SUSY-Yukawa Sum Rule at the LHC

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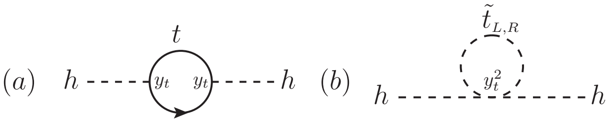
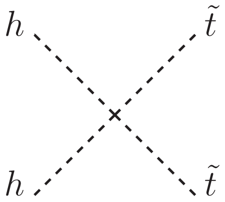
Introduction

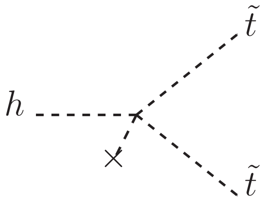
- Hierarchy problem: In the SM, Higgs mass receives quadratically divergent corrections, most importantly from the top quark
- In SUSY, top contribution cancelled by stop

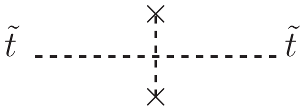


- This relies on both particle content and coupling relations. **We want to test the coupling relations.**

How to probe the Quartic Higgs Coupling?







Look at diagonal sfermion mass terms!

SUSY-Yukawa Sum Rule

Look at 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:

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

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

We want to test this sum rule at a collider!

Defining an observable to test the Sum Rule

- Assume SUSY-like particle content $\left(\tilde{t}_L, \tilde{b}_L\right)$, $\tilde{t}_R$, $\tilde{b}_R$ but not the SUSY coupling relations.
- Before EWSB, $M^2_{\tilde{t}} = \begin{pmatrix} M^2_L & \\ & M^2_t \end{pmatrix}$, $M^2_{\tilde{b}} = \begin{pmatrix} M^2_L & \\ & M^2_b \end{pmatrix}$
- After EWSB, can parameterize quartic higgs coupling 'model-independently':

$$(M^2_{\tilde{t}})_{11} \to M^2_L + v^2 Y^t_{11} \quad , \quad (M^2_{\tilde{b}})_{11} \to M^2_L + v^2 Y^b_{11}$$

Define a new observable to probe the quartic higgs coupling:

$$\Upsilon \equiv \frac{1}{v^2}\left(m^2_{t1} c^2_t + m^2_{t2} s^2_t - m^2_{b1} c^2_b - m^2_{b2} s^2_b\right)$$
$$= Y^t_{11} - Y^b_{11} \text{ at tree level}$$

SUSY prediction for Υ & Radiative Corrections

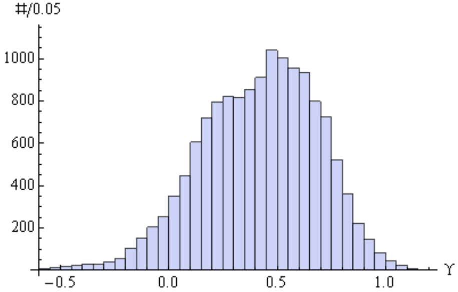
Tree-Level Prediction for Υ from SUSY-Yukawa Sum Rule

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

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

- **In a generic theory, only 'requirement' is $|\Upsilon| \lesssim 16\pi$.**
- Radiative Corrections wash out SUSY tree-level prediction for Υ.
- Worst case scenario (`SuSpect`) $\rightarrow$
- Can narrow predicted range with more measurements (see later).

TeV-scale SUSY: $|\Upsilon| \lesssim 1$.



Prospects at the LHC

- Fully measuring Υ requires lepton collider.
- Can make some progress at LHC in favorable regions of MSSM parameter space. $\Rightarrow$ Could then use Υ to constrain stop/sbottom parameters.
- Demonstrate feasibility of partial Υ-measurement with a particular Benchmark Point:

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)

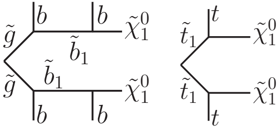
m_{t1}	m_{t2}	s_t	m_{b1}	m_{b2}	s_b	$m_{\tilde{g}}$	$m_{\tilde{\chi}_1^0}$
371	800	-0.095	341	1000	-0.011	525	98

- Small mixing angles and light $\tilde{t}_1, \tilde{b}_1 \implies$ rewrite

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

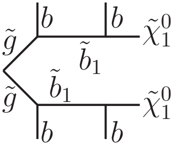
- Most of $\Upsilon = 0.423$ comes from $\Upsilon' = 0.350$. $\Delta\Upsilon_t \lesssim O(0.1)$ can be estimated [1]. $\Delta\Upsilon_b$ can't be measured at LHC.

- **We will measure Υ'**
  - Need to determine m_{t1}, m_{b1}
  - Analyse gluino & stop pair production & decay
  - Extract kinematic- and M_{T2}-edges to get all the masses $\Rightarrow \Upsilon'$



[1] MP, Weiler 2008

(I) Gluino Pair Production

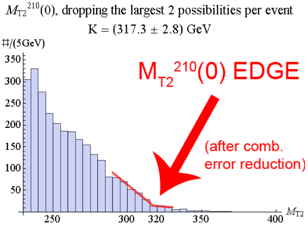


- Analyze the process[2]
  $\tilde{g}\tilde{g} \to 2\tilde{b}_1 + 2b \to 4b + 2\tilde{\chi}_1^0$.
- $\sigma_{\tilde{g}\tilde{g}} \approx 11.6\ \mathrm{pb}$ @ $\sqrt{s} = 14\,\mathrm{TeV}$.
- Impose basic p_T, MET-cuts and require 4 *b*-tags.
- Use $\mathcal{L} = 10\ \mathrm{fb}^{-1}$. After cuts we are left with 4800 signal events.
- No SUSY-BG. SM-BG suppressed by *b*-tag requirement.
- Even with parton-level pure signal, full mass extraction is challenging!

[2] 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[3] 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 $\Rightarrow$

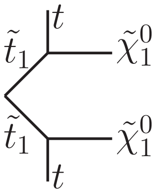
mass	th.	68 % c.l.
m_{b1}	341	(316, 356)
$m_{\tilde{g}}$	525	(508, 552)
$m_{\tilde{\chi}_1^0}$	98	(45*, 115)

[3] 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[4].



- 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)

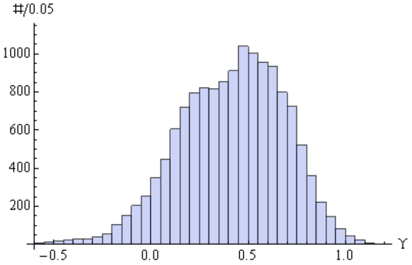
[4] Meade, Reece 2006

Υ' Measurement and SUSY-prediction for Υ

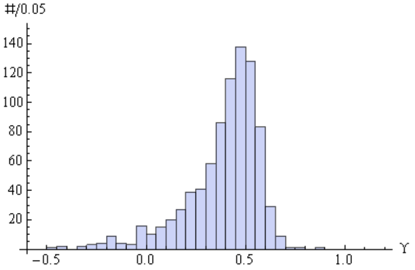
Putting all these measurements together, we get

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

The measurements of the $\tilde{b}_1, \tilde{t}_1, \tilde{g}, \tilde{\chi}_1^0$ masses also allow us to make the SUSY-prediction for Υ more precise:



$\longrightarrow$



Summary & Conclusions

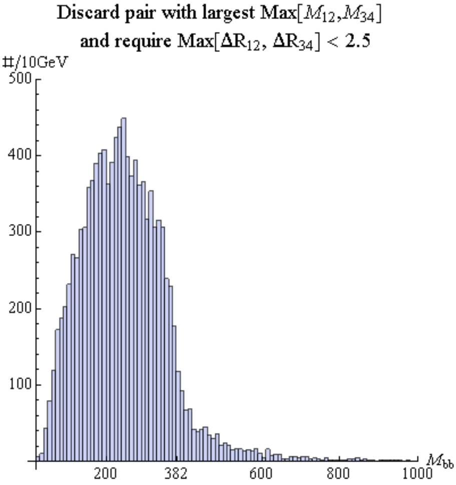
- Confirmation of SUSY-Yukawa Sum Rule

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

  would be strong support for TeV-scale SUSY as the solution for hierarchy problem.
- Full measurement will have to wait for Lepton Collider.
- Can make significant progress at LHC in some regions of parameter space.
- 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.

Gluino Pair Production: Kinematic Edge

- $M_{bb}^{\max} = \sqrt{\frac{(m_{\tilde{g}}^2 - m_{b1}^2)(m_{b1}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{b1}^2}}$
- 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.

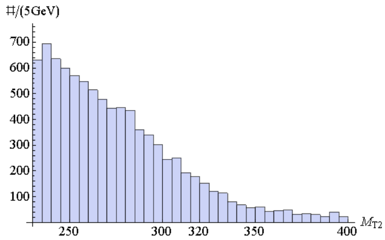


$M_{bb}{}^{\max}_{\text{meas}} = 395 \pm 15\,\text{GeV}$

Gluino Pair Production: M_{T2}-subsystem Edges

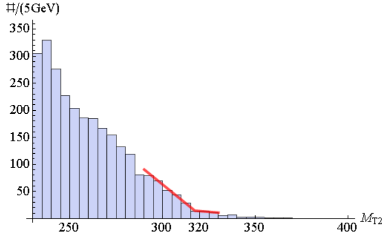
- The distributions of M_{T2} subsystem variables[5] also have edges we can measure. Look at $M_{T2}^{210}(0)$.
- Combinatorial Background is more dangerous.
  - To calculate M_{T2}^{210}, have to divide $4b$ into an upstream and downstream pair: 6 possibilities.
  - The M_{T2}-distribution for wrong pairings is more featured than M_{bb}.
- One way to reduce CB:
  Drop largest 2 M_{T2}^{210}'s per event $\rightarrow$

$M_{T2}{}^{210}(0)$ without combinatorial error reduction



$M_{T2}{}^{210}(0)$, dropping the largest 2 possibilities per event

K = (317.3 ± 2.8) GeV



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

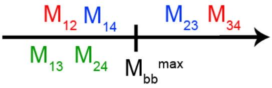
Gluino Pair Production: M_{T2}-subsystem Edges

Another way to reduce CB:

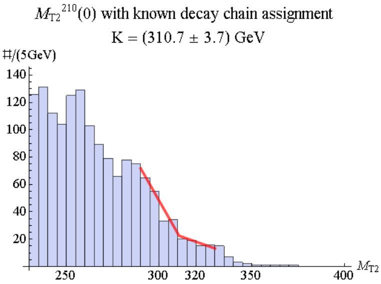
Use Kinematic Edge Measurement!

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.)