# Baryogenesis & Superpartner Oscillations in Minimal R-symmetric SSM

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In collaboration with Ricky Fox, Graham Kribs, and Adam Martin
arXiv: 1208.2784

In collaboration with Yuval Grossman, and Bibhushan Shakya
working in progress

UC Davis, 15 Oct 2012

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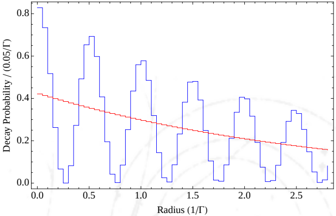
# Things that can happen in MRSSM

- Earlier Universe: Electroweak baryogenesis
- Collider: Superpartner oscillations



# Minimal $R$-Symmetric SUSY Standard Model

G. Kribs, E. Poppitz and N. Weiner (08)

| Field | $(SU(3)_c, SU(2)_L)_{U(1)_Y}$ | $U(1)_R$ |
|---|---|---|
| $Q_L$ | $(\mathbf{3},\mathbf{2})_{1/6}$ | 1 |
| $U_R$ | $(\bar{\mathbf{3}},\mathbf{1})_{-2/3}$ | 1 |
| $D_R$ | $(\bar{\mathbf{3}},\mathbf{1})_{1/3}$ | 1 |
| $L_L$ | $(\mathbf{1},\mathbf{2})_{-1/2}$ | 1 |
| $E_R$ | $(\mathbf{1},\mathbf{1})_{1}$ | 1 |
| $\Phi_{\tilde{B}}$ | $(\mathbf{1},\mathbf{1})_{0}$ | 0 |
| $\Phi_{\tilde{W}}$ | $(\mathbf{1},\mathbf{3})_{0}$ | 0 |
| $\Phi_{\tilde{g}}$ | $(\mathbf{8},\mathbf{1})_{0}$ | 0 |
| $H_u$ | $(\mathbf{1},\mathbf{2})_{1/2}$ | 0 |
| $H_d$ | $(\mathbf{1},\mathbf{2})_{-1/2}$ | 0 |
| $R_u$ | $(\mathbf{1},\mathbf{2})_{-1/2}$ | 2 |
| $R_d$ | $(\mathbf{1},\mathbf{2})_{+1/2}$ | 2 |

$U(1)_R$ forbids

- $M_\lambda \lambda\, \lambda$
- $W \supset \mu\, H_u\, H_d$
- $A\, \tilde{Q}_L^*\, y_u\, H_u\, \tilde{U}_R^*$

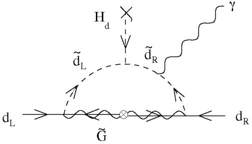
Instead,

- $M_\lambda \lambda\, \psi_\lambda$
- $W \supset \mu\, H_u\, R_d$
- additional term
  $W \supset \lambda_u\, H_u\, \Phi_{B,W}\, R_u$

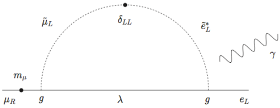
# Significantly relax the flavor constraints

Most of the FCNC processes in MSSM are induced by Majorana mass and LR mixing scalar masses. e.g. $\mu \to e\gamma$ and EDM

MSSM




MRSSM




$\mu \to e\gamma$, $b \to s\gamma$, $\overline{K} - K$, EDM and strong CP all come from higher order diagrams and give no significant constraints in MRSSM. G. Kribs, E. Poppitz and N. Weiner (08)

# Gaugino mass

$M_D\,\lambda\,\psi_\lambda$ is given by the $D$-type spurion, $\Phi_a \equiv (\psi_a,\ A_a)$

$$\int d^2\theta\, \frac{\theta_\alpha \mathbf{D}}{M}\, W_i^\alpha\, \Phi_i + h.c., \qquad \mathbf{D}/M = M_D$$

$$\frac{\mathbf{D}}{M}\left(\lambda\,\psi + h.c. + D_a(A^a + A^{a*})\right) = M_D\left(\lambda\,\psi + h.c. + 2D_a\, Re(A^a)\right)$$

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- For $M_D \gg \mu, m_s$, the leading order $D_a = 0$.
- There are light CP odd scalars $Im\, A^a$.

# The $\lambda$-term

The superpotential contains

$$\lambda_B^u \, \Phi_B \, H_u \, R_u + \lambda_B^d \, \Phi_B \, R_d \, H_d + \lambda_W^u \, \Phi_W^a \, H_u \, \tau^a \, R_u + \lambda_W^d \, \Phi_W^a \, R_d \, \tau^a \, H_d$$

$$V \supset \mu^* \lambda_u^{*B} \, A_B^* \, |H_u|^2 + \mu^* \lambda_d^{*B} \, A_B^* \, |H_d|^2 + c.c.$$

This gives an important contribution to phase transition.

# EWPM constraints on gaugino mass

The SU(2) triplet acquires a vev $\langle A_W \rangle = \frac{\sqrt{2}\, g\, v^2\, \cos 2\beta}{8\, m_D}$, which gives a correction to the $\rho$ parameter. The precision measurement sets a bound

$$m_{\tilde{W}} > 1\,\text{TeV}$$

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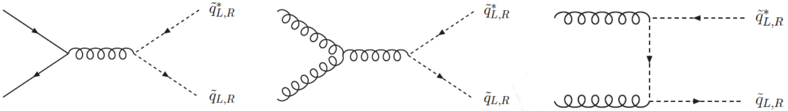
SUSY production is suppressed and squark-initiated:
Graham Kribs, Adam Martin (12)



# Light Higgs mass

$$m_h^2 = m_{h,\,\text{tree}}^2 + \delta m_{h,\,\tilde{t}}^2 + \delta m_{h,\,\lambda}^2$$

MRSSM has

- a small $D$-term
- a new tree-level contribution ($\lambda$-term)

The $\lambda$ term gives

$$\lambda\,\mu\,\langle A\rangle |H|^2 \sim \lambda\,\mu\,\frac{g}{M_D}\,|H|^2|H|^2 = \frac{\lambda\,\mu\,g}{M_D}\,|H|^4$$

$m_h = 125$ GeV requires $\lambda \sim 1.5$, $m_{\tilde{t}} > 3$ TeV.

# Short conclusion

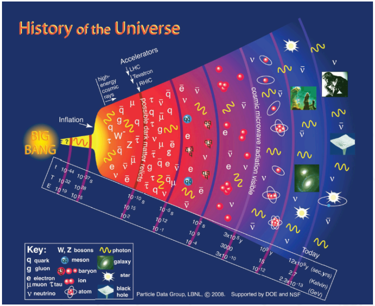
The $R$-symmetric model has following features:

- Dirac mass terms for gauginos and higgsinos
- $m_{\tilde{W}} >$ TeV from EWPM
- a suppressed $D$-term
- a light CP odd scalar (*Im A*)
- a 125 GeV Higgs with large $\lambda$ and $m_{\tilde{q}}$

# Electroweak Baryogenesis

Dynamically generate

$$\eta_s \equiv \frac{n_B - n_{\overline{B}}}{s} \simeq 6 \cdot 10^{-10}$$




see also, P. Kumar and E. Ponton, JHEP 1111, 037 (2011)

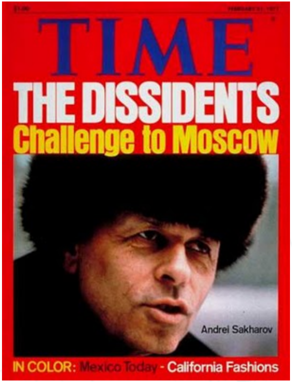
# As usual: Sakharov conditions

**Conditions for dynamically generating the B-asymmetry:**

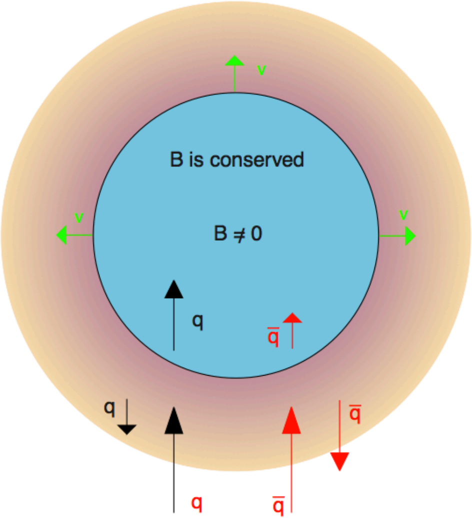
- baryon number violation
- C and CP violation
- out of thermal equilibrium

To get these, we have

- sphaleron effect
- chiral theory, CPV coupling
- strong 1st order phase transition

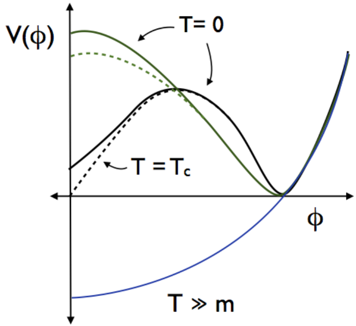


# EW baryogenesis



# 1st order phase transition in MRSSM

To quantify the "strength" of phase transition: $\phi_c \,/\, T_c$



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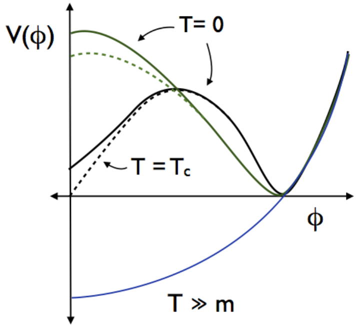


The "flatter" R-symm potential generates a strong PT.

# EWBG in MSSM gets some trouble!

M. Carena, G. Nardini, M. Quiros and C. E. M. Wagner (08)

**The ONLY realization of EWBG in MSSM**

Requires a mostly right-handed stop lighter than tops.

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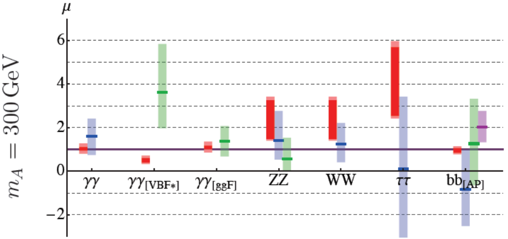
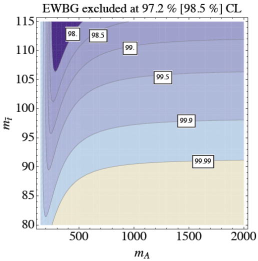
**The ONLY realization of EWBG in MSSM**

Requires a mostly right-handed stop lighter than tops.

Has been excluded by the Higgs related searches to 95% C.L..

D. Curtin, P. Jaiswal and P. Meade ; T. Cohen, D. Morrissey and A. Pierce (12)



# MRSSM vs MSSM

MRSSM has the following advantages:

- stronger phase transition
- thermal correction from additional color-neutral particles
- does not require a light stop
- no CP violation bound from EDM

# The importance of the CP odd scalars

$$V = V_{tree} + V_{CW} + V_T + V_{ring}$$

The finite temperature term, $V_T$, is the most important one

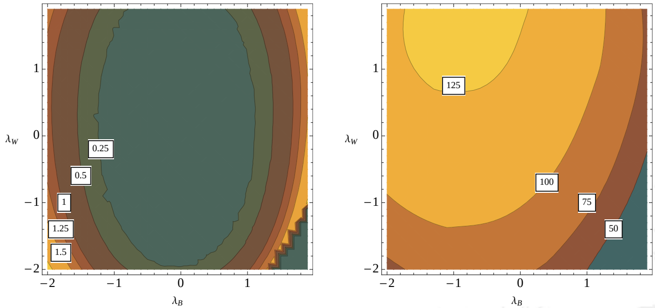
$$V_T\,(boson) = \begin{cases} \frac{-|n_i|\,T^4\,\pi^2}{90} & T \gg m \\ -|n_i|\;T^4\left(\frac{m^2}{2\pi\;T^2}\right)^{3/2} e^{-m/T} & T \ll m \end{cases}$$

- fields with $m \propto \phi$ lower the potential in the symmetric vacuum
- the more these fields are, the stronger the phase transition is

The light CP odd scalars carring $m^2 \propto \lambda^2\phi^2$ give large thermal corrections

# Numerical scan: $\phi_c/T_c$ and $m_{Higgs}$

- integrating out the gauginos
- consider the $m^2 \propto \phi^2$ fields only
- the only important parameters are $\mu$, $\lambda_B$, $\lambda_W$

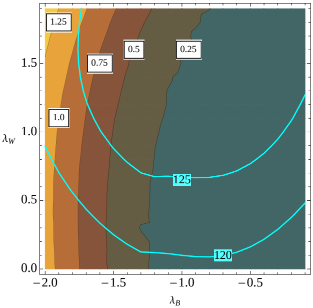



$\mu = 200$ GeV, $M_D = 1$ TeV, $\tan\beta = 4$, $m_A = 300$ GeV,
$m_{scalar} = 0$ GeV, $m_{\tilde{t}_L} = m_{\tilde{R}} = 3$ TeV.

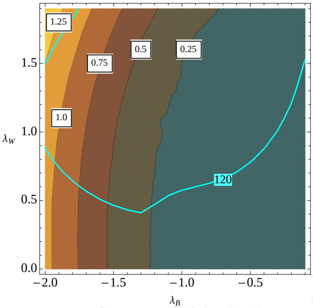
# Numerical scan: $\phi_c / T_c$ and $m_{Higgs}$

Zoom in to the interesting region

$M_D = 1$ TeV



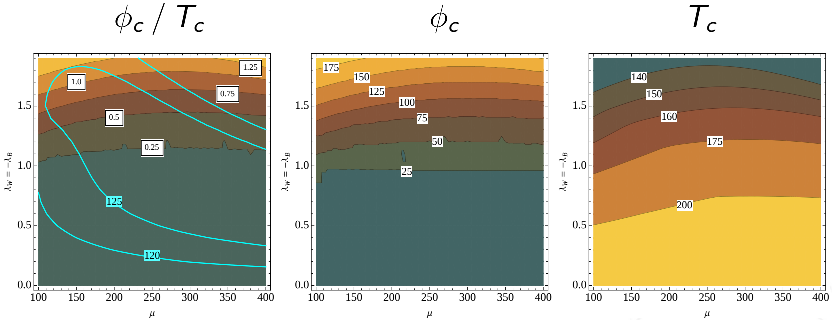

$M_D = 2$ TeV




$\mu = 200$ GeV, $\tan\beta = 4$, $m_A = 300$ GeV,

$m_{scalar} = 0$ GeV, $m_{\tilde{t}_L} = m_{\tilde{R}} = 3$ TeV.

# Numerical scan: the $\mu$ dependence




$\lambda_W = -\lambda_B$, $M_D = 1$ TeV, $\tan\beta = 4$, $m_A = 300$ GeV,
$m_{scalar} = 0$ GeV, $m_{\tilde{t}_L} = m_{\tilde{R}} = 3$ TeV.

# Baryon asymmetry

Can generate a large asymmetry while having the right $m_{Higgs}$.

- the phase $Arg(\mu\, M\, \lambda_{B,W})$ source CP violation in the higgsino sector
- the higgsino-higgs interactions generates the asymmetry
- e.g., for $\lambda_W = -\lambda_B = 2$, $M_D = 1$ TeV, $\mu = 200$ GeV, $m_A = 300$ GeV, $\tan\beta = 4$, $m_S = 0$ GeV and $\Delta q = \pi$

$\Rightarrow T_c \simeq 135$ GeV and $\eta \simeq 4 \times 10^{-10}$

# Superpartner Oscillations

# Gaugino oscillation in the MRSSM

## Gaugino mass

$$M_D \, \lambda \, \psi$$

# Gaugino oscillation in the MRSSM

## Gaugino mass

$$M_D \lambda \psi + M_M \lambda \lambda$$

$M_M = \frac{\beta(g^2)}{2g^2} m_{3/2}$ is the anomaly-mediated Majorana mass

G. F. Giudice, M. A. Luty, H. Murayama and R. Rattazzi (98); L. Randall and R. Sundrum (98)

$$\mathcal{H} = \begin{pmatrix} \lambda & \overline{\psi} \end{pmatrix} \begin{pmatrix} M_M & M_D \\ M_D & 0 \end{pmatrix} \begin{pmatrix} \lambda \\ \psi \end{pmatrix}, \qquad M_M \ll M_D$$

e.g. SUSY breaking with $\sqrt{F} = 100$ TeV has

$$M_M{}^{-1} = (5 \cdot 10^{-14}\,\text{TeV})^{-1} \sim 0.04\ \text{mm}$$

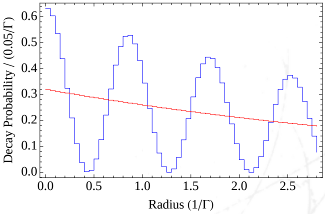
# Gaugino oscillation in the MRSSM

$M_M \ll M_D \Rightarrow$ Maximal mixing!

$\lambda, \psi$ oscillate in the interacting basis with frequency $\sim M_M$.

$$P(\lambda \to \lambda(t_{lab})) \propto e^{-2\Gamma t_{lab}} [1 + \cos(M_M t_{lab})]$$
$$P(\lambda \to \psi(t_{lab})) \propto e^{-2\Gamma t_{lab}} [1 - \cos(M_M t_{lab})]$$

If $\lambda$ decays only, the decay probability oscillates



# Higgsino oscillation in the MRSSM

Higgsino gets mass splitting between $(\tilde{h}, R)$ by mixing to gauginos:

$$\Delta m_{\tilde{h}} = \left( \frac{\sin\beta \, \sin\theta_w \, v \, \mu}{M_D^2} \right)^2 M_M$$

For $\sqrt{F} = 100$ TeV, $M_D = 1$ TeV and $\mu \sim v$,

$$\Delta m_{\tilde{h}}^{-1} \sim 10 \text{ cm}$$

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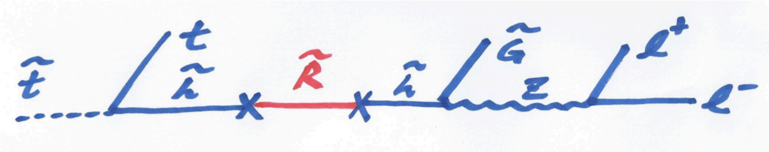
For $\sqrt{F} = 100$ TeV, $M_D = 1$ TeV and $\mu \sim v$,

$$\Delta m_{\tilde{h}}^{-1} \sim 10 \text{ cm}$$

**A macroscopic distance that can be seen at colliders!**

# Decay of $\tilde{h}$ as the NLSP

Consider the following decay,




assume

- gauge-mediation type of model with a higgsino NLSP
- heavy scalars $\Rightarrow$ *R*-fermion does not decay
- the following mass spectrum

| | $\bar{\tilde{g}}\tilde{g}'$ | $\bar{\tilde{W}}\tilde{W}'$ | $\bar{\tilde{B}}\tilde{B}'$ | $\bar{\tilde{h}}_d\tilde{h}_d'$ | $\bar{\tilde{h}}_u\tilde{h}_u'$ | $\tilde{t}^*_{L,R}\tilde{t}_{L,R}$ | $\bar{\tilde{G}}\tilde{G}'$ |
|---|---|---|---|---|---|---|---|
| $m_{\text{Dirac}}$ (TeV) | 3 | 1 | 0.5 | 0.13 | 0.12 | 0.6 | $F/M_{\text{pl}}$ |

# The oscillation

The above spectrum gives

- the oscillation length $\Delta m_{\tilde{h}}^{-1} \simeq 5$ mm
- the decay length

$$c\tau \simeq \left(\frac{\sqrt{F}}{100\ \text{TeV}}\right)^4 \left(\frac{100\ \text{GeV}}{m_{\chi_1^0}}\right)^5 \left(1 - \frac{m_Z^2}{m_{\chi_1^0}^2}\right)^{-4} \times 0.2\,\text{mm} \ \simeq\ 18\,\text{cm}$$

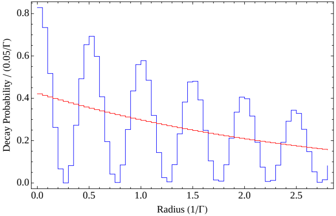
**The displaced vertex can be well constructed at ATLAS and CMS.**

P. Meade, M. Reece and D. Shih (10) ; P. W. Graham, D. E. Kaplan, S. Rajendran and P. Saraswat

# The smearing effect

Assuming the SM BG is well studied, we expect to see the higgsino decay as

(naively)



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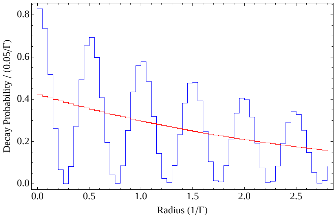
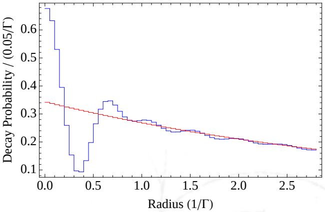



but instead, we see




The smearing comes from

- uncertainty when measuring the angles (can be improved)
- time dilation (cannot be improved)

# Event simulation

Decay probability P(r) in the lab frame

$$P(r) = N \int_1^{\infty} d\gamma \, Prob(\gamma) \times e^{-\Gamma \, t_{lab}/\gamma} \left(1 + \cos \Delta m \, t_{lab}/\gamma\right)$$

To get $Prob(\gamma)$, we do a parton-level analysis using Madgraph5

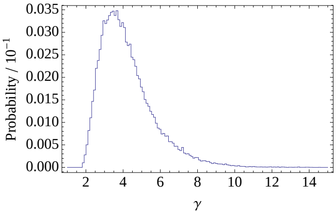
with the pre-selection cuts:

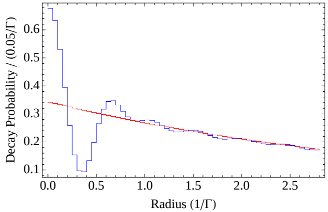
- lepton $|\eta| \leq 1.5$, $p_T > 20$
- $\Delta R > 0.4$ between leptons
- each lepton has $E > 100$ GeV

# Uncover the oscillation

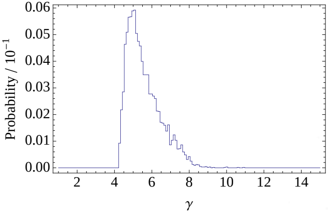
However, we can reduce the time dilation effect by setting energy cuts on outgoing leptons, $E_{\ell^+\ell^-}$

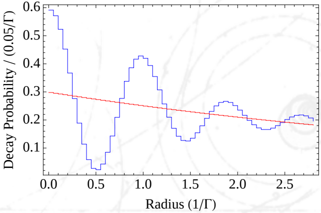
$$0.2 \text{ TeV} < E_{\ell^+\ell^-} < 2 \text{ TeV}$$



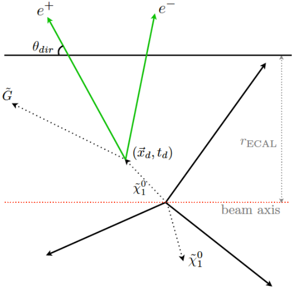



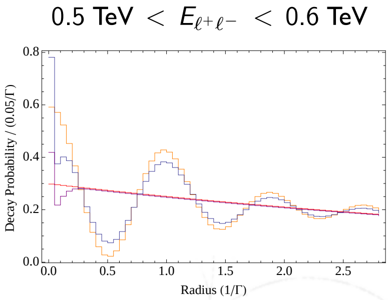

$$0.5 \text{ TeV} < E_{\ell^+\ell^-} < 0.6 \text{ TeV}$$



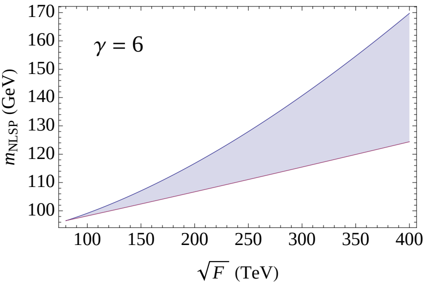
# Smearing from the angular measurement




With the mass spectrum, we need at least 150 fb$^{-1}$ of data to distinguish the oscillation from a pure decay to $3\,\sigma$.

# Parameter space for an observable oscillation




Need to satisfy the following conditions:

- $\Delta m_h^{-1} >$ the precision of the displaced vertex measurement
- $\Delta m_h^{-1} <$ the outer radius of the silicon track
- $\Gamma^{-1} >$ the oscillation wavelength
- $\Gamma^{-1} <$ the outer radius of the silicon track

# Conclusion

## In the MRSSM model, we can have

- a strong 1st order phase transition
- successful EWBG
- 125 GeV Higgs (with a large $m_{\tilde{t}}$ and $\lambda$)
- hissino oscillation that can be seen at LHC