# New directions in weak scale supersymmetry

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*The talk is about*
*a few aspects of*
*phenomenology*
*of*
*weak scale supersymmetry*

*but not directly about*
*MSSM*

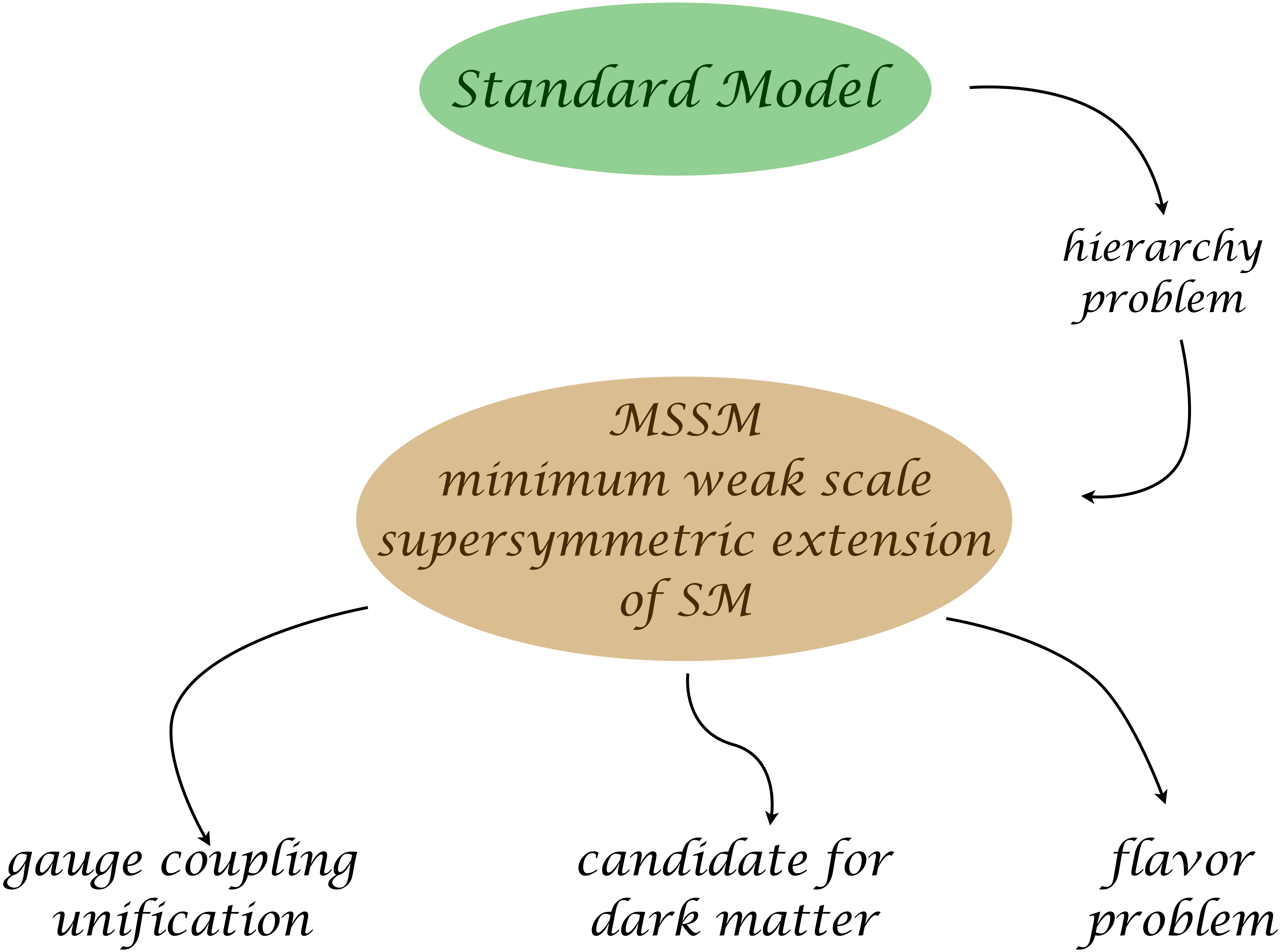
*but before beginning*
*let's recap*

# Particle zoo in the MSSM

SM particles: $A^a_\mu$ $q_i$ $h$

new particles: $\lambda^a$ $\tilde{q}_i$ $\{\, h_u \,,\, \tilde{H}_u \} \equiv H_u$ $\{\, h_d \,,\, \tilde{H}_d \} \equiv H_d$

new mass terms: $M_a\, \lambda^a\, \lambda^a$ $m^2_{ij}\, \tilde{q}^*_i\, \tilde{q}_j$ $\mu\, H_u\, H_d$ $B_\mu\, h_u\, h_d$


Standard Model
hierarchy problem
MSSM
minimum weak scale supersymmetric extension of SM
gauge coupling unification
candidate for dark matter
flavor problem

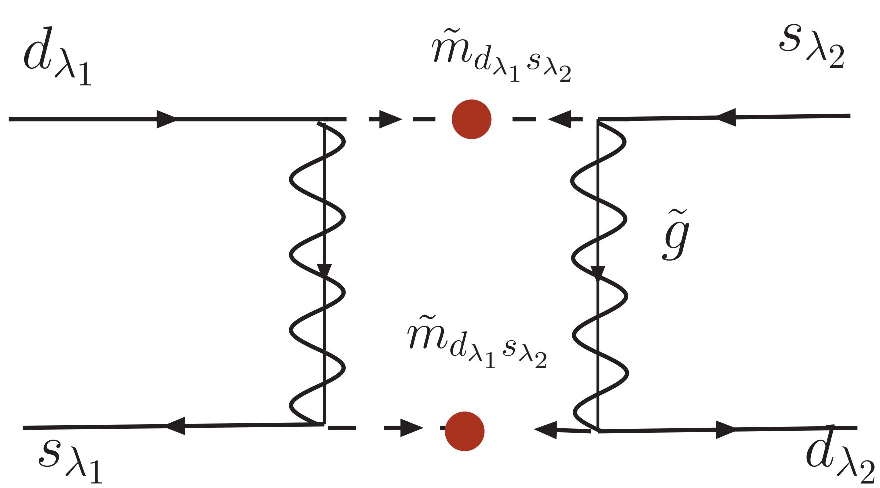
# Supersymmetric Flavor problem

take for example, $m_{ij}^2 \, \tilde{q}_i^* \, \tilde{q}_j$

arbitrary $m_{ij}^2$ is totally ruled out

# *For example,* $K_0 - \bar{K}_0$ *mixing*

*has conribution from superpartner loops*




$$\delta_{12} \equiv \frac{\tilde{m}^2_{12}}{\tilde{m}^2_q} < 0.06 \to 10^{-3} \quad \left\{ \begin{array}{l} \tilde{m}_q = 500\,\mathrm{GeV} \\ M_{\tilde{g}} = 500\,\mathrm{GeV} \end{array} \right.$$

# 20 Years of model building

susy breaking is communicated through flavor universal messengers

at weak scale soft terms have restricted flavor structure

MSSM is characterized by rather lack of flavor

# A new direction

don't kill flavor

make the flavor
violating observables rather
insensitive to mixing elements

# A new direction

*give up minimality of the MSSM*

*Recipe:*

*supersymmetrize standard model*
*and*
*impose an additional* $\mathrm{U}(1)_{\mathrm{R}}$ *symmetry*

*Kribs, Poppitz, Weiner (0712.2039)*

# The Minimal R-symmetric Supersymmetric Model

Kribs, Poppitz, Weiner

$$\frac{X}{\Lambda} W_a W_a \longrightarrow \frac{W'}{\Lambda} W_a \Phi_a$$

$$\mu H_u H_d \longrightarrow \begin{array}{c} \mu_u H_u R_u \\ \mu_d H_d R_d \end{array}$$

# The Minimal R-symmetric Supersymmetric Model

Kribs, Poppitz, Weiner

$M\lambda_a\lambda_a \longrightarrow \frac{W'}{\Lambda}W_a\Phi_a$

$\mu H_u H_d \longrightarrow \begin{array}{c}\mu_u H_u R_u \\ \mu_d H_d R_d\end{array}$

# The Minimal R-symmetric Supersymmetric Model

Kribs, Poppitz, Weiner

$$M\lambda_a\lambda_a \longrightarrow M\lambda_a\psi_a$$

$$\mu H_u H_d \longrightarrow \begin{matrix} \mu_u H_u R_u \\ \mu_d H_d R_d \end{matrix}$$

# Flavor physics is different in the MRSSM because:

- Dirac gluinos can naturally be far heavier than squarks/sleptons
- No L-R sfermion mixing
- new higgsino mass  term

# *Supersoft*

(Fox, Nelson, Weiner '02)

$$\int d^4\theta \; \frac{1}{\Lambda^6} \, |W'W'|^2 Q^\dagger Q$$

$$\frac{M^4}{\Lambda^2} \, \tilde{Q}^\dagger \tilde{Q}$$

*gaugino mass*

*extra suppression*

*no counterterm is needed and hence D-term induces finite contribution to the scalars*

# heavy Dirac gaugino and no dimensional 5 operators

Flavor violating operators
in

| MSSM | MRSSM |
| --- | --- |
| leading contribution is due to 'n' insertions of Majorana masses | leading contribution is due to '2n' insertions of Dirac masses |
| leading operator is dimensional 5 | leading operator is dimensional 6 |

see Kribs, Poppitz, Weiner (0712.2039)

# some sort of outline

- Introducing Minimal R-symmetric Supersymmetric Standard Model.

- Unconventional features of the MRSSM:
  1. its delicious
  2. it has a surprising ino-mass hierarchy

- Implications at the collider

# Particle zoo in the MRSSM

MSSM particles

new particles

| Fields | $SU(3)_C$ | $SU(2)_W$ | $U(1)_Y$ | $U(1)_R$ |
|---|---|---|---|---|
| $Q$ | $3$ | $2$ | $\frac{1}{6}$ | $1$ |
| $U$ | $\bar{3}$ | $1$ | $-\frac{2}{3}$ | $1$ |
| $D$ | $\bar{3}$ | $1$ | $\frac{1}{3}$ | $1$ |
| $L$ | $1$ | $2$ | $-\frac{1}{2}$ | $1$ |
| $E$ | $1$ | $1$ | $1$ | $1$ |
| $\Phi_{\tilde{B}}$ | $1$ | $1$ | $0$ | $0$ |
| $\Phi_{\tilde{W}}$ | $1$ | $3$ | $0$ | $0$ |
| $\Phi_{\tilde{g}}$ | $8$ | $1$ | $0$ | $0$ |
| $H_u$ | $1$ | $2$ | $\frac{1}{2}$ | $0$ |
| $H_d$ | $1$ | $2$ | $-\frac{1}{2}$ | $0$ |
| $R_u$ | $1$ | $2$ | $-\frac{1}{2}$ | $2$ |
| $R_d$ | $1$ | $2$ | $\frac{1}{2}$ | $2$ |

# *neutralinos and charginos*

*MSSM inos*

$\tilde{W}^{\pm}$ $\tilde{W}_3^0$ $\tilde{B}$ $\tilde{H}_u^+$ $\tilde{H}_d^-$ $\tilde{H}_u^0$ $\tilde{H}_d^0$

*new inos*

$\psi^{\pm}$ $\psi_3$ $\psi_0$ $\tilde{R}_u^-$ $\tilde{R}_d^+$ $\tilde{R}_u^0$ $\tilde{R}_d^0$

# *The neutralino mass marix*

$$\begin{bmatrix} \tilde{B} & \tilde{W}_3^0 & \tilde{R}_u^0 & \tilde{R}_d^0 \end{bmatrix} \begin{bmatrix} M_1 & 0 & -g' v_u/\sqrt{2} & g' v_d/\sqrt{2} \\ 0 & M_2 & g v_u/\sqrt{2} & -g v_d/\sqrt{2} \\ 0 & 0 & \mu_u & 0 \\ 0 & 0 & 0 & \mu_d \end{bmatrix} \begin{bmatrix} \psi_0 \\ \psi_3 \\ \tilde{H}_u^0 \\ \tilde{H}_d^0 \end{bmatrix}$$

$\mathcal{R}$ = +1

$\mathcal{R}$ = -1

# *The chargino mass system*

$$\begin{bmatrix} \psi^+ & \tilde{H}_u^+ \end{bmatrix} \begin{bmatrix} M_2 & 0 \\ -gv_u & \mu_u \end{bmatrix} \begin{bmatrix} \tilde{W}^- \\ \tilde{R}_u^- \end{bmatrix}$$

$\mathcal{R}$ = +1
$\mathcal{Q}$ = +1

$\mathcal{R}$ = -1
$\mathcal{Q}$ = -1

$$\begin{bmatrix} \tilde{W}^+ & \tilde{R}_d^+ \end{bmatrix} \begin{bmatrix} M_2 & -gv_d \\ 0 & \mu_d \end{bmatrix} \begin{bmatrix} \psi^- \\ \tilde{H}_d^- \end{bmatrix}$$

$\mathcal{R}$ = -1
$\mathcal{Q}$ = +1

$\mathcal{R}$ = +1
$\mathcal{Q}$ = -1

$$\begin{pmatrix} M_1 & 0 & -\frac{g' v_u}{\sqrt{2}} & \frac{g' v_d}{\sqrt{2}} \\ 0 & M_2 & \frac{g v_u}{\sqrt{2}} & -\frac{g v_d}{\sqrt{2}} \\ 0 & 0 & \mu & 0 \\ 0 & 0 & 0 & \mu \end{pmatrix}$$

$$\begin{pmatrix} M_2 & 0 \\ g v_u & \mu \end{pmatrix}$$

$$\begin{matrix} M_1 & 0 & -\frac{g' v_u}{\sqrt{2}} & 0 \\ 0 & M_2 & \frac{g v_u}{\sqrt{2}} & -\frac{g v_d}{\sqrt{2}} \\ 0 & 0 & \mu & 0 \\ 0 & 0 & 0 & \mu \end{matrix}$$

$$\begin{matrix} M_2 & 0 \\ g v_u & \mu \end{matrix}$$

| | | | |
|---|---|---|---|
| $M_1$ | $0$ | $-\frac{g' v_u}{\sqrt{2}}$ | $0$ |
| $0$ | $M_2$ | $\frac{g v_u}{\sqrt{2}}$ | $0$ |
| $0$ | $0$ | $\mu$ | $0$ |
| $0$ | $0$ | $0$ | $\mu$ |

| | |
|---|---|
| $M_2$ | $0$ |
| $g v_u$ | $\mu$ |

$$\begin{pmatrix} M_1 & 0 & -\frac{g' v_u}{\sqrt{2}} & 0 \\ 0 & M_2 & \frac{g v_u}{\sqrt{2}} & 0 \\ 0 & 0 & \mu & 0 \\ 0 & 0 & 0 & \mu \end{pmatrix}$$

$$\begin{pmatrix} M_2 & 0 \\ g v_u & \mu \end{pmatrix}$$

$$\begin{pmatrix} M_1 & 0 & -\frac{g' v_u}{\sqrt{2}} & 0 \\ 0 & M_2 & \frac{g v_u}{\sqrt{2}} & 0 \\ 0 & 0 & \mu & 0 \\ 0 & 0 & 0 & \mu \end{pmatrix}$$

$$\begin{pmatrix} M_2 & 0 \\ g v_u & \mu \end{pmatrix}$$

*At tree level*

*a chargino can be lighter*

*than the lightest neutralino*

*see Kribs, Martin, Roy (0807.4936)*

*At tree level*
*a neutralino is always lighter than*
*all charginos in the MSSM*
*unless*

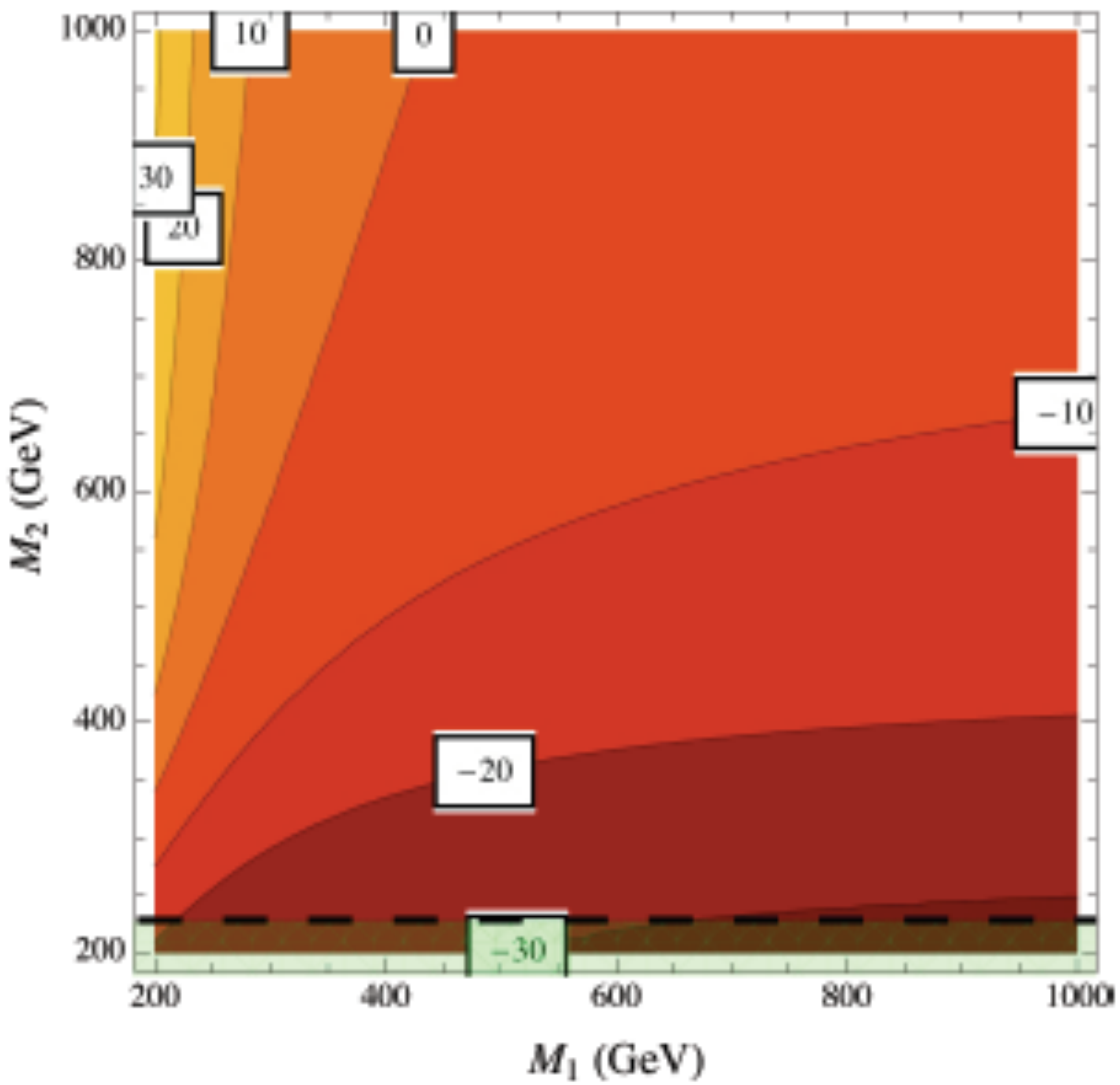
$$\mathrm{sign}(M_1) \neq \mathrm{sign}(M_2)$$

*At loop level*
*also holds in*

| *bino limit* | *wino limit* | *Higgsino limit* |
|---|---|---|
| $M_1 \ll M_2$ and $\mu$ | $M_2 \ll M_1$ and $\mu$ | $\mu \ll M_1$ and $M_2$ |
| *(obviously)* | *(e.g. hep-ph/9904350)* | *(e.g. hep-ph/9512337)* |

*for example:*

$$\Delta m_\chi = m_{\tilde{\chi}_\pm} - m_{\tilde{\chi}_0} \text{ (GeV)}$$




$$\tan\beta = 10, \;\; \mu = 200 \text{ GeV}$$

*collider implications:*

*a chargino can be the NLSP when gravitino is the LSP*

# Traditional NLSPs
# when gravitino is the LSP

| charge \ spin | 0 | 1/2 |
|---|---|---|
| 0 | *sneutrino* | *neutralino* |
| 1 | *slepton* | × |

# Traditional NLSPs

| charge \ spin | 0 | 1/2 |
|---|---|---|
| 0 | *sneutrino* | *neutralino* |
| 1 | *slepton* | × |

*chargino*

# LHC Signatures: Chargino NLSP, Gravitino LSP

two on-shell **W**
in every
supersymmetry event

NLSP is charged

if long-lived leaves track
in the detector

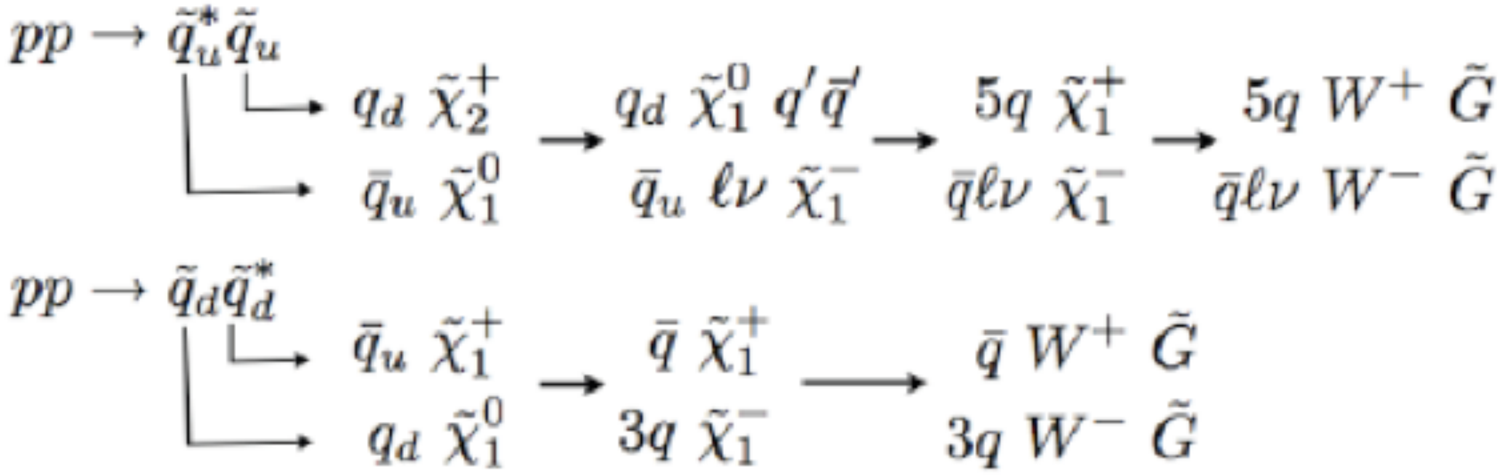
# LHC Signatures: Chargino NLSP, Gravitino LSP

$$pp \to W^+W^- + \mathrm{MET} + X$$

NLSP is charged

if long-lived leaves track
in the detector

# LHC Signatures: Chargino NLSP, Gravitino LSP




*NLSP is charged*

*if long-lived leaves track in the detector*

# LHC Signatures: Chargino NLSP, Gravitino LSP

two on-shell **W**
in every
supersymmetry event

NLSP is charged

if long-lived leaves track
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# LHC Signatures: Chargino NLSP, Gravitino LSP

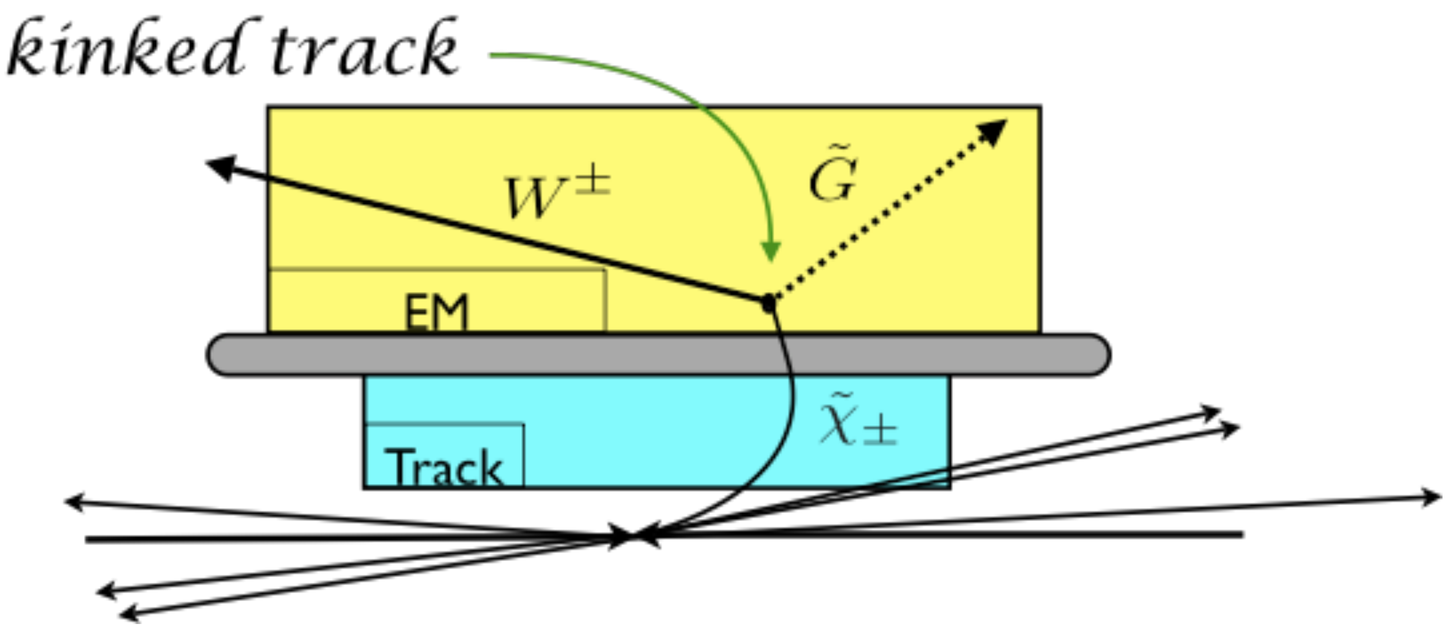
two on-shell **W**
in every
supersymmetry event

$m_{\tilde{\chi}^{\pm}} \sim m_W$ $\qquad$ $m_{\tilde{e}} \gg m_e$

chargino NLSP and slepton NLSP
have different kinematics

# LHC Signatures: Chargino NLSP, Gravitino LSP

two on-shell **W**
in every
supersymmetry event



# *LHC Signatures: Chargino NLSP, Gravitino LSP*

*Detection method depends on the lifetime:*

*lifetime crucially depends on gravitino mass*

$$\tau_{\rm NLSP} \approx 0.07 \left( \frac{1 \, \rm ev}{m_{3/2}} \right)^2 \rm ns$$

*for 100 GeV NLSP*

# supersymmetry breaking interactions renormalize all susy soft masses

- scalar soft masses are modified with respect to the gauginos as well as with respect to each other
- gravitino masses are modified with respect to the rest of the spectrum

Cohen, Roy, Schmaltz (hep-ph/0612100)

Roy, Schmaltz (0708.3593)

Murayama, Nomura, Poland(0709.0775)

# *Lesson:*

*take gravitino mass as a free parameter*

# LHC Signatures: Chargino NLSP, Gravitino LSP

Detection method depends on the lifetime:

$$\gamma_{\tilde{\chi}_\pm} \ll 1 \text{ ns}$$

$$(m_{3/2} \lesssim 1 \text{ eV})$$

*immediate decay. Conventional variables for discovery*

$$H_T = \sum_{\text{leptons}} p_T + \sum_{\text{jets}} p_T \,, \quad M_{eff} = H_T + \text{MET}$$

# LHC Signatures: Chargino NLSP, Gravitino LSP

Detection method depends on the lifetime:

$$\gamma_{\tilde{\chi}^{\pm}} \sim \mathcal{O}(5\ \mathrm{ns})$$

$$\left(m_{3/2} \sim 10\,\mathrm{eV}\right)$$

displaced vertex but no trigger resolution issues.
timing can reduce many background

kink + displaced jets/leptons $\longrightarrow$ chargino NLSP

# LHC Signatures: Chargino NLSP, Gravitino LSP

Detection method depends on the lifetime:

$$\gamma_{\tilde{\chi}^{\pm}} \sim \mathcal{O}(25\ \mathrm{ns})$$

$$\left(m_{3/2} \sim 10 - 100\,\mathrm{eV}\right)$$

displaced vertex, but length of decay
causes triggering issues.
Rely on other decay-chain particles
for triggering

# LHC Signatures: Chargino NLSP, Gravitino LSP

Detection method depends on the lifetime:

$$\gamma_{\tilde{\chi}_\pm} \gg \mathcal{O}(100\ \mathrm{ns})$$

$$\left(m_{3/2} \gg 100\ \mathrm{eV}\right)$$

decay occurs outside detector,
subject to massive
(stable) charged particle limits

# Hunt for flavor at the LHC

MRSSM could be full
of flavors but can LHC
see them?

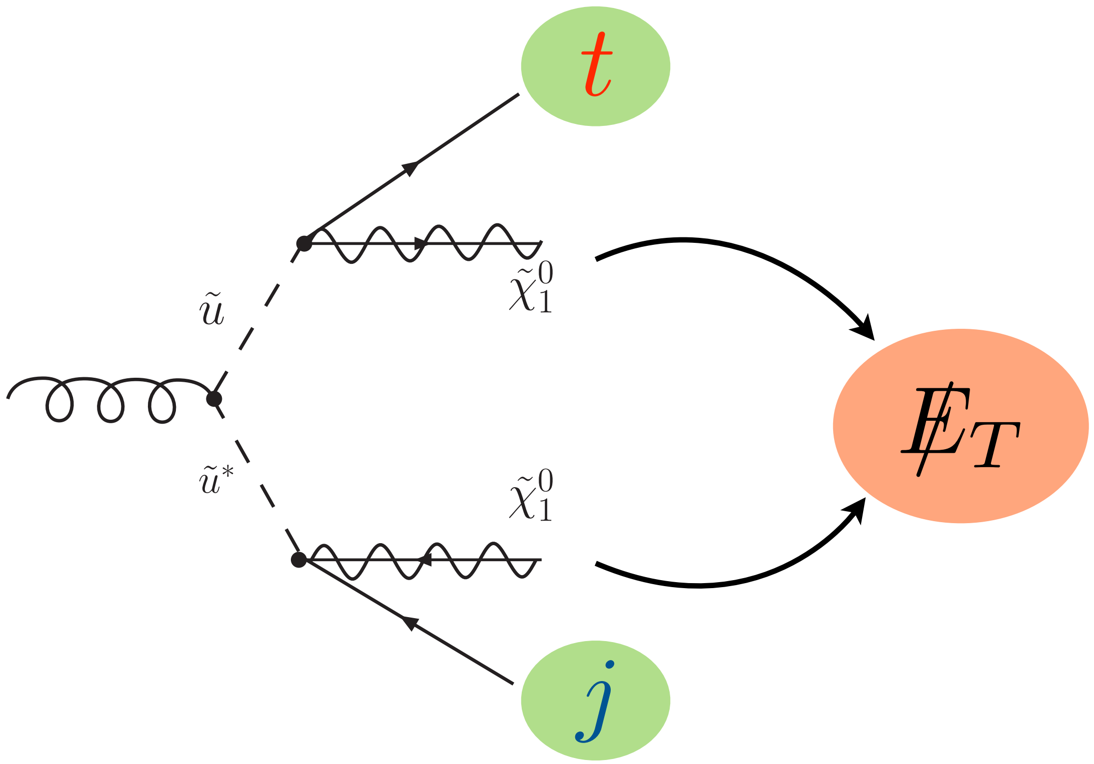
# 3 signals of 3 cases

- Case I: neutralino is the $\not{E}_T$
- Case II: gravitino is the $\not{E}_T$
  neutralino is the NLSP
- CaseIII: gravitino is the $\not{E}_T$
  chargino is the NLSP

(Kribs, Martin, Roy 0901.4105)

- *Case I: neutralino is the* $\not{E}_T$

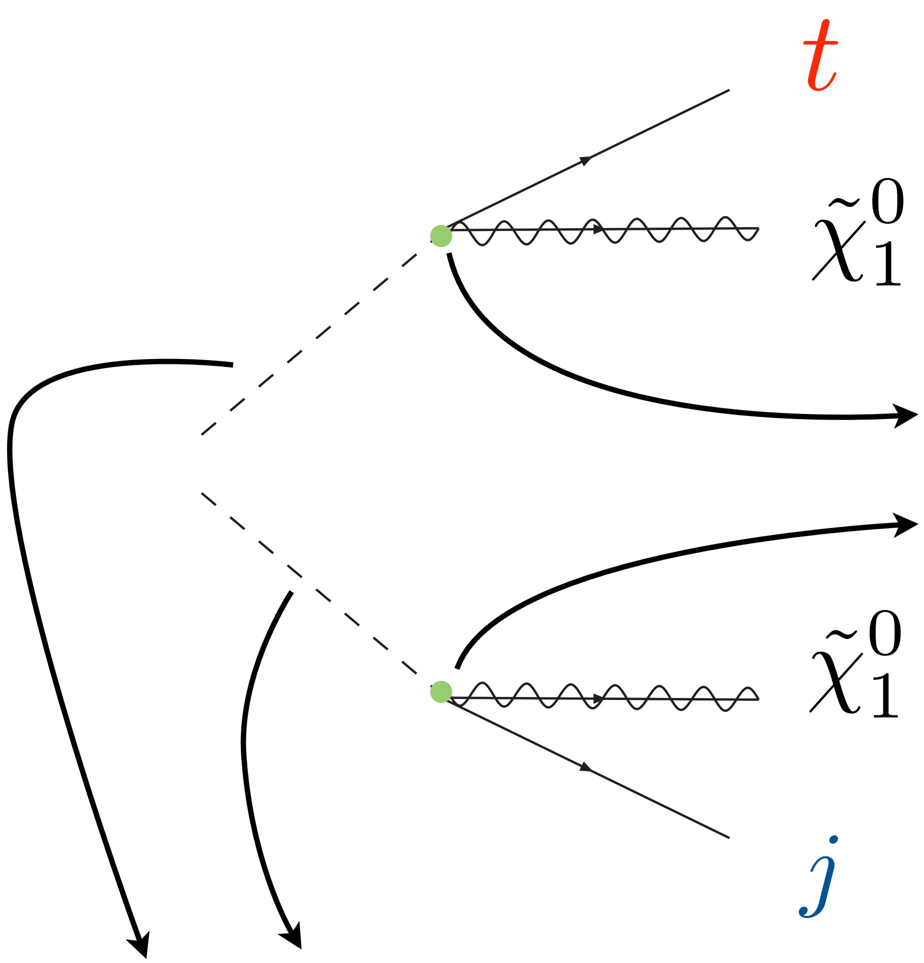
*MRSSM single top excess:*




$$pp \longrightarrow \tilde{u}^* \tilde{u} \longrightarrow t + j + \not{E}_T$$

$$\longrightarrow b + W(l)$$

- *Case I: neutralino is the* $\not{E}_T$



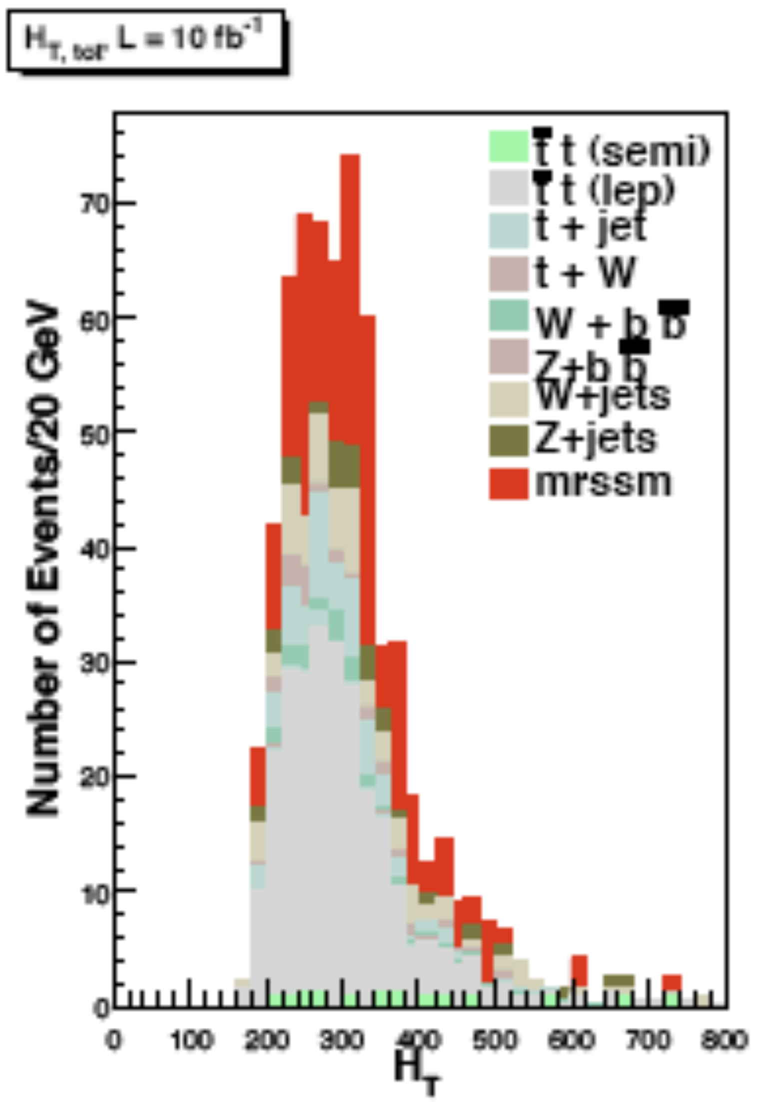

*both the vertices need to be sizable*

$\tilde{\chi}_1^0$ *should mostly be a bino*

*need to be summed over all up-squarks*

*squark masses must not be degenerate*

## • *Case I: neutralino is the* $\not{E}_T$



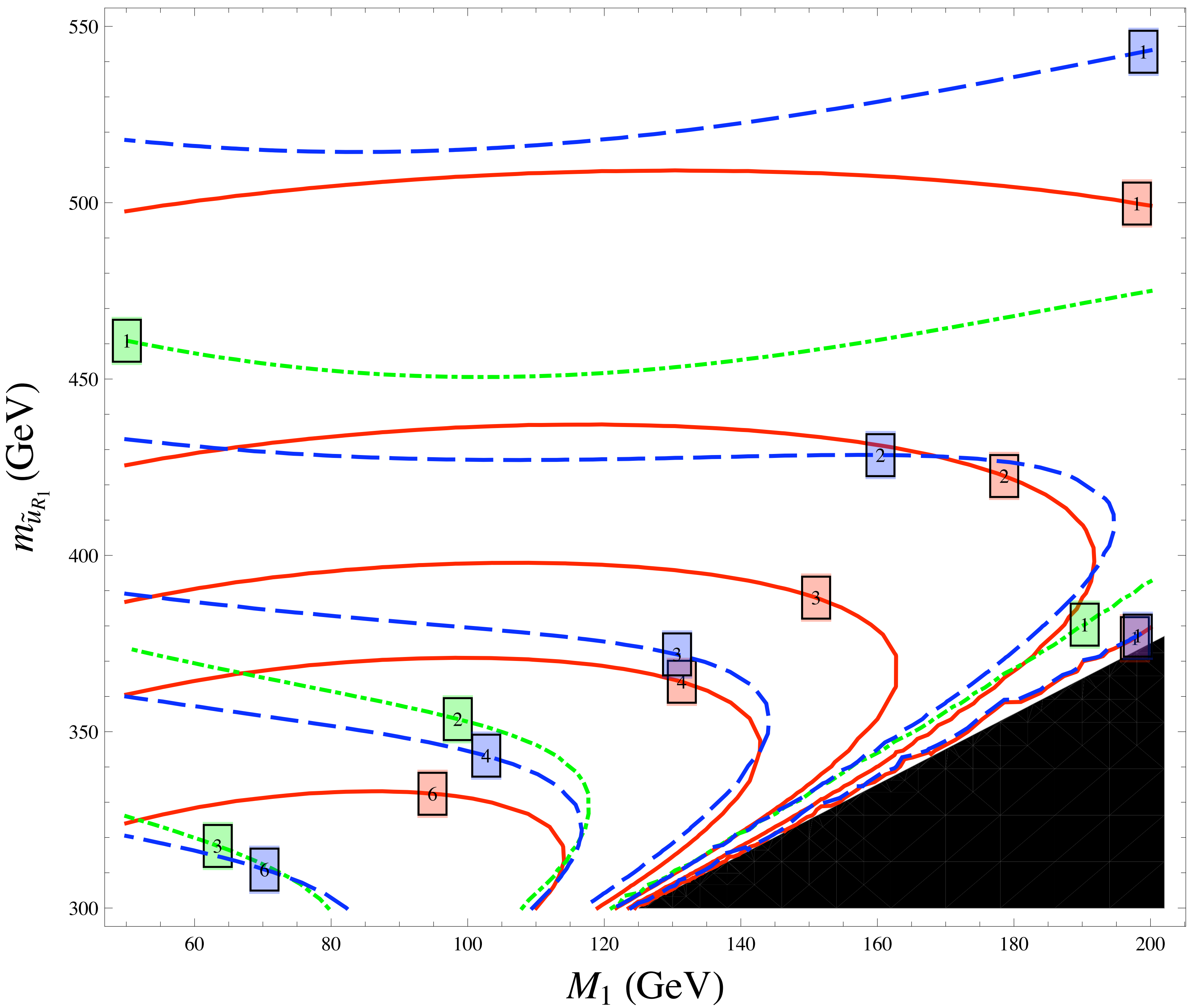

- Exactly 1 lepton, $p_T > 30$ GeV, $|\eta| < 2.5$.
- Exactly 2 jets and one $b$-tagged
- $\not{E}_T > 100$ GeV
- $\not{E}_T > 0.25 \times M_{eff}$
- Transverse mass of the $W$, $m_{T,W} > 120$ GeV

$$m_{\tilde{u}_{L_1}} = m_{\tilde{u}_{R_1}} = 1 \text{ TeV}, \qquad m_{\tilde{u}_{L_3}} = 1 \text{ TeV}, \quad m_{\tilde{u}_{R_3}} = 300 \text{ GeV},$$
$$M_1 = 50 \text{ GeV}, \qquad M_2 = 1 \text{ TeV}, \qquad M_3 = 3 \text{ TeV},$$
$$\mu_u = \mu_d = 1 \text{ TeV}, \qquad \text{and} \quad \tan\beta = 10$$
$$\theta_R = \pi/3, \qquad \theta_L = 0 \, .$$

*(full study in Kribs, Martin, Roy 0901.4105)*

- *Case I: neutralino is the* $\not{E}_T$

significance $\mathcal{S} = \frac{S}{\sqrt{S+B}}$



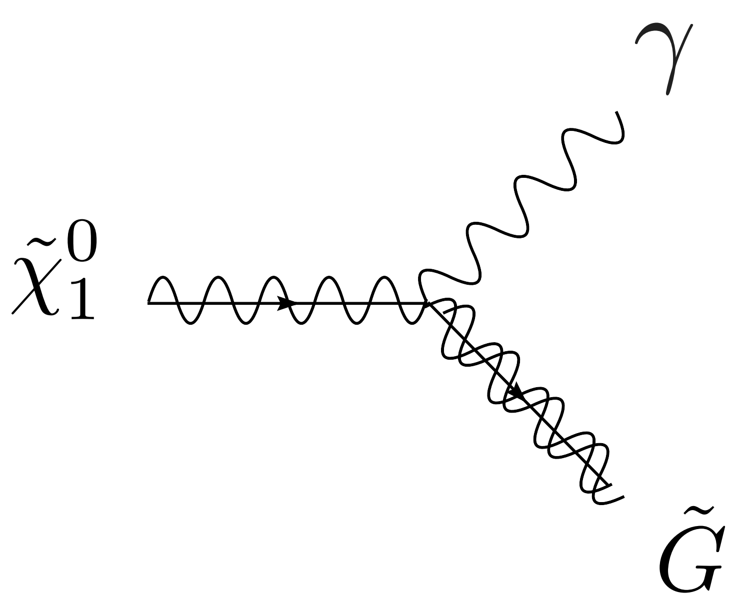

$\theta_R = \frac{\pi}{6}$

$\theta_R = \frac{\pi}{4}$

$\theta_R = \frac{\pi}{3}$

- *Case II:* *gravitino is the* $\not{E}_T$

  *neutralino is the NLSP*




*2 extra hard photons*

*almost background free signal*

- *Case II: gravitino is the* $\not{E}_T$

  *neutralino is the NLSP*

| Process | # events in 10 fb$^{-1}$ |
|---|---|
| $\tilde{u}_{R,i}\tilde{u}^*_{R,i} \to tj\chi_1\,\overline{\chi}_1 \to \ell bj\gamma\gamma + \not{E}_T$<br>$m_{\tilde{u}_R} = 300$ GeV, $m_{\tilde{\chi}_1} = 50$ GeV | 481 |
| $t\bar{t} \to b\bar{b}j\ell\nu$ | 1.3 |
| $t\bar{t} \to \ell\ell'\nu\nu'$ | 1.4 |
| $t+q \to bj\ell\nu$ | 0 |
| $t+b \to bb\ell\nu$ | 0 |
| $t(\text{inc.}) + W(\ell\nu)$ | 0 |
| $t(\text{inc.}) + W(\ell\nu) + j$ | $\leq 1$ |
| $W + \bar{b}b \to \bar{b}b\ell\nu$ | 0 |
| $Z + \bar{b}b \to \bar{b}b\nu\bar{\nu}$ | 0 |
| $WZ + \text{jets} :\to 3\ell + \nu + \text{jets}$ | 0 |
| $W(\ell\nu) + \text{jets}$ | $\leq 1$ |
| $Z(\ell^+\ell^-) + \text{jets}$ | 0 |
| $Z(\bar{\nu}\nu) + \text{jets}$ | 0 |
| Total Background | $\leq 5$ |

- **Case III:** gravitino is the $\not{E}_T$

  chargino is the NLSP

chargino is the NLSP in the Higgsino scenario
when squarks decay exclusively to top

very few signal events

If NLSP is long-lived - almost background
free signal - even a handful of events can
be picked up

# Conclusion

- MRSSM is the new direction of weak scale supersymmetry
  - it addresses the hierarchy and the flavor problem together
  - it is qualitatively different from MSSM
    - No L-R sfermion mixing
    - gauginos are ~10 times heavier than scalars
- prospect of unconventional signature at the LHC
  - signatures of gravitino LSP and a longlived chargino NLSP
  - plenty of flavor to be discovered in the single top channel if we are lucky - even flavor in the squark sector