Testing the SUSY weak scale stabilization at the LHC

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Outline

MB, D. Curtin, M. Perelstein, 1004.5350

The gauge hierarchy problem

Gauge hierarchy problem:

- huge hierarchy between the fundamental gravity scale M_{Pl} and the electroweak scale Λ_{EWSB}
- even if $\Lambda_{\mathsf{EWSB}}/M_{\mathsf{Pl}} \sim 10^{-16}$ is imposed at tree-level, loop corrections push $\Lambda_{\mathsf{EWSB}} \sim M_{\mathsf{Pl}}$
- tremendous fine-tuning required to keep $\Lambda_{\mathsf{EWSB}} \sim 1\,\mathsf{TeV}$

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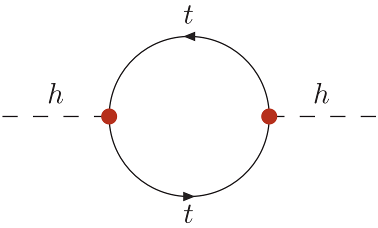
Two possible solutions:

- either accept finely tuned Λ_{EWSB}
- *or* introduce New Physics at the TeV scale to restore naturalness

SUSY cancellation of quadratic divergences

- loop contributions of SM particles (e. g. tops) let the Higgs potential depend quadratically on the cut-off scale



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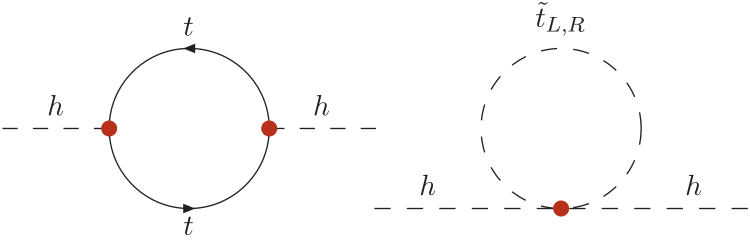
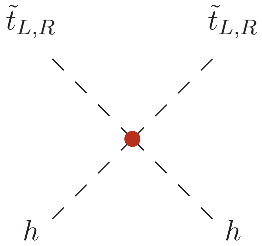


- new particles (stops) with sub-TeV masses required to cancel these contributions
- couplings to the Higgs boson have to be equal

How to access the stop-Higgs coupling at the LHC?

We want to measure the coupling $hh\tilde{t}_{L,R}\tilde{t}^c_{L,R}$:



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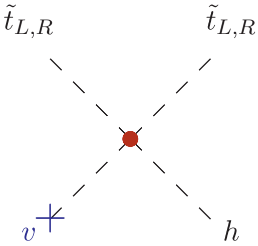

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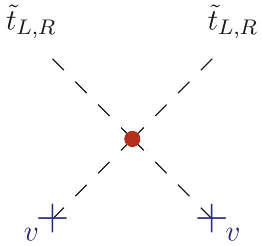

- direct measurement not feasible at the LHC
- $h\tilde{t}_{L,R}\tilde{t}^c_{L,R}$ easier, but still (most probably) too hard
- contribution to stop mass matrix – should be doable!

Top Yukawas & the stop superpotential

- top Yukawas arise from the superpotential

$$\mathcal{W} = \lambda_t H_u Q_3 t_R + \mu H_u H_d + \ldots$$

- scalar potential (F-terms)

$$V_{\mathsf{SUSY}} = {\lambda_t}^2 |H_u \tilde{Q}_3|^2 + {\lambda_t}^2 |H_u|^2 |\tilde{t}_R|^2 + |\mu H_d + \lambda_t \tilde{Q}_3 \tilde{t}_R|^2$$

- these terms contribute to stop masses after EWSB

$$\longrightarrow {m_t}^2(|\tilde{t}_L|^2 + |\tilde{t}_R|^2) + \mu m_t \cot\beta(\tilde{t}_L^c \tilde{t}_R + \tilde{t}_R^c \tilde{t}_L)$$

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- in addition: soft breaking terms

$$V_{\mathsf{soft}} = m_L^2 |\tilde{Q}_3|^2 + m_R^2 |\tilde{t}_R|^2 + A_t H_u^\dagger \tilde{Q}_3 \tilde{t}_R^c + h.c.$$

The stop mass matrix

- stop mass matrix: $\mathcal{L} = (\tilde{t}_L^c, \tilde{t}_R^c)\mathcal{M}_t^2(\tilde{t}_L, \tilde{t}_R)$

$$\mathcal{M}_t^2 = \begin{pmatrix} m_L^2 + {m_t}^2 + \Delta_u & m_t(A_t + \mu\cot\beta) \\ m_t(A_t + \mu\cot\beta) & m_R^2 + {m_t}^2 + \Delta_{\bar{u}} \end{pmatrix}$$

- rotation to mass eigenstates via

$$\begin{aligned} \tilde{t}_1 &= \cos\theta_t\, \tilde{t}_L + \sin\theta_t\, \tilde{t}_R \\ \tilde{t}_2 &= -\sin\theta_t\, \tilde{t}_L + \cos\theta_t\, \tilde{t}_R \end{aligned}$$

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- then re-express $\mathcal{M}_{11}^2$

$$m_L^2 + {m_t}^2 + \Delta_u = m_{\tilde{t}_1}^2\cos^2\theta_t + m_{\tilde{t}_2}^2\sin^2\theta_t$$

- analogously (for $\sin\theta_b \ll 1, m_b \to 0$)

$$m_L^2 + \Delta_d = m_{\tilde{b}_1}^2$$

The SUSY-Yukawa sum rule

eliminating m_L^2 yields the SUSY-Yukawa sum rule

$$\boxed{{m_t}^2 + (\Delta_u - \Delta_d) = m_{\tilde{t}_1}^2 \cos^2\theta_t + m_{\tilde{t}_2}^2 \sin^2\theta_t - m_{\tilde{b}_1}^2}$$

where $\Delta_u - \Delta_d = m_Z^2 \cos^2\theta_W \cos 2\beta \approx -m_W^2$

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- sum rule expresses stop-Higgs coupling in terms of measurable quantities (masses, mixing angles)
- SUSY weak scale stabilization (in principle) testable at the LHC!

if sum rule is falsified

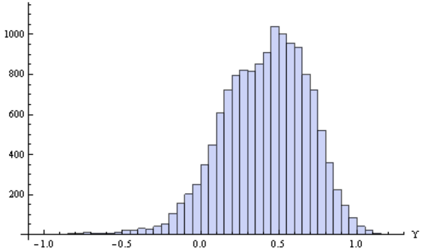
- ➢ nature is non-supersymmetric
- ➢ SUSY is broken non-softly
- ➢ more complicated realization of SUSY (e. g. additional Higgs doublets)

. . . and what about radiative corrections?

- above derivation valid at tree level
- to quantify effect of radiative corrections, define

$$\Upsilon = \frac{1}{v^2}(m^2_{\tilde{t}_1}\cos^2\theta_t + m^2_{\tilde{t}_2}\sin^2\theta_t - m^2_{\tilde{b}_1})$$

- SUSY tree level prediction: $\Upsilon_{\text{tree}} = 0.28 \quad (\tan\beta > \text{a few})$



SuSpect scan over pMSSM parameter space yields

$$\Upsilon \lesssim 1$$

Parameters to be determined

- masses

$$m_{\tilde{t}_1}$$
$$m_{\tilde{t}_2}$$
$$m_{\tilde{b}_1} \quad (\tilde{b}_1 = \tilde{b}_L)$$

- mixing angles

$\sin\theta_t$

$\sin\theta_b$ (usually small)

$\tan\beta$ (minor impact)

- helpful (to evaluate part of the radiative corrections): $m_{\tilde{g}}$

Mass measurements in missing energy events

see e. g. Burns, Kong, Matchev, Park, 08105576

SUSY mass measurements complicated, as event cannot fully be reconstructed (LSP escapes detection)

- **endpoint method**
  measure kinematic endpoints of invariant mass distributions of SM decay products
- **polynomial method**
  attempt exact event reconstruction
- $\boldsymbol{M_{T2}}$ **method**
  reconstruct endpoint of transverse invariant mass

for short decay chains ($n \leq 2$), we need to rely on M_{T2}!

Recall: how to measure the W mass

- consider decay $W \to \ell\nu$: invariant mass

$$m_W^2 = m_\ell^2 + m_\nu^2 + 2p_\ell \cdot p_\nu$$

- but we know only $\boldsymbol{p}_T^\nu = \not{\boldsymbol{p}}_T$
- consider transverse mass instead

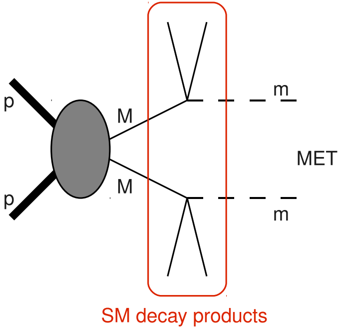
$$\boxed{m_T^2 = m_\ell^2 + m_\nu^2 + 2(E_T^\ell E_T^\nu - \boldsymbol{p}_T^\ell \cdot \boldsymbol{p}_T^\nu)}$$

- m_W is then determined by the endpoint

$$\boxed{m_W = \max_{\text{all events}} \{m_T\}}$$

- Note: m_ν and $\boldsymbol{p}_T^\nu$ are known

The stransverse mass M_{T2}



Barr, Lester, Stephens, hep-ph/0304226

SUSY events complicated by

- two missing particles
- LSP mass unknown

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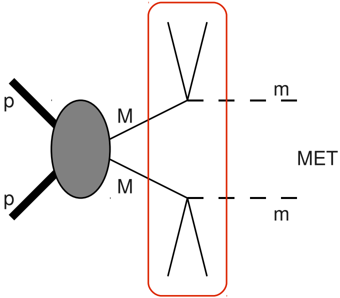


Barr, Lester, Stephens, hep-ph/0304226

SUSY events complicated by

- two missing particles
- LSP mass unknown

➢ **the best we can do**

- use trial LSP mass χ
- minimize over all possible LSP momentum configurations

➢ define the stransverse mass M_{T2} by

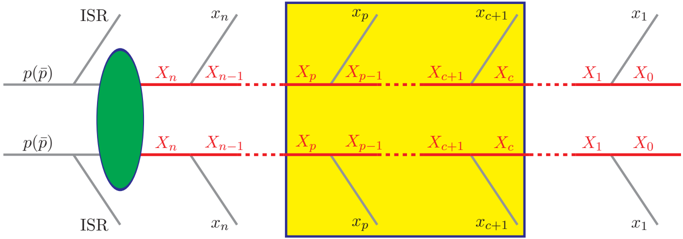
$$M_{T2}(\chi) = \min_{\boldsymbol{p}_T^{(1)}+\boldsymbol{p}_T^{(2)}=\not{\boldsymbol{p}}_T} \left\{ \max\{m_T^{(1)}, m_T^{(2)}\} \right\}$$

edge of distribution: $M_{T2}(\chi)_{\text{max}} = \frac{M^2-m^2}{2M} + \sqrt{(\frac{M^2-m^2}{2M})^2 + \chi^2}$

Extension: the subsystem M_{T2}

BURNS, KONG, MATCHEV, PARK, 0810.5576

for $n > 1$ step decay chains:



generalize M_{T2} concept to subsystem $M_{T2}^{(n,p,c)}(\chi)$

(n: grandparent index, p: parent index, c: child index)

➢ $M_{T2}^{(n,p,c)}(\chi)$ endpoint yields relation between m_n, m_p and m_c

Main virtues of our benchmark scenario

$m_{\tilde{t}_1}$	=	370 GeV	$\sigma(pp \to \tilde{t}_1 \tilde{t}_1^c)$	=	2 pb
$m_{\tilde{t}_2}$	=	800 GeV	$\sigma(pp \to \tilde{g}\tilde{g})$	=	11 pb
$\sin\theta_t$	=	-0.09			
$m_{\tilde{b}_1}$	=	341 GeV	$Br(\tilde{g} \to b\tilde{b}_1)$	=	100%
$m_{\tilde{g}}$	=	525 GeV	$Br(\tilde{b}_1 \to b\tilde{\chi}_1^0)$	=	100%
$m_{\tilde{\chi}_1^0}$	=	98 GeV	$Br(\tilde{t}_1 \to t\tilde{\chi}_1^0)$	=	100%

➢ study $pp \to \tilde{t}_1\tilde{t}_1^c \to t\bar{t} + \not{p}_T$ and $pp \to \tilde{g}\tilde{g} \to bb\tilde{b}_1\tilde{b}_1 \to 4b + \not{p}_T$

Some technical details

- SUSY spectrum and decays calculated using `SUSY-HIT`
- parton-level analysis for $\sqrt{s} = 14\,\text{TeV}$ pp collisions
- Monte Carlo event samples generated by `MadGraph/MadEvent`
- fully decayed final state obtained with `BRIDGE`
- leading order analysis, using CTEQ6l1 pdf sets
- Gaussian smearing of jet energies

$$\frac{\Delta E}{E} = \frac{50\%}{\sqrt{E[\text{GeV}]}} \oplus 3\%$$

to simulate detector response

$4b + \not{p}_T$ – signal and backgrounds

require cuts

- four tagged b-jets with $p_T > 40\,\text{GeV}$, $p_T^{\text{max}} > 100\,\text{GeV}$
- $\not{p}_T > 200\,\text{GeV}$
- $|\eta| < 2.5$ and $\Delta R > 0.4$

then the SM background is negligible!

$4b + \not{p}_T$ – signal and backgrounds

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BUT combinatorial background – which b-jet is which?
➢ ideal treatment depends on observable considered

We always require successful edge determination using two different methods$^{(*)}$ of background reduction, in order to avoid "fake edges".

$^{(*)}$ I will show only one here for the sake of simplicity.

The invariant mass endpoint

for b-jets from the *same* decay chain

$$M_{bb} \leq \sqrt{\frac{(m^2_{\tilde{b}_1} - m^2_{\tilde{\chi}^0_1})(m^2_{\tilde{g}} - m^2_{\tilde{b}_1})}{m^2_{\tilde{b}_1}}}$$

three possible ways to pair the b-jets

- each combination gives two M_{bb} values ➢ keep only the larger
- take the smallest of these three values

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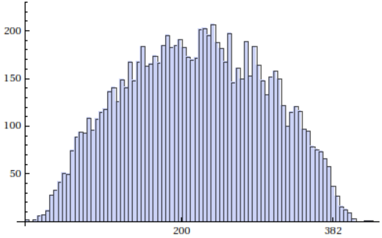
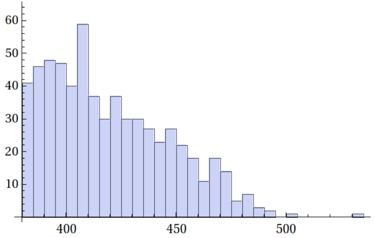


linear kink fit yields $(M_{bb})_{\text{max}} = (395 \pm 5)$ GeV theory: 382.3 GeV

The $M_{T2}^{(2,2,0)}$ edge

$$M_{T2}^{(2,2,0)}(\chi = 0) \leq \frac{m_{\tilde{g}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{g}}}$$

combinatoric background ➢ reduced by making use of invariant mass information



fit result:

$(M_{T2}^{(2,2,0)})_{\text{max}} = (492.1 \pm 4.8)$ GeV

theory prediction: 506.7 GeV

The subsystem $M_{T2}^{(2,1,0)}$ edge

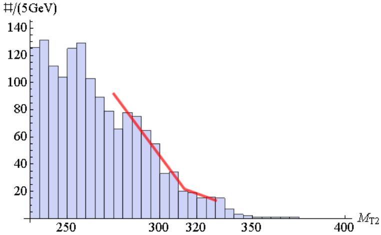
$$M_{T2}^{(2,1,0)}(\chi = 0) \leq \sqrt{\frac{(m_{\tilde{b}_1}^2 - m_{\tilde{\chi}_1^0}^2)(m_{\tilde{g}}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{g}}^2}}$$

combinatoric background: those combinations of bs which stem from the same decay chain yield significantly larger $M_{T2}^{(2,1,0)}$ values than the others ➢ drop the largest two values

linear kink fit

$$(M_{T2}^{(2,1,0)})_{\mathsf{max}} = (314.0 \pm 4.6)\ \mathrm{GeV}$$

theory prediction: 320.9 GeV



Results for $m_{\tilde{b}_1}$, $m_{\tilde{g}}$ and $m_{\tilde{\chi}_1^0}$ $(10\,\mathsf{fb}^{-1})$

inflating errors by a factor of 3 to account for systematic error from kink fit:

$$\begin{aligned}
(M_{bb})_{\mathsf{max}} &= (395 \pm 15)\,\mathsf{GeV} \\
(M_{T2}^{(2,1,0)})_{\mathsf{max}} &= (314 \pm 14)\,\mathsf{GeV} \\
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combining those, we obtain the mass measurements (68% C.L.)

$$316\ \text{GeV} \leq m_{\tilde{b}_1} \leq 356\ \text{GeV}$$
$$508\ \text{GeV} \leq m_{\tilde{g}} \leq 552\ \text{GeV}$$
$$45\ \text{GeV}^{(*)} \leq m_{\tilde{\chi}_1^0} \leq 115\ \text{GeV}$$

$^{(*)}$ LEP lower bound

$t\bar{t} + \not{p}_T$ – signal and background

- need to fully reconstruct top momenta ➢ hadronic tops
- impose cuts (following Meade, Reece, hep-ph/0601124)
  - two b-tagged jets and four other jets with $E_T > 30\,\text{GeV}$, $E_T^{\text{max}} > 100\,\text{GeV}$
  - $\not{p}_T > 100\,\text{GeV}$ and $\not{p}_T + \sum p_T > 500\,\text{GeV}$
  - $|\eta| < 2.5$ and $\Delta R > 0.4$
  - two Ws and two tops can be reconstructed in $\pm 20\,\text{GeV}$ windows

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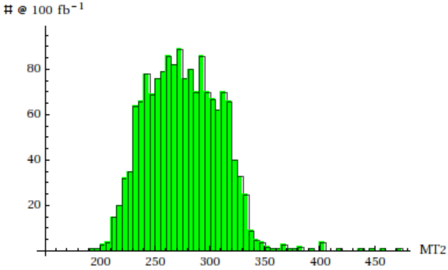
  - $|\eta| < 2.5$ and $\Delta R > 0.4$
  - two Ws and two tops can be reconstructed in $\pm 20\,\text{GeV}$ windows
- dominant background: $t\bar{t}(Z \to \nu\bar{\nu})$
- with these cuts: $S/B \simeq 14$, $S/\sqrt{B} = 140$ $(100\,\text{fb}^{-1})$
- this time no combinatoric background

The M_{T2} edge and $m_{\tilde{t}_1}$

$$M_{T2}(\chi = 0) \leq \frac{m^2_{\tilde{t}_1} - m^2_{\tilde{\chi}^0_1}}{m_{\tilde{t}_1}}$$



- SM background featureless ➢ M_{T2} edge clearly visible
- kink fit yields $(M_{T2})_{\text{max}} = (340 \pm 4)$ GeV theory: 336.7 GeV

The M_{T2} edge and $m_{\tilde{t}_1}$

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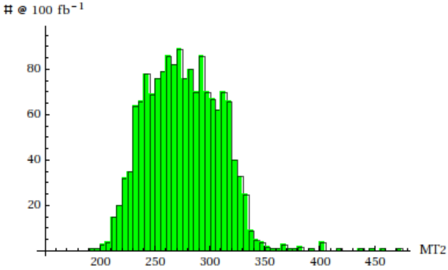


- SM background featureless ➢ M_{T2} edge clearly visible
- kink fit yields $(M_{T2})_{\text{max}} = (340 \pm 4)$ GeV theory: 336.7 GeV
- using our $m_{\tilde{\chi}_1^0}$ measurement we find (68% C.L.)

$$356\,\text{GeV} \leq m_{\tilde{t}_1} \leq 414\,\text{GeV}$$

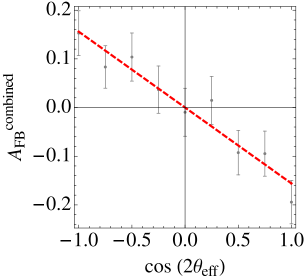
Top polarization – the key to $\sin\theta_t$

Perelstein, Weiler, 0811.1042

- $\tilde{t}_1 \to t\tilde{\chi}_1^0$ governed by vertex

$$g_{\text{eff}}\tilde{t}_1\tilde{\chi}_1^0(\cos\theta_{\text{eff}}\, P_L + \sin\theta_{\text{eff}}\, P_R)t$$

- this leads to polarized tops and consequently a forward-backward asymmetry in its decay products

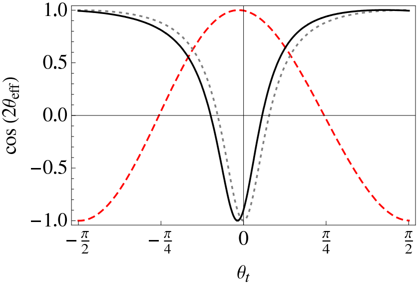


$\boxed{\Delta\cos 2\theta_{\text{eff}} \simeq 0.3}$ $(10\,\text{fb}^{-1})$

issues:

- two-fold ambiguity in θ_{eff}
- extracting θ_t requires prior knowledge of neutralino mixing

Constraint on stop mixing



$\tilde{\chi}_1^0$ pure bino
$\tilde{\chi}_1^0$ pure higgsino
our benchmark scenario

suppose we knew about neutralino mixing

➢ expected measurement for our benchmark point $(100\,\text{fb}^{-1})$

$$|\sin\theta_t| \lesssim 0.2$$

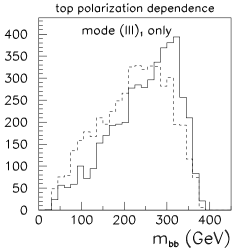
Alternative approaches to measure θ_t

ROLBIECKI ET AL, 0909.3196

- consider $t_1 \to t\chi_j^0$ and $t_1 \to b\chi_j^+$
- ratios of branching ratios depend on stop mixing angle (but also on chargino and neutralino mixings)

HISANO ET AL, HEP-PH/0304214

- consider decay chain $\tilde{g} \to t\tilde{t}_1 \to bbW\chi_1^+$
- θ_t manifest in top polarization
- reflected in angle between b's
- M_{bb} is harder (softer) for left-(right-) handed tops



Both approaches are not accessible for our benchmark scenario!

Resulting accuracy for testing the sum rule

- rewrite Υ as

$$\Upsilon = \frac{1}{v^2}(m^2_{\tilde{t}_1} - m^2_{\tilde{b}_1}) + \frac{\sin^2\theta_t}{v^2}(m^2_{\tilde{t}_2} - m^2_{\tilde{t}_1}) = \Upsilon' + \Delta\Upsilon_t$$

- our measurements yield

$$\boxed{\Upsilon' = 0.53^{+0.20}_{-0.15}}$$

theory: 0.35

Resulting accuracy for testing the sum rule

- rewrite Υ as

$$\Upsilon = \frac{1}{v^2}(m_{\tilde{t}_1}^2 - m_{\tilde{b}_1}^2) + \frac{\sin^2\theta_t}{v^2}(m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) = \Upsilon' + \Delta\Upsilon_t$$

- our measurements yield

$$\boxed{\Upsilon' = 0.53^{+0.20}_{-0.15}}$$ theory: 0.35

- without measuring $m_{\tilde{t}_2}$ we can only estimate $\Delta\Upsilon_t$
  ➢ assuming $|\sin\theta_t| \lesssim 0.2$ and $m_{\tilde{t}_2} \lesssim 1$ TeV

$$0 < \Delta\Upsilon_t \lesssim 0.58$$

- altogether we find $0.4 \lesssim \Upsilon \lesssim 1.3$ (theory: 0.42)

Resulting accuracy for testing the sum rule

- rewrite Υ as

$$\Upsilon = \frac{1}{v^2}(m^2_{\tilde{t}_1} - m^2_{\tilde{b}_1}) + \frac{\sin^2\theta_t}{v^2}(m^2_{\tilde{t}_2} - m^2_{\tilde{t}_1}) = \Upsilon' + \Delta\Upsilon_t$$

- our measurements yield

$$\boxed{\Upsilon' = 0.53^{+0.20}_{-0.15}}$$

theory: 0.35

- without measuring $m_{\tilde{t}_2}$ we can only estimate $\Delta\Upsilon_t$
  ➢ assuming $|\sin\theta_t| \lesssim 0.2$ and $m_{\tilde{t}_2} \lesssim 1$ TeV

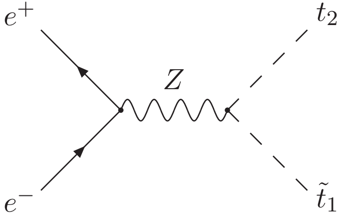
$$0 < \Delta\Upsilon_t \lesssim 0.58$$

- altogether we find $0.4 \lesssim \Upsilon \lesssim 1.3$ (theory: 0.42)

Not yet a strong test of SUSY naturalness, but non-trivial result!

. . . and at the ILC?

- $m_{\tilde{t}_1}$ from $\tilde{t}_1$ pair production
- $m_{\tilde{t}_2}$ *and* θ_t from $\tilde{t}_1\tilde{t}_2$ production



➢ resonance appears at $\sqrt{s} = m_{\tilde{t}_1} + m_{\tilde{t}_2} \simeq 1.2\,\mathrm{TeV}$ (!)
➢ cross-section proportional to $\sin^2 2\theta_t$

Summary

- for our benchmark scenario, masses of the lightest stop and sbottom can be quite precisely determined at the LHC
- measurement of $\sin\theta_t$ is more involved and requires knowledge of neutralino mixing (or other ideas to access θ_t!)
- if stop mixing is sizable, also $m_{\tilde{t}_2}$ is required to test the sum rule
  ➢ ideas needed!
- mass measurements may be more involved for less favorable spectrum

Summary

- for our benchmark scenario, masses of the lightest stop and sbottom can be quite precisely determined at the LHC
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  ➢ ideas needed!
- mass measurements may be more involved for less favorable spectrum

If nature is kind to us, we can test the SUSY stabilization of the weak hierarchy at the LHC!

And if not, we have another good reason to build the ILC ☺

Definition of benchmark scenario

parameter	EWSB scale value
M_1	100 GeV
$M_{2,3}$	450 GeV
A_t	390 GeV
μ	400 GeV
$\tan\beta$	10
M_A	600 GeV
$m_{\tilde{e}_{L,R},\tilde{\tau}_{L,R},\tilde{q}_L\tilde{u}_R,\tilde{d}_R}$	1000 GeV
$m_{\tilde{Q}_L}$	310 GeV
$m_{\tilde{t}_R}$	780 GeV

SM backgrounds to $4b + \not{p}_T$

Background	Generator	$\epsilon_{\rm b}\sigma$	$\epsilon_{\rm b}\epsilon_{\rm kin}\sigma$
$4j + (Z \to \nu\nu)$	MGME, ALPGEN	$10\,\mathrm{fb}$	
diboson + jets	—	$< 10\,\mathrm{fb}$	
$tt \to n\tau + X$	MGME, BRIDGE	$21.6\,\mathrm{pb}$	$25\,\mathrm{fb}$
t	—		$\ll 30\,\mathrm{fb}$

assumed b-tagging efficiencies: 0.6 (b), 0.1 (c, τ), 0.01 (light jet)