ATLAS, CMS

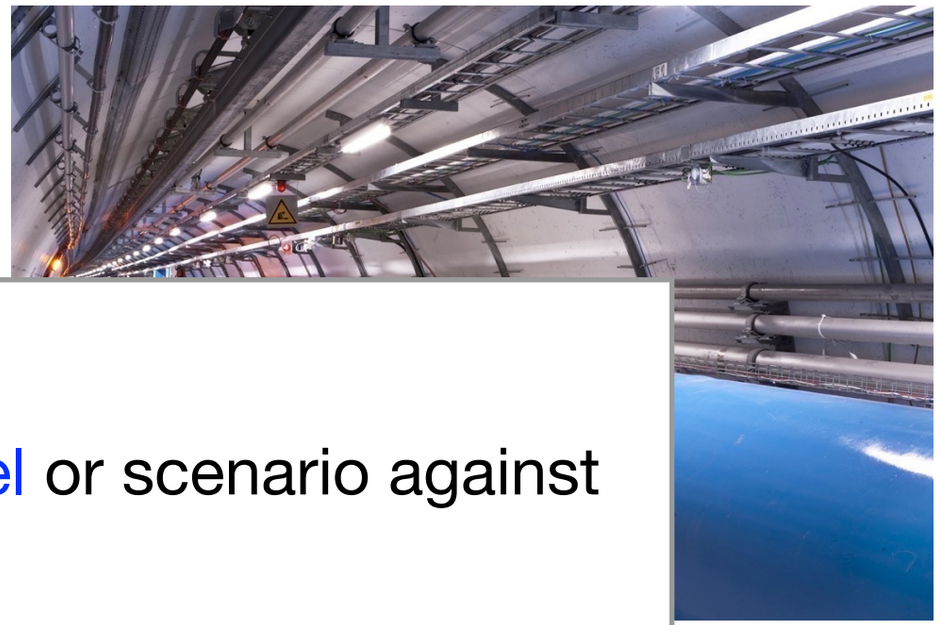
Interpretation of LHC results for new physics

Sabine Kraml

Rencontre de Physique des Particules • 23-25 Jan 2019 • LPC Clermont

Motivation

- **Experiments** at the LHC are searching for new phenomena **beyond the SM (BSM)** in many different channels
  - In Run 1, ATLAS and CMS each performed ~20 d
  - Re-d
    e.g. m
- **Results**
  collabo
  specific
- Howeve
  constrain other models than considered in the experimental publication
- A full (complex) theoretical model is often constrained by **more than one analysis**



We want to be able to test any model or scenario against the plethora of LHC results :

- understand full theoretical implications (e.g. naturalness, DM models);
- give feedback to the experiments about loopholes in the searches;
- elucidate underlying theory in case of a discovery.

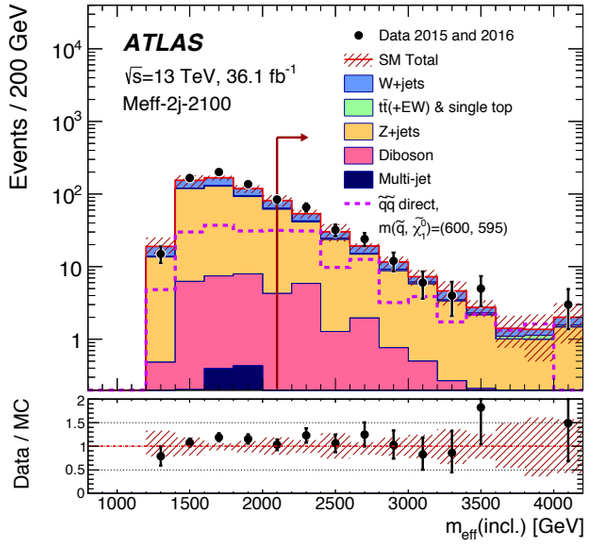
Example: ATLAS search for gluinos and squarks

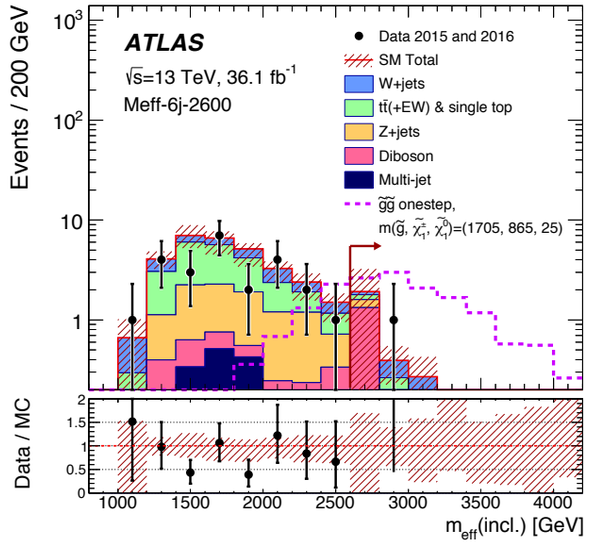
- Final states with 2-6 jets and large missing transverse energy, 0 leptons

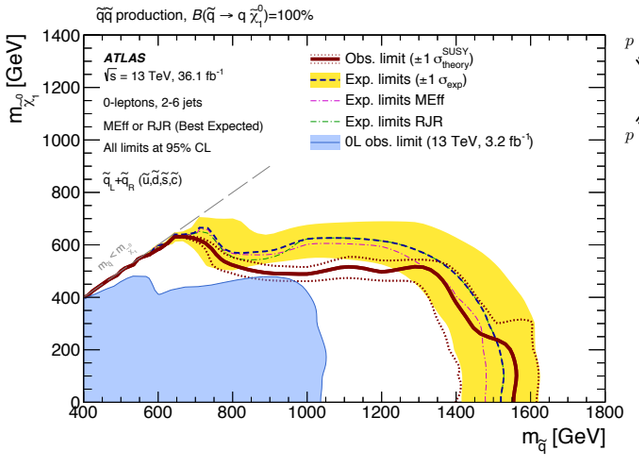
Two approaches: 1) M_{eff}-based search and 2) a recursive jigsaw technique

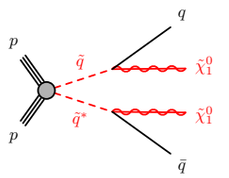
M_{eff}-based search:

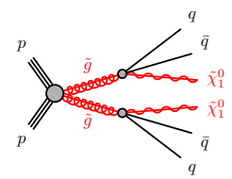
- ≥2 jets, p_T(jets) > 50 GeV,
- lepton veto (no e,μ with p_T>7 GeV)
- E_T^{miss} > 250 GeV
- **24 inclusive signal regions**: bins in jet multiplicity N_j=2-6 and M_{eff}
  - increasing requirements on min. p_T, $E_T^{miss}/M_{eff}(N_j)$ or $E_T^{miss}/\sqrt{H_T}$, …
  - 2 signal regions with large radius jets

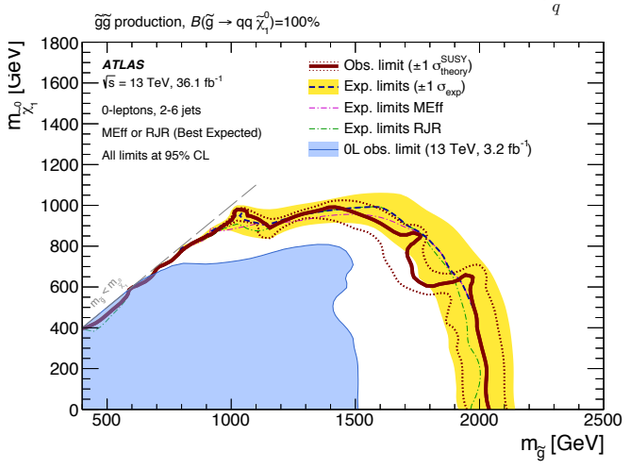












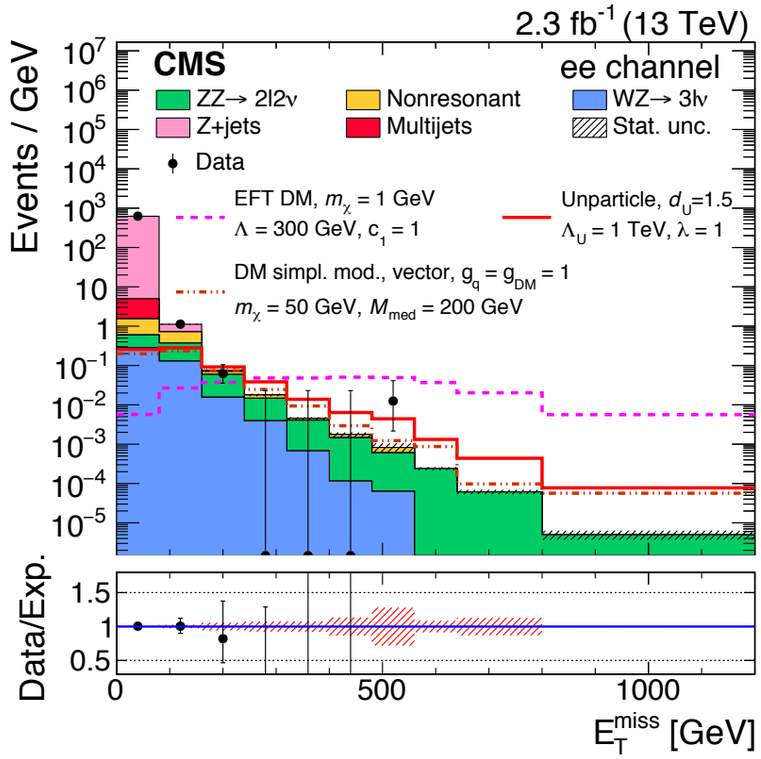
2 analogous analyses in CMS with 174 or 213 exclusive signal regions

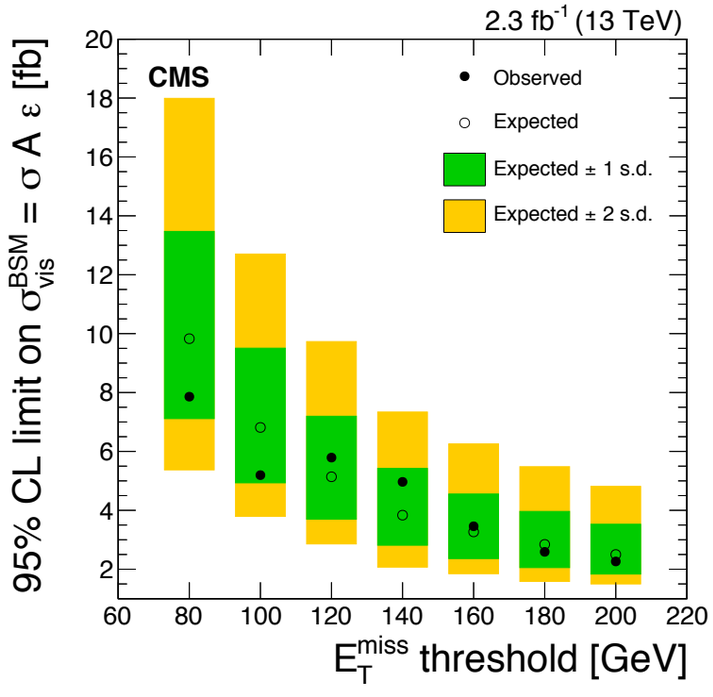
M_{eff} := scalar sum of p_T(jets) and E_T^{miss}

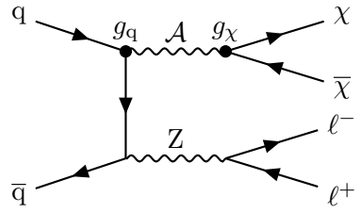
Example: CMS mono-Z search (dark matter)

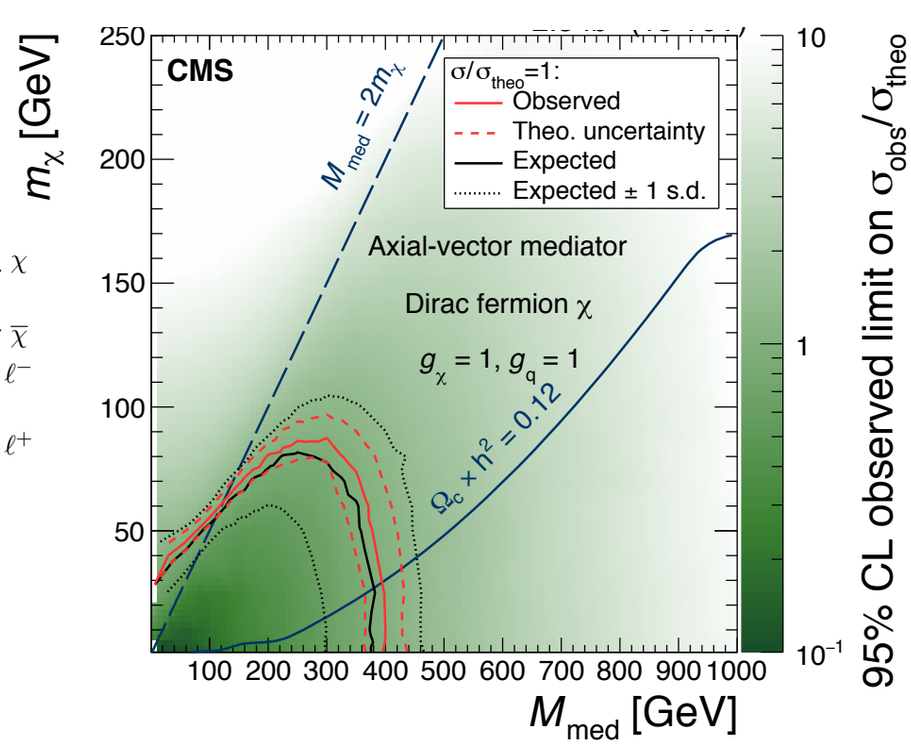
- Final state: di-leptons ($Z \rightarrow l^+l^-$) plus MET

	Variable	Requirements
Preselection	p_T^ℓ	>20 GeV
	$\lvert m_{\ell\ell} - m_Z \rvert$	<10 GeV
	Jet counting	≤1 jet with $p_T^j > 30$ GeV
	$p_T^{\ell\ell}$	>50 GeV
	3rd-lepton veto	$p_T^{e,\mu} > 10$ GeV, $p_T^\tau > 20$ GeV
	Top quark veto	Veto on b jets and soft muons
Selection	$\Delta\phi_{\ell\ell,\vec{p}_T^{\,miss}}$	>2.7 radians
	$\lvert E_T^{miss} - p_T^{\ell\ell} \rvert / p_T^{\ell\ell}$	<0.2
	E_T^{miss}	>80 GeV

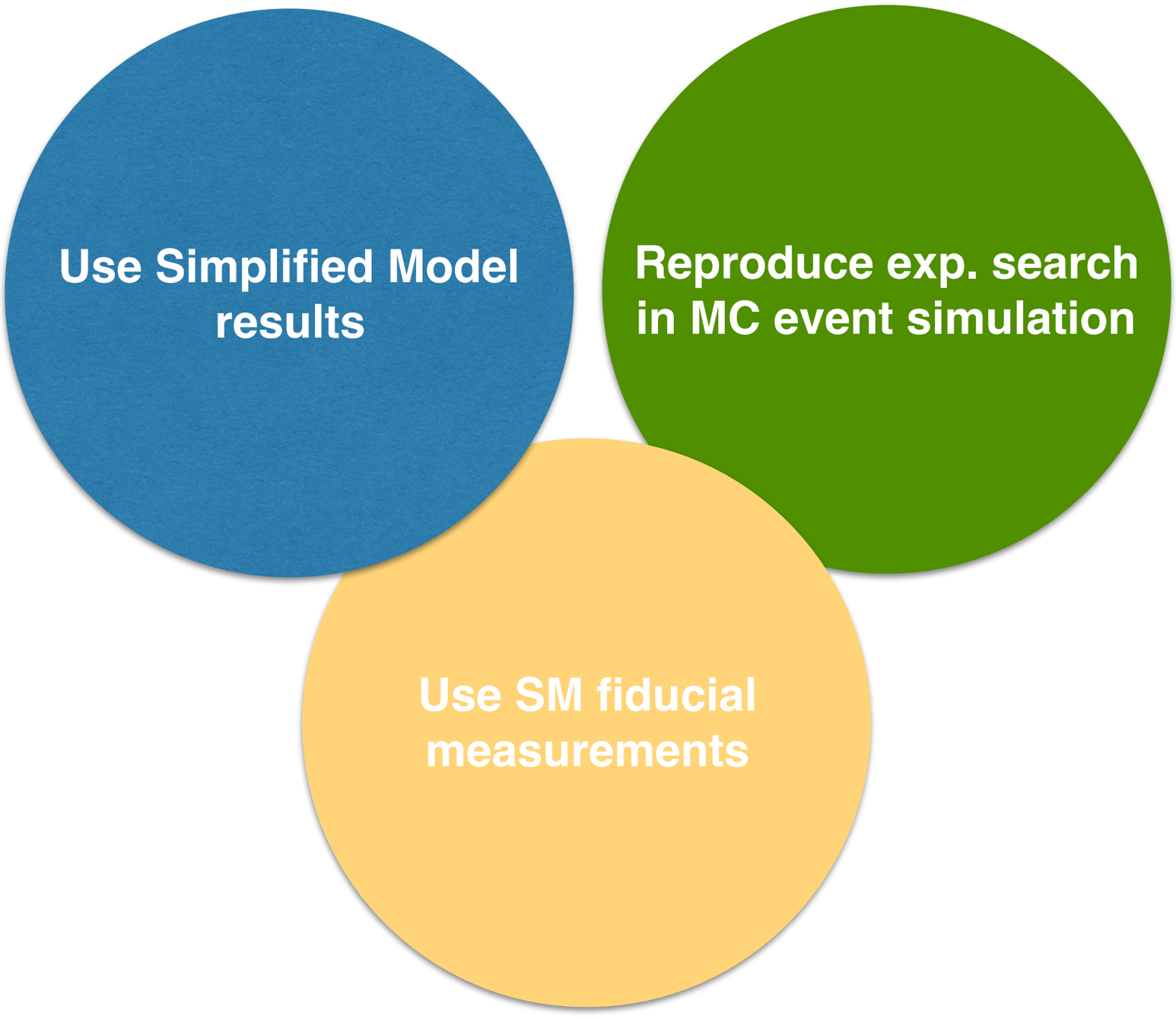








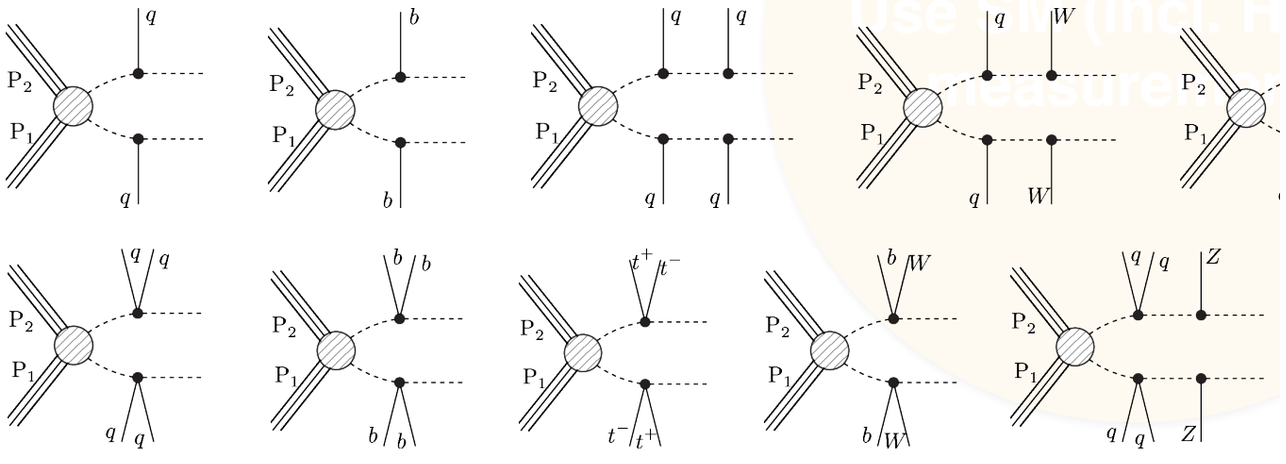
Ways of (re)interpretation

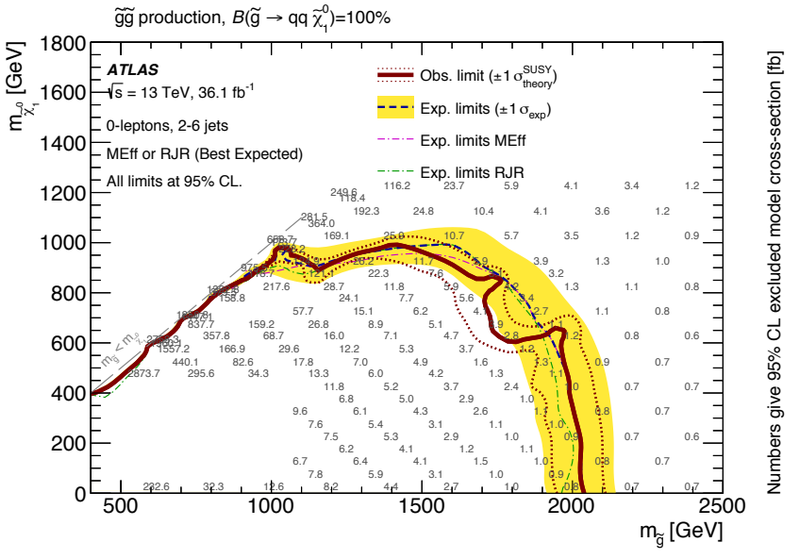


Ways of (re)interpretation

Use Simplified Model results

- **Cross section limits** or **signal selection efficiencies (ε×Acc.)** for specific signal topologies, assuming a simple/ified BSM scenario with just few, typically **2–3 new particles.**
- **Applicable to other models with same ε×Acc.** for this topology, i.e. if kinematical distributions don't change too much.
- Valid for **simple rescaling** of production/decay rates (**σ×BR**); other cases need to be verified.





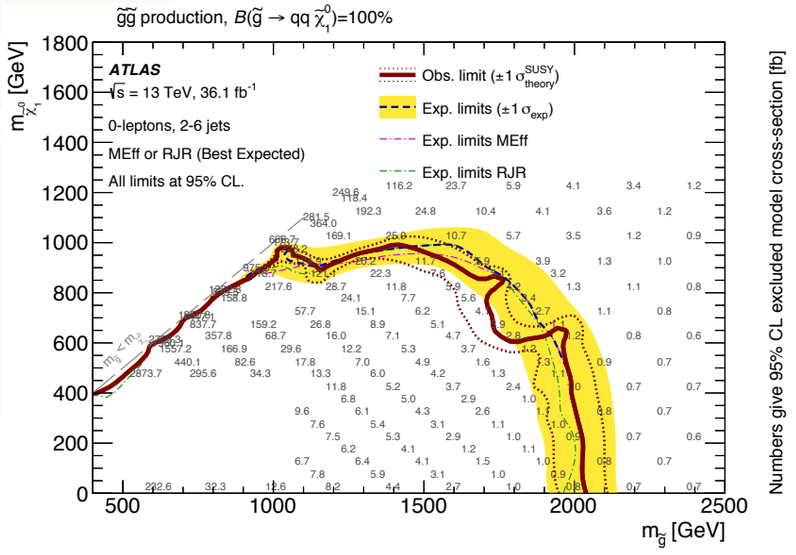
gluino-neutralino simplified model

Ways of (re)interpretation

Use Simplified Model results

- **Cross section limits** or **signal selection efficiencies (ε×Acc.)** for specific signal topologies, assuming a simple/ified BSM scenario with just few, typically **2–3 new particles.**
- **Applicable to other models with same ε×Acc.** for this topology, i.e. if kinematical distributions don't change too much.
- Valid for **simple rescaling** of production/decay rates (**σ×BR**); other cases need to be verified.

- Advantages: simplicity and **speed !** very fast, no need for event simulation → well suited for large scans and model surveys
- Easy classification of unconstrained cross section, uncovered signatures



gluino-neutralino simplified model

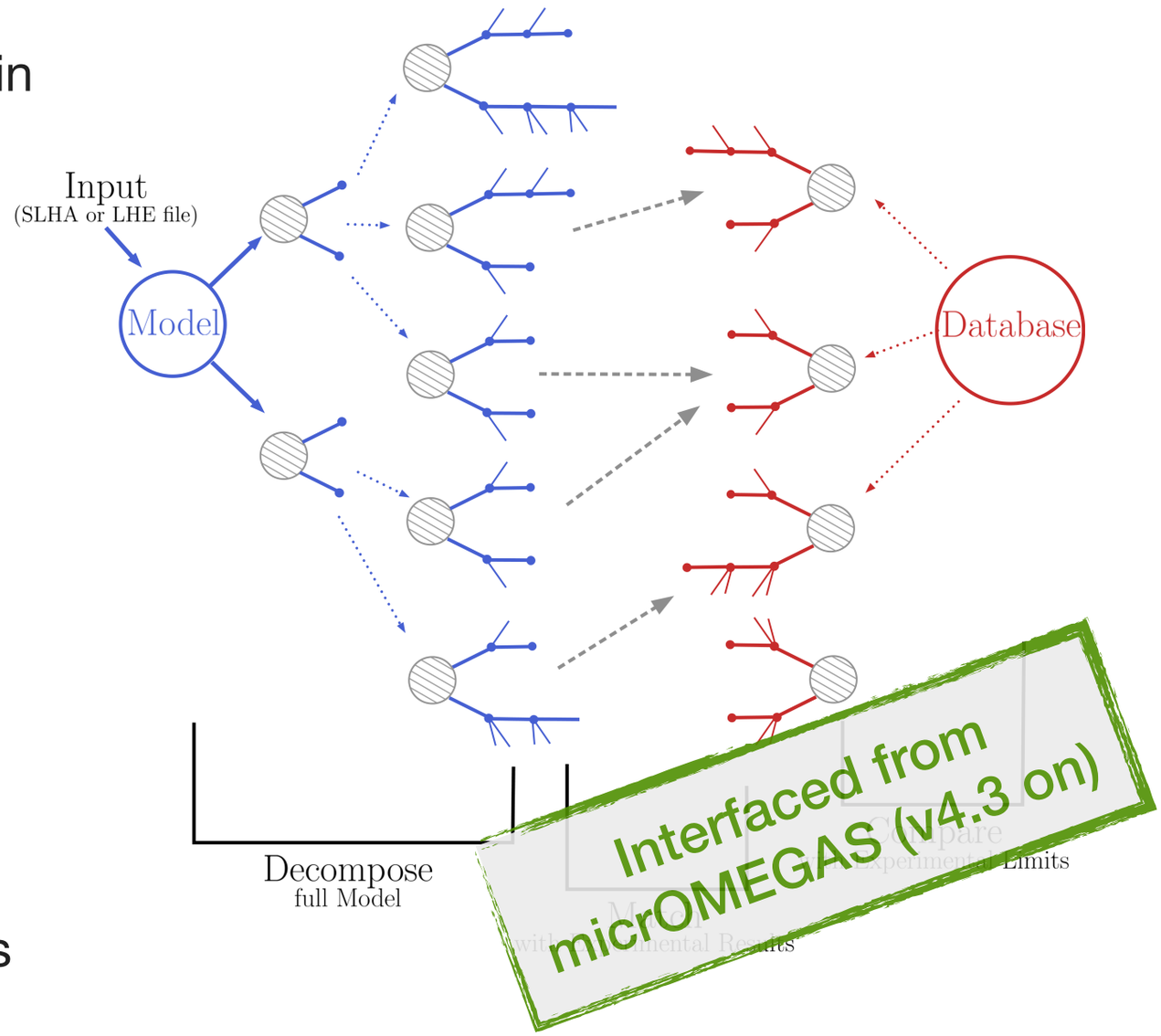
SK et al., 1312.4175
F. Ambrogi et al., 1701.06586
F. Ambrogi et al., 1811.10624

- **Automatised tool** for the interpretation of simplified model results from the LHC within **any BSM scenario** respecting a **Z_2-like symmetry** (→two-branch structure of topologies)

- Output:
  - ratio of topology weights (σ×BR) over 95% CL excl. cross section: “r-value”
  - detailed report and classification of unconstrained topologies

- v1.2 onwards can also treat long-lived particle (LLP) signatures

- Large database of experimental results: cross section section upper limit (UL) maps and efficiency maps (EMs)



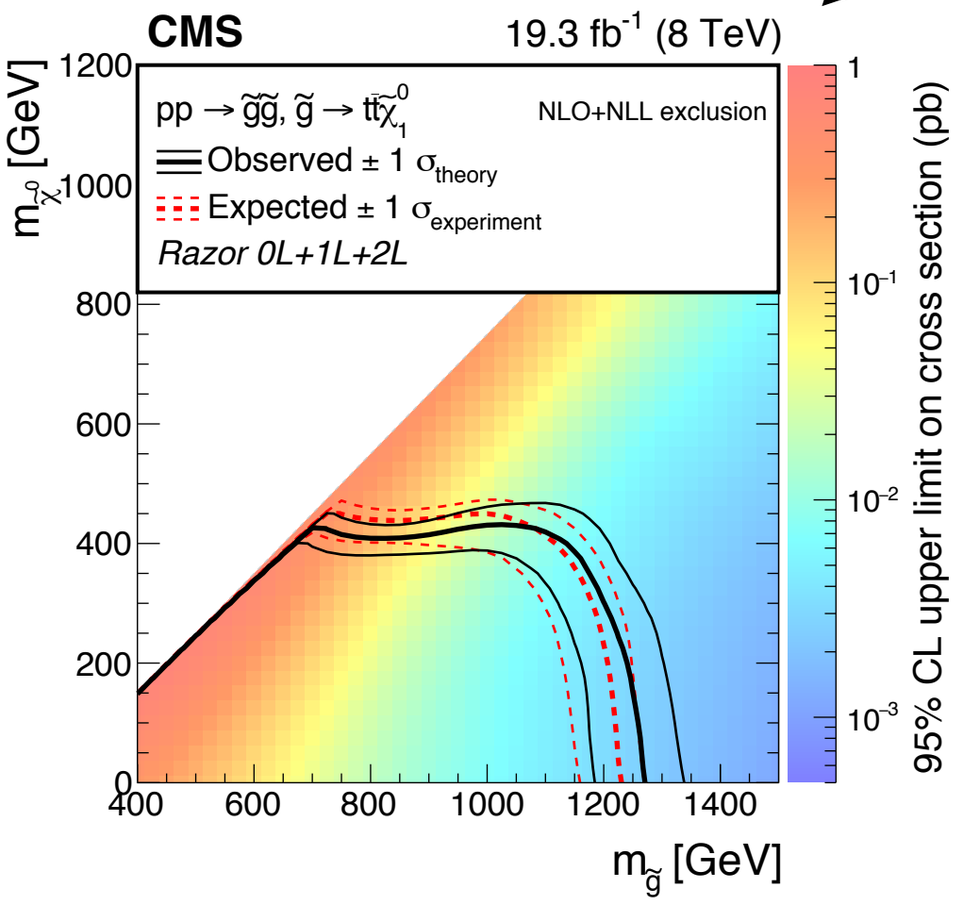
For Run 2, the database now comprises 9 UL and 3 EM results from 10 ATLAS analyses, as well as 89 UL (of which 3 LLP) and 10 EM (of which 8 LLP) results from 21 CMS analyses;

n.b. LLP so far means HSCP and R-hadron results

Two types of results

need these in numerical form!

Upper Limit (UL) maps

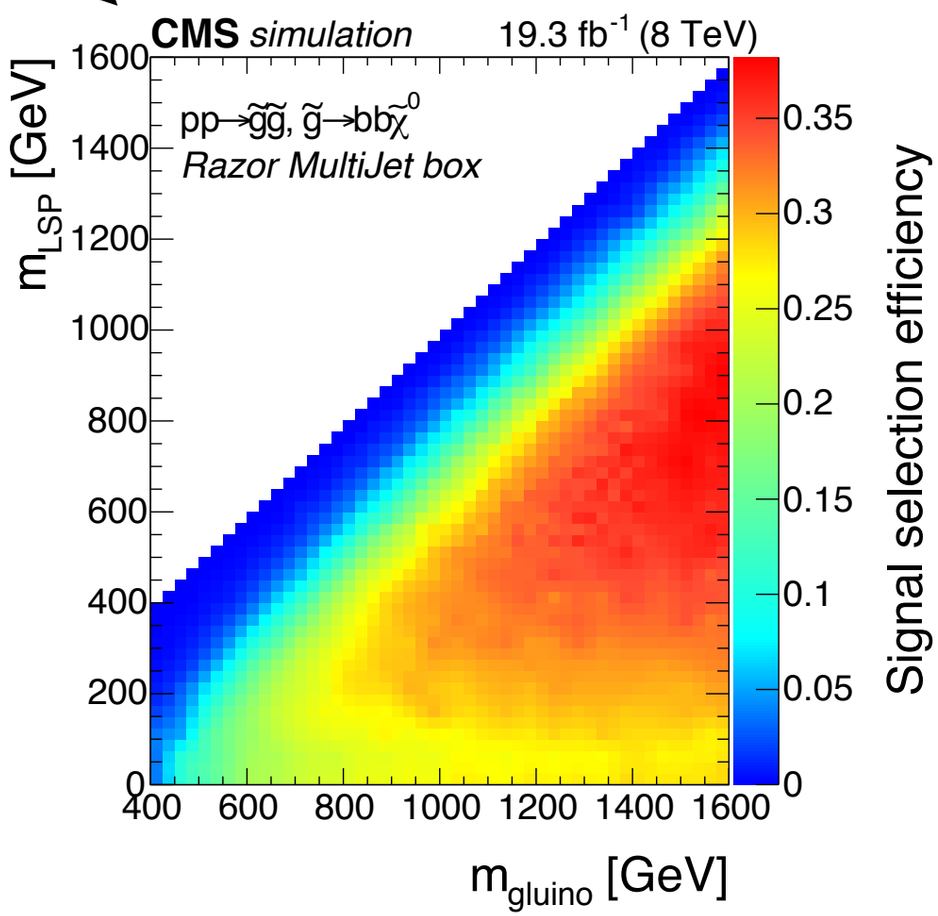


Upper Limit maps give the 95% CL upper limit on cross section x branching ratio for a specific SMS.

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.

Limit on σ×BR

Efficiency maps (EM)



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 Σε×σ×BR

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

Assumptions in SModelS

- BSM particles are described only by their masses, production cross sections and branching ratios.

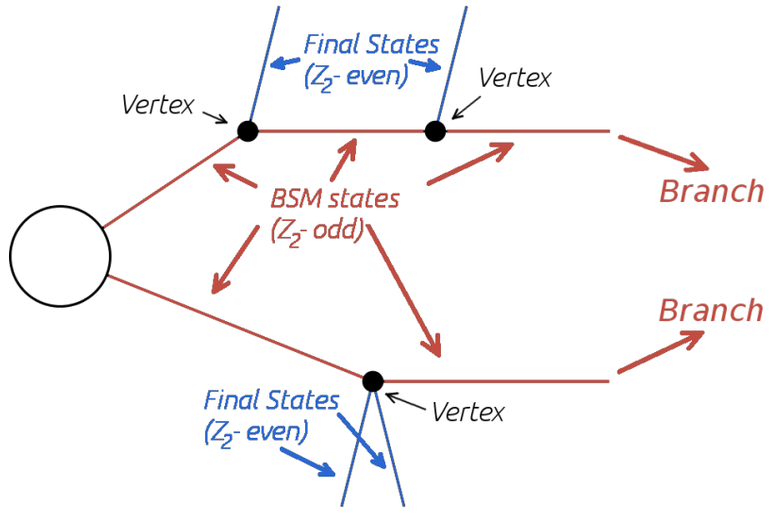
- Underlying assumption is that differences in the event kinematics from, e.g., different production mechanisms or the spins of the BSM particles, do not significantly affect the signal selection efficiencies.

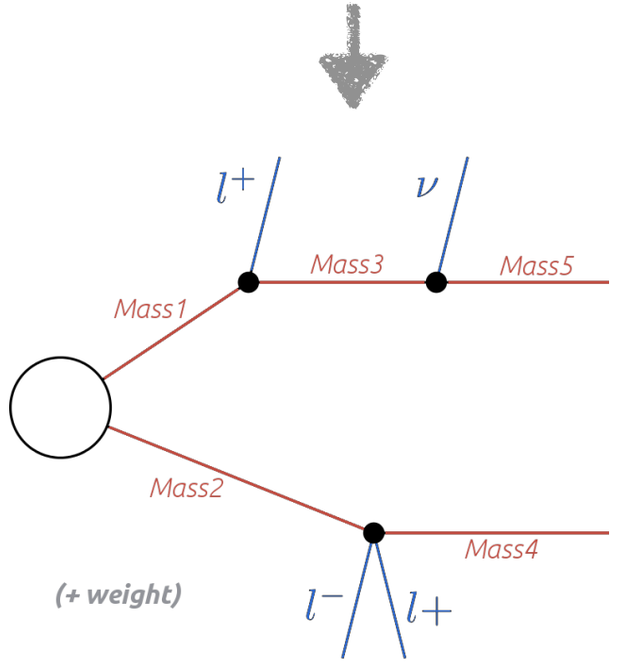
Arkani-Hamed et al., hep-ph/0703088
Alves et al., 1105.2838

- Procedure applicable to any model with a Z_2 symmetry

- Tested for and successfully applied to minimal and non-minimal SUSY (NMSSM, UMSSM, sneutrino LSP), as well as extra quark, UED models …

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, 1707.09036.

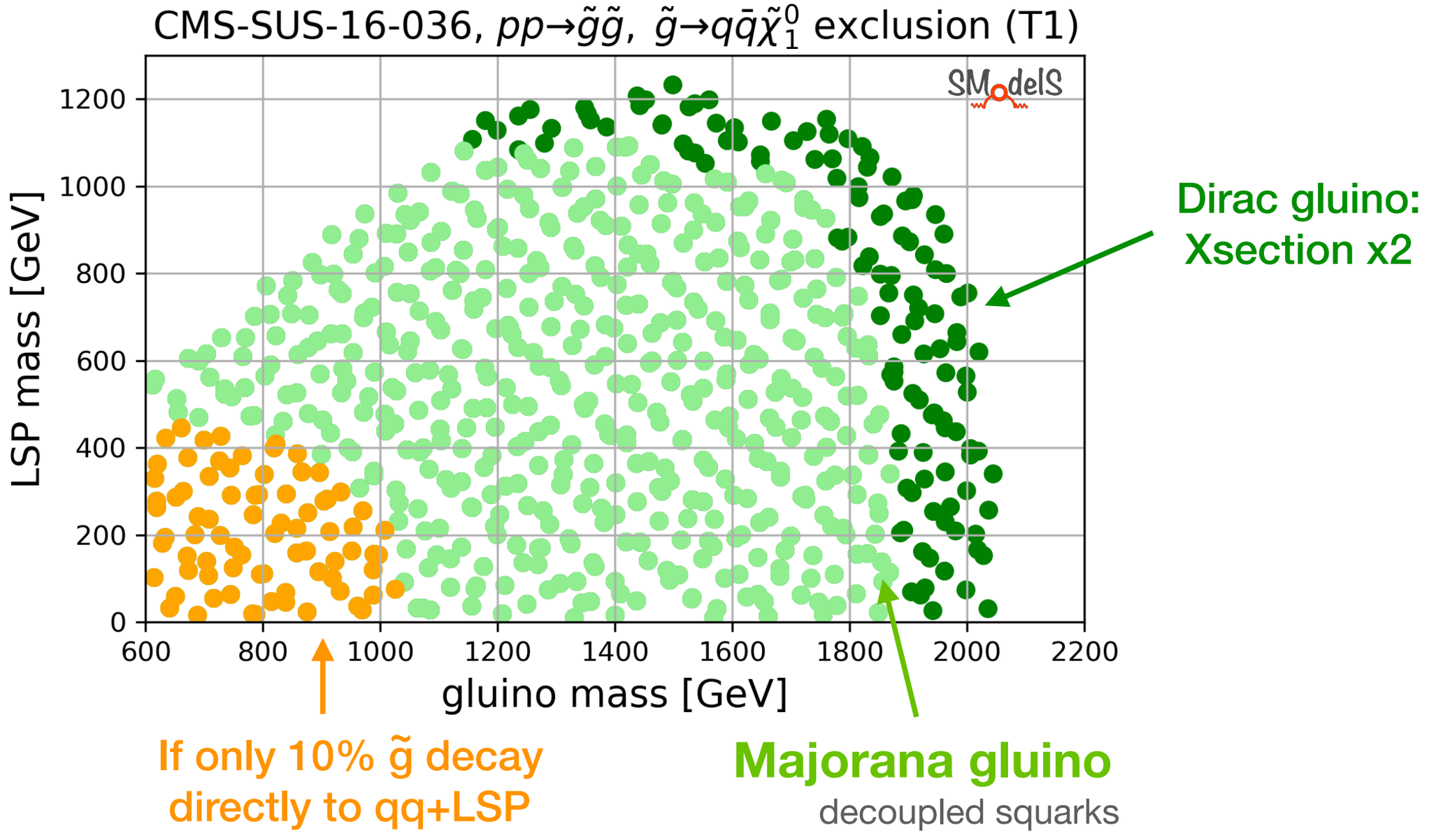




Information used to classify topologies

Caveat

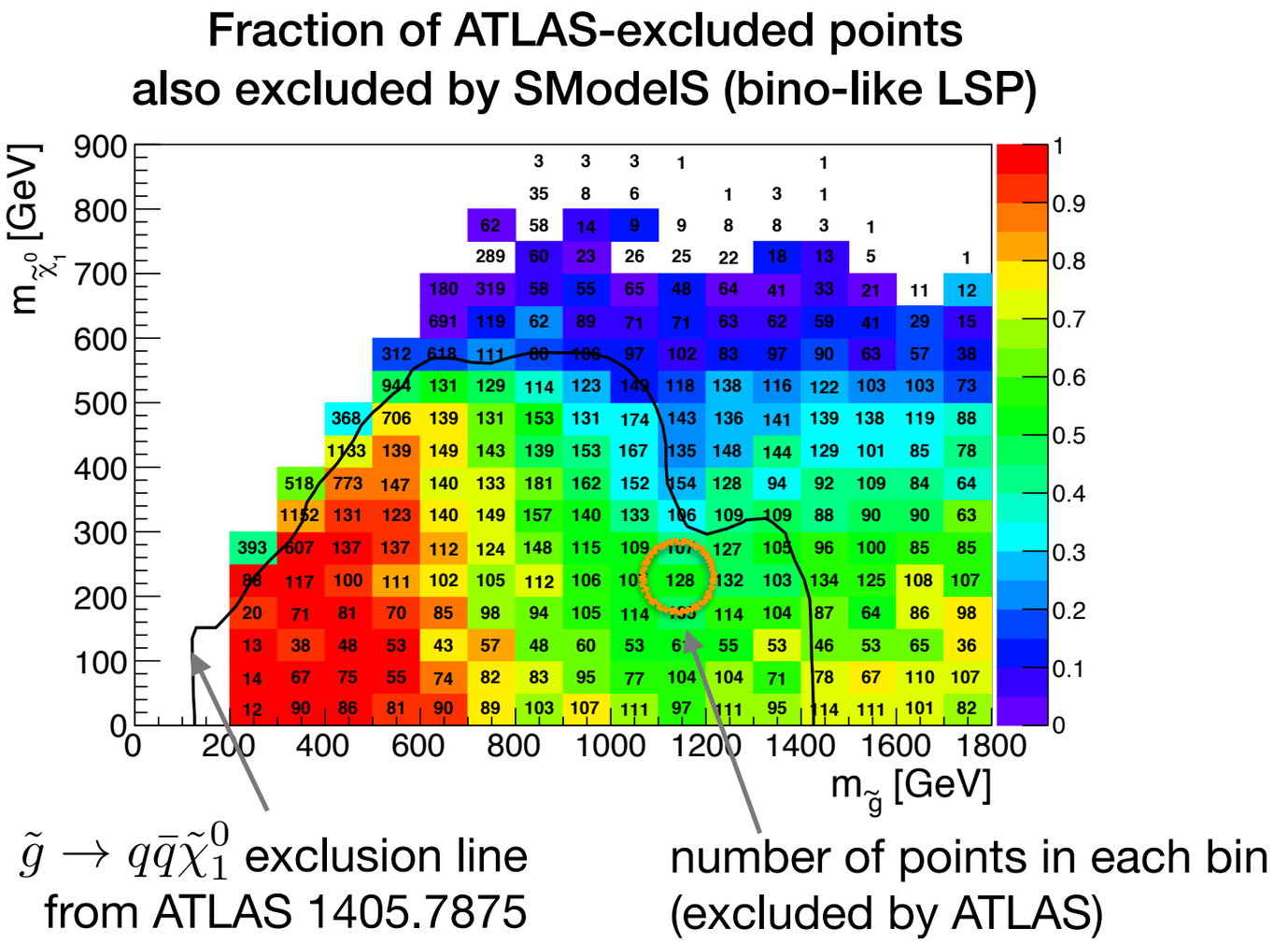
Coverage of total BSM cross section limited by two facts:
most simplified model results are for symmetric topologies and only available as UL maps



F. Ambrogi et al., 1707.09036

Coverage of pMSSM compared to ATLAS (8 TeV)

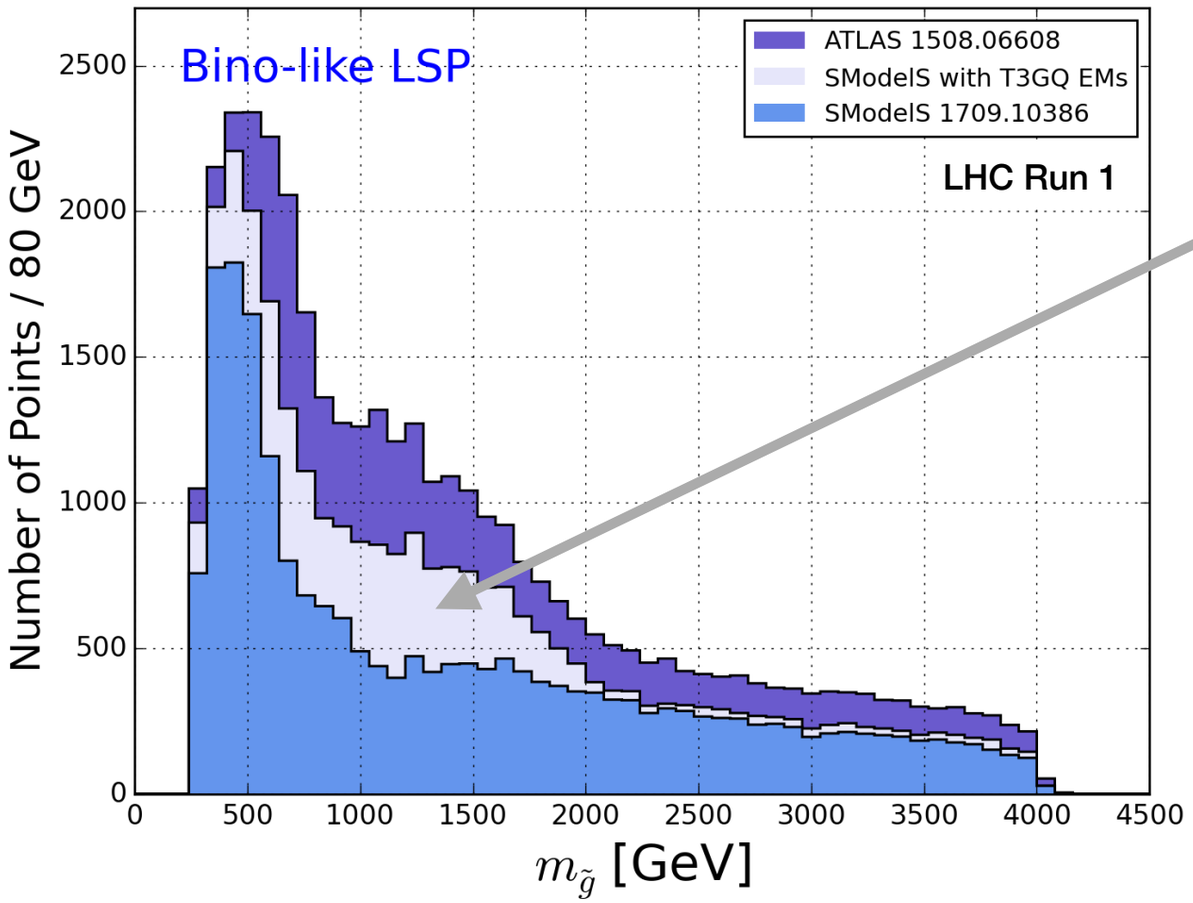
pMSSM : phenomenological MSSM with 19 free parameters defined at the SUSY scale; large scan by ATLAS in 1508.06608



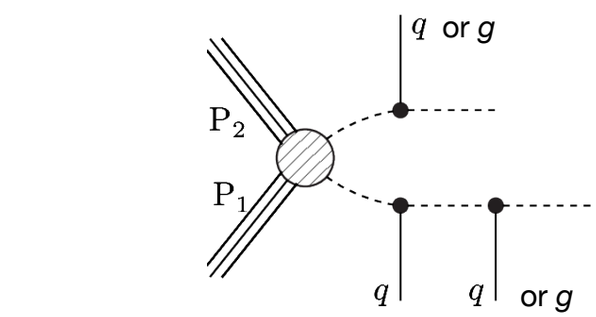
- Only the part of the cross section that goes into simplified model topologies, for which results (UL or EM maps) are available, can be constrained by SModelS.
- **Coverage drops** for intermediate gluino masses, where a **larger variety of decay channels** becomes available; more pronounced for bino than for higgsino LSP.

Need simplified-model efficiency maps for large enough variety of topologies

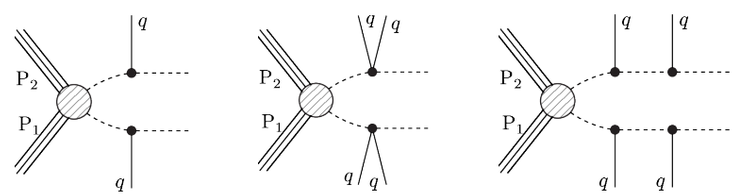
if not available from ATLAS/CMS → produce them ourselves by recasting



Improvement due to “home-grown” efficiency maps for 3-jet signatures from gluino-squark associated production



+



F. Ambrogi et al., work in progress

Ways of (re)interpretation: “recasting”

Simulation of **hard scattering process(es)**
(e.g. MadGraph)

⬇

Showering and hadronization,
incl. matching & merging
(Pythia)

⬇

emulation of **detector effects**:
object reconstruction, efficiencies, …
(e.g. DELPHES)

⬇

application of **signal selection cuts**

⬇

statistical evaluation
(background numbers usually from exp. pub.)

Libraries of public, validated implementations are being built in CheckMATE and MadAnalysis5

Some BSM analyses also exist in RIVET, but w/o backend for statistical evaluation, i.e. computing a limit, CLs value, …

Reproduce exp. search in MC event simulation

- **More generic and more precise** than simplified model results; applicable to any new signal
- **Very CPU expensive**
- So far possible only for cut-and-count analyses; detailed information needed from experiment

The difficulty with recasting

- **Searches**, in contrast to measurements, are **not unfolded**
- **Non-collaboration members do not have access** to the experimental data, nor the Monte Carlo (MC) event set simulated with an official collaboration detector simulation.
- This **makes the implementation and validation** of ATLAS/CMS analyses for re-interpretation in general contexts **a tedious task**, even more so as the **information** given in the experimental papers is **often incomplete** in this respect.

Les Houches recommendations

- **Searches**, in contrast to measurements, are **not unfolded**
- **Non-collaboration members do not have access** to the experimental data, nor the Monte Carlo (MC) event set simulated with an official collaboration detector simulation.
- This **makes the implementation and validation** of ATLAS/CMS analyses for re-interpretation in general contexts **a tedious task**, even more so as the **information** given in the experimental papers is **often incomplete** in this respect.

"The community should identify, develop and adopt a common platform to store analysis databases, collecting object definitions, cuts, and all other information, including well-encapsulated functions, necessary to reproduce or use the results of the analyses [...]"

"The tools needed to provide extended experimental information will require some dedicated efforts in terms of resources and manpower, to be supported by both the experimental and the theory communities."

Searches for New Physics: Les Houches Recommendations for the Presentation of LHC Results
SK et al., Eur.Phys.J. C72 (2012) 1976, arXiv:1203.2489

Validation

- Detailed comparisons against official **cut-flows** and **distributions** for specific benchmark points
- Often the most **tedious and time-consuming** part of the work, in particular if additional information is needed from the experimental collaboration
- Each implementation should come with a dedicated validation note

- ATLAS and CMS SUSY groups nowadays (usually) provide ample validation material, like
  - SLHA files for exact benchmark definitions
  - details on MC settings for the simulation
  - trigger, MET, etc. efficiencies
  - detailed cut-flows for all signal regions

Unfortunately not the same in Exotics groups :-(

$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ (2000/0) cutflow
for SR $4j - 2600$

cut	# events (scaled to σ and $\mathcal{L}$)	relative change	# events (official)	relative change (official)
Initial number of events	35.4	35.4		
Preselection cuts	32.5	-8.2%	31.6	31.6
$N_j \geq 2$	32.5	-0.0%	31.6	-0.0%
$N_j \geq 4$	31.0	-4.6%	29.8	-5.7%
$\Delta\phi(\text{jet}_{1,2,(3)}, E_T^{\text{miss}})_{\text{min}} > 0.4$	25.0	-19.4%	24.1	-19.1%
$\Delta\phi(\text{jet}_{i>3})_{\text{min}} > 0.4$	18.8	-24.8%	18.2	-24.5%
$p_T(j_4) > 150$ GeV	14.1	-25.0%	13.9	-23.6%
$\lvert\eta(\text{jets})\rvert < 2.0$	13.0	-7.8%	13.1	-5.8%
Aplanarity > 0.04	9.2	-29.2%	9.21	-29.7%
$E_T^{\text{miss}}/m_{\text{eff}}(4j) > 0.20$	6.6	-28.3%	6.64	-27.9%
$m_{\text{eff}}(\text{incl.}) > 2600$ GeV	6.0	-9.1%	6.0	-9.6%

Example cut-flow for ATLAS 2-6 jets + MET analysis, comparing MA5 to official ATLAS numbers

Available analyses:

ATLAS analyses, 13 TeV

Analysis	Short Description	Implemented by
ATLAS-SUSY-2015-06	Multijet + missing transverse momentum	S. Banerjee, B. Fuks, B. Zaldivar
ATLAS-SUSY-2016-07	Multijet + missing transverse momentum (36.1 fb-1)	G. Chalons, H. Reyes-Gonzalez
ATLAS-EXOT-2015-03	Monojet (3.2 fb-1)	D. Sengupta
ATLAS-EXOT-2016-25	Mono-Higgs (36.1 fb-1)	S. Jeon, Y. Kang, G. Lee, C. Yu
ATLAS-EXOT-2016-27	Monojet (36.2 fb-1)	D. Sengupta
ATLAS-EXOT-2016-32	Monophoton (36.1 fb-1)	S. Baek, T.H. Jung
ATLAS-CONF-2016-086	b-pair + missing transverse momentum	B. Fuks & M. Zumbihl

CMS analyses, 13 TeV

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

Each analysis code comes with a detailed validation note. D.O.I. from Inspire → individually citeable.

B. Dumont et al., *Towards a public analysis database for LHC new physics searches using MadAnalysis 5*, 1407.3278
Detailed manual: E. Conte, B. Fuks, *Confronting new physics theories to LHC data with MadAnalysis 5*, 1808.00480

Available analyses:

Check **M**odels **A**t **T**erascale **E**nergies

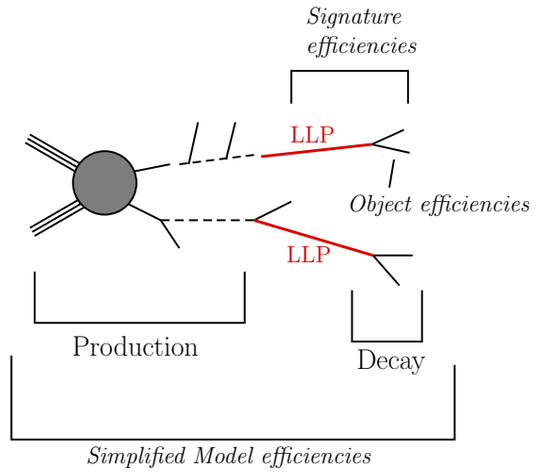
ATLAS 13 TeV		**lumi [fb-1]**
atlas_1604_01306	photon + MET	3.2
atlas_1605_09318	>= 3 b-jets + 0-1 lepton + etmiss	3.3
atlas_1609_01599	ttV cross section measurement at 13 TeV	3.2
atlas_conf_2015_082	leptonic Z + jets + etmiss	3.2
atlas_conf_2016_013	4 top quark (1 lepton + jets, vector like quark search)	3.2
atlas_conf_2016_050	1-lepton + jets + etmiss (stop)	13.3
atlas_conf_2016_054	1-lepton + jets + etmiss (squarks and gluino)	14.8
atlas_conf_2016_076	2 leptons + jets + etmiss	13.3
atlas_conf_2016_096	2-3 leptons + etmiss (electroweakino)	13.3
atlas_conf_2016_066	search for photons, jets and met	13.3
atlas_conf_2017_060	monojet search	36.1
atlas_1704_03848	monophoton dark matter search	36.1
atlas_1712_08119	electroweakinos search with soft leptons	36.1
atlas_1712_02332	squarks and gluinos, 0 lepton, 2-6 jets	36.1
atlas_1709_04183	stop pair production, 0 leptons	36.1
atlas_1802_03158	search for GMSB with photons	36.1
atlas_1708_07875	electroweakino search with taus and MET	36.1
atlas_1706_03731	same-sign or 3 leptons RPC and RPV SUSY	36.1

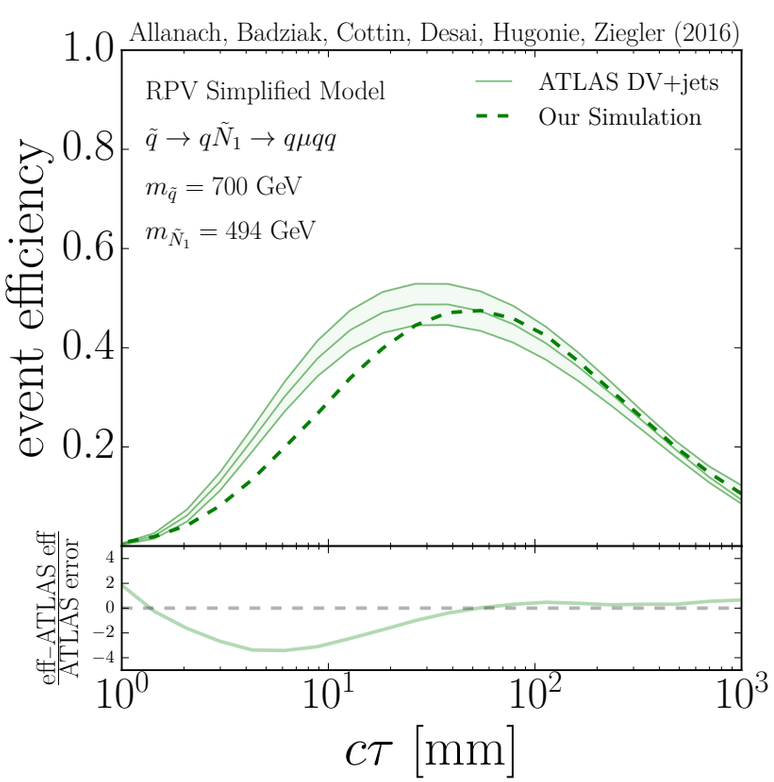
CMS 13 TeV		**lumi [fb-1]**
cms_pas_sus_15_011	2 leptons + jets + MET	2.2
cms_sus_16_025	electroweak-ino and stop, compressed spectra	12.9
cms_sus_16_039	electroweak-inos in multilepton final state	35.9
cms_sus_16_048	two soft opposite sign leptons	35.9

M. Drees et al, *CheckMATE: Confronting your Favourite New Physics Model with LHC Data*, 1312.2591
D. Derks et al., *CheckMATE 2: From the model to the limit*, 1611.09856

Long-lived particles (LLPs)

- Searches for LLPs have seen an **enormous rise**
  displaced vertices, disappearing tracks, emerging jets, ….
- **Very sensitive to the detector response**; cannot be easily emulated by a fast detector simulation.
- **Detailed information** concerning the detector performance and object reconstruction **is needed**.
- Can in principle be provided in the format of efficiencies: reconstruction efficiencies, selection efficiencies, overall signal efficiencies
- Information needed is **very analysis dependent** → additional workload for the analysis groups to provide this on a case-by-case basis.
- Standard DELPHES needs to be extended (so far does not handle vertex information)
- Lots of private codes but the implementation in **public recasting** tools is **still in its infancy**.
  (only 1 example in MadAnalysis)





Ways of (re)interpretation

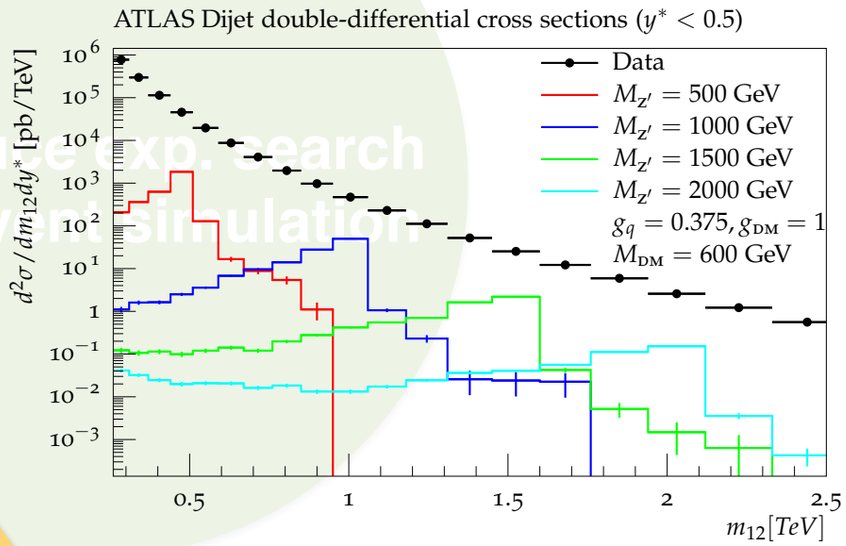
Standard Model precision measurements can provide important additional constraints, as **SM cross sections, distributions, etc. must not be altered too much by BSM effects**

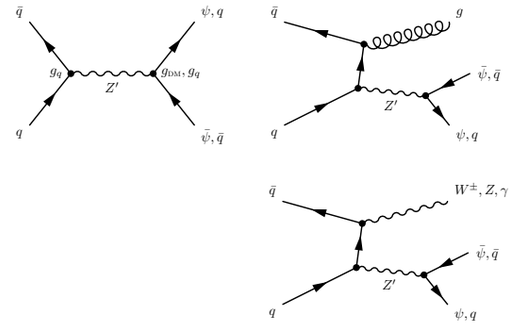
- Bins of **fiducial cross sections** in the tails of "SM" distributions (jet, top, EW bosons, …) can be viewed as equivalent to signal regions of BSM searches.
- Unfolded measurements: only **particle-level simulation** needed.
- RIVET routines provided by exp. collaborations
- Reference data connection to HEPData
- Difficulty is to compute the SM predictions; rarely provided on HEPData
- SM-BSM interferences effects? e.g., Djouadi et al, 1901.03417

Use Simplified Model results

Reproduce exp. search in MC event simulation

Use SM fiducial measurements





Butterworth et al., 1606.05296
https://contur.hepforge.org/

International effort

Forum on the Interpretation of the LHC Results for BSM studies

The quest for new physics beyond the Standard Model is arguably the driving topic for Run 2 of the LHC. Indeed, the LHC collaborations are pursuing searches for new physics in a vast variety of channels. While the collaborations typically provide themselves interpretations of their results, for instance in terms of simplified models, **the full understanding of the implications of these searches requires the interpretation of the experimental results in the context of all kinds of theoretical models.** This is a very active field, with close theory-experiment interaction and with several public tools being developed.

With this forum, we want to provide a platform for continued discussion of topics related to the BSM (re)interpretation of LHC data, including the development of the necessary **public** RecastingTools and related infrastructure.

If you have questions or want to contribute, contact Sabine Kraml, sabine.kraml@gmailNOSPAMPLEASE.com, or any of the topical contacts given below.

Meetings

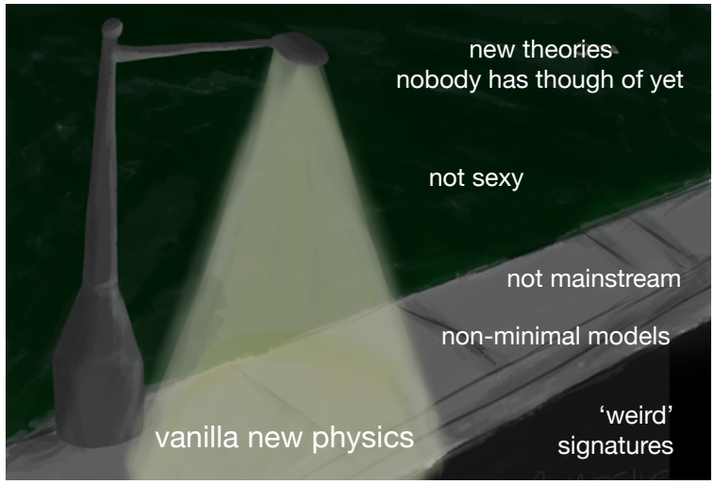
Meetings of this forum

- **4th workshop**, 14-16 May 2018 at CERN
- **3rd workshop**, 16-18 Oct 2017 at Fermilab
- **2nd workshop**, 12-14 Dec 2016 at CERN
  - Agenda | introduction | final discussion | WorkshopSummaryNotes
- **Kick-off workshop:** (Re)interpreting the results of new physics searches at the LHC, 15-17 June 2016 at CERN
  - Agenda | general discussion | KickoffSummaryNotes

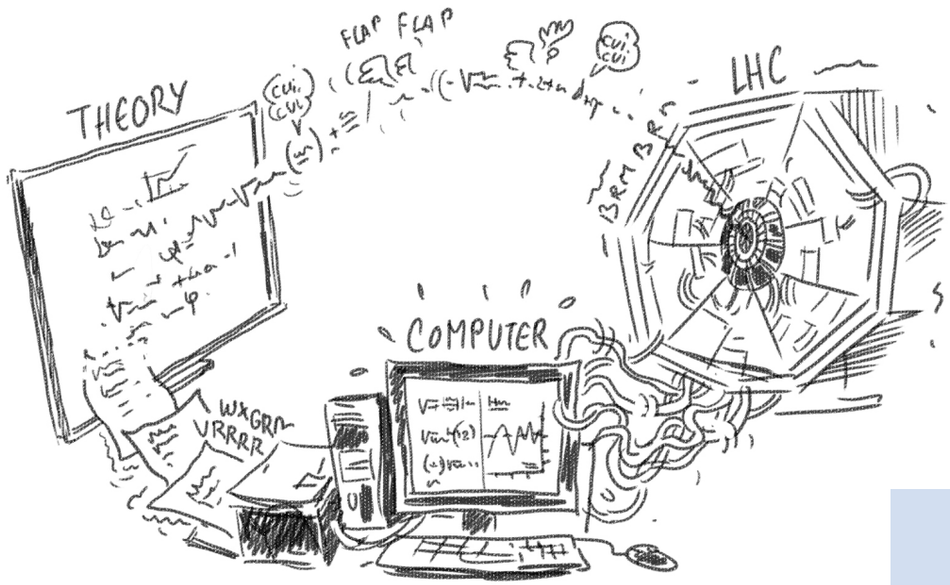
next meeting likely in April at Imperial College (tbc)

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/InterpretingLHCresults

Conclusions



Absence of unambiguous sign of new physics (NP) so far, along with the **lack of clear guidance from theory** side about the nature and scale of NP, imposes today more than ever to **work out the detailed implications of the LHC results** for all kinds of theoretical models and scenarios.

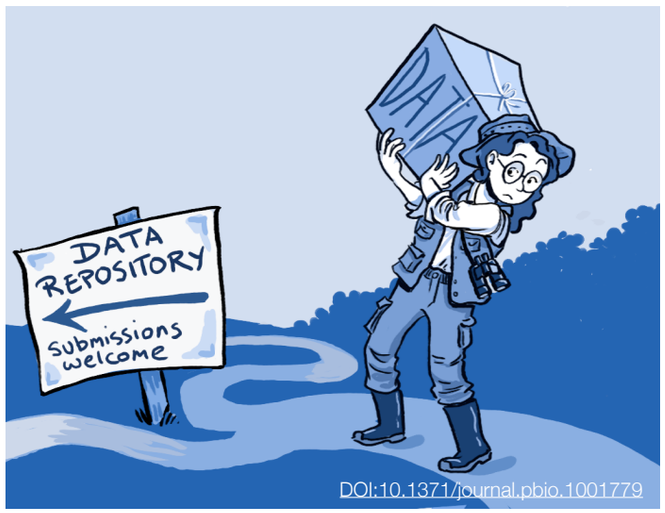


© lison bernet

Large effort in the theory community

- to build **public tools** necessary for this endeavour
- to exploit them in the best possible way

Strong French involvement!
(n.b. IN2P3-theory project!)



making progress, but there's still a looong way to go …

Backup

micrOMEGAs — SModelS interface

in main.c

```
#define SMODELS
…
…

#ifdef 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 http://smodels.hephy.at/wiki/SmsDictionary
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
```

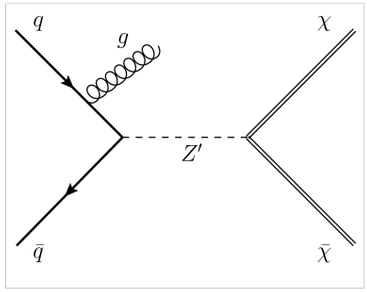
Dark matter simplified model results

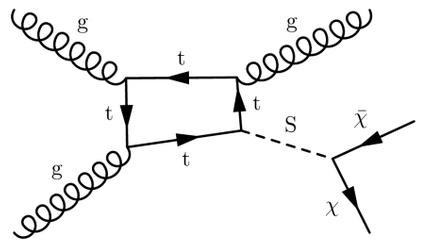
- At the LHC, DM production is searched for in mono-X signatures, e.g. mono-jet, or in association with heavy flavour quarks.

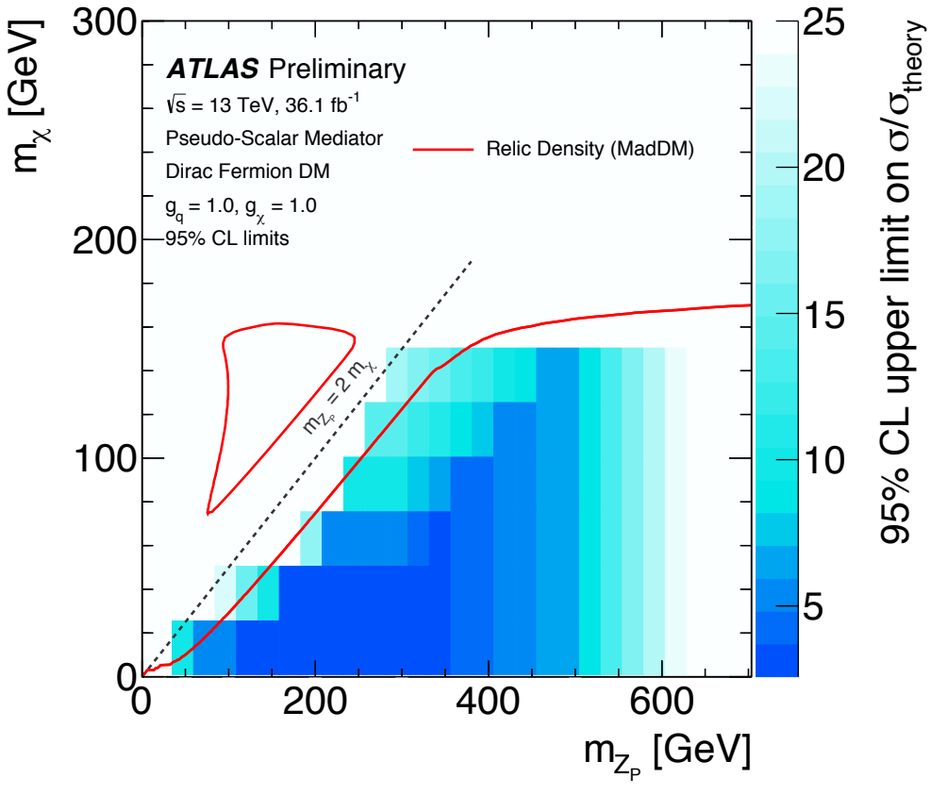
- Interpreted in terms of EFT or simplified model with a **DM particle plus a mediator**.

- *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







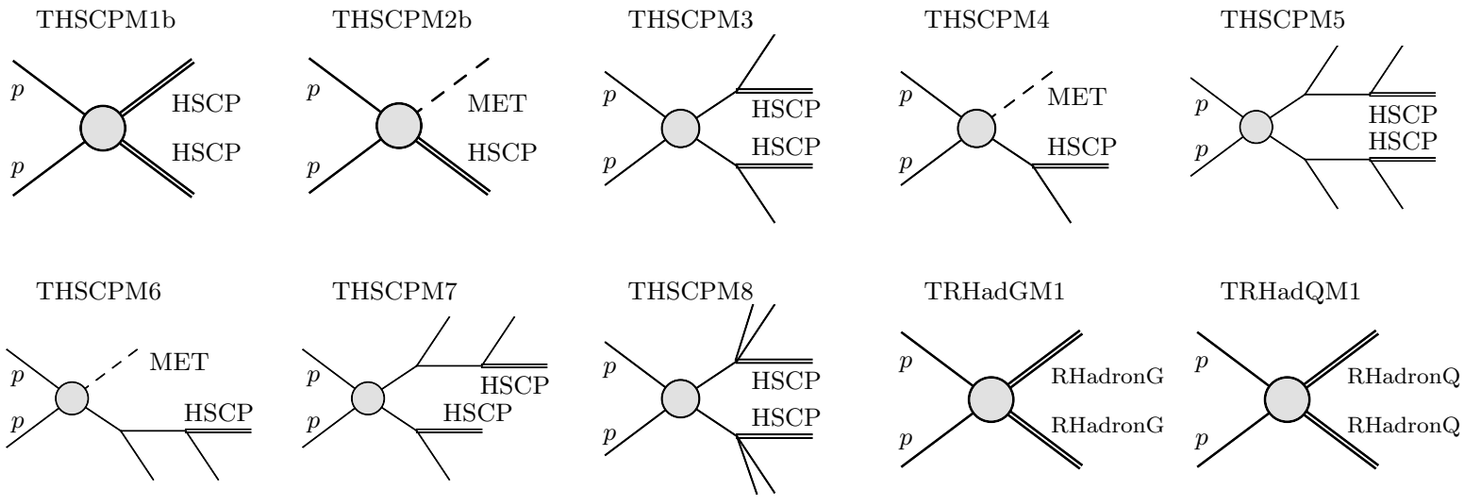
- In practice, constraints are presented by ATLAS and CMS as **95%CL limits on σ/σ_{theory}**, which is **highly model dependent**.

  - Need to unfold σ_{theory} to use these results, but reference cross section not provided. Source of systematic uncertainty.

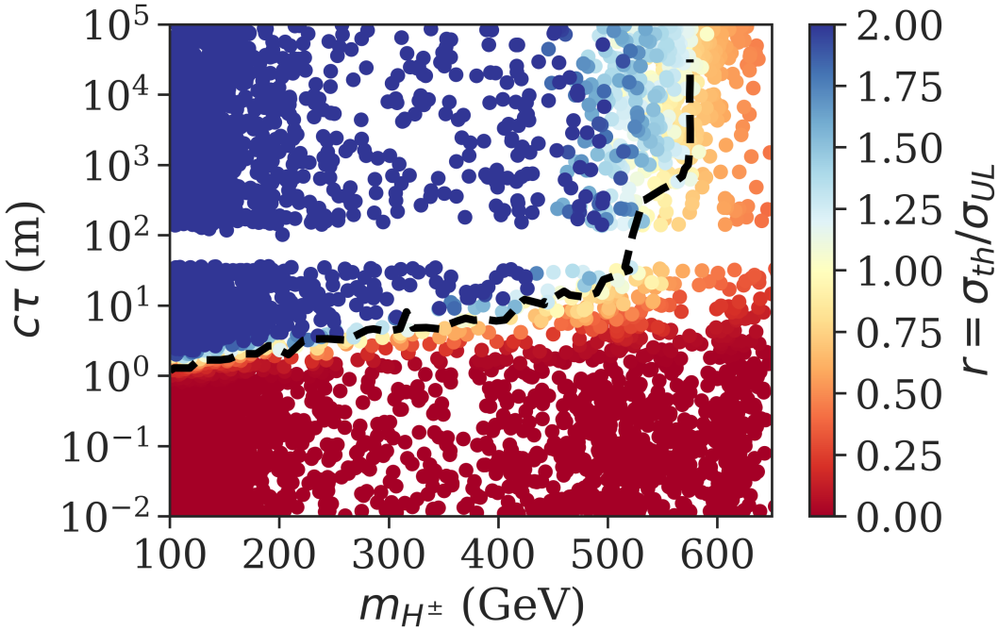
- When variety of signal topologies exists, efficiency maps would b useful.

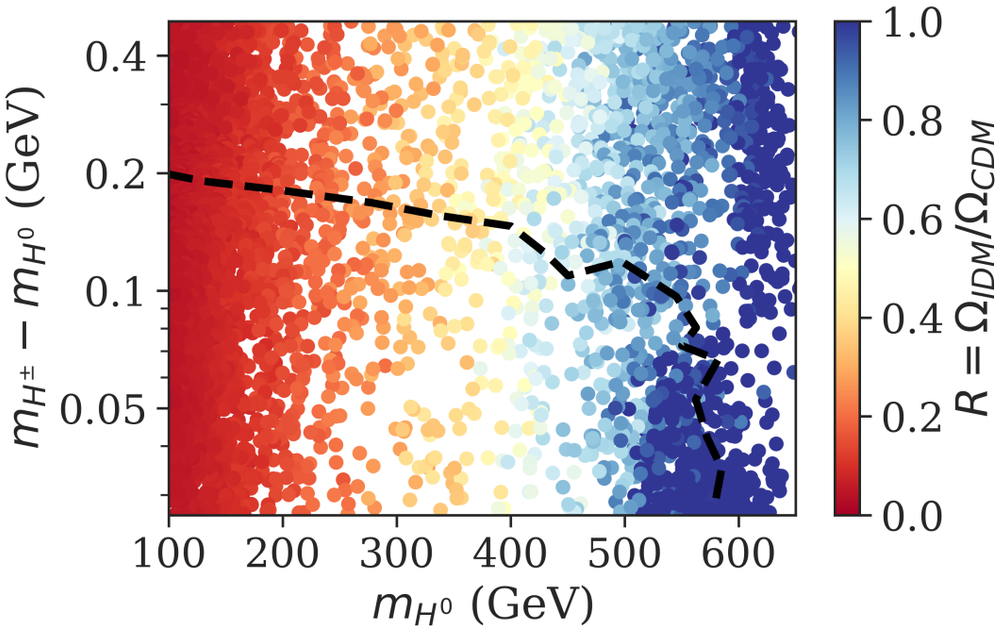
J. Heisig, SK, A. Lessa, 1808.05229
F. Ambrogi et al., 1811.10624

LLP simplified models in SModelS



Starts to put constraints on cosmologically interesting region of the Inert Doublet Model:





From recasting mini-workshop in Grenoble, Sep. 2014

Wish list from phenomenologists – what is needed for each analysis

Analysis implementation

- ☐ Clear description of all the cuts, incl. their sequence
- ☐ Efficiencies for physics objects: electrons, muons, taus, b-tagging, mis-tagging, ...
- ☐ Efficiencies for "triggers", event cleaning, ... (everything we cannot reproduce in the fastsim)

Validation

- ☐ Clearly defined benchmark points for all SRs:
  SLHA files, input files for specific generators, or parton-level LHE files
- ☐ Exact configuration of MC tools (versions, run card settings, input scripts)
- ☐ Detailed cut flows for the benchmark points, best incl. every step of (pre)selection
- ☐ Plots of kinematic distributions after specific cuts

Statistical interpretation

- ☐ Observed #events and expected background in all SRs
- ☐ When relevant, correlation matrix for combining bins (problem: shape fits)

Recommendations from LLP white paper (to appear)

1. Provide LLP **reconstruction and selection efficiencies** at the signature or object level.
   Although the parametrization of efficiencies is strongly analysis dependent, it is of advantage if they are given as a function of model-independent variables (such as functions of displaced vertex d_0, p_T, η, etc.), so they do not rely on a specific LLP decay or production mode;
2. Present results for **at least 2 distinct benchmark** models with different event topologies,
   since it greatly helps to validate the recasting. For clarity, the input cards for the benchmark points should also be provided;
3. Present **cut-flow tables**, for both the signal benchmarks and the background, since these are very useful for validating the recasting;
4. When an analysis is superseded, **differences and commonalities** with previous versions of the same analysis **should be made clear**, especially if the amount of information presented in both analyses differs. The understanding to which extent the information presented in an old version can be used directly in a later version greatly helps the recasting procedure, and also highlights ways in which the new search gains or loses sensitivity relative to the superseded analysis;
5. **Provide all this material in numerical form**, preferably on HEPdata, or on the collaboration wiki page. […] **truth-code snippets** illustrating the event and object selections, such as the one from the ATLAS disappearing-track search (1712.02118) provided in HEPdata under ``Common Resources".

+ set of recommendations for LLP simplified model results