

Weighing Neutrinos at the LHC through Stop LSP Decays

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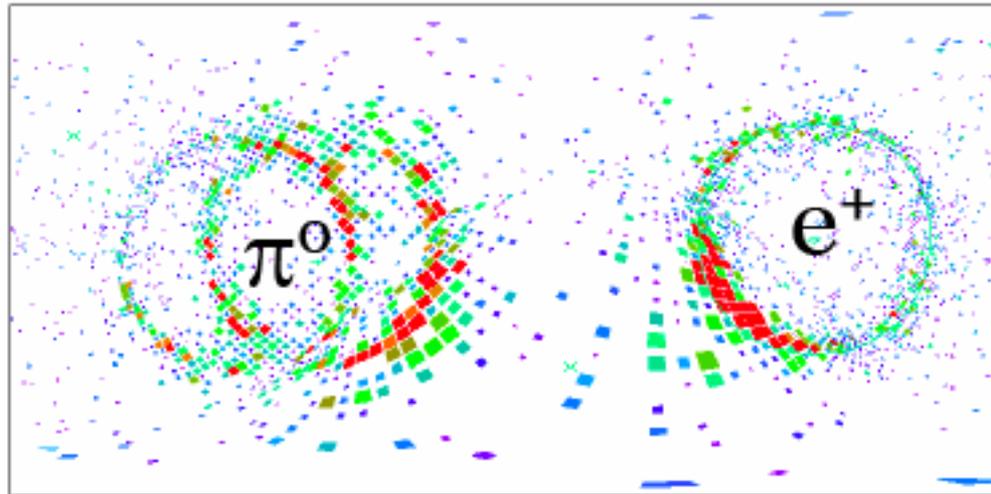
References

- Z. Marshall, B. Ovrut, A. Purves, [S.S.](#) --- Stop/sbottom LSP decay
arXiv:1402.5434, **PLB** 732:325 (2014)
- P. Fileviez Perez, [S.S.](#) --- Minimal SUSY Left-Right Model
PLB 673:251 (2009)
- V. Barger, P. Fileviez Perez, [S.S.](#) --- Minimal SUSY U(1) B-L Model
PRL102:181802 (2009)a
- L. Everett, P. Fileviez Perez, [S.S.](#) --- Minimal SUSY U(1)_{B-L} X U(1)_{3R} Model
PRD80:05507 (2009)
- V. Barger, P. Fileviez Perez, [S. S.](#) --- Neutrino sector for minimal models
PLB696:509 (2011)
- P. Fileviez Perez, [S. S.](#) --- Pheno in Minimal SUSY B-L and cosmology
JHEP1204,118 (2012), 1308.0524
- B. Ovrut, A. Purves, [S.S.](#) --- Minimal SUSY B-L properties from strings
JHEP1211, 026 (2012)

Outline

- Motivation
- The Minimal SUSY B–L Model
- Neutrino Physics
- Phenomenology: Stop LSP
- Conclusion

Motivation



SUSY

- Despite the fact that SUSY
 - Solves the Gauge–Hierarchy problem.
 - Contains a dark matter candidate.
 - Unifies gauge couplings.
 - Allows radiative electroweak symmetry breaking.
 - ...
 - SUSY is bad news for the proton!

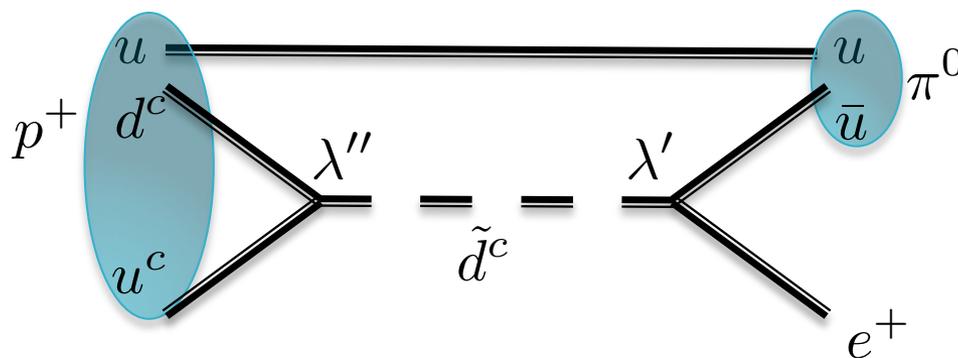
MSSM and $B-L$ violation

- No accidental $B-L$ as in the SM

$$\Delta B = 1 : \lambda'' u^c d^c d^c$$

$$\Delta L = 1 : \lambda' Q L d^c$$

- Rapid, tree-level proton decay:



$$\tau_p > 10^{32} \text{ years}$$

- Untenable with bounds:

$$|\lambda' \lambda''| < 10^{-26}$$

R- and M-parity



- Matter Parity: $M_p = (-1)^{3(B-L)}$
- Subgroup of B-L
- Forbids *all* B violation and L violation
 - But, just B violation or just L violation ok

R-parity

$$R_P = (-1)^{3(B-L)+2S}$$

- Super Z_2 :
 - RP(SM particle) = 1 RP(SUSY particle) = -1
- Interactions: even number of SUSY particles
 - LSP must be neutral:
 - Dark matter candidate.
 - Missing energy at collider.

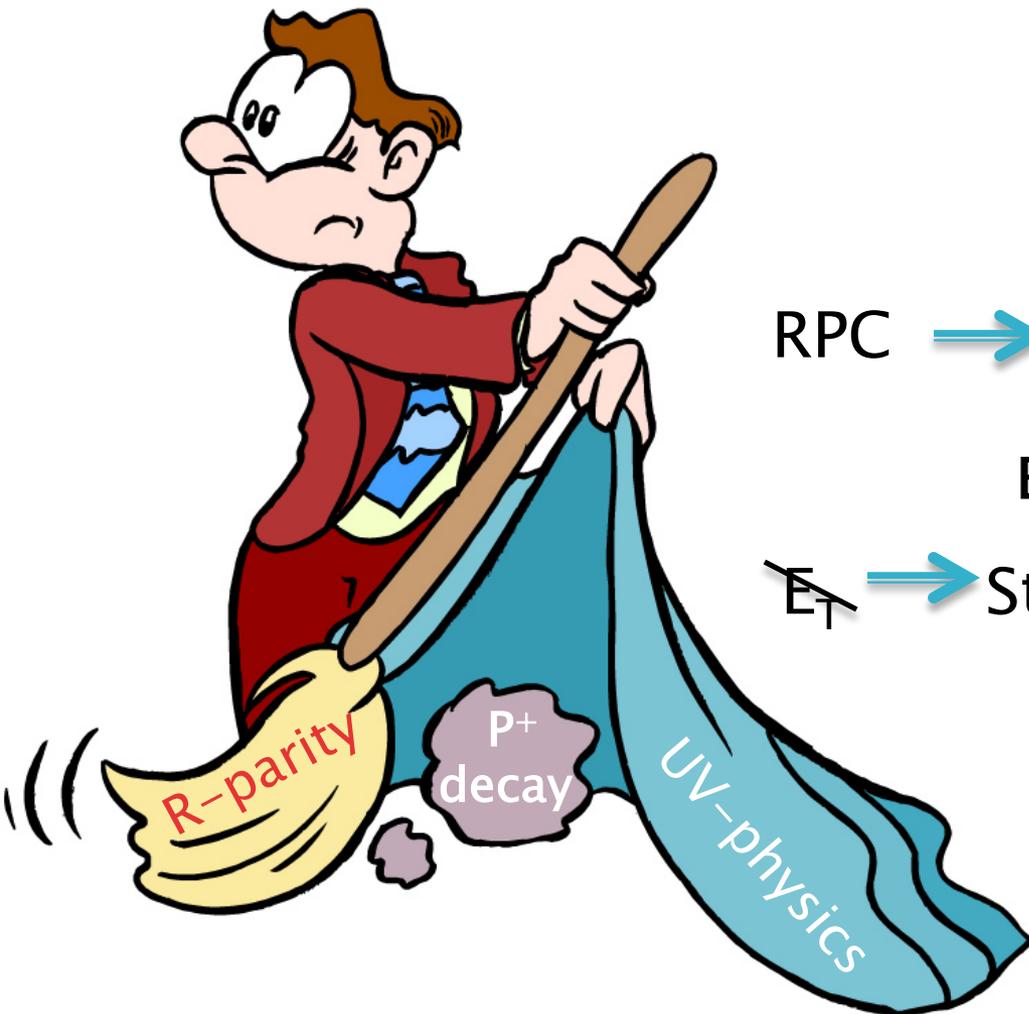
Open question:

What is the origin of R-parity
(stability of the proton)?

Two general viewpoints

UV R-parity

- Possible, but can be challenging.



Remember that

RPC \Rightarrow stable neutral LSP \Rightarrow ~~E_{τ}~~

BUT NOT necessarily

~~E_{τ}~~ \Rightarrow Stable neutral LSP \Rightarrow RPC

R -parity at the TeV Scale

- Well motivated to consider gauged B-L
 - M-parity is a subgroup.
- Prediction for R -parity, other testable predictions possible.
- More exciting!
 - Potentially test the mechanism for proton stability.

The Minimal SUSY B-L Model

Consider: $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

Field	B-L
Quarks	$\frac{1}{3}$
Leptons	-1
Higgs	0

Must break B-L

B-L Higgs?

Even B-L: R-parity conservation.

Odd B-L: R-parity violation.

Right-handed (s)neutrinos

3 generations of r-h neutrinos for anomaly cancellation!

ν^c SM singlet, B-L = 1

Contains the perfect B-L Higgs: r-h sneutrino!

Anomaly cancellation dictates Higgs sector

$$\langle \tilde{\nu}^c \rangle \sim \frac{2\sqrt{2}}{g_{BL}} |m_{\tilde{\nu}^c}|$$

$$\langle \tilde{\nu} \rangle \ll \langle \tilde{\nu}^c \rangle$$

P. Fileviez Perez, [S.S.](#), **PLB** '09
V. Barger, P. Fileviez Perez, [S.S.](#), **PRL** '09

Related to Mohapatra '86

From Strings: Ambroso, Ovrut '09

Symmetry Breaking

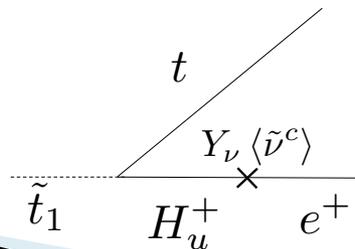
- R-h sneutrino is B-L odd
 - Spontaneous R-parity violation (lepton number violation).

$$W_{\text{RPV}} \supset Y_\nu \langle \tilde{\nu}^c \rangle LH_u = Y_\nu \langle \tilde{\nu}^c \rangle (\nu H_u^0 - e H_U^+)$$

- Plays two roles:
 - Generates Majorana neutrino masses:

$$\begin{array}{ccccccc}
 & Y_\nu \langle \tilde{\nu}^c \rangle & & m_{\chi^0} & & Y_\nu \langle \tilde{\nu}^c \rangle & \\
 \longrightarrow & \mathbf{X} & \longleftarrow & \mathbf{X} & \longrightarrow & \mathbf{X} & \longleftarrow \\
 \nu_i & & \chi^0 & & \chi^0 & & \nu_j
 \end{array}$$

- Allows LSP to decay through neutralino-neutrino mixing

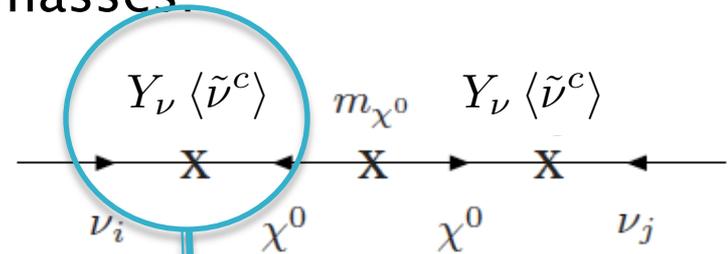


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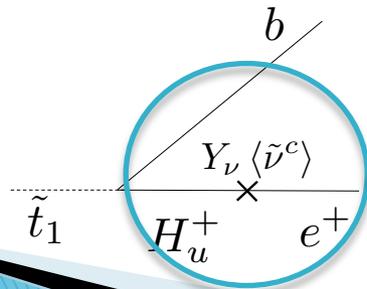
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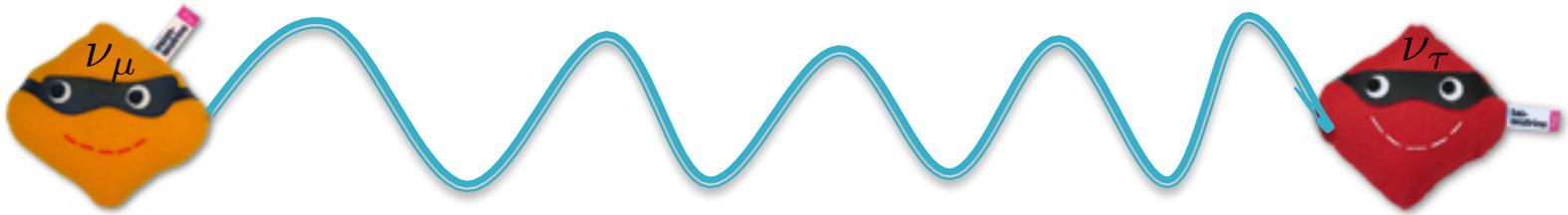


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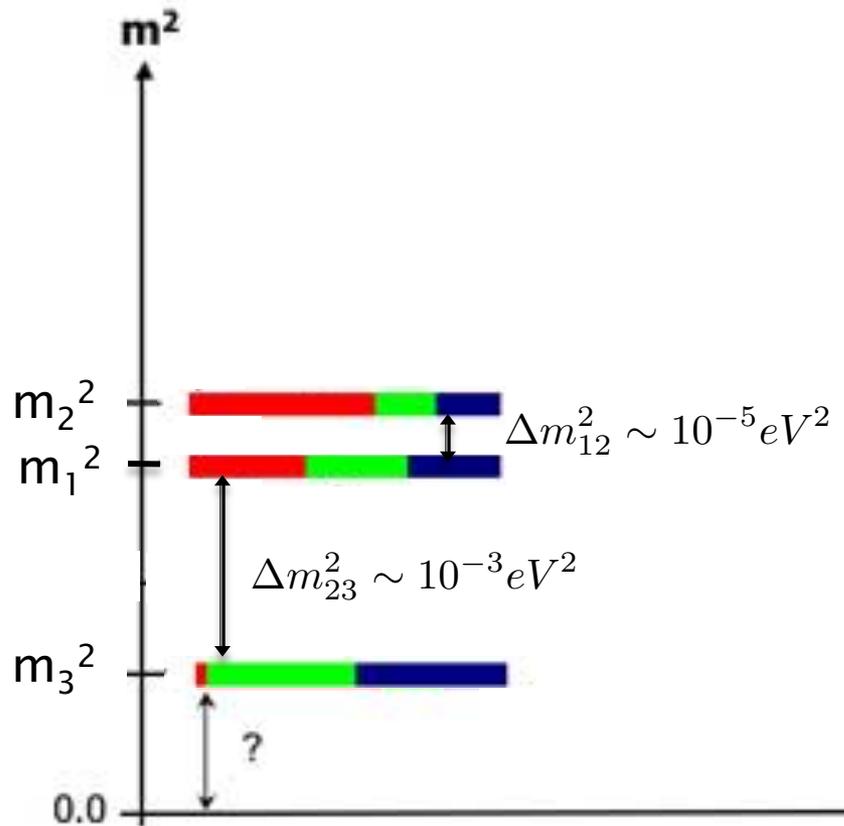
RPV connects neutrino masses to LHC physics!

Neutrino Physics

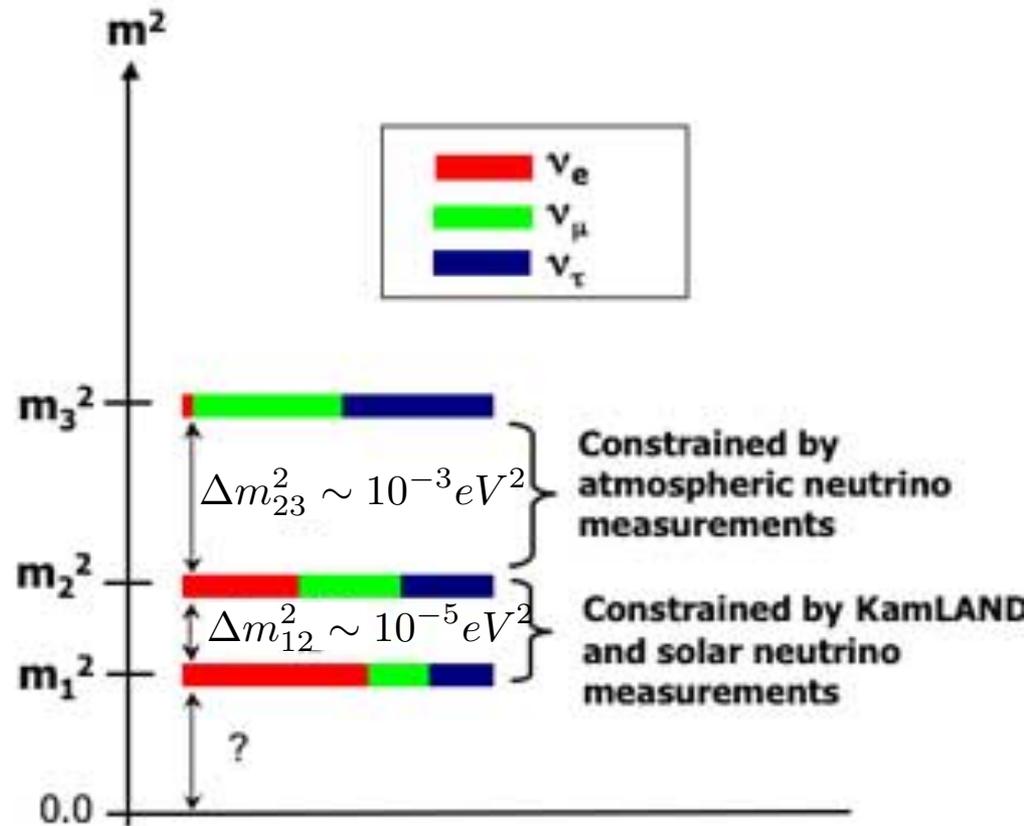


Two Possible Mass Hierarchies

Inverted Hierarchy



Normal Hierarchy



Cosmology implies $\Sigma m_\nu < 0.23 \text{ eV}$

Minimal SUSY B-L and Neutrino Masses

$$Y_{\nu_{i3}} L_i H_u \nu_3^c \quad m_{\nu_{ij}} = A \langle \tilde{\nu}_i \rangle \langle \tilde{\nu}_j \rangle + B (\langle \tilde{\nu}_i \rangle Y_{\nu_{j3}} + \langle \tilde{\nu}_j \rangle Y_{\nu_{i3}}) + C Y_{\nu_{i3}} Y_{\nu_{j3}}$$

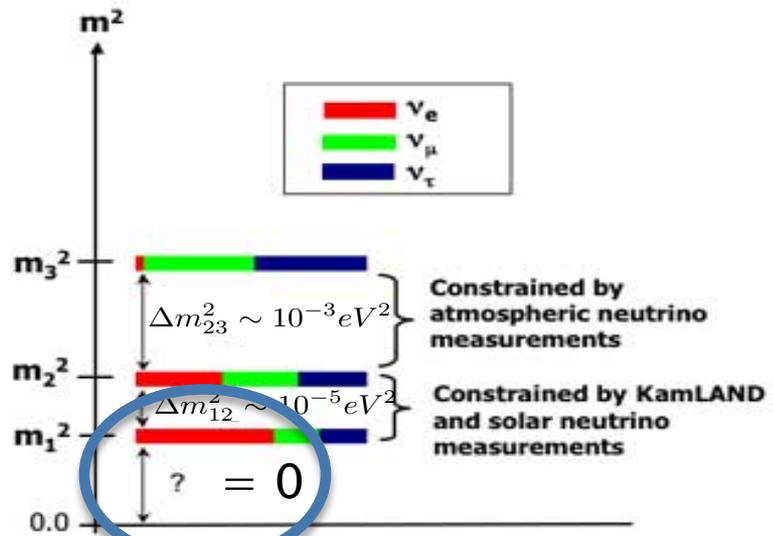
- Already very predictive.
 - Flavor structure: lightest neutrino massless.
 - Sets the neutrino scale.

Normal Hierarchy

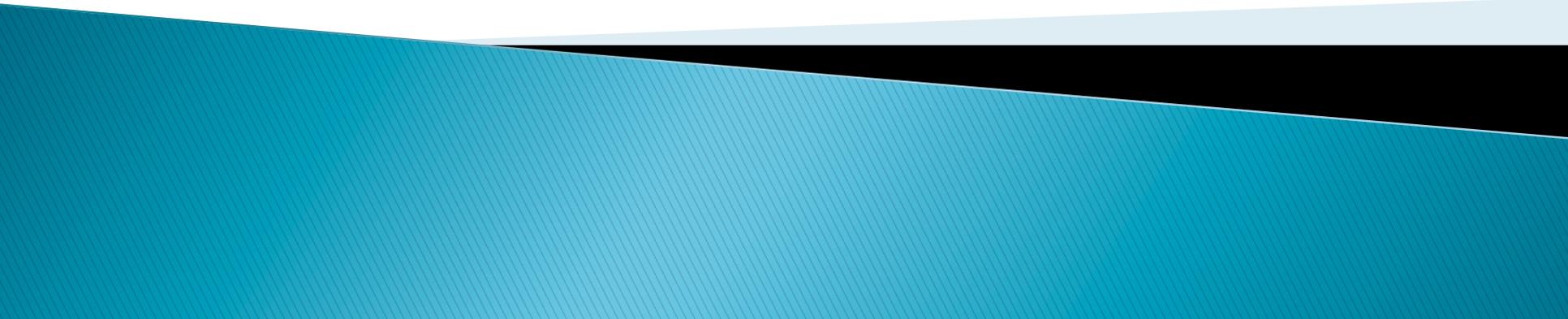
$$m_1 = 0, m_2 \sim 7 \text{ meV}, m_3 \sim 50 \text{ meV}$$

Inverted Hierarchy

$$m_1 \sim m_2 \sim 50 \text{ meV}, m_3 = 0$$



Phenomenology: Stop LSPs



Quick Summary

- Predictive model:
 - Minimal: Particle content = MSSM + r.h. neutrino
– no new Higgs!
 - Neutrino: sterile masses close to actives: 3+2
 - $B-L$ scale (Z_{BL}) = RPV scale = SUSY mass scale.
- No rapid proton decay.
- Radiative symmetry breaking possible. Ambroso, Ovrut '09, '10
- LSP Gravitino dark matter possible. Takayama, Yamaguchi '00

Basic Stop Phenomenology

Stops have a crucial role in SUSY: fine tuning and Higgs mass.

Motivates study of Stop LSPs

Gauge eigenstates

$$\tilde{t} \quad \tilde{t}^c$$

Interested in LSP, \tilde{t}_1

$$\tilde{t}_1 = \cos \theta_t \tilde{t} + \sin \theta_t \tilde{t}^{c*}$$

EWSB



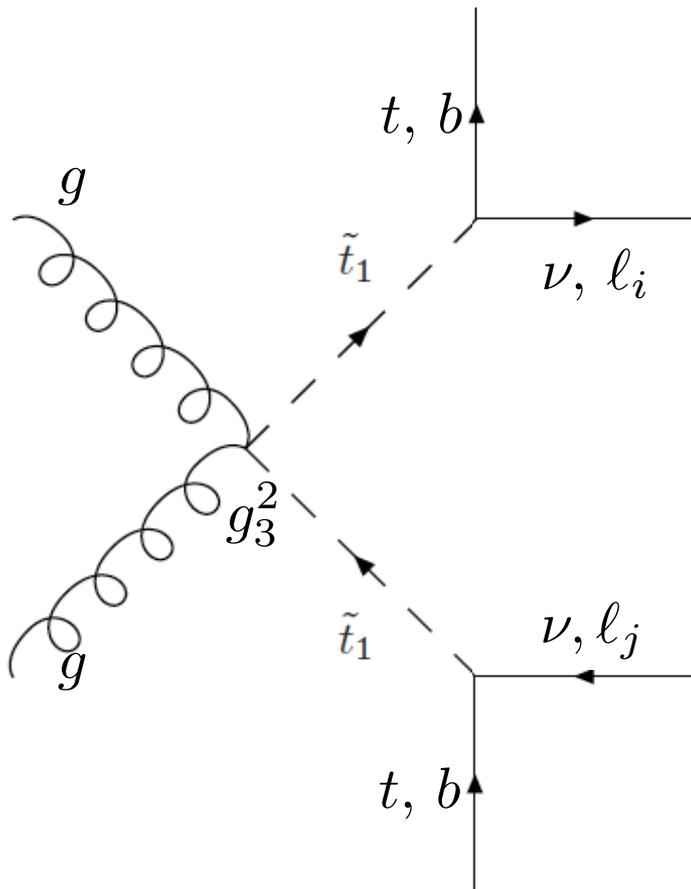
Mass eigenstates

$$\tilde{t}_1 \quad \tilde{t}_2$$
$$m_{\tilde{t}_1} < m_{\tilde{t}_2}$$

Stop LSP can be pure right-handed or left-right admixture.

Squark LSP Phenomenology

Stop decay: $\tilde{t}_1 \rightarrow b \ell_i^+$ $\tilde{t}_1 \rightarrow t \nu_i$



Possible stop final states:

$$2t + \cancel{E_T} \quad \text{MSSM-like}$$

$$2b + \ell_i^- \ell_j^+$$

$$t + b + \ell_i + \cancel{E_T}$$

If stop not purely right-handed:

Charged lepton channel dominates

$$\tilde{t}_1 \rightarrow b e^+$$

$$\tilde{t}_1 \rightarrow b \mu^+$$

$$\tilde{t}_1 \rightarrow b \tau^+$$

Branching Ratios

- Branching Ratio (Br), probability for decay for a certain channel.
- Since admixture stop has negligible Br to neutrinos its decays can be described by 3 dependent Brs:

$$\text{Br}(\tilde{t}_1 \rightarrow be^+) + \text{Br}(\tilde{t}_1 \rightarrow b\tau^+) + \text{Br}(\tilde{t}_1 \rightarrow b\tau^+) = 1$$

- Can present parameter space in $\text{Br}(\tilde{t}_1 \rightarrow b\tau^+) - \text{Br}(\tilde{t}_1 \rightarrow be^+)$

Wide scan for numerical results:

$$\mu \in (150, 1000) \text{ GeV}$$

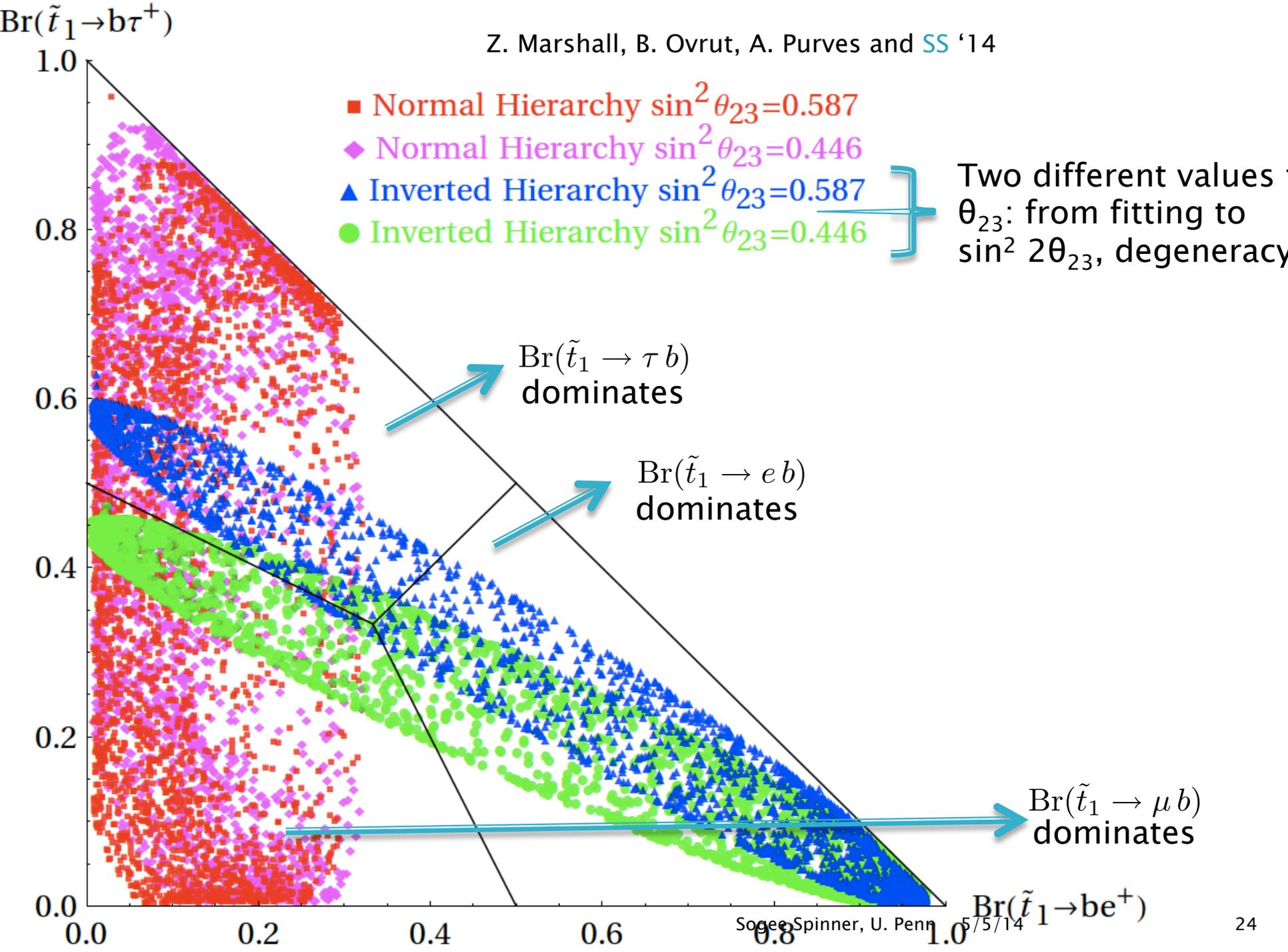
$$M_3 \in (1500, 8000) \text{ GeV} \longrightarrow M_1 : M_2 : M_3 = 1 : 2 : 5$$

$$\tan \beta \in (1.5, 50)$$

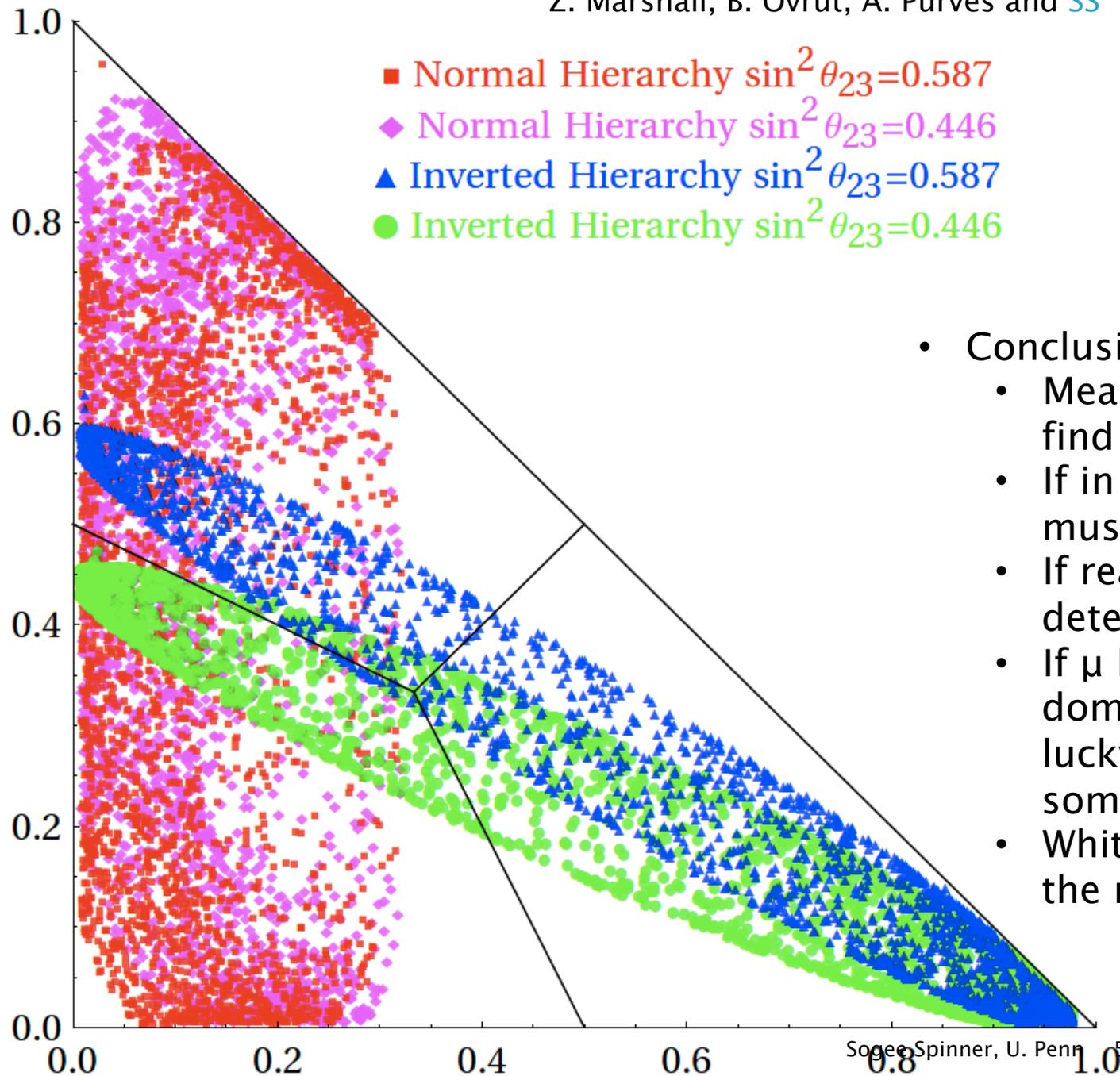
$$M_{Z'} \in (2000, 8000) \text{ GeV}$$

$$|\epsilon_i| \in (10^{-3}, 10^{-1}) \text{ GeV}$$

Due to neutrino data, neutrino sector determine by one ϵ_i , and two signs.



$\text{Br}(\tilde{t}_1 \rightarrow b\tau^+)$



- Conclusion:
 - Measure stop decay, find on plot.
 - If in e b domination, must be NH.
 - If really lucky can determine θ_{23} .
 - If μb or τb dominated, have to be lucky, but might say something.
 - White space rules out the model.

Neutrino Hierarchy

- Measuring the neutrino hierarchy is one of the goals of the intensity frontier.
- Many experiments lined up for this task:

White paper: Cahn, Dwyer, Freedman *et al*:1307.5487

LBNE + T2K/NOA – 3σ by 2030

Hyper-Kamiokande $\sim 3\sigma$ by 2030

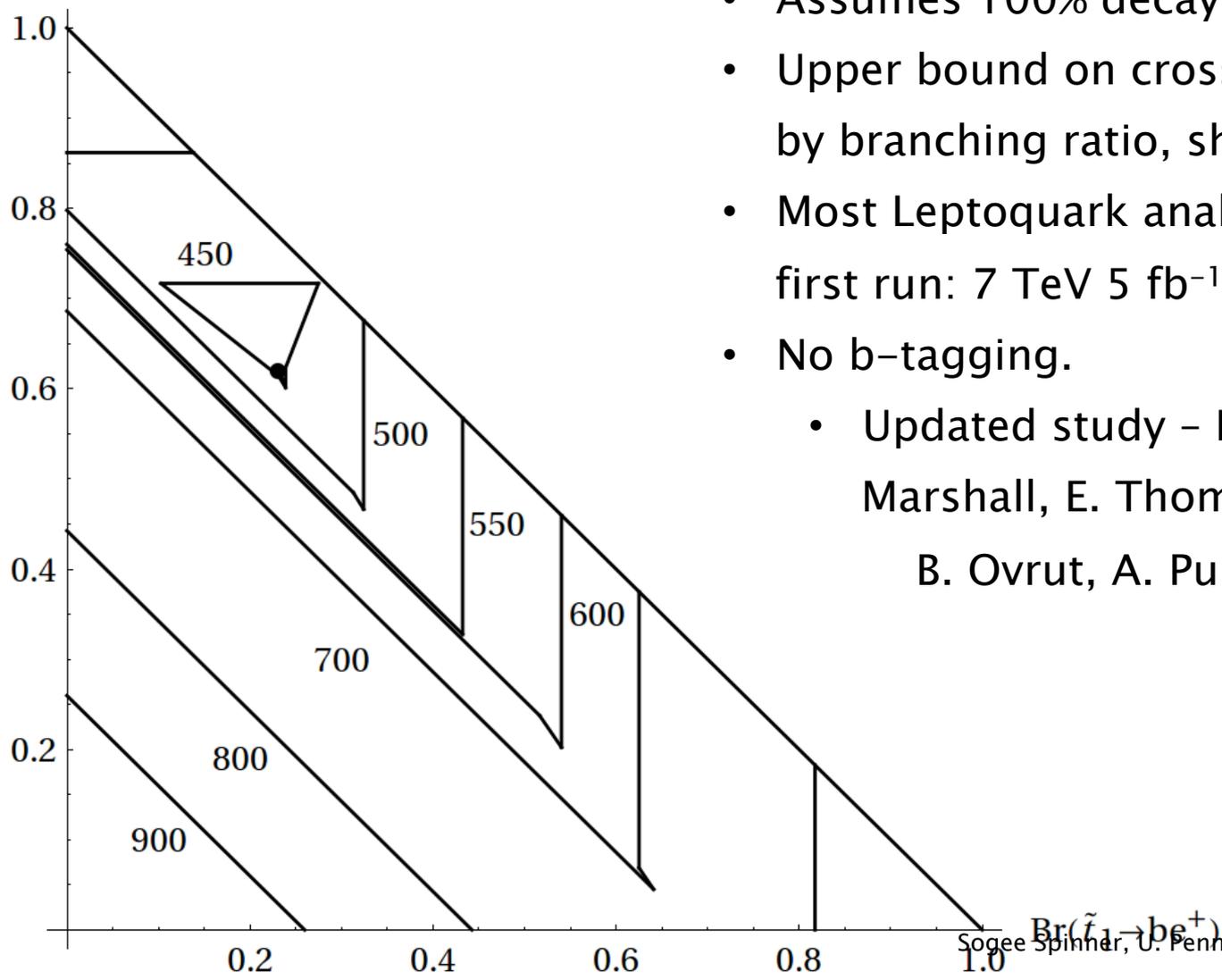
LAGUNA-LBNO – 5σ shorter time scale, status not certain...

- Also important in $0\nu 2\beta$ decay: IH much easier to measure.

A very exciting and surprising connection
from SUSY!

Curves of constant stop lower bound (GeV)

$\text{Br}(\tilde{t}_1 \rightarrow b\tau^+)$



Atlas current leptoquark data:

- Assumes 100% decays to only one family.
- Upper bound on cross section weighted by branching ratio, show strongest bound.
- Most Leptoquark analysis only from the first run: 7 TeV 5 fb⁻¹ of data.
- No b-tagging.
 - Updated study – B. Jackson, J. Kroll, Z. Marshall, E. Thomson, B. Ovrut, A. Purves, S. Spinner

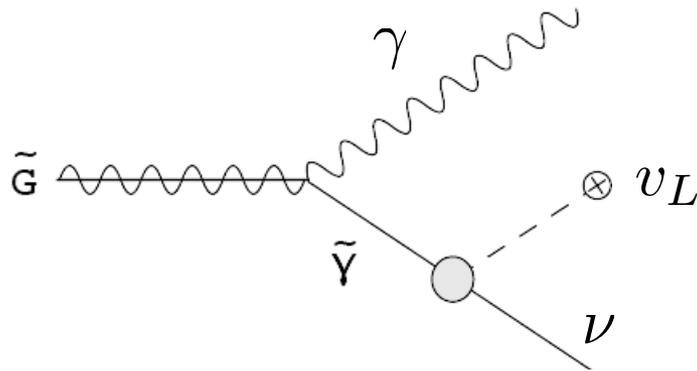
Conclusions

- B-L:
 - A deep origin for RPC and RPV.
 - Minimal model: anomaly cancellation determines new Higgs sector. Yields a predictive framework.
 - String theory compatible.
- LSP decay determined by neutrino sector:
 - Might provide a clue to the neutrino hierarchy
- Lower bounds: signals are unusual for SUSY
 - A lot of room for improvement.

Backups

Dark Matter

LSP Gravitino decay: suppressed by Planck scale and neutrino masses



$$\mathcal{M} \sim \frac{v_L m_{3/2}}{M_P m_{\chi^0}}$$

$$\Gamma \sim \frac{m_{3/2}^3 v_L^2}{M_P^2 m_{\chi^0}^2}$$

$$\tau \sim 10^{26} \text{ sec} \times \left(\frac{m_{\chi^0}}{1000 \text{ GeV}} \right)^2 \left(\frac{1 \text{ GeV}}{m_{3/2}} \right)^3 \left(\frac{10^{-4} \text{ GeV}}{v_L} \right)^2$$

From Strings

Braun, He, Ovrut, Pantev, JHEP '06

- Can arise from $E_8 \times E_8$ heterotic superstring vacuum
 - MSSM + $B-L$ + three right-handed neutrino superfields.
 - No further exotics.
 - Can achieve radiative $B-L$ breaking. Ambroso, Ovrut '09, '10

Ovrut, Pures, [S.S.](#) JHEP '12

- **Canonical $B-L$ basis:** $SU(3)_C \times SU(2)_L \times U(1)_{3R} \times U(1)_{B-L}$
 - $U(1)_{3R} \times U(1)_{B-L} \xrightarrow{\langle \tilde{\nu}^c \rangle \neq 0} U(1)_Y$
 - No $U(1)$ - $U(1)$ mixing as RGE evolve from UV scale.

Radiative Symmetry Breaking

- In the MSSM: $Y_t \sim 1$ drives EWSB:

$$\frac{d}{dt} m_{H_u}^2 \sim 6Y_t^2 \left(m_{H_u}^2 + m_{\tilde{Q}_3}^2 + m_{\tilde{t}^c}^2 \right) - 6g_2^2 M_2^2 - \frac{6}{5}g_1^2 M_1^2 + \frac{3}{5}g_1^2 S_1$$

- No such large Yukawa for ν^c , $Y_\nu < 10^{-5}$
- S -term in general:

$$16\pi^2 \frac{d}{dt} m_\phi^2 \sim Y^2 m^2 - g^2 M^2 + 2g^2 Q_\phi S_Q$$

$$S_Q = \text{tr} \left(Q_\phi m_\phi^2 \right)$$

- Can be positive, driving m_ϕ^2 negative

Radiative Symmetry Breaking

- Depends on boundary conditions, choose:

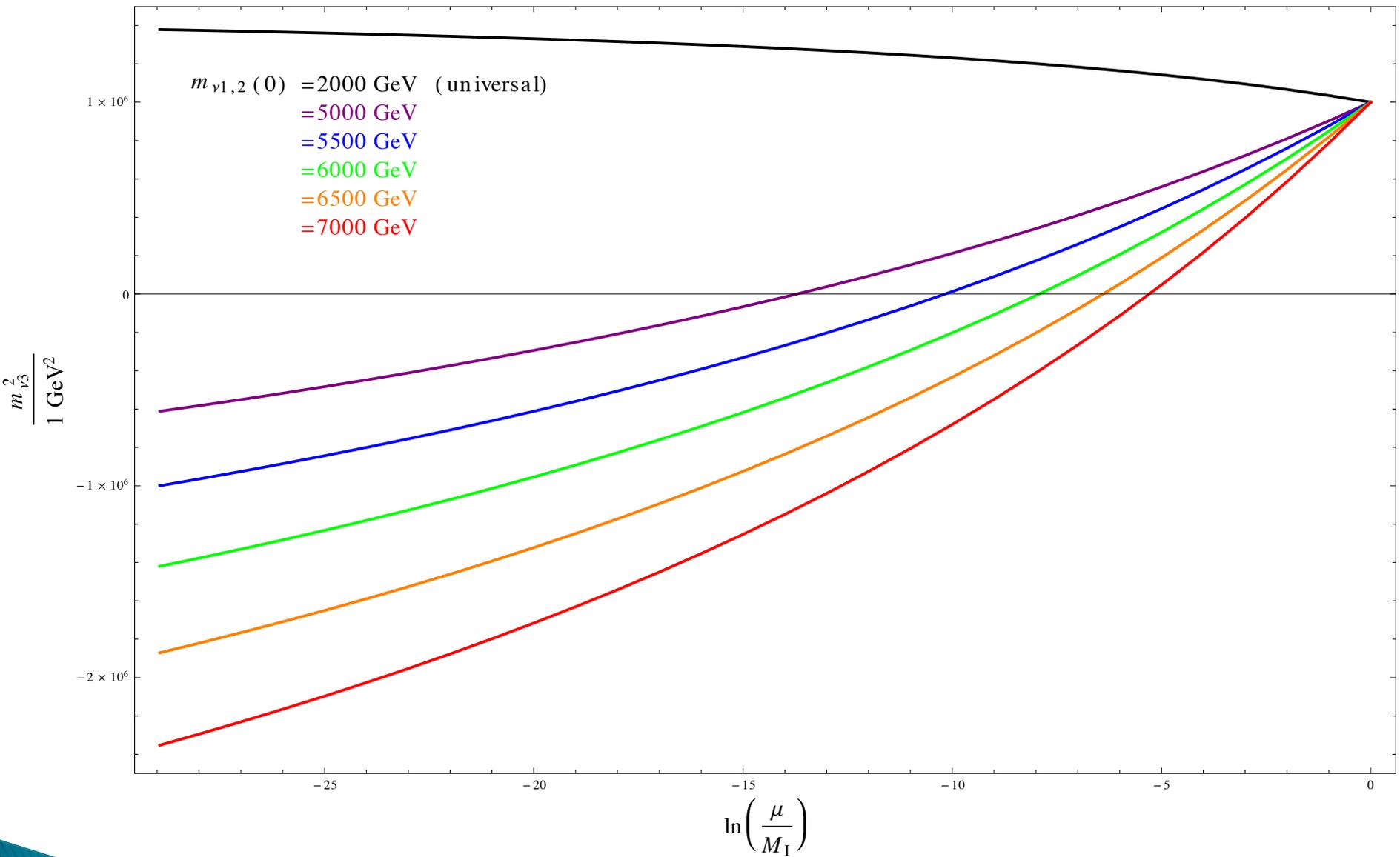
All MSSM soft masses degenerate ($m_{\tilde{Q}}^2, m_{\tilde{L}}^2$) : m_0^2

$$m_{\tilde{\nu}_{1,2}^c} = P m_0^2$$

$$m_{\tilde{\nu}_3^c} = Q m_0^2$$

$$\begin{aligned} S_{BL} &= \text{Tr} \left(2m_{\tilde{Q}}^2 - m_{\tilde{u}^c}^2 - m_{\tilde{d}}^2 - 2m_{\tilde{L}}^2 + m_{\tilde{e}^c}^2 + m_{\tilde{\nu}^c}^2 \right) \\ &= (2P + Q - 3)m_0^2 \end{aligned}$$

- Need $(2P + Q - 3) > 0$



RPV Pheno: General Comments

- RPV small due to neutrino masses $\epsilon \lesssim 10^{-3}$:
 - SUSY particles produced in pairs: no single production as in RPC
 - SUSY decays unaltered except LSP (NLSP with gravitino LSP)
- LSP decays: due to neutralino/neutralino and chargino/charged lepton mixings

New LSP possibilities:

RPC	RPV
Neutralino χ^0	Neutralino χ^0
Sneutrino ($\tilde{\nu}$)	Sneutrino $\tilde{\nu}$
	Stau $\tilde{\tau}$
	Chargino χ^\pm
	Stop \tilde{t}
	Sbottom \tilde{b}
	Glino \tilde{g}

In RPC, sneutrino not often studied because ruled out as Dark Matter.

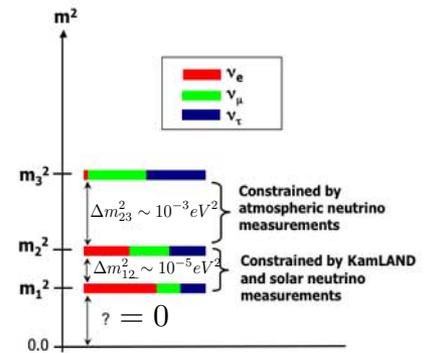
Squarks: strong production, stops an essential part of SUSY fine-tuning, Higgs mass.

Z. Marshall, B. Ovrut, A. Purves and SS '14

The Results Analytically

- Remember neutrino mass matrix:

$$m_{\nu ij} = An_i^* n_j^* + B(n_i^* \epsilon_j + n_j^* \epsilon_i) + C \epsilon_i \epsilon_j$$



- Diagonalized by PMNS matrix

$$m_{\nu}^D = V_{\text{PMNS}}^T m_{\nu} V_{\text{PMNS}} \quad \longrightarrow \quad \text{Define:} \quad \begin{aligned} N_l &\equiv n_j^* V_{\text{PMNS}}^*_{jl} \\ E_l &\equiv \epsilon_j V_{\text{PMNS}}_{jl} \end{aligned}$$

- Given that we have one massless neutrino:

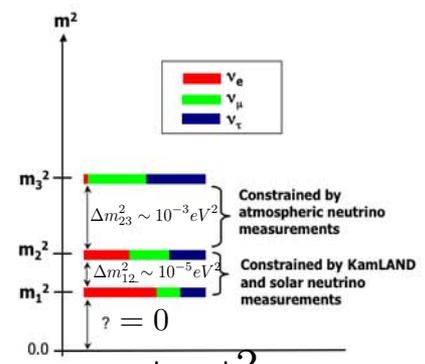
$$\begin{aligned} \text{NH: } N_1 = E_1 = 0; & \quad \epsilon_i = E_2 V_{\text{PMNS}}_{i2} + E_3 V_{\text{PMNS}}_{i3} \\ \text{IH: } N_3 = E_3 = 0 & \quad \longrightarrow \quad \epsilon_i = E_1 V_{\text{PMNS}}_{i1} + E_2 V_{\text{PMNS}}_{i2} \end{aligned}$$

- Using $\epsilon_i = E_2 V_{\text{PMNS}i2} + E_3 V_{\text{PMNS}i3}$

$$\epsilon_i = E_1 V_{\text{PMNS}i1} + E_2 V_{\text{PMNS}i2}$$

- And remembering

$$\mathcal{A}(\tilde{t} \rightarrow b l_i^+) \sim Y_b \frac{\epsilon}{\mu} \quad \longrightarrow \quad \Gamma(\tilde{t} \rightarrow b l_i^+) \sim \frac{1}{16\pi} Y_b^2 m_{\tilde{t}_1} \left| \frac{\epsilon}{\mu} \right|^2$$



Can scan E 's, parametrically plot Brs (solid ellipses).

Reproduce numerical results:

Therefore results depend on massless neutrino and VPMNS but not on assumptions:
 parameter range in scan.
 GUT relations.

