Searches for Dark Matter with the ATLAS Experiment at the LHC

Phenomenology Symposium 2023 @ Pittsburgh

JiaJian TEOH
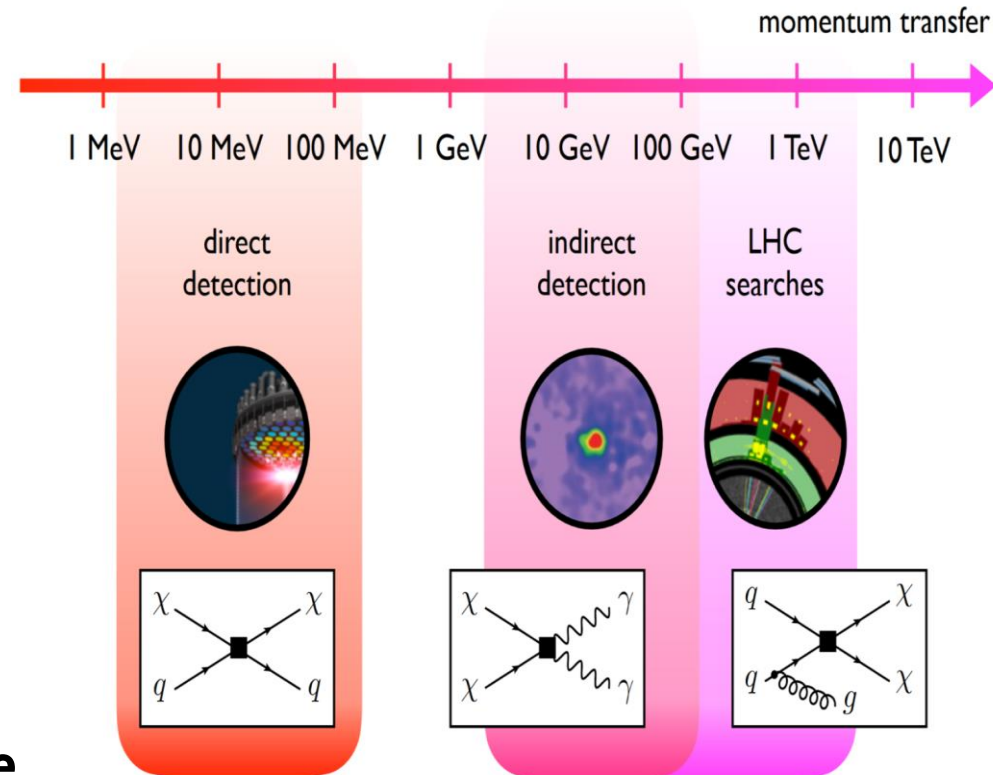
On behalf of the ATLAS Experiment

Search for Dark Matter (DM)

Strong cosmological and astrophysical evidences support the existence of DM.

Assuming SM-BM weak interaction enables complementary search strategies

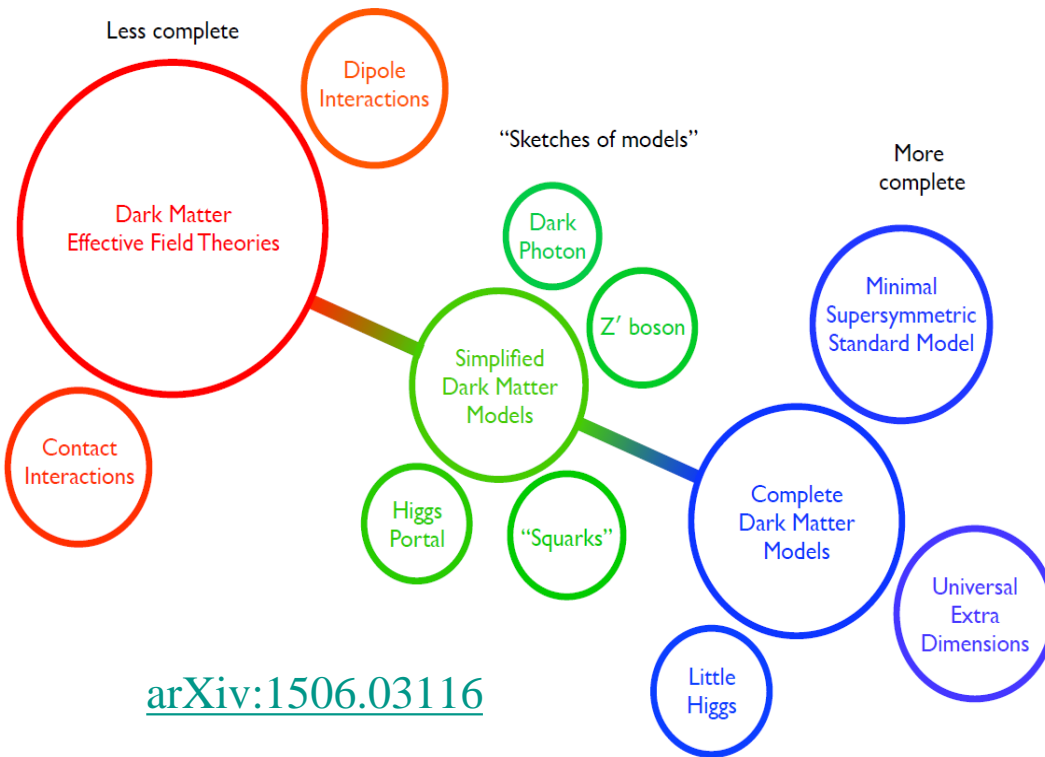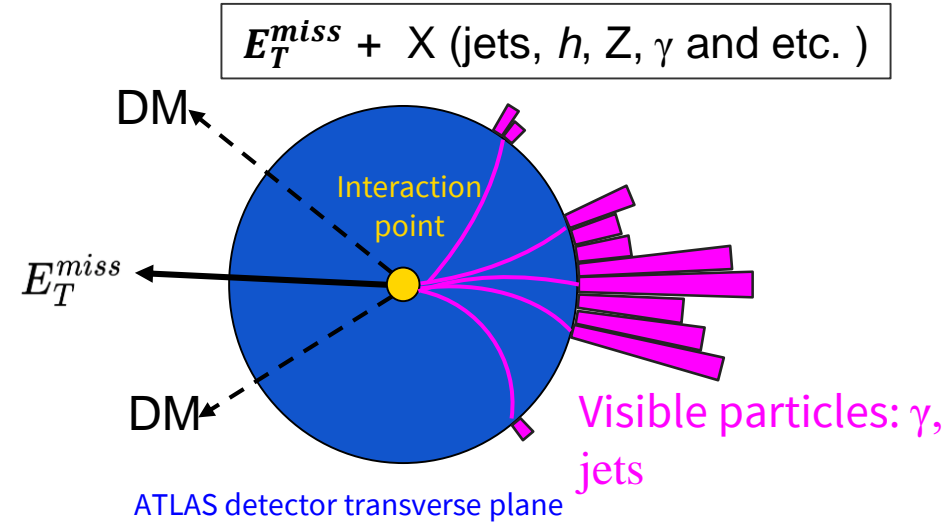Search for direct DM production at colliders (e.g LHC)
- **sensitive over large kinematic range**
- provide **complementary information**
  - can be designed to probe the SM-DM interaction in greater detail

momentum transfer

| MeV   10 MeV   100 MeV   1 GeV   10 GeV   100 GeV   1 TeV   10 TeV

direct detection

indirect detection

LHC searches

arXiv:1810.09420

Dark Matter searches at the ATLAS Experiment

No direct trace in the detector, but could be **reconstructed as E_T^{miss}**

$$E_T^{miss} + \text{X (jets, } h, Z, \gamma \text{ and etc.)}$$

DM

Interaction point

E_T^{miss}

DM

Visible particles: γ, jets

ATLAS detector transverse plane

Less complete

Dipole Interactions

"Sketches of models"

More complete

Dark Matter Effective Field Theories

Dark Photon

Z' boson

Simplified Dark Matter Models

Minimal Supersymmetric Standard Model

Contact Interactions

Higgs Portal

"Squarks"

Complete Dark Matter Models

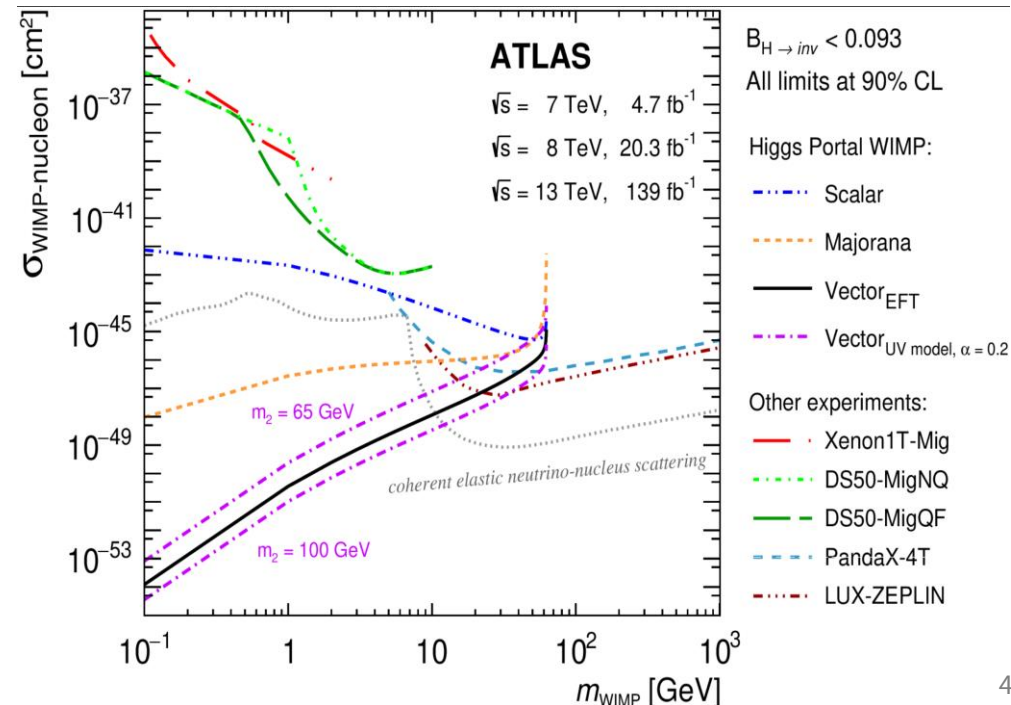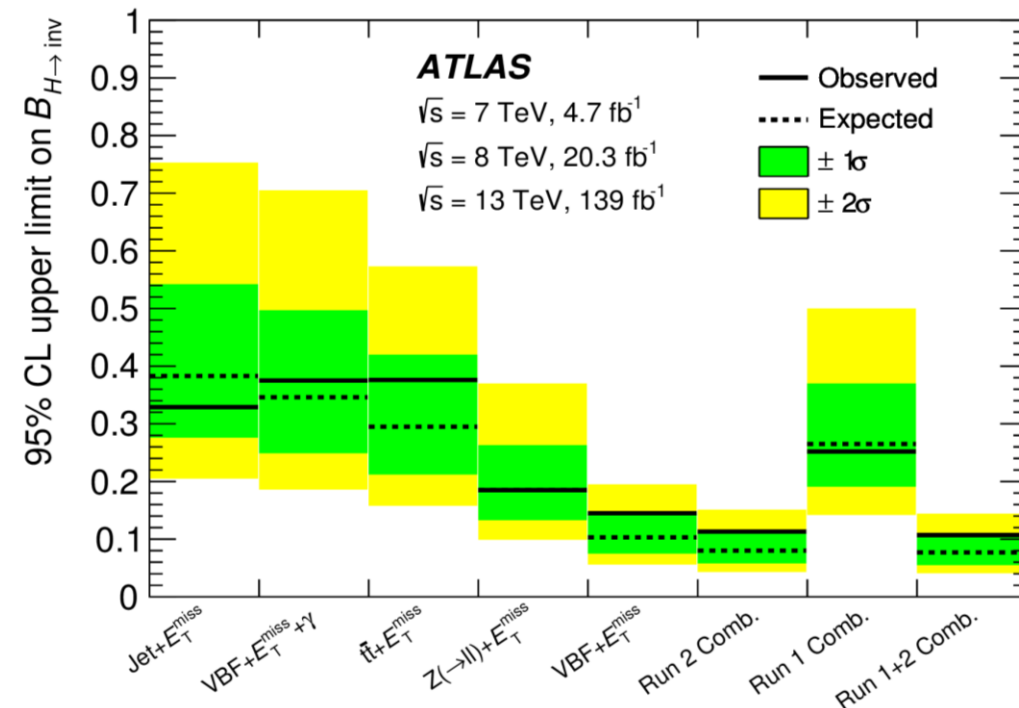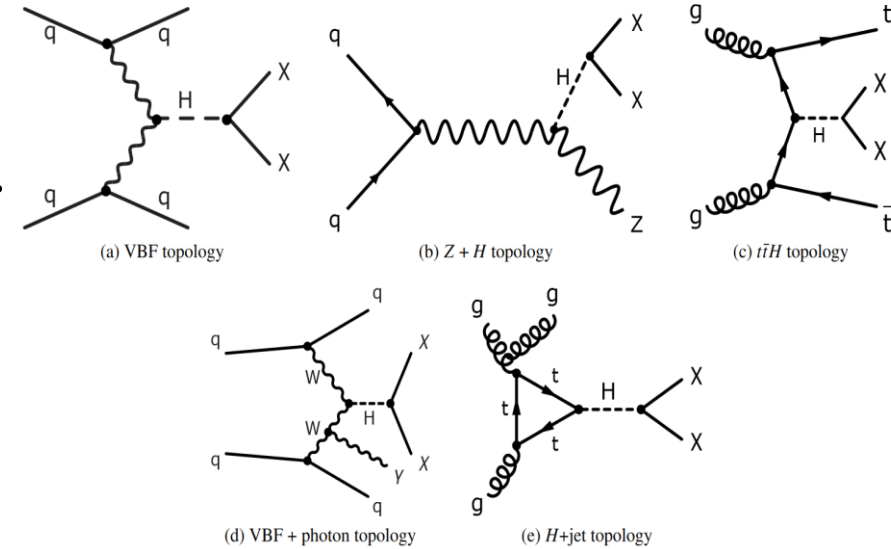Universal Extra Dimensions

Little Higgs

arXiv:1506.03116

A large number of qualitatively different DM models in three distinct classes.

- **could lead to non- E_T^{miss} signature**
- have their own pros and cons,
- all well-motivated and interesting

Only a selection of recent results are presented today.

SM Higgs Portal: Higgs → Invisible   arXiv:2301.10731

- **Combination of five independent**
  $H \rightarrow Inv$ **searches** using full Run 2 data.
- Further combination with Run 1 data
  - with BR(H→inv) < 0.107 (0.077) @ 95% C.L.

- $B_{H \rightarrow Inv}$ <0.093 at 90% CL interpreted on
  $\sigma_{\text{WIMP-Nucleon}}$

(a) VBF topology   (b) Z + H topology   (c) $t\bar{t}H$ topology

(d) VBF + photon topology   (e) H+jet topology
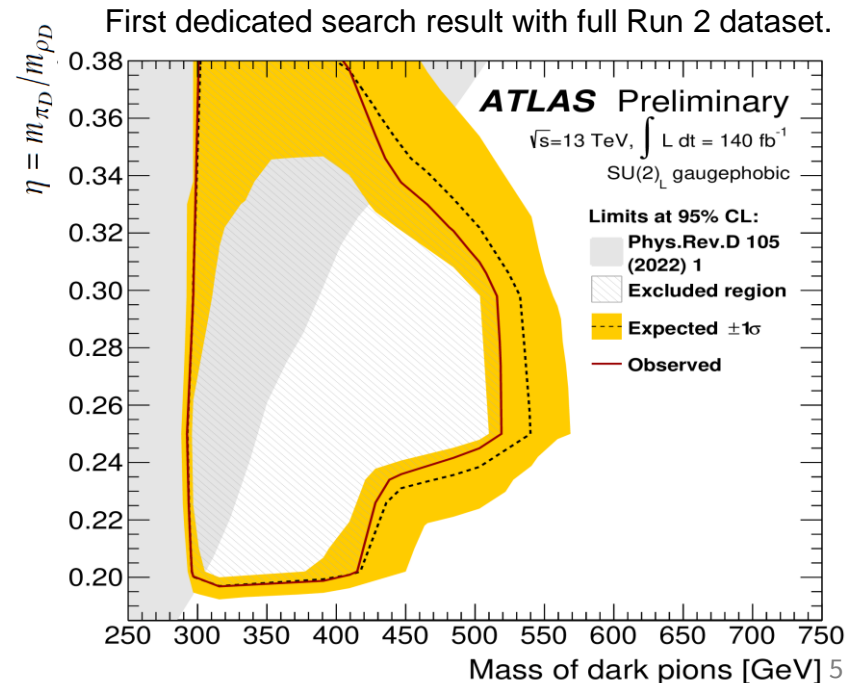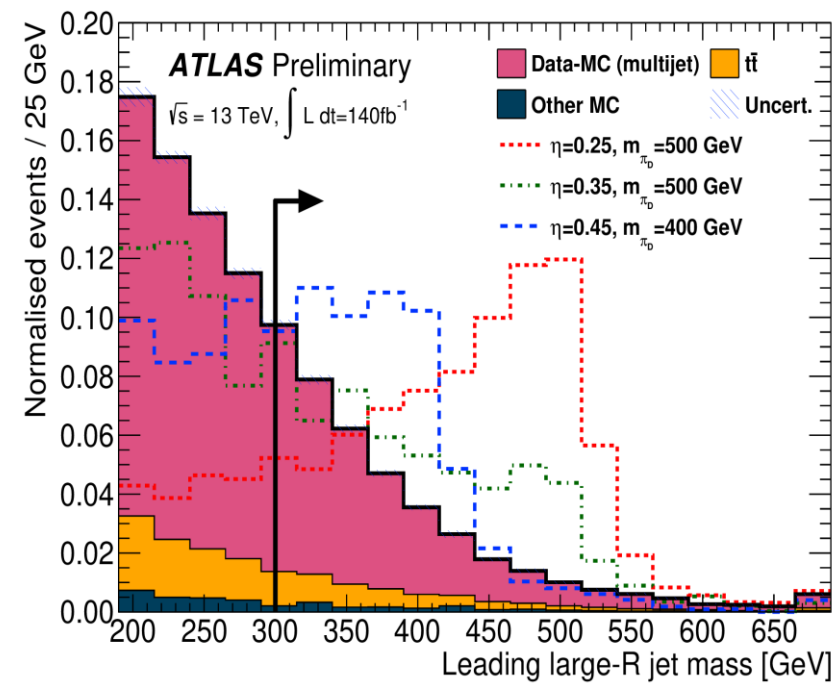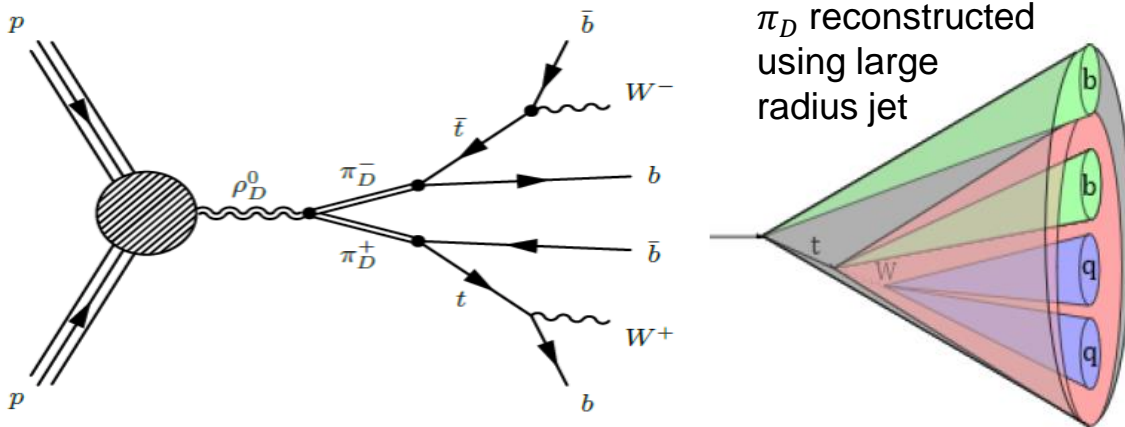
Dark Mesons →ttbb/tttb

Simplified "gaugephobic" $SU(2)_L$ model

- fully defined by $m_{\pi_D}, m_{\rho_D}, N_D = 4$
- $\sigma \sim \eta = m_{\pi_D}/m_{\rho_D}$ (< 0.5)
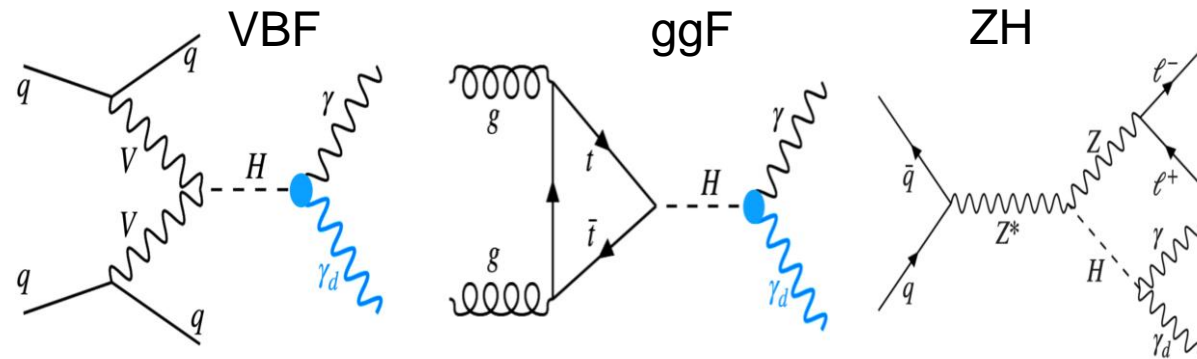- **dominant final states: *ttbb* or *tttb***

Fully hadronic top decay channel:

- dominant bkgd: multi-jet, $t\bar{t}$ and V+jets
- signal region: no lepton,
  ≥3 b-jets, two **large radius jets as π_D candidates**

No significant excess over the SM bkgd expectation

π_D reconstructed using large radius jet

First dedicated search result with full Run 2 dataset.

5

Massless Dark Photon Searches through Higgs decay

VBF ggF ZH

Coupled with the Higgs boson through a U(1) unbroken dark sector

Recent ATLAS results targeting VBF and ZH production

New analysis search for dark photon from **heavy Higgs decay** (0.4 – 3 TeV)

- **ggF and VBF** production modes
  - ggF signal acceptance limited by high E_T^{miss} and single photon trigger threshold

- **RECAST strategy reinterpret** previous $\gamma + E_T^{miss}$ results
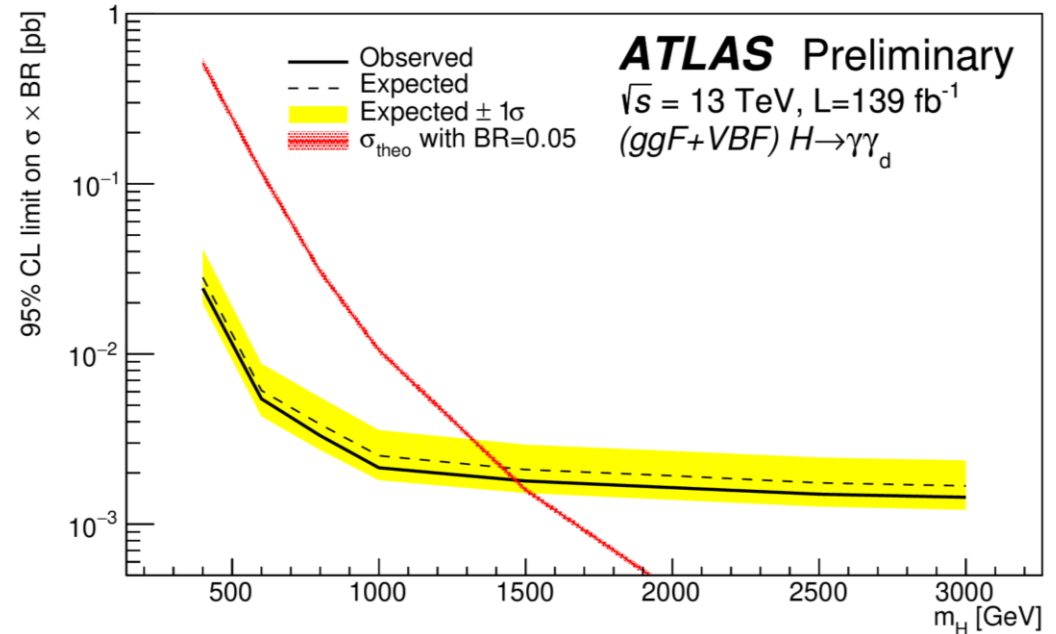
Efforts to combine all three analyses are underway

- to place better constraint on H(125)$\rightarrow \gamma\gamma_D$ and explore a wider m_H range

Massive Dark Photon (A') Search With Rare Z decays

- Dark Higgs-strahlung process, $\boldsymbol{Z \rightarrow A' h_D}$ with
  - $m_{A'} + m_{h_D} < m_Z$,
  - A' is the lightest particle in the DS, $A' \rightarrow f\bar{f}$ (SM)
  - $pp \rightarrow Z \rightarrow A' h_D \rightarrow A' A' A'^{(*)} \rightarrow 4l + X$
    (at least two same-flavour opposite-charge lepton pairs in the final state)
 - sensitive to $\alpha_D \varepsilon^2$,the coupling of A' to h_D
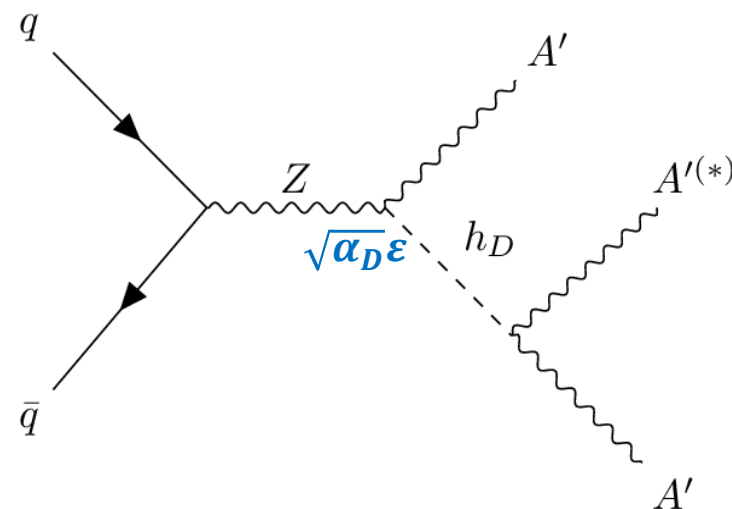
- Dominant bkgds: $qq \rightarrow 4l$

- Final discriminant: $\bar{m}_{ll}$

- The data are found to be consistent with the SM background prediction.

- [previous search](#) at Belle via
  $e^+ e^- \rightarrow A' h_D \rightarrow A' A' A'$,
  $A' \rightarrow e^+ e^-, \mu^+\mu^-, \text{ or } \pi^+\pi^-$
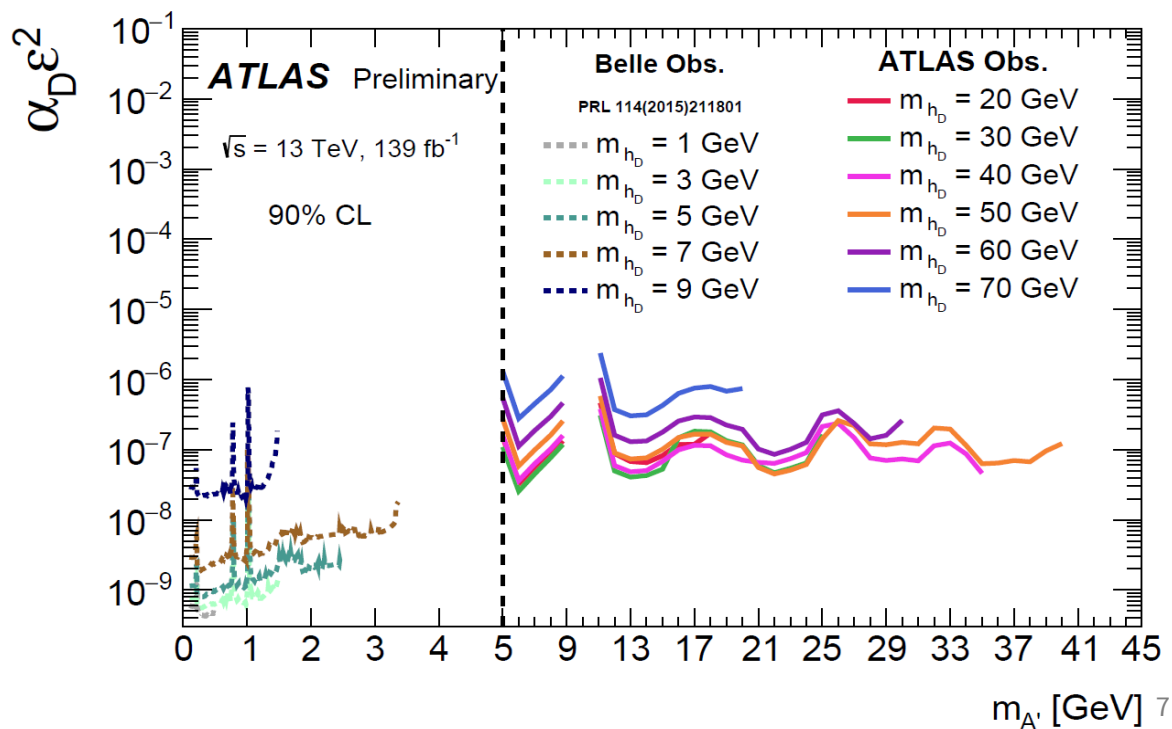
Dark Higgs (S) - Two Mediator DM Model

$S+E_T^{miss}$ signature

- $S \to WW/ZZ \to qqqq$ | earlier result |
- $S \to bb$ | earlier result, RECAST, **dedicated search ongoing** |
- $S \to WW \to qq\ell\nu$ | **New result** |
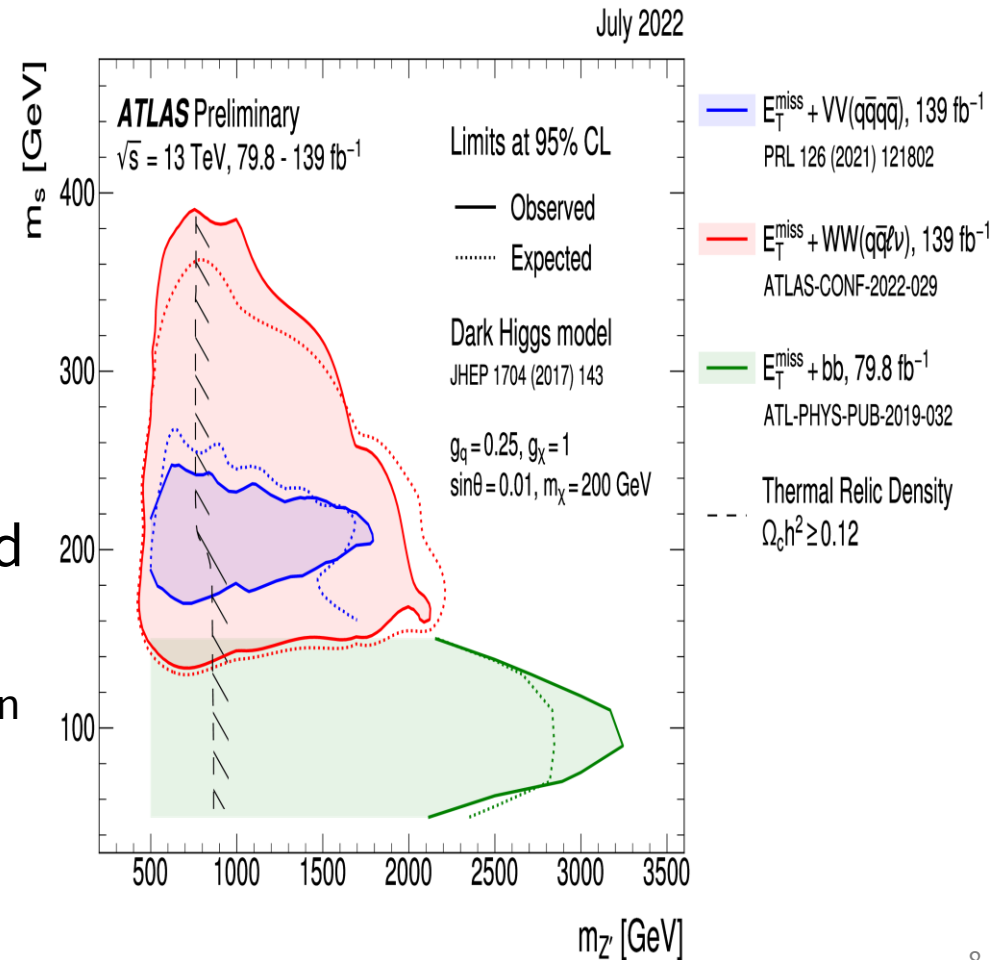

Boosted topology   Resolved topology
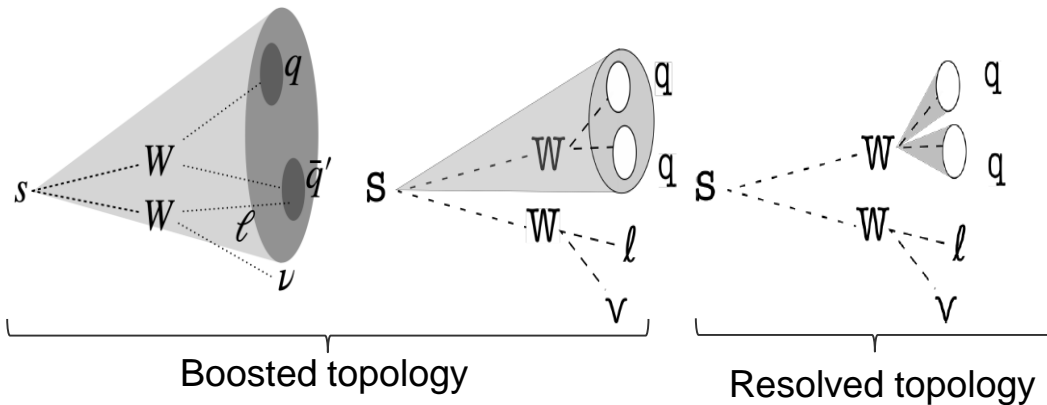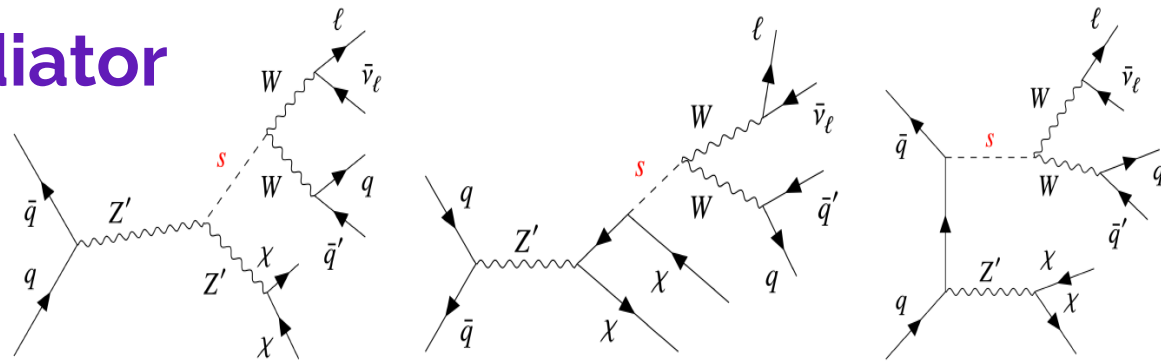
Special technique to reconstruct boosted hadronically decaying W

- using both the calorimeter and tracking information

Final observable: m_s

Data agree with SM prediction

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 79.8 - 139 fb^{-1}

July 2022

Limits at 95% CL

— Observed
······ Expected

Dark Higgs model
JHEP 1704 (2017) 143

$g_q = 0.25$, $g_\chi = 1$
$\sin\theta = 0.01$, $m_\chi = 200$ GeV

E_T^{miss} + VV($q\bar{q}q\bar{q}$), 139 fb^{-1}
PRL 126 (2021) 121802

E_T^{miss} + WW($q\bar{q}\ell\nu$), 139 fb^{-1}
ATLAS-CONF-2022-029

E_T^{miss} + bb, 79.8 fb^{-1}
ATL-PHYS-PUB-2019-032

Thermal Relic Density
$\Omega_c h^2 \geq 0.12$
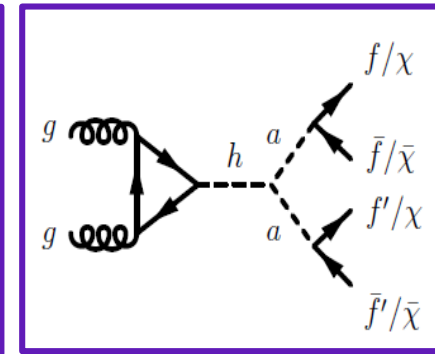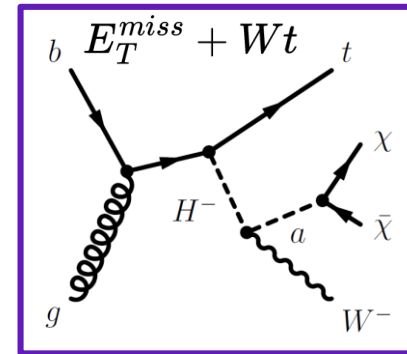
m_s [GeV]

$m_{Z'}$ [GeV]

8

2HDM+Pseudoscalar (a) Model

LHC Dark Matter Working Group recommends as the **simplest UV-complete benchmark with a pseudoscalar mediator** to evaluate LHC potential on DM searches. [arxiv:1810.09420]

- **rich phenomenology** with a wide range of relevant signatures

Vigorous efforts to **summarize ~20 analyses in 10** representative **benchmark** scenarios
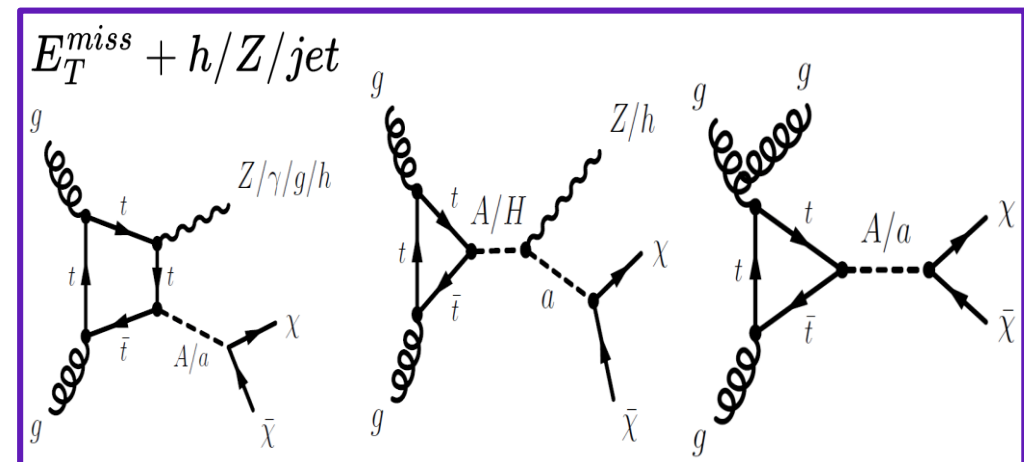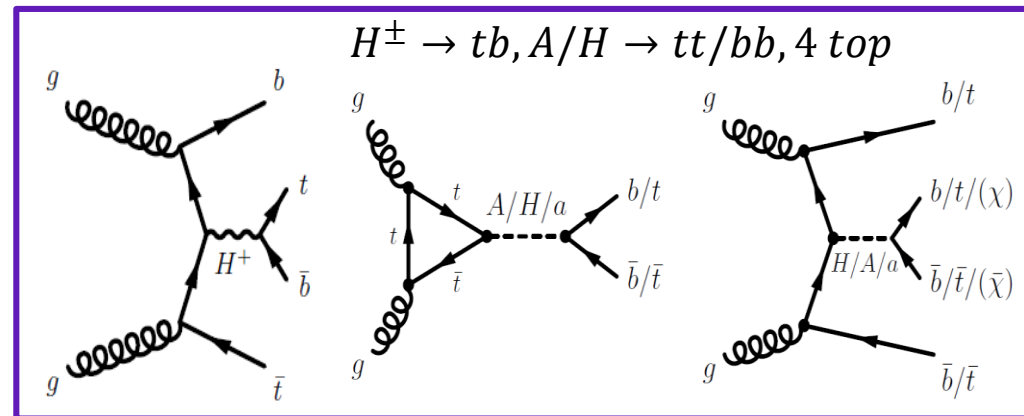
# Highlights of Ongoing 2HDM+a Combination & Summary

Most sensitive channels

$(E_T^{miss} + h(bb), E_T^{miss} + Z(ll)$ and $H^{\pm} \to tb)$
are **combined statistically**
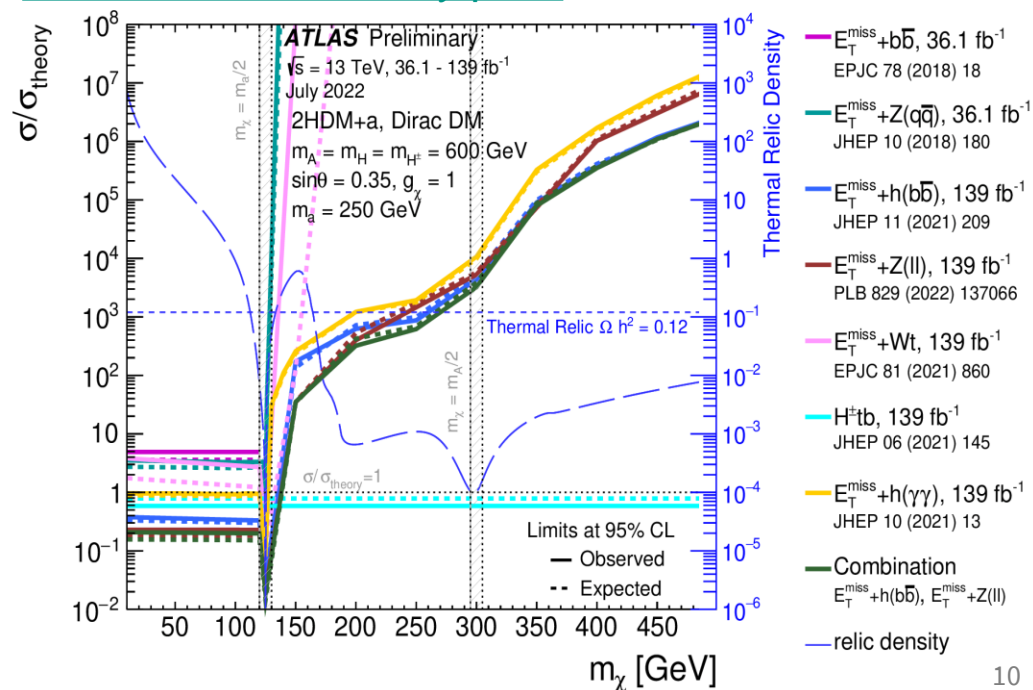
- extends the sensitivity to the 2HDM+a

Showcase possibilities for lighter pseudoscalar mediators, **and the interplay** of light resonance searches with the E_T^{miss} signatures

Analysis is in final review stage

- will be the most comprehensive set of constraints on the 2HDM+a obtained to date.
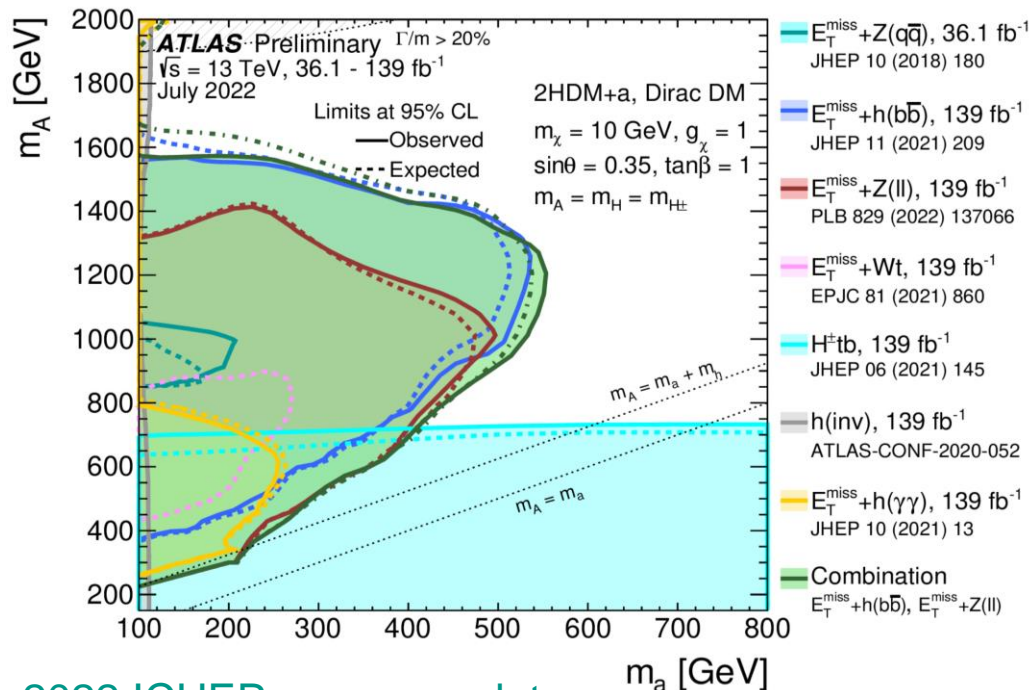
2022 ICHEP summary plots

Ongoing Studies and Towards LHC Run-3

Many **new dedicated analyses/combination in the pipelines**, e.g:

- Promptly-decaying dark jet resonance
- E_T^{miss} +S(bb)
- Dark photon ($H \to \gamma \gamma_D$) combination covering ggH, VBF and ZH production mode

ATLAS intensively iterating with theorists & experimentalists via LHCDMWG to prepare/**update new benchmarks for Run 3**, e.g:

- t-channel DM model [Phys. Lett. B 813 136038, *Eur. Phys. J. C* **80**, 409 (2020) etc.]

Synergy/harmonization

- among the LHC DM community to converge to **a common prescription** in Run 3 ATLAS/CMS results
- among ATLAS analyses to **explore** the **prospect of unconventional signatures** in search for non-WIMP/WIMP DM, e.g
  - Emerging jets
  - Long live particle phenomenology in 2HDM+a model

Summary

Selected example of **recent ATLAS full Run 2 results** are shown.

**Diverse searches** for dark matter candidates in ATLAS

- covering different range of experimental signatures and benchmark models.
- complex interplay underlines the **importance of studying different collider signatures**

Many Run 2 analyses still in the pipelines while Run 3 benchmarks are in preparation

- **stay tuned for updates**!

Additional Slides

E_T^{miss} +Wt

- Analysis optimized for 2HDM+a signals
- Different final states are considered: 0L/1L/2L
- Background: Z+jets, tt and W+jets
- Final exclusion results include both the single top and tt signal contributions, with 0L/1L/2L channels combined
- Besides published exclusion results, additional parameter scans have also been produced for overlying in 2HDM+a summary
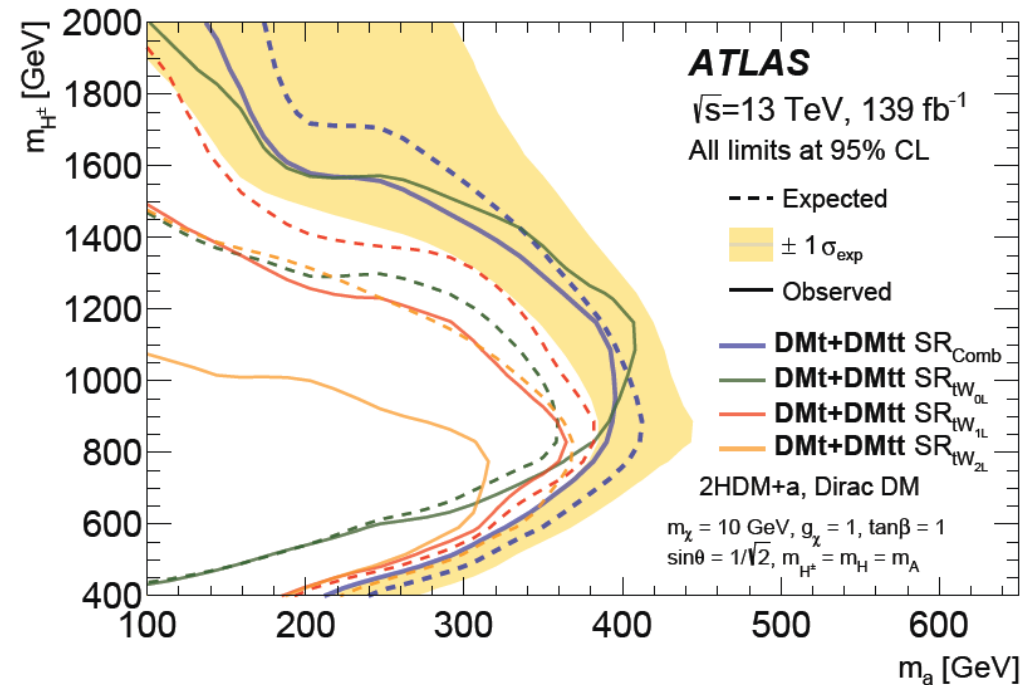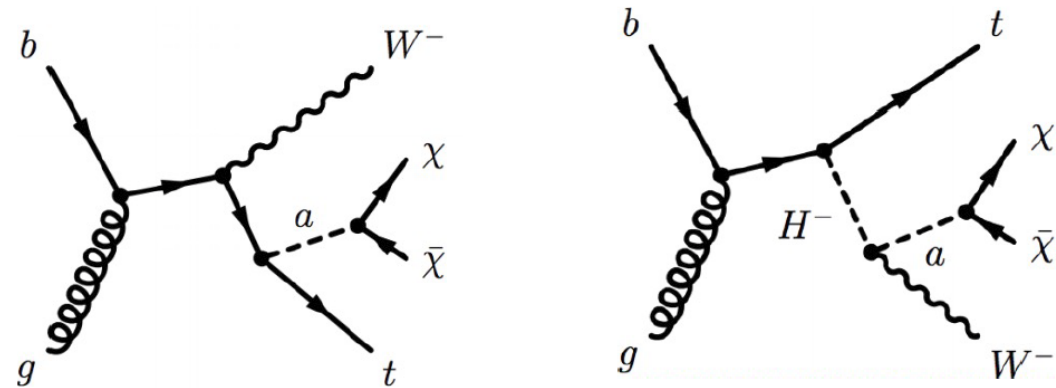
Semi-visible jets

Dark hadrons geometrically contained in a jet

- leads to event E_T^{miss} direction close to one of the jets.

Leading bkgd:

- multijet, V+jets, $t\bar{t}$ and single top processes

Key discriminants:

- scalar sum of p_T of jets in the event
- p_T balance and difference in the angle between the closest and farthest jet from E_T^{miss}

Observed yield in agreement with SM bkgd expectation

95% CL upper limits on λ