WORKSHOP ON THE PHYSICS OF HL-LHC, AND PERSPECTIVES AT HE-LHC

CERN, JUNE 18, 2018

IMPLICATIONS OF A STOP SECTOR SIGNAL AT THE HL-LHC

BASED ON:
HEP-PH 1611.00771 W/ AARON PIERCE

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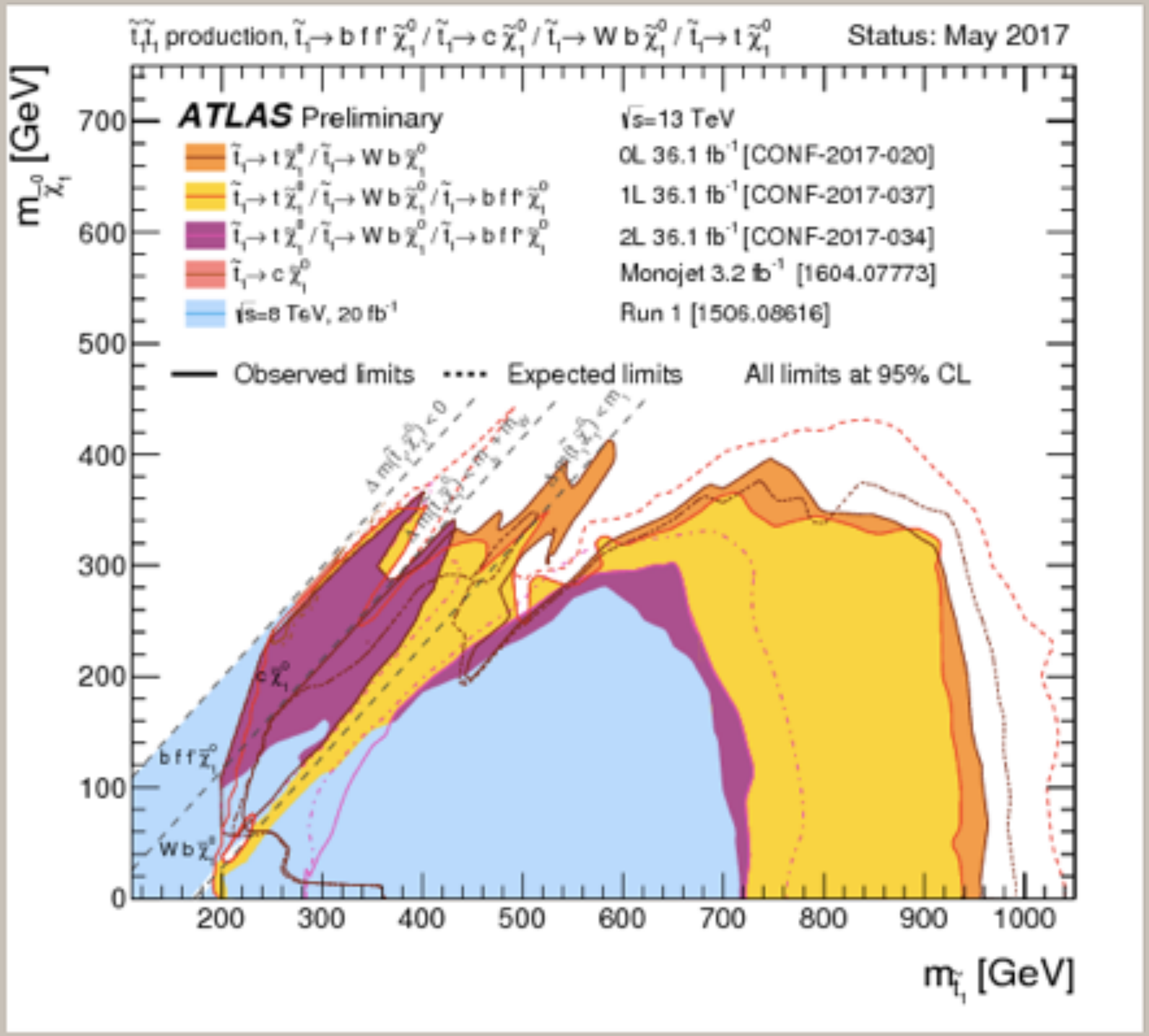
THE SEARCH FOR STOPS AT THE LHC



- strong constraints, but plenty of space left
- fine tuned, but not disastrous
- discovery of stops at HL/HE LHC with high significance still possible

THIS TALK

- IMPLICATIONS OF DISCOVERING A STOP SECTOR SIGNAL:

- Not only a discovery of BSM physics, but an opportunity at the HL-LHC to
- test the Higgs mass relation and the underlying theory
- predict masses and properties of other supersymmetric particles

HOW HEAVY ARE STOPS?

$$m_h^2 = m_Z^2 \cos^2(2\beta) + \frac{3 \sin^2 \beta \, y_t^2}{4\pi^2} \left[m_t^2 \ln \left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right) + c_t^2 s_t^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) \ln \left(\frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2} \right) \right.$$
$$\left. + \, c_t^4 s_t^4 \left\{ (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)^2 - \frac{1}{2} (m_{\tilde{t}_2}^4 - m_{\tilde{t}_1}^4) \ln \left(\frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2} \right) \right\} / m_t^2 \right],$$

Supersymmetry Primer

Higgs mass at one loop in the MSSM

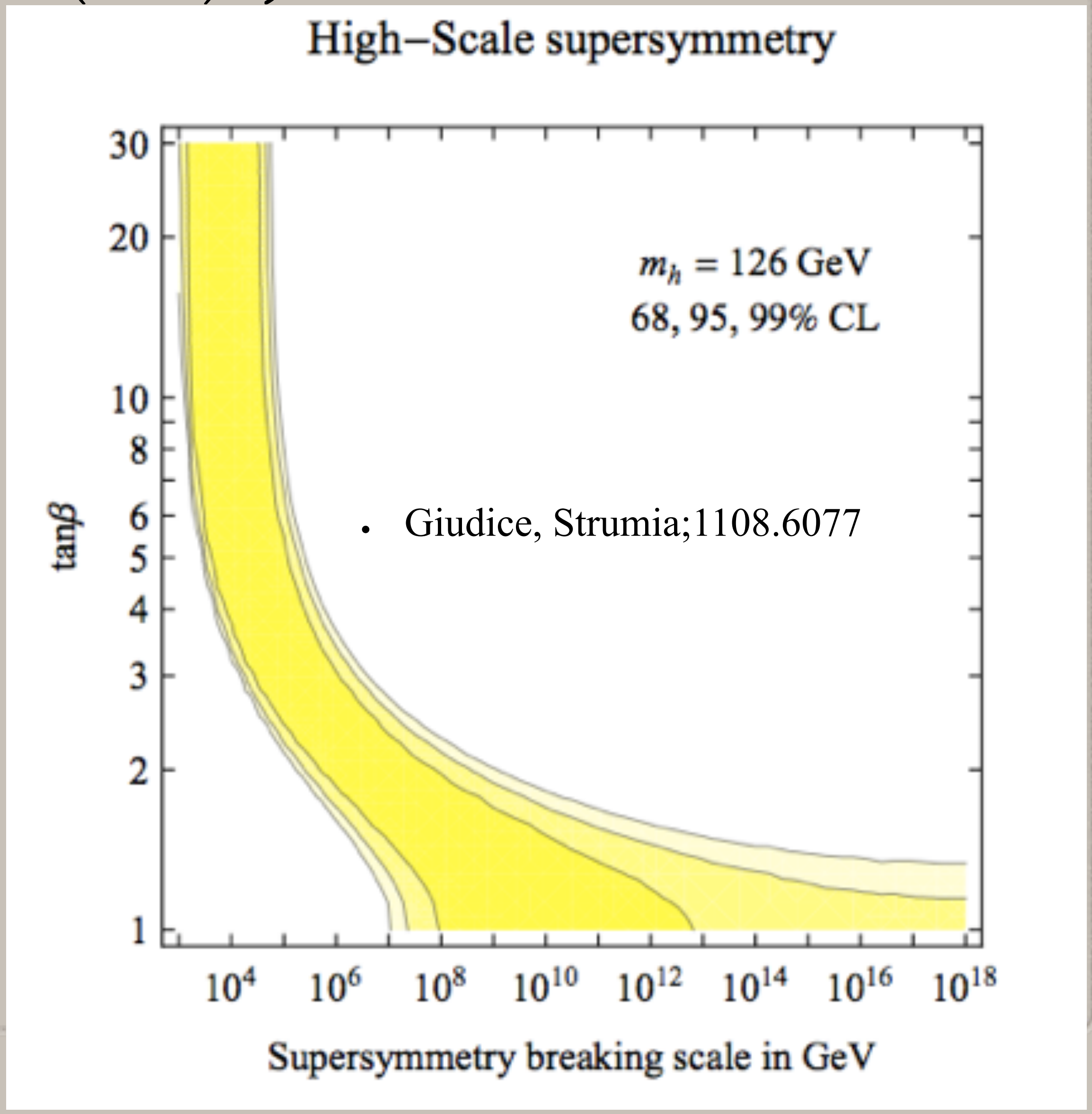
- Determined by four parameters: two stop masses, mixing angle, tan beta (mild dependence)
- at higher order, depends on other parameters (e.g. gluino mass)
- 1 loop formula within 5 GeV of the correct mass

HOW HEAVY ARE STOPS?

$$m_h^2 = m_Z^2 \cos^2(2\beta) + \frac{3\sin^2\beta\, y_t^2}{4\pi^2}\left[m_t^2 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + c_t^2 s_t^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) \ln\left(\frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2}\right)\right.$$

$$\left. + c_t^4 s_t^4 \left\{ (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)^2 - \frac{1}{2}(m_{\tilde{t}_2}^4 - m_{\tilde{t}_1}^4) \ln\left(\frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2}\right)\right\} / m_t^2 \right],$$

Knowing the Higgs mass does not constrain the stop mass scale: Arbitrarily high stop masses compatible with the observed Higgs mass



HOW HEAVY ARE STOPS?

$m_h^2 = m_Z^2$ … $- m_{\tilde{t}_1}^2) \ln\left(\frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2}\right)$

$+ c_t^4 s_t^4$ …

Knowi…
not cons…
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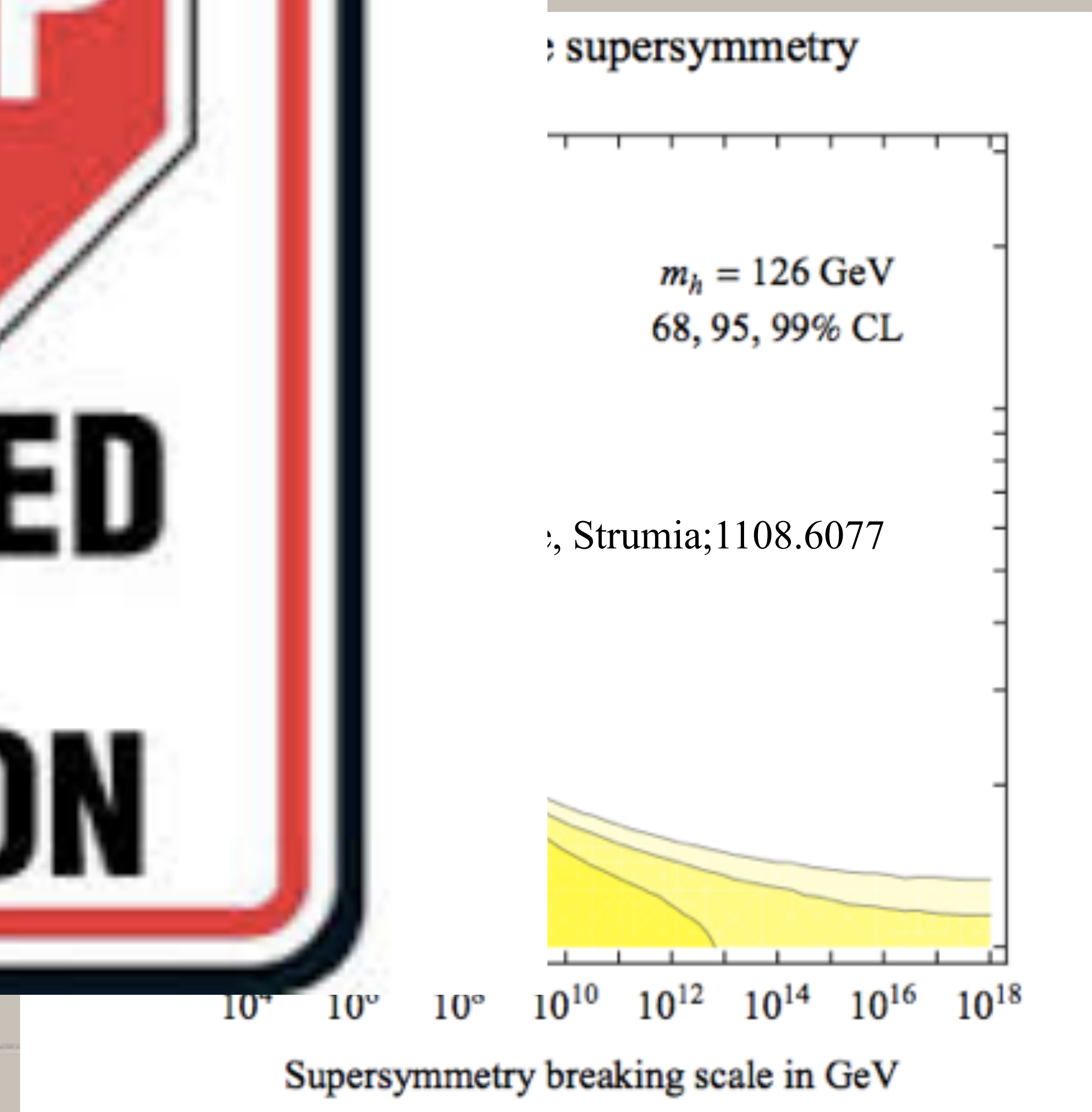


HOW HEAVY ARE STOPS?

$$m_h^2 = m_Z^2 \cos^2(2\beta) + \frac{3\sin^2\beta\, y_t^2}{4\pi^2}\left[\, m_t^2 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + c_t^2 s_t^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) \ln\left(\frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2}\right)\right.$$

$$\left. + c_t^4 s_t^4 \left\{ (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)^2 - \frac{1}{2}(m_{\tilde{t}_2}^4 - m_{\tilde{t}_1}^4) \ln\left(\frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2}\right) \right\} / m_t^2 \,\right],$$

This outlook COMLPETELY changes if a stop discovered!

- Can no longer push the second stop mass arbitrarily high! (for nonzero mixing) - negative corrections to the Higgs mass!
- Stop discovery → an upper bound on the heavier stop mass [in the MSSM]

BASIC IDEA

- Three parameters (two stop masses and the stop mixing angle) determine the Higgs mass at 1 loop in the MSSM
- **ONE** measurement allows strong constraints on the two remaining parameters
- **TWO** measurements allow prediction of the third parameter. Falsifying this prediction rules out the MSSM
- **THREE** measurements allow a consistency check of the Higgs mass, MSSM

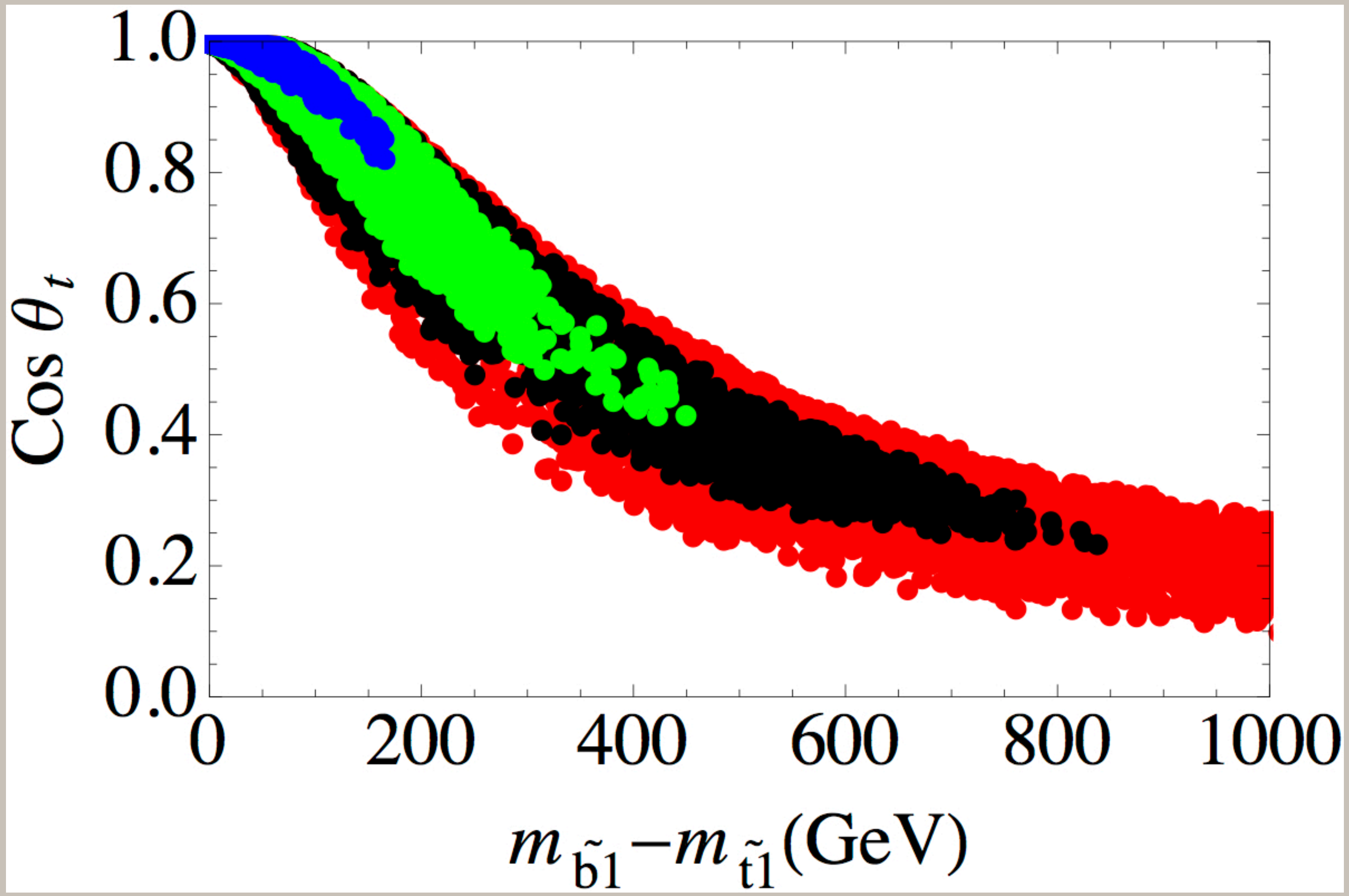
- EXAMPLE 1

$$\tilde{b}_1$$

- A SBOTTOM SIGNAL IN MULTILEPTONS

[LET HANDED] SBOTTOM: PART OF THE STOP SECTOR

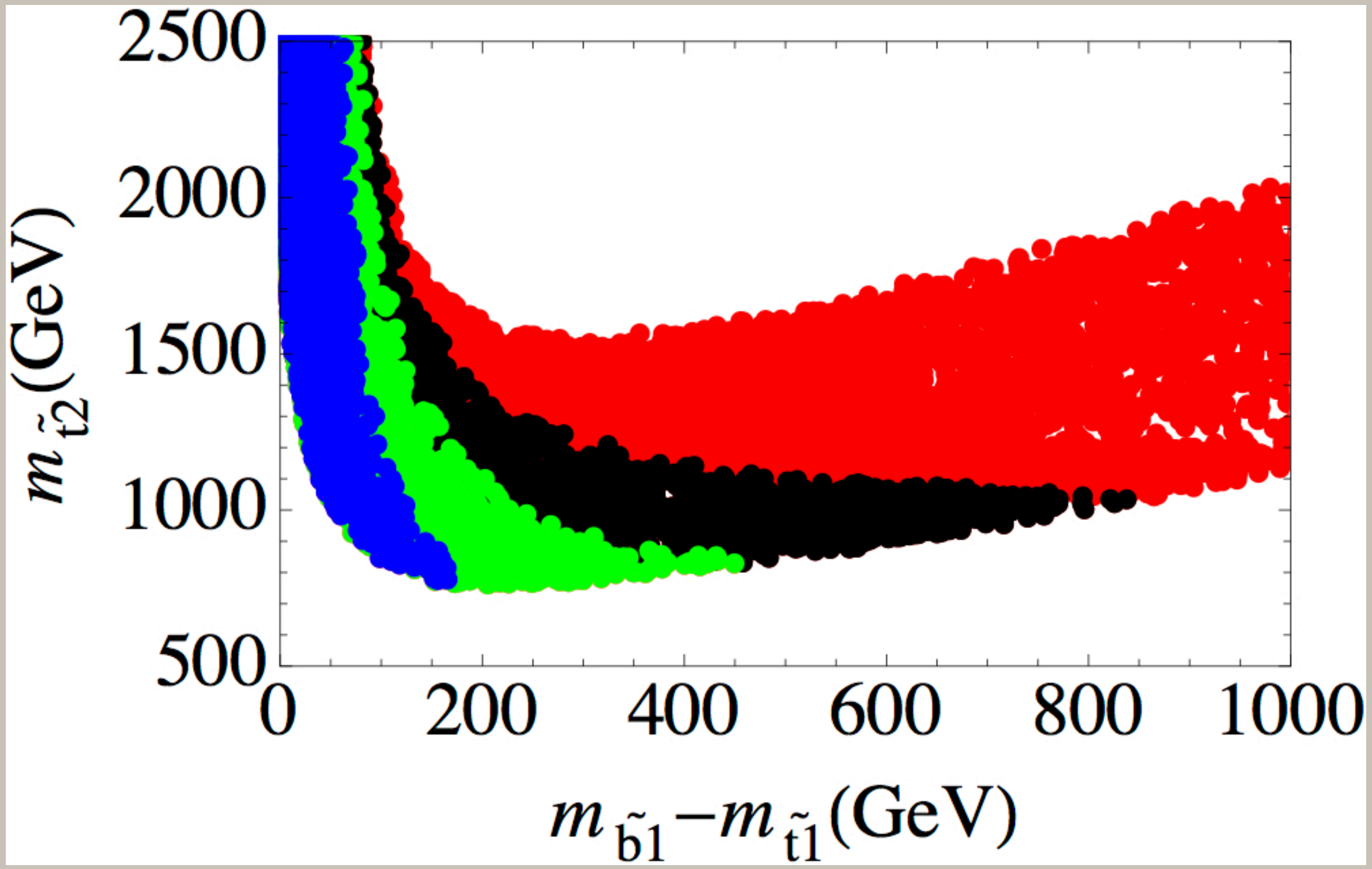
$$m^2_{\tilde{b}_1} = m^2_{\tilde{t}_2} \sin^2\theta_{\tilde{t}} + m^2_{\tilde{t}_1} \cos^2\theta_t - m^2_t + m^2_W$$



red, black, green, blue : $m_{\tilde{b}_1} > 1000$, $750 < m_{\tilde{b}_1} < 1000$, $500 < m_{\tilde{b}_1} < 750$, and $m_{\tilde{b}_1} < 500$ GeV respectively

Scan points consistent with $120 < m_h < 130\,\mathrm{GeV}$ and $m_{\tilde{t}_1} < 1$ TeV

[LET HANDED] SBOTTOM: PART OF THE STOP SECTOR



red, black, green, blue : $m_{\tilde{b}_1} > 1000$, $750 < m_{\tilde{b}_1} < 1000$, $500 < m_{\tilde{b}_1} < 750$, and $m_{\tilde{b}_1} < 500$ GeV respectively

Scan points consistent with $120 < m_h < 130\,\mathrm{GeV}$ and $m_{\tilde{t}_1} < 1$ TeV

BENCHMARK SCENARIO

$$\tilde{t}_2: \quad m_{\tilde{t}_2} = 1022.2\ \text{GeV}, \quad \text{BR: } \tilde{t}_1 Z\ 79\%,\ \tilde{b}_1 W\ 15\%,\ \tilde{t}_1 h\ 2\%, \quad \sin\theta_t = 0.75$$

$$\tilde{b}_1: \quad m_{\tilde{b}_1} = 885.4\ \text{GeV}, \quad \text{BR: } \tilde{t}_1 W\ 99.5\%$$

$$\tilde{t}_1: \quad m_{\tilde{t}_1} = 646.1\ \text{GeV}, \quad \text{BR: } t\chi_0\ 100\%$$

$$\chi_0: \quad m_\chi = 445.7\ \text{GeV}, \quad \text{LSP}$$

$$h: \quad m_h = 123.2\ \text{GeV}$$

- sbottom decays give a multilepton signal

ANALYSIS

- Implement existing CMS search strategies

Search for SUSY in same-sign dilepton events at 13 TeV, Tech. Rep. CMS-PAS-SUS-16-020

Search	σ_{prod}/fb	efficiency(ϵ) ($\times 10^{-4}$)	no. of signal events (S)	background events (B)	$\mathcal{S}$ $\sigma_{bg}=0$	$\mathcal{S}$ $\sigma_{bg}=0.1$	$\mathcal{S}$ $\sigma_{bg}=0.3$
SSDL	-	-	72	235	4.7	2.6	1.0
$\tilde{b}_1$ contribution	14	14	61	-	-	-	-
$\tilde{t}_2$ contribution	5	8	11	-	-	-	-

Search for SUSY with multileptons in 13 TeV data, Tech. Rep. CMS-PAS-SUS-16-022
+ b-jet requirement, stronger MET cut

Search	σ_{prod}/fb	efficiency(ϵ) ($\times 10^{-4}$)	no. of signal events (S)	background events (B)	$\mathcal{S}$ $\sigma_{bg}=0$	$\mathcal{S}$ $\sigma_{bg}=0.1$	$\mathcal{S}$ $\sigma_{bg}=0.3$
$\geq 3l$offZ	-	-	102	297	5.9	3.0	1.1
$\tilde{b}_1$ contribution	14	19	81	-	-	-	-
$\tilde{t}_2$ contribution	5	14	21	-	-	-	-

HEAVIER STOP SEARCH

- knowing mass range and dominant decay channel for stop2, can optimize search strategy

Search for SUSY with multileptons in 13 TeV data, Tech. Rep. CMS-PAS-SUS-16-003

+ Z requirement instead of Z veto

Search	σ_{prod}/fb	efficiency(ϵ) ($\times 10^{-4}$)	no. of signal events (S)	background events (B)	$\mathcal{S}$ $\sigma_{bg}=0$	$\mathcal{S}$ $\sigma_{bg}=0.1$	$\mathcal{S}$ $\sigma_{bg}=0.3$
>3$l$onZ	-	-	152	432	7.3	3.2	1.2
$\tilde{t}_2$ contribution	14	78	117	-	-	-	-
$\tilde{b}_1$ contribution	5	8	35	-	1.7	0.7	0.3

- EXAMPLE 2

$$\tilde{t}_2$$

- A HEAVIER STOP SIGNAL IN BOOSTED DIBOSONS

HEAVIER STOP IN MULTIPLE CHANNELS

- High lumi LHC can detect heavier stops in multiple decay channels
- Relative abundance of various channels contains information about the underlying parameters!

$$R_{hZ} \equiv \frac{\Gamma(\tilde{t}_2 \to \tilde{t}_1\, h)}{\Gamma(\tilde{t}_2 \to \tilde{t}_1\, Z)} = \left[\left(1 - \frac{m^2_{\tilde{t}_1}}{m^2_{\tilde{t}_2}}\right)\cos 2\theta_{\tilde{t}} + \frac{m^2_W}{m^2_{\tilde{t}_2}}\left(1 - \frac{5}{3}\tan^2\theta_W\right)\right]^2 \approx \left(1 - \frac{m^2_{\tilde{t}_1}}{m^2_{\tilde{t}_2}}\right)^2 \cos^2 2\theta_{\tilde{t}}$$

- Experimentally: measure the ratio as

$$R_{hZ} \sim \frac{2\, n_{hh}}{n_{Zh}}$$

BENCHMARK SCENARIO

$$
\begin{array}{lll}
\tilde{t}_2: & m_{\tilde{t}_2} = 994.2 \text{ GeV}, & \text{BR: } \tilde{t}_1 Z \ 52\%, \ \tilde{t}_1 h \ 28\%, \quad \sin^2\theta_t = 0.988 \\
\tilde{b}_1: & m_{\tilde{b}_1} = 977.5 \text{ GeV}, & \text{decays dominantly to } \tilde{t}_1 W \\
\tilde{t}_1: & m_{\tilde{t}_1} = 486.0 \text{ GeV}, & \text{decays dominantly to } c\chi_0 \\
\chi_0: & m_{\chi} = 406.0 \text{ GeV}, & \text{LSP} \\
h: & m_h = 109.2 \text{ GeV} &
\end{array}
$$

BOOSTED DIBOSONS SEARCH

- Implemented search strategy for boosted dibosons from

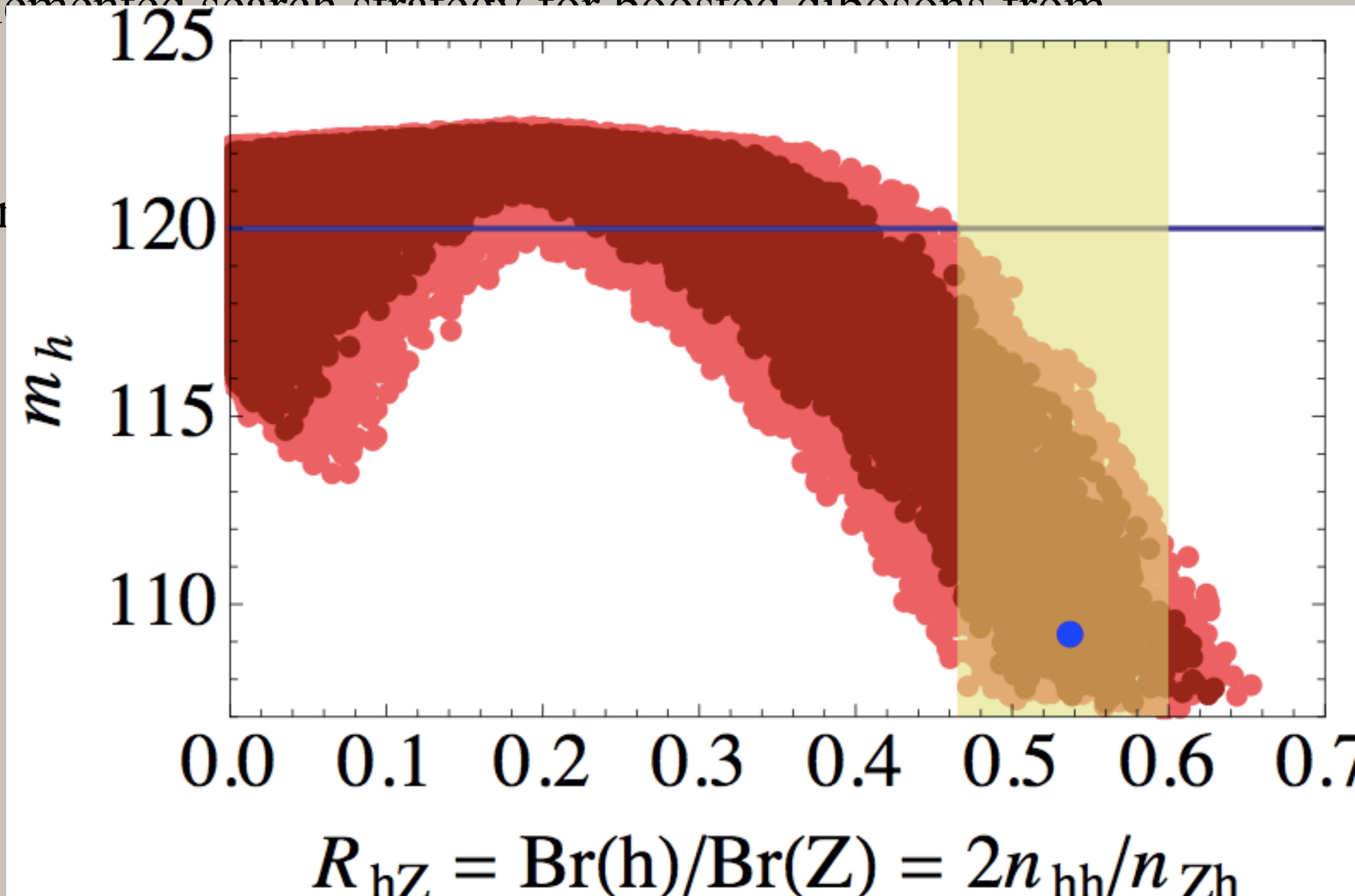
  D. Ghosh, Phys. Rev. **D88**, 115013 (2013), arXiv:1308.0320 [hep-ph]

- We end up with $n_{hh} = 47, \quad n_{Zh} = 176$

BOOSTED DIBOSONS SEARCH

- Implemented search strategy for boosted dibosons from

- We e



- Light red: $440 \leq m_{\tilde{t}_1} \leq 520\,\mathrm{GeV}$ and $930 \leq m_{\tilde{t}_2} \leq 1030\,\mathrm{GeV}$
- Dark red: $450 \leq m_{\tilde{t}_1} \leq 510\,\mathrm{GeV}$ $\quad 945 \leq m_{\tilde{t}_2} \leq 1015\,\mathrm{GeV}$

SUMMARY

- Stop sector intricately tied to the Higgs mass. Stop sector discovery is an opportunity to test the Higgs mass relation
- can predict masses and properties of other supersymmetric particles, aiding in their discovery (example: sbottom signal in multileptons)
- can perform consistency checks to identify the underlying theory / rule out the MSSM (example: heavier stop decays in boosted dibosons)