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

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(Re)interpretation of the LHC results for new physics, 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 from a user perspective?

- One can reuse the background estimation as well as systematic uncertainties from the original search as well as observed data.
- One does not need to follow a detailed experimental analysis, to constrain their model.
- Only input that is required from the user, is the signal events, lhe/hepmc.
- Can be used to constrain any BSM model.
- Design own analysis and make future projections.

CHECKMATE

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

Courtesy : Krzysztof

Statistical Framework

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.

After likelihood based hypothesis testing with profile-likelihood ratio as the test statistic:

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

Inert Doublet Model in a nutshell

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

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

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

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

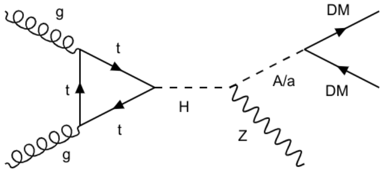
- We consider H to be the stable DM candidate.
- $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$ is the dark-portal coupling with Higgs, takes part in both annihilation (relic) and DM-nucleon scattering (direct detection).
- Co-annihilation between H and $A, H^\pm$ opens up when the mass difference 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 $Z(\ell^+\ell^-) + \not{E}_T$ using full run-2 data (139 fb^{-1})

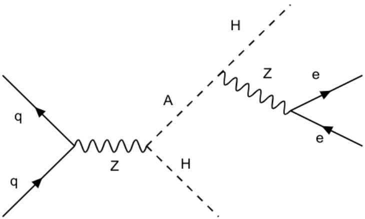
ATLAS Collaboration, Phys.Lett.B 829 (2022) 137066.

- 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 $Z(\ell^+\ell^-) + \not{E}_T$ 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
- $\Delta R_{\ell\ell} < 1.8$

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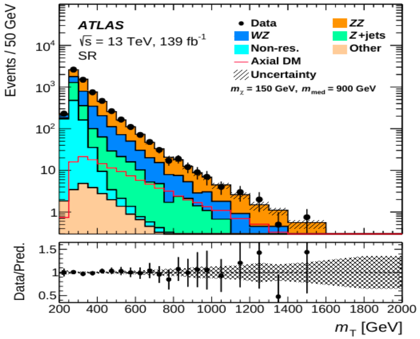
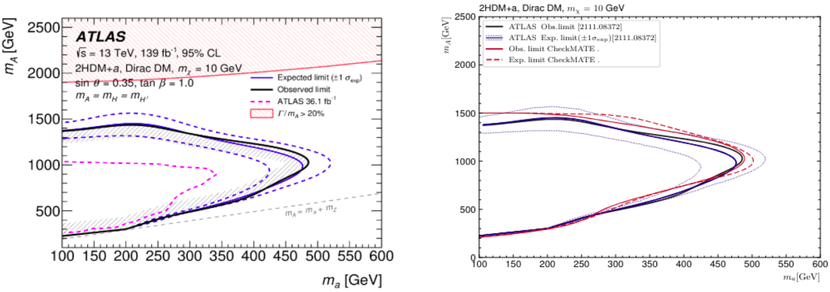


Final discriminant is m_T.

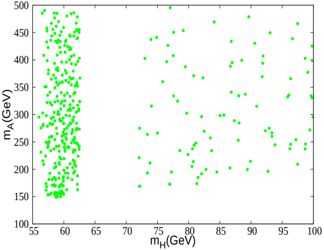
Validation



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

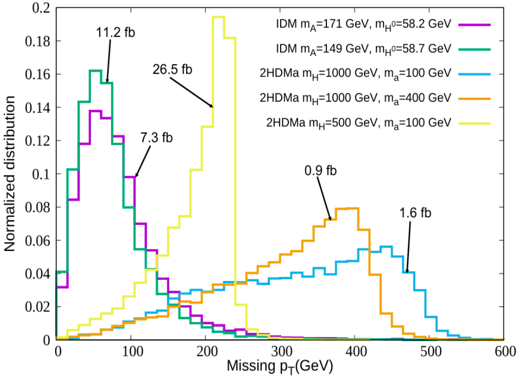
After Recasting with CheckMATE2

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



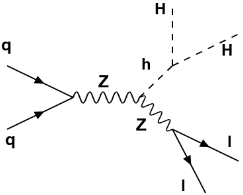
Scanned points taken from *Phys.Rev.D 93(2016)5,055026* Ilnicka, Krawczyk, Robens and later updated with new results.

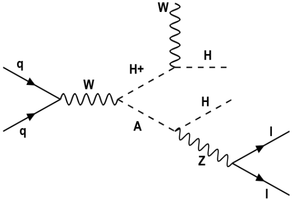
Comparison of kinematics

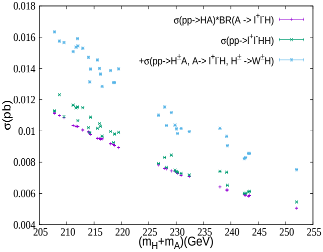


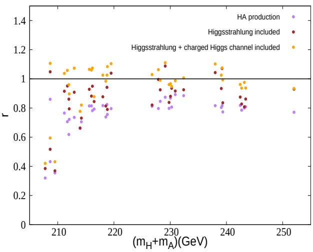
2HDMa benchmarks shown here are all excluded, and IDM benchmarks are allowed.

Sub-leading contributions





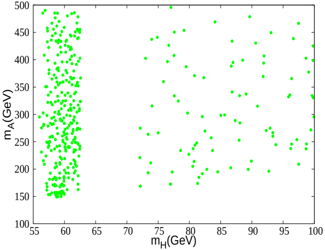




r is the inverse of upper limit on μ.

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.



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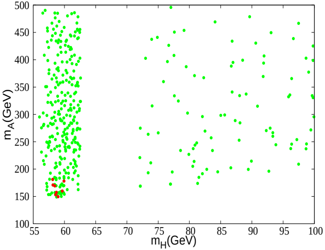

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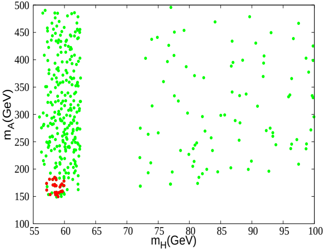

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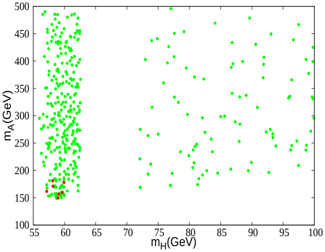
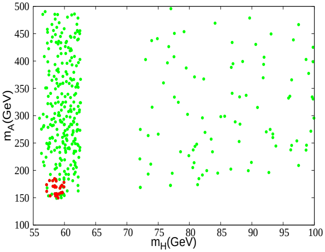
Comparison between best signal-region and multibin analysis

Best SR :



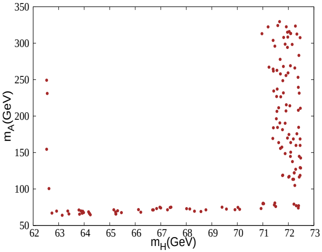
Comparison between best signal-region and multibin analysis

Multibin :



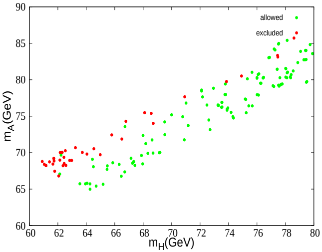
Recasting soft-lepton search (completely off-shell Z)

- Co-annihilation between H and A can reduce relic density and simultaneously satisfy direct detection bound with smaller 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.

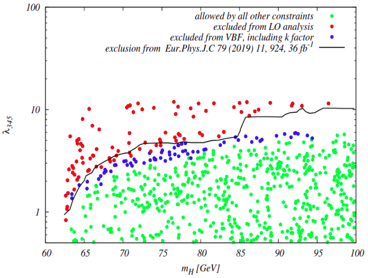
- From LEP search for neutralino pair production, and further reinterpretation in terms of IDM, allowed region for $m_A < 100$ GeV and $m_H < 80$ GeV is $m_A - m_H < 8 GeV$.



- Difficult to get contour, due to several contributions.
- $\Delta m \gtrsim$ 5GeV 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.
$M_H, M_A, M_{H^\pm}, \lambda_2, \lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$

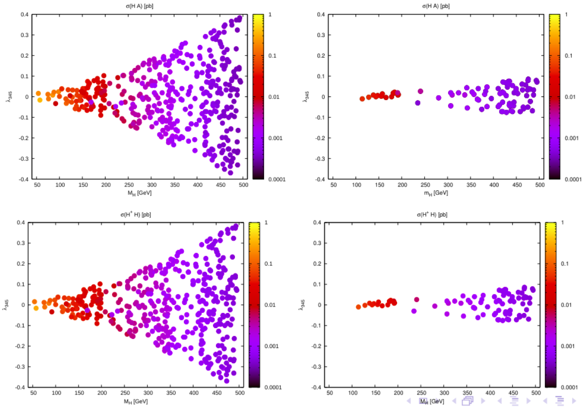
Theoretical Constraints: Positivity of the potential, vacuum stability, perturbativity

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]

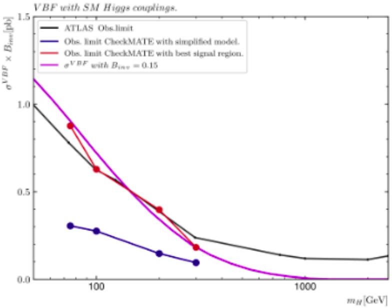
LUX **LUX-ZEPLIN**



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

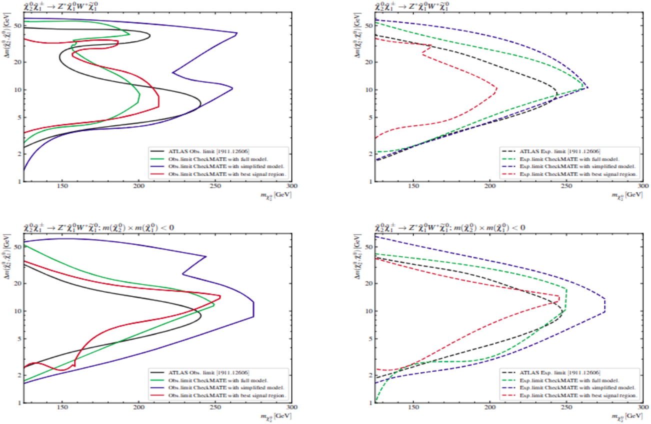
Dercks and Robens Eur.Phys.J.C 79 (2019) 11, 924

Validation-VBF



$p_{T\,j} > 70, 40$ GeV, $m_{jj} > 500$ GeV, $\Delta R > 3$
simplified likelihood, best signal region method, K-factor 1.67

Validation-soft lepton



ISR > 70 GeV required.
Full likelihood is provided, best SR