Recent Developments in Tools for Beyond the Standard Model Phenomenology Studies

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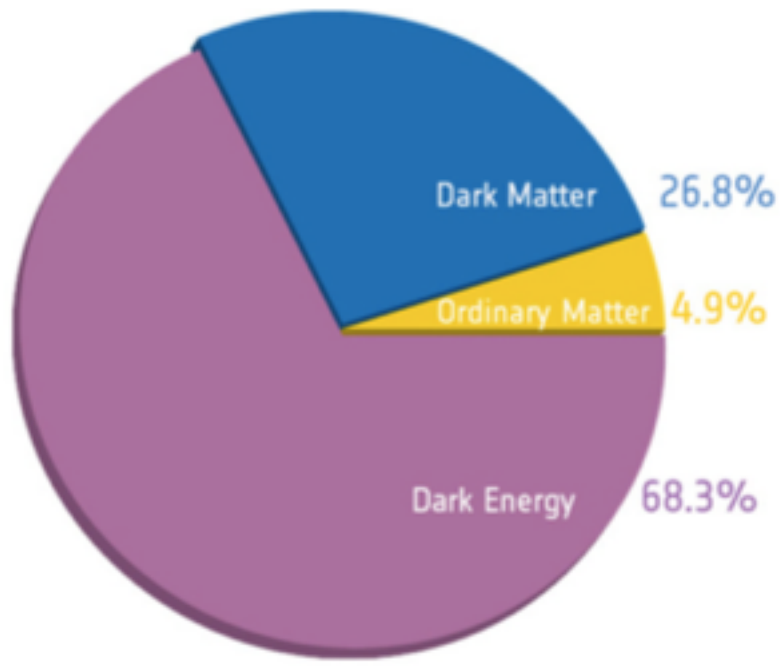
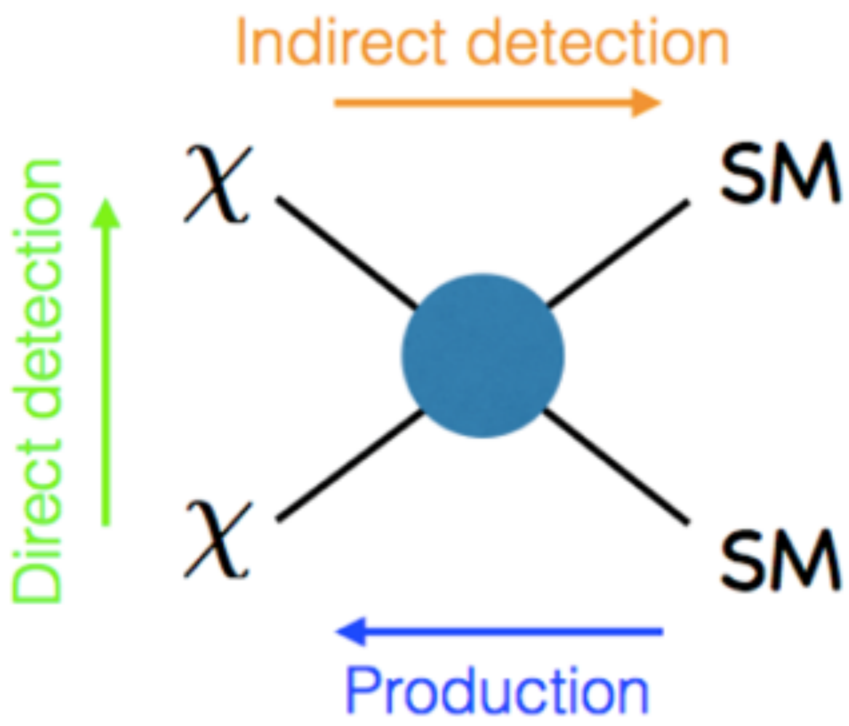
Seminar @ Univie, 16/10/2018

Need for Beyond the Standard Models (BSM) Theories: Dark Matter (DM)

Planck 2015 results. XIII. Cosmological parameters
arXiv:1502.01589





A Universe filled with DM:
DM constitute more than 1/4 of the total energy budget of the universe

Experimental Searches
- *production of DM at colliders (e.g. proton proton collisions @ LHC)*
- *DM annihilation in regions of DM high density and Cosmic Rays production*
- *Scattering of DM particles onto heavy nuclei*

Introduction and Overview (2)

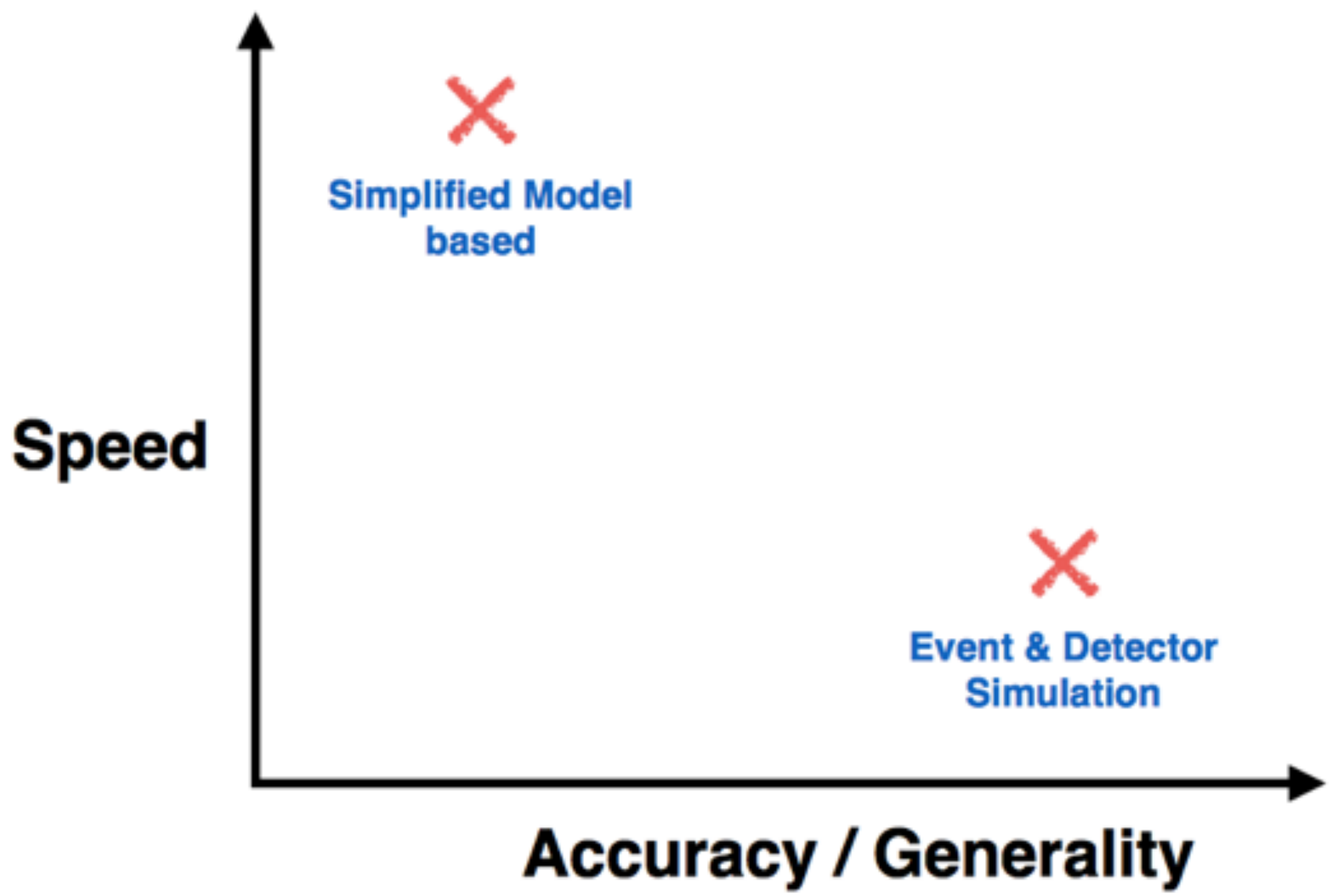
- Many BSM theories can provide a DM candidate compatible with various astrophysical measurements
- Many experimental searches try to catch traces of such elusive particles
- The parameters space, often very large, of many BSM theories can be constrained by the same experimental data i.e. *many BSM theories offer the same experimental signature*

Idea of Re-interpretation Tools

Take the experimental results from the various experiments,
and constrain alternative BSM scenarios
in a systematic and automated way

Key aspect: Computing time vs Accuracy

Speed vs Accuracy: Different Approaches for Reinterpretation



U.Laa, EPS 2017

I will discussed three different Tools:

- Simplified model approach
- ‘Full recast’ approach

SModelS

MadAnalysis 5

MadDM

SUSY Results from the LHC Searches: Simplified Model Spectra (1)

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

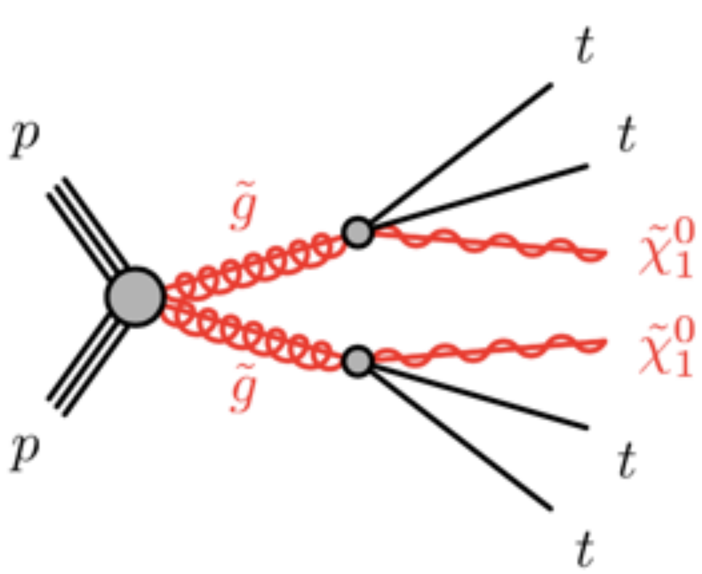
Simplified Models for a First Characterization of New Physics at the LHC

Johan Alwall, Philip Schuster, Natalia Toro

arXiv:0810.3921

(Submitted on 22 Oct 2008 (v1), last revised 4 Jun 2009 (this version, v2))

…If an excess of such events is seen in LHC data, a theoretical framework in which to describe it will be essential to constraining the structure of the new physics. We propose a basis of four deliberately simplified models, each specified by only 2-3 masses and 4-5 branching ratios, for use in a first characterization of data.

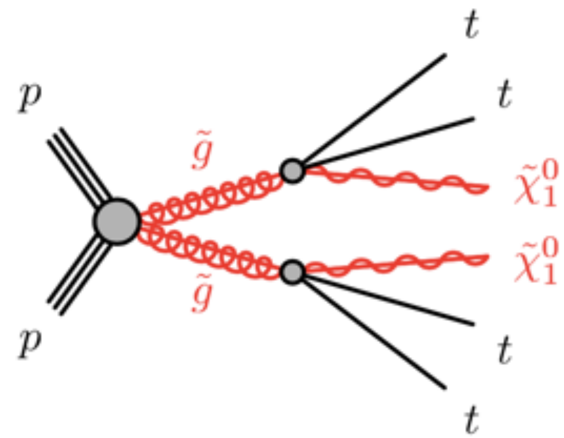


Completely described by:

- mass spectrum $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$
- production cross section $\sigma(pp \to \tilde{g}\tilde{g})$
- decay branching ratio $BR(\tilde{g} \to \chi_1^0 t\bar{t}) \equiv 100\%$

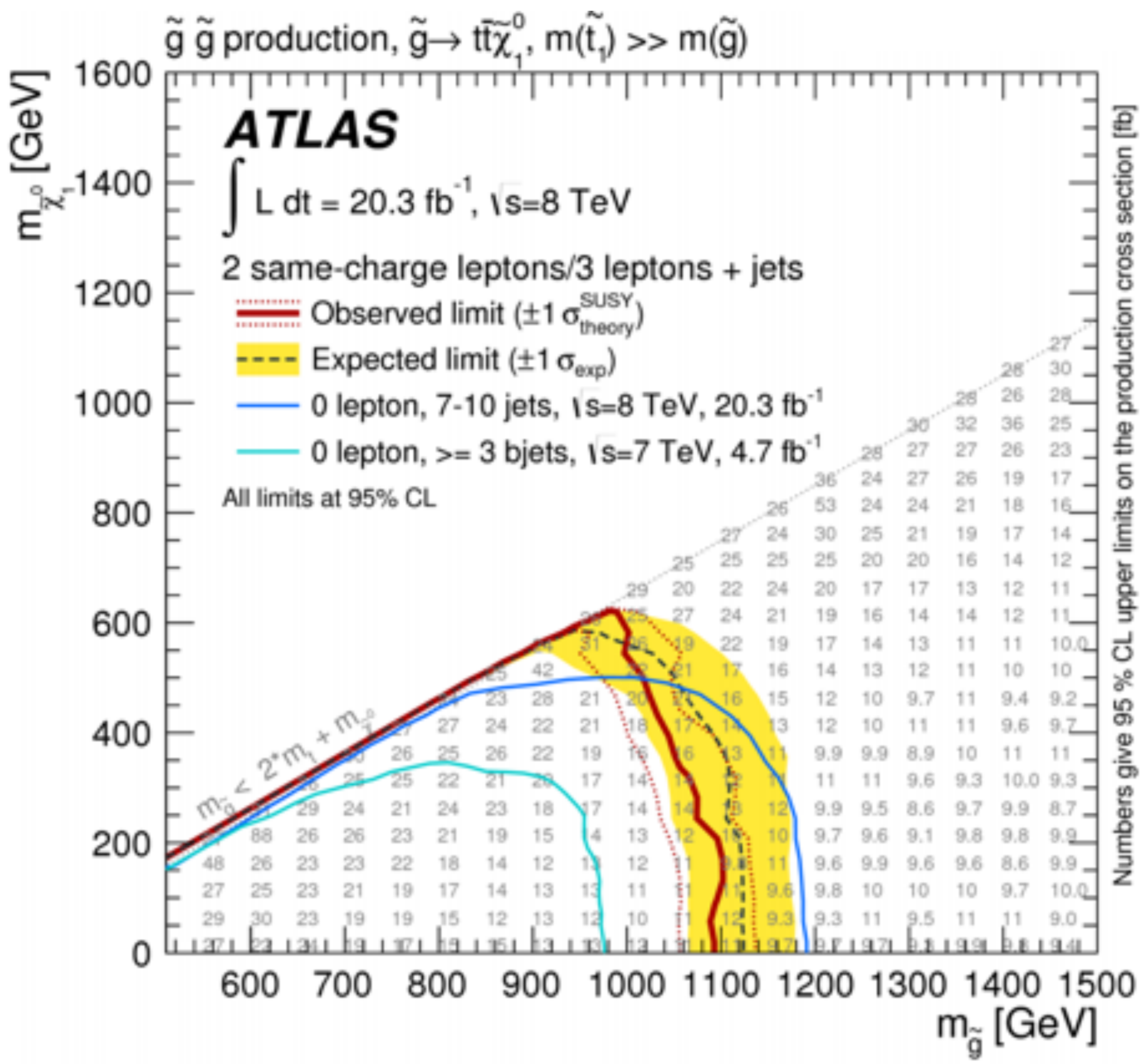
SUSY Results from the LHC Searches: Simplified Model Spectra (2)

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



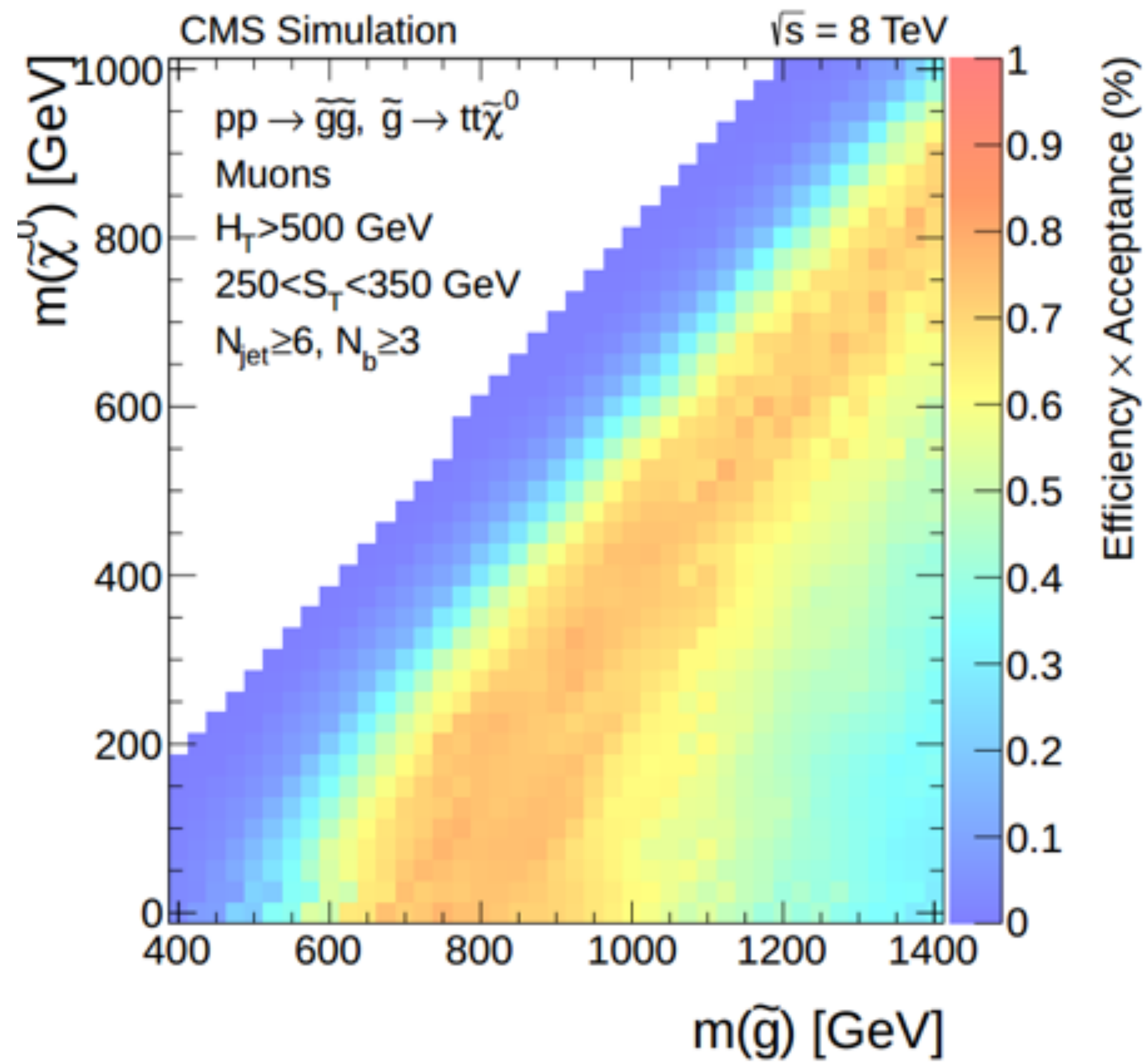
Upper Limit (UL) Map

ATLAS-SUSY-2013-09



Signal Efficiency Map (EM)

CMS-SUS-13-007



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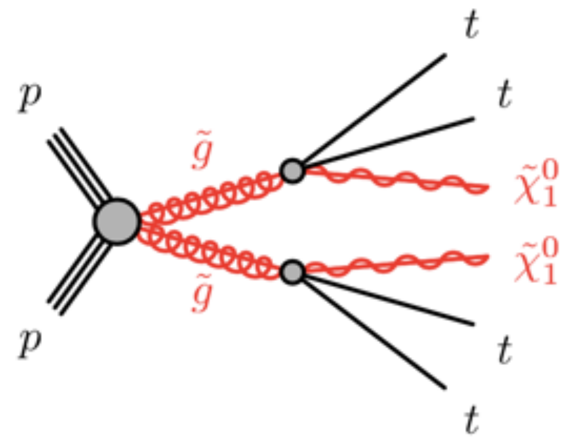

Signal Efficiency Map (EM)
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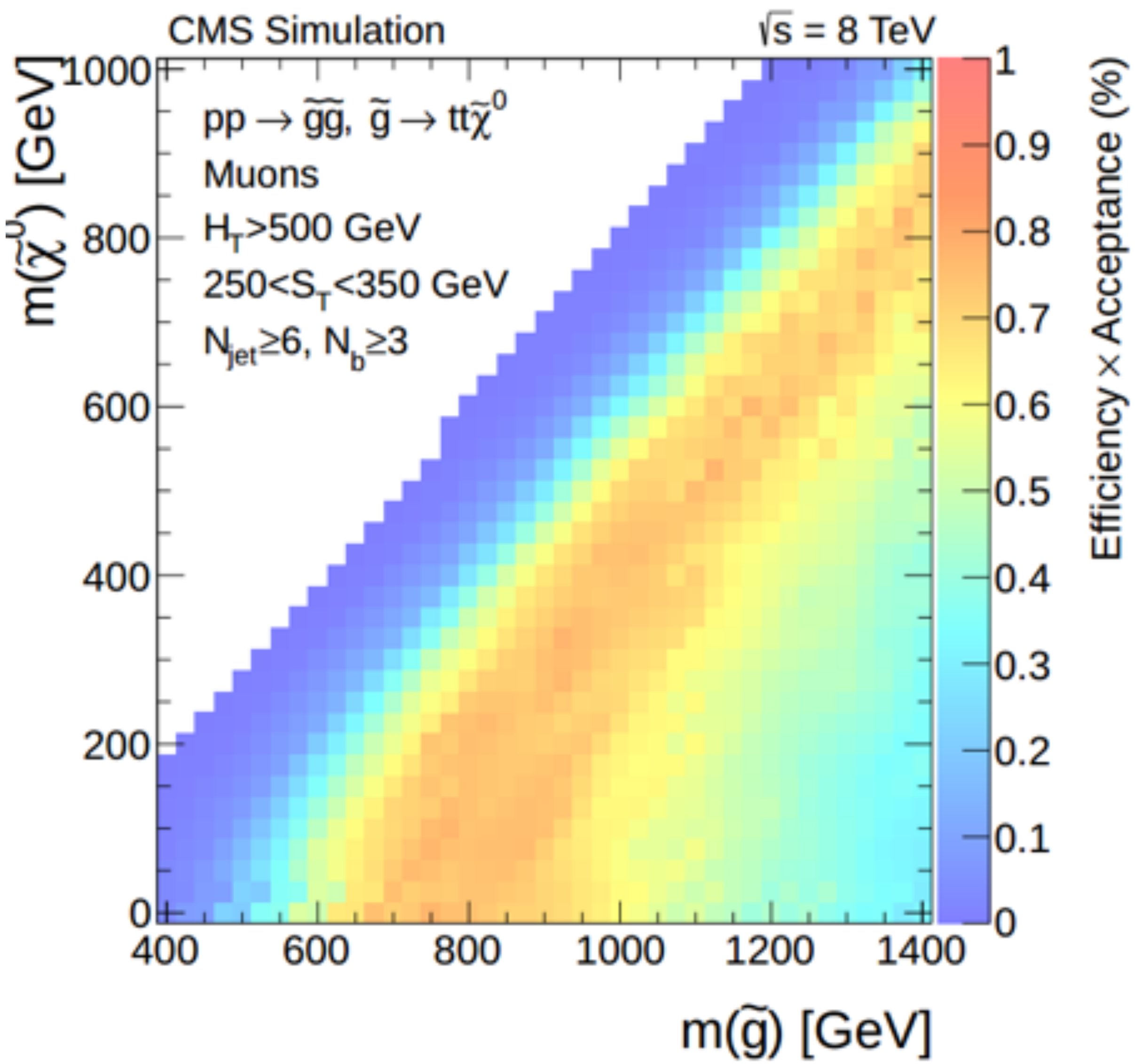


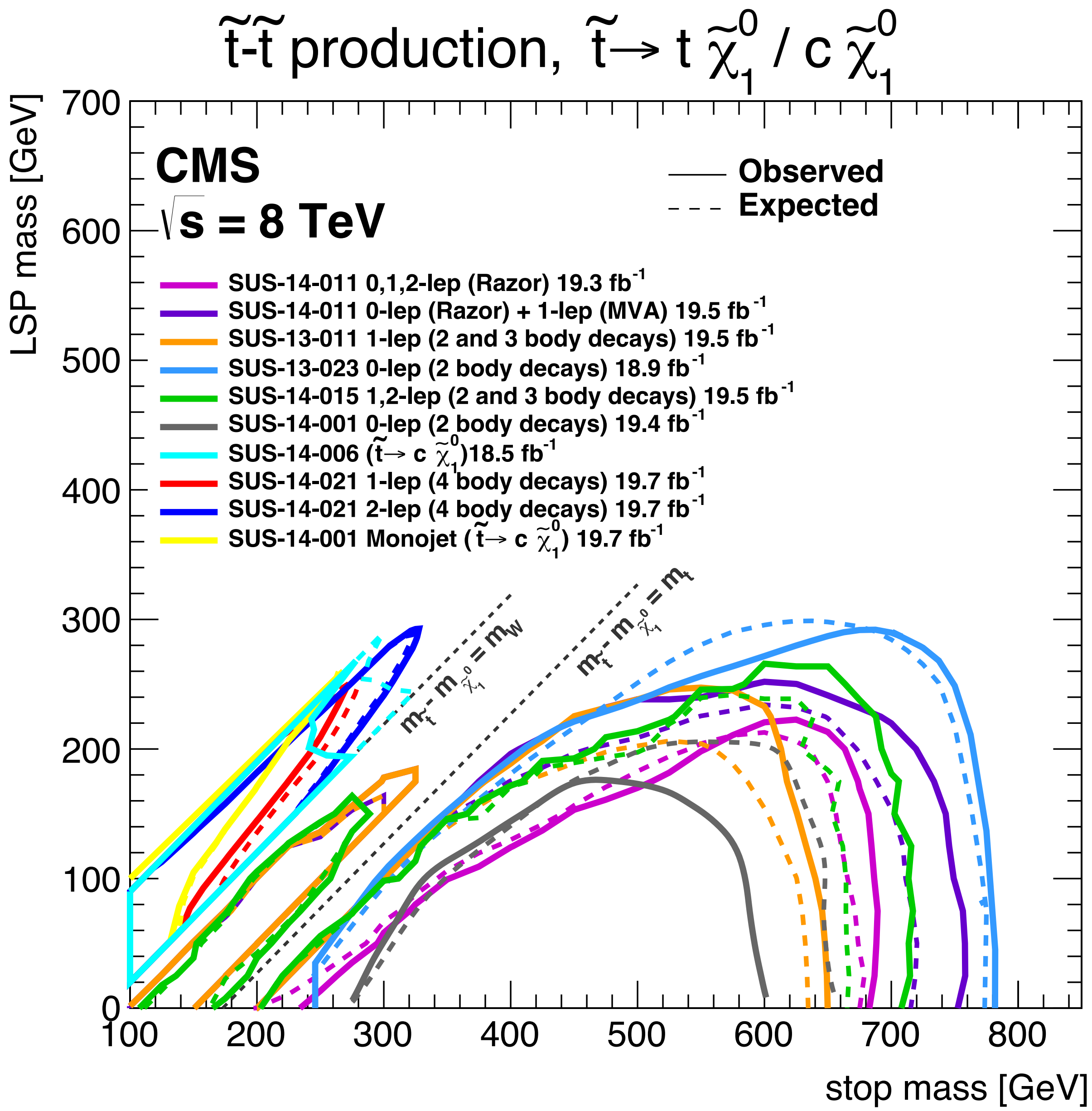
Definition of ***Efficiency***
(precisely: ***Acceptance x Efficiency***)

It is the ratio of the events passing all the selection cuts of an analysis, divided by the total number of Monte Carlo event generated

It measures the sensitivity of the analysis to a particular BSM signal

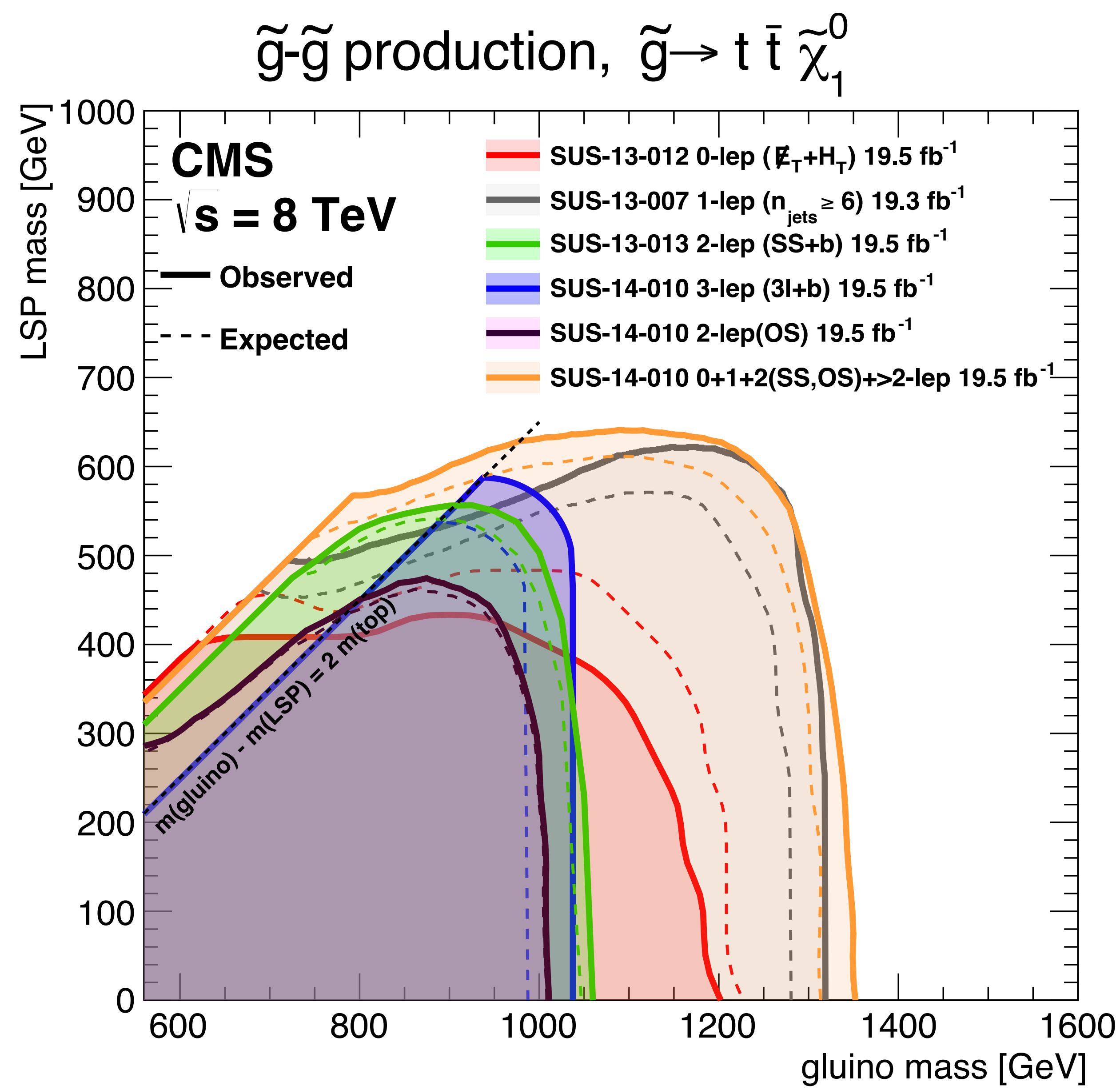
SUSY Simplified Model Results (8 TeV)

Run 1 Total integrated luminosity ~ 20 fb^{-1}

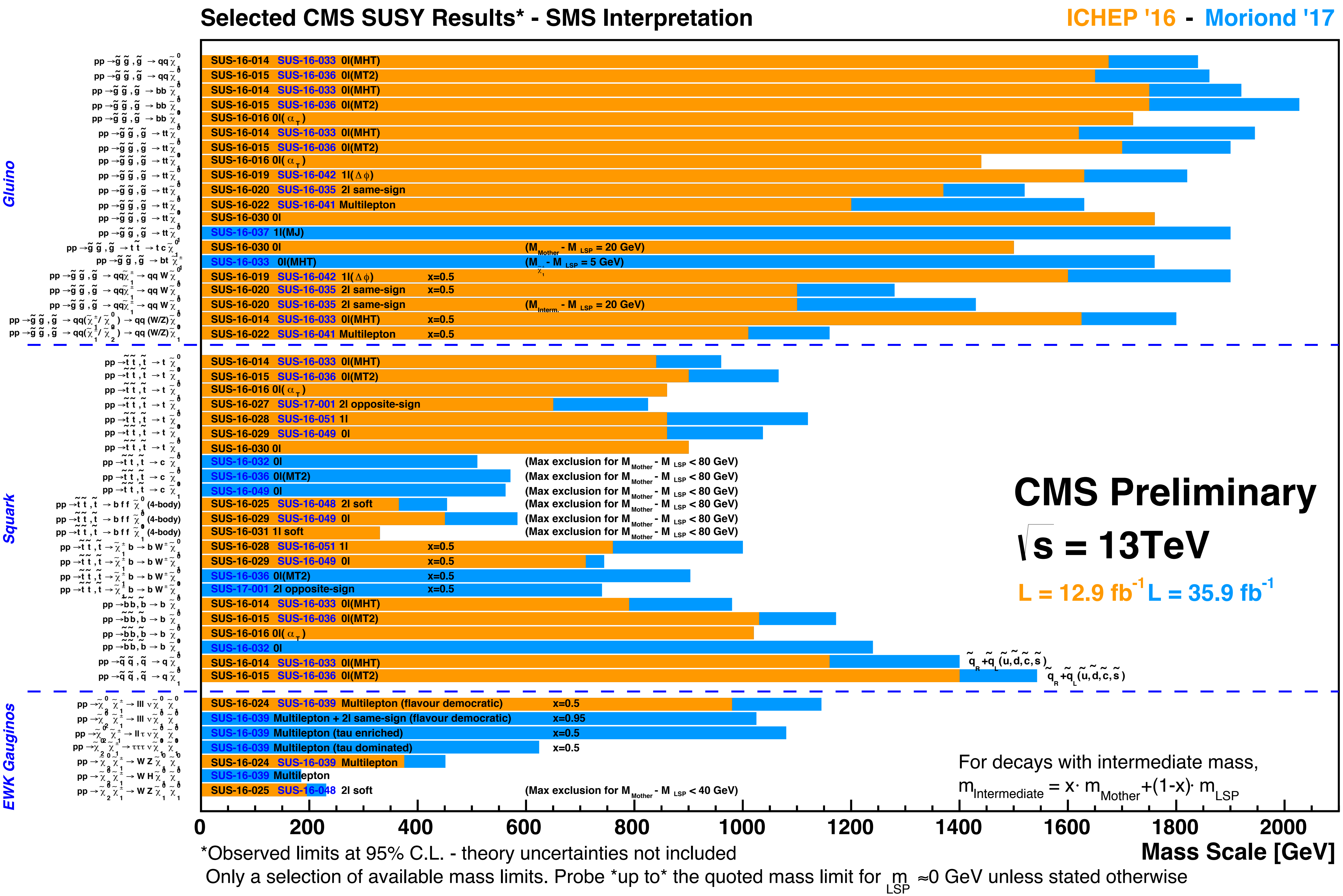


Stops excluded up to 800 GeV mass (under SMS assumptions)

Gluinos excluded up to 1.4 TeV mass (under SMS assumptions)



SUSY Simplified Model Results (13 TeV)



Recasting of the **CMS-SUS-16-033** analysis with **MadAnalysis 5**

Principles of Analysis Recasting (1)

- Searches for new physics at the LHC (e.g. SUSY, DM, long-lived particles, heavy resonances etc.) are sensitive to numerous different BSM models

- Experimental Collaborations can provide results only for selected full/simplified models

Recasting tools are a powerful instrument able to constrain generic BSM models using the results from LHC searches

CheckMATE, Rivet
MadAnalysis 5

Basic ideas:

- reproduce the flow (selection of events) of an analysis outside the experiments
- calculate cross section UL for the model
- compare experimental results with theory prediction and determine if the model is excluded/allowed

Principles of Analysis Recasting (2)

The ‘slow’ way

Monte Carlo events generation
(for BSM signals)

Detector simulation
(ATLAS,CMS)

Analysis recast
(extract the efficiency)

“Fast” ~10 min

!!! Up to several hours for a single BSM point !!!

Pro:

- most accurate method, since it is based on full event simulation
- based on standard Monte Carlo sample events: can be used with generic BSM model

Principles of Analysis Recasting (3)

The 'slow' way

Analysis recast
(extract the efficiency)

MadAnalysis 5 Physics Analyses Database (PAD)

https://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase

CMS analyses, 13 TeV

Analysis	Short Description	Implemented by	Code
CMS-SUS-16-033	Supersymmetry in the multijet plus missing energy channel (35.9 fb-1)	F. Ambrogi and J. Sonneveld	Inspire
CMS-SUS-16-039	Electroweakinos in the SS2L, 3L and 4L channels (35.9 fb-1)	B. Fuks and S. Mondal	Inspire
CMS-SUS-16-052	SUSY in the 1l + jets channel (36 fb-1)	D. Sengupta	Inspire
CMS-SUS-17-001	Stops in the OS dilepton mode (35.9 fb-1)	S.-M. Choi, S. Jeong, D.-W. Kang, J. Li *et al.*	Inspire
CMS-EXO-16-010	Mono-Z-boson (2.3 fb-1)	B. Fuks	Inspire
CMS-EXO-16-012	Mono-Higgs (2.3 fb-1)	S. Ahn, J. Park, W. Zhang	Inspire
CMS-EXO-16-022	Long-lived leptons (2.6 fb-1)	J. Chang	Inspire
CMS-TOP-17-009	SM four-top analysis (35.9 fb-1)	L. Darmé and B. Fuks	Inspire

ATLAS analyses, 8 TeV

Analysis	Short Description	Implemented by	Code
ATLAS-SUSY-2013-05 (published)	stop/sbottom search: 0 leptons + 2 b-jets	G. Chalons	Inspire
ATLAS-SUSY-2013-11 (published)	EWK-inos, 2 leptons + MET	B. Dumont	Inspire
ATLAS-HIGG-2013-03 (published)	ZH->ll+invisible	B. Dumont	Inspire
ATLAS-EXOT-2014-06 (published)	mono-photons + MET	D. Barducci	MA5tune v1.2/Delphes3
ATLAS-SUSY-2014-10 (published)	2 leptons + jets + MET	B. Dumont	Inspire
ATLAS-SUSY-2013-21 (published)	0 leptons + mono-jet/c-jets + MET	G. Chalons, D. Sengupta	Inspire
ATLAS-SUSY-2013-02 (published)	0 leptons + 2-6 jets + MET	G. Chalons, D. Sengupta	Inspire
ATLAS-SUSY-2013-04 (published)	0 leptons + >6 jets + MET	B. Fuks, M. Blanke, I. Galon	Inspire

Example: Validation of CMS-SUS-16-033

Search for supersymmetry in multijet events with missing transverse momentum in proton-proton collisions at 13 TeV

arXiv:1704.07781

http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-16-033/

From the analysis description to the implementation

4 Event selection and search regions

Events considered as signal candidates are required to satisfy:

- $N_{\mathrm{jet}} \geq 2$, where jets must appear within $|\eta| < 2.4$;
- $H_{\mathrm{T}} > 300\,\mathrm{GeV}$, with H_{T} the scalar p_{T} sum of jets with $|\eta| < 2.4$;
- $H_{\mathrm{T}}^{\mathrm{miss}} > 300\,\mathrm{GeV}$, where $H_{\mathrm{T}}^{\mathrm{miss}}$ is the magnitude of $\vec{H}_{\mathrm{T}}^{\mathrm{miss}}$, the negative of the vector p_{T} sum of jets with $|\eta| < 5$; an extended η range is used to calculate $H_{\mathrm{T}}^{\mathrm{miss}}$ so that it better represents the total missing transverse momentum in an event;
- no identified, isolated electron or muon candidate with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$;
- no isolated track with $m_{\mathrm{T}} < 100\,\mathrm{GeV}$ and $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ ($p_{\mathrm{T}} > 5\,\mathrm{GeV}$ if the track is identified as a PF electron or muon), where m_{T} is the transverse mass [40] formed from the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and isolated-track p_{T} vector, with $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ the negative of the vector p_{T} sum of all PF objects;

Example: Validation of CMS-SUS-16-033

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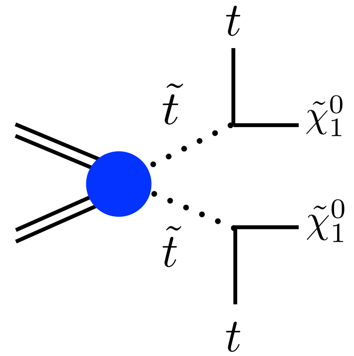
From the analysis description to the implementation

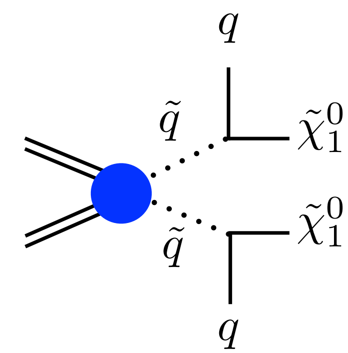
```
// Define the preselection cuts (not including Jet,Nb,HT,MHT binnings)
Manager()->AddCut("Njet>=2")           ; // more or equal 2 jets with |eta|<2.4
Manager()->AddCut("HT>300")            ; // HT = scalar sum of jets pt>30 GeV
Manager()->AddCut("MHT>300")           ; // HTM = magnitude of the the vector HTMiss, i.e. negative of
Manager()->AddCut("NoIsoMuons")        ; // No isolated muons with pt>10 GeV
Manager()->AddCut("NoMuonsTracks")     ; // No isolated muons tracks
Manager()->AddCut("NoIsoElectrons")    ; // No isolated electron with pt>10 GeV
Manager()->AddCut("NoElectronsTracks") ; // No isolated electron tracks
Manager()->AddCut("NoIsoTracks")       ; // no isolated tracks with mT<100 GeV and pT>10 GeV
                                         // (pT > 5 GeV if track is a PF electron or muon)
                                         // mT = transverse mass formed with the pTmiss (all pT of the

Manager()->AddCut("DPhi(MHTj1)>0.5") ; // Azimutal angle between MHT and the pT of the 'i' jet
Manager()->AddCut("DPhi(MHTj2)>0.5") ;
Manager()->AddCut("DPhi(MHTj3)>0.3") ;
Manager()->AddCut("DPhi(MHTj4)>0.3") ;
```

Next Step:
Validation of the code

CMS-SUS-16-033 Validation: Cutflow

Pre-selection cuts





	T2tt=(700,50)					**T2=(1000,100)**				
	Absolute			Relative		Absolute			Relative	
Cut	**MA5**	**CMS**	**Diff(%)**	**MA5**	**CMS**	**MA5**	**CMS**	**Diff(%)**	**MA5**	**CMS**
$n_{jet} \geq 2$	98.90	99.80	0.90			97.82	98.90	1.09		
H_T >300	92.30	96.40	4.25	-6.67	-3.41	97.12	98.60	1.50	-0.72	-0.30
$\not{H}_T$ >300	54.13	57.80	6.35	-41.36	-40.04	79.16	80.00	1.04	-18.49	-18.86
NoIsoMuons	48.16	46.60	-3.35	-11.02	-19.38	79.16	79.90	0.92	-0.00	-0.12
NoMuonsTracks	47.74	46.10	-3.55	-0.88	-1.07	79.14	79.80	0.82	-0.03	-0.13
NoIsoElectrons	43.32	37.40	-15.82	-9.26	-18.87	79.14	79.60	0.57	0.00	-0.25
NoElectronsTracks	42.78	36.90	-15.94	-1.23	-1.34	79.12	79.30	0.23	-0.03	-0.38
NoIsoTracks	42.16	35.80	-17.77	-1.45	-2.98	78.96	78.70	-0.33	-0.20	-0.76
$\Delta\phi(\not{H}_T$,j1)>0.5	42.03	35.70	-17.74	-0.30	-0.28	78.89	78.60	-0.36	-0.09	-0.13
$\Delta\phi(\not{H}_T$,j2)>0.5	40.03	34.00	-17.73	-4.77	-4.76	73.58	74.50	1.24	-6.73	-5.22
$\Delta\phi(\not{H}_T$,j3)>0.3	38.77	33.10	-17.13	-3.14	-2.65	70.24	70.60	0.50	-4.53	-5.23
$\Delta\phi(\not{H}_T$,j4)>0.3	35.45	31.80	-11.48	-8.56	-3.93	67.65	67.90	0.36	-3.69	-3.82

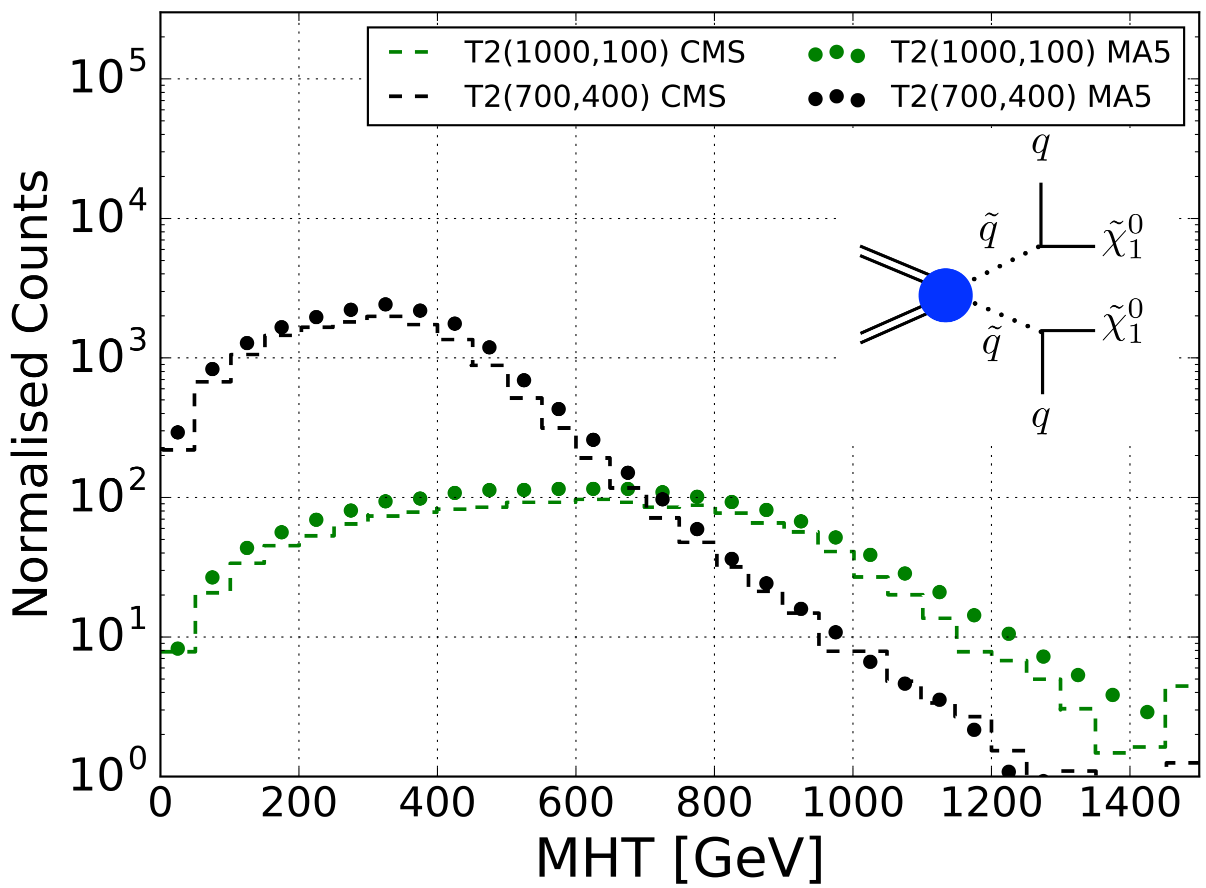
Obtained with MA5

Provided by CMS

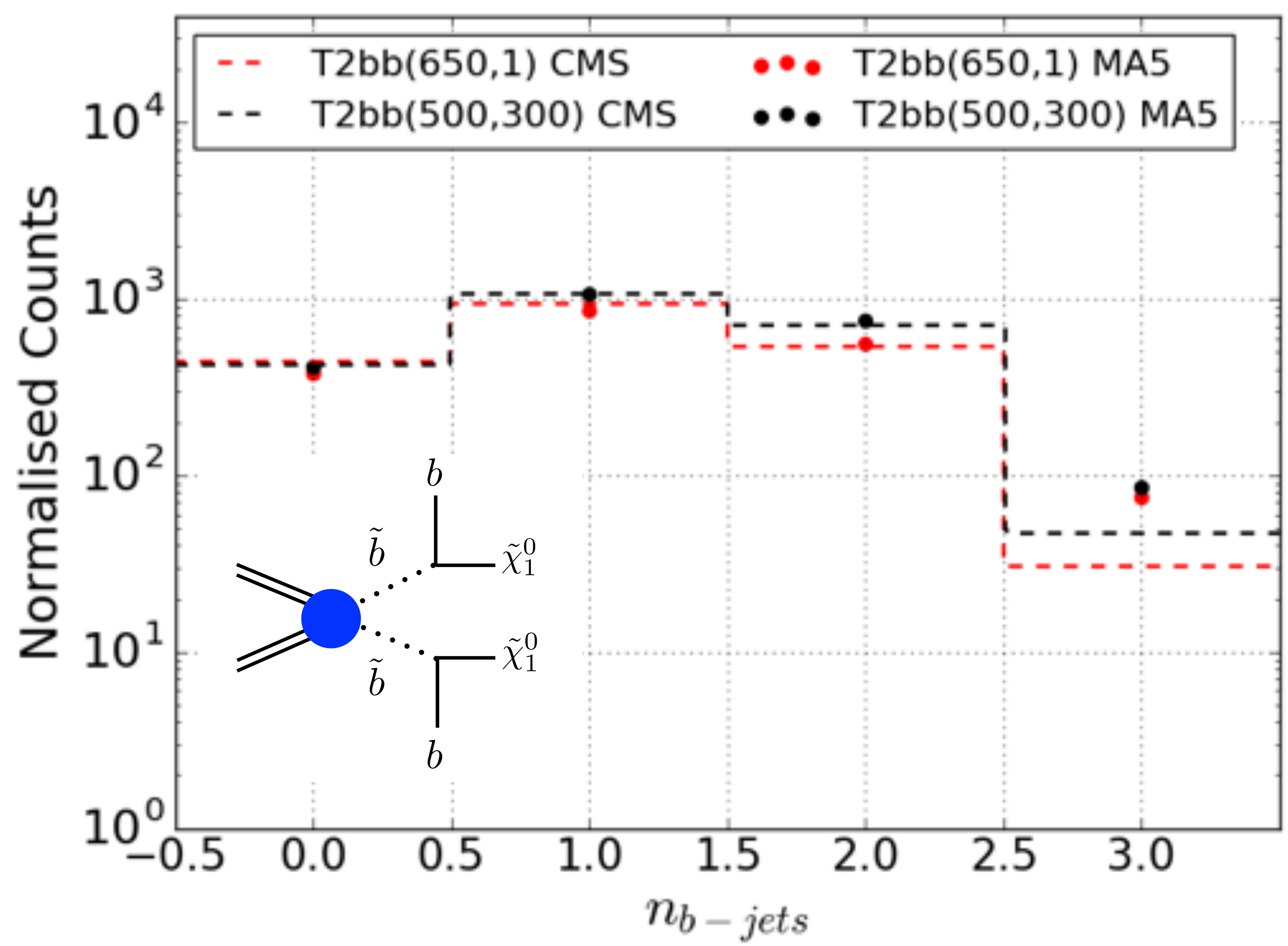
$$\not{H}_T = |\vec{\not{H}}_T| = \left| \sum_{jets(p_T>30)} \vec{p}_T \right|$$

$$H_T = \sum_{jets(p_T>30)} |\vec{p}_T|$$

CMS-SUS-16-033 Validation: Kinematic Distributions



Validation needed for several mass points of the same simplified model (to check mass dependent effects)



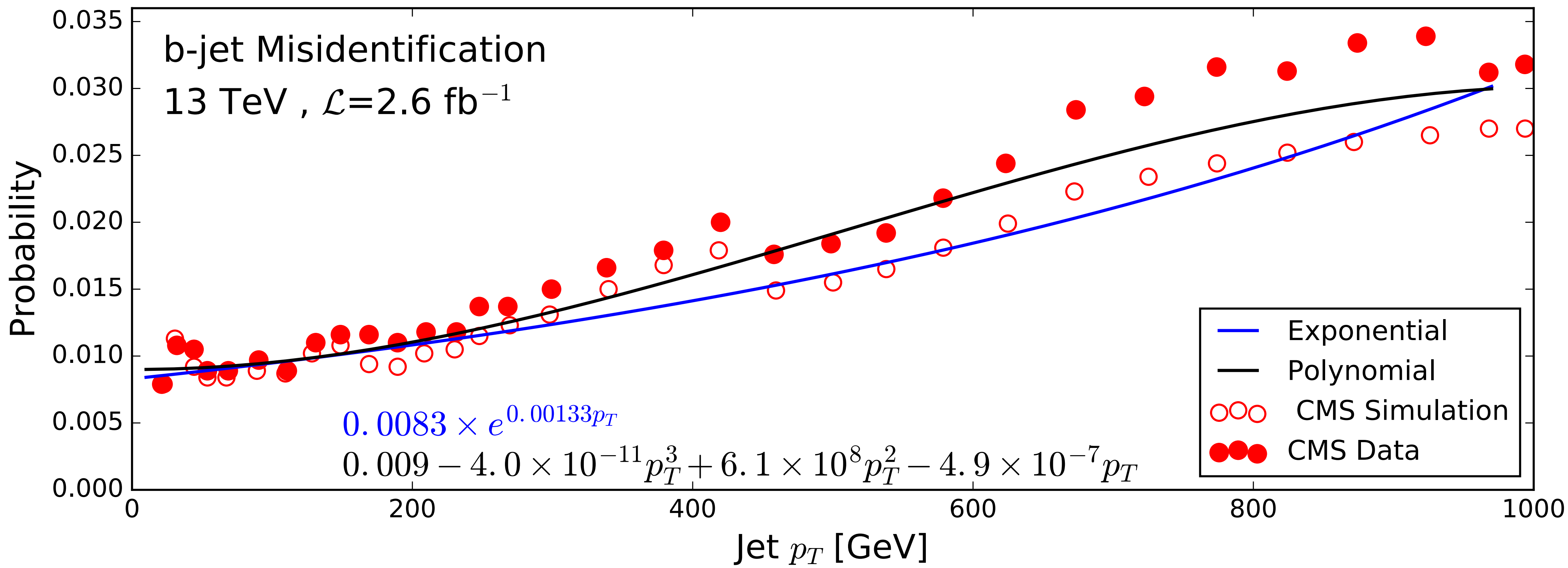
T2 = (1000,100), (700,400)
T2bb= (650,1) , (500,300)

Large mass gap   Small mass gap

On the Validation

- An analysis is considered validated if MA5 results are compatible within ~20/30 % wrt official results
- Implementing the code is easy if the selection cuts are properly described in the paper
- Very important: description of the object selection efficiency (at the detector simulation or at the analysis level, e.g. b-tagging efficiency)
- Different Monte Carlo production settings might play a big role

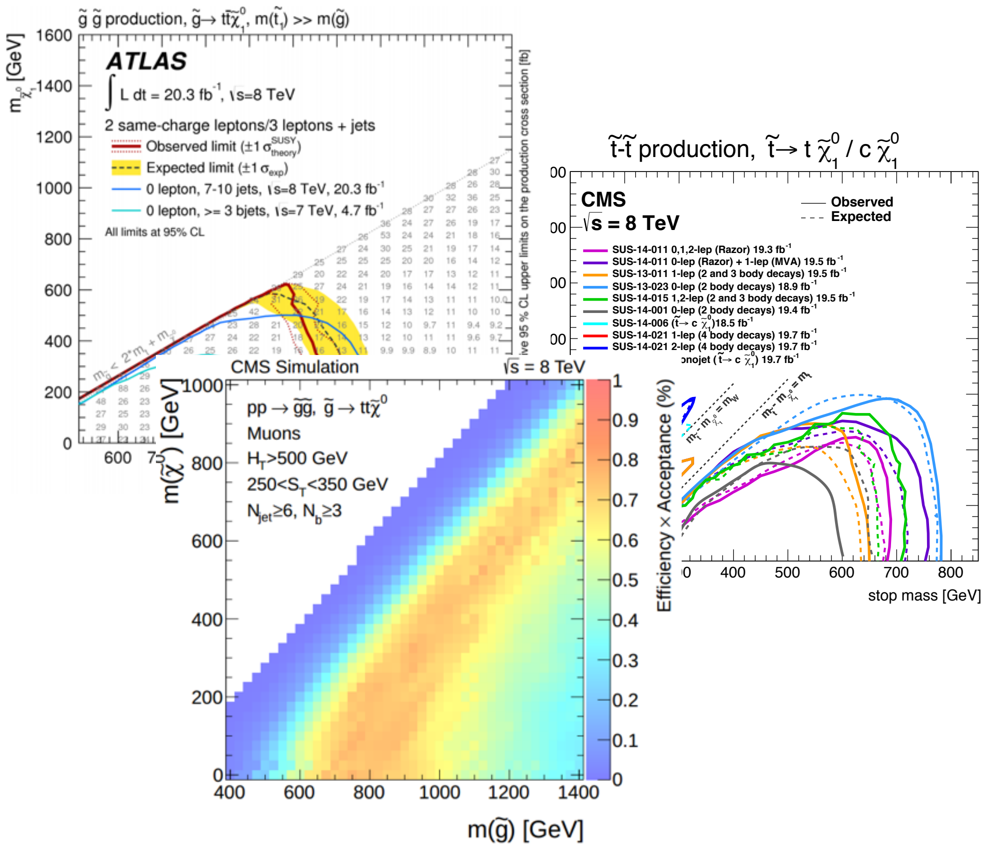
Example: b-jet misidentification



Making Systematic Use of Simplified Models Results from the LHC Searches with **SModelS**

Making Systematic Use of Simplified Model Results

Basic Idea: use the simplified models results from the ATLAS and CMS collaboration, to constrain generic BSM model



Constrain generic BSM model

SModelS

http://smodels.hephy.at/wiki

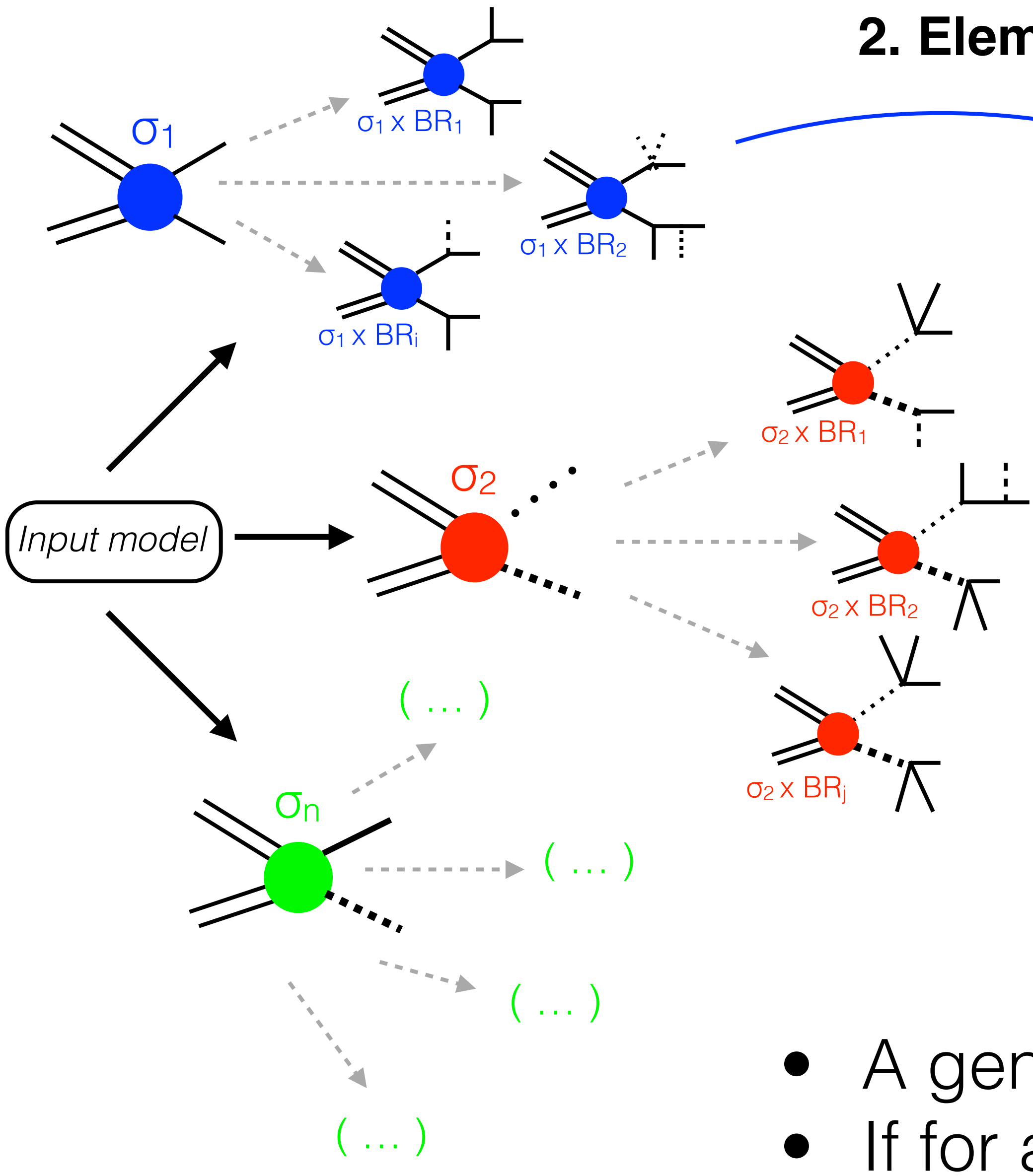
Tool designed to constrain any BSM model (with a Z_2 symmetry e.g. R-parity for SUSY models) with the Simplified Models Results from the LHC

From v1.2 onwards: exotic signatures e.g. long-lived charged particles
Future extension: resonances, …

SModelS: Basic Principles

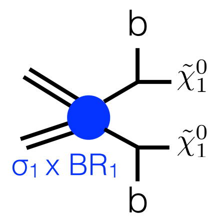
1. Decomposition

2. Element Combination



Theory Module

3. Comparison with LHC constraints



$$w = \sigma_{(pp\to\tilde{b}\tilde{b}^*)} \times BR_{(\tilde{b}\to b\tilde{\chi}_1^0)}$$

Database

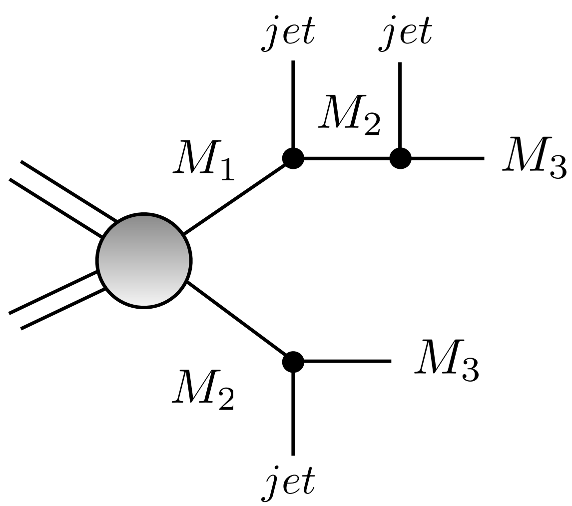
Database results:
ATLAS-SUSY-2013-05
CMS-PAS-SUS-12-024
CMS-SUS-13-012-eff
…

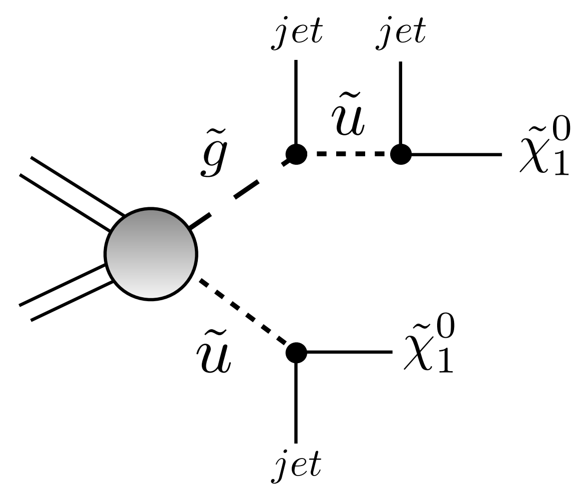
- A generic input model is decomposed into its SMS
- If for a element/combination of elements

$$\sigma_{Theo} > \sigma_{UL} \quad \text{or} \quad \boxed{\text{rvalue} = \frac{\sigma_{Theo}}{\sigma_{UL}} > 1}$$

the point is considered Excluded

Theory Module: Decomposition into SMS, SModelS Elements





= [['jet'],['jet']]

= [['jet']]

[[['jet'],['jet']],['jet']]]

$([[m_{\tilde{g}}, m_{\tilde{u}}, m_{\tilde{\chi}_1^0}],[m_{\tilde{u}}, m_{\tilde{\chi}_1^0}]])$

$[[[M_1,M_2,M_3]],[M_2,M_3]]]$

(Experimental) Constraint

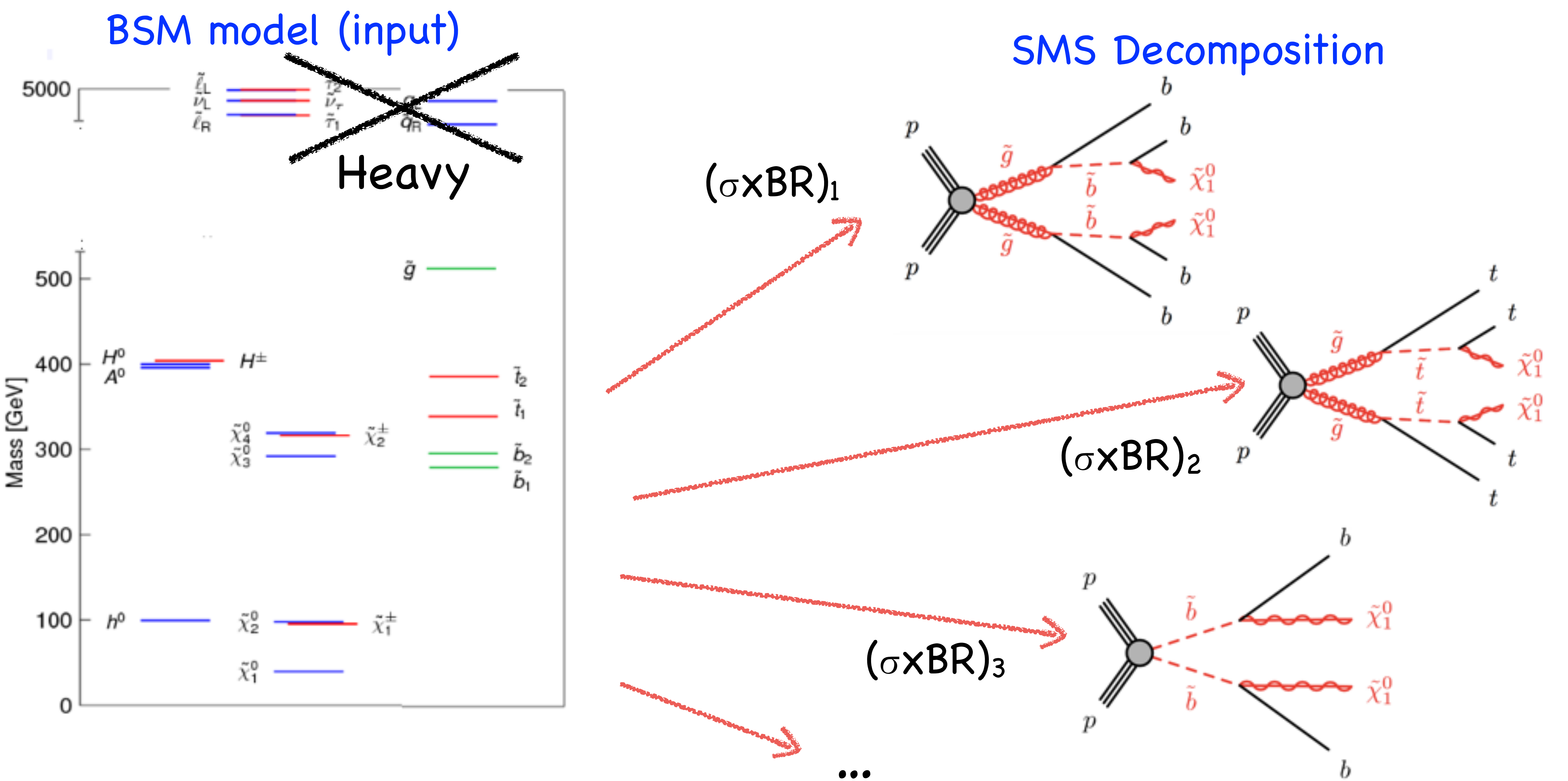
The decomposition maps each BSM model into its SMS spectra

Each element is characterised by:

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

Theory Module: Decomposition Example

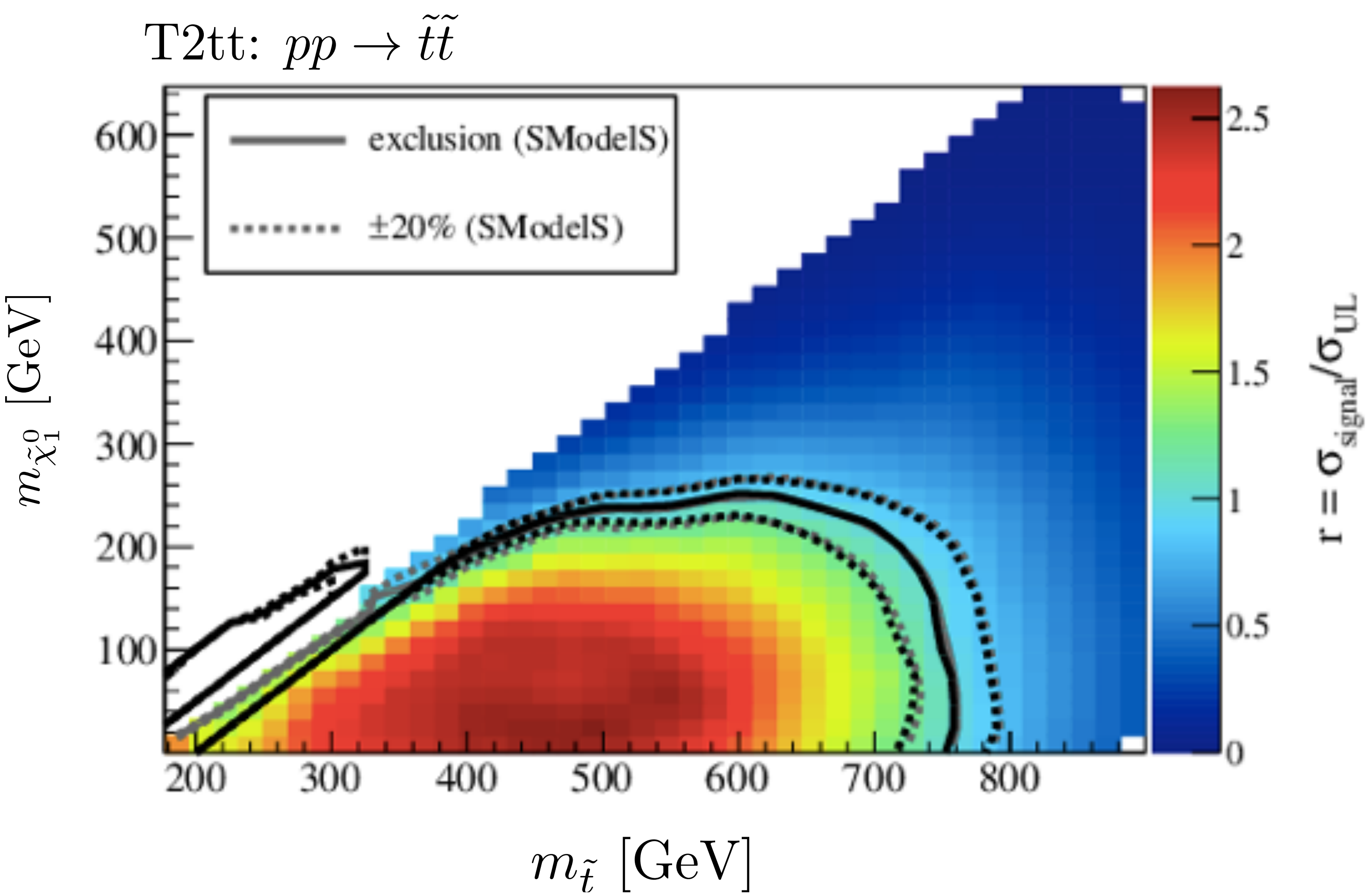
A generic BSM model is decomposed into its SMS
(a Z_2 symmetry is required, e.g. R-parity for SUSY models)



SModelS: Validation of the Implemented Results

CMS-SUS-13-004 T2tt UL result

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



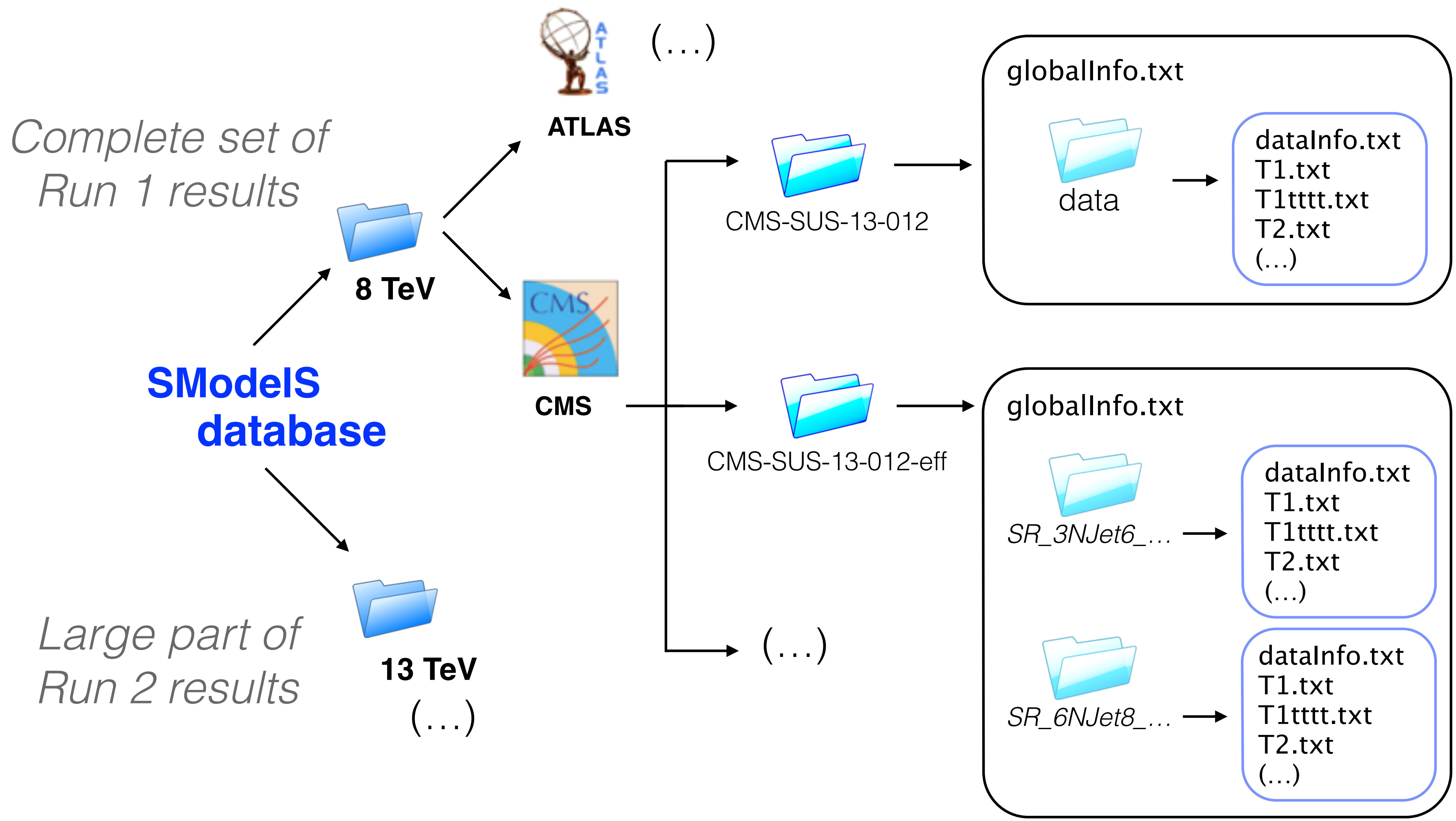
$\sigma_{\text{th.}} = \sigma(pp>t\sim t\sim)$

Validation Procedure

- Run SModelS over a grid of T2tt points
- Compare $\sigma_{\text{th.}}$ with CMS σ_{UL}
- Extract SModelS exclusion

Only '*validated*' analyses enter the database

SModelS: Database of Experimental Results



EM maps results

Official ATLAS and CMS

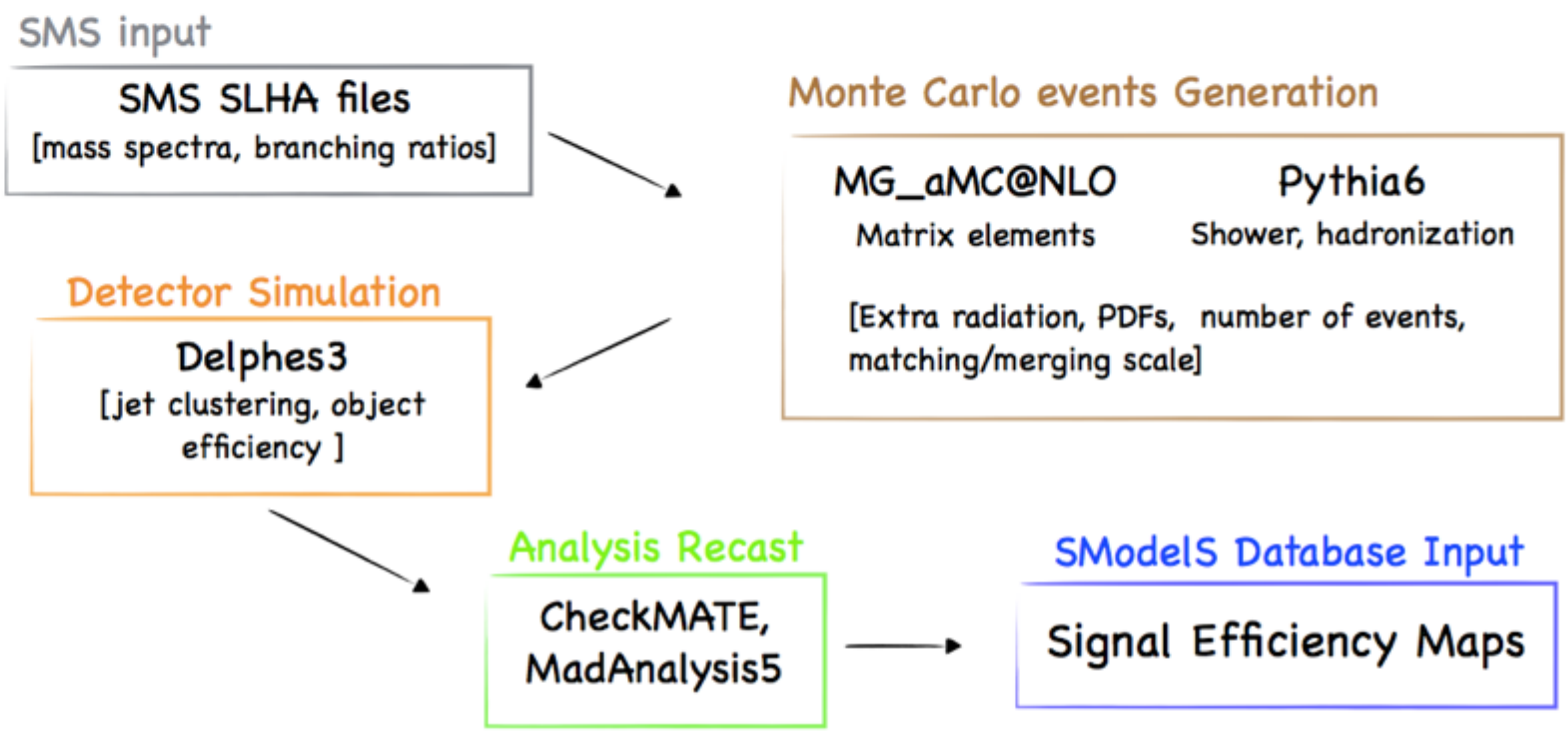
FastLim Collaboration*

SModelS Homegrown*

SModelS: Efficiency Maps Bakery

* EMs produced by Phenomenologists: FastLim Collaboration and SModelS

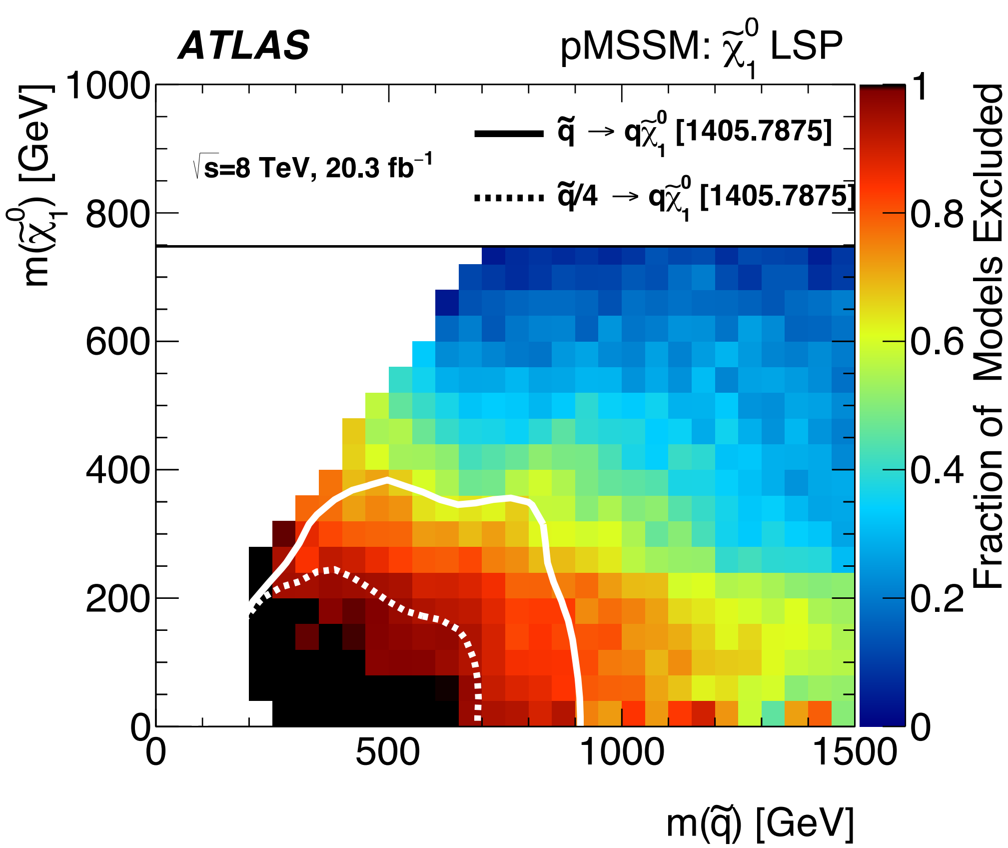
Idea: using recasting tools to produced recast EMs for simplified models which are not covered by the existing experimental results



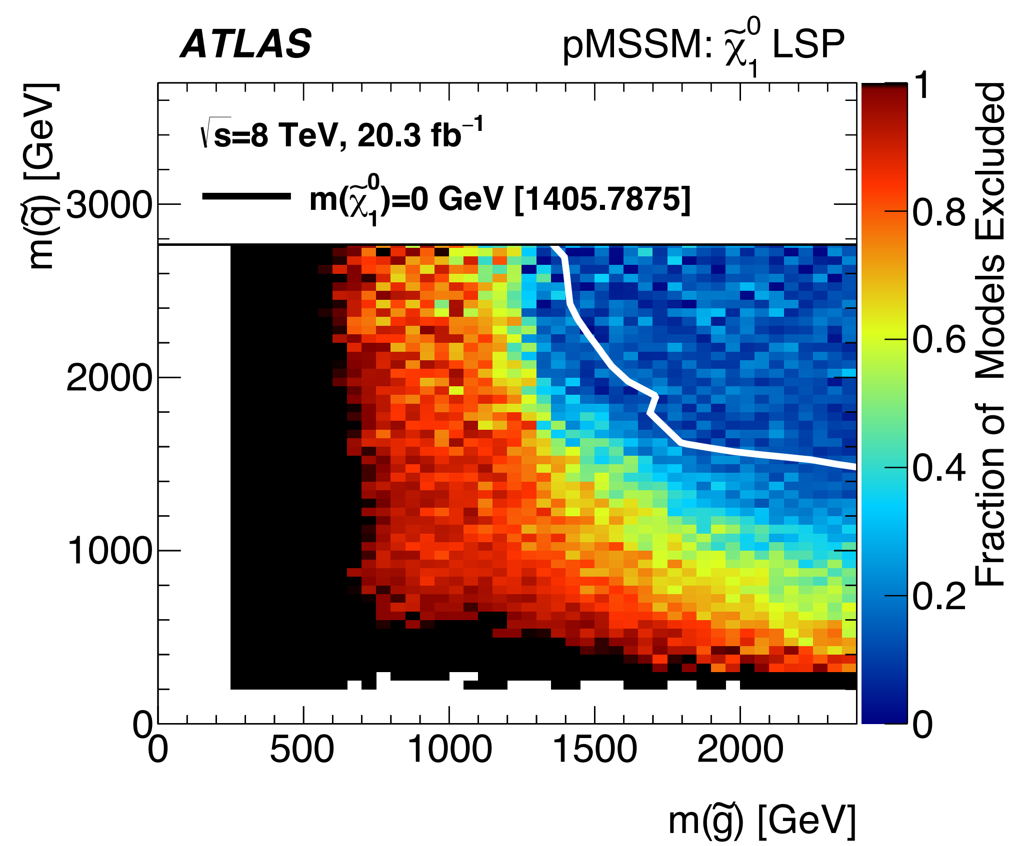
MC production only run once, and then the EMs in the database will be used for any BSM model tested

- The phenomenological Minimal Supersymmetric Standard Model (**pMSSM**) is a widely studied “full” SUSY model
- It reduces the full MSSM to only *~20 free parameters*
- Used as a benchmark by ATLAS and CMS to quantify the impact of Run 1 searches on a full SUSY model (leaving the SMS assumptions)

Realistic models are needed to capture "*the complex effects that can result from large numbers of competing production and decay processes*"



(b) Lightest (1st/2nd gen) squark / LSP



(a) All LSP types

- The phenomenological Minimal Supersymmetric Standard Model (**pMSSM**) is a widely studied “full” SUSY model
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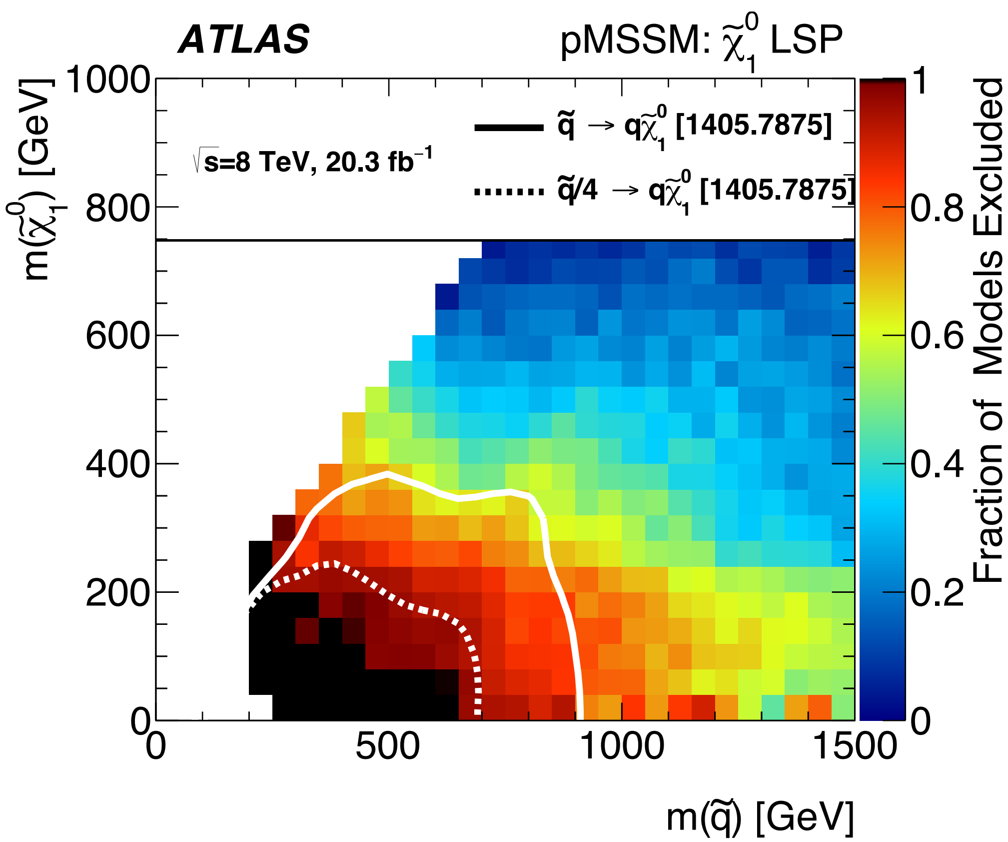


(b) Lightest (1st/2nd gen) squark / LSP

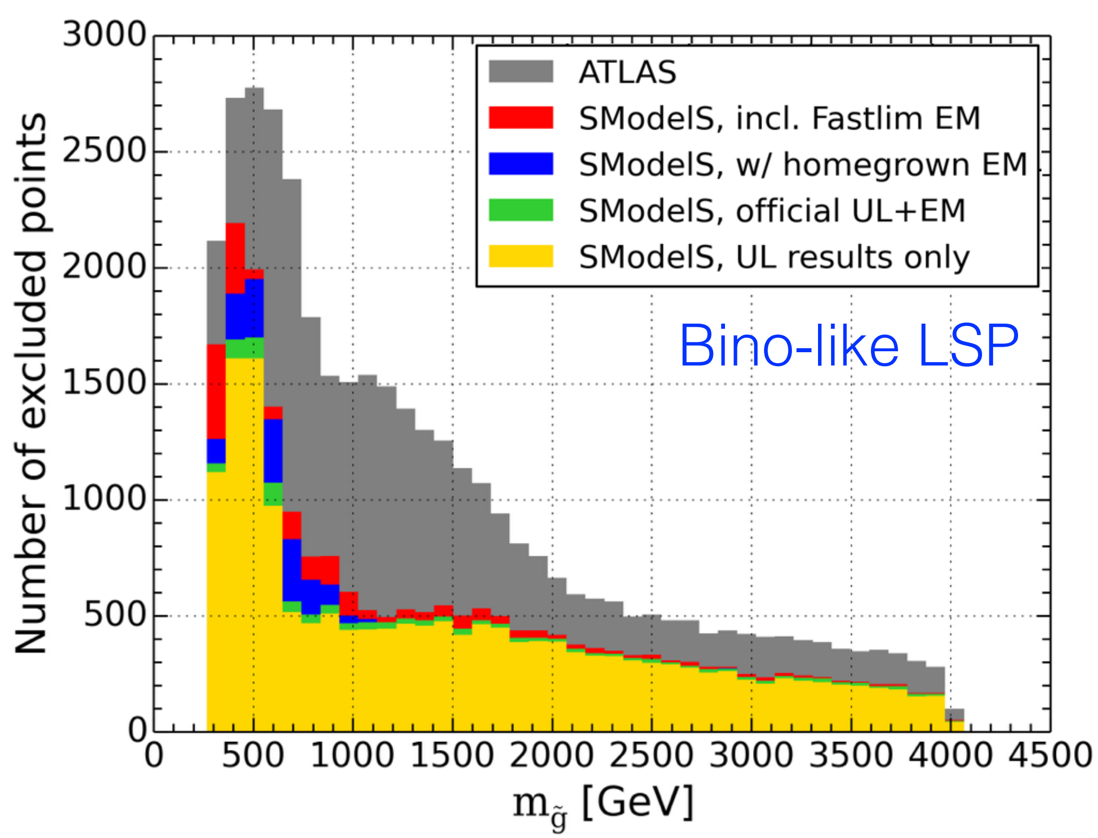
Due to complex decay chains, the mass limits of SUSY particles in realistic model can be largely different wrt the interpretation with SMS

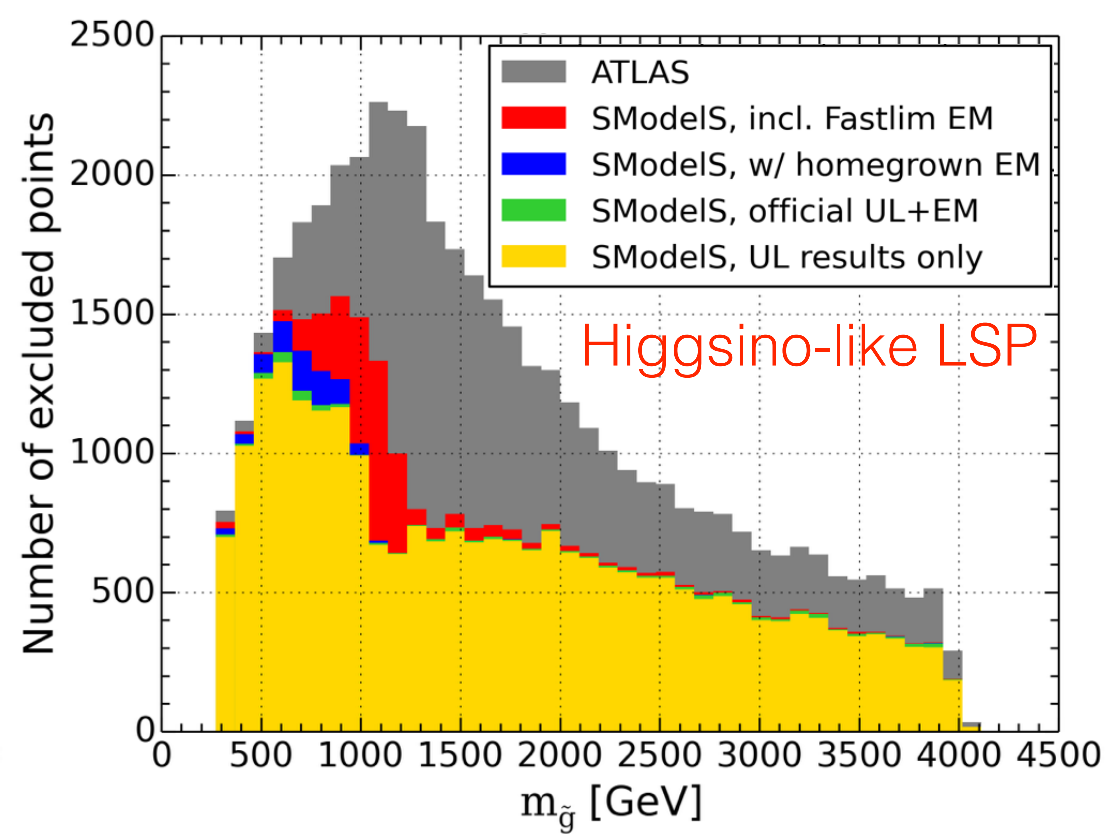
Constraining the pMSSM with SModelS

- We want to test how well a simplified model based interpretation performs wrt a full reinterpretation as done by ATLAS in the case of the pMSSM
- ATLAS provided all the model points tested
- We focused on the points *excluded* by ATLAS

Number of Points	**Bino-like** LSP	**Higgsino-like LSP**
Total	38575	45594
Excluded by UL	16957 (44 %)	25024 (55 %)
Excluded by UL+EM	21151 (55 %)	28669 (63 %)

arXiv:1707.09036



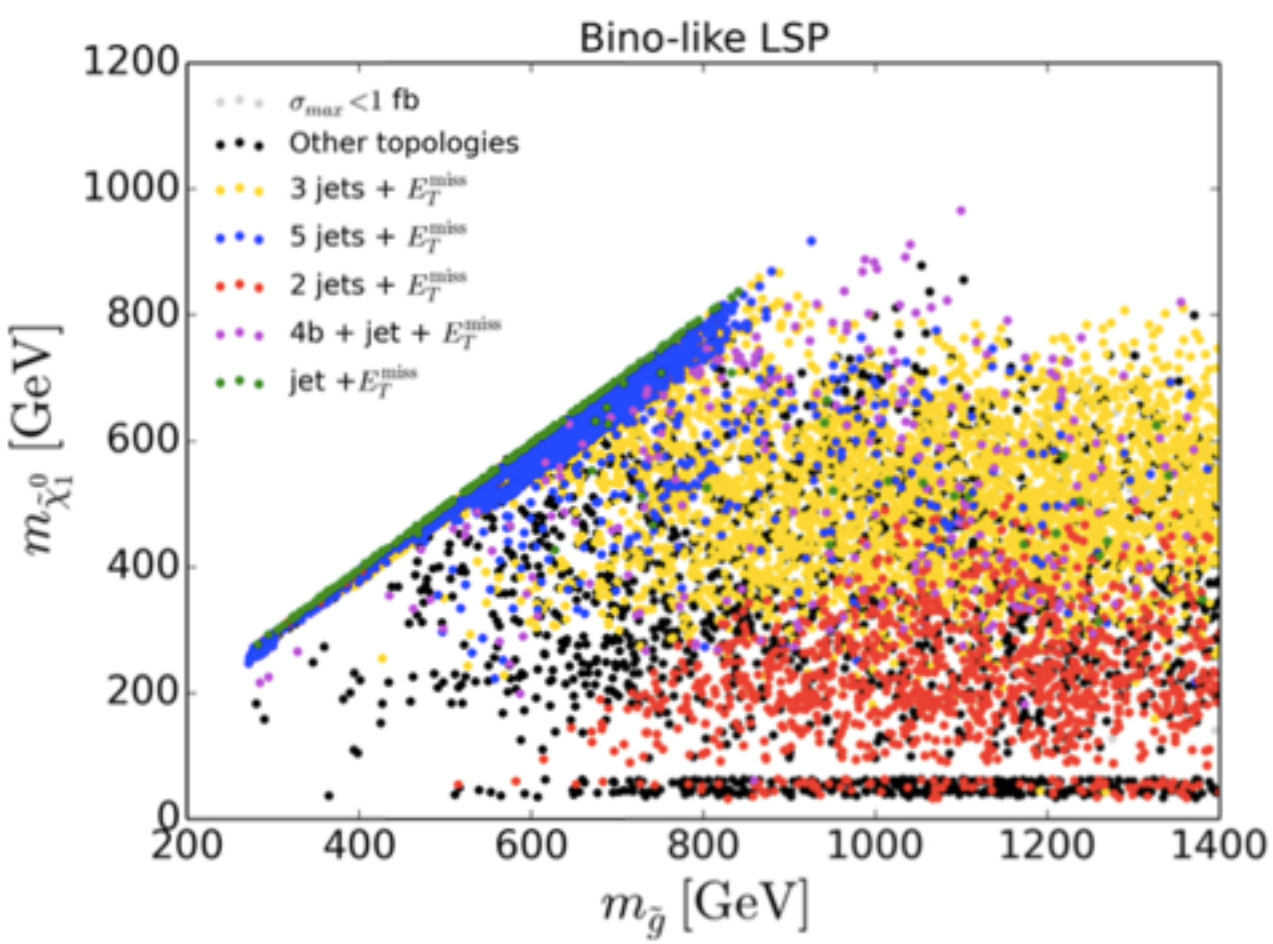


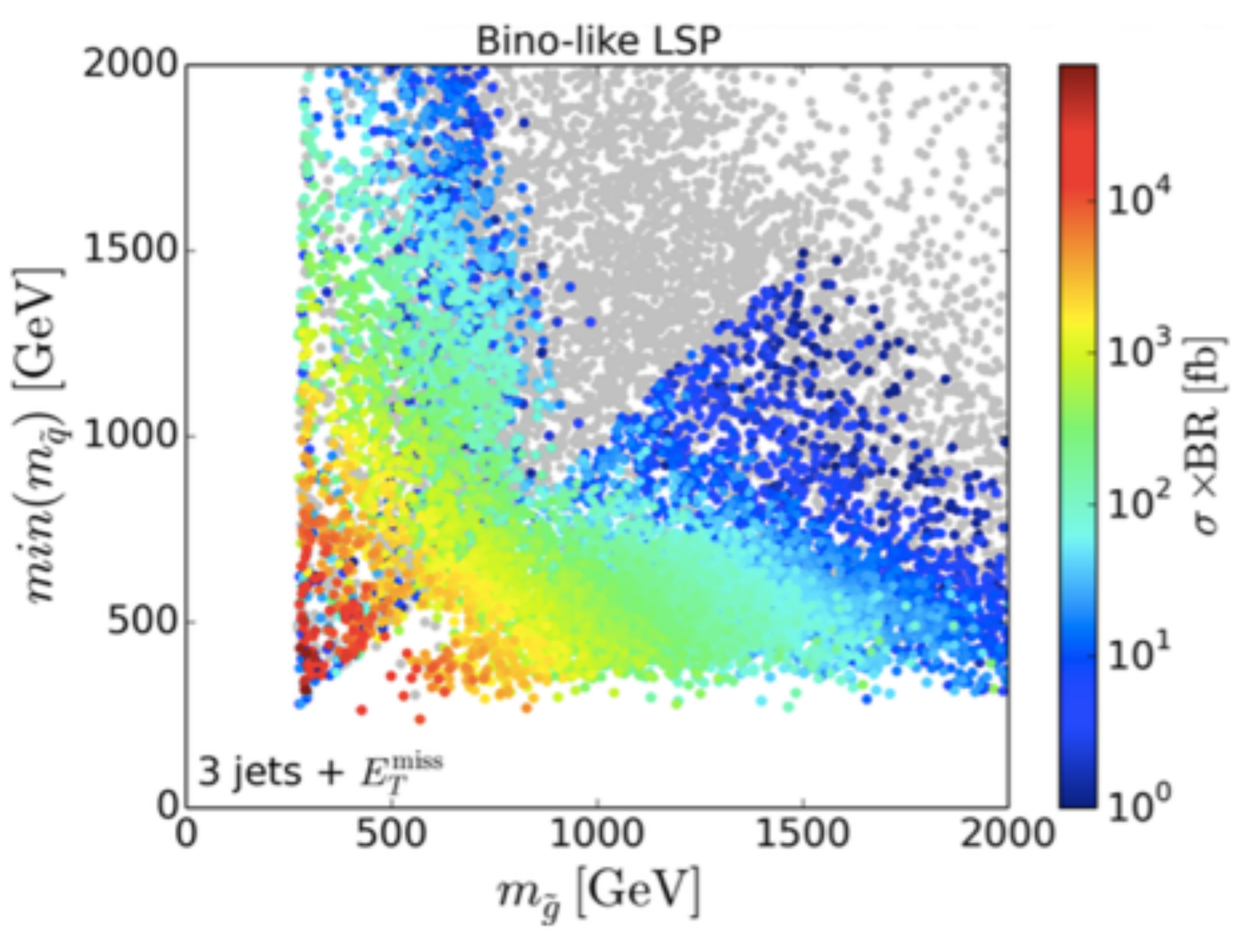
Constraining the pMSSM with SModelS: Missing Topologies

- Missing topologies: elements with the highest weight (cross section x BR) that are not included in the database
- Results for SMS that could potentially constrain the model tested if added to the database

```
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]]]
```

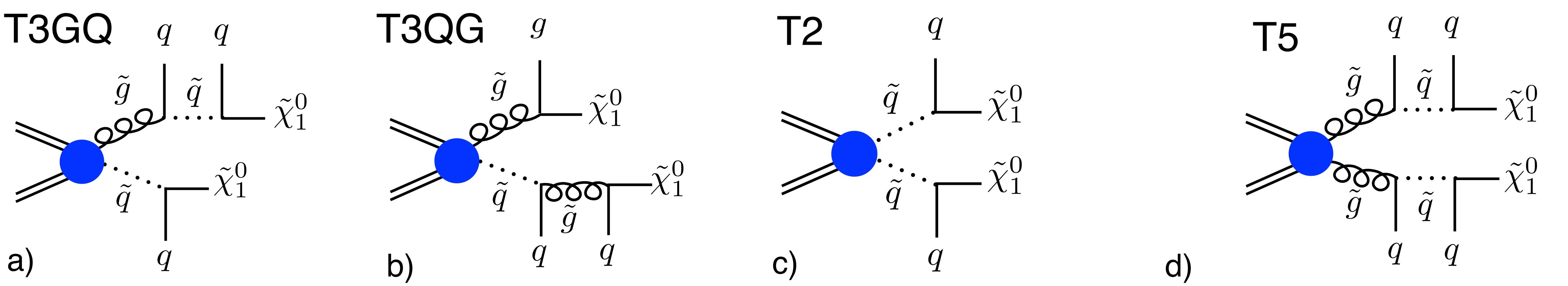
SModelS Missing topologies for an example pMSSM point





Missing Topology

Combined with the T3GQ model

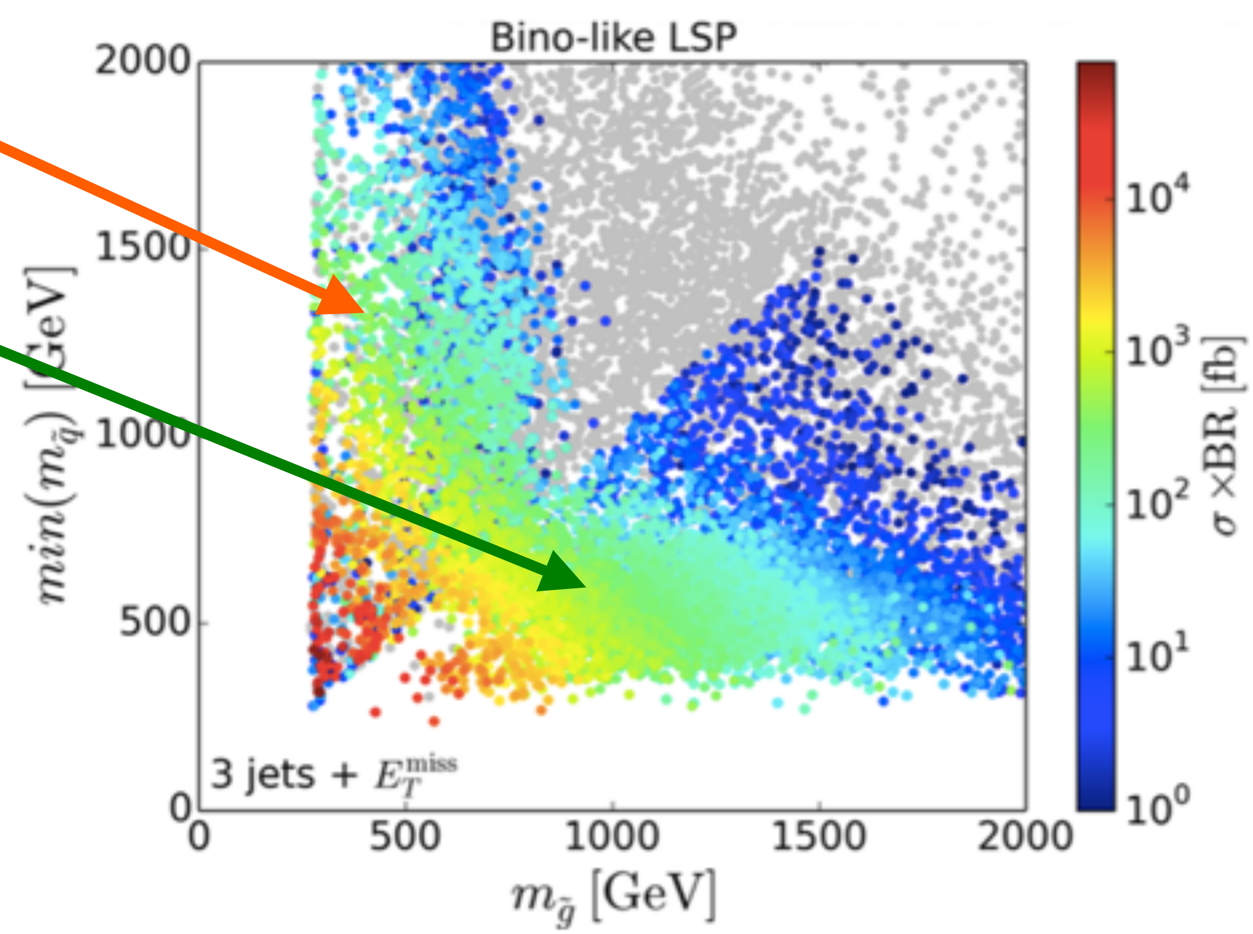


[[['jet']],[['jet'],['jet']]]

[[['jet']],[['jet']]]

[[['jet'],['jet']],[['jet'],['jet']]]

$m_{\tilde{g}} > min(m_{\tilde{q}})$ $min(m_{\tilde{q}}) > m_{\tilde{g}}$



- Special topology corresponding to two mass hierarchies
- pMSSM-19 has 3 light squark mass parameters

$$m_{\tilde{u}_L} = m_{\tilde{d}_L} = m_{\tilde{c}_L} = m_{\tilde{s}_L}$$
$$m_{\tilde{u}_R} = m_{\tilde{c}_R}$$
$$m_{\tilde{d}_R} = m_{\tilde{s}_R}$$

Extending the database: EMs production for T3GQon, T2, and T5

- Use the EM Bakery machinery to produce results for T3GQon, T2, and T5
- Implement the new results in SModelS database
- Check the new constraints

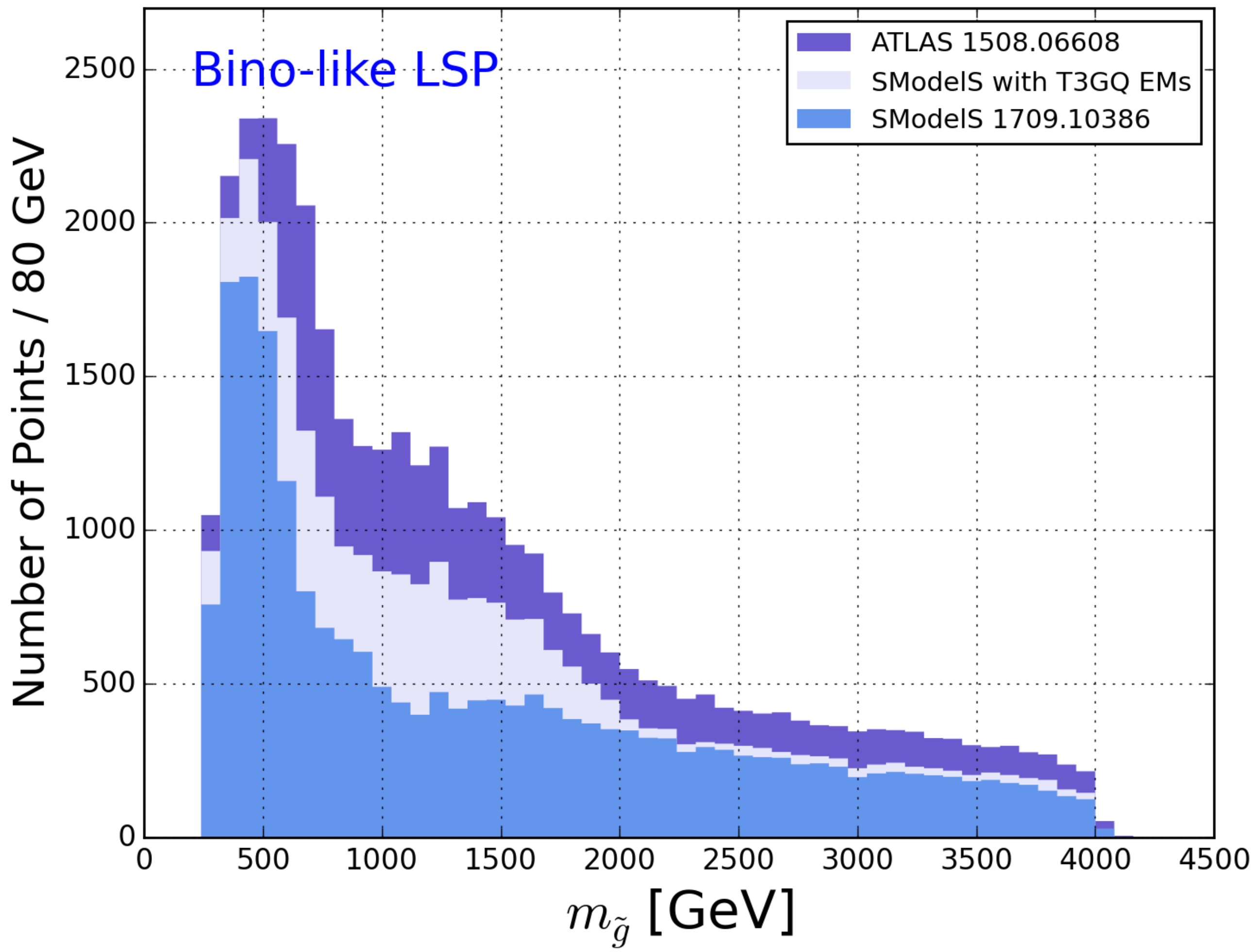
Txname	Mass Planes	Description
T2	-	$\Delta M(\tilde{q}, \tilde{\chi}_1^0)$ as low as 5 GeV
T5	x = (0.05 , 0.50, 0.95)	-
	$\Delta M(\tilde{g}, \tilde{q}) = 5$ GeV	-
	$\Delta M(\tilde{q}, \tilde{\chi}_1^0) = 5$ GeV	-
T3GQon	Fixed $m_{\tilde{g}}$ = 200,250,...,1200	$m_{\tilde{g}}$ in 50 GeV bins
	Fixed $m_{\tilde{g}}$ = 1300,1400,...,2000	$m_{\tilde{g}}$ in 100 GeV bins
		$m_{\tilde{q}}$ in 50 GeV bins (up to 1 TeV)
		$\Delta M(\tilde{q}, \tilde{\chi}_1^0)$ as low as 5 GeV

Improving the pMSSM Coverage

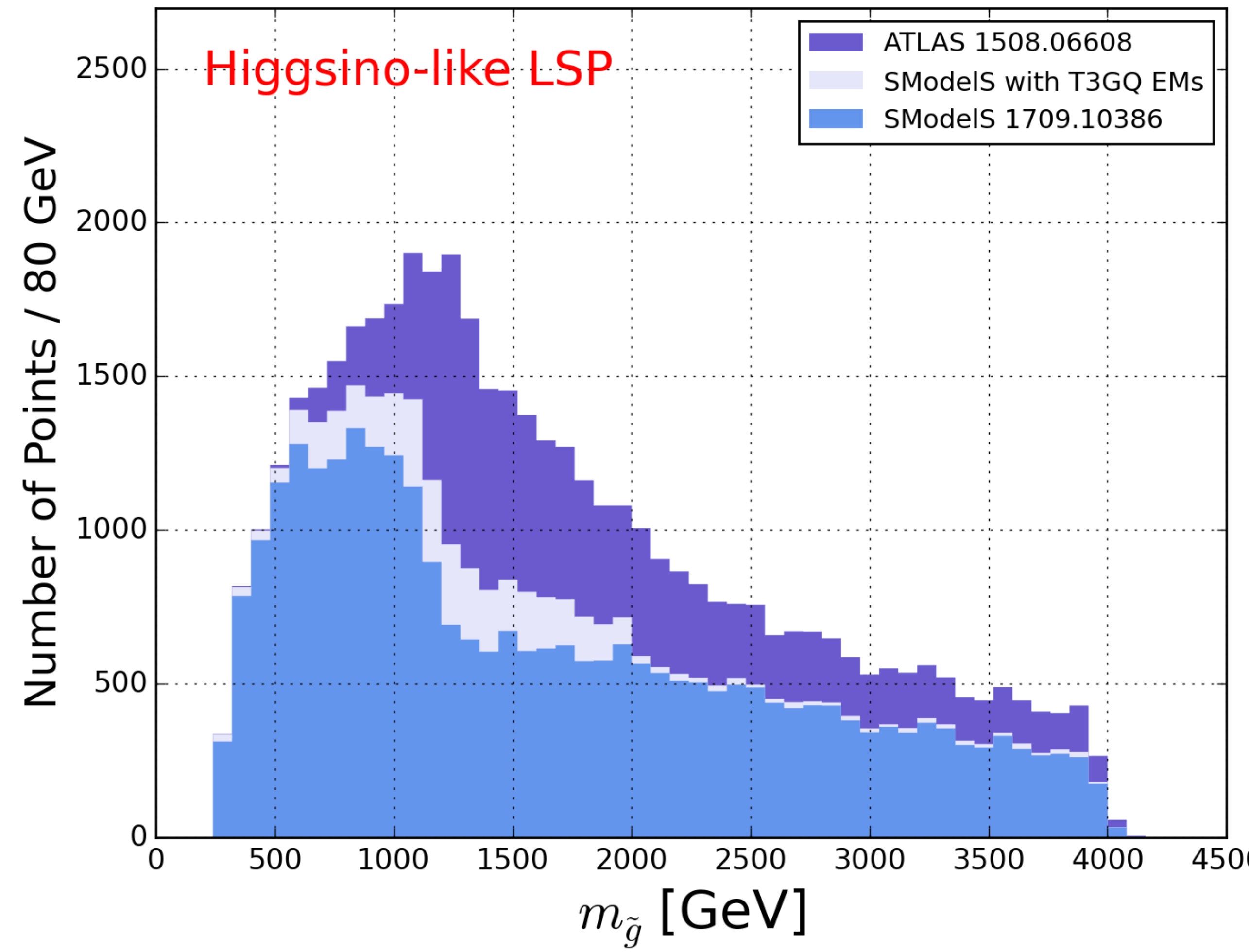
New Results

Number of Points	Bino-like LSP	Higgsino-like LSP
Total	38527	45345
Excluded by UL+EM	28761 (74 %)	32297 (71 %)

+ 19%



+ 8%



Constraining DM models with signals from the space: **MadDM (v.3.0)**

MadDM https://arxiv.org/abs/1804.00044

MadDM v.3.0: a Comprehensive Tool for Dark Matter Studies

Federico Ambrogi, Chiara Arina, Mihailo Backovic, Jan Heisig, Fabio Maltoni, Luca Mantani, Olivier Mattelaer, Gopolang Mohlabeng

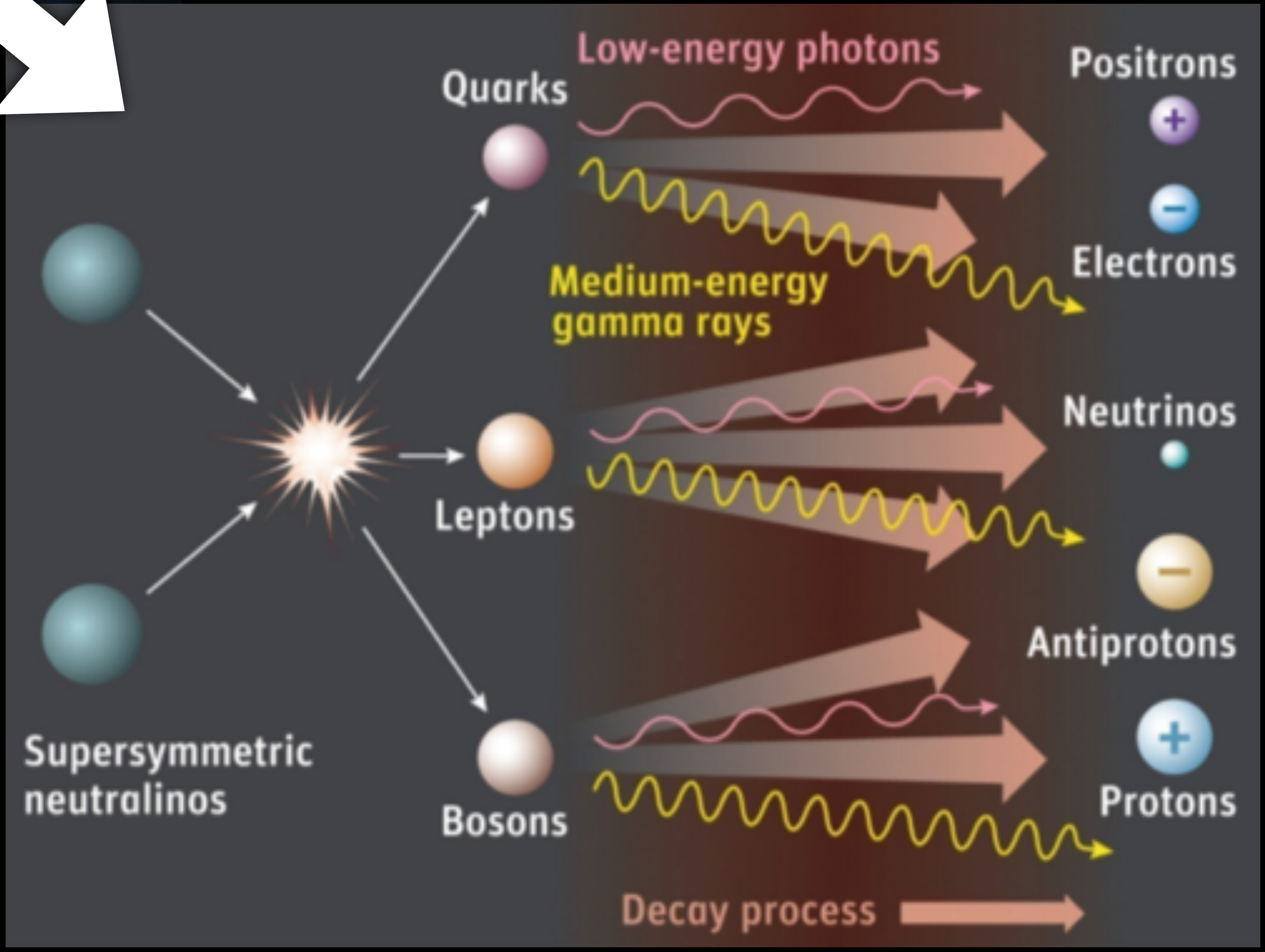
- **MadDM** is now a MadGraph5_aMC@NLo plugin
- to install: ./bin/mg5_aMC
  install madd

https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/MadDm

- MadDM v.1.0 : relic density
- MadDM v.2.0 : direct detection
- ***MadDM v.3.0 : indirect detection***

✦ dedicated module for DM indirect detection theory predictions
✦ module for *experimental constraints*
✦ inherits the capabilities of MG5 to automatically compute and generate ‘complicated’ processes
✦ advanced functionalities for scanning from MG5 or PyMultiNest

DM annihilation in the halos
(external galaxies or in the Milky way)

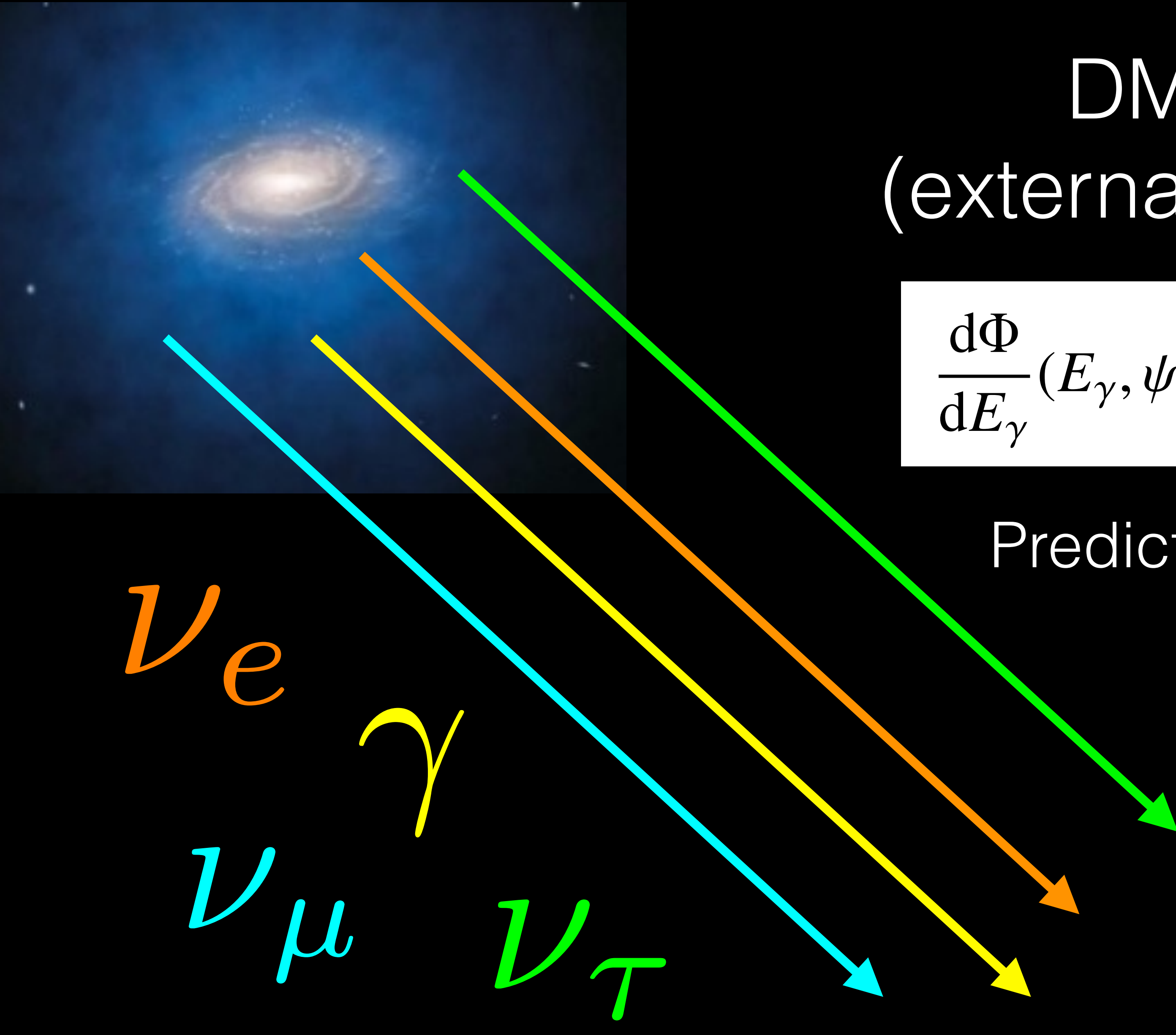


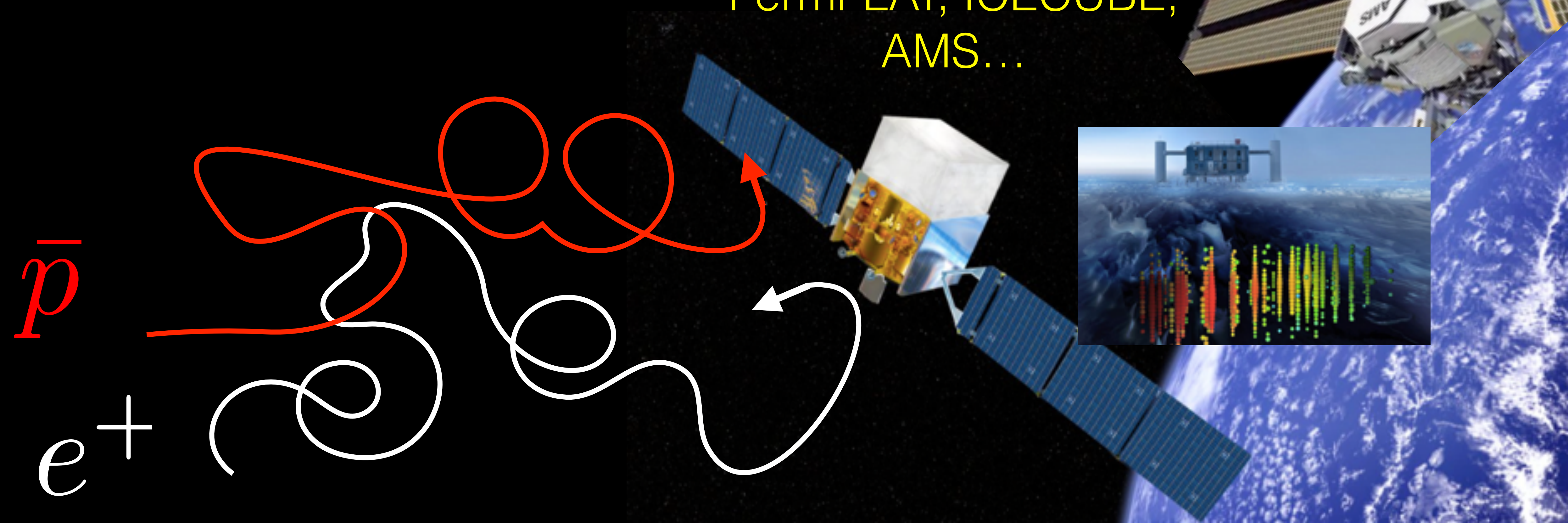
(Possible DM candidate)

DM annihilation in the halos (external galaxies or in the Milky way)

$$\frac{d\Phi}{dE_\gamma}(E_\gamma,\psi) = \frac{\langle\sigma v\rangle}{2m_\chi^2} \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \frac{1}{4\pi} \int_\psi \frac{d\Omega}{\Delta\psi} \int_{\text{los}} \rho^2(\psi,l)\, dl$$

Prediction for the differential flux of cosmic rays at the point of detection





Indirect Detection Module - Keywords

Main observable for indirect detection:
differential flux of cosmic rays at detection (e.g. Gamma Rays)

sum taken over all the particle species

$$\frac{d\Phi}{dE_\gamma}(E_\gamma,\psi) = \boxed{\frac{\langle \sigma v \rangle}{2m_\chi^2}} \sum_i B_i \boxed{\frac{dN_\gamma^i}{dE_\gamma}} \frac{1}{4\pi} \boxed{\int_\psi \frac{d\Omega}{\Delta\psi} \int_{\text{los}} \rho^2(\psi, l)\, dl}$$

[particles/(GeV sr cm^2 s)]

MadDM calculates the velocity averaged annihilation cross section

MadDM produces the energy spectra of the cosmic rays

J-factor from astrophysical observation

Velocity Averaged Annihilation Cross Section

General expression for <σv>

$$\langle\sigma v\rangle = \int \mathrm{d}^3\boldsymbol{v}_1 \mathrm{d}^3\boldsymbol{v}_2 P_{\boldsymbol{r}}(\boldsymbol{v}_1) P_{\boldsymbol{r}}(\boldsymbol{v}_2)\, \sigma v_{\mathrm{rel}}$$

Inclusive

- Very fast, but considers only **DM DM -> 2-body** (SM or BSM) at LO
- Takes $P(v) = \delta_D(v_{rel})$, integrates over angles
- 10-20 % agreement wrt the other two more precise methods

MadEvent

- Amplitudes for all relevant subprocesses + full phase space integration
- Generic **DM DM -> n-body**
- Generates unweighted events to pass to Pythia8

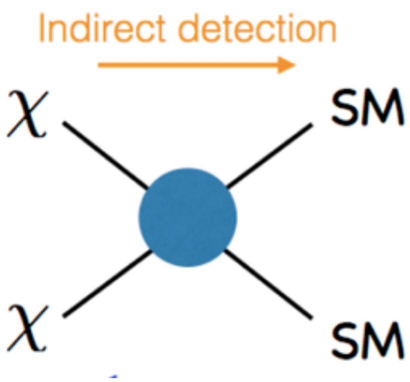
Reshuffling

- MadEvent + events re-weighting with a Maxwell-Boltzmann distribution

$$\tilde{P}_{\boldsymbol{r},\mathrm{rel}}(v_{\mathrm{rel}}) = \sqrt{\frac{2}{\pi}}\, \frac{v_{\mathrm{rel}}^2}{v_0^3} \exp\left(-\frac{v_{\mathrm{rel}}^2}{2v_0^2}\right)$$

Energy Spectra from Cosmic Rays (1)

CR Energy spectra and indirect detection limits are typically presented in terms of DM annihilation into SM channels



g ratio

$$\chi\chi \quad \rightarrow \quad gg, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$$
$$\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, ZZ, W^+W^-, hh$$

decay, shower, hadronization with Pythia8

CR energy spectra at source

$$\boxed{\gamma, \nu_e, \nu_\mu, \nu_\tau, e^+, \bar{p}}$$

Two ways of extracting the spectra

PPPC4DMID Tables

- Requires the installation of the PPPC4DMID module
- Fast but precise if annihilation is dominated by SM

Pythia8 Spectra

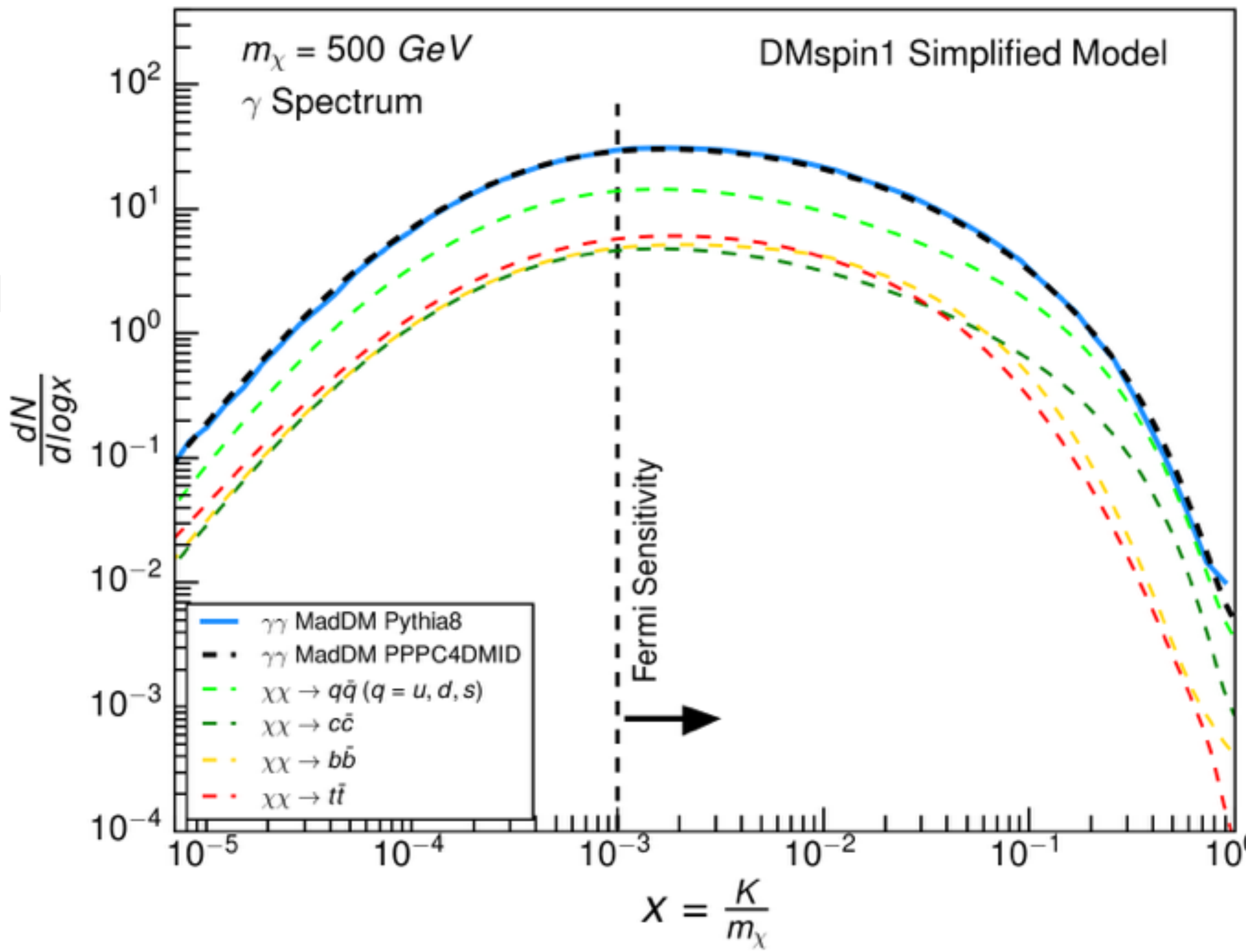
- Includes decays of BSM final states

Energy Spectra from Cosmic Rays (2)

PPPC4DMID = *A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection* http://www.marcocirelli.net/PPPC4DMID.html

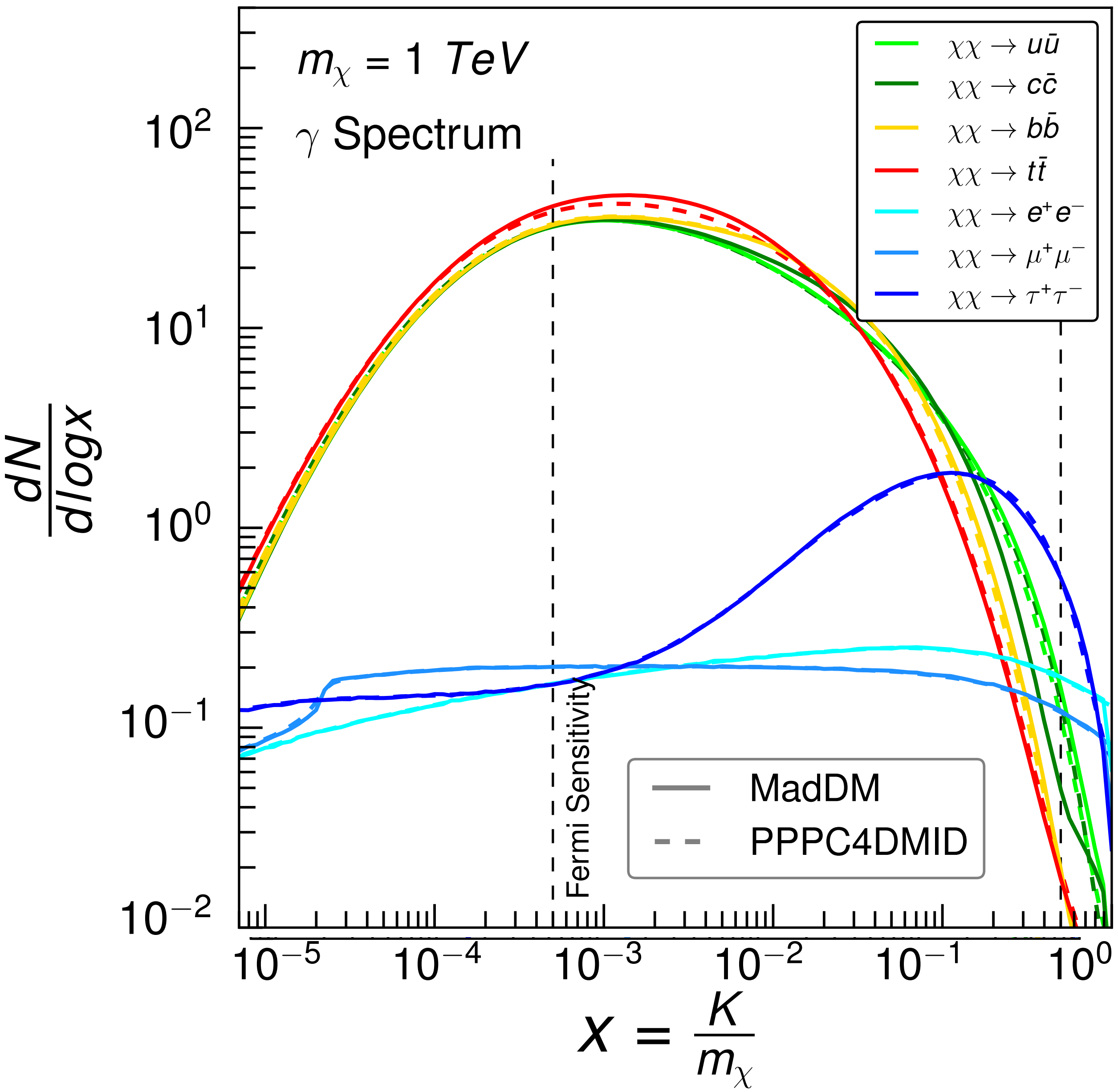
$$\chi\chi \quad \rightarrow \quad q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}$$

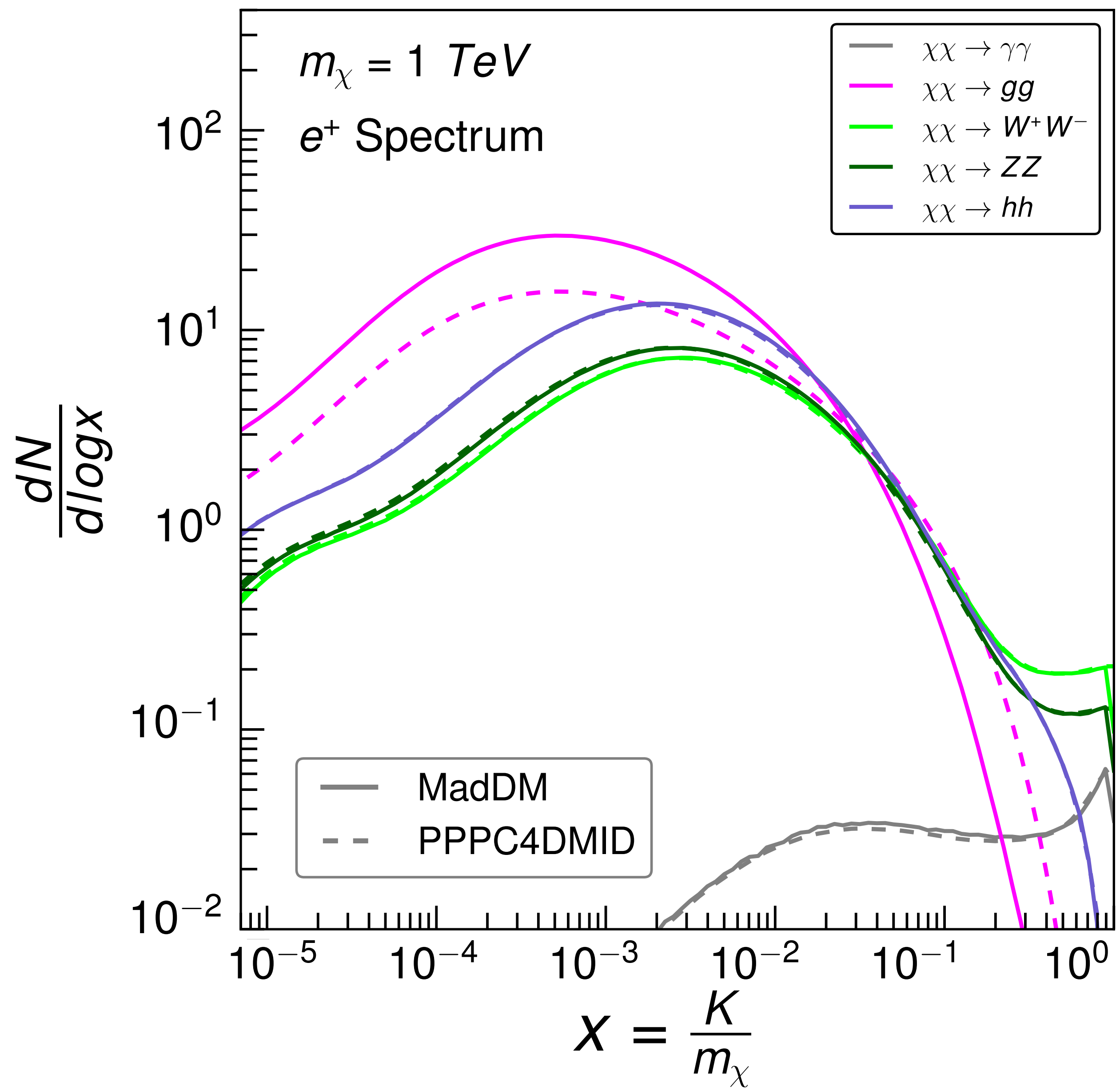
- MadDM includes the PPPD4DMID tabulated energy spectra for ***DM DM > SM SM***
- CR spectra added up according to their cross section (branching fraction)



Energy Spectra from Cosmic Rays (3)

$$\chi\chi \quad \rightarrow \quad gg, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$$
$$\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, ZZ, W^+W^-, hh$$





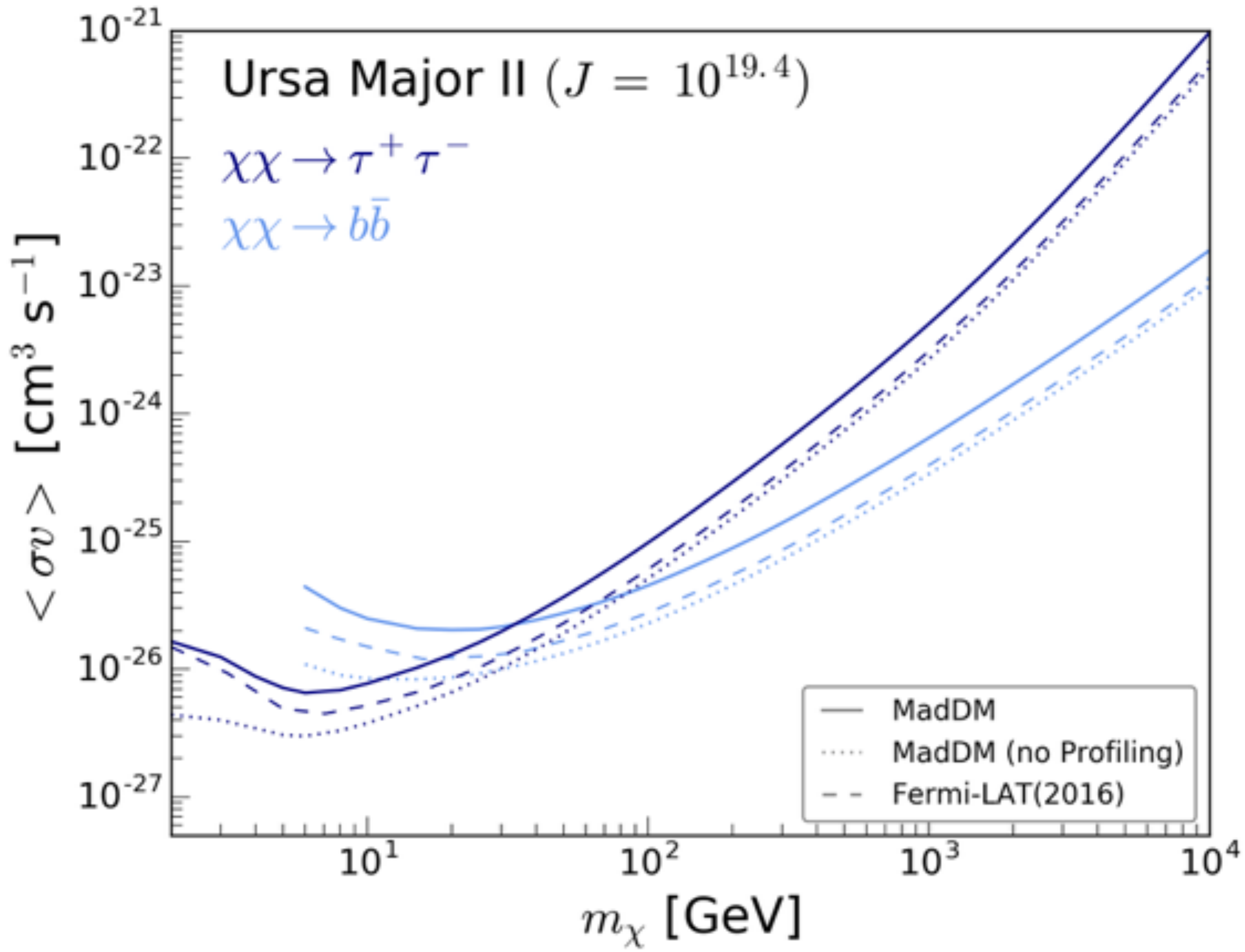
Fermi-LAT sensitive to γ in the energy range ~ [0.5 - 500 GeV]

Fermi-LAT Limits (1)

- The Fermi-LAT Collaboration gives limits on DM annihilation into two channels:

DM DM > $b\bar{b}$, $\tau^+\tau^-$

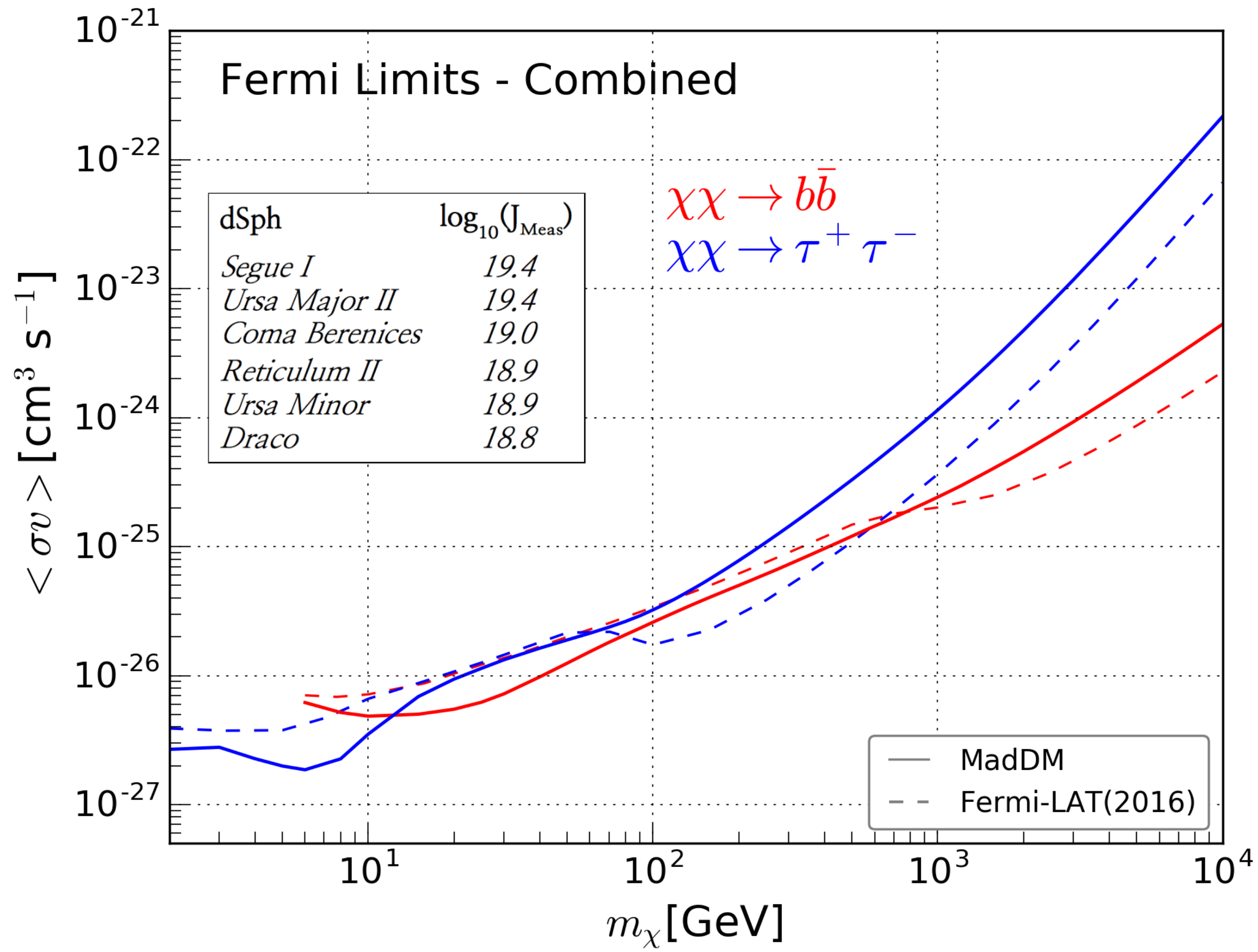
- They also made available the likelihood profiles for a set of dwarf spheroidal galaxies to derive the upper limits (UL) on <σv>

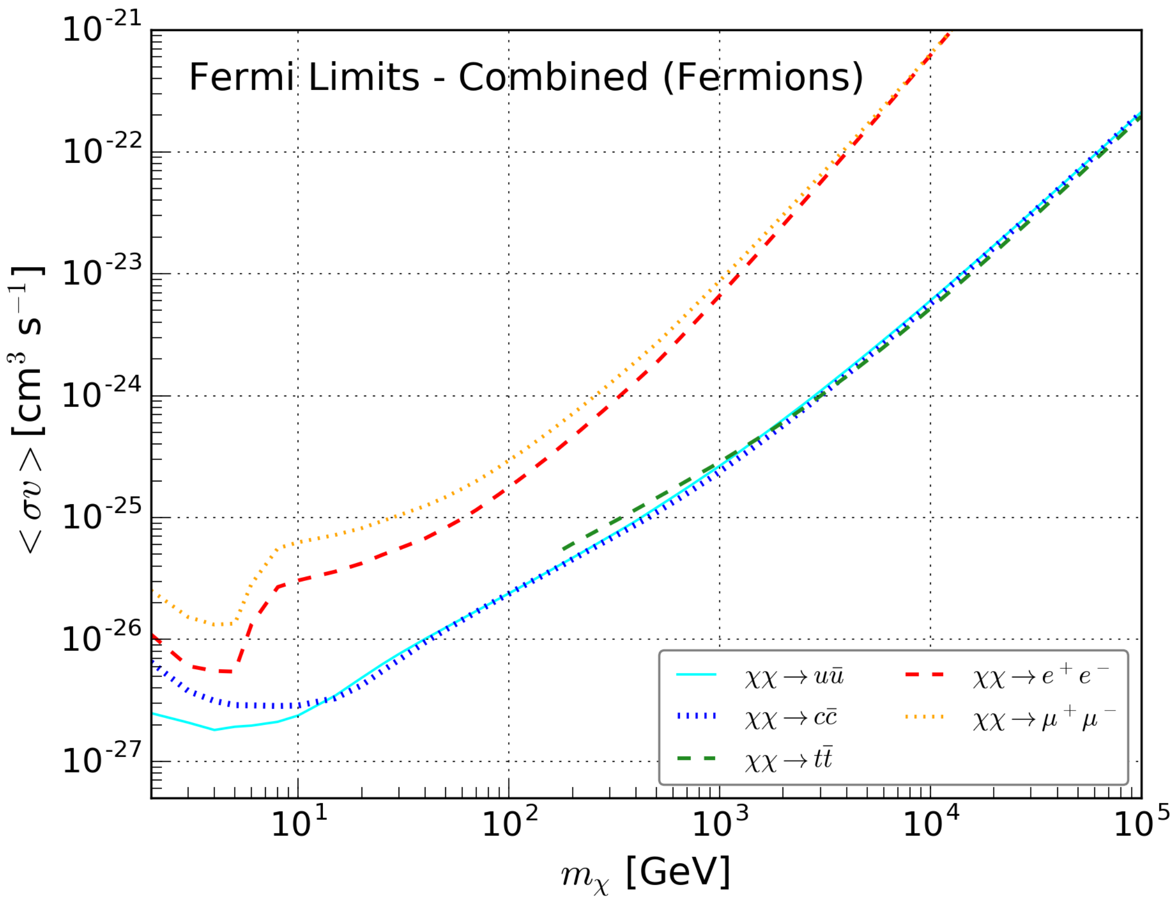


Fermi-LAT Limits (3)

- MadDM makes use of the likelihood profiles for the 6 dwarf spheroidal galaxies with the highest J-factors to extract the combined limits
- It is possible to calculate the limits for arbitrary

DM DM > SM SM



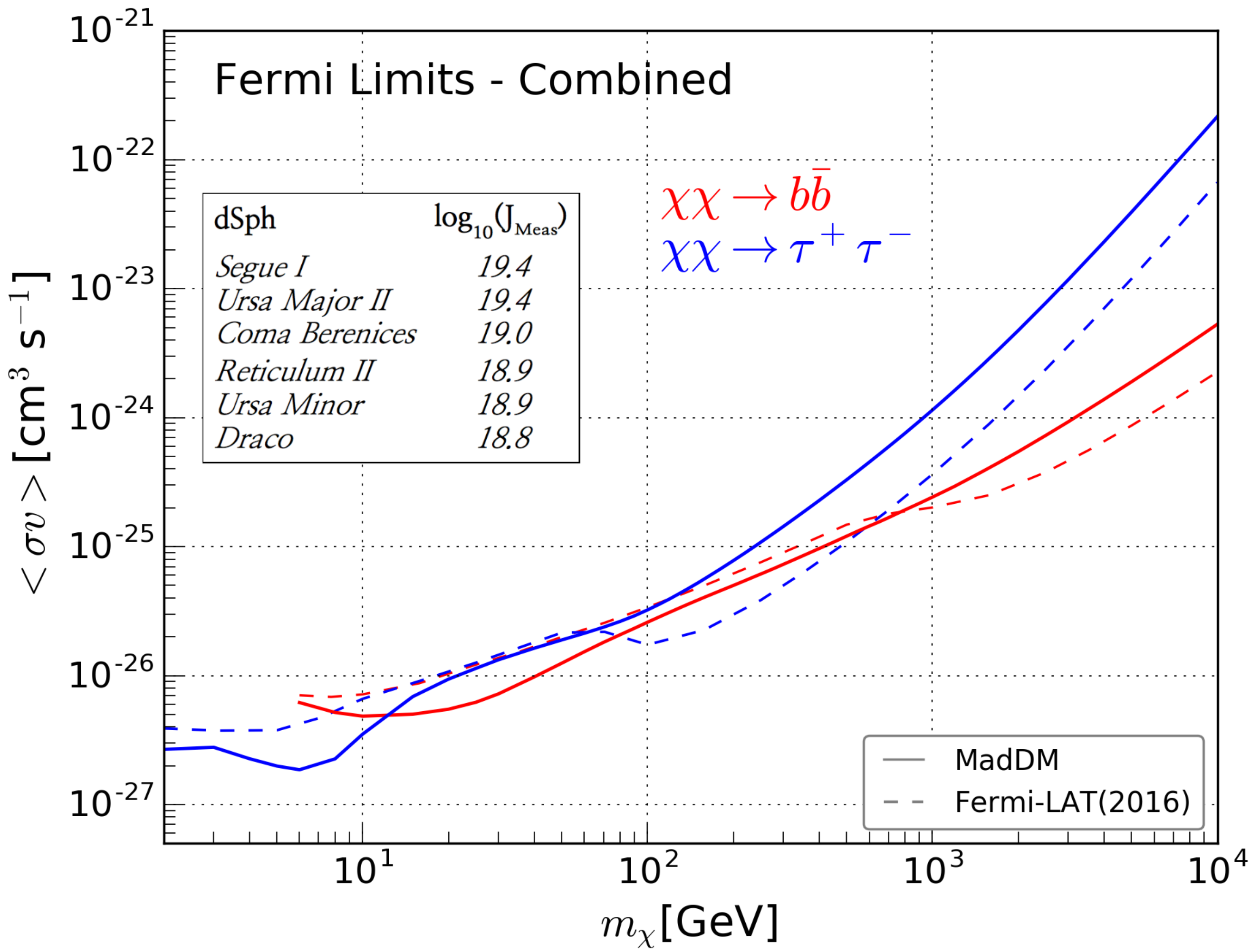


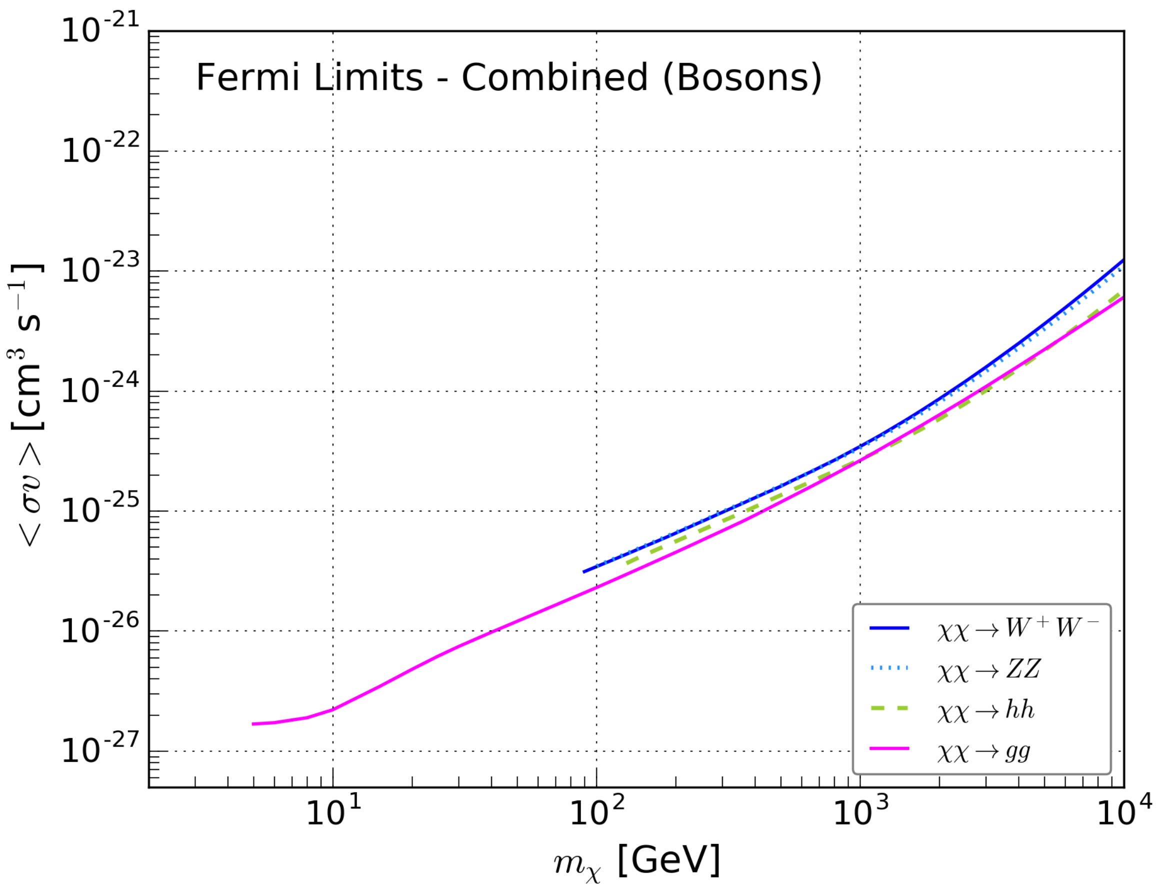
- We calculated the limits of any **DM DM > SM SM**
- Added the new limits in the Exp. constraints module

Fermi-LAT Limits (3)

- MadDM makes use of the likelihood profiles for the 6 dwarf spheroidal galaxies with the highest J-factors to extract the combined limits
- It is possible to calculate the limits for arbitrary

DM DM > SM SM





- We calculated the limits of any **DM DM > SM SM**
- Added the new limits in the Exp. constraints module

Two methods for calculation of indirect detection predictions

	Fast	*Precision*
$\langle \sigma v \rangle$	**Inclusive**	**Reshuffling (Madevent)**
Processes	DM DM > SM SM	DM DM > n-body
Spectra at Source	**PPPC4DMID_ew** (**PPPC4DMID**) *only* from SM channels	**Pythia8** from any final state
Flux at Earth	Propagate and oscillate γ and ν_i e^+: **PPPC4DMID_ep** e^+ and p : **DRAGON**	Propagate and oscillate γ and ν_i e^+ and p : **DRAGON**
Constraints	Fermi-LAT UL for each SM channels + SM combination	Fermi-LAT UL for each SM channels + limit for total gamma-ray spectrum including BSM states

—> See Table C.2 page 26 of the manual for the extended summary

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma}(E_\gamma,\psi) = \frac{\langle\sigma v\rangle}{2m_\chi^2} \sum_i B_i \frac{\mathrm{d}N_\gamma^i}{\mathrm{d}E_\gamma} \frac{1}{4\pi} \int_\psi \frac{\mathrm{d}\Omega}{\Delta\psi} \int_{\mathrm{los}} \rho^2(\psi,l)\,\mathrm{d}l$$

[particles/(GeV sr cm^2 s)]

- **Neutrinos oscillations (from far galaxies to Earth)**

- **PPPC4DMID Tables for e+**

  Halo profile: **NFW, Moore, Einasto, Isothermal**
  Galactic magnetic field model: **MF1, MF2, MF3**
  Propagation model: **MIN, MED, MAX**

- **DRAGON**

  Interface with the fully numerical code *DRAGON* for the propagation of positrons/antiprotons within the galaxy

Conclusions

- Plethora of experimental results available from several types of experiments (not discussed: SM precision measurements e.g. flavour sector, Higgs etc.) able to constrain BSM theories
- Many existing tools can be efficiently used to constrain, in an automated way, the parameter space of many theories
- Tools are being constantly updated using the latest experimental input

Thank You !

MAD Analysis 5 SModelS MadDM