Beyond simplified DM models

DM (re)interpretation of LHC searches

public tools, some examples, discussion

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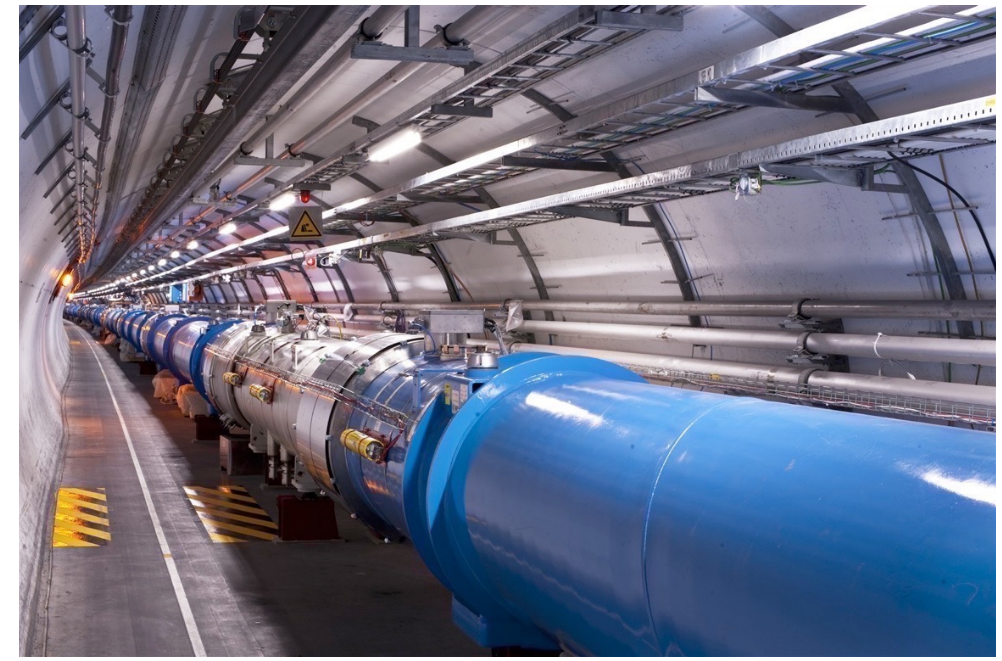
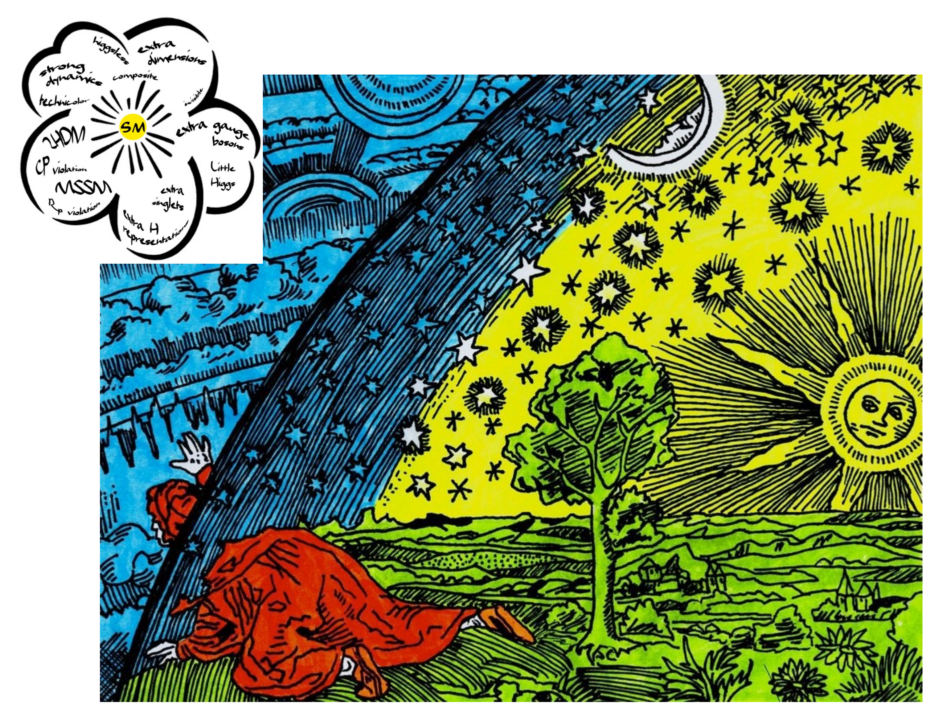
Dark Matter Identification: Connecting Theory and Signature Space

11/04/2019

Motivation

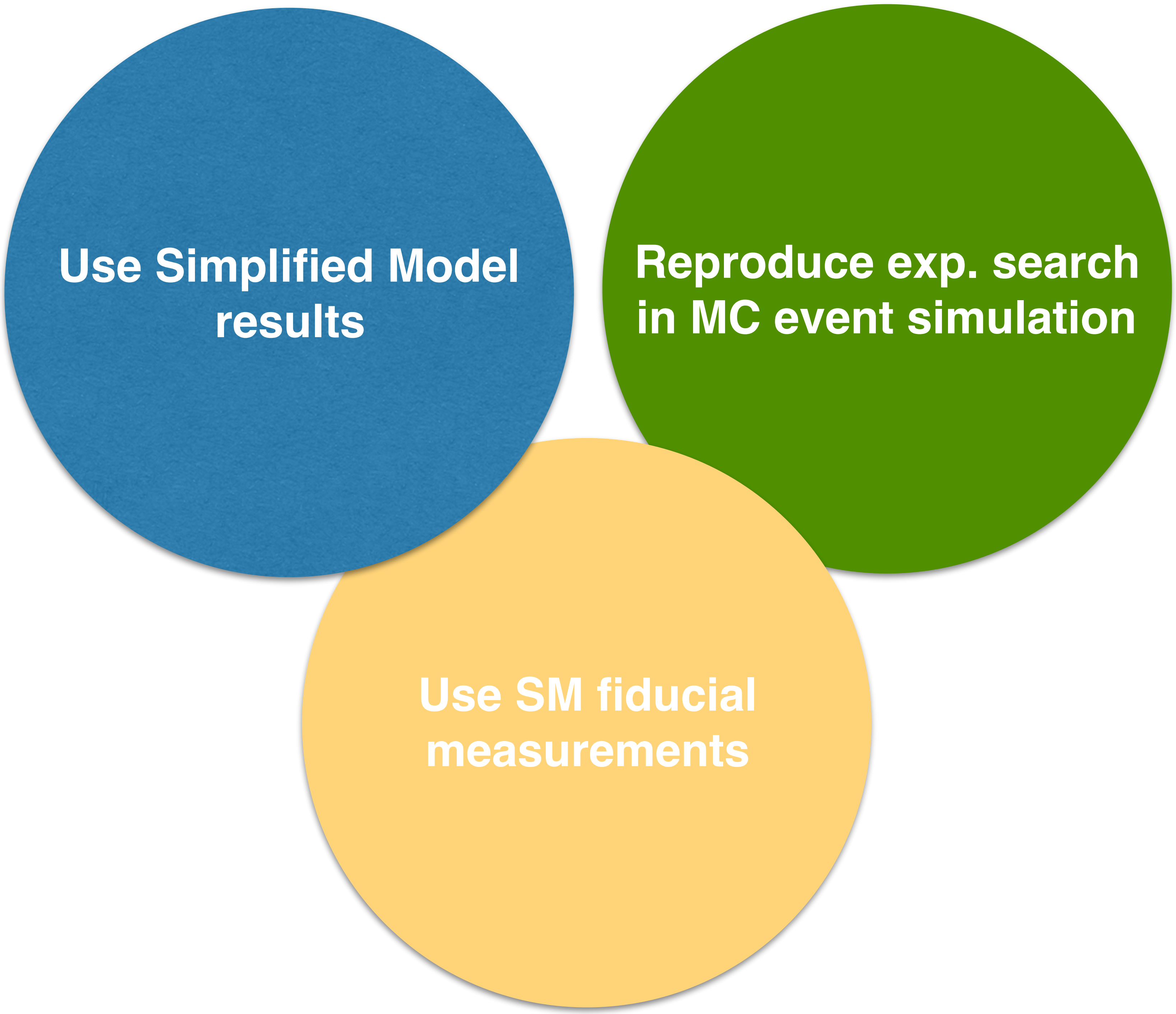
- **Experiments** at the LHC are searching for new phenomena **beyond the SM (BSM)** in many different channels
  - In Run 1, ATLAS and CMS each performed ~20 diff. SUSY and ~20 “Exotics” searches
  - Includes many “DM-motivated” searches, typically mono-X + missing energy
  - Re-done and extended for Run 2 data; e.g. many new analyses for long-lived particles
- However, a particular analysis may **also constrain other models** than considered in the experimental publication
- A full (complex) theoretical model is often constrained by **more than one analysis**





nb: mono-X searches are very useful but
not always the most sensitive for DM
… in particular in a full model

Ways of (re)interpretation



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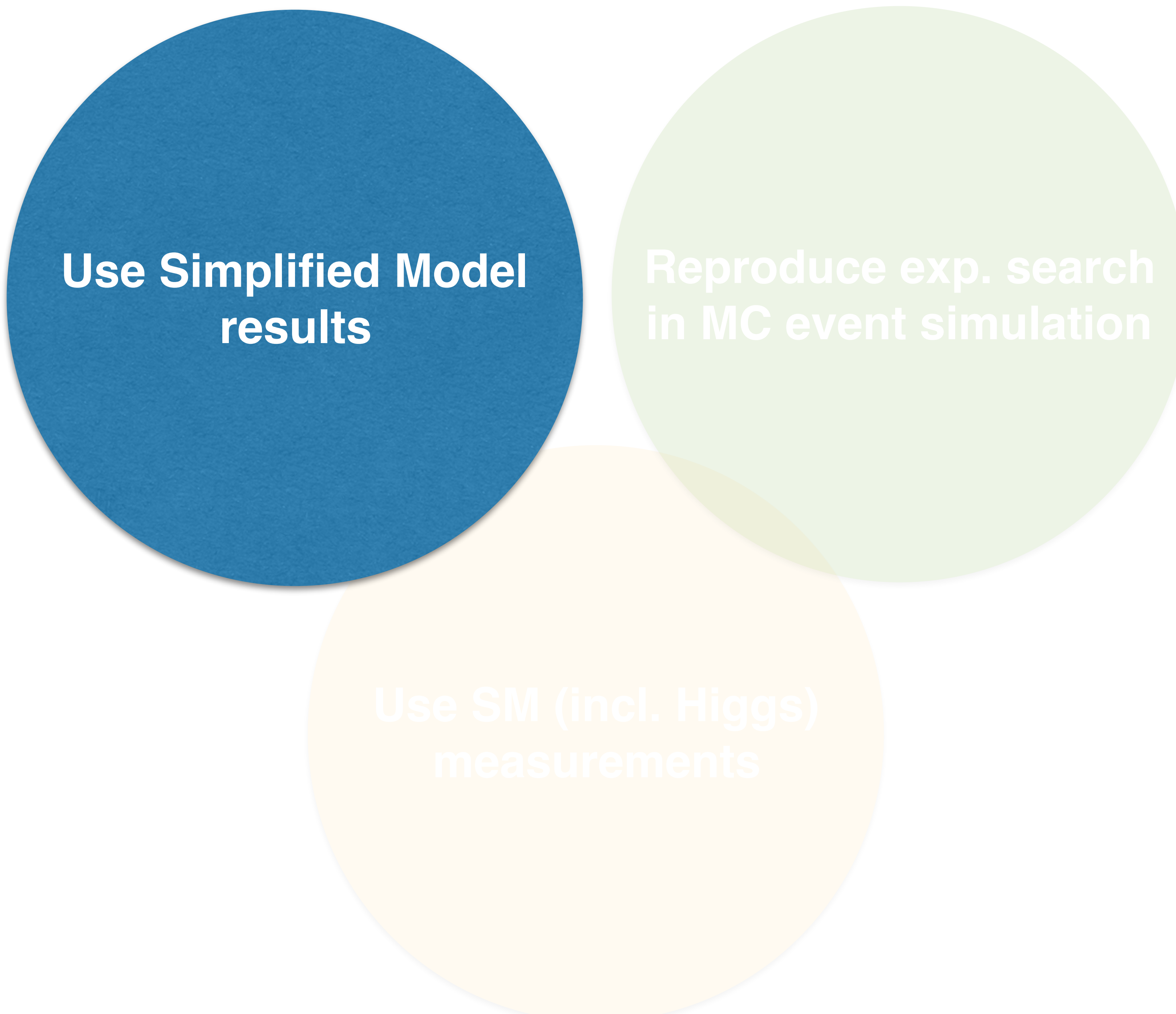

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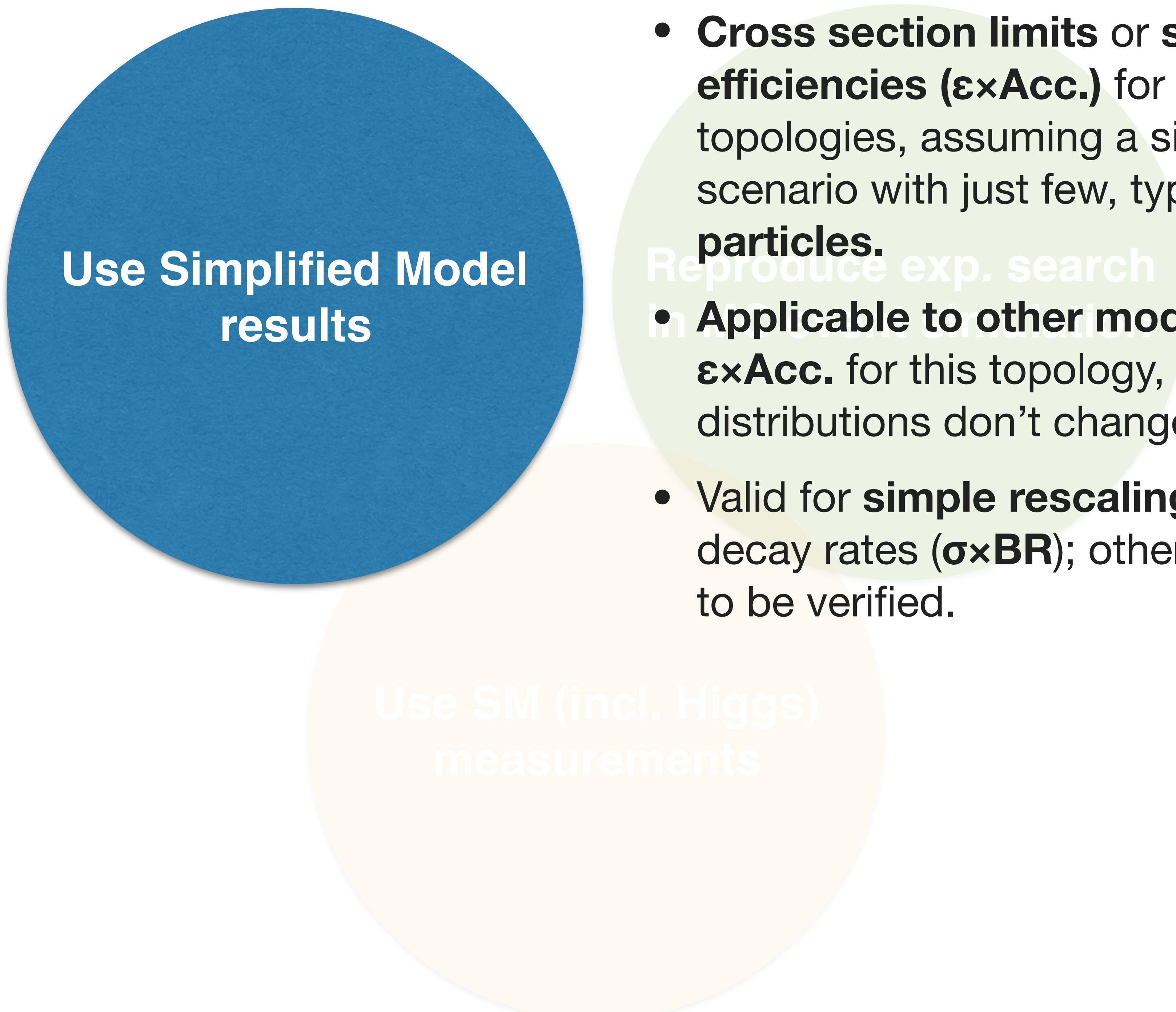

- **Cross section limits** or **signal selection efficiencies (ε×Acc.)** for specific signal topologies, assuming a simple/ified BSM scenario with just few, typically **2–3 new particles.**
- **Applicable to other models with same ε×Acc.** for this topology, i.e. if kinematical distributions don't change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

Ways of (re)interpretation

Use Simplified Model results

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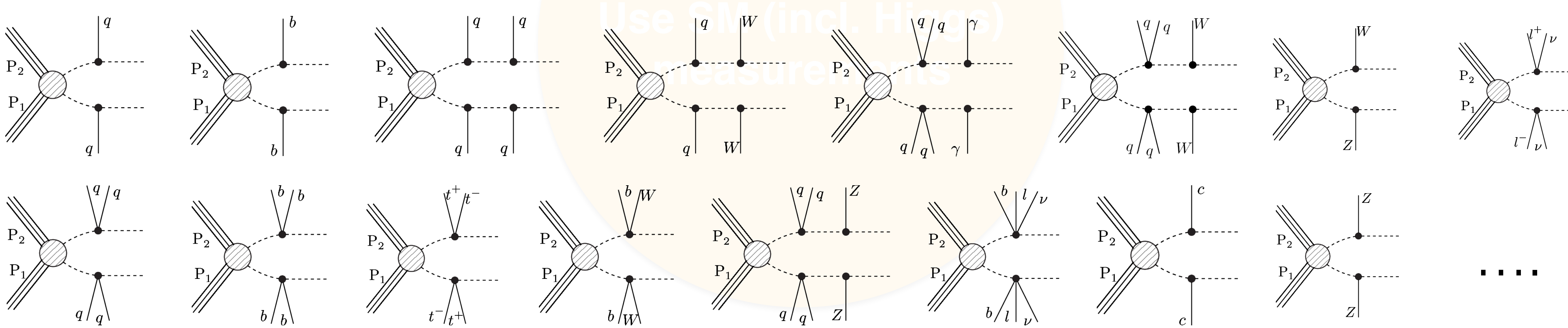

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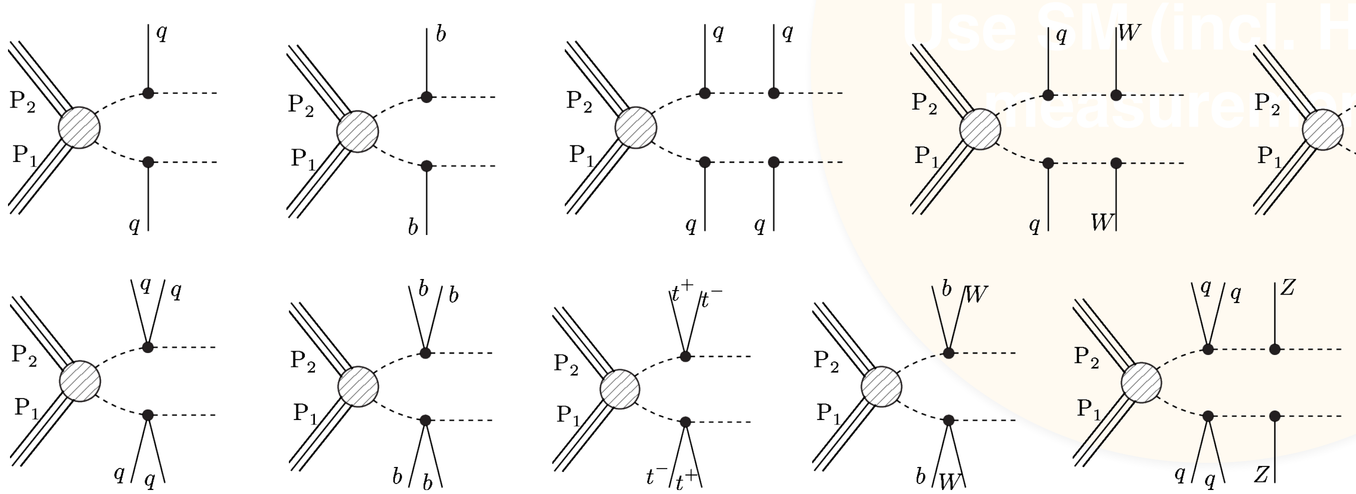

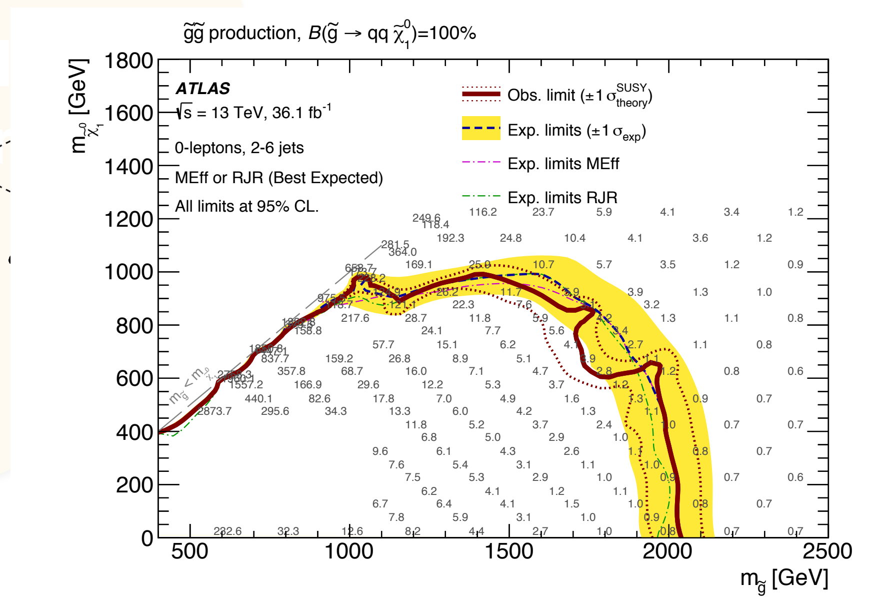

gluino-neutralino simplified model

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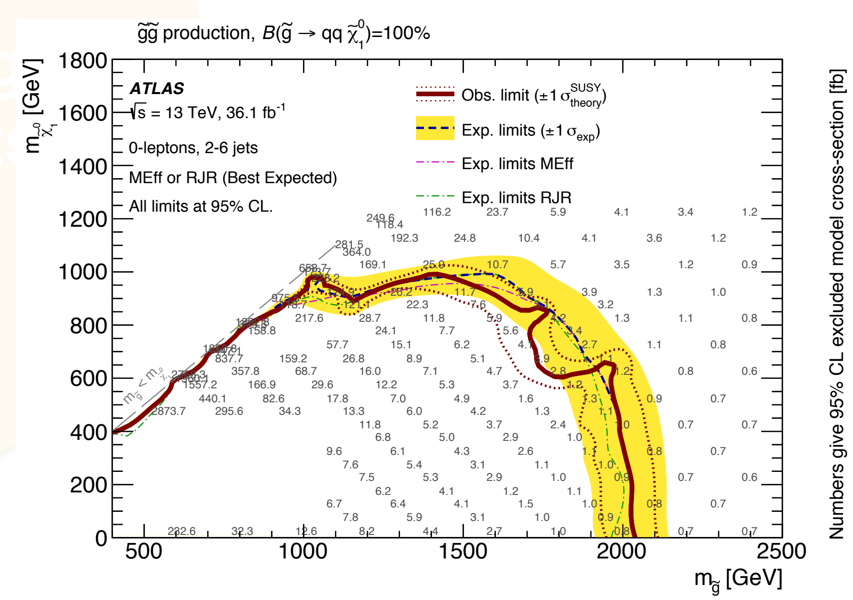
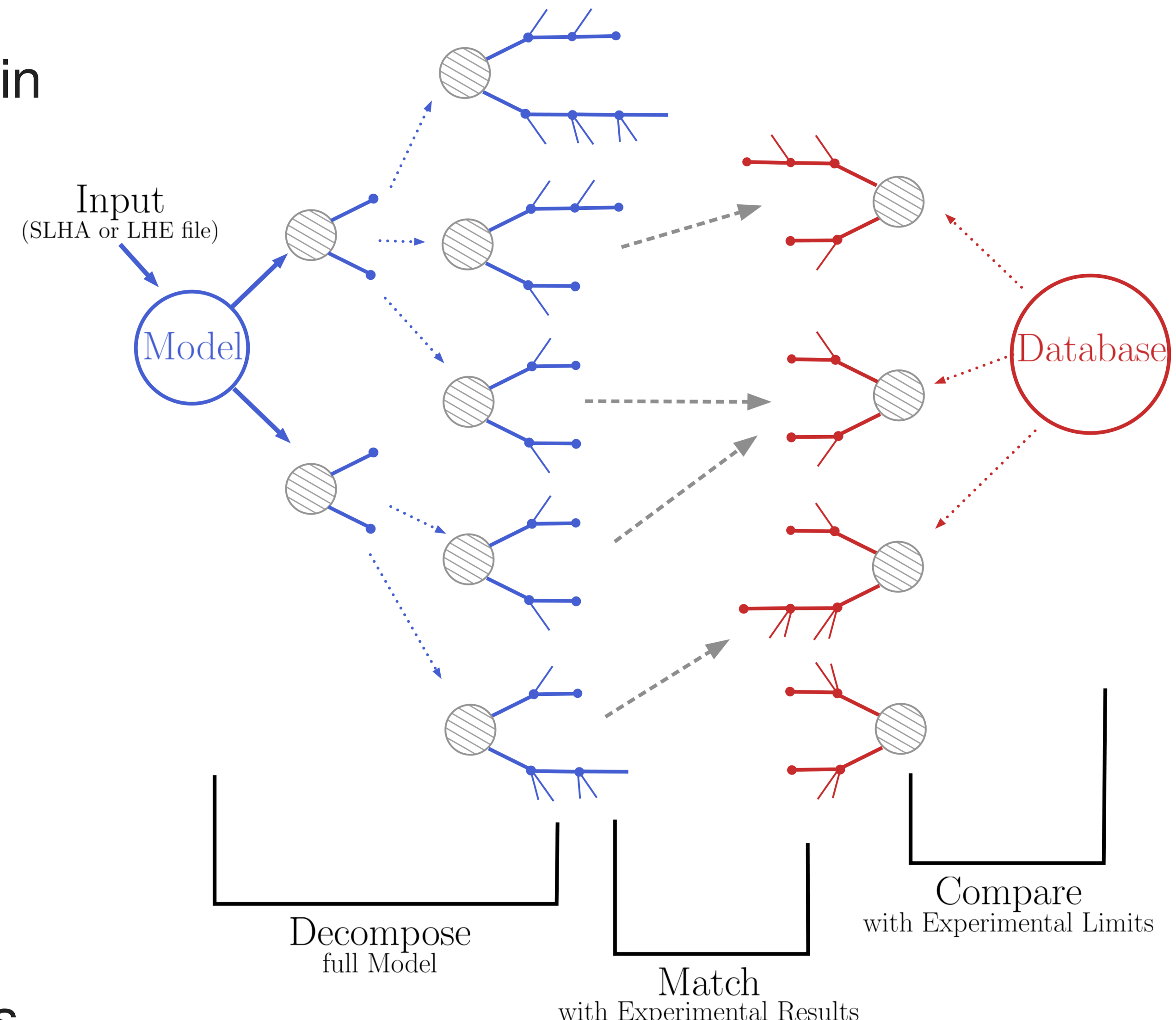
- Advantages: simplicity and **speed !** very fast, no need for event simulation → well suited for large scans and model surveys
- Easy classification of unconstrained cross section, uncovered signatures



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

SMOdelS

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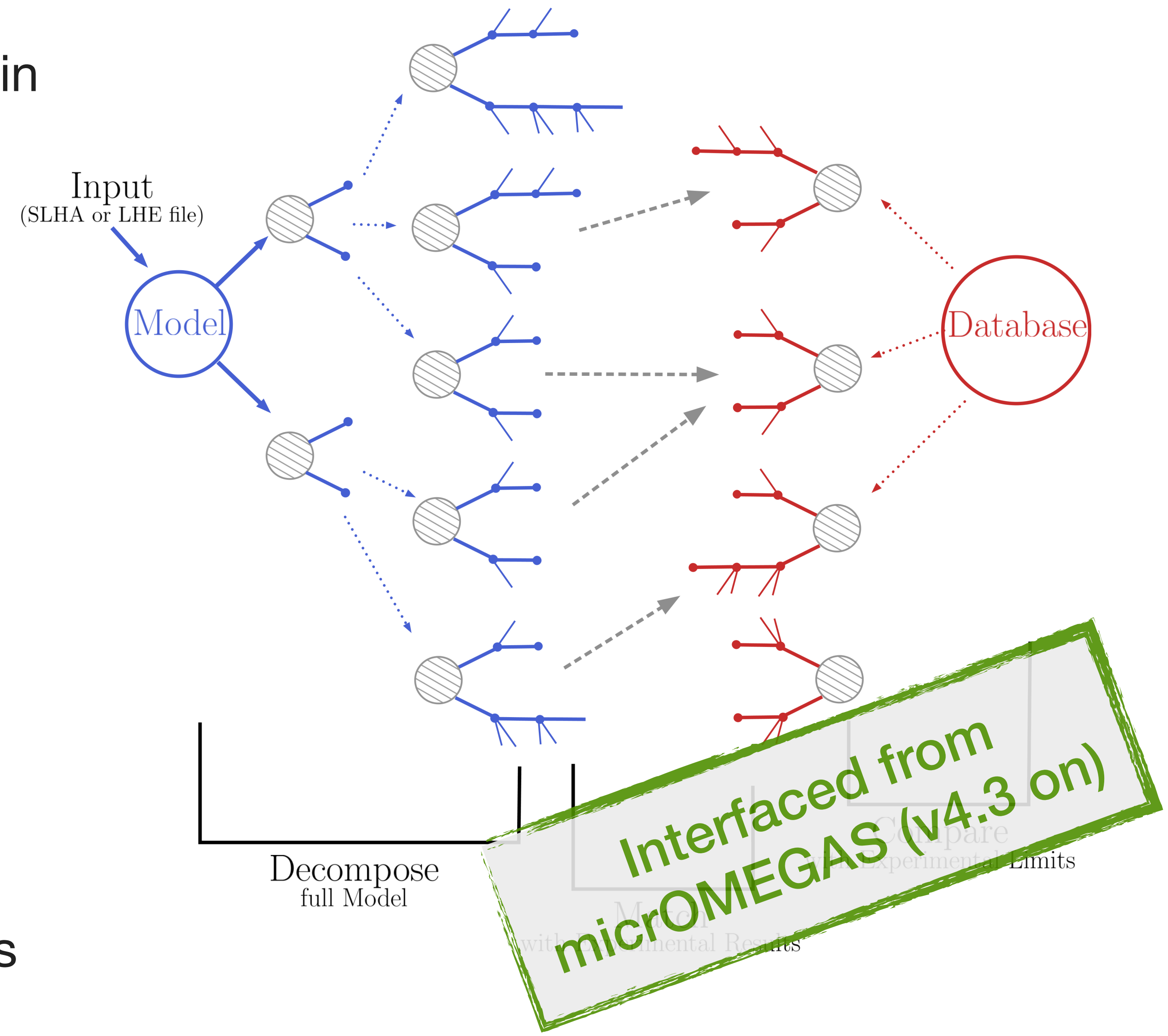

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micrOMEGAs — SModelS interface

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;

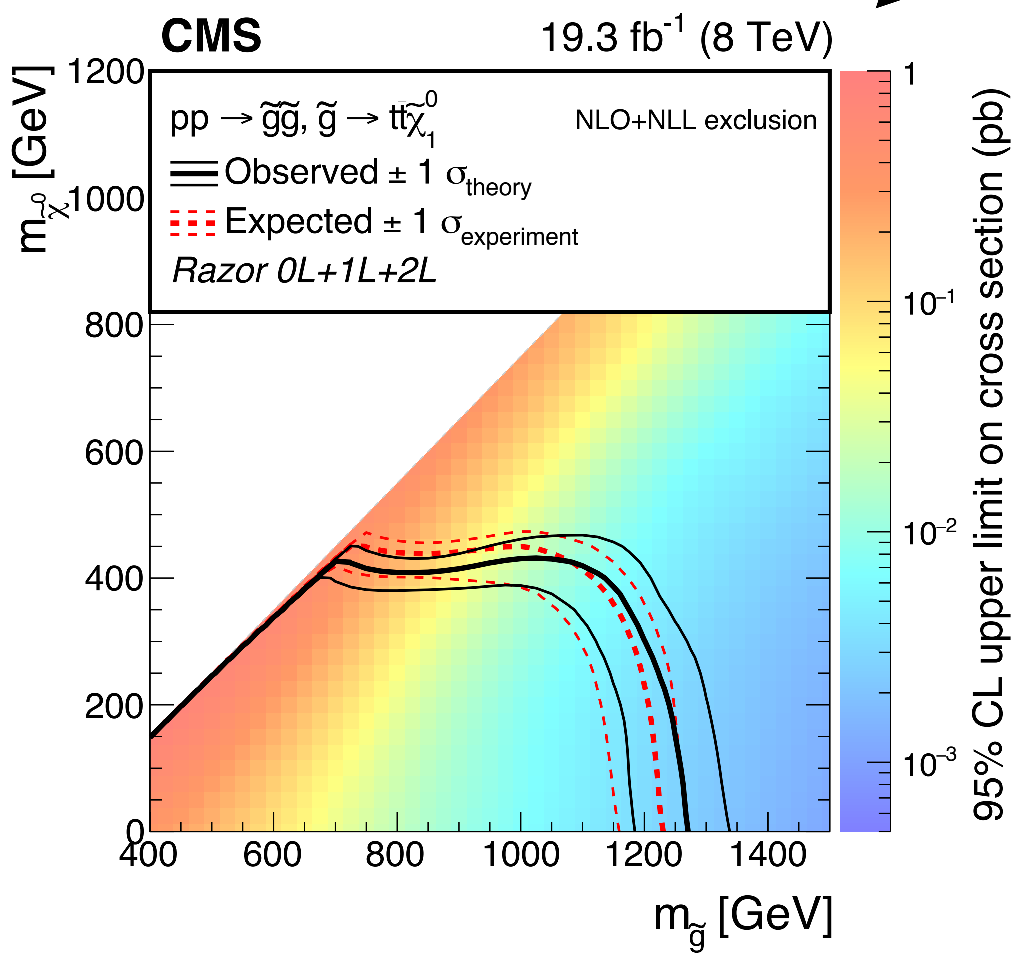
SModelS specific settings can be chosen in `parameters.ini`

```
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
```

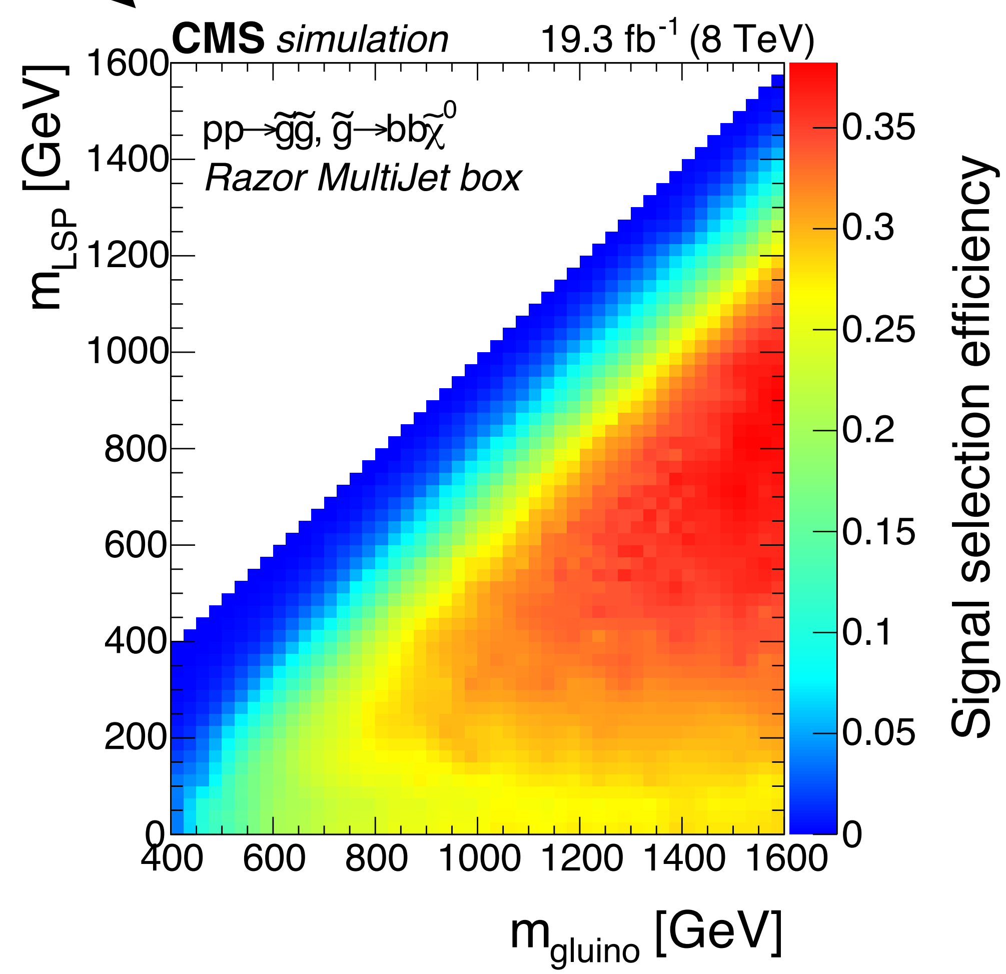
Two types of results

need these in numerical form!

Upper Limit (UL) maps



Efficiency maps (EM)



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

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

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

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

Limit on σ×BR

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.

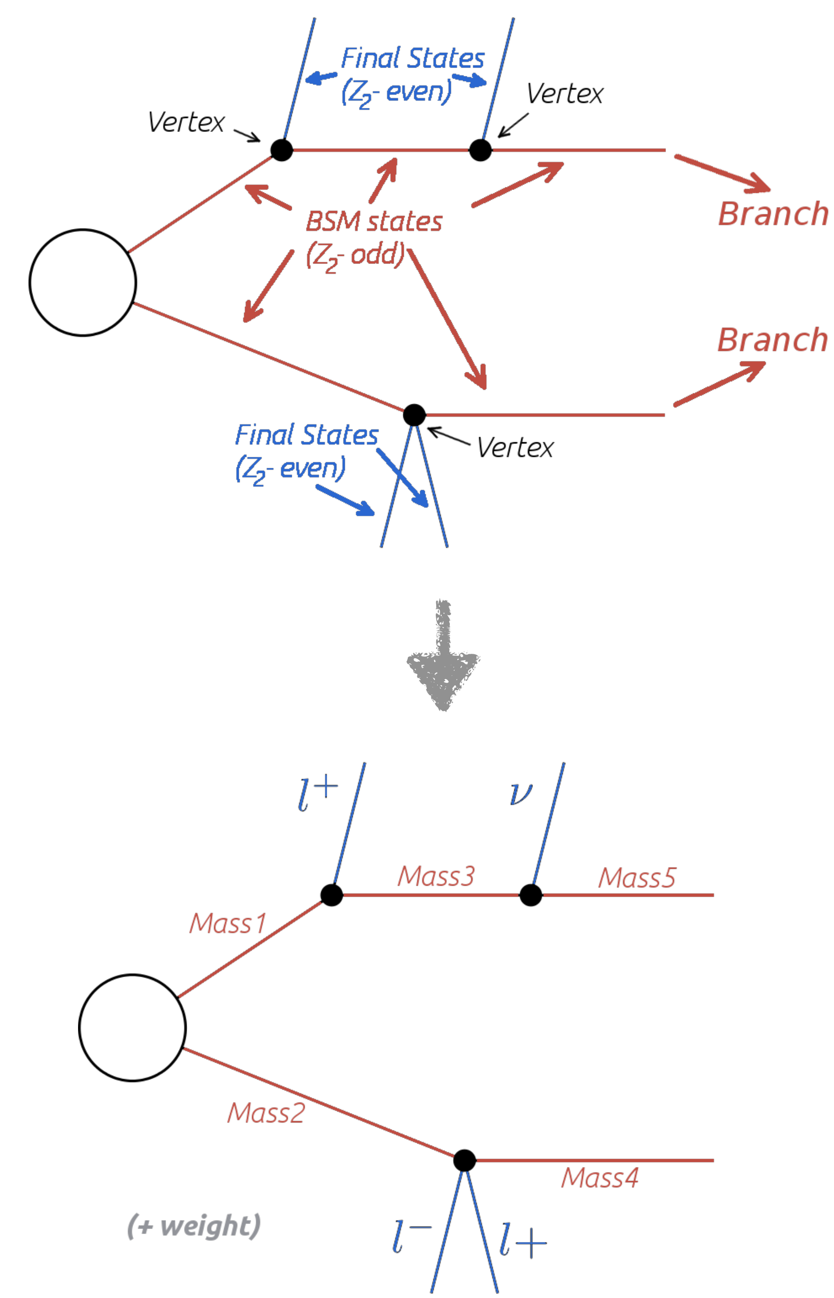
- Underlying assumption is that differences in the event kinematics from, e.g., different production mechanisms or the spins of the BSM particles, do not significantly affect the signal selection efficiencies.

  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

Example 1: MSSM + RH sneutrino dark matter

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

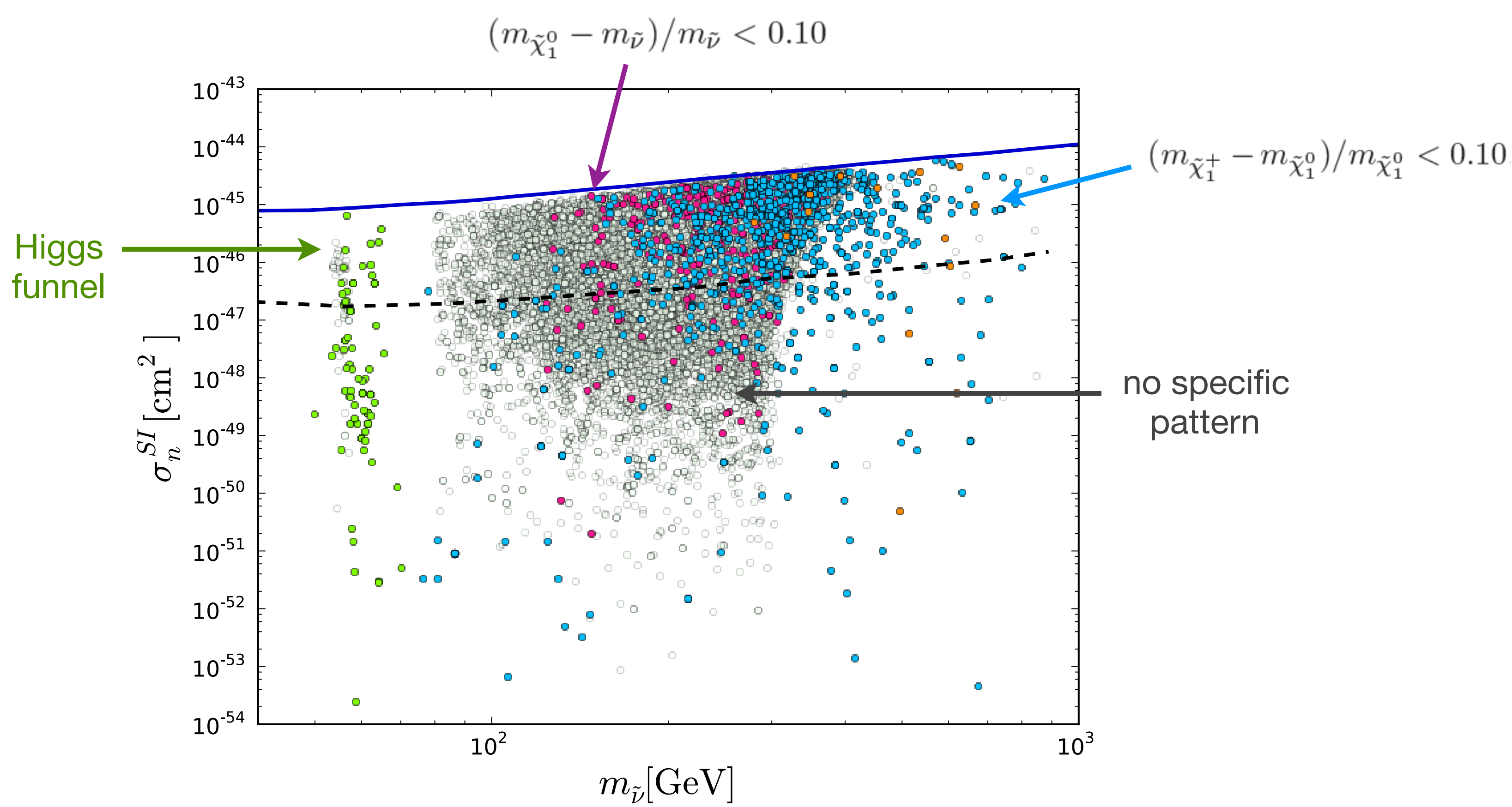
$$m^2_{\tilde{\nu}} = \begin{pmatrix} m^2_{\tilde{L}} + \frac{1}{2} m^2_Z \cos 2\beta & \frac{1}{\sqrt{2}} A_{\tilde{\nu}}\, v \sin\beta \\ \frac{1}{\sqrt{2}} A_{\tilde{\nu}}\, v \sin\beta & m^2_{\widetilde{N}} \end{pmatrix}$$

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

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

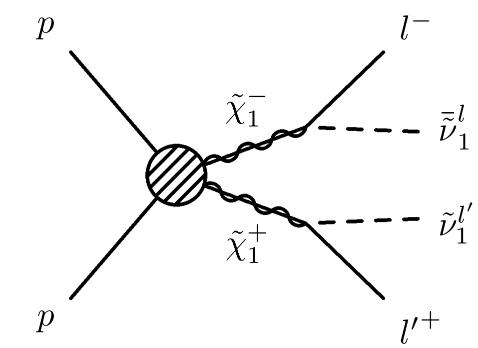
$M_1, M_2, M_3, m_L, m_R, m_N, m_Q, m_H, A_l, A_{\tilde{\nu}}, A_q, \tan\beta, \mathrm{sgn}\mu$.

[Arina, Cabrera, 1311.6549]



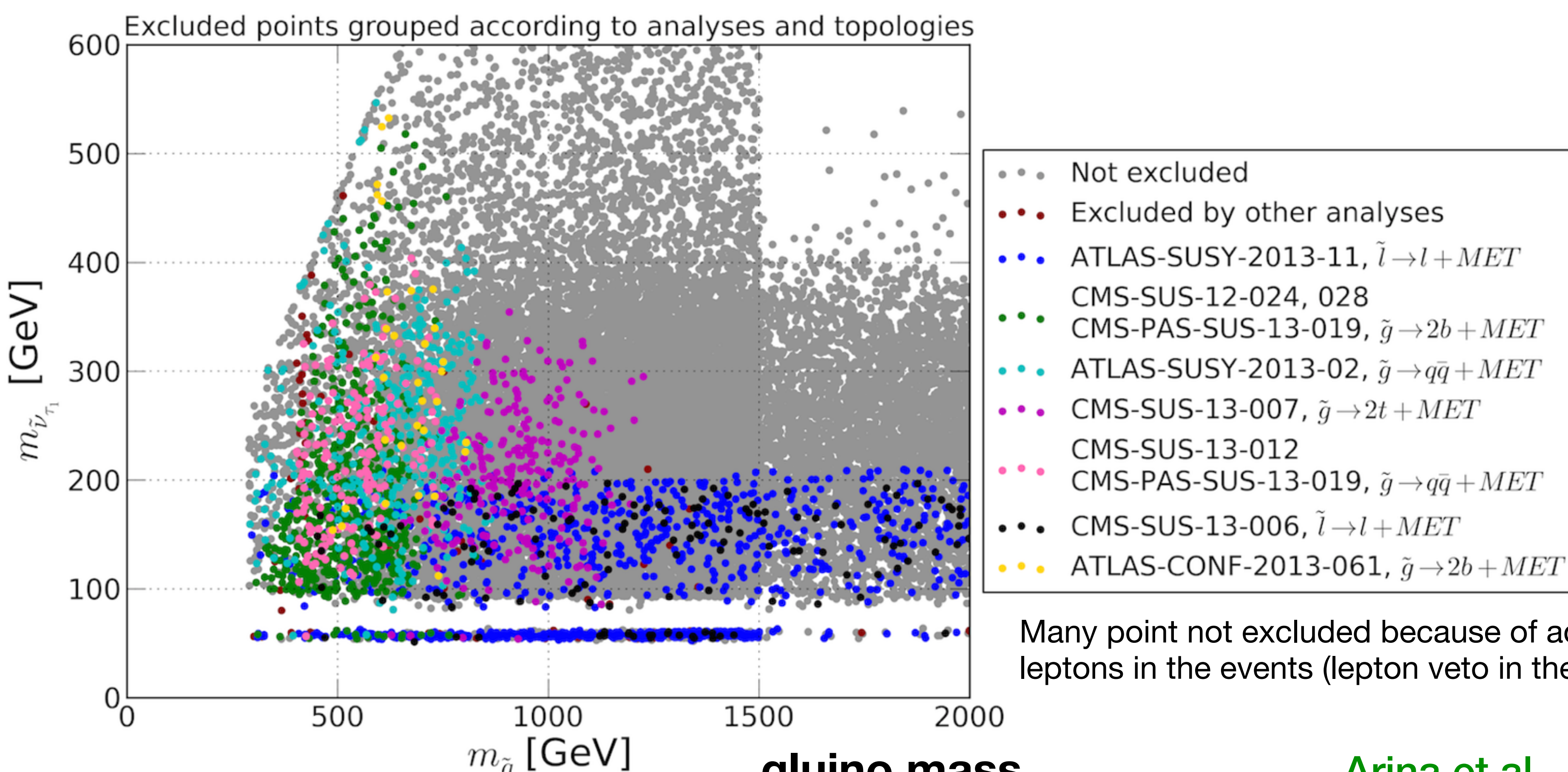
Example 1: MSSM + RH sneutrino dark matter

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



- Can have several invisible sparticles in a decay chain!

sneutrino mass



Many point not excluded because of additional leptons in the events (lepton veto in the analysis)

gluino mass

Arina et al., arXiv:1503.02960

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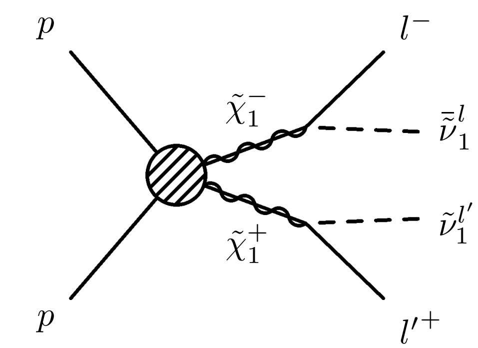

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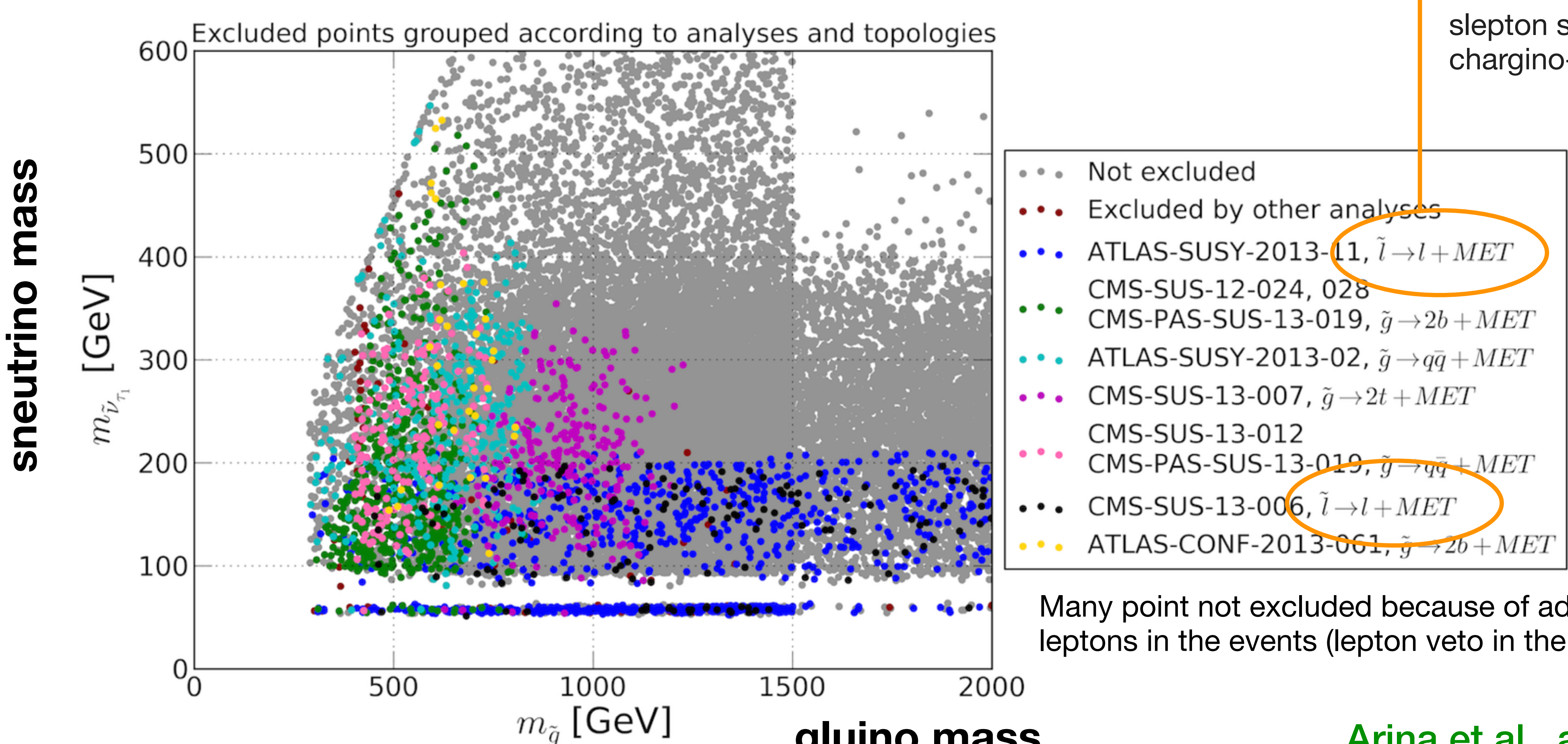

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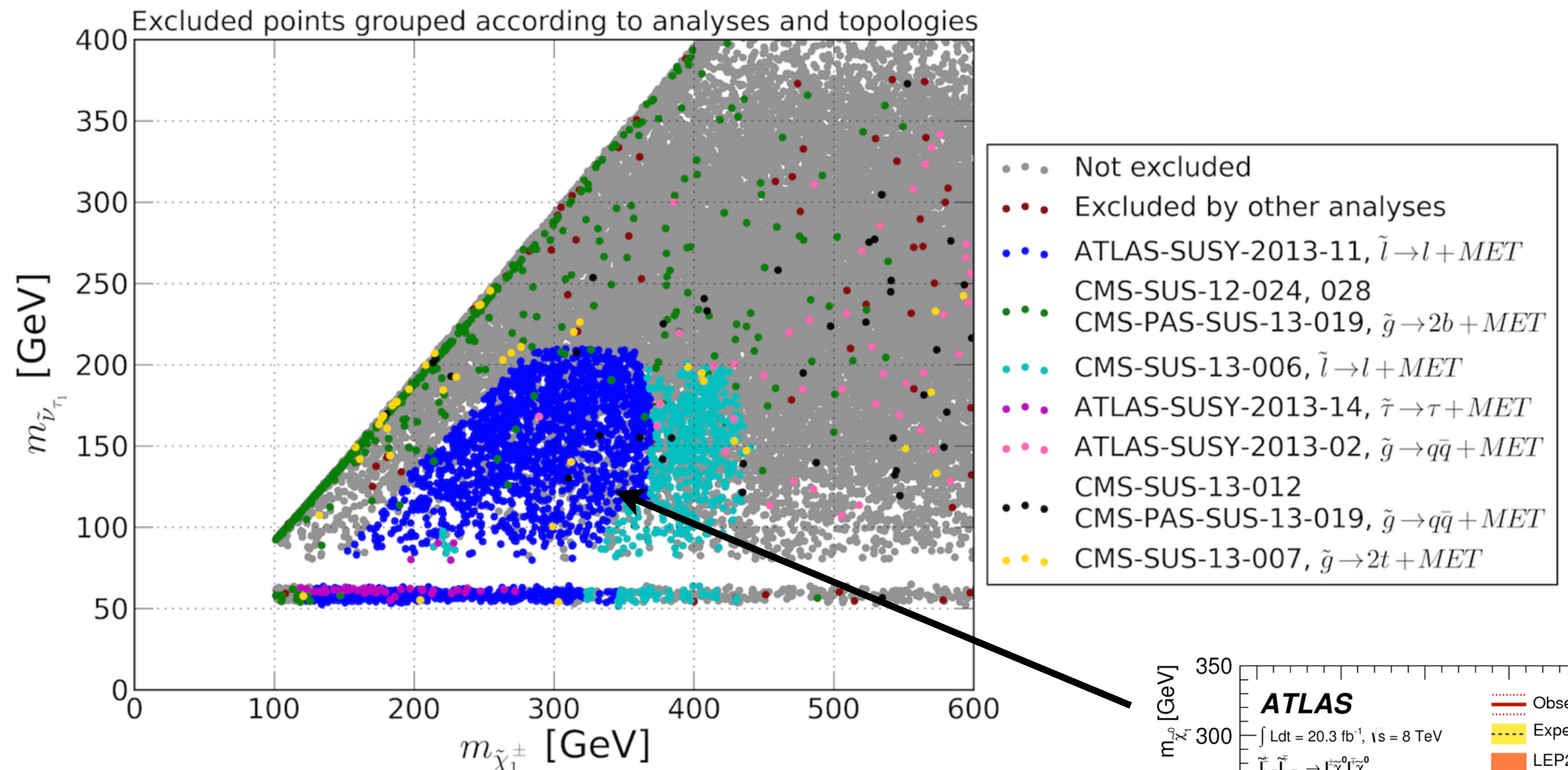
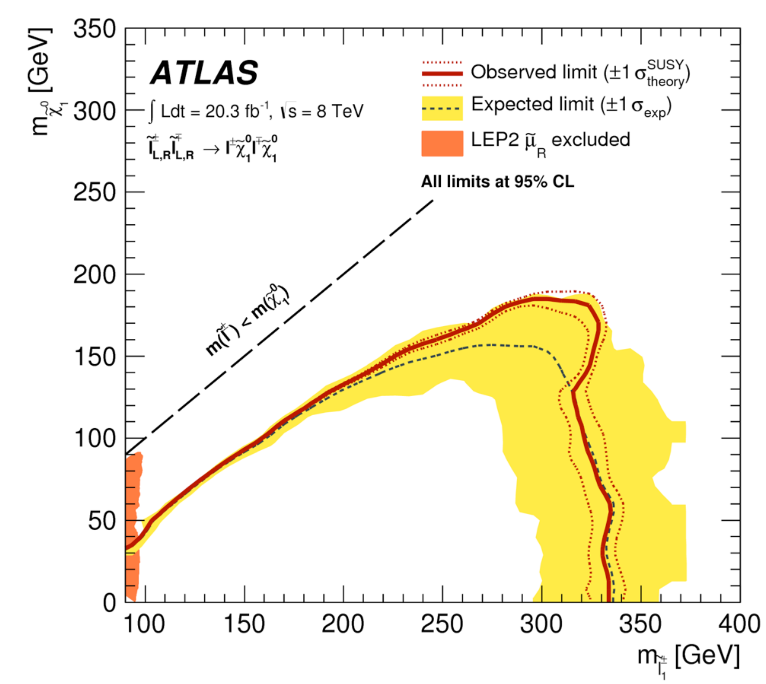
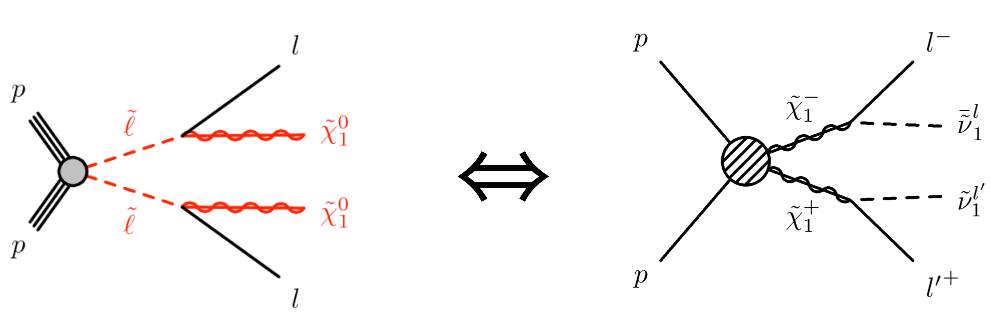
… in sneutrino vs. chargino mass plane:

Arina et al., arXiv:1503.02960



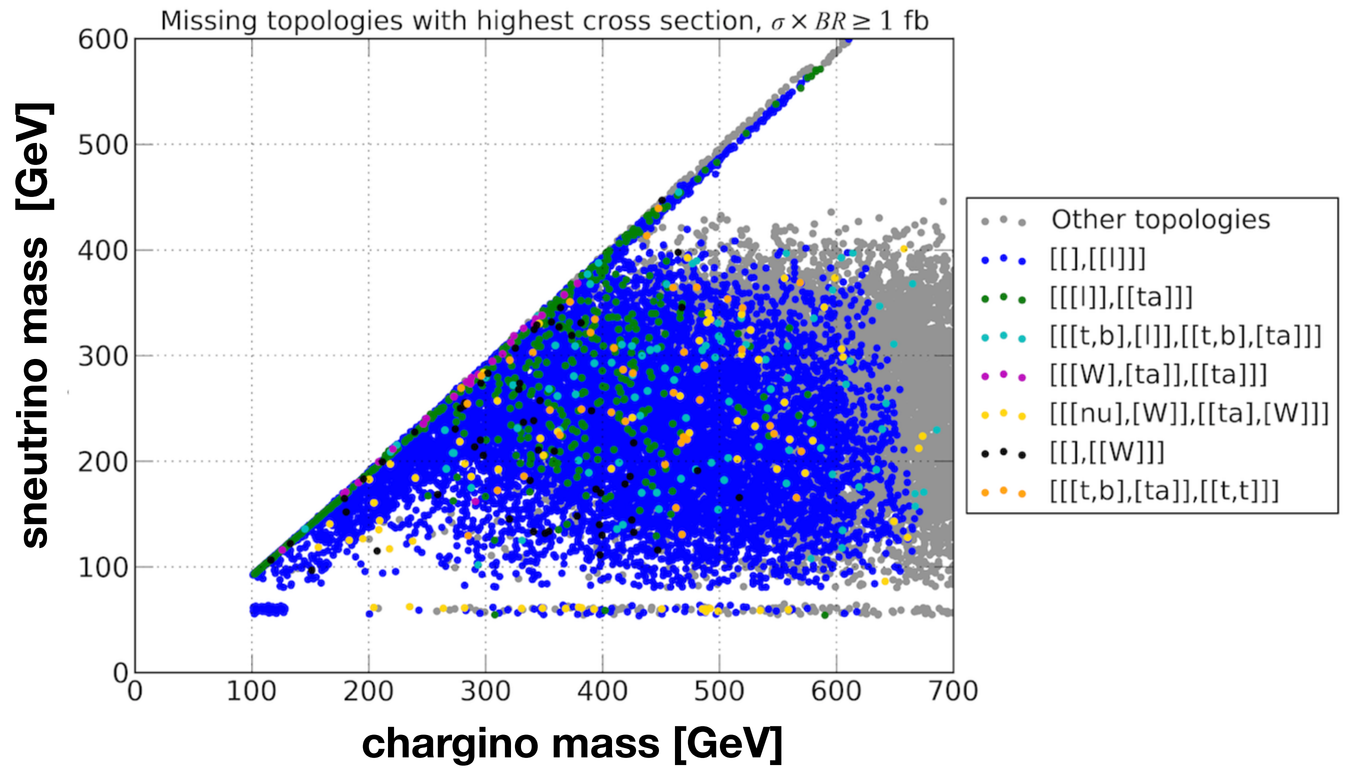




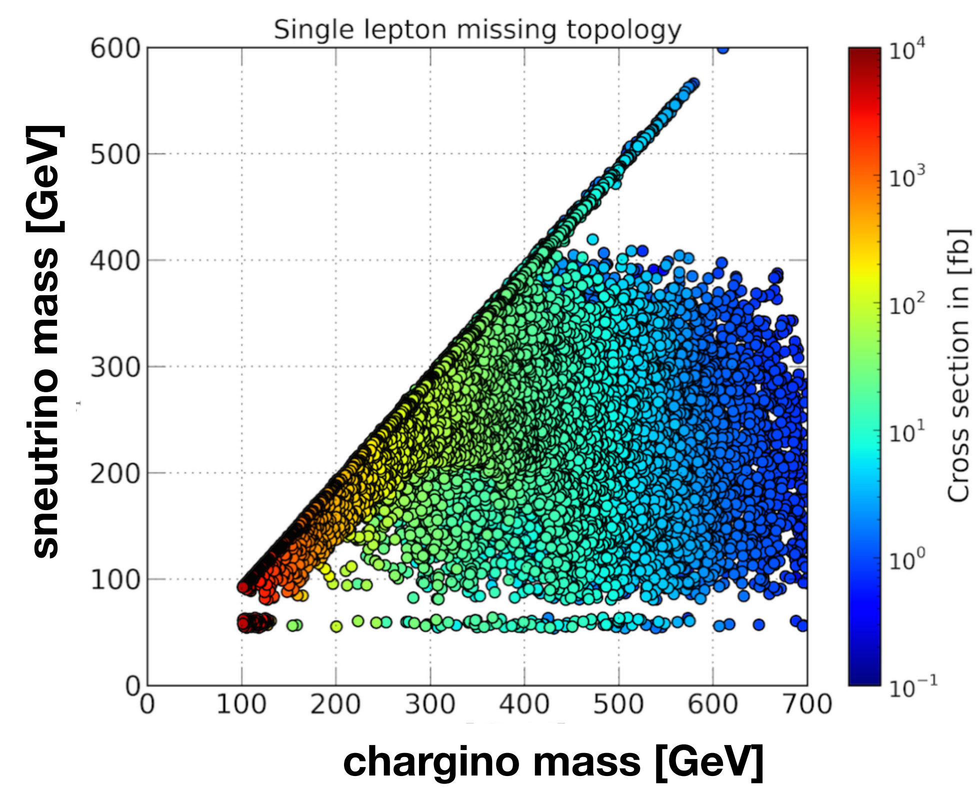
Example 1: MSSM + RH sneutrino dark matter

Missing topologies

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



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



Arina et al., arXiv:1503.02960

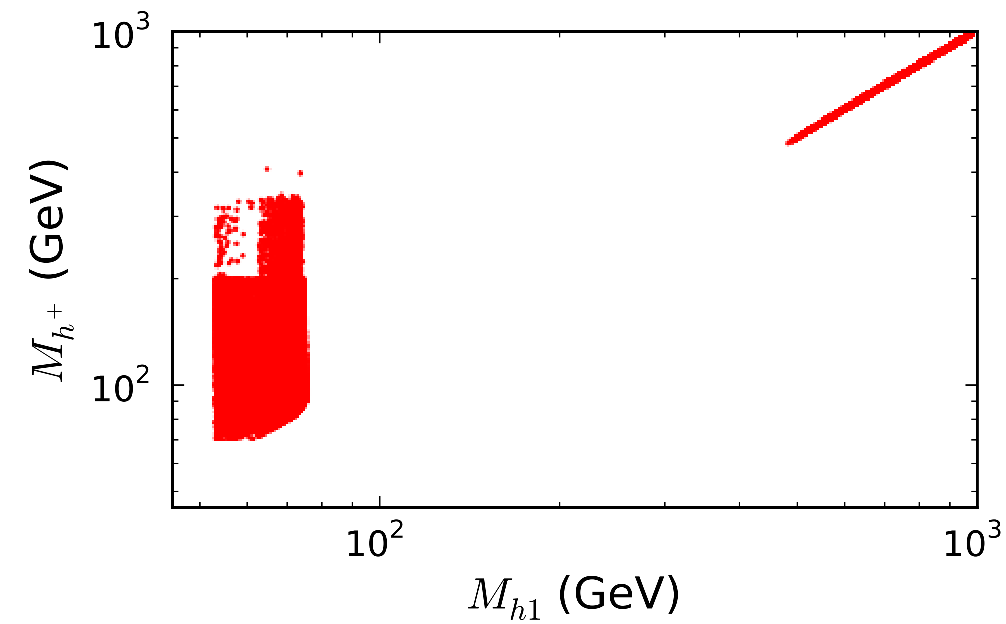
Example 2: Inert Doublet Model

High-mass region features a high degree of degeneracy of the three inert Higgs bosons.

For DM masses **around 500 GeV**, the necessary mass splitting for $\Omega h^2 \sim 0.1$ is O(0.2–0.25) GeV.

- **Long-lived H±**, decay length of 10 cm or more
- testable with disappearing-track but also HSCP searches

Belyaev, Cacciapaglia, Ivanov, Rojas-Abatte, Thomas, 1612.00511



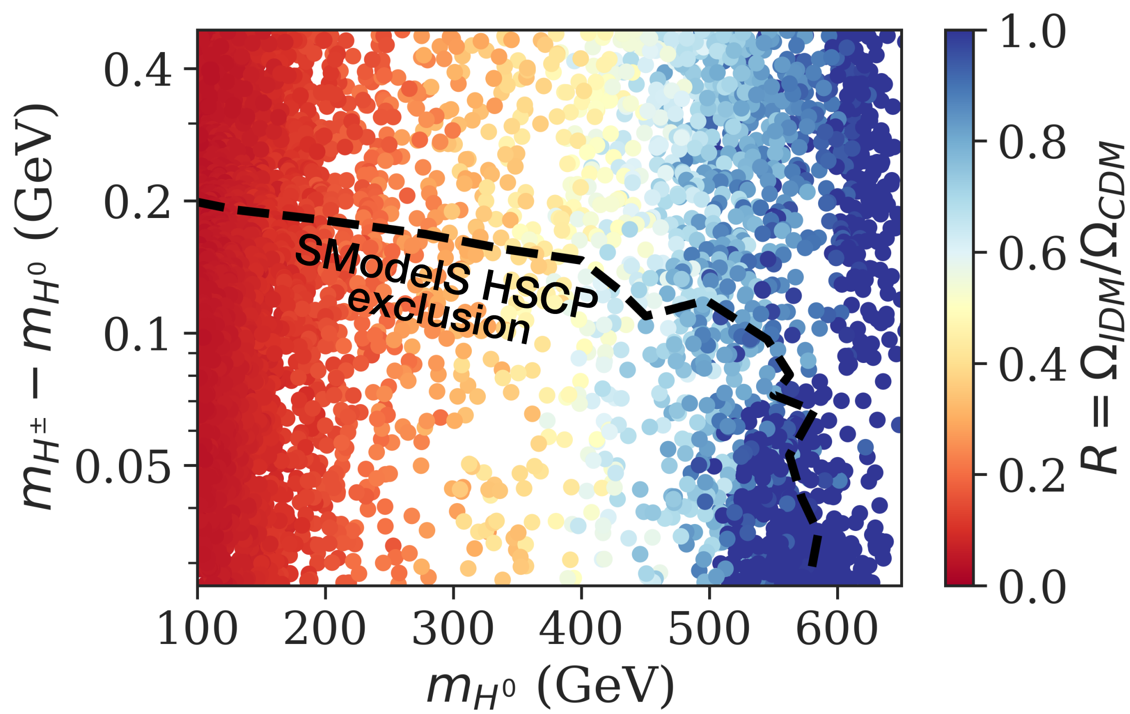
HSCP results in SModelS v1.2:

★ exclude H± masses up to 580 GeV in the quasi-stable limit

★ start to constrain interesting Δm region where the IDM can account for all the DM

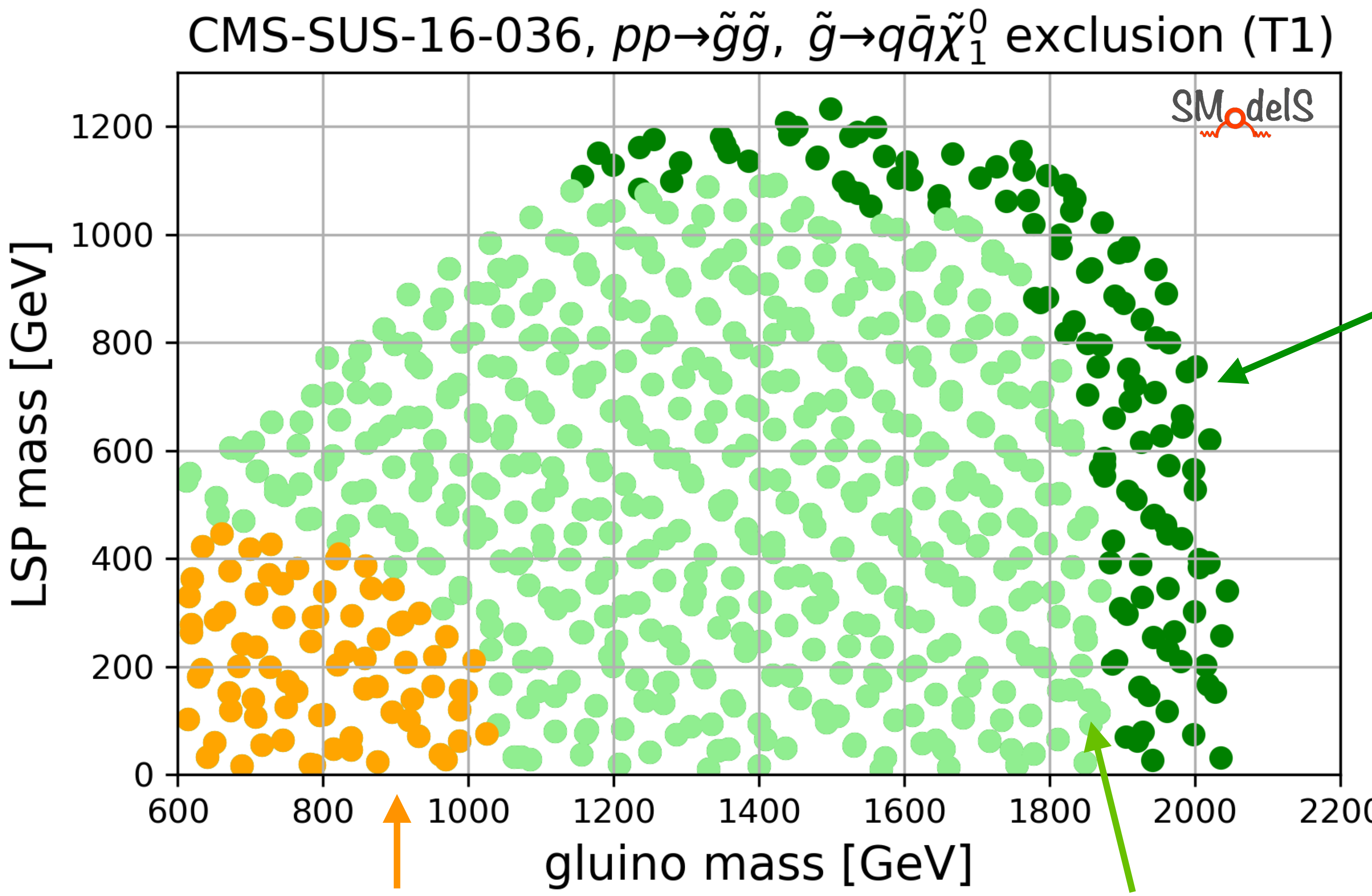
will be very relevant to include also disappearing track results (next SModelS release?)

J. Heisig, SK, A. Lessa, 1808.05229



Caveat

Coverage of total BSM cross section limited by the facts that most simplified model results are 1. for symmetric topologies and 2. only available as UL maps



Dirac gluino:
Xsection x2

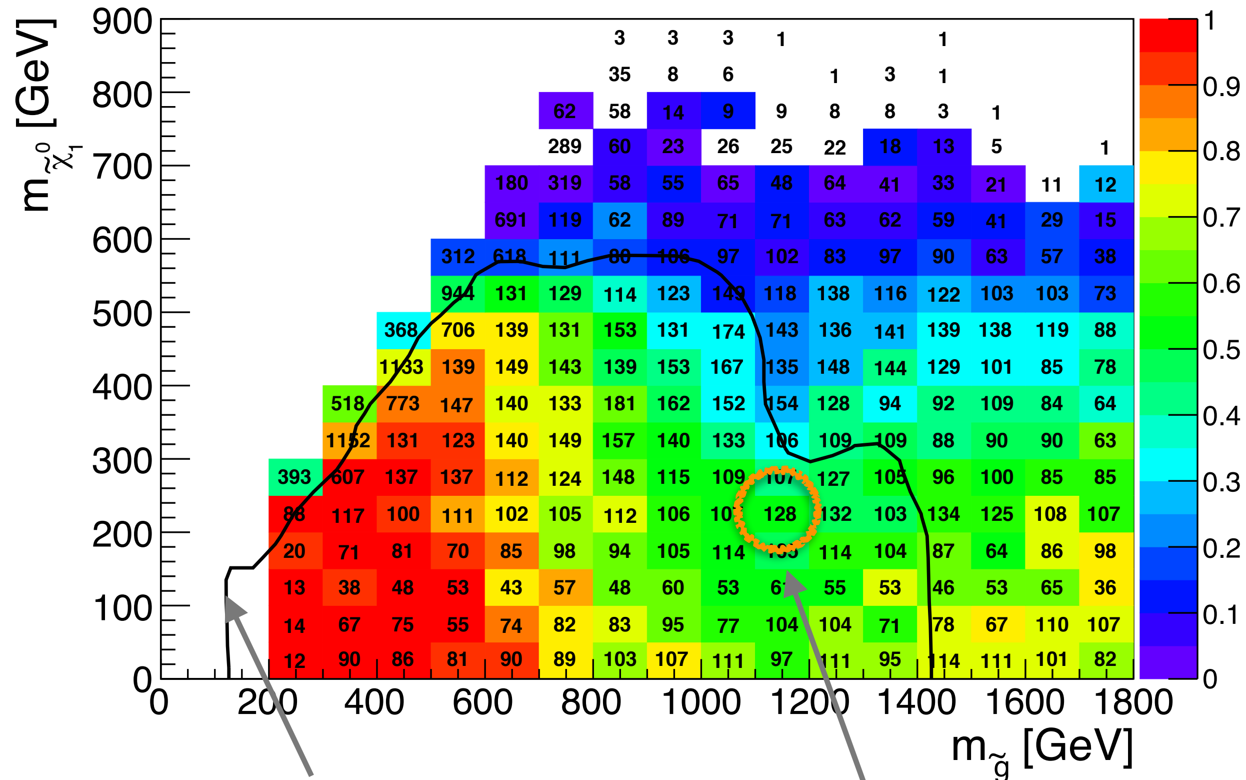
If only 10% $\tilde{g}$ decay
directly to qq+LSP

Majorana gluino
decoupled squarks

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

Fraction of ATLAS-excluded points also excluded by SModelS (bino-like LSP)



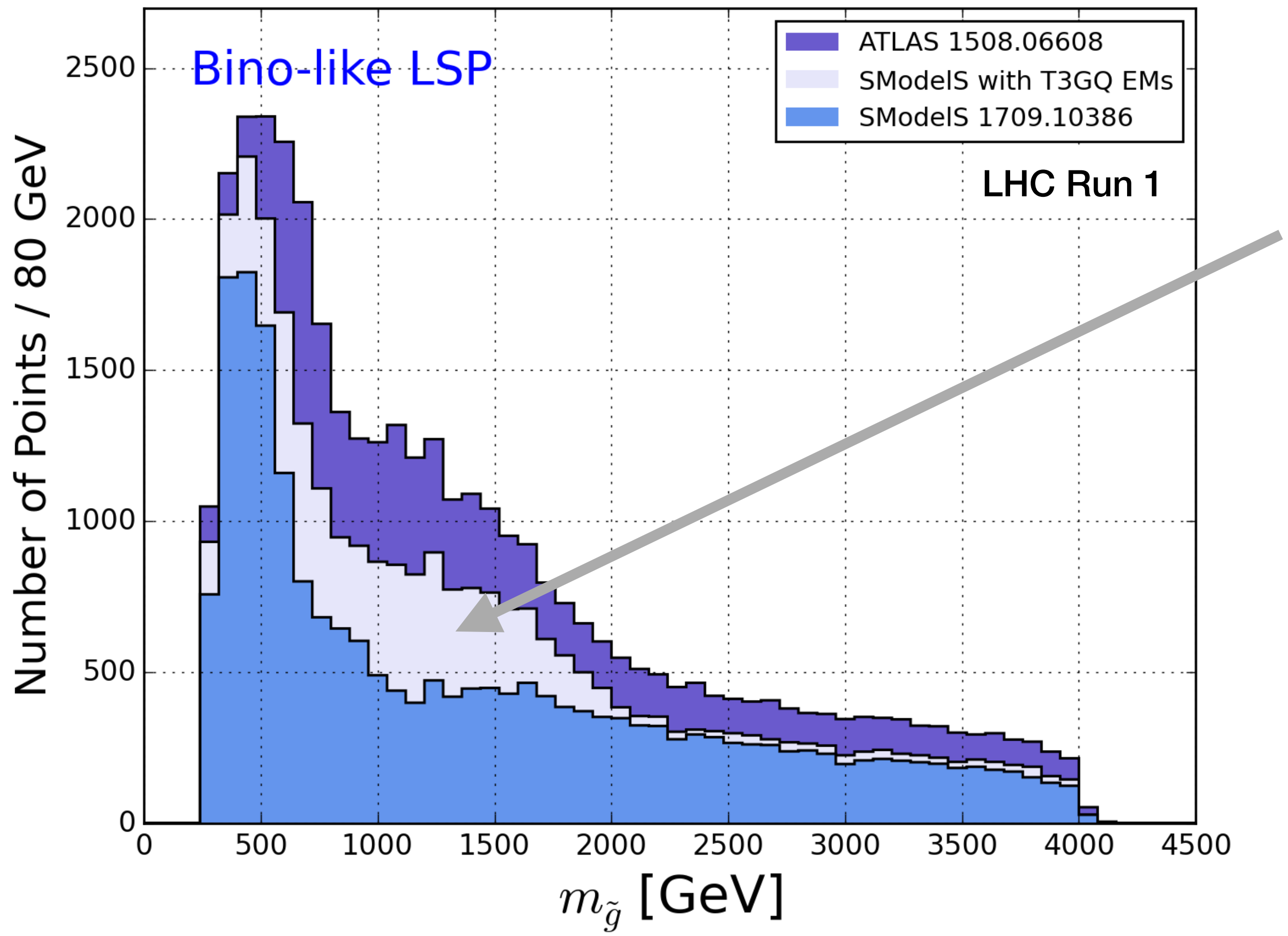
$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ exclusion line from ATLAS 1405.7875

number of points in each bin (excluded by ATLAS)

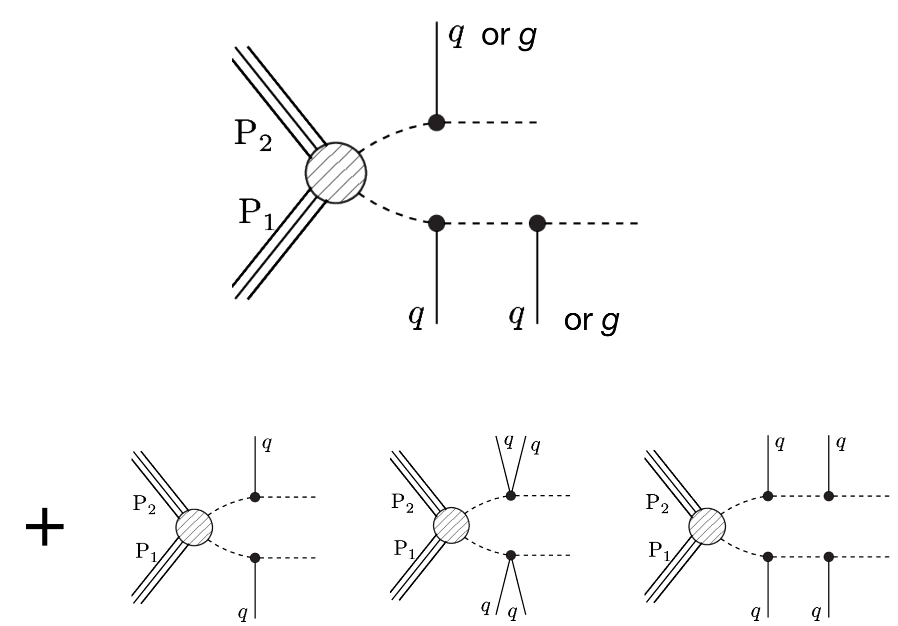
- Only the part of the cross section that goes into simplified model topologies, for which results (UL or EM maps) are available, can be constrained by SModelS.
- **Coverage drops** for intermediate gluino masses, where a **larger variety of decay channels** becomes available; more pronounced for bino 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 (@8TeV)



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.

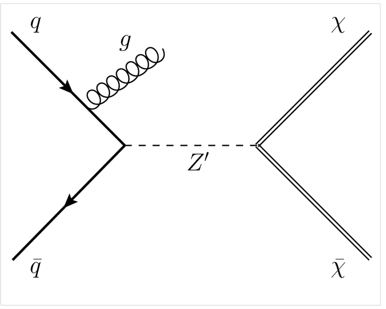
- Interpreted in terms of EFT or simplified model with a **DM particle plus a mediator**.

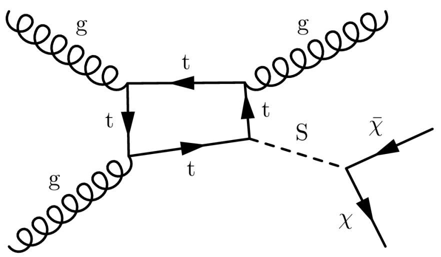
- *Primary presentation recommended […] are plots of the experimental confidence level (CL) limits on the signal cross sections as a function of the two mass parameters m_{DM} and M_{med} .*

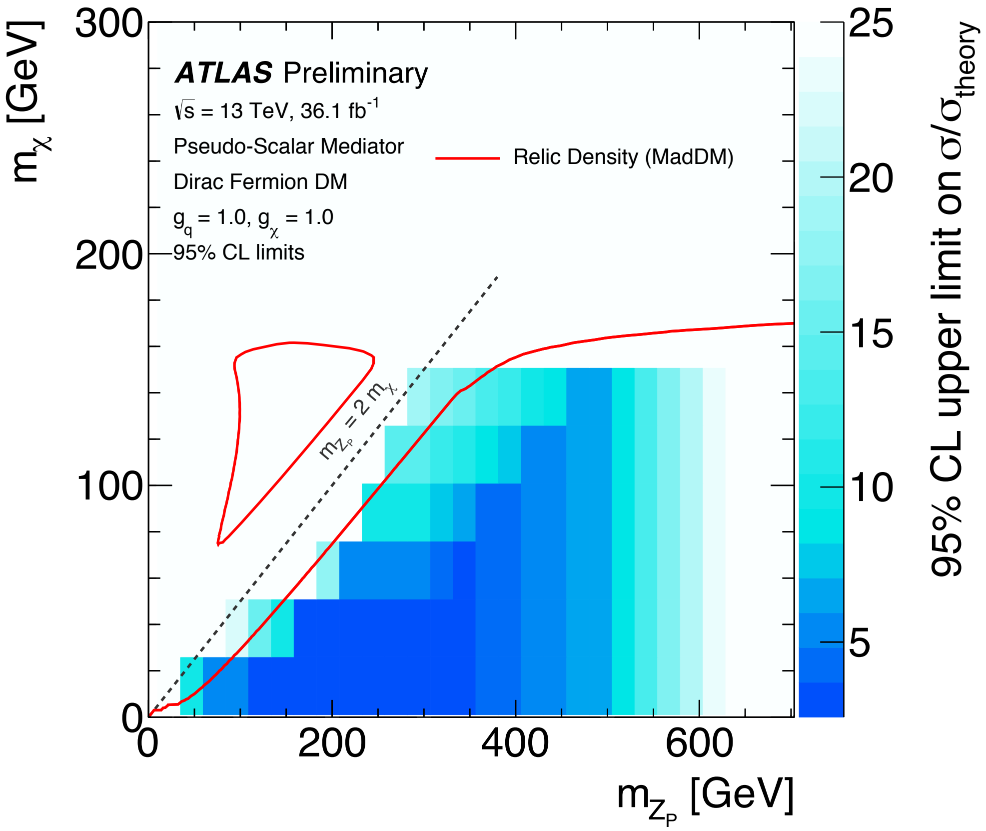
LHC DM WG,1603.04156

- 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.

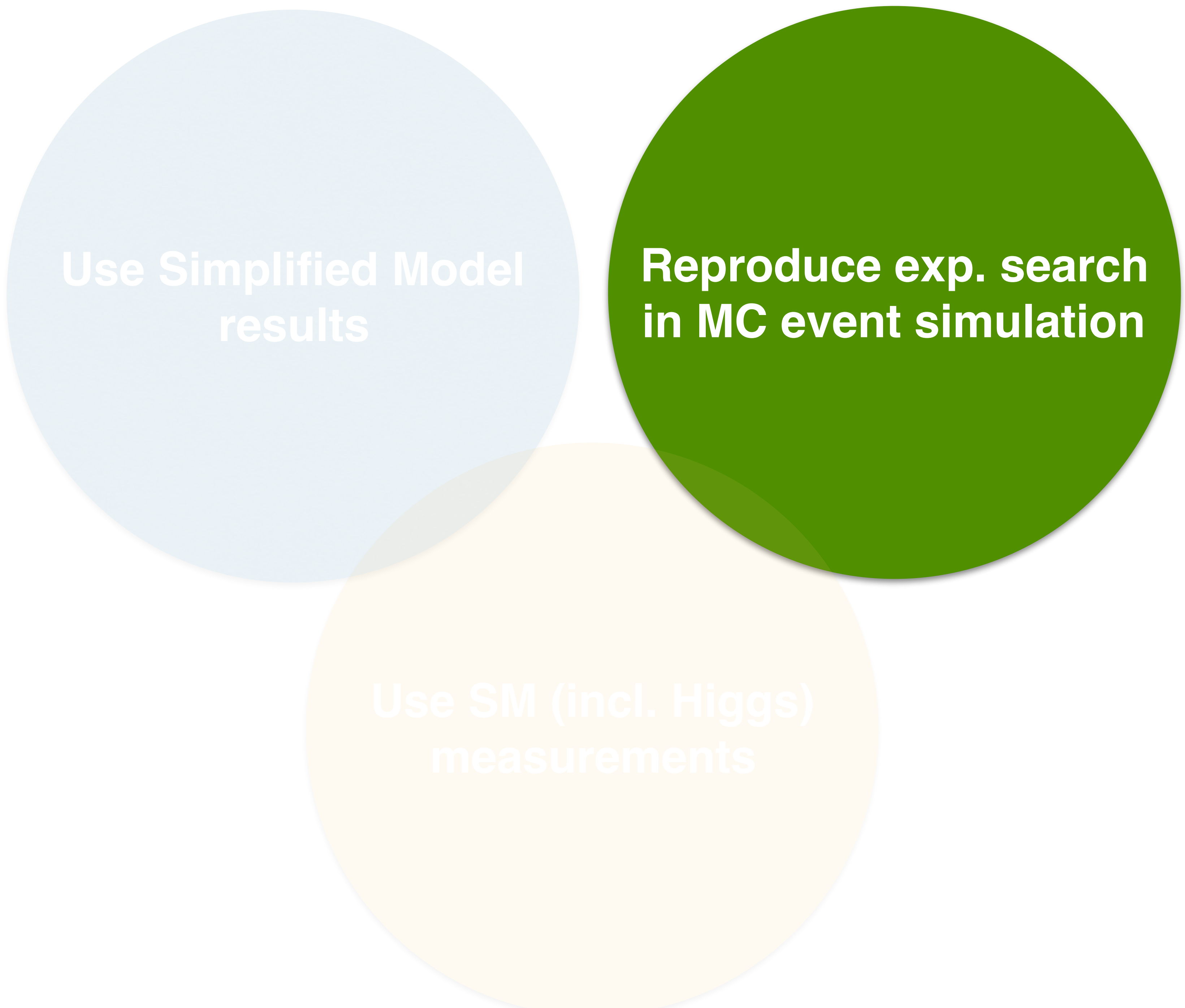






- When variety of signal topologies exists, efficiency maps would be useful.

Ways of (re)interpretation: “recasting”



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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.)

Reproduce exp. search in MC event simulation

Use SM (incl. Higgs) measurements

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- **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

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Libraries of public, validated implementations are being built in different frameworks: CheckMATE, MadAnalysis5 and Gambit

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

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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

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> “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%
$\Delta\phi(\mathrm{jet}_{1,2,(3)}, E_T^{\mathrm{miss}})_{\mathrm{min}} > 0.4$	25.0	−19.4%	24.1	−19.1%
$\Delta\phi(\mathrm{jet}_{i>3})_{\mathrm{min}} > 0.4$	18.8	−24.8%	18.2	−24.5%
$p_T(j_4) > 150$ GeV	14.1	−25.0%	13.9	−23.6%
$\lvert\eta(\mathrm{jets})\rvert < 2.0$	13.0	−7.8%	13.1	−5.8%
Aplanarity > 0.04	9.2	−29.2%	9.21	−29.7%
$E_T^{\mathrm{miss}}/m_{\mathrm{eff}}(4j) > 0.20$	6.6	−28.3%	6.64	−27.9%
$m_{\mathrm{eff}}(\mathrm{incl.}) > 2600$ 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: MadAnalysis 5

showing only Run2 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:

CHECKMATE

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

showing only Run2 analyses

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

Available analyses: Gambit’s ColliderBit

showing only Run2 analyses with ≥36/fb

```
ATLAS_13TeV_0LEP_36invfb
ATLAS_13TeV_0LEPStop_36invfb
ATLAS_13TeV_1LEPStop_36invfb
ATLAS_13TeV_2LEPStop_36invfb
ATLAS_13TeV_2bMET_36invfb
ATLAS_13TeV_3b_36invfb
```

```
ATLAS_13TeV_4LEP_36invfb
ATLAS_13TeV_MultiLEP_36invfb
ATLAS_13TeV_PhotonGGM_36invfb
ATLAS_13TeV_RJ3L_lowmass_36invfb
ATLAS_13TeV_ZGammaGrav_CONFNOTE_80invfb
```

```
CMS_13TeV_0LEP_36invfb
CMS_13TeV_1LEPStop_36invfb
CMS_13TeV_1LEPbb_36invfb
CMS_13TeV_2LEPStop_36invfb
CMS_13TeV_2LEPsoft_36invfb
CMS_13TeV_2OSLEP_36invfb
CMS_13TeV_MONOJET_36invfb
CMS_13TeV_MultiLEP_36invfb
```

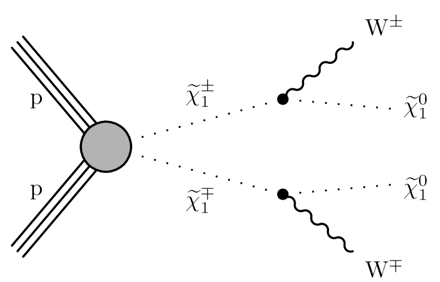
relies on BuckFast for detector simulation (smearing+ obj.efficiencies); probably less precise than DELPHES but much faster

user-friendly backend for running ColliderBit standalone would be very interesting

Example: Dilepton constraints on IDM

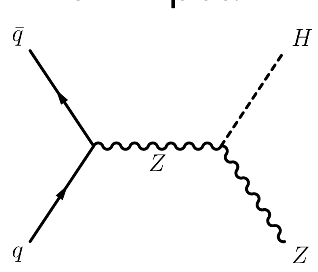
- Most important channel: **pp → AH, A→Z(*)H**
- recasted 2 ATLAS analyses from Run1: dilepton SUSY and ZH, H→inv. searches

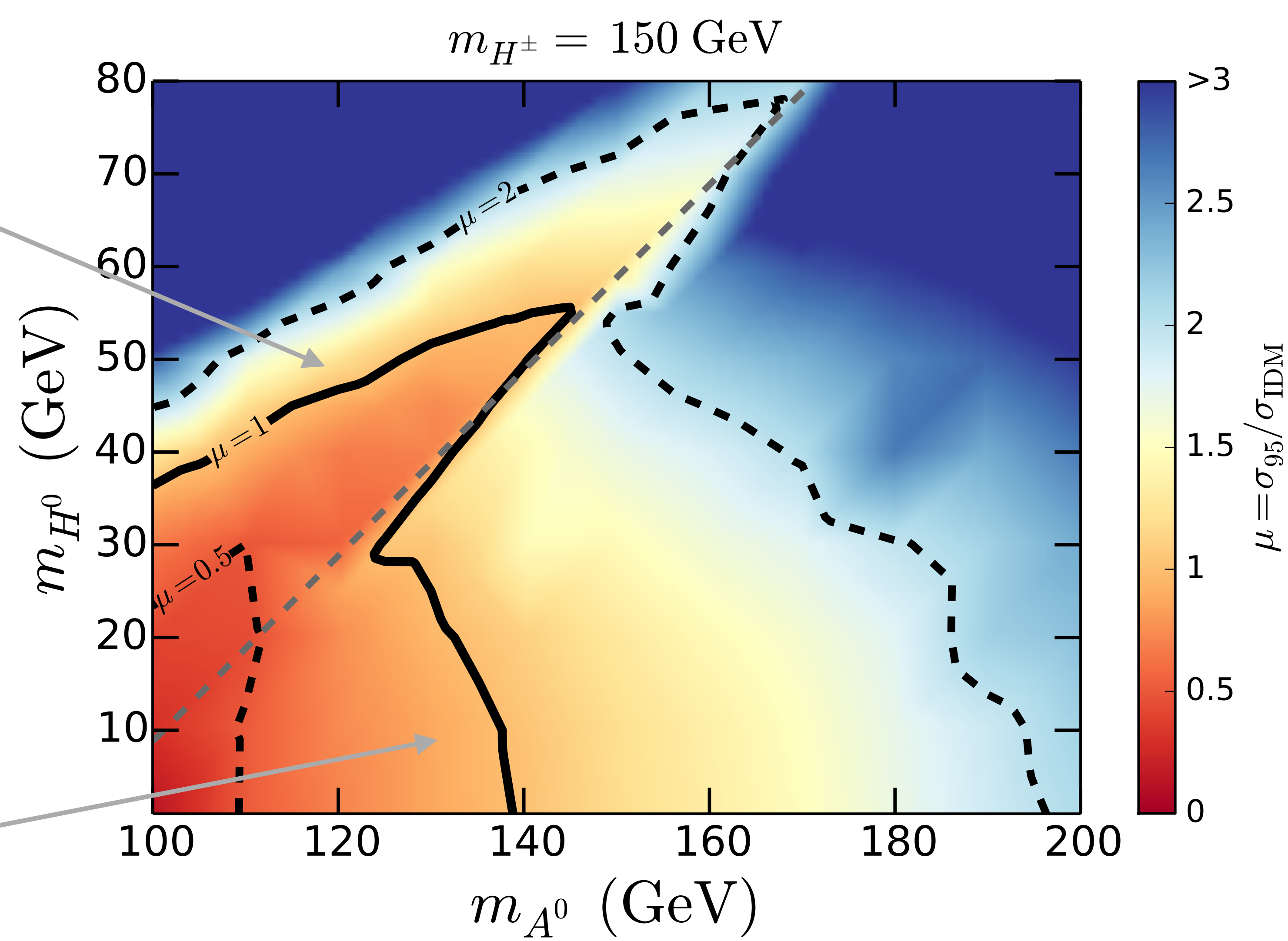
assuming H as the inert scalar DM candidate, but results don't change when H↔A.



off-Z peak

on-Z peak





to be compared to / combined with mono-jet constraints from pp→HH (+jet), see Belyaev et al. 2016

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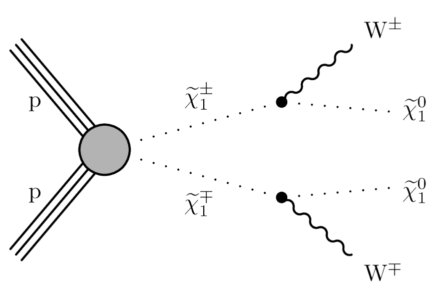
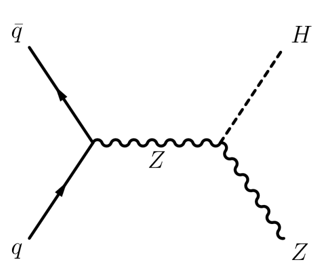
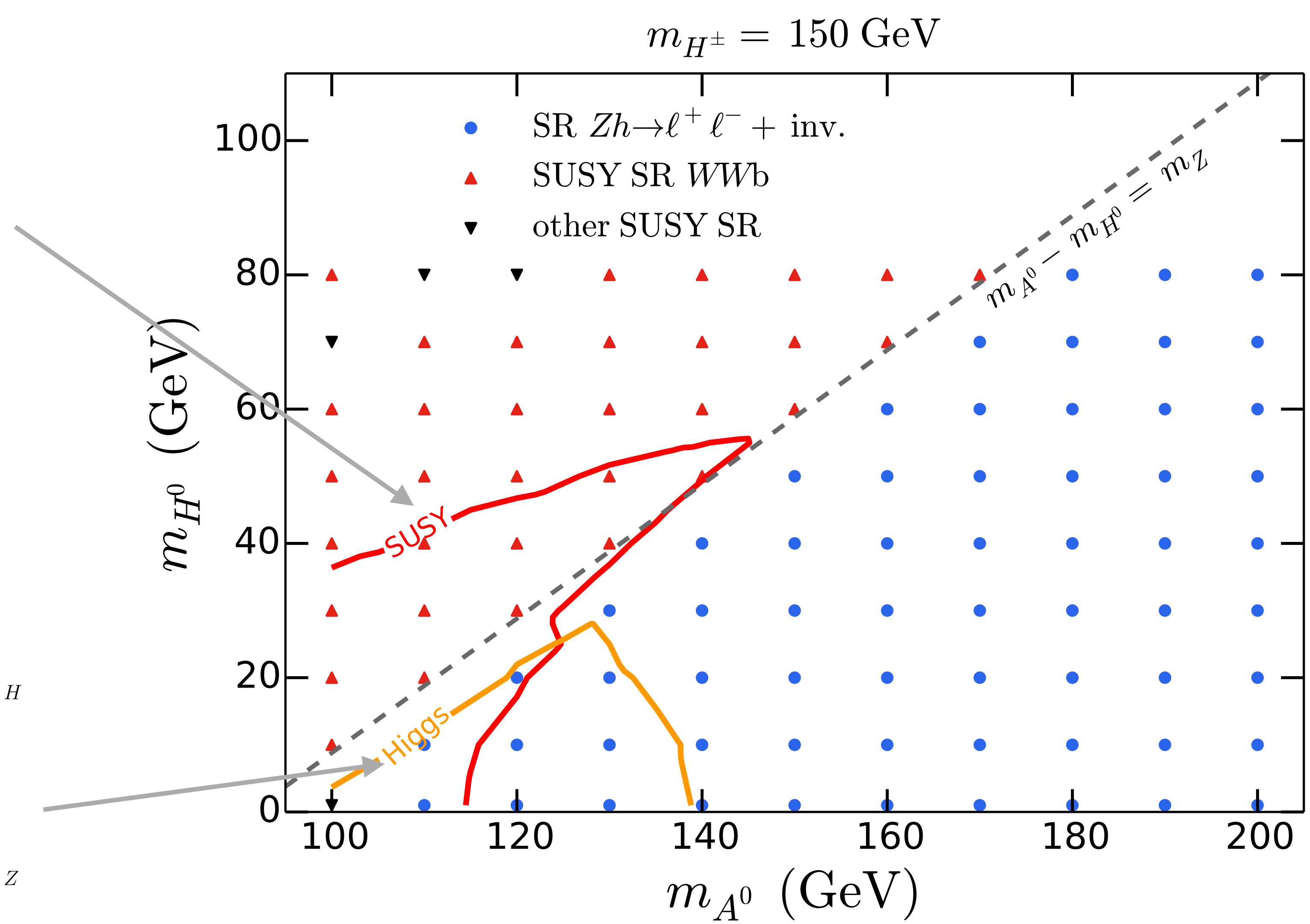


off-Z peak

on-Z peak





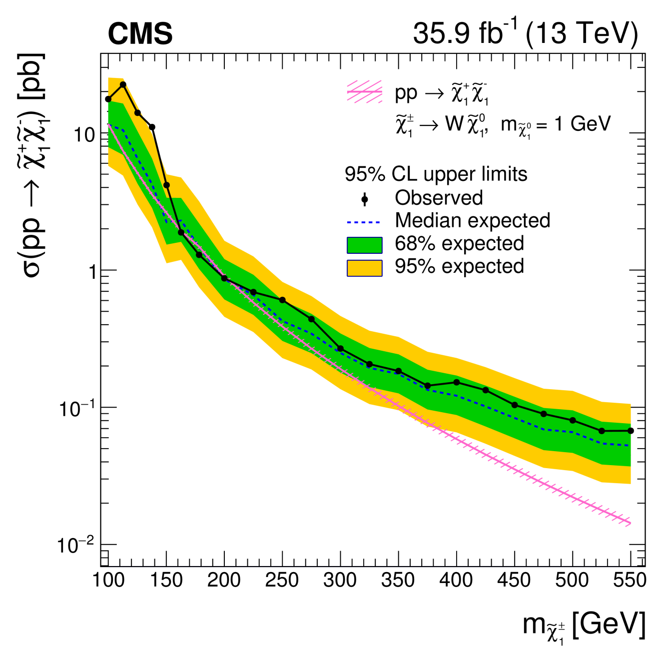
to be compared to / combined with mono-jet constraints from pp→HH (+jet), see Belyaev et al. 2016

Run 2 SUSY searches in dilepton + MET final state

CMS-SUS-17-010

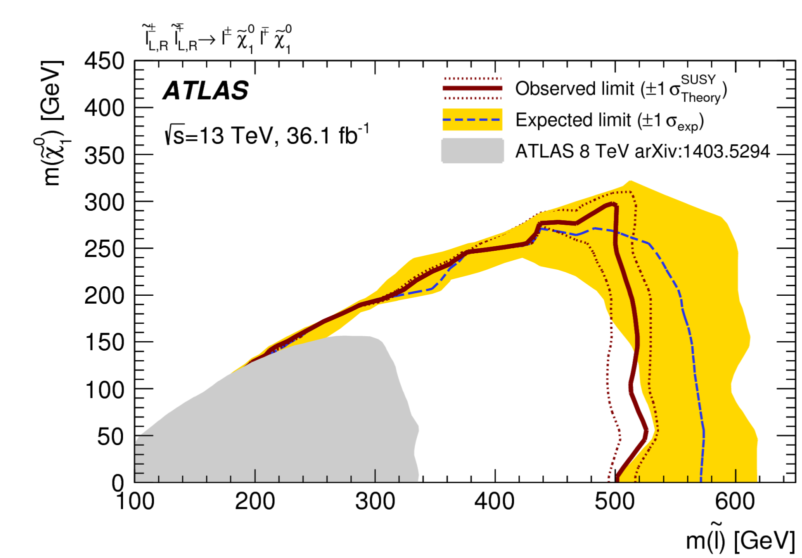
Variable	Selection
Lepton flavor	e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$
Leading lepton	$p_T \geq 25\,\text{GeV}$, $\lvert\eta\rvert < 2.4$
Trailing lepton	$p_T \geq 20\,\text{GeV}$, $\lvert\eta\rvert < 2.4$
Third lepton veto	$p_T \geq 15\,\text{GeV}$, $\lvert\eta\rvert < 2.4$
$m_{\ell\ell}$	$\geq 20\,\text{GeV}$
$\lvert m_{\ell\ell} - m_Z\rvert$	$>15\,\text{GeV}$ only for ee and $\mu\mu$ events
p_T^{miss}	$\geq 140\,\text{GeV}$

	$SR1^{0jet}_{0tag}$	$SR1^{jets}_{0tag}$	$CR1_{tags}$	$SR2^{0jet}_{0tag}$	$SR2^{jets}_{0tag}$	$CR2_{tags}$	$SR3_{0tag}$	$CR3_{tags}$
p_T^{miss} [GeV]	140–200	140–200	140–200	200–300	200–300	200–300	$\geq$300	$\geq$300
$N_{b\ jets}$	0	0	$\geq$1	0	0	$\geq$1	0	$\geq$1
N_{jets}	0	$\geq$1	$\geq$1	0	$\geq$1	$\geq$1	$\geq$0	$\geq$1
Channels	SF, DF	SF, DF	SF, DF	SF, DF	SF, DF	SF, DF	SF, DF	SF, DF
$m_{T2}(\ell\ell)$	0–20, 20–40, 40–60, 60–80, 80–100, 100–120, $\geq$120 GeV							



ATLAS-SUSY-2016-24

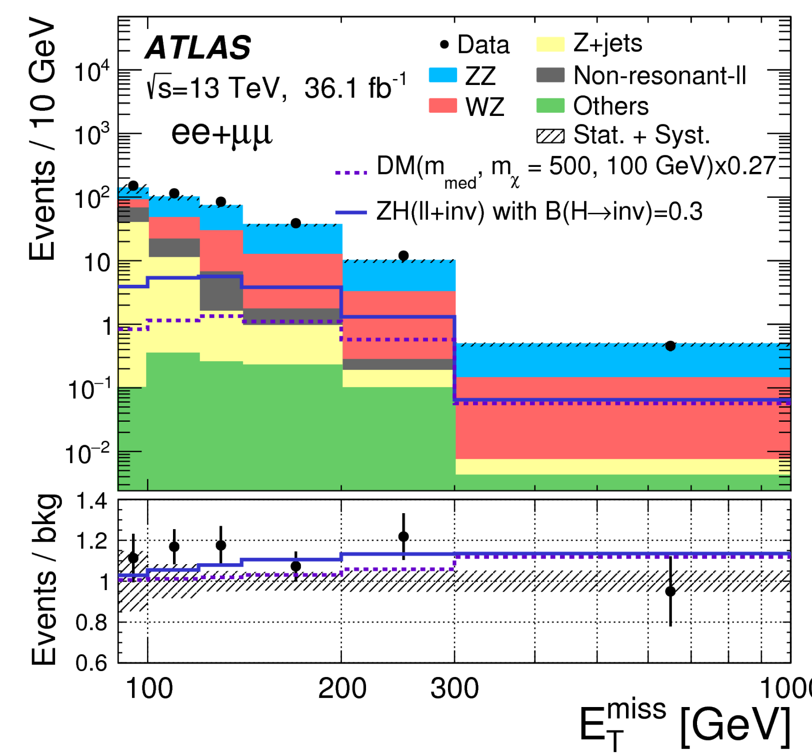
2ℓ+0jets exclusive signal region definitions			
m_{T2} [GeV]	$m_{\ell\ell}$ [GeV]	SF bin	DF bin
100–150	111–150	SR2-SF-a	SR2-DF-a
	150–200	SR2-SF-b	
	200–300	SR2-SF-c	
	> 300	SR2-SF-d	
150–200	111–150	SR2-SF-e	SR2-DF-b
	150–200	SR2-SF-f	
	200–300	SR2-SF-g	
	> 300	SR2-SF-h	
200–300	111–150	SR2-SF-i	SR2-DF-c
	150–200	SR2-SF-j	
	200–300	SR2-SF-k	
	> 300	SR2-SF-l	
> 300	> 111	SR2-SF-m	SR2-DF-d
2ℓ+0jets inclusive signal region definitions			
> 100	> 111	SR2-SF-loose	-
> 130	> 300	SR2-SF-tight	-
> 100	> 111	-	SR2-DF-100
> 150	> 111	-	SR2-DF-150
> 200	> 111	-	SR2-DF-200
> 300	> 111	-	SR2-DF-300

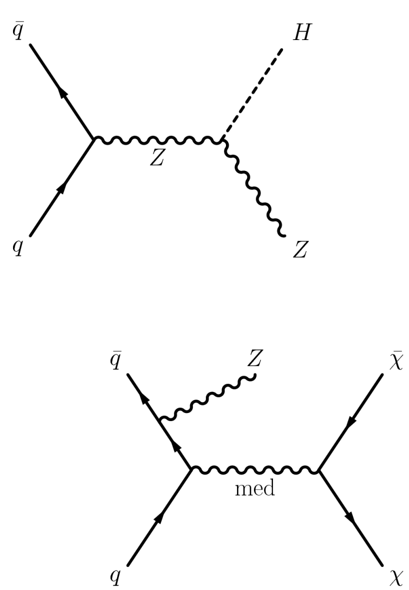


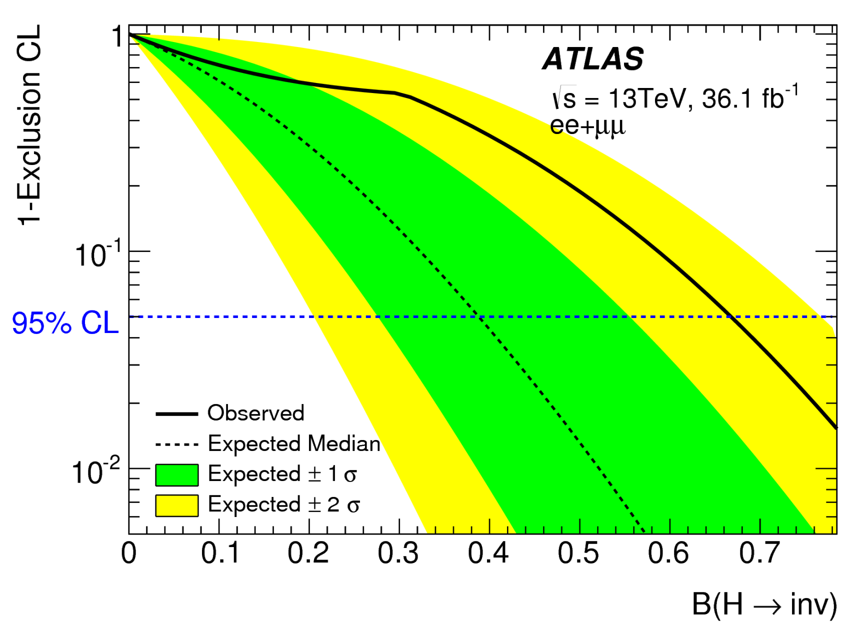
ATLAS ZH, H→inv. analysis

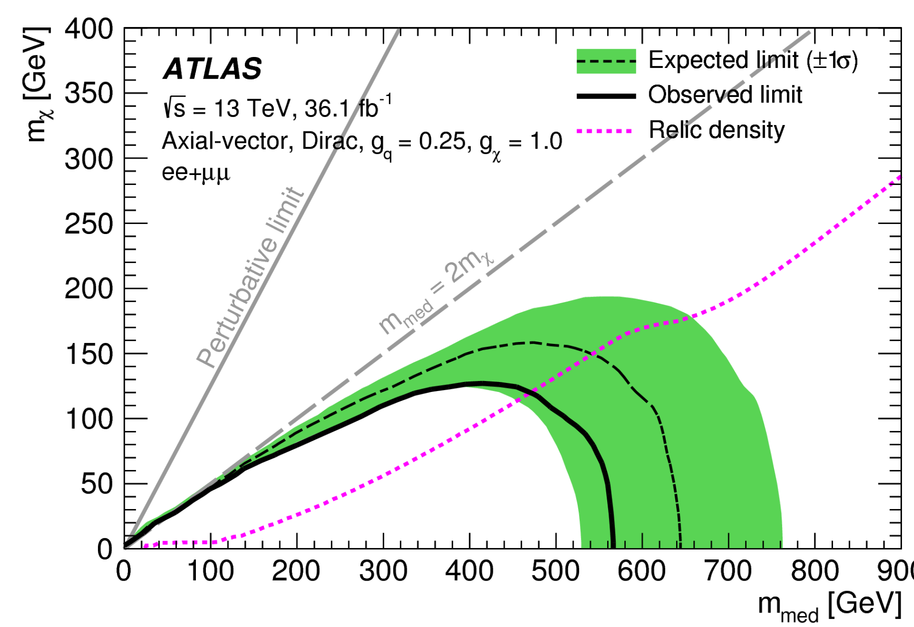
- Final state: di-leptons ($Z \to l^+l^-$) plus MET

	Selection criteria
Two leptons	Two opposite-sign leptons, leading (subleading) $p_T > 30$ (20) GeV
Third lepton veto	Veto events if any additional lepton with $p_T > 7$ GeV
$m_{\ell\ell}$	$76 < m_{\ell\ell} < 106$ GeV
E_T^{miss} and E_T^{miss}/H_T	$E_T^{miss} > 90$ GeV and $E_T^{miss}/H_T > 0.6$
$\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{miss})$	$\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{miss}) > 2.7$ radians
$\Delta R_{\ell\ell}$	$\Delta R_{\ell\ell} < 1.8$
Fractional p_T difference	$\left\| p_T^{\ell\ell} - p_T^{miss,jets} \right\| / p_T^{\ell\ell} < 0.2$
b-jets veto	$N(b\text{-jets}) = 0$ with b-jet $p_T > 20$ GeV and $\|\eta\| < 2.5$







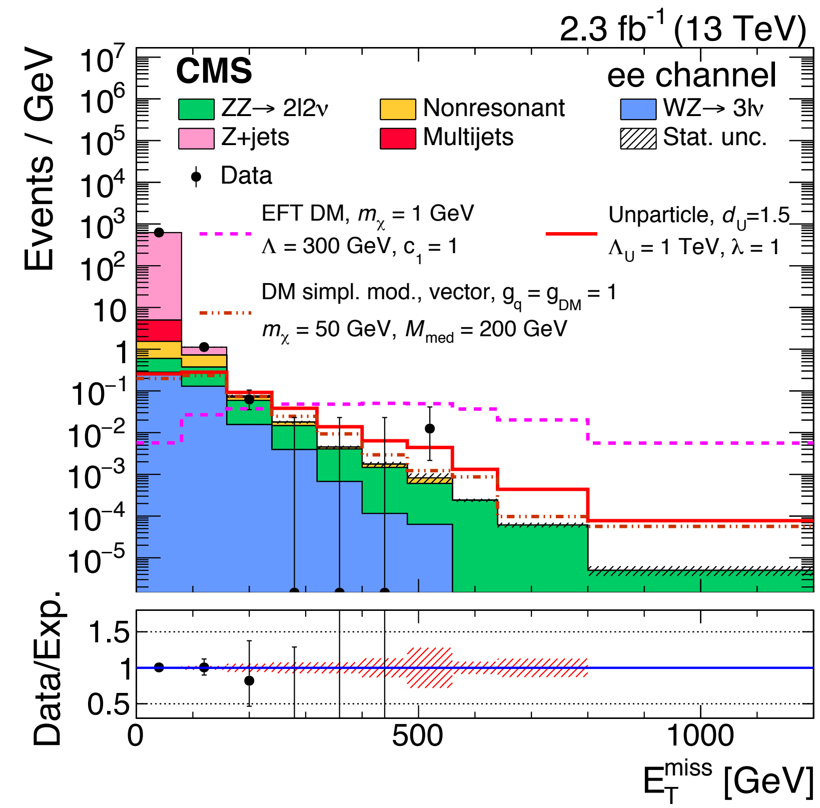


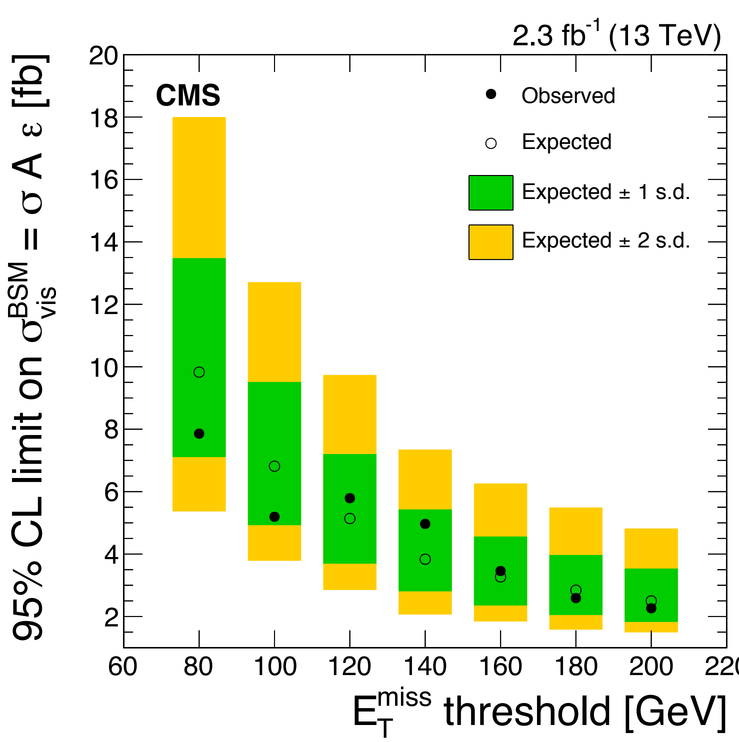
CMS mono-Z search (dark matter)

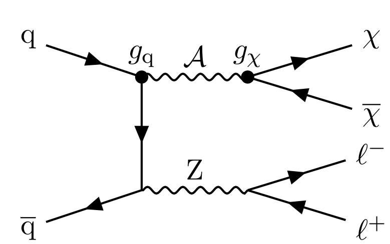
available in MadAnalysis PAD

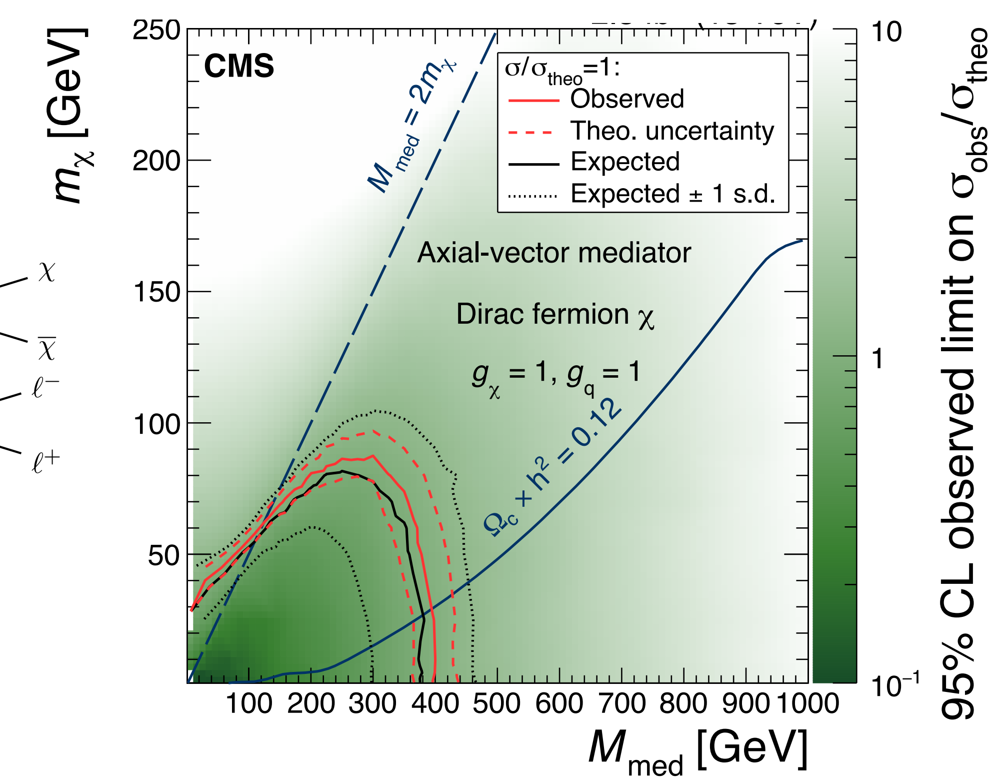
- Final state: di-leptons ($Z \to l^+l^-$) plus MET

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



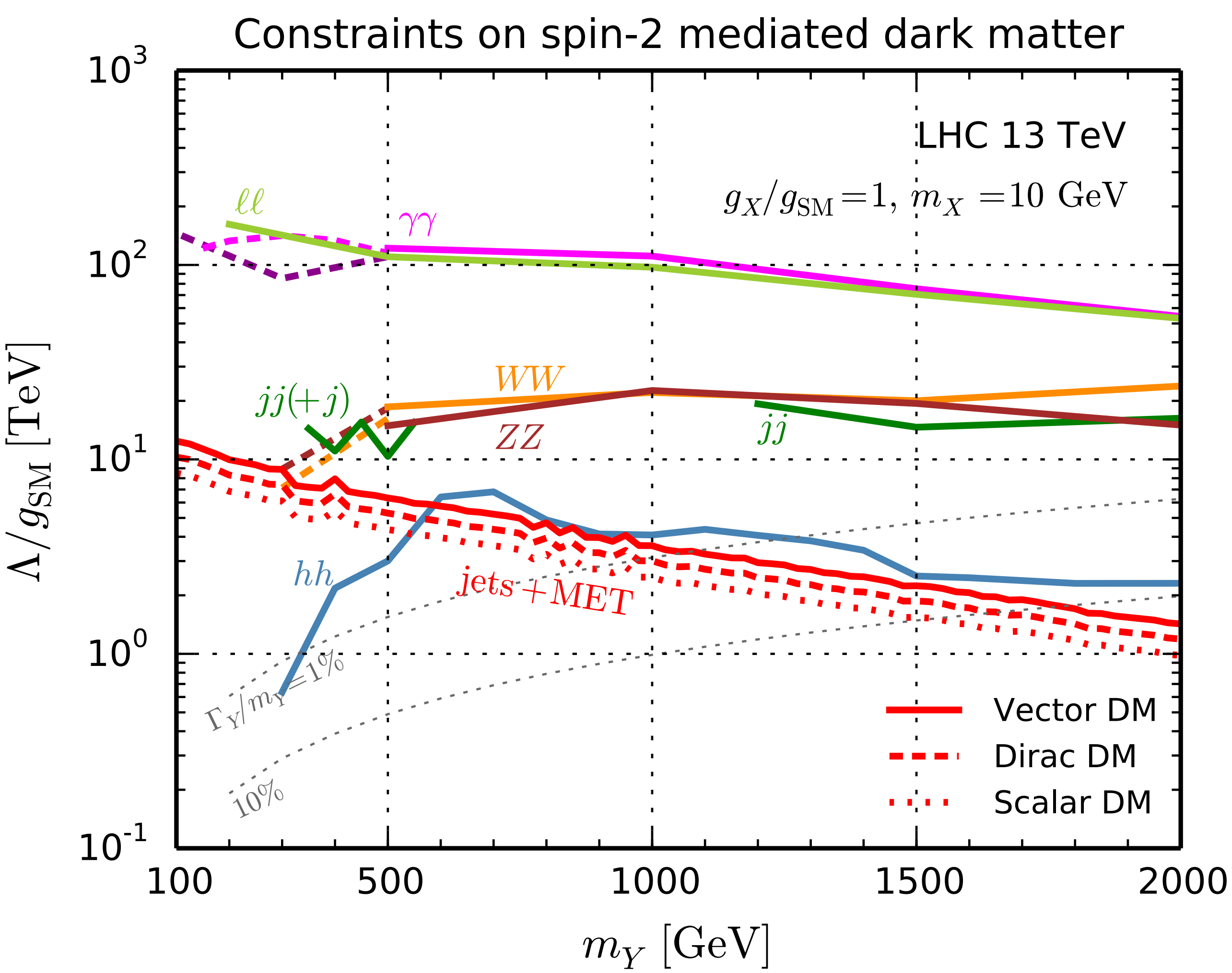






DM simplified model with spin-2 mediator

- Simplified dark matter model with spin-2 mediator (universal couplings)
- Study constraints from the current LHC data; complementarity among different searches, in particular jet(s)+MET and resonance searches.
- LHC DM WG focuses on mono-jet searches. Strongest constraints however come from di-photon and di-lepton resonance searches.
- Only if these modes are suppressed, missing-energy searches can be competitive in constraining dark matter models with a spin-2 mediator.



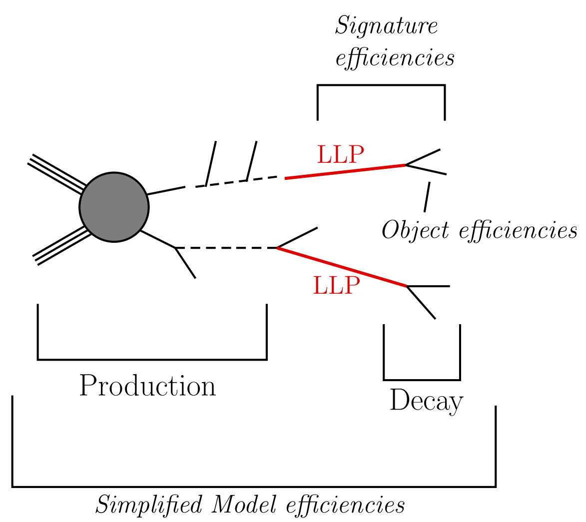
$$\mathcal{L}_{\rm SM}^{Y_2} = -\frac{1}{\Lambda}\sum_i g_i^T\, T^i_{\mu\nu} Y_2^{\mu\nu}\,,\quad \mathcal{L}_X^{Y_2} = -\frac{1}{\Lambda} g_X^T\, T^X_{\mu\nu} Y_2^{\mu\nu}\,,$$

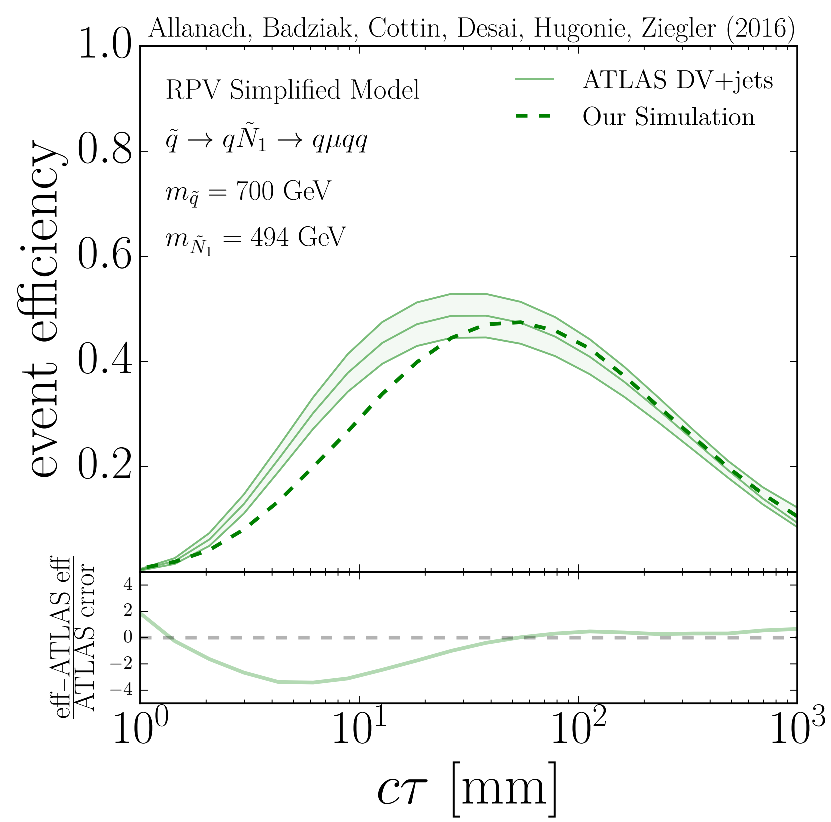
For spin-0 and spin-1, see LHC DM WG report:
A. Boveia et al., arXiv:1603.04156

Long-lived particles (LLPs)

LLP@LHC "white paper": 1903.04497

- 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)





setting up a GitHub repository to collect private codes

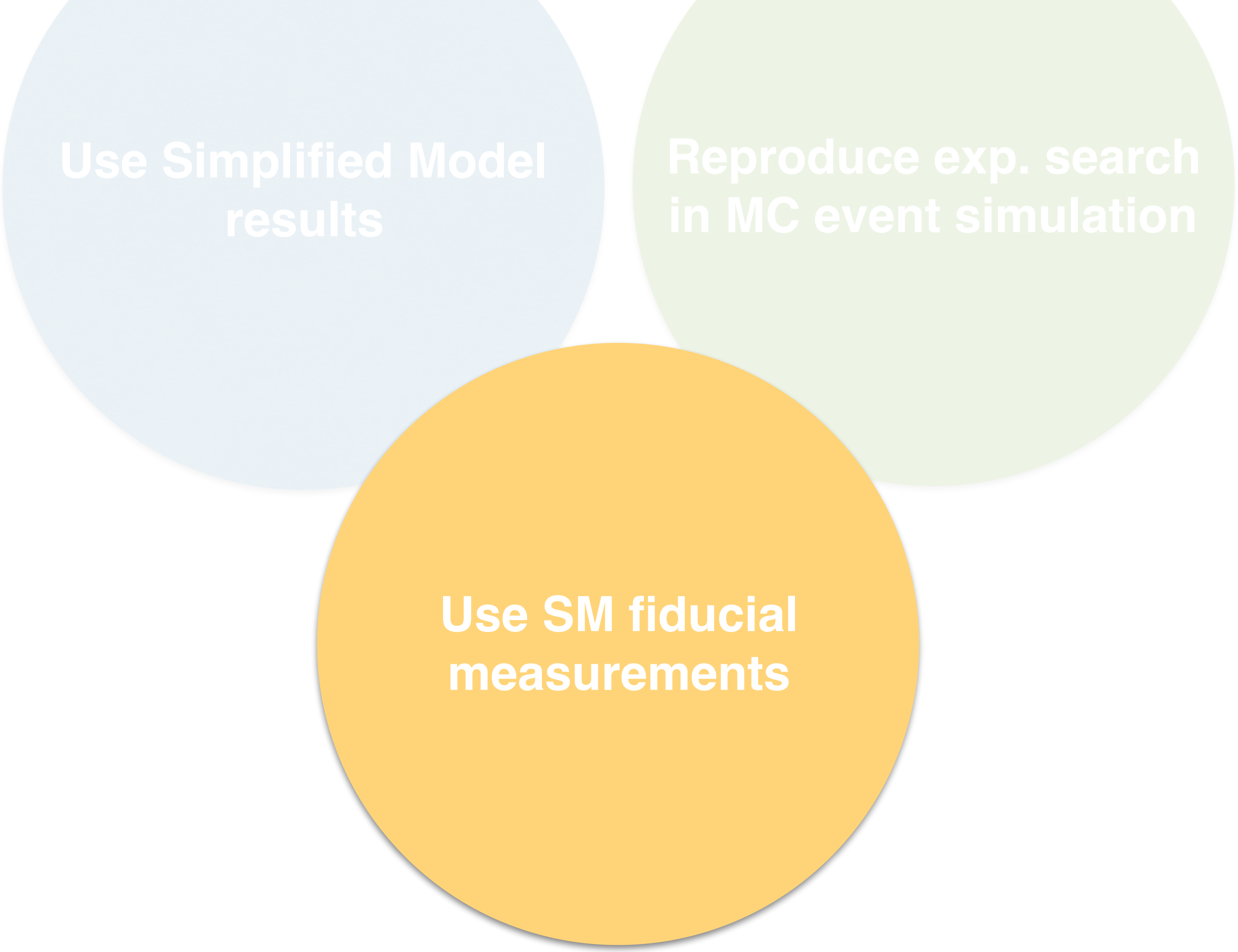
Recommendations from LLP white paper (1903.04497)

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

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**



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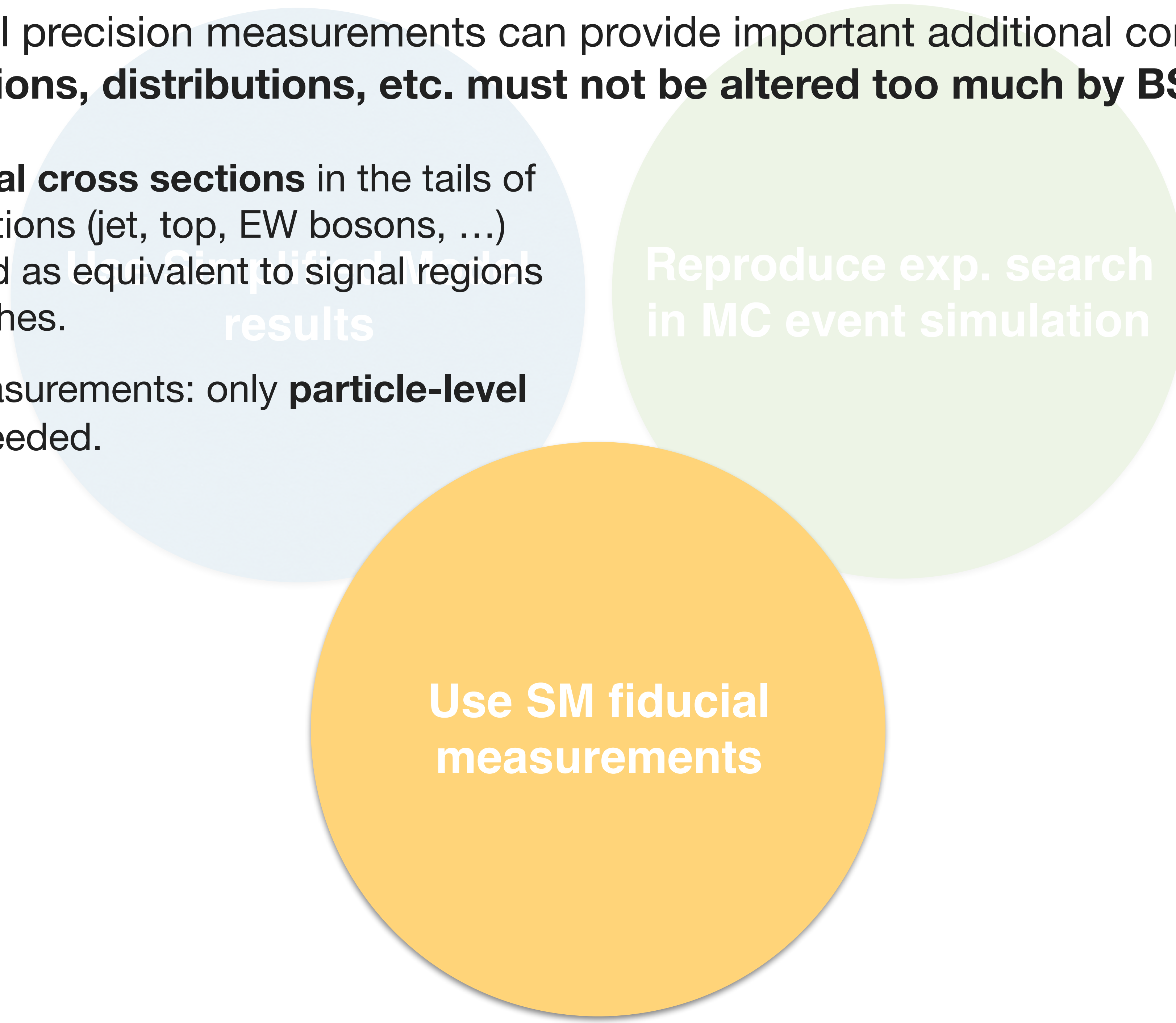
Standard Model precision measurements can provide important additional constraints, as **SM cross sections, distributions, etc. must not be altered too much by BSM effects**

- 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.



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- 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

Reproduce exp. search in MC event simulation

Use SM fiducial measurements

Ways of (re)interpretation

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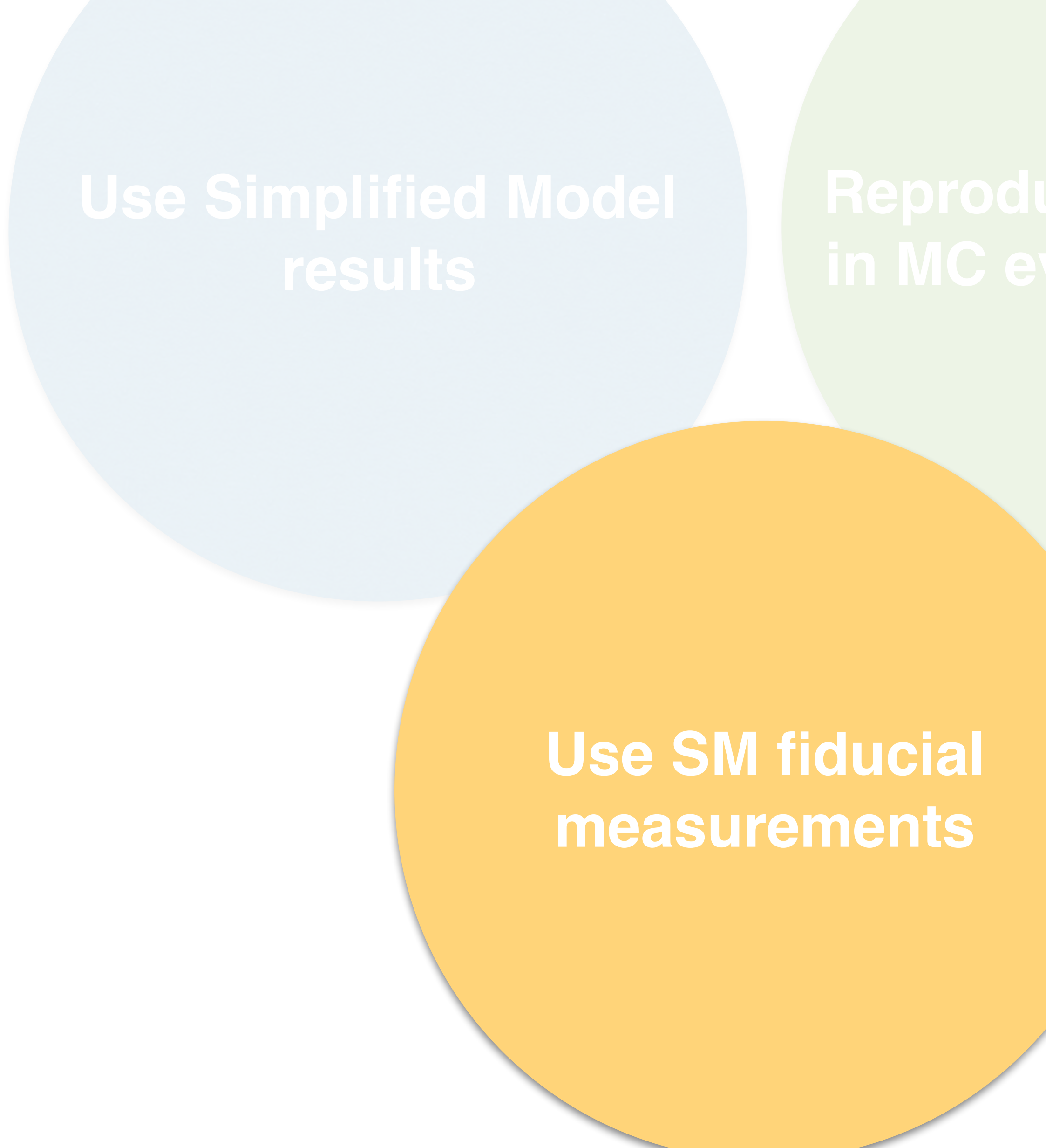

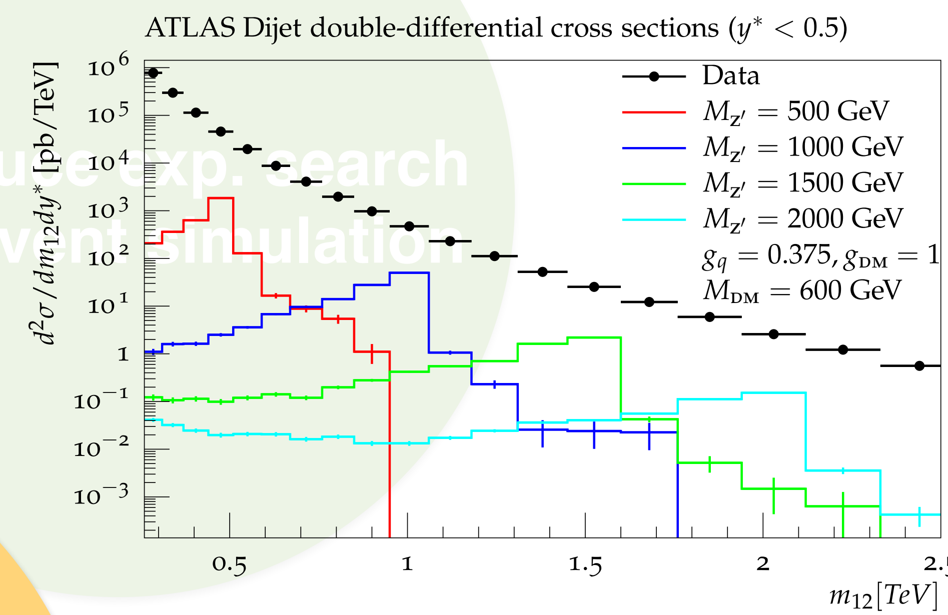

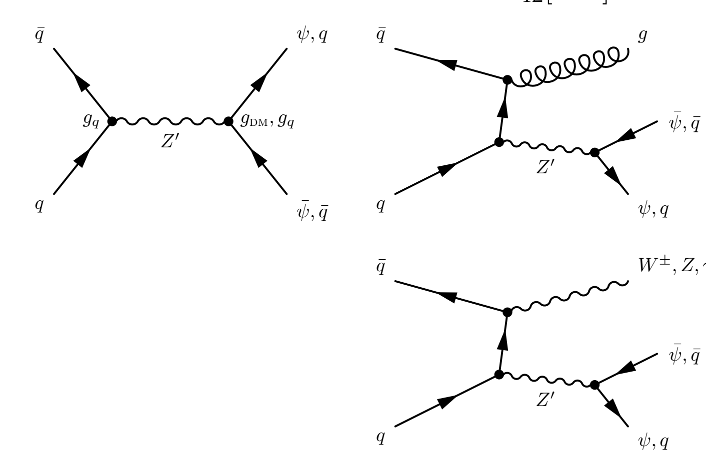

Butterworth et al., 1606.05296
https://contur.hepforge.org/

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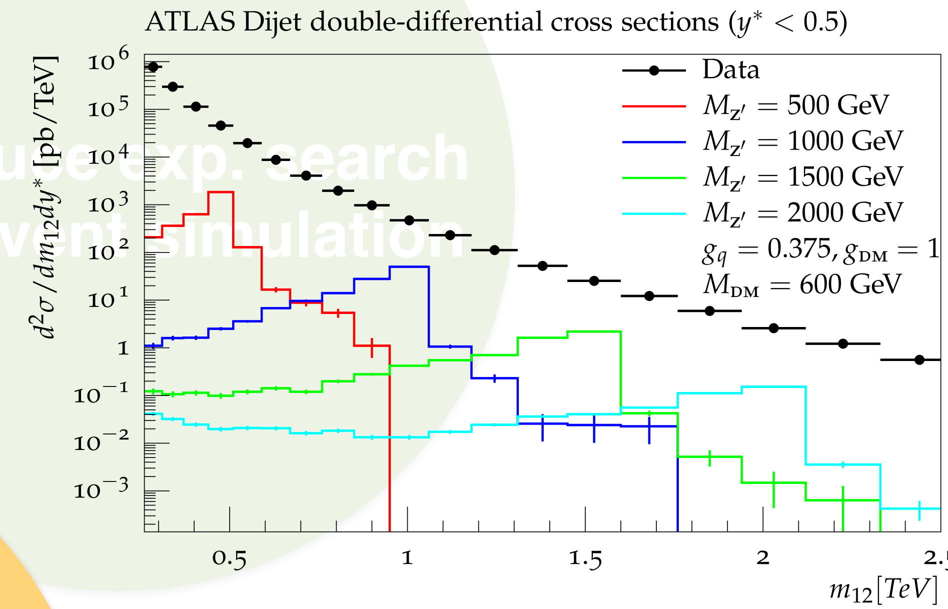
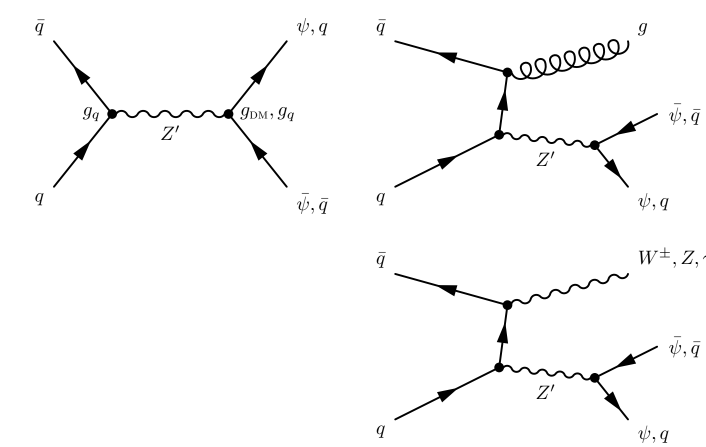
Use SM fiducial measurements





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

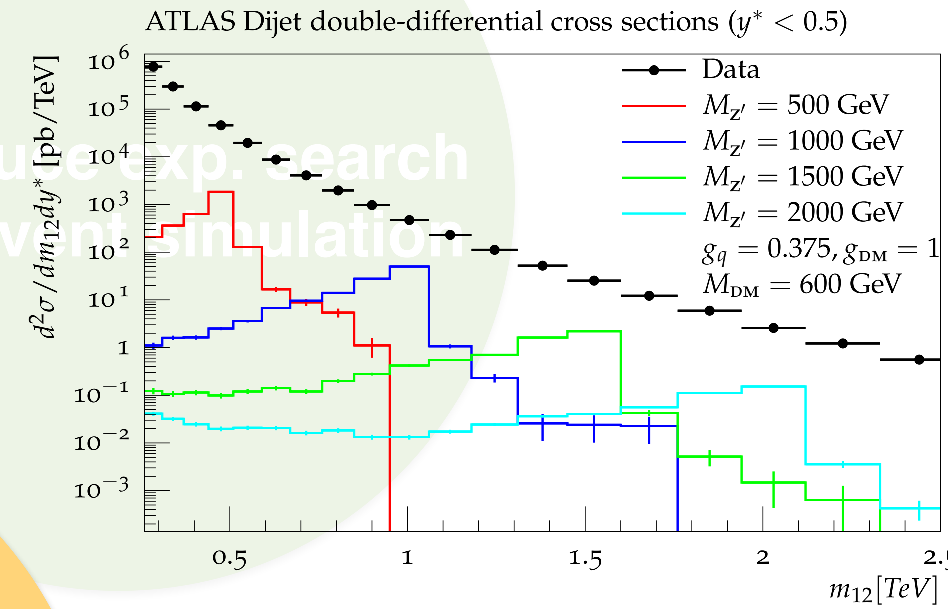
Ways of (re)interpretation

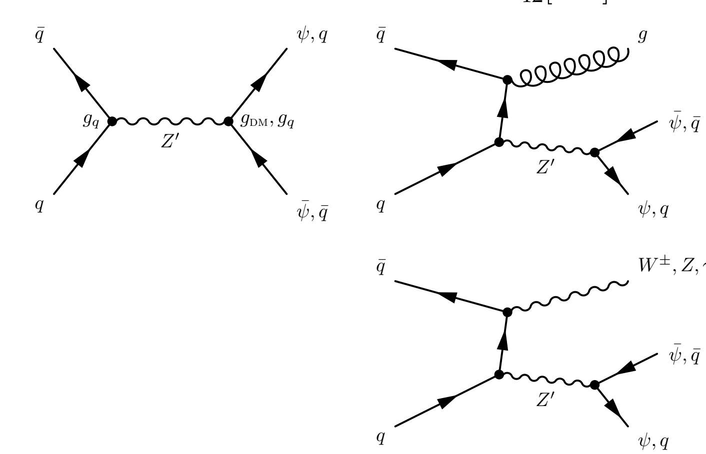
Standard Model precision measurements can provide important additional constraints, as **SM cross sections, distributions, etc. must not be altered too much by BSM effects**

- 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

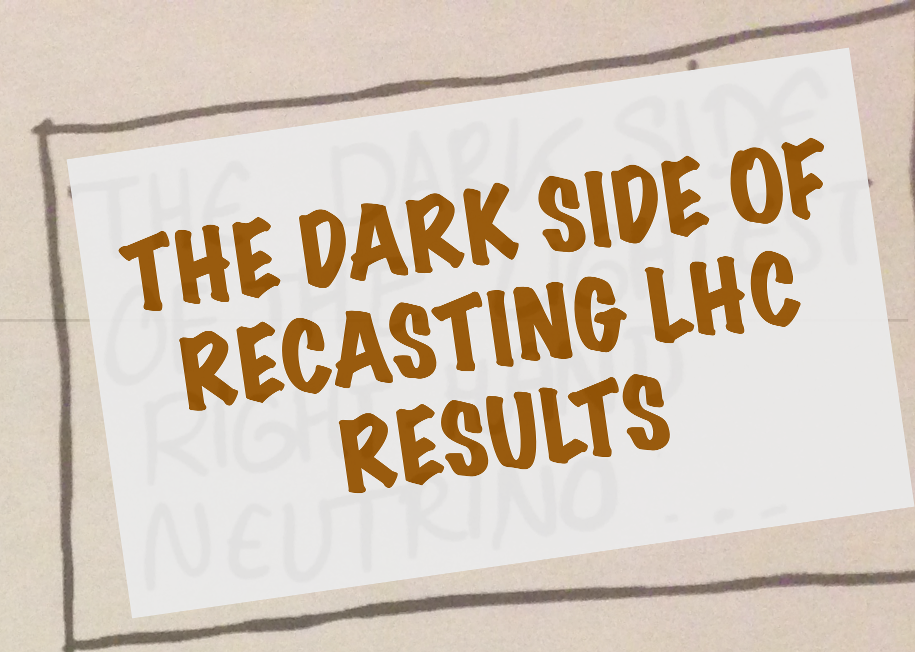
Use SM fiducial measurements

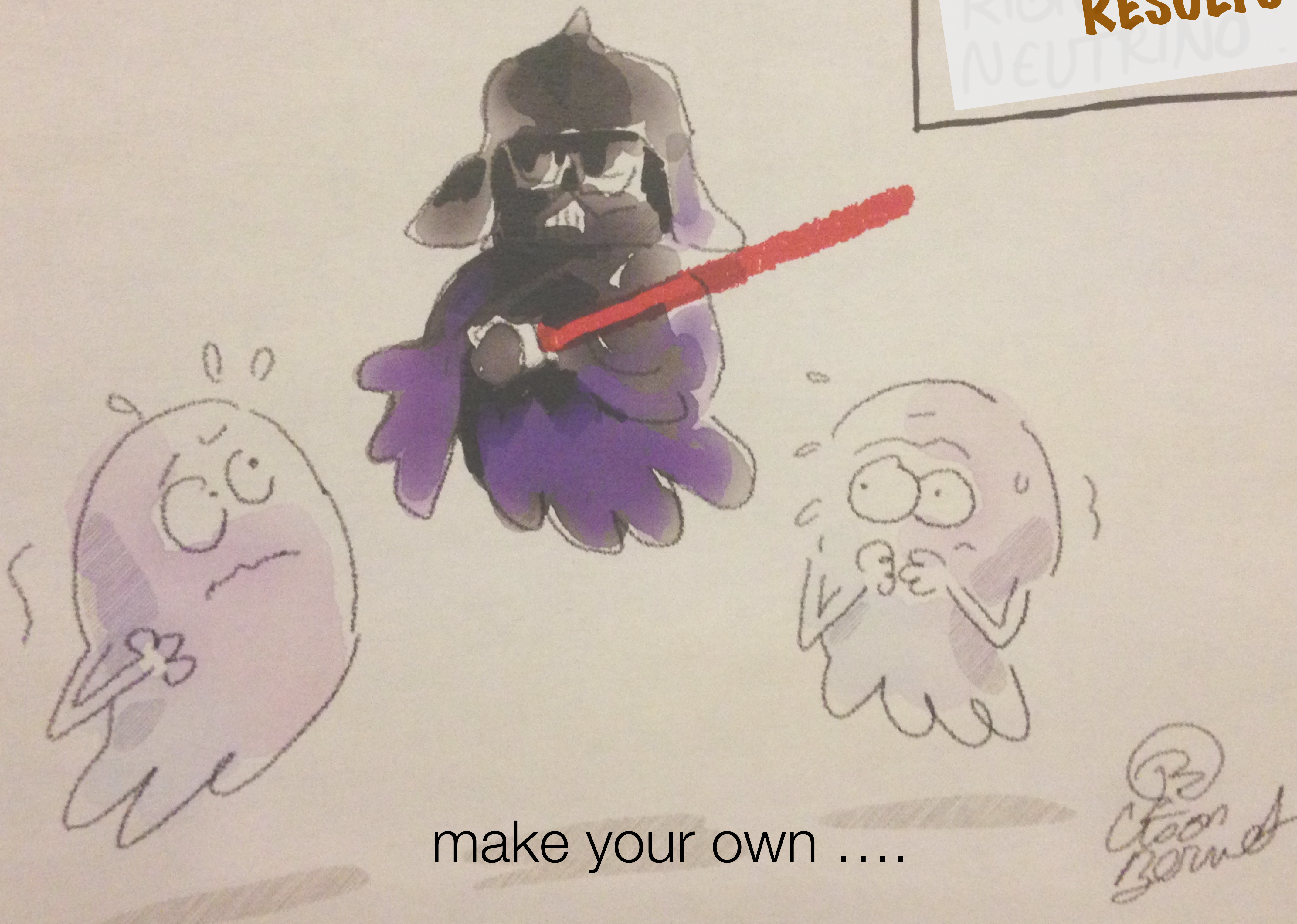




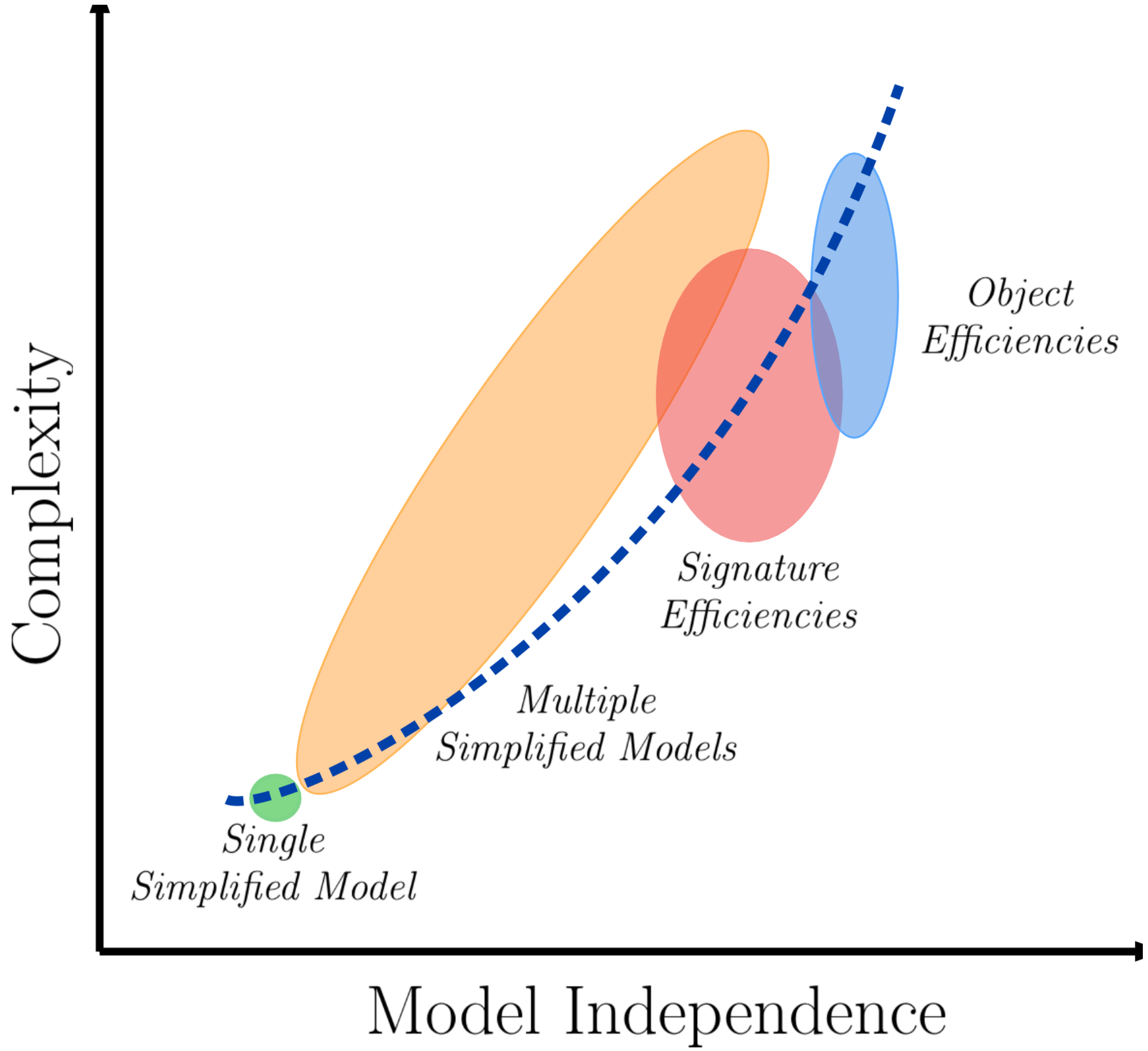
Butterworth et al., 1606.05296
https://contur.hepforge.org/

Conclusions ?



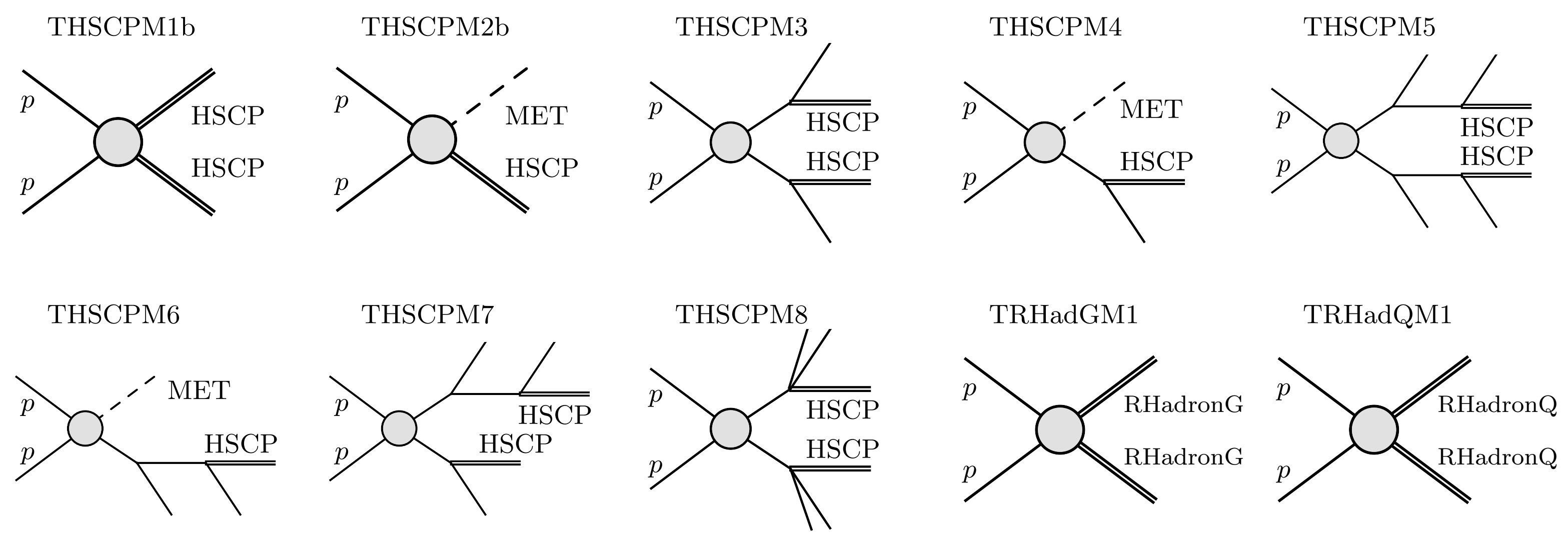


make your own ....


Complexity
Object
Efficiencies
Signature
Efficiencies
Multiple
Simplified Models
Single
Simplified Model
Model Independence

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

LLP simplified models in SModelS



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, covariance matrix for combining bins (problem: shape fits)