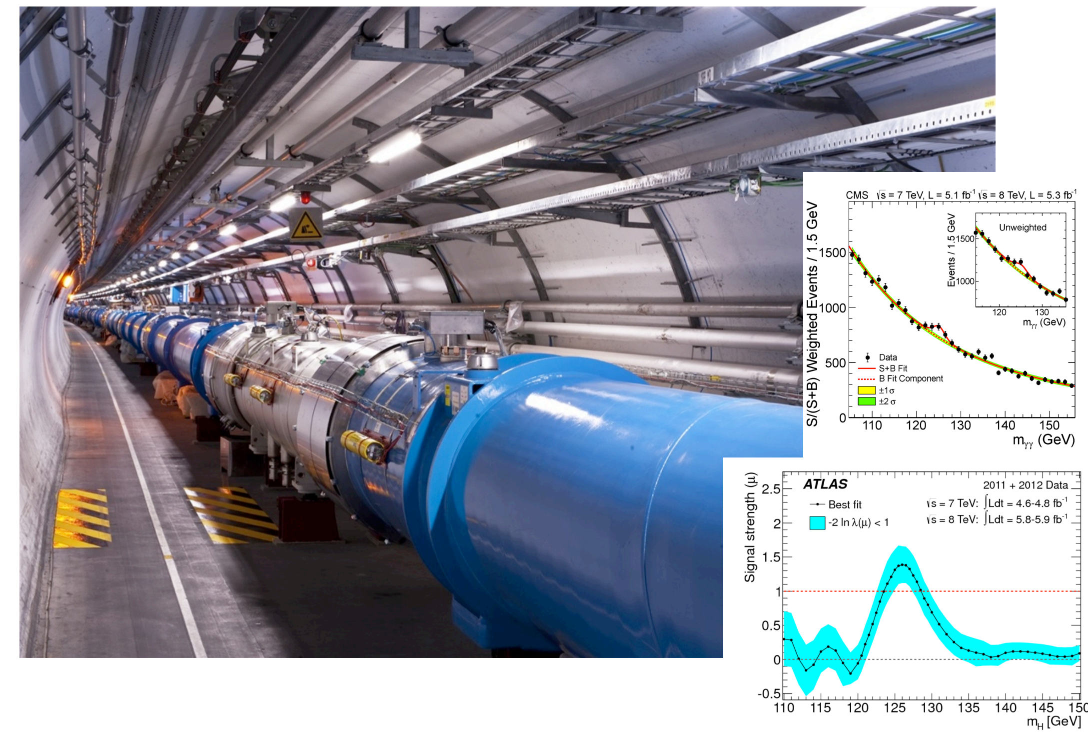
Recasting LHC searches:
The case of the Inert Doublet Model ~~(and other examples)~~

Sabine Kraml
LPSC Grenoble

based on work with/of D. Barducci, G. Belanger, S. Bein, G. Chalons, E. Conte, C. Delauney, B. Dumont, B. Fuks, B. Herrmann, A. Goudelis, S. Kulkarni, S. Pandey, S. Sharma, D. Sengupta, C. Wymant

The LHC endeavor

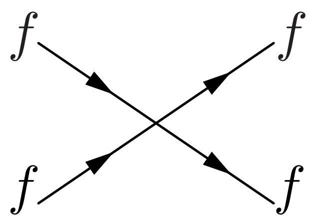
- The LHC was built as a **discovery machine** to explore new physics at the **TeV energy scale**.
- The discovery of a Standard Model (SM)-like **Higgs boson** was a tremendous first success for the LHC physics program.
- However, while the Higgs discovery completes our picture of the SM, it still leaves **many fundamental questions open** (naturalness, hierarchy problem, ...)
- **Run 2** of the LHC just started; the search for new phenomena **beyond the SM (BSM)** is one of its top priorities.
- The BSM theory might also provide the **dark matter** (DM) and generally enhance our understanding of the early Universe.



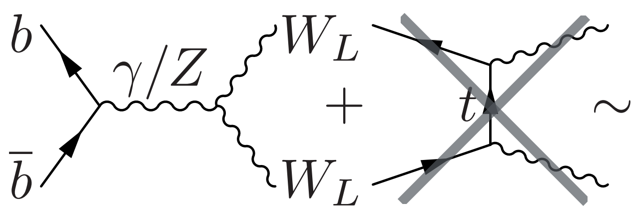
A. Wulzer, EPS-HEP 2015
arXiv:1510.05159

No more no-loose theorem

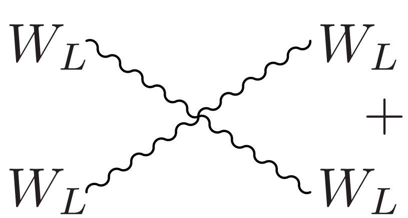
Guaranteed discoveries in the history of HEP (unitarity of scattering amplitudes):



$$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \longrightarrow m_W < 4\pi v$$



$$\sim g_W^2 E^2/m_W^2 < 16\pi^2 \longrightarrow m_t < 4\pi v$$

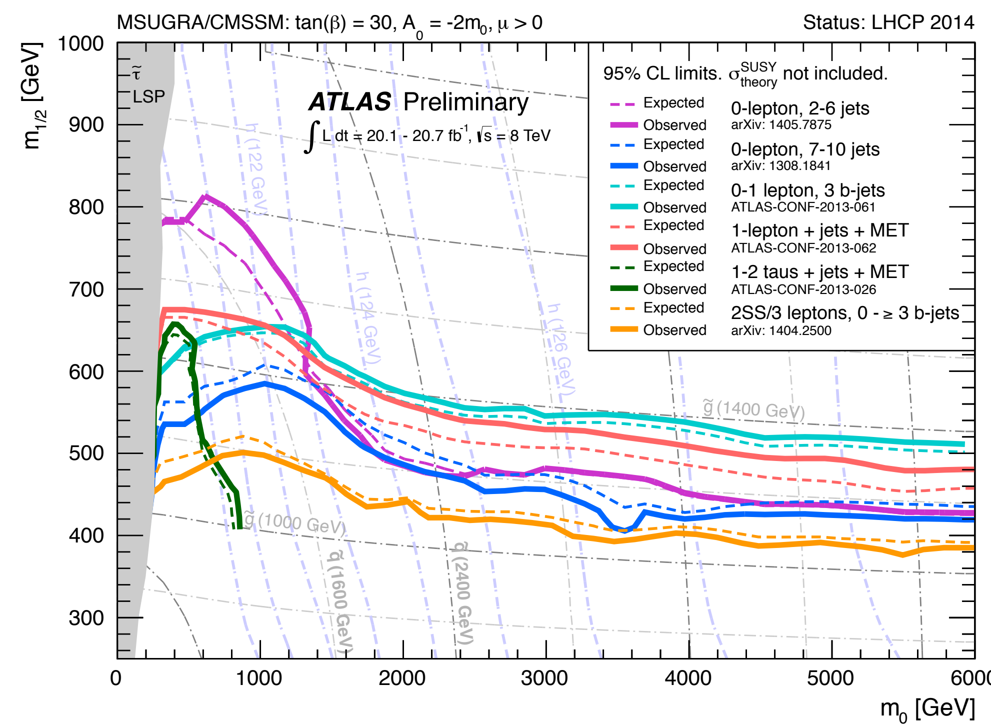


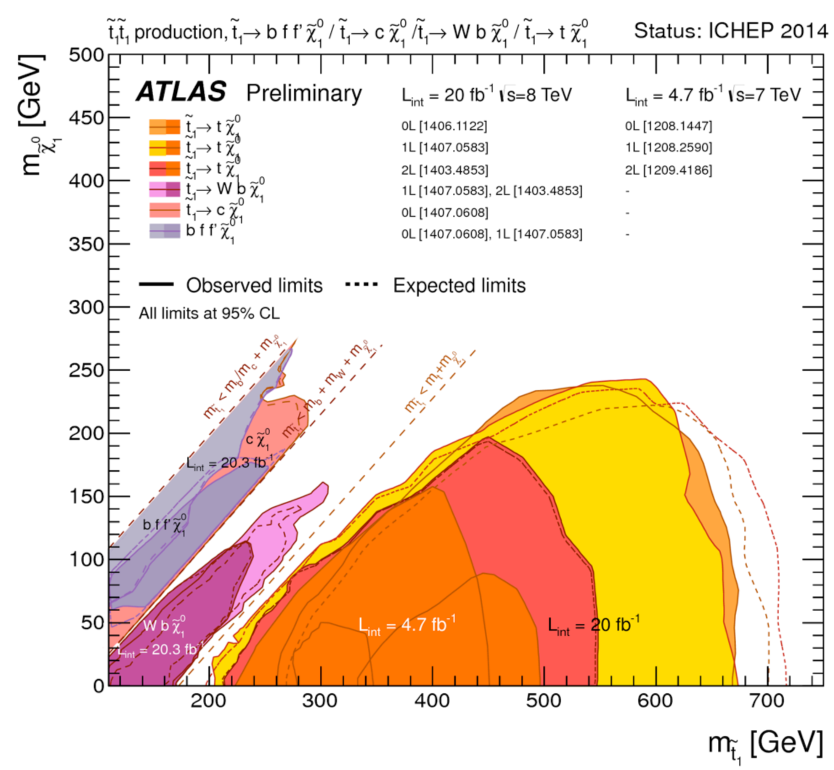
$$+ \ldots \sim g_W^2 E^2/m_W^2 < 16\pi^2 \longrightarrow m_H < 4\pi v$$ ~3 TeV

The Higgs discovery completes the SM — and leaves us without any no-loose theorem to exploit for future discoveries.

New physics searches

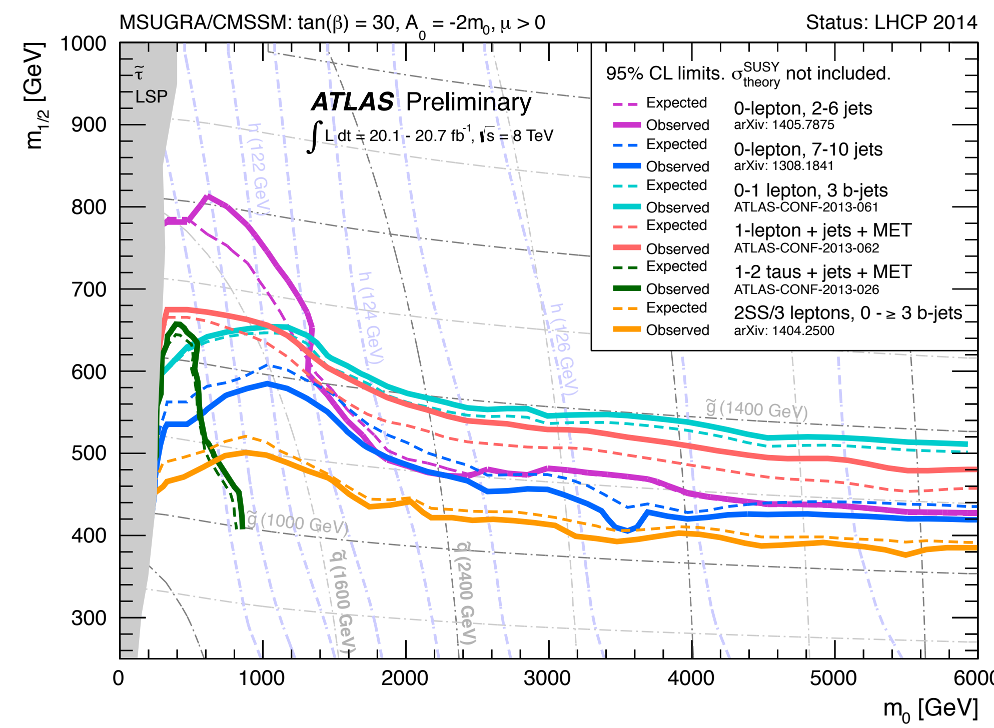
- ATLAS and CMS perform **searches for new physics in many different channels**.
- In the experimental publications, the **results are** typically **interpreted within popular models** as well as within topology-based “Simplified Model Spectra” (SMS).
- SUSY, VLQ, extra gauge bosons, DM models, other exotics, extra Higgses, etc.
- However, there **exists a plethora of models** and scenarios ....

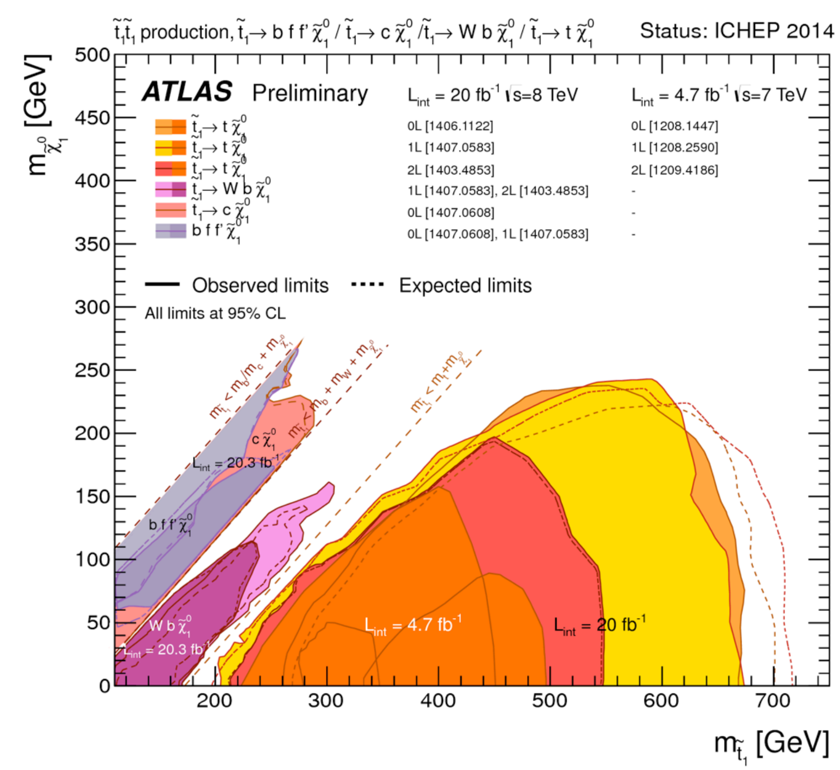




A plethora of searches
Need for interpretation studies

- ATLAS and CMS perform **searches** for new physics **in many different channels**.
- They also provide **interpretations** of their results within **constrained models**, like the CMSSM, or within topology-based **“Simplified Model Spectra”** (SMSs).
- However, there **exists a plethora of** different **BSM models and scenarios**
- Need to interpret LHC results in the contexts of all kinds of models of new physics
  - important for deriving the current limits on them, and for finding existing loopholes;
  - crucial once there is a discovery, if we are to unravel the correct theory and determine its parameters.





A plethora of searches

Examples of SUSY and exotics searches from ATLAS and CMS

Displaced vertex [RPV, GMSB, split-SUSY] NEW	Search for third-generation scalar leptoquarks in the top+tau channel NEW
Heavy resonance to eμ, eτ, μτ [RPV-LFV, Z'-LFV] NEW	Search for high mass resonances decaying to Z and Higgs bosons NEW
2 leptons (on/off-Z) + jets + Etmiss [incl. squarks & gluinos, GGM] NEW	Search for physics beyond the standard model in the Dilepton Mass Distribution NEW
Multijets [RPV] NEW	Reinterpretation of HSCP Analysis in the pMSSM and other scenarios NEW
Monojet + Etmiss (gravitino-squark, gravitino-gluino) NEW	Search for Stopped Long-Lived Particles NEW
Chargino neutralino decaying via Higgs NEW	Search for Heavy Majorana Neutrinos with same sign dimuons NEW
1/2 leptons + jets + Etmiss [incl. squarks & gluinos, mUED] NEW	Search for Resonances using the Dijet Mass Spectrum NEW
Search for scalar charm NEW	Search for pair-produced resonances decaying to jet pairs NEW
Top spin correlations (stealth stop)	Search for displaced dilepton pairs NEW
Long-lived particles (sleptons, charginos, R-hadrons)	Search for contact interactions and extra dimensions in dijet angular distributions NEW
Mono-photon + Etmiss [Degenerate squark/neutralino]	Search for new physics with monophotons NEW
Non-pointing, delayed photons [LLP, GMSB]	Search for new physics with monojets NEW
0 leptons + mono-jet/c-jets + Etmiss [Stop in charm+LSP]	Search for Dark Matter, extra-dimensions, W' and contact interactions in lepton+MET final states NEW
1 lepton + 4(1 b-)jets + Etmiss [Medium / heavy stop]	Search for long-lived neutral particles decaying to dijets
1-2 taus + 0-1 leptons + jets + Etmiss [GMSB]	Search for disappearing tracks
0-1 leptons + >=3 b-jets + Etmiss [3rd gen. squarks]	
2 taus + Etmiss [EW production]	
Stop constraints from precise ttbar cross-section [Light stop]	
0 lepton + 6 (2 b-)jets + Etmiss [Heavy stop]	
0 leptons + 2-6 jets + Etmiss [Incl. squarks & gluinos]	
4 leptons + Etmiss [EW production, RPV]	
2 same-sign / 3 -leptons + 0-3 b-jets + Etmiss [Incl. squarks & gluinos]	

A plethora of searches
Need for interpretation studies

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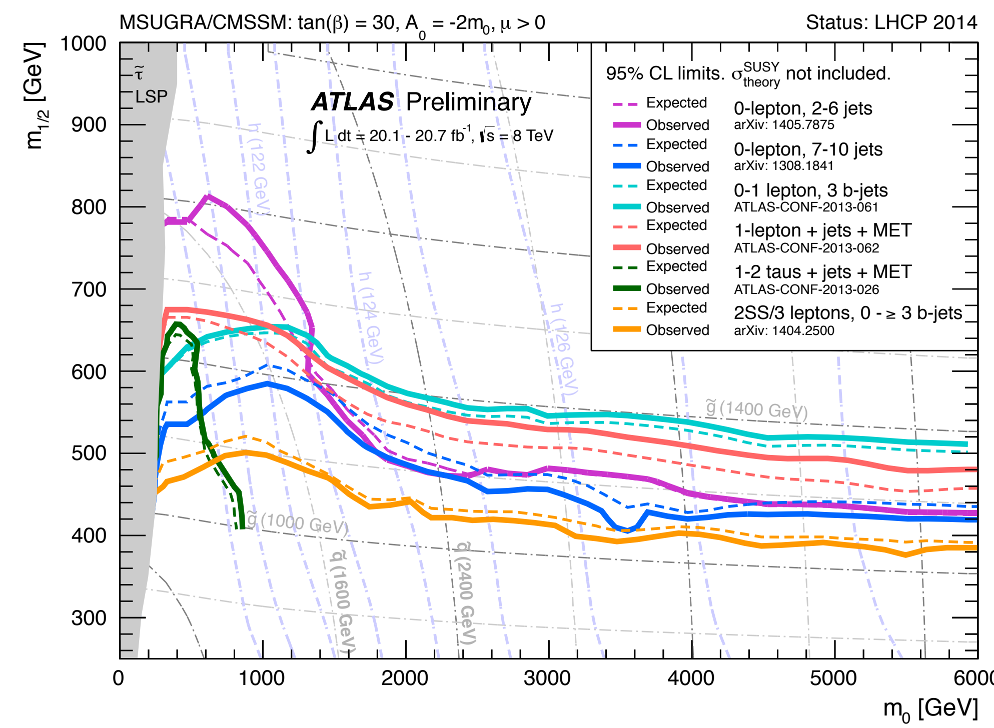
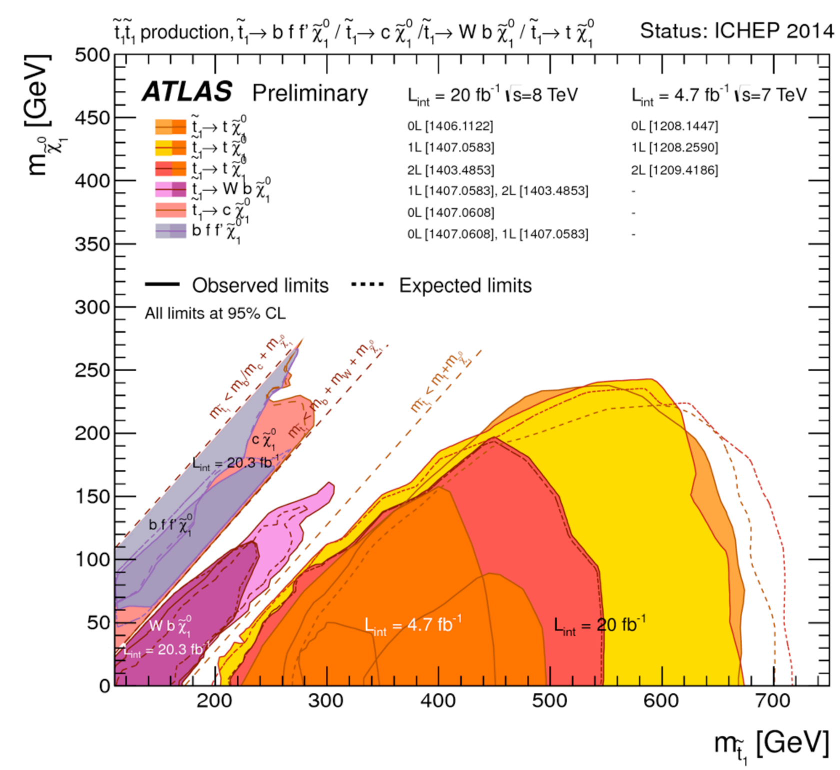
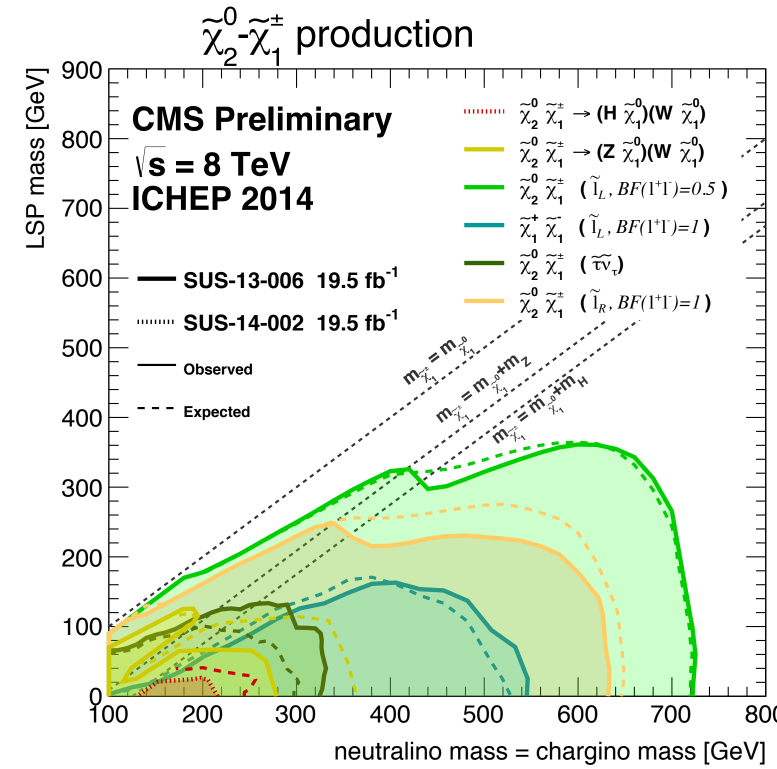
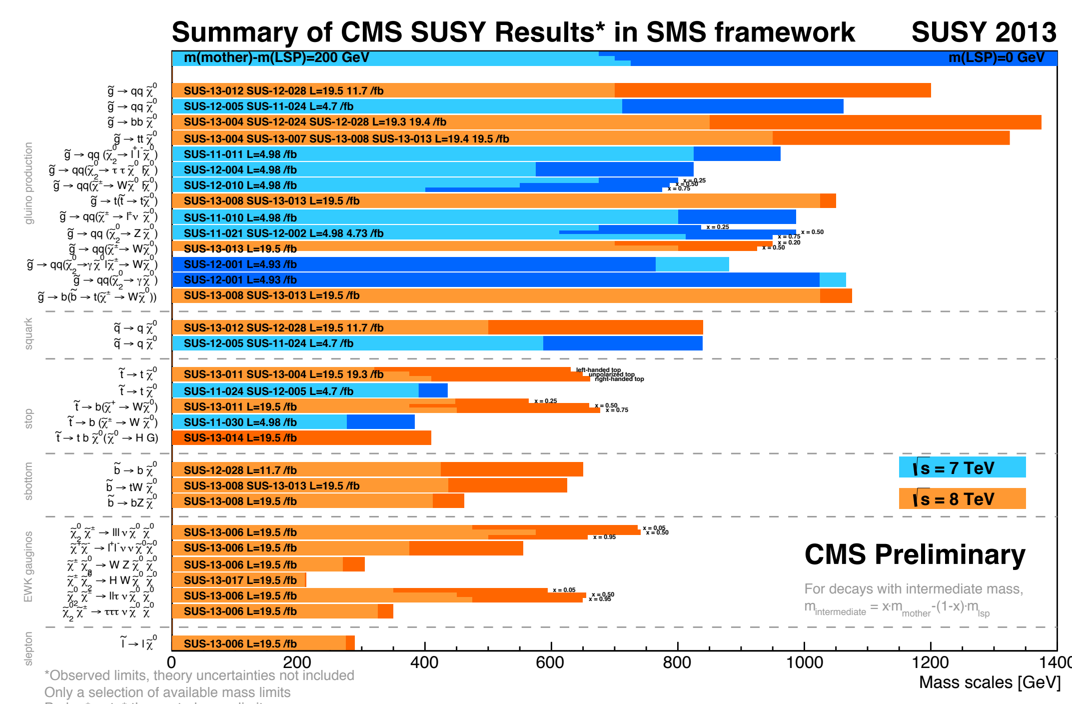




Need for interpretation studies

- SUSY limits depend a lot on **assumptions on the mass spectrum**, and disappear for small mass splittings, mLSP>600 GeV, etc.
- Limits also depend on **particle content** of the model (different decay modes and branching ratios, reduced MET, ...)
- Most SUSY studies assume the **MSSM** with a bino-like **neutralino LSP**. Different choices are possible and may lead to quite different conclusions. [cf. Nazila's talk]
- There **exists a plethora of models** and scenarios; constantly new ones
- Need the means to **interpret** the LHC results in the contexts of **all kinds of models**
  ⇨ crucial for working out the implications for new physics and unravelling the correct theory beyond the SM
  ⇨ dedicated theory+experiment effort





The difficulty

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.

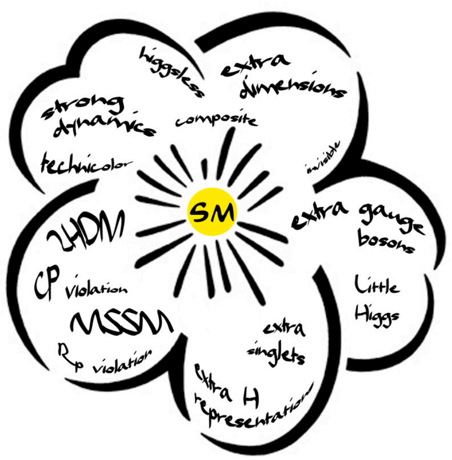
Therefore, the implementation and validation of ATLAS and CMS analyses for **re-interpretation of the experimental results in general contexts is a tedious task**, even more so as the information given in the experimental papers is often incomplete.

Searches for New Physics: Les Houches Recommendations ....,
SK, B.C. Allanach, M. Mangano et al., arXiv:1203.2489

➩ More open information exchange
➩ Public tools

Untested by ATLAS and CMS:

Inert Doublet Model



Michael Tytgat, Bogumila Swiezewska,
Tania Robens, Saereh Najjari

The Inert Doublet Model

- In the IDM, the SM is extended by the addition of a **second scalar, Φ,** transforming as a doublet under $SU(2)_L$. This Φ is **odd under a new discrete Z_2 symmetry**.

$$H = \begin{pmatrix} \boldsymbol{G^+} \\ \frac{\mathbf{1}}{\sqrt{\mathbf{2}}}\left(\boldsymbol{v}+\boldsymbol{h}+\boldsymbol{iG^0}\right) \end{pmatrix}, \quad \Phi = \begin{pmatrix} \boldsymbol{H^+} \\ \frac{\mathbf{1}}{\sqrt{\mathbf{2}}}\left(\boldsymbol{H^0}+\boldsymbol{iA^0}\right) \end{pmatrix}$$

- **Scalar potential**

$$V_0 = \mu_1^2|H|^2 + \mu_2^2|\Phi|^2 + \lambda_1|H|^4 + \lambda_2|\Phi|^4 + \lambda_3|H|^2|\Phi|^2 + \lambda_4|H^\dagger\Phi|^2 + \frac{\lambda_5}{2}\left[(H^\dagger\Phi)^2 + \text{h.c.}\right].$$

$$m_h^2 = \mu_1^2 + 3\lambda_1 v^2$$
$$m_{H^0}^2 = \mu_2^2 + \lambda_L v^2$$
$$m_{A^0}^2 = \mu_2^2 + \lambda_S v^2$$
$$m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$$

$$\lambda_{L,S} = \frac{1}{2}\left(\lambda_3 + \lambda_4 \pm \lambda_5\right)$$

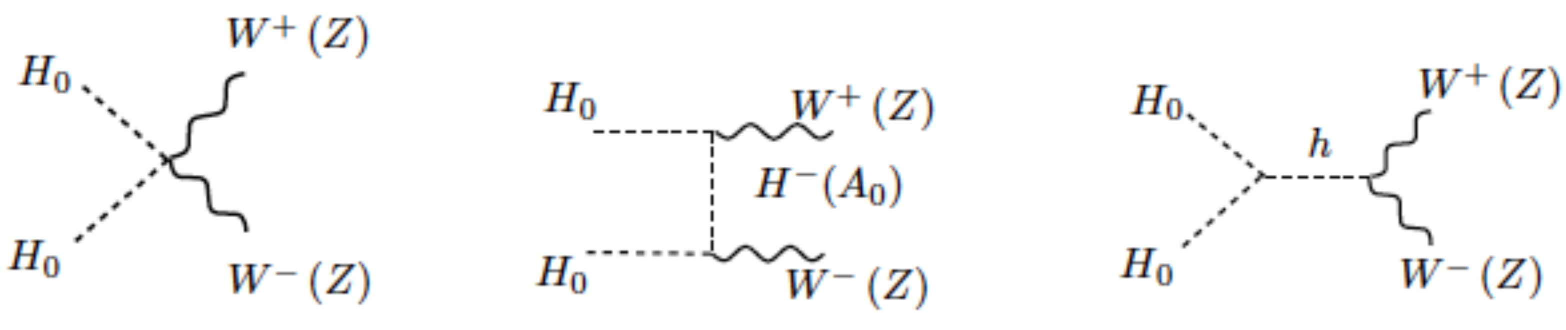
The Z_2 symmetry forbids mixing among the components of H and Φ and renders the lightest Z_2-odd particle stable.
→ H^0 or A^0 can play the role of a **DM candidate**.

NB: all fermions couple to H, i.e. **2HDM Type-I** Yukawa couplings

[Lopez-Honorez, Nezri, Oliver, Tytgat, hep-ph/0612275]

DM annihilation channels

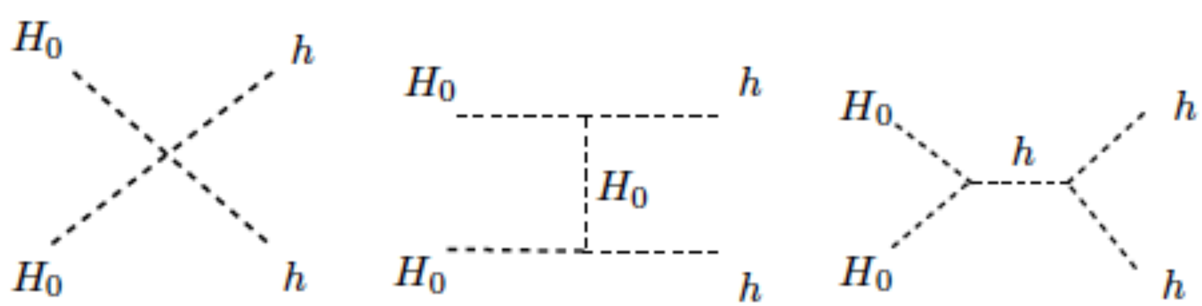
(taking H^0 as the DM candidate)



g^2 g^2 $\lambda_L g$

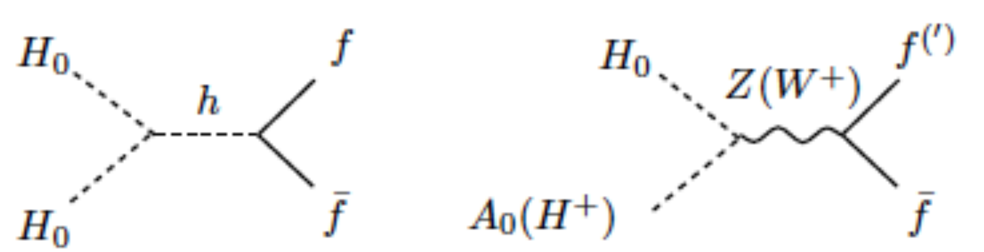
annihilation into gauge bosons

$$\lambda_L = \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)$$



λ_L λ_L^2 $\lambda_L \lambda_1$

annihilation into Higgs

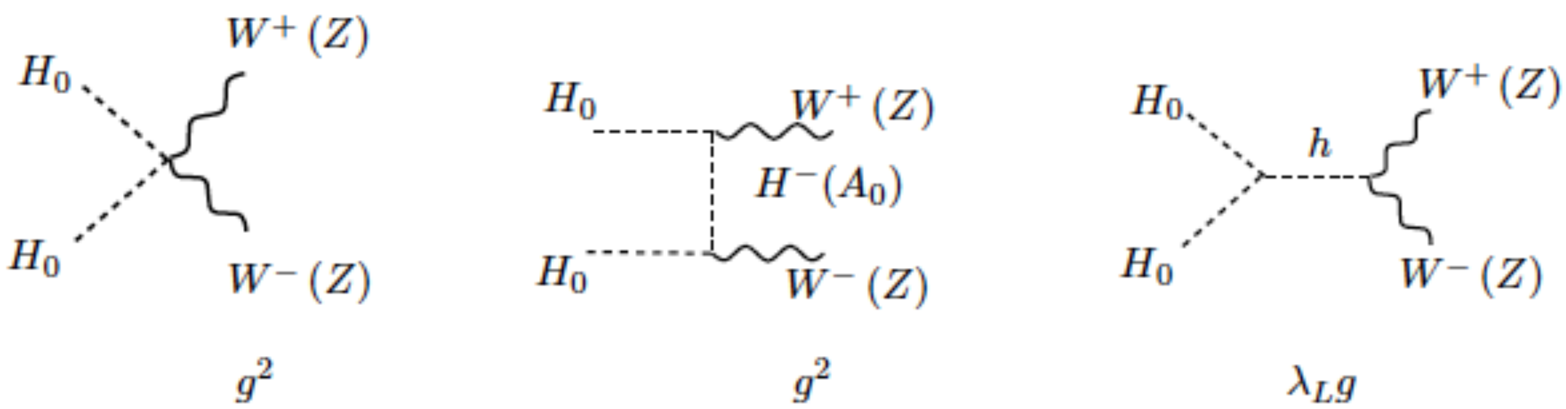


$\lambda_L y_f$ g^2

annihilation into fermions

DM annihilation channels

(taking H^0 as the DM candidate)



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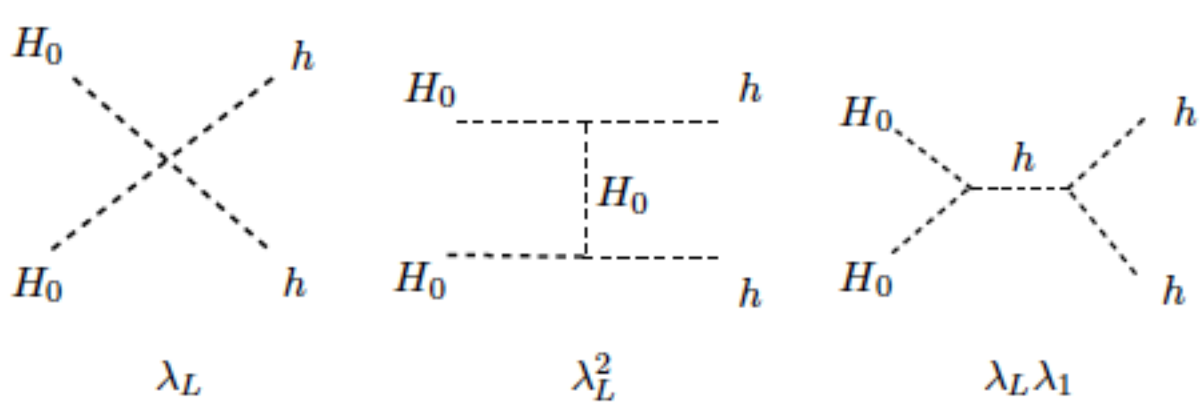

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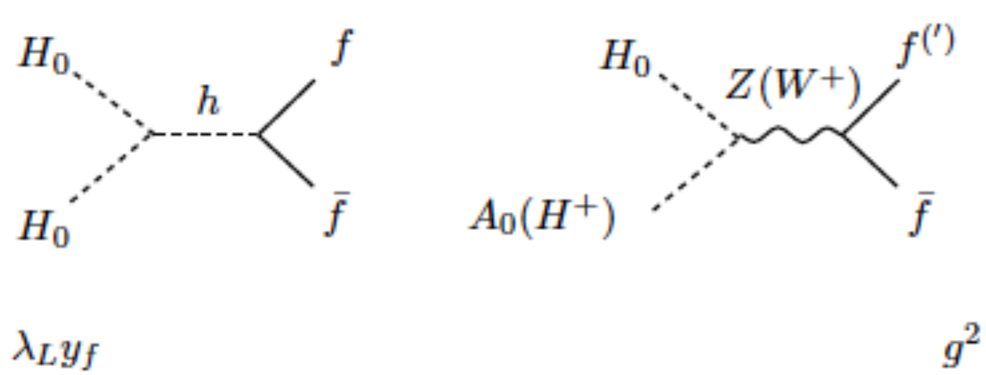
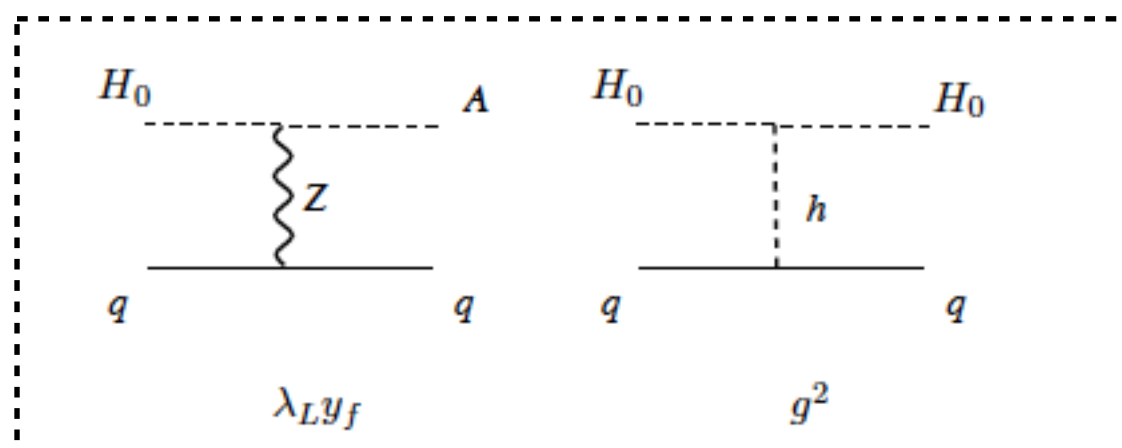


Direct DM detection



Constraints on the model

- **Stability** of the EW vacuum

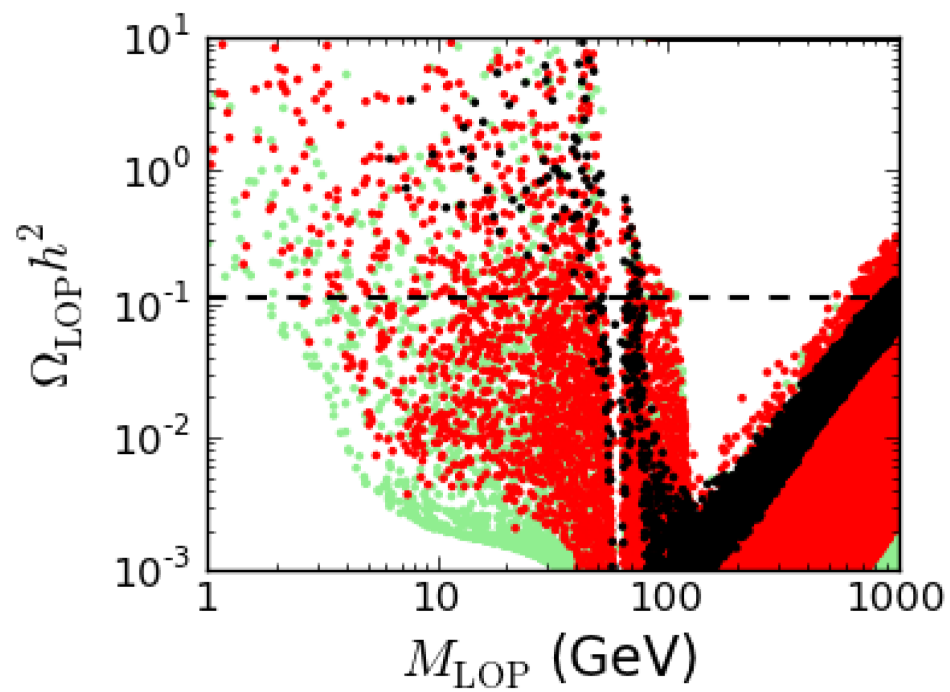
$$\lambda_1, \lambda_2 > 0$$
$$\lambda_3 > -2\sqrt{\lambda_1\lambda_2}$$
$$\lambda_3 + \lambda_4 - |\lambda_5| > -2\sqrt{\lambda_1\lambda_2}$$

- **Perturbativity** of all couplings and perturbative unitarity of S-matrix
- **Oblique parameters S, T and U**
- Neutralino and chargino searches at **LEP** impose $m_{A0} > 100$ GeV and $m_{H\pm} > m_W$.
- Total width of EW gauge bosons: $m_{A,H} + m_{H\pm} > m_W$, $m_A + m_H > m_Z$, $2m_{H\pm} > m_Z$

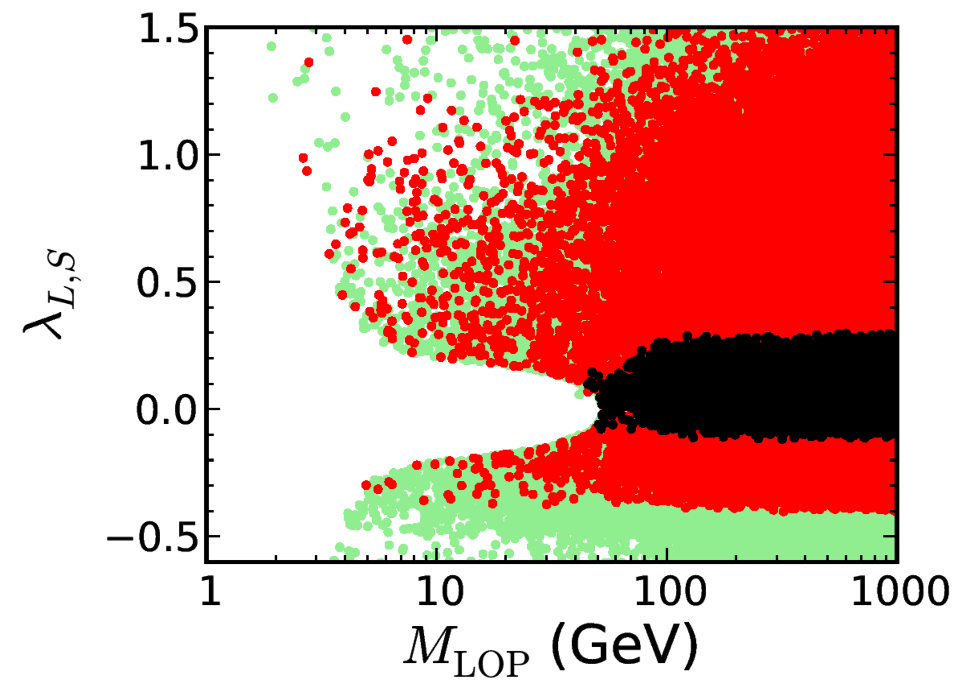
green: points valid at the input scale Λ = MZ,
red: points which remain valid up to Λ = 10 TeV,
black: points valid up to the GUT scale of 10^{16} GeV

[Goudelis, Herrmann, Stal, 1303.3010]

LOP = lightest odd particle



$\Omega h^2 \sim 0.1$



Constraints on the model

- **Relic density** (vanilla picture of thermal DM)
  - low-mass regime ($m_{H0} < m_W$): relevant parameters are λ_L and the distance of m_{H0} from $m_h/2$
  - intermediate-mass region ($m_W < m_{H0} < 115$ GeV): relic density depends on m_{H0} and λ_L,
  - high-mass regime: all parameters of the scalar potential except λ_2 drastically affect the DM relic abundance
- For $m_{H0} \leq m_h/2$, **BR(h→inv)** < 12% at 95% CL implies $\lambda_L < 6\times10^{-3}$
- **Direct DM** searches eliminate $m_{H0} < 115$ GeV DM region apart from $m_{H0} \sim m_h/2$

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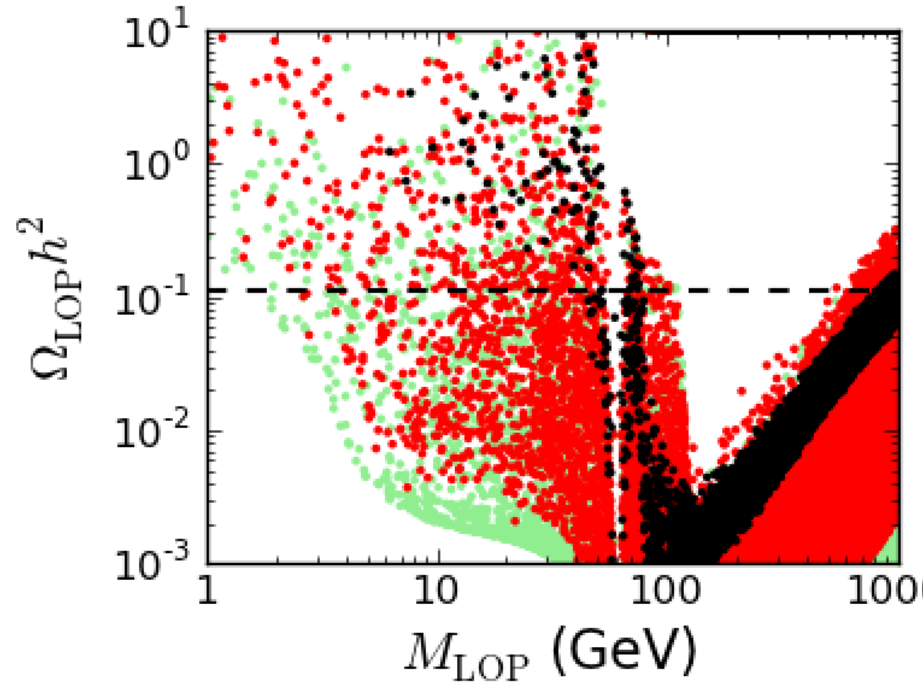

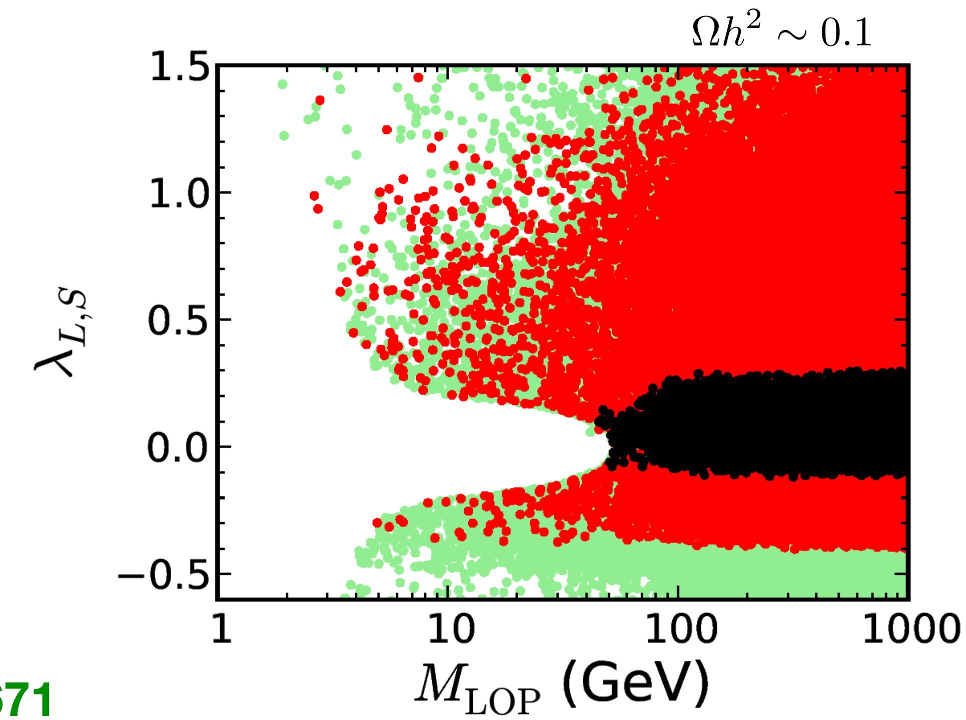

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[Goudelis, Herrmann, Stal, 1303.3010]

Most recent update: **A. Ilnicka, M. Krawczyk, T. Robens, 1508.01671**

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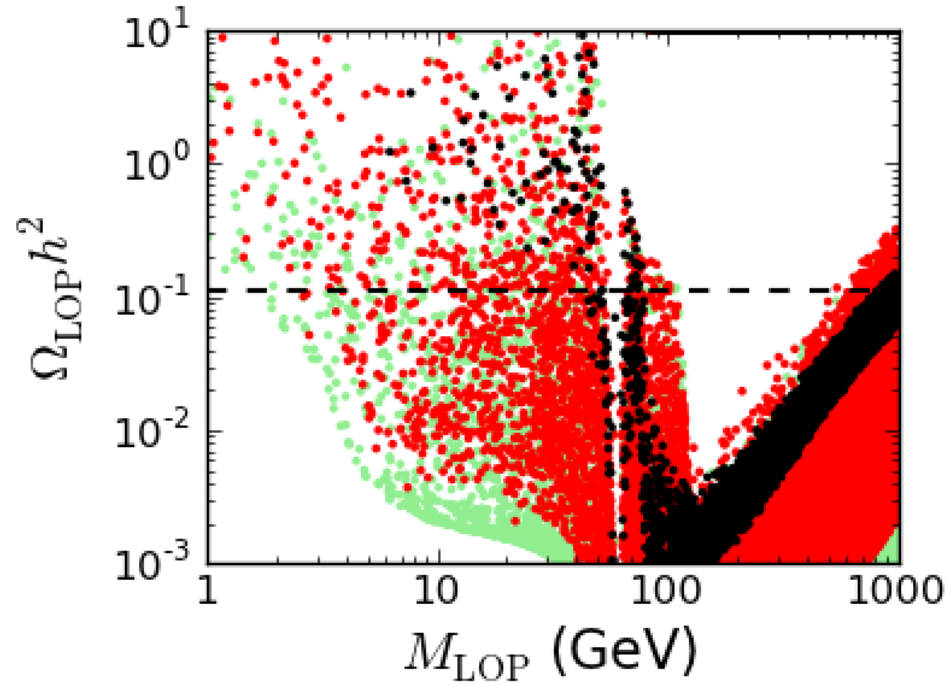

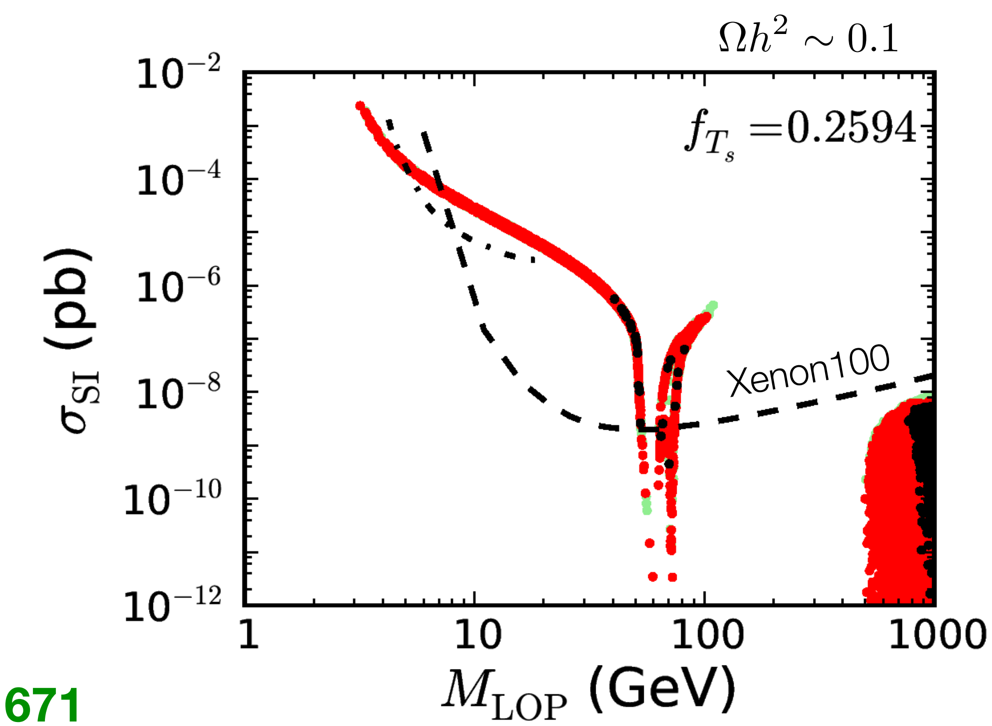

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[Goudelis, Herrmann, Stal, 1303.3010]

Most recent update: **A. Ilnicka, M. Krawczyk, T. Robens, 1508.01671**

- **All constraints coming from invisible Higgs decays or from direct detection experiments vanish in the limit $\lambda_L \to 0$.**

- In the "vanilla picture" of the thermal history of the Universe, vanishing λ_L leads to an overabundance of DM. However, various possibilities exist to eventually dilute the DM density.
  [see e.g. Gelmini et al., hep-ph/0605016]

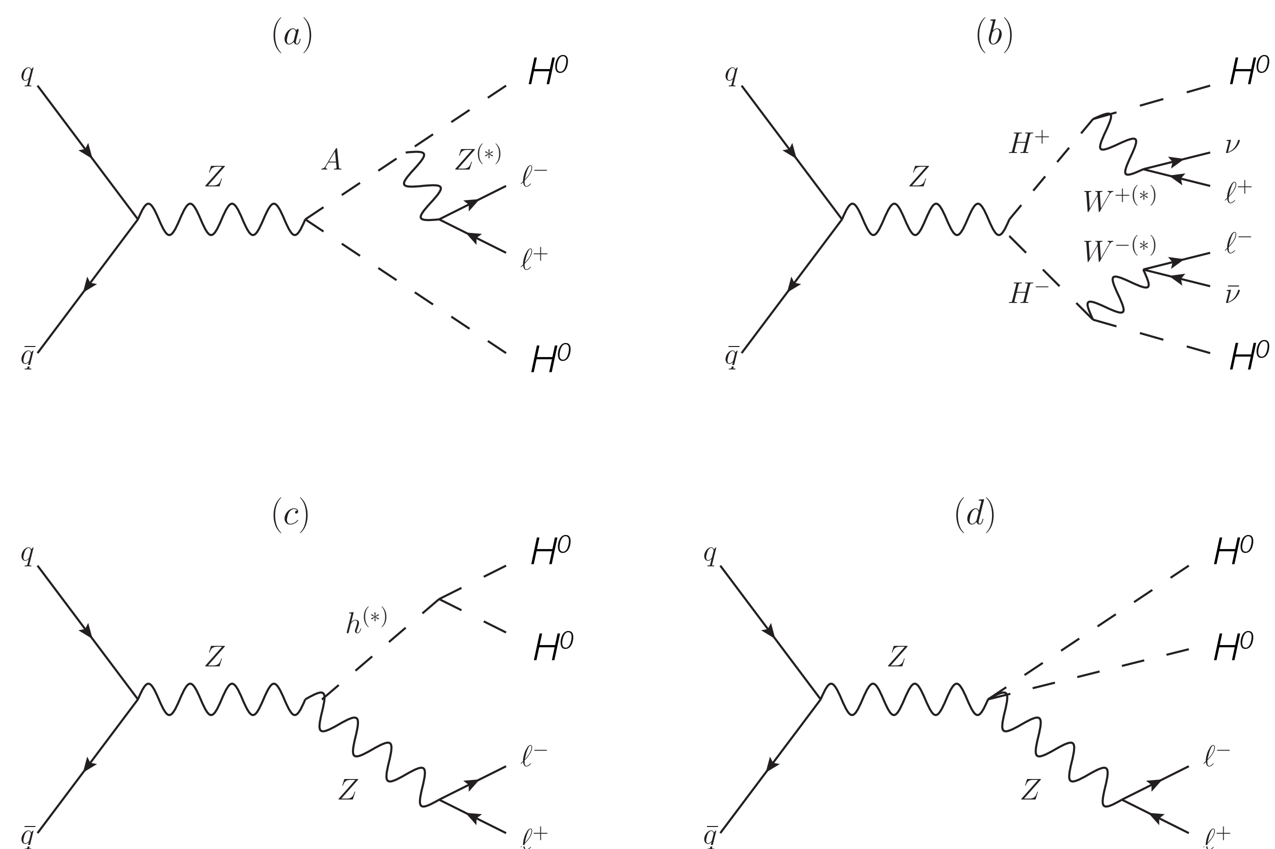
- Independent collider constraints are interesting, as they do not depend in any way upon astrophysical or cosmological assumptions.

  ➡ How do LHC Run 1 results constrain the IDM ?

LHC signatures (assuming $m_{H^0} < m_{A^0}$)

- At the LHC, inert scalars can be pair-produced via virtual Z or W exchange (H^+H^- also via γ)
- The unstable A^0 or $H^\pm$ then decay into the H^0 plus a Z or W
- Most promising signatures:
  SF or DF dileptons l^+l^- + E_T^{miss}
  (same flavor or different flavor)

E. Dolle et al., arXiv:0909.0394



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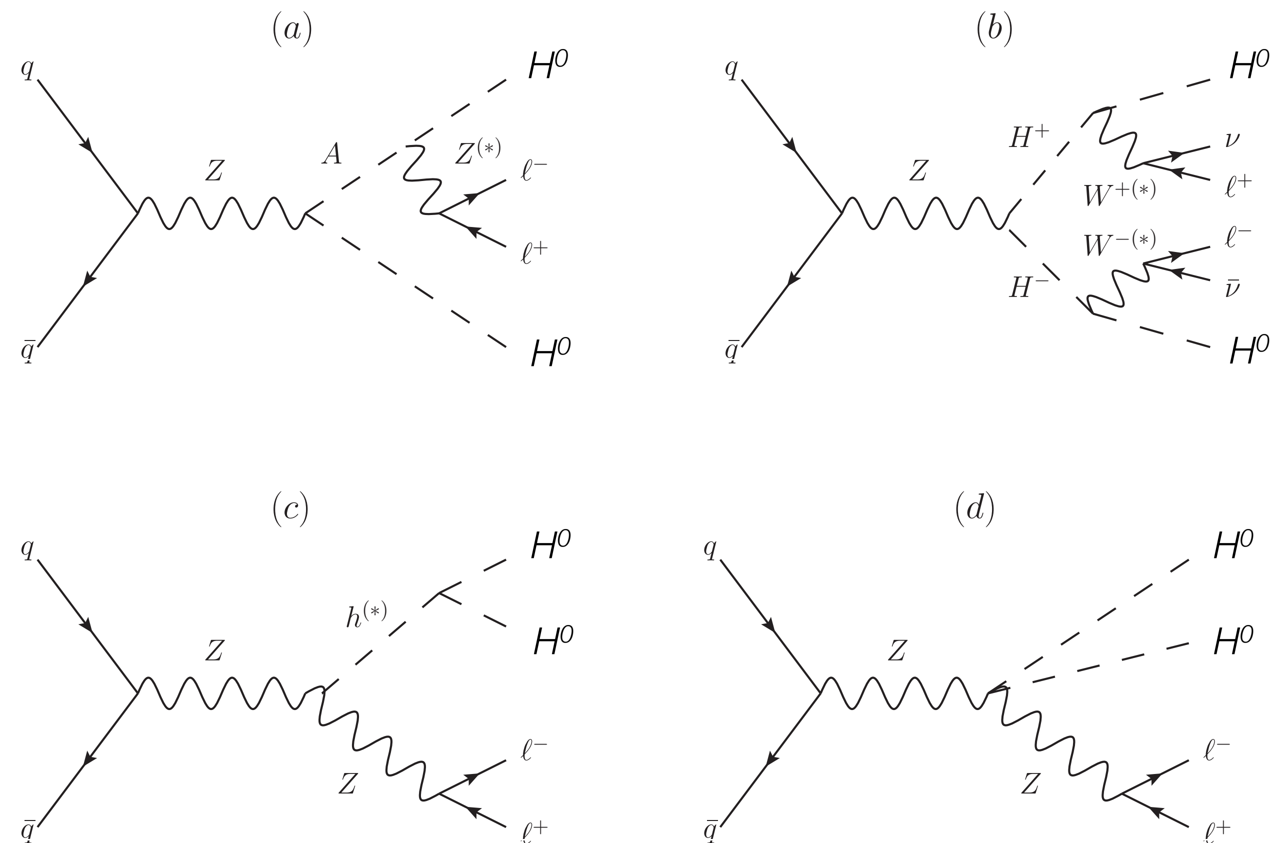

- Both ATLAS + CMS have searched for opposite-sign dileptons + E_T^{miss} at Run 1. While no interpretation was given for the IDM, note that
  - the **SUSY equivalent of process *(a)*** is $q\bar{q} \to \tilde{\chi}_2^0\tilde{\chi}_1^0$ with $\tilde{\chi}_2^0 \to Z^{(*)}\tilde{\chi}_1^0$
  - **process *(b)*** resembles the signature of chargino-pair production $\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$
  - **process *(c)*** is Zh production with h→inv.; (also *(a)* can look like Zh, h→inv.)
  - processes *(c)* and *(d)* are negligible, contribution from *(b)* is small.

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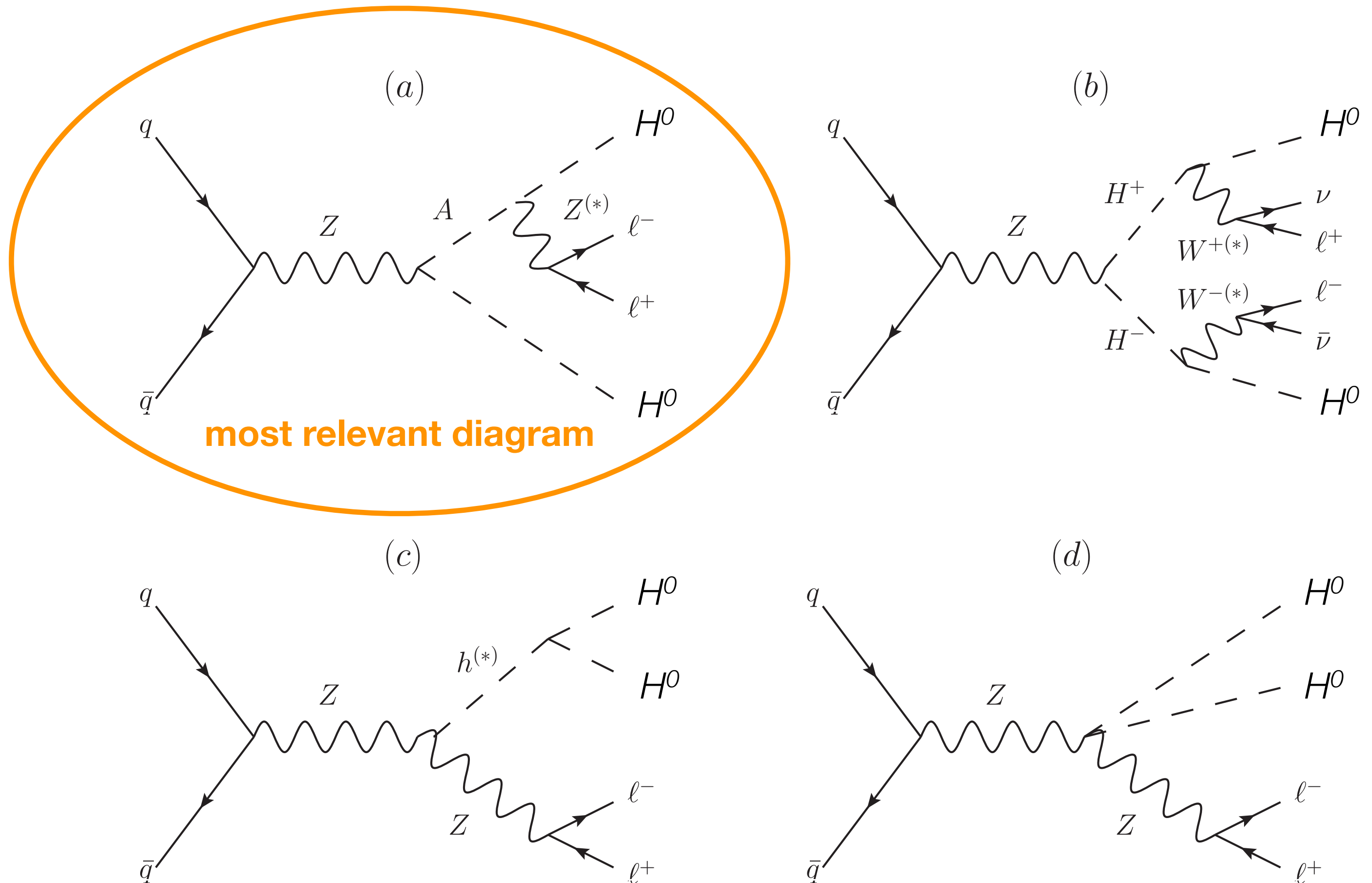

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Recasting l^+l^- + E_T^{miss} analyses for the IDM

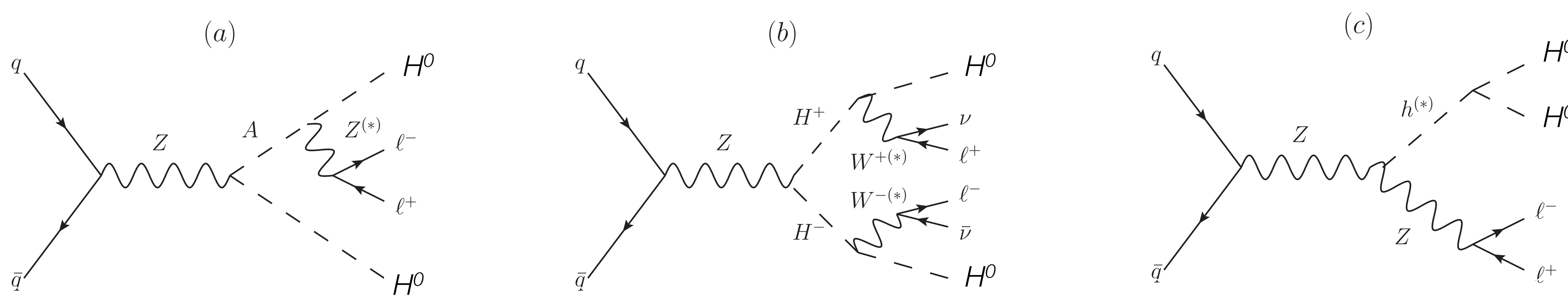
- **Implemented 2 ATLAS dilepton analyses** in the MA5 PAD
  (PAD = Public Analysis Database)

  - **SUSY-2013-11: Chargino, neutralino and slepton search** **[arXiv:1403.5294]**

    Various signal regions optimized for chargino, neutralino, slepton signals or mass regions; all leptonic signal regions regions require $|m_{ll} - m_Z| > 10$ GeV, i.e. on-shell Z bosons are vetoed; mostly relevant for $m_A < m_H + m_Z$

  - **HIGG-2013-03: ZH → l^+l^- + inv. search** **[arXiv:1402.3244]**

    Requires $|m_{ll} - m_Z| < 15$ GeV ; can be matched onto processes (c) and (d), and for $m_{A0} - m_{H0} > m_Z$ also onto (a); relevant for $m_A > m_H + m_Z$



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Dumont, Fuks, SK et al, 1407.3278

Towards a public analysis database (PAD)

We think it would be of great value for the whole community to have a database of LHC analyses based on fast simulation.

→ we propose to create such a database using the MadAnalysis 5 framework

- Validated analysis codes, easy to check and to use for everybody.
- Can serve for the interpretation of the LHC results in a large variety of models.
- Convenient way of documentation; helps long-term preservation of the analyses performed by ATLAS and CMS.
- Modular approach, easy to extend, everybody who implements and validates an existing ATLAS or CMS analysis can publish it within this framework.
- Provides feedback to the experiments about documentation and use of their results. (The ease with which an experimental analysis can be implemented and validated may actually serve as a useful check for the experimental collaborations for the quality of their documentation.)

We are not the only ones

checkmate.hepforge.org

CheckMATE (**Check M**odels **A**t **T**erascale **E**nergies) is a program package which accepts simulated event files in many formats for any given model. The program then determines whether the model is excluded or not at 95% C.L. by comparing to many recent experimental analyses. Furthermore the program can calculate confidence limits and provide detailed information about signal regions of interest. It is simple to use and the program structure allows for easy extensions to upcoming LHC results in the future.

beta version of CheckMATE with 30 analyses [...] only partially validated so a test against the published results is recommended before using these in a real study.

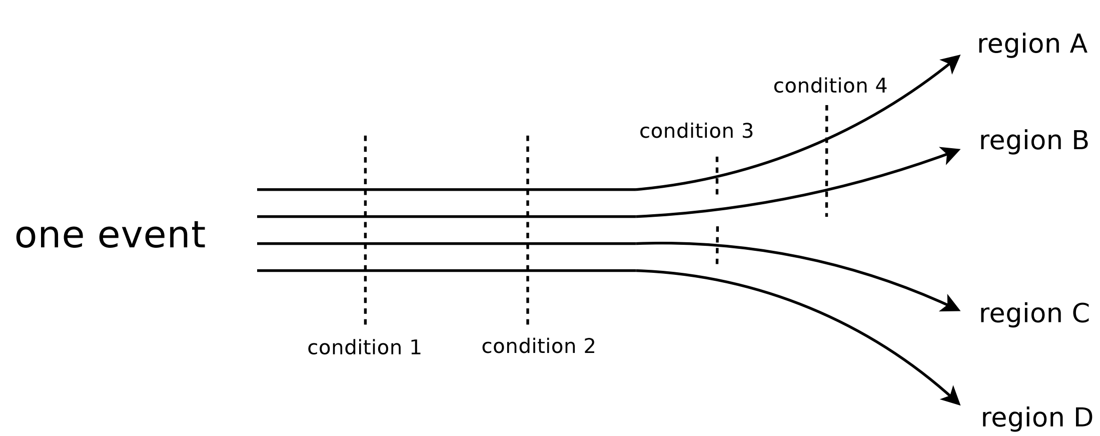
Manuel Drees,
Herbi Dreiner,
Daniel Schmeier,
Jamie Tattersall,
Jong Soo Kim,
arXiv:1312.2591

Other efforts: ATOM (based on the RIVET toolkit), GAMBIT, etc. are on the way but not public yet.

What is MadAnalysis 5 ?

E. Conte, B. Fuks, G. Serret, arXiv:1206.1599
E. Conte, B. Fuks, arXiv:1309.7831

- Public framework for analyzing Monte Carlo events
- Different levels of sophistication: partonic, hadronic, detector reconstructed
- Input formats: StdHep, HepMC, LHE, LHCO, Delphes ROOT files
- Emulation of detector response using DELPHES 3
- Normal mode: intuitive commands typed in the Python interface human-readable output: HTML and LaTeX
- Expert mode: C++/ROOT programming within the SampleAnalyzer framework
- Powerful tool, well-suited for phenomenological studies for particle colliders and for recasting LHC analyses (efficient treatment of different signal regions in the same analysis)



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

Analysis implementation and validation

1. Read and understand the experimental paper
2. Write the C++ analyzer code for MadAnalysis 5

reasonably **easy**

3. Get missing information from the experimental collaboration. Needed, but not always publicly available, are:

-essential- but often quite difficult

- efficiencies for trigger, electron, muons, b-tagging, event cleaning, ... treatment of ISR, jet energy scale } p_T dependence
- exact configuration of MC tools (versions, run card settings)
- benchmark points: SLHA, LHE files or other
- cut flows for the benchmark points
- expected final number of events in each signal region

4. Digitize the histograms from the experimental paper
(stupid work; direct numerical form would be highly welcome → HepData, Twiki !)

5. Produce your own cut flows and histograms and compare, improve and iterate until reasonable agreement is achieved

wiki: PublicAnalysisDatabase

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MadAnalysis 5 Public Analysis Database for recasting LHC results

ATLAS analyses, 8 TeV

Analysis	Short Description	Implemented by	Code	Validation note
ATLAS-SUSY-2013-05 (published)	stop/sbottom search: 0 leptons + 2 b-jets	G. Chalons	Inspire	PDF (figures)
ATLAS-SUSY-2013-11 (published)	EWK-inos, 2 leptons + MET	B. Dumont	Inspire	PDF (source)
ATLAS-HIGG-2013-03 (published)	ZH->ll+invisible	B. Dumont	Inspire	PDF (source)
ATLAS-EXOT-2014-06 (published)	mono-photons + MET	D. Barducci	Inspire	PDF MadGraph cards
ATLAS-SUSY-2014-10 (published)	2 leptons + jets + MET	B. Dumont	Inspire	PDF (source)
ATLAS-SUSY-2013-21 (published)	0 leptons + mono-jet/c-jets + MET	G. Chalons, D. Sengupta	Inspire	PDF (source)
ATLAS-SUSY-2013-02 (published)	0 leptons + 2-6 jets + MET	G. Chalons, D. Sengupta	Inspire	PDF

CMS analyses, 8 TeV

Analysis	Short Description	Implemented by	Code	Validation note
CMS-SUS-13-011 (published)	stop search in the single lepton mode	B. Dumont, B. Fuks, C. Wymant	Inspire [1]	PDF (source)
CMS-SUS-13-012 (published)	gluino/squark search in jet multiplicity and missing energy	S. Bein, D. Sengupta	Inspire	PDF (source)
CMS-SUS-13-016 (PAS)	search for gluinos using OS dileptons and b-jets	D. Sengupta, S. Kulkarni	Inspire	PDF (source)
CMS-SUS-14-001 (published)	Searches for third-generation squarks in fully hadronic final states (monojet analysis)	S. Sharma, S. Pandey	Inspire	PDF
CMS-B2G-12-012 (published)	T5/3 top partners in same-sign dilepton channel	D. Barducci, C. Delaunay	Inspire	PDF (source), cards

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

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MadAnalysis 5 Public Analysis Database for recasting LHC results

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ATLAS-SUSY-2014-10 (pub	[illegible]	[illegible]	[illegible]	PDF (source)
ATLAS-SUSY-2013-21 (pub	[illegible]	[illegible]	[illegible]	PDF (source)
ATLAS-SUSY-2013-02 (pub	[illegible]	[illegible]	[illegible]	PDF

open source project

everybody who implements an ATLAS or CMS analysis can contribute it to the PAD (validation note required)

CMS analyses, 8 TeV

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Recast codes individually published on InSpire

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MadAnalysis 5 implementation of ATLAS-SUSY-2013-11: di-leptons plus MET

Dumont, Beranger (LPSC, Grenoble)

Cite as: (2014) authors, http://doi.org/10.7484/INSPIREHEP.DATA.HLMR.T56W.2

Description: This is the MadAnalysis 5 implementation of the ATLAS search for direct production of charginos, neutralinos and sleptons in final states with two leptons and missing transverse momentum with 20.3/fb of data at 8 TeV, to be used for re-interpretation studies.

Note: Information how to use this code as well as a detailed validation summary are available at http://madanalysis.irmp.ucl.ac.be/wiki/PhysicsAnalysisDatabase. The ATLAS analysis is documented at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2013-11/

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citations can be followed here

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Sengupta, Dipan

Profile Name | Search

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2015-12-04 11:17:13

Personal Details (HepNames)

Name	Dipan Sengupta
Current Institution	LPSC, Grenoble
E-mail	dipan@lpsc.in2p3.fr
Fields	HEP-PH
Identifiers	BAI: D.Sengupta.1 INSPIRE: INSPIRE-00360133

Period	**Rank**	**Institution**
2009 – 2013	PHD	Tata Inst.
2013	PD	LPSC, Grenoble

Publications Datasets External

1. Confronting the Inert Doublet Model with results from Run 1 of the LHC
2. Revisiting LHC gluino mass bounds through radiative decays using MadAnalysis 5
3. Closing in on compressed gluino-neutralino spectra at the LHC
4. Probing the NMSSM via Higgs boson signatures from stop cascade decays at the LHC
5. Dilepton constraints in the Inert Doublet Model from Run 1 of the LHC
6. Toward a public analysis database for LHC new physics searches using MADANALYSIS 5
7. Les Houches 2013: Physics at TeV Colliders: New Physics Working Group Report
8. Probing the flavor violating scalar top quark signal at the LHC
9. Stop and sbottom search using dileptonic M_{T2} variable and boosted top technique at the LHC
10. Looking for an Invisible Higgs Signal at the LHC

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Sengupta, Dipan

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Personal Details (HepNames)

Name	Dipan Sengupta
Current Institution	LPSC, Grenoble
E-mail	dipan@lpsc.in2p3.fr
Fields	HEP-PH
Identifiers	BAI: D.Sengupta.1 INSPIRE: INSPIRE-00360133

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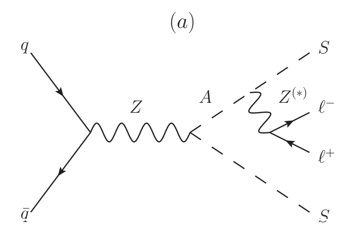
Publications | Datasets | External

1. Madanalysis 5 implementation of the ATLAS multi jet analysis documented in arXiv:1405.7875, JHEP 1409 (2014) 176
2. MadAnalysis 5 implementation of CMS-SUS-13-016
3. MadAnalysis 5 implementation of CMS-SUS-13-012
4. Madanalysis 5 implementation of the ATLAS monojet analysis documented in arXiv:1407.0608, Phys. Rev. D. 90, 052008

)

Recasting l^+l^- + E_T^{miss} analyses for the IDM

arXiv:1503.07367



- **Implemented 2 ATLAS dilepton analyses** in the MA5 PAD:
  - SUSY-2013-11: Chargino, neutralino and slepton search [arXiv:1403.5294]

    Various signal regions optimized for chargino, neutralino or slepton signals/mass regions; all leptonic signal regions regions require $|m_{ll} - m_Z| > 10$ GeV, i.e. on-shell Z bosons are vetoed
  - HIGG-2013-03: ZH → l^+l^- + inv. search [arXiv:1402.3244]

    Requires $|m_{ll} - m_Z| < 15$ GeV ; can be matched onto *(c)* and *(d)*, and for $m_{A0} - m_{H0} > m_Z$ also onto *(a)*

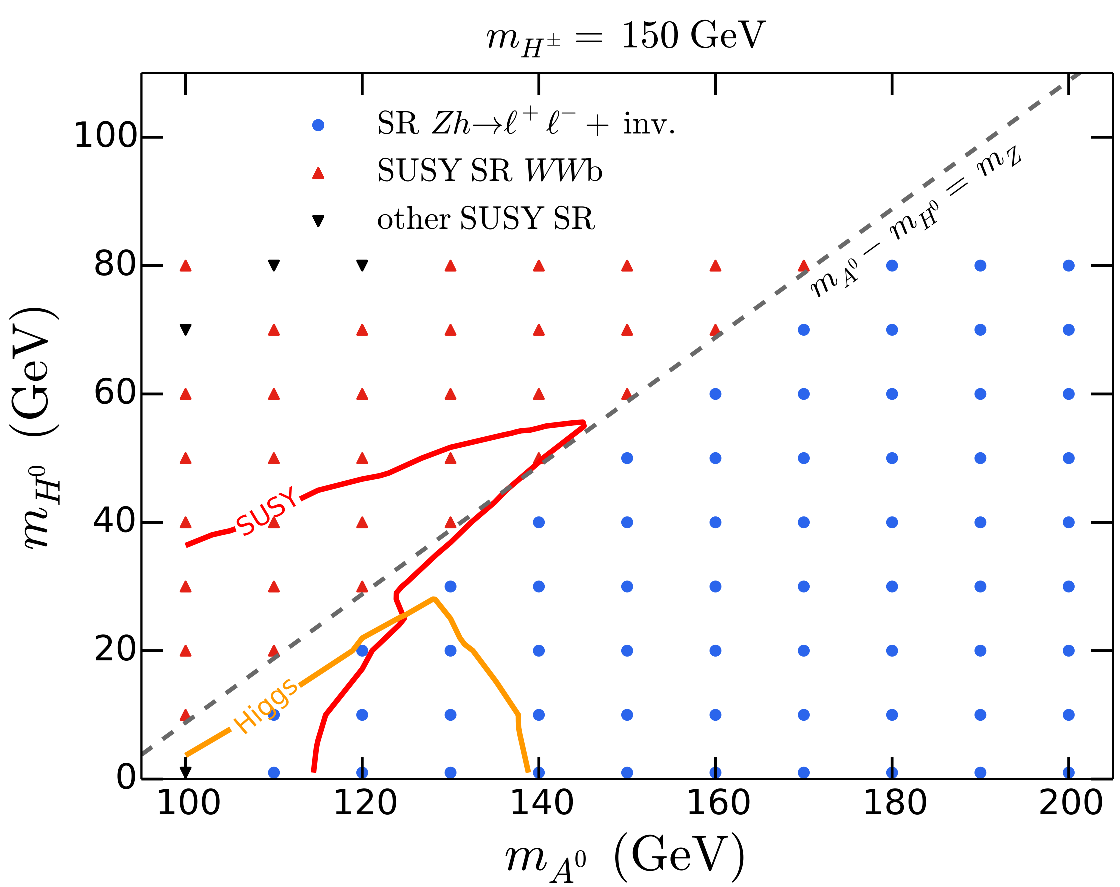
- The MadAnalysis 5 codes and detailed validation notes are **publicly available**

  10.7484/INSPIREHEP.DATA.HLMR.T56W.2
  10.7484/INSPIREHEP.DATA.RT3V.9PJK

- **Simulated signal in (m_{H0}, m_{A0}) plane** for fixed $m_{H\pm}$ and $\lambda_L = 0$

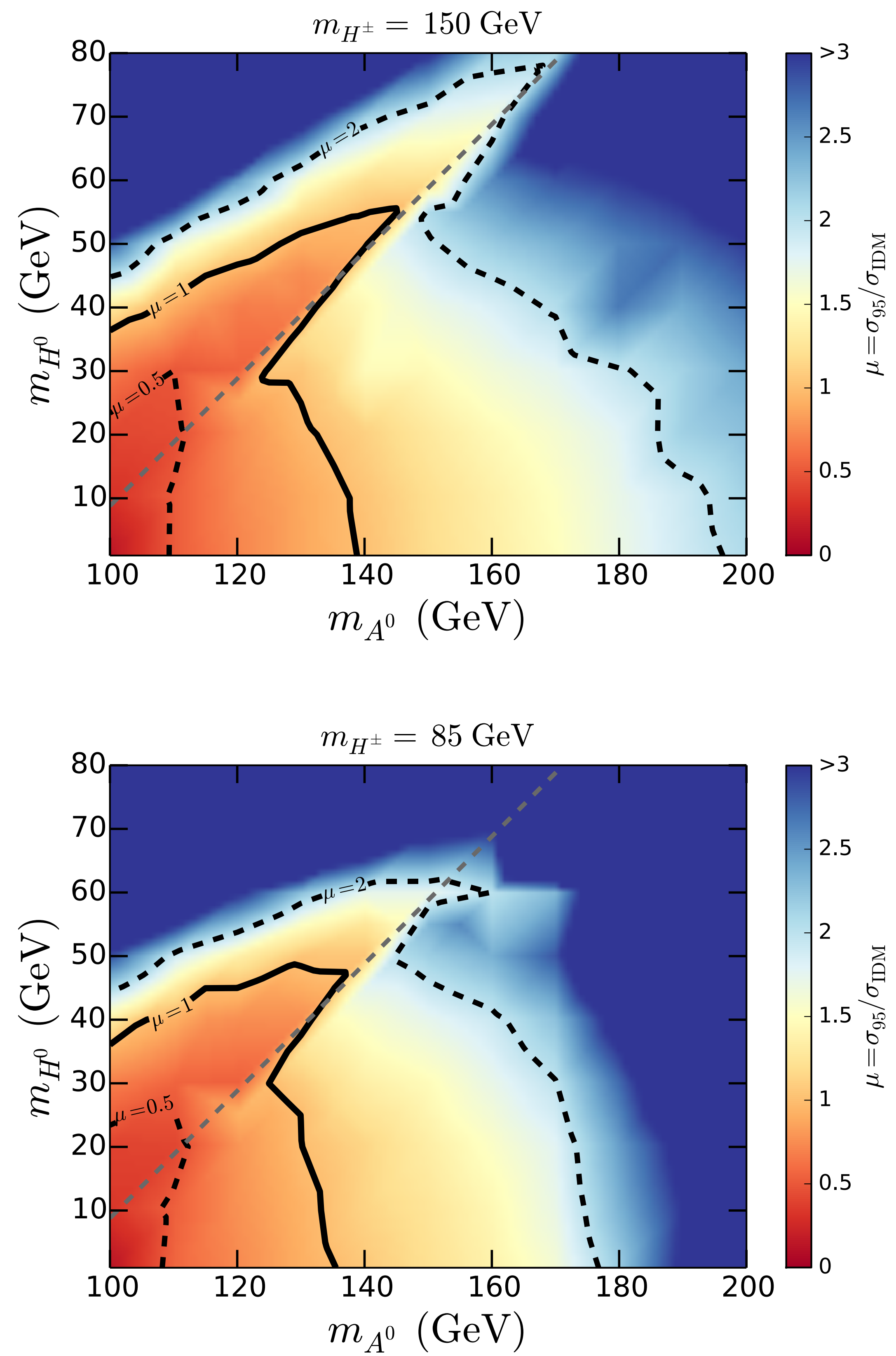
  MadGraph5 + Feynrules + CalcHEP + Delphes3 + MadAnalysis5

- Background numbers taken from the experimental papers to compute CLs



Comments

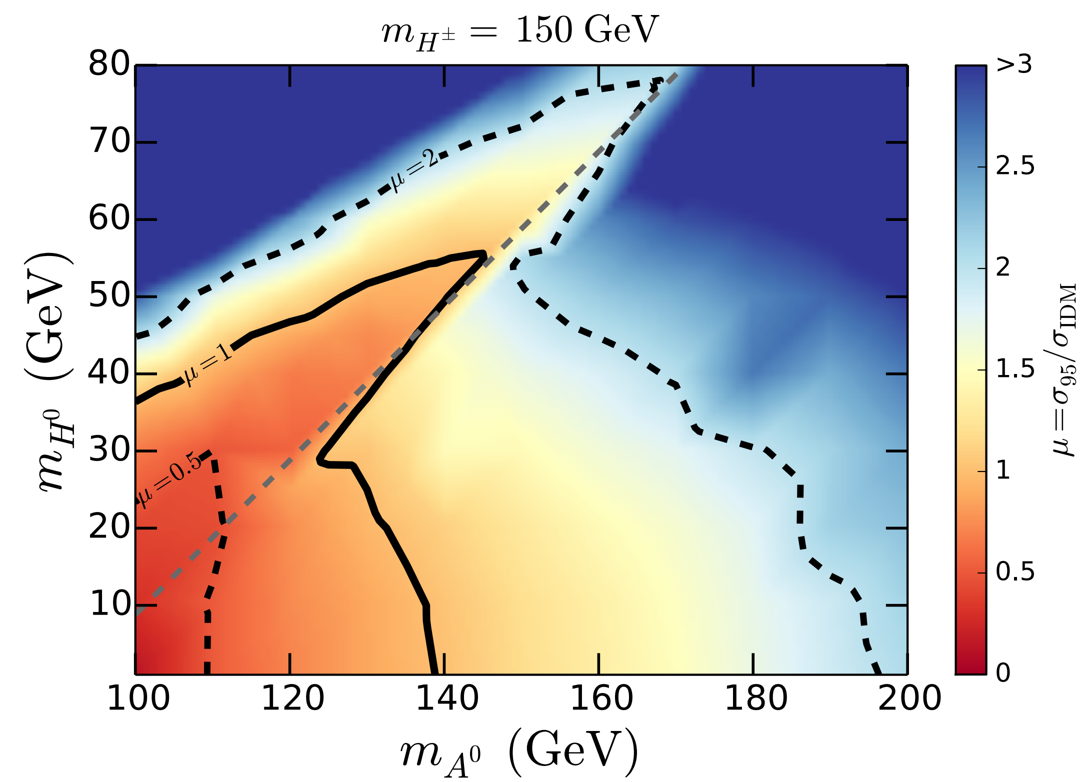
- The Run 1 ATLAS searches exclude, at 95% CL, $m_{H0} < 35$ GeV for $m_{A0} \approx 100$ GeV.
- The limit becomes stronger for heavier A^0, up to $m_{H0} \approx 45$-55 GeV for $m_{A0} \approx 140$-145 GeV (depending on $m_{H\pm}$)
- The m_{A0} dependence comes from the fact that the leptons from $A^0 \to ZH^0$, $Z \to l^+l^-$ are harder for heavier A^0.
  (and softer for lighter A^0 / smaller mass differences)
- $m_{H\pm}$ dependence: Xsection is larger for lighter $H^\pm$, but decay leptons are very soft and don't pass the signal selection cuts. Also, $A^0 \to WH^\pm$ competes with $A^0 \to ZH^0$, when kinematically allowed, reducing the signal.



Outlook for Run 2

- Naive rescaling of signal and BG numbers: at 13 TeV and L=100 fb^{-1} the 95% CL reach should go up to **$\mu \approx$ 1.2 (1.6)** above (below) the line of $m_A = m_H + m_Z$

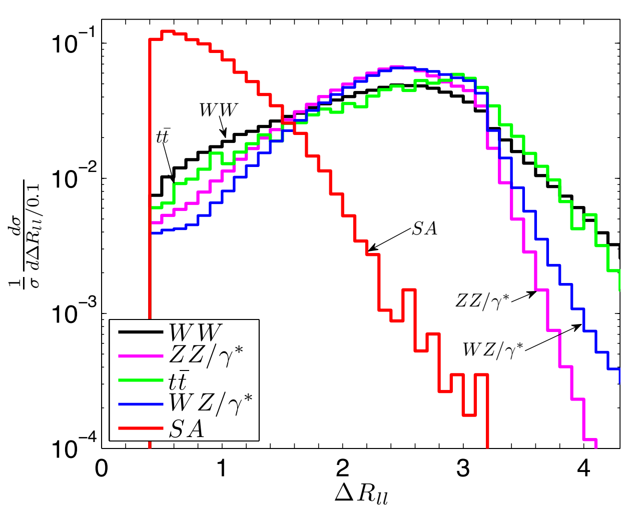
  → starts testing the funnel region $m_H \sim m_h/2$



- Exploration of benchmark points in 1508:0167 seems difficult → high luminosity option?

  Take point I with m_H = 57.5 GeV and m_A = 113 GeV: σ(pp→HA) = 371 fb but incl. BR(Z→ll)~7% and a cut acceptance of ~1% this reduces to ~0.25 fb visible XS

- The experimental analyses we recasted are not optimized for the IDM signal



Could improve sensitivity by exploiting angular separation of signal and backgrounds (cf. Dolle et al., 0909.0394)

Perhaps exploit m_{ll} inv. mass distribution?

→ **Dedicated analysis at Run 2 would be highly interesting**

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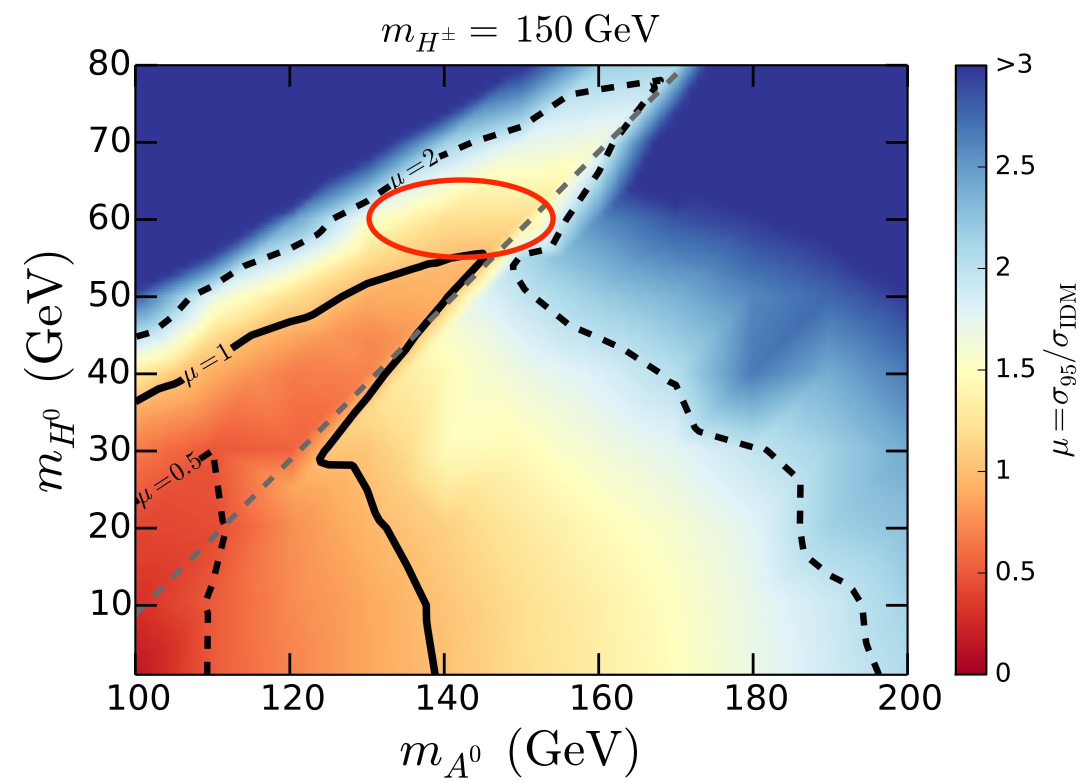

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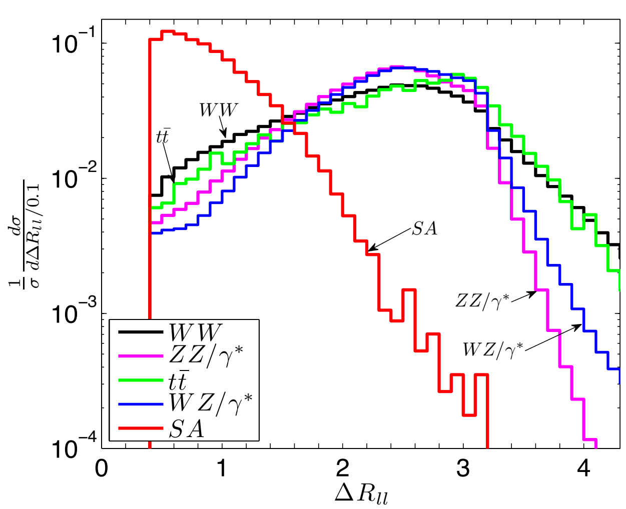

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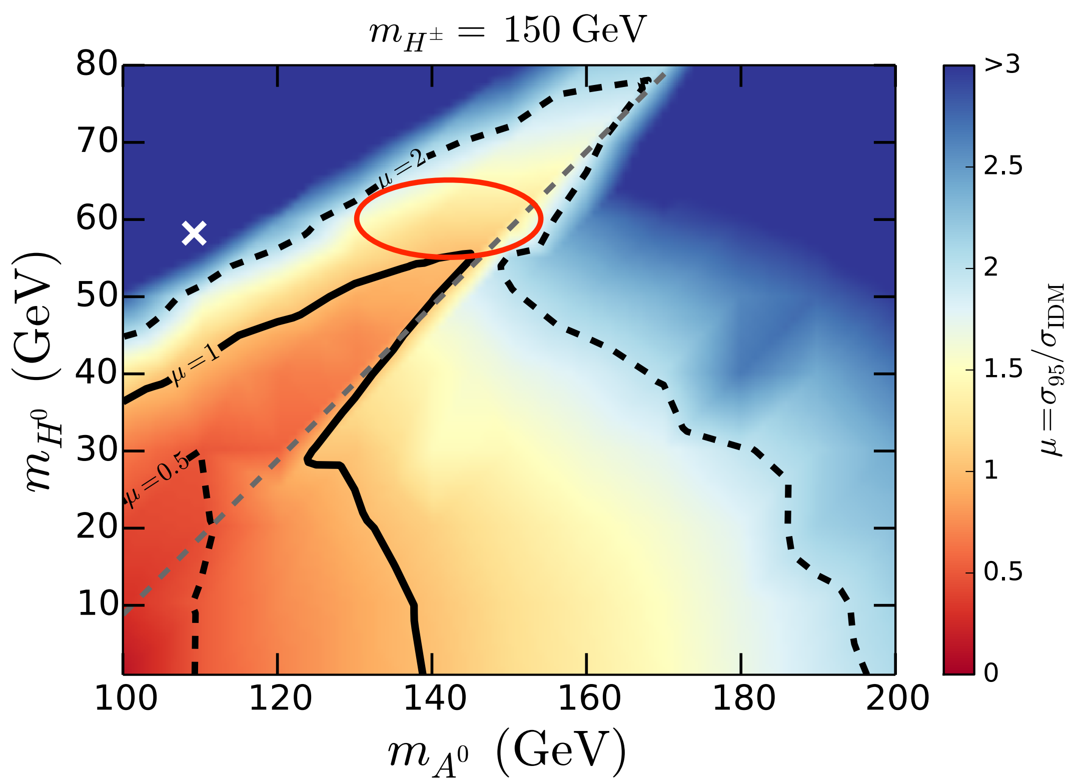

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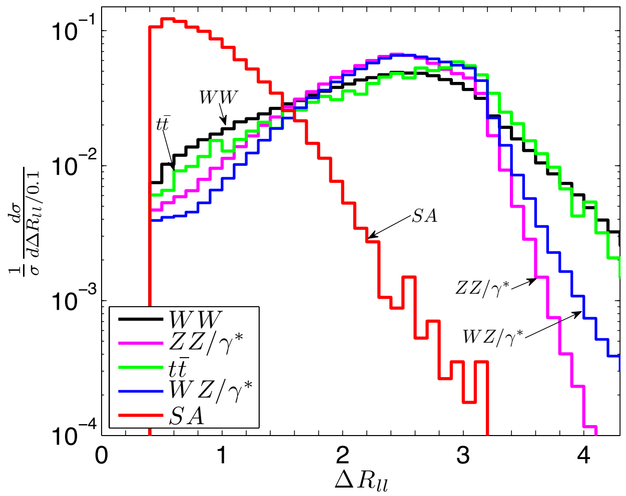

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To take home

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From Wikipedia, the free encyclopedia

> **Reproducibility** is the ability of an entire experiment or study to be reproduced, either by the researcher or by someone else working independently. It is one of the main principles of the scientific method [...]

thanks to*)

Daniele Barducci
Genevieve Belanger
Samuel Bein
Guillaume Chalons
Eric Conte
Cedric Delauney
Beranger Dumont
Benjamin Fuks
Andreas Goudelis
Bjorn Herrmann
Suchita Kulkarni
Shubham Pandey
Seema Sharma
Dipan Sengupta
Chris Wymant

*) in bold: IDM study

Backup

Public tools for the (re)interpretation of LHC results

Public tools are useful to and get tested by a large number of people. Helps remove bugs, and avoids to constantly re-invent the wheel. Currently on the market:

Simplified Models (SMS)

- SModelS: generic decomposition into SMS topologies; cross section upper limits from more than 50 ATLAS and CMS SMS results [SK et al., 1312.4175]
- Fastlim: reconstructs visible cross sections for SMS SUSY topologies from pre-calculated efficiency and cross section tables for 10 ATLAS analyses [Papucci et al., 1402.0492]
- XQCAT: determines exclusion CL for BSM scenarios with heavy extra quarks; efficiency maps for 7 CMS results [Barducci et al., 1409.3116]

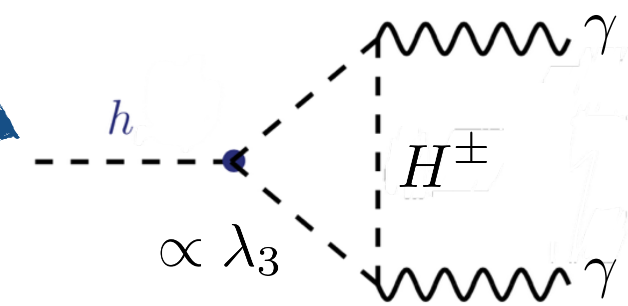
Event Simulation

- CheckMATE : checks 95% CL limits for simulated events of any model; currently has several ATLAS SUSY analyses implemented [Drees et al., 1312.2591]
- MadAnalysis5 PAD: public analysis database within the MadAnalysis5 framework; currently 7 ATLAS + 5 CMS analyses, more in progress [Dumont et al., 1407.3278]

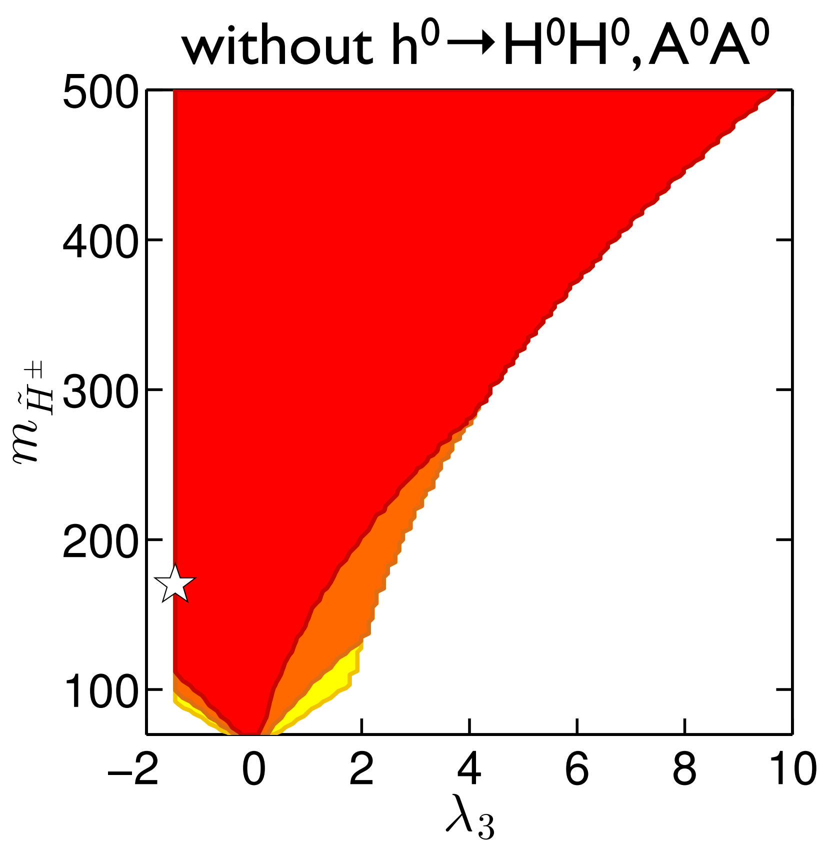
- Other efforts: ATOM (based on the RIVET toolkit), GAMBIT, etc. are on the way but not public yet.

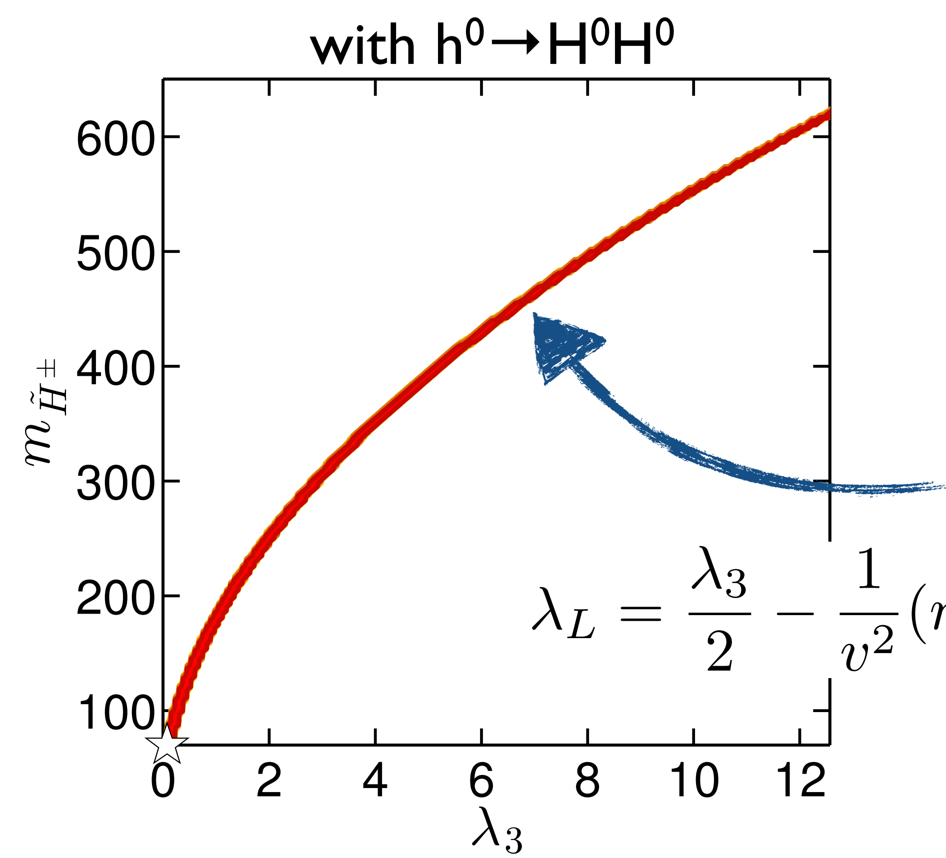
IDM: limits from invisible Higgs decays

couplings of the h^0: SM-like at tree-level
at loop-level: charged Higgs contribution to $h^0 \to \gamma\gamma$



from a global fit to the properties of the Higgs boson:
[G. Bélanger, BD, U. Ellwanger, J. F. Gunion, S. Kraml, arXiv:1306.2941]





$$\lambda_L = \frac{\lambda_3}{2} - \frac{1}{v^2}(m_{H^\pm}^2 - m_{H^0}^2)$$

ATLAS-SUSY-2013-11 cutflow (WWb signal region)

$\tilde{\chi}_1^+\tilde{\chi}_1^-$ (140/20) cutflow for SR WWbee				
cut	# events (scaled to σ and $\mathcal{L}$)	relative change	# events (official)	relative change (official)
Initial number of events	3375.0	3375.0		
2 OS leptons	545.8	−83.8%		
$m_{\ell\ell} > 20$ GeV	537.8	−1.5%		
τ veto	537.8	−0.0%		
ee leptons	132.4	−75.4%	139.6	139.6
jet veto	79.2	−40.2%	65.7	−52.9%
Z veto	67.3	−15.0%	55.5	−15.5%
$m_{T2} > 90$ GeV	5.3	−92.1%	4.5	−91.9%
$m_{\ell\ell} < 170$ GeV	4.3	−18.9%	3.9	−13.3%

ATLAS-SUSY-2013-11

[arXiv:1407.3278]

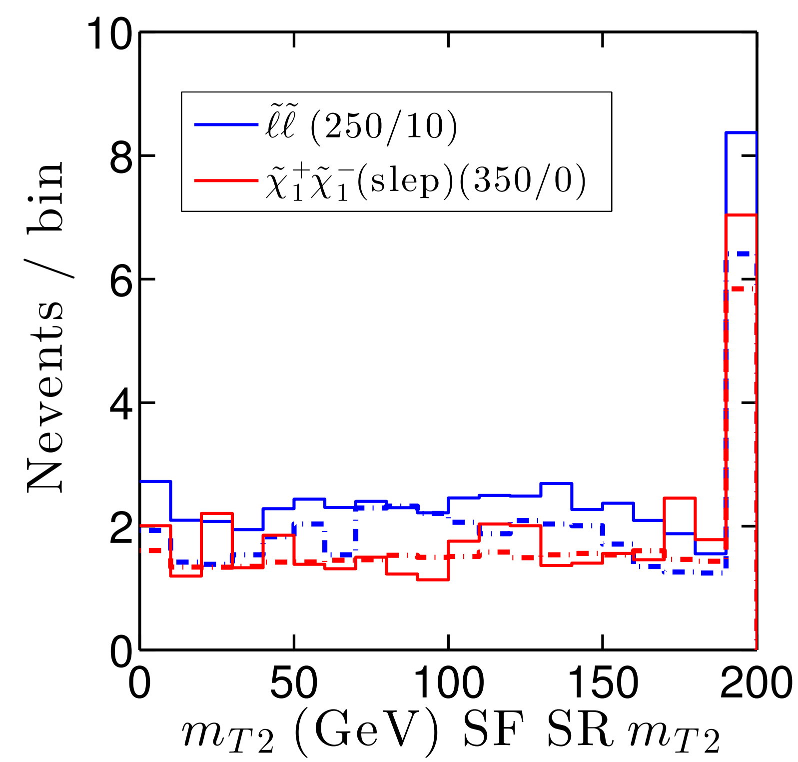
- ATLAS search for electroweak-inos and sleptons in the 2 lepton + MET final state

SR	m_{T2}^{90}	m_{T2}^{120}	m_{T2}^{150}	WWa	WWb	WWc	$Zjets$
lepton flavour	DF,SF	DF,SF	DF,SF	DF,SF	DF,SF	DF,SF	SF
central light jets	0	0	0	0	0	0	≥ 2
central b-jets	0	0	0	0	0	0	0
forward jets	0	0	0	0	0	0	0
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	> 10	> 10	> 10	> 10	> 10	> 10	< 10
$m_{\ell\ell}$ [GeV]	—	—	—	< 120	< 170	—	—
$E_T^{\text{miss,rel}}$ [GeV]	—	—	—	> 80	—	—	> 80
$p_{T,\ell\ell}$ [GeV]	—	—	—	> 80	—	—	> 80
m_{T2} [GeV]	> 90	> 120	> 150	—	> 90	> 100	—
$\Delta R_{\ell\ell}$	—	—	—	—	—	—	[0.3,1.5]
m_{jj} [GeV]	—	—	—	—	—	—	[50,100]

- SR-m_{T2} target:
  $pp \to \tilde{\ell}^+\tilde{\ell}^- \to \ell^+\tilde{\chi}_1^0\ell^-\tilde{\chi}_1^0$
  $pp \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to \ell^+\nu\tilde{\chi}_1^0\ell^-\nu\tilde{\chi}_1^0$
- SR-WW target:
  $pp \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to W^+\tilde{\chi}_1^0W^-\tilde{\chi}_1^0$
- SR-Zjets targets:
  $pp \to \tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to W^\pm\tilde{\chi}_1^0Z\tilde{\chi}_1^0$

- validation results include:

cut	ATLAS result	MA5 result
Initial number of events		152.2
2 OS leptons		46.9
$m_{\ell\ell} > 20$ GeV		46.9
τ veto		46.9
$\mu\mu$ leptons	16.4	24.2
≥ 2 central light jets	13.2	15.4
b and forward jet veto	9.5	12.4
Z window	9.1	11.6
$p_{T,\ell\ell} > 80$ GeV	8.0	10.1
$E_T^{\text{miss,rel}} > 80$ GeV	5.1	7.0
$0.3 < \Delta R_{\ell\ell} < 1.5$	4.2	5.9
$50 < m_{jj} < 100$ GeV	2.7	3.6
$p_T(j_1, j_2) > 45$ GeV	1.8	1.6



ATLAS-HIGG-2013-03

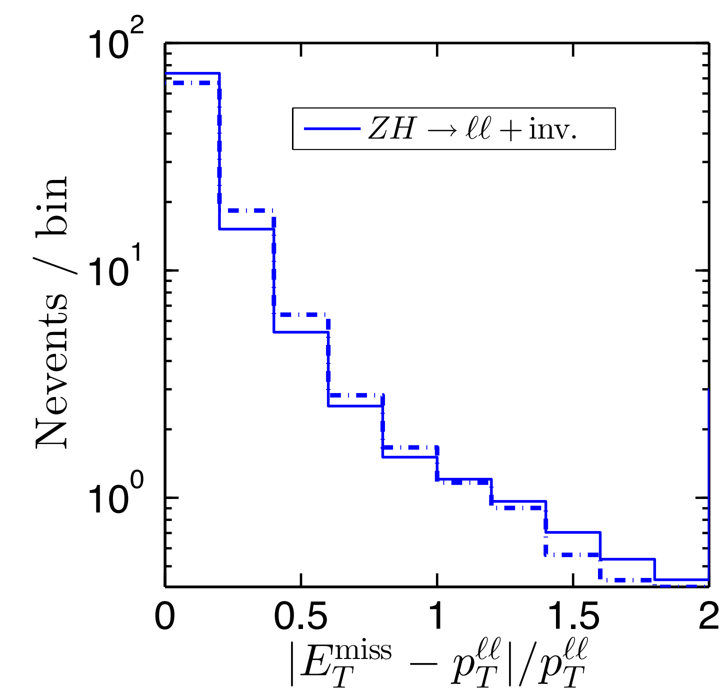
[arXiv:1402.3244]

- ATLAS search for invisible decays of the Higgs boson in the 2 lepton + MET final state

- only one SR, where it is required:
  - $|m_{\ell\ell} - m_{Z^0}| < 15$ GeV
  - $E_T^{\rm miss} > 90$ GeV
  - $\Delta\phi(p_T^{\ell\ell}, E_T^{\rm miss}) > 2.6$
  - $\Delta\phi(\ell, \ell) < 1.7$
  - $|E_T^{\rm miss} - p_T^{\ell\ell}|/p_T^{\ell\ell} < 0.2$
  - no jet
  - $\Delta\phi(E_T^{\rm miss}, p_T^{\rm miss}) < 0.2$ (avoid fake MET from misreconstructed energy in the calorimeter)

- validation results include:

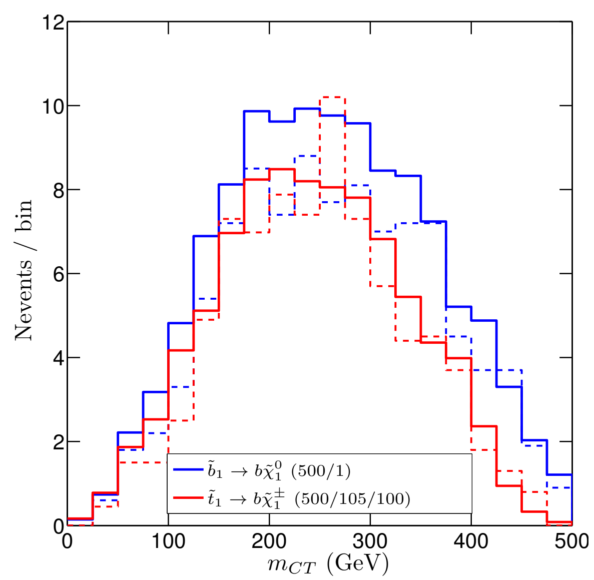
cut	ATLAS result	MA5 result
Initial number of events		838.9
2 OS leptons		256.2
$\lvert m_{\ell\ell} - m_{Z^0}\rvert < 15$ GeV	243	244.1
$E_T^{\rm miss} > 90$ GeV	103	105.1
$\Delta\phi(p_T^{\ell\ell}, E_T^{\rm miss}) > 2.6$		91.7
$\Delta\phi(\ell, \ell) < 1.7$		82.9
$\Delta\phi(E_T^{\rm miss}, p_T^{\rm miss}) < 0.2$		76.5
$\lvert E_T^{\rm miss} - p_T^{\ell\ell}\rvert/p_T^{\ell\ell} < 0.2$		63.2
jet veto	$44 \pm 1 \pm 3$	54.8



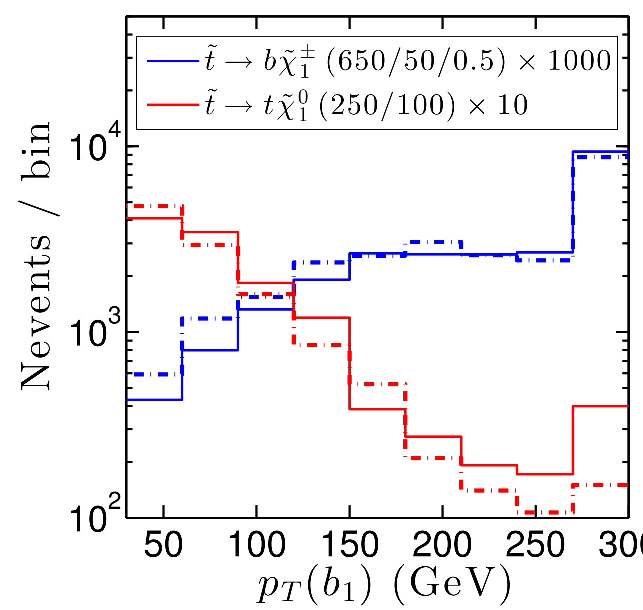
Validation: cut flows, distributions, limits

broken lines: official ATLAS or CMS results, full lines: MadAnalysis 5 results

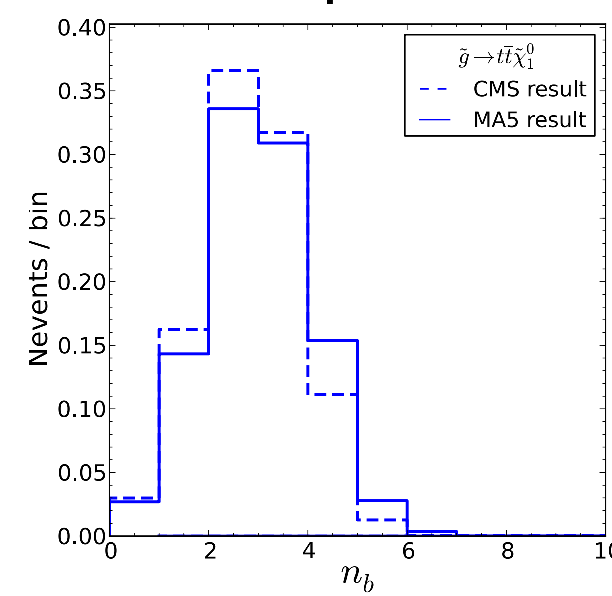
ATLAS 0 lepton 2b



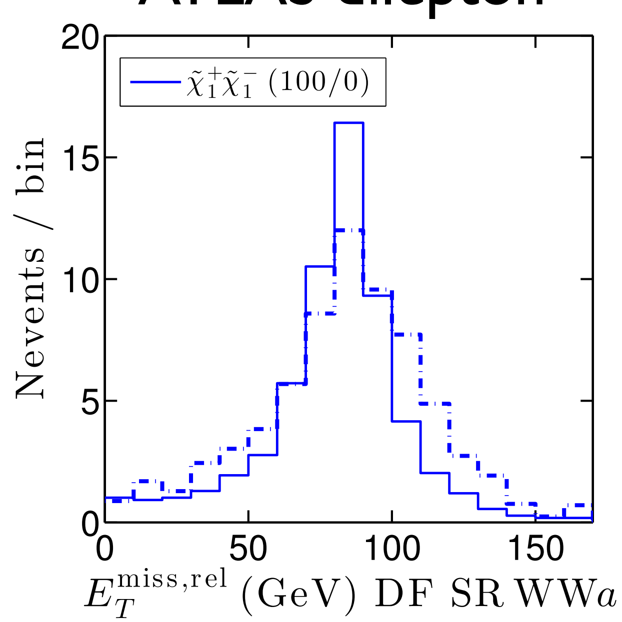
CMS 1 lepton



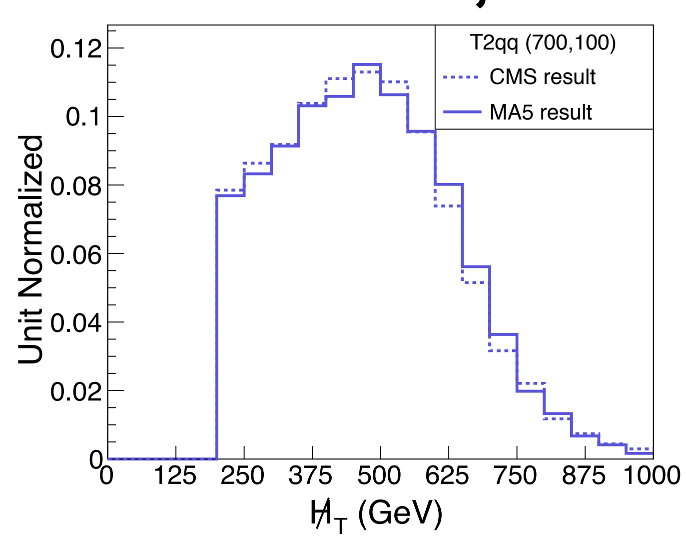
CMS dileptons + b's

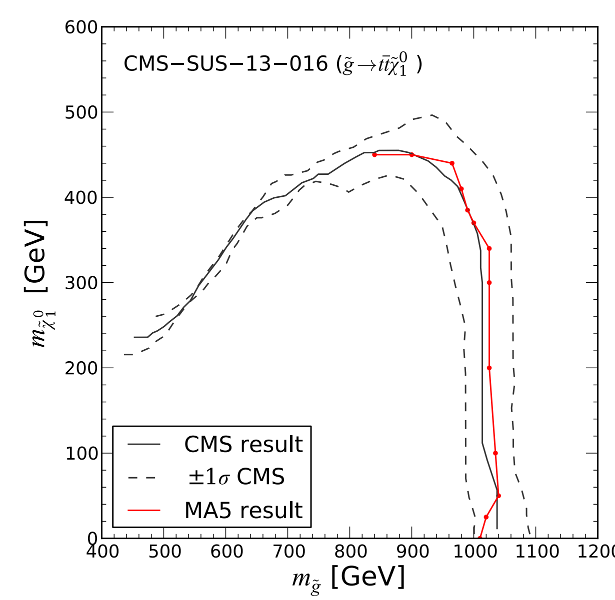


ATLAS dilepton



CMS multi-jet





10.7484/INSPIREHEP.DATA.922E.4BN6

Detailed validation notes

ATLAS-EXOT-2014-04 (mono-photon)

Cut	ATLAS	Rel. decr.	MA5 (ul ul~)	Rel. decr.
Nominal	9989		9989	
a. Trigger	8582			
b. Good Vertex	8574			
c. Cleaning cuts	8213			
0. $E_T^{\rm miss} > 150$ GeV	4131		4384	
1. 1 loose γ, $p_T > 125$ GeV, $\lvert\eta\rvert < 2.37$	2645	−36.0	2637	−39.8
2. Tight leading γ with $\lvert\eta\rvert < 1.37$	2068	−21.8	2052	−22.2
3. Isolated leading γ	1898	−8.2	1856	−9.6
4. $\Delta\phi(\gamma^{\rm leading}, E_T^{\rm miss}) > 0.4$	1887	−0.6	1840	−0.8
5. $N_{\rm jet} \leq 1$ and $\Delta\phi(jet, E_T^{\rm miss}) > 0.4$	1219	−35.4	1234	−33.0
6. Lepton veto	1188	−2.5	1233	−0.1

rescaling applied according to ATLAS numbers

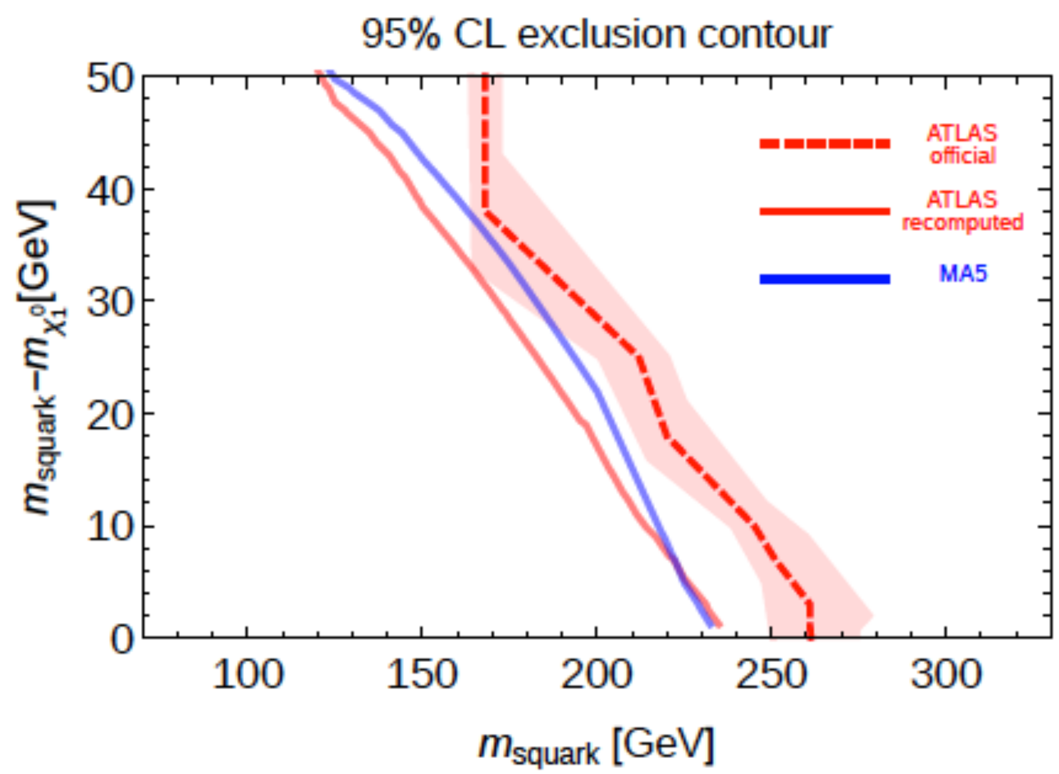
essential to see the step-by-step agreement

TABLE I: Cut flow for the nominal point with $m_{\tilde q} = 200$ GeV and $m_{\chi_1^0} = 195$ GeV, comparing our simulation to the official ATLAS results [5] for the case of pair production of first and second generation squarks. Reported are the absolute event numbers after each cut as well as the relative decreases in %.

Also reproduced efficiency maps from the ATLAS publication.

Done by Daniele Barducci (LAPTh) with help from Marie-Helene Genest (ATLAS)

[missing information concerned mainly the MC setup]



Wish / check list – what is needed for each 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 directly 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

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to assess the quality of the recast code it is important to precisely reproduce the signal generation of the collaboration

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unfortunately, the available validation material is still often insufficient

Example for missing information

ATLAS-EXOT-2013-10
(mono-lepton search)

- **Monte Carlo Simulation**

“The W′ signal events are generated at leading order (LO) with Pythia v8.165 [35, 36] using the MSTW2008 LO [37] parton distribution functions (PDFs). Pythia is also used for the fragmentation and hadronisation of $W^* \to \ell\nu$ events that are generated at LO with CalcHEP v3.3.6 [38] using the CTEQ6L1 PDFs [39]. DM signal samples are generated at LO with Madgraph5 v1.4.5 [40] using the MSTW2008 LO PDFs, interfaced to Pythia v8.165.”

“For all samples, final-state photon radiation from leptons is handled by Photos [48].”

The relevant **run cards/input files would be very helpful**
to precisely reproduce the signal generation

- **Cut flows**

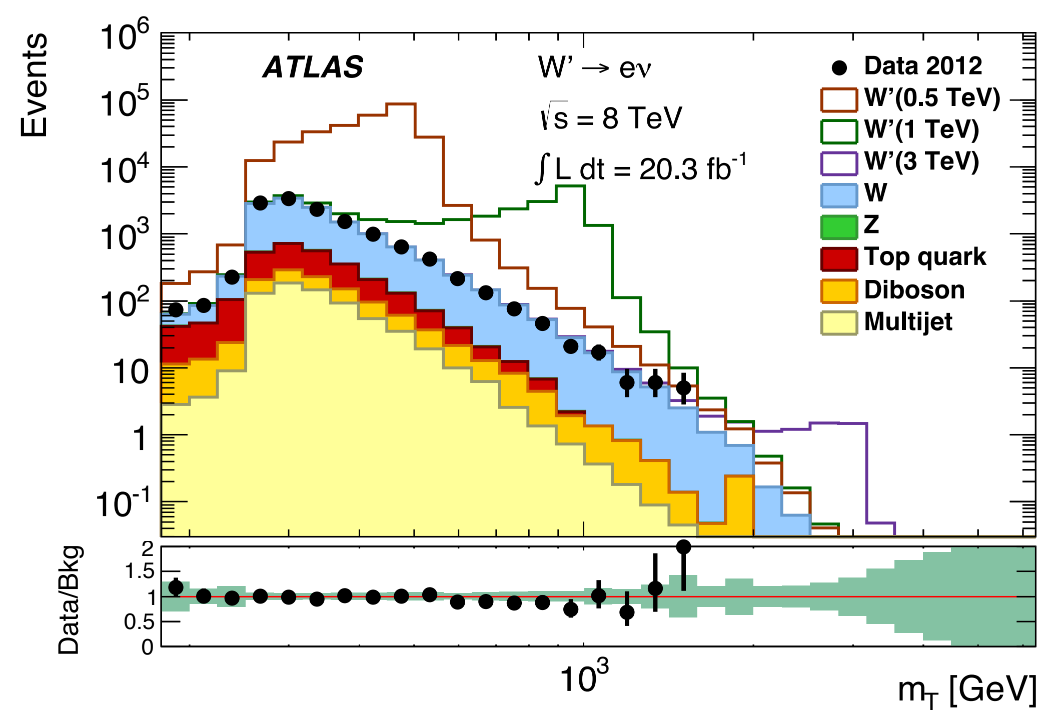
None available

- **Kinematic distributions**

In principle available in Figure 1.

However, only background distributions are on HEPDATA, not the signal ones.

Log-scale plot is difficult to digitize.

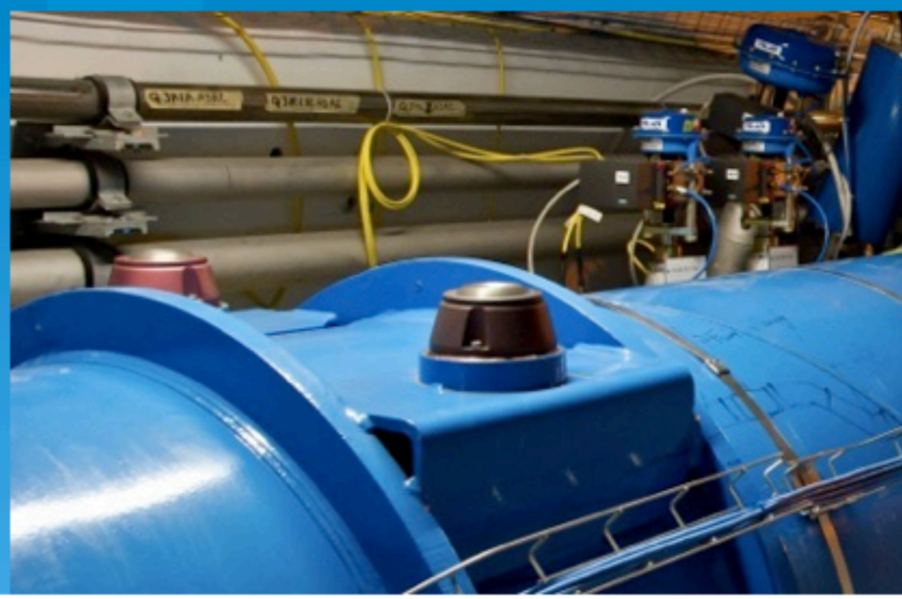


The RECAST initiative [by Kyle Cranmer]

recast.perimeterinstitute.ca

RECAST [beta]

Home | Analyses Catalog | Requests | About | Developers | News | Help



Anyone can upload alternative signals in the LHE format and *request* that any given analysis is "recast" for their alternative model.

Experimentalists can accept the request, process these alternative signals with the full simulation, reconstruction, and analysis selection.

Latest Requests

Request	Analysis	Model	Status
1408.0043	Search for direct third-generation squark pair production in final states with missing transverse momentum and two b-jets in $\sqrt{s}$= 8 TeV pp collisions with the ATLAS detector	3-body decay of sbottom into b-quark and two invisible final states	Active
1408.0042	Search for direct top-squark pair production in final states with two leptons in pp collisions at sqrt(s)=8TeV with the ATLAS detector	3-body decay of stop into top and two invisible final states	Active
1408.0041	Search for direct pair production of the top squark in all-hadronic final states in proton-proton collisions at $\sqrt{s}$=8 TeV with the ATLAS detector	3-body decay of stop into top and two invisible final states	Active
1408.0040	Search for direct third-generation squark pair production in final states with missing transverse momentum and two b-jets in $\sqrt{s}$= 8 TeV pp collisions with the ATLAS detector	3-body decay of sbottom into b-quark and two invisible final states	Cancelled

None the less, theorists want -and need!- to do their own studies

(question of time; treat several analyses simultaneously, incl. CMS ones; not everything merits full sim, ...)