

Constraining Exotic Signatures Using Simplified Models

André Lessa



São Paulo, Brazil

SUSY 2016

Melbourne, July 7th, 2016

Work done in collaboration with J. Heisig and L. Quertenmoint - *JHEP 1512 (2015) 087*

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**Exotic for CMS, but not ATLAS!*

Simplified Models Results@ LHC

- There is a continuous effort from the experimental collaborations to present/interpret LHC results on BSM physics in terms of **Simplified Models (SMS)**:

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2016

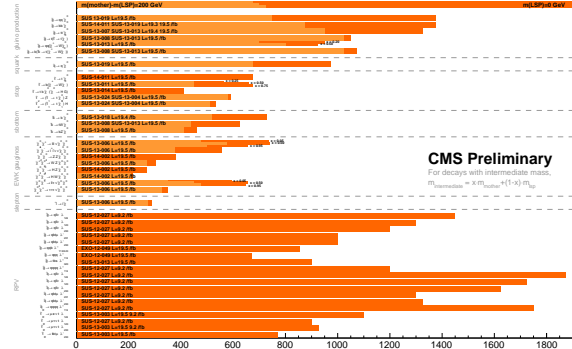
Model	$\epsilon, \mu, \tau, \gamma$	Jets	E_{miss}^{min}	$L_{int} d(\text{fb}^{-1})$	Mass limit	
Inclusive Searches	MSUGRA/CMSSM	0-3 e, μ, τ	2-10 jets	Yes	20.3	
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0	2-6 jets	Yes	3.2	
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}$ (compressed)	mono-jet	1-3 jets	Yes	3.2	
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}(\tilde{\nu}_\tau/\tilde{\nu}_\tau)$	2 e, μ (opt-Z)	2 jets	Yes	2.0	
	$\tilde{g}, \tilde{t} \rightarrow t\tilde{g}$	0	2-6 jets	Yes	3.2	
	$\tilde{g}, \tilde{t} \rightarrow t\tilde{q}\tilde{q}$	1 e, μ	2-6 jets	Yes	3.0	
	$\tilde{g}, \tilde{t} \rightarrow t\tilde{q}\tilde{q}(\tilde{\nu}_\tau/\tilde{\nu}_\tau)$	2 e, μ	0-3 jets	Yes	2.0	
	$\tilde{g}, \tilde{b} \rightarrow b\tilde{g}$	0	7-10 jets	Yes	3.2	
	GMSB (\tilde{t} NLSP)	1-2 + 0-1 f	0-2 jets	Yes	20.3	
	GGM (bino NLSP)	2 γ	Yes	20.3	3.2	
3 rd gen. squarks direct production	GGM (higgsino-bino NLSP)	1 b	Yes	20.3	3.2	
	GGM (higgsino-bino NLSP)	2 γ	2 jets	Yes	20.3	3.2
	GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	3.2
	Gravitino LSP	0	mono-jet	Yes	20.3	3.2
	$\tilde{g}, \tilde{b} \rightarrow b\tilde{g}$	0	3-6	Yes	3.0	
	$\tilde{g}, \tilde{b} \rightarrow b\tilde{q}\tilde{q}$	0-1 e, μ	3-6	Yes	3.0	
	$\tilde{g}, \tilde{b} \rightarrow b\tilde{q}\tilde{q}$	0	3-6	Yes	20.1	
	$\tilde{t}, \tilde{b}, \tilde{b} \rightarrow b\tilde{t}$	0	2-6	Yes	3.2	
	$\tilde{t}, \tilde{b}, \tilde{b} \rightarrow b\tilde{q}\tilde{q}$	2 e, μ (SS)	0-3-6	Yes	3.2	
	$\tilde{t}, \tilde{b}, \tilde{b} \rightarrow b\tilde{q}\tilde{q}$ or $\tilde{q}\tilde{q}$	1-2 e, μ	1-2-6	Yes	4.7-20.3	
EW direct	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ (natural GMSB)	2 e, μ (Z)	0-2 jets	2-6	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ (natural GMSB)	2 e, μ (Z)	1-6	Yes	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ (natural GMSB)	2 e, μ (Z)	3-6	1-6	Yes	20.3
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ (natural GMSB)	1 e, μ	3 jets + 2 b	Yes	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ (natural GMSB)	1 e, μ	3 jets + 2 b	Yes	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ (natural GMSB)	2 e, μ	0	Yes	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ (natural GMSB)	2 e, μ	0	Yes	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ (natural GMSB)	2 e, μ	0	Yes	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ (natural GMSB)	2 e, μ	0	Yes	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ (natural GMSB)	2 e, μ	0	Yes	20.3	
Long-lived particles	Direct \tilde{t}, \tilde{t} prod., long-lived \tilde{t}	Disapp. tk	1 jet	Yes	20.3	
	Direct \tilde{t}, \tilde{t} prod., long-lived \tilde{t}	0E/dx tk	-	Yes	18.4	
	Stable, stop-produced \tilde{t} -hadron	0	1-10 jets	Yes	27.0	
	Metastable \tilde{t} -hadron	0E/dx tk	-	-	3.2	
	GMSB, stable \tilde{t} ($\tilde{t} \rightarrow \tilde{t}, \tilde{b}, \tilde{q}, \tilde{q}, \tilde{q}, \tilde{q}$)	1 b	-	-	19.1	
	GMSB, $\tilde{t} \rightarrow \tilde{t}, \tilde{q}, \tilde{q}$, long-lived \tilde{t}	2 γ	-	-	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ (natural GMSB)	disapp. $\nu_\tau/\tilde{\nu}_\tau$	-	-	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ (natural GMSB)	disapp. $\nu_\tau/\tilde{\nu}_\tau$	-	-	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ (natural GMSB)	disapp. $\nu_\tau/\tilde{\nu}_\tau$	-	-	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ (natural GMSB)	disapp. $\nu_\tau/\tilde{\nu}_\tau$	-	-	20.3	
RPV	LFV $\tilde{g}\tilde{g} \rightarrow \tilde{b}, \tilde{t}, \tilde{q}, \tilde{q}, \tilde{q}, \tilde{q}$	disapp. $\nu_\tau/\tilde{\nu}_\tau$	-	-	20.3	
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3-6	Yes	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ ($\tilde{t} \rightarrow W\tilde{t}, \tilde{t} \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}$)	4 e, μ	-	Yes	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ ($\tilde{t} \rightarrow W\tilde{t}, \tilde{t} \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}$)	3 $e, \mu + \tau$	-	Yes	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ ($\tilde{t} \rightarrow W\tilde{t}, \tilde{t} \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}$)	0	6-7 jets	-	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ ($\tilde{t} \rightarrow W\tilde{t}, \tilde{t} \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}$)	0	6-7 jets	-	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ ($\tilde{t} \rightarrow W\tilde{t}, \tilde{t} \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}$)	2 e, μ (SS)	0-3-6	Yes	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ ($\tilde{t} \rightarrow W\tilde{t}, \tilde{t} \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}$)	0	2 jets + 2 b	-	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ ($\tilde{t} \rightarrow W\tilde{t}, \tilde{t} \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}$)	2 e, μ	2-6	-	20.3	
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{t}$ ($\tilde{t} \rightarrow W\tilde{t}, \tilde{t} \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}$)	2 e, μ	2-6	-	20.3	
Other	Scalar charm, $\tilde{b} \rightarrow b\tilde{t}$	0	2 c	Yes	20.3	

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13$ TeV

Reference

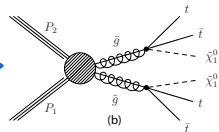
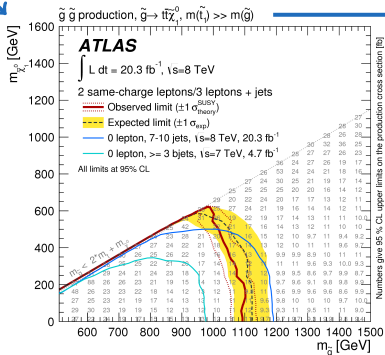
Summary of CMS SUSY Results* in SMS framework ICHEP 2014



*Observed limits, theory uncertainties not included
 Only a selection of available mass limits
 Probe "up to" the quoted mass limit

Simplified Models Results @ LHC

3 rd gen. R med.	$\tilde{g}\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	3.3	\tilde{g}	1.78 TeV	$m(\tilde{t}_1) < 800$ GeV	ATLAS-CONF-2015-067 To appear 1407.0600
	$\tilde{g}\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	3.3	\tilde{g}	1.76 TeV	$m(\tilde{t}_1) = 0$ GeV	
	$\tilde{g}\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	\tilde{g}	1.37 TeV	$m(\tilde{t}_1) < 300$ GeV	



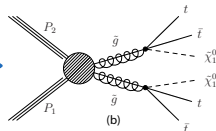
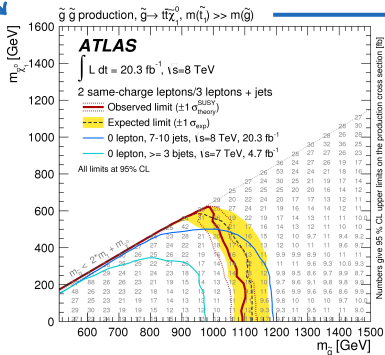
Simplified Model $\sim \mathcal{L}_{\text{eff}}$, where...

- ▶ Particles not appearing in the process are decoupled
- ▶ Masses are free parameters
- ▶ $\sigma \times BR$ is a free parameter

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To appear
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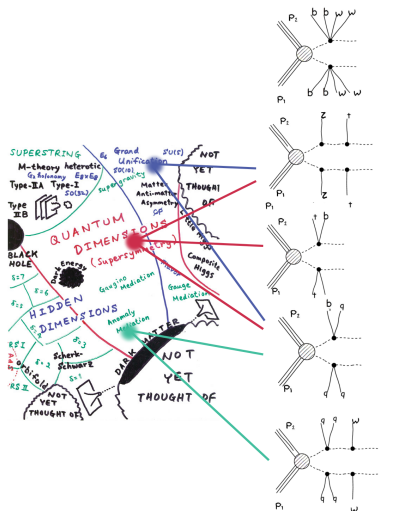
*Exclusion curve:

$\sigma(M_1, M_2, \dots) \times BR$ is fixed!

→ Rarely matches any full BSM model

Why Simplified Models?

Simplified Models (SMS) Philosophy:



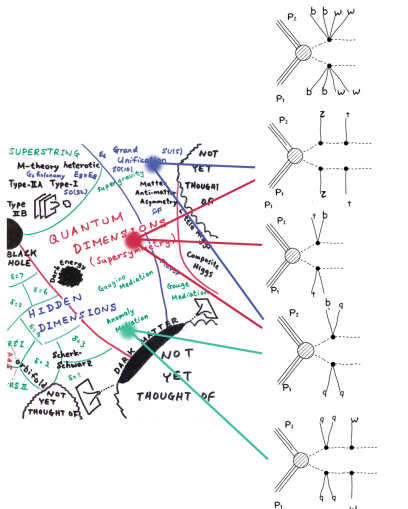
Large Number of
Full Models

Smaller Number of
Simplified Models

- SMS parametrize possible model signatures with few parameters:
 - ▶ BSM masses
 - ▶ SM final states
 - ▶ Decay topology, ...
- Allow to recast model interpretations
- Include several approximations (spins, interference,...)
 - ▶ *Suitable for inclusive searches*

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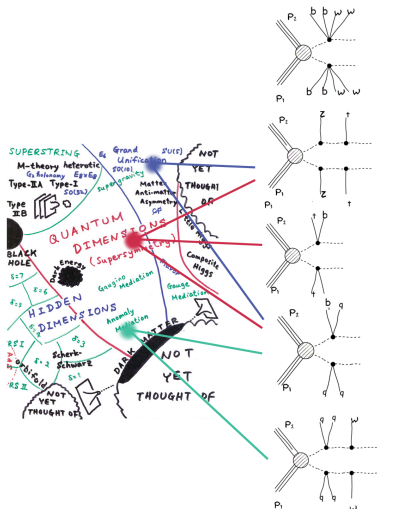
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Public tools for recasting SMS limits:

Fastlim, **SModels**

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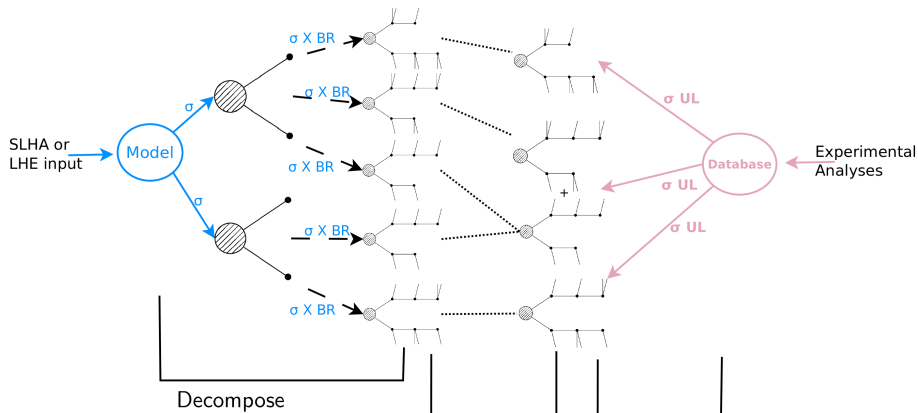
Fastlim, **SModels**

A few words about SModels...

SModels Overview

SModels basic idea:

(see F. Ambrogio's talk)



* No MC simulation required

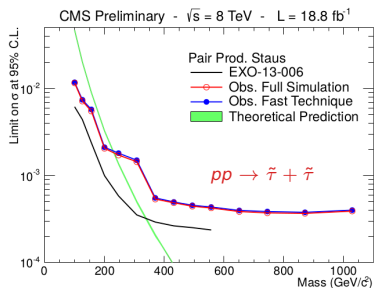
* Comprehensive number of experimental constraints

Simplified Models and Exotic Searches

- **Simplified models are not as widely used in Exotic Results**
 - ▶ Only one or two topologies are considered (exclusive production)
 - ▶ Model-dependent results

Simplified Models and Exotic Searches

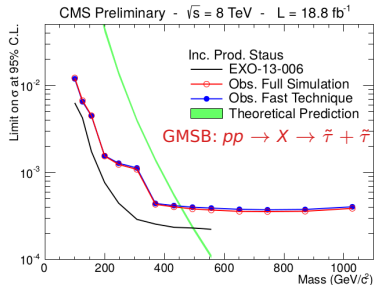
- Simplified models are not as widely used in Exotic Results
 - ▶ Only one or two topologies are considered (exclusive production)
 - ▶ Model-dependent results
- Example: CMS Long-Lived Charged Particle Search (EXO-13-006)



Exclusive production:

$$m_{\tilde{\tau}} > 260 \text{ GeV}$$

~ Model independent



Inclusive production:

$$m_{\tilde{\tau}} > 450 \text{ GeV}$$

Model dependent

Long-Lived Charged Particles

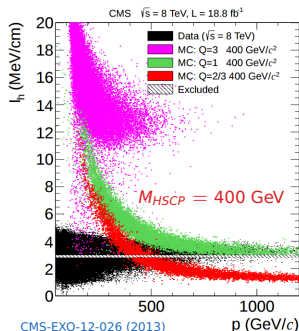
- Exotic searches → Heavy Stable Charged Particles (HSCPs)

Long-Lived Charged Particles

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- HSCPs may appear in models...
 - ▶ with compressed spectra (stau co-annihilation,...)
 - ▶ suppressed couplings (gravitino/axino decays,...)

Long-Lived Charged Particles

- Exotic searches → Heavy Stable Charged Particles (HSCPs)
- HSCPs may appear in models...
 - ▶ with compressed spectra (stau co-annihilation,...)
 - ▶ suppressed couplings (gravitino/axino decays,...)
- HSCP searches:



- Signatures: dE/dx , time of flight
- The signal efficiency, $\epsilon = \frac{\sigma_{\text{after cuts}}}{\sigma_{\text{total}}}$, mostly depends on:
 - ▶ HSCP mass and lifetime
 - ▶ β, p_T, η of the HSCP
 - ▶ number of HSCPs
- Efficiencies are almost independent of the event's additional activity
→ Inclusive search

Simplified Models for HSCPs

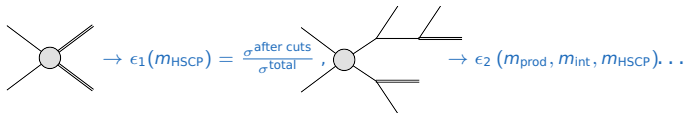
- How to apply HSCP constraints to full models using SMS?

Simplified Models for HSCPs

- How to apply HSCP constraints to full models using SMS?

0. Compute efficiencies for classes of HSCP simplified models

→ build a efficiencies database



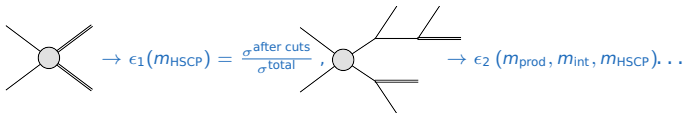
~ only depends on the decay structure and the masses

Simplified Models for HSCPs

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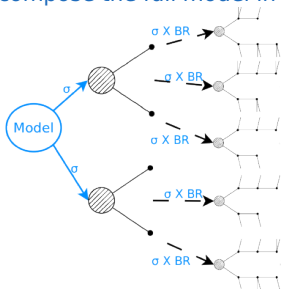
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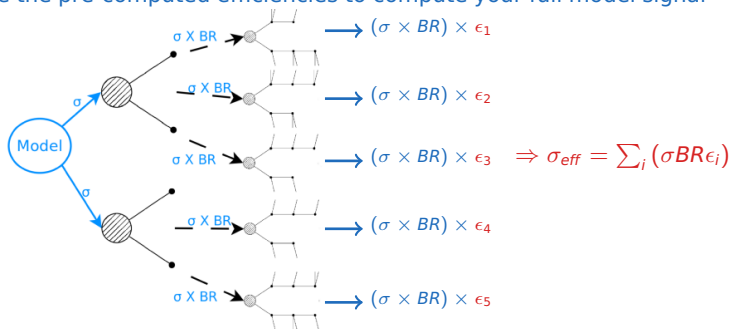
1. Decompose the full model in a coherent sum of SMS (SModelS)



Simplified Models for HSCPs

- How to apply HSCP constraints to full models using SMS?

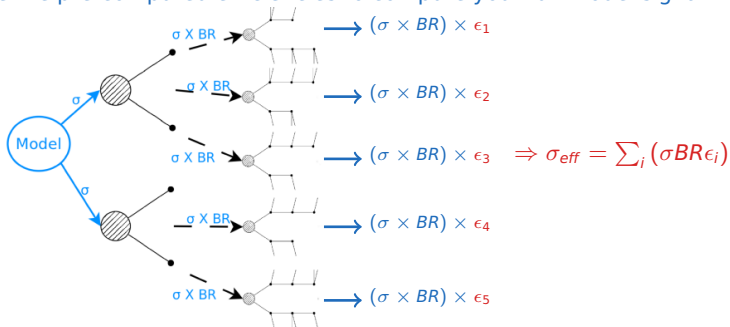
2. Use the pre-computed efficiencies to compute your full model signal



Simplified Models for HSCPs

- How to apply HSCP constraints to full models using SMS?

2. Use the pre-computed efficiencies to compute your full model signal



3. Compare to the experimental UL: $\sigma_{eff} > \sigma_{UL} \rightarrow$ **excluded**

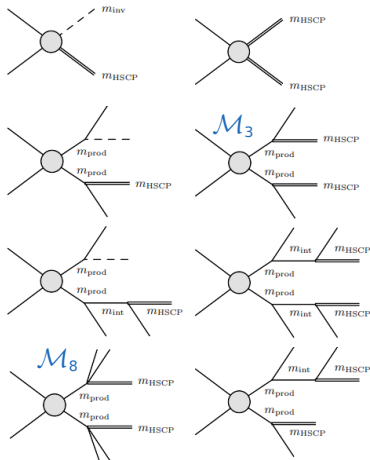
Simplified Models for HSCPs

Computing efficiencies (MadGraph + Pythia + CMS probabilities)

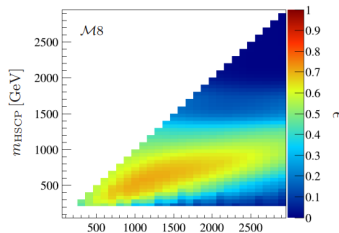
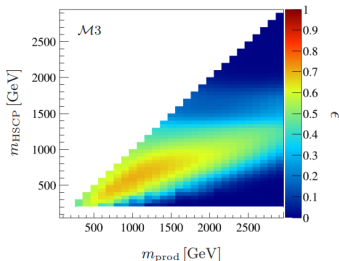
Simplified Models for HSCPs

Computing efficiencies (MadGraph + Pythia + CMS probabilities)

- Simplified Models:



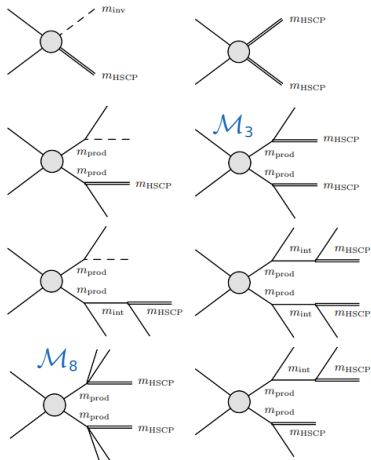
- Efficiency Maps:



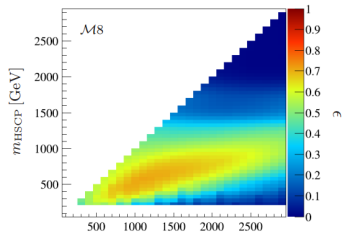
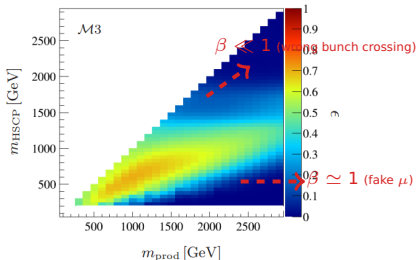
Simplified Models for HSCPs

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- Simplified Models:



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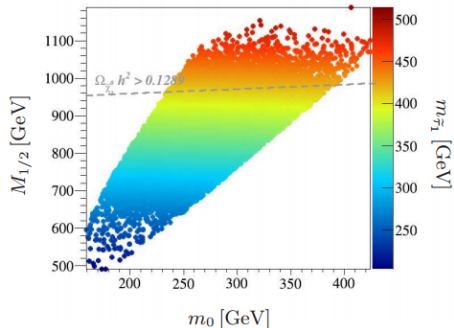
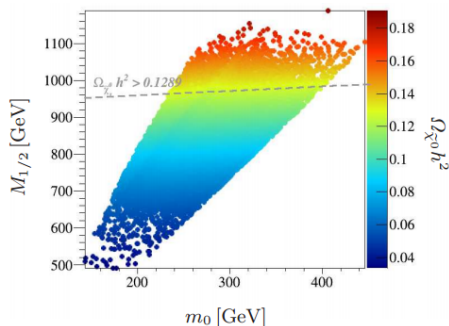


- Application to the CMSSM

- **Application to the CMSSM+** Solution to the Lithium-7 Problem:
 - ▶ Neutralino LSP, stau NLSP
 - ▶ $Y_{\tilde{\tau}} > 10^{-13}$
 - ▶ $\tau_{\tilde{\tau}} > 1s$ ($m_{\tilde{\tau}} - m_{N1} < m_{\tau}$)
 - ▶ $\tan \beta = 10$

CMSSM with long-lived $\tilde{\tau}$ s

- Application to the CMSSM+ Solution to the Lithium-7 Problem:
 - ▶ Neutralino LSP, stau NLSP
 - ▶ $Y_{\tilde{\tau}} > 10^{-13}$
 - ▶ $\tau_{\tilde{\tau}} > 1s$ ($m_{\tilde{\tau}} - m_{N_1} < m_{\tau}$)
 - ▶ $\tan \beta = 10$
- Scan over $m_0, M_{1/2}, A_0, \mu > 0$ ($\sim 14k$ points):



CMSSM with long-lived $\tilde{\tau}$ s: LHC Constraints

- LHC Constraints:

- ▶ MET signatures: $\tilde{q} + \tilde{q} \rightarrow qq + \tilde{\chi}_1^0 + \tilde{\chi}_1^0 \sim 70\%$
- ▶ HSCP signatures: $\tilde{\chi}_1^\pm + \tilde{\chi}_1^\pm \rightarrow \nu_\tau + \tilde{\tau}_1^\pm + \nu_\tau + \tilde{\tau}_1^\pm \sim 10\%$
- ▶ Mixed signatures: $\tilde{\chi}_1^\pm + \tilde{\chi}_2^0 \rightarrow \nu_\tau + \tilde{\tau}_1^\pm + Z + \tilde{\chi}_1^0 \sim 20\%$

CMSSM with long-lived $\tilde{\tau}$ s: LHC Constraints

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- For HSCP and mixed \rightarrow use efficiencies database
- For MET \rightarrow apply UL to single SMS (**SModelS**)

CMSSM with long-lived $\tilde{\tau}$ s: LHC Constraints

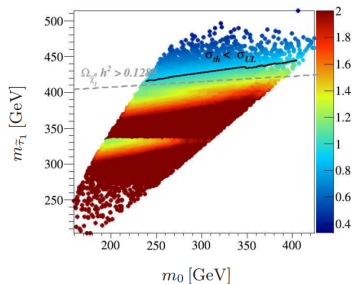
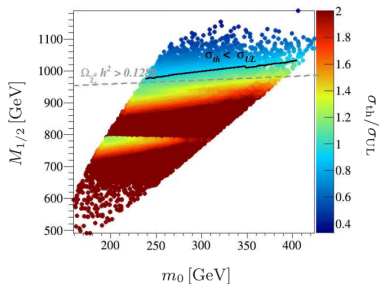
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- **Results:**



CMSSM with long-lived $\tilde{\tau}$ s: LHC Constraints

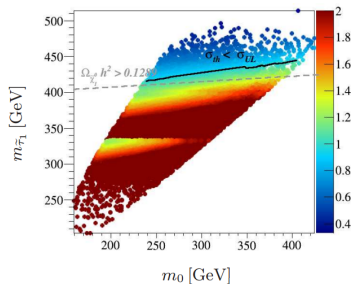
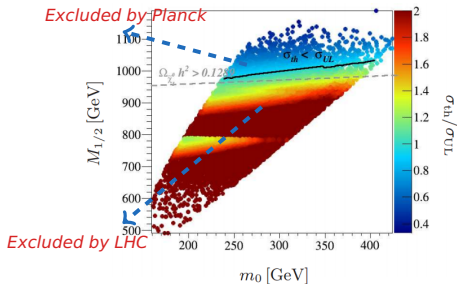
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- For HSCP and mixed \rightarrow use efficiencies database

- For MET \rightarrow apply UL to single SMS (SModelS)

- **Results:**



CMSSM with long-lived $\tilde{\tau}$ s: LHC Constraints

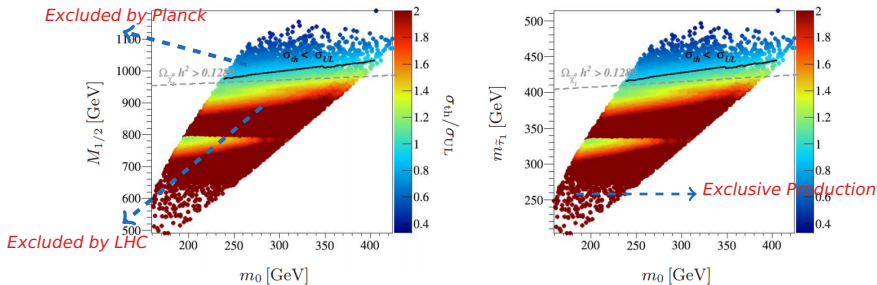
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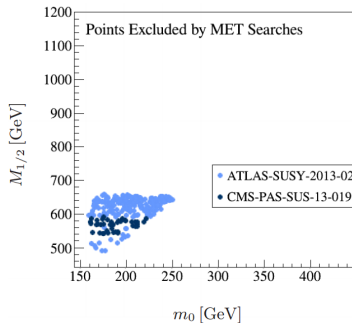
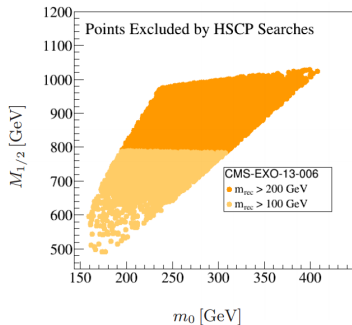
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- Results: MET vs HSCP

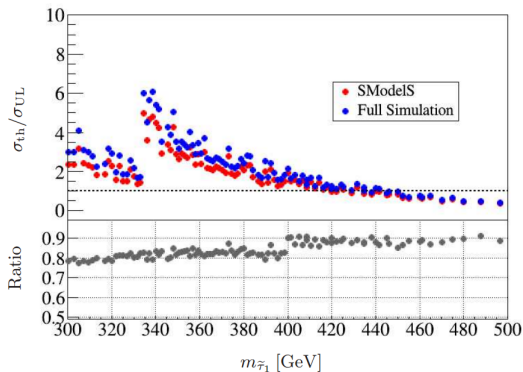


- HSCP constraints dominate (even though the HSCP signal is only $\sim 30\%$)
- MET constraints are smaller than in the usual CMSSM (MET signal $\sim 70\%$)

CMSSM with long-lived $\tilde{\tau}$ s: LHC Constraints

- How does SMS + efficiencies compare with the full sim?

Full signal vs. SMS signal:



→ Signal coverage: 80 – 90%

Conclusions

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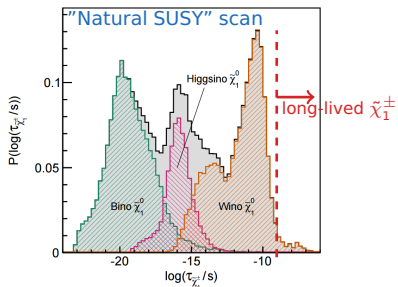
<http://smodels.hephy.at/>

Thanks!

Why Long-Lived Charged (S)Particles?

- In SUSY, heavy stable charged particles (HSCPs) typically appear when:

$m_{NLSP} \simeq m_{LSP}$
(degenerate spectra)

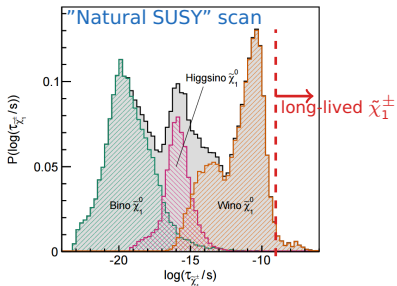


N.-E. Bomark et al., JHEP 05, 007 (2014)

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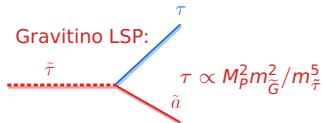
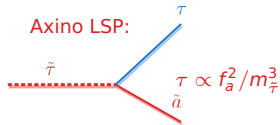
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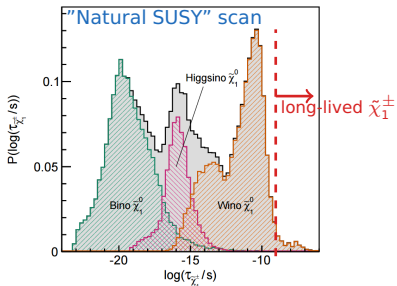
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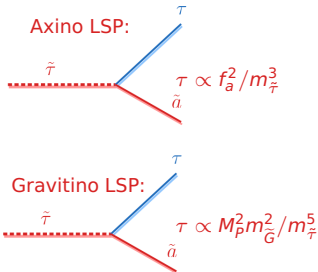
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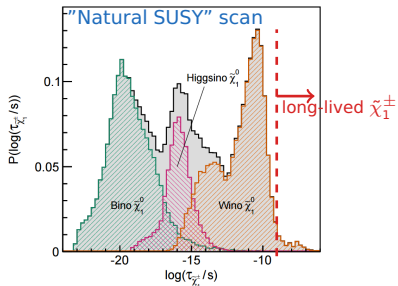


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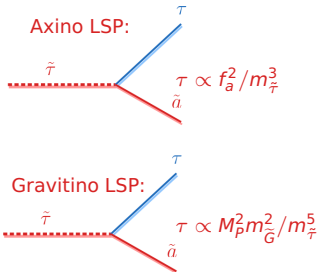
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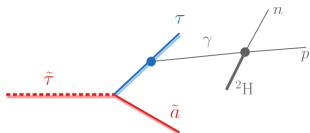
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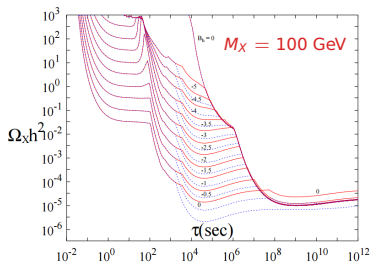
- Most of these scenarios are DM-motivated
- $\tau \gtrsim 1 - 10$ ns \rightarrow long-lived

HSCPs and Cosmology: Big-Bang Nucleosynthesis

- BBN constraints:



(Depletion of light elements)

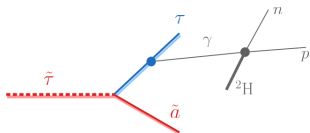


K. Jedamzik, Phys. Rev. D74, 103509, 2006

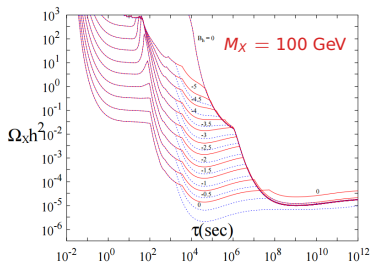
→ $\tau_{HSCP} < 0.01 - 1 \text{ s}$

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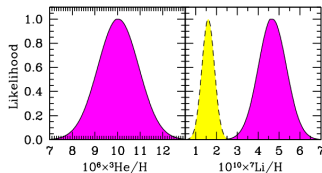
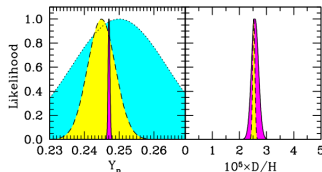
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$$\rightarrow \tau_{HSCP} < 0.01 - 1 \text{ s}$$

- SBBN predictions:



B. Cyburt, B. Fields, K. Olive and T.-H. Yeh, arXiv:1505.01076 (2015)

$$\left(\frac{{}^7\text{Li}}{\text{H}}\right)_{\text{theo}} = (4.68 \pm 0.67) \times 10^{-10}$$

$$\left(\frac{\text{Li}}{\text{H}}\right)_{\text{exp}} = (1.6 \pm 0.3) \times 10^{-10}$$

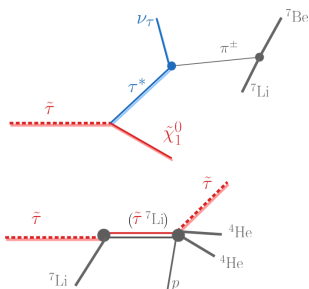
HSCPs and Cosmology: ${}^7\text{Li}$ Problem

How to deplete the primordial Lithium abundance?

HSCPs and Cosmology: ${}^7\text{Li}$ Problem

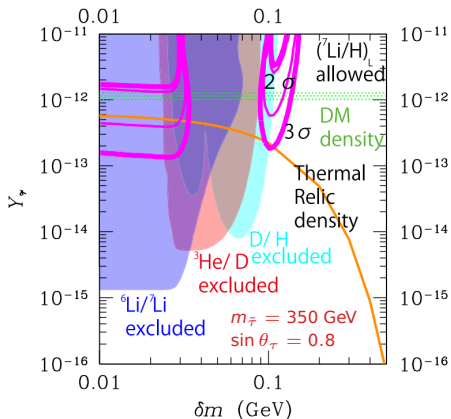
How to deplete the primordial Lithium abundance?

- ${}^7\text{Li}$ depletion with long-lived $\tilde{\tau}$:



- A solution is possible with:

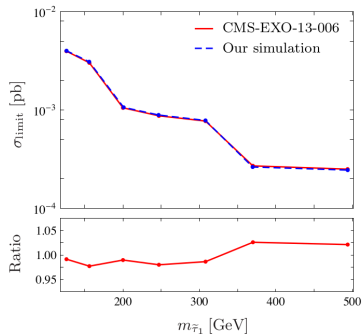
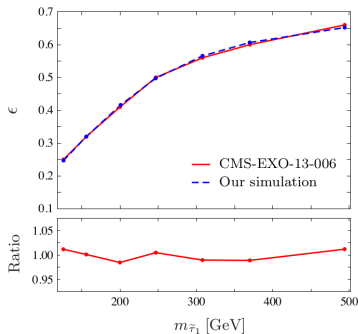
- $Y_{\tilde{\tau}} > 10^{-13}$
- $\tau_{\tilde{\tau}} > 1 - 100\text{s}$



T. Jittoh et al., Phys.Rev. D84 035008 (2011)

Simplified Models for HSCPs: Validation

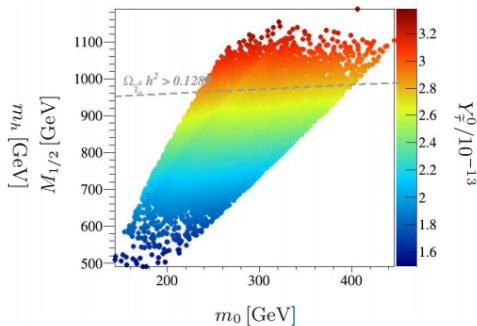
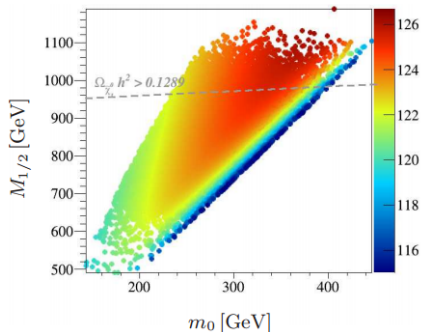
- Validation (GMSB):



agreement within $\lesssim 5\%$

CMSSM with long-lived $\tilde{\tau}$ s

- Higgs and Dark Matter constraints:



- We require:

- ▶ $120 \text{ GeV} < m_h < 130 \text{ GeV}$