Low Energy Probes of PeV Scale Sfermions

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PERIMETER INSTITUTE

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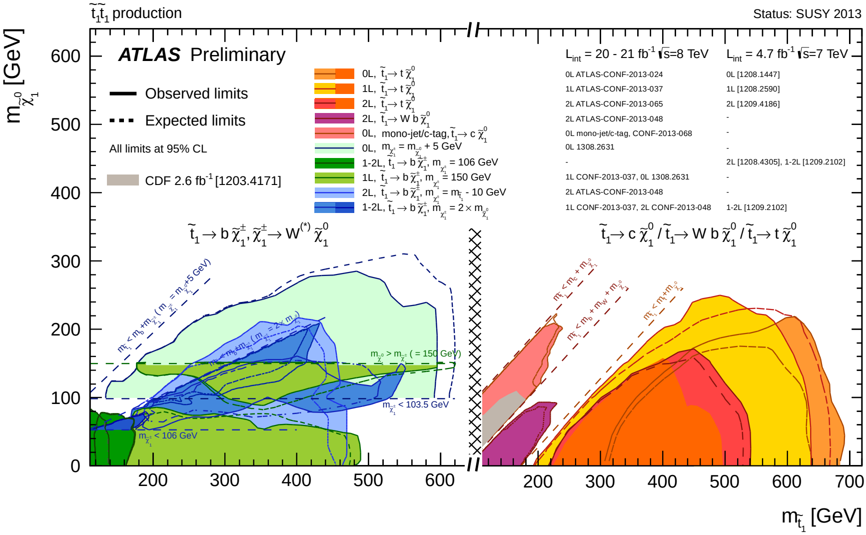
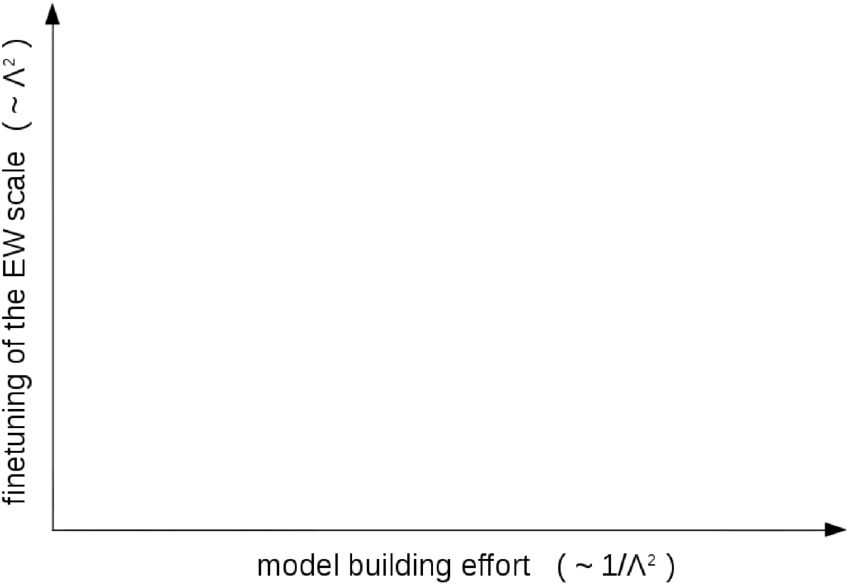
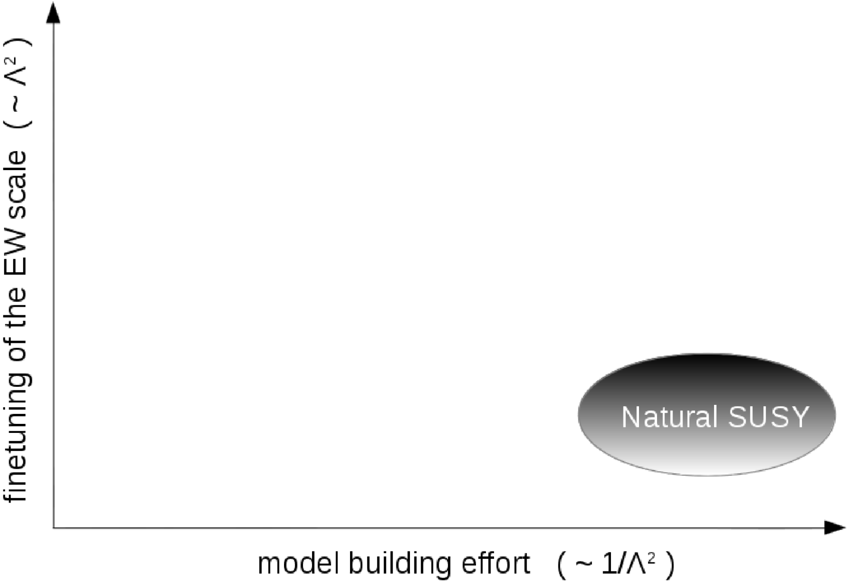
Oh SUSY Where Art Thou?




finetuning of the EW scale (~ Λ²)
model building effort (~ 1/Λ²)


finetuning of the EW scale (~ Λ²)
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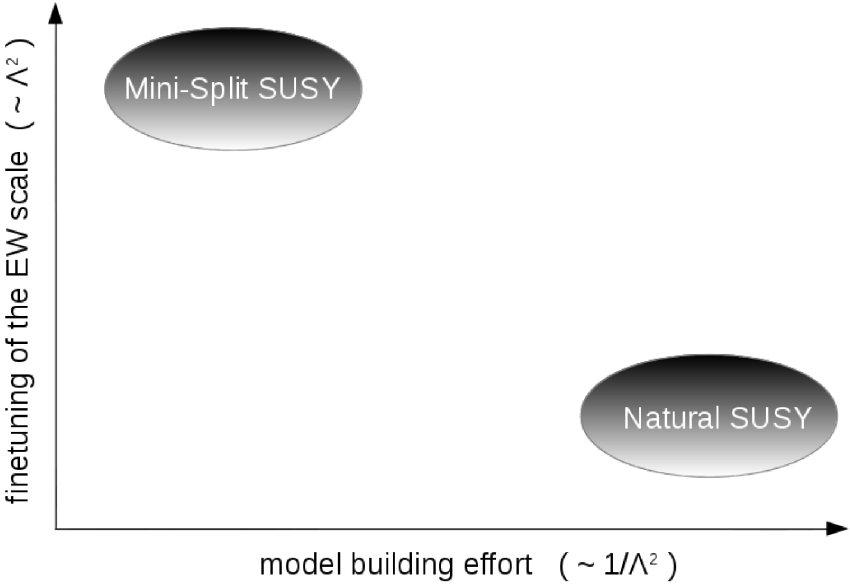
Mini-Split SUSY
Natural SUSY
finetuning of the EW scale (~ Λ²)
model building effort (~ 1/Λ²)

Outline

WA, Roni Harnik, Jure Zupan

JHEP **1311**, 202 (2013) [arXiv:1308.3653 [hep-ph]]

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1. The Mini-Split SUSY Framework
2. Meson Mixing
3. Charged Lepton Flavor Violation
4. Electric Dipole Moments
5. Implications for Models of Fermion Masses
6. Conclusions

The Mini-Split SUSY Framework

Soft SUSY Breaking

Introduce soft SUSY breaking terms to get a phenomenologically viable spectrum

scalar masses: $\frac{1}{M_*^2}\int d^4\theta (X^\dagger X)(\Phi^\dagger \Phi)$

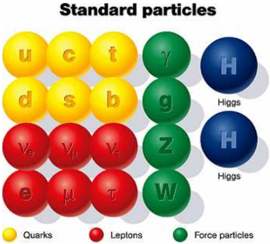
gaugino masses: $\frac{1}{M_*}\int d^2\theta Y (W^\alpha W_\alpha)$

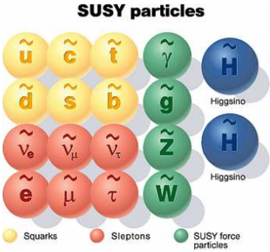
trilinear couplings: $\frac{1}{M_*}\int d^2\theta Y (H_u Q U^c)$

- X, Y: hidden sector chiral super-fields with F-term vev's
- no requirements on quantum numbers of X
- Y has to be a singlet (not generically present)

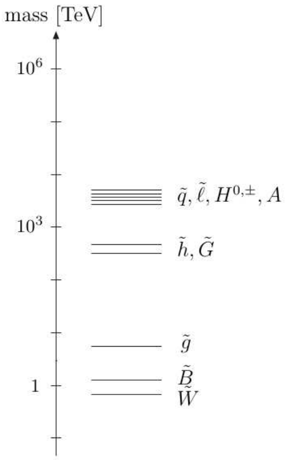
$\rightarrow$ gaugino masses and trilinears generically smaller than scalar masses

(Arkani-Hamed et al. '12)





A “Simply Unnatural” SUSY Spectrum



Hall, Nomura ’11

Arvanitaki et al. ’12

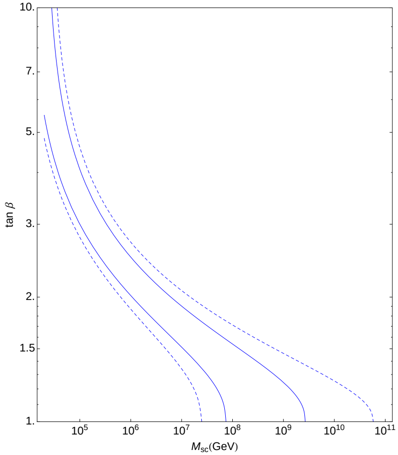
Arkani-Hamed et al. ’12 ...

$$\mathcal{L}_{\rm SB} \supset \frac{1}{M_*^2} \int d^4\theta (X^\dagger X)(\Phi^\dagger \Phi + H_u H_d)$$

$$- \frac{\alpha_i b_i}{4\pi} \frac{m_{3/2}}{2} \lambda_i \lambda_i - \frac{m_{3/2}}{2} \tilde{G}\tilde{G} + \int d^4\theta (H_u H_d)$$

- scalar masses of the order $F_X / M_* \gtrsim F_X / M_{\rm Pl} \sim m_{3/2}$
- gaugino masses from anomaly mediation, 1-loop factor below the gravitino mass
- small A terms (1-loop suppressed contributions from anomaly mediation)
- Higgsino mass model dependent: could be order gravitino mass or additionally suppressed (breaks Peccei-Quinn symmetry)

The Higgs Mass and the Squark Scale



Arkani-Hamed et al. '12;
Giudice, Strumia '11; Hall, Nomura '11;
Ibe, Yanagida '11; Kane et al. '11; ...

$$m_h^2 \simeq M_Z^2 \cos^2(2\beta)$$
$$+\frac{3}{16\pi^2}\frac{m_t^4}{v^2}\frac{X_t^2}{m_{\tilde t}^2}\left(1-\frac{X_t^2}{12m_{\tilde t}^2}\right)$$
$$+\frac{3}{16\pi^2}\frac{m_t^4}{v^2}\log\left(\frac{m_{\tilde q}^2}{m_t^2}\right)$$

- $X_t = A_t - \mu/\tan\beta$ typically small
- for moderate $\tan\beta$ and scalars at O(100 TeV) – O(1000 TeV) a 125 GeV Higgs is "effortless"
- upper bound on the squark scale from the Higgs mass

New Sources of Flavor and CP Violation

- mini-split SUSY philosophy:
  no model building effort

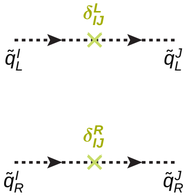
→ generic flavor structure for squarks and sleptons

- parametrization in terms of mass insertions

$$\hat{M}^2_{\tilde{q}} = m^2_{\tilde{q}}(\mathbb{1} + \delta_q)$$

$$\hat{M}^2_{\tilde{\ell}} = m^2_{\tilde{\ell}}(\mathbb{1} + \delta_\ell)$$

- going to sfermion mass eigenstates leads to flavor and CP violating fermion-sfermion-gaugino interactions
- for TeV scale sfermions:
  SUSY flavor problem
- for 1000 TeV sfermions:
  generic flavor violation possible



- mass insertion approximation:
  treat δ's as perturbations and expand to leading order

(in the plots of the talk: $|\delta_{ij}| = 0.3$)

Low Energy Probes of PeV Scale Sfermions

a large host of low energy observables can probe
the 0.1 - 1 PeV scale in the near future

Meson Mixing

Charged Lepton Flavor Violation

Electric Dipole Moments

Meson Mixing

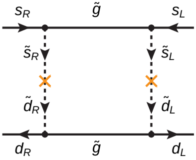
Meson Mixing

meson mixing observables probe
generic New Physics at very high scales

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

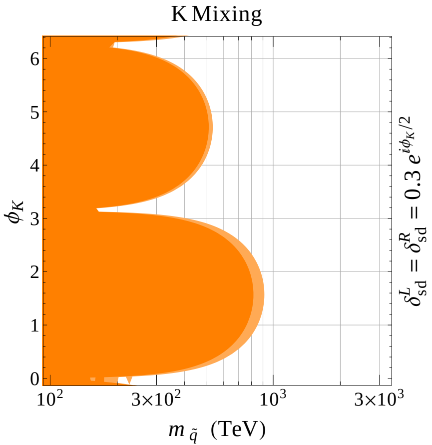
Operator	Bounds on Λ [TeV] ($C=1$)		Bounds on C ($\Lambda = 1\,\text{TeV}$)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2	2.2×10^2	7.6×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\ S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2	7.4×10^2	1.3×10^{-5}	3.0×10^{-6}	$\Delta m_{B_s};\ S_{\psi\phi}$

Isidori, Nir, Perez '10

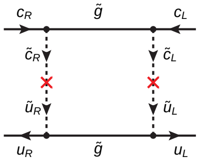


$$M_{12}^K \propto \frac{\alpha_s^2}{m_{\tilde{q}}^2} \left(\delta_{sd}^L \delta_{sd}^R\right)$$

- contributions depend to an excellent approximation only on the squark masses (not on higgsino or gaugino masses)
- scales of several 100 - 1000 TeV can be probed if relevant phases are not suppressed

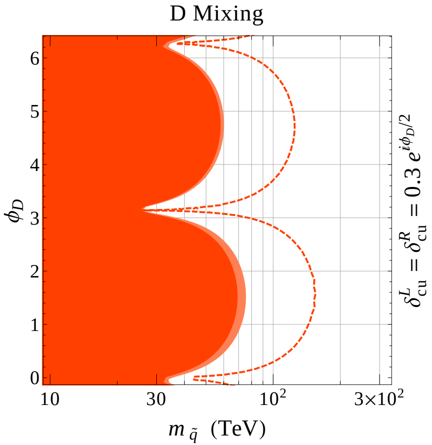


WA, Harnik, Zupan ’13



$$M_{12}^D \propto \frac{\alpha_s^2}{m_{\tilde{q}}^2} \left(\delta_{cu}^L \delta_{cu}^R\right)$$

- scales of O(50 TeV) can be probed for O(1) phases
- experimental bounds on CPV in charm mixing can still improve substantially (LHCb and Belle II)



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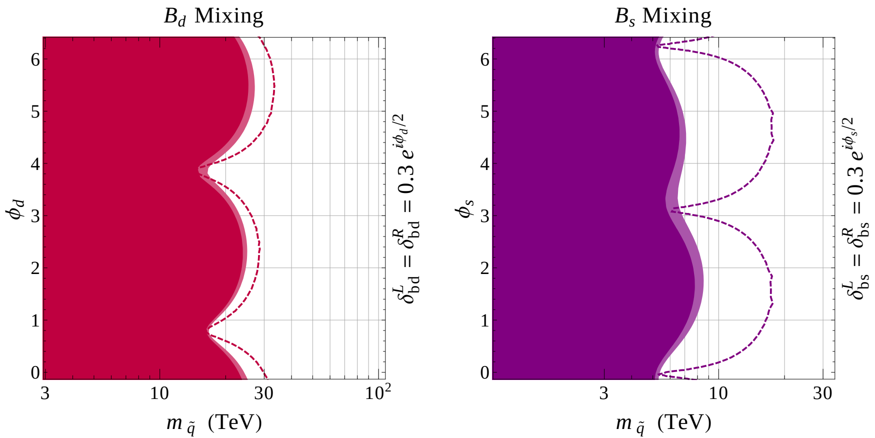
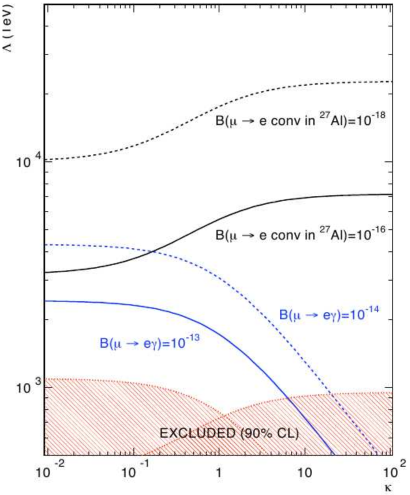


- scales of 20 - 30 TeV can be probed for O(1) phases with improved experimental results on CP violation (LHCb + Belle II)

Charged Lepton
Flavor Violation

Charged Lepton Flavor Violation

de Gouvea, Vogel '13

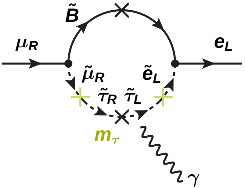


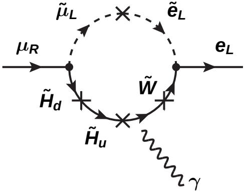
- strongest constraints come from $\mu \to e$ transitions

$$\begin{aligned} \text{BR}(\mu \to e\gamma) &\leq 5.7 \times 10^{-13} \quad @\ 90\%\ \text{C.L.} \\ \text{BR}(\mu \to 3e) &\leq 1.0 \times 10^{-12} \quad @\ 90\%\ \text{C.L.} \\ \text{BR}(\mu \to e \text{ in Au}) &\leq 7.0 \times 10^{-13} \quad @\ 90\%\ \text{C.L.} \end{aligned}$$

- current limits probe generic NP at 1000 TeV
- bounds can be improved significantly (Mu2e, Mu3e)

SUSY Contributions to $\mu \to e\gamma$





$+ \cdots$

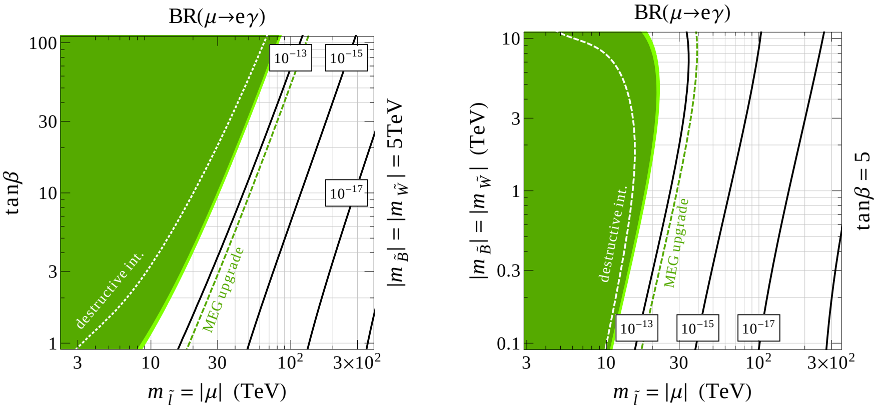
$$\mathcal{A}^{\tilde{B}}_{L,R} \propto \frac{\alpha_1}{4\pi} \frac{m_\tau}{m_\mu} \frac{\mu m_{\tilde{B}}}{m^4_{\tilde{\ell}}} \tan\beta \, (\delta^{L,R}_{\mu\tau} \delta^{L,R}_{\tau e})$$

$$\mathcal{A}^{\tilde{W}}_{L} \propto \frac{\alpha_2}{4\pi} \frac{1}{m^2_{\tilde{\ell}}} \frac{m_{\tilde{W}}}{\mu} \tan\beta \, (\delta^{L}_{\mu e}) \log\left(\frac{m^2_{\tilde{W}}}{m^2_{\tilde{\ell}}}\right) + \ldots$$

- Bino loops are enhanced by the tau mass
- grow linearly with Higgsino mass

- Wino loops are log enhanced
- become dominant for small Higgsino masses

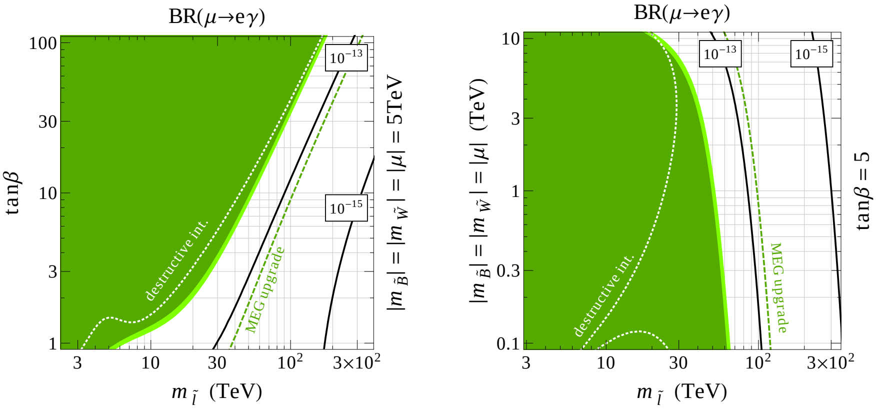
WA, Harnik, Zupan '13; (see also Moroi, Nagai '13; McKeen, Pospelov, Ritz '13)



- scales of 10 TeV - 100 TeV can be probed
- BR bound can be improved by one order of magnitude with a MEG upgrade

Constraints from $\mu \to e\gamma$

WA, Harnik, Zupan '13; (see also Moroi, Nagai '13; McKeen, Pospelov, Ritz '13)



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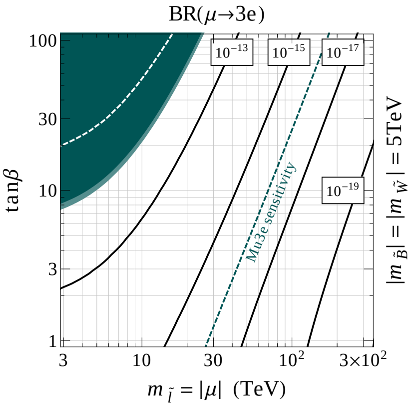
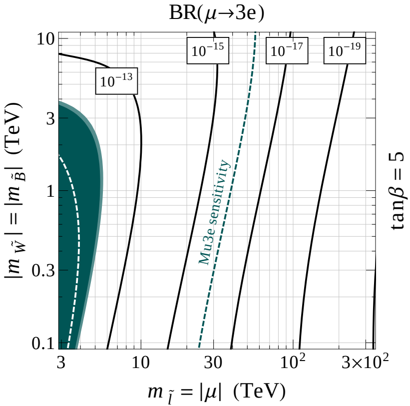




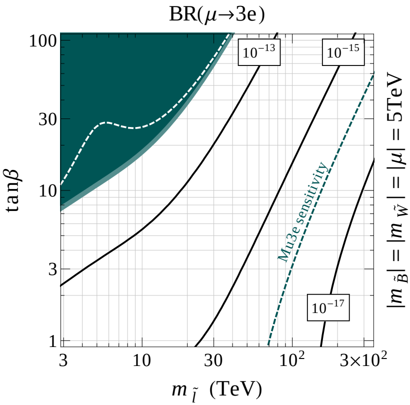
- dipole dominance:

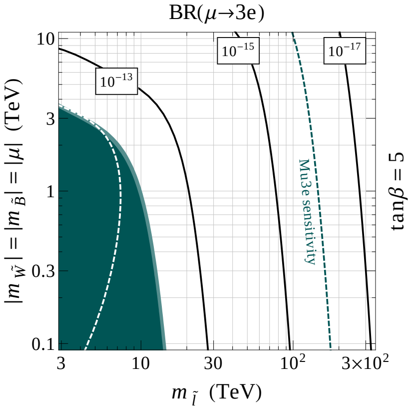
$$\frac{\text{BR}(\mu \to 3e)}{\text{BR}(\mu \to e\gamma)} \simeq \frac{\alpha_{\text{em}}}{3\pi}\left(\log\left(\frac{m_\mu^2}{m_e^2}\right) - \frac{11}{4}\right) \simeq 6\times10^{-3}$$

- ultimate sensitivity of Mu3e would be stronger than the bounds from a MEG upgrade

Constraints from $\mu \to 3e$

WA, Harnik, Zupan '13; (see also Moroi, Nagai '13; McKeen, Pospelov, Ritz '13)





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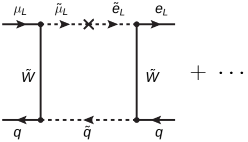
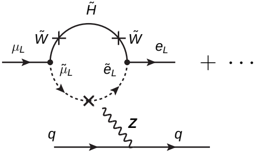
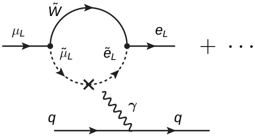
- ultimate sensitivity of Mu3e would be stronger than the bounds from a MEG upgrade contributions from dipoles, boxes, Z penguins, and photon penguins

dipoles are dominant for large $\tan\beta$







$$\mathcal{A}^{\text{box}} \propto \frac{\alpha_2^2}{\max(m_{\tilde{\ell}}^2, m_{\tilde{q}}^2)} (\delta^L_{\mu e})$$

- usually negligible in mini-split SUSY

$$\mathcal{A}^{Z} \propto \frac{\alpha_2^2}{m_{\tilde{\ell}}^2} (\delta^L_{\mu e}) \log\left(\frac{\mu^2}{m_{\tilde{\ell}}^2}\right) + \ldots$$

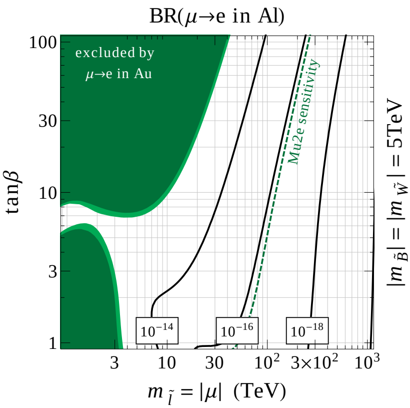
- log enhanced for light Higgsinos

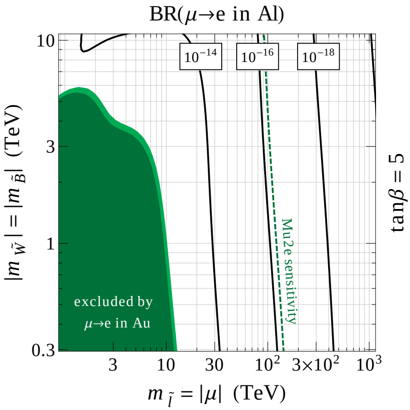
$$\mathcal{A}^{\gamma} \propto \frac{\alpha_{\text{em}}\alpha_2}{m_{\tilde{\ell}}^2} (\delta^L_{\mu e}) \log\left(\frac{m_{\tilde{W}}^2}{m_{\tilde{\ell}}^2}\right)$$

- log enhanced for light Winos; typically dominant for low $\tan\beta$

Constraints from $\mu \to e$ Conversion

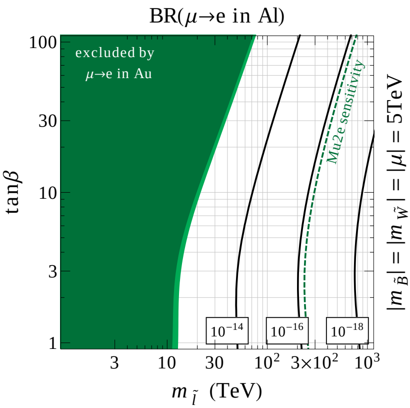
WA, Harnik, Zupan '13; (see also Moroi, Nagai '13; McKeen, Pospelov, Ritz '13)

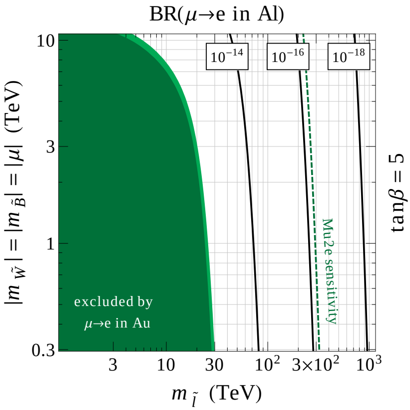




- current constraints are still weak, of order 10's of TeV
- Mu2e can improve limits down to BR $\lesssim 10^{-16} - 10^{-17}$

WA, Harnik, Zupan '13; (see also Moroi, Nagai '13; McKeen, Pospelov, Ritz '13)





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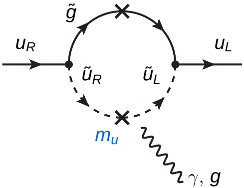
Electric Dipole Moments

Flavored EDMs

in the flavor blind case, EDMs
are proportional to 1st gen. fermion masses



$$d_e \quad \propto \quad \frac{\alpha_1}{4\pi} \frac{m_e}{m_{\tilde{\ell}}^2} \frac{\mu m_{\tilde{B}}}{m_{\tilde{\ell}}^2} \tan\beta$$

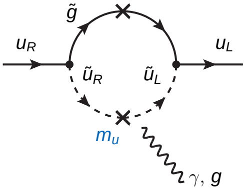
$$d_u \quad \propto \quad \frac{\alpha_s}{4\pi} \frac{m_u}{m_{\tilde{q}}^2} \frac{\mu m_{\tilde{g}}}{m_{\tilde{q}}^2} \frac{1}{\tan\beta}$$

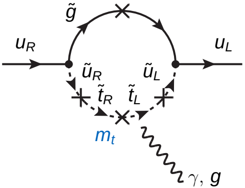
$$\tilde{d}_u \quad \propto \quad \frac{\alpha_s}{4\pi} \frac{m_u}{m_{\tilde{q}}^2} \frac{\mu m_{\tilde{g}}}{m_{\tilde{q}}^2} \frac{1}{\tan\beta} \log\left(\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}\right)$$

Flavored EDMs

in the flavor blind case, EDMs
are proportional to 1st gen. fermion masses

flavor effects strongly enhance EDMs
(see e.g. Hisano, Nagai, Paradisi '08)





$$d_e \propto \frac{\alpha_1}{4\pi}\frac{m_e}{m_{\tilde{\ell}}^2}\frac{\mu m_{\tilde{B}}}{m_{\tilde{\ell}}^2}\tan\beta$$

$$d_u \propto \frac{\alpha_s}{4\pi}\frac{m_u}{m_{\tilde{q}}^2}\frac{\mu m_{\tilde{g}}}{m_{\tilde{q}}^2}\frac{1}{\tan\beta}$$

$$\tilde{d}_u \propto \frac{\alpha_s}{4\pi}\frac{m_u}{m_{\tilde{q}}^2}\frac{\mu m_{\tilde{g}}}{m_{\tilde{q}}^2}\frac{1}{\tan\beta}\log\left(\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}\right)$$

$$d_e \propto \frac{\alpha_1}{4\pi}\frac{m_\tau}{m_{\tilde{\ell}}^2}\frac{\mu m_{\tilde{B}}}{m_{\tilde{\ell}}^2}\tan\beta\,(\delta^R_{e\tau}\delta^L_{\tau e})$$

$$d_u \propto \frac{\alpha_s}{4\pi}\frac{m_t}{m_{\tilde{q}}^2}\frac{\mu m_{\tilde{g}}}{m_{\tilde{q}}^2}\frac{1}{\tan\beta}\,(\delta^R_{ut}\delta^L_{tu})$$

$$\tilde{d}_u \propto \frac{\alpha_s}{4\pi}\frac{m_t}{m_{\tilde{q}}^2}\frac{\mu m_{\tilde{g}}}{m_{\tilde{q}}^2}\frac{1}{\tan\beta}\,(\delta^R_{ut}\delta^L_{tu})\log\left(\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}\right)$$

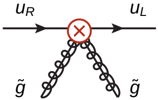
in the presence of O(1) sfermion mixing,
1st generation EDMs are proprotional to 3rd generation masses

Parenthesis: Log Resummation

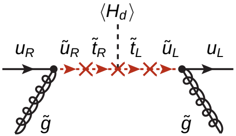
- two step matching:

  integrate out squarks at $m_{\tilde{q}}$,
  run down to $m_{\tilde{g}}$ with RGEs,
  integrate out gluinos at $m_{\tilde{g}}$

- integrating out squarks induces the dipole operators and CP violating 4 fermion operators

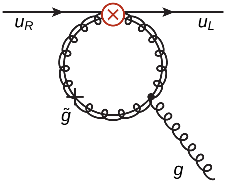


e.g. $$O_{q\tilde{g}} = \frac{g_s^2}{m_{\tilde{g}}} \Big[(\bar{q}_\alpha \tilde{g}_a)(\bar{\tilde{g}}_b \gamma_5 q_\beta) + (\bar{q}_\alpha \gamma_5 \tilde{g}_a)(\bar{\tilde{g}}_b q_\beta) \Big] f_{abc} T^a_{\alpha\beta}$$



$$C_{u\tilde{g}}(m_{\tilde{q}}) = -\frac{1}{2} \frac{m_t}{m_{\tilde{q}}^2} \frac{|\mu m_{\tilde{g}}|}{m_{\tilde{q}}^2} \frac{1}{t_\beta} (\delta^R_{ut} \delta^L_{tu}) \sin \phi_u$$

- the 4 fermion operator mixes into the chromo dipole operator under renormalization



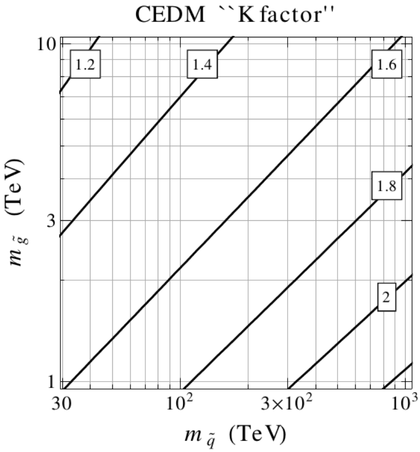
Parenthesis: Log Resummation

- log is resummed in the renormalization group running from the squark scale down to the gluino scale
- large "K factor"

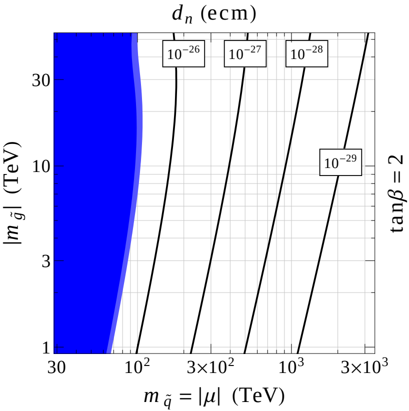
  up to $\sim$ 100% correction
  due to the log resummation

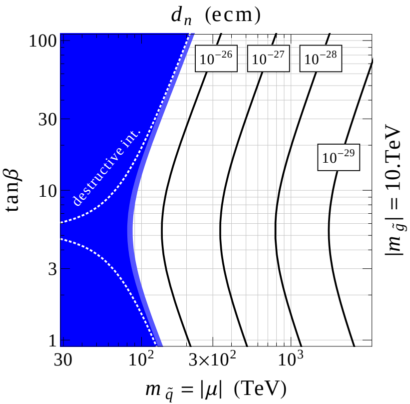
WA, Harnik, Zupan '13

Fuyuto, Hisano, Nagata, Tsumura '13



WA, Harnik, Zupan ’13; (see also McKeen, Pospelov, Ritz ’13)





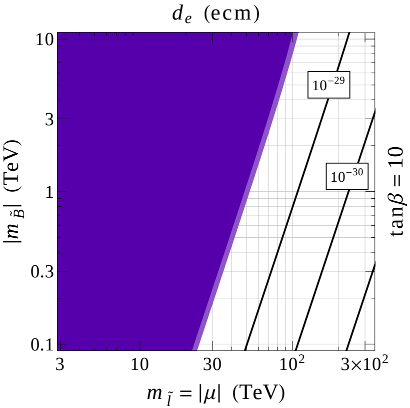
- assuming O(1) phases:

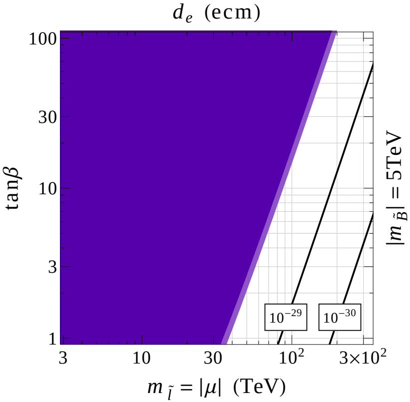
  electron EDM probes scales of O(50 TeV)
  hadronic EDMs probe scales of O(100 TeV)

- EDM bounds can be improved by *several* orders of magnitude!

  electron EDM: $d_e \lesssim 10^{-30}$ecm
  neutron EDM: $d_n \lesssim 10^{-28}$ecm

WA, Harnik, Zupan '13; (see also McKeen, Pospelov, Ritz '13)





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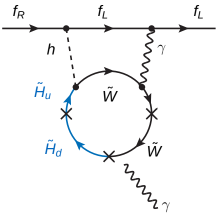
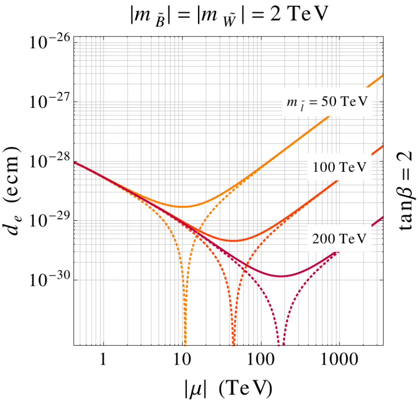
  Giudice, Romanino '05





WA, Harnik, Zupan '13

- improved measurements of EDMs probe the mini-split SUSY framework over a broad range of Higgsino masses

2-loop Contributions from Light Higgsinos

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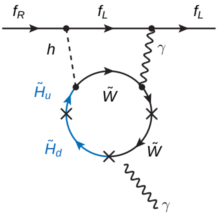

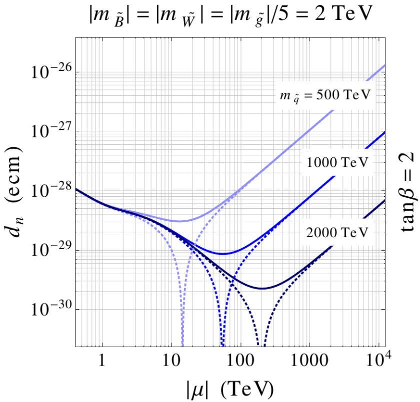

WA, Harnik, Zupan '13

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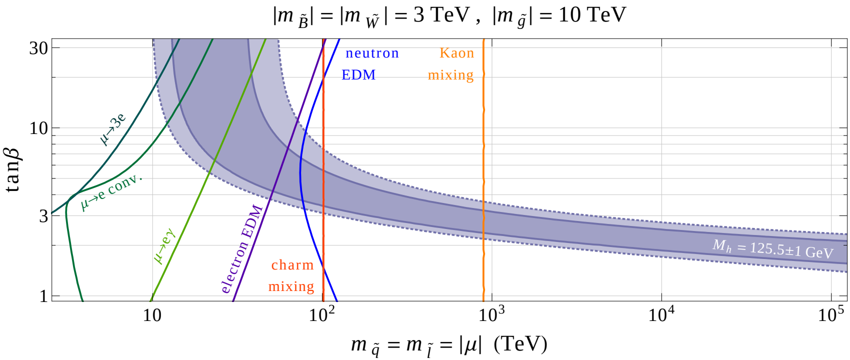
Summary of Current Constraints

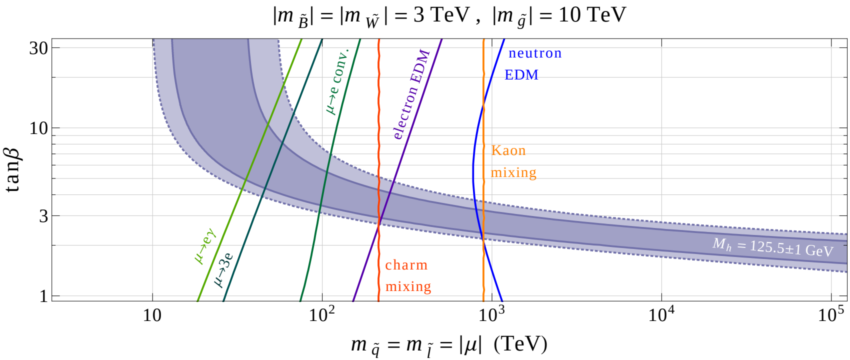


- only low energy process that currently probes O(1000 TeV) squarks is CP violation in Kaon mixing
- CP violation in charm mixing and the neutron EDM reach up to O(100 TeV)

assumptions for the plot:

- all relevant mass insertions $|\delta_{ij}| = 0.3$
- all relevant phases $\sin\phi_i = 1$
- no large cancelations between the various contributions

Summary of Future Constraints



- neutron EDM (and in general EDMs of hadronic systems) probe squarks at O(1000 TeV)
- electron EDM and $\mu \to e$ conversion probe sleptons above 100 TeV

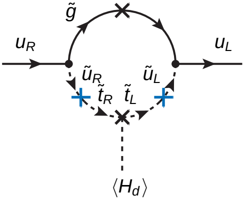
assumptions for the plot:

- all relevant mass insertions $|\delta_{ij}| = 0.3$
- all relevant phases $\sin\phi_i = 1$
- no large cancelations between the various contributions

Implications for Models of Fermion Masses

Radiative Fermion Masses

- generic squark flavor violation can lead to large radiative contributions to light quark masses
- most important effect in the up-quark mass, due to the large top Yukawa $Y_t = \mathrm{O}(1)$

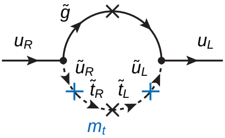


$$\Delta m_u = \frac{\alpha_s}{4\pi}\frac{8}{9}\frac{m_{\tilde{g}}\mu}{m_{\tilde{q}}^2}\, m_t\, \frac{1}{t_\beta}(\delta^L_{ut}\delta^R_{tu})$$

- in mini-split SUSY, gluino mass is $\sim$ 1-loop below the squark masses
- correction is effectively 2-loop and can be just of the right size to generate the up quark mass from SUSY loops
- radiative fermion masses imply lower bounds on the amount of flavor violation

EDMs and Radiative Fermion Masses

- radiatively generated up-quark mass and the up-quark (C)EDM are strongly related



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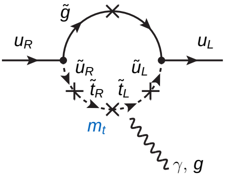
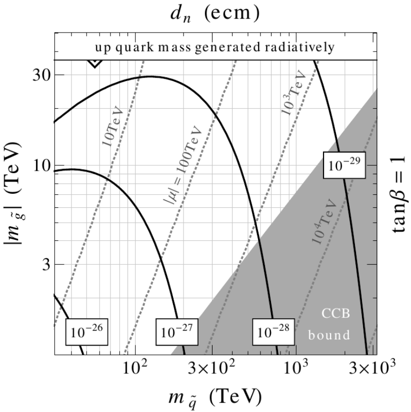


- assuming that the up quark mass comes fully from SUSY loops

$$\tilde{d}_u \propto \frac{m_u}{m_{\tilde{q}}^2} \times \log\left(\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}\right)$$



WA, Harnik, Zupan '13

Froggatt-Nielsen Models: Fermion Textures

(Froggatt-Nielsen '79; Leurer, Nir, Seiberg '93, '94)

- SM fermions are charged under a $U(1)$ flavor symmetry
- symmetry is broken by a spurion with charge -1 and size of the Cabbibo angle $\lambda \simeq 0.23$

ferm./gen.	1	2	3
Q	3	2	0
U	3	1	0
D	3	2	2
L	3	3	3
E	5	2	0

induced Yukawa textures of the shown example charges

$$Y_u \sim \begin{pmatrix} \lambda^6 & \lambda^4 & \lambda^3 \\ \lambda^5 & \lambda^3 & \lambda \\ \lambda^3 & \lambda & 1 \end{pmatrix} , \qquad Y_d \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^5 \\ \lambda^5 & \lambda^4 & \lambda^4 \\ \lambda^3 & \lambda^2 & \lambda^2 \end{pmatrix} , \qquad Y_\ell \sim \begin{pmatrix} \lambda^8 & \lambda^5 & \lambda^3 \\ \lambda^8 & \lambda^5 & \lambda^3 \\ \lambda^8 & \lambda^5 & \lambda^3 \end{pmatrix}$$

$\rightarrow$ good description of the observed hierarchies

Froggatt-Nielson Models: Sfermion Textures

the $U(1)$ charges dictate also the flavor structure of the sfermion masses

$$m^2_{\tilde{q}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} , \quad m^2_{\tilde{u}} \sim \begin{pmatrix} 1 & \lambda^2 & \lambda^3 \\ \lambda^2 & 1 & \lambda \\ \lambda^3 & \lambda & 1 \end{pmatrix} , \quad m^2_{\tilde{d}} \sim \begin{pmatrix} 1 & \lambda & \lambda \\ \lambda & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix}$$

$$m^2_{\tilde{l}} \sim \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} , \quad m^2_{\tilde{e}} \sim \begin{pmatrix} 1 & \lambda^2 & \lambda^5 \\ \lambda^2 & 1 & \lambda^3 \\ \lambda^5 & \lambda^3 & 1 \end{pmatrix}$$

$\rightarrow$ excessive FCNCs for a TeV spectrum

viable Froggatt-Nielsen type models with TeV spectrum require more elaborate flavor symmetries. e.g. $U(1)_1 \times U(1)_2$

for a PeV spectrum, simple $U(1)$ models are viable and might lead to visible effects in Kaon mixing and LFV processes

Conclusions

- avoiding model building efforts leads to a mini-split SUSY spectrum:

  $\rightarrow$ gauginos at 1 - 10 TeV
  $\rightarrow$ squarks and sleptons at 100 - 1000 TeV

- a 125 GeV Higgs can be easily accommodated

- PeV scale sfermions open up possibilities of explaining the hierachical SM fermion masses

- low energy observables can test this framework:

  $\rightarrow$ CP Violation in Kaon mixing probes already the *PeV scale*
  $\rightarrow$ several other observables (charm mixing, EDMs, $\mu \rightarrow e$ in Al) will reach sensitivity to scales of 100 - 1000 TeV in the future