

A scenic photograph of a mountain range under a clear blue sky. The mountains are rugged with rocky peaks and green, grassy slopes. A large, prominent peak is visible in the background.

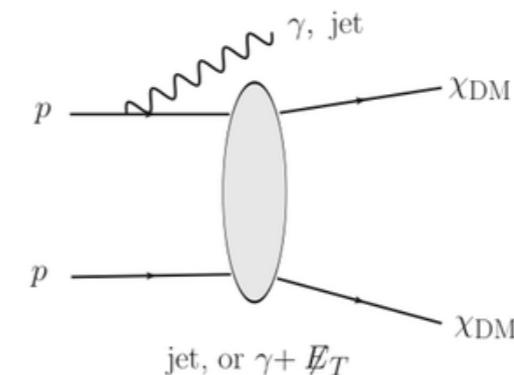
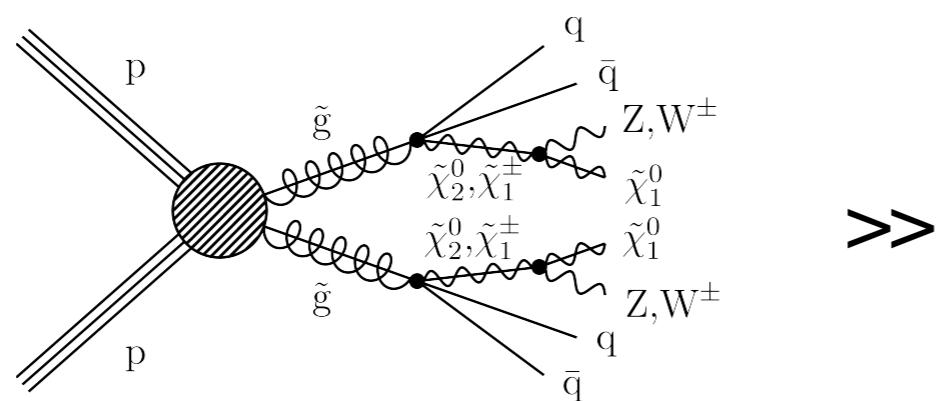
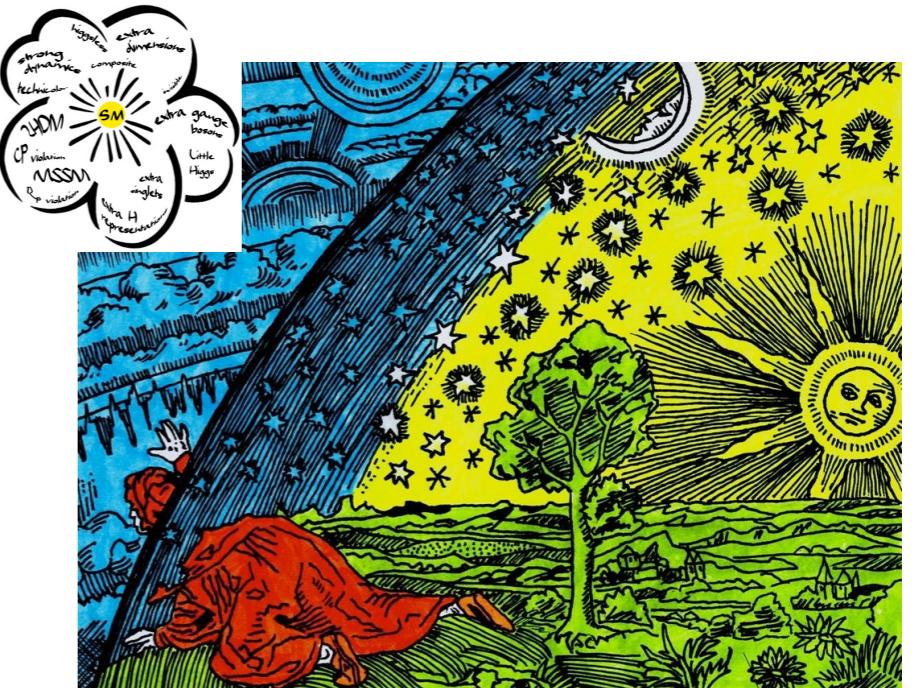
# Use and limitations of simplified-model constraints from the LHC

**Sabine Kraml**  
LPSC Grenoble

# Motivation

see also today's talks by B Clerbaux and F. Conventi

- Dark matter (DM) models often assume just a DM candidate and a mediator
- This does the job for many useful considerations related to DM. However, there is ample motivation for more extensive beyond the Standard Model (BSM) physics
- “Full” BSM theories, like SUSY & Co, typically have a rather complicated spectrum, and **DM production at the LHC might primarily come from cascade decays of other new particles ...**

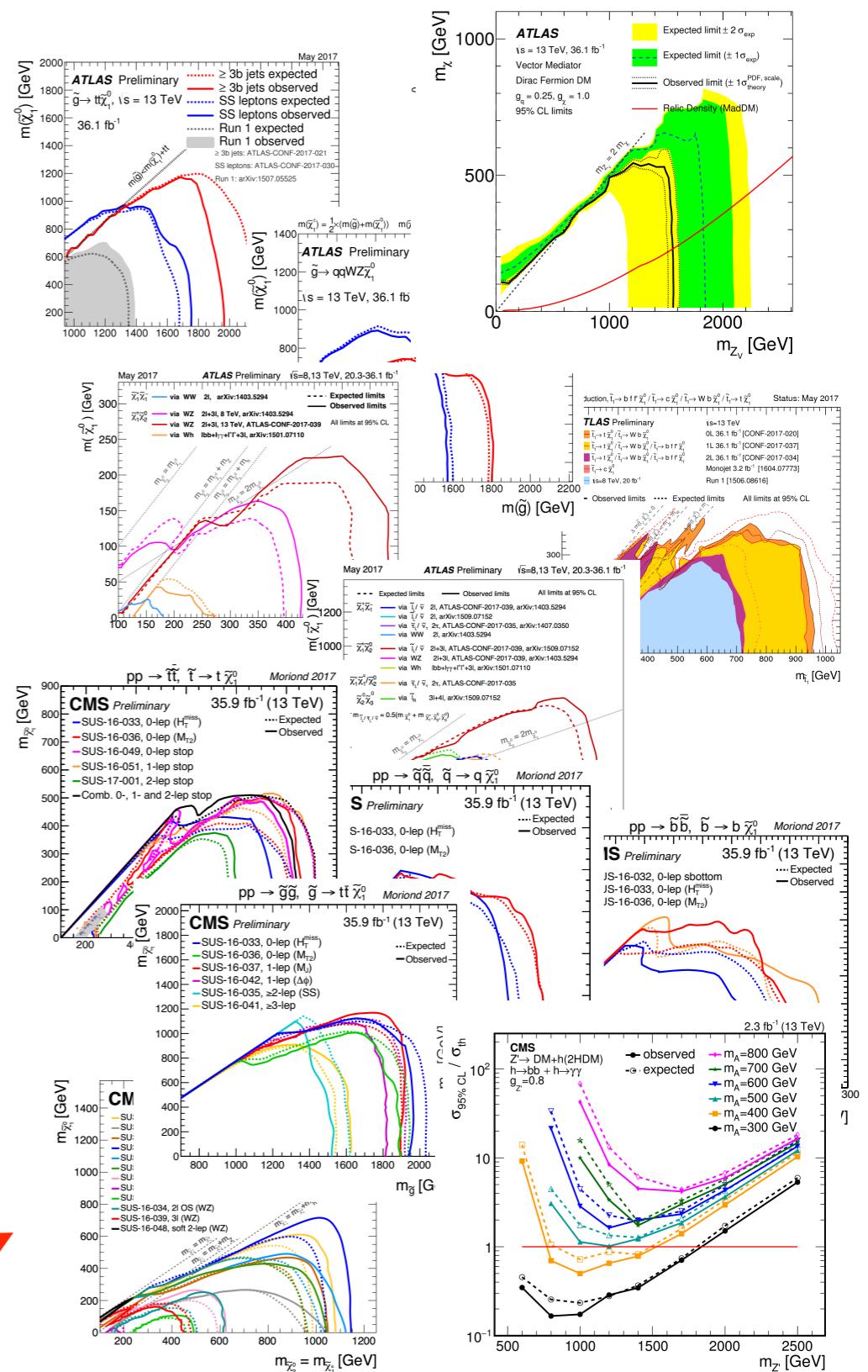


- Need to know how the LHC **searches in events with jets and/or leptons + MET** affect DM candidates in full BSM models.

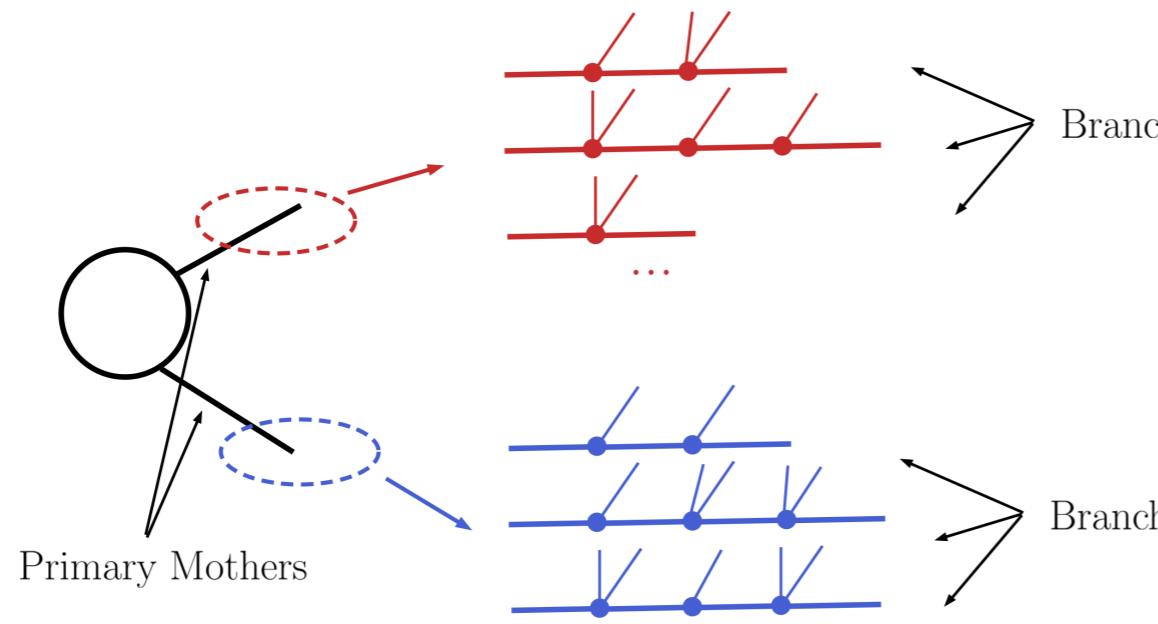
# LHC constraints: SMS

- It has become standard that ATLAS and CMS present the results of their BSM searches in terms of “**simplified model**” constraints.
- Simplified models (SMS) **reduce full models** with a plethora of particles and parameters **to subsets with just 2-3 new states** and a simple decay pattern, mostly assuming 100% BR.
- Concept used by SUSY, Exotics, DM searches
- Very convenient for **optimising** analyses that look for a particular final state, as well as for **comparing** the reach of different strategies.
- **Understanding how SMS results constrain a realistic model** with a multitude of parameters, relevant production channels and decay modes is, however, a **non-trivial task**.

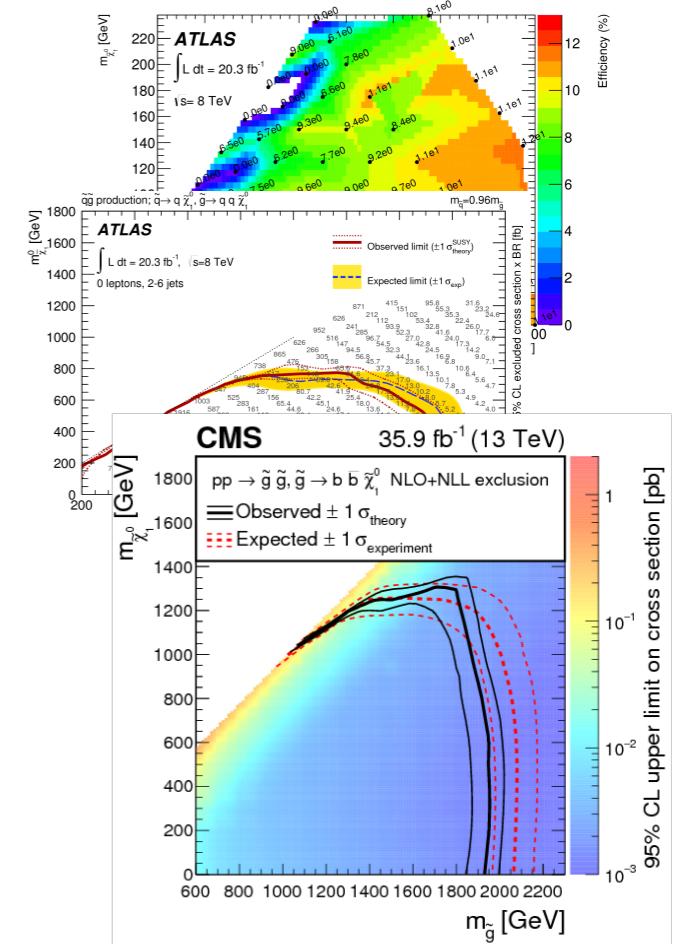
what do these mean for my model?



SModelS provides an automatic **decomposition** of the collider signatures of a BSM model **into** all its relevant **SMS topologies**. Topology weights ( $\sigma \times BR$ ) are then compared against the experimental constraints in a large database.



Input: mass spectrum with decay table and cross section information (SLHA format), or particle level MC events (LHE file)

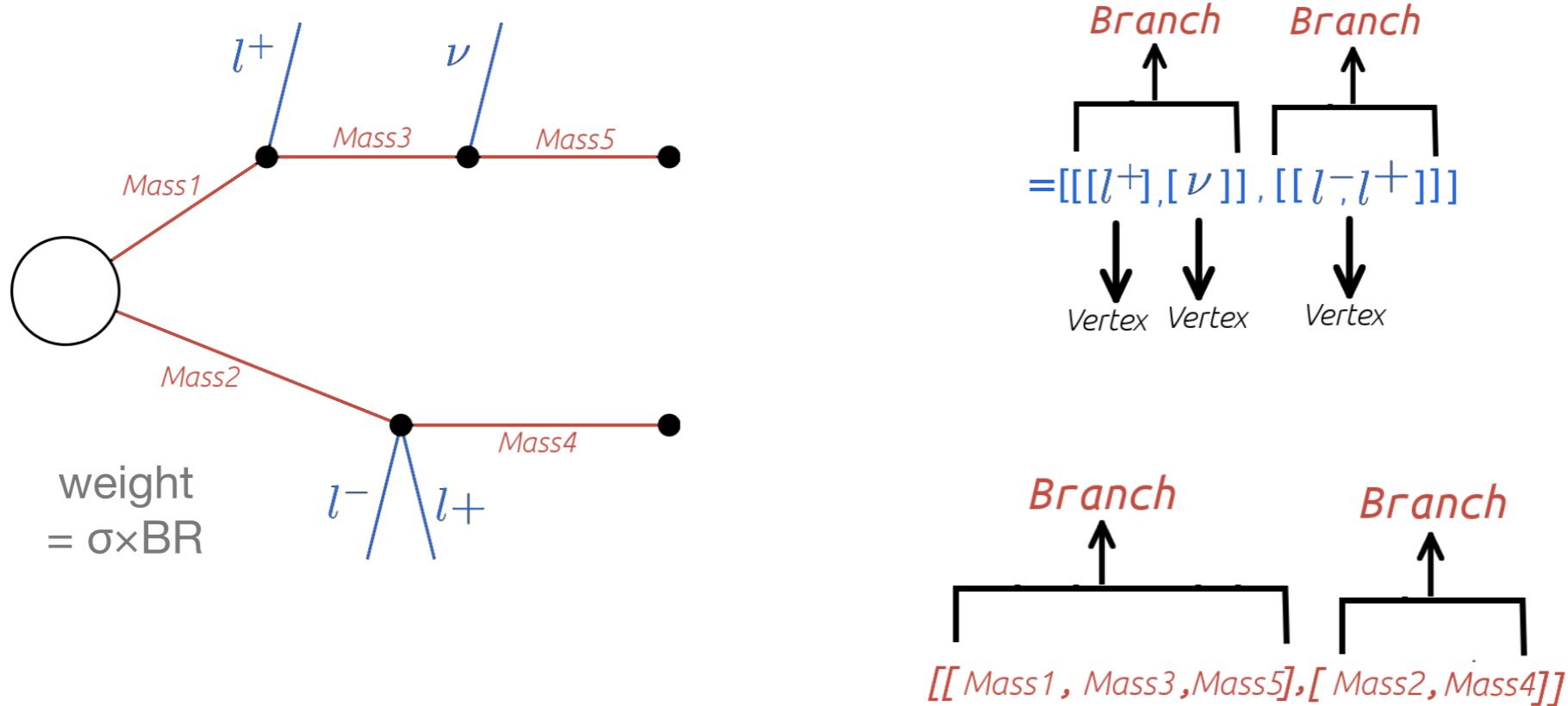


Also identifies the most important ‘missing topologies’ for which no experimental result is available.

Working assumption:  **$Z_2$  symmetry**; i.e. new particles are produced in pairs (2-branch structure) and cascade-decay promptly to the lightest one, which is stable and leads to missing energy.

# Topology description

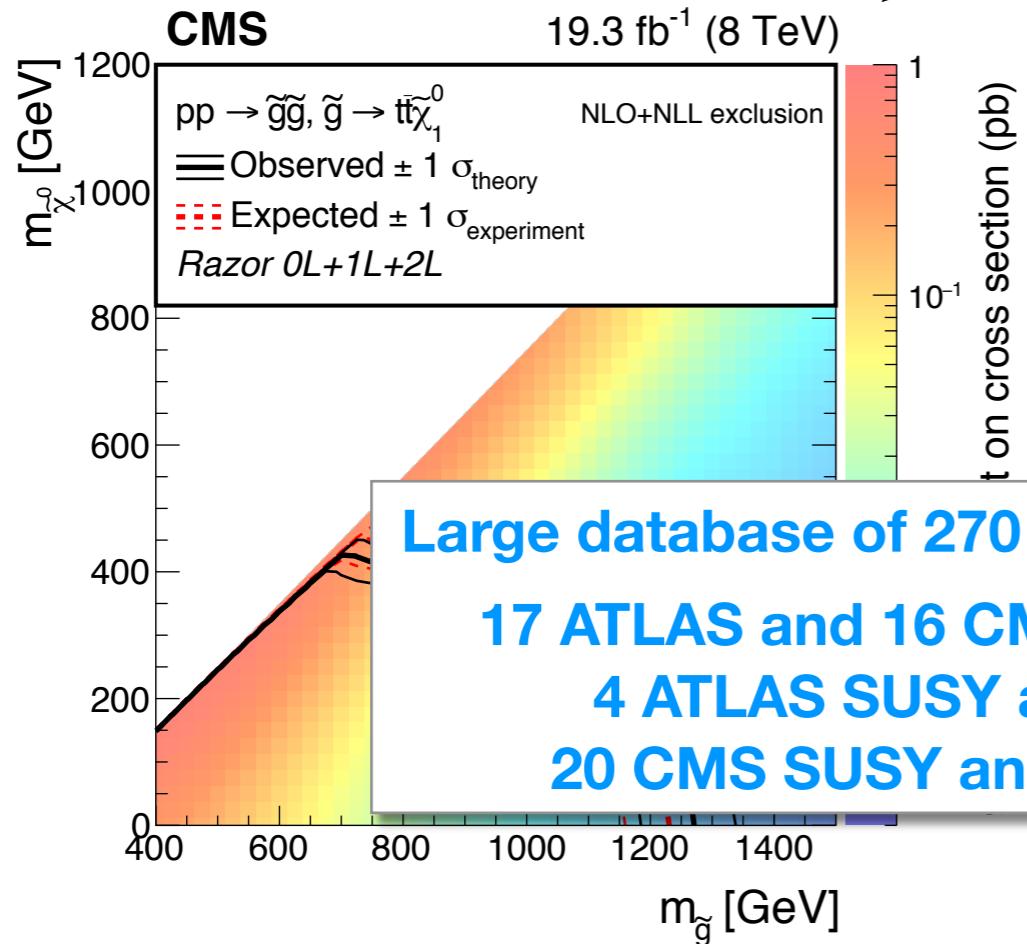
An SMS topology is entirely defined by the **number of vertices in each branch** together with the **SM particles originating from each vertex** (final states) and a **mass array** containing the ordered  $Z_2$ -odd masses



**Mass compression:** decays of almost degenerate BSM particles into each other are treated as invisible.  
**Invisible compression:** several inv. final-state particles at the end of the decay chain are combined into one.

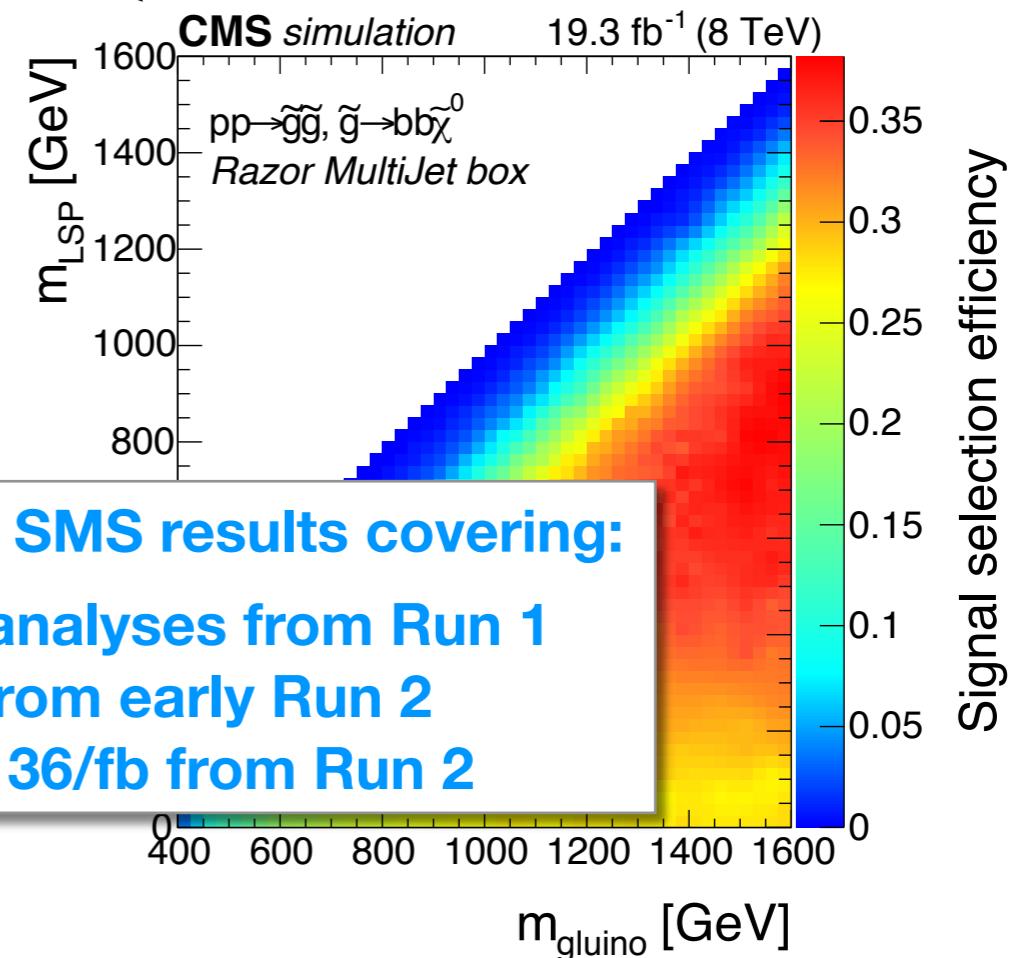
# Experimental constraints

## Upper Limit (UL) maps



need these in numerical form

## Efficiency maps (EM)



Upper Limit maps give the 95% CL upper limit on cross section x branching ratio for a specific SMS.

The UL values can be based on the best SR (for each point in parameter space), a combination of SRs or more involved limits from other methods.

Efficiency maps correspond to a grid of simulated acceptance x efficiency values for a specific signal region for a specific simplified model.

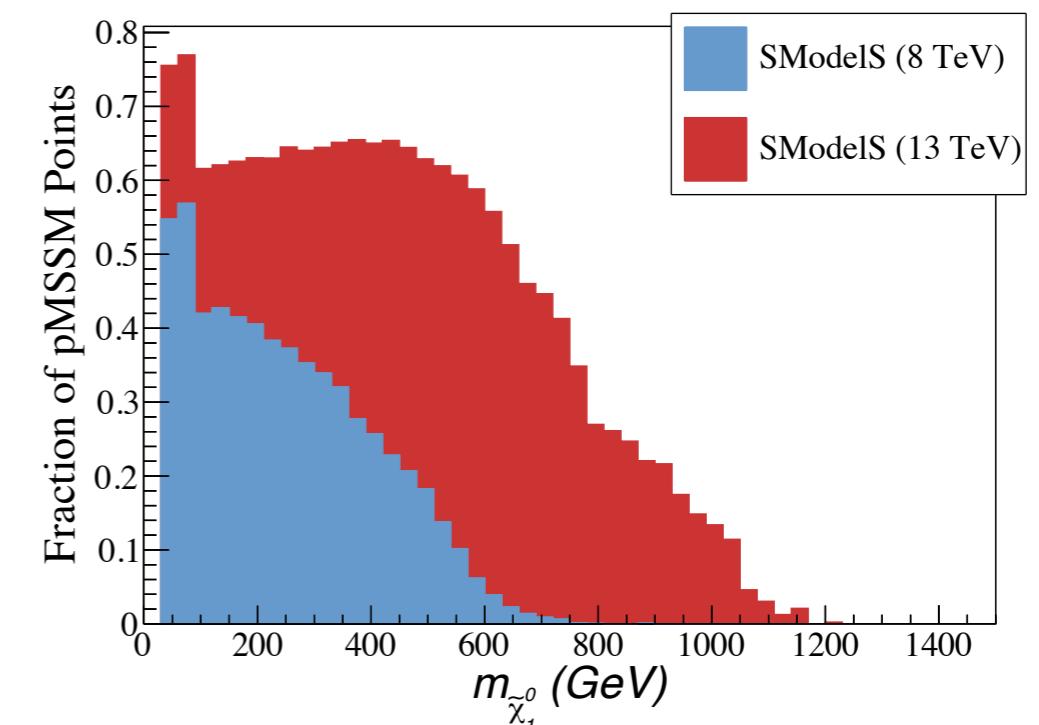
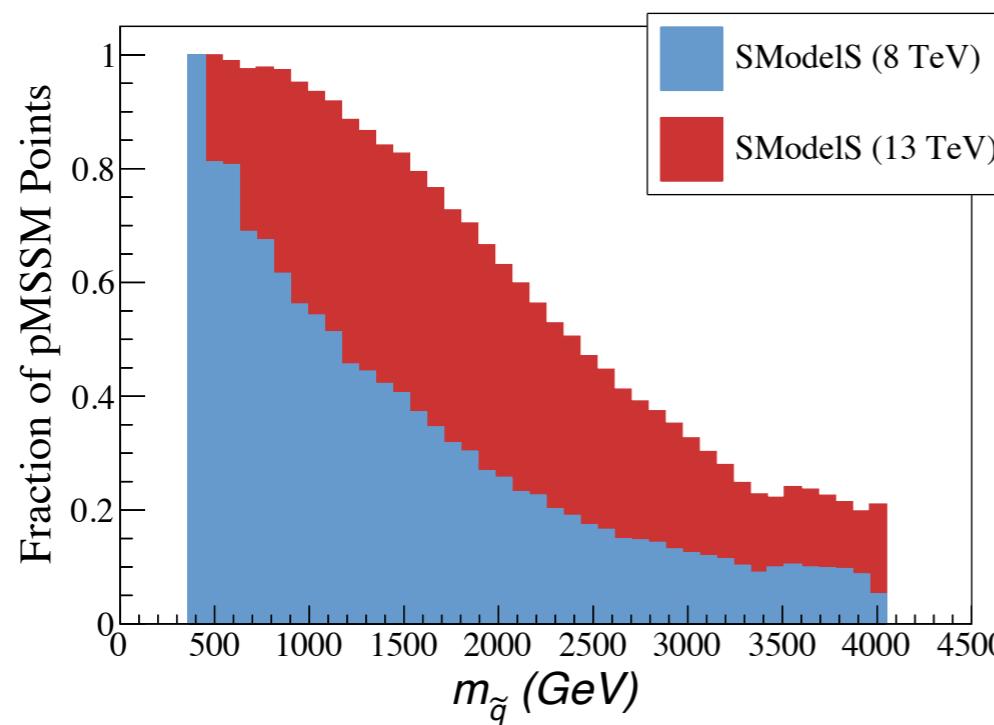
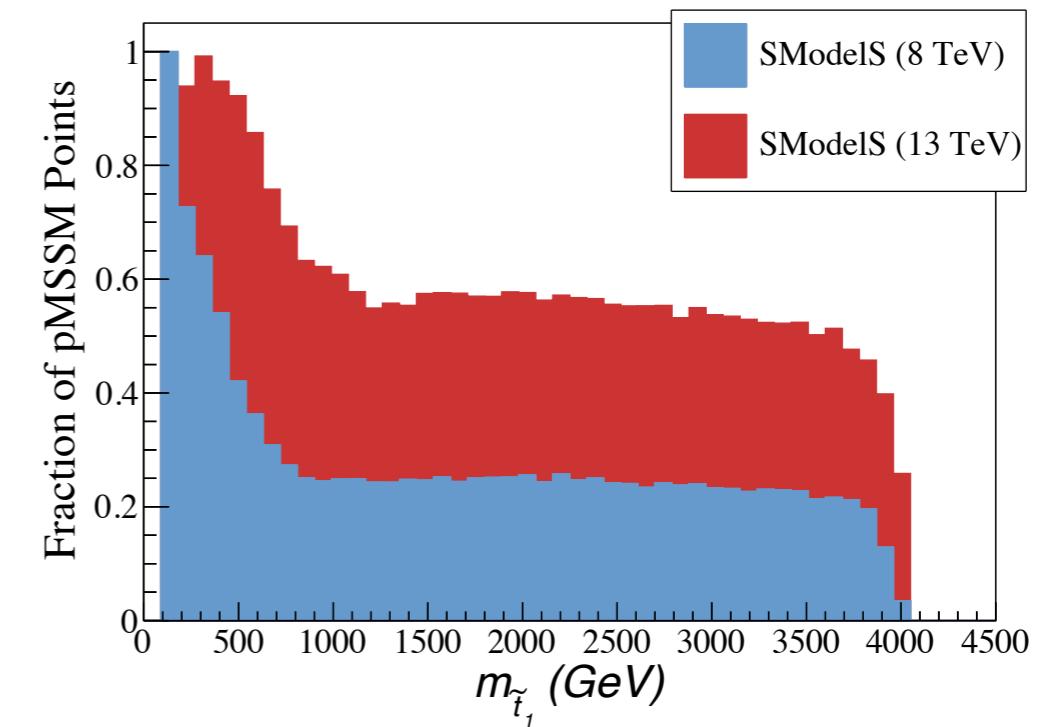
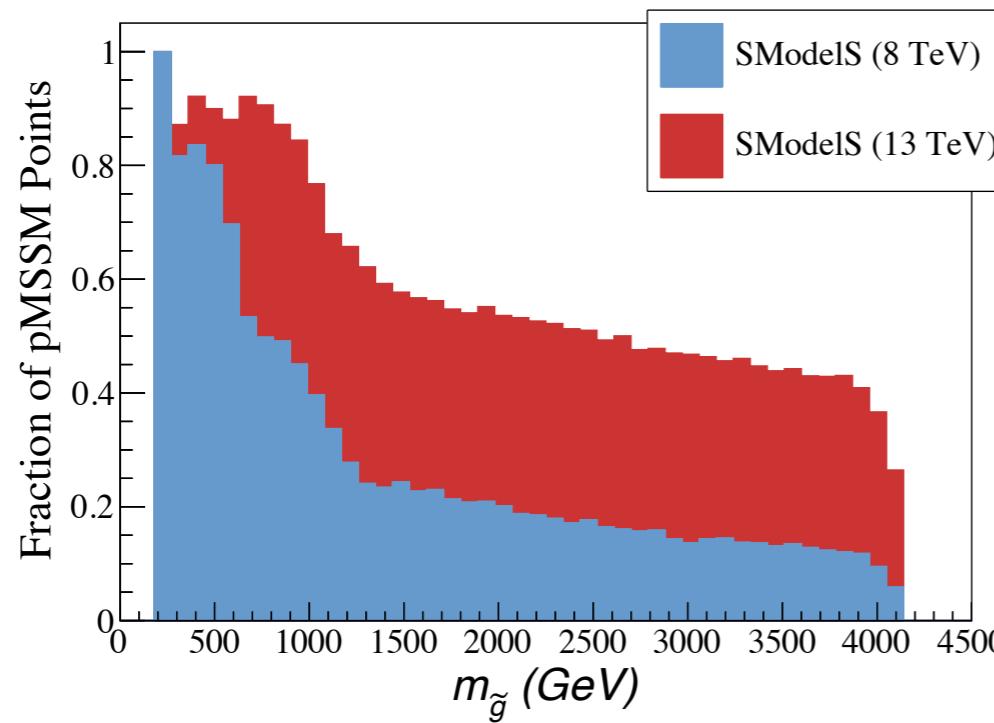
Together with the observed and expected #events in each SR, this allows to compute a likelihood.

Limit on  $\sigma \times BR$

NB: the 95%CL exclusion curve is not used, cannot be re-interpreted

Limit on  $\Sigma \epsilon \times \sigma \times BR$

# Impact on pMSSM



19 free parameters; using ATLAS pMSSM scan from arXiv:1508.06608

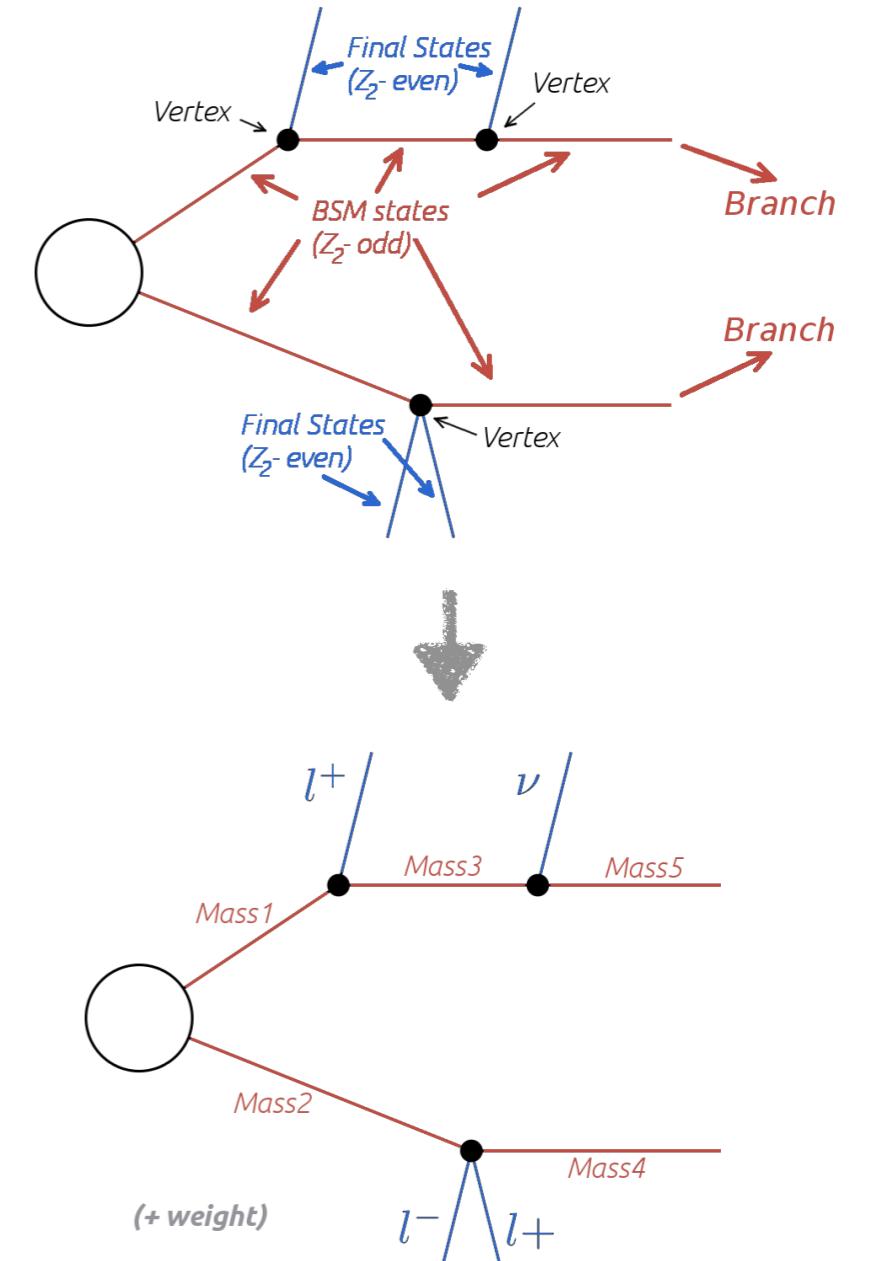
# Procedure applicable to any model with a $Z_2$ symmetry

- BSM particles are described only by their masses, production cross sections and branching ratios.
- Underlying **assumption** is that **differences in the event kinematics from**, e.g., different production mechanisms or the spins of the BSM particles, **do not significantly affect the signal selection efficiencies**.

Arkani-Hamed et al., hep-ph/0703088  
Alves et al., arXiv:1105.2838

- **Tested** for and successfully applied to minimal and non-minimal SUSY (NMSSM, UMSSM, sneutrino LSP), as well as non-SUSY models (XQ, UED ...)

SK et al, 1312.4175;  
Belanger et al, 1308.3735;  
Barducci et al., 1510.00246;  
Arina et al., 1503.02960;  
Edelhauser et al., 1501.03942;  
Belanger et al, 1506.00665;  
SK et al, 1607.02050 and 1707.09036.



Information used to  
classify topologies

# Integration in micrOMEGAs (v4.3 onwards)

in main.c

```
#define SMODELS
...
...
#endif SMODELS
{
    int result=0;
    double Rvalue=0;
    char analysis[30]={},topology[30]={};
    int LHCrun=LHC8 | LHC13;
#include "../include/SMODELS.inc"
}
#endif
```

Automatically writes the input needed by SModelS:

- an [SLHA-type input file](#), containing the mass spectrum, decay tables and production cross sections for the parameter point under investigation;
- the [particles.py file](#) defining the particle content of the model, specifically which particles are even and which ones are odd under the  $Z_2$  symmetry;

SModelS specific settings can be chosen in `parameters.ini`

## BLOCK SModelS\_Exclusion

0 0 1	#output status (-1 not tested, 0 not excluded, 1 excluded)
1 0 T2	#txname, see <a href="http://smodeles.hephy.at/wiki/SmsDictionary">http://smodeles.hephy.at/wiki/SmsDictionary</a>
1 1 1.514E+01	#r value ... theory prediction / 95% CL exp. upper limit
1 2 N/A	#expected r value
1 3 0.00	#condition violation
1 4 CMS-SUS-16-033	#analysis

# Integration in micrOMEGAs (v4.3 onwards)

in main.c

```
#define SMODELS
...
...
#endif SMODELS
{
    int result=0;
    double Rvalue=0;
    char analysis[30]={},topology[30]={};
    int LHCrun=LHC8 | LHC13;
#include "../include/SMODELS.inc"
}
#endif
```

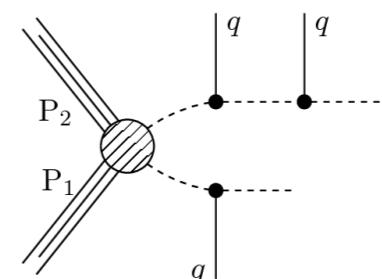
Automatically writes the input needed by SModelS:

- an [SLHA-type input file](#), containing the mass spectrum, decay tables and production cross sections for the parameter point under investigation;
- the [particles.py file](#) defining the particle content of the model, specifically which particles are even and which ones are odd under the  $Z_2$  symmetry;

SModelS specific settings can be chosen in `parameters.ini`

## BLOCK SModelS\_Missing\_Topos #sqrt[s][TeV] weight[fb] description

0	13	2.635E+02	<code>[[[jet]], [[jet], [jet]]]</code>	←
1	13	7.355E+01	<code>[[[jet], [jet]], [[jet], [jet]]]</code>	
2	13	4.716E+01	<code>[[[jet]], [[jet], [W], [Z]]]</code>	



Applicable ‘out of the box’  
beyond the MSSM (also non-SUSY)

Example: MSSM + sneutrino DM

# MSSM + RH sneutrino

Model: MSSM augmented by a RH sneutrino superfield; L-R sneutrino mixing due to large A-terms that are not proportional to Yukawa couplings

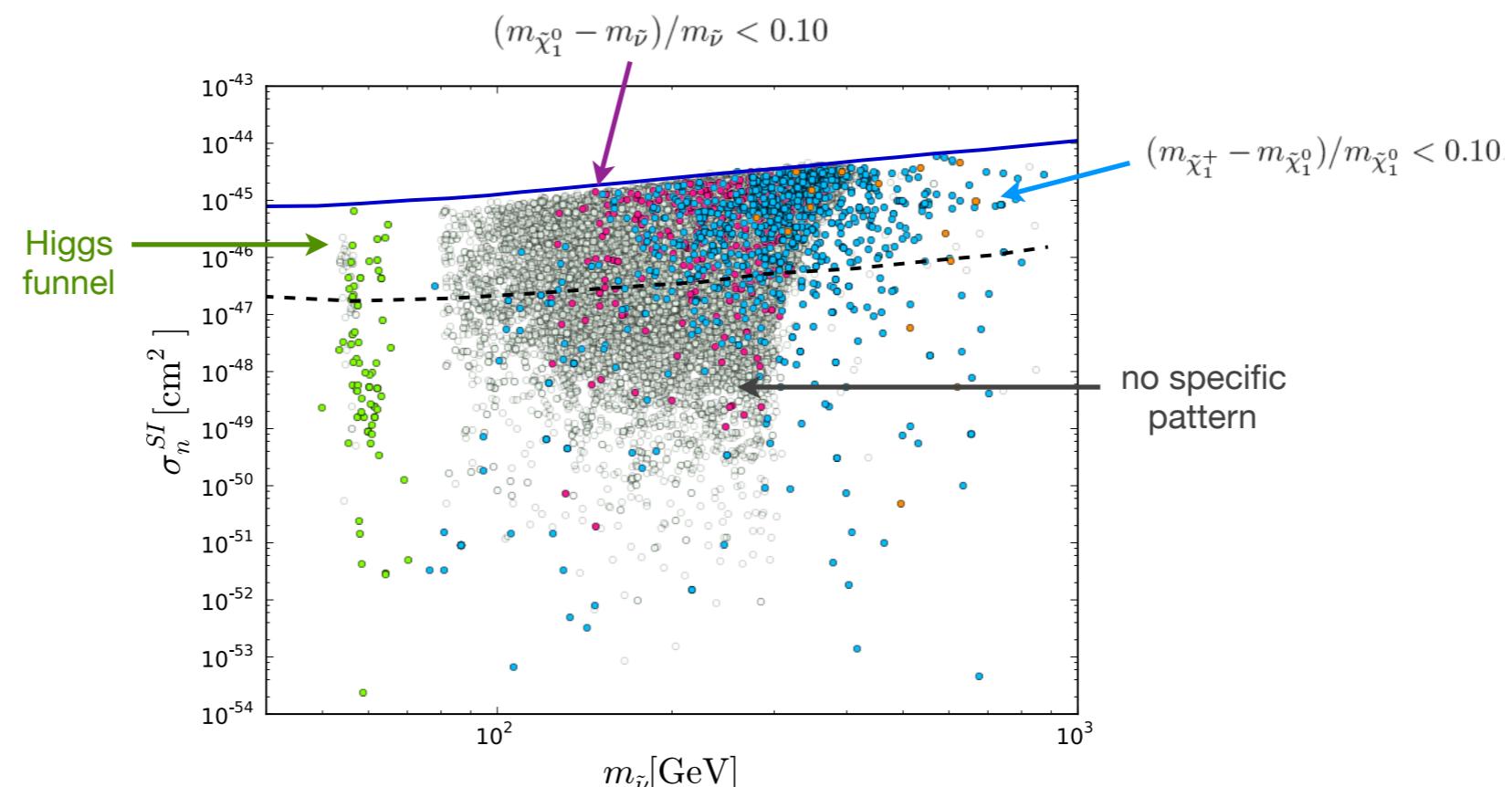
$$m_{\tilde{\nu}}^2 = \begin{pmatrix} m_{\tilde{L}}^2 + \frac{1}{2}m_Z^2 \cos 2\beta & \frac{1}{\sqrt{2}}A_{\tilde{\nu}} v \sin \beta \\ \frac{1}{\sqrt{2}}A_{\tilde{\nu}} v \sin \beta & m_{\tilde{N}}^2 \end{pmatrix}$$

Arkani-Hamed et al., hep-ph/0006312  
Borzumati, Nomura, hep-ph/0007018

Mostly RH sneutrino LSP can be good dark matter candidate; 12 parameter scan

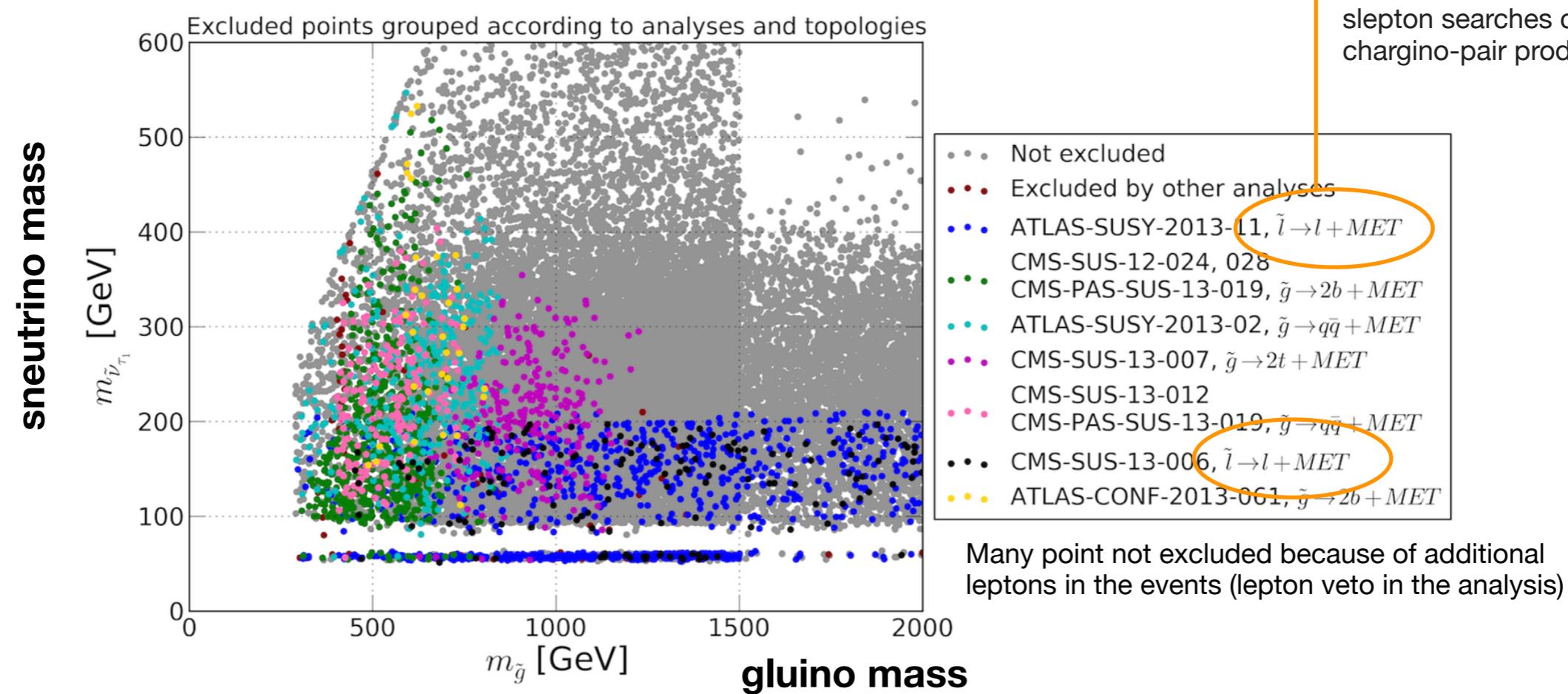
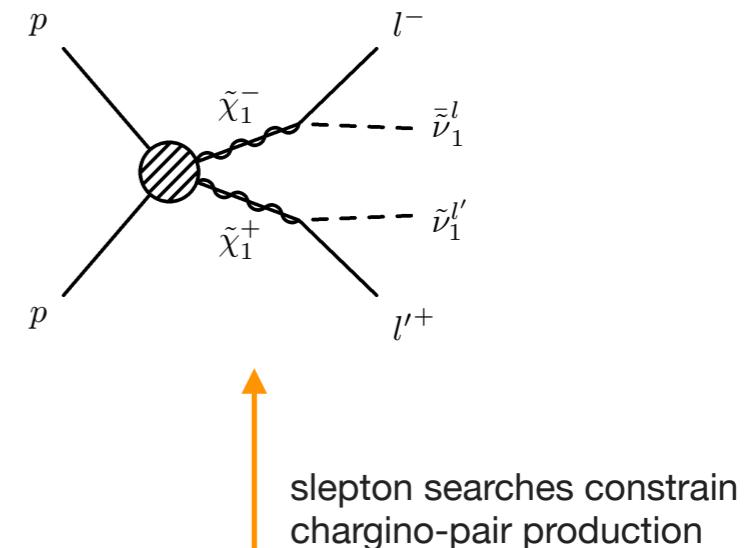
$M_1, M_2, M_3, m_L, m_R, m_N, m_Q, m_H, A_l, A_{\tilde{\nu}}, A_q, \tan \beta, \text{sgn}\mu$ .

Arina, Cabrera, 1311.6549



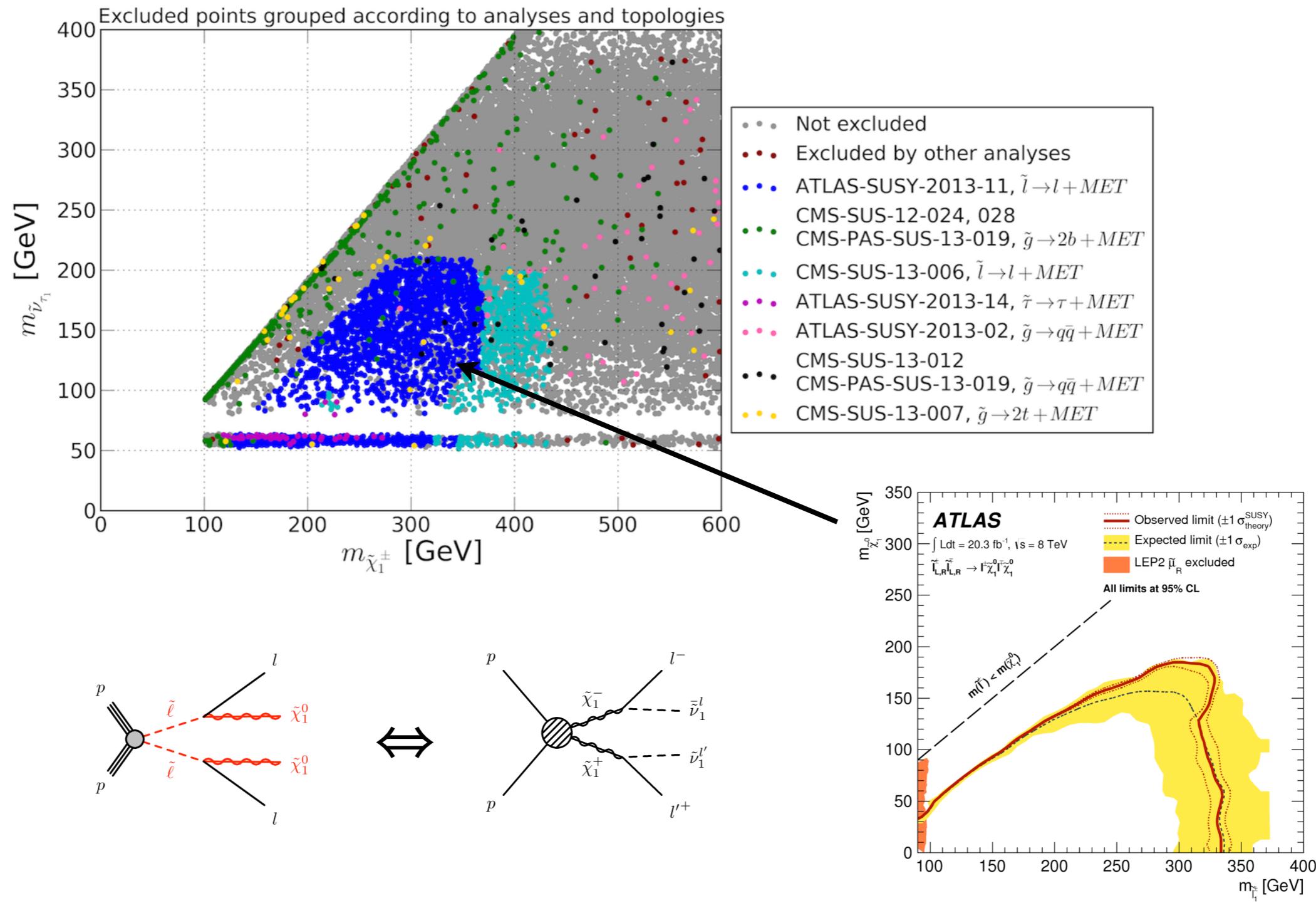
# MSSM + RH sneutrino: LHC constraints on mixed sneutrino dark matter

- The addition of a (mostly RH) sneutrino LSP to the spectrum significantly alters SUSY signals at the LHC w.r.t. expectations in the MSSM.
  - Charginos can decay to  $l^\pm \tilde{\nu}_1$  [lepton-enriched signatures]
  - Neutralinos can decay to  $\tilde{\nu}_1$  [invisible]
- Can have several invisible sparticles in a decay chain!



# MSSM + RH sneutrino: LHC constraints on mixed sneutrino dark matter

... in sneutrino vs. chargino mass plane:

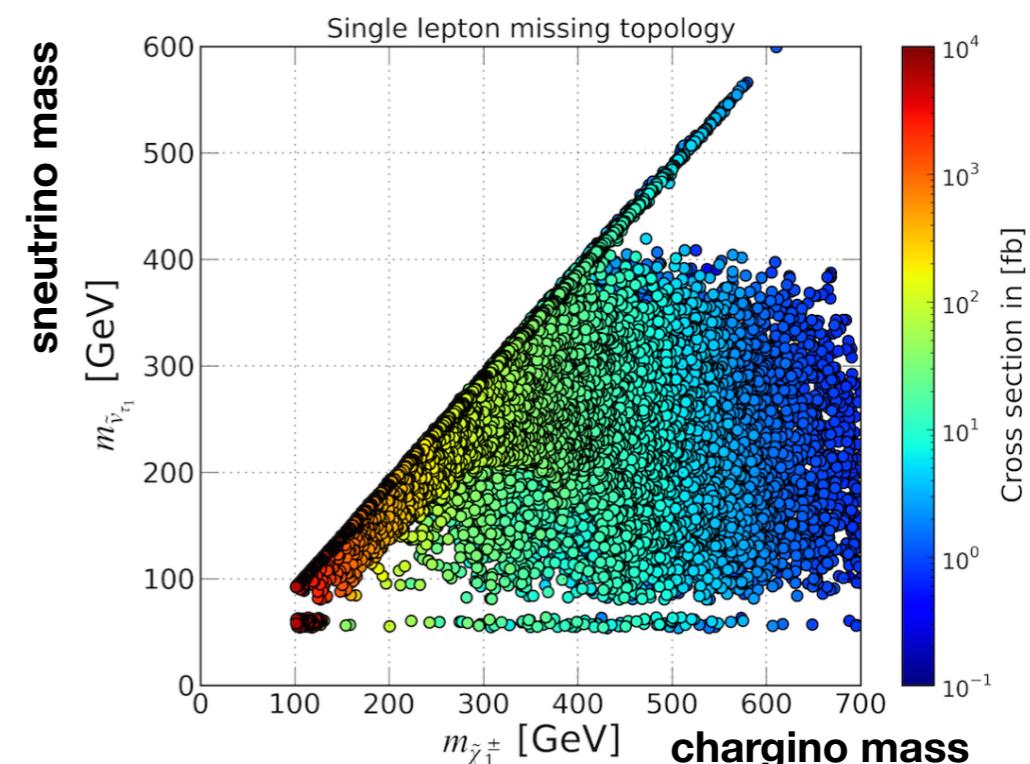
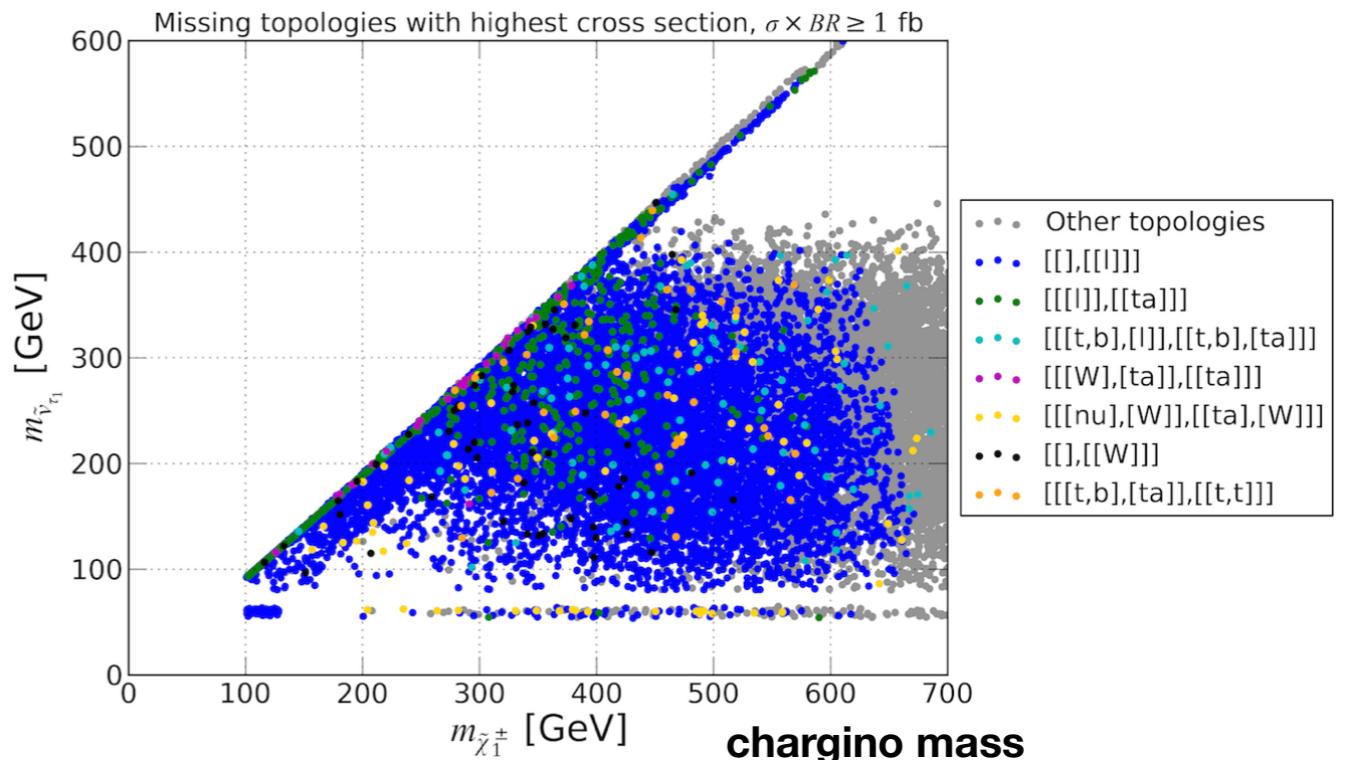


# MSSM + RH sneutrino: LHC constraints on mixed sneutrino dark matter

## Missing topologies

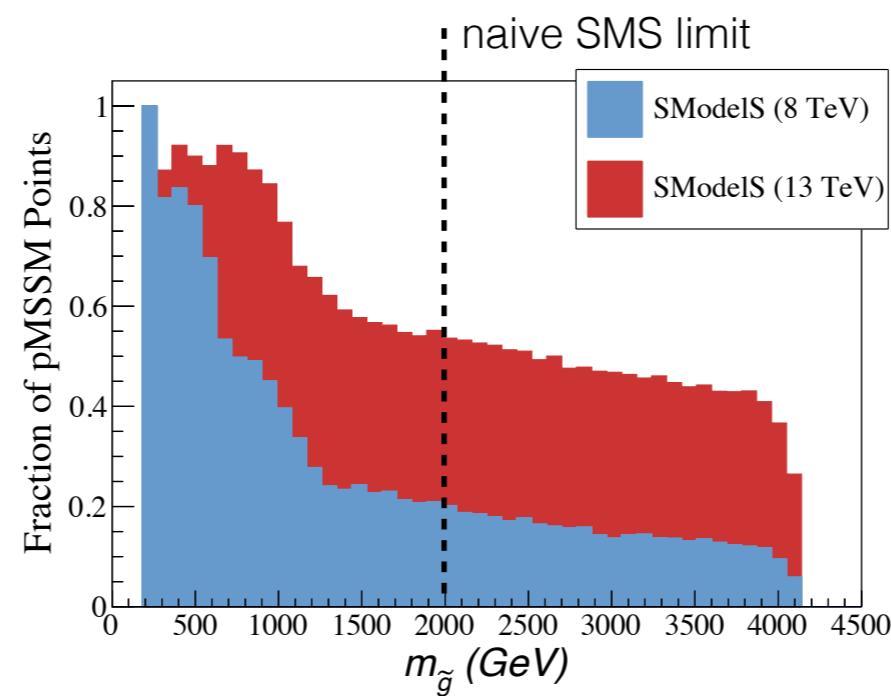
- The most important signature for which we do not have any applicable SMS result is single lepton + MET
- For chargino masses <500 GeV this can have a very large cross section.
- Mono-lepton + MET searches were performed by both ATLAS and CMS in the context of W' searches, but have too hard a MET cut. (also, not enough information provided for recasting)

Observability of mono-lepton signature from sneutrino LSP discussed recently by Chatterjee, Dutta, Rai, 1710.10617



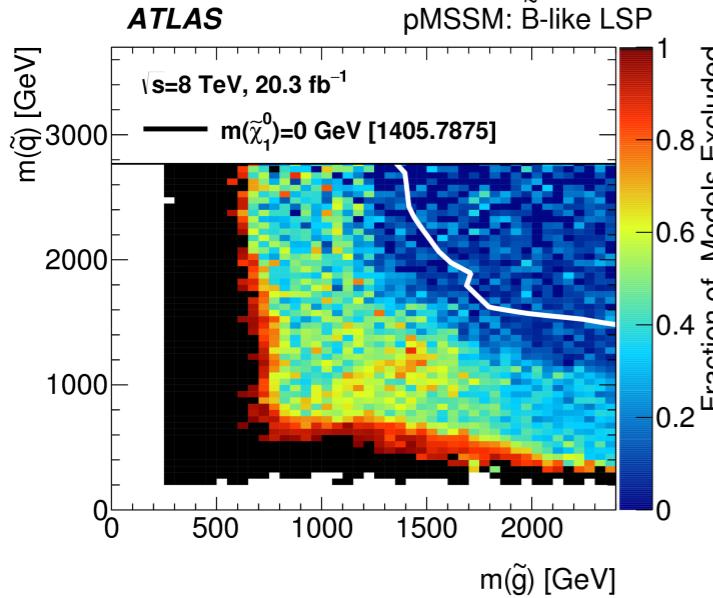
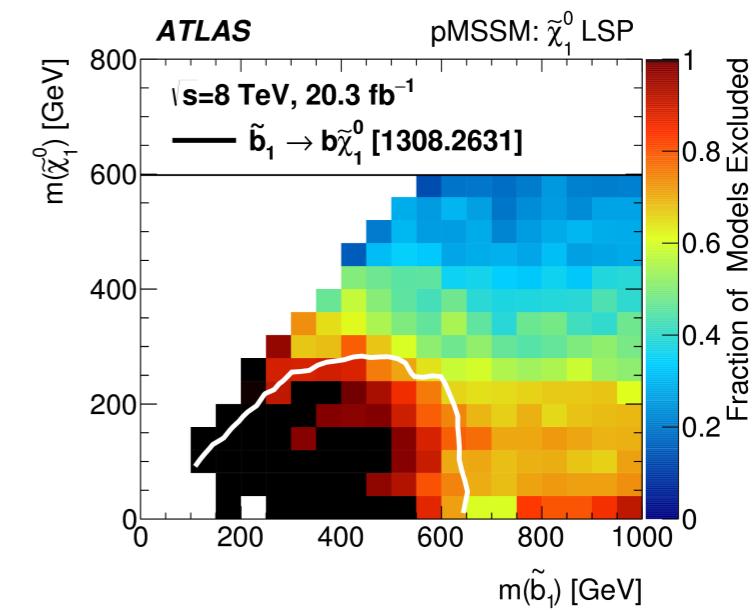
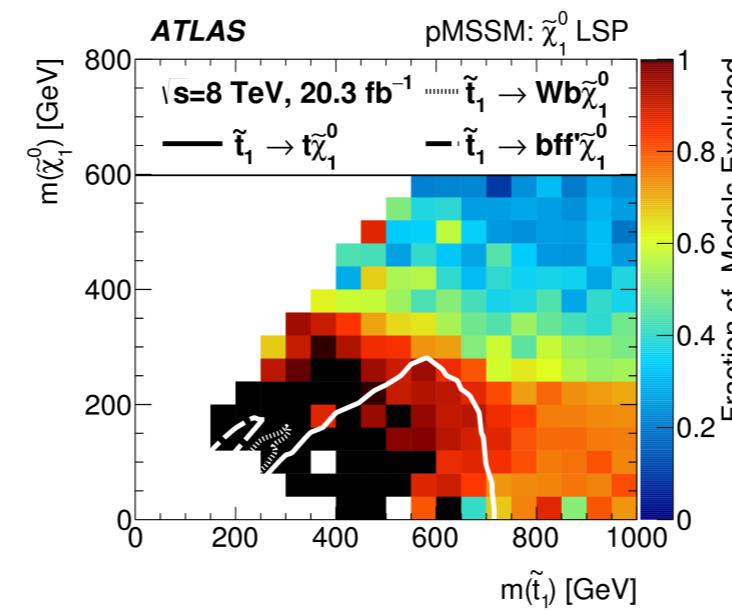
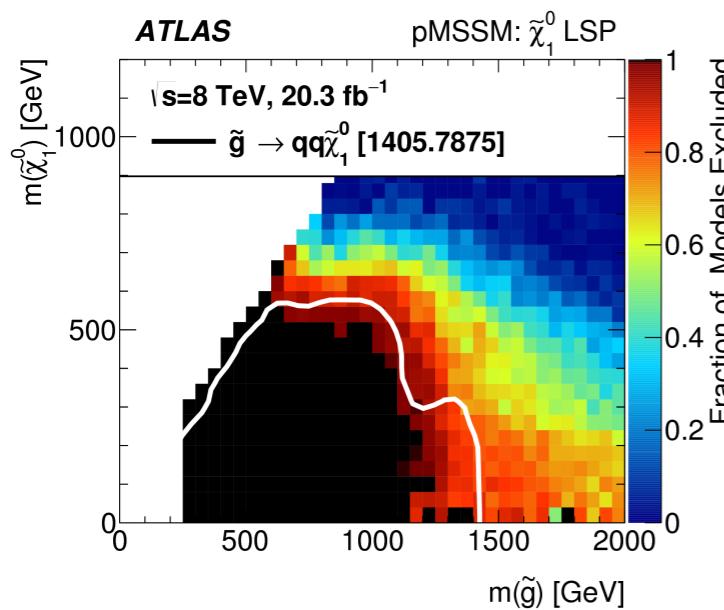
Full models can be decomposed into simplified model components.

To what extent do the available SMS results map a full model?



# Compare with ATLAS pMSSM study (8 TeV)

In 1508.06608, ATLAS interpreted the results from 22 separate ATLAS searches in the context of the 19-parameter phenomenological MSSM (pMSSM) [vast scan]



How well can we reproduce the ATLAS exclusion by using simplified model results?

SHLA files from the scan are [public on HepData](#) together with the information whether or not they are excluded, and by which search. So [let's run them through SModelS ...](#)

# 8 TeV results in SModelS v1.1.1 database

**ATLAS**

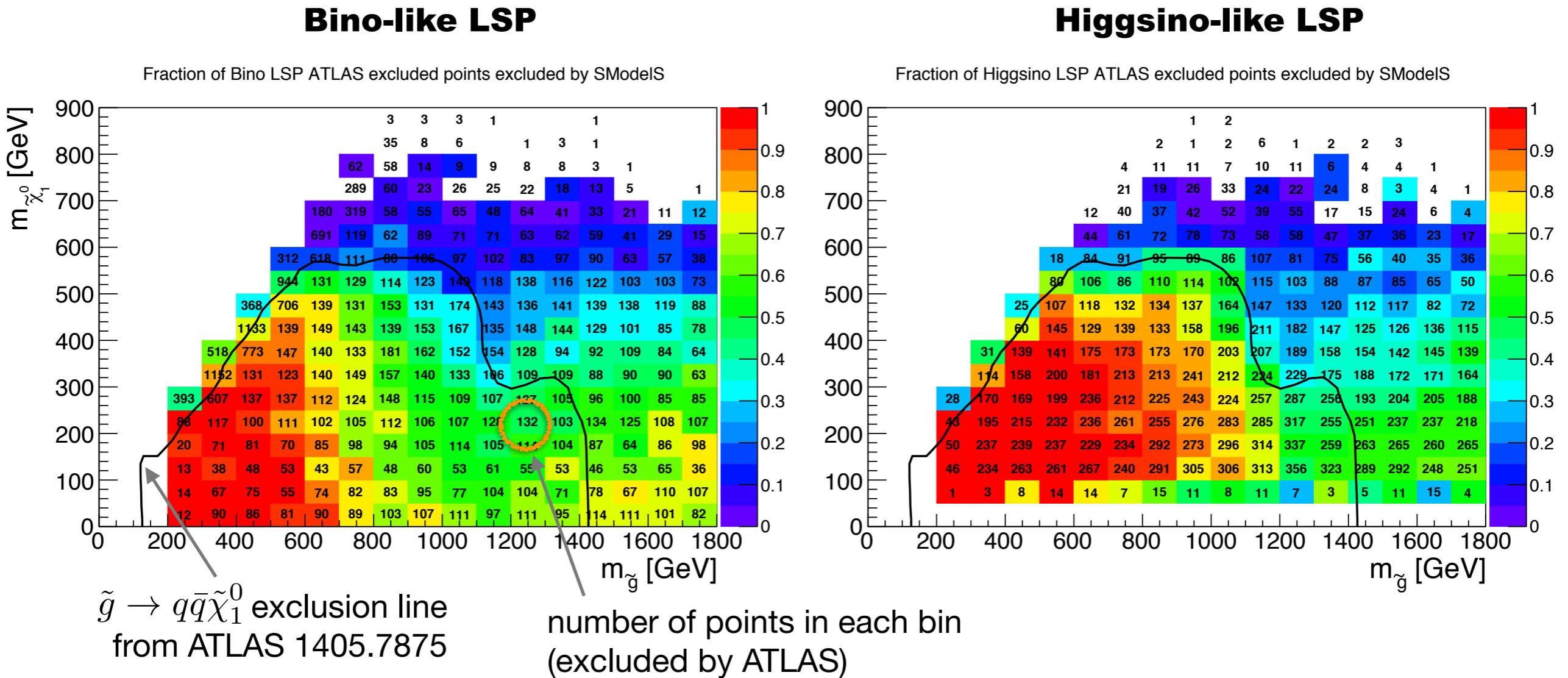
**CMS**

	<b>Analysis</b>	<b>ID</b>	<b>SModelS database</b>		<b>Analysis</b>	<b>ID</b>	<b>SModelS database</b>
Inclusive	0-lepton + 2–6 jets + $E_T^{\text{miss}}$	SUSY-2013-02*	6 UL, 2 EM		jets + $E_T^{\text{miss}}, \alpha_T$	SUS-12-028	4 UL
	0-lepton + 7–10 jets + $E_T^{\text{miss}}$	SUSY-2013-04*	1 UL, 10 EM <sup>‡</sup>		3(1b-)jets + $E_T^{\text{miss}}$	SUS-12-024	2 UL, 3 EM
	1-lepton + jets + $E_T^{\text{miss}}$	SUSY-2013-20*	1 UL from CONF-2013-089		jet multiplicity + $H_T^{\text{miss}}$	SUS-13-012	4 UL, 20 EM <sup>‡</sup>
	$\tau(\tau/\ell) + \text{jets} + E_T^{\text{miss}}$	SUSY-2013-10	—		$\geq 2$ jets + $E_T^{\text{miss}}, M_{T2}$	SUS-13-019	8 UL
	SS/3-leptons + jets + $E_T^{\text{miss}}$	SUSY-2013-09	1 UL (+5 UL, CONF-2013-007)		$\geq 1b + E_T^{\text{miss}}$ , Razor	SUS-13-004	5 UL
	0/1-lepton + 3b-jets + $E_T^{\text{miss}}$	SUSY-2013-18*	2 UL, 2 EM		1 lepton + $\geq 2b$ -jets + $E_T^{\text{miss}}$	SUS-13-007	3 UL, 2 EM
Third generation	Monojet	—	— (but monojet stop, see below)		2 OS lept. + $\geq 4(2b)$ -jets + $E_T^{\text{miss}}$	PAS-SUS-13-016	2 UL
	0-lepton stop	SUSY-2013-16*	1 UL, 1 EM		2 SS leptons + $b$ -jets + $E_T^{\text{miss}}$	SUS-13-013	4 UL, 2 EM
	1-lepton stop	SUSY-2013-15*	1 UL, 1 EM		$b$ -jets + 4 Ws + $E_T^{\text{miss}}$	SUS-14-010	2 UL
	2-leptons stop	SUSY-2013-19*	2 UL		0 lepton + $\geq 5(1b)$ -jets + $E_T^{\text{miss}}$	PAS-SUS-13-015	2 EM
	Monojet stop	SUSY-2013-21	4 EM		0 lepton + $\geq 6(1b)$ -jets + $E_T^{\text{miss}}$	PAS-SUS-13-023	4 UL
	Stop with $Z$ boson	SUSY-2013-08	1 UL		1 lepton + $\geq 4(1b)$ -jets + $E_T^{\text{miss}}$	SUS-13-011	4 UL, 2 EM
	$2b$ -jets + $E_T^{\text{miss}}$	SUSY-2013-05*	3 UL, 1 EM <sup>‡</sup>		$b$ -jets + $E_T^{\text{miss}}$	PAS-SUS-13-018	1 UL
Electroweak	$tb+E_T^{\text{miss}}$ , stop	SUSY-2014-07	—		soft leptons, few jets + $E_T^{\text{miss}}$	SUS-14-021	2 UL
	$\ell h$	SUSY-2013-23*	1 UL		multi-leptons + $E_T^{\text{miss}}$	SUS-13-006	6 UL
	2-leptons	SUSY-2013-11	4 UL, 4 EM <sup>‡</sup>		incl. ‘home-grown’ EMs produced with MadAnalysis5 or CheckMATE recasting.		
	$2\tau$	SUSY-2013-14	—				
	3-leptons	SUSY-2013-12	5 UL				
	4-leptons	SUSY-2013-13	—				
Other	Disappearing Track	SUSY-2013-01	<i>n.a. in current framework</i>				
	Long-lived particle	—	<i>n.a. in current framework</i>				
	$H/A \rightarrow \tau^+\tau^-$	—	<i>n.a. in current framework</i>				

\* plus Fastlim EMs for preliminary version (conf note) of the analysis.

† incl. ‘home-grown’ EMs produced with MadAnalysis5 or CheckMATE recasting.

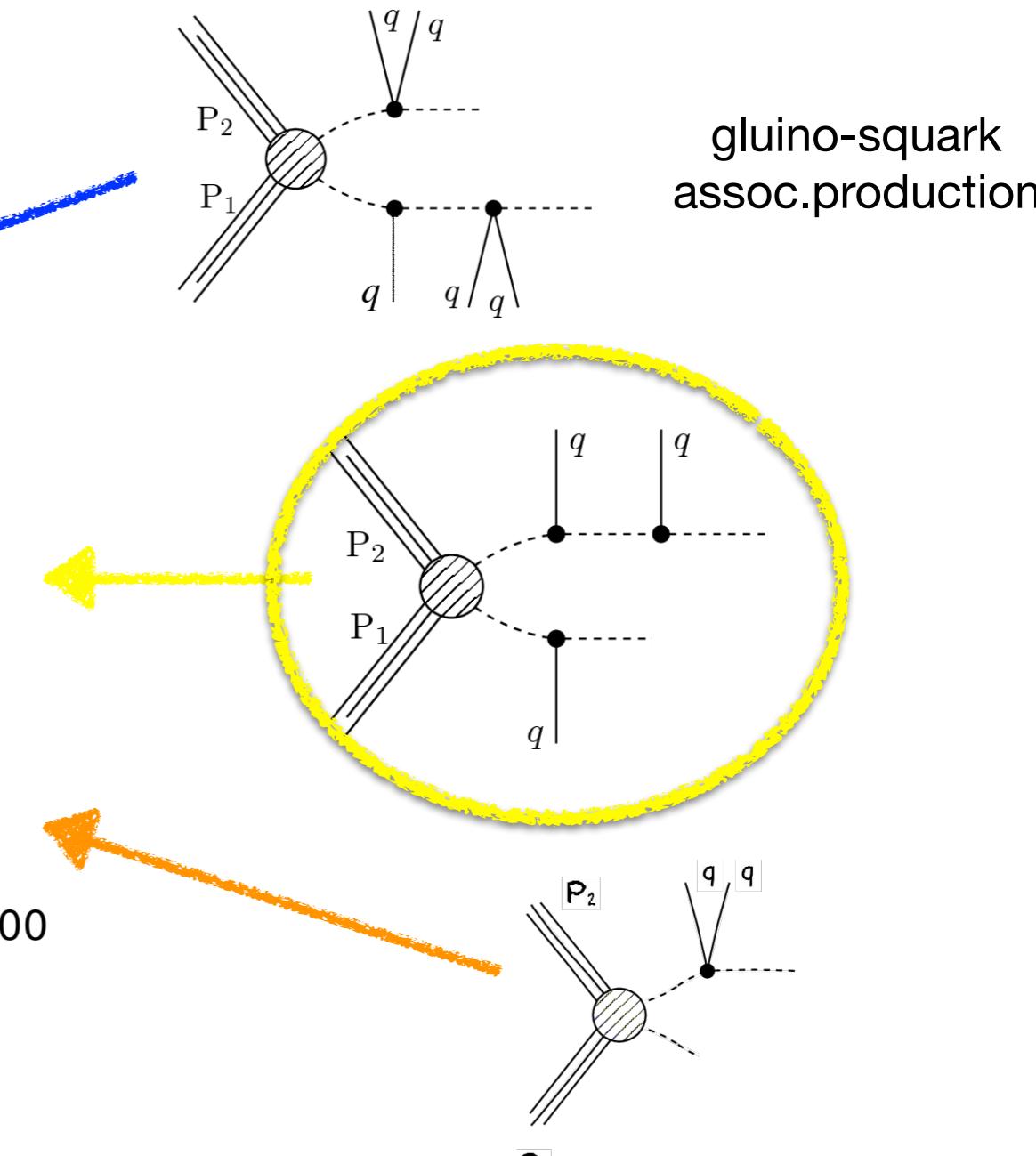
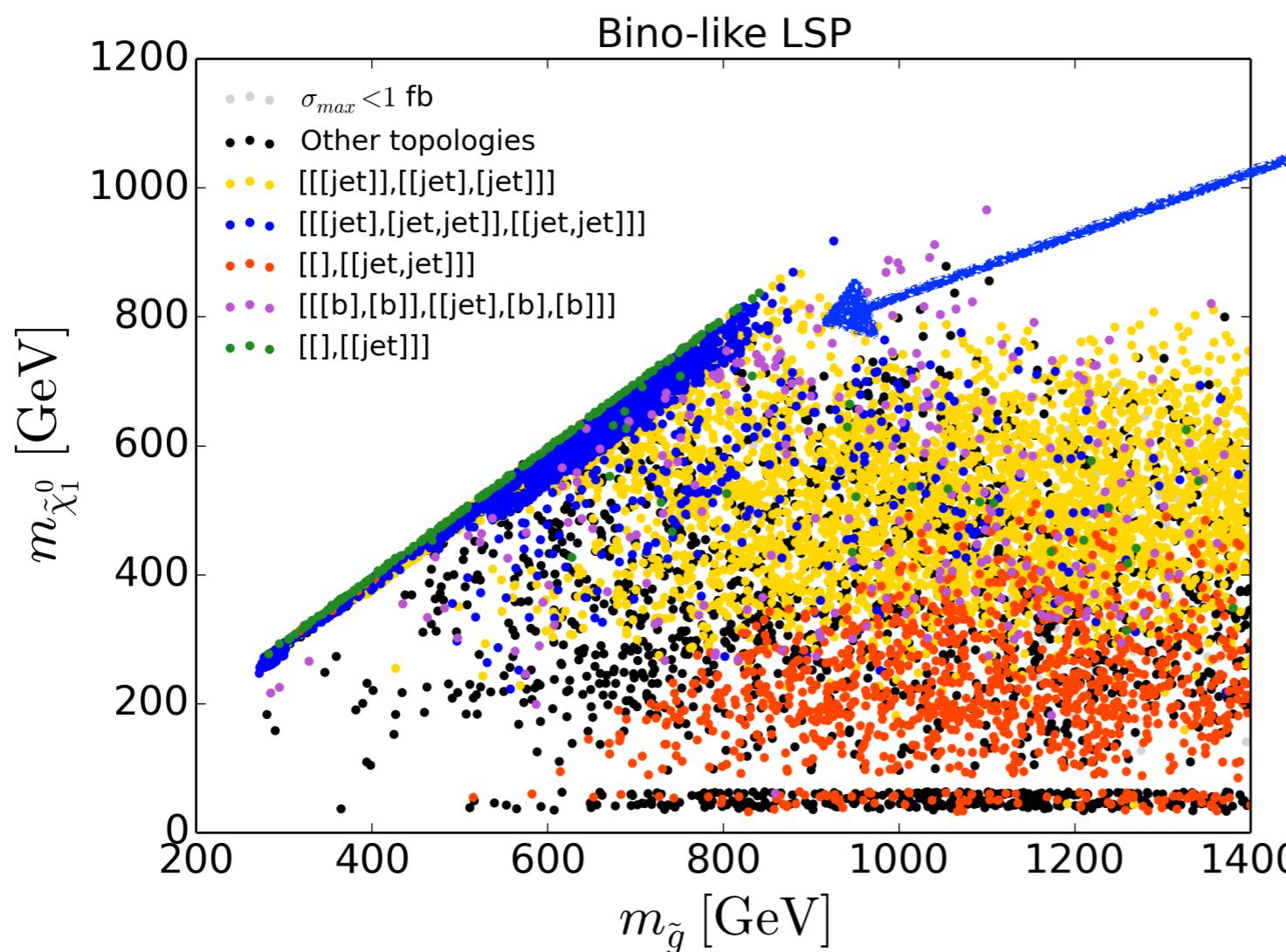
# Coverage in gluino vs. neutralino mass plane



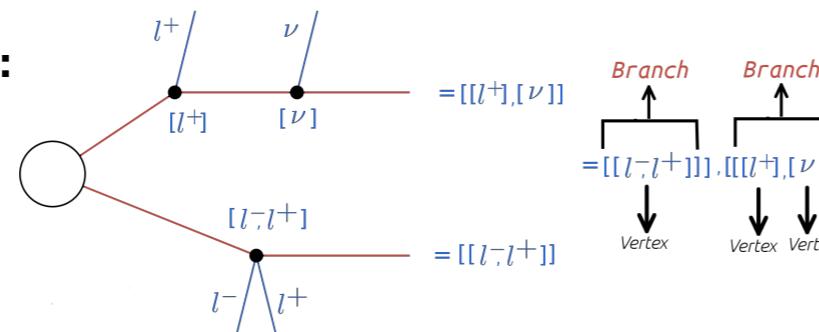
- Coverage drops for intermediate gluino masses, where a larger variety of decay channels becomes available; more pronounced for bino than for higgsino LSP.
- NB only the part of the cross section that goes into simplified model topologies, for which SMS results are available, can be constrained by SModelS.

# Most important missing topologies

i.e. topologies for which no SMS results are available



**Bracket notation:**

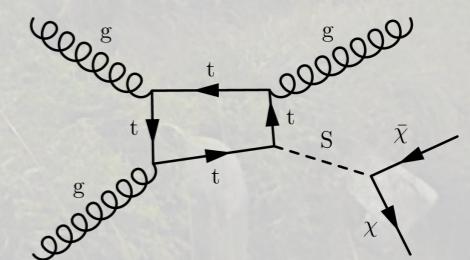


# Conclusions & outlook

- SModelS is an automated public tool for testing BSM scenarios with a  $Z_2$  symmetry against ATLAS and CMS searches in the context of simplified model spectra results
- Interfaced from micrOMEGAs for fast testing of DM scenarios against LHC constraints
- Also identifies relevant missing SMS topologies
- Caution: full models can be decomposed into SMS components, but **SMS do not fully map a complex model** → **limits are conservative**



- Combination of signal regions : v1.1.3 to be released soon
- Inclusion of lifetimes to be able to treat also LLP results
- Extension to general topologies **beyond the 2-branch structure** to include also constraints for mono-X searches  
→ need to revisit SMS assumptions, perhaps include quantum numbers topologies





# thanks to:

Federico Ambrogi, Juhi Dutta, Humberto Reyes Gonzalez, Suchita Kulkarni,  
Ursula Laa, Andre Lessa, Veronika Magerl, Jory Sonneveld, Michael Traub,  
Wolfgang Waltenberger, Matthias Wolf

plus people collaborating on physics projects: Chiara Arina, Genevieve Belanger, Mark Goodsell, Sophie Williamson, ....

# Backup

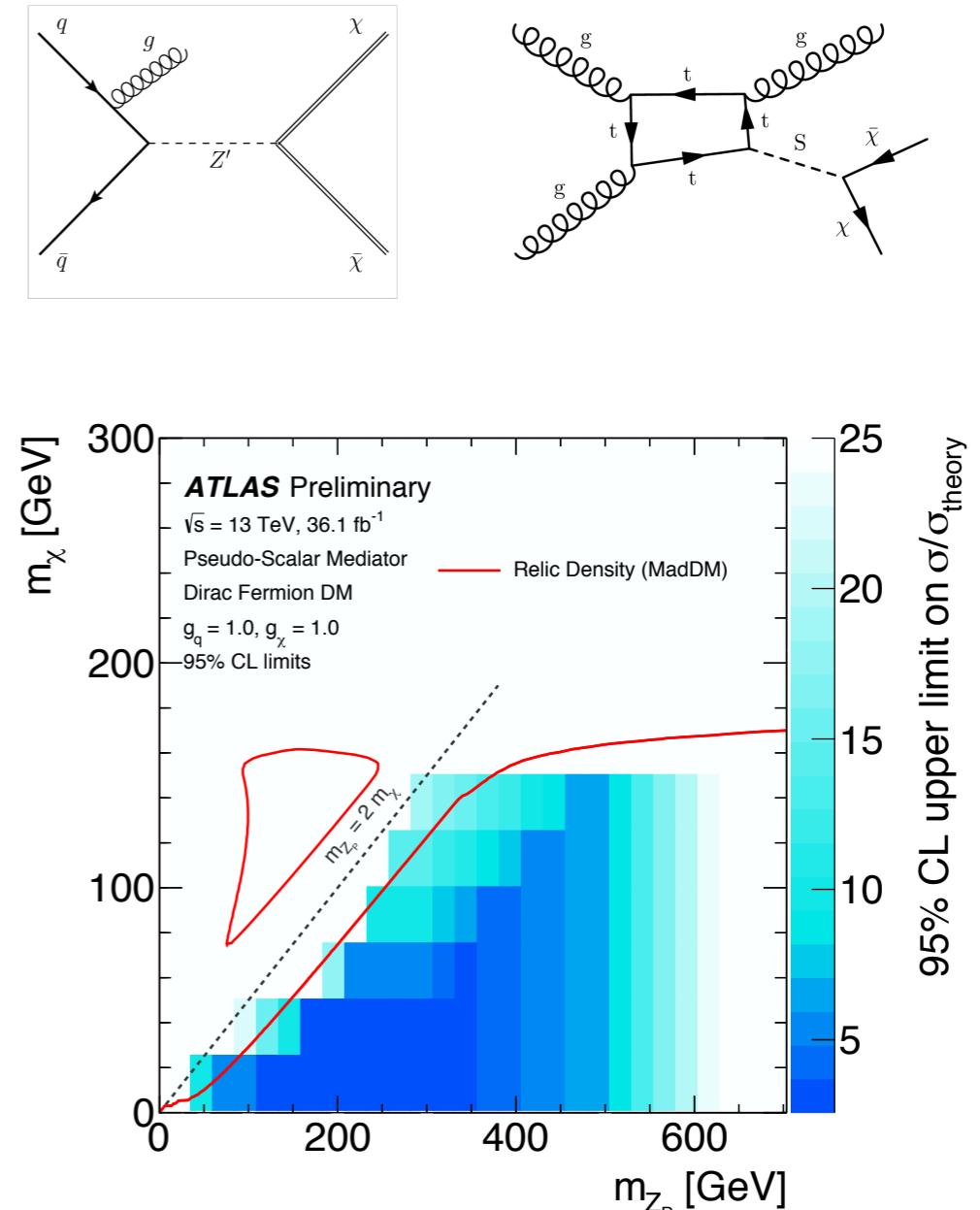
# Dark matter simplified model results

- At the LHC, DM production is searched for in mono-X signatures, e.g. mono-jet, or in association with heavy flavour quarks.
- Interpreted in terms of EFT or simplified model with a **DM particle plus a mediator**.
- *Primary presentation recommended [...] are plots of the experimental confidence level (CL) limits on the signal cross sections as a function of the two mass parameters  $m_{DM}$  and  $M_{med}$*  .

LHC DM WG, 1603.04156

- In practice, constraints are presented by ATLAS and CMS as **95% CL limits on  $\sigma/\sigma_{\text{theory}}$** , which is **highly model dependent**.

- Would need to **unfold  $\sigma_{\text{theory}}$**  to use these results, but reference cross section not provided.  
Source of systematic uncertainty.



- When variety of signal topologies exists, efficiency maps would b useful.

# (Re)interpretation methods

## Plus

- Fast, suitable for scans and model surveys
- Easy classification of uncovered signatures

## Minus

- Only simple topologies
- Availability of re-usable results (useful format)
- Validity of SMS assumptions

[SModelS, Fastlim, XQCUT]

**Use Simplified Model results**

**Reproduce exp. analyses in MC event simulation**

**Machine learning techniques**

- train an algorithm onto relation btw theory parameters and data

Fast and precise, but so far model-specific  
[SUSY-AI, SCINet]

## Plus

- More general, more precise
  - Can test prospects of improving an analysis

## Minus

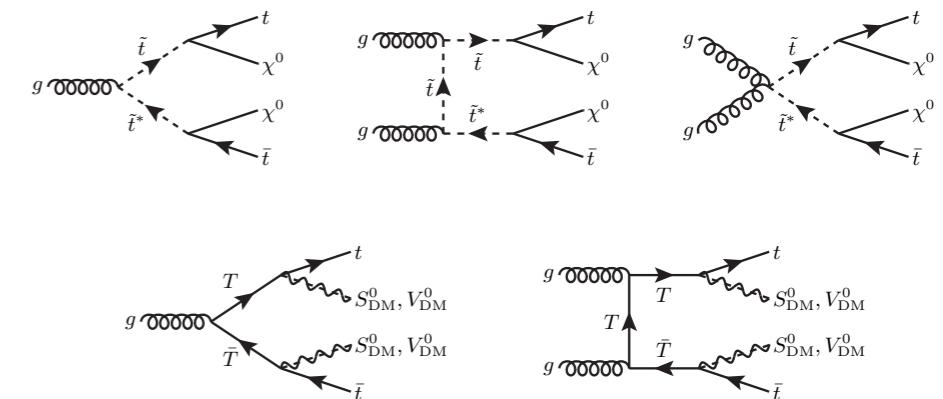
- Need detailed information from experiment about each analysis
- Need emulation of detector effects
- Very CPU time consuming
- So far only cut&count analyses

[CheckMATE, MadAnalysis5, Rivet, Gambit]

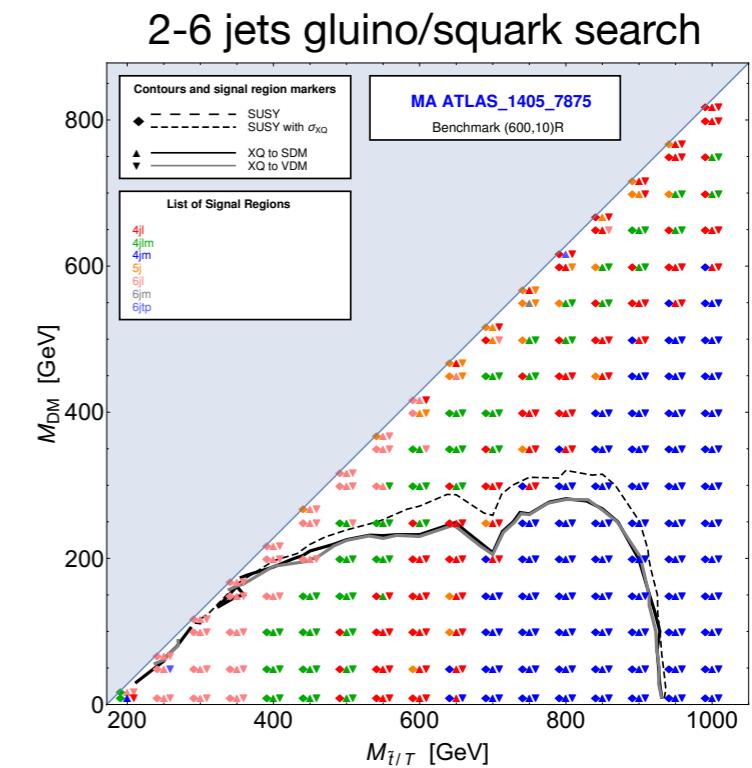
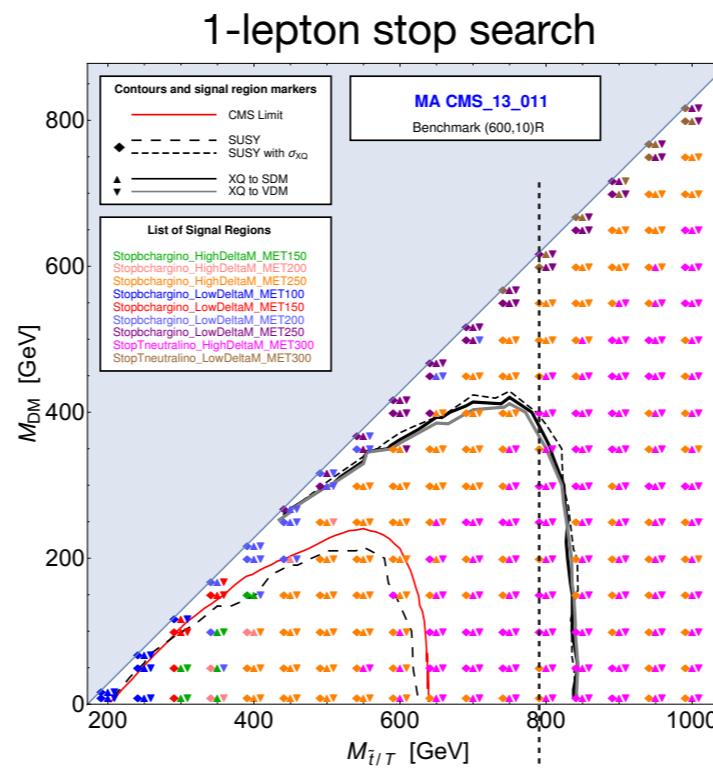
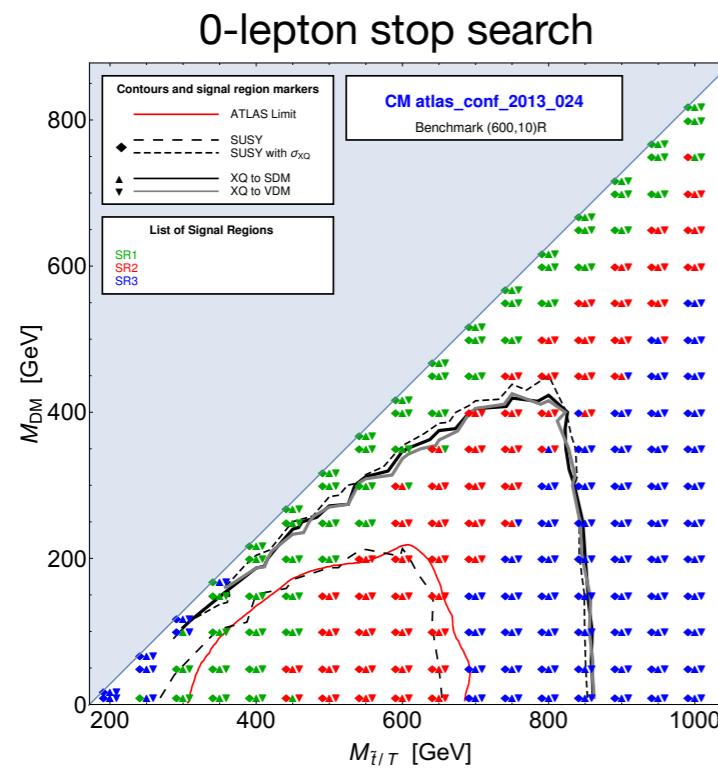
# Scalar versus fermionic top-partner interpretation of ttbar + MET searches

SK, Laa, Panizzi, Prager, 1607.02050

- Used ATLAS and CMS SUSY searches in ttbar+MET final state at Run 1 to constrain scenarios with a fermionic top partner and a dark matter candidate.
- Efficiencies in all-hadronic, 1-lepton and 2-lepton channels are very similar for scalar and fermionic top partners.
- SMS results for stop–neutralino simplified models can also be applied to fermionic top-partner models, provided the narrow width approximation holds in the latter.
- Official eff. maps don't extend to high enough masses, so we provide our own: <http://lpsc.in2p3.fr/projects-th/recasting/susy-vs-vlq/ttbarMET/>



Generic gluino/squark search can also provide a limit on fermionic top partners, due to higher  $M_{\text{eff}}$  than for stops.



official plots stop here