Combination of ATLAS dark matter searches interpreted in a 2HDM with a pseudo-scalar mediator using 139 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collision data

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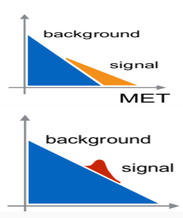
Abstract: Results obtained from various searches,with and without missing transverse momentum(E_T^{miss}), are used to constrain a Two-Higgs-Doublet Model (2HDM) with an additional pseudo-scalar that mediates the interaction between ordinary and dark matter (2HDM+a). The analyses utilize a dataset of up to 139 fb^{-1} of proton-proton collisions at a center-of-mass energy of $\sqrt{s}$ = 13 TeV, with the ATLAS detector data at the Large Hadron Collider between 2015 and 2018. The results from three highly sensitive searches are statistically combined. These searches focus on signatures involving significant E_T^{miss} with a leptonically decaying Z boson, large E_T^{miss} in association with a Higgs boson decaying into bottom quarks, and the production of charged Higgs bosons in final states with top and bottom quarks. Constraints are derived for several benchmark scenarios in the 2HDM+a.

Searching for Dark Matter at LHC:

- DM existence is supported by astrophysical measurements.
- One of the proposed and most interesting DM candidates is a Weakly Interactive Massive Particle.
- WIMP passes invisibly through the detector $\Longrightarrow$ detectable as Missing trasverse energy (E_T^{miss}) due to p_T imbalance
- Search for a signature of X+E_T^{miss}, where "X" represents some visible SM particle(s)

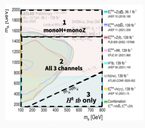
General analysis strategy:

① Definition of a set of signal region(s) (SR):
→ E_T^{miss}-X signatures: Require MET; Select for X (Z,h,jet...); Veto other objects
→ Resonance search: The mediator decays back into quarks



② Definition of a set of control regions (CR) to with certain background processes enriched in order to normalize the MC expectation in the SR
③ Validate the background estimation technique in a Validation Region (VR)
③ Unblinding ⇨ Is there an **excess**?
④ If no excess is found the results are interpreted in terms of **limits** on models under study

Combination strategy:

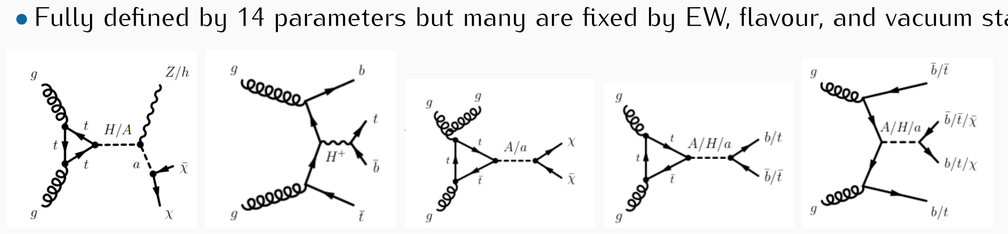


- To improve sensitivity: $H \longrightarrow tb$ added to statatistical combination with E_T^{miss}+Z(ll) and E_T^{miss}+h(bb).
- Hybrid combination approach: exclude channels that have negligible sensitivities in a certain region.

① $m_A > 1500GeV$: E_T^{miss}+Z(ll) and E_T^{miss}+h(bb)
② $m_A < 1500GeV$ and $m_A > m_a$: all 3 channels combined.
② $m_A < m_a$: off-shell region for E_T^{miss}-X searches: only $H \longrightarrow tb$

2HDM+pseudo scalar model:

- 2HDM+a: Type-II Two-Higgs-Doublet Model with an additional pseudoscalar mediator between visible and dark sectors [1].
- 2HDM+a has rich phenomenology predicting wide range of signatures, including X+E_T^{miss} and non-E_T^{miss} signatures.
- Fully defined by 14 parameters but many are fixed by EW, flavour, and vacuum stability constraints



Free parameters:
- $M_H = M_{H^\pm} = M_A$.
- M_a , M_χ
- $\tan\beta$, $\sin\theta$

Scans:
- $m_a - m_A$
- $m_A - \tan\beta$
- $m_a - m_\chi$
- $\sin\theta$

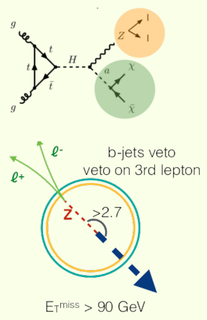
Most sensitive analyses:

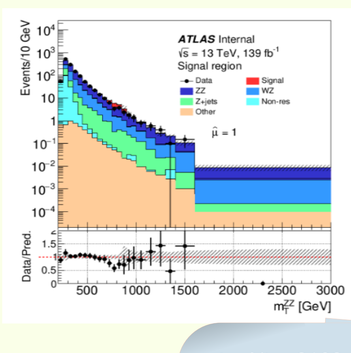
E_T^{miss}+Z(ll):

➜arXiv: 2111.08372

- Search for the production of DM candidates in association with a Z boson decaying to two leptons(e,μ)
- Backgrounds:ZZ, WZ, Z+jets, tt
- Three Control Regions (CRs) used to constrain SM background Monte Carlo predictions in SR for all signal models: 3l CR, 4l CR and eμ CR
- look for excess of events in the m_T^{ZZ}:

$$m_T^{ZZ} = \sqrt{\left(\sqrt{m_Z^2 + |\overrightarrow{p_T}^{ll}|^2} + \sqrt{m_Z^2 + |\overrightarrow{E_T}^{miss}|^2}\right)^2 - \left|\overrightarrow{p_T}^{ll} + \overrightarrow{E_T}^{miss}\right|^2}$$

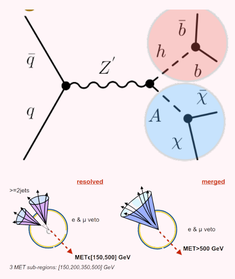


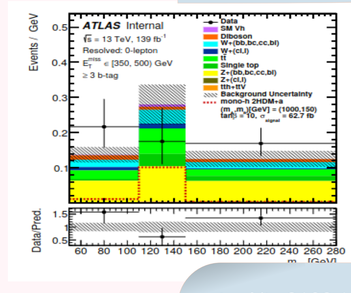


E_T^{miss}+h(bb):

➜arXiv: 2108.13391

- Search for the production of DM candidates in association with a SM Higgs boson
- Resolved and merged topologies are used in the reconstruction of $h \longmapsto bb$.
- Dominant backgrounds: tt and W/Z +jet, estimated using 1 or 2 leptons CRs

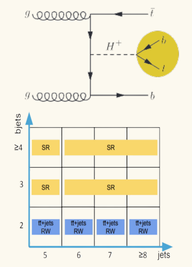


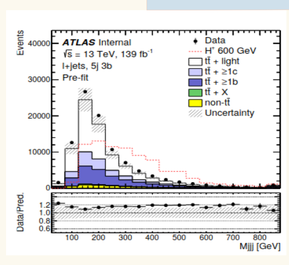


$tbH^\pm(H^\pm \to tb)$:

➜arXiv:2102.10076

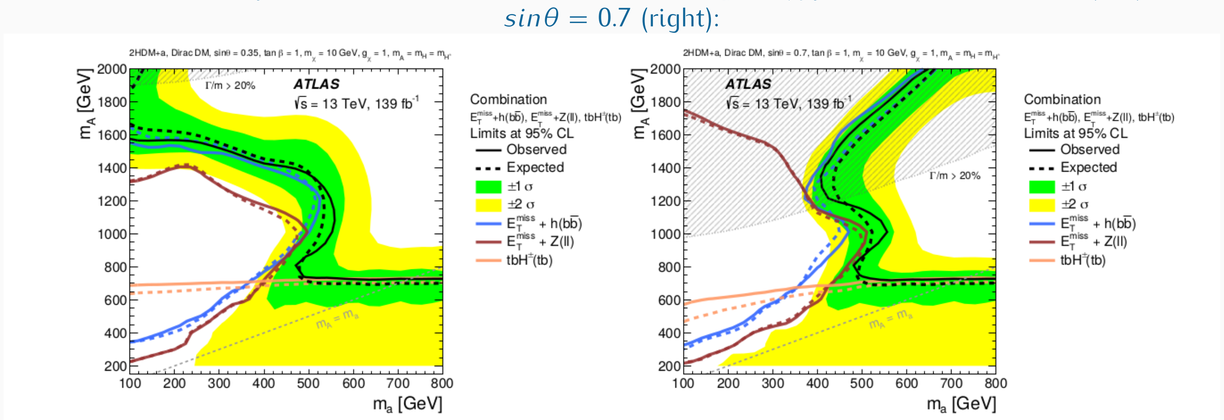
- search for charged Higgs bosons decaying into top and bottom quarks.
- Events classi ed into 4 separated SRs according to number of jets and number of b-jets.
- Backgrounds: $t\bar{t}$+ jets,Wt and single-top.



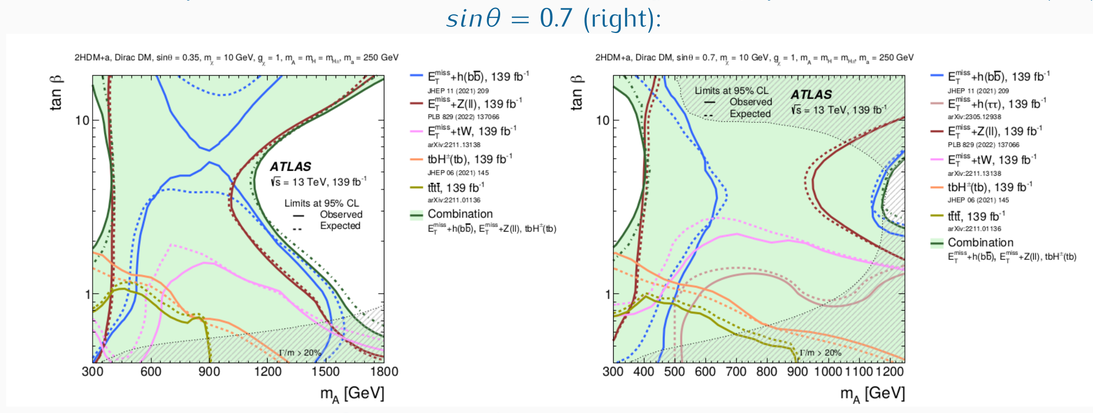


Summary of constraints on 2HDM+a:

① Observed and expected exclusion limits at 95% CL on $m_a - m_A$ planes for $sin\theta = 0.35$ (left) and $sin\theta = 0.7$ (right):



② Observed and expected exclusion limits at 95% CL on $m_a - \tan\beta$ planes for $sin\theta = 0.35$ (left) and $sin\theta = 0.7$ (right):



① $m_a - m_A$ planes:

- The E_T^{miss}+Z(ll) and E_T^{miss}+h(bb) dominate sensitivity in high-m_A,while $tbH^\pm(H^\pm \to$tb) gives complementary sensitivity in low-m_A.
- The combination increases the excluded parameter space, especially the excluded m_a range for m_A ≈800 GeV and for sin θ=0.35 m_A ≈700 GeV for sin θ=0.7.

② $m_a - \tan\beta$ planes:

- E_T^{miss}+Z(ll) and E_T^{miss}+h(bb) sensitivities driven by the transition from gg- to bb-initiated production with a decrease at $\tan\beta \approx 5$.

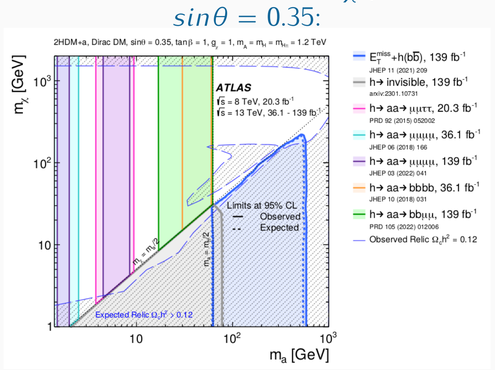
③ $m_a - m_\chi$ scan:

- $H \to aa$ searches can exclude everything up to $m_a = \frac{m_h}{2}$, and then bounded by kinematic limits of $m_\chi = \frac{m_a}{2}$ due to $a \to \chi\chi$, $h \to$invisible and E_T^{miss} +h(bb) sensitivity is also bounded by the kinematic limits $m_a = \frac{m_h}{2}$ and $m_\chi = \frac{m_a}{2}$

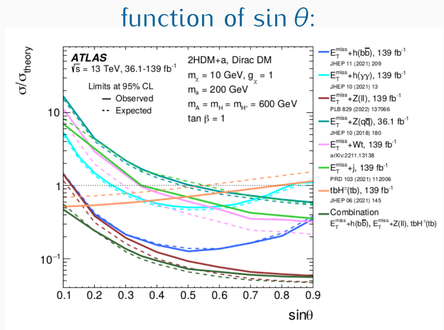
④ sin θ scan:

- E_T^{miss}+Z(ll) and E_T^{miss}+h(bb) provide strongest limits.Significant improvement from combination, almost the whole range excluded

③ Observed and expected exclusion limits at 95% CL fon $m_a - m_\chi$ planes for $sin\theta = 0.35$:



④ Observed and expected exclusion limits at 95% CL for the 2HDM+a as a function of sin θ:



References: [1] Recommendations of the LHC Dark Matter Working Group (arXiv:1703.05703).
[2] Combination and summary of ATLAS dark matter searches interpreted in a 2HDM with a pseudo-scalar mediator using 139 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collision data (arXiv:2306.00641).