Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

DESY.

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Sensitivity of LHC searches to Inert Doublet Model via Recasting with CheckMATE2

Jayita Lahiri
II. Institut für Theoretische Physik, Universität Hamburg
Extended Scalar Sectors From All Angles, CERN

Based on ongoing work in collaboration with Tania Robens and Krzysztof Rolbiecki

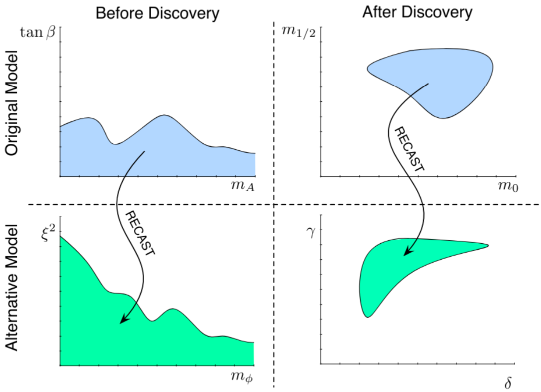
Motivation

- Dark matter remains one of the most elusive aspects of nature and SM of particle physics fails to provide an answer.
- Over past decades many models for DM beyond SM have been proposed by theorists, testable at the current and future collider experiments.
- Any such search analysis is extremely time and resource consuming.
- Ideally, a search *could be* sensitive to a broader class of models : central idea of *Recasting*.
- How much impact does an existing analysis designed to probe one hypothesis have on an alternate signal hypothesis?

Why is Recasting so powerful?

- One can reuse the background estimation as well as systematic uncertainties from the original search as well as observed data.
- One does not require to design event selection criteria.
- Only input that is required from the user, is the signal events.
- Can be used to constrain any BSM model.

A Schematic representation



Taken from JHEP 04 (2011) 038

Current Members: Manimala Chakraborti, Nishita Desai, Florian Domingo, Jong Soo Kim, Krzysztof Rolbiecki, Roberto Ruiz de Austri, Ipsita Saha, Liangliang Shang, Mangesh Sonawane, Zeren Simon Wang, Yuanfang Yue

Former Members: Daniel Dercks, Manuel Drees, Herbert Dreiner, Frederic Ponzca, Jamie Tattersall, Thorsten Weber

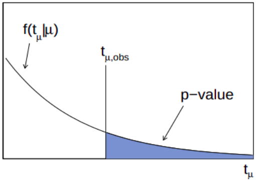
- CheckMATE is a general tool for recasting arbitrary model
- Accepts events as .hepmc, .lhe; integration with Pythia and MadGraph
- based on Delphes for detector simulation
- using existing LHC searches calculates a limit on a given parameter point
- From SLHA file to the limit in one click
- one can easily constrain models that were not covered in the original ATLAS/CMS search
- currently more than 40 searches at 13 TeV coded, including 14 with full luminosity
- long-lived particles branch
- https://checkmate.hepforge.org/ and https://github.com/CheckMATE2/checkmate2

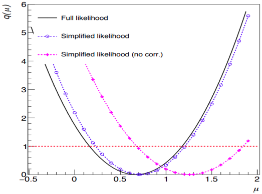
s_i and b_i predicted signal and background events in i-th bin and n_i is the observed number i.e $E[n_i] = \mu s_i + b_i$,
Simplified Likelihood :

$$L(\mu) = \prod_{i=1}^{N} \mathcal{P}(n_i|\mu s_i + b_i) = \prod_{i=1}^{N} \frac{(\mu s_i + b_i)^{n_i}}{n_i!} e^{-(\mu s_i + b_i)}$$

$\mu = 0 \rightarrow$ background-only hypothesis and $\mu = 1 \rightarrow$ signal hypothesis.
To test a hypothesis a profile likelihood ratio is defined

$$\lambda(\mu) = \frac{L(\mu)}{L(\hat{\mu})}\ ,\ t_\mu = -2\ln\lambda(\mu)\ ,\ p_\mu = \int_{t_{\mu,\mathrm{obs}}}^{\infty} f(t_\mu|\mu)\, dt_\mu\ .$$





If upper limit of $\mu < 1$, signal hypothesis is excluded at at least 95% CL.

Inert Doublet Model in a nutshell

$$V(\phi_S,\phi_D) = \frac{1}{2}\left[m_{11}^2(\phi_S^\dagger\phi_S)+m_{22}^2(\phi_D^\dagger\phi_D)\right] + \frac{\lambda_1}{2}(\phi_S^\dagger\phi_S)^2\frac{\lambda_2}{2}(\phi_D^\dagger\phi_D)^2$$
$$+ \lambda_3(\phi_S^\dagger\phi_S)(\phi_D^\dagger\phi_D) ++\lambda_4(\phi_S^\dagger\phi_D)(\phi_D^\dagger\phi_S) + \frac{\lambda_5}{2}\left[(\phi_S^\dagger\phi_D)^2+(\phi_D^\dagger\phi_S)^2\right].$$

$$\phi_D \to -\phi_D,\ \phi_S \to \phi_S,\ \text{SM} \to \text{SM},$$

$\langle\phi_S\rangle \neq 0, \langle\phi_D\rangle = 0$

$$\Phi_1 = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v+h+i\xi) \end{pmatrix}, \quad \Phi_D = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H+iA) \end{pmatrix},$$

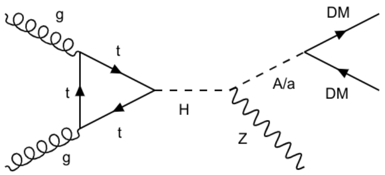
- We consider H to be the stable DM candidate.
- $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$ is the dark-portal coupling with Higgs, takes part in both annihilation (relic) and DM-nucleon scattering (direct detection).
- Co-annihilation between H and $A, H^\pm$ opens up when the mass difference between H and $A, H^\pm$ is small.
- Free parameters $m_H, m_A, m_{H^\pm}, \lambda_2, \lambda_{345} \to$ extremely predictive.
- Direct detection bounds especially after LZ, extremely stringent.

Recasting $Z(\ell^+\ell^-) + E\!\!\!/_T$ using full run-2 data (139 fb^{-1})

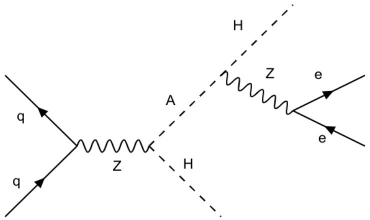
ATLAS Collaboration, Phys.Lett.B 829 (2022) 137066.

- Benchmark model for experimental search : 2HDM + pseudoscalar
- CP-even neutral scalars h, H, charged scalar $H^{\pm}$ and two CP-odd scalars A, a.
- Fermionic DM candidate χ.
- Relatively relaxed direct detection bound due to pseudoscalar portal mechanism.

2HDMa:



Inert Doublet Model:



ATLAS Analysis cuts

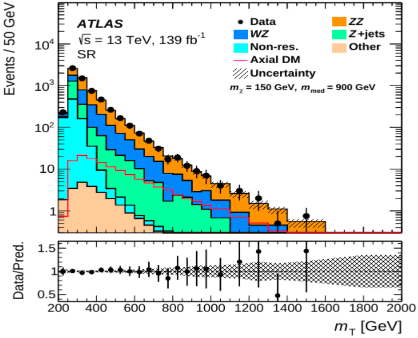
The most sensitive search in the $\ell^+\ell^- + \not{E}_T$ channel comes from ATLAS collaboration *ATLAS Collaboration, Phys.Lett.B 829 (2022) 137066*. The following signal region was chosen.

- p_T of the leptons $> 20, 30$ GeV
- 76 GeV $< m_{\ell\ell} <$ 106 GeV
- $\not{E}_T >$ 90 GeV
- $\Delta R_{\ell\ell} < 1.8$

ATLAS Analysis cuts

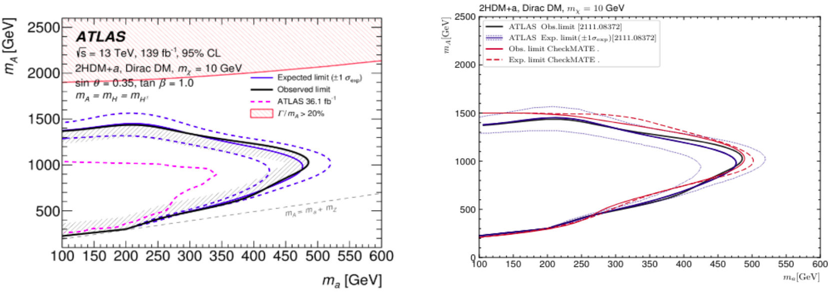
The most sensitive search in the $\ell^+\ell^- + \not{E}_T$ channel comes from ATLAS collaboration *ATLAS Collaboration, Phys.Lett.B 829 (2022) 137066*. The following signal region was chosen.

- p_T of the leptons $> 20, 30$ GeV
- 76 GeV $< m_{\ell\ell} <$ 106 GeV
- $\not{E}_T > 90$ GeV
- $\Delta R_{\ell\ell} < 1.8$



Final discriminant is m_T.

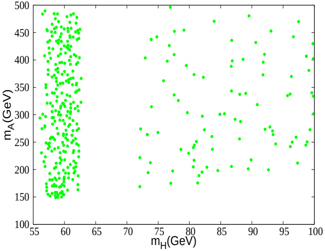
Validation with CheckMATE2



Constraint from *ATLAS Collaboration, Phys.Lett.B 829 (2022) 137066* and validation within CheckMATE courtesy I. Lara.

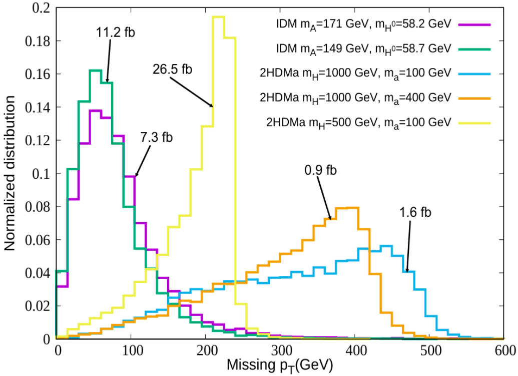
After Recasting with CheckMATE2

The major contribution comes from $pp \to HA$ production.



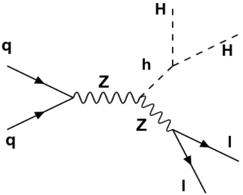
Scanned points taken from *Phys.Rev.D 93(2016)5,055026* Ilnicka, Krawczyk, Robens and later updated with new results.

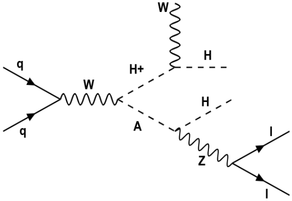
Comparison of kinematics

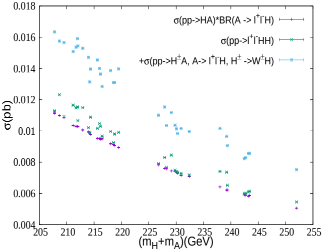


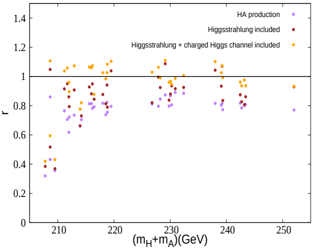
2HDMa benchmarks shown here are all excluded, and IDM benchmarks are allowed.

Sub-leading contributions





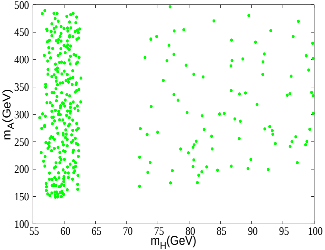




r is the inverse of upper limit on μ.

After Recasting with CheckMATE2

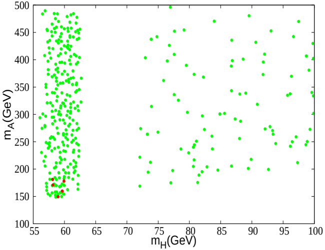
The major contribution comes from $pp \to HA$ production. But there are contributions $\lesssim 25 - 30\%$ from other diagrams, e.g Higgs-strahlung with Higgs invisible decay and $H^{\pm}A$ production.



Scanned points taken from *Phys.Rev.D 93(2016)5,055026* Ilnicka, Krawczyk, Robens and later updated with new results.

After Recasting with CheckMATE2

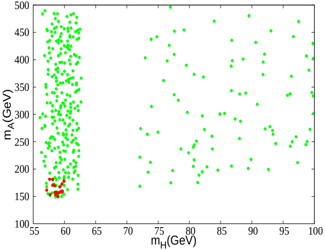
The major contribution comes from $pp \to HA$ production. But there are contributions $\lesssim 25 - 30\%$ from other diagrams, e.g Higgs-strahlung with Higgs invisible decay and $H^{\pm}A$ production.



Scanned points taken from *Phys.Rev.D 93(2016)5,055026* Ilnicka, Krawczyk, Robens and later updated with new results.

After Recasting with CheckMATE2

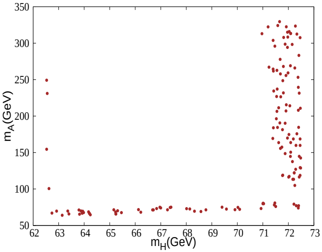
The major contribution comes from $pp \to HA$ production. But there are contributions $\lesssim 25 - 30\%$ from other diagrams, e.g Higgs-strahlung with Higgs invisible decay and $H^{\pm}A$ production.



Scanned points taken from *Phys.Rev.D 93(2016)5,055026* Ilnicka, Krawczyk, Robens and later updated with new results.

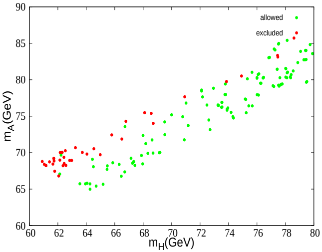
Recasting soft-lepton search (completely off-shell Z)

- Co-annihilation between H and A can reduce relic density and simultaneously satisfy direct detection bound with larger λ_{345}.
- The under-relic points also gives rise to small DD cross-section due to the scaling factor $\frac{\Omega}{\Omega_{tot}}$.



Recasting ATLAS search for SUSY compressed mass spectra Phys.Rev.D 101 (2020) 5, 052005, production with ISR jet with $p_T > 70$ GeV.

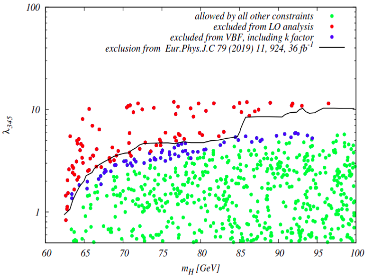
- From LEP search for neutralino pair production, and further reinterpretation in terms of IDM, allowed region for $m_A < 100$ GeV and $m_H < 80$ GeV is $m_A - m_H < 8 GeV$.



- Difficult to get contour, due to several contributions.
- $\Delta m \gtrsim 5$GeV and $m_H \lesssim 64$ GeV is typically disfavored from the soft-lepton search.

Recasting VBF production of SM Higgs decaying invisibly

ATLAS search for VBF production of Higgs to invisible decay JHEP 08 (2022) 104 using full run-II data (139 fb^{-1}) We applied for off-shell Higgs decay to pair of DM.



- $\lambda_{345} < 2-3$ for DM masses 70-80 GeV.
- Approximately factor 2 improvement compared to Dercks and Robens Eur.Phys.J.C 79 (2019) 11, 924, used early run-II data (35.9 fb^{-1}).

Summary

- Our aim is to recast existing LHC searches to Inert Doublet model using CheckMATE2.
- $Z(\ell^+\ell^-)$+MET search from LHC is optimized in the context of 2HDM+pseudoscalar model.
- We see that the search is *not* very sensitive to IDM in the regions that are allowed from the dark matter observations as well as theoretical and experimental constraints due to kinematical differences between the two models.
- Inclusion of subleading contributions changes the picture.
- Small mass-gap between DM and its partner $(A, H^{\pm})$ is interesting from the DM phenomenology point of view. This region is probed and partly excluded by recasting ATLAS soft lepton search.
- We have also studied the VBF production of offshell-Higgs decaying invisibly. This search can become crucial in the regions where DD constraints are relaxed due to Higgs resonance or co-annihilation.

Back-up : Number of free parameters and constraints

The Model has 5 free parameters once v and m_h is fixed.
$M_H, M_A, M_{H^\pm}, \lambda_2, \lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$

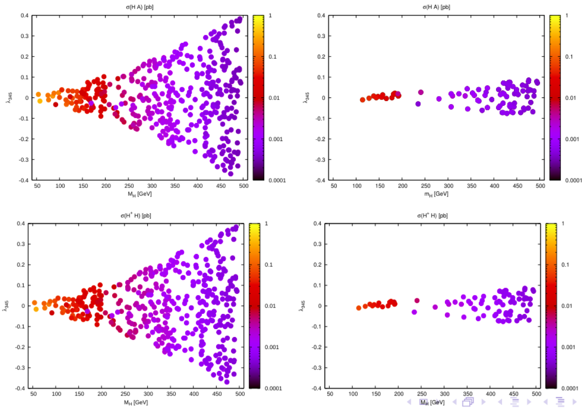
Theoretical Constraints: Positivity of the potential, vacuum stability, perturbativity

Experimental Constraints: Total width of h, W, Z, electroweak precision observables namely S, T, U, Higgs signal strength measurement, direct search for heavy scalars, reinterpreted/recasted LHC/LEP SUSY searches, dark matter relic density and direct detection constraints.

Allowed parameter space of IDM

Updated constraints [LUX-ZEPLIN] [arXiv:2207.03764]

LUX **LUX-ZEPLIN**



CheckMATE identifier	Search designed for	#SR	L_{int}
atlas_1602_09058	Supersymmetry in final states with jets and two SS leptons or 3 leptons	4	3.2
atlas_1604_01306	New phenomena in events with a photon and $\not{E}_T$	1	3.2
atlas_1604_07773	New phenomena in final states with an energetic jet and large $\not{E}_T$	13	3.2
atlas_1605_03814	$\tilde{q}$ and $\tilde{g}$ in final states with jets and $\not{E}_T$	7	3.2
atlas_1605_04285	Gluinos in events with an isolated lepton, jets and $\not{E}_T$	7	3.3
atlas_1605_09318	Pair production of $\tilde{g}$ decaying via $\tilde{t}$ or $\tilde{b}$ in events with b-jets and $\not{E}_T$	8	3.3
atlas_1606_03903	$\tilde{t}$ in final states with one isolated lepton, jets and $\not{E}_T$	3	3.2
atlas_1609_01599	Measurement of ttV cross sections in multilepton final states	9	3.2
atlas_conf_2015_082	Supersymmetry in events with leptonically decaying Z, jets and $\not{E}_T$	1	3.2
atlas_conf_2016_013	Vector-like t pairs or 4 t in final states with leptons and jets	10	3.2
atlas_conf_2016_050	$\tilde{t}$ in final states with one isolated lepton, jets and $\not{E}_T$	5	13.3
atlas_conf_2016_054	$\tilde{q}$, $\tilde{g}$ in events with an isolated lepton, jets and $\not{E}_T$	10	14.8
atlas_conf_2016_076	Direct $\tilde{t}$ pair production and DM production in final states with 2ℓ	6	13.3
atlas_conf_2016_078	Further searches for $\tilde{q}$ and $\tilde{g}$ in final states with jets and $\not{E}_T$	13	13.3
atlas_conf_2016_096	Supersymmetry in events with 2ℓ or 3ℓ and $\not{E}_T$	8	13.3
atlas_conf_2017_022	$\tilde{q}$, $\tilde{g}$ in final states with jets and $\not{E}_T$	24	36.1
atlas_conf_2017_039	**Electroweakino production in final states with 2 or 3 leptons**	37	36.1
atlas_conf_2017_040	**Dark Matter or invisibly decaying h, produced in associated with a Z**	2	36.1
atlas_conf_2017_060	**New phenomena in final states with an energetic jet and large $\not{E}_T$**	13	36.1
cms_pas_sus_15_011	New physics in final states with an OSSF lepton pair, jets and $\not{E}_T$	47	2.2
cms_pas_hig_17_023	**Search for invisible decays of h produced through VBF**	10	36.1

Dercks and Robens Eur.Phys.J.C 79 (2019) 11, 924