The rise and fall of light stops in the LHC top quark sample

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Based on arXiv:2312.09794 in collaboration with

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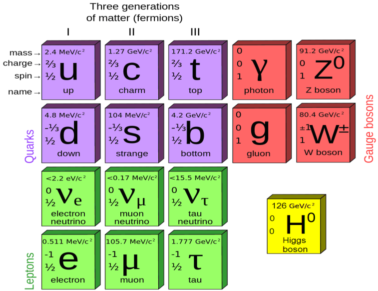
Overview

1. The Standard Model and its drawbacks

2. New physics from precise measurement of top quark features
   - Motivation
   - Signal and Background
   - Methodology
   - Results

3. Conclusion

Brief Review of The Standard Model



Particle Spectrum of The Standard Model

Although the Standard Model is the most celebrated theory till today, it cannot explain nature completely.

Drawbacks Of The Standard Model

- Masses of Neutrino ⟶ Type-I, Type-II, Type-III seesaw models, Georgi-Machacek model etc.
- Existence of Dark Matter ⟶ RPC Supersymmetry (SUSY), alternative left-right symmetric model etc.
- The Higgs mass instability problem in the Electroweak (EW) sector ⟶ SUSY

No new physics has been found yet in experiments.

Hence, all exotic particles that can vouch for any of the above Beyond Standard Model (BSM) scenarios lie beyond the current LHC reach.

BSM Beyond LHC

Natural SUSY: Higgsinos at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3\ ab^{-1}$.

H. Baer, V. Barger, **D. S.** and Xerxes Tata, Phys.Rev.D 105 (2022) 9, 095017

Natural SUSY: Winos at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3\ ab^{-1}$.

H. Baer, V. Barger, J. S. Gainer, M. Savoy, **D. S.** and X. Tata, Phys.Rev.D 97 (2018) no.3, 035012

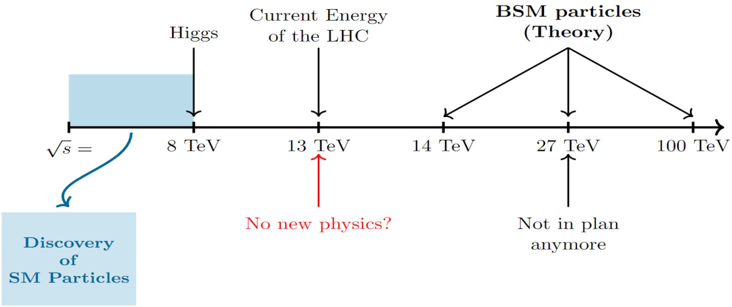
Natural SUSY: Winos at $\sqrt{s} = 27$ TeV and $\mathcal{L} = 3\ ab^{-1}$.

Type-III seesaw model: Lightest exotic fermions ($\Sigma^{\pm,0}$) at $\sqrt{s} = 27$ TeV and $\mathcal{L} = 15\ ab^{-1}$.

Type-II seesaw model/Georgi-Machacek model: H^{++} at $\sqrt{s} = 27$ TeV and $\mathcal{L} = 15\ ab^{-1}$.

C.W. Chiang, S. Jana, **D. S.**, Phys.Rev.D 105 (2022) 5, 055014

BSM Beyond LHC



Energy line of SM and BSM particles

Searches for new physics $\Longrightarrow$ Future colliders.

Our Proposal: Study well-known observables to reveal new physics.

This work: Precise measurement of top quark observables

Motivation

- **The LHC**, being a **“top quark factory”**, helps in precise measurement of various properties of the top quark.
- Deviation from the SM prediction in measuring these properties of the top quark can, very efficiently, shed light on new physics signal.
- We study the invariant mass of the b-jet and the lepton ($m_{b\ell}$).
  - used to extract the top quark mass, assuming leptonic decay of the $W^{\pm}$ boson arising from pair produced top quarks.

ArXiv: 2312.09794 [hep-ph] by E. Bagnaschi, G. Corcella, R. Franceschini, **D.S.**.

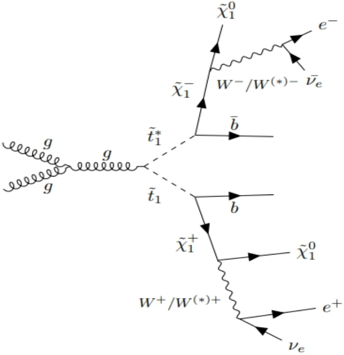
Motivation

- **Our goal:** To check if there exist a BSM particle with mass around m_t and which can mimic the final state of fully leptonic decay of pair-produced top quarks, can it cause any deviation in the $m_{b\ell}$ distribution ?

- Works for any BSM scenario that can accommodate such a particle.

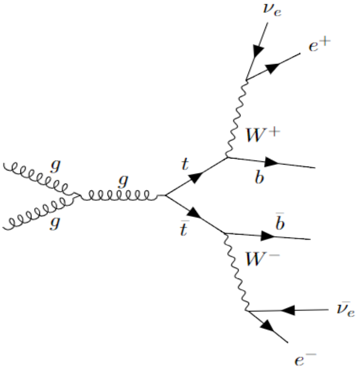
- As an example we assume the Minimal Supersymmetric Standard Model (MSSM) scenario with mass of the lightest stop quark (the superpartner of the top quark) $(m_{\tilde{t}_1})=$ 180, 200 and 220 GeV.

MSSM Signal



MSSM signal where the lightest stop $\tilde{t_1}$ decays to the lightest chargino $\tilde{\chi_1^{\pm}}$ and b and $\tilde{\chi_1^{\pm}}$ decays to the Lightest SUSY particle (LSP) $\tilde{\chi_1^0}$ leptonically via a real or a virtual $W^{\pm}$ boson.Therefore, final state: opposite sign dileptons + 2 b-jets + $\not{E_T}$

SM Background



SM Background where the top quark t decays to the b and $W^\pm$ which further decays leptonically. Therefore, final state: opposite sign dileptons + 2 b-jets + $E\!\!\!/_T$

Methodology

Several parameter space points with fixed $m_{\tilde{t_1}}$ but different $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^0}$ have been generated using `SPheno-` 4.0.3 interfaced with `SARAH-` 4.15.1 by setting the input parameters as follows:

- $m_{\tilde{u}}(1,1)^2 = m_{\tilde{u}}(2,2)^2 = m_{\tilde{q}}(i,i)^2 = m_{\tilde{l}}(i,i)^2 = m_{\tilde{e}}(i,i)^2 = m_{\tilde{d}}(i,i)^2 = 1.2 \cdot 10^7$ GeV^2.
- $m_{\tilde{u}}(3,3)^2 = 1.7 \cdot 10^5$ GeV^2.
- All the off-diagonal mass terms $= 0$
- $M_A^2 = 2 \cdot 10^6$ GeV^2
- $M_2 = 1$ TeV
- $M_3 = 3.5$ TeV
- $tan\ \beta = 10$
- M_1: varying from 5 GeV to 1 TeV
- μ: varying from 100 GeV to $m_{\tilde{t_1}}$
- $A_t(3,3)$: varying from ($x_t + \mu\ cot\ \beta$ - 100) GeV to ($x_t + \mu\ cot\ \beta$ + 100) GeV where x_t is derived for one particular point by trial-and-error so as to get the desired $m_{\tilde{t_1}}$.
- All other trilinear couplings $= 0$
- mass of top quark $m_t = 173.2$ GeV

- $m_{\tilde{q}} \approx m_{\tilde{l}} \approx 3.5$ TeV $\neq m_{\tilde{t_1}}$
- $m_{\tilde{g}} \approx 3.6$ TeV
- 122 GeV $\leq m_h \leq$ 128 GeV
- LSP: $\tilde{\chi}_1^0$
- NLSP: $\tilde{\chi}_1^\pm$

Methodology

- Each of these parameter space points are passed through `smodels-` 2.3.3 which evaluates the value r for the parameter space points.

  $r < 1 \implies$ allowed by the current experimental constraints.

  arXiv: 2306.17676 [hep-ph] by Sabine Kraml et. al.

  Next, events corresponding to these parameter space points are simulated using `Pythia` 8.3 with PDF = NNPDF2.3 QCD+QED LO . We impose the following set of cuts motivated by experimental papers:

  cuts: $p_T(\ell) \geq 25$ GeV, $|\eta(\ell)| < 2.5$, $R(j) = 0.4$, $p_T(j) \geq 25$ GeV, $|\eta(j)| < 2.5$, $\Delta R(\ell j) > 0.2$, $\Delta R(\ell\ell) > 0.1$, $\Delta R(jj) > 0.4$

  Tech. Rep. ATLAS-CONF-2019-038, M. Aaboud et al. (ATLAS), Eur. Phys. J. C 78, 129 (2018), arXiv:1709.04207 [hep-ex].

  The jets are clustered according to anti-k_T jet algorithm.

Benchmark points

After the simulation, we obtain the $m_{b\ell}$ distributions for all the parameter space points.

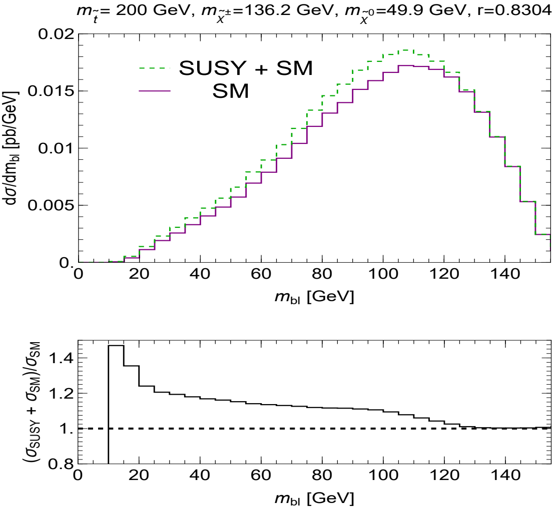
Here we show the $m_{b\ell}$ distributions for two benchmark points, namely, BM1 and BM2 which are:

BM1: $m_{\tilde{t}_1} \sim 200$ GeV, $m_{\tilde{\chi}_1^\pm} \sim 136.165$ GeV, $m_{\tilde{\chi}_1^0} \sim 49.9$ GeV, $r=$ 0.8304

and

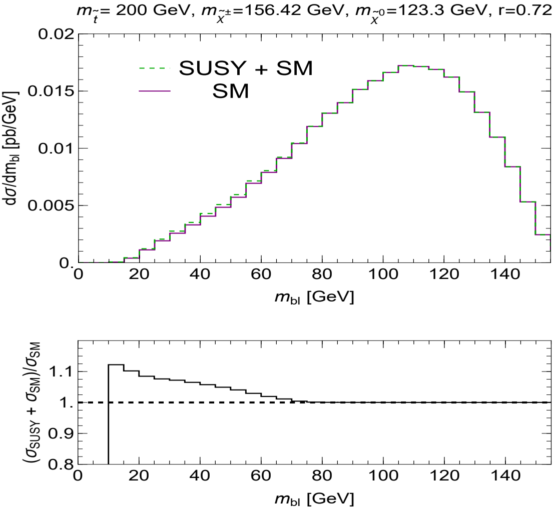
BM2: $m_{\tilde{t}_1} \sim 200$ GeV, $m_{\tilde{\chi}_1^\pm} \sim 156.42$ GeV, $m_{\tilde{\chi}_1^0} \sim 123.3$ GeV, $r=$ 0.71606

$m_{b\ell}$ distribution



$m_{b\ell}$ distribution at $\sqrt{s} = 13$ TeV for BM1 after cuts

$m_{b\ell}$ distribution



$m_{b\ell}$ distribution at $\sqrt{s} = 13$ TeV for BM2 after cuts

Significance

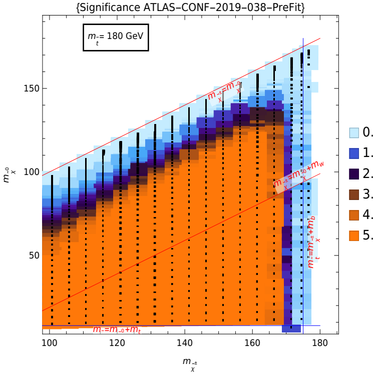
Significance $= \sqrt{\sum_i (S_i/(B_i * u_{B_i}))^2}$ at $\mathcal{L} = 139\ fb^{-1}$ where
$S_i=$ number of signal events in the i^{th} bin
$B_i=$ number of BG events in the i^{th} bin
$u_{B_i}=$ Relative uncertainity in the BG in the i^{th} bin extracted from ATLAS and CMS

BM1: Significance (u_{B_i} from ATLAS) $\sim$ 10.8, Significance (u_{B_i} from CMS) $\sim$ 4.1

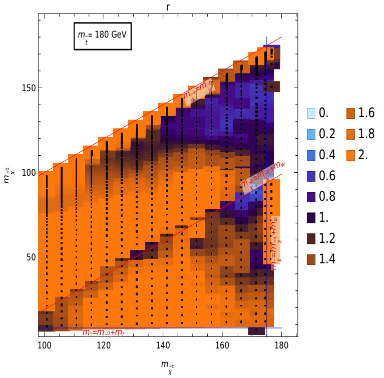
BM2: Significance (u_{B_i} from ATLAS) $\sim$ 2.6, Significance (u_{B_i} from CMS) $\sim$ 0.9

Tech. Rep. ATLAS-CONF-2019-038, A. M. Sirunyan et al. (CMS), Eur. Phys. J. C 79, 368 (2019), arXiv:1812.10505 [hep-ex].

$m_{\tilde{t}_1} = 180$ GeV



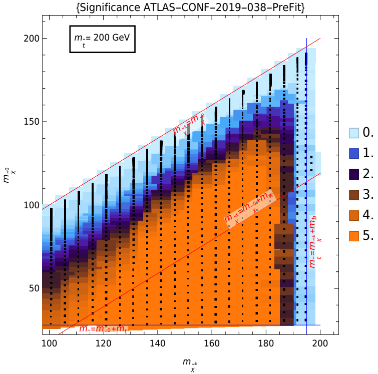
Significance with u_B from ATLAS

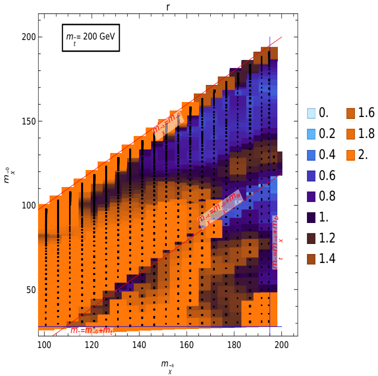


Values of r calculated using `smodels`- 2.3.3

Significance $\geq$ 5 $\Longrightarrow$ DISCOVERY

$m_{\tilde{t}_1} = 200$ GeV



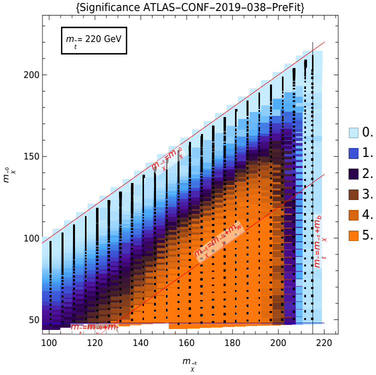


Significance with u_B from ATLAS

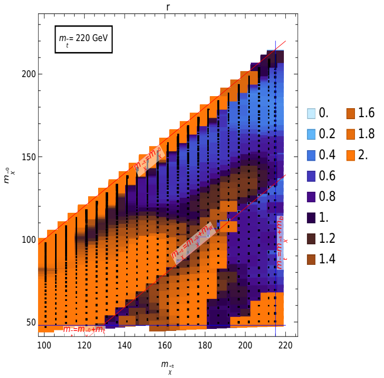
Values of r calculated using `smodels-` 2.3.3

Significance $\geq$ 5 $\Longrightarrow$ DISCOVERY

$m_{\tilde{t}_1} = 220$ **GeV**



Significance with u_B from ATLAS



Values of r calculated using `smodels`- 2.3.3

Significance $\geq$ 5 $\Longrightarrow$ DISCOVERY

Conclusion

- Currently the usual trend is to look for **new physics** at energies beyond the reach of the LHC but accessible by **future colliders**.

- However, here we show that a thorough study of well-known kinematic observables may hint towards the existence of new physics.

- We carefully investigate the $m_{b\ell}$ distribution in the MSSM signal and the SM background with the final state: opposite sign dileptons + 2 b-jets + $\not{E}_T$ and with $m_{\tilde{t}_1} \approx m_t$ for all possible values of $m_{\tilde{\chi}_1^{\pm}}$ and $m_{\tilde{\chi}_1^0}$

- In $m_{b\ell}$ distribution after cuts at $\sqrt{s} = 13$ TeV and $\mathcal{L} = 139$ fb^{-1}, we were able to see some excess in signal in some parameter space points.

Thank You

Questions ?

Back Up Slides

r from SMODELS

UL-type result: Theory prediction is a list of signal cross sections for each data set. Each theory prediction must then be compared to its corresponding upper limit.

EM-type result: Theory prediction is a single signal cross section value for each data set. This value must be compared to the upper limit for the corresponding signal region.

$r_{exp} =$ (theory prediction)/(expected limit)

arXiv: 2306.17676 [hep-ph] by Sabine Kraml et. al.

BM points

BM	μ	M_1	A_t	m_{χ^+}	m_{χ^0}	z_{CMS}	z_{ATLAS}	$r(old)$	$r(221)$	$r(233)$	$m_{SMHiggs}$
	$m_{\tilde{t}} = 200$ GeV										
ON1	185	95	2820.5	186.6	85.6	[0.8,1.7]	[2.7,14.3]	0.89738	0.96022	0.96022	125.04
ON1	185	115	2820.5	186.65	102.78	[0.85,1.7]	[2.7,15.4]	0.52199	0.52199	0.52199	125.04
OFF1	155	160	2857.5	156.4	123.3	[0.9,1.8]	[2.6,14.8]	0.71606	0.71606	0.71606	125.3
OFF2	175	145	2839.5	176.6	123.5	[1.5,3.]	[5.1,25.5]	0.78765	1.0205	1.02059	125.2
OFF2	175	125	2829.5	176.6	109.05	[1.7,3.45]	[5.6,27.75]	0.80101	0.82341	0.82365	125.1
T1	135	65	2895.5	136.2	54.	[4.,7.7]	[10.7,61.3]	0.8143	0.8143	0.81429	125.5
T2	135	60	2895.5	136.2	49.9	[4.1,7.9]	[10.8,60.6]	0.83036	0.83036	0.83035	125.5
	$m_{\tilde{t}} = 220$ GeV										
OFF3	155	150	3140.5	156.4	118.6	[0.7,1.4]	[1.9,10.9]	0.81382	0.81382	0.81382	126.6
OFF4	170	160	3122	171.5	130.8	[0.9,1.8]	[2.5,13.7]	0.58165	0.64545	0.64544	126.5
ON2	190	95	3104	191.7	86.1	[2.1,4.3]	[6.1,32.8]	0.66529	0.80242	0.80242	126.4
OFF5	190	145	3104	191.7	127.7	[1.4,2.8]	[4.2,22.5]	0.62446	1.33641	1.33674	126.4
OFF5	190	165	3094	191.7	141.7	[1.15,2.34]	[3.5,18.4]	0.65437	0.74534	0.74548	126.4
ON3	190	65	3104	191.7	58.9	[1.9,3.7]	[5.3,28.7]	0.80811	0.90652	0.90652	126.4
ON3	190	60	3104	191.67	54.25	[1.9,3.9]	[5.5,29.6]	0.84207	0.87302	0.87302	126.4
	$m_{\tilde{t}} = 180$ GeV										
OFF6	165	115	2570.5	166.5	99.2	[1.2,2.5]	[4.8,22.9]	0.84225	1.51918	1.51928	123.5
OFF6	165	140	2560.5	166.522	116.926	[0.95,1.96]	[4.2,18.74]	0.81006	0.881	0.8812	123.5
OFF7	160	105	2580	161.5	90.4	[2.2,4.5]	[7.2,36.3]	0.78658	1.72047	1.71936	123.6
OFF7	160	145	2570	161.476	118.073	[1.4,2.8]	[5.3,24.4]	0.91869	0.91869	0.91869	123.5
OFF8	160	170	2570	161.5	130.3	[0.6,1.2]	[2.4,11.2]	0.57605	0.60568	0.60550	123.5
OFF9	155	150	2579.5	156.4	118.5	[1.6,3.2]	[5.3,27.2]	0.83351	0.83351	0.83351	123.6
OFF10	145	175	2598.5	146.3	122.2	[0.8,1.6]	[2.4,12.7]	0.83802	0.83802	0.83802	123.7