Constraining Low Fine Tuned Supersymmetric Models With Simplified Models Spectra Results Based On CMS And ATLAS Searches

Veronika Magerl

Application for PhD Position HEPHY:
Measurement of quarkonium production to probe QCD at the LHC

October 09, 2015

A tool for interpreting simplified model results from the LHC

http://smodels.hephy.at/wiki/SModelS

Sabine Kraml, Suchita Kulkarni, Ursula Laa, Andre Lessa, *Veronika Magerl*, Wolfgang Magerl, Doris Proschofsky, Michael Traub, Wolfgang Waltenberger

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

HEPHY
Institut für Hochenergiephysik

USP
Universidade de São Paulo
Brasil

SMS – Full Model

- **Experiment** → SMS
  - effective Lagrangian description, involves only a **reduced number of SUSY particles**
  - purely **phenomenological** → parameters directly related to collider physics observables
  - SUSY search results are presented as upper limit (UL) maps ⇒ hold 95% C.L. upper limits on **topology weight ($\sigma \times BR$) as function of masses** of involved sparticles
- **Theory** → full model
- constraining a full model by applying relevant SMS results is **not straight forward** ⇒ **SModelS**

SMS – Full Model

- **SMS** = interpretation event counts in terms of **specific decays**
  - effective Lagrangian description, involves only a **reduced number of SUSY particles**
  - purely **phenomenological** $\rightarrow$ parameters directly related to collider physics observables
  - SUSY search results are presented as upper limit (UL) maps $\Rightarrow$ hold 95% C.L. upper limits on **topology weight** **($\sigma \times BR$) as function of masses** of involved sparticles
- **full model**
- constraining a full model by applying relevant SMS results is **not straight forward** $\Rightarrow$ **SModelS**

SMS – Full Model

- **SMS** = interpretation event counts in terms of **specific decays**
  - effective Lagrangian description, involves only a **reduced number of SUSY particles**
  - purely **phenomenological** $\rightarrow$ parameters directly related to collider physics observables
  - SUSY search results are presented as upper limit (UL) maps $\Rightarrow$ hold 95% C.L. upper limits on **topology weight ($\sigma \times BR$) as function of masses** of involved sparticles
- **full model**
- constraining a full model by applying relevant SMS results is **not straight forward** $\Rightarrow$ **SModelS**

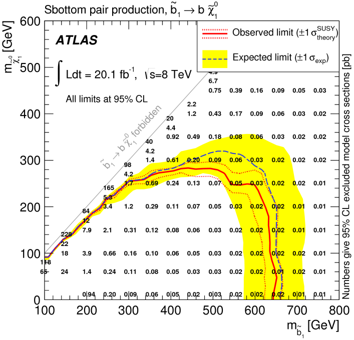
SMS – Full Model

- **SMS** = interpretation event counts in terms of **specific decays**
  - effective Lagrangian description, involves only a **reduced number of SUSY particles**
  - purely **phenomenological** $\rightarrow$ parameters directly related to collider physics observables
  - SUSY search results are presented as upper limit (UL) maps $\Rightarrow$ hold 95% C.L. upper limits on **topology weight ($\sigma \times BR$) as function of masses** of involved sparticles
- **full model**
- constraining a full model by applying relevant SMS results is **not straight forward** $\Rightarrow$ **SModelS**

SMS – Full Model

- **SMS** = interpretation event counts in terms of **specific decays**
  - effective Lagrangian description, involves only a **reduced number of SUSY particles**
  - purely **phenomenological** $\rightarrow$ parameters directly related to collider physics observables
  - SUSY search results are presented as upper limit (UL) maps $\Rightarrow$ hold 95% C.L. upper limits on **topology weight ($\sigma \times$ *BR*) as function of masses** of involved sparticles

ATLAS-SUSY-2013-05: upper limit map for T2bb model of ATLAS 2b-jets + $\not{E}_T$ analysis

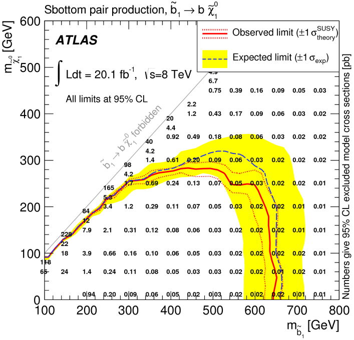


- **full model**
- constraining a full model by applying relevant SMS results is **not straight forward** $\Rightarrow$ **SModelS**

SMS – Full Model

- **SMS** = interpretation event counts in terms of **specific decays**
  - effective Lagrangian description, involves only a **reduced number of SUSY particles**
  - purely **phenomenological** $\rightarrow$ parameters directly related to collider physics observables
  - SUSY search results are presented as upper limit (UL) maps $\Rightarrow$ hold 95% C.L. upper limits on **topology weight ($\sigma \times BR$) as function of masses** of involved sparticles

ATLAS-SUSY-2013-05: upper limit map for T2bb model of ATLAS 2b-jets + $\not{E}_T$ analysis

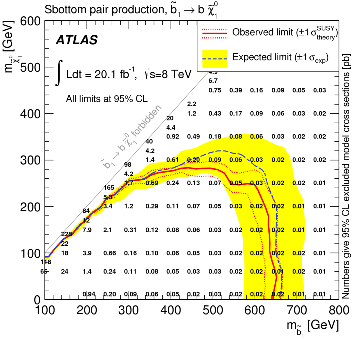


- **full model** (e.g. the pMSSM) provides mass spectrum and decay patterns for whole set of BSM states $\Rightarrow$ includes contributions of **several SMS topologies**
- constraining a full model by applying relevant SMS results is **not straight forward** $\Rightarrow$ **SModelS**

SMS – Full Model

- **SMS** = interpretation event counts in terms of **specific decays**
  - effective Lagrangian description, involves only a **reduced number of SUSY particles**
  - purely **phenomenological** $\rightarrow$ parameters directly related to collider physics observables
  - SUSY search results are presented as upper limit (UL) maps $\Rightarrow$ hold 95% C.L. upper limits on **topology weight** **($\sigma \times$ *BR*) as function of masses** of involved sparticles

ATLAS-SUSY-2013-05: upper limit map for T2bb model of ATLAS 2b-jets + $\not{E}_T$ analysis



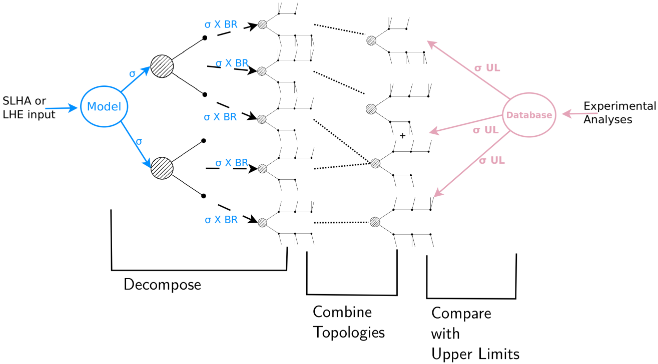
- **full model** (e.g. the pMSSM) provides mass spectrum and decay patterns for whole set of BSM states $\Rightarrow$ includes contributions of **several SMS topologies**
- constraining a full model by applying relevant SMS results is **not straight forward** $\Rightarrow$ **SModelS**

Basic Concepts

SModelS: general procedure to decompose $\mathbb{Z}_2$ symmetric BSM collider signatures into SMS topologies

- **SMS assumption:** acceptance times efficiency $(\mathcal{A} \times \epsilon)$ and kinematics of a process are function of BSM masses, do not depend on other characteristics
  $\Rightarrow$ possibility to map the signal of a full BSM model point onto its signal topologies
- **3 basic ingredients** define point in the parameter space:
  1. mass spectrum
  2. production cross sections σ_{prod} of involved BSM particles
  3. branching ratios *BR* for all possible decays

Basic Concepts



"SModelS: a tool for interpreting simplified- model results from the LHC and its application to supersymmetry"
arXiv:1312.4175

"SModelS v1.0: a short user guide"
arXiv:1412.1745

SModelS method of operating:

1. input of a full theoretical $\mathbb{Z}_2$ symmetric model
2. decomposition into its signal topologies
3. combination of topologies and comparison against the experimental database

$\Rightarrow$ overview of the **status of the current SUSY searches** and identification of **blind spots** in the parameter space

Constraints (a model independent, terse and clearly structured labelling system)

constraints

- start with arbitrary SMS topology
- overall structure determined by R-parity conservation:

  [[*branch I*],[*branch II*]]
- empty bracket is inserted for every vertex in a branch:

  [[[ ]],[[ ]]]
- specification by means of outgoing SM particles in every vertex:
  $[[[\ell,\ \nu]],[[Z]]]$

mass vector

Constraints (a model independent, terse and clearly structured labelling system)

constraints $\rightarrow$ the **SModelS** equivalent of SMS topologies:

- start with arbitrary SMS topology
- overall structure determined by R-parity conservation:

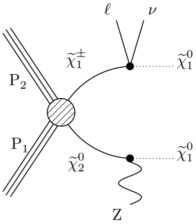
  $\big[\big[$***branch I***$\big],\big[$***branch II***$\big]\big]$
- empty bracket is inserted for every vertex in a branch:

  $\big[\big[[\ ]\big],\big[[\ ]\big]\big]$
- specification by means of outgoing SM particles in every vertex:

  $\big[\big[[\ell,\ \nu]\big],\big[[Z]\big]\big]$

mass vector

Constraints (a model independent, terse and clearly structured labelling system)



constraints $\rightarrow$ the **SModelS** equivalent of SMS topologies:

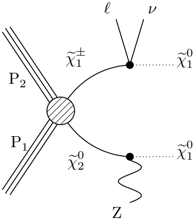
- start with arbitrary SMS topology
- overall structure determined by R-parity conservation:

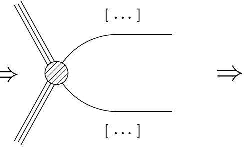
  [[***branch I***],[***branch II***]]
- empty bracket is inserted for every vertex in a branch:

  [[[ ]],[[ ]]]
- specification by means of outgoing SM particles in every vertex:
  [[[ℓ, ν]],[[Z]]]

mass vector

Constraints (a model independent, terse and clearly structured labelling system)





constraints $\rightarrow$ the **SModelS** equivalent of SMS topologies:

- start with arbitrary SMS topology
- overall structure determined by R-parity conservation:

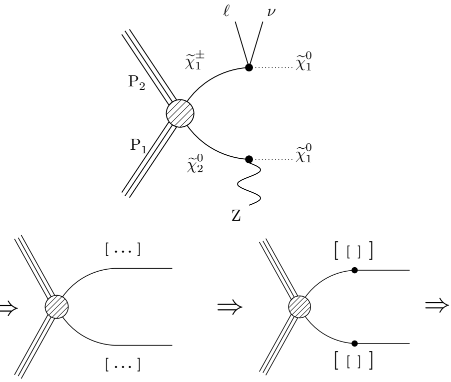
  [[*branch I*],[*branch II*]]
- empty bracket is inserted for every vertex in a branch:

  [[[ ]],[[ ]]]
- specification by means of outgoing SM particles in every vertex:

  $[[[\ell,\ \nu]],[[Z]]]$

mass vector

Constraints (a model independent, terse and clearly structured labelling system)



constraints $\rightarrow$ the **SModelS** equivalent of SMS topologies:

- start with arbitrary SMS topology
- overall structure determined by R-parity conservation:

  [[*branch I*],[*branch II*]]

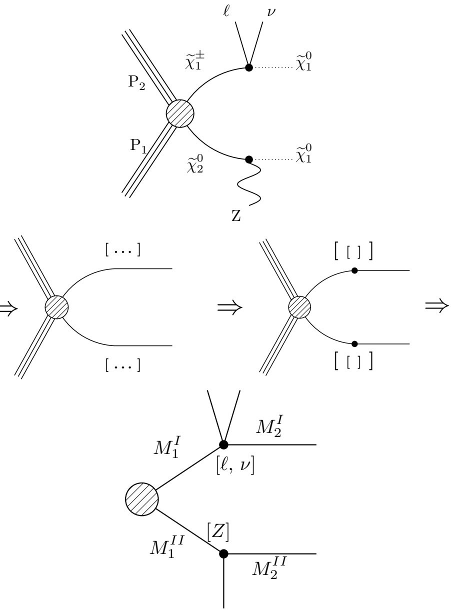
- empty bracket is inserted for every vertex in a branch:

  [[[ ]],[[ ]]]

- specification by means of outgoing SM particles in every vertex: [[[ℓ, ν]],[[Z]]]

mass vector

Constraints (a model independent, terse and clearly structured labelling system)



constraints → the **SModelS** equivalent of SMS topologies:

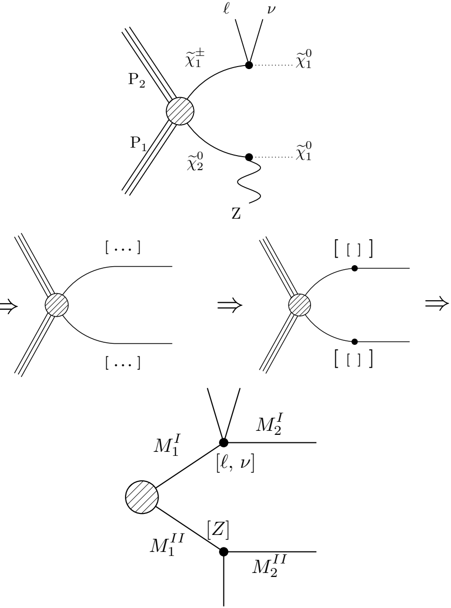
- start with arbitrary SMS topology
- overall structure determined by R-parity conservation:

  [[*branch I*],[*branch II*]]
- empty bracket is inserted for every vertex in a branch:

  [[[ ]],[[ ]]]
- specification by means of outgoing SM particles in every vertex:
  [[[ℓ, ν]],[[Z]]]

mass vector

Constraints (a model independent, terse and clearly structured labelling system)



constraints → the **SModelS** equivalent of SMS topologies:

- start with arbitrary SMS topology
- overall structure determined by R-parity conservation:

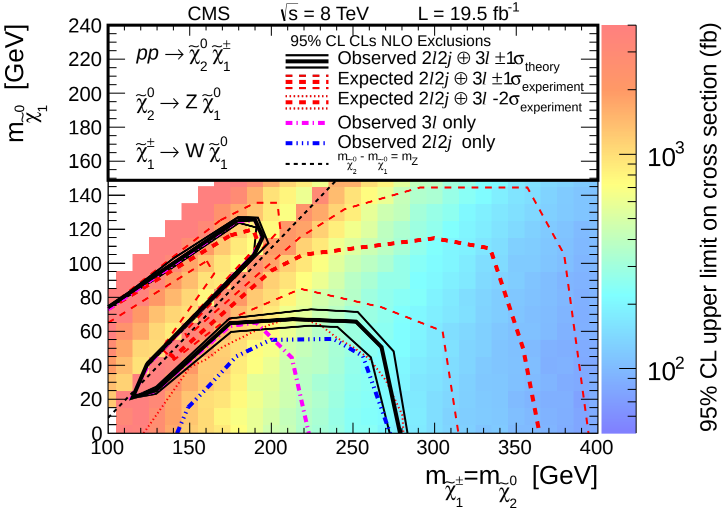
  [[*branch I*],[*branch II*]]
- empty bracket is inserted for every vertex in a branch:

  [[[ ]],[[ ]]]
- specification by means of outgoing SM particles in every vertex:
  [[[ℓ, ν]],[[*Z*]]]

mass vector (for each branch) links the topology to the BSM states involved:
[[M_1^I, M_2^I],[M_1^{II}, M_2^{II}]]

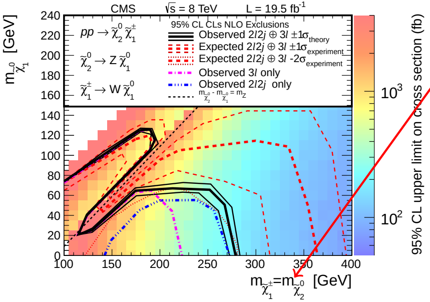
Taking into account Analyses Assumptions

CMS-SUS-13-006: upper limit map of CMS eweakino analysis for TChiWZ model



Taking Into Account Analyses Assumptions

CMS-SUS-13-006: upper limit map of CMS eweakino analysis for TChiWZ model



- **analysis:** masses are assumed to be equal

  $\Downarrow$

  SModelS mass vector:
  $[[m_{\tilde{\chi}_1^\pm}/m_{\tilde{\chi}_2^0},\, m_{\tilde{\chi}_1^0}],[m_{\tilde{\chi}_1^\pm}/m_{\tilde{\chi}_2^0},\, m_{\tilde{\chi}_1^0}]]$

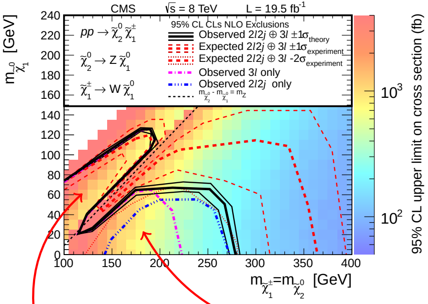
- **analysis:** combined on- and off-shell region
  $\tilde{\chi}^\pm, \tilde{\chi}_2^0 \rightarrow W^{(*)}\tilde{\chi}_1^0, Z^{(*)}\tilde{\chi}_1^0$

  $\Downarrow$

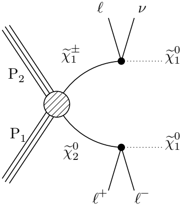
  SModelS constraints:
  only information about final states

Taking Into Account Analyses Assumptions

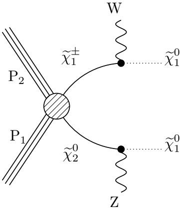
CMS-SUS-13-006: upper limit map of CMS eweakino analysis for TChiWZ model



off-shell:



on-shell:



- **analysis:** masses are assumed to be equal

  $\Downarrow$

  SModelS mass vector:
  $[[m_{\tilde{\chi}_1^\pm}/m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}], [m_{\tilde{\chi}_1^\pm}/m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}]]$

- **analysis:** combined on- and off-shell region

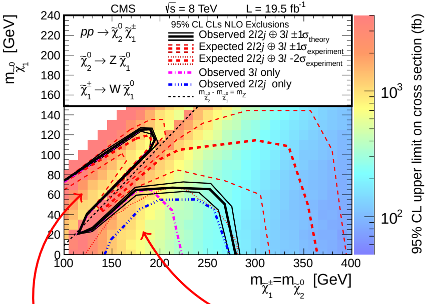
  $\tilde{\chi}^\pm, \tilde{\chi}_2^0 \to W^{(*)}\tilde{\chi}_1^0, Z^{(*)}\tilde{\chi}_1^0$

  $\Downarrow$

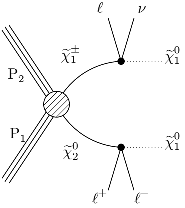
  SModelS constraints:
  only information about final states

Taking Into Account Analyses Assumptions

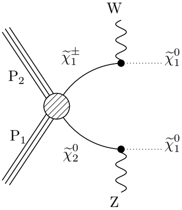
CMS-SUS-13-006: upper limit map of CMS eweakino analysis for TChiWZ model



off-shell:



on-shell:



- **analysis:** masses are assumed to be equal

  $\Downarrow$

  SModelS mass vector: $[[m_{\tilde{\chi}_1^\pm}/m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}], [m_{\tilde{\chi}_1^\pm}/m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}]]$

- **analysis:** combined on- and off-shell region

  $\tilde{\chi}^\pm, \tilde{\chi}_2^0 \to W^{(*)}\tilde{\chi}_1^0, Z^{(*)}\tilde{\chi}_1^0$

  $\Downarrow$

  SModelS constraints: only information about final states $\to$ result described by:

constraint: TChiWZoff

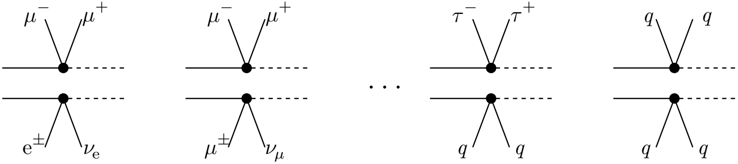
```
71.*(
[[['mu+','mu-']],[['l','nu']]]
+
[[['e+','e-']],[['l','nu']]])
```

constraint: TChiWZ

```
[[['W']],[['Z']]]
```

Decomposition (a minimal example)

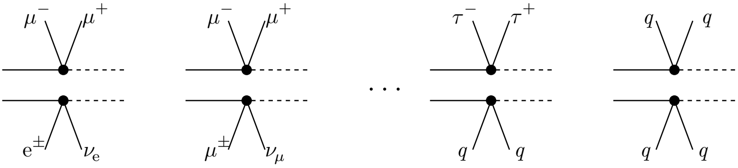
input of full model
SModelS decomposition



$[[[\mu^-, \mu^+]], [[e, \nu]]]$ $[[[\mu^-, \mu^+]], [[\mu, \nu]]]$ ... $[[[\tau^-, \tau^+]], [[q, q]]]$ $[[[q, q]], [[q, q]]]$

Decomposition (a minimal example)

input of full model
SModelS decomposition



$[[[\mu^-, \mu^+]], [[e, \nu]]]$ $[[[\mu^-, \mu^+]], [[\mu, \nu]]]$ ... $[[[\tau^-, \tau^+]], [[q, q]]]$ $[[[q, q]], [[q, q]]]$

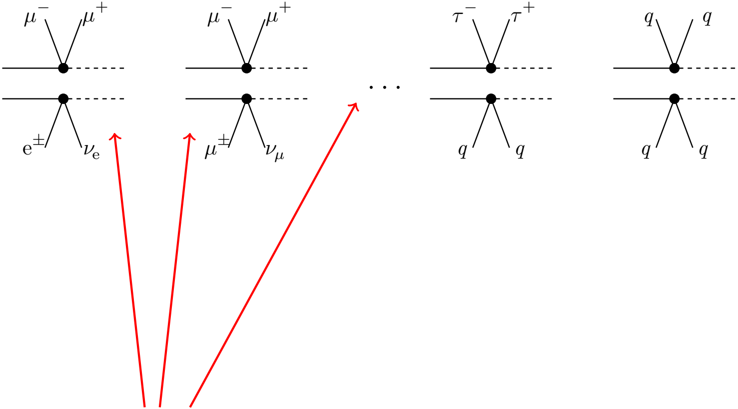
constraint: TChiWZoff

```
71.*(
[[['mu+','mu-']],[['l','nu']]]
+
[[['e+','e-']],[['l','nu']]])
```

RESULTS DATABASE:
CMS eweakino analysis (CMS-SUS-13-006) for TChiWZ

Decomposition (a minimal example)

input of full model
SModelS decomposition



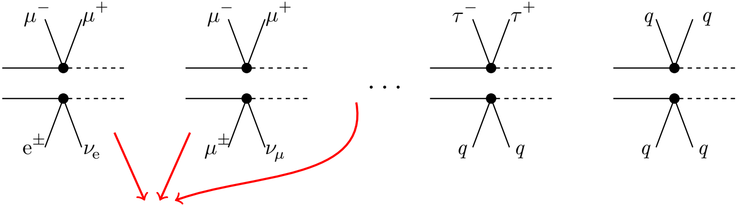
constraint: TChiWZoff

```
71.*(
[[['mu+','mu-']],[['l','nu']]]
+
[[['e+','e-']],[['l','nu']]])
```

RESULTS DATABASE:
CMS eweakino analysis (CMS-SUS-13-006) for TChiWZ

Decomposition (a minimal example)

input of full model
SModelS decomposition



$$\frac{(\sigma \times BR)_{theory}}{(\sigma \times BR)_{UL}} \begin{cases} > 1 \\ < 1 \end{cases}$$

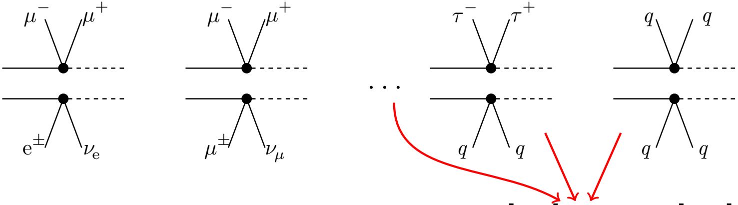
constraint: TChiWZoff

```
71.*(
[[['mu+','mu-']],[['l','nu']]]
+
[[['e+','e-']],[['l','nu']]])
```

RESULTS DATABASE:
CMS eweakino analysis (CMS-SUS-13-006) for TChiWZ

Decomposition (a minimal example)

input of full model
SModelS decomposition



$$\frac{(\sigma \times BR)_{theory}}{(\sigma \times BR)_{UL}} \begin{cases} > 1 \\ < 1 \end{cases}$$

missing topologies

```
[[[tau,tau]],[[jet,jet]]]
[[[jet,jet]],[[jet,jet]]]
```

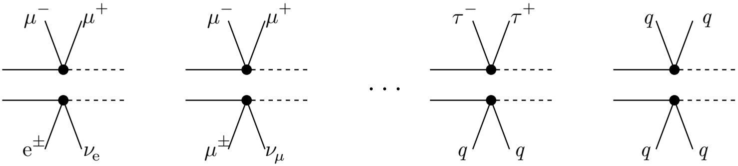
constraint: TChiWZoff

```
71.*(
[[['mu+','mu-']],[['l','nu']]]
+
[[['e+','e-']],[['l','nu']]])
```

RESULTS DATABASE:
CMS eweakino analysis (CMS-SUS-13-006) for TChiWZ

Decomposition (a minimal example)

input of full model
SModelS decomposition



$$\frac{(\sigma \times BR)_{theory}}{(\sigma \times BR)_{UL}} \begin{cases} > 1 \\ < 1 \end{cases}$$

excluded - not excluded

missing topologies

```
[[[tau,tau]],[[jet,jet]]]
[[[jet,jet]],[[jet,jet]]]
```

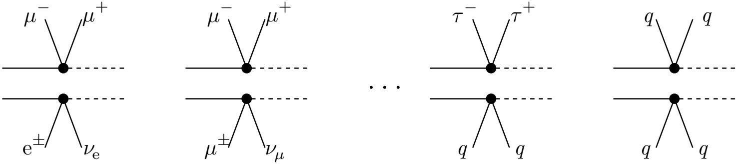
constraint: TChiWZoff

```
71.*(
[[['mu+','mu-']],[['l','nu']]]
+
[[['e+','e-']],[['l','nu']]])
```

RESULTS DATABASE:
CMS eweakino analysis (CMS-SUS-13-006) for TChiWZ

Decomposition (a minimal example)

input of full model
SModelS decomposition



$$\frac{(\sigma \times BR)_{theory}}{(\sigma \times BR)_{UL}} \begin{cases} > 1 \\ < 1 \end{cases}$$

excluded - not excluded

missing topologies

```
[[[tau,tau]],[[jet,jet]]]
[[[jet,jet]],[[jet,jet]]]
```

blind spots

constraint: TChiWZoff

```
71.*(
[[['mu+','mu-']],[['l','nu']]]
+
[[['e+','e-']],[['l','nu']]])
```

RESULTS DATABASE:
CMS eweakino analysis (CMS-SUS-13-006) for TChiWZ

Why investigating a Low Fine Tuning Scenario?

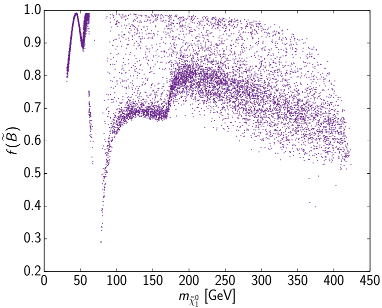
- **fine tuning** = parameter must be chosen very carefully to predict "right value" for observable
  e.g. electroweak symmetry breaking in pMSSM ⇒
  tension between masses of stop, lightest Higgs and Z boson
  ⇒ $\boldsymbol{m_{\tilde{t}_1}}$, $\boldsymbol{m_{\tilde{g}}}$, $\boldsymbol{\mu}$ should be light
- finely tuned theory seems **unnatural** ⇒ consensus about **tolerable amount** of fine tuning **grows** with experimental constraints on SUSY particles ⇒
  - Has the parameter space of the pMSSM that could provide LFT model points **already been targeted** by current interpretations of SUSY searches at LHC?
  - How can experimental results be **reinterpreted** in order to improve their applicability on such LFT model points?
  - Which **additional interpretations** may be beneficial in order to probe this region of parameter space in the current $\sqrt{s} = 13$ TeV run of the LHC?

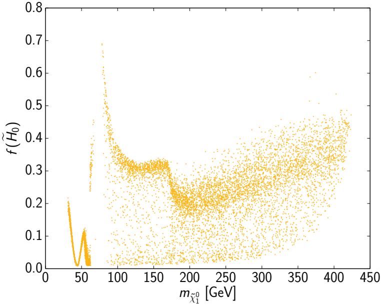
⇒ **investigation of such a scenario using SModelS**

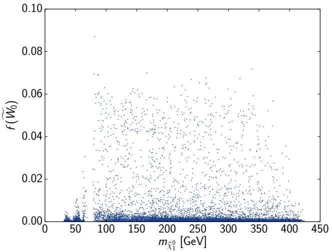
Model Selection

- SLHA files originally created for:
  "pMSSM Studies at the 7, 8 and 14 TeV LHC"
  (arXiv:1307.8444[hep-ph])
- LFT scenario = small **subset of bigger set of randomly generated pMSSM points** subjected to various experimental and theoretical constraints, e.g.
  - "correct" relic density ($\Omega h^2 = 0.1153 \pm 0.095$)
  - "correct" SM Higgs mass ($m_h = 126 \pm 3\ GeV$)
  - low amount of fine tuning better than 1%
    measured by the Ellis-Barbieri-Giudice parameter
- $\mathbf{10.2 \times 10^3}$ **models survived** this selection procedure

Nature of the $\tilde{\chi}_1^0$







- contributions of **wino** can be **neglected**
- generally neutralino is **heavily mixed**
- roughly **60%** of all models have LSP masses below gap $\rightarrow$ **bino LSP around $m_{\tilde{\chi}_1^0} \simeq 50$ GeV**
- **40%** show **bino higgsino mixture** with tendency to higher fractions of bino content
- nature of the LSP determined by the mechanisms to achieve **correct relic density**

Applying SModelS to the LFT Model Set

- calculate **production cross sections** for $\sqrt{s} = 8$ TeV using SModelS' internal **cross section computer** (based on Pythia and NLLfast) $\Rightarrow \sigma_{theory}$
- subject every model point to **decomposition** $\Rightarrow (\sigma \times BR)_{theory}$
- confront it with **full results database** $\Rightarrow (\sigma \times BR)_{UL}$
- interpret **SModelS** output to:
  - sort model points into "**excluded**" and "**not excluded**"

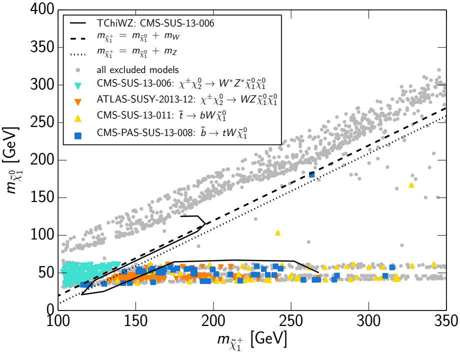
$$\frac{(\sigma \times BR)_{theory}}{(\sigma \times BR)_{UL}} \quad \begin{cases} > 1 & \textit{excluded} \\ < 1 & \textit{not excluded} \end{cases}$$

  - find most **relevant experimental results**
  - find **missing topologies** = signal topologies without experimental constraints $\rightarrow$ sum over all signal topologies described by same constraint $\rightarrow$ information about involved SUSY particles is lost

Investigation of Excluded Models

Which **experimental results** have **highest significance** in the LFT scenario? ⇒ concentrate on the **excluded points**:

- every excluded model point is **projected** onto the respective **mass plane**
- topologies **irrelevant** to a given mass plane are **ignored**
- plots are overlaid with **official exclusion lines** for most relevant results

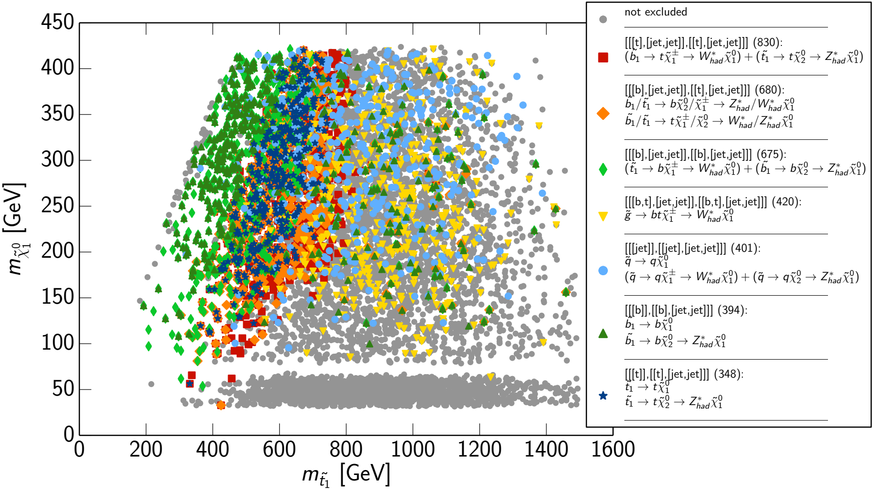


$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ plane

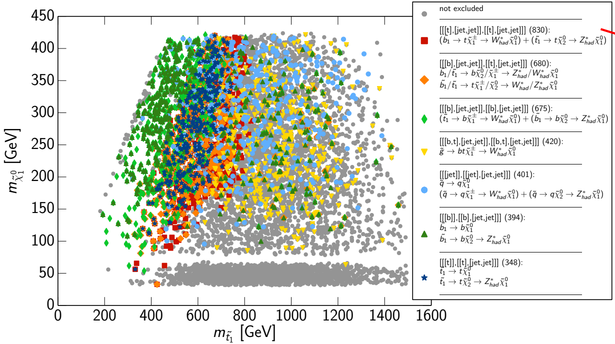
- most interesting topology: **TChiWZ** $(\tilde{\chi}^\pm, \tilde{\chi}_2^0 \to W\tilde{\chi}_1^0, Z\tilde{\chi}_1^0)$
- kinematic edge for W (Z) boson indicated by dashed (dotted) line
- W/Z on-shell:
  ATLAS *3 leptons* $(e, \mu, \tau) + \not{E}_T$
- W/Z off-shell:
  CMS *EW productions with decays to leptons, W, Z and Higgs*

Constraining Mass of $\tilde{t}$ – Missing Topologies

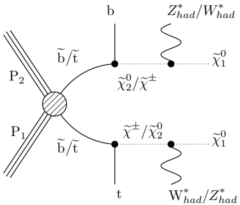
- most frequent topologies in $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ plane
- relevant topologies show correlation with $m_{\tilde{t}_1}$



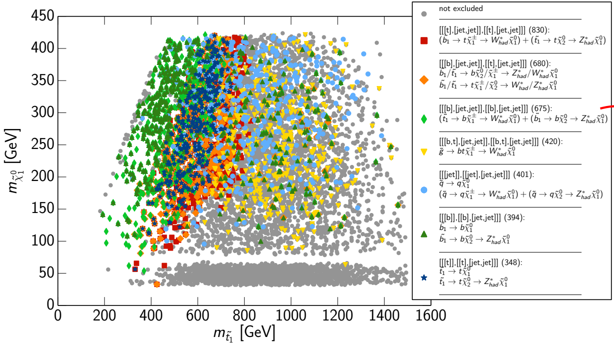
Constraining Mass of $\tilde{t}$ – Missing Topologies



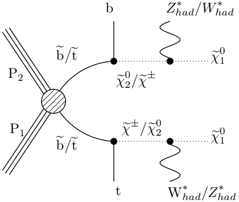
[[[b], [jet, jet]], [[t], [jet, jet]]]



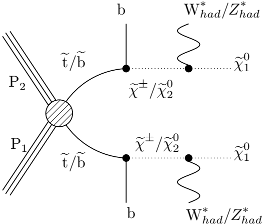
Constraining Mass of $\tilde{t}$ – Missing Topologies



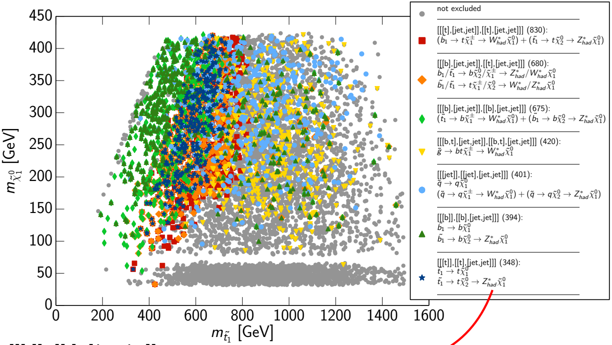
$[[[b],[jet,jet]],[[t],[jet,jet]]]$



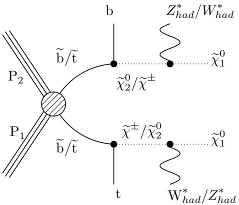
$[[[b],[jet,jet]],[[b],[jet,jet]]]$



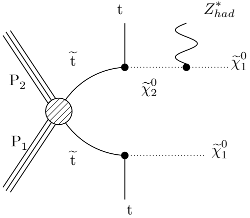
Constraining Mass of $\widetilde{t}$ – Missing Topologies



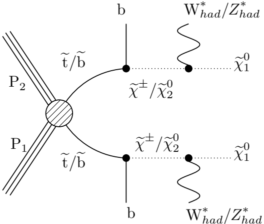
$[[[b], [jet, jet]], [[t], [jet, jet]]]$



$[[[t]], [[t], [jet, jet]]]$



$[[[b], [jet, jet]], [[b], [jet, jet]]]$



Summary of Findings

- current SMS interpretations of experimental SUSY searches are of **limited suitability** in LFT scenario ⇒ only 22% of all points excluded
- model set dominated by various eweakino decays producing mostly **hadronically decaying W, Z** and **Higgs** bosons
- final states of **gluino decays** with tops, bottoms and $W^{(*)}$
- symmetric and asymmetric **stop or sbottom topologies**
- general assertions for future interpretations:
  - gluino decays with **non-decoupled** third generation squarks and vice versa
  - **hadronic off-shell** regime for SM vector bosons (events with multiple jets, zero-leptons and MET)

Summary of Findings

- current SMS interpretations of experimental SUSY searches are of **limited suitability** in LFT scenario ⇒ only 22% of all points excluded
- model set dominated by various eweakino decays producing mostly **hadronically decaying W, Z** and **Higgs** bosons
- final states of **gluino decays** with tops, bottoms and $W^{(*)}$
- symmetric and asymmetric **stop or sbottom topologies**
- general assertions for future interpretations:
  - gluino decays with **non-decoupled** third generation squarks and vice versa
  - **hadronic off-shell** regime for SM vector bosons (events with multiple jets, zero-leptons and MET)

Summary of Findings

- current SMS interpretations of experimental SUSY searches are of **limited suitability** in LFT scenario ⇒ only 22% of all points excluded
- model set dominated by various eweakino decays producing mostly **hadronically decaying W, Z** and **Higgs** bosons
- final states of **gluino decays** with tops, bottoms and $W^{(*)}$
- symmetric and asymmetric **stop or sbottom topologies**
- general assertions for future interpretations:
  - gluino decays with **non-decoupled** third generation squarks and vice versa
  - **hadronic off-shell** regime for SM vector bosons (events with multiple jets, zero-leptons and MET)

Summary of Findings

- current SMS interpretations of experimental SUSY searches are of **limited suitability** in LFT scenario $\Rightarrow$ only 22% of all points excluded
- model set dominated by various eweakino decays producing mostly **hadronically decaying W, Z** and **Higgs** bosons
- final states of **gluino decays** with tops, bottoms and $W^{(*)}$
- symmetric and asymmetric **stop or sbottom topologies**
- general assertions for future interpretations:
  - gluino decays with **non-decoupled** third generation squarks and vice versa
  - **hadronic off-shell** regime for SM vector bosons (events with multiple jets, zero-leptons and MET)

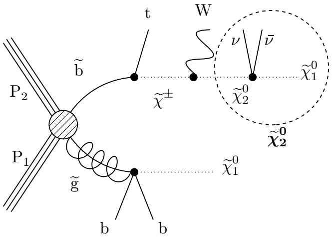
Summary of Findings

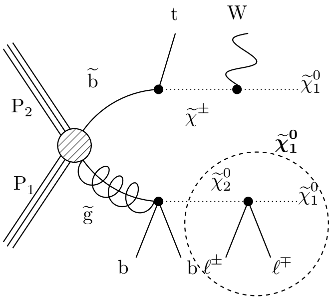
- current SMS interpretations of experimental SUSY searches are of **limited suitability** in LFT scenario $\Rightarrow$ only 22% of all points excluded
- model set dominated by various eweakino decays producing mostly **hadronically decaying W, Z** and **Higgs** bosons
- final states of **gluino decays** with tops, bottoms and $W^{(*)}$
- symmetric and asymmetric **stop or sbottom topologies**
- general assertions for future interpretations:
  - gluino decays with **non-decoupled** third generation squarks and vice versa
  - **hadronic off-shell** regime for SM vector bosons (events with multiple jets, zero-leptons and MET)

THANKS FOR YOUR ATTENTION!

BACK UP

Compression (invisible decays and soft final states)





invisible decays

- $m_{\tilde{\chi}_1^0}$ replaced by $m_{\tilde{\chi}_2^0}$
- $[[[t],[W],[\nu,\bar{\nu}]],[[b,b]]]$ replaced by $[[[t],[W]],[[b,b]]]$
- must occur at end of decay chain, no visible particle after the invisible one

soft final states

- if two BSM states can be seen as quasi degenerate
- energy of the SM particles produced is negligibly small from experimental point of view
- decay will be completely ignored and topology will be replaced by a simpler one

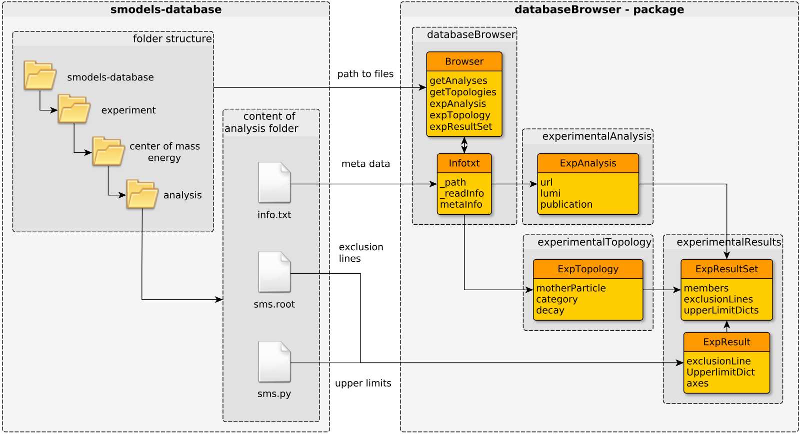
List of ATLAS Analyses

ID	*short description*	*L*	*Tx names*
ATLAS-SUSY-2013-02	0 leptons + 2–6 jets + $\not{E}_T$	20.3	T1, T2
ATLAS-SUSY-2013-04	0 leptons + $\geq$7–10 jets + $\not{E}_T$	20.3	T1tttt
ATLAS-SUSY-2013-05	0 leptons + 2 b-jets + $\not{E}_T$	20.1	T2bb
ATLAS-SUSY-2013-11	2 leptons (e, μ) + $\not{E}_T$	20.3	TChiWZ, TSlepSlep
ATLAS-SUSY-2013-12	3 leptons (e, μ, τ) + $\not{E}_T$	20.3	TChiWH, TChiWZ(off)
ATLAS-SUSY-2013-14	2 taus + $\not{E}_T$	20.3	TStauStau
ATLAS-SUSY-2013-15	1 lepton + 4(1 b-)jets + $\not{E}_T$	20.3	T2tt, T2bbWW
ATLAS-SUSY-2013-19	2 leptons + (b)jets + $\not{E}_T$	20.3	T2tt, T2bbWW, T6bbWW
ATLAS-CONF-2012-105	2 SS leptons + $\geq$4 jets + $\not{E}_T$	5.7	T1tttt
ATLAS-CONF-2013-007	2 SS leptons + 0–3 b-jets + $\not{E}_T$	20.7	T1tttt
ATLAS-CONF-2013-024	0 lepton + 6 (2 b-)jets + $\not{E}_T$	20.5	T2tt
ATLAS-CONF-2013-061	0–1 leptons + $\geq$3 b-jets + $\not{E}_T$	20.1	T1bbbb, T1tttt
ATLAS-CONF-2013-065	2 leptons + (b)jets + $\not{E}_T$	20.3	T2tt

List of CMS Analyses

ID	*short description*	*L*	*Tx names*
CMS-SUS-12-024	0 leptons + $\geq$3(1 b-)jets + $\not{E}_T$	19.4	T1bbbb, T1tttt(off), T5tttt
CMS-SUS-12-028	jets + $\not{E}_T$, α_T	11.7	T1, T1bbbb, T1tttt, T2, T2bb
CMS-SUS-13-002	$\geq$3 leptons (+jets) + $\not{E}_T$	19.5	T1tttt
CMS-SUS-13-006	EW productions with decays to leptons, W, Z, and Higgs	19.5	TChiWZ(off), TSlepSlep, TChiChipmSlepL, TChiChipmSlepStau
CMS-SUS-13-007	1 lepton + $\geq$2 b-jets + $\not{E}_T$	19.3	T1tttt(off)
CMS-SUS-13-011	1 lepton + $\geq$4(1 b-)jets + $\not{E}_T$	19.5	T2tt, T6bbWW
CMS-SUS-13-012	jet multiplicity + $\not{H}_T$	19.5	T1, T1tttt(off), T2
CMS-SUS-13-013	2 SS leptons + (b-)jets + $\not{E}_T$	19.5	T1tttt(off),
CMS-PAS-SUS-13-008	3 leptons + (b)jets + $\not{E}_T$	19.5	T6ttWW, T1tttt
CMS-PAS-SUS-13-016	2 OS leptons + $\geq$4(2b-)jets + $\not{E}_T$	19.7	T1tttt(off)
CMS-PAS-SUS-13-018	1–2 b-jets + $\not{E}_T$, M_{CT}	19.4	T2bb
CMS-PAS-SUS-13-019	hadronic M_{T2}	19.5	T1, T1bbbb, T1tttt(off), T2, T2tt, T2bb
CMS-PAS-SUS-14-011	razor with b-jets	19.3	T1bbbb, T1tttt(off), T2tt

databaseBrowser



`databaseBrowser` = object oriented python package to access the results database

suitable as command line tool and as part of **SModelS**

What is natural?

good physical theory should be "natural" $\Rightarrow$ What is natural?
$\Rightarrow$ theories which require finely tuned parameters seem to be unnatural

hierarchy problem: Yukawa coupling of fermion to the Higgs $\Rightarrow$ squared mass of the Higgs boson at one loop level $\Rightarrow$ naive characterisation of naturalness:

$$m_h^2 \approx m_{h\,bare}^2 - Y_f^2 \Lambda^2 \xrightarrow{\Lambda \approx M_{Planck}} \mathcal{N} = \frac{\delta m_h^2}{m_h^2} \approx 10^{34}$$

$\Rightarrow$ finely tuned cancellation is cured by SUSY up to logarithmic term

tolerable amount of fine tuning is very subjective quantity $\Rightarrow$ objective definition of fine tuning = Ellis-Barbieri-Giudice measure

$$\Delta = \left| \frac{p}{O(p)} \; \frac{\partial O(p)}{\partial p} \right|$$

effect of variation of parameter p on observable $O(p)$:
for large Δ a small change in p results in a severe change in O

$\Rightarrow$ p has to be tuned very carefully

Low Fine Tuning in the pMSSM

SUSY = natural solution to hierarchy problem but causes further fine tuning

"little hierarchy problem": in pMSSM SUSY is explicitly broken at weak scale
$\Rightarrow$ two different types of mass terms in Higgs potential

1. SUSY preserving mass parameter $|\mu|^2$
2. soft masses for both Higgs doublets $m^2_{H_u}$ and $m^2_{H_d}$

$\Rightarrow$ tree level relation

$$m_Z^2 \approx \frac{m^2_{H_d} - m^2_{H_u} \tan\beta}{\tan^2\beta - 1} - |\mu|^2$$

1. Higgs doublets mix to form mass eigenstates $\Rightarrow$ lightest neutral scalar h_0 needs positive corrections with dominant contributions from stops

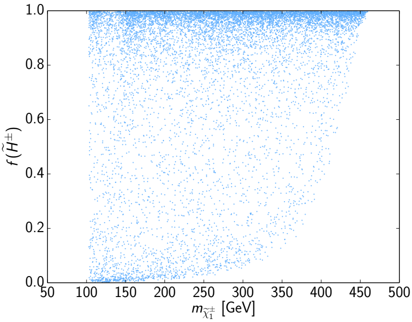
$$\delta m^2_{h_0} \propto Y_t \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

2. leading contributions to m_{H_u} and m_{H_d} arise from Yukawa interactions of stops

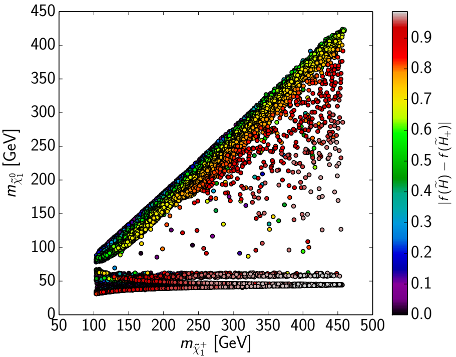
$\Rightarrow$ tension between the masses of the stop, the lightest Higgs and the Z boson

$\Rightarrow$ potential fine tuning in pMSSM e.g. soft higgs mass parameters, the mass of the stop, the mixing in the stop sector etc.

Nature of the $\widetilde{\chi}^{\pm}$ and the electroweak sector

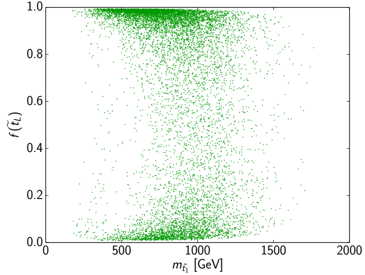


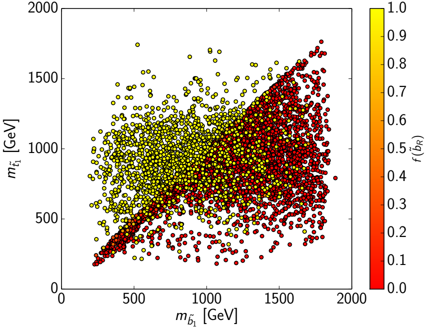
- lower bound on $m_{\widetilde{\chi}_1^{\pm}}$ is given by the LEP limit $m_{\widetilde{\chi}_1^{\pm}} > 103.5$ GeV
- 60% have a $\widetilde{\chi}_1^{\pm}$ with $f(\widetilde{\mathrm{H}}^{\pm}) > 0.9$
- rest of models have mostly higgsino like $\widetilde{\chi}_1^{\pm}$
- infrequently models provide wino like chargino



- light higgsino parameter $\mu \Rightarrow$ degenerate $m_{\widetilde{\chi}_1^0}$, $m_{\widetilde{\chi}_2^0}$ and $m_{\widetilde{\chi}_1^{\pm}}$
- eweakinos in diagonal region controlled by the μ parameter
- off diagonal region ($m_{\widetilde{\chi}_1^0} \simeq 50$ GeV) neutralino $\approx$ 100% bino
- difference between the higgsino fractions of $\widetilde{\chi}_1^0$ and $\widetilde{\chi}_1^{\pm}$ is minimised at diagonal

Nature of $\tilde{t}$ and $\tilde{b}$



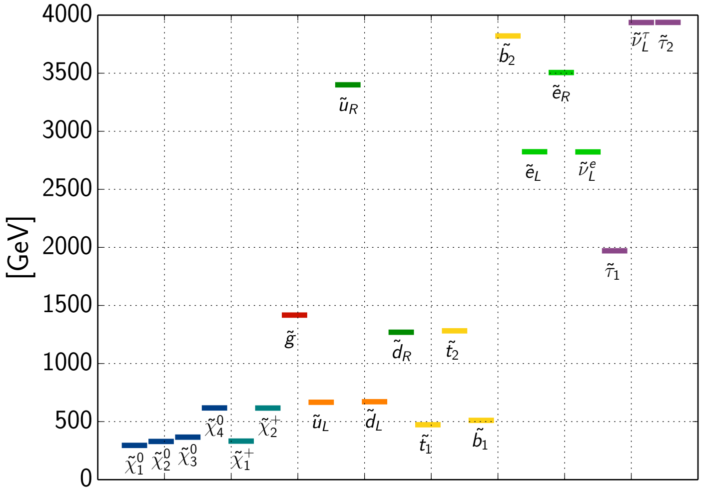


- **stops are relatively light** in the LFT scenario
- $\boldsymbol{\tilde{t}_1}$ is **mostly left handed** for the bigger part of the models

- **LH stops and sbottoms** are enclosed in an $SU(2)$ doublet $\Rightarrow$ are **close in mass** in case $\tilde{b}_1$ is also mostly left handed

- $\boldsymbol{\tilde{b}_1}$ in a pure **gauge eigenstate**
- **80%** of all models have a **light sbottom** that is **left handed** to more than 90%
- clearly RH for $m_{\tilde{b}_1} < m_{\tilde{t}_1}$

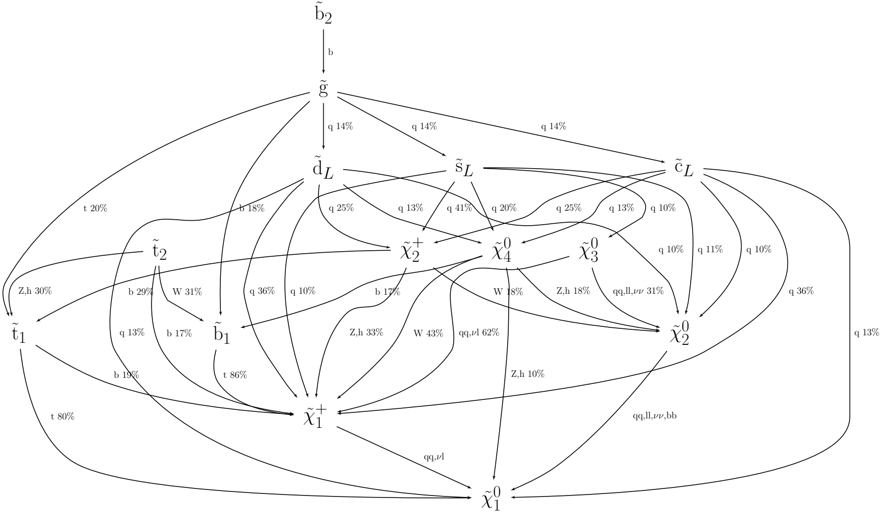
Typical Mass Spectrum of LFT Model Points



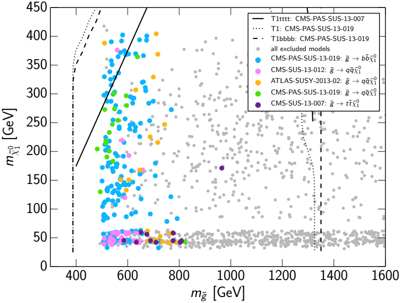
Typical Decay Pattern of LFT Model Points

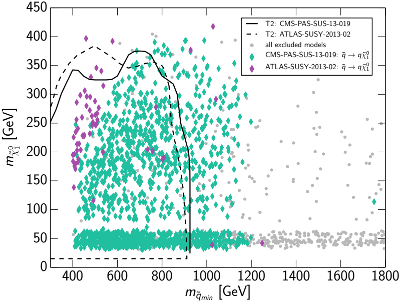
generated with **SModelS walkding for the pMSSM model**

http://smodels.hephy.at/online/pmssm.py



Investigation of Excluded Models





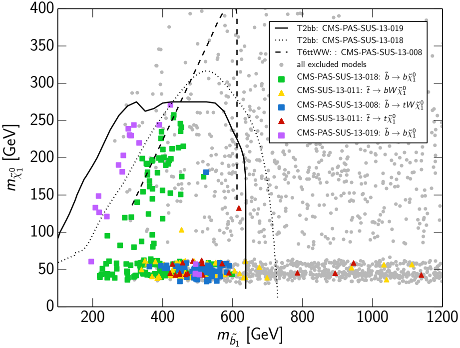
$m_{\tilde g} - m_{\tilde\chi^0_1}$ plane

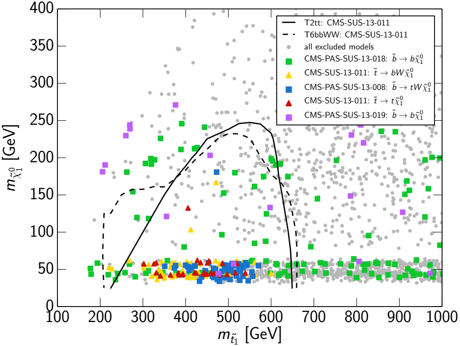
- most constraining analyses are **CMS**: *hadronic M_{T2}* and *1 lepton + ≥2 b-jets + $\not\!\!E_T$* for gluino decays (T1, T1tttt and T1bbbb)
- excluded region **way below** official exclusions
- in LFT: typical masses and BR favour gluino decays via on-shell stops and sbottoms ⇒ nearly **no T1tttt**

$m_{\tilde q_{min}} - m_{\tilde\chi^0_1}$ plane

- most constraining: T2 ($\tilde q \to q\tilde\chi^0_1$) results from **CMS** *hadronic M_{T2}* and **ATLAS** *0 leptons + 2–6 jets + $\not\!\!E_T$*
- both analyses assume **mass degenerate squarks** and **decoupled gluinos**
- in LFT **over-exclusion** because:
  - gluinos not decoupled ⇒ increasing $\sigma(\tilde q)$
  - squarks not degenerate ⇒ $m_{\tilde q_{min}}$

Investigation of Excluded Models ($m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0}$ and $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ plane)

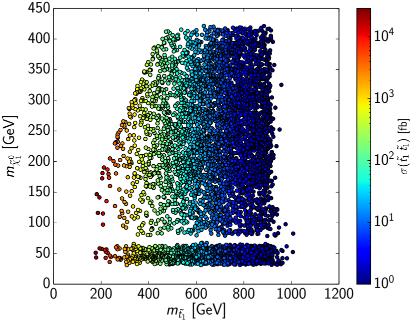


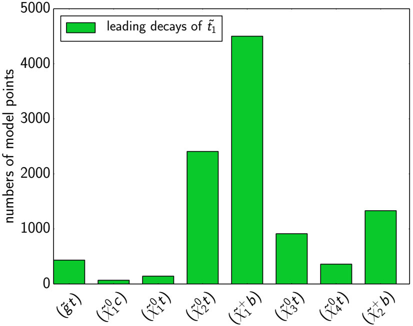


under-exclusion for stops

Stops (production and decay)

roughly **1%** of the LFT models can be **excluded by** applying **stop results** (T2tt and T6bbWW) $\rightarrow$ **Why?**
$\Rightarrow$ **check model set**:

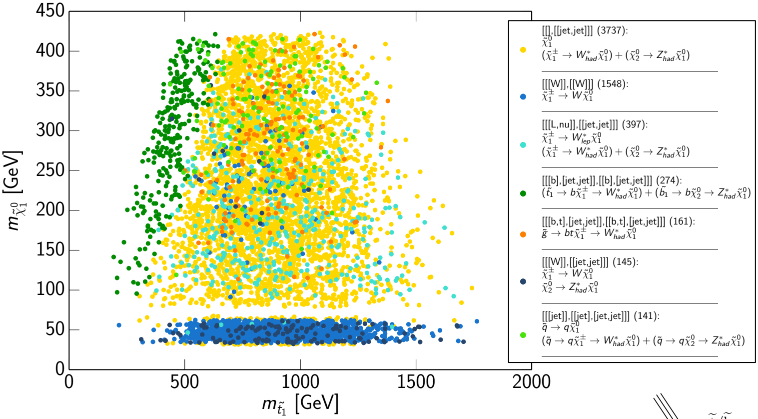




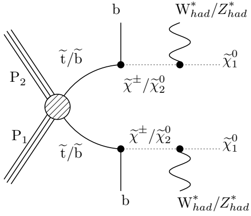
- $\sigma_{production}$ for stop pair production $\Rightarrow$ comparable to CMS reference cross sections
- number of models for most relevant decay channels

$\Rightarrow$ **check missing topologies**

Stops (Missing Topologies With Highest Weight)

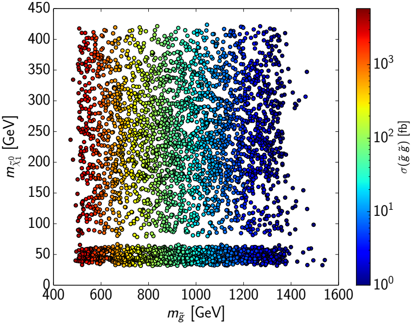


- **interpretation** of missing topologies is **not straight forward** $\Rightarrow$ first step: missing topology with **highest ($\sigma \times BR$)** for not excluded points
- for missing topologies **information about BSM masses is lost** $\Rightarrow$ may comprise **several decays** with the same signature
- interesting signatures show **correlation with mass** of the stop: $[[[b],[jet,jet]],[[b],[jet,jet]]]$

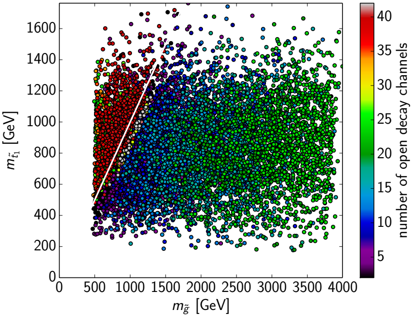


Gluinos (production and decay)

gluino exclusion way below ATLAS and CMS exclusions → one reason: common SMS results assume squarks decoupled but they are not in LFT scenario ⇒ **check model set**:



$\sigma > 1$ *fb in* $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$ *plane*

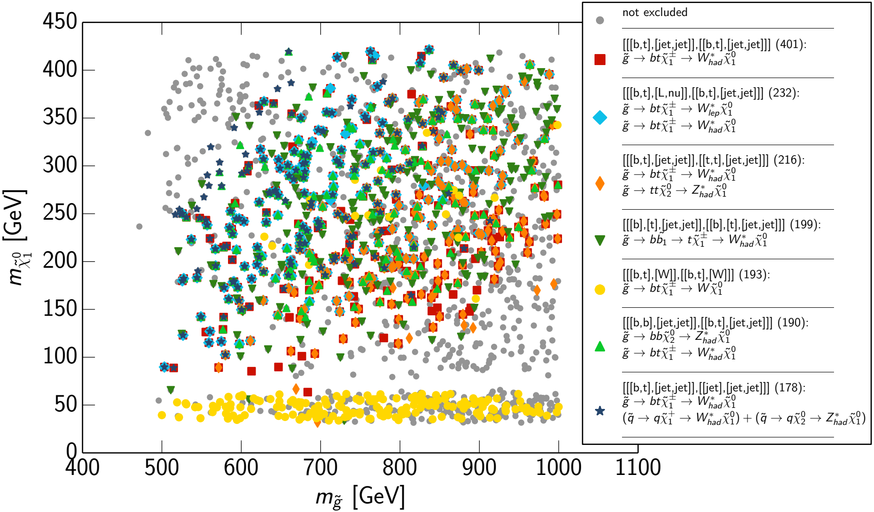


number of gluino decays in $m_{\tilde{g}} - m_{\tilde{t}_1}$ *plane*
(white line marks kinematic edge $m_{\tilde{g}} = m_{\tilde{t}_1}$*)*

- additional production channels may **increase** $\boldsymbol{\sigma}$
- slight preponderance above CMS reference cross sections but **can be neglected**

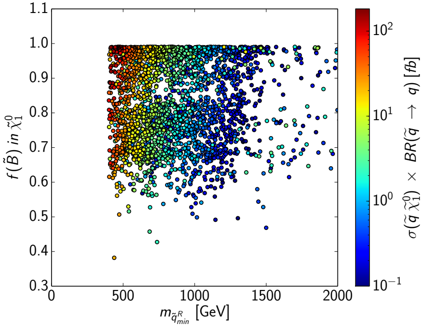
- **increases number of possible decay channels** (decays of gluinos via on-shell squarks are always favoured)

Gluinos (Most Frequent Missing Topologies)

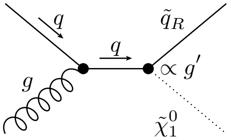


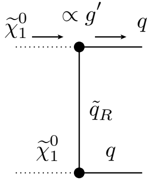
- complex decay patterns ⇒ **weights** for individual gluino topologies are **rather low** and often restricted to small regions
- interesting decay channel: $\tilde{\mathbf{g}} \to \mathbf{bt}\tilde{\chi}^\pm$ (T5btbtWW or T7btbtWW)

Monojet



($\sigma \times BR$) as function of **minimal RH squark mass** and **bino content of LSP** $f(\widetilde{\mathrm{B}})$





- missing topology characterised by **single hadronic jet and MET** final state
- co-production of a RH light flavoured **squark and bino neutralino**
- associated productions of strongly and weakly coupling sparticles $\to$ surprisingly it occurs in roughly **60% of all LFT model points**
- vertex in Feynman graphs of production controlled by **coupling** $\propto \boldsymbol{g'}$ (coupling constant of $U(1)_Y$)
- **annihilation processes of DM**: squark mediated annihilation mode in early universe (before freeze-out)
  $\Rightarrow$ if monojet signature would be found at LHC
  $\Rightarrow$ by measuring its coupling strength information about **nature of LSP and its thermal relic**