Interpreting the simplified models results from the LHC with SModelS

Federico Ambrogi

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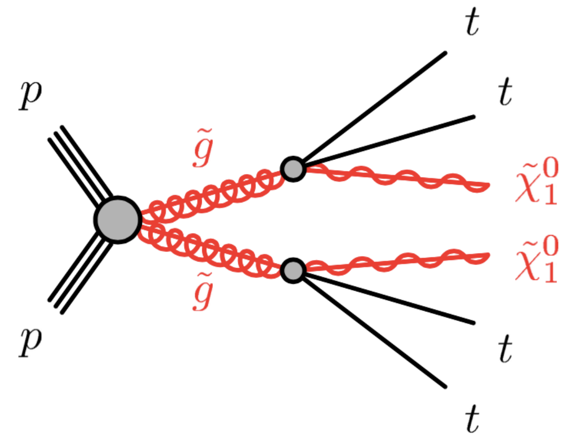
In collaboration with Sabine Kraml, Suchita Kulkarni, Ursula Laa, Andre Lessa, Veronika Magerl, Wolfgang Waltenberger

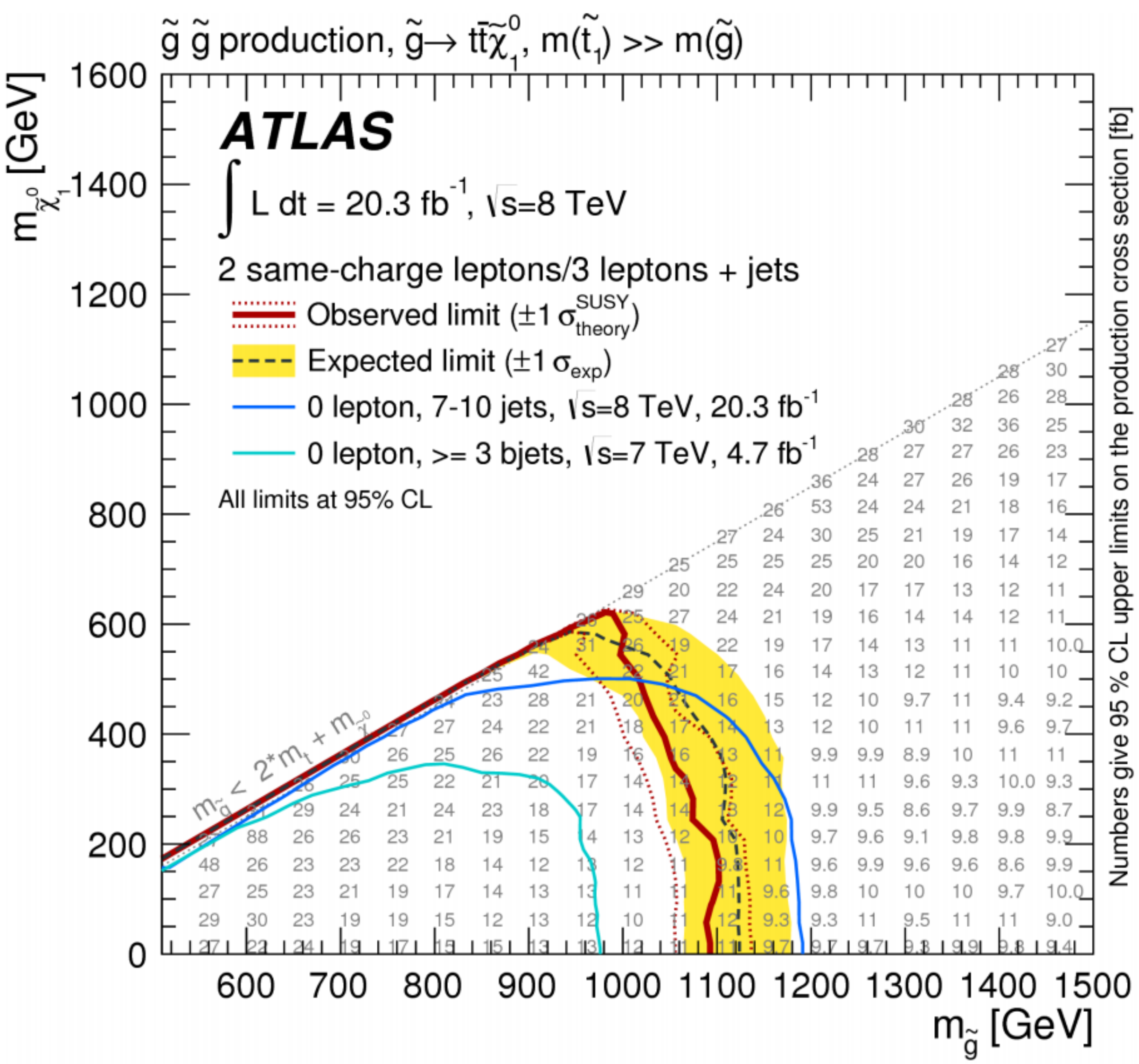
Introduction: Simplified Model Interpretation

Typically results for Beyond Standard Model (BSM) searches are presented in terms of Simplified Models Spectra (SMS).



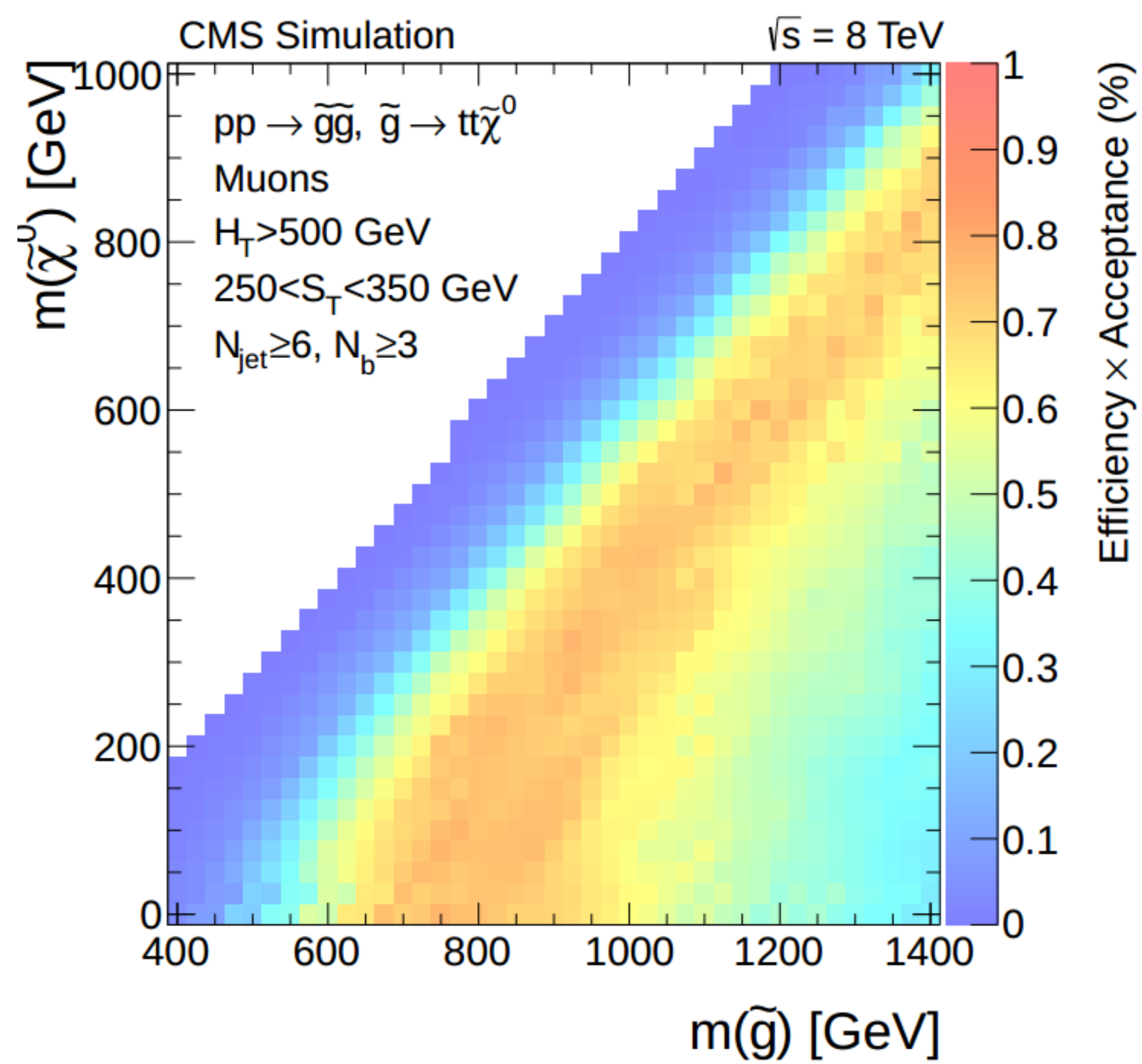
Upper Limit (UL) Map

ATLAS-SUSY-2013-09



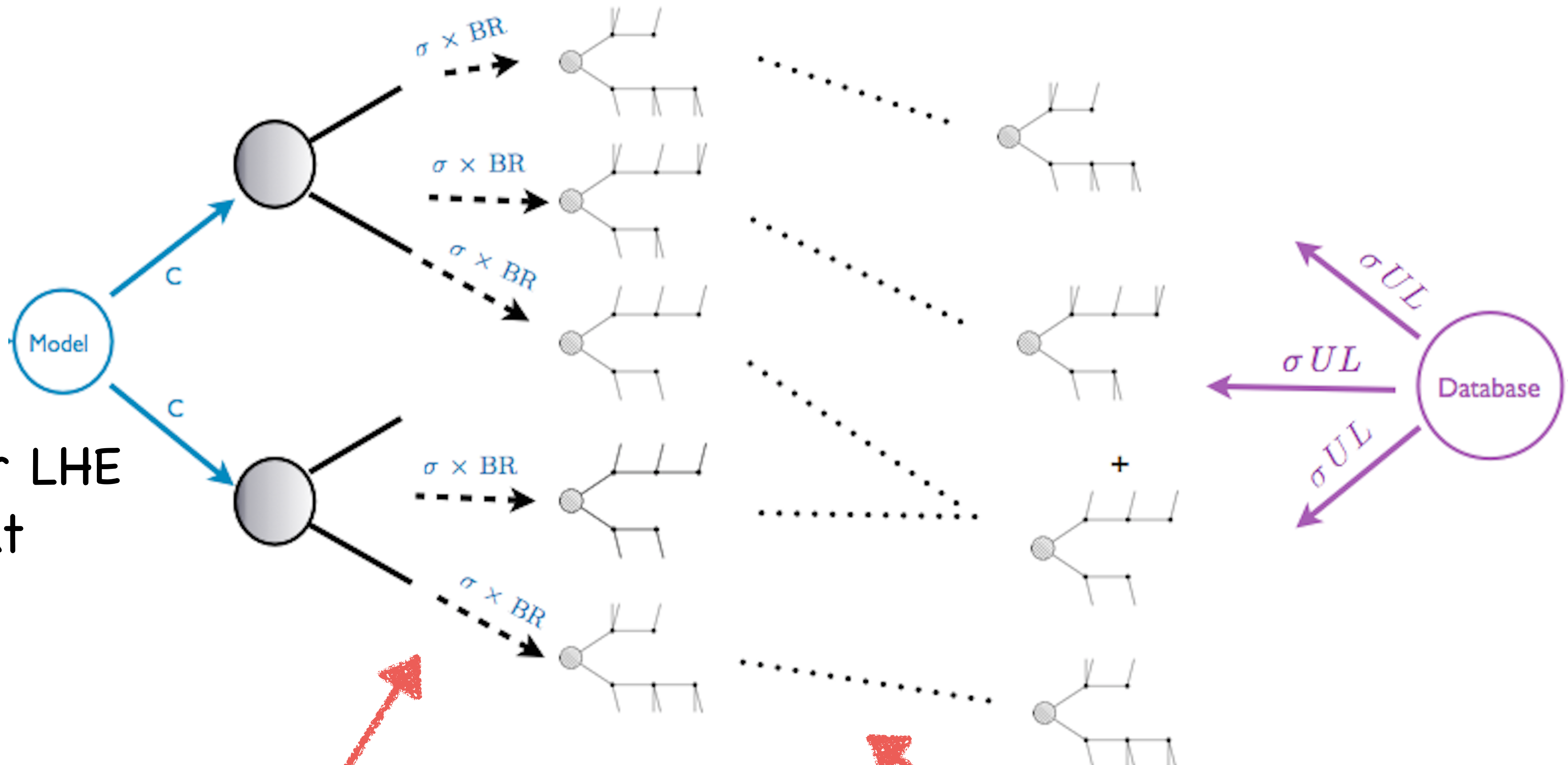
Signal Efficiency Map (EM)

CMS-SUS-13-007



SModelS: Basic Concepts

SModelS is designed to constrain generic BSM models using the LHC SMS results



SLHA or LHE input

Decomposition

Theory Module

Comparison

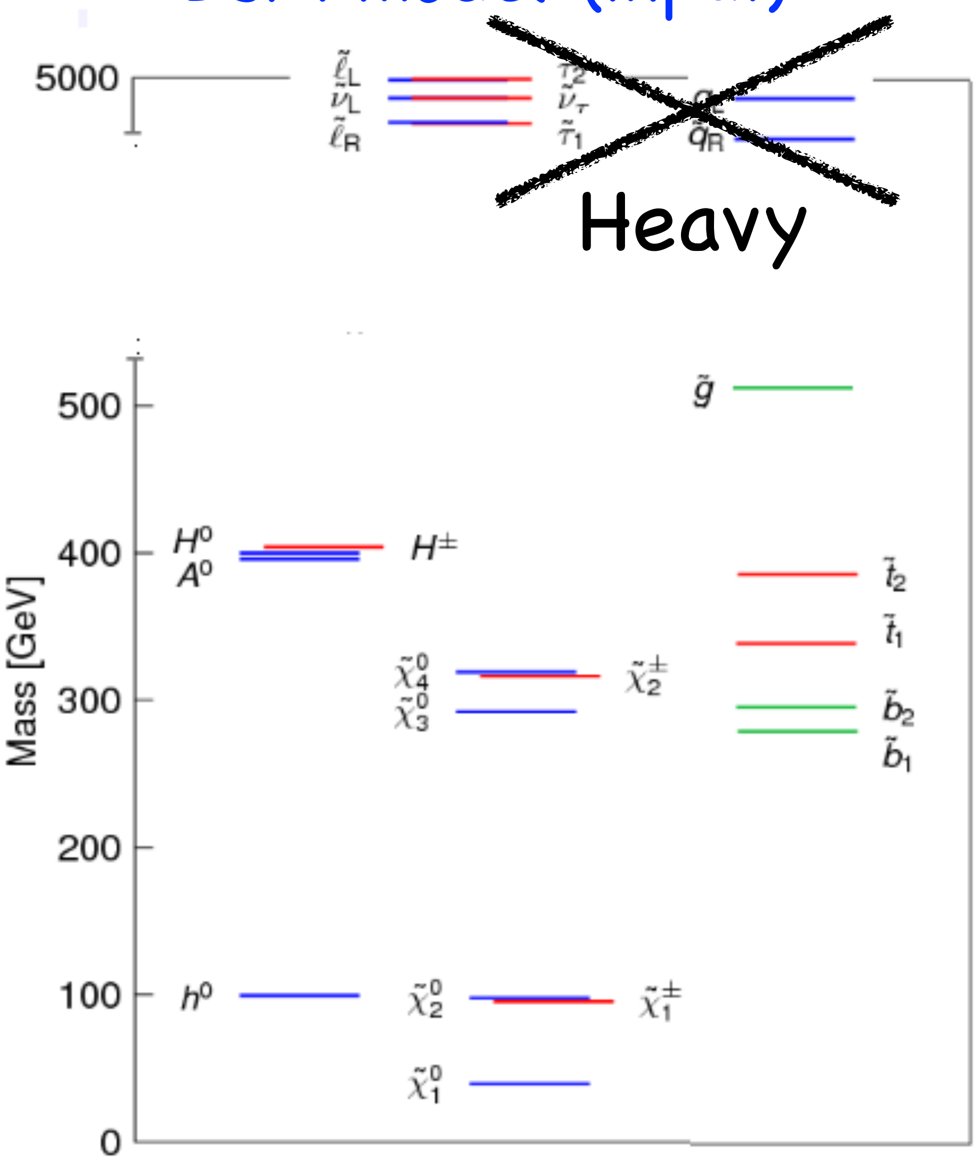
Database of experimental results

Theory Module

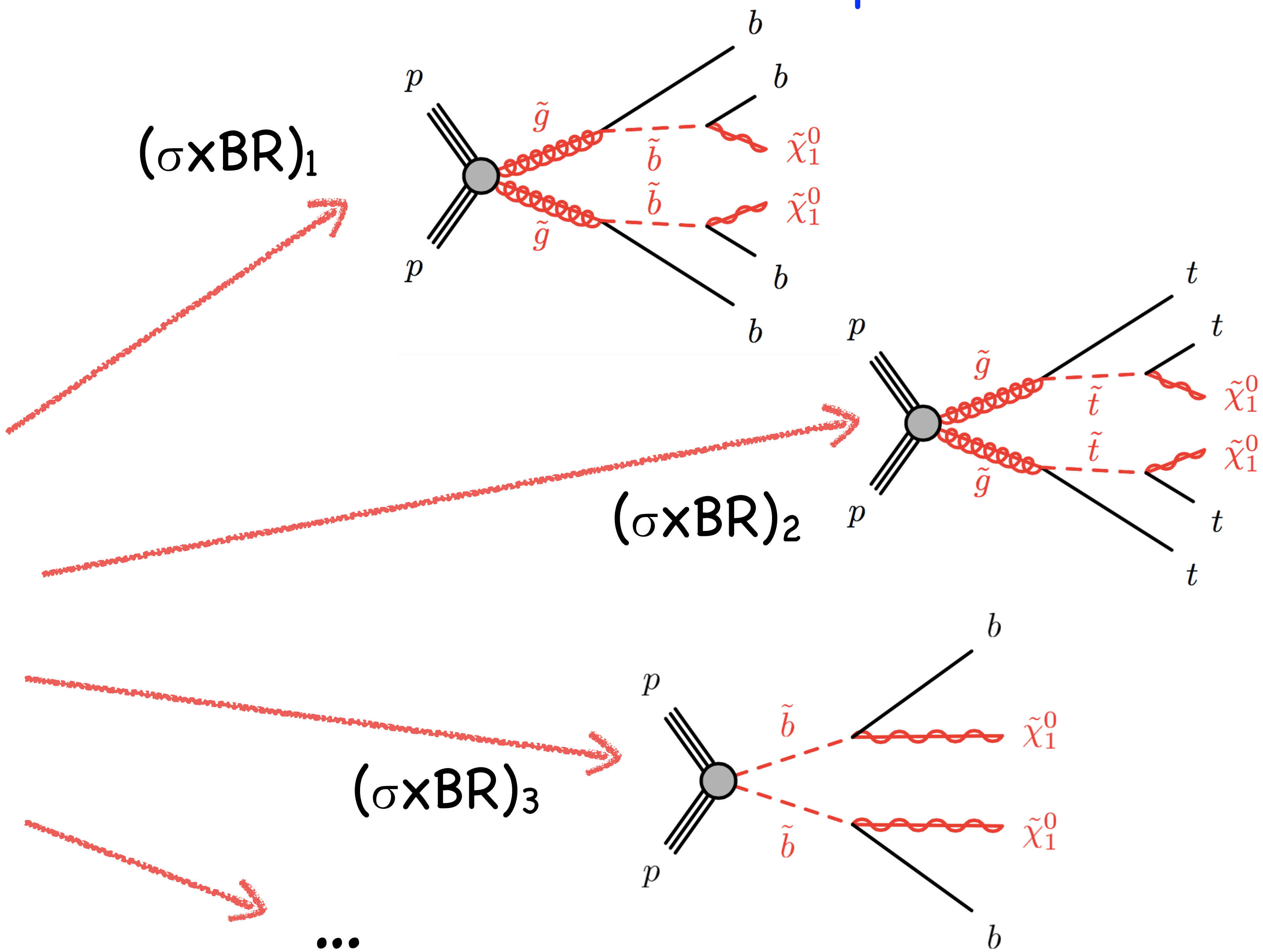
Decomposition

A generic BSM model is decomposed into its SMS
(a Z_2 symmetry is required, e.g. R-parity for SUSY models)

BSM model (input)



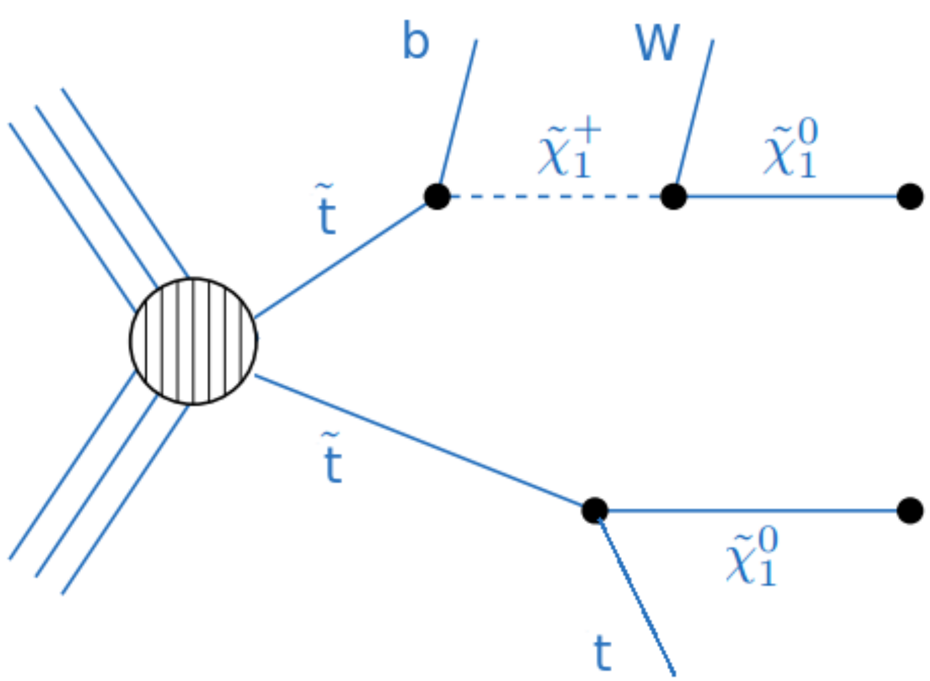
SMS Decomposition

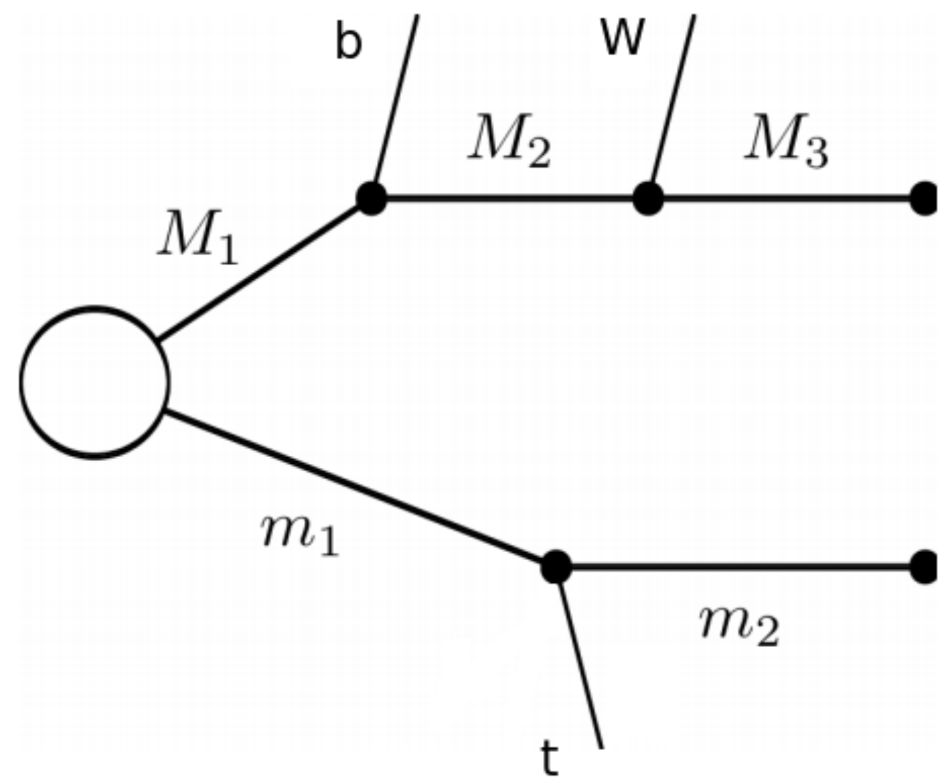


Theory Module

The decomposition maps each BSM model into its SMS spectra; each element or topology is characterised by:

- the spectrum of particles
- σ x BR
- the decay chain





= [[[b],[W]] , [[t]]]

SModelS bracket notation

How can we use the decomposed topologies to constrain the generic model ?

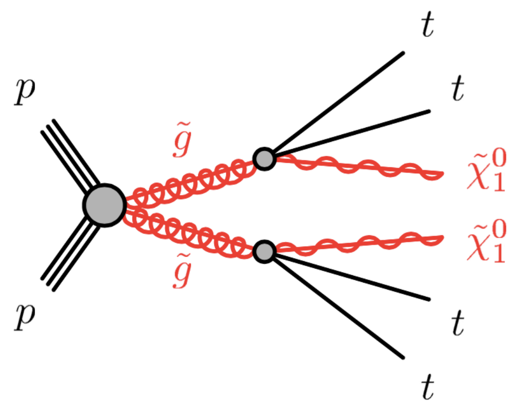
Theory vs Experimental Results: Comparison

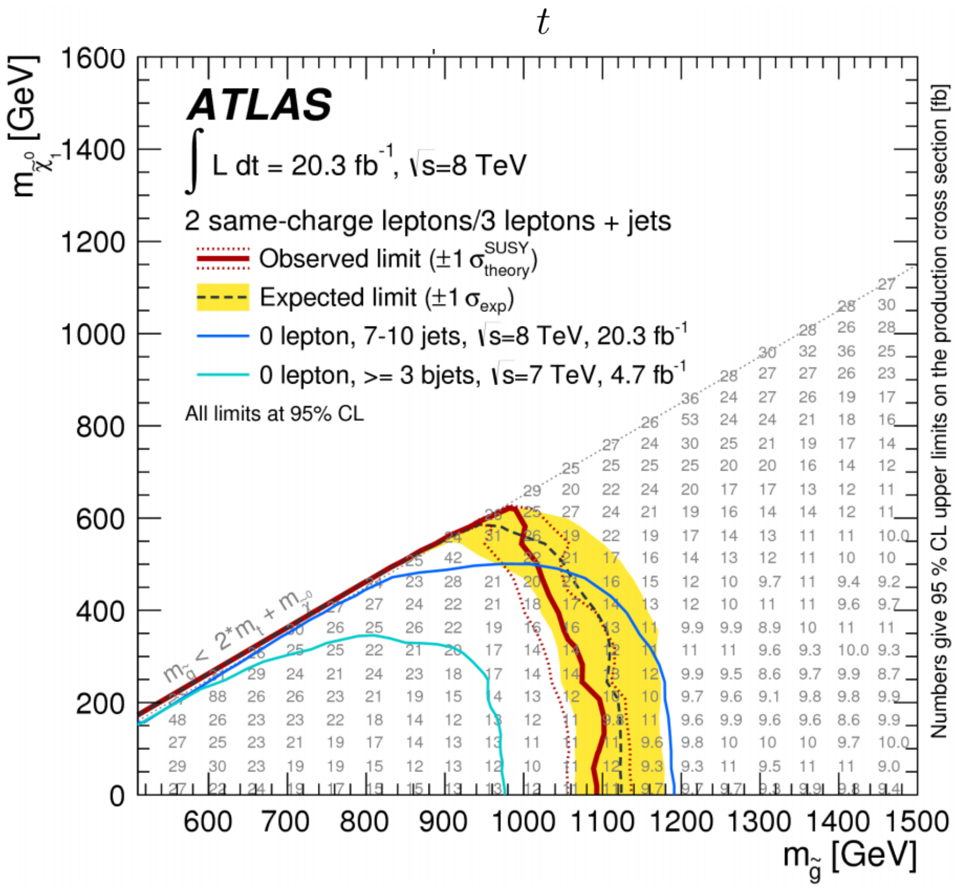
For every topology:

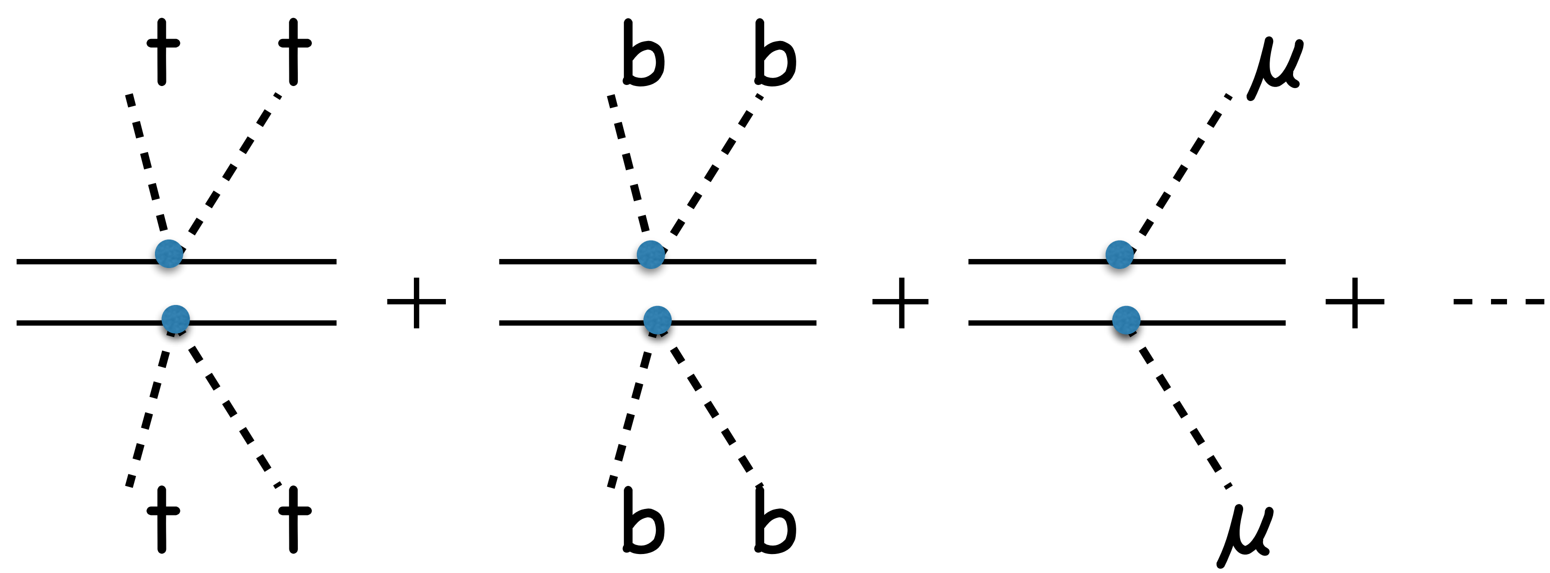
- Search in the database for analyses constraining this SMS
- Evaluate the theory prediction

UL Theory Prediction

$$\text{Th. Prediction} = \Sigma_i \, \text{Weight}_i \times (\sigma \times BR)_i$$







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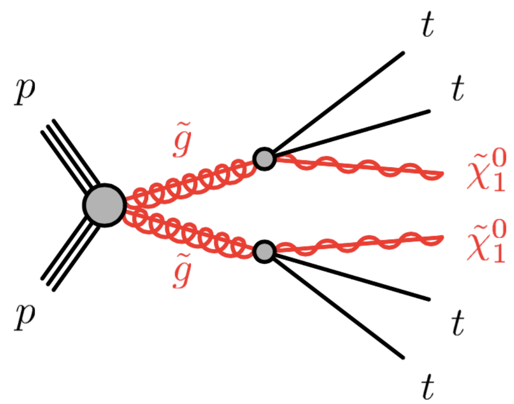
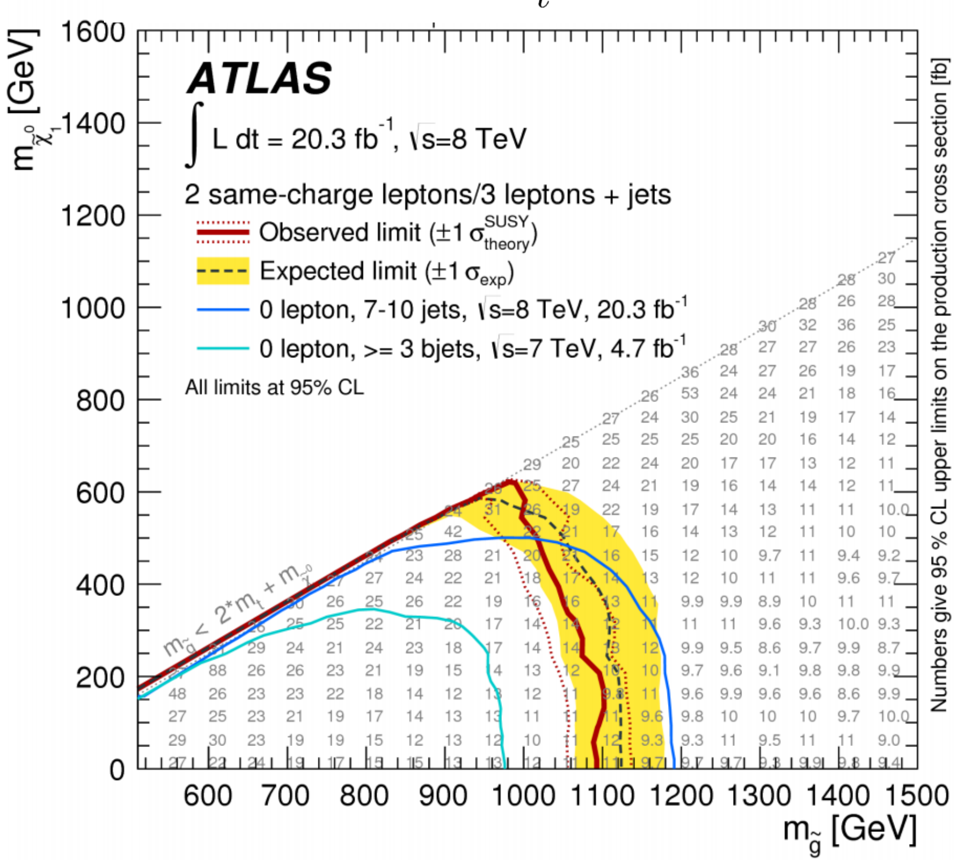
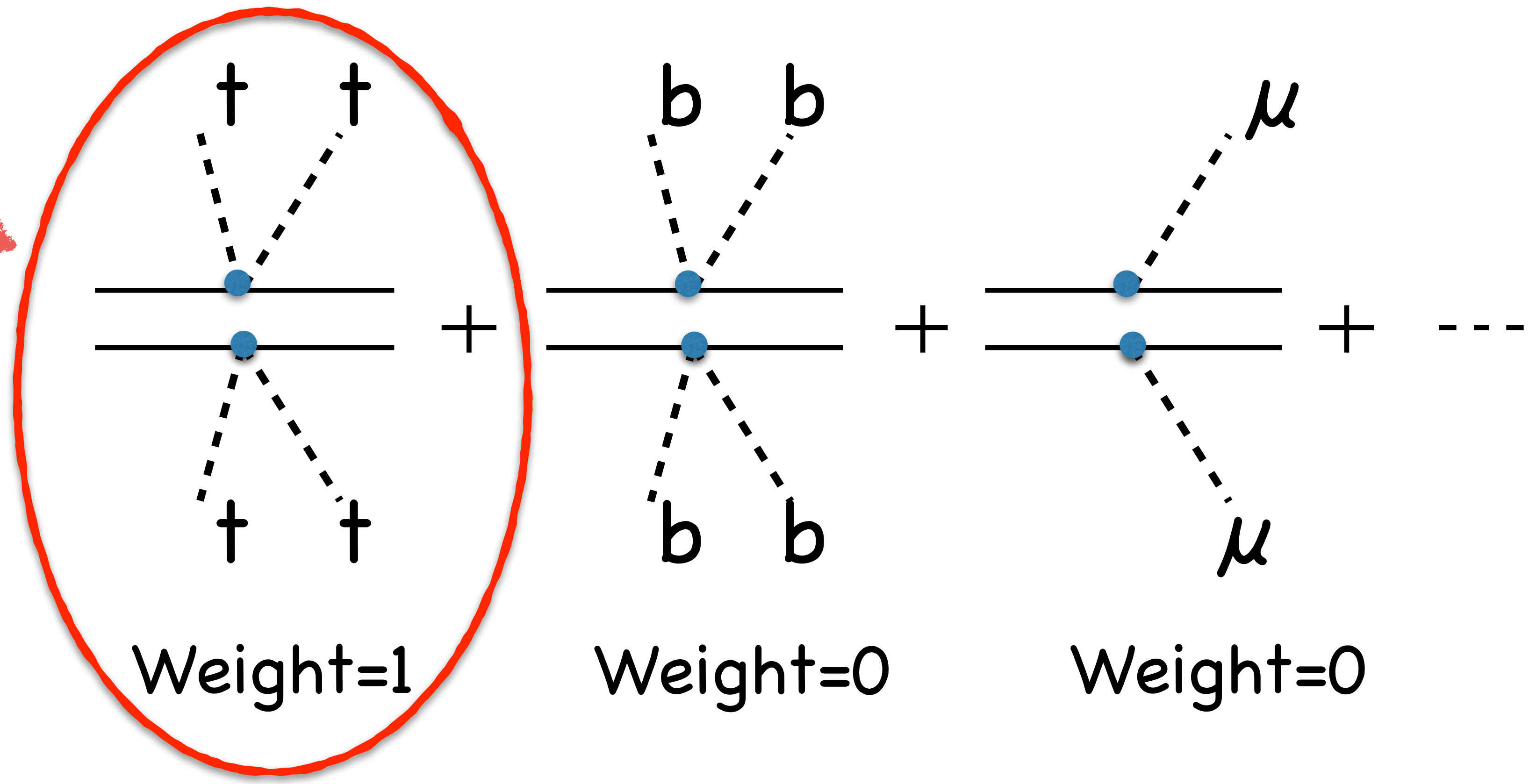






<u>Only the element associated to the UL result considered contributes with a non-zero weight</u>

Theory vs Experimental Results: Comparison

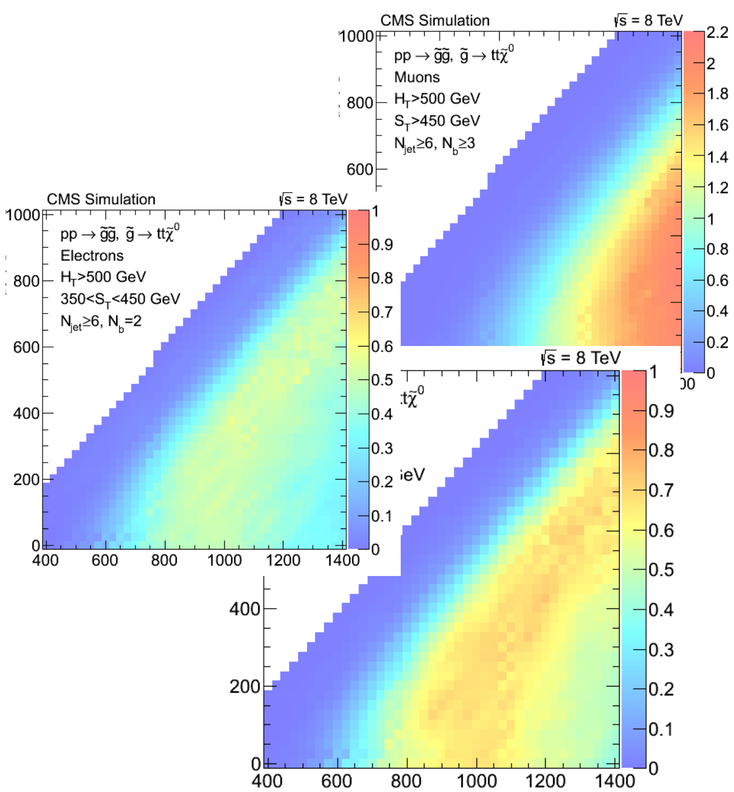
For every topology:

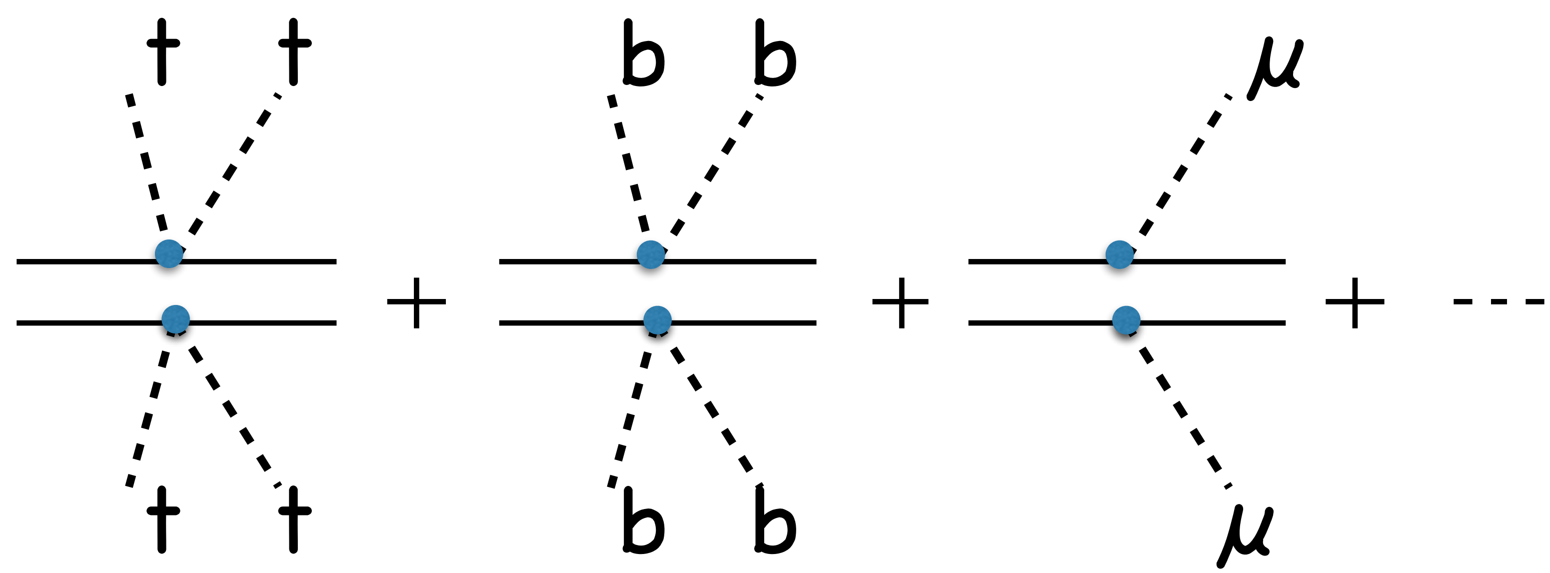
- Search in the database for analyses constraining this SMS
- Evaluate the theory prediction

EM Theory Prediction

$$\boxed{\text{Th. Prediction} = \Sigma_i\ \text{Weight}_i \times (\sigma \times BR)_i}$$

EM for all the Signal Regions





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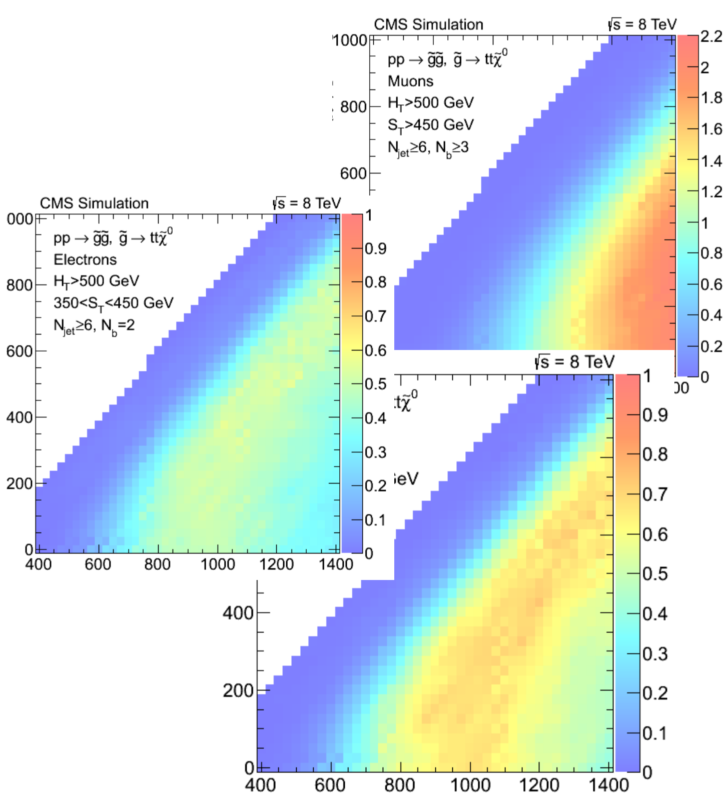

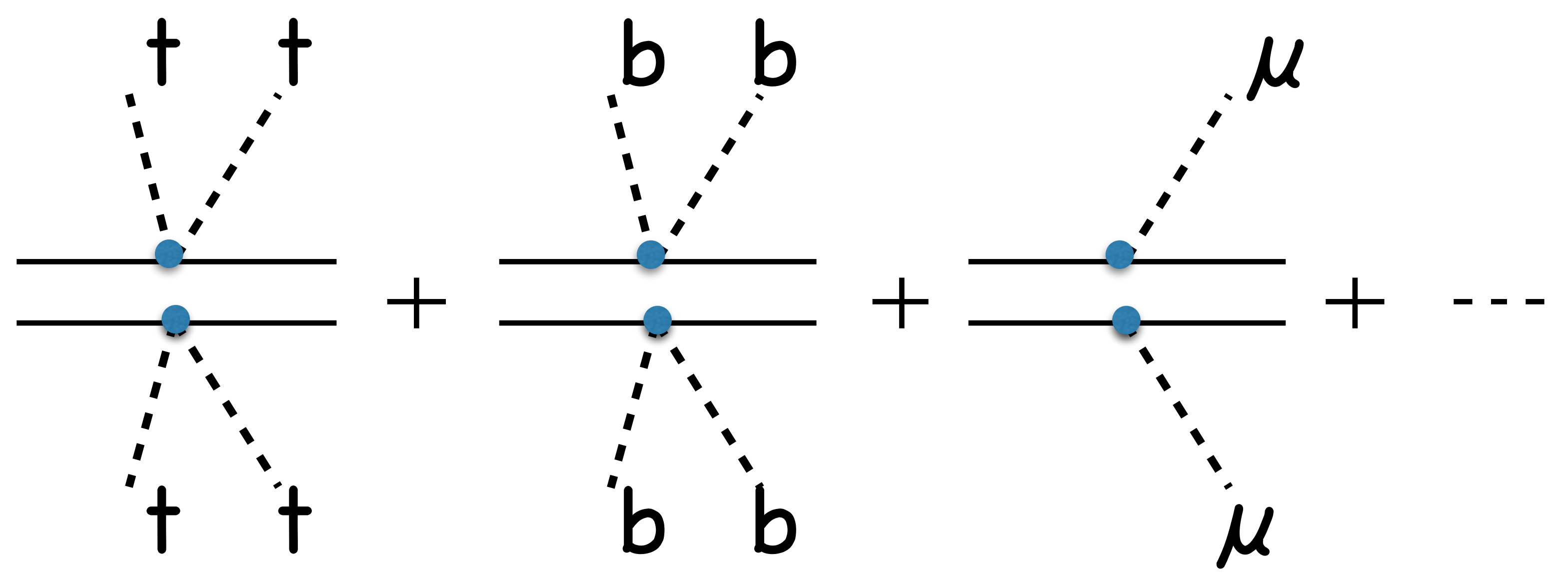

Weight=ϵ_1 Weight=ϵ_2 Weight=ϵ_3

Each topology is weighted by the proper efficiency value*

*The "best signal region", leading to the best expected limit, is used

Theory vs Experimental Results: Comparison

For every topology:

- Search in the database for analyses constraining this SMS
- Evaluate the theory prediction
- Compare with experimental results

If: $$\boxed{\frac{\sigma_{Theo}}{\sigma_{Exp}} > 1}$$ for at least one of the experimental analysis, the model is considered **excluded**

Main advantages of using EM:

- combination of results for different topologies
- it is possible to create "homegrown" EM thanks to the use of public recasting tools such as MadAnalysis5[1] and CheckMATE[2]

[1]Eur.Phys.J. C74 (2014) 3103
[2]arXiv:1312.2591

SModelS: Output Example

```
Input status: 1
Decomposition output status: 1 #decomposition was successful
# Input File: inputFiles/slha/gluino_squarks.slha
# maxcond = 0.2
# minmassgap = 5.
# sigmacut = 0.03
# Database version: 1.0.91
======================================================================
#Analysis  Sqrts  Cond. Violation  Theory_Value(fb)  Exp_limit(fb)  r

     CMS-SUS-13-019  8.00E+00    0.0  1.773E+00  3.762E+00  4.714E-01
 Signal Region:  (UL)
 Txnames:  T2
----------------------------------------------------------------------
 ATLAS-SUSY-2013-02  8.00E+00    0.0  6.617E+00  1.718E+01  3.851E-01
 Signal Region:  (UL)
 Txnames:  T6WW
----------------------------------------------------------------------
 ATLAS-SUSY-2013-02  8.00E+00    0.0  5.525E-01  1.839E+00  3.005E-01
 Signal Region:  SR2jt
 Txnames:  T1, T2
....
======================================================================
The highest r value is = 4.71E-01
======================================================================
Missing topologies with the highest cross-sections (up to 10):
Sqrts (TeV)   Weight (fb)        Element description
  8.0   5.958E+01    #                          [[[W]],[[W]]]
  8.0   1.567E+01    #               [[[jet],[W]],[[jet,jet],[W]]]
...
```

The output includes:

- list of analyses constraining each topology
- "best signal region" used to derive the UL
- experimental UL
- r values for each result
- …

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=====================================================================
#Analysis  Sqrts  Cond. Violation  Theory_Value(fb)  Exp_limit(fb)  r

     CMS-SUS-13-019  8.00E+00    0.0  1.773E+00  3.762E+00  4.714E-01
 Signal Region:  (UL)
```

The output includes:

- list of analyses constraining each topology
- "best signal region" used to derive the UL
- experimental UL
- r values for each result
- ...

Missing topologies: topologies with the highest cross sections not implemented in the SModelS database

It helps individuating the SMS that can better constrain the parameters space of the model tested

```
=====================================================================
Missing topologies with the highest cross-sections (up to 10):
Sqrts (TeV)   Weight (fb)        Element description
  8.0   5.958E+01    #                          [[[W]],[[W]]]
  8.0   1.567E+01    #              [[[jet],[W]],[[jet,jet],[W]]]
...
```

Experimental Database

SModelS features an up-to-date and comprehensive database of SMS results from the searches performed by ATLAS and CMS (data from ATLAS/CMS twiki and HepData)

SModelS v.1.0.4 -> UL results

SModelS v. 1.1 (upcoming) -> UL and EM results

$\sim$ 14 publications + 16 CONF notes

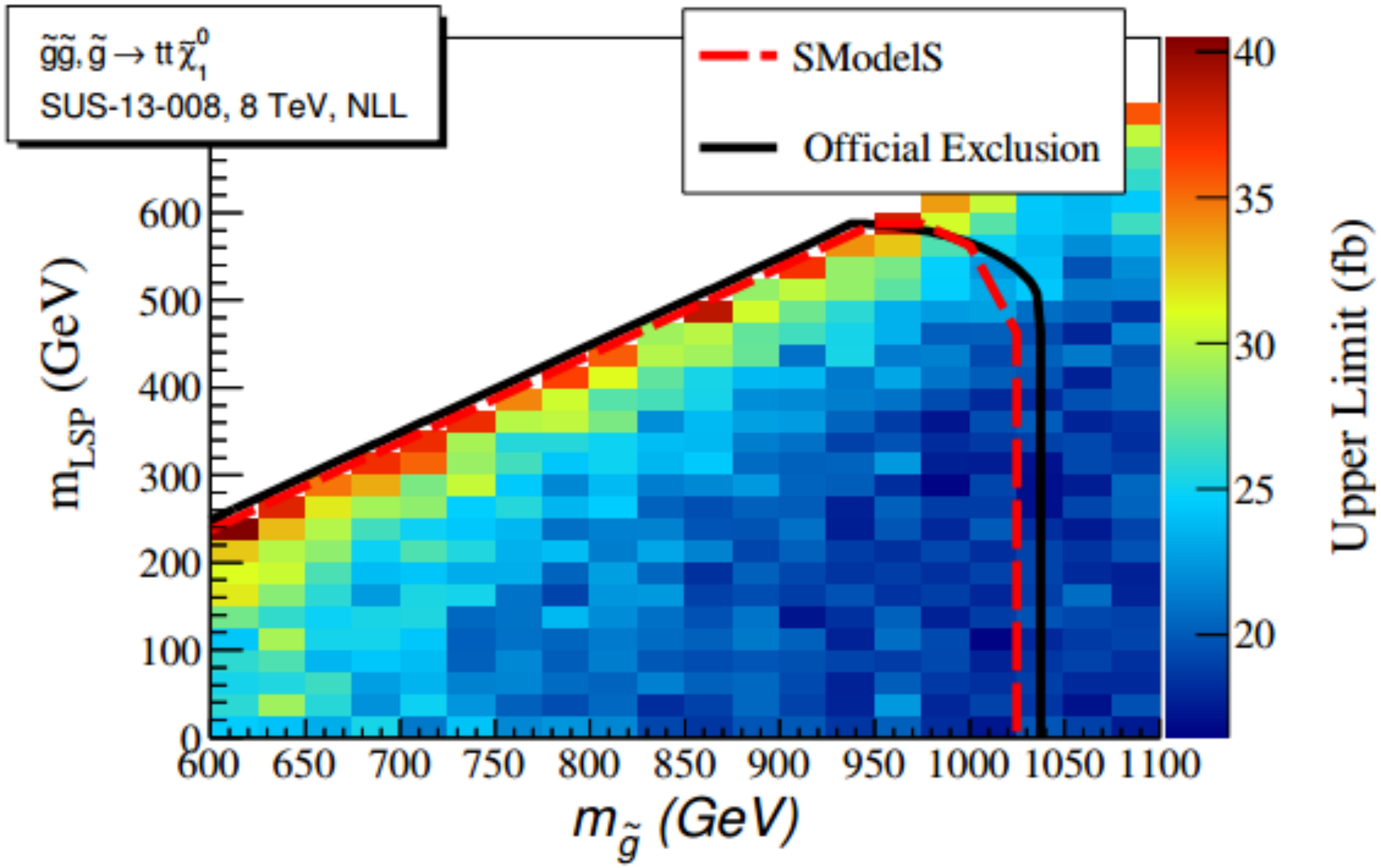
Experimental Result	$\sqrt{s}$	lumi	data type
ATLAS-CONF-2012-105	8	5.8	upperLimit
ATLAS-CONF-2012-166	8	13.0	upperLimit
ATLAS-CONF-2013-001	8	12.8	upperLimit
ATLAS-CONF-2013-007	8	20.7	upperLimit
...	...	...	...
ATLAS-SUSY-2013-14	8	20.3	upperLimit
ATLAS-SUSY-2013-15	8	20.3	efficiencyMap
ATLAS-SUSY-2013-15	8	20.3	upperLimit
ATLAS-SUSY-2013-16	8	20.1	efficiencyMap
ATLAS-SUSY-2013-16	8	20.1	upperLimit
ATLAS-SUSY-2013-18	8	20.1	efficiencyMap
ATLAS-SUSY-2013-18	8	20.1	upperLimit
ATLAS-SUSY-2013-19	8	20.3	upperLimit
ATLAS-SUSY-2013-23	8	20.3	upperLimit
ATLAS-SUSY-2014-03	8	20.3	efficiencyMap
ATLAS-SUSY-2015-09	13	3.2	upperLimit

$\sim$ 13 publications + 5 PAS

Experimental Result	$\sqrt{s}$	lumi	data type
CMS-SUS-12-024	8	19.4	efficiencyMap
CMS-SUS-12-024	8	19.4	upperLimit
CMS-SUS-12-028	8	11.7	upperLimit
CMS-SUS-13-002	8	19.5	upperLimit
CMS-SUS-13-004	8	19.3	upperLimit
CMS-SUS-13-006	8	19.5	upperLimit
CMS-SUS-13-007	8	19.3	efficiencyMap
CMS-SUS-13-007	8	19.3	upperLimit
CMS-SUS-13-011	8	19.5	efficiencyMap
CMS-SUS-13-011	8	19.5	upperLimit
CMS-SUS-13-012	8	19.5	efficiencyMap
CMS-SUS-13-012	8	19.5	upperLimit
CMS-SUS-13-015	8	19.4	efficiencyMap
CMS-SUS-13-015	8	19.4	upperLimit
CMS-SUS-13-019	8	19.5	upperLimit
...	...	...	...
CMS-SUS-PAS-13-016	8	19.7	upperLimit
CMS-SUS-PAS-13-018	8	19.4	upperLimit
CMS-SUS-PAS-15-002	13	2.2	upperLimit

Database Validation

We release only "validated" results in the database



-> for each experimental analysis we run SModelS on a grid of SLHA files for the considered simplified model in order to reproduce the official exclusion curve

The validation procedure is usually more complicated in the case of EM results:

- Only the best signal region (i.e. giving the best expected limits) is used
- An approximate procedure for the computation of the 95% CL of the UL is used
- For **"homegrown" maps**, uncertainties coming from analysis recasting and Monte Carlo generation of the samples are introduced

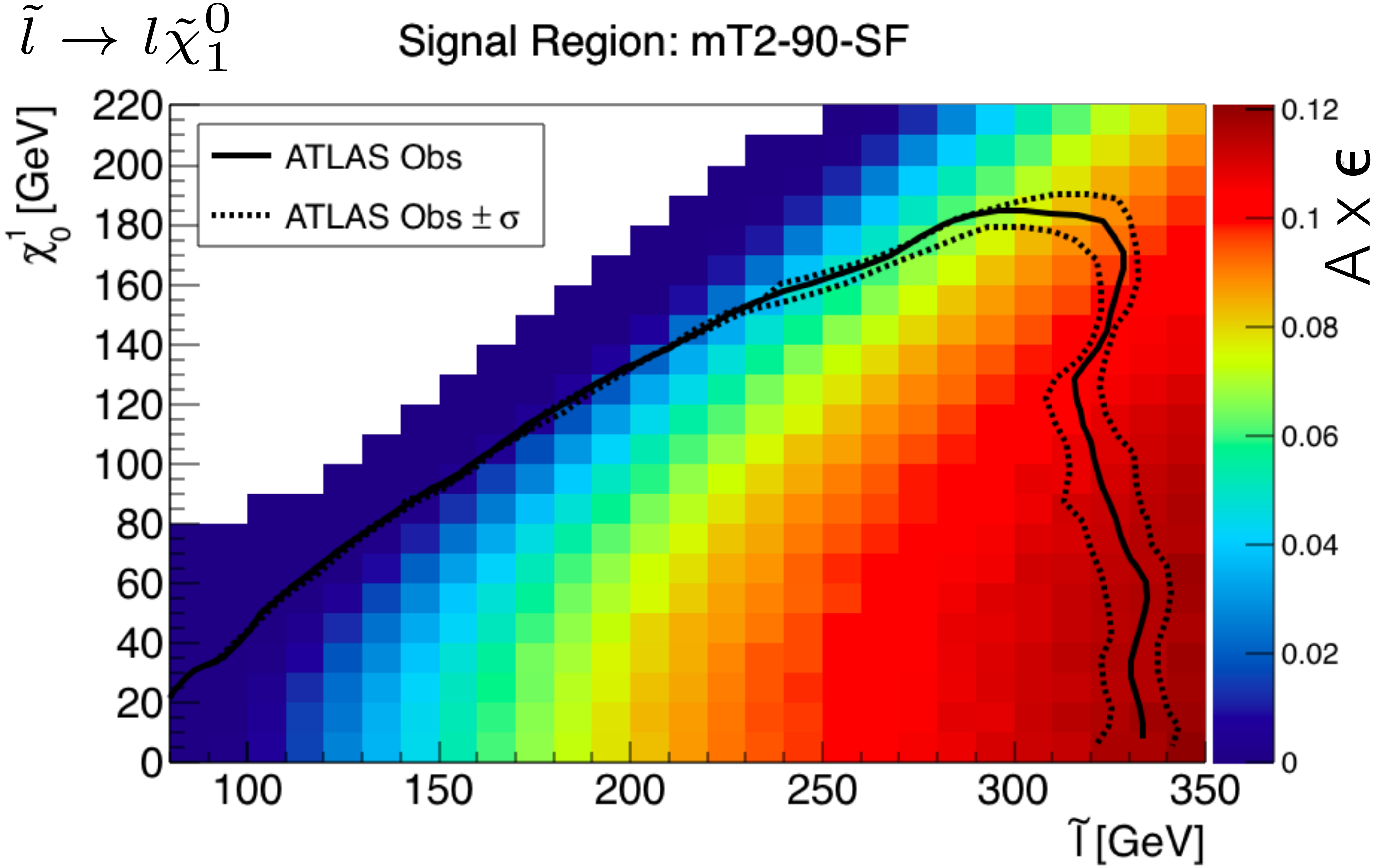
"Homegrown" Maps

There are no available ATLAS/CMS EM for the production of sleptons

-> We used **MadAnalysis5** recasting of ATLAS-SUSY-2013-11 to produce "homegrown" efficiency maps

ATLAS-SUSY-2013-11

$pp \to \tilde{l}\tilde{l}, \tilde{l} \to l\tilde{\chi}_1^0$



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ATLAS-SUSY-2013-11

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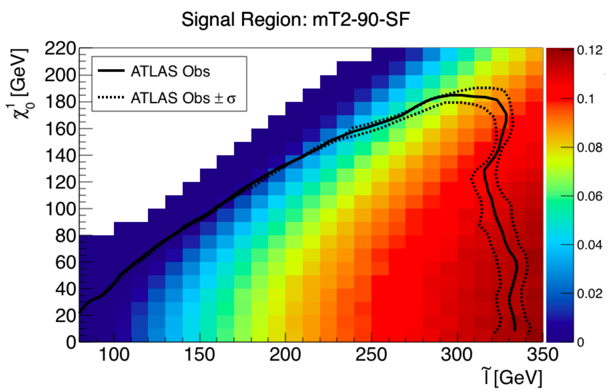
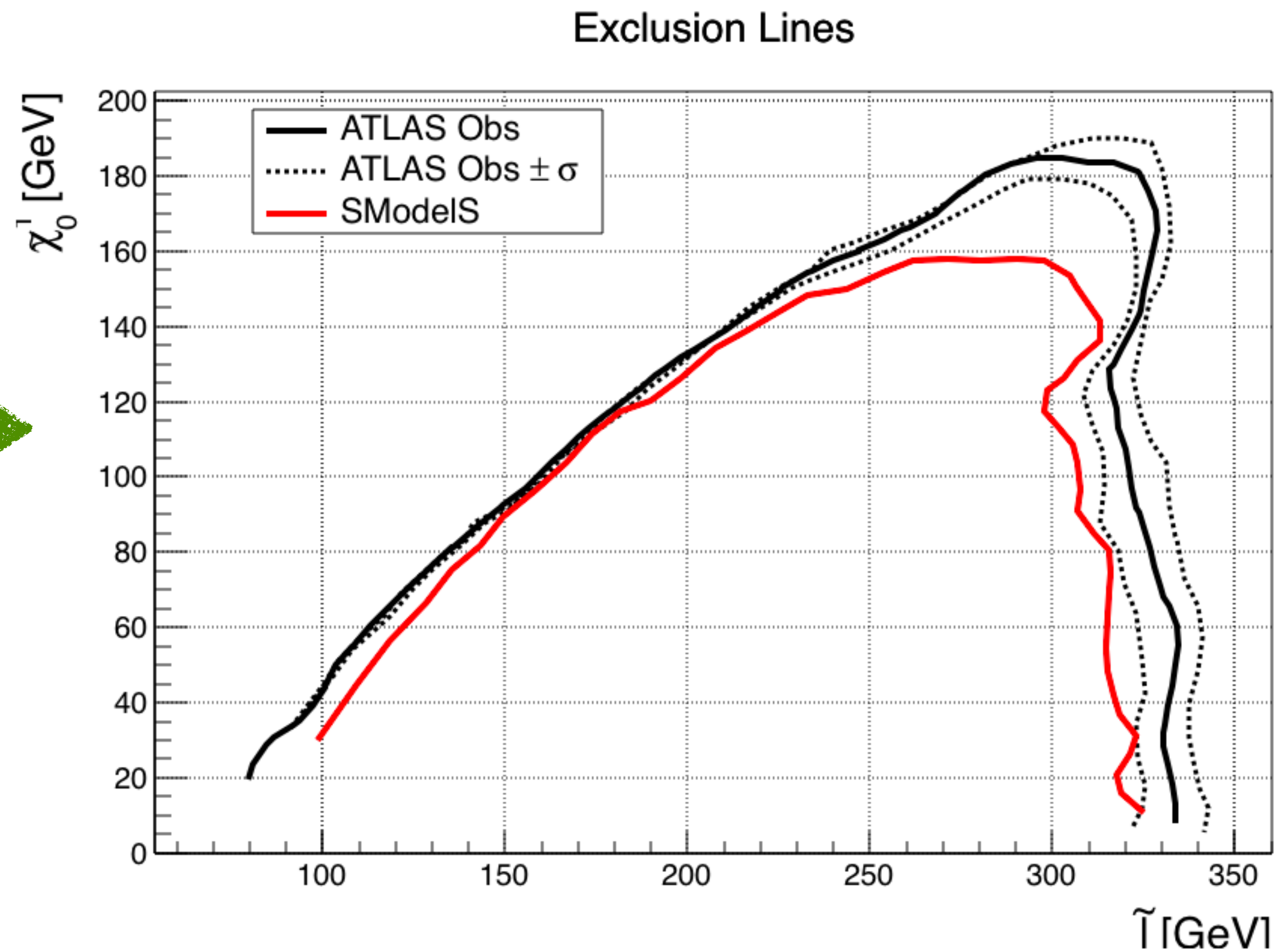


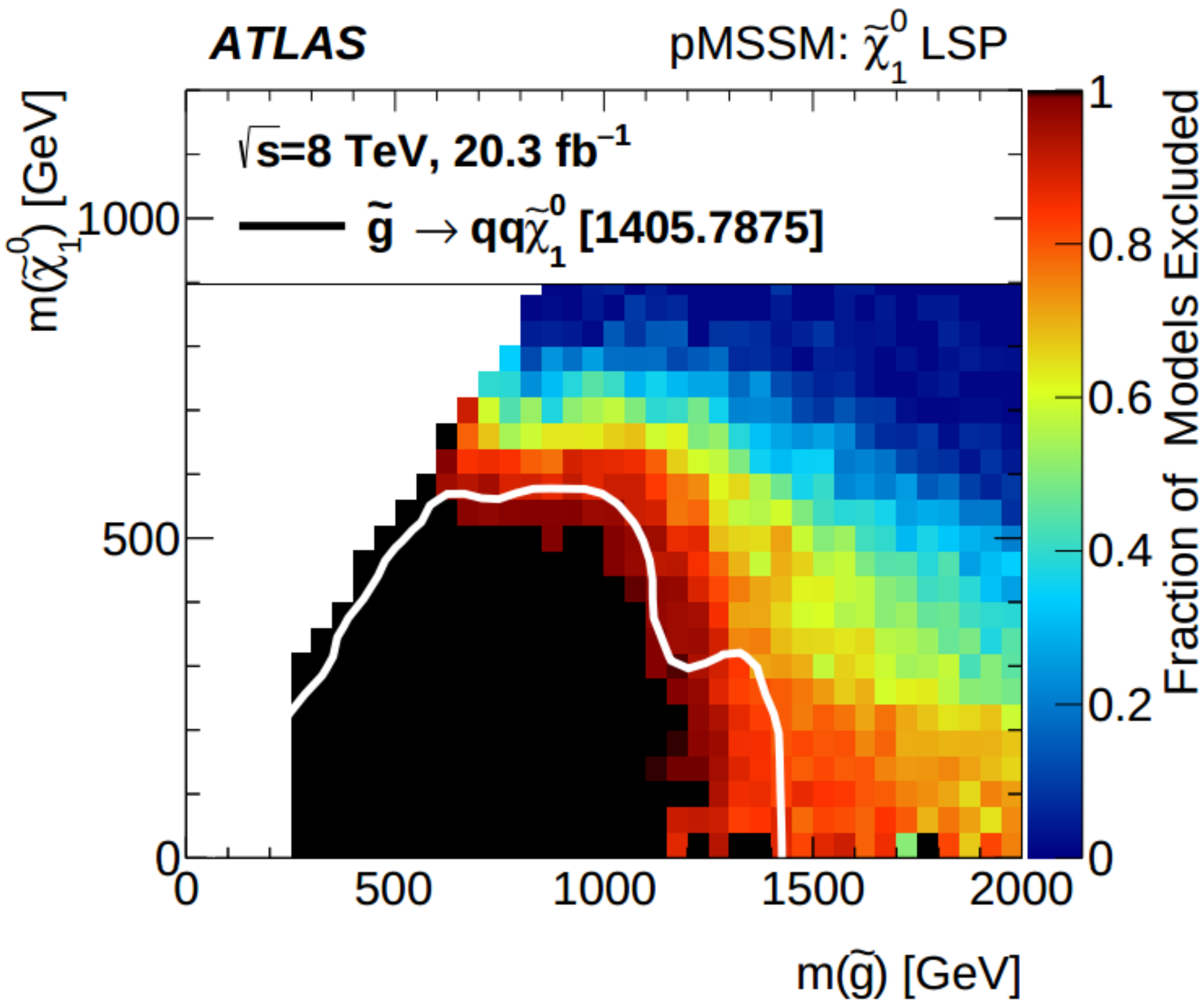
All signal regions efficiency maps

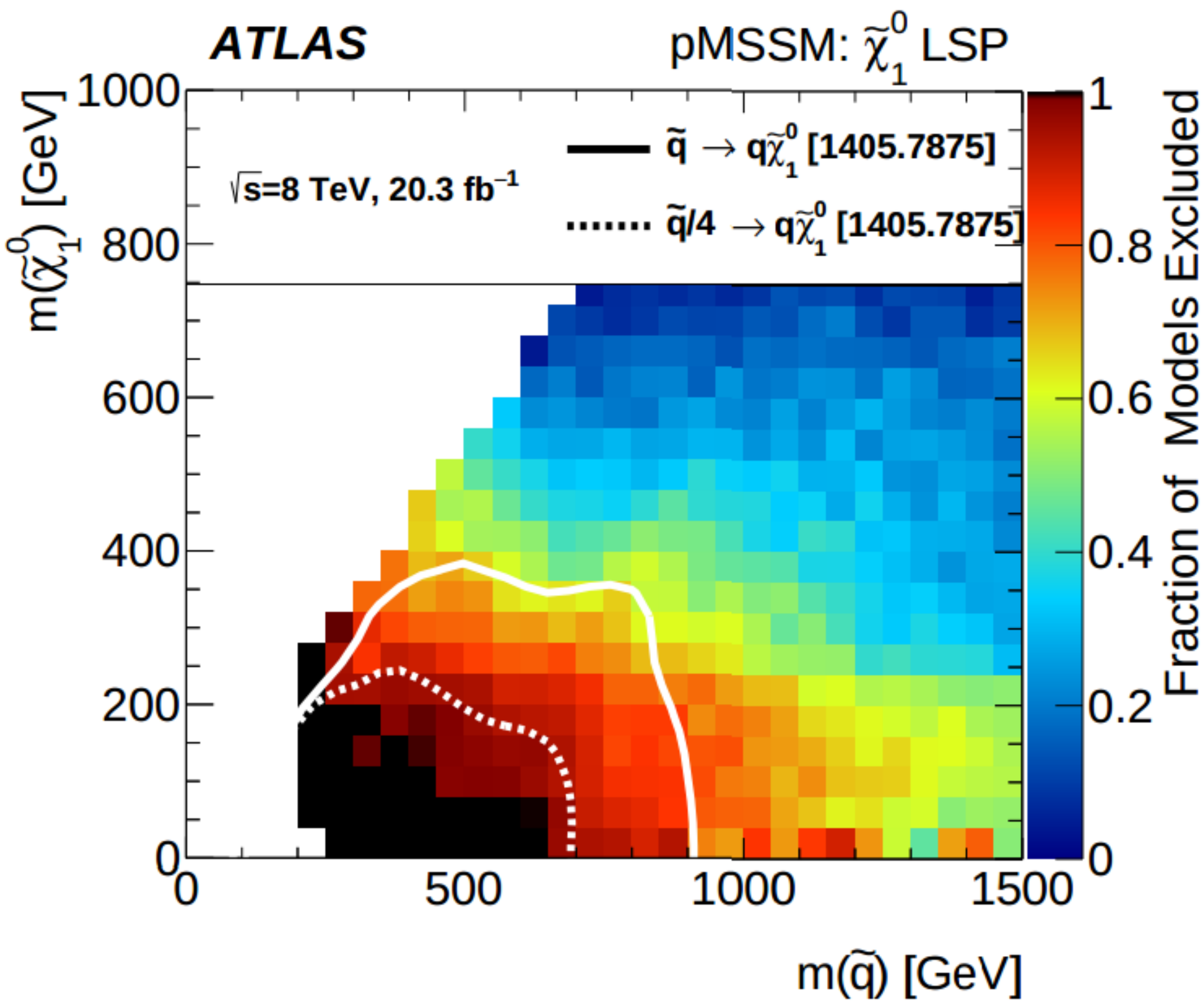


Study Case: ATLAS pMSSM interpretation

pMSSM interpretation by ATLAS (SUSY searches 8 TeV): JHEP 10 (2015) 134

Data files: http://hepdata.cedar.ac.uk/view/ins1389857



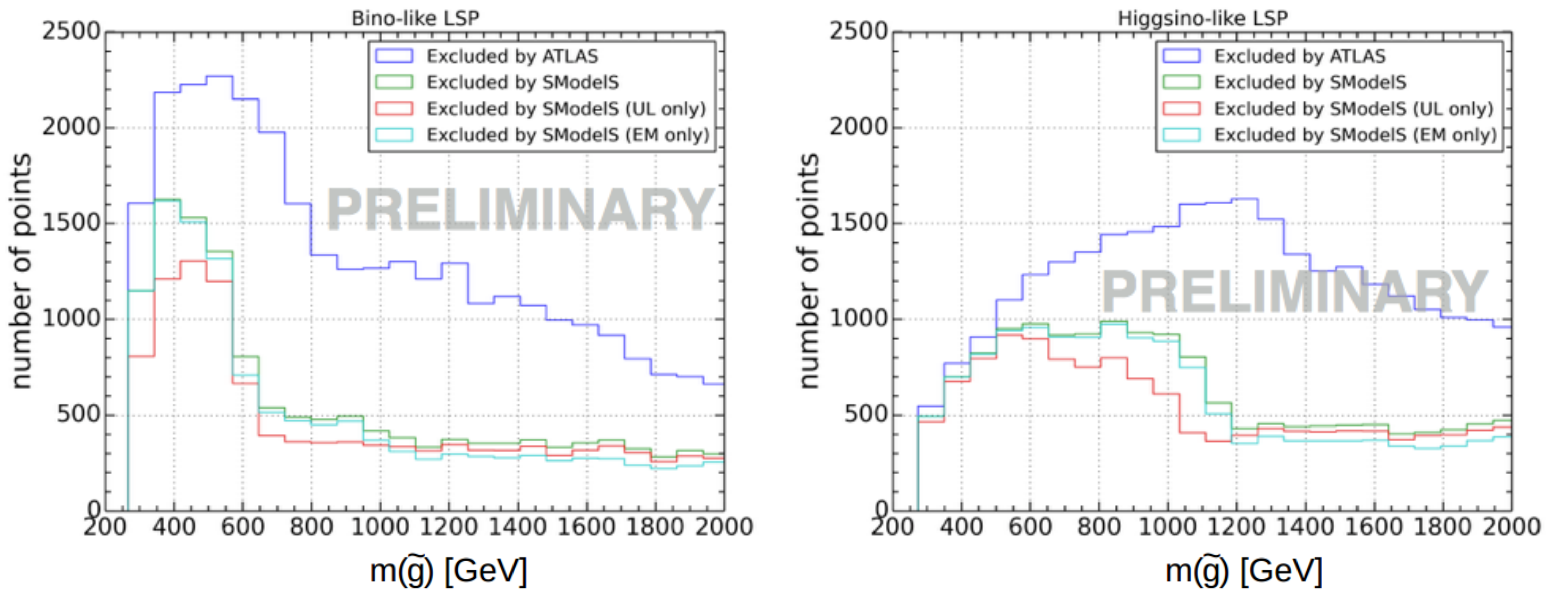


Light $\tilde{g}$ and $\tilde{q}$ tightly constrained by 8 TeV ATLAS SUSY searches

We used the same SLHA files as an input for SModelS to test the pMSSM coverage using **only** SMS results

Study Case: ATLAS pMSSM interpretation

Preliminary SModelS results



Results:	Bino LSP	Higgsino LSP
# points excluded by ATLAS	42039	48703
# points excluded by SModelS	18461	25260
coverage in SModelS	44%	52%

PRELIMINARY

SModelS does not exclude a large fraction of points excluded by ATLAS study
(only around 50% of points excluded)

Study Case: ATLAS pMSSM interpretation

List of analyses used by the ATLAS collaboration

	Analysis	Category
	0-lepton + 2–6 jets + E_T^{miss}	Inclusive
	0-lepton + 7–10 jets + E_T^{miss}	Inclusive
	1-lepton + jets + E_T^{miss}	Inclusive
	$\tau(\tau/\ell)$ + jets + E_T^{miss}	Inclusive
	SS/3-leptons + jets + E_T^{miss}	Inclusive
	0/1-lepton + 3b-jets + E_T^{miss}	Inclusive
★	Monojet	Inclusive
	0-lepton stop	Third generation
	1-lepton stop	Third generation
	2-leptons stop	Third generation
	Monojet stop	Third generation
	Stop with Z boson	Third generation
	2b-jets + E_T^{miss}	Third generation
	tb+E_T^{miss}, stop	Third generation
	ℓh	Electroweak
	2-leptons	Electroweak
	2-τ	Electroweak
	3-leptons	Electroweak
★	4-leptons	Electroweak
★	Disappearing Track	Electroweak
★	Long-lived particle	Other
★	$H/A \to \tau^+\tau^-$	Other

Only a subset of experimental results can be implemented and validated with SModelS

We used the complete set of ATLAS and CMS analyses in SModelS database (both UL and EM results) + a set of EM produced by the FastLim[1] collaboration

[1]arxiv:1402.0492

★Analyses that do not have a simple SMS interpretation or a MET final state

Study Case: ATLAS pMSSM interpretation

Example of a non-excluded point 489804839.slha

Mass spectrum

```
# PDG code          mass         particle
   1000001       7.37182646E+02   # ~d_L
   2000001       1.17572389E+03   # ~d_R
   1000002       7.33259013E+02   # ~u_L
   2000002       5.02158051E+02   # ~u_R
   1000003       7.37182646E+02   # ~s_L
   2000003       1.17572389E+03   # ~s_R
   1000004       7.33259013E+02   # ~c_L
   2000004       5.02158051E+02   # ~c_R
   1000005       3.86685459E+03   # ~b_1
   2000005       4.00843110E+03   # ~b_2
   1000006       2.74516322E+03   # ~t_1
   2000006       3.93556802E+03   # ~t_2
   1000021       6.51578232E+02   # ~g
   1000022       4.87251524E+02   # ~chi_10
   1000023       8.85267547E+02   # ~chi_20
   1000025      -3.97532163E+03   # ~chi_30
   1000035       3.97575507E+03   # ~chi_40
   1000024       8.85433637E+02   # ~chi_1+
   1000037       3.97611803E+03   # ~chi_2+
```

Decay table

```
#         PDG            Width
DECAY   1000021      5.10223642E+00   # gluino decays
#          BR          NDA      ID1        ID2
     2.50004966E-01     2      2000002         -2    # BR(~g -> ~u_R  ub)
     2.50004966E-01     2     -2000002          2    # BR(~g -> ~u_R* u )
     2.49995034E-01     2      2000004         -4    # BR(~g -> ~c_R  cb)
     2.49995034E-01     2     -2000004          4    # BR(~g -> ~c_R* c )
#         PDG            Width
DECAY   2000002      4.42213104E-03   # sup_R decays
#          BR          NDA      ID1        ID2
     1.00000000E+00     2      1000022          2    # BR(~u_R -> ~chi_10 u)
#         PDG            Width
DECAY   2000004      4.03417627E-03   # scharm_R decays
#          BR          NDA      ID1        ID2
     1.00000000E+00     2      1000022          4    # BR(~c_R -> ~chi_10 c)
```

Missing topologies

```
Missing topologies with the highest cross-sections (up to 10):
Sqrts (TeV)   Weight (fb)        Element description
  8.0   1.554E+03    #             [[[jet]],[[jet],[jet]]]
  8.0   7.577E+02    #       [[[jet],[jet]],[[jet],[jet],[jet]]]
  8.0   5.975E+02    #             [[[jet],[jet]],[[jet],[jet]]]
```

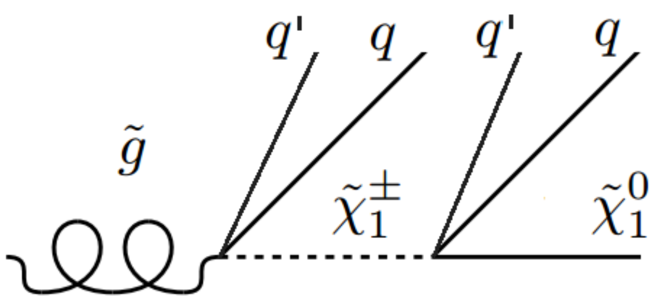
Missing topologies include multi jets final states

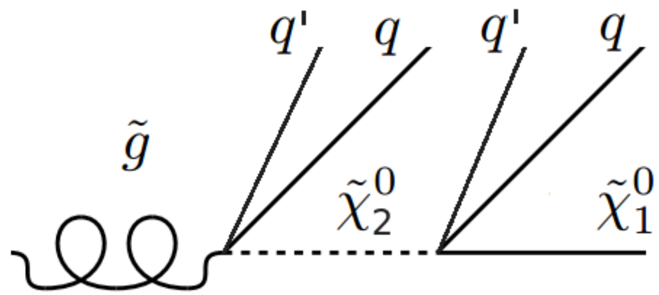
- Long cascade (>1 intermediate sparticles) decays
- Decays via squarks
- Decays via charginos/neutralinos

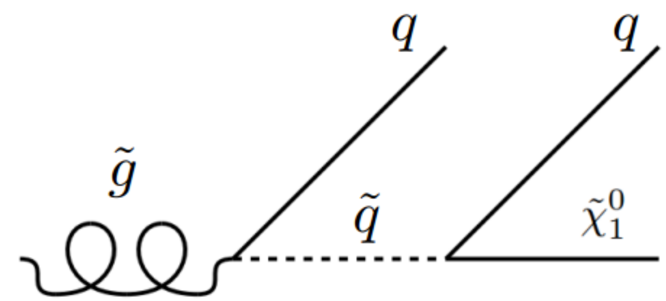
Study Case: Missing Topologies

Examples of Missing Topologies

Non-degenerate right and left handed squarks

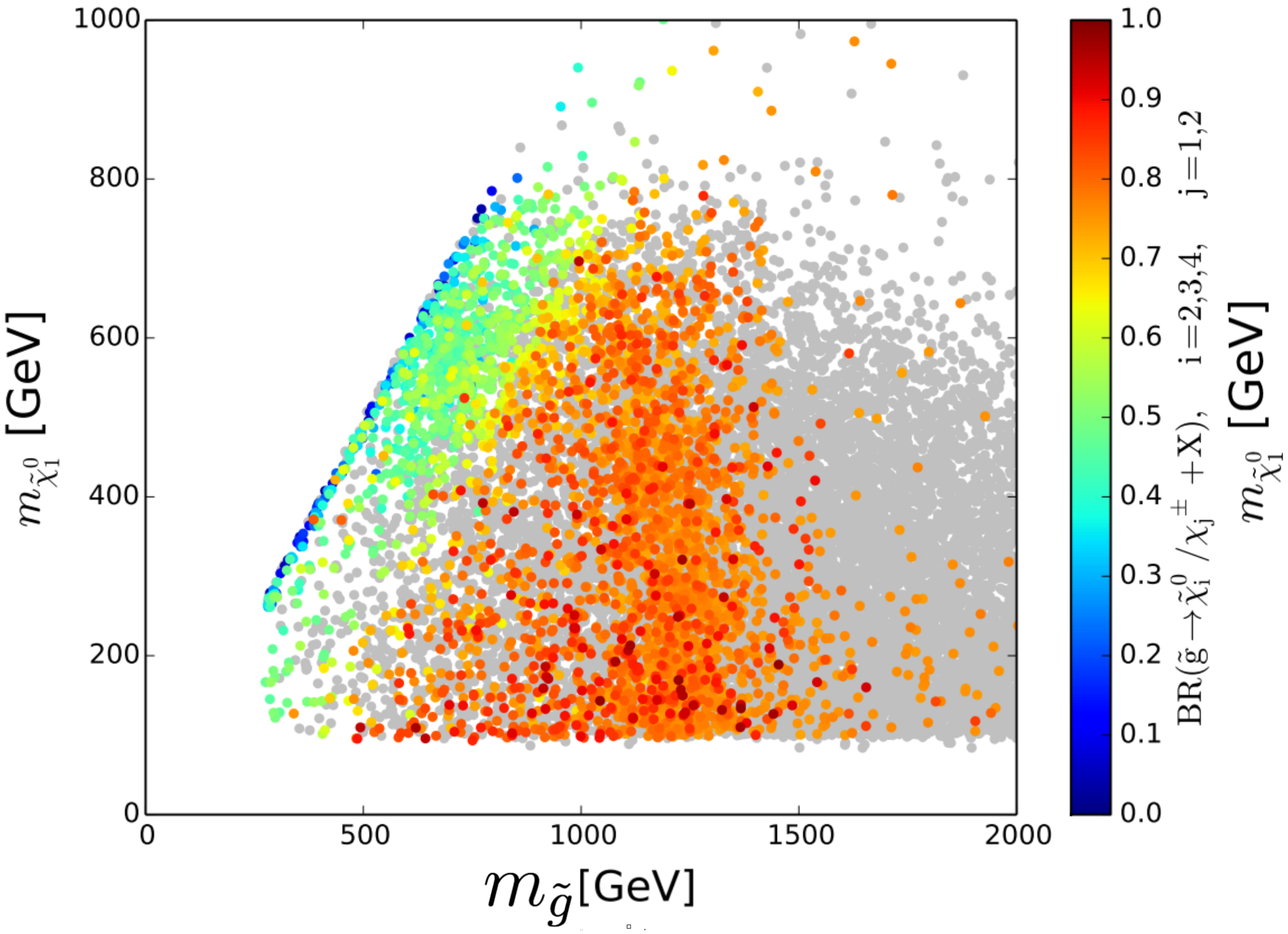




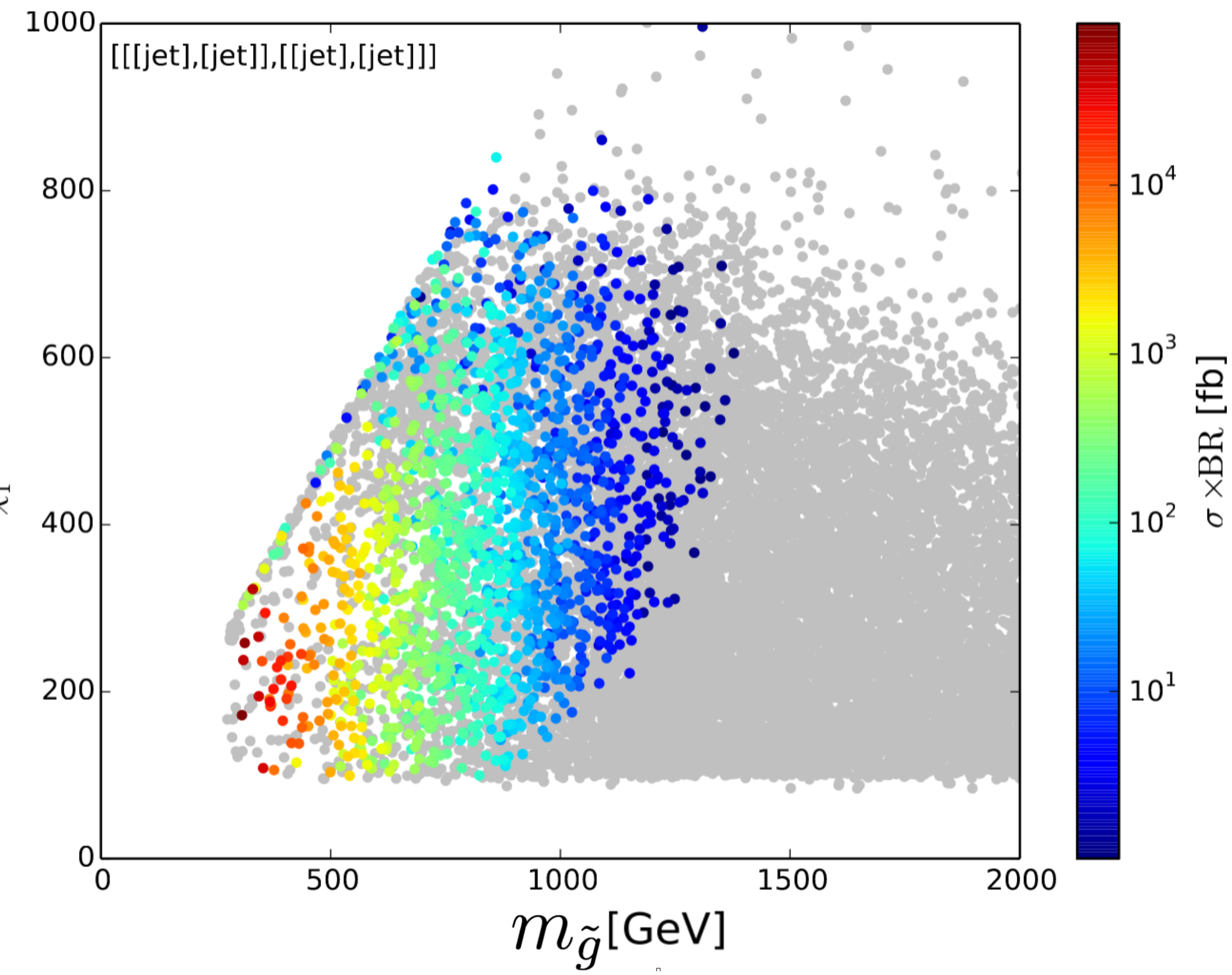


Branching Ratio Plot

$\mathrm{BR}(\tilde{g} \rightarrow \tilde{\chi}_i^0 / \chi_j^{\pm} + X)$



Plot (σxBR)



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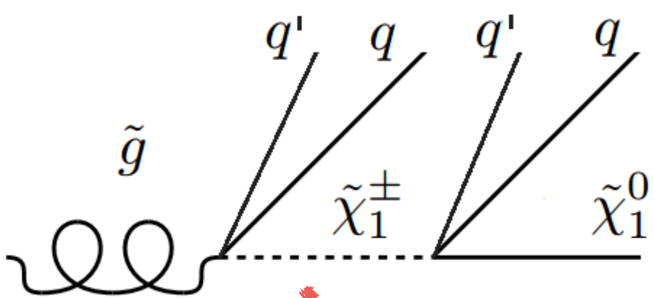
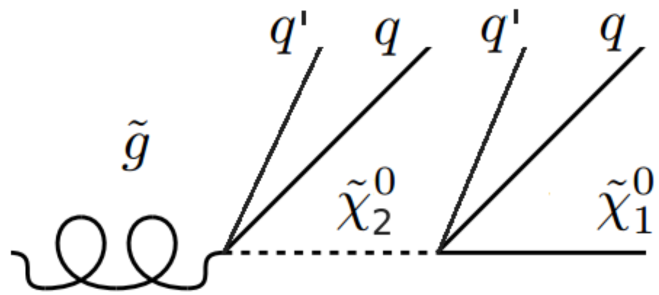
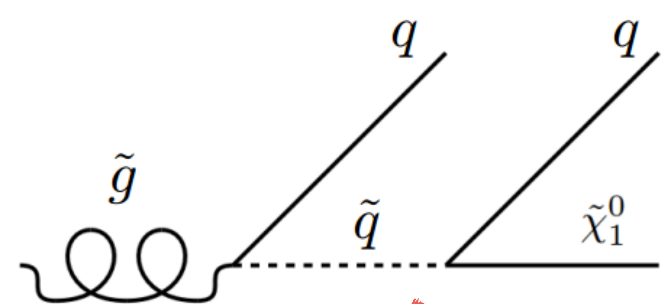
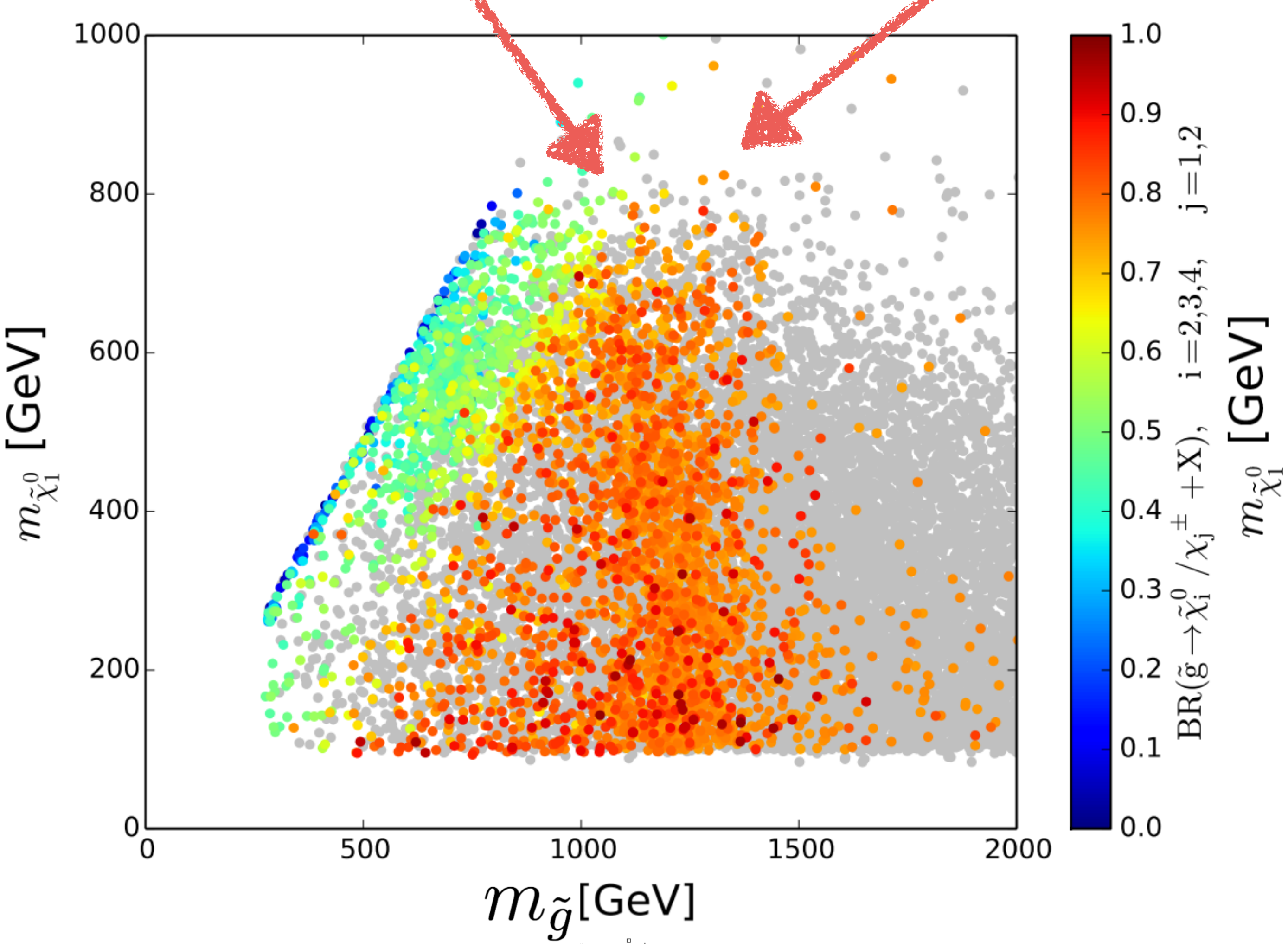


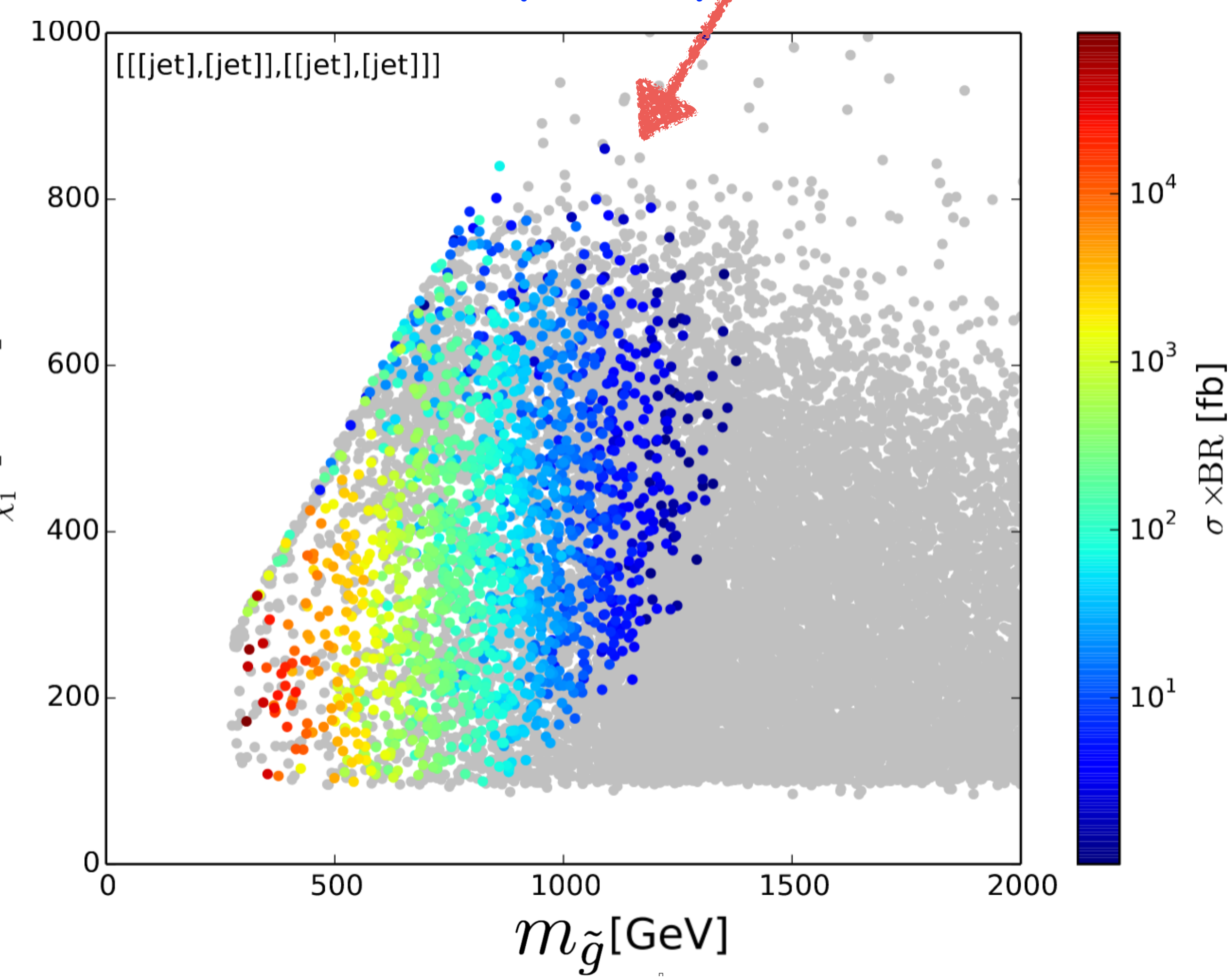




Branching Ratio Plot $\mathrm{BR}(\tilde{g} \rightarrow \tilde{\chi}_i^0/\chi_j^{\pm} + \mathrm{X})$

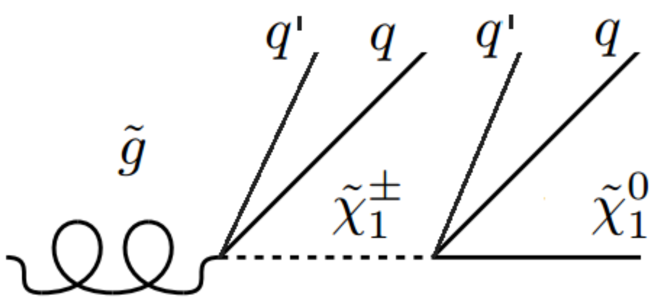


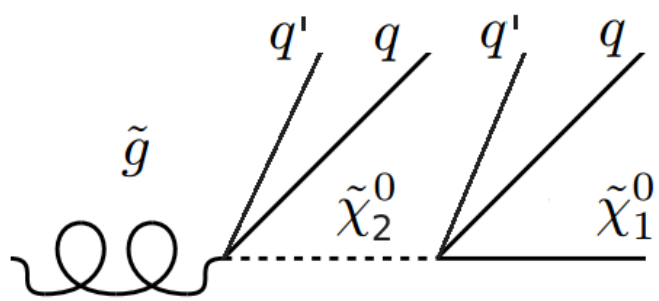
Plot (σxBR)



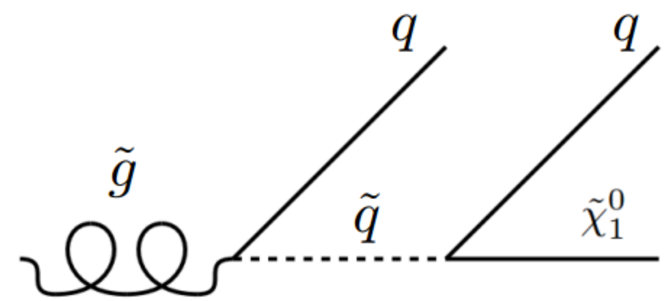
Study Case: Missing Topologies

Examples of Missing Topologies





Non-degenerate right and left handed squarks



We are producing "Homegrown" efficiency maps in order to cover important missing topologies and improve SModelS constraining power

Summary and Conclusions

- SModelS is a powerful tool to quickly confront generic BSM models (featuring a Z_2 symmetry) with SMS results from the LHC searches

- It can be used also for non-MSSM and non-SUSY models obeying Z_2 symmetry

  See e.g. UED model arxiv:1501.03942 , HSCP arxiv:1509.00473 , U(1)MSSM ext. arxiv:1505.06243

  Talk by Andre Lessa on Thursday

- Upcoming v1.1 will feature the use of efficiency maps, increasing SModelS constraining power by combining different SMSes

- The preliminary results of the comparison with the ATLAS pMSSM study shows that almost half of the points with light gluinos evade the available SMS constraints

- SModelS can help highlighting which SMS results are not currently covered by the experimental searches

- We are producing "homegrown" EM maps for missing SMS in order to extend the experimental database and better constrain realistic models http://smodels.hephy.at/

Thank you!

UL and CLs computation for EM results

Included in module "statistics.py" see arxiv:1407.3278

Table 5: Observed numbers of events and corresponding SM background estimates,

	$E_T^{miss} < 25\,\mathrm{GeV}$	$25 < E_T^{miss} < 50\,\mathrm{GeV}$	$50 < E_T^{miss} < 60\,\mathrm{GeV}$
Z+jets background	56.7 ± 1.9	43.3 ± 2.3	5.7 ± 1.2
Flavor symmetric background	0.4 ± 0.3	0.4 ± 0.3	0.4 ± 0.3
Other SM background	<0.1	0.1 ± 0.1	0.1 ± 0.1
Total SM background	57.2 ± 1.9	43.8 ± 2.3	6.2 ± 1.2
Data	54	47	7

For each signal region (SR) we use as input:

- predicted SM background $\hat{n}_b$
- error on SM background Δn_b
- observed number of events n_{obs}

The "best" SR (yielding the best expected limit) is determined based on the background only assumption

n_s = number of signal events = Luminosity x ϵ_{ff} x σ

We generate O(100k) Monte Carlo toy experiments

The number of SM events is assumed to be Gaussianly distributed around the central value $\hat{n}_b$ with mean Δn_b

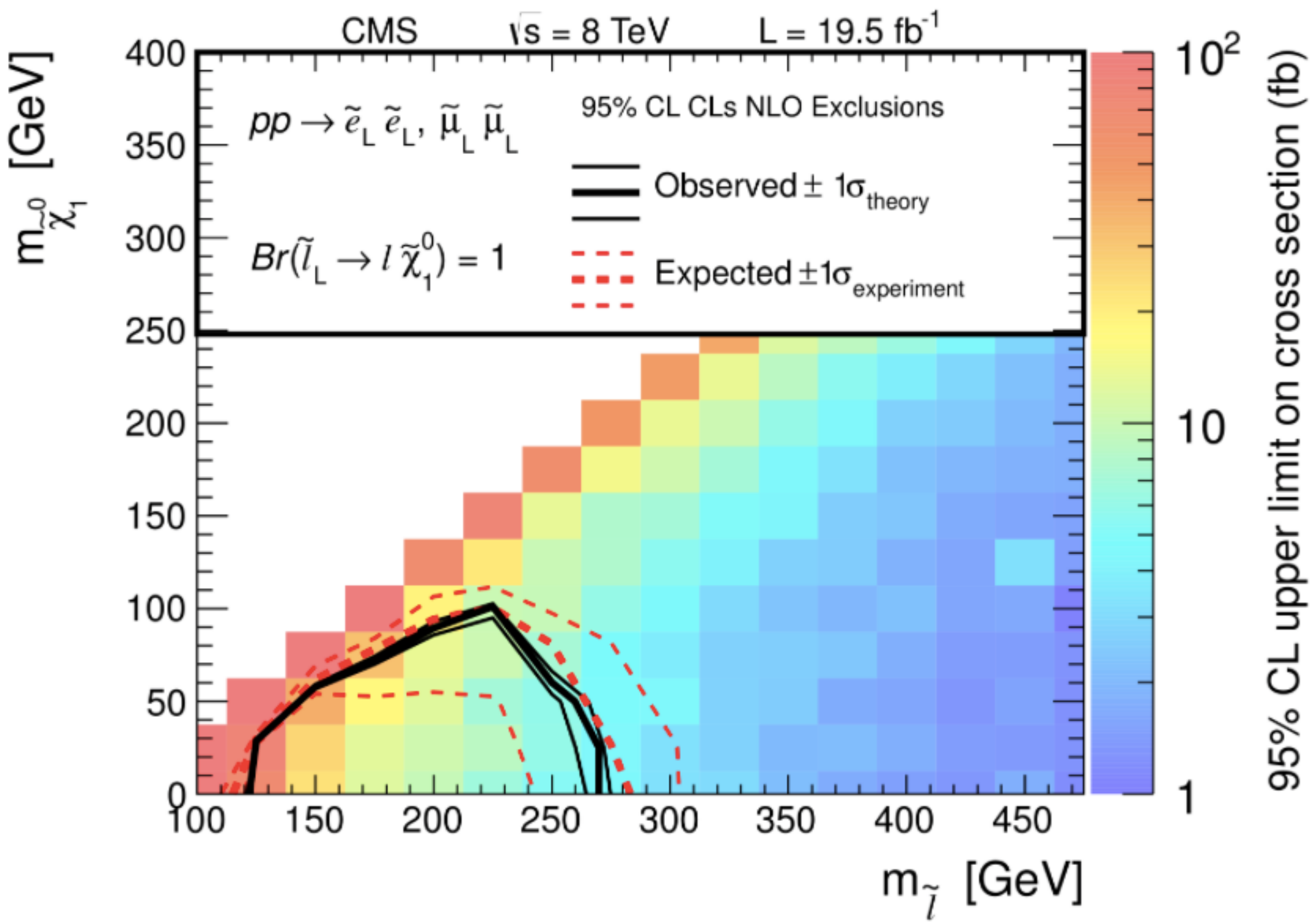
We evaluate the percentile of scores for the set of MCs for a Poissonian distribution of events, in the case of background only and background+signal hypotheses

We extract the exclusion confidence level

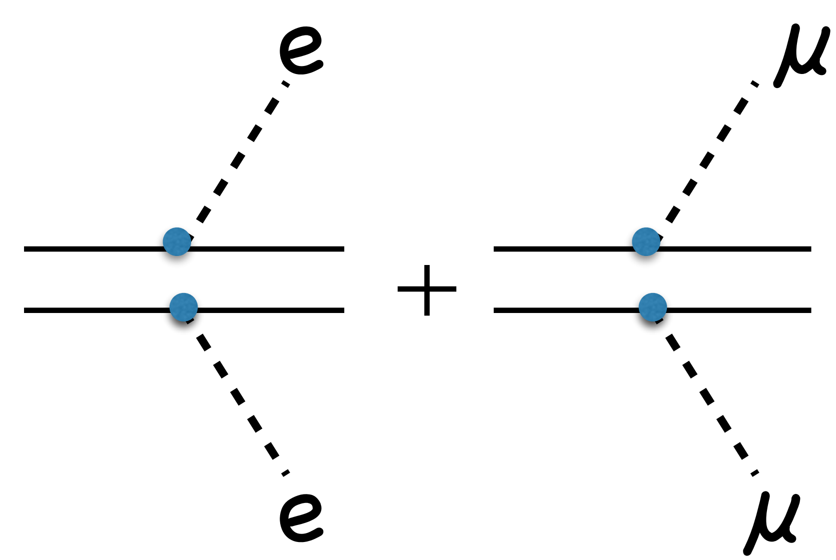
Backup: Elements Combination

Before the evaluation of the theory prediction, elements must be grouped according to the analysis' constraints:

CMS-SUS-13-006



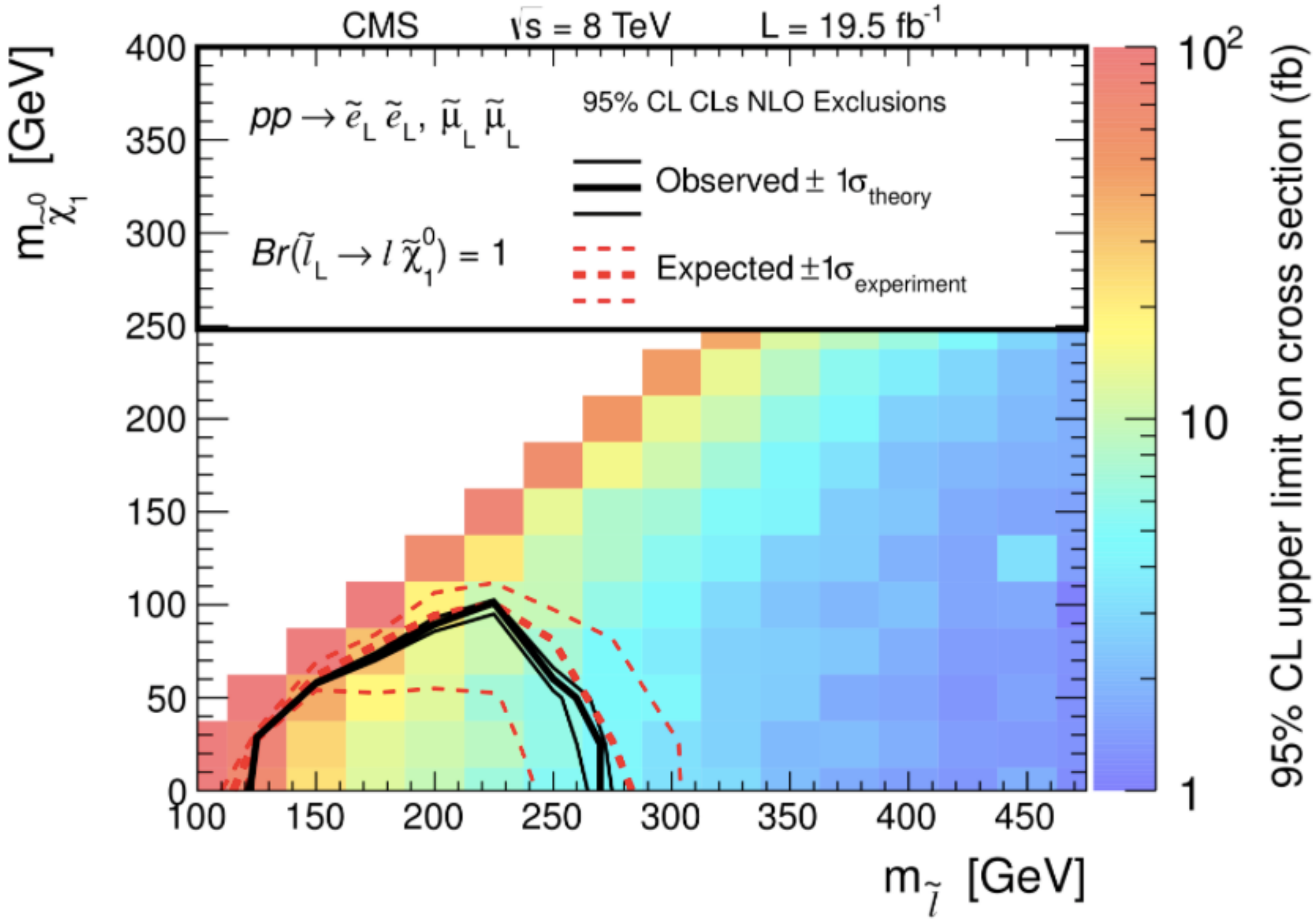
UL analysis constraint



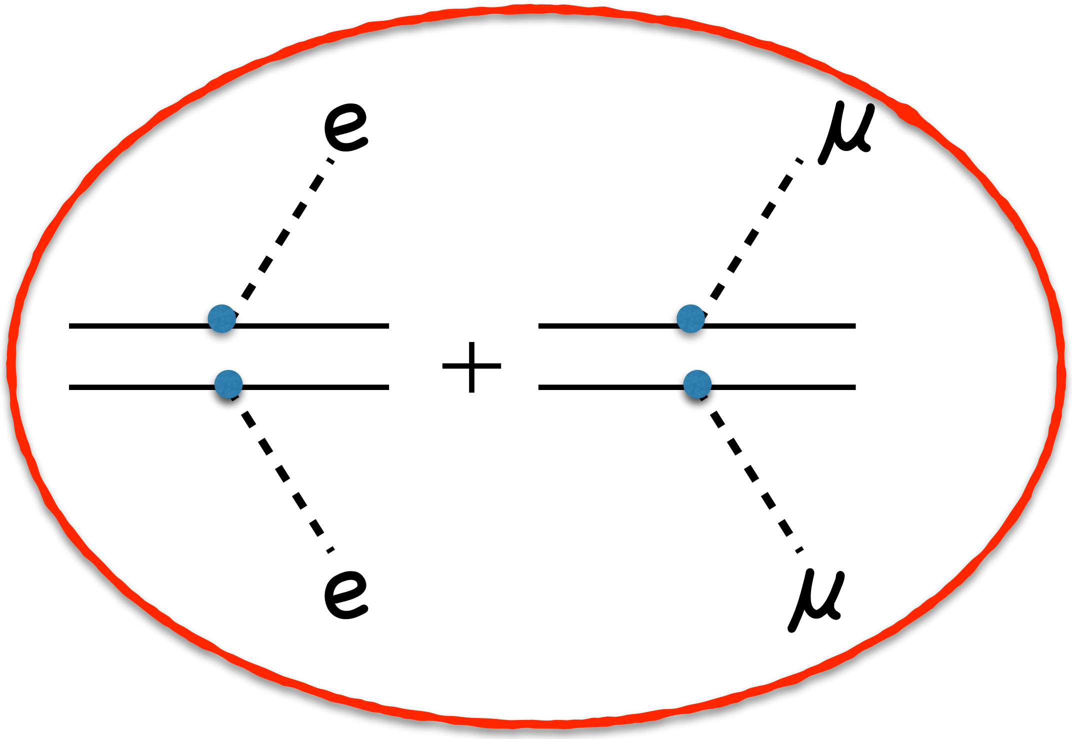
Backup: Elements Combination

Before the evaluation of the theory prediction, elements must be grouped according to the analysis' constraints:

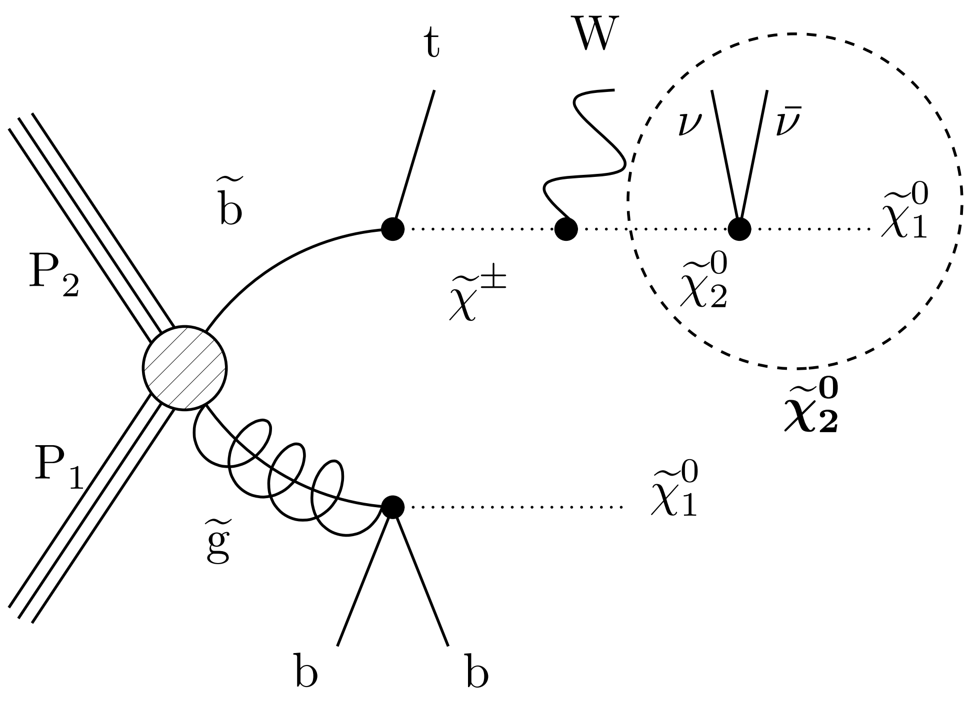
CMS-SUS-13-006



UL analysis constraint

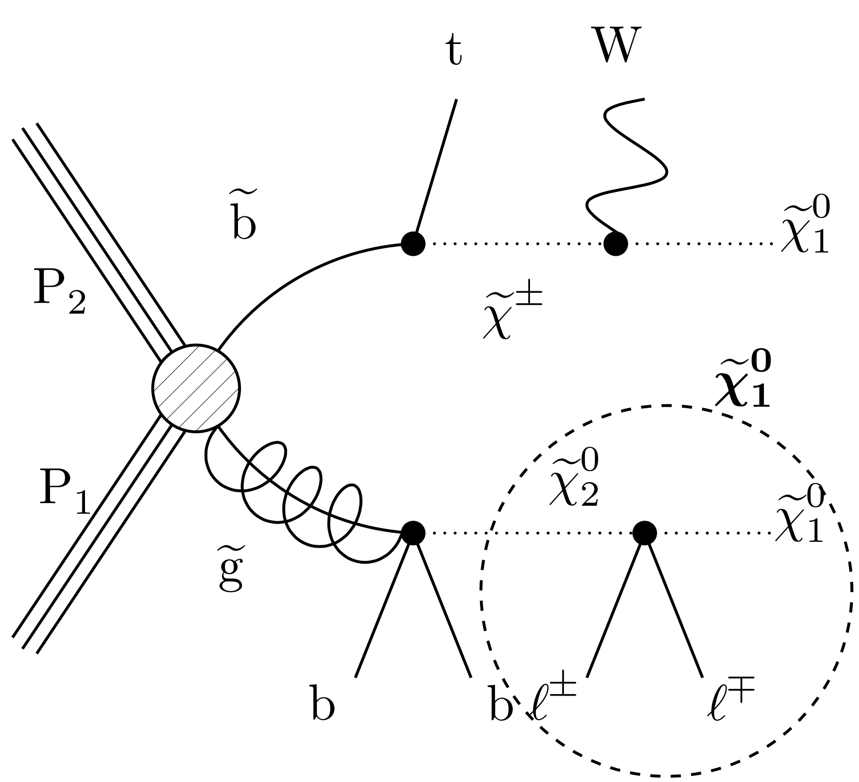


The effective element to be compared to the UL result is the sum of the two elements



Invisible decay

In this case (occuring at the end of the decay chain), the final state containing ν and $\tilde{\chi}_1^0$ is replaced by a $\tilde{\chi}_2^0$ final state



Soft final state

When the two neutrinos are nearly mass degenerate, the SM final state become invisible.

The final state considered is then simply $\tilde{\chi}_1^0$

Backup: Database for pMSSM study

ATLAS Analyses

ATLAS-SUSY-2013-02
ATLAS-SUSY-2013-04
ATLAS-SUSY-2013-05
ATLAS-SUSY-2013-08
ATLAS-SUSY-2013-09
ATLAS-SUSY-2013-11
ATLAS-SUSY-2013-12
ATLAS-SUSY-2013-14
ATLAS-SUSY-2013-15
ATLAS-SUSY-2013-16
ATLAS-SUSY-2013-18
ATLAS-SUSY-2013-19
ATLAS-SUSY-2013-23
ATLAS-SUSY-2014-03

+ various CONF notes

CMS Analyses

CMS-SUS-12-024
CMS-SUS-12-028
CMS-SUS-13-002
CMS-SUS-13-004
CMS-SUS-13-006
CMS-SUS-13-007
CMS-SUS-13-011
CMS-SUS-13-012
CMS-SUS-13-019
CMS-SUS-14-010
CMS-SUS-14-011
CMS-SUS-14-021

+ various PAS

CONF and PAS analyses are not used when superseded by a published analyses

Backup: ATLAS scan details

Scan parameters

Parameter	Min value	Max value	Note
$m_{\tilde{L}_1} (= m_{\tilde{L}_2})$	90 GeV	4 TeV	Left-handed slepton (first two gens.) mass
$m_{\tilde{e}_1} (= m_{\tilde{e}_2})$	90 GeV	4 TeV	Right-handed slepton (first two gens.) mass
$m_{\tilde{L}_3}$	90 GeV	4 TeV	Left-handed stau doublet mass
$m_{\tilde{e}_3}$	90 GeV	4 TeV	Right-handed stau mass
$m_{\tilde{Q}_1} (= m_{\tilde{Q}_2})$	200 GeV	4 TeV	Left-handed squark (first two gens.) mass
$m_{\tilde{u}_1} (= m_{\tilde{u}_2})$	200 GeV	4 TeV	Right-handed up-type squark (first two gens.) mass
$m_{\tilde{d}_1} (= m_{\tilde{d}_2})$	200 GeV	4 TeV	Right-handed down-type squark (first two gens.) mass
$m_{\tilde{Q}_3}$	100 GeV	4 TeV	Left-handed squark (third gen.) mass
$m_{\tilde{u}_3}$	100 GeV	4 TeV	Right-handed top squark mass
$m_{\tilde{d}_3}$	100 GeV	4 TeV	Right-handed bottom squark mass
$\lvert M_1 \rvert$	0 GeV	4 TeV	Bino mass parameter
$\lvert M_2 \rvert$	70 GeV	4 TeV	Wino mass parameter
$\lvert \mu \rvert$	80 GeV	4 TeV	Bilinear Higgs mass parameter
M_3	200 GeV	4 TeV	Gluino mass parameter
$\lvert A_t \rvert$	0 GeV	8 TeV	Trilinear top coupling
$\lvert A_b \rvert$	0 GeV	4 TeV	Trilinear bottom coupling
$\lvert A_\tau \rvert$	0 GeV	4 TeV	Trilinear τ lepton coupling
M_A	100 GeV	4 TeV	Pseudoscalar Higgs boson mass
$\tan\beta$	1	60	Ratio of the Higgs vacuum expectation values

Additional constraints

Parameter	Minimum value	Maximum value
$\Delta\rho$	-0.0005	0.0017
$\Delta(g-2)_\mu$	-17.7×10^{-10}	43.8×10^{-10}
$\mathrm{BR}(b \to s\gamma)$	2.69×10^{-4}	3.87×10^{-4}
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	1.6×10^{-9}	4.2×10^{-9}
$\mathrm{BR}(B^+ \to \tau^+\nu_\tau)$	66×10^{-6}	161×10^{-6}
$\Omega_{\tilde{\chi}_1^0} h^2$	—	0.1208
$\Gamma_{\mathrm{invisible(SUSY)}}(Z)$	—	2 MeV
Masses of charged sparticles	100 GeV	—
$m(\tilde{\chi}_1^\pm)$	103 GeV	—
$m(\tilde{u}_{1,2}, \tilde{d}_{1,2}, \tilde{c}_{1,2}, \tilde{s}_{1,2})$	200 GeV	—
$m(h)$	124 GeV	128 GeV

"The results are interpreted in the context of the 19-parameter phenomenological minimal supersymmetric standard model, in which the lightest supersymmetric particle is a neutralino, taking into account constraints from previous precision electroweak and flavour measurements as well as from dark matter related measurements." JHEP 10 (2015) 134