Vacuum Stability Bounds on Lepton Flavor Violating Tri-linear Soft-terms in the General MSSM

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in collaboration w/ O. Eberhardt, A. Paul, and L. Silvestrini
[arXiv:1607.0XXXX]
Mass of the Higgs is around 125 GeV
Higgs is parity even and spin-0
Higgs properties in Run-1 look “SM-like”
Higgs Discovery at LHC

- Mass of the Higgs is around 125 GeV
- Higgs is parity even and spin-0
- Higgs properties in Run-1 look “SM-like”

Discovery of 125 GeV Higgs at LHC puts constraints on the MSSM parameters.
Testing SUSY
Direct Search

producing sparticles at the colliders like LHC, ILC

insists constraints on sparticle masses like

• gluinos are ruled out up to masses 1–1.25 TeV

• stops, sbottoms are > 600 GeV

• first two generations of squarks are > 0.9 TeV
Scenarios A1 and A2 represent models of gluino pair production resulting in the $t\bar{t}$ with third-generation squarks. The decay chains under consideration are shown schematically.

Next, we present limits on the parameter spaces of four R-parity-conserving SUSY models. These limits are calculated using simulated proton-proton (pp) collisions at the LHC. The acceptance, including branching fractions, at the median is 0.29 pb for 90 TeV collisions.

The results from SR1 and SR2 are used to set limits on the cross section for same-sign top-quark production, which is ruled out up to masses 1–1.25 TeV. Stops, sbottoms are > 600 GeV, and first two generations of squarks are > 0.9 TeV.
Testing SUSY

Direct Search

producing sparticles at the colliders like LHC, ILC

Indirect Search

Flavor

sparticles in the loops of the SM flavor processes like, $\text{Br}(b \to s\gamma)$, $\text{Br}(B_s \to \mu\mu)$, $\text{Br}(\mu \to e\gamma)$ etc.

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dark matter

presence of new vertices → efficient annihilation

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sparticles in the loops of the SM flavor processes like, \( \text{Br}(b \rightarrow s\gamma) \), \( \text{Br}(B_s \rightarrow \mu \mu) \), \( \text{Br}(\mu \rightarrow e\gamma) \) etc.

flavor

presence of new vertices \( \rightarrow \) efficient annihilation

impact parameter search

puts constraints on masses and couplings
SUSY Flavor Violation

- In exact SUSY, equal masses for particles and its super-partners.

- To realize in nature, SUSY must be broken.

- 3 kinds of soft-breaking terms introduced in the Lagrangian.

- soft-masses and tri-linear couplings => New sources of flavor violation. Flavor-changing neutral currents (e.g. $b \rightarrow s \gamma$, $\mu \rightarrow e \gamma$)

\[ \mathcal{L}_{\text{soft}}^{\text{MSSM}} = -\frac{1}{2}\left( M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + \text{c.c.} \right) \]

\[ -\left( \tilde{u}^a \tilde{Q} H_u - \tilde{d}^a \tilde{Q} H_d - \tilde{e}^a \tilde{L} H_d + \text{c.c.} \right) \]

\[ -\tilde{Q}^\dagger m_Q^2 \tilde{Q} - \tilde{L}^\dagger m_L^2 \tilde{L} - \tilde{u}^a m_u^2 \tilde{u}^a - \tilde{d}^a m_d^2 \tilde{d}^a - \tilde{e}^a m_e^2 \tilde{e}^a \]

\[ -m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c.}) \]
Charge breaking constraint

Soft-breaking tri-linear term in the Lagrangian

\[ \mathcal{L}_{\text{soft}} = -\tilde{e} a^l \tilde{L} H_d + \text{c.c.} \]

In the presence of \( H_d, \tilde{\tau}_L \) and \( \tilde{\mu}_R \)

\[ \mathcal{V} = (m_{H_d}^2 + \mu^2) |H_d|^2 + m_{\tilde{\mu}_R}^2 |\tilde{\mu}_R|^2 + m_{\tilde{\tau}_L}^2 |\tilde{\tau}_L|^2 
- (A^l_{23} H_d \tilde{\mu}_R^* \tilde{\tau}_L + \text{c.c.}) + Y_{\tau}^2 |H_d \tilde{\tau}_L|^2 + Y_{\tilde{\mu}}^2 |H_d \tilde{\mu}_R|^2 
+ \frac{g_1^2}{8} (2|\tilde{\mu}_R|^2 - |\tilde{\tau}_L|^2 - |H_d|^2)^2 + \frac{g_2^2}{8} (|\tilde{\tau}_L|^2 - |H_d|^2)^2 \]

the CCB minima of the potential around the D-flat direction

\[ |H_d| = |\tilde{\tau}_L| = |\tilde{\mu}_R| \equiv a \]

\[ \mathcal{V} = (m_{H_d}^2 + \mu^2 + m_{\tilde{\mu}_R}^2 + m_{\tilde{\tau}_L}^2) a^2 - 2|A^l_{23}| a^3 + (Y_{\tilde{\mu}}^2 + Y_{\tau}^2) a^4 \]
Charge breaking constraint

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\[ V = (m_{H_d}^2 + \mu^2) |H_d|^2 + m_{\mu_R}^2 |\tilde{\mu}_R|^2 + m_{\tau_L}^2 |\tilde{\tau}_L|^2 \]
\[ - (A_{23}^l H_d \tilde{\mu}_R^* \tilde{\tau}_L + c.c.) + Y_\tau^2 |H_d \tilde{\tau}_L|^2 + Y_\mu^2 |H_d \tilde{\mu}_R|^2 \]
\[ + \frac{g_1^2}{8} (2|\tilde{\mu}_R|^2 - |\tilde{\tau}_L|^2 - |H_d|^2)^2 + \frac{g_2^2}{8} (|\tilde{\tau}_L|^2 - |H_d|^2)^2 \]

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Soft-breaking tri-linear term in the Lagrangian

\[ \mathcal{L}_{\text{soft}} = -\tilde{e} a^l \tilde{\phi} H_d + \text{c.c.} \]

In the presence of \( H_d, \tilde{\tau}_L \) and \( \tilde{\mu}_R \)

\[ \mathcal{V} = (m_{H_d}^2 + \mu^2) |H_d|^2 + m_{\tilde{\mu}_R}^2 |\tilde{\mu}_R|^2 + m_{\tilde{\tau}_L}^2 |\tilde{\tau}_L|^2 \\
- (A_{23}^l H_d \tilde{\mu}_R^* \tilde{\tau}_L + \text{c.c.}) + Y_{\tau}^2 |H_d \tilde{\tau}_L|^2 + Y_{\mu}^2 |H_d \tilde{\mu}_R|^2 \\
+ \frac{g_1^2}{8} (2|\tilde{\mu}_R|^2 - |\tilde{\tau}_L|^2 - |H_d|^2)^2 + \frac{g_2^2}{8} (|\tilde{\tau}_L|^2 - |H_d|^2)^2 \]

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In the presence of \( H_d, \tilde{\tau}_L \) and \( \tilde{\mu}_R \)

\[ \mathcal{V} = (m_{H_d}^2 + \mu^2)|H_d|^2 + m_{\mu_R}^2 |\tilde{\mu}_R|^2 + m_{\tau_L}^2 |\tilde{\tau}_L|^2 \]

\[ - (A_{23}^l H_d \tilde{\mu}_R^* \tilde{\tau}_L + \text{c.c.}) + Y_\mu^2 |H_d\tilde{\tau}_L|^2 + Y_\tau^2 |H_d\tilde{\mu}_R|^2 \]

\[ + \frac{g_1^2}{8} \left( 2|\tilde{\mu}_R|^2 - |\tilde{\tau}_L|^2 - |H_d|^2 \right)^2 + \frac{g_2^2}{8} \left( |\tilde{\tau}_L|^2 - |H_d|^2 \right)^2 \]

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absolute stability

Quiros '94, Kusenko et al. '96, Carena et al. '96

meta-stability

meta-stability: $\Gamma / V \sim H_0^4$

Claudson et al. '83

$\Gamma = A e^{-S[\phi]}$

$|A_{23}^l|^2 \leq Y_T^2 (m_{H_d}^2 + \mu^2 + m_{H_R}^2 + m_{H_L}^2)$

$S[\phi] \geq 400$

Coleman et al. '77

$|A_{23}^l| <$

$|A_{23}^l| >$

Quiros '94, Kusenko et al. '96, Carena et al. '96

$A \sim 2 |A_{23}^l| / Y_T^2$

$T=H=Q$

$|A_{23}^l| <$

$|A_{23}^l| >$
BR(\tau \rightarrow \mu \gamma)

In the presence of \text{A}^{l_{23}} and \text{A}^{l_{32}} the branching fraction is

\text{BR}(\tau \rightarrow \mu \gamma) \propto \frac{M_1^2 \tan \beta^2}{|\mu|^2} \left[ (\delta_{23}^{LR})^2 \left| \frac{m_R m_L}{m_\tau \mu \tan \beta} I_B \right|^2 + (\delta_{23}^{RL})^2 \left| \frac{m_R m_L}{m_\tau \mu^* \tan \beta} I_B \right|^2 \right]

\delta_{23}^{RL} \equiv \frac{A_{23}^{l} \langle H_d^0 \rangle}{m_\tilde{l}^2} \quad m_\tilde{l} \equiv \sqrt{m_R^2 m_L^2}
• Flexible open-source C++ code to do calculations with various observables in the SM and beyond:
  • Simple user-defined models and/or observables
  • Stand-alone or library modes to compute single observables.
  • Optional Bayesian fitting framework to do global statistical analyses (run-time optimized, parallelized; can be replaced by a different one)

For more details, look at the talk by J. de Blas this afternoon
$\tan \beta = 5$

Current bound

Belle-II projection
\( \tan \beta = 5 \)

**Current bound**

**Belle-II projection**

\( (\delta_{23})_{RL} \)

**stable**

\( m_{\tilde{t}} \text{ [TeV]} \)
$\tan \beta = 5$

- **Current bound**
- **Belle-II projection**

- **Stable**
- **Meta-stable**

$(\delta_{23})_{RL} \sim$ $10^{-2}$

$m_{\tilde{t}}$ [TeV]
\( \tan \beta = 10 \)

- meta-stable
- stable

Current bound

Belle-II projection
\( \tan \beta = 30 \)

- Meta-stable
- Stable

Current bound
Belle-II projection

\( (\delta_{23})_{RL} \) vs. \( m_{\tilde{t}} \) [TeV]
Conclusion

* Unlike the FCNC bounds, the strength of the CCB and UFB bounds does not decrease as the scale of supersymmetry breaking increases.

* meta-stability relaxes the bounds on the flavor violating tri-linear couplings.

* Future flavor factories, e.g. Belle-II will be able to probe large factions of the meta-stable region for $A_{123}^1$. 
Thank You!!
Extras
Summary of CMS SUSY Results* in SMS framework

CMS Preliminary

For decays with intermediate mass, 
\[ m_{\text{intermediate}} = x \cdot m_{\text{mother}} + (1-x) m_{\text{LSP}} \]

Mass scales [GeV]

LSP mass [GeV]

\[ \tilde{t}\tilde{t} \text{ production, } \tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0 \]

CMS Preliminary

\[ \sqrt{s} = 8 \text{ TeV} \]

\[ \tilde{t}\tilde{t} \text{ production, } \tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0 \]

*Observed limits, theory uncertainties not included

Only a selection of available mass limits

Probe "up to" the quoted mass limit
ATLAS SUSY Searches - 95% CL Lower Limits

Status: July 2015

$\sqrt{s} = 7, 8$ TeV

**Model**

- $e^+\mu^-\gamma$, $e^+\mu^-\tau^-$
- $e^+\mu^-\tau^-$, [R hadron]
- $e^+\mu^-$, long-lived $\tau$
- $e^+\mu^-$, long-lived $\tau$
- $e^+\mu^-$, [R hadron]
- $e^+\mu^-$, [R hadron]
- $e^+\mu^-$, [R hadron]
- $e^+\mu^-$, [R hadron]

**Jets**

- $3 \to 3$ jets
- $3 \to 2$ jets
- $3 \to 2$ jets
- $3 \to 2$ jets
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- $3 \to 2$ jets
- $3 \to 2$ jets
- $3 \to 2$ jets

**Reference**

- 1405.5086
- 1501.07110
- 1507.05493
- 1502.05686
- 1503.03290
- 1507.05525

**Mass scale (TeV)**

- 1.0

**ATLAS**

- #b= TeV, 20 fb
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**Legend**

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**Observed limits**

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**Expected limits**

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**All limits at 95% CL**

**m_{T1} [GeV]**

- 0
- 100
- 200
- 300
- 400
- 500
- 600
- 700
- 800

**m_{chi10} [GeV]**

- 0
- 100
- 200
- 300
- 400
- 500
- 600
- 700
- 800

- Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus $5\sigma$ theoretical signal cross section uncertainty.

- $\chi$ is the neutralino, $\tilde{t}$ is the first stops, $\tilde{b}$ is the first bino.

- Reference: 1501.07110

- Preliminary
• The Standard model has passed almost all the experimental tests over decades.

• In spite of these successes SM has quite a few shortcomings, like
  • Neutrino mass
  • Dark matter
  • Baryon asymmetry of the Universe
  • Fine tuning ....

• To address these issues SM has to be extended.

• Many possible extensions are proposed, like SUSY, Composite Higgs, Extra Dimensions ...
Supersymmetry

- Symmetry between fermions and bosons. One supersymmetric multiplet for every standard model particle.

- In conserved SUSY particles in a multiplet share the same couplings and masses.

- To realize in nature SUSY must be broken.
Advantages of SUSY

- protects the Higgs mass by introducing a new physics scale.
- calculable and thus in principle, predictable.
- provides a viable Dark Matter candidate if R-parity is conserved.
- lightest Higgs boson can be SM-like in regions of parameter space.
- unifies the SM gauge couplings.