Dilepton constraints in the Inert Doublet Model from Run 1 of the LHC

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G. Belanger, B. Dumont, A. Goudelis, B. Herrmann, SK, D. Sengupta

arXiv:1503.07367

SUSY 2015, Aug 23-29, Lake Tahoe, California

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**.

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

- **Scalar potential**

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

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

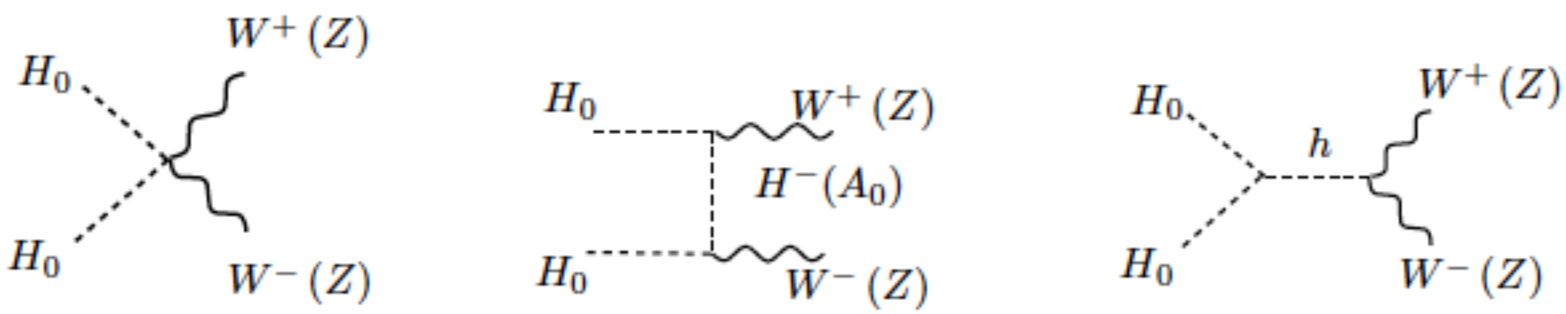
$$\lambda_{L,S} = \frac{1}{2}\left(\lambda_3 + \lambda_4 \pm \lambda_5\right)$$

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

DM annihilation channels

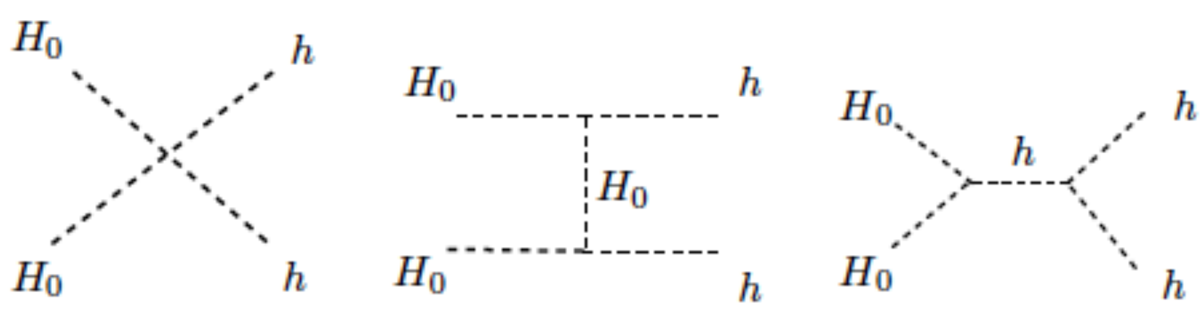
(taking H^0 as the DM candidate)



g^2 g^2 $\lambda_L g$

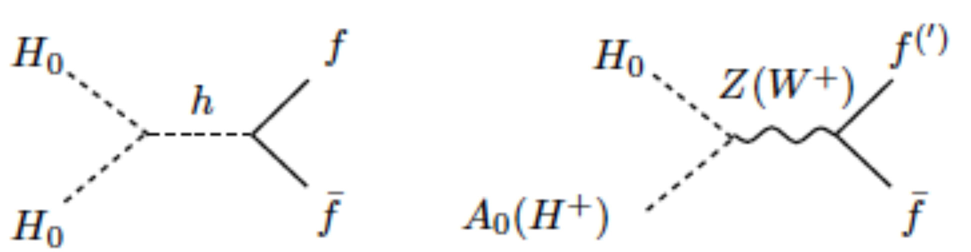
annihilation into gauge bosons

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



λ_L λ_L^2 $\lambda_L \lambda_1$

annihilation into Higgs



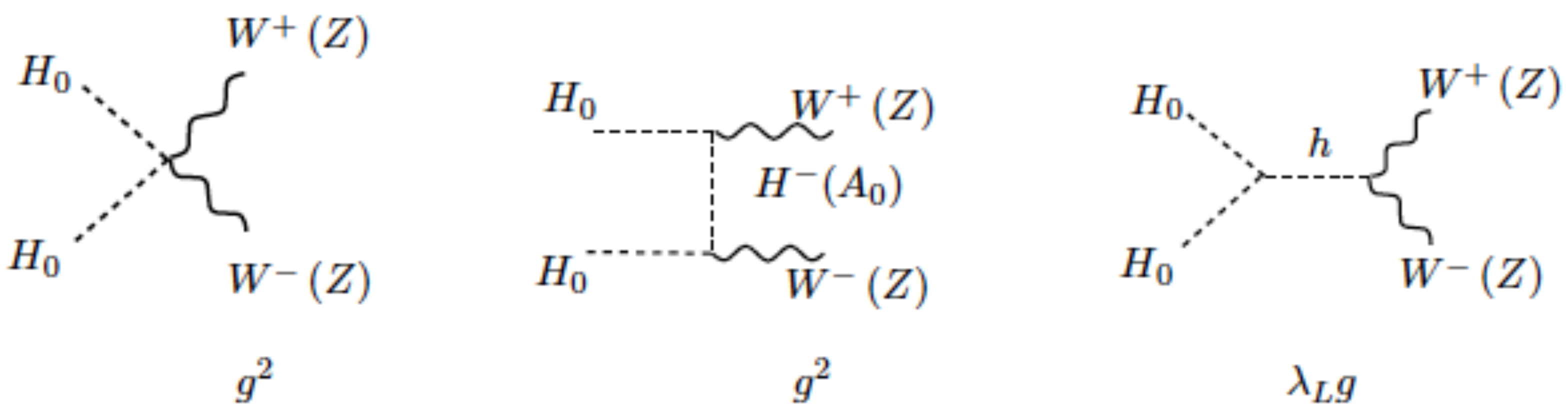
$\lambda_L y_f$ g^2

annihilation into fermions

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

DM annihilation channels

(taking H^0 as the DM candidate)



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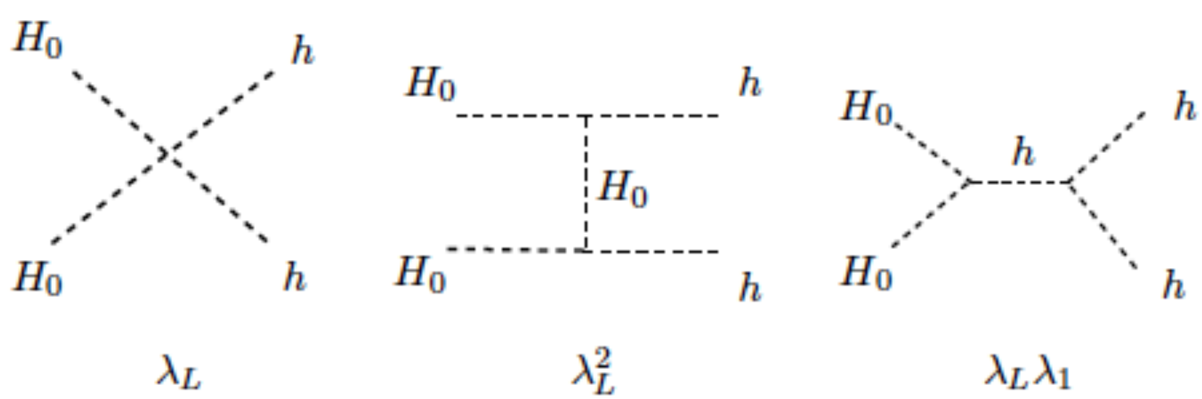

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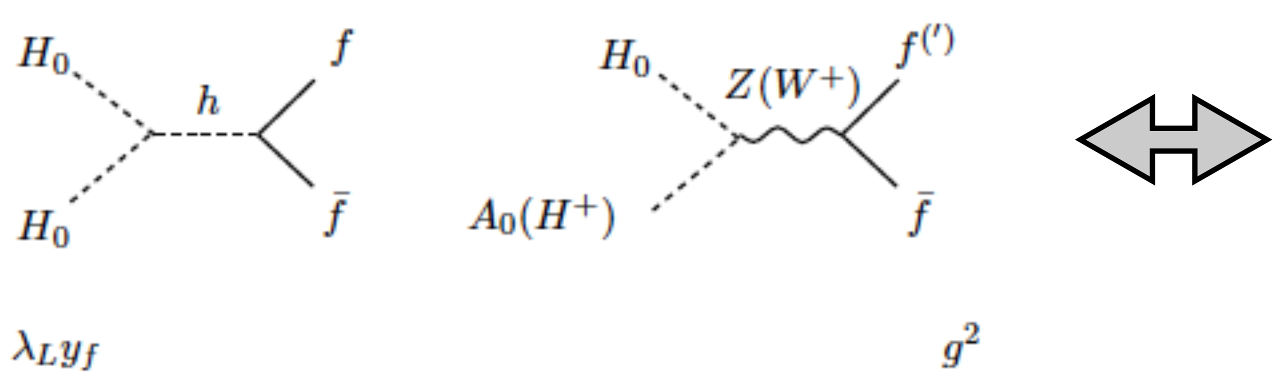
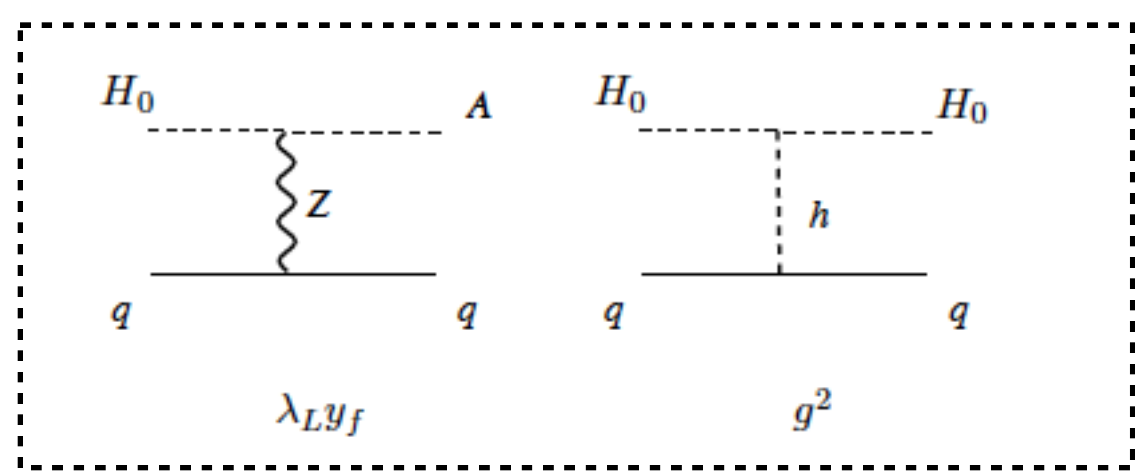


Direct DM detection



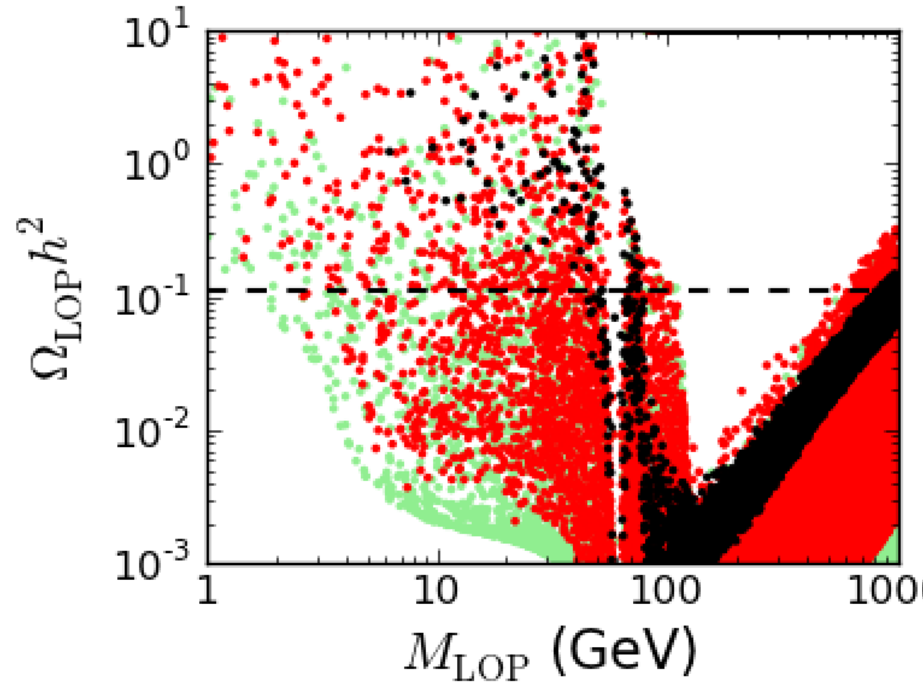
Constraints on the model

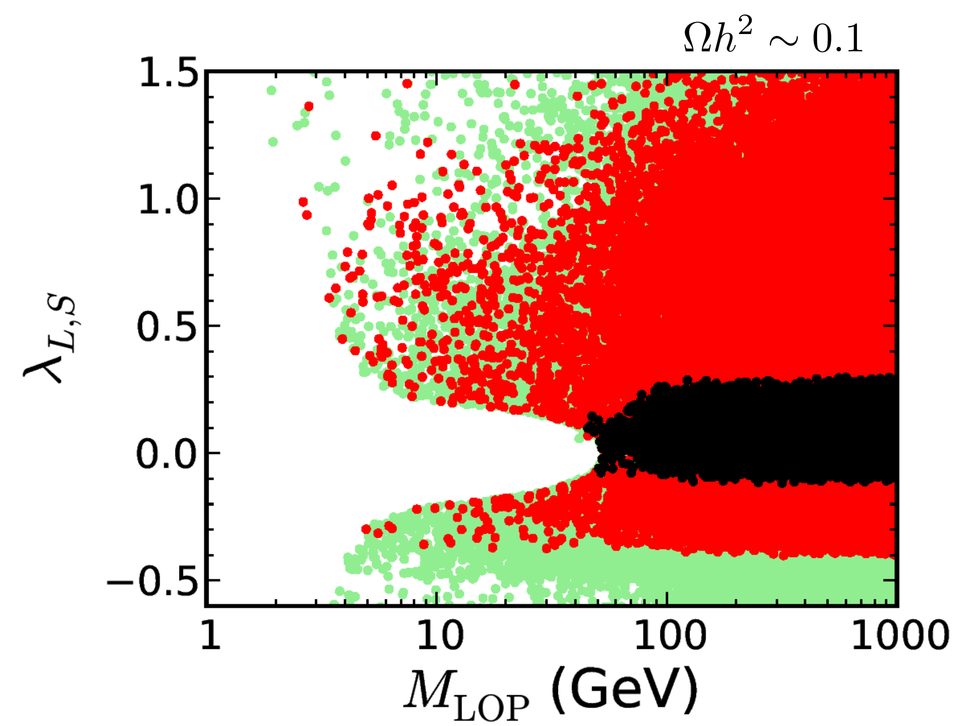
- **Stability** of the EW vacuum

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

- **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 .

LOP = lightest odd particle





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]

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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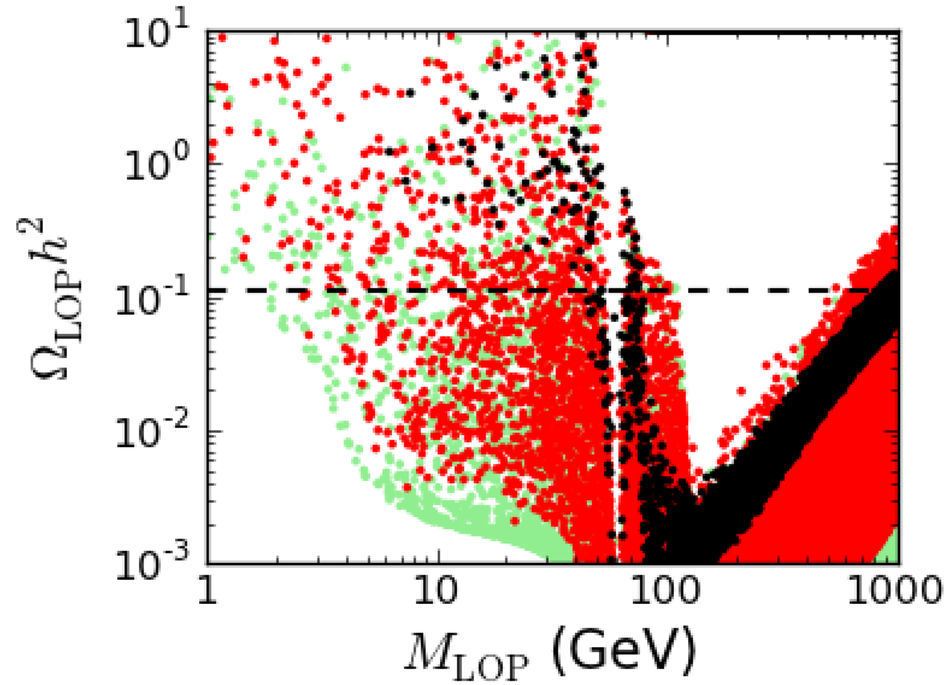
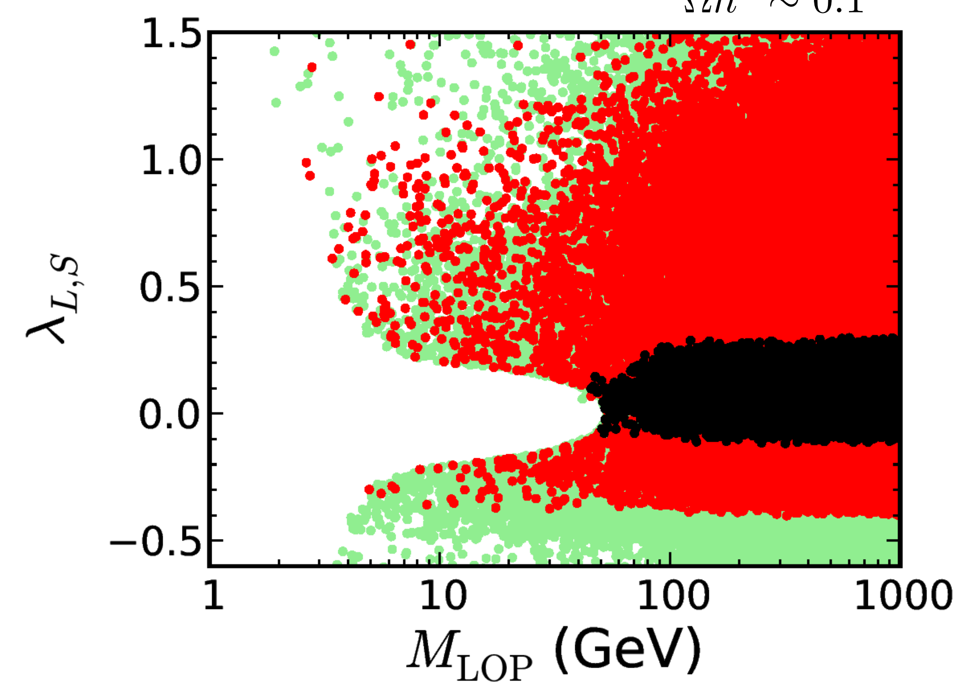


$\Omega h^2 \sim 0.1$



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see also Ilnicka, Krawczyk, Robens, 1508.01671

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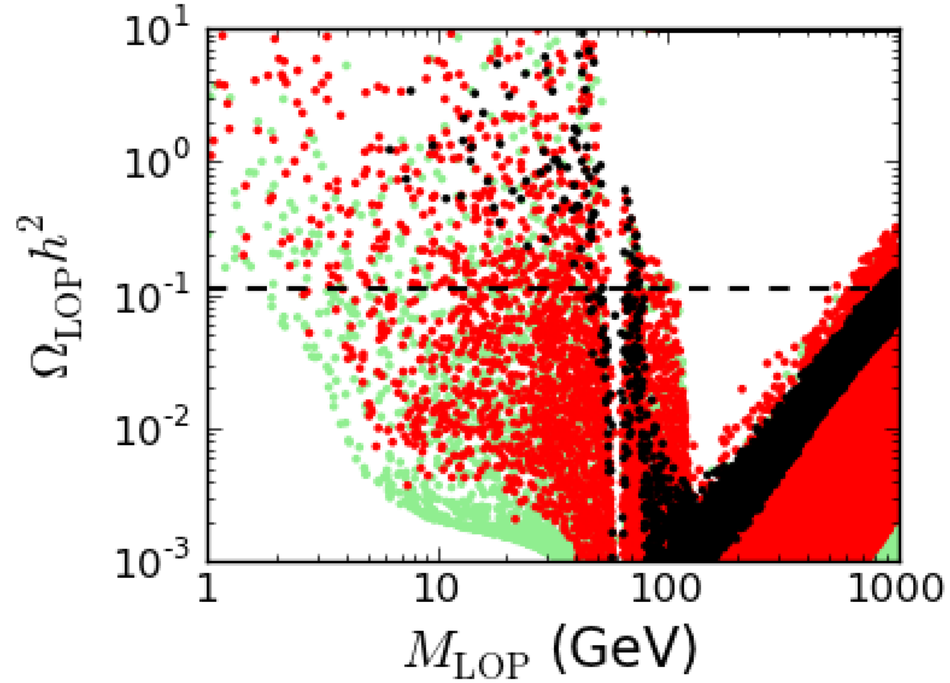

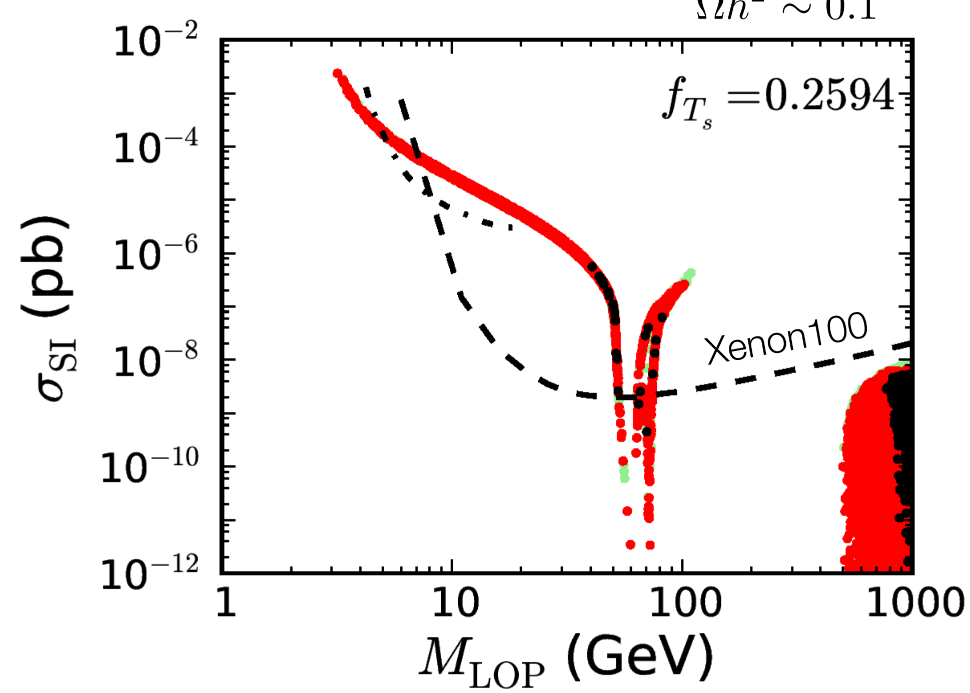

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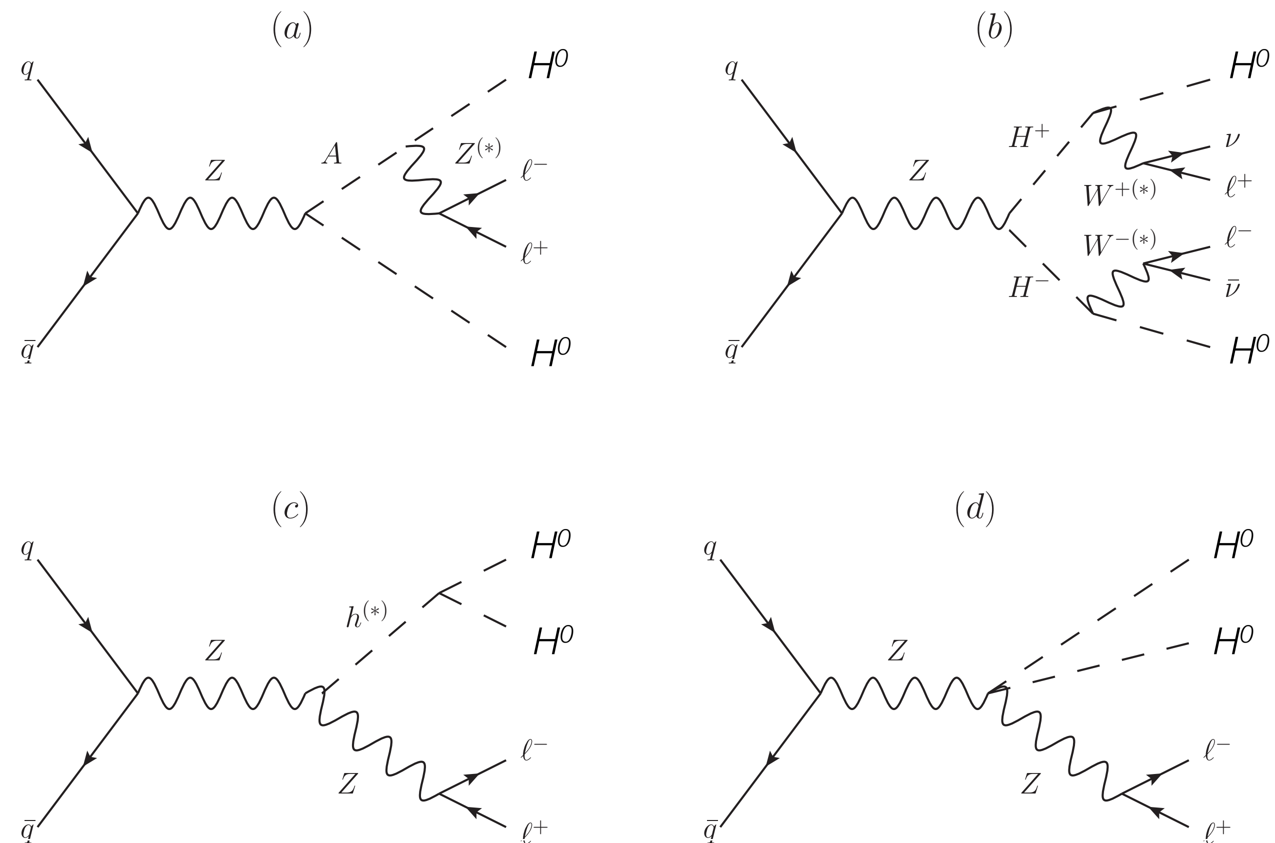
- **All constraints coming from invisible Higgs decays or from direct detection experiments vanish in the limit $\lambda_L \to 0$.**
- In the "vanilla picture" of the thermal history of the Universe, vanishing λ_L leads to an overabundance of DM. However, various possibilities exist to eventually dilute 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



$$q\bar{q} \to \tilde{\chi}_2^0 \tilde{\chi}_1^0 \qquad \tilde{\chi}_2^0 \to Z^{(*)} \tilde{\chi}_1^0$$
$$\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$$

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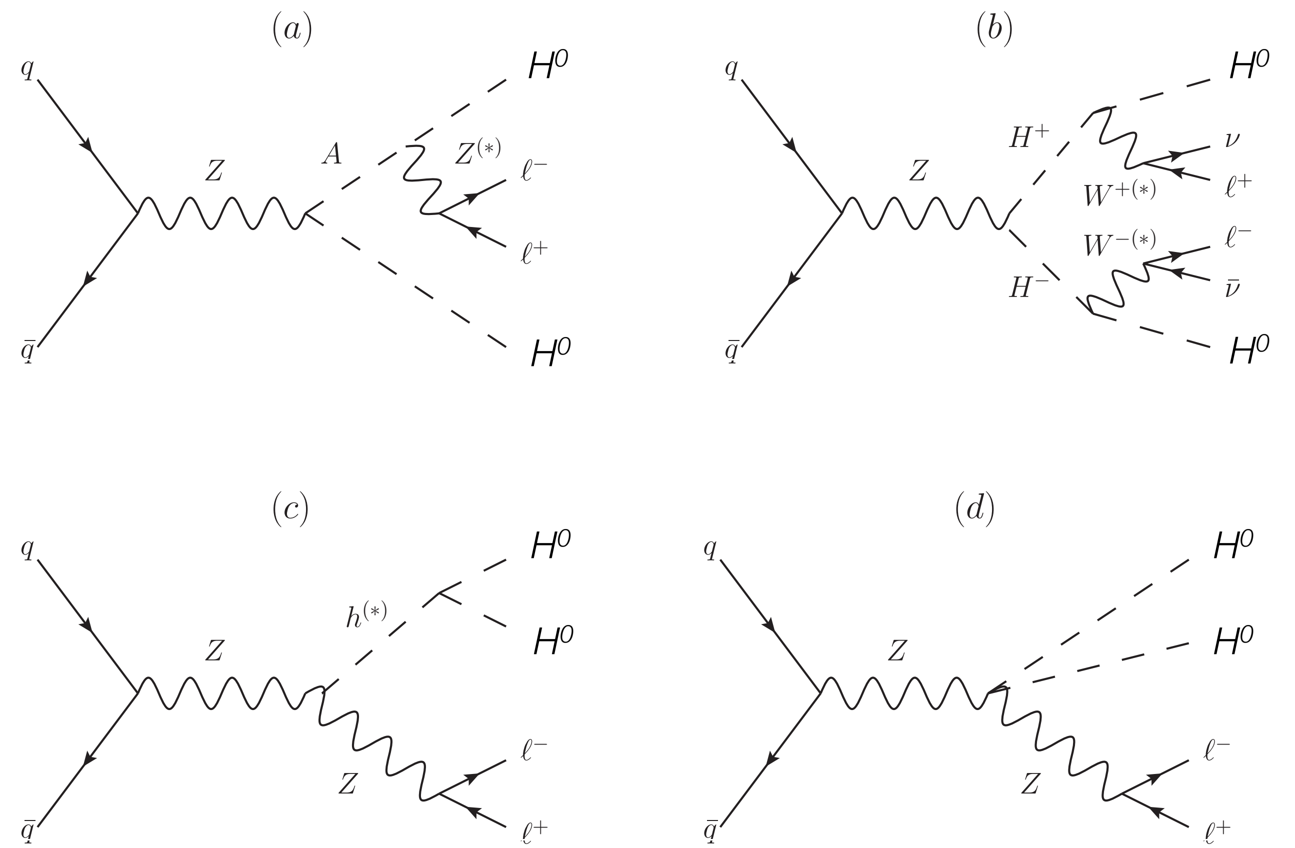

- Both ATLAS + CMS have searched for opposite-sign dileptons + E_T^{miss} at Run 1. While no interpretation was given for the IDM, note that
  - the **SUSY equivalent of process *(a)*** is $q\bar{q} \to \tilde{\chi}^0_2\tilde{\chi}^0_1$ with $\tilde{\chi}^0_2 \to Z^{(*)}\tilde{\chi}^0_1$
  - **process *(b)*** resembles the signature of chargino-pair production $\tilde{\chi}^\pm_1 \to W^\pm\tilde{\chi}^0_1$
  - **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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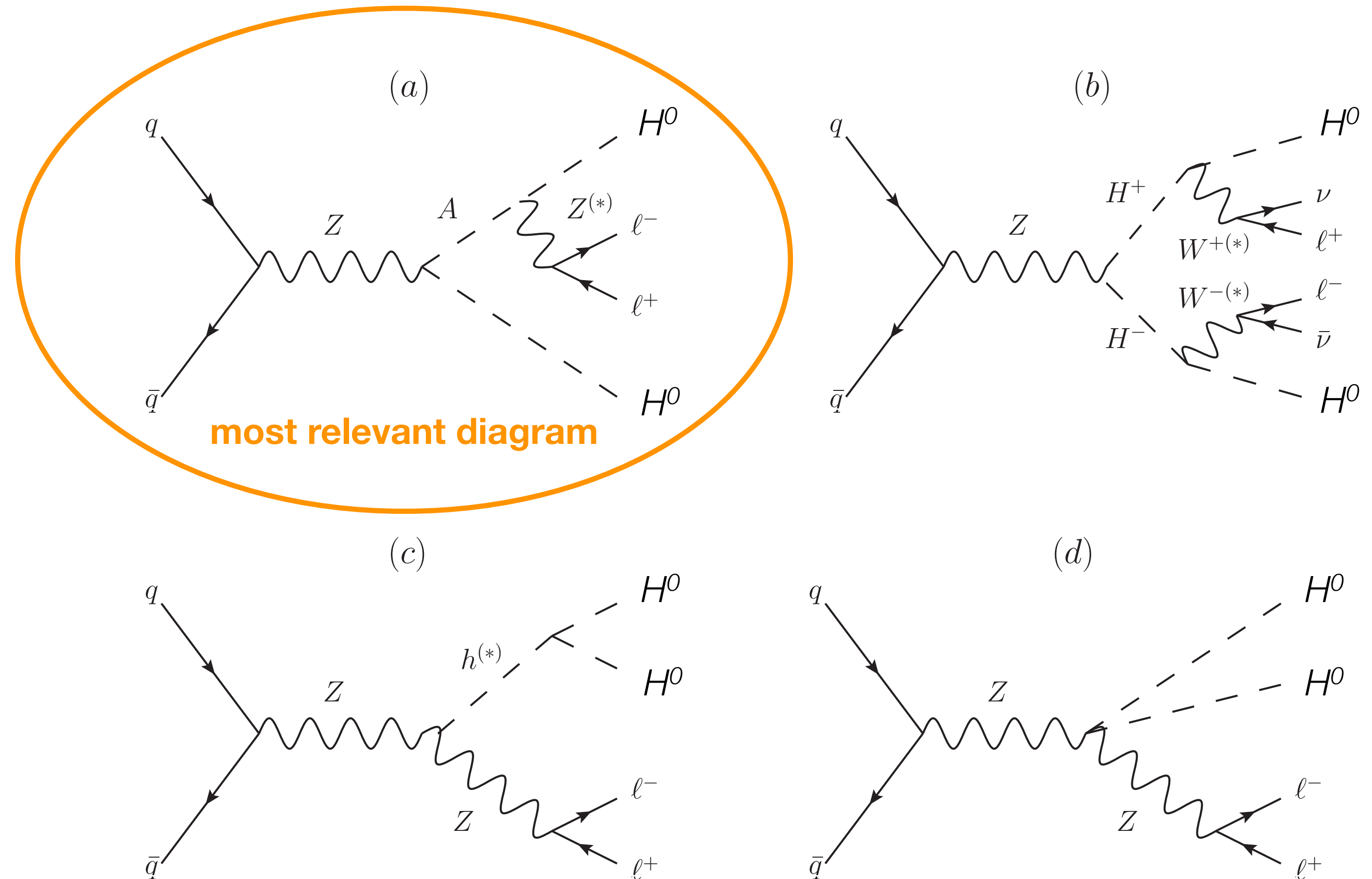

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Recasting l^+l^- + E_T^{miss} analyses for the IDM

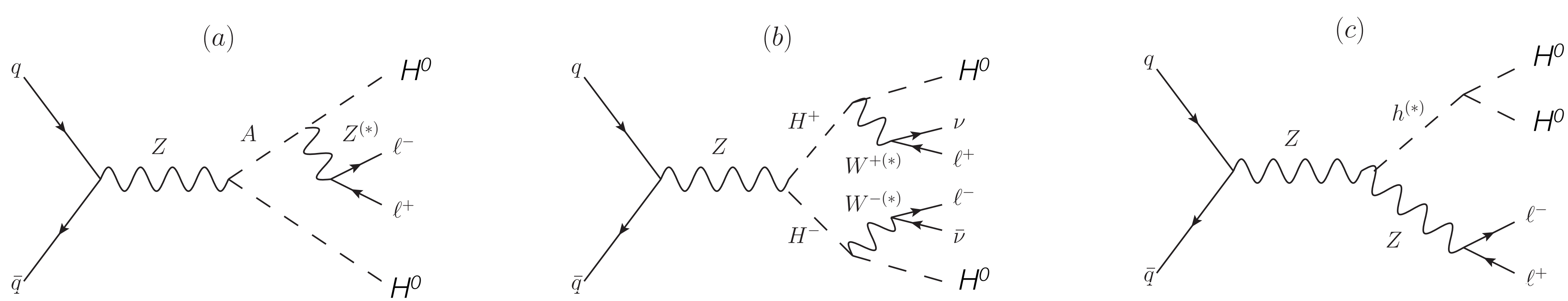
- **Implemented 2 ATLAS dilepton analyses** in the MA5 PAD
  (PAD = Public Analysis Database)

  - **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

  - **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)



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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.)

see also Jamie's talk on tools in the plenary session 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

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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)

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

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

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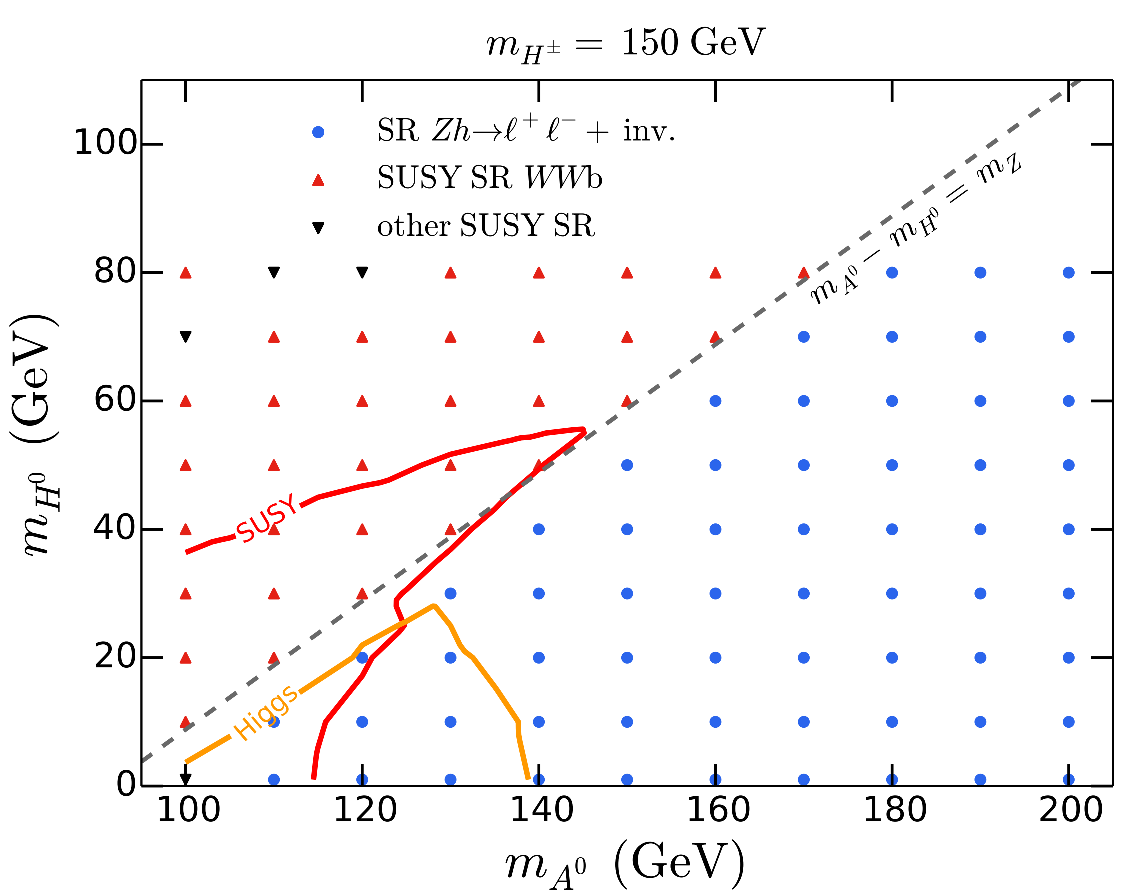
- The MadAnalysis 5 codes and detailed validation notes are **publicly available**

  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

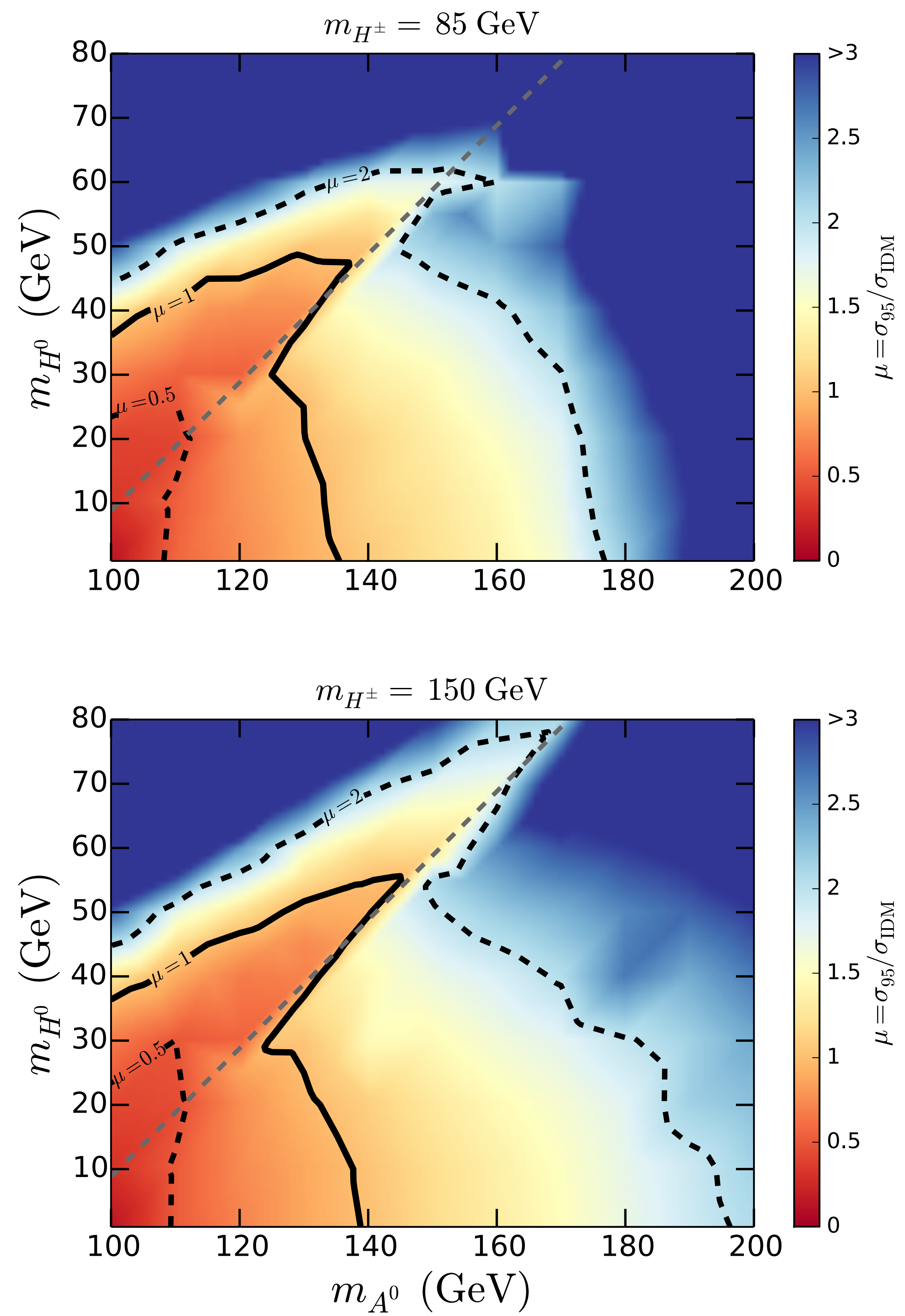
- Background numbers taken from the experimental papers to compute CLs



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.
- $m_{H\pm}$ 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.

- At Run 2 it should be possible to test the Higgs funnel region $m_{H0} \approx m_h/2$.



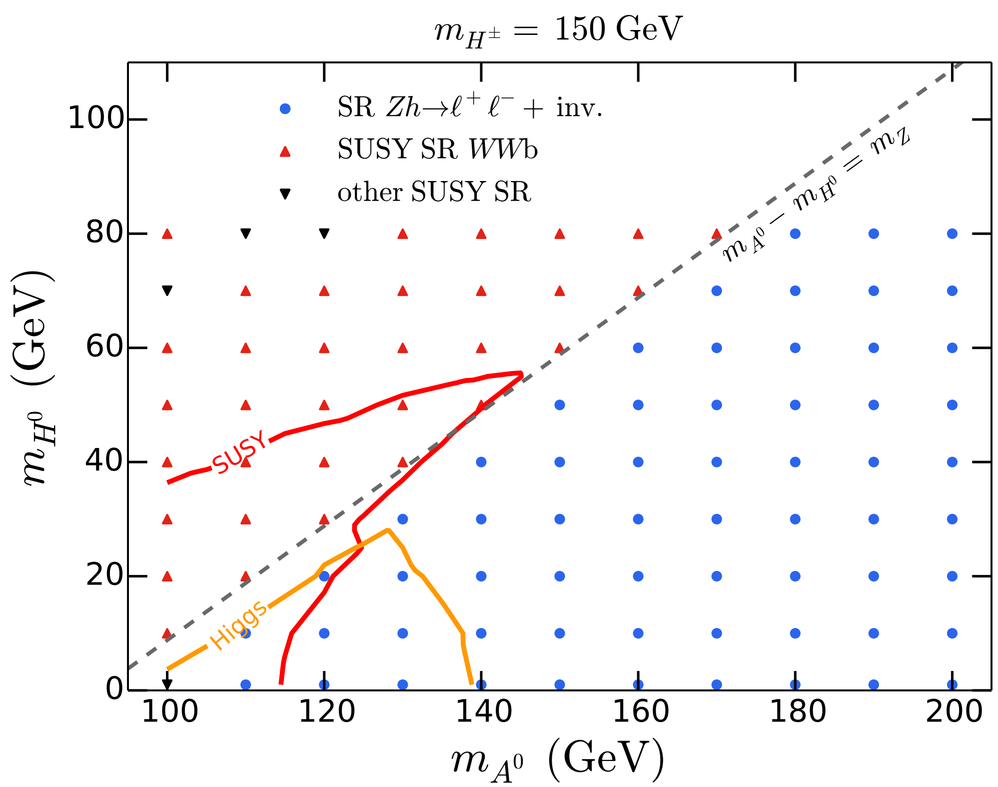
To conclude

arXiv:1503.07367

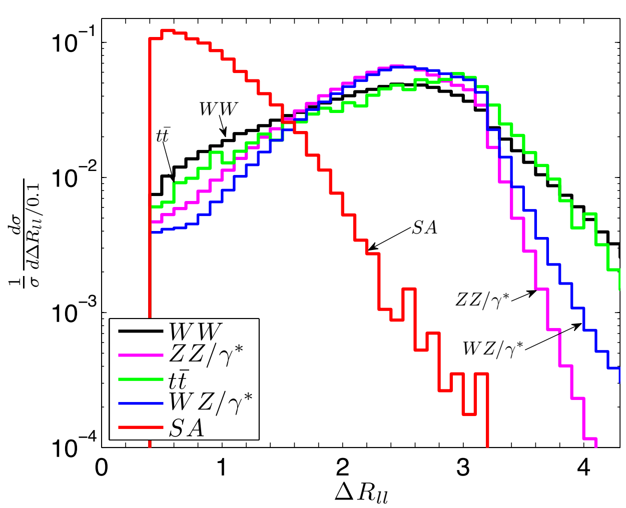
- We recasted two Run 1 ATLAS analyses
  - dilepton + MET SUSY search (off-Z)
  - ZH → l^+l^- + inv. search (on-Z)

  to obtain collider limits on inert scalars.

- Complementary to DM constraints, as they do not depend on astrophysical or cosmological assumptions.



- 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)

→ Dedicated analysis at Run 2 would be highly interesting

Thanks to

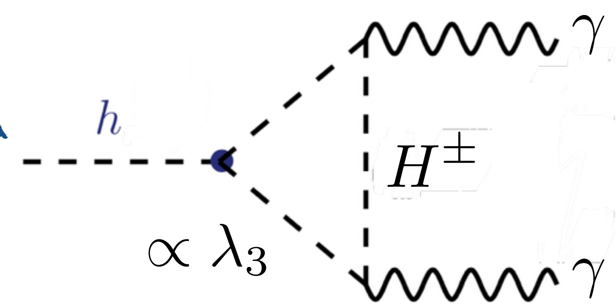
Beranger Dumont,
Andreas Goudelis,
Dipan Sengupta

who did most of the work presented here.

Backup

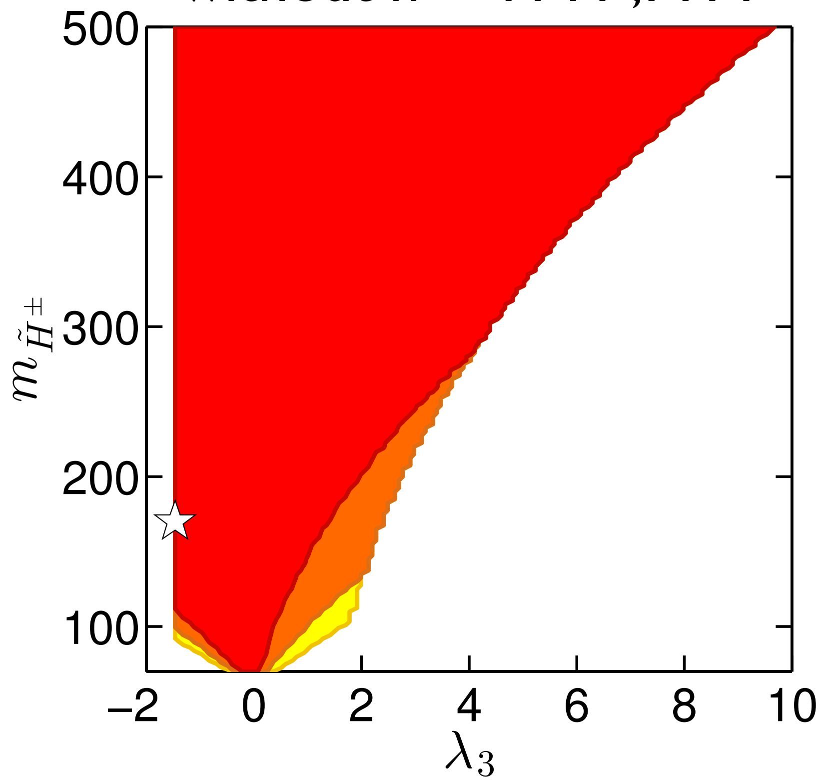
IDM: limits from invisible Higgs decays

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

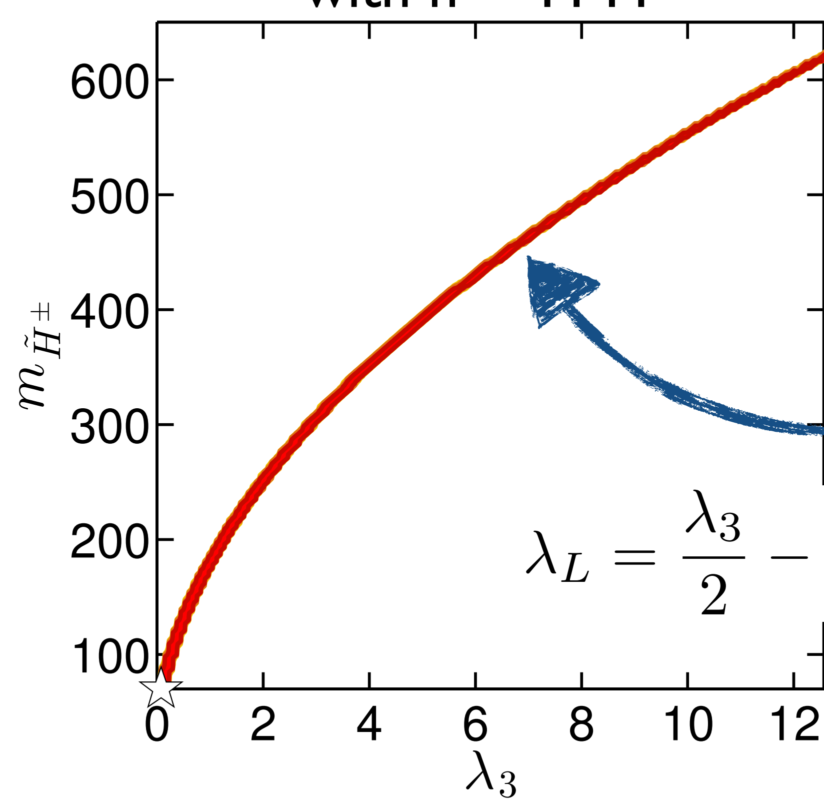


from a global fit to the properties of the Higgs boson:
[G. Bélanger, BD, U. Ellwanger, J. F. Gunion, S. Kraml, arXiv:1306.2941]

without $h^0 \to H^0H^0, A^0A^0$



with $h^0 \to H^0H^0$



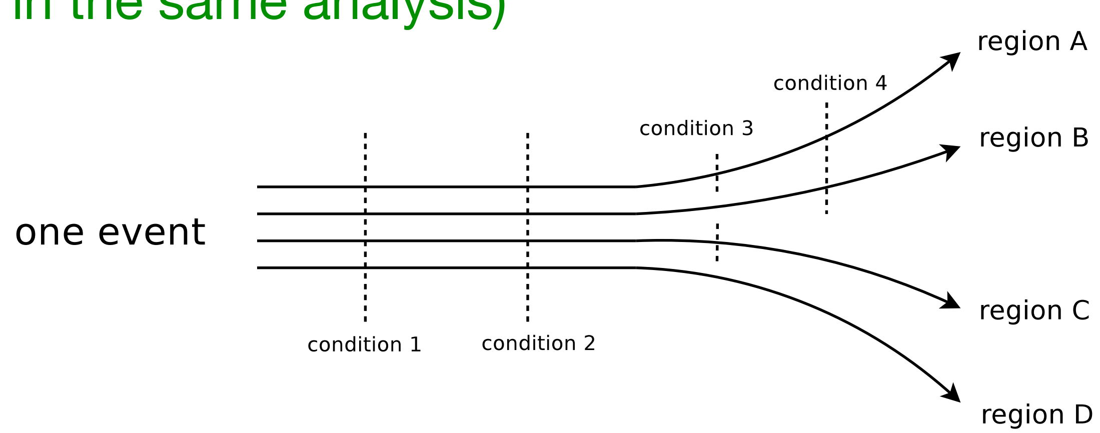
vanishing λ_L

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

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 (tuned version)
- 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, recently extended for recasting LHC analyses (efficient treatment of different signal regions in the same analysis)



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

ATLAS-SUSY-2013-11

[arXiv:1407.3278]

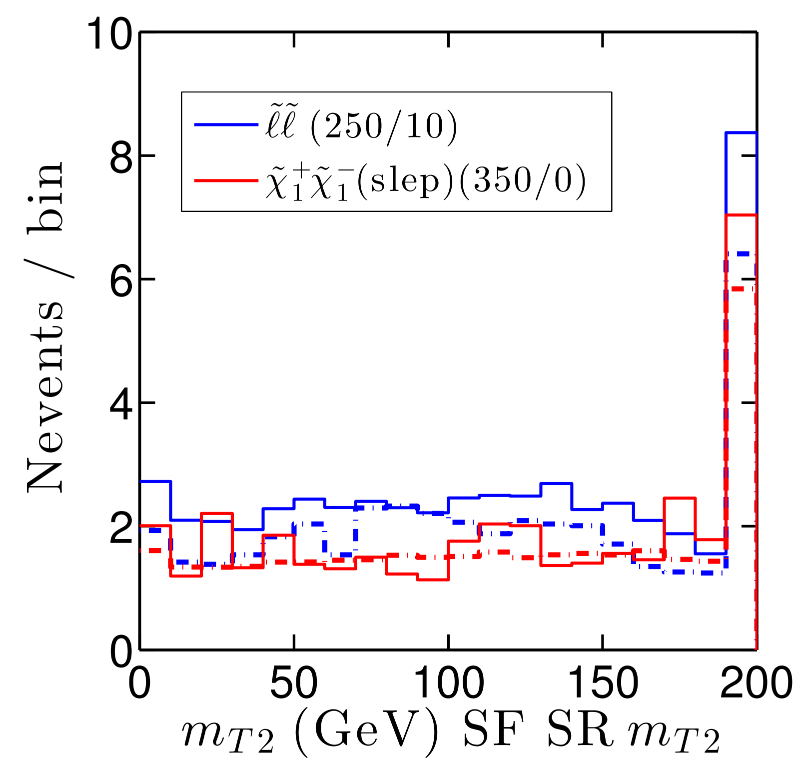
- ATLAS search for electroweak-inos and sleptons in the 2 lepton + MET final state

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	—	—
$E_{\mathrm{T}}^{\mathrm{miss,rel}}$ [GeV]	—	—	—	> 80	—	—	> 80
$p_{\mathrm{T},\ell\ell}$ [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$_{\mathrm{T2}}$ 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
$E_T^{\mathrm{miss,rel}} > 80$ 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