MEASURING STOP MIXING ANGLE AT THE LHC

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Motivation

- stops play an important role in the mechanism of radiative electroweak symmetry breaking
- CP-violating phase in stop sector can have a large impact on the Higgs sector of MSSM and play significant role in baryogenesis
- can be inaccessible at the linear collider (at least at the first stage)
  $\Rightarrow$ extract as much information as possible from LHC
  $\Rightarrow$ for what can be done at the ILC see:
  Bartl ea. '95-'99, '04, Kraml '99
- here we propose a new method to determine properties of the stop sector at the LHC

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Stop sector of the MSSM

- defined by soft SUSY breaking masses for squarks $\widetilde{M}_Q$, $\widetilde{M}_U$, soft trilinear coupling A_t, $\tan\beta$ and μ parameter
- mass matrix for scalar top quarks in gauge eigenstate basis $\tilde{t}_L$, $\tilde{t}_R$

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} m_t^2 + m_{LL}^2 & m_{LR}^* m_t \\ m_{LR} m_t & m_t^2 + m_{RR}^2 \end{pmatrix}$$

with

$$\begin{aligned} m_{LL}^2 &= \widetilde{M}_Q^2 + m_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{2}{3} s_W^2\right) \\ m_{RR}^2 &= \widetilde{M}_U^2 + \frac{2}{3} m_Z^2 \cos 2\beta \, s_W^2 \\ m_{LR} &= A_t - \mu^* (\cot\beta) \end{aligned}$$

Stop sector of the MSSM

- diagonalize mass matrix with unitary matrix $U_{\tilde{t}}$

$$U_{\tilde{t}} \mathcal{M}^2_{\tilde{t}} U^\dagger_{\tilde{t}} = \mathrm{diag}(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2})$$

- obtain mass matrix eigenstates $\tilde{t}_1$ and $\tilde{t}_2$

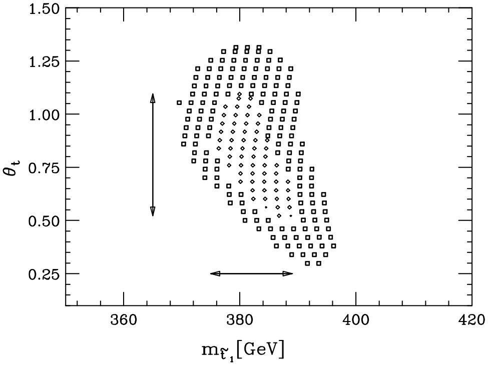
$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = U_{\tilde{t}} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{t}} & \sin\theta_{\tilde{t}}\, \mathrm{e}^{-\mathrm{i}\phi_{\tilde{t}}} \\ -\sin\theta_{\tilde{t}}\, \mathrm{e}^{\mathrm{i}\phi_{\tilde{t}}} & \cos\theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

- stops interactions can be parametrized in terms of $\cos\theta_{\tilde{t}}$ and $\phi_{\tilde{t}}$

Methods to determine $\cos\theta_{\tilde{t}}$

- take stops from gluino decays
  $\tilde{g} \to t\tilde{t} \to tb\tilde{\chi}_1^+$
  $\tilde{g} \to b\tilde{b}_i \to tb\tilde{\chi}_1^+$
- combine the analysis of sbottom and stop sectors
- fit to stop mass and mixing angle gives:
  $\Delta m_{\tilde{t}_1} = 7 \text{ GeV}$
  $\Delta\theta_{\tilde{t}} = 0.29$

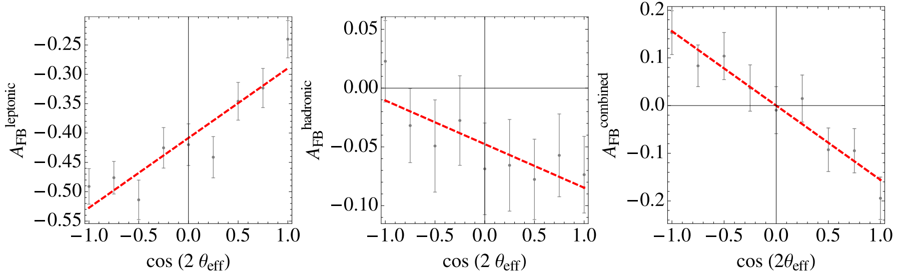
Hisano, Kawagoe, Nojiri '03



Methods to determine $\cos\theta_{\tilde{t}}$

- measurement of top polarization in the decay $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 t$
- use hadronic and semileptonic top decays and forward-backward asymmetries A_{FB} of decay products
- A_{FB} have linear dependence on effective stop mixing angle

  Perelstein, Weiler '08



Stop couplings

- consider the coupling to charged gauginos and higgsinos

$$\mathcal{L} \supset \mathrm{i}g_2\, \tilde{t}_L^*\, \tilde{W}^+ b_L + Y_t\, \tilde{t}_R^*\, \tilde{H}_u^+ b_L + Y_b\, \tilde{t}_L^*\, \tilde{H}_d^+ b_R + \mathrm{h.c.}$$

- $\cos\theta_{\tilde{t}}$ gives content of $\tilde{t}_L$ and $\tilde{t}_R$ states in $\tilde{t}_1$ and $\tilde{t}_2$

$$\tilde{t}_L = \tilde{t}_1 \cos\theta_{\tilde{t}} - \tilde{t}_2 \sin\theta_{\tilde{t}}$$

- for mass eigenstates we have

$$\mathcal{L} \supset \mathrm{i}g_2 \cos\theta_{\tilde{t}}\, \tilde{t}_1^*\, \tilde{W}^+ b_L - \mathrm{i}g_2 \sin\theta_{\tilde{t}}\, \tilde{t}_2^*\, \tilde{W}^+ b_L + \ldots$$

$\Rightarrow$ for $\cos\theta_{\tilde{t}} = 0$ coupling of $\tilde{t}_1^*$ to wino vanishes
$\Rightarrow$ for $\cos\theta_{\tilde{t}} = 1$ coupling of $\tilde{t}_1^*$ to wino maximal

Our method

- measuring relative strength of the coupling to charginos and neutralinos gives information on the structure of stop sector
- take light stops from a direct pair production process to avoid background from sbottoms
- absolute measurement of branching ratios difficult
  $\Rightarrow$ look at the relative number of stops decaying to different charginos and neutralinos
- depending on the realized model one can get information on stop mixing (including phase) and mass
  $\Rightarrow$ can be combined with information from other methods

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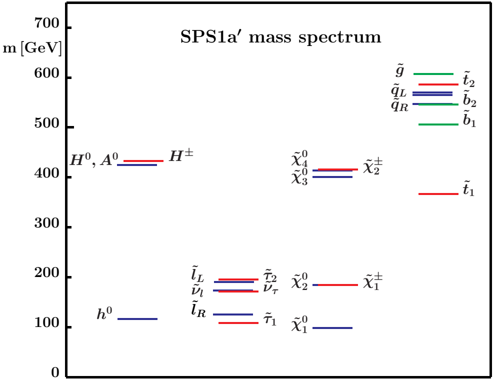
Parameter point – SPS1a′

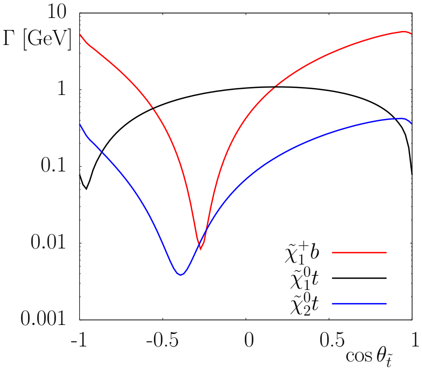
- masses:

  $m_{\tilde{t}_1} = 366$ GeV
  $m_{\tilde{\chi}_1^\pm} = 184$ GeV
  $m_{\tilde{\chi}_1^0} = 98$ GeV
  $m_{\tilde{\chi}_2^0} = 184$ GeV
- mixing angle: $\cos\theta_{\tilde{t}} = 0.56$, $\phi_{\tilde{t}} = 0$
- decay modes:

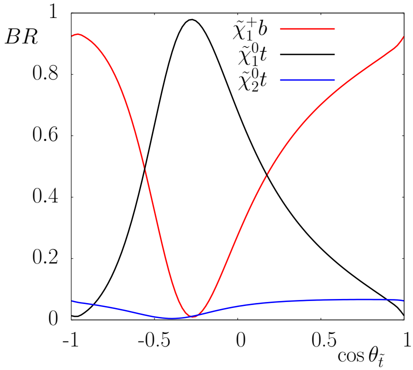
  $BR(\tilde{t}_1 \to \tilde{\chi}_1^+ b) = 72\%$
  $BR(\tilde{t}_1 \to \tilde{\chi}_1^0 t) = 22\%$
  $BR(\tilde{t}_1 \to \tilde{\chi}_2^0 t) = 7\%$
- $\sigma^{14\ \mathrm{TeV}}(pp \to \tilde{t}_1 \tilde{t}_1^*) = 3.4$ pb



Stop decays



widths for different decay modes of $\tilde{t}_1$ as a function of $\cos\theta_{\tilde{t}}$



BRs for different decay modes as a function of $\cos\theta_{\tilde{t}}$

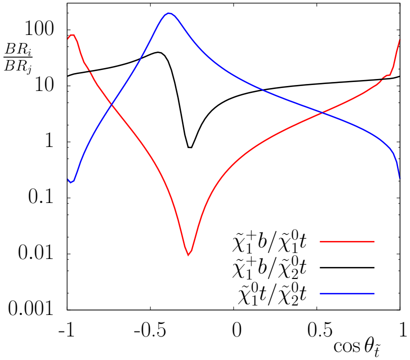
Ratios of branching ratios

- define the following quantities in $\tilde{t}_1$ decay modes:

$$R^{1b}_{1t} = \frac{BR(\tilde{t}_1 \to \tilde{\chi}^+_1 b)}{BR(\tilde{t}_1 \to \tilde{\chi}^0_1 t)}$$

$$R^{1b}_{2t} = \frac{BR(\tilde{t}_1 \to \tilde{\chi}^+_1 b)}{BR(\tilde{t}_1 \to \tilde{\chi}^0_2 t)}$$

$$R^{1t}_{2t} = \frac{BR(\tilde{t}_1 \to \tilde{\chi}^0_1 t)}{BR(\tilde{t}_1 \to \tilde{\chi}^0_2 t)}$$



ratios of BRs for different decay modes as a function of $\cos\theta_{\tilde{t}}$

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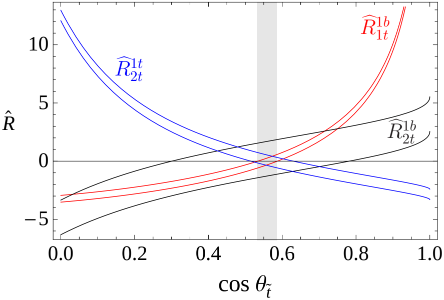
Determination of stop mixing angle

- number of events for any two decay modes give one of the ratios R^i_j
  $\Rightarrow$ best constraints from R^{1b}_{1t} and R^{1t}_{2t}
  $\Rightarrow$ no information on other decay modes required



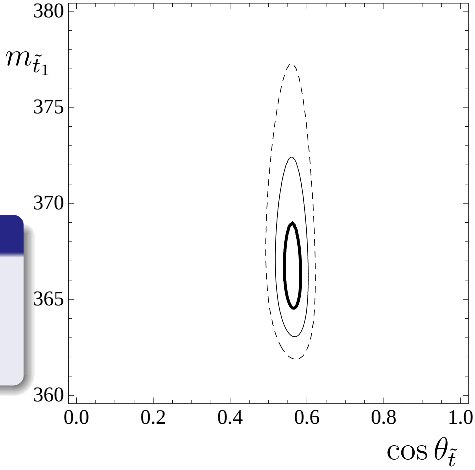
- here ratios are normalized to their nominal values with 1-σ statistical error bands

Fit results for $\cos\theta_{\tilde{t}}$ and $m_{\tilde{t}_1}$

- 1000 events of stop production
- χ^2 fit to all 3 ratios
- error = statistical only

Results

$$\cos\theta_{\tilde{t}} = 0.56 \pm 0.04$$
$$\theta_{\tilde{t}} = 0.98 \pm 0.05$$
$$m_{\tilde{t}_1} = 366^{+3}_{-2}\ \text{GeV}$$



SM Backgrounds

- Standard Model background:
  $t\bar{t} \to 4j\, 2b\,, \quad 2j\, 2b\, \ell + E_{\rm miss}\,, \quad 2b\, 2\ell + E_{\rm miss}$

- cuts proposed by Perelstein, Weiler '08
  $\Rightarrow$ large missing transverse energy $E_{\rm miss} > 125$ GeV
  $\Rightarrow$ semileptonic top veto (using neutrino momentum reconstruction)
  $\Rightarrow$ hadronic top reconstruction to eliminate $W+$jets background
  $\Rightarrow$ angular and separation cuts

SUSY Backgrounds

- gluino pairs decaying to:
  $\tilde{g}\tilde{g} \to \tilde{b}_i b + \tilde{b}_j b\,, \quad \tilde{b}_i b + \tilde{t}_1 t\,, \quad \tilde{t}_1 t + \tilde{t}_1 t$
  $\Rightarrow$ good b tagging efficiency needed to reject these
- production of $\tilde{b}_i \tilde{b}_j^*$ and $\tilde{t}_2 \tilde{t}_2^*$ is order of magnitude smaller than the signal
- different final states within the signal may fake each other when top decays leptonically:
  $\tilde{t}_1 \to t\tilde{\chi}_1^0 \to b\,\ell + E_{\rm miss}$ and $\tilde{t}_1 \to b\tilde{\chi}_1^+ \to b\,\ell + E_{\rm miss}$
  $\Rightarrow$ can be combined together without spoiling the fit

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Conclusions

- if stops are too heavy for ILC we have to use maximum information from LHC
- proposed method can give useful constraints on parameters of stop sector
- additional precision measurement of gaugino/higgsino sector may be required from the linear collider
  $\Rightarrow$ example of LHC-ILC interplay
- combination with CP-odd observables can resolve CP properties of top squarks
- more detailed experimental study needed to asses viability of this method

Additional slides

Possible final states

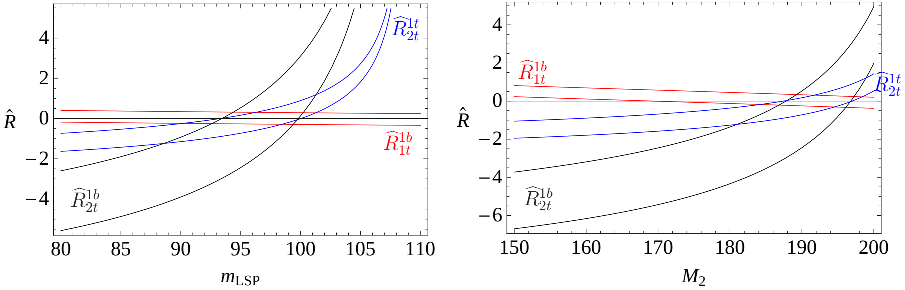
- for decay modes with t quark require top reconstruction
- neutralino decay modes include tau leptons
- number of events for integrated luminosity $\mathcal{L} = 100$ fb^{-1}

decay mode	# events
$\tilde{t}_1\tilde{t}_1^* \to t\tilde{\chi}_2^0 + \bar{t}\tilde{\chi}_2^0 \to t\ell\bar{\ell}\tilde{\chi}_1^0 + \bar{t}\ell\bar{\ell}\tilde{\chi}_1^0 \to 4\ell\ 4j\ 2b\ + E_{\text{miss}}$	225
$\tilde{t}_1\tilde{t}_1^* \to t\tilde{\chi}_2^0 + \bar{t}\tilde{\chi}_1^0 \to t\ell\bar{\ell}\tilde{\chi}_1^0 + \bar{t}\tilde{\chi}_1^0 \to 2\ell\ 4j\ 2b + E_{\text{miss}}$	1270
$\tilde{t}_1\tilde{t}_1^* \to t\tilde{\chi}_2^0 + b\tilde{\chi}_1^+ \to t\ell\bar{\ell}\tilde{\chi}_1^0 + b\bar{\ell}\nu_\ell\tilde{\chi}_1^0 \to 3\ell\ 2j\ 2b + E_{\text{miss}}$	6230
$\tilde{t}_1\tilde{t}_1^* \to t\tilde{\chi}_1^0 + \bar{t}\tilde{\chi}_1^0 \to 4j\ 2b + E_{\text{miss}}$	7100
$\tilde{t}_1\tilde{t}_1^* \to t\tilde{\chi}_1^0 + b\tilde{\chi}_1^+ \to t\tilde{\chi}_1^0 + b\bar{\ell}\nu_\ell\tilde{\chi}_1^0 \to \ell\ 2j\ 2b\ + E_{\text{miss}}$	35000
$\tilde{t}_1\tilde{t}_1^* \to \bar{b}\tilde{\chi}_1^- + b\tilde{\chi}_1^+ \to \bar{b}\ell\bar{\nu}_\ell\tilde{\chi}_1^0 + b\bar{\ell}\nu_\ell\tilde{\chi}_1^0 \to 2\ell\ 2b\ + E_{\text{miss}}$	170000

Dependence on gaugino parameters

ratios of BRs show only moderate dependence on LSP mass (keeping $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ fixed) and wino mass parameter M_2

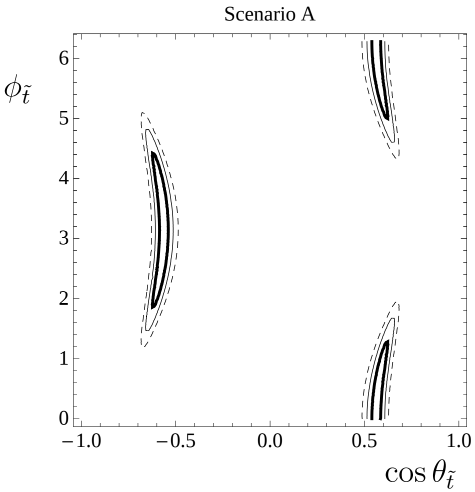
$\Rightarrow$ no precise knowledge needed to get useful constraints



$\Rightarrow$ stronger dependence only for decay to $\tilde{\chi}_2^0 t$ which is close to kinematical limit

Fit results for $\cos\theta_{\tilde{t}}$ and $\phi_{\tilde{t}}$

- 1000 events of stop production
- χ^2 fit to all 3 ratios
- error = statistical only
- the CP phase is unconstrained



Higgsino scenario

Features: bino LSP $\tilde{\chi}_1^0$; higgsino $\tilde{\chi}_1^+$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$;