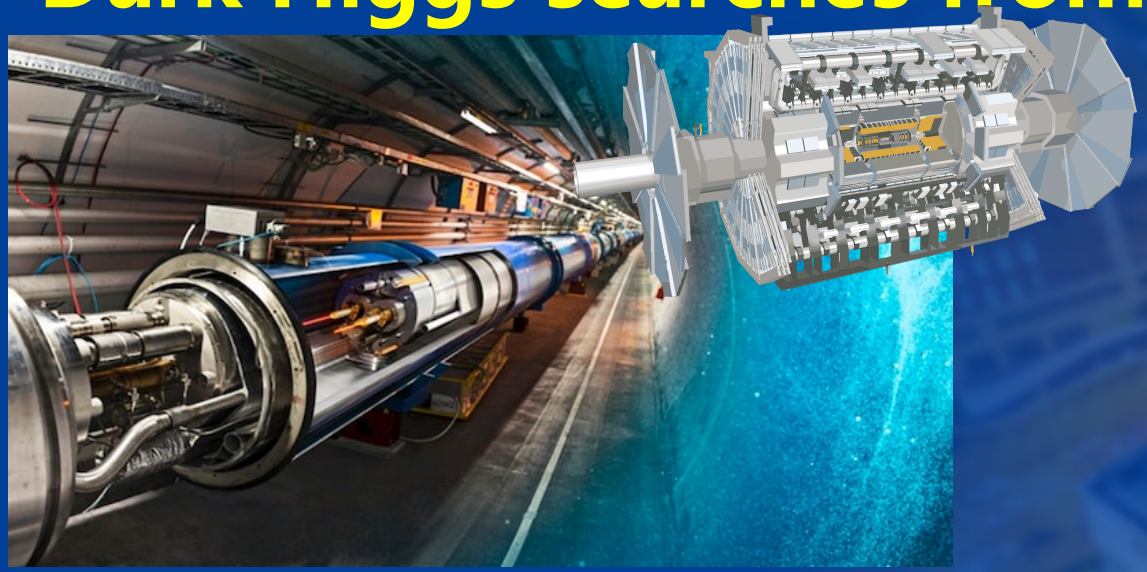
李政道研究所
TSUNG-DAO LEE INSTITUTE

ATLAS EXPERIMENT

# Recent Dark Matter combination summary and Dark Higgs searches from ATLAS

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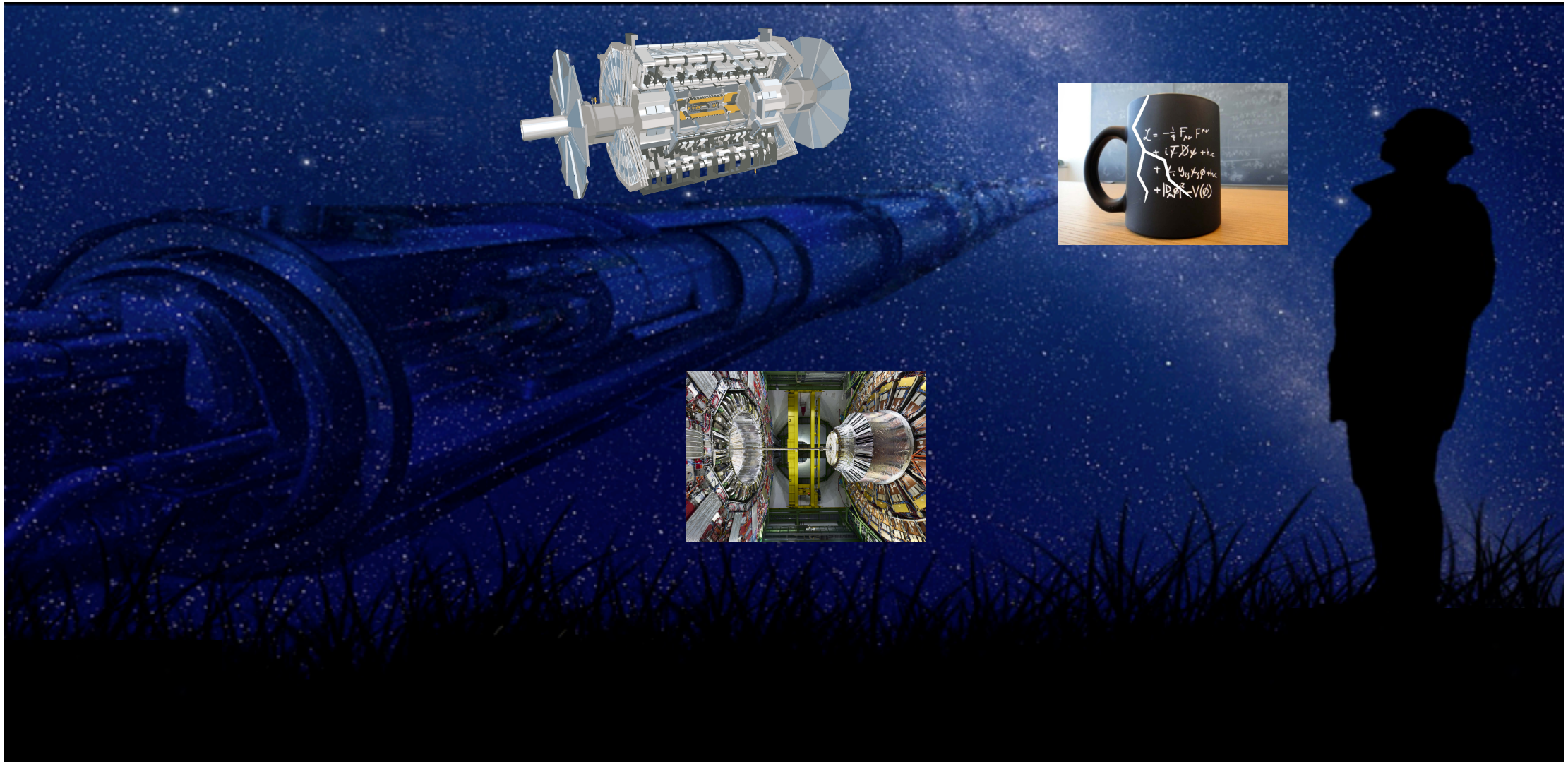
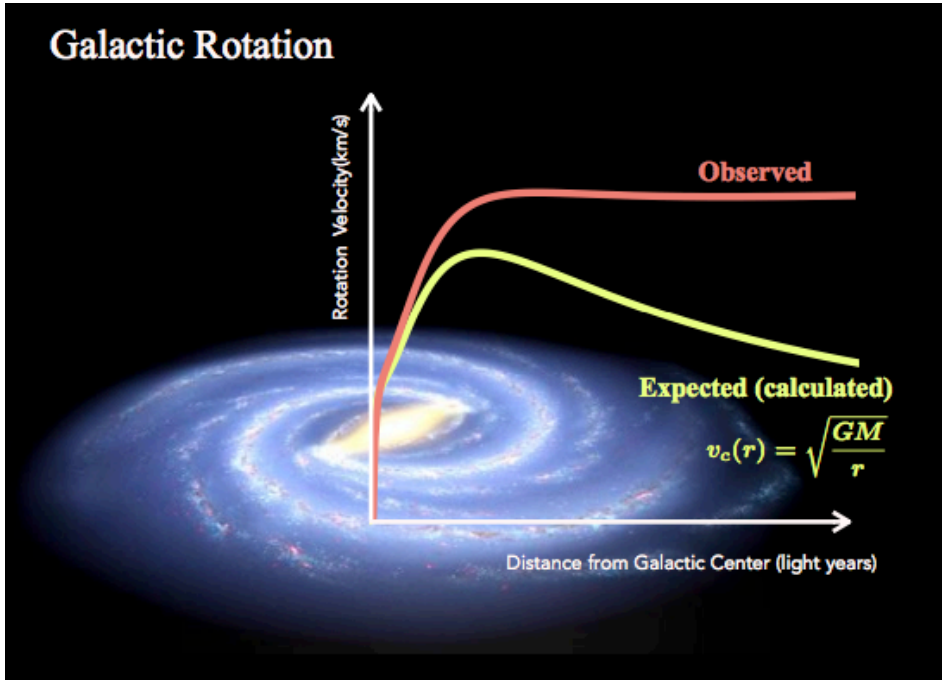
09/05/2024

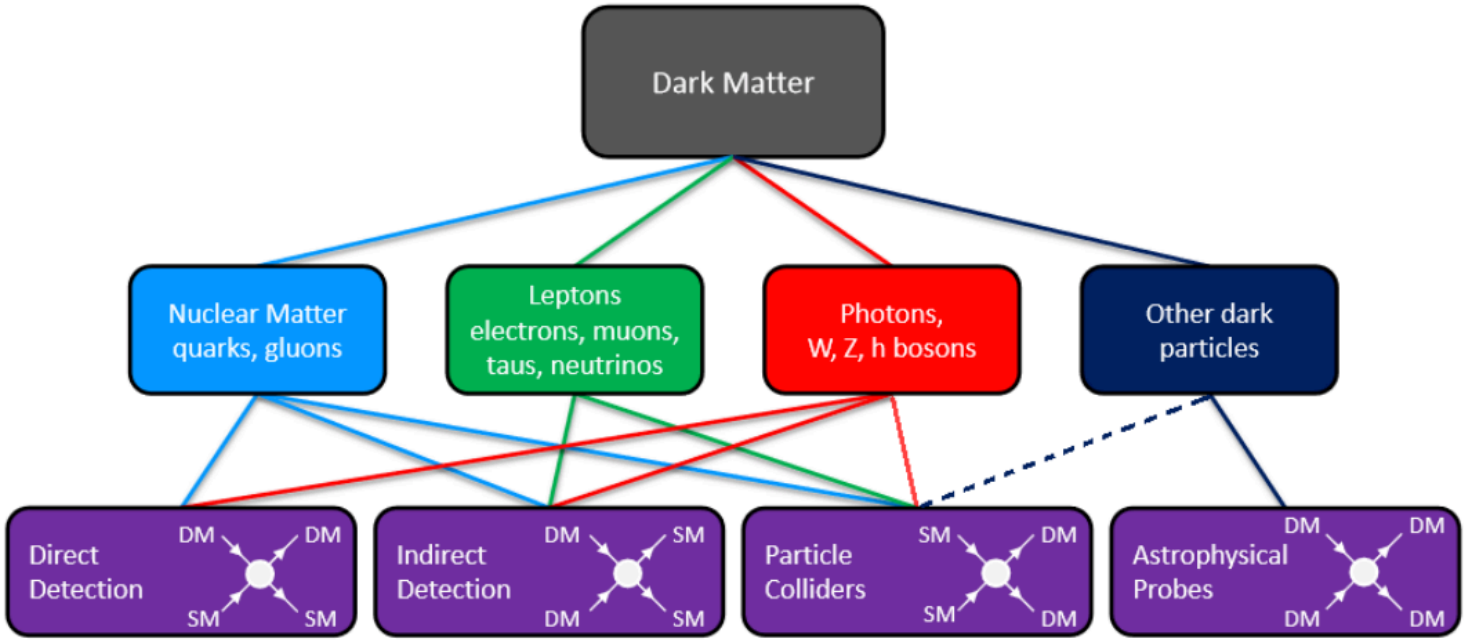
第三届地下和空间粒子物理与宇宙物理前沿问题研讨会 @ 西昌

# LHC primary goals: looking into the “unknowns”



# Dark Matter Evidence and Theory Context in a nutshell



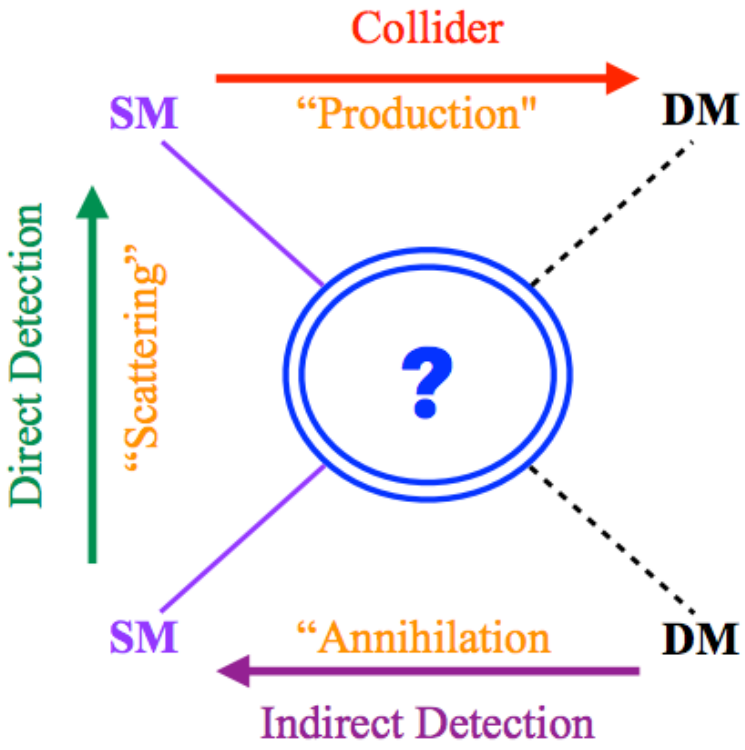

- DM evidence from astronomical observations and gravitational effects:
  - Galactic rotation curves, Gravitational lensing, Cosmic Microwave Background anisotropies, …
- Characteristics: Non-baryonic, massive, electrically neutral, gravitational, stable → WIMP context

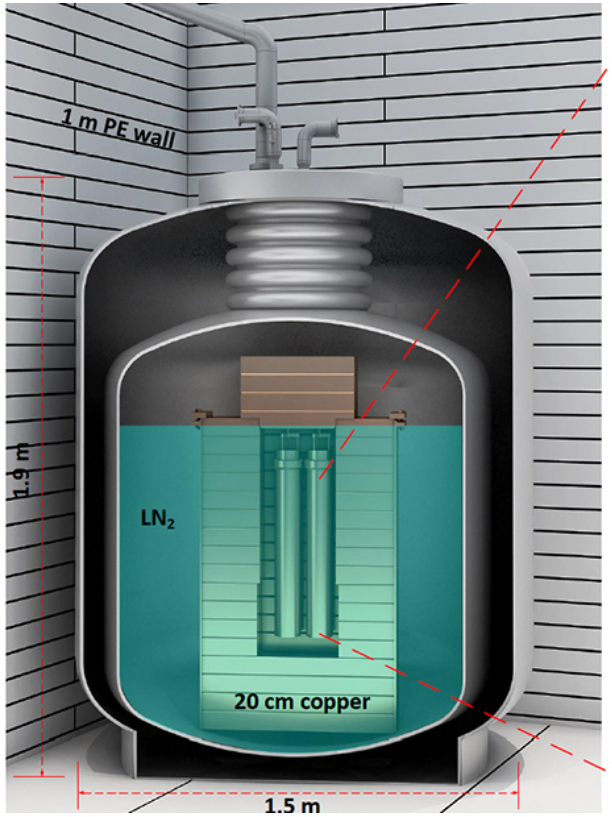
- BSM models predict weakly interacting massive particle (WIMP) -> Dark Matter Candidate. In SUSY models, the lightest SUSY particle LSP is a candidate for dark matter. Being LSP stable in most Models.
- Any WIMP DM produced at collider experiments will interact weakly and pass invisibly through detectors. Inferred through ‘Missing $E_T$’ when event does not balance in plane transverse to beam.

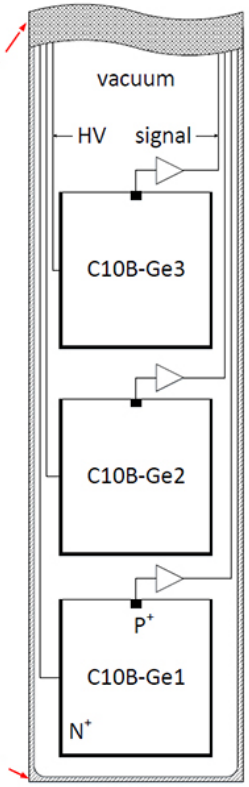
# Frontiers that DM can reach out

# Dark Matter Direct Detections

- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (CDEX, PandaX, LZ, XENONnT, …)
- Indirect Detection (ID): products from DM annihilation (DAMPE, HESS, IceCube, ..)
- Colliders: DM production in high-energy collisions, focusing on the productions of a SM particle(s) (X) with large missing $E_T$

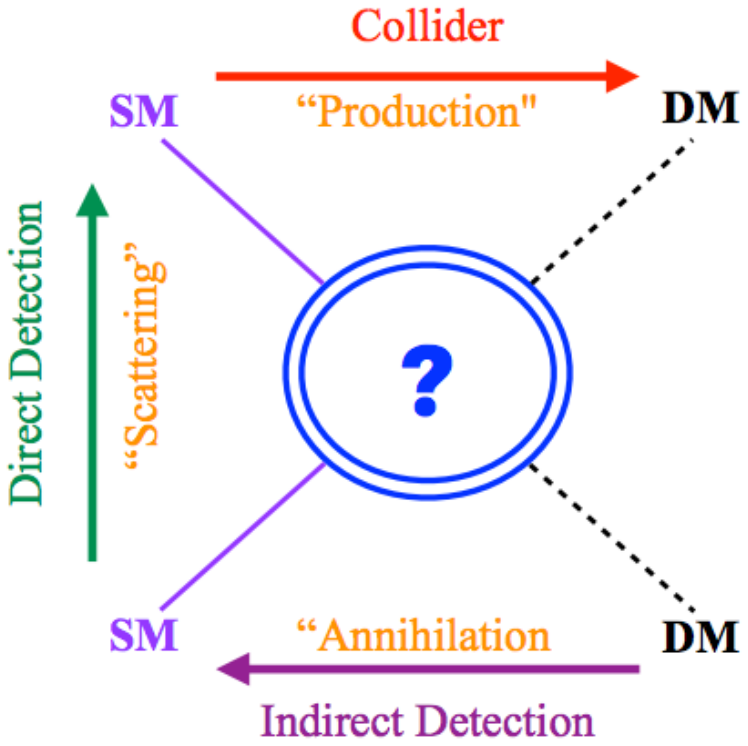


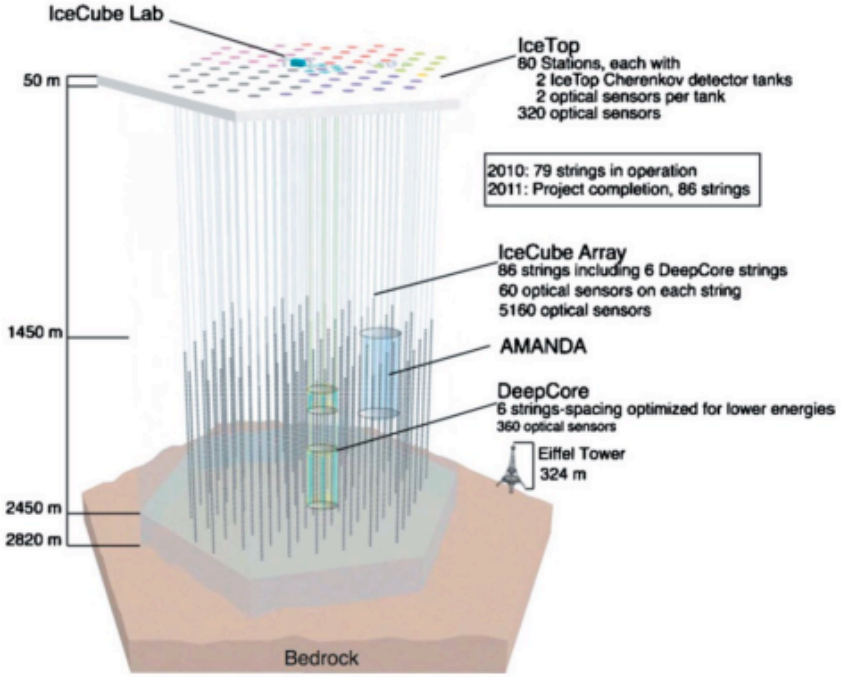




# Dark Matter Indirect Detections

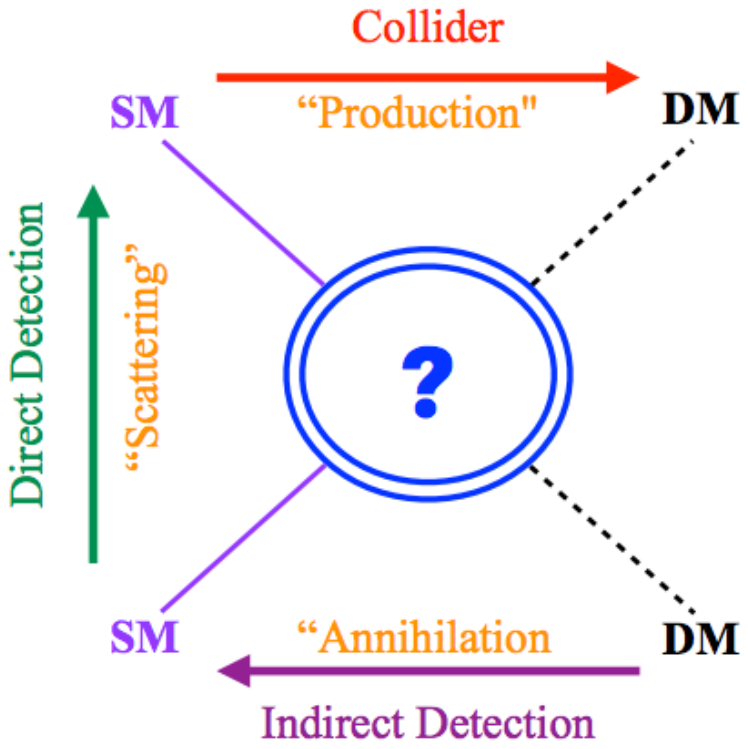
- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (CDEX, PandaX, LZ, XENONnT, …)
- Indirect Detection (ID): products from DM annihilation (DAMPE, HESS, IceCube, ..)
- Colliders: DM production in high-energy collisions, focusing on the productions of a SM particle(s) (X) with large missing $E_T$

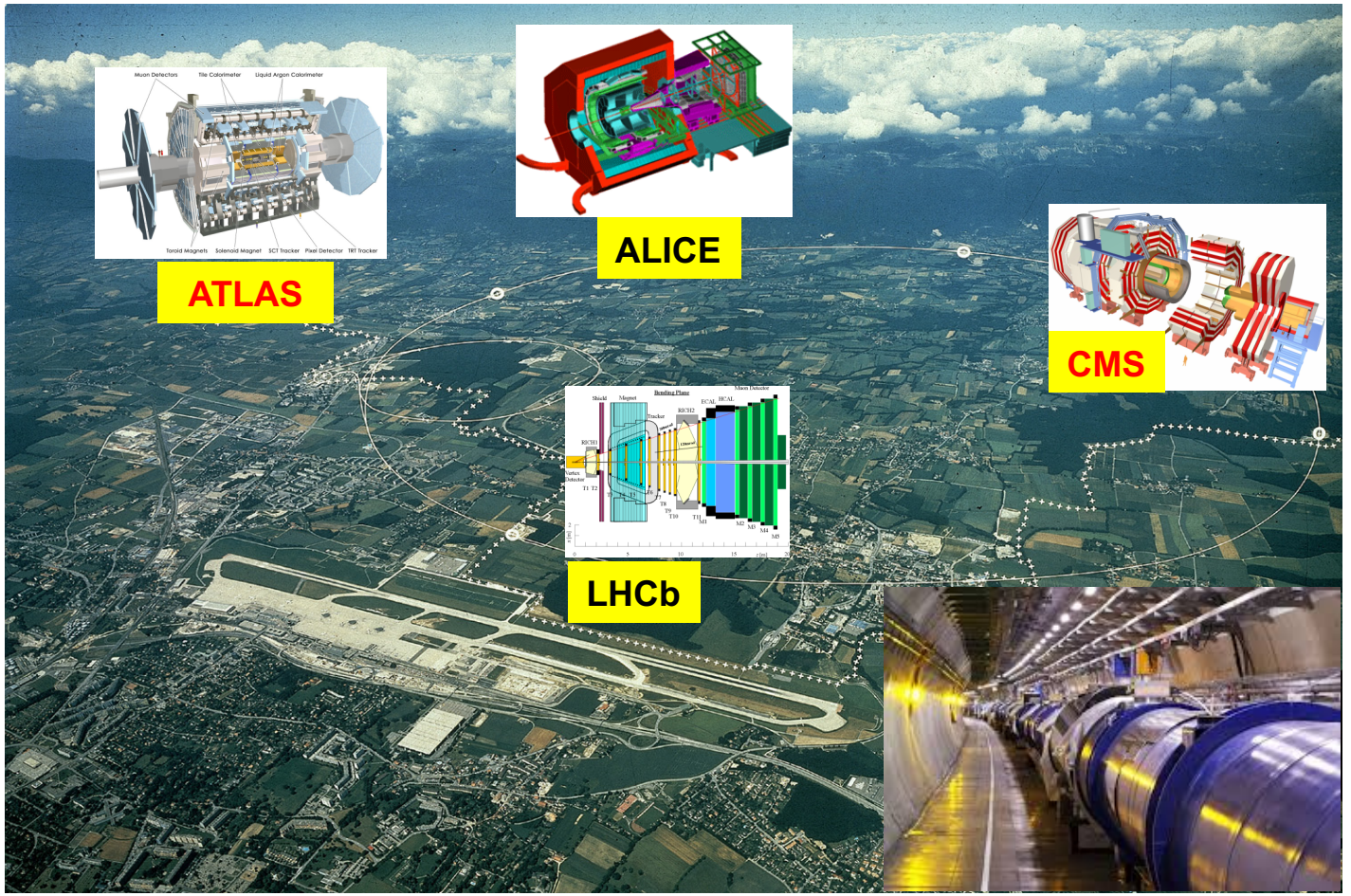


# Dark Matter Collider productions

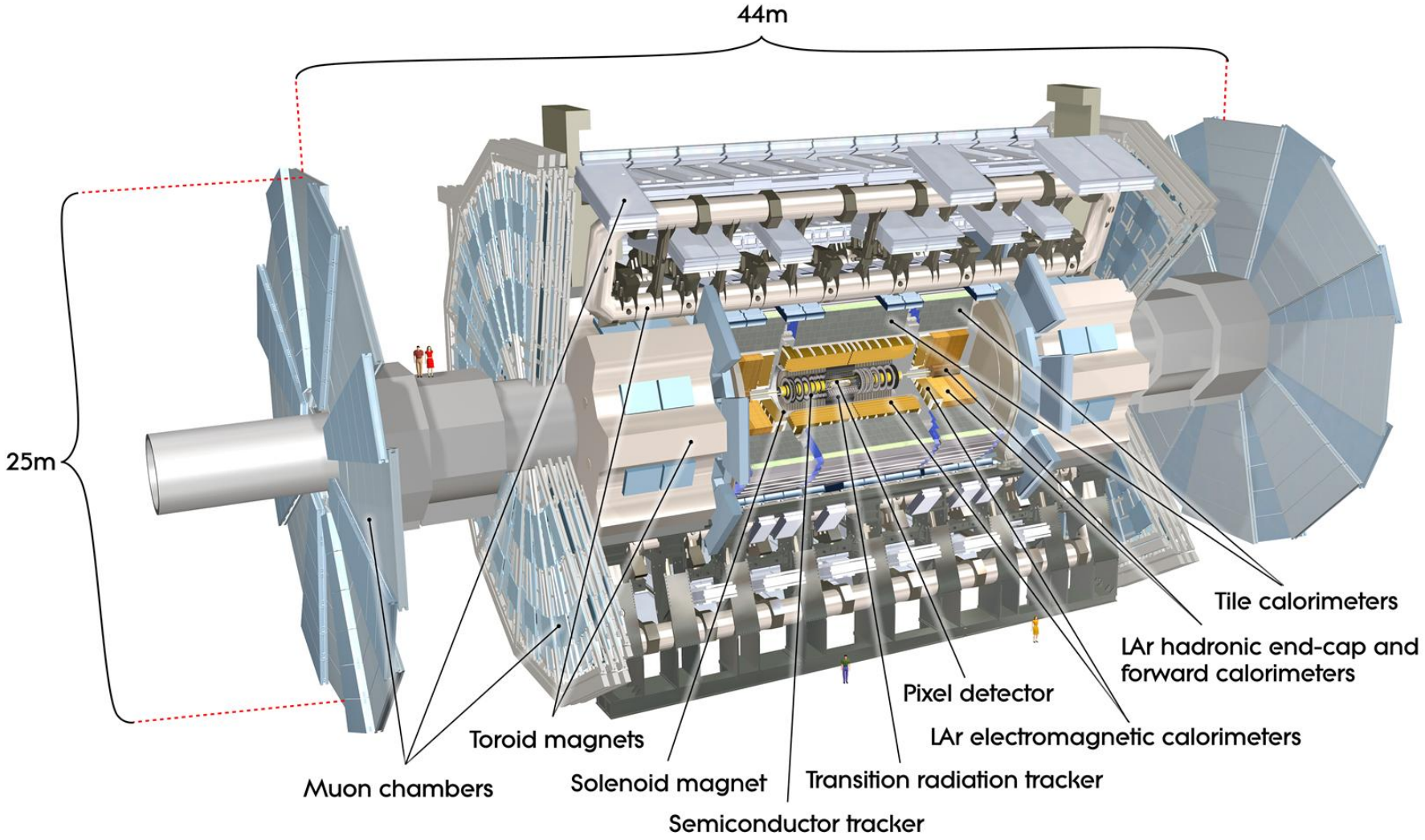
- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (CDEX, PandaX, LZ, XENONnT, …)
- Indirect Detection (ID): products from DM annihilation (DAMPE, HESS, IceCube, ..)
- Colliders: DM production in high-energy collisions, focusing on the productions of a SM particle(s) (X) with large missing $E_T$



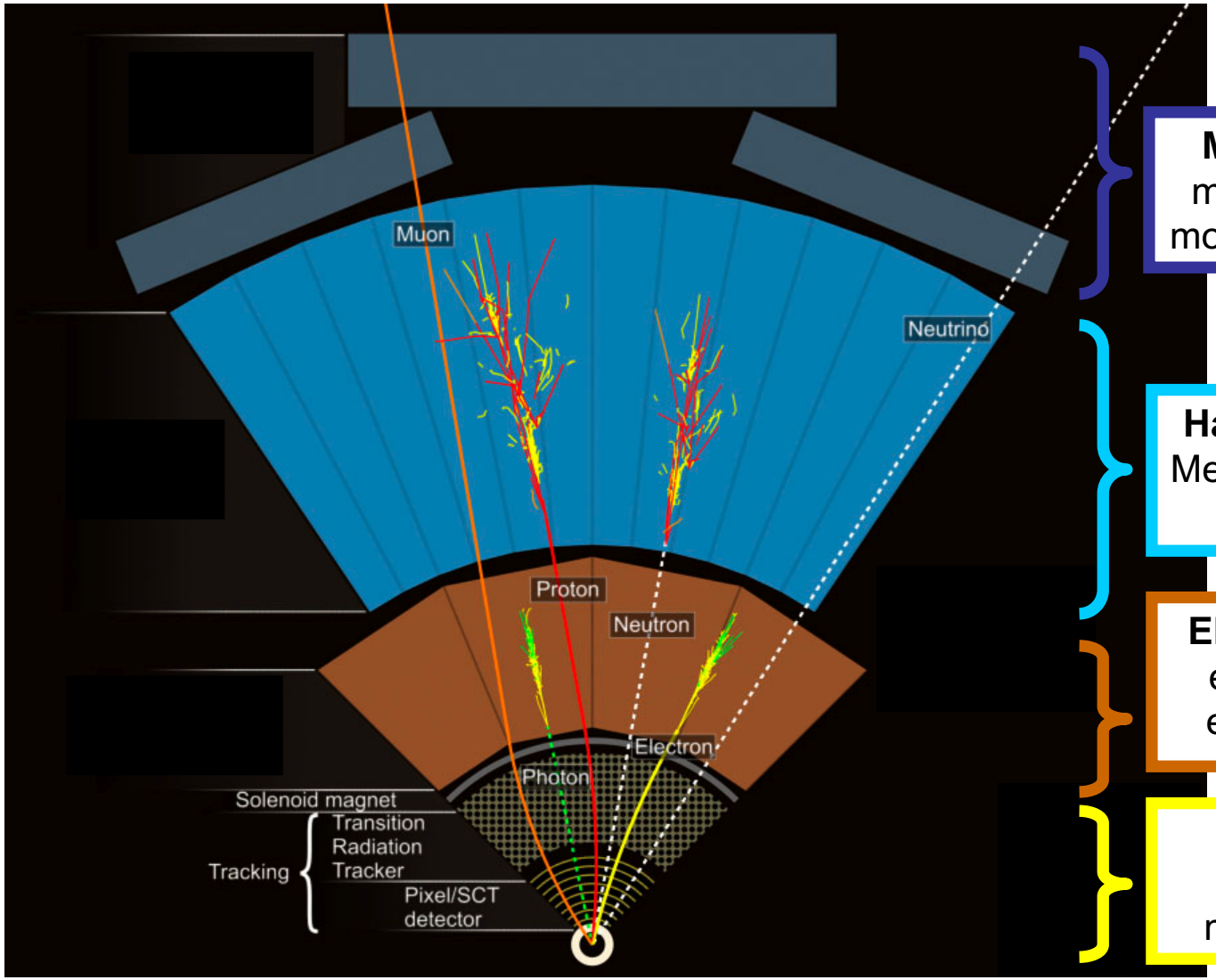



# The ATLAS Experiment

45x25m, 7k tons, ~6000 members (~3000 authors)



# ATLAS Detector System



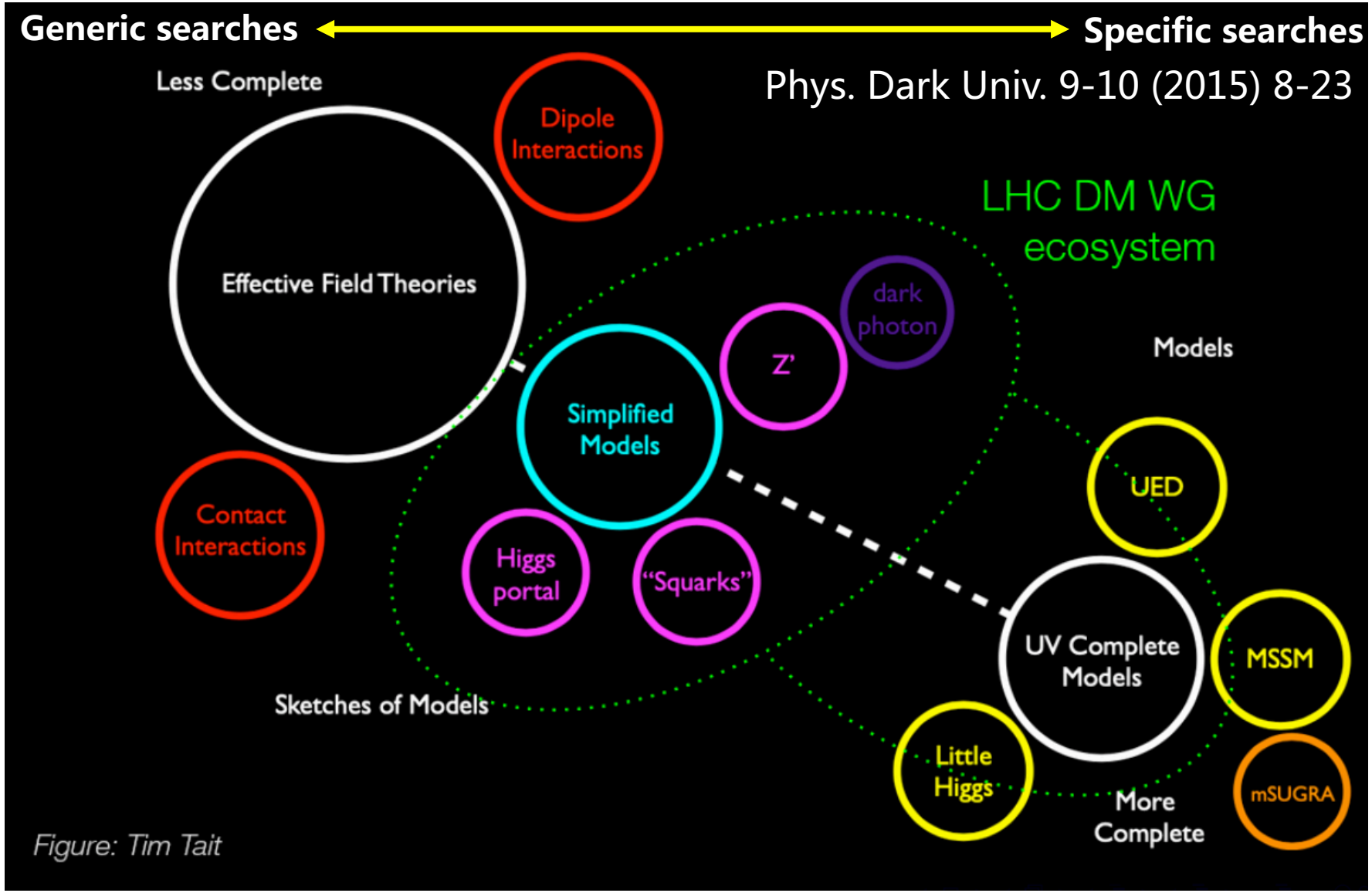

**Muon Spectrometer:**
muon identification and momentum measurement

**Hadronic calorimeter:**
Measurement of jets and missing energy

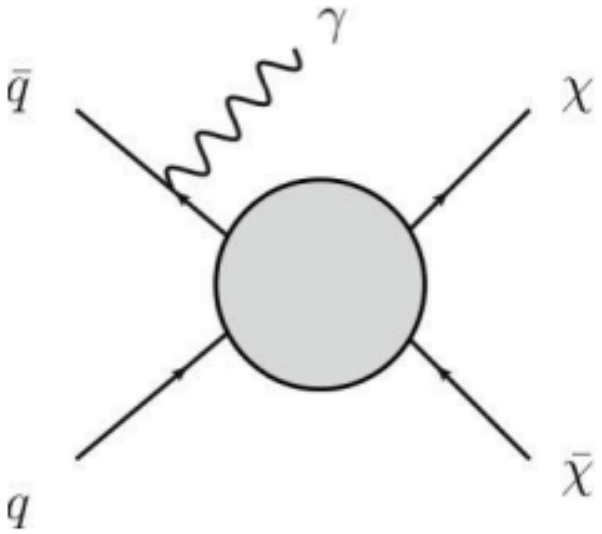
**Electromagnetic calo:**
e/γ identification and energy measurement

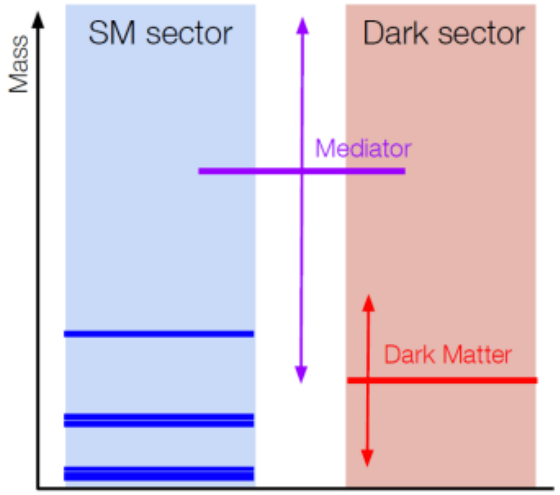
**Tracking system:**
Charged particle momentum, vertexing

# Dark Matter Models for LHC

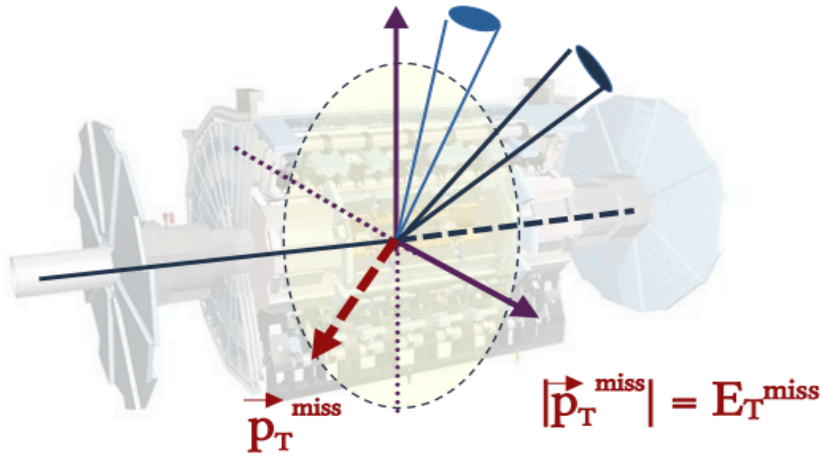


# S-channel Mediator Simplified Models




**DM produced together with a visible object**
e.g. γ, jet, Z-boson, W-boson, Higgs-boson




Escape
Detection

**Missing transverse momentum** inferred from momentum conservation

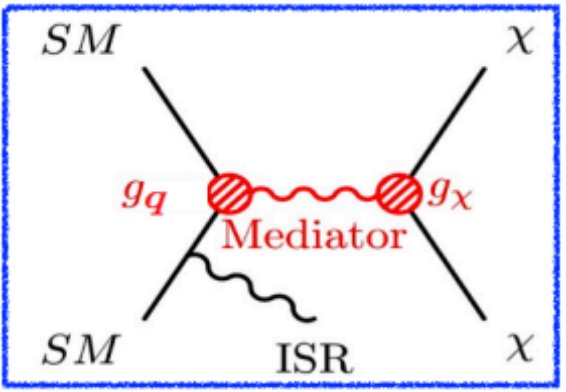
Simplified model:
- Starting point to build complete theories
- Colliders can search for the mediator directly
- Benchmark model @ Run II

Two complementary approaches:
- Look for DM - mono-X signature
- Look for mediator - resonance search

# Dark Matter Search programs at LHC



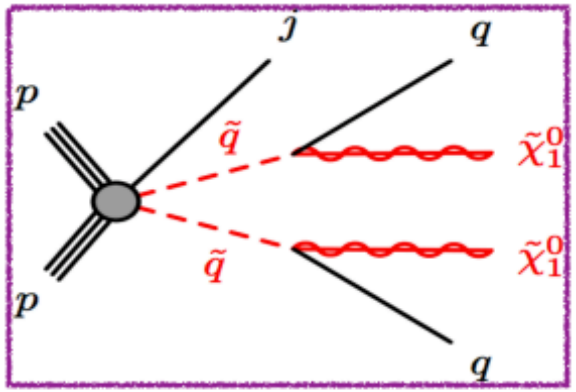
## Simplified models




SM-DM boson mediator:

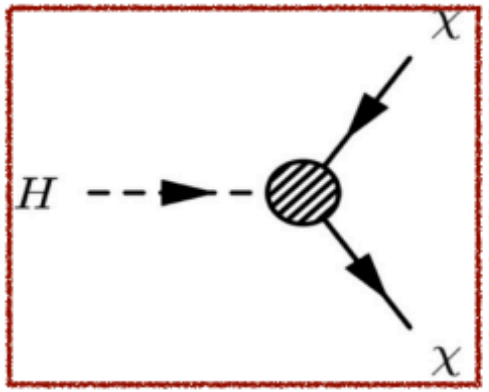
- Spin-0: Scalar (S) or pseudo-scalar (a)
- Spin-1: Vector (V/Z') or axial-vector (A)
- Minimal set of parameters: $M_\chi$, $M_{mediator}$, $g_\chi$, $g_q$, $g_\ell$

## SUSY



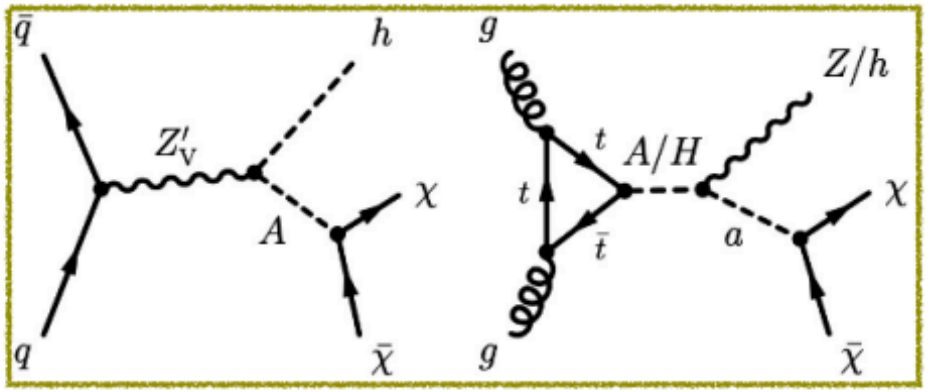

- Provides good candidate for DM
- R-parity conservation
- Lightest supersymmetric Particle (LSP)
- Model-dependent limit on DM candidate

## Higgs portal




- Higgs boson mediates DM-SM interaction: $H \rightarrow invisible$
- Parameters: $m_\chi$, $\chi$ spin

## Extended Higgs sector




- More complete models (more free parameters and better sensitivity) involving several Higgs-like (or scalar) bosons: 2HDMa, Dark Higgs, ..

PART 01

# Recent Dark Matter Combination Summary from ATLAS in the context of 2HDM+a

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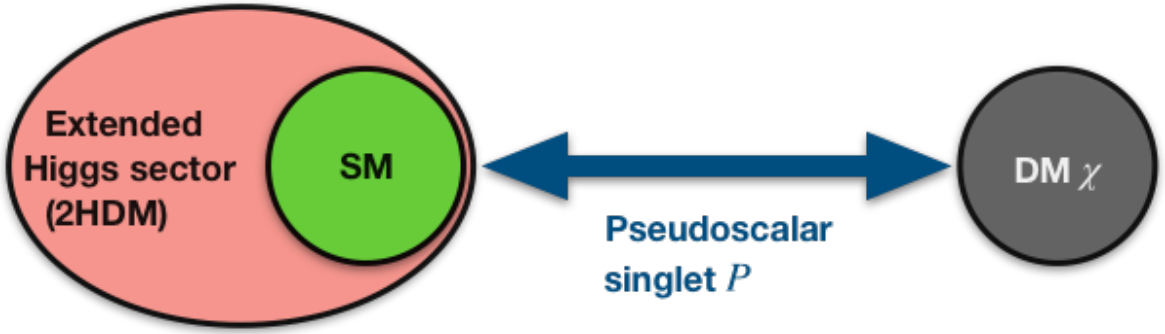
# 2HDM+a context

arXiv:2306.00641
(Science Bulletin Accepted)

- One of the popular ATLAS DM benchmark context
  - Searches interpreted in Two-Higgs-Doublet Model plus a pseudo-scalar mediator (2HDM+a):
  - Minimal, UV-complete extension.
  - EWK Symmetry Breaking:
    - 5 Higgs: h, H, $H^{\pm}$, A
    - 1 light pseudo-scalar: a




2HDM+a fully defined by 14 parameters

$$v,\ M_h,\ M_A,\ M_H,\ M_{H^\pm},\ M_a,\ m_\chi$$
$$\cos(\beta-\alpha),\ \tan\beta,\ \sin\theta,$$
$$y_\chi,\ \lambda_3,\ \lambda_{P1},\ \lambda_{P_2}$$

EWK, flavour constraints and to simplify parameter space

5 unconstrained parameters

| | |
|---|---|
| $m_A = m_H = m_{H^\pm}$ | masses of heavy Higgs |
| $m_a$ | mass of pseudo-scalar mediator |
| $m_\chi$ | DM mass |
| $\sin\theta$ | mixing angle between CP-odd states $a$ and $A$ |
| $\tan\beta$ | ratio of 2 Higgs doublet VEVs |

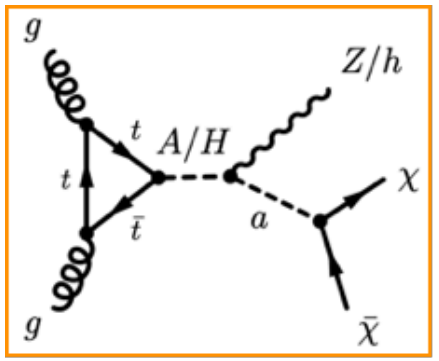
**LHC Dark Matter Working Group**
Phys. Dark Univ. 27 (2020) 100351
**Bauer, Haisch, Kahlhoefer**
JHEP05(2017) 138

*$h$: SM-like CP-even Higgs with mass of 125 GeV

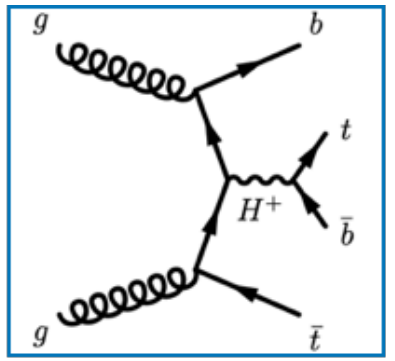
# 2HDM+a Experimental Signatures at ATLAS

arXiv:2306.00641
(Science Bulletin Accepted)

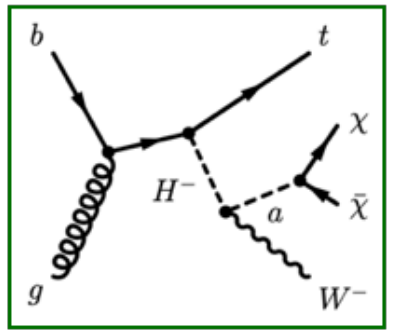
- 2HDM+a has rich phenomenology predicting wide range of signatures with both visible and invisible decays
  - resonant production of $E_T^{miss}$ +Z/h
  - additional (pseudo-)scalar bosons, e.g. tbH$^{\pm}$(tb)
  - new signatures, e.g. $E_T^{miss}$ +tW



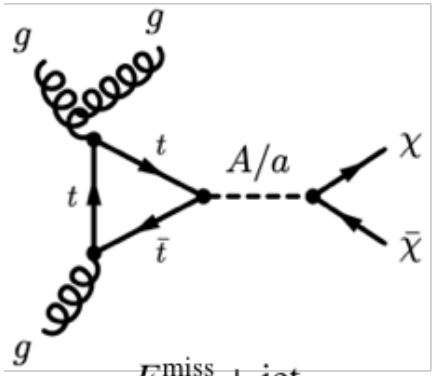

$E_T^{miss} + Z/h$



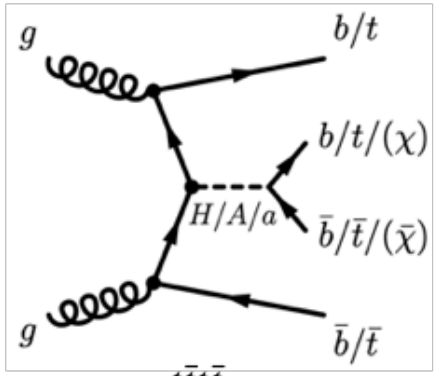

$tbH^{\pm}(tb)$



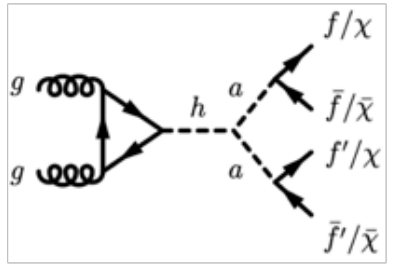

$E_T^{miss} + tW$




$E_T^{miss}$ + jet




$t\bar{t}t\bar{t}$

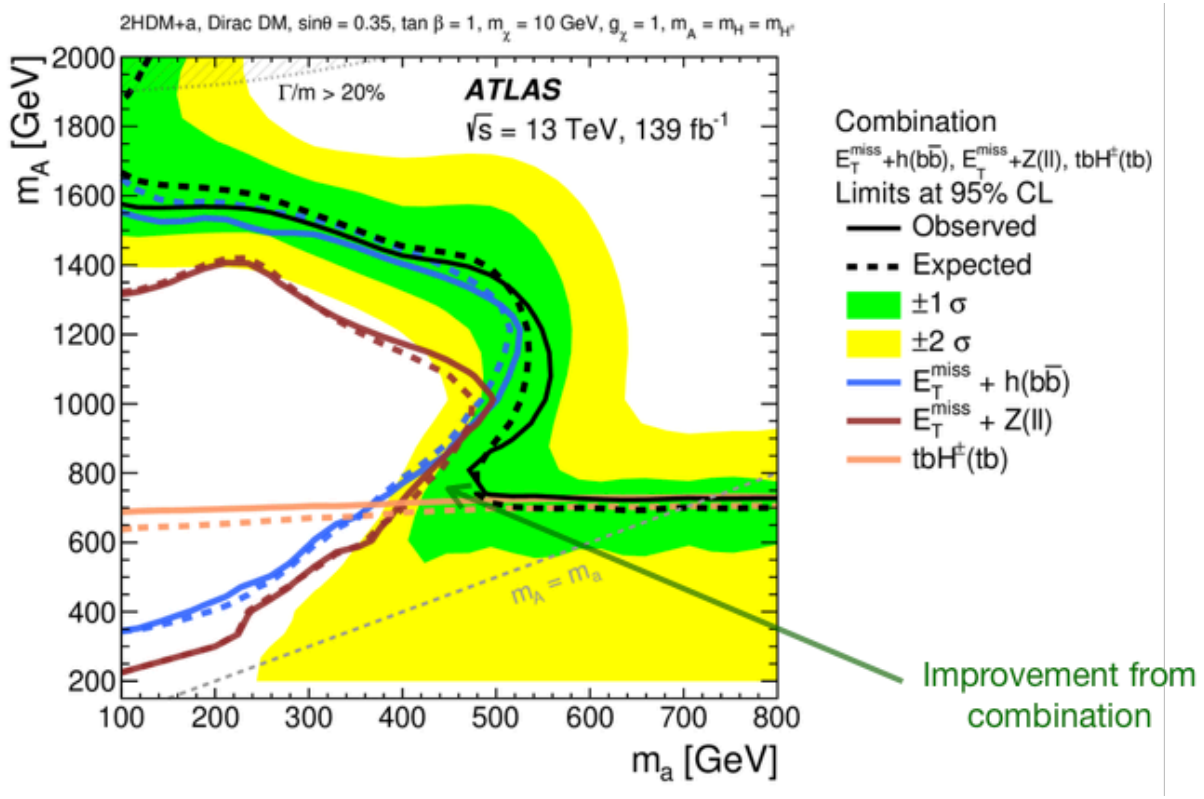



$h \to aa \to 4f\,/\,h \to$ invisible

# Statistical Combination

arXiv:2306.00641
(Science Bulletin Accepted)

- $E_{\mathrm{T}}^{\mathrm{miss}} + h(bb)$, $E_{\mathrm{T}}^{\mathrm{miss}} + Z(ll)$ and $tbH^{\pm}(tb)$: Most constraining signatures of 2HDM+a.
  - $tbH^{\pm}(tb)$ gives significant complementarity to sensitivities of $E_{\mathrm{T}}^{\mathrm{miss}} + X$
  - stat. combination of 3 channels to maximize 2HDM+a constraints in parameter space.
- Combined exclusion limits obtained from **profile likelihood ratio** corresponding to **3-channel-combined likelihood**.
- Decorrelate over-constrained/pulled uncertainties to avoid any phase-space-specific biases across channels.



# Summary of constraints on 2HDM+a

- constraints on 2HDM+a interpreted in 6 benchmark scenarios.
  - highlight diverse phenomenology of 2HDM+a.
  - study the interplay and complementarities between different signatures.

| Scenario | | Fixed parameter values | | | | Varied parameters |
|---|---|---|---|---|---|---|
| | | $\sin\theta$ | $m_A$ [GeV] | $m_a$ [GeV] | $\tan\beta$ | |
| 1 | a | 0.35 | – | – | 1.0 | $(m_a, m_A)$ |
| | b | 0.70 | – | – | 1.0 | |
| 2 | a | 0.35 | – | 250 | – | $(m_A, \tan\beta)$ |
| | b | 0.70 | – | 250 | – | |
| 3 | a | 0.35 | 600 | – | – | $(m_a, \tan\beta)$ |
| | b | 0.70 | 600 | – | – | |
| 4 | a | – | 600 | 200 | 1.0 | $\sin\theta$ |
| | b | – | 1000 | 350 | 1.0 | |
| 5 | | 0.35 | 1000 | 400 | 1.0 | $m_\chi$ |
| 6 | | 0.35 | 1200 | – | 1.0 | $(m_a, m_\chi)$ |

shows interplay due to mass hierarchies

motivated by similar scans done for general 2HDMs

illustration $a$-$A$ mixing parameter effect

connection with cosmological constraints and direct/indirect searches

showed for the 1st time

$m_\chi$ set to 10 GeV in all scenarios, except 5 and 6

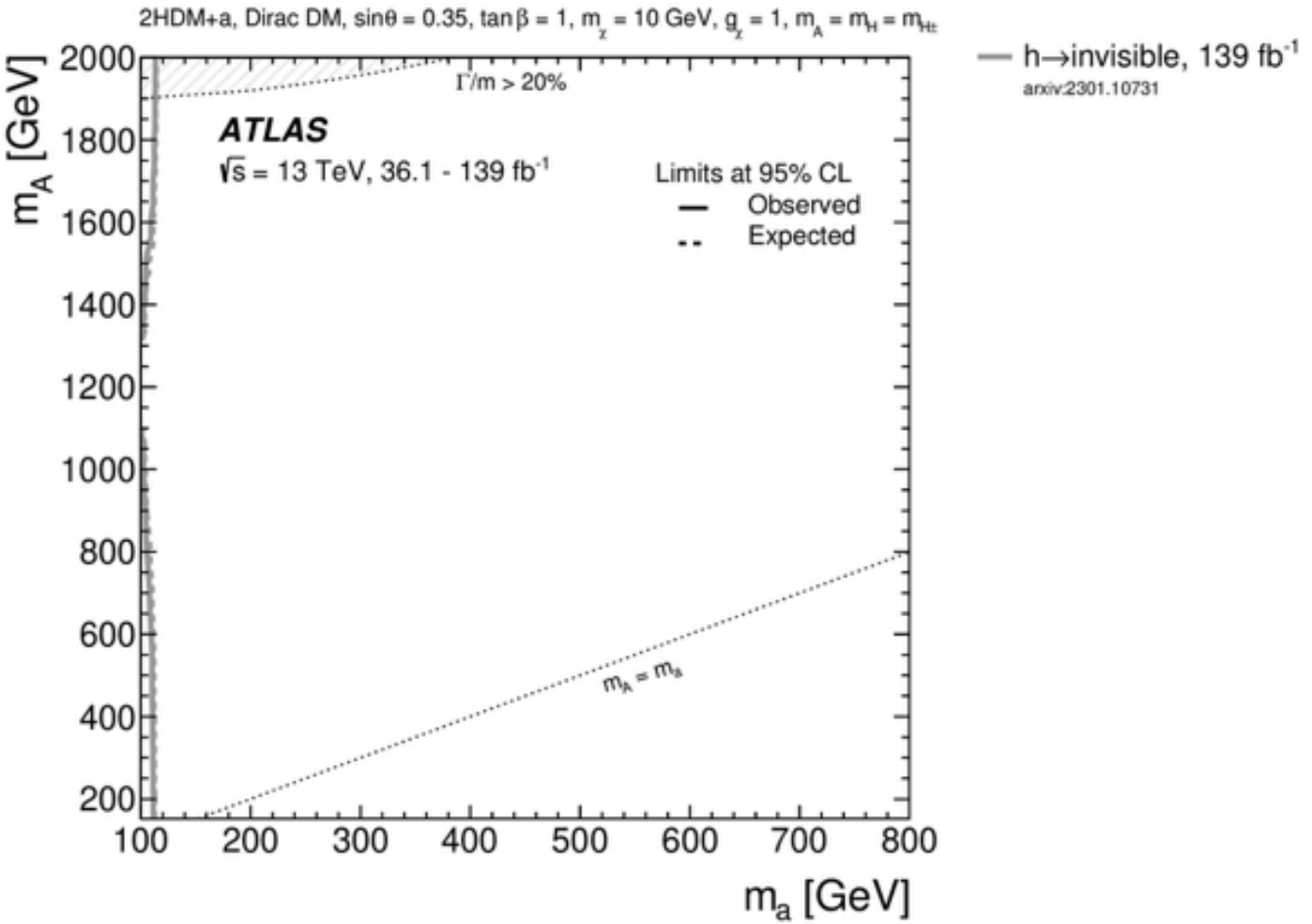
# Summary of constraints on 2HDM+a

Variety of searches interpreted in the context of different 2HDM+a benchmark scenarios

| Analysis/Scenario | 1a | 1b | 2a | 2b | 3a | 3b | 4a | 4b | 5 | 6 |
|---|---|---|---|---|---|---|---|---|---|---|
| $E_{\mathrm{T}}^{\mathrm{miss}} + Z(\ell\ell)$ [74] | x | x | x | x | x | x | x | x | x | |
| $E_{\mathrm{T}}^{\mathrm{miss}} + h(b\bar{b})$ [75] | x | x | x | x | x | x | x | x | x | x |
| $E_{\mathrm{T}}^{\mathrm{miss}} + h(\gamma\gamma)$ [84] | x | x | | | x | x | x | x | | |
| $E_{\mathrm{T}}^{\mathrm{miss}} + h(\tau\tau)$ [78] | x | | | x | | | | | | |
| $E_{\mathrm{T}}^{\mathrm{miss}} + tW$ [77] | x | x | x | x | x | x | x | x | | |
| $E_{\mathrm{T}}^{\mathrm{miss}} + j$ [45] | x | x | | | x | x | x | x | | |
| $h \to$ invisible [86] | x | x | | | x | | | | | x |
| $E_{\mathrm{T}}^{\mathrm{miss}} + Z(q\bar{q})$ [127] | x | | | | | | x | x | | |
| $E_{\mathrm{T}}^{\mathrm{miss}} + b\bar{b}$ [128] | | | | | | | x | x | | |
| $E_{\mathrm{T}}^{\mathrm{miss}} + t\bar{t}$ [128,129] | | | | | | | x | x | | |
| $t\bar{t}t\bar{t}$ [85] | x | x | x | x | x | x | x | x | x | |
| $tbH^{\pm}(tb)$ [76] | x | x | x | x | x | x | x | x | x | |
| $h \to aa \to f\bar{f}f'\bar{f}'$ [79,80,81,82,83] | | | | | | | | | | x |

# Scenario 1a: sin$\theta$=0.35, $m_A$ - $m_a$ plane

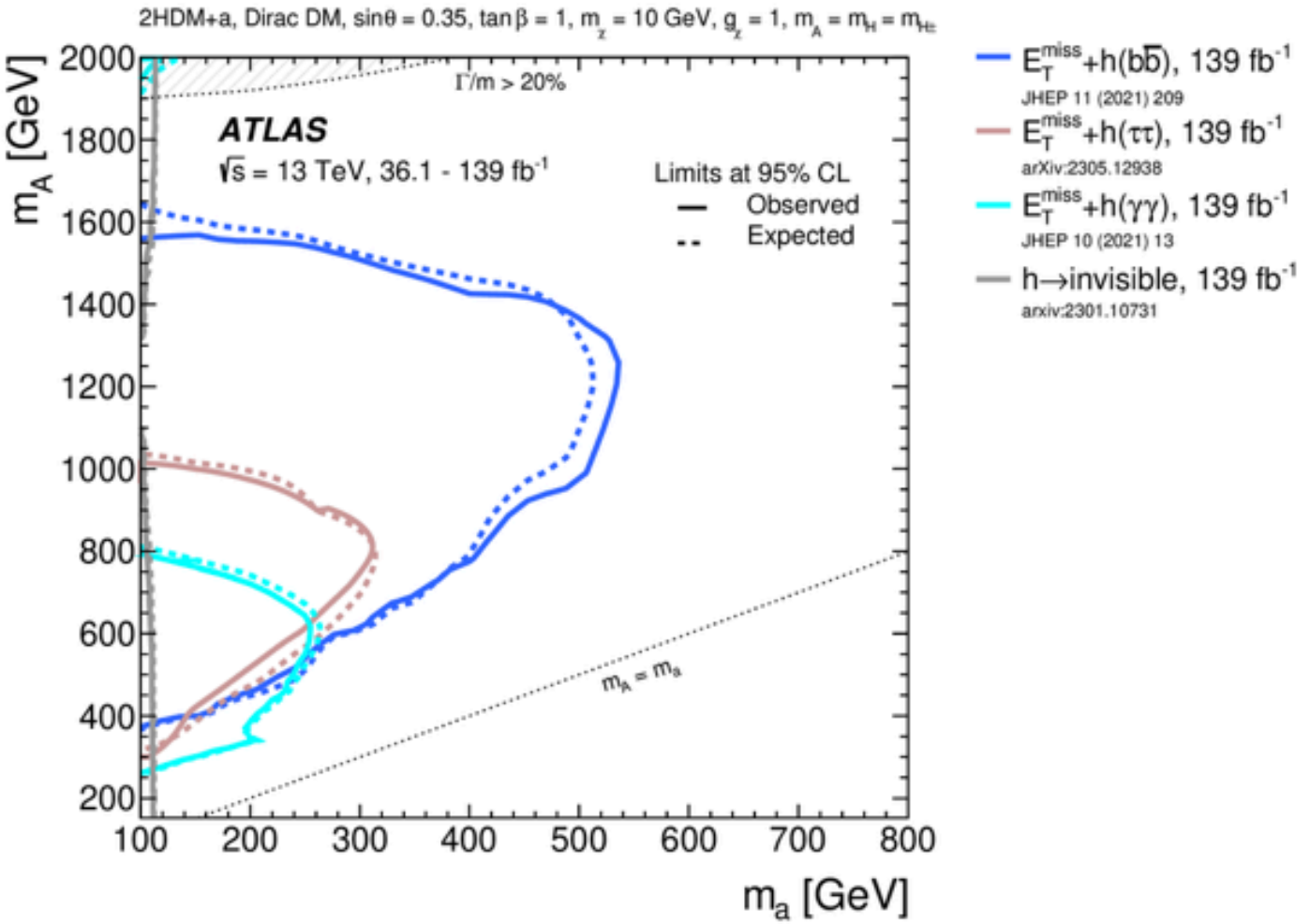
- $h \rightarrow$ invisible constrains very low $m_a$.



# Scenario 1a: sin$\theta$=0.35, $m_A$ - $m_a$ plane

- $h \rightarrow$ invisible constrains very low $m_a$.

- constraints from $E_{\mathrm{T}}^{\mathrm{miss}} + h$ signatures: similar $m_A$-$m_a$ dependence, with $h \rightarrow bb$ most sensitive.



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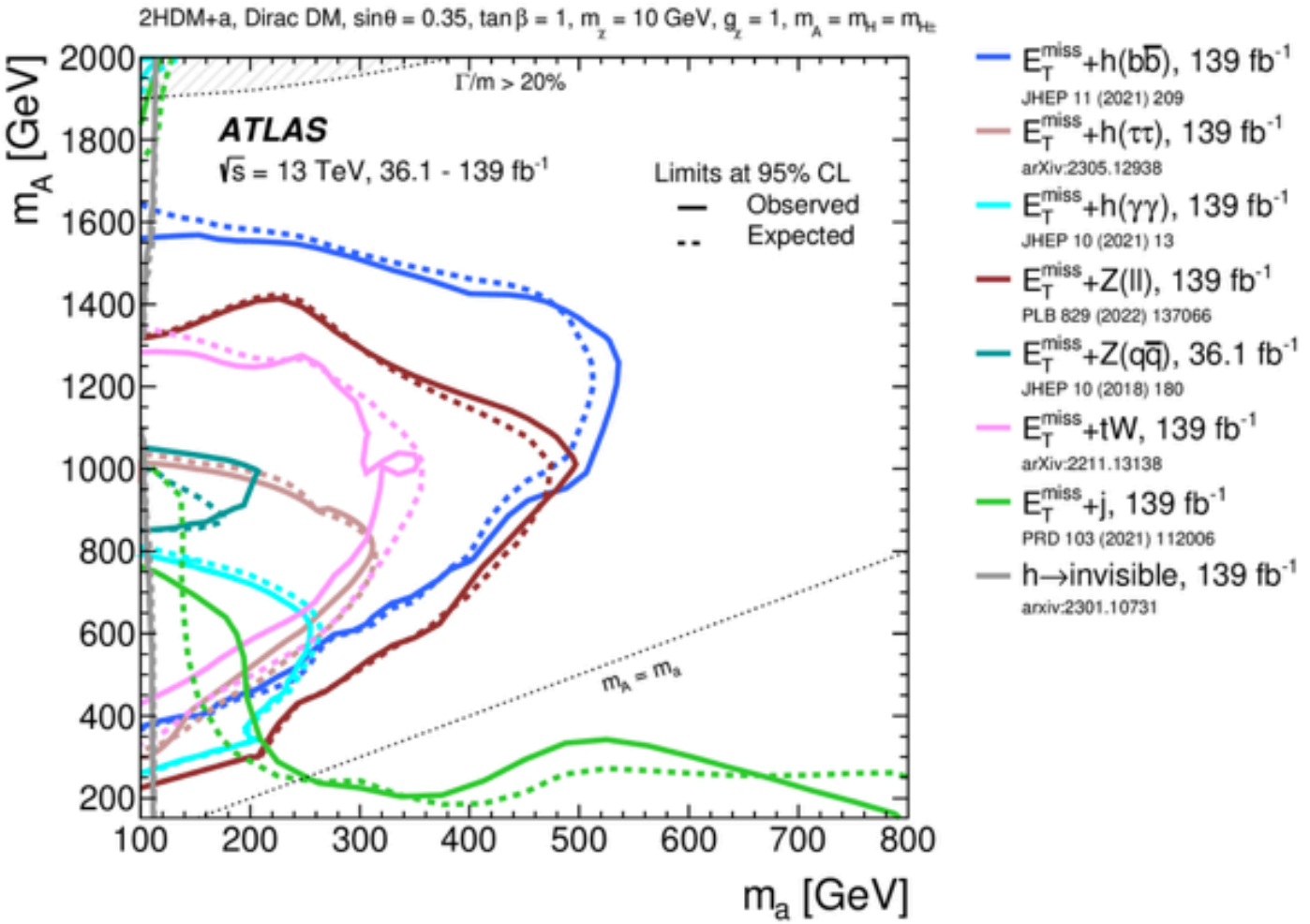
- $h \rightarrow$ invisible constrains very low $m_a$.
- constraints from $E_{\mathrm{T}}^{\mathrm{miss}} + h$ signatures: similar $m_A$-$m_a$ dependence, with $h \rightarrow bb$ most sensitive.
- $E_{\mathrm{T}}^{\mathrm{miss}} + tW$ similar to $E_{\mathrm{T}}^{\mathrm{miss}} + Z(ll)$ but with smaller excl. region.
- $E_{\mathrm{T}}^{\mathrm{miss}} +$ jet sensitivity notably different from those of $E_{\mathrm{T}}^{\mathrm{miss}} + Z$ and $E_{\mathrm{T}}^{\mathrm{miss}} + h$.



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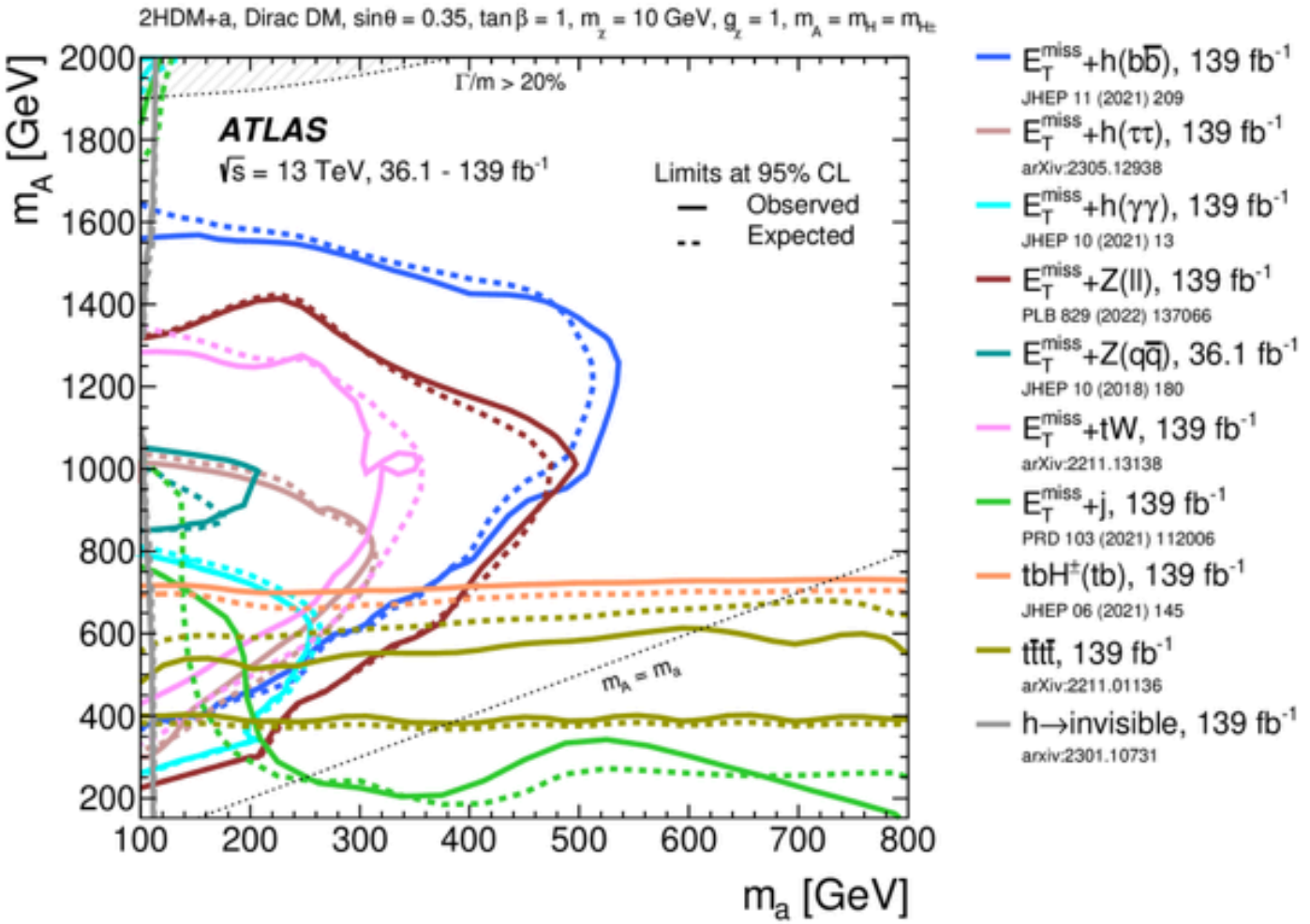
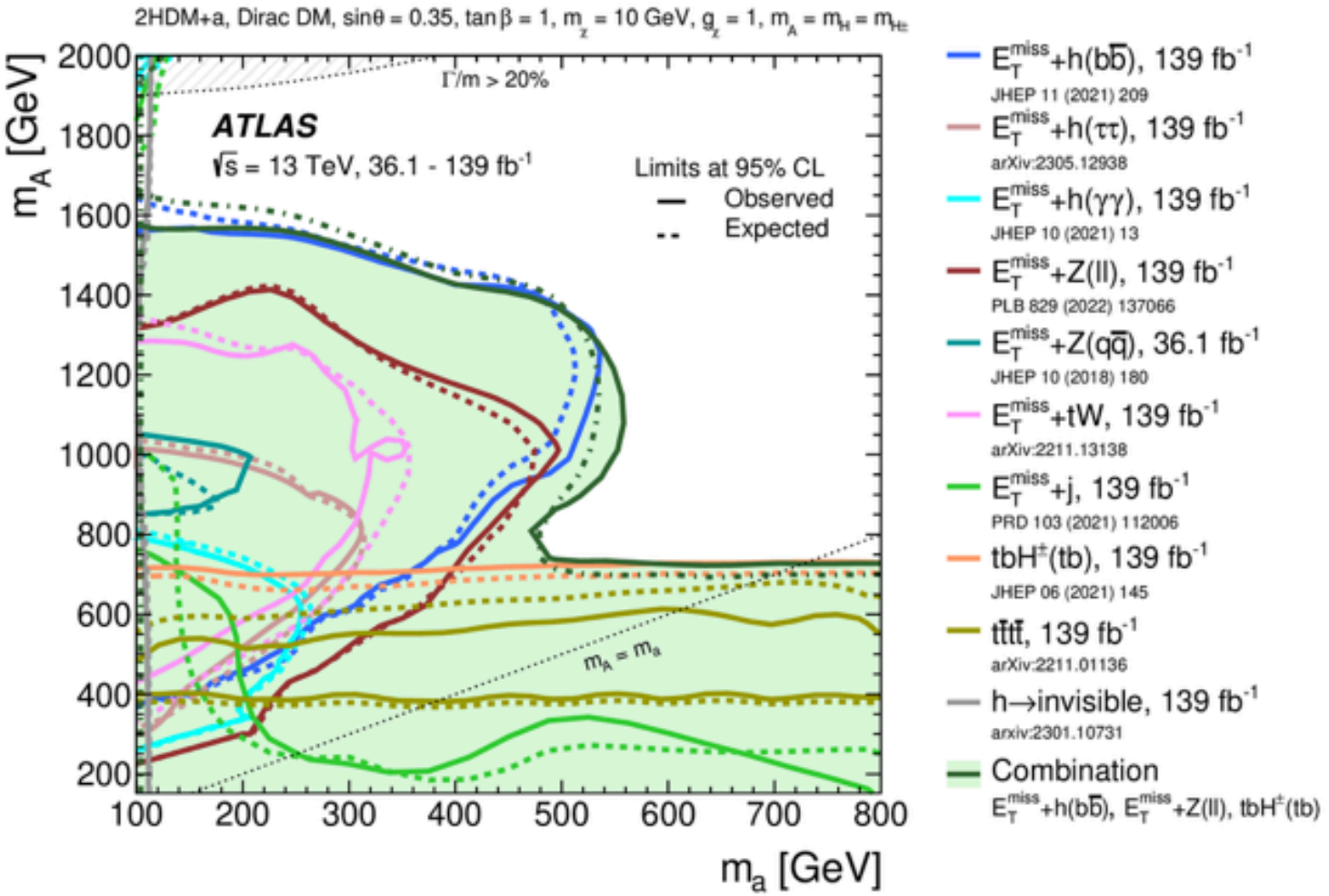
- Complementary constraints from searches not targeting DM.



# Scenario 1a: sin$\theta$=0.35, $m_A$ - $m_a$ plane

arXiv:2306.00641
(Science Bulletin Accepted)

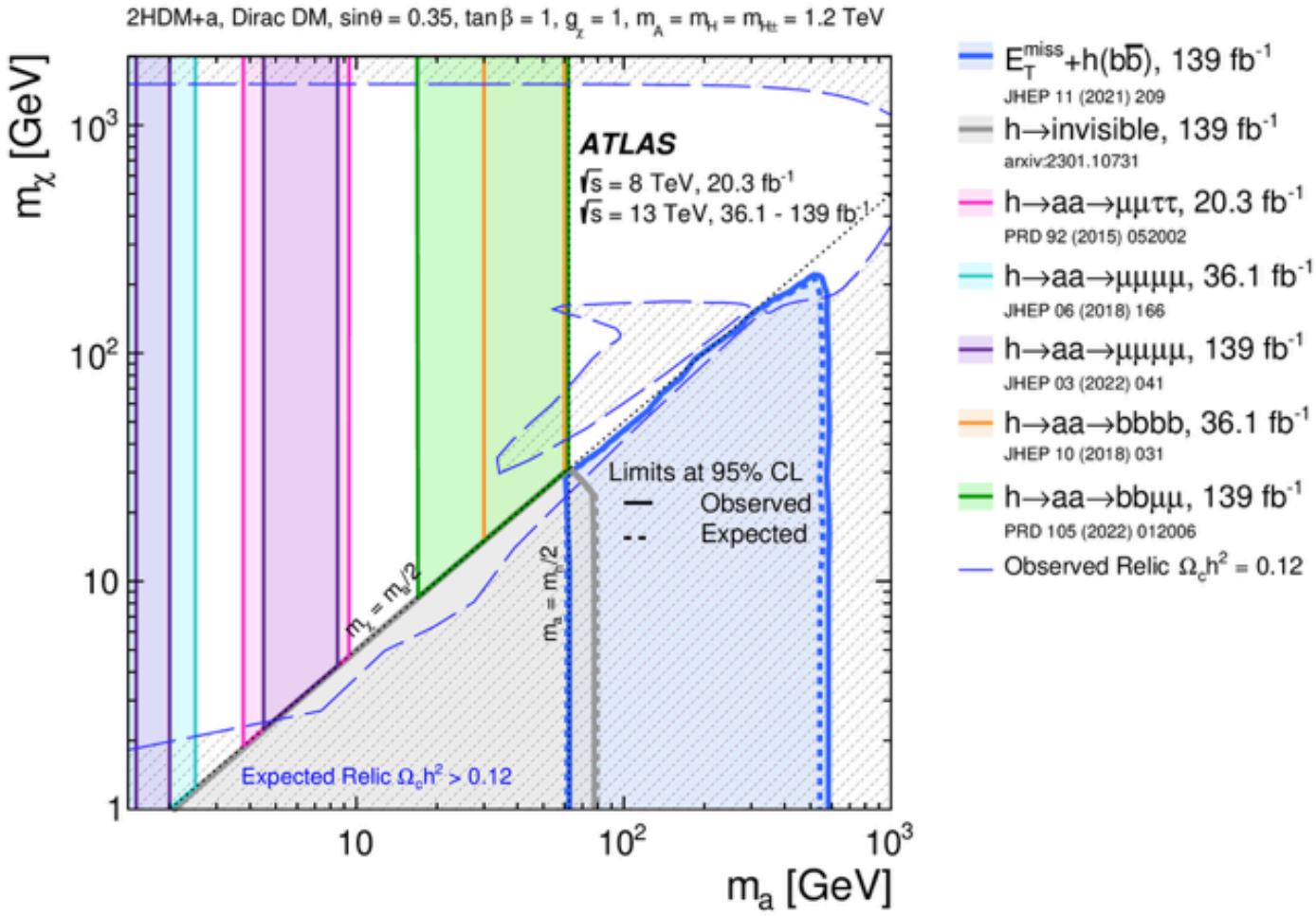
- $h \rightarrow$ invisible constrains very low $m_a$.
- constraints from $E_{\mathrm{T}}^{\mathrm{miss}} + h$ signatures: similar $m_A$-$m_a$ dependence, with $h \rightarrow bb$ most sensitive.
- $E_{\mathrm{T}}^{\mathrm{miss}} + tW$ similar to $E_{\mathrm{T}}^{\mathrm{miss}} + Z(ll)$ but with smaller excl. region.
- $E_{\mathrm{T}}^{\mathrm{miss}} +$ jet sensitivity notably different from those of $E_{\mathrm{T}}^{\mathrm{miss}} + Z$ and $E_{\mathrm{T}}^{\mathrm{miss}} + h$.
- Complementary constraints from searches not targeting DM.
- Sensitivity of 2HDM+a driven by the combination.



# Scenario 6: $m_a$ - $m_\chi$ plane

arXiv:2306.00641
(Science Bulletin Accepted)

- New interpretation in $m_a$ - $m_\chi$ plane:
- Searches for SM Higgs decaying to 4 fermions via  constrain previously unprobed region of 2HDM+a.
- Complementarity to h→inv. and $E_T^{miss}$+h(bb) searches.



PART 02

# (Recent) Dark Higgs Searches

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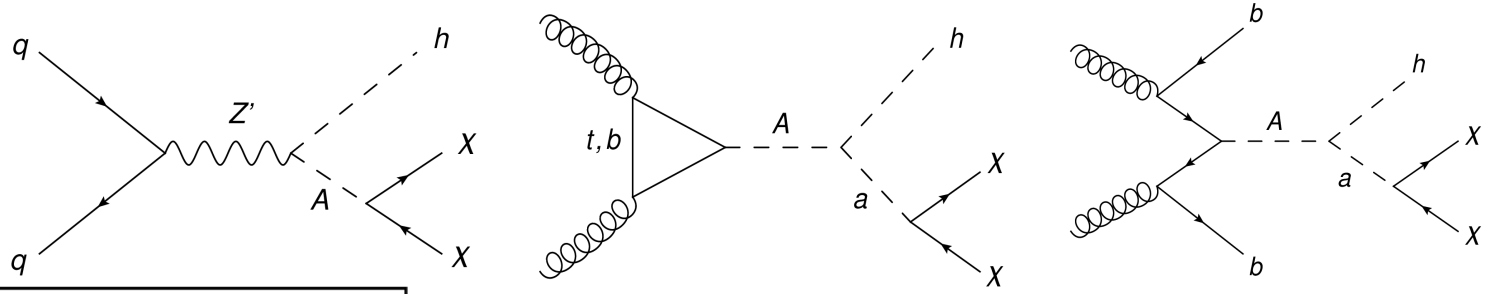
# Higgs portal to DM: Mono-H(bb)

JHEP 11 (2021) 209




**Resolved topology**

$150 < E_T^{miss} < 500$ GeV

$50\ GeV < m_h < 280\ GeV$

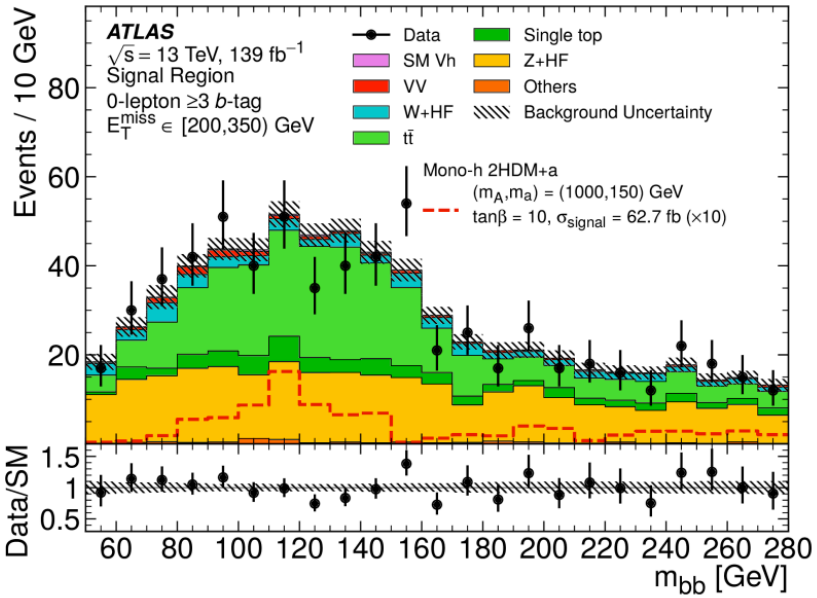
At least 2 small-R jets

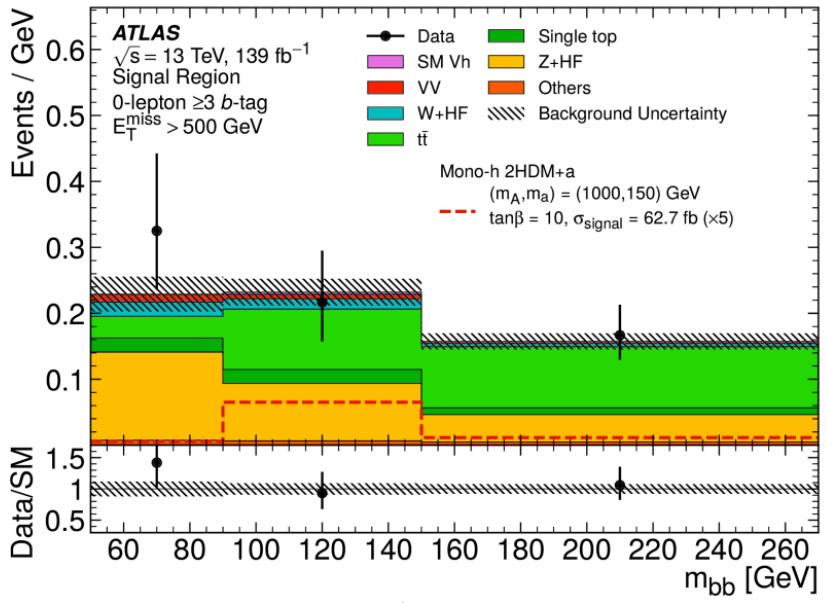
**Merged topology**

$E_T^{miss} > 500$ GeV

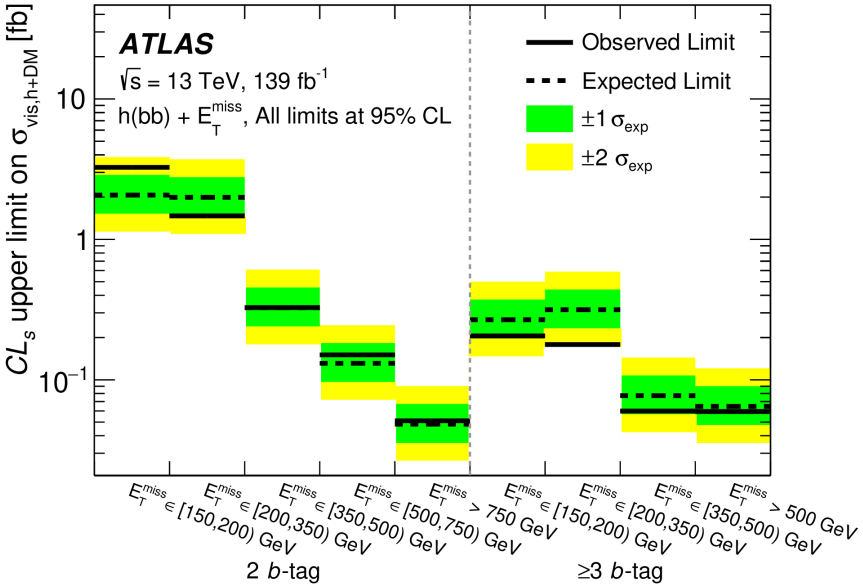
$50\ GeV < m_h < 270\ GeV$

At least 1 large-R jet



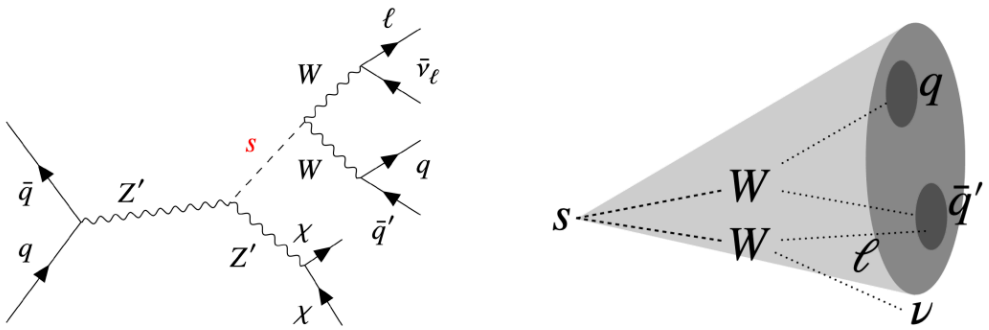




- Interpreted with 2HDM+Z’ , 2HDM+a in both ggF and bbH.
- Also Model-independent upper limits on the visible cross-section



# Dark Higgs Search: Mono-S(→WW) semileptonic

JHEP 07 (2023) 116
PRL 126 (2021) 121802

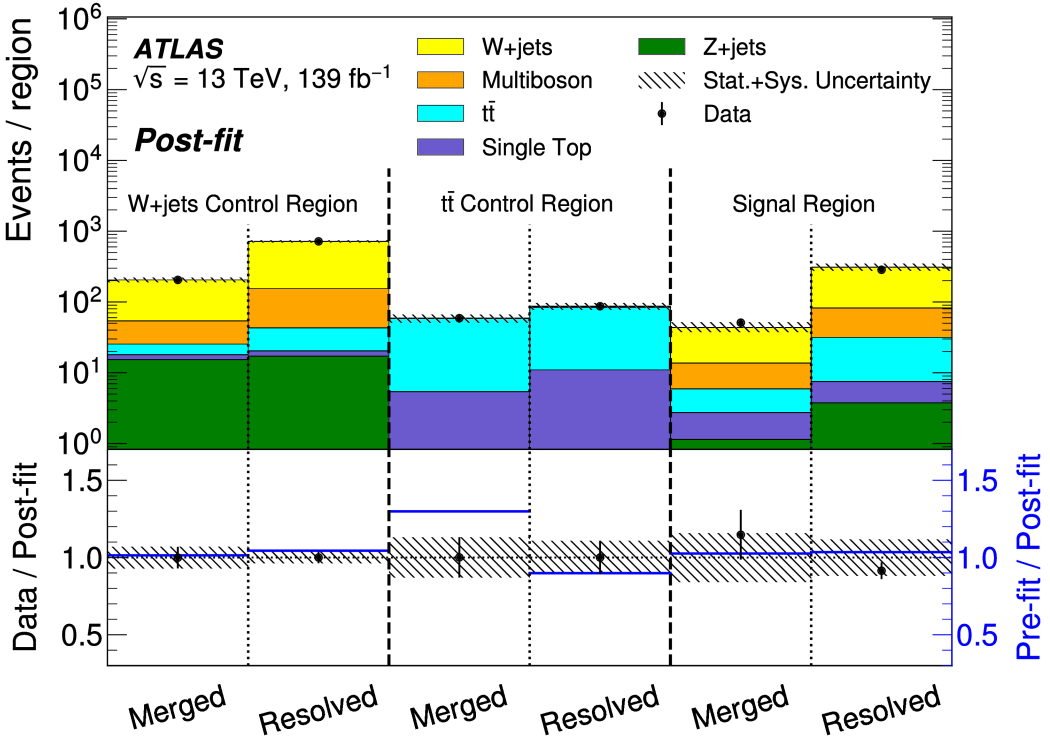


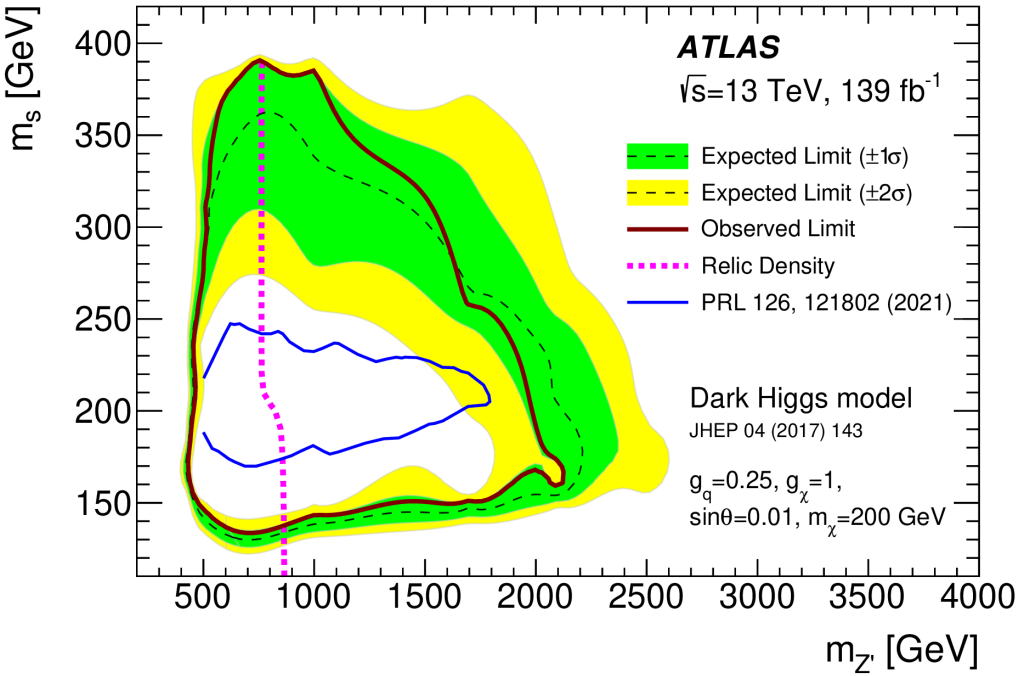




- Two mediator model: Z′ + Dark Higgs
- Utilize both resolved calorimeter-measured jet pair or merged from track-assisted reclustered jets

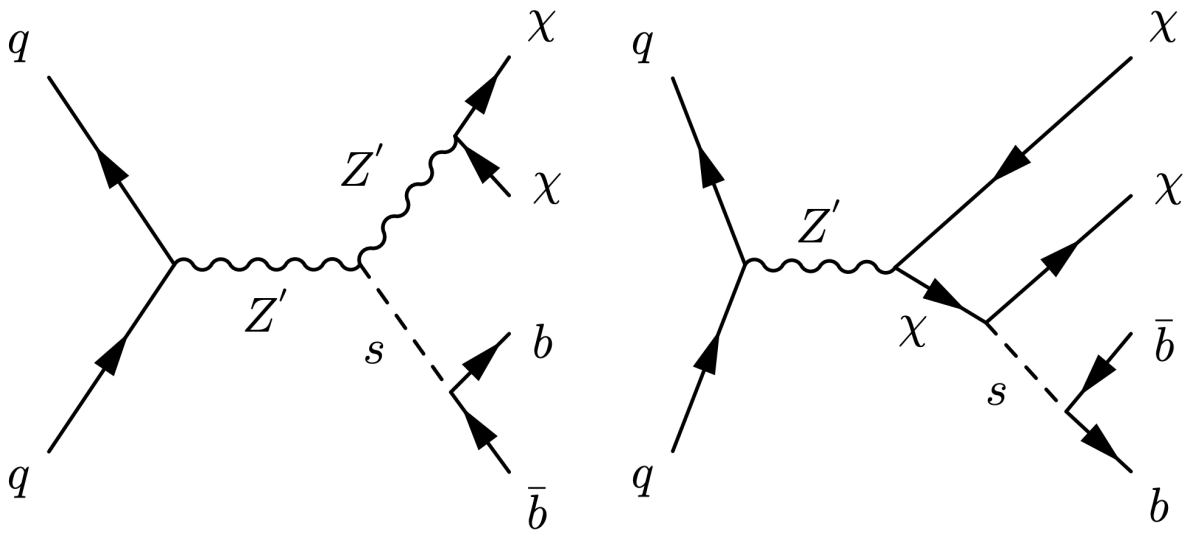
- Scenarios with dark Higgs boson masses ranging between 140 and 390 GeV are excluded.



# NEW Dark Higgs Search: Mono-S(→bb)

ATLAS-CONF-2024-004




$$\mathcal{L}_\chi = -\frac{1}{2} g_\chi Z'^\mu \bar{\chi}\gamma^5\gamma_\mu\chi - g_\chi \frac{m_\chi}{m_{Z'}} s\bar{\chi}\chi + 2\, g_\chi\, Z'^\mu Z'_\mu \left(g_\chi\, s^2 + m_{Z'} s\right)$$

- Dark Higgs boson (scalar particle $s$) introduced together with $Z'$ and Majorana DM [Ref. JHEP 04 (2017) 143]
- New annihilation channel to SM opened up ($\chi\chi \rightarrow s \rightarrow ...$): relax the constraint from cosmology → Prevent DM Relic Density ($\Omega h^2$) over-production issue of common WIMP model
- Scalar particle mixing with SM Higgs: detectable decay products depending on mass, s→VV, s→bb
- Done Searches for high mass dark Higgs in Mono-S(VV) analyses (previous slide)

**First search aiming for a low-mass dark Higgs boson + new benchmark scenarios**

# NEW Dark Higgs Search: Mono-S(→bb)

ATLAS-CONF-2024-004

- Six parameters controlling the interaction with SM and DM
- Fixed-g$\chi$ search as benchmark (scenario 1)
  - Scan mS v.s. mZ′ with fixed m$\chi$= 200 GeV, g$\chi$= 1.0
- Cosmological constraint: freeze-out relic density $\Omega h^2$
  - Observation from PLANCK2018: $\Omega h^2$ = 0.1200 ± 0.0012
- Introduce two new benchmark scenarios [**First time**!] satisfying the observed relic density (scenario 2, 3)
  - Scan mS v.s. mZ′ with fixed m$\chi$=900 GeV
  - Scan m$\chi$ v.s. mZ′ with fixed mS=70 GeV

| Parameter | Explain |
|---|---|
| $m_s$ | mass of dark higgs |
| $m_\chi$ | mass of DM to search |
| $m_{Z'}$ | mass of heavy mediator |
| $g_\chi$ | coupling in dark sector between s, X, Z' |
| $g_q$ | coupling with SM: q<->Z' fixed 0.25 as benchmark |
| $\theta$ | mixing angle of SM Higgs<->dark Higgs fixed according to [1] |

[1] JHEP 04 (2017) 143

ATLAS-CONF-2024-004

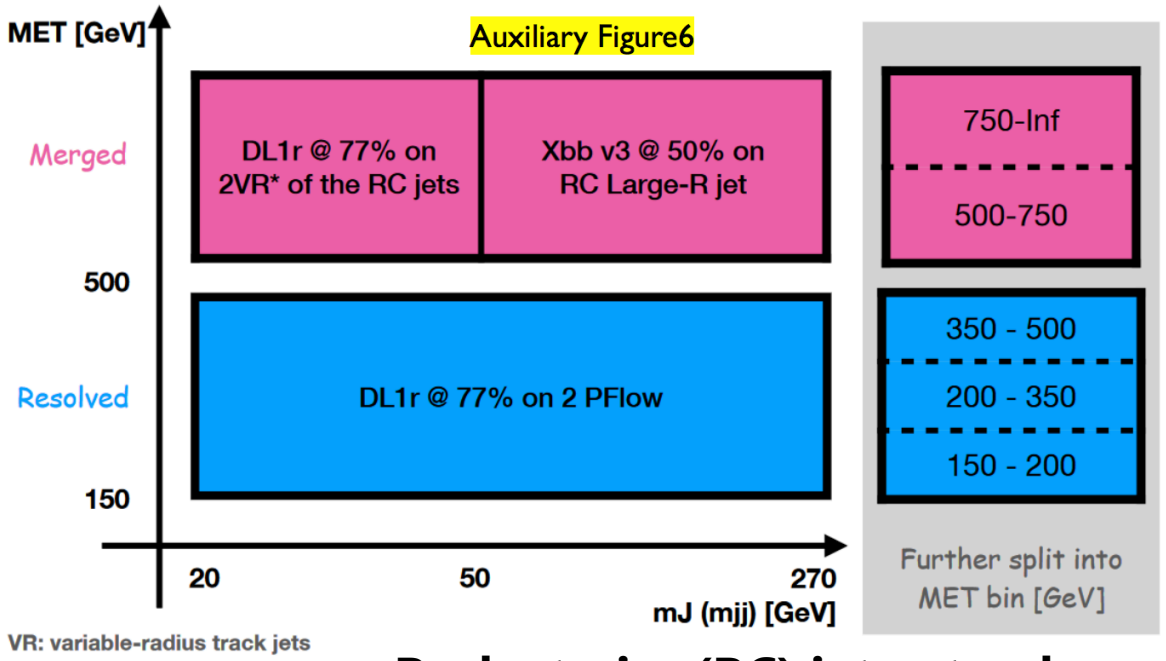
# NEW Dark Higgs Search: Mono-S(→bb)

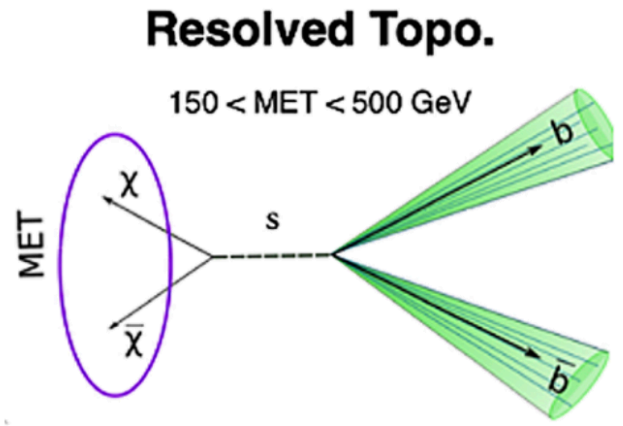
Analysis Strategy overview

- Search for low mass dark Higgs with bb+MET signature
- Data triggered with MET and search starts from 150GeV
- Regions divided by MET: from resolved to merged topology to cover all the interesting phase space

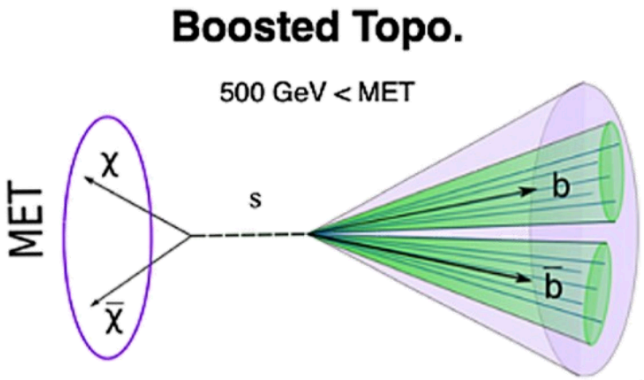
Resolved regions: reconstructed by 2 small-R jets and tagged using DL1r 77%

Merged region: 1 reclustering large-R jet and mixed tagging methods → benefit from advanced techniques




Good statistics



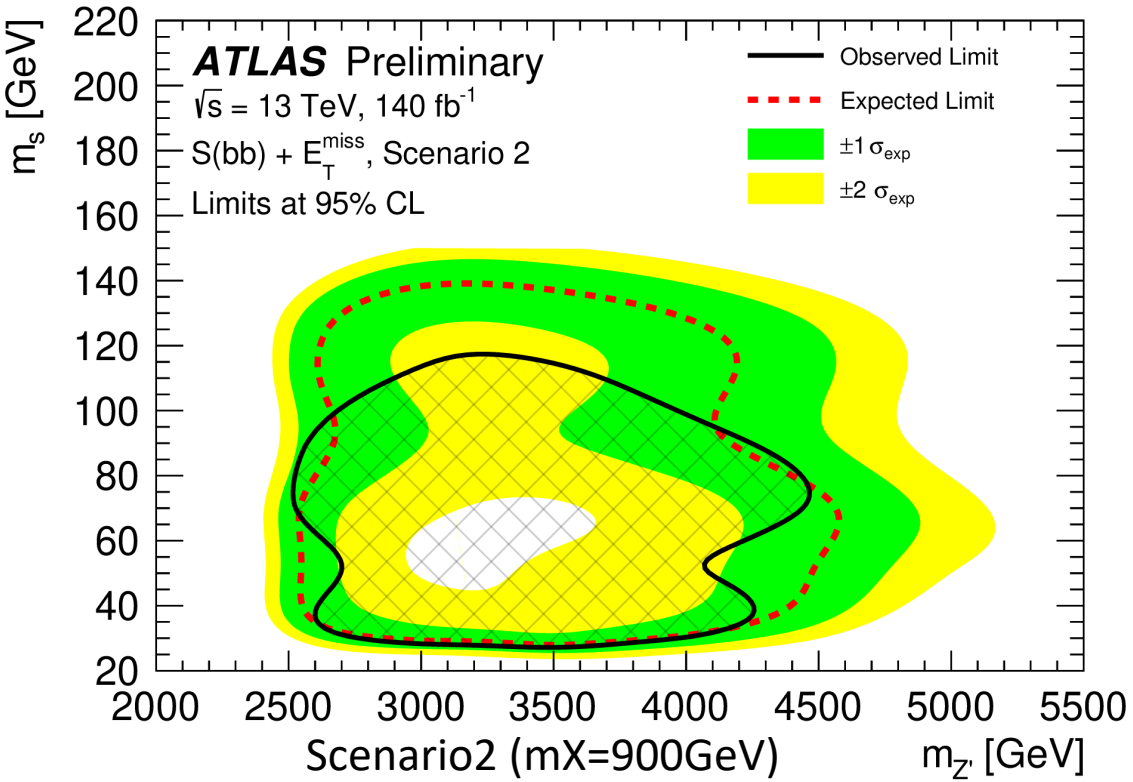

Sensitive to high mZ'
dominates for mZ'>2 TeV

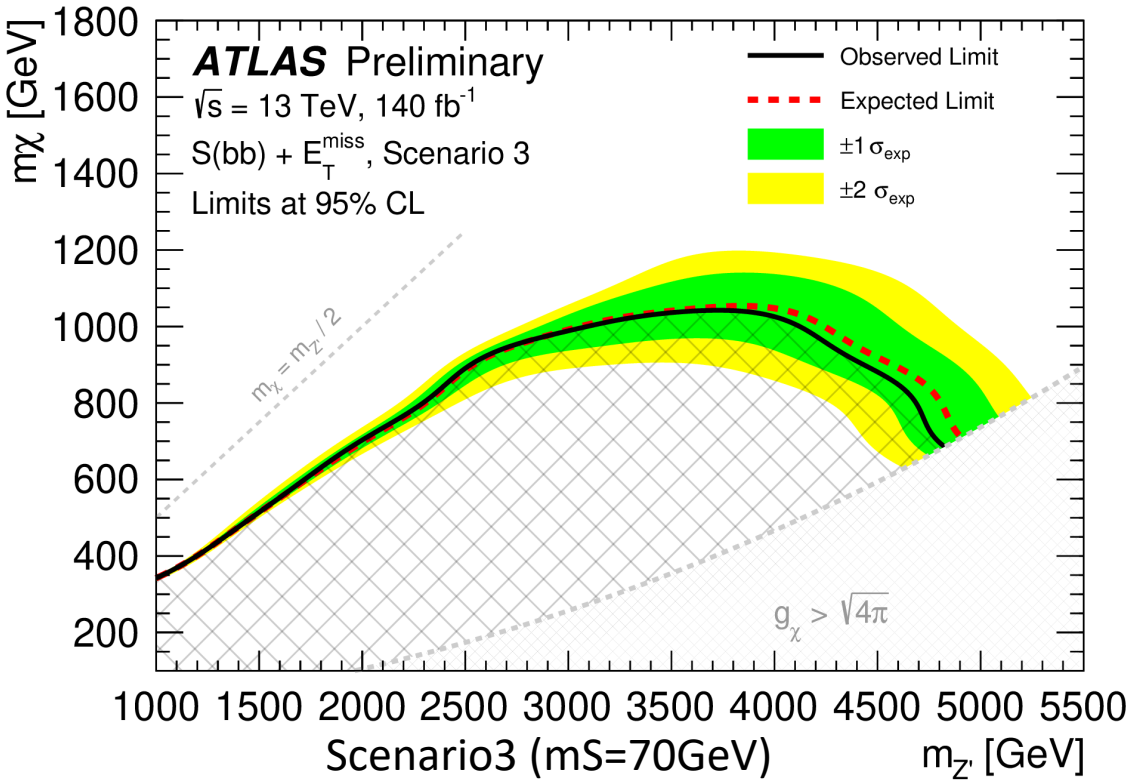
**Reclustering(RC) jet extend searched scalar mass down to 20GeV**
**Large-R jet kin. and sub-jet info. combined for boosted Xbb tagging: DXbb**

# Mono-S(bb) Exclusion Limit: relic-density inspired scenario

DM coupling varies to satisfy the observed relic density throughout

- $mZ'$ excluded up to 4.1 TeV with fixed m$\chi$ at 900GeV (scenario2)
- $mZ'$ excluded up to the perturbative limit and m$\chi$ excl. to 1TeV at mS=70GeV (scenario3)

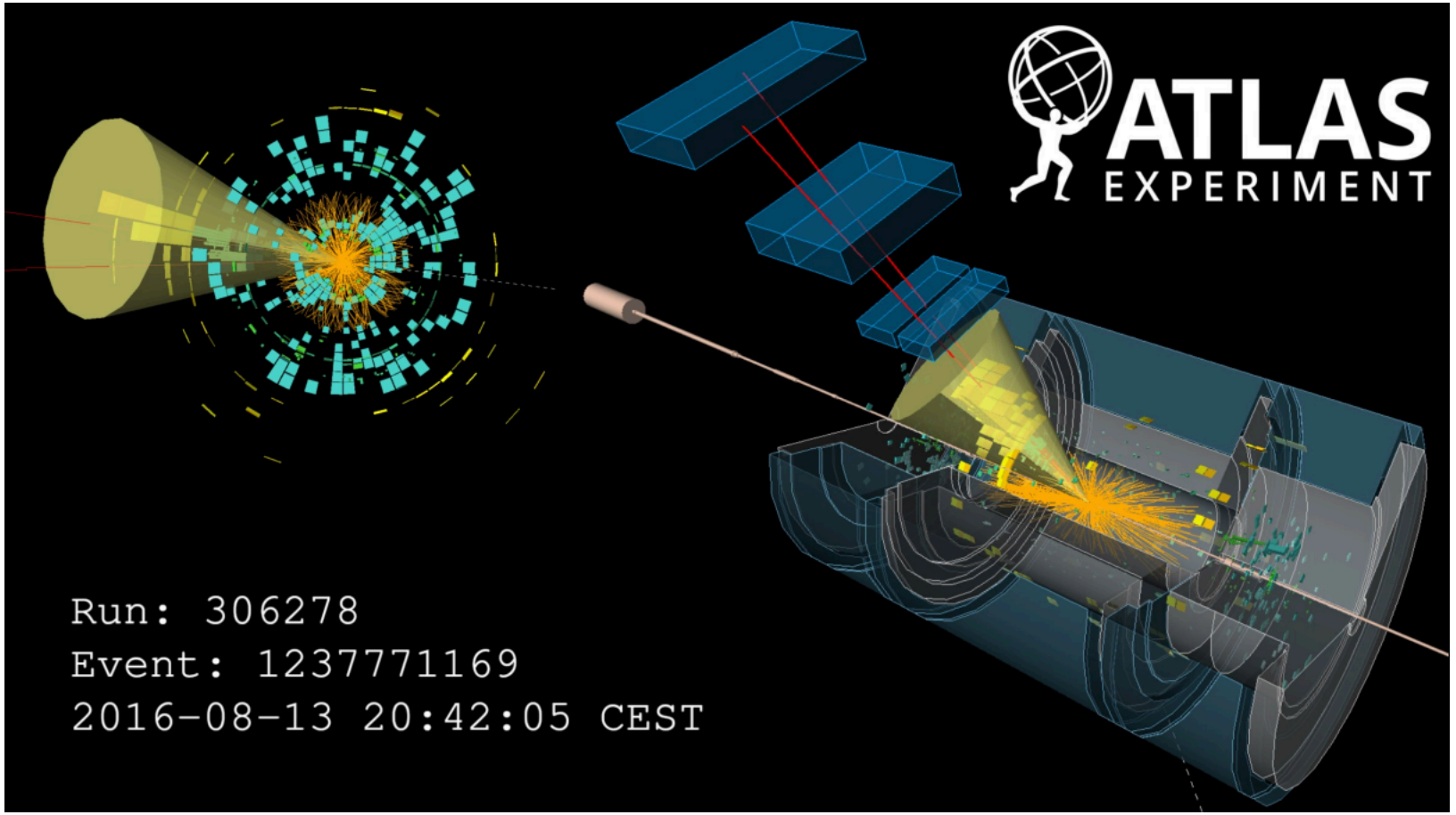



First LHC dark Higgs search in cosmology coherent context

# Event Display

ATLAS-CONF-2024-004



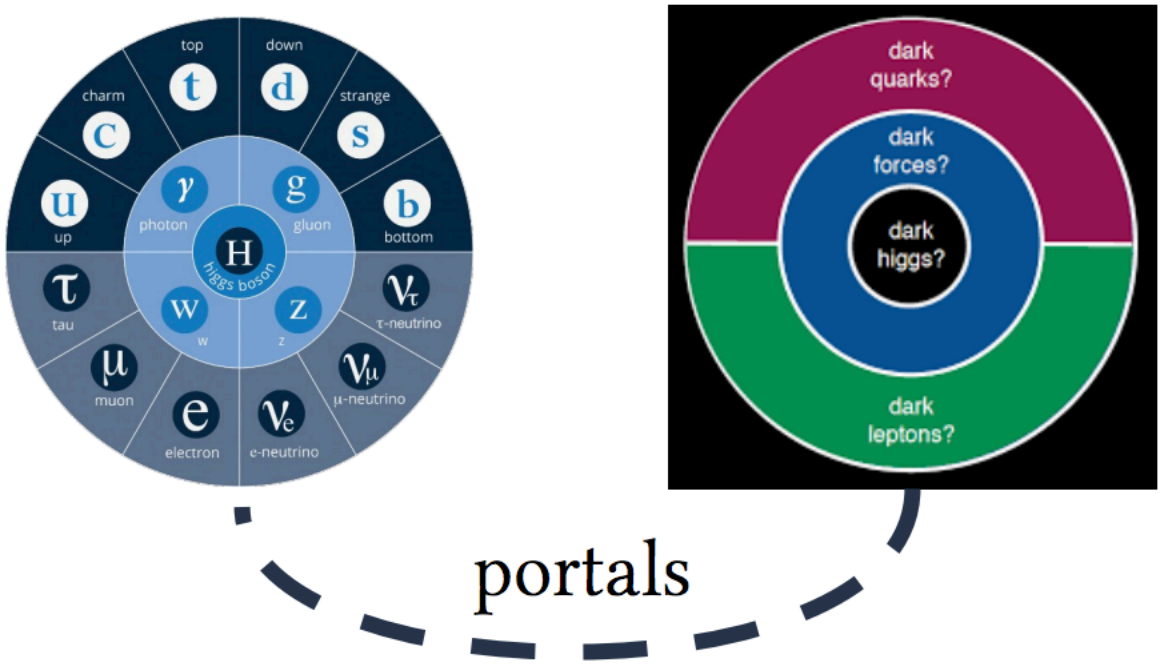

Signal-like event in resolved region: $E_T^{miss}$ =559.5GeV, m(J) = 53.8GeV, $p_T$(J)=486.9GeV

PART 03

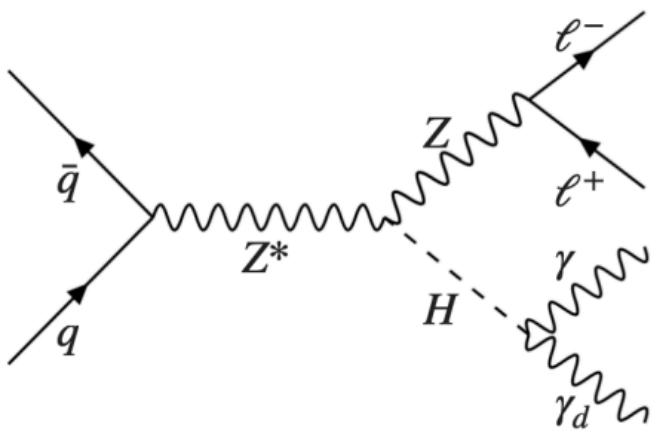
# Dark Photon Search and Combination Prospect at ATLAS

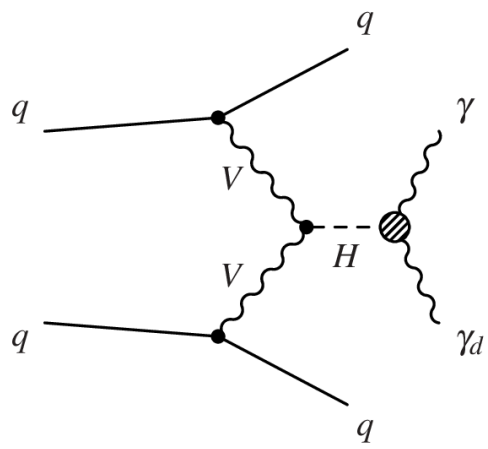
TSUNG-DAO LEE INSTITUTE

# Dark Higgs → more Dark Portals connecting hidden sectors



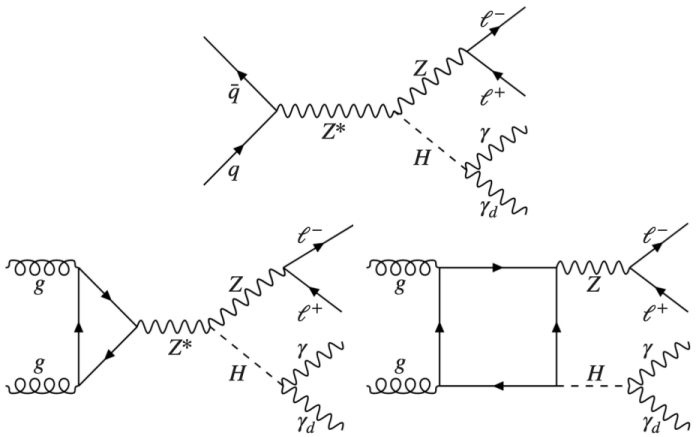

- Dark Photon BSM extensions:
  - U(1) extension of the SM
  - Hidden gauge boson A′ → kinetic mixing (ε) with the SM photon
  - the magnitude of ε affects production rate and lifetime



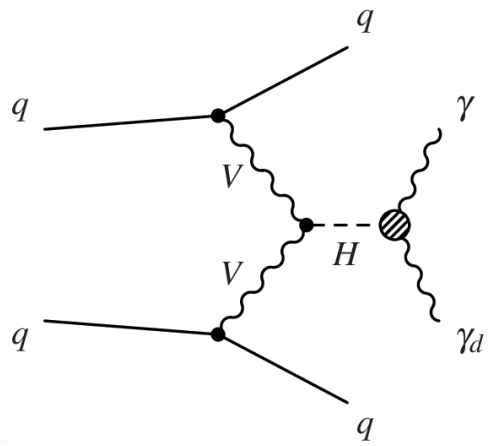

- Vector portal – dark photons
- Scalar portals - dark Higgs
- Neutrino portal
- Axion portal

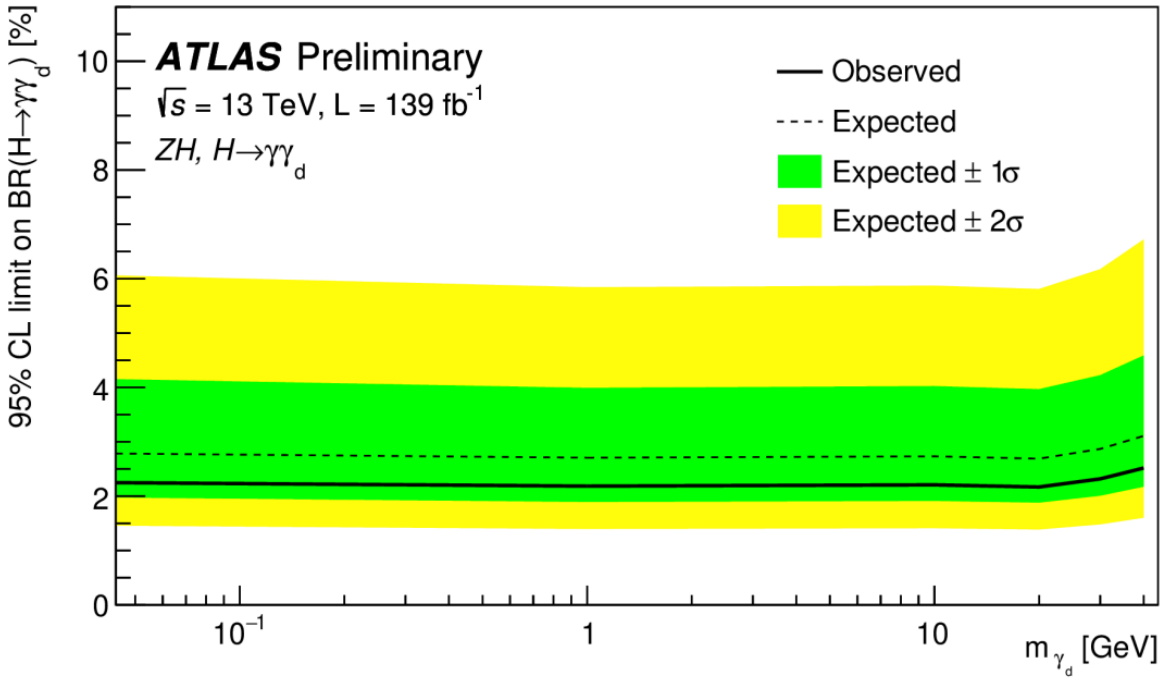
# Dark Photon searches: ZH and VBF

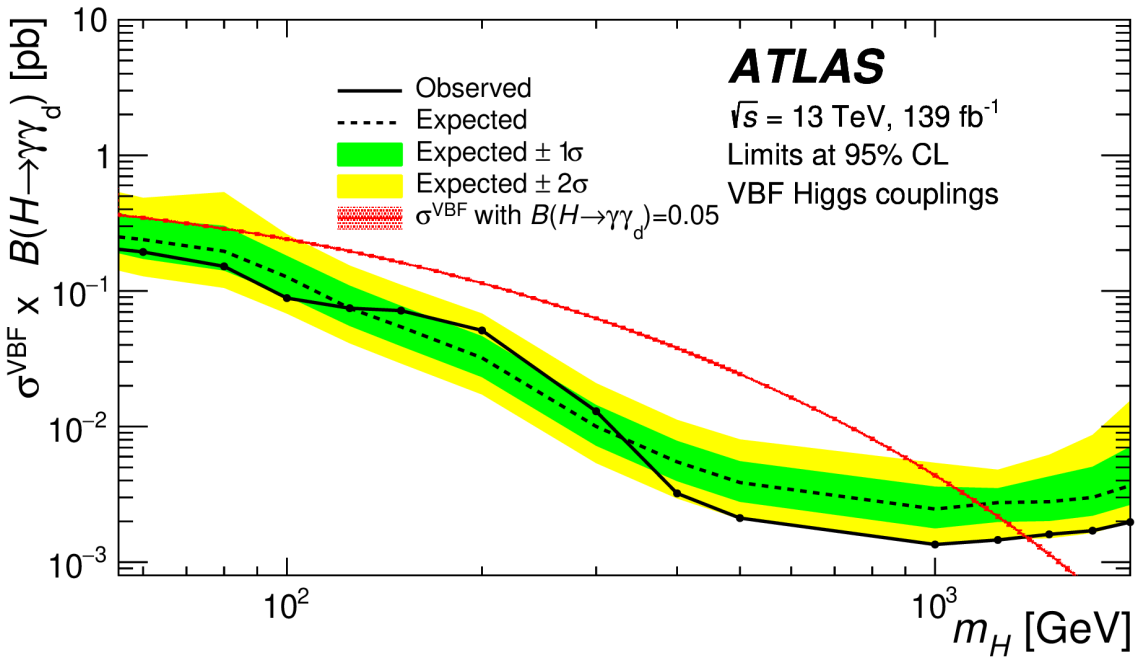



For massless $\gamma_d$

| | | Obs. | Exp. | |
|---|---|---|---|---|
| **CMS** | **VBF** | 3.5% | 2.8% | JHEP03(2021)011 |
| **CMS** | **ZH** | 4.6% | 3.6% | JHEP10(2019)139 |
| **ATLAS** | **VBF** | 1.8% | 1.7% | CERN-EP-2021-137 |
| **ATLAS** | **ZH** | 2.3% | 2.8% | ATLAS-CONF-2022-064 |



# ATLAS Dark Photon Combination Prospects

- Combination of VBF and ZH channels for SM Higgs (125 GeV) decaying into photon and massless dark photon
- Combination of VBF and ATLAS mono-photon re-interpretation for heavy Higgs decaying into photon and massless dark photon. (Our ongoing work)

| Production | ZH | VBF | Combined |
|---|---|---|---|
| ATLAS | 2.3(2.8)% | 1.8(1.7)% | Our ongoing work |
| CMS | 4.6(3.6)% | 3.5(2.8)% | 2.9(2.1)% |

# Summary

- LHC continues to deliver highly valuable physical results while Run-3 is started with new results in the pipeline
- Dark Matter mystery remains puzzling while collider searches provide sensitivity complementarity with non-collider DM searches
- Many hypotheses, diverse processes and signatures are broadly surveyed and searched for but by far no hints of Dark Matter
- Need to further diversify the data mining aspects in the collisions covering more unconventional signatures and untouched stones



Dark matter searches at CMS and ATLAS
D Perez Adan - 2022