LHC Signatures of the MSSM Golden Region

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Work with Christian Spethmann, hep-ph/0702038, JHEP0704:070,2007
+ work in progress with Andreas Weiler

Motivation: MSSM and Naturalness

- In the SM: $V(H) = -\mu^2|H|^2 + \lambda|H|^4$ $\mu, \lambda \to v, m_h$
- So, m_h is theoretically a free parameter
- In the MSSM, potential is more complicated (2 doublets), but the values of some of the coupling constants are constrained by supersymmetry (related to gauge couplings!)
- Consequence: at tree level, there is a firm upper bound on the mass of the lightest of the two CP-even Higgs bosons:

$$m(h^0) < M_Z$$

- Experimentally, $m(h^0) > 114 \text{ GeV}$
- Either the MSSM is wrong, or loop corrections to $m(h^0)$ are large (25%)

Higgs and Stops

- In the SM, the strongest coupling of the Higgs is the top Yukawa, $\lambda h \bar{t} t, \quad \lambda = 1.0$
- The same is (almost always) true in the MSSM: the Higgs's strongest coupling is to top quark and its superpartners, two scalar "supertops" or stops, $\tilde{t}_L, \quad \tilde{t}_R$
- Stop mass eigenstates $\tilde{t}_1, \quad \tilde{t}_2$ are mixtures of $\tilde{t}_L, \quad \tilde{t}_R$
- Three parameters: 2 stop eigenmasses $m_1, \quad m_2$ + 1 mixing angle θ_t; or stop mass matrix in the gauge basis: m_L, m_R, A_t
- One-loop correction to the Higgs mass is a function of these parameters: $\Delta m_h^{1-\mathrm{loop}} = F(m_1, m_2, \theta_t)$
- Other contributions (gaugino and sbottom loops) are subdominant as long as $M_1/M_{\tilde{t}} \lesssim 4, \quad M_2/M_{\tilde{t}} \lesssim 2, \quad M_3/M_{\tilde{t}} \lesssim 10, \quad M_{\tilde{b}} \lesssim \frac{35 M_{\tilde{t}}}{\tan\beta}.$

Higgs and Stops, Cont'd

- Loop corrections to the Higgs potential from top and stop loops can also change the Higgs vev, not just its mass!

$$m_Z^2 = -m_u^2\left(1 - \frac{1}{\cos 2\beta}\right) - m_d^2\left(1 + \frac{1}{\cos 2\beta}\right) - 2|\mu|^2 .$$

- If the top/stop loop correction to the vev is BIG, it needs to be precisely cancelled by other (a priori unrelated) terms ⇨ classic example of fine-tuning!

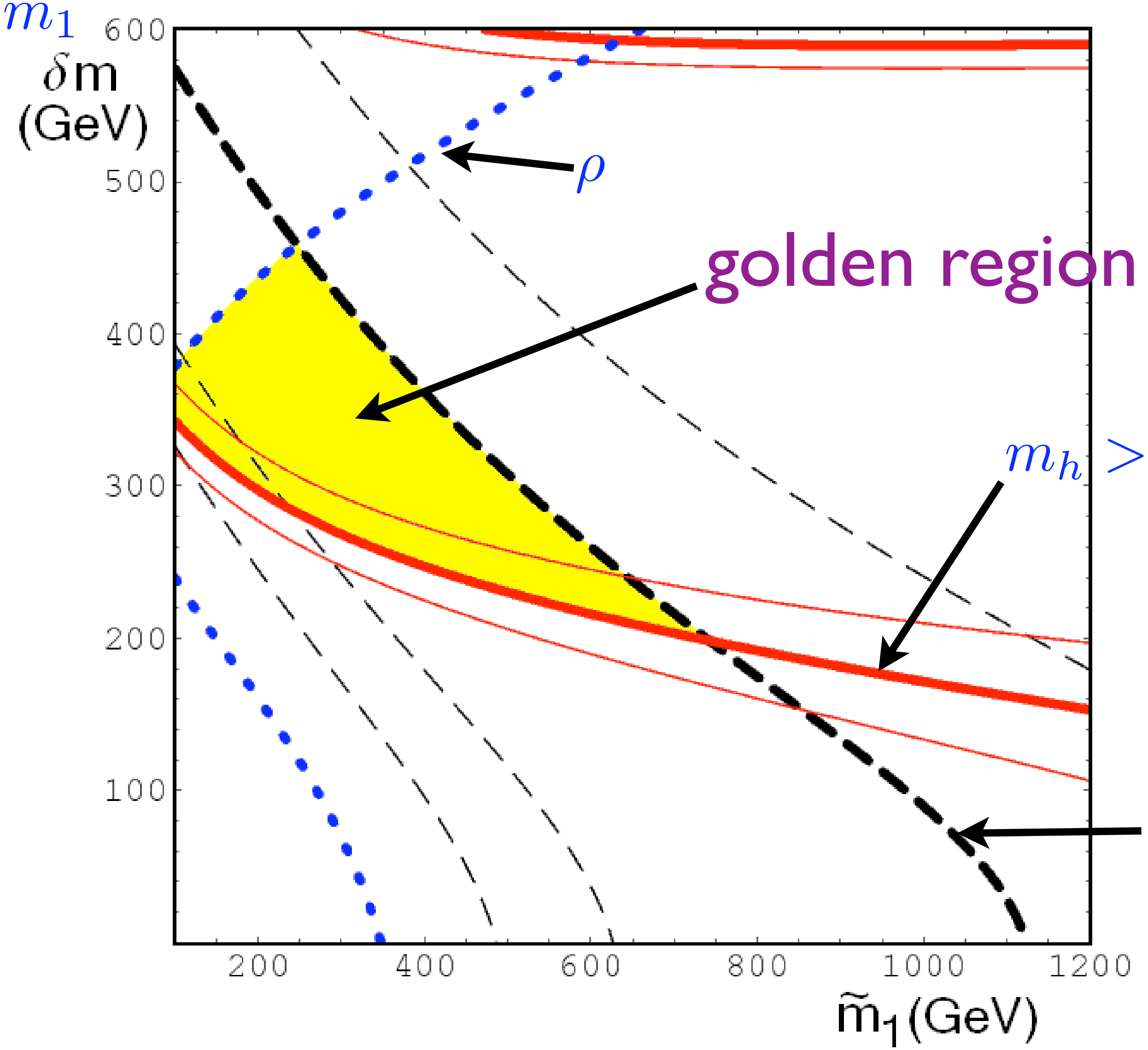
- So: need top/stop loops to change Higgs mass by a lot while not changing the Higgs vev by a lot ⇨ difficult!

- Negative spin: this only happens in a small region of parameter space, some tuning inevitable, the MSSM sucks...

- Positive spin: this tells us what the right version of the MSSM is! (or at least determines 3 parameters out of 120...)

The Golden Region in the MSSM

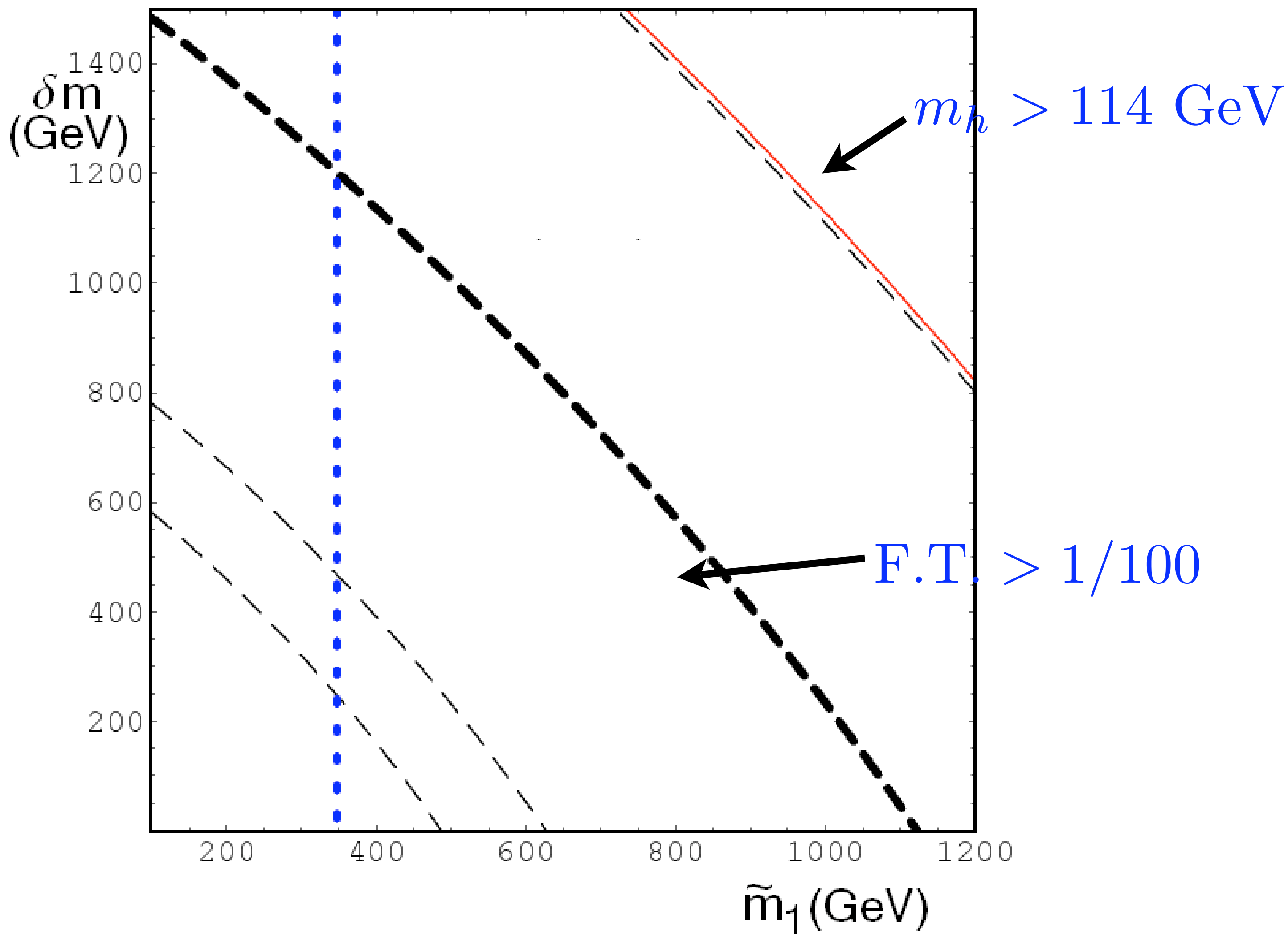
$\delta m = m_2 - m_1$



$m_h > 114$ GeV

F.T. $> 1/100$
$(\Lambda = 100$ TeV$)$

$\theta_t = \pi/4, \quad \tan\beta = 10$



$\theta_t = 0, \tan\beta = 10$

No golden region without stop mixing!

Probing the Golden Region

- So, the golden region has the following properties:
  - Lighter stop between 200 and 700 GeV
  - Two stops split by 200-400 GeV
  - Large mixing angle in the stop sector
- Can this hypothesis be tested at the LHC?
- Both stops will be within reach!
- A simple test: the decay mode $\tilde{t}_2 \to \tilde{t}_1 + Z$ has a big branching ratio in the golden region ⇨ look for this decay! [MP + Spethmann, 2007]
- A more direct test: stop mixing angle measurement in $\tilde{t}_1 \to \tilde{\chi}^0 t$ [MP + Weiler, 2008]

[Alternative: indirect measurement of stop parameters via hgg - Dermisek and Low]

Benchmark Point

- To estimate observability of $\tilde{t}_2 \to \tilde{t}_1 Z$, we choose a benchmark point in the center of the golden region:

$$m_1 = 400 \text{ GeV}, m_2 = 700 \text{ GeV}, \theta_t = \pi/4$$

- Non-stop parameters also fixed, although their precise values are unimportant: $\tan\beta = 10, \mu = 250 \text{ GeV}, \ldots$

- At this point, Br($\tilde{t}_2 \to \tilde{t}_1 + Z$) = 31%; the rest made up by other decay modes: $\chi_0 + t, \chi^+ + b, W^+ + \tilde{b}$

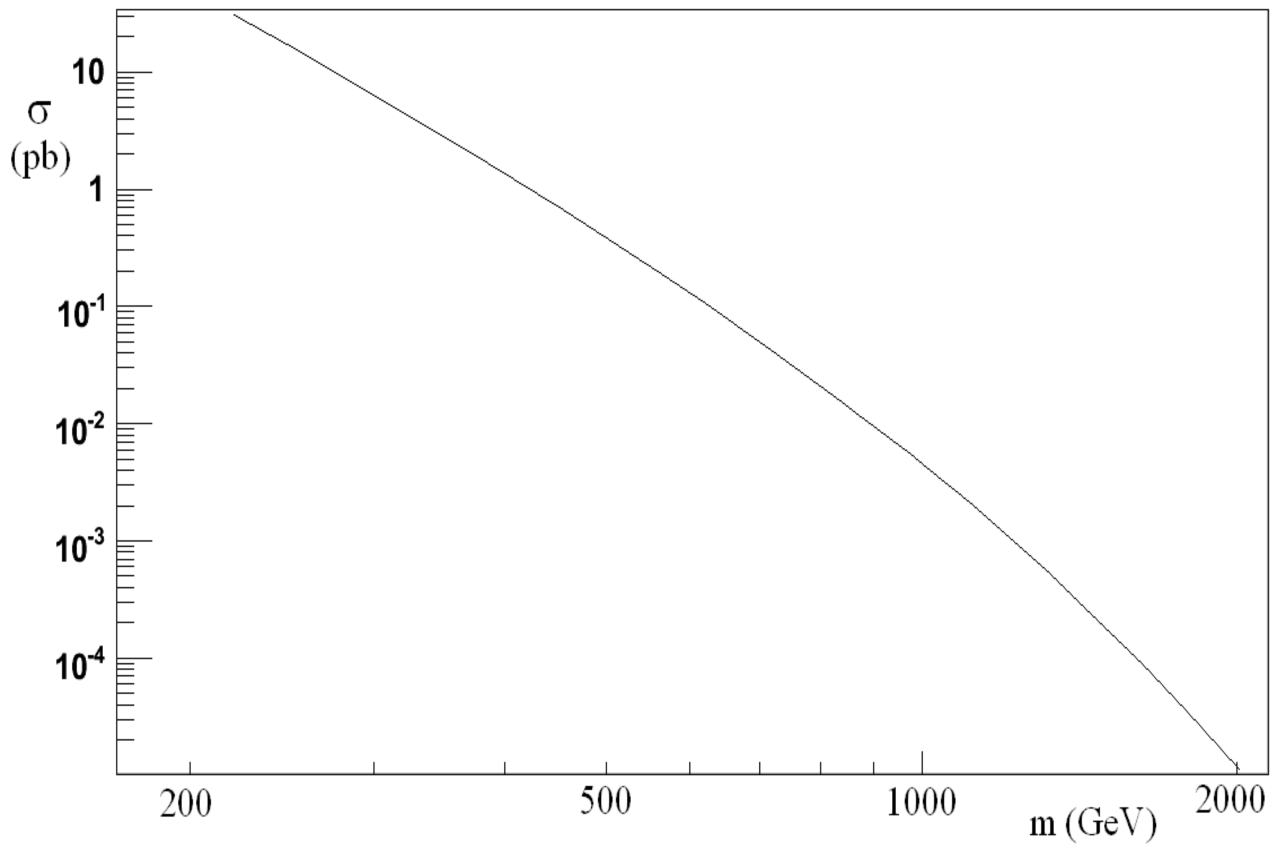
- This branching is robust (typically 20-40% throughout the golden region, incl. scanning non-stop parameters)

- Exception: if $m(\tilde{g}) \ll m(\tilde{t}_2)$, $\tilde{t}_2 \to \tilde{g}t$ may dominate (but this is disfavored by the Tevatron bounds!)

- Note: WIMP relic density wrong, but it is possible to choose non-top-sector parameters to get it right

[Kasahara, Freese, Gondolo, 0805.0999]

Stops at the LHC



$$\sigma(\tilde{t}_2\tilde{t}_2^*) \;=\; 5 \text{ fb} \quad \text{for } m_2 = 700 \text{ GeV}$$

$$50\ \tilde{t}_2 \text{ pairs/year @ } 10 \text{ fb}^{-1}/\text{yr}$$

NOT start-up physics!

Signature

- The interesting decay $\tilde{t}_2 \rightarrow \tilde{t}_1 + Z$ is followed by stop and Z decays; the detector signature depends on those decays
- Assume leptonic (e or mu) Z decays - clean, QCD background rejection
- Stop decay pattern very model dependent, but all decays involve a b quark and the LSP (missing energy)
- To retain robustness, focus on an inclusive signature:

$$\tilde{t}_1 \rightarrow b + \chi_0 + X$$

- Second $\tilde{t}_2$ decay (pair-produced!): $\tilde{t}_2 \rightarrow b + \chi_0 + X$ where X may or may not include a Z
- So: look for $Z(\ell^+\ell^-) + 2j_b + \text{ MET}$ + X

Backgrounds

$$Z(\ell^+\ell^-) + 2j_b + \text{ MET}$$

- Physical SM backgrounds:

$$jjZZ, \text{ with } Z_1 \to \ell^+\ell^-, \quad Z_2 \to \nu\bar{nu}$$

$$t\bar{t}Z, \text{ with } Z \to \ell^+\ell^- \text{ and leptonic top(s)}$$

$$t\bar{t}, \text{ with 2 leptonic tops and } \sqrt{s(\ell^+\ell^-)} \approx M_Z \text{ accidentally}$$

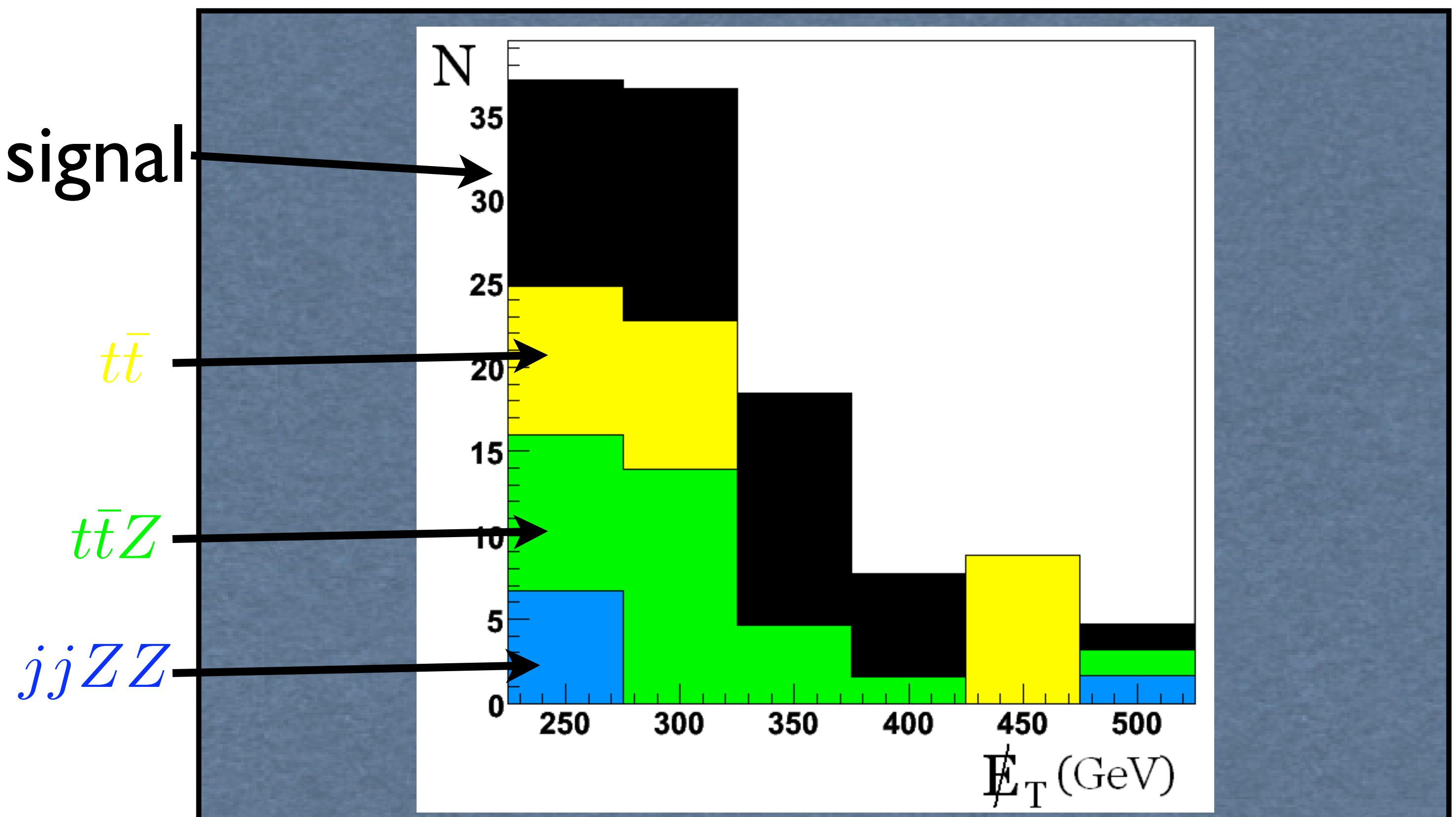
- Instrumental backgrounds

$$jjZ, \text{ with MET due to jet mismeasurement}$$

- Strategy: simulate statistically significant samples of these processes using MadGraph+Pythia, use PGS ("pretty good simulator", by J. Conway, LHCO version) as a toy detector simulation, off-line cuts and statistical analysis in ROOT

	signal: $\tilde{t}_2\tilde{t}_2^*$	$jjZZ$	$t\bar{t}Z$	$t\bar{t}$	jjZ
σ_{prod}(pb)	0.051	0.888	0.616	552	824
total simulated	9964	159672	119395	3745930	1397940
1. leptonic Z(s)	1.4	4.5	2.6	0.04	2.1
2(a). $p_t(j_1) > 125$ GeV	89	67	55	21	41
2(b). $p_t(j_2) > 50$ GeV	94	93	92	76	84
3. b-tag	64	8	44	57	5
4. $\gamma(Z) > 2.0$	89	66	69	26	68
5. $\not{E}_T > 225$ GeV	48	2.2	4.4	1.7	< 0.9 (95% c.l.) 0 (ext.)
$N_{\text{exp}}(100\ fb^{-1})$	16.4	2.8	10.8	8.8	< 177 (95% c.l.) 0 (ext.)

Table 4: Summary of the analysis of observability of the supersymmetric golden region signature (24). First row: Production cross section for the signal and background processes at the LHC. Second row: Number of Monte Carlo events used in the analysis. Rows 3–8: Cut efficiencies, in%. Last row: The expected number of events for an integrated luminosity of 100 fb^{-1}.



Observability

- Assuming statistical uncertainties dominate, 3-sigma observation requires 75 fb-1, 5-sigma discovery requires 210 fb-1
- Did not try to estimate systematics
- Note: ttbar contribution to the background (~50%) can be shoulder-subtracted ⇨ probably statistics-dominated
- Also, ttbarZ can be controlled with control samples (e.g. with 2 hadronic and 1 had+1 lep tops)
- Alternative sets of rectangular cuts tried (e.g. 2 b-tags), not much improvement
- Fancier analysis methods (e.g. neural nets, decision trees) may give substantial improvement?

Confusability

- If an excess of events in the $Z(\ell^+\ell^-) + 2j_b + \text{ MET}$ channel is observed, can one conclude that it's due to . $\tilde{t}_2 \to \tilde{t}_1 + Z$?

- Not really: even within the MSSM there are alternative explanations, e.g. $\tilde{t} \to t\chi_2^0, \quad \chi_2^0 \to Z\chi_1^0$

- Expect no preference for b-tagged events if Zs come from neutralino/chargino decays...

- Spin correlation observables: scalar > Z + scalar vs. fermion > Z + fermion (detailed study is needed)

chargino-Z coupling chiral; c.f. Barr, Yavin and Wang, etc.

Stop Mixing Angle from Top Polarization

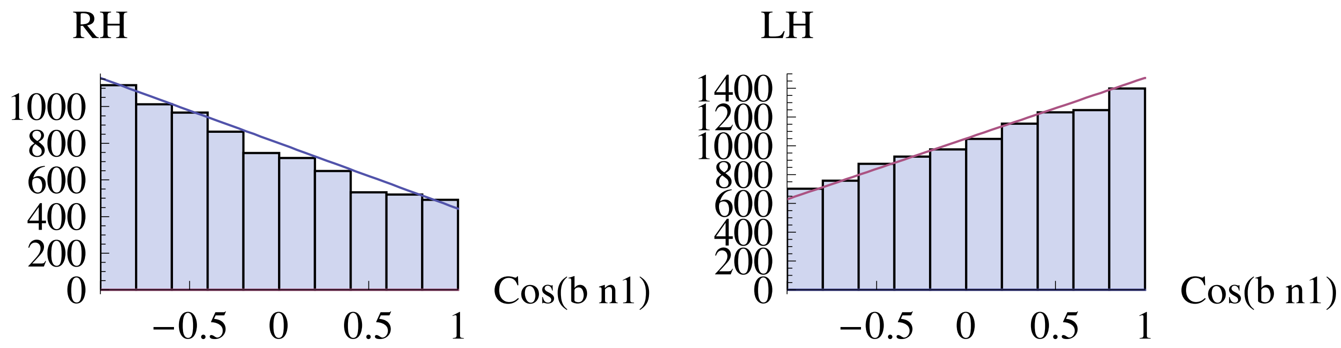
[work in progress with Andreas Weiler]

- In the golden region, low $\tilde{t}_1$ mass is likely ➡ a large sample of $\tilde{t}_1$ pairs may be available (e.g. $\sigma(\tilde{t}_1\tilde{t}_1^*) = 3\ \mathrm{pb}$)
  $M(\tilde{t}_1) = 340\ \mathrm{GeV}$
- Consider the decay $\tilde{t}_1 \to t\tilde{\chi}^0$
- Couplings: $\tilde{t}_L t_L \tilde{B},\ \tilde{t}_L t_L \tilde{W}^3,\ \tilde{t}_L t_R \tilde{H}_u;$

  $$\tilde{t}_R t_R \tilde{B},\ \tilde{t}_R t_R \tilde{W}^3,\ \tilde{t}_R t_L \tilde{H}_u$$
- Top decay products carry information about top helicity
- If the neutralino is predominantly gaugino, top helicity = stop handedness (and opposite if neutralino=higgsino)
- If independent information on the neutralino content is available, top helicity measurement = stop mixing angle measurement!

Stop Mixing Angle from Top Polarization: Example

- We consider $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0,\ t \rightarrow bW$ with $\tilde{\chi}_1^0 = \tilde{B}$
- Top helicity analyzer: b direction w.r.t. neutralino momentum (in top rest frame)



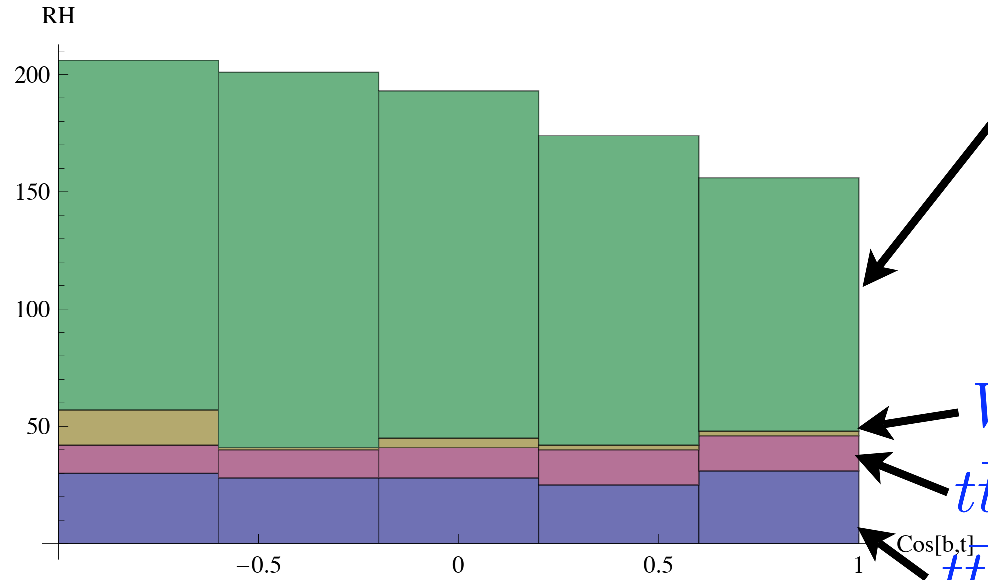
- Neutralino and top approximately back-to-back in lab frame (stops produced close to threshold) ⇨ slightly smaller but still sizable effect in cos(b, top)
- Need fully reconstructed tops for this measurement
- Extra MET from neutralinos ⇨ use only hadronic tops

Stop Mixing Angle from Top Polarization: Backgrounds

- Full signature: $\tilde{t}_1 \to t\tilde{\chi}_1^0,\ \tilde{t}_1^* \to \bar{t}\tilde{\chi}_1^0$
- Opposite asymmetry for t and $\bar{t}$ ⇒ require 1 hadronic (fully reconstructed) and 1 semileptonic top, use lepton charge to infer the reconstructed top charge
- Final state: $t(3j) + j + \ell + \mathrm{MET}$
- SM backgrounds: $t\bar{t}\ (t \to \ell + \nu + b),\ t\bar{t}Z,\ W + \mathrm{jets}$
- ttbar background most dangerous: B/S>100 with no cuts
- In ttbar events with e or mu, MET from neutrino reconstructs W, top ⇒ very effective rejection!
- Similar (somewhat less effective) cut removes ttbar events with leptonic taus

Stop Mixing Angle from Top Polarization: Observability

$t(3j) + j + \ell + \text{MET}$



signal $\tilde{t}_1 = \tilde{t}_R$

$M(\tilde{t}_1) = 340$ GeV

$M(\tilde{\chi}_1^0) = 100$ GeV

$\text{Br}(\tilde{t}_1 \to t\tilde{\chi}_1^0) = 100\%$

$W + \text{jets}$

$t\bar{t}, t \to \ell + \ldots$

$t\bar{t}, t \to \tau_\ell + \ldots$

$L = 10 \text{ fb}^{-1}$

$a_{\text{FB}} = -0.125 \pm 0.065$

[preliminary!]

[parton level, no combinatoric BGs, cuts not optimized]

Conclusions

- In the MSSM, data (esp. Higgs mass bound) and naturalness give us a hint about some of the model parameters (stop sector)
- The preferred "golden" region has a distinct spectrum: two stops split by 200-400 GeV, large mixing
- The decay $\tilde{t}_2 \to \tilde{t}_1 + Z$ has a substantial branching fraction throughout the golden region, independently of the other 117 parameters (except weird corners)
- Evidence for this decay can be observed with ~100 fb-1 of data at the LHC (but other SUSY interpretations possible)
- May be possible to measure the stop mixing angle directly by analyzing top polarization in $\tilde{t}_1 \to t\tilde{\chi}^0$ decays

Stop Physics Will Be Important If the MSSM Is Right!