Remarks on the Higgs and on supersymmetry

Yuval Grossman

Cornell

What did I learn from you?

How to write papers...

SLAC-PUB-7423
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Sneutrino Mixing Phenomena

Yuval Grossman [a] and Howard E. Haber [b]

[a] *Stanford Linear Accelerator Center*
Stanford University, Stanford, CA 94309

[b] *Santa Cruz Institute for Particle Physics*
University of California, Santa Cruz, CA 95064

Abstract

In any model with nonzero Majorana neutrino masses, the sneutrino and antisneutrino of the supersymmetric extended theory mix. We outline the conditions under which sneutrino-antisneutrino mixing is experimentally observable. The mass-splitting of the sneutrino mass eigenstates and sneutrino oscillation phenomena are considered.

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- Our paper received, 1/14/97
- Those who scoped us, 1/16/97

Outline

- Higgs
  - How can we tell how many Higgses there are?
  - How can we check for CPV in $H \to \gamma\gamma$?
- MFV SUSY
  - The model
  - Experimental signatures

Higgs

Higgs

- There are indications for a Higgs around 125 GeV
- Still room for a lot of non-standard Higgs
  - Couplings
  - Width
  - CP properties and CPV
  - Number of states

How many Higgses?

YG, Surujon, Zupan, 1301.0328; See also Haber et. al. 1211.3131

- Central values are still away from the SM
- How can we check if it comes from more than one resonance?

P\D	$\gamma\gamma$	WW^*	$\tau\bar{\tau}$	ZZ^*	$b\bar{b}$
gg	1.6 ± 0.35	0.8 ± 0.3	1.2 ± 0.8	1.0 ± 0.3	–
VBF	2.1 ± 0.9	-0.2 ± 0.6	0.3 ± 0.7	–	–
VH	1.9 ± 2.6	-0.3 ± 2.1	1.0 ± 1.8	–	0.8 ± 0.6
$t\bar{t}h$	–	–	–	–	< 3.8

Rank

- Consider n_R non-interfering resonances, with different couplings
- Consider the production and decay matrix, R_{ij}
- For one resonance $R_{ij} = \sigma_i \Gamma_j$
- The rank of R is 1
- What can we say about the rank if there are more resonances?

Some linear algebra

Consider 4 real vectors, a, b, c, d

- The rank of $a_i b_j$ is 1
- The rank of $a_i b_j + c_i d_j$ is 2
- The rank of $|a_i b_j + e^{i\alpha} c_i d_j|^2$ is 3
- For complex vectors the rank of $|a_i b_j + c_i d_j|^2$ is 4
- One can generalized the above results

$$2 \to n \qquad 3 \to \frac{n(n+1)}{2} \qquad 4 \to n^2$$

Rank

Consider again the case of n_R resonances

- Without interferences

$$\mathrm{Rank}(R) = n_R$$

- With interferences

$$\mathrm{Rank}(R) = n_R^2$$

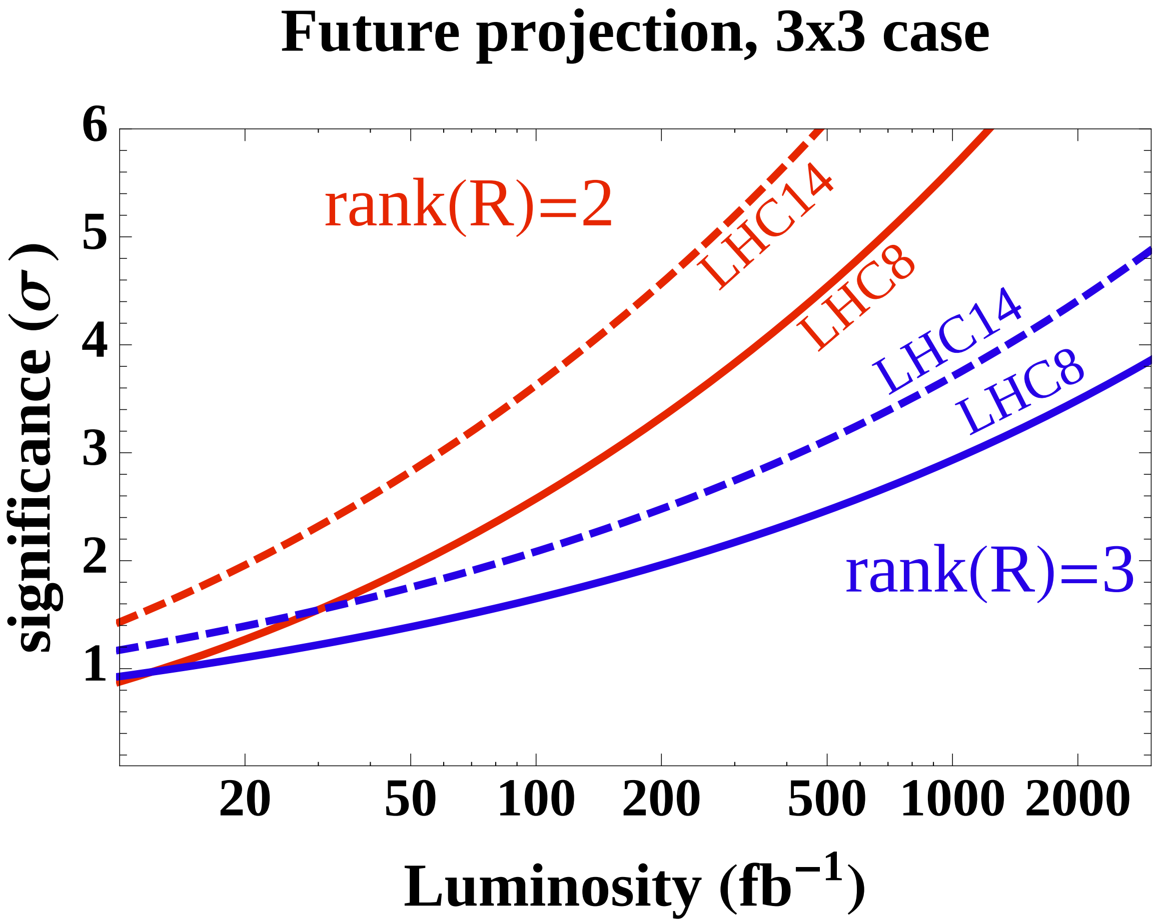
- If the phases are universal (CP conserving case)

$$\mathrm{Rank}(R) = n_R(n_R + 1)/2$$

- When CP is approximate, or when interference effects are small, the “extra” singular values are “small”

Future sensitivity

Assuming current central values and no correlations



CPV in Higgs decay

How to look for CPV?

Voloshin, 1208.4303; Bishara, YG, Harnik, Robinson, Shu, Zupan, 1301.nnnn

Q: How to tell a scalar from a pseudoscalar?

A: By some angular distributions.

- It can be done best in $H \to ZZ \to 4\ell$
- The fact that the Higgs is assumed to be a scalar is used in the $H \to WW$ analyses
- How $H \to \gamma\gamma$ changes if we have CPV in the Higgs sector?

$$A = \hat{c}\frac{\alpha}{\pi v} h \langle F_{\mu\nu} F^{\mu\nu} \rangle + \frac{\tilde{c}}{2}\frac{\alpha}{\pi v} h \langle F_{\mu\nu} \tilde{F}^{\mu\nu} \rangle$$

- In the SM $\tilde{c} = 0$. It can be finite with new CPV physics

Angular distribution

- Consider $H \to ZZ$ with ϕ the angle between the polarization of the two Zs

$$\frac{d\Gamma}{d\phi} \propto \left|\cos(\phi + \xi)\right|^2 \qquad \xi \equiv \tan^{-1}(\tilde{c}/\hat{c})$$

- This is a general result for any vector boson
- How can we measure the polarization?
  - In $H \to ZZ \to 4\ell$, via the directions of the charged leptons
  - How can we do it in $H \to \gamma\gamma$?

Higgs Bethe-Heitler

We need to look for converted photons

- The BH process $\gamma \to e^+e^-$ probe the photon polarization
- The e^+e^- plane is correlated with the polarization
- The angle between the plans generated by the two pairs, is sensitive to ξ
- Under some assumptions

$$\frac{d\Gamma}{d\phi} \propto (A + B\cos[2(\xi + \phi)])$$

Measuring the polarization

- Theoretically, this is a $3 \to 6$ process, it is an EPR type of experiment
- One cannot work in the Higgs rest frame and boost, as the detector is part of the process
- The opening angle is very small, typically 10^{-4}
- About half of the photons are converted, and they are used in the analysis
- It is for sure hard, but maybe it can be done

MFV SUSY

SUSY

- The future does not look bright
- The little hierarchy problem is more like a teenager
- Flavor problems
- Proton decay

Can we help?

How to save SUSY?

- Normal susy: strong bounds on sparticle masses
- We need to hide it and have light stops
- Flavor bounds make it harder
- Many ideas. Our idea is to give up on R-parity and use MFV instead
  - The LSP decays fast, and thus most bounds are avoided
  - We get R-parity as an approximate accidental symmetry
  - Due to MFV, flavor bounds are satisfied

RPV

- Recall, R-parity is used to kill baryon and lepton number violating terms

$$\mu L H_u + \lambda LLE + \lambda' LQD + \lambda'' UDD$$

- R-parity also takes care of soft susy breaking terms
- R-parity is what set SUSY phenomenology (missing energy, neutral LSP)
- We can have tiny RPV, but the question is why and how

MFV

Minimal Flavor Violation (MFV)

- In an EFT way of thinking, let us define MFV as a guide to the full theory
- The NP flavor structure comes from the SM Yukawas
- We think of the Yukawas as small (beside the top) so we have approximate flavor symmetries
- MFV basically solves the NP flavor problem: the NP operators are suppressed by small Yukawas

MFV: Definition

- Without Yukawas the flavor group is

$$U(3)_Q \times U(3)_U \times U(3)_D$$

- The Yukawas are spurions
- Recall $U(3) = SU(3) \times U(1)$. The diagonal $U(1)$ is baryon number

$$Q(3,1,1) \quad U(1,3,1) \quad D(1,1,3) \quad Y_D(3,1,\bar{3}) \quad Y_U(3,\bar{3},1)$$

- The idea of MFV is that the Yukawas are the only spurions that break the flavor symmetry

MFV: can we use it for more?

MFV is a nice idea to solve the NP flavor problem

Q: Can we use it to solve other problems or make other predictions?

A: Yes!

MFV instead of R-parity

Nikolidakis and Smith, 0710.3129; Csaki, YG, Heidenreich, 1111.1239

- We consider only renormelizable terms
- We impose $SU(3)$ MFV. The $U(1)$ is baryon number, and it is “unfair” to impose it
- We can get the B violating term with three Ys

$$(Y_u Y_d Y_d)\,(UDD) \quad \Rightarrow \quad \lambda^{''} \sim Y_u Y_d Y_d$$

- Using powers of Y_e we cannot get the L violating terms due to an accidental conserved Z_3 lepton number
- The L violating terms can be generated if we have neutrino masses

Huge suppression!

Bounds from $\Delta B = 2$ processes

Without massive neutrinos, the proton is stable

- Bounds from $n - \overline{n}$ oscillation and dinucleon decay

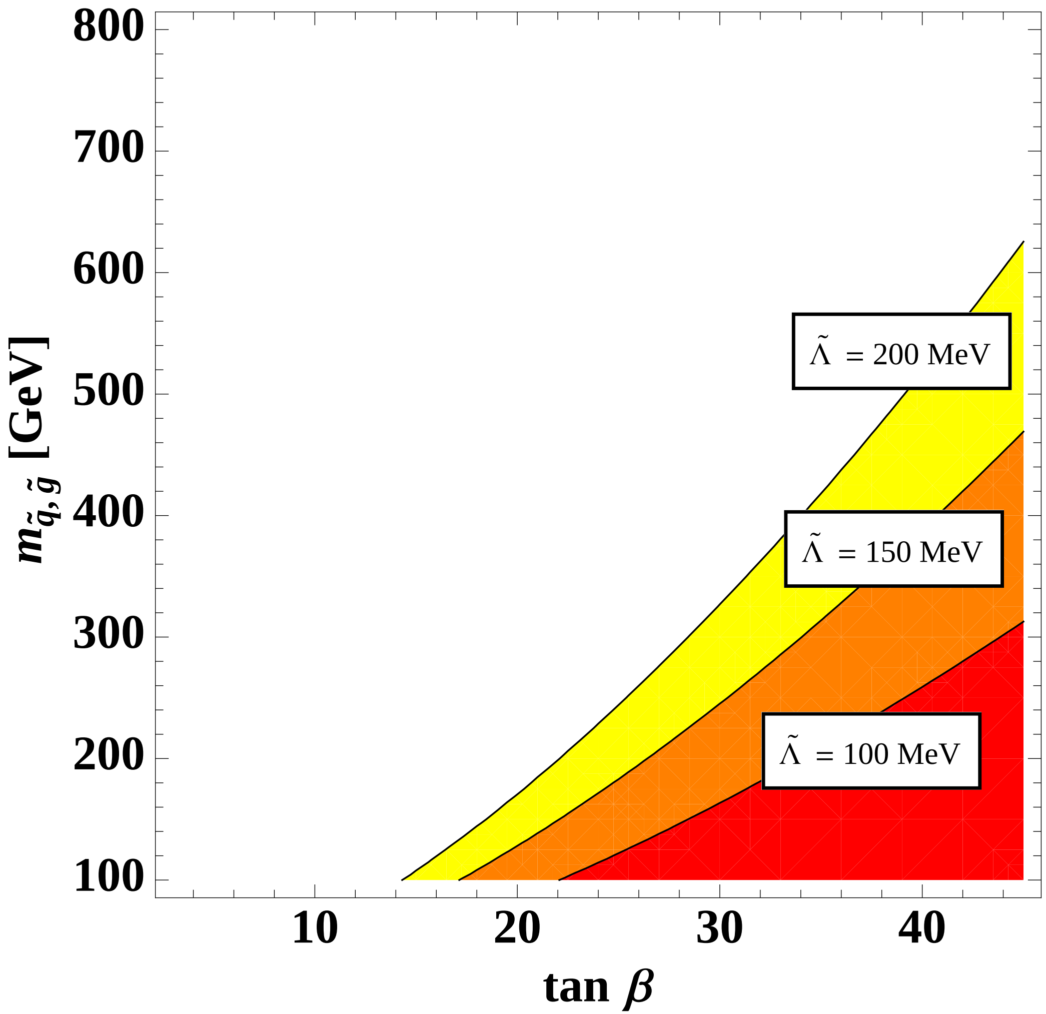
$$^{16}O \rightarrow ^{14}C + K^- + K^-$$

- The dinucleon bounds are stronger (it involves second generation quarks)

$$\tau \sim 1.7 \times 10^{32}\ \text{years} \left(\frac{\tilde{m}}{100\ \text{GeV}}\right)^{10} \left(\frac{17}{\tan\beta}\right)^{16}$$

- Already cut the parameter space and it is a good probe of the model

Low energy bounds



Neutrino masses

- With only the Yukawas, the neutrinos are exactly massless
- This is due to a residual Z_3 lepton number symmetry
- We need to add something. The simplest modification is to add heavy RH neutrinos
- We also add one more spurion that come with the RH mass matrix
- We can then generate neutrino masses and the L violating terms

MFV for proton decay

- The small Yukawas and need for neutrino mass can save the proton
- The problem is the bilinear RPV term

$$\tau_P \sim 10^{23}\,\mathrm{s} \times X^2 \tan^8\beta \qquad X \equiv \frac{M_R^2 m_\nu}{\Lambda_R}$$

We need some extra suppression from the neutrino sector

- It is model dependent as it depends on how the bilinear term is generated

Experimental signals

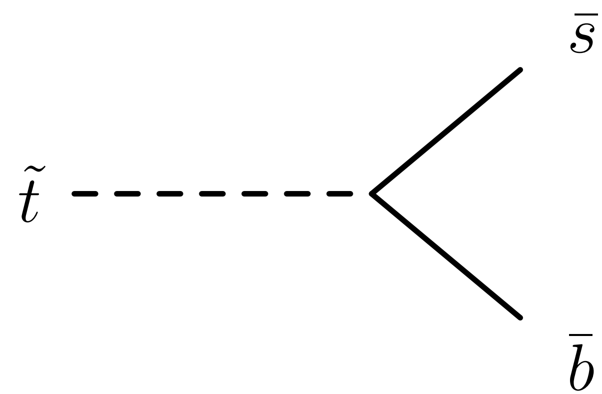
LHC signals

- Production of sparticle is still mainly pair wise
- Beside the LSP, most decays are like in RPC susy
- LSP may not be neutral
- The phenomenology very much depend on the LSP
  - Stop or sbottom (2 body decay)
  - gluino, neutralino or chargino (3 body decay)
  - Sleptons (4 body decay)

Stop LSP

Franceschini, Torre, 1212.3622; Berger, Csaki, YG, Lee, in progress

Stop decay via RPV vertex



- $c\tau \sim 10^{-6} m$ strongly depends on the parameters
- No secondary vertex (in "most" of the cases)
- The stop decay via ϵ QCD vertex, not a normal jets
- Can we find such events? We hope so
- Light gluino is excluded from same sign top searches

Asano, Rolbiecki, Sakurai, 1209.5778

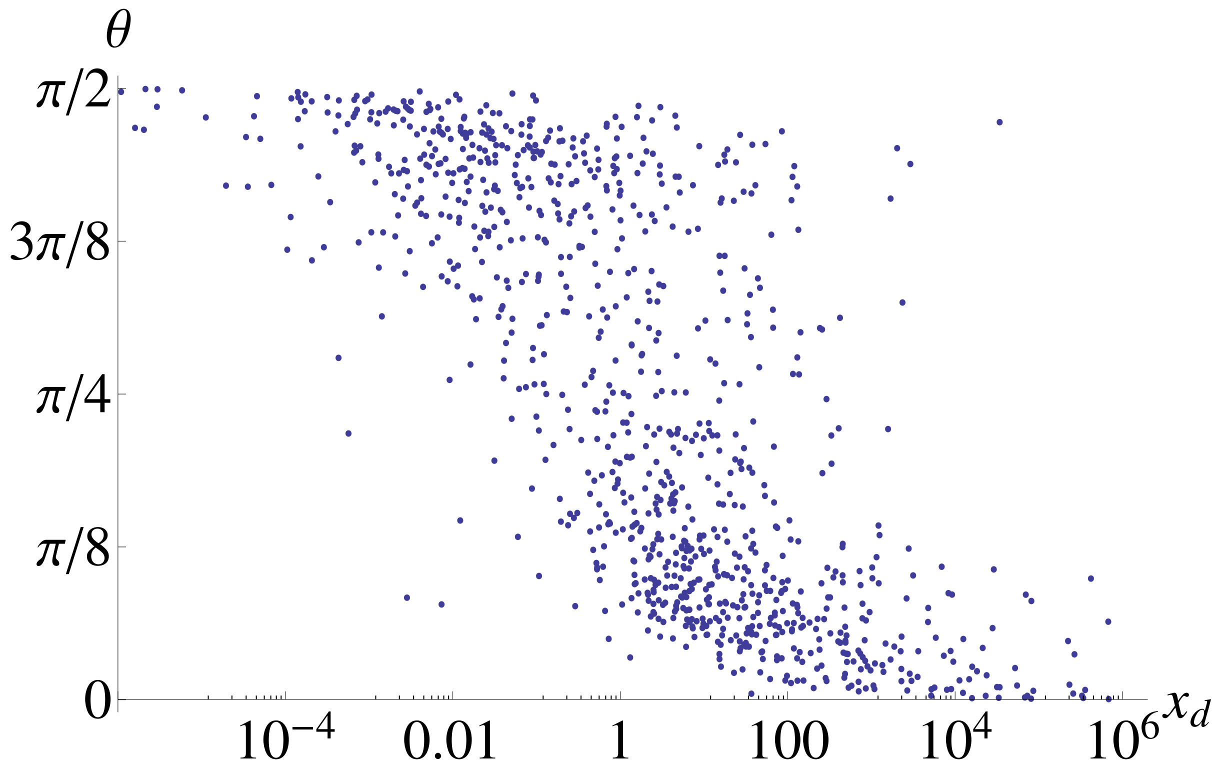
Sbottom LSP: mesino oscillation

Sarid, Thomas, hep-ph/9909349; Berger, Csaki, YG, Heidenreich, 1209.4645

- Long lived squarks hadronized, and then we can have mesino oscillation (with $\tilde{B} = \tilde{b}\bar{d}$)
- Since the sbottom decay to top, we can have same sign top signal which is a very clean signal
- Unlike meson oscillation, in SUSY we can have mesino oscillation at tree level via gluino exchange

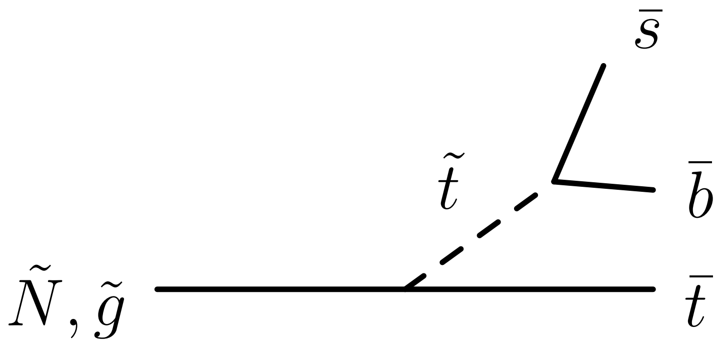
$$\Delta m = g_s^2 \left| (U^D_{d_L,1})^2 + (U^D_{d_R,1})^2 \right| f^2_{\tilde{B}} \left(1 - \frac{1}{N_c^2} \right) \frac{m_{\tilde{g}}}{m^2_{\tilde{g}} - m^2_{\tilde{b}}}$$

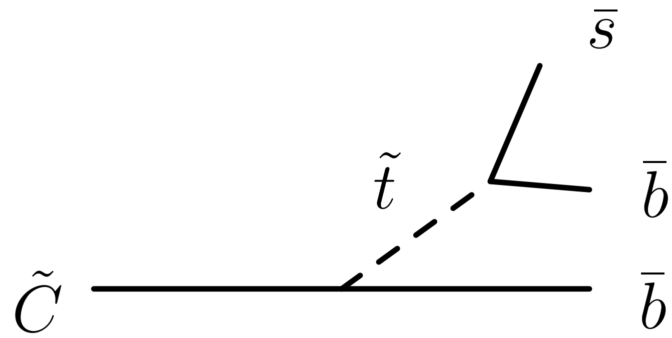
Oscillation probability



- Large part of parameter space have $x \gtrsim 1$ and we can get same sign lepton signal

Chargino or neutralino as LSP





- t and b or two b
- $c\tau \sim 10^{-5} m$. Can get secondary vertex
- High-P_T secondary. Not the standard one, and need a dedicated analysis
- It looks very promosing

UV completion

Csaki, Heidenreich, to appear; See also Krnjaic, Stolarski, 1212.4860

- Different than incorporating MVF in RPC susy
- Gauge SU(3) flavor symmetry and add heavy vector like quarks
- The breaking of the flavor symmetry generate the Yukawa and RPV couplings at the same time
- Can be incorporated into GUT, but not a simple SU(5)
- More of a “proof” that one can come with a UV completion

What else?

- DM? Maybe the gravitino
- Higgs at 126 GeV? Need something else to do it as the stops are light, maybe NMSSM
- ???

Conclusions

Thanks!