Low Energy Probes of PeV Scale Sfermions

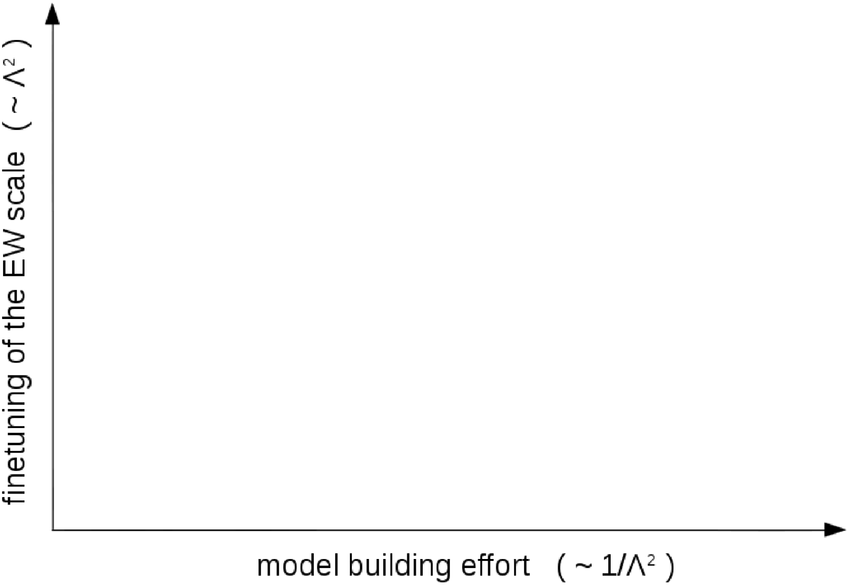
Wolfgang Altmannshofer

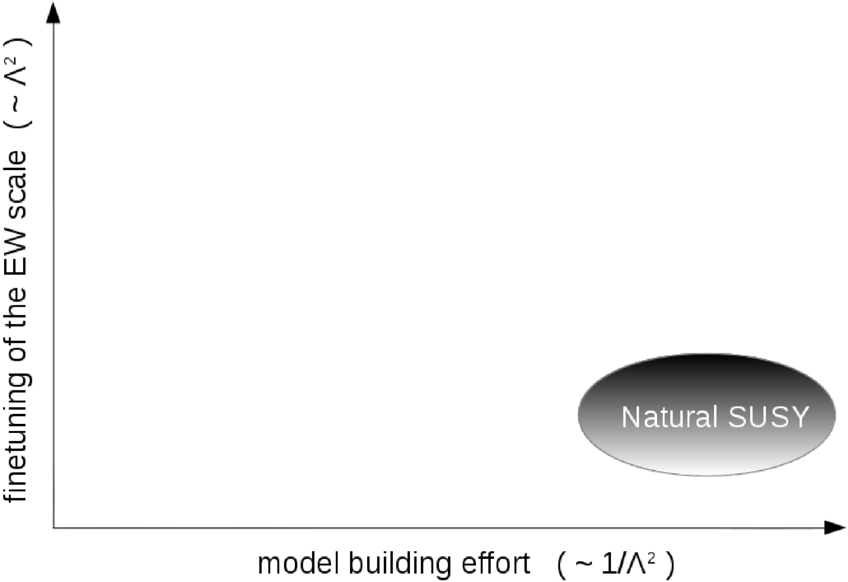
Fermilab

KITP Conference
LHC - The First Part of the Journey

July 11, 2013

based on WA, Roni Harnik, Jure Zupan
in preparation [arXiv:1307.soon [hep-ph]]


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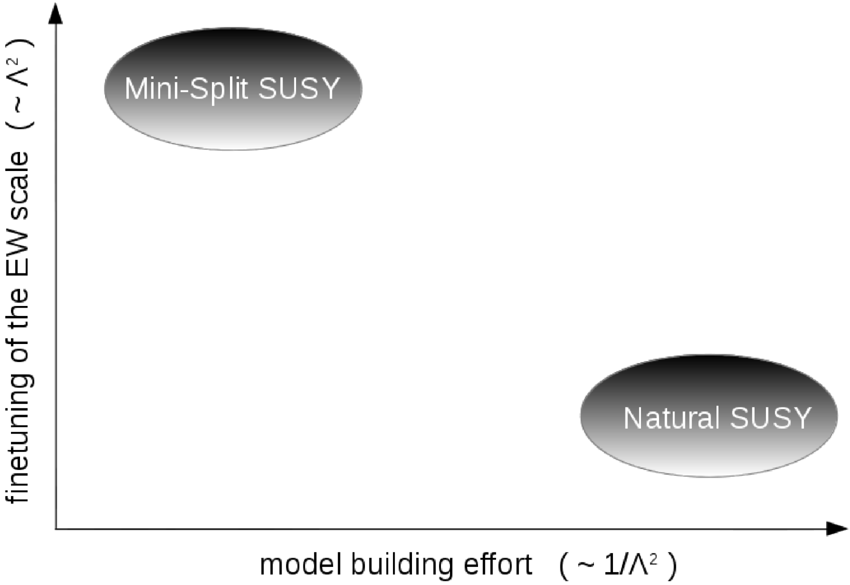
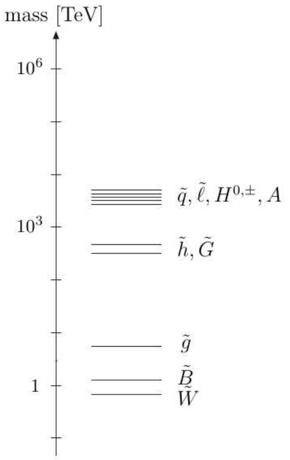

Mini-Split SUSY
Natural SUSY
finetuning of the EW scale (~ Λ²)
model building effort (~ 1/Λ²)

A "Simply Unnatural" SUSY Spectrum

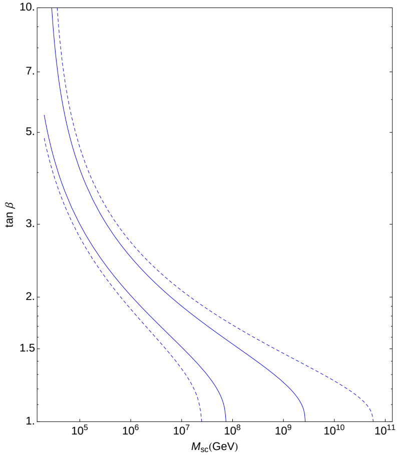


Hall, Nomura '11
Arvanitaki et al. '12
Arkani-Hamed et al. '12 ...

$$\mathcal{L}_{\rm SB} \supset \frac{1}{M_*^2}\int d^4\theta (X^\dagger X)(\Phi^\dagger\Phi + H_u H_d) - \frac{\alpha_i b_i}{4\pi}\frac{m_{3/2}}{2}\lambda_i\lambda_i - \frac{m_{3/2}}{2}\tilde{G}\tilde{G} + \int d^4\theta (H_u H_d)$$

- 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; ...

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

- $X_t = A_t - \mu / \tan\beta$ typically small
- for moderate $\tan\beta$ and scalars at O(100 TeV) – O(1000 TeV) a 125 GeV Higgs is "effortless"

Low Energy Probes of PeV Scale Sfermions

- mini-split SUSY philosophy: no model building effort

→ generic flavor structure for squarks and sleptons

$$m_Q^2 = \tilde{m}_{\tilde{q}}^2(\mathbb{1} + \delta_q)\ , \quad m_D^2 = \tilde{m}_{\tilde{q}}^2(\mathbb{1} + \delta_d)\ , \quad m_U^2 = \tilde{m}_{\tilde{q}}^2(\mathbb{1} + \delta_u)$$

$$m_L^2 = \tilde{m}_{\tilde{\ell}}^2(\mathbb{1} + \delta_\ell)\ , \quad m_E^2 = \tilde{m}_{\tilde{\ell}}^2(\mathbb{1} + \delta_e)$$

- all mass insertions δ are order 1
  (in the plots of this talk: $|\delta_{ij}| = 0.3$)

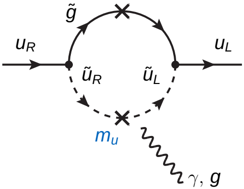
- a large host of low energy observables can probe the 0.1 - 1 PeV scale in the near future

Electric Dipole Moments	Meson Mixing	Charged Lepton Flavor Violation

Electric Dipole Moments

Flavored EDMs

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



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

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

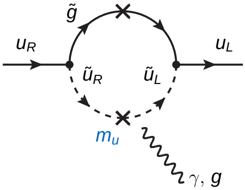
$$\tilde{d}_u \propto \frac{\alpha_s}{4\pi} \frac{m_u}{m_{\tilde{q}}^2} \frac{\mu m_{\tilde{g}}}{m_{\tilde{q}}^2} \frac{1}{\tan\beta} \log\left(\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}\right)$$

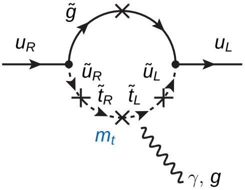
1-loop EDMs and chromo EDMs grow linearly with the μ term
quark chromo EDMs are enhanced by a large log

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)





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

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

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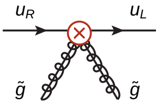
1-loop EDMs and chromo EDMs grow linearly with the μ term
quark chromo EDMs are enhanced by a large log

Parenthesis: Log Resummation

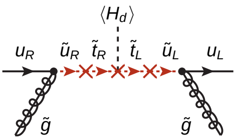
- two step matching:

  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 a CP violating 4 fermion operator

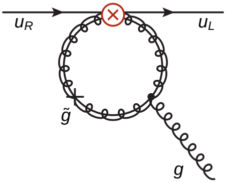


$$O_{q\tilde{g}} = \frac{g_s^2}{m_{\tilde{g}}} \Big[(\bar{q}_\alpha \tilde{g}_a)(\bar{\tilde{g}}_b \gamma_5 q_\beta) + (\bar{q}_\alpha \gamma_5 \tilde{g}_a)(\bar{\tilde{g}}_b q_\beta) \Big] f_{abc} T^a_{\alpha\beta}$$



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

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



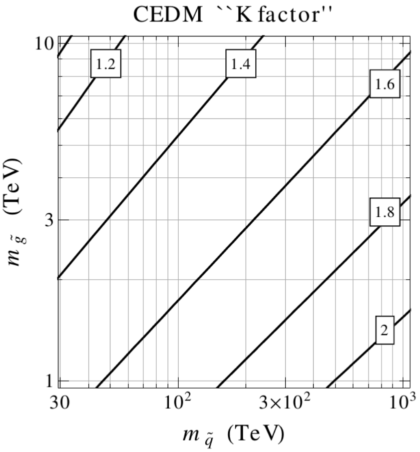
- resummed result for the CEDM

$$\tilde{d}_q(m_{\tilde{g}}) = \eta^{\frac{2}{15}} \tilde{d}_q(m_{\tilde{q}}) + \frac{18}{41}\left(\eta^{\frac{2}{15}} - \eta^{-\frac{13}{5}}\right) C_{q\tilde{g}}(m_{\tilde{q}})$$

$$\eta = \frac{\alpha_s(m_{\tilde{q}})}{\alpha_s(m_{\tilde{g}})}$$

- large "K factor"

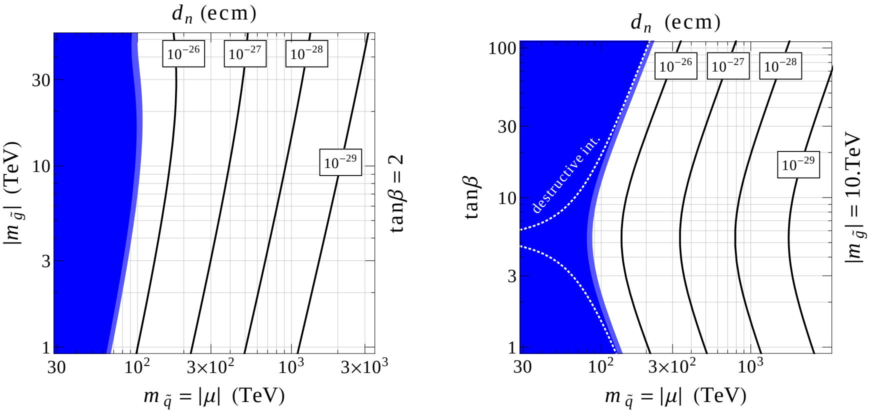
up to $\sim$ 100% correction due to the log resummation



WA, Harnik, Zupan '13

EDM Constraints

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



- assuming O(1) phases:

  electron EDM probes scales of O(30 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

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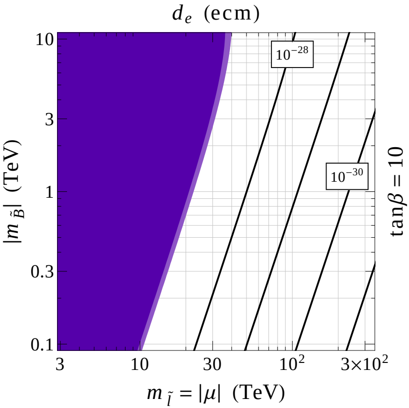

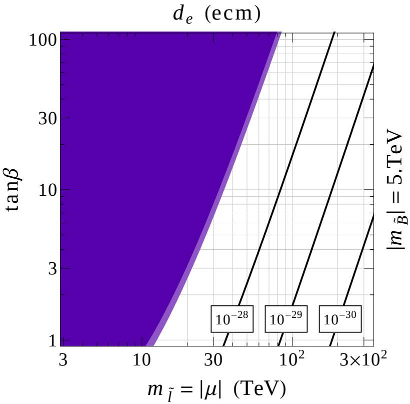

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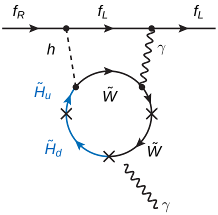
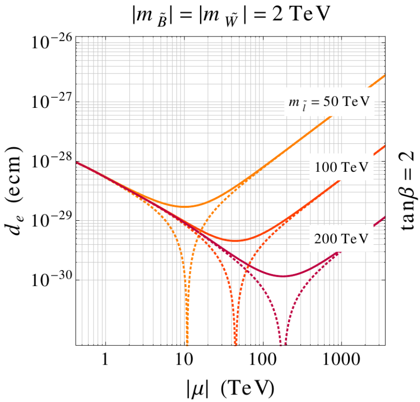
2-loop Contributions from Light Higgsinos

- 2-loop Barr-Zee diagrams can give sizable contributions to EDMs if both Winos and Higgsinos are light
  Giudice, Romanino '05





WA, Harnik, Zupan '13

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

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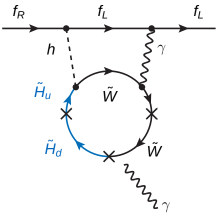

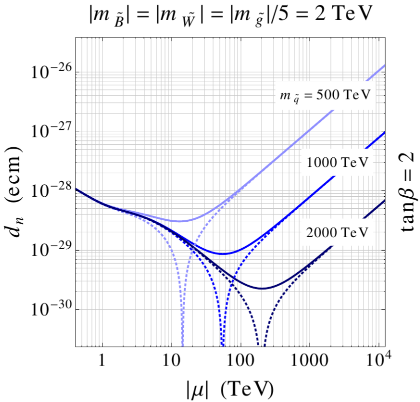

WA, Harnik, Zupan '13

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Meson Mixing

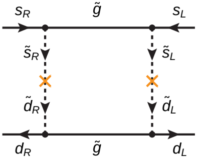
meson mixing observables probe
generic New Physics at very high scales

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

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}	Δm_K; ϵ_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}	Δm_K; ϵ_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}	Δm_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}	Δm_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}	Δm_{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}	Δm_{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}	Δm_{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}	Δm_{B_s}; $S_{\psi\phi}$

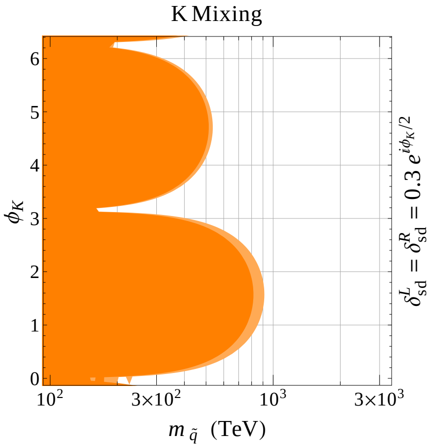
Isidori, Nir, Perez ’10

Kaon Mixing

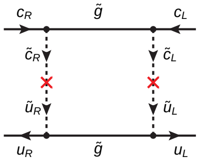


$$M_{12}^K \propto \frac{\alpha_s^2}{m_{\tilde{q}}^2} \left(\delta_{sd}^L \delta_{sd}^R\right)$$

- 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

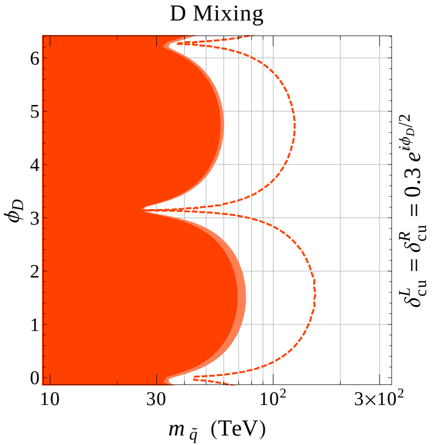


WA, Harnik, Zupan '13



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

- 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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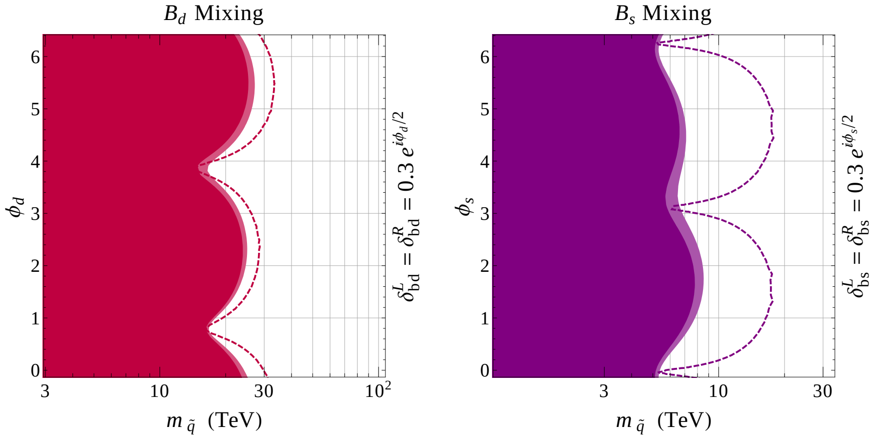
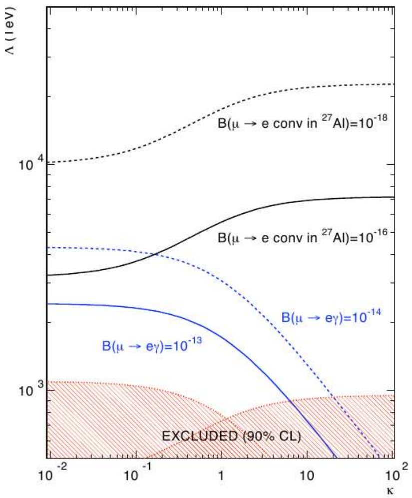


- scales of 20 - 30 TeV can be probed for O(1) phases with improved experimental results on CP violation (LHCb + Belle II)

Charged Lepton Flavor Violation

de Gouvea, Vogel '13

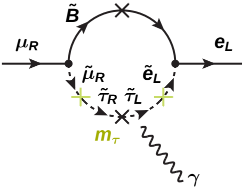


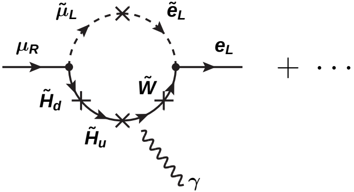
- strongest constraints come from $\mu \to e$ transitions

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

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

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





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

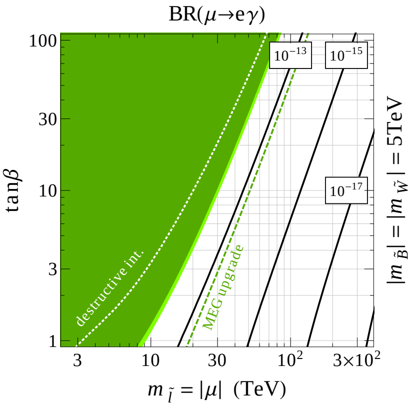
$$\mathcal{A}^{\tilde{W}}_{L} \propto \frac{\alpha_2}{4\pi} \frac{1}{m^2_{\tilde{\ell}}} \frac{m_{\tilde{W}}}{\mu} \tan\beta \, (\delta^{L}_{\mu e}) \log\left(\frac{m^2_{\tilde{W}}}{m^2_{\tilde{\ell}}}\right) + \ldots$$

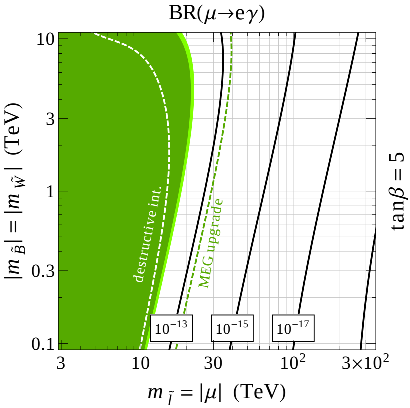
- Bino loops are enhanced by the tau mass
- grow linearly with Higgsino mass

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

Constraints from $\mu \to e\gamma$

WA, Harnik, Zupan ’13;   (see also Moroi, Nagai ’13)





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

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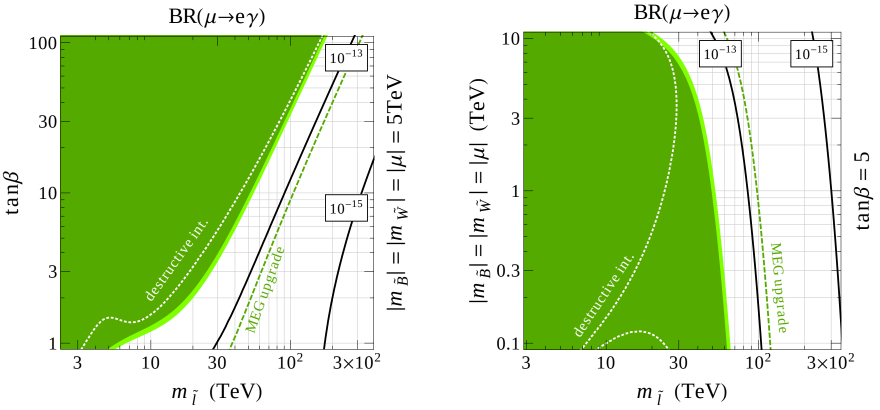

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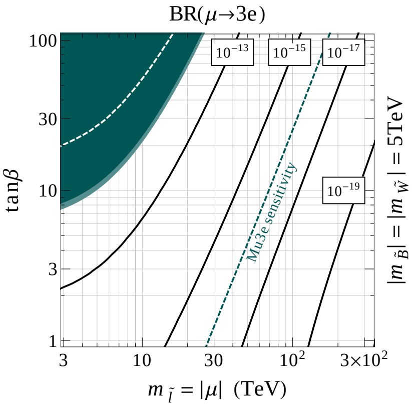
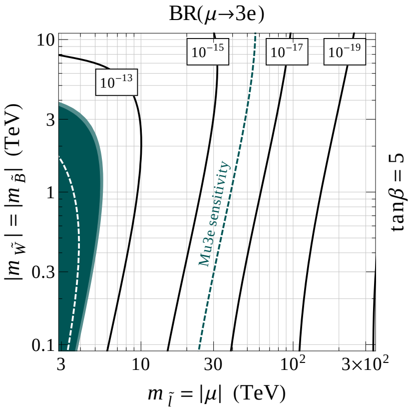


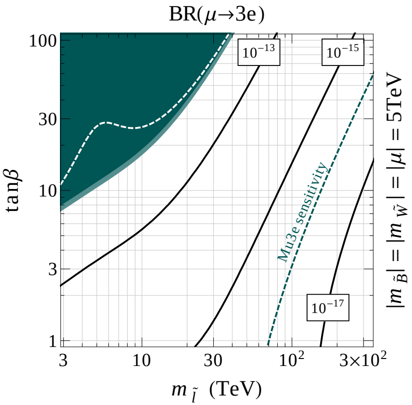


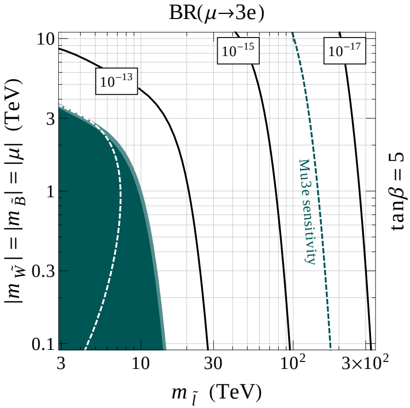
- dipole dominance:

$$\frac{\text{BR}(\mu \to 3e)}{\text{BR}(\mu \to e\gamma)} \simeq \frac{\alpha_{\text{em}}}{3\pi}\left(\log\left(\frac{m_\mu^2}{m_e^2}\right) - \frac{11}{4}\right) \simeq 6\times 10^{-3}$$

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

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





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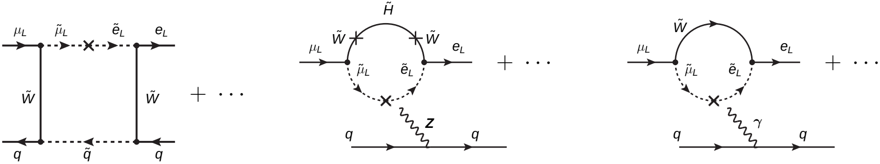
- ultimate sensitivity of Mu3e would be stronger than the bounds from a MEG upgrade contributions from dipoles, boxes, Z penguins, and photon penguins

dipoles are dominant for large $\tan\beta$



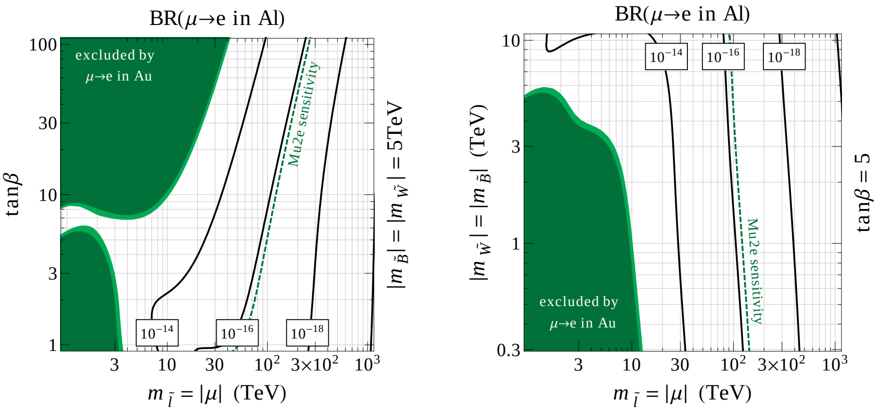
$$\mathcal{A}^{\text{box}} \propto \frac{\alpha_2^2}{\max(m_{\tilde{\ell}}^2, m_{\tilde{q}}^2)} (\delta_{\mu e}^L)$$

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

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

- usually negligible in mini-split SUSY
- log enhanced for light Higgsinos
- log enhanced for light Winos; typically dominant for low $\tan\beta$

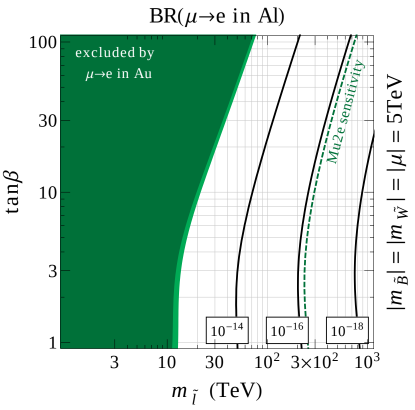
WA, Harnik, Zupan '13; (see also Moroi, Nagai '13)

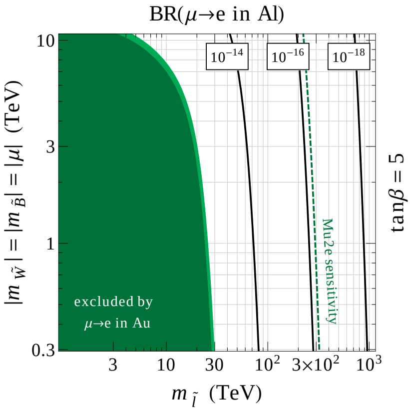


- current constraints are still weak, of order 10's of TeV
- Mu2e can improve limits down to BR $\lesssim 10^{-16} - 10^{-17}$

Constraints from $\mu \to e$ Conversion

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





- current constraints are still weak, of order 10's of TeV
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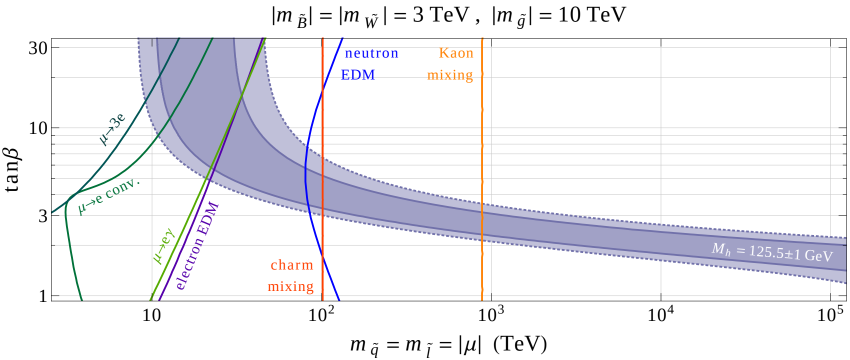
Summary of Current Constraints

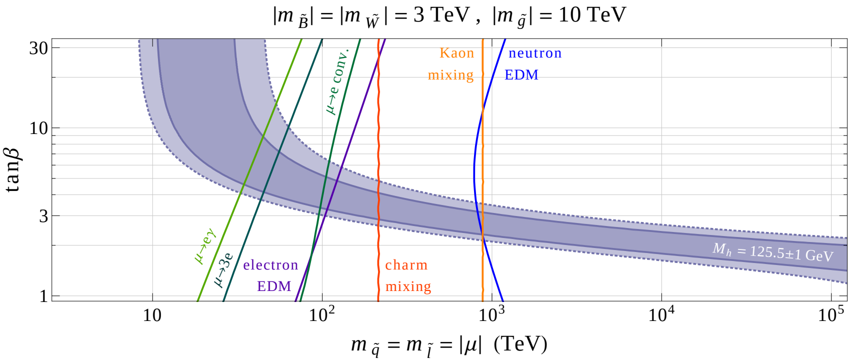


- only low energy process that currently probes O(1000 TeV) squarks is CP violation in Kaon mixing
- CP violation in charm mixing and the neutron EDM reach up to O(100 TeV)

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

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

- generic squark flavor violation opens up the possibility of radiatively induced quark masses

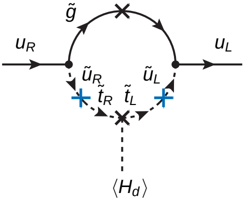
- low energy observables can test this framework:

  $\rightarrow$ 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

Back Up

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 $Y_t = O(1)$

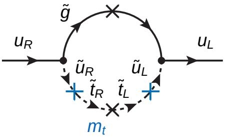


$$\Delta m_u = \frac{\alpha_s}{4\pi} \frac{8}{9} \frac{m_{\tilde{g}} \mu}{m_{\tilde{q}}^2} m_t \frac{1}{t_\beta} (\delta^L_{ut} \delta^R_{tu})$$

- 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
- strong correlation with “flavored EDMs”

EDMs and Radiative Fermion Masses

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



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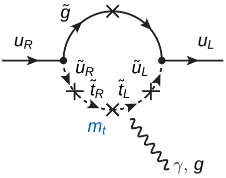
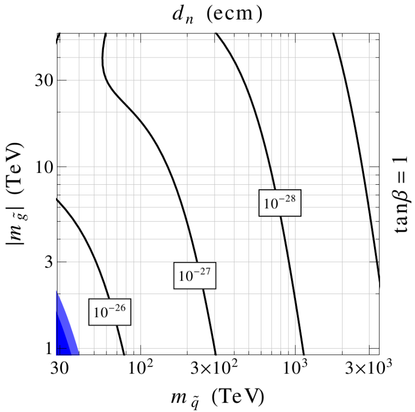


- assuming that the up quark mass comes fully from SUSY loops

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



WA, Harnik, Zupan '13