}^2} \right\rangle Y'_{\alpha\beta\gamma} + \frac{\mathcal{N} \partial Y_{\alpha\beta\gamma}}{\partial \langle h_m \rangle} \right] \\
&\quad - \langle \mathcal{F}^m \rangle \left[\left\langle \tilde{K}^{\delta\bar{\rho}} \, (\partial_m \tilde{K}_{\bar{\rho}\alpha}) \right\rangle Y'_{\delta\beta\gamma} + (\alpha \leftrightarrow \beta) + (\alpha \leftrightarrow \gamma) \right] ,
\end{aligned}
$$

$\longrightarrow \quad \langle \mathcal{F}^m \rangle$ Depend non trivially on flavon fields (Scalars breaking the FS) hence in general

$$(a^f)_{ij} = c^f_{ij} A_{\tilde{f}} Y^f_{ij}$$

Trilinear couplings & squared mass terms are **NOT** proportional to Yukawa couplings

$$
\begin{aligned}
m'^2_{\tilde{F}^\dagger \tilde{F}} &\neq m_0^2 \; \mathbb{1} \\
m'^2_{\tilde{f}^c \tilde{f}^{c\dagger}} &\neq m_0^2 \; \mathbb{1}
\end{aligned}
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MFV Lost even at MPlanck

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In g2-MSSM models?

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Fixed (Moduli stabilization)

The rest of the terms, regard matter K and while compatible with mSUGRA, there may be deviations that are worth exploring

Important Constraints: No new CP phases appearing

Kane, Kumar & Shao, PRD 82, 0905.2986

Strategy: Start probing with Yukawa textures that are well known and deviations from minimality at MPlanck

$$m'^2_{\tilde F^\dagger\tilde F} = m_0^2\ \mathbb{1}$$
$$m'^2_{\tilde f^c\tilde f^{c\dagger}} = m_0^2\ \mathbb{1}$$

$$(a^f)_{ij} = c^f_{ij}A_{\tilde f}Y^f_{ij}$$

REAL

CONSTRAINTS FROM VACUUM STABILITY

Vacuum stability of the effective MSSM scalar potential

When K_M trivial there is no problem (like msugra → just worry about Higgs scalar sector) ✔

ACHARYA & BOBKOV, 0810.3285

When trilinears and mass squared terms not trivial, there are some extra-constaints

$$
\begin{aligned}
-\mathcal{L}_{\rm soft} \;=\;& \tilde{q}^\dagger_{Li}(m^2_{\tilde{Q}})^{ij}\tilde{q}_{Lj} + \tilde{u}_{Rj}(m^2_{\tilde{u}})^{ji}\tilde{u}^*_{Ri} + \tilde{d}_{Rj}(m^2_{\tilde{d}})^{ji}\tilde{d}^*_{Ri} \\
&+ \tilde{l}^\dagger_{Li}(m^2_{\tilde{L}})^{ij}\tilde{l}_{Lj} + \tilde{e}_{Rj}(m^2_{\tilde{e}})^{ji}\tilde{e}^*_{Ri} + \tilde{\nu}_{Rj}(m^2_{\tilde{\nu}})^{ji}\tilde{\nu}^*_{Ri} \\
&+ m^2_{h_d}h^\dagger_d h_d + m^2_{h_u}h^\dagger_u h_u + \left(B\mu\, h_d h_u + \frac{1}{2}B^{ij}_\nu M^{ij}_\nu \tilde{\nu}^*_{Ri}\tilde{\nu}^*_{Rj} + \text{h.c.}\right) \\
&+ \Big(-a^{ij}_d h_d \tilde{d}^*_{Ri}\tilde{q}_{Lj} + a^{ij}_u h_u \tilde{u}^*_{Ri}\tilde{q}_{Lj} - a^{ij}_l h_d \tilde{e}^*_{Ri}\tilde{l}_{Lj} + a^{ij}_\nu h_u \tilde{\nu}^*_{Ri}\tilde{l}_{Lj} \\
&\quad + \frac{1}{2}M_1\widetilde{B}\widetilde{B} + \frac{1}{2}M_2\widetilde{W}^a\widetilde{W}^a + \frac{1}{2}M_3\widetilde{G}^a\widetilde{G}^a + \text{h.c.}\Big),
\end{aligned}
$$

- An undesiderable deep CCB minimum appears, unless

$$
\begin{aligned}
|\hat{a}^e_{ij}|^2 &\leq ((\hat{Y}^e_{ii})^2 + (\hat{Y}^e_{jj})^2)(m^2_{\tilde{e}_{L_i}} + m^2_{\tilde{e}_{R_j}} + m^2_{H_d} + |\mu|^2), \\
|\hat{a}^d_{ij}|^2 &\leq ((\hat{Y}^d_{ii})^2 + (\hat{Y}^d_{jj})^2)(m^2_{\tilde{d}_{L_i}} + m^2_{\tilde{d}_{R_j}} + m^2_{H_d} + |\mu|^2), \\
|\hat{a}^u_{ij}|^2 &\leq ((\hat{Y}^u_{ii})^2 + (\hat{Y}^u_{jj})^2)(m^2_{\tilde{u}_{L_i}} + m^2_{\tilde{u}_{R_j}} + m^2_{H_u} + |\mu|^2)
\end{aligned}
$$

- UFB require

$$
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|\hat{a}^u_{ij}|^2 &\leq ((\hat{Y}^u_{ii})^2 + (\hat{Y}^u_{jj})^2)(m^2_{\tilde{u}_{L_i}} + m^2_{\tilde{u}_{R_j}} + m^2_{\tilde{e}_{L_p}} + m^2_{\tilde{e}_{R_q}})
\end{aligned}
$$

CCB & UFB problems do not go away with heavy scalars

CONSTRAINTS FROM FLAVOUR & CP VIOLATION

- FLAVOUR & CP PROBLEMS: Arbitrary values of masses and trilinear terms in supersymmetric breaking terms give arbitrary FCNC and can easily exceed CP bounds!

- With heavy scalars, is there a problem?
  - Strong constraints from Kaon mixing
  - Tachyonic particles?

Arkani-hamed & Murayama, PRD d56, ph/9703259

Giudice, nardecchia & romanino, npb 813, ph/0812.3610

I. FCNC: need to check signals in all these processes:

1. $\Delta F = 1$ processes
   (a) $l_i \to l_j \gamma$
   (b) $b \to s\gamma$
   (c) $b \to s l^+ l^-$, in particular $l = \mu$ and $l = \nu$
   (d) $s \to d\gamma$
   (e) top decays
2. $\Delta F = 2$ processes
   (a) $B_q - \bar{B}_q$, in particular $q = s$
   (b) $K_0 - \bar{K}_0$ mixing (ϵ_k)
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Other observables:

3. $g - 2$
4. $B^- \to \tau^- \bar{\nu}_\tau$
5. Precision observables
   (a) M_W
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   (b) $K_0 - \bar{K}_0$ mixing (ϵ_k)
   (c) $D_0 - \bar{D}_0$ mixing

Other observables:

3. $g - 2$
4. $B^- \to \tau^- \bar{\nu}_\tau$
5. Precision observables
   (a) M_W
   (b) $\sin^2 \theta_{eff}$
   (c) M_z
   (d) m_h

I. FCNC: need to check signals in all these processes:

1. $\Delta F = 1$ processes
   (a) $l_i \to l_j \gamma$
   (b) $b \to s\gamma$
   (c) $b \to s l^+ l^-$, in particular $l = \mu$ and $l = \nu$
   (d) $s \to d\gamma$
   (e) top decays

Really Important!

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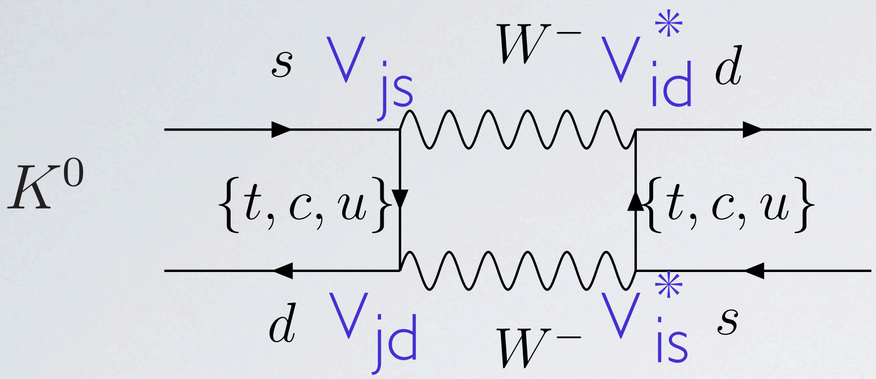
Kaon Mixing in the SM



$$\epsilon = \frac{\exp(i\pi/4)}{\sqrt{2}} \frac{\mathrm{Im}\langle K^0|H_{\text{eff}}^{\Delta S=2}|\bar{K}^0\rangle}{\Delta m_K}$$

$$A_{0,2}e^{i\delta_{0,2}} = \langle \pi\pi(0,2)|\mathcal{H}_{\Delta F=1}|K'\rangle$$

$$\epsilon' = \frac{e^{i\pi/4}}{\sqrt{2}} \frac{1}{\mathrm{Re}A_0} \left(\mathrm{Im}A_2 - \frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} \mathrm{Im}A_0 \right)$$

$$\mathrm{Im}\langle K^0|H_{\text{eff}}^{\Delta S=2}|\bar{K}^0\rangle \quad \propto \quad \sum_{i,j} V_{js} V^*_{id} V_{jd} V^*_{is} \quad S\left(\frac{m_i^2}{M_W^2}, \frac{m_j^2}{M_W^2}\right)$$

Due to the unitarity of V O(1) contributions cancel (GIM mechanism),

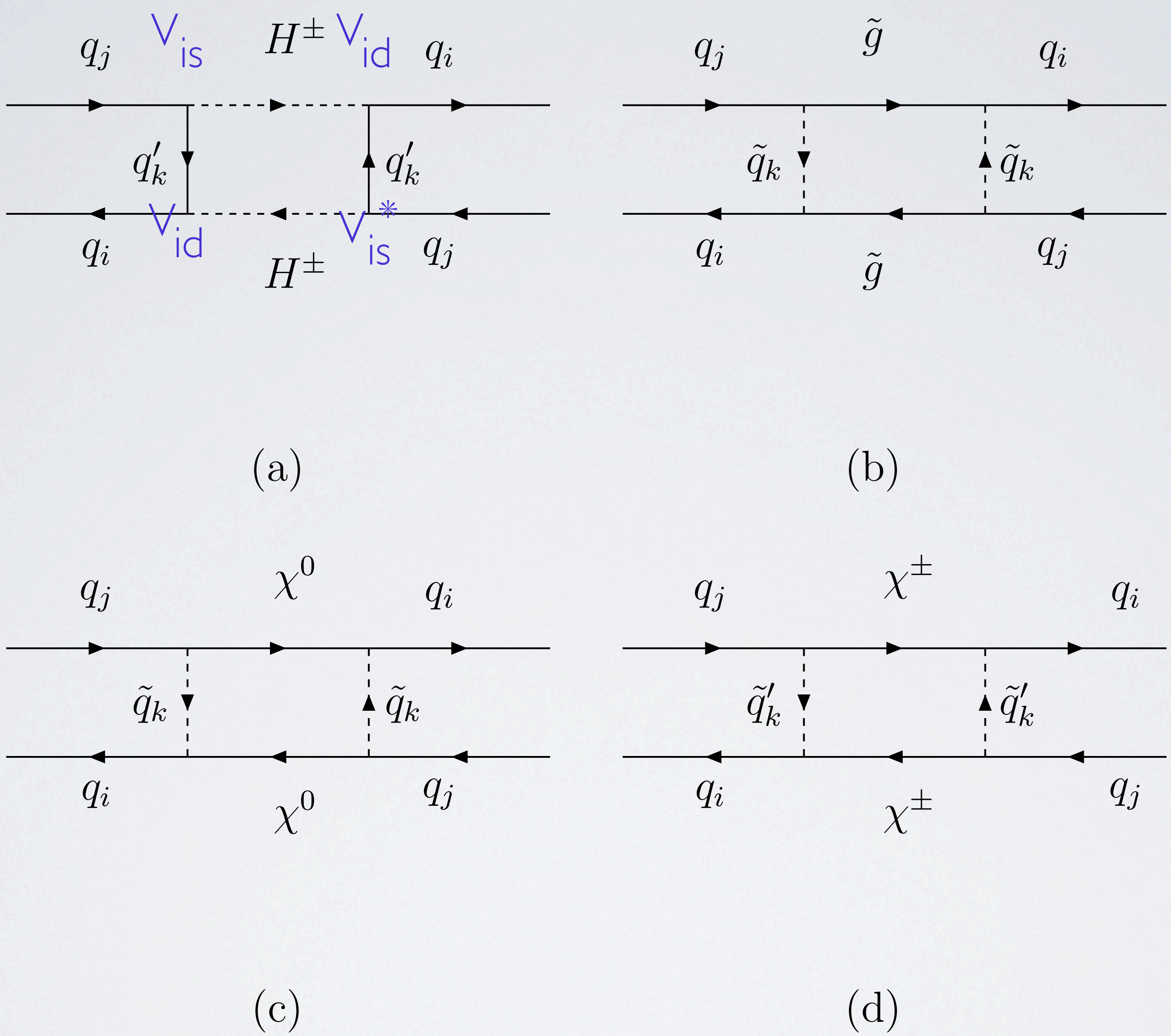
$$\begin{aligned} \epsilon^{\text{SM}} &= (1.91 \pm 0.30) \times 10^{-3}, \\ |\epsilon|^{\text{exp}} &= (2.228 \pm 0.011) \times 10^{-3} \end{aligned}$$

$$0 \ < \ \mathrm{Re}(\epsilon'/\epsilon)_{SM} \ < \ 3.3 \times 10^{-3}$$

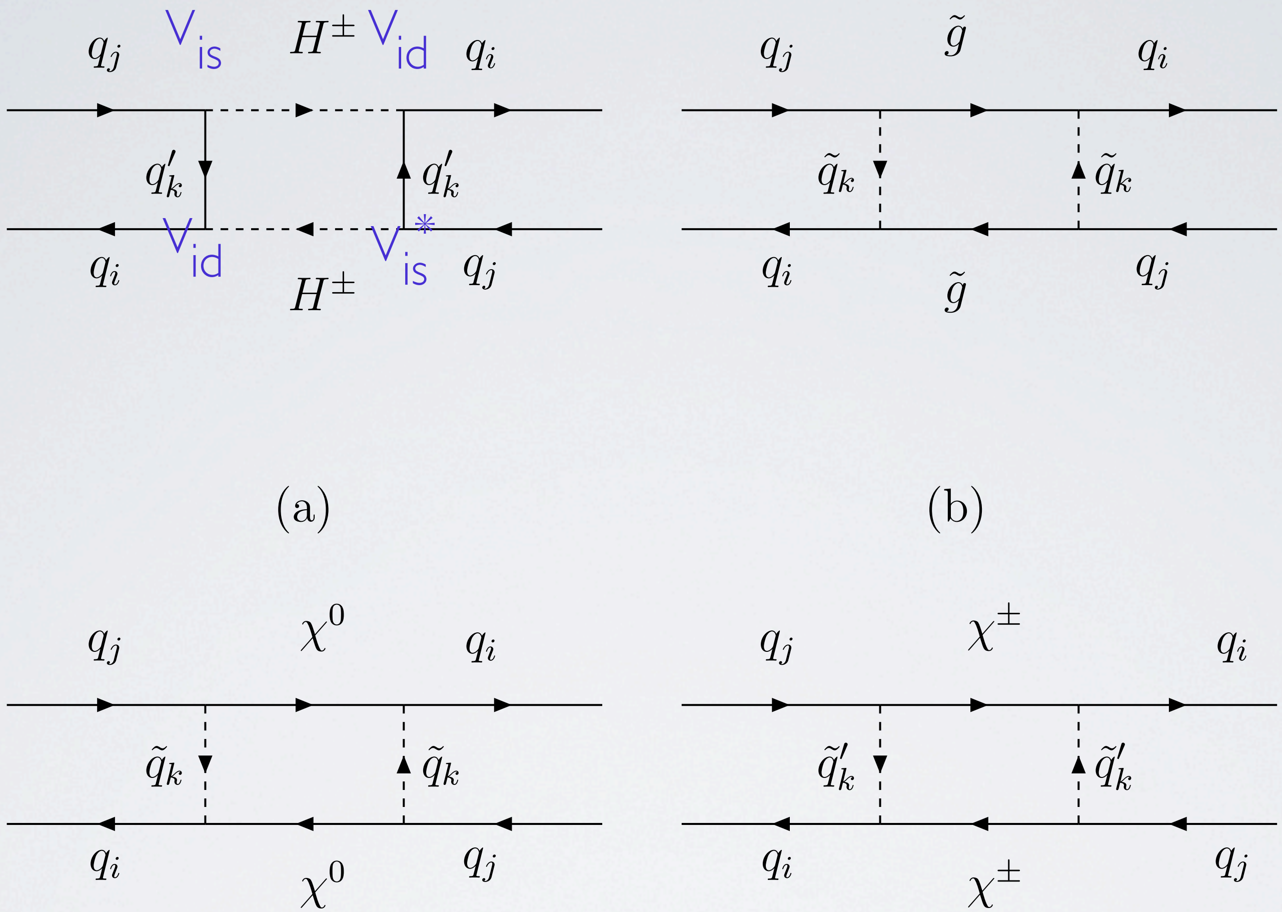
$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)_{exp} = (1.65 \pm 0.26) \times 10^{-3}$$

Very large hadronic uncertainties but in some SUSY models, contributions could be fairly large

Kaon mixing in MSSM



Kaon mixing in MSSM



(a) (b) (c) (d)

General features:

Constructive contributions with light $H^\pm$

Both signs contributions with light gluinos

Strategy: Start probing with Yukawa textures that are well known and also deviations from minimality at MPlanck

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Textures:

$$Y^d = \frac{\sqrt{2}m_b}{v\cos\beta}0.27\begin{bmatrix} 0.0014+0.0007i & 0.0009+0.0111i & 0.13+0.13i \\ 0.0055 & 0.046+0.118i & 0.35+0.19i \\ 0.0018-0.0009i & 0.069+0.058i & -0.90+0.08i \end{bmatrix}$$

$$Y^u = \frac{\sqrt{2}m_t}{v\sin\beta}0.53\begin{bmatrix} -1.58\times10^{-6}-0.000017i & -0.000076+0.000032i & 0.0020+0.0020i \\ -0.00034+0.00024i & 0.0020+0.0002i & 0.011+0.011i \\ -0.0057-0.0024i & 0.0044+0.0115i & 0.70+0.71i \end{bmatrix}$$

$$Y^e = \frac{\sqrt{2}m_\tau}{v\cos\beta}\begin{bmatrix} 0.0014-0.0007i & 0.0005-0.0056i & 0.13-0.13i \\ 0.0082 & 0.023-0.059i & 0.18-0.1i \\ 0.0018+0.0009i & 0.035-0.029i & -0.99-0.09i \end{bmatrix}$$

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KANE, KING, PEDDIE & V-S, JHEP 0508, PH/0504038

These textures can be explained in the context of $SU(5)_{GUT} \times U(1)_{\text{Family Symmetry}}$ model

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Deviations:

$$(a^f)_{ij} = c^f_{ij} A_{\tilde{f}} Y^f_{ij} \begin{cases} (a) \; c^f_{ij} = 1, \\ (b) \; c^f_{ij} = x^f_{ij}, \; x^f_{ij} \in (0, \sqrt{2}) \text{ a random number} \end{cases}$$

G2-MSSM benchmark points:

Acharya & bobkov, 0810.3285

parameter	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7
$m_{3/2}$	20000	20000	20000	20000	30000	50000	30000
δ	-15	-12	0	-15	15	-15	-15
c	0	0	0	0.1	0.5	0	0
$\tan\beta$	3	2.65	2.65	3	3	2.5	3
μ	-11943	-13377	-13537	-10969	-10490	-34019	+17486
LSP type	Wino	Wino	Bino	Bino	Bino	Wino	Bino
M_1	165	173	203	181	484	434	252
M_2	158	173	225	189	662	421	242
M_3	262	297	423	328	1328	673	395
$m_{\tilde{g}}$	401	449	622	492	1784	1001	596.8
$m_{\tilde{\chi}_1^0}$	145.1	155.6	189	170	473	373.4	271
$m_{\tilde{\chi}_2^0}$	153	159	214.3	181.5	702.4	397	334.2
$m_{\tilde{\chi}_3^0}$	11905	13321	13479	10938	10486	33886	17441
$m_{\tilde{\chi}_4^0}$	11906	13322	13479	10939	10487	33886	17442
$m_{\tilde{\chi}_1^\pm}$	145.2	155.8	214.5	181.7	702.6	373.6	334.2
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$m_{\tilde{d}_L}, m_{\tilde{s}_L}$	19799	19803	19809	18785	21052	49524	29727
$m_{\tilde{u}_L}, m_{\tilde{c}_L}$	19801	19812	19818	18784	21034	49600	29725
$m_{\tilde{b}_1}$	15342	15250	15224	14635	16783	38473	23236
$m_{\tilde{t}_1}$	9130	8779	8662	8928	11151	22887	14264
$m_{\tilde{e}_L}, m_{\tilde{\mu}_L}$	19948	19948	19951	18926	21164	49889	29930
$m_{\tilde{\nu}_{e_L}}, m_{\tilde{\nu}_{\mu_L}}$	19950	19954	19952	18927	21168	49903	29934
$m_{\tilde{\tau}_1}$	19934	19941	19940	18914	21156	49874	29909
$m_{\tilde{\nu}_{\tau_L}}$	19936	19944	19942	18916	21158	49876	29913
$m_{\tilde{d}_R}$	19848	19851	19845	18832	21096	49694	29794
$m_{\tilde{u}_R}, m_{\tilde{c}_R}$	19850	19853	19858	18832	21094	49700	29792
$m_{\tilde{s}_R}$	19849	19851	19856	18832	21096	49695	29767
$m_{\tilde{b}_2}$	19829	19833	19838	18810	21075	49669	29758
$m_{\tilde{t}_2}$	15342	15251	15224	14635	16783	38470	23235
$m_{\tilde{e}_R}, m_{\tilde{\mu}_R}$	19978	19977	19977	18953	21196	49948	29966
$m_{\tilde{\tau}_2}$	19948	19957	19955	18930	21174	49904	29928
m_{h_0}	116.4	114.3	114.6	116.0	115.9	115.1	114.6
$m_{H_0}, m_{A_0}, m_{H^\pm}$	24614	25846	25943	23158	25029	65690	36623
$\tilde{A}_t$	12159	11539	11445	10898	9626	30139	18812
$\tilde{A}_b$	27381	27321	27427	24744	21850	68441	41148
$\tilde{A}_\tau$	30068	30092	30124	27109	23022	75221	45099

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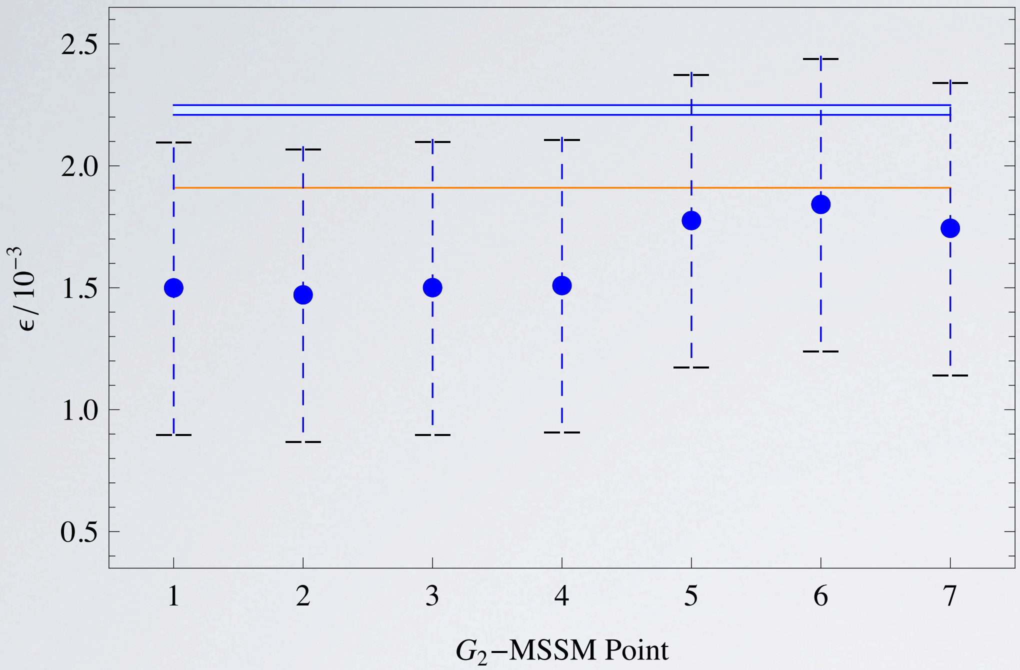
a) $(a^f)_{ij} = A_{\tilde{f}} Y^f_{ij}$

KADOTA, KANE, KERSTEN & V-S, 1107.3105



Experimental ϵ @ 95% C.L.

SM central value

G2 MSSM + SM 95% C.L.

b) $(a^f)_{ij} = c^f_{ij} A_{\tilde{f}} Y^f_{ij}$

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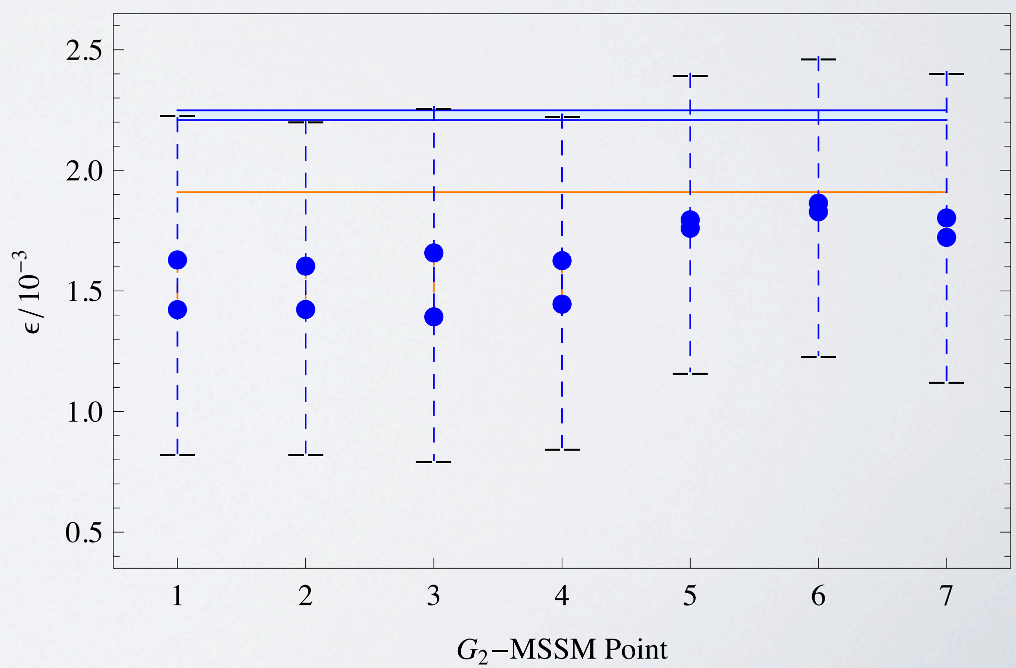


$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) \sim 10^{-8}$

Really safe (mainly due to boundary conditions)

$$m'^2_{\tilde{F}^\dagger \tilde{F}} = m_0^2 \, \mathbb{1}$$

$$m'^2_{\tilde{f}^c \tilde{f}^{c\dagger}} = m_0^2 \, \mathbb{1}$$

Tachyonic particles here are not an issue

All other bounds really safe!

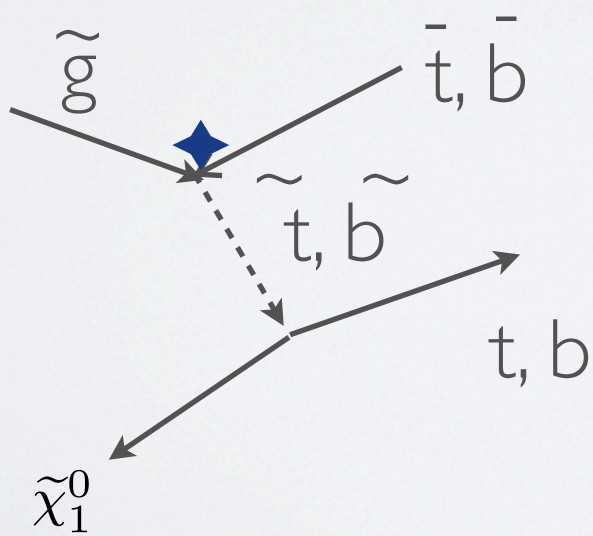
How important are the absence of new phases?

COULD THERE BE SIGNALS AT THE LHC?

- In general of G2-MSSM: Sure! special signatures of low gluinos with heavy scalars

FELDMAN, KANE, LU & NELSON, 1002.2430
KANE, KUFLIK, LU & WANG, 1101.1963

- In particular regarding Yukawa & other flavour couplings: difficult but not impossible due to the involved couplings in the typical decay chains



✦ Gluino coupling: flavour blind, involved couplings just

$f, \tilde{f}$

SUMMARY

- Typical flavour structure in G2-models: $Y_{ij}^f = e^{-V_{ij}}$
  - Couplings:
  - Squared mass matrices

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REAL

- Vij can be constrained

- FCNC under control with specific forms of Yukawa couplings, Yu small mixings, while Yd can allow certain large mixings

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REAL

Really at the limit of what it could be!

- Vij can be constrained
- FCNC under control with specific forms of Yukawa couplings, Yu small mixings, while Yd can allow certain large mixings

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