SUSY-Yukawa Sum Rule at the LHC

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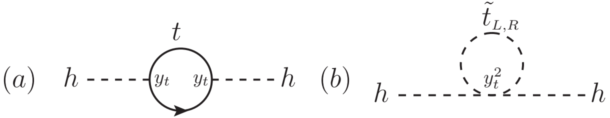
Outline

1. Introducing the SUSY-Yukawa Sum Rule
2. How can we use it at the LHC?
3. A Simple LHC Case Study

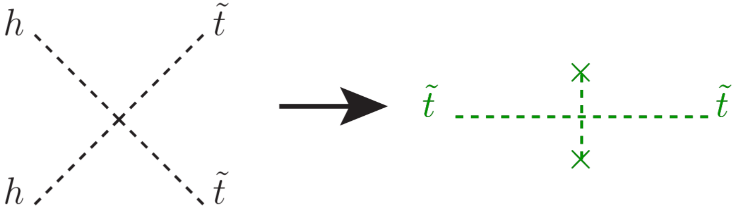
Introducing the SUSY-Yukawa Sum Rule

- Hierarchy problem: In the SM, Higgs mass receives quadratically divergent corrections, most importantly from the top quark
- In SUSY, top contribution cancelled by stop



- This relies on both particle content and coupling relations. **We want to test the coupling relations.**

How to probe the Quartic Higgs Coupling?



$$M^2_{\tilde{t}_i \tilde{t}_j} = \begin{bmatrix} M_L^2 + \hat{m}_t^2 + g_{u_L} \hat{m}_Z^2 c_{2\beta} & m_t(A_t + \mu \cot\beta) \\ m_t(A_t + \mu \cot\beta) & M_T^2 + \hat{m}_t^2 + g_{uR} \hat{m}_Z^2 c_{2\beta} \end{bmatrix}$$

$$= \begin{bmatrix} m_{t1}^2 c_t^2 + m_{t2}^2 s_t^2 & c_t s_t (m_{t1}^2 - m_{t2}^2) \\ c_t s_t (m_{t1}^2 - m_{t2}^2) & m_{t1}^2 s_t^2 + m_{t2}^2 c_t^2 \end{bmatrix}$$

Extract this contribution to diagonal sfermion mass terms!

SUSY-Yukawa Sum Rule

Consider stop/sbottom *LL* mass terms at tree level:

$$M^2_{\tilde{t}_L \tilde{t}_L} = M_L^2 + \hat{m}_t^2 + g_{uL} \hat{m}_Z^2 \cos 2\beta = m_{t1}^2 c_t^2 + m_{t2}^2 s_t^2 \quad (1)$$
$$M^2_{\tilde{b}_L \tilde{b}_L} = M_L^2 + \hat{m}_b^2 + g_{bL} \hat{m}_Z^2 \cos 2\beta = m_{b1}^2 c_b^2 + m_{b2}^2 s_b^2 \quad (2)$$

Soft masses Higgs Quartic Coupling D-term contributions measurable

(1) − (2) eliminates the soft mass:

$$\hat{m}_t^2 - \hat{m}_b^2 = \mathbf{m_{t1}^2 c_t^2} + \mathbf{m_{t2}^2 s_t^2} - \mathbf{m_{b1}^2 c_b^2} - \mathbf{m_{b2}^2 s_b^2} - \hat{m}_Z^2 \cos^2\theta_w \cos 2\beta$$

We call this the **SUSY-Yukawa Sum Rule:** It has its origins in the same coupling relations that cancel higgs mass corrections.

Testing this sum rule at a collider would constitute a highly nontrivial check on SUSY.

How to test the sum rule?

SUSY-Yukawa Sum Rule:

$$\hat{m}_t^2 - \hat{m}_b^2 = \mathbf{m_{t1}^2 c_t^2} + \mathbf{m_{t2}^2 s_t^2} - \mathbf{m_{b1}^2 c_b^2} - \mathbf{m_{b2}^2 s_b^2} - \hat{m}_Z^2 \cos^2\theta_w \cos 2\beta$$

Define an observable Υ for which the sum rule gives a definite prediction:

$$\Upsilon \equiv \frac{1}{v^2}\left(m_{t1}^2 c_t^2 + m_{t2}^2 s_t^2 - m_{b1}^2 c_b^2 - m_{b2}^2 s_b^2\right)$$

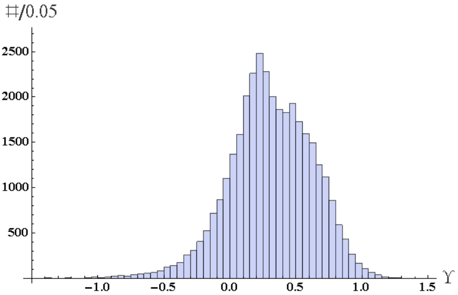
Tree-Level Prediction for Υ from SUSY-Yukawa Sum Rule

$$\Upsilon_{\text{SUSY}}^{\text{tree}} = \frac{1}{v^2}\left(\hat{m}_t^2 - \hat{m}_b^2 + m_Z^2 \cos^2\theta_W \cos 2\beta\right)$$

$$= \begin{cases} 0.39 & \text{for } \tan\beta = 1 \\ \mathbf{0.28} & \text{for } \tan\beta \to \infty \text{ (converges quickly for } \tan\beta \gtrsim 5) \end{cases}$$

Radiative Corrections

- Radiative Corrections wash out SUSY tree-level prediction for Υ
- MSSM Parameter Scan with `SuSpect` for $M_{\mathrm{SUSY}} < 2\,\mathrm{TeV}$:



- $\Upsilon^{\mathrm{tree}}_{\mathrm{SUSY}} \approx 0.3 \longrightarrow |\Upsilon_{\mathrm{SUSY}}| \lesssim 1$

  (For comparison, the 'generic' perturbative theory prediction is $|\Upsilon| \lesssim 16\pi^2$.)

- Sidenote: R.C. can be constrained by measuring additional parameters.

Upshot

- Introduce the SUSY-Yukawa Sum Rule,

$$\hat{m}_t^2 - \hat{m}_b^2 = m_{t1}^2 c_t^2 + m_{t2}^2 s_t^2 - m_{b1}^2 c_b^2 - m_{b2}^2 s_b^2 - \hat{m}_Z^2 \cos^2\theta_w \cos 2\beta$$

  which relies on the same coupling relations that cancel contributions from stop & top loops to the higgs coupling.

- Introduce new observable which can be measured at a collider:

$$\Upsilon \equiv \frac{1}{v^2}\left(m_{t1}^2 c_t^2 + m_{t2}^2 s_t^2 - m_{b1}^2 c_b^2 - m_{b2}^2 s_b^2\right)$$

- SUSY-Yukawa Sum Rule $\Rightarrow$ $|\Upsilon| \lesssim 1$

- Measuring Υ constitutes a powerful nontrivial check that SUSY is the solution to the hierarchy problem.

How can we use the SUSY-Yukawa Sum Rule at the LHC?

SUSY-Yukawa Sum Rule at the LHC

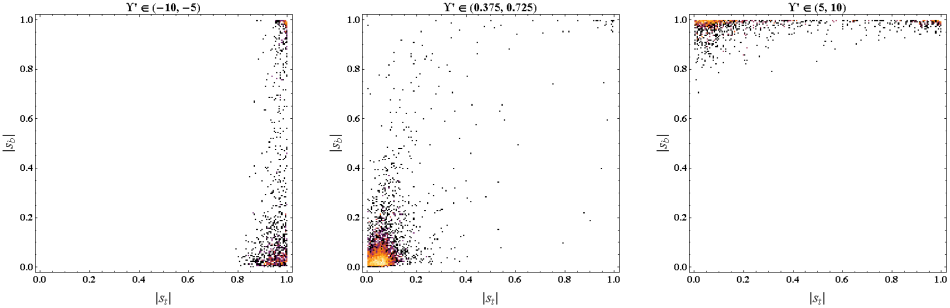
- To measure every ingredient of Υ (especially θ_b) we probably need a lepton collider.
- What good is the sum rule at the LHC? $\Rightarrow$ Use SUSY-prediction for Υ to constrain 'unmeasurable' parameters!
- Which parts can we measure? Often m_{t1}, m_{b1} are the lightest two masses.

$$\Upsilon = \underbrace{\frac{1}{v^2}\left(m_{t1}^2 - m_{b1}^2\right)}_{\Upsilon'} + \underbrace{\frac{s_t^2}{v^2}\left(m_{t2}^2 - m_{t1}^2\right)}_{\Delta\Upsilon_t} - \underbrace{\frac{s_b^2}{v^2}\left(m_{b2}^2 - m_{b1}^2\right)}_{\Delta\Upsilon_b}$$

We can try to measure Υ' at the LHC.

What does Υ' tell us?

$$\Upsilon = \Upsilon' + \frac{s_t^2}{v^2}\left(m_{t2}^2 - m_{t1}^2\right) - \frac{s_b^2}{v^2}\left(m_{b2}^2 - m_{b1}^2\right)$$



$\Upsilon' \ll 0 \Rightarrow$ RH $\tilde{t}_1$ $\qquad$ $\Upsilon' \sim 0 \Rightarrow$ LH $\tilde{t}_1, \tilde{b}_1$ $\qquad$ $\Upsilon' \gg 0 \Rightarrow$ RH $\tilde{b}_1$

Even a rough measurement of Υ' gives strong constraints on the stop and/or sbottom mixing angles!

A Simple LHC Case Study

Measuring Υ' at the LHC

- Want to demonstrate that the SUSY-Yukawa Sum Rule can be used to measure stop & sbottom mixing angles at the LHC.
- Choose a particular MSSM Benchmark Point with light $\tilde{t}_1, \tilde{b}_1$ and small mixing:

Parameters:

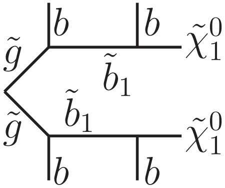
$\tan\beta$	M_1	M_2	M_3	μ	M_A	M_{Q3L}	M_{tR}	A_t
10	100	450	450	400	600	310.6	778.1	392.6

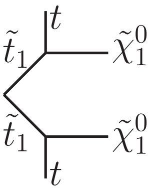
Spectrum: (GeV)

m_{t1}	m_{t2}	s_t	m_{b1}	m_{b2}	s_b	$m_{\tilde{g}}$	$m_{\tilde{\chi}_1^0}$
371	800	-0.095	341	1000	-0.011	525	98

Outline of Measurement

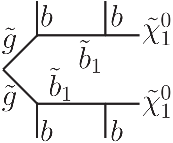
- **We will measure** $\Upsilon' = \frac{1}{v^2}(m_{t1}^2 - m_{b1}^2)$
- Parton-level Analysis with gaussian momentum smearing. (More realistic analysis in progress.)
- Gluino pair production $\Longrightarrow m_{b1}$ (Bonus: $m_{\tilde{g}}$ and $m_{\chi_1^0}$)
- Stop pair production $\Longrightarrow m_{t1}$





(I) Gluino Pair Production

- Analyze the process[1]
  $\tilde{g}\tilde{g} \to 2\tilde{b}_1 + 2b \to 4b + 2\tilde{\chi}^0_1$.
- $\sigma_{\tilde{g}\tilde{g}} \approx 11.6\ \mathrm{pb}$ @ $\sqrt{s} = 14\,\mathrm{TeV}$.

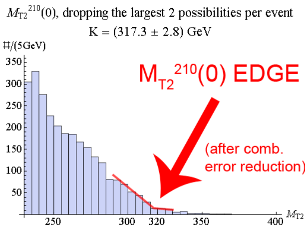


- Impose basic p_T, MET-cuts and require 4 *b*-tags.
- No SUSY-BG. SM-BG suppressed by *b*-tag requirement.
- Use $\mathcal{L} = 10\ \mathrm{fb}^{-1}$. After cuts we are left with 4800 signal events.
- Even with parton-level pure signal, full mass extraction is challenging!

[1] MadGraph/Madevent & BRIDGE

Edge Extraction & Mass Measurement

- To measure masses at hadron colliders with invisible massive particles in the final state, we go Edge Hunting!



- Distributions of M_{T2}-subsystem-variables[2] and M_{bb} show edges which tell us mass combinations.

- Big Problem: Combinatorial Error (especially for M_{T2}'s).

We are able to successfully measure $\mathbf{M_{bb}}$, $\mathbf{M_{T2}^{210}(0)}$ and $\mathbf{M_{T2}^{220}(0)}$ edges $\Rightarrow$

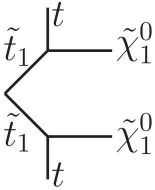
mass	th.	68 % c.l.
m_{b1}	341	(316, 356)
$m_{\tilde{g}}$	525	(508, 552)
$m_{\tilde{\chi}_1^0}$	98	(45^*, 115)

[2] Barr, Lester, Stephens, 2003; Cho, Choi, Kim, Park 2008; Burns, Kang, Matchev, Park 2009

* LEP bound

(II) Stop Pair Production

- Analyze the process $\tilde{t}_1 \tilde{t}_1^* \to t\bar{t} + 2\tilde{\chi}_1^0$.
- $\sigma_{\tilde{t}_1 \tilde{t}_1^*} \approx 2$ pb @ $\sqrt{s} = 14$ TeV.
- Impose standard cuts & use hadronic tops[3].



- Use $\mathcal{L} = 100\ \text{fb}^{-1}$. After cuts: 1481 signal and 105 BG events.
- Easy to extract $M_{T2}^{\max}$ edge $\Longrightarrow$ Gives $m_{t1}(m_{\tilde{\chi}_1^0})$
- Combine with (I) $\Rightarrow$

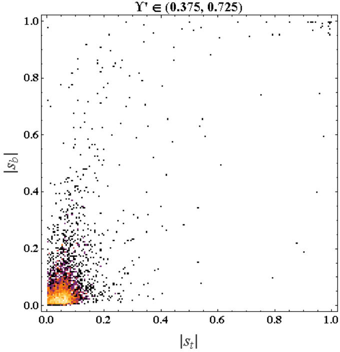
	th.	68 % c.l.
m_{t1}	371	(356, 414)

[3] Meade, Reece 2006

Υ' Measurement and SUSY-prediction for Υ

Putting all these measurements together, we get

	th.	meas.
Υ'	0.350	$0.525^{+0.20}_{-0.15}$
Υ	0.423	—



Unless there is a strong accidental cancelation, such a small Υ' measurement implies that both stop and sbottom mixing angles are small, $\lesssim 0.2$.

Compare to actual values:

$$s_t = -0.095$$

$$s_b = -0.011$$

Conclusions

Summary & Conclusions

- Confirmation of the SUSY-Yukawa Sum Rule

$$\hat{m}_t^2 - \hat{m}_b^2 = m_{t1}^2 c_t^2 + m_{t2}^2 s_t^2 - m_{b1}^2 c_b^2 - m_{b2}^2 s_b^2 - \hat{m}_Z^2 \cos^2\theta_w \cos 2\beta$$

  (probably at a lepton collider) would be strong support for TeV-scale SUSY as the solution for hierarchy problem.

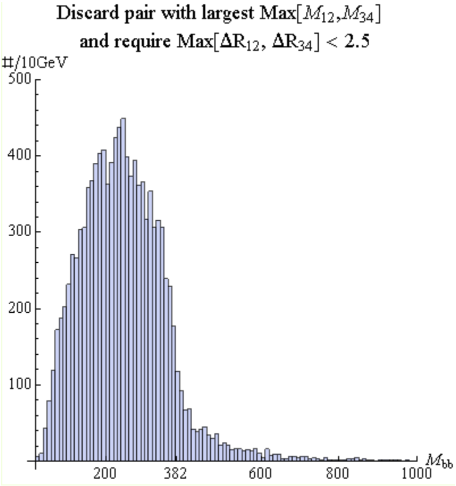
- At the LHC, the sum rule provides powerful constraints on stop and sbottom mixing angles (hard to come by otherwise) using only a mass measurement .

- We developed new techniques for reducing M_{T2}-combinatorial background, allowing us to measure $\tilde{t}_1, \tilde{b}_1, \tilde{g}, \tilde{\chi}_1^0$ masses at our benchmark point.

Backup Slides

Gluino Pair Production: Kinematic Edge

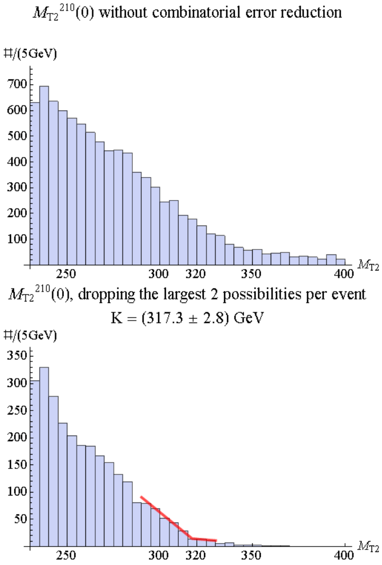
- $M_{bb}^{\max} = \sqrt{\dfrac{(m_{\tilde{g}}^2 - m_{b1}^2)(m_{b1}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{b1}^2}}$
- With known decay chain assignments get $(M_{b_1 b_2}, M_{b_3 b_4})$ for each event, plot M_{bb}-distribution
  $\Rightarrow$ edge at 382 GeV.
- Main problem:
  Combinatorial Background!
- Can reduce CB with ΔR cuts and dropping largest M_{bb}'s per event.



$M_{bb}{}^{\max}_{\text{meas}} = 395 \pm 15\,\text{GeV}$

Gluino Pair Production: M_{T2}-subsystem Edges

- The distributions of M_{T2} subsystem variables[4] also have edges we can measure. Look at $M_{T2}^{210}(0)$.
- Combinatorial Background is more dangerous.
  - To calculate M_{T2}^{210}, have to divide $4b$ into an upstream and downstream pair: 6 possibilities.
  - The M_{T2}-distribution for wrong pairings is more featured than M_{bb}.
- One way to reduce CB: Drop largest 2 M_{T2}^{210}'s per event →



[4] Barr, Lester, Stephens, 2003; Cho, Choi, Kim, Park 2008; Burns, Kang, Matchev, Park 2009

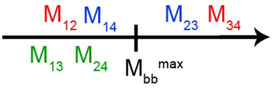
Gluino Pair Production: M_{T2}-subsystem Edges

Another way to reduce CB:

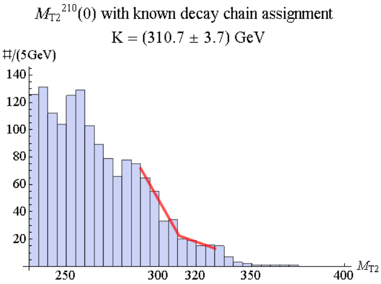
Use Kinematic Edge Measurement!

Possible M_{bb} pairs: (M_{12}, M_{34}), (M_{13}, M_{24}), (M_{14}, M_{23})

For ~30% of events, situation like:



Can deduce correct decay chain assignment!



For edge measurement, require two methods to agree!

edge	th.	measurement
M_{bb}	382	395 ± 15
$M_{T2}^{210}(0)$	321	$314 \pm 13\,\mathrm{GeV}$
$M_{T2}^{220}(0)$	507	$492 \pm 14\,\mathrm{GeV}$

$\Longrightarrow$

mass	th.	68 % c.l.
m_{b1}	341	(316, 356)
$m_{\tilde{g}}$	525	(508, 552)
$m_{\tilde{\chi}_1^0}$	98	(45, 115)

(Imposed $m_{\tilde{\chi}_1^0} > 45\,\mathrm{GeV}$ bound from LEP measurement of invisible Z decay width.)