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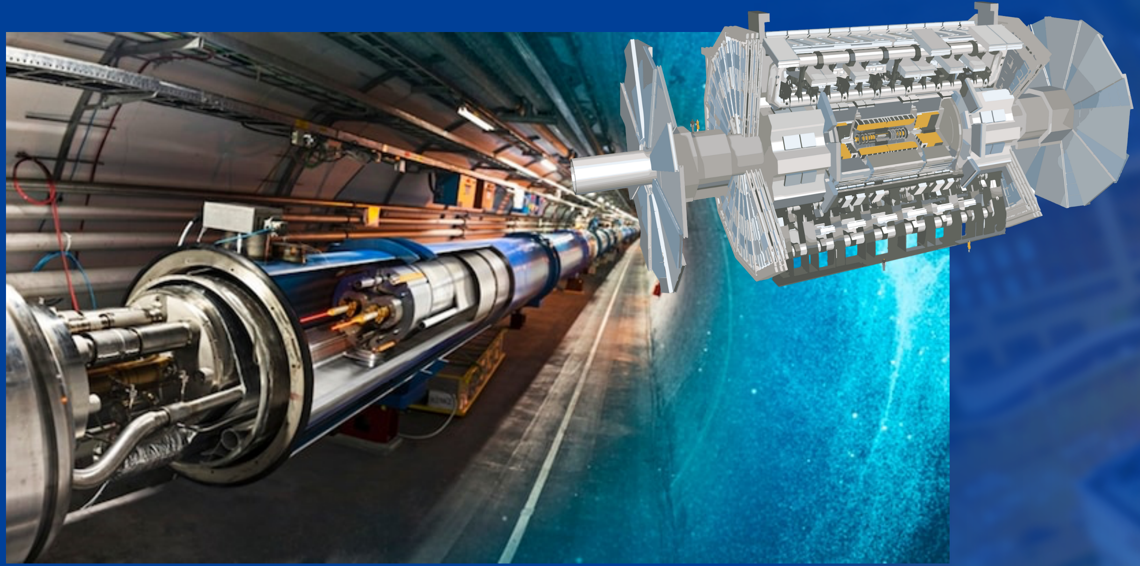
ATLAS
EXPERIMENT

Recent Dark Matter combination summary from ATLAS



李数

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31/12/2023

紫金山暗物质研讨会 2023 @ NNU

Dark Matter Evidence and Theory Context in a nutshell

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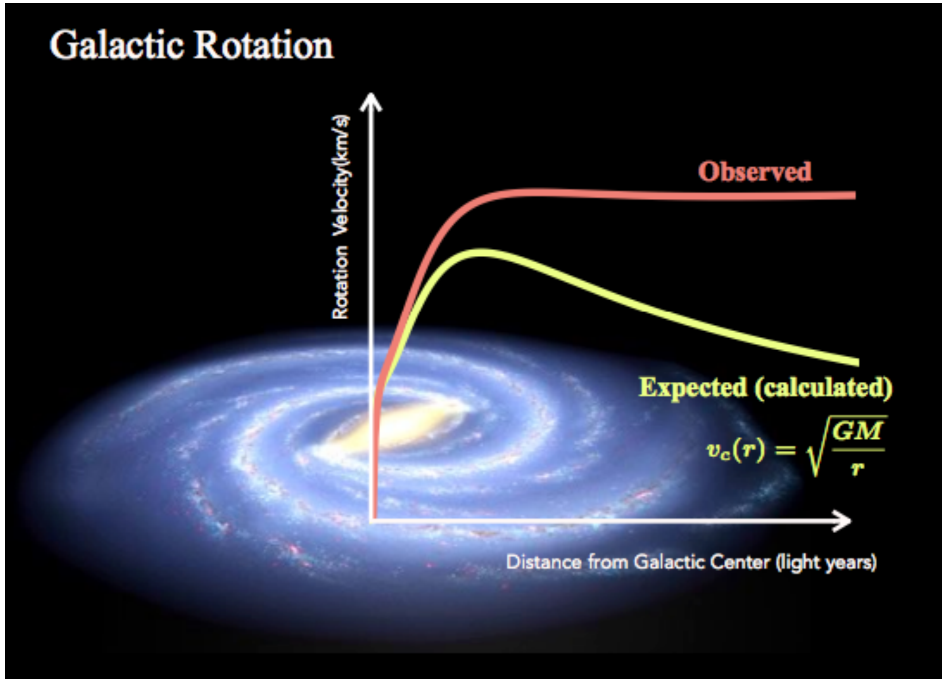
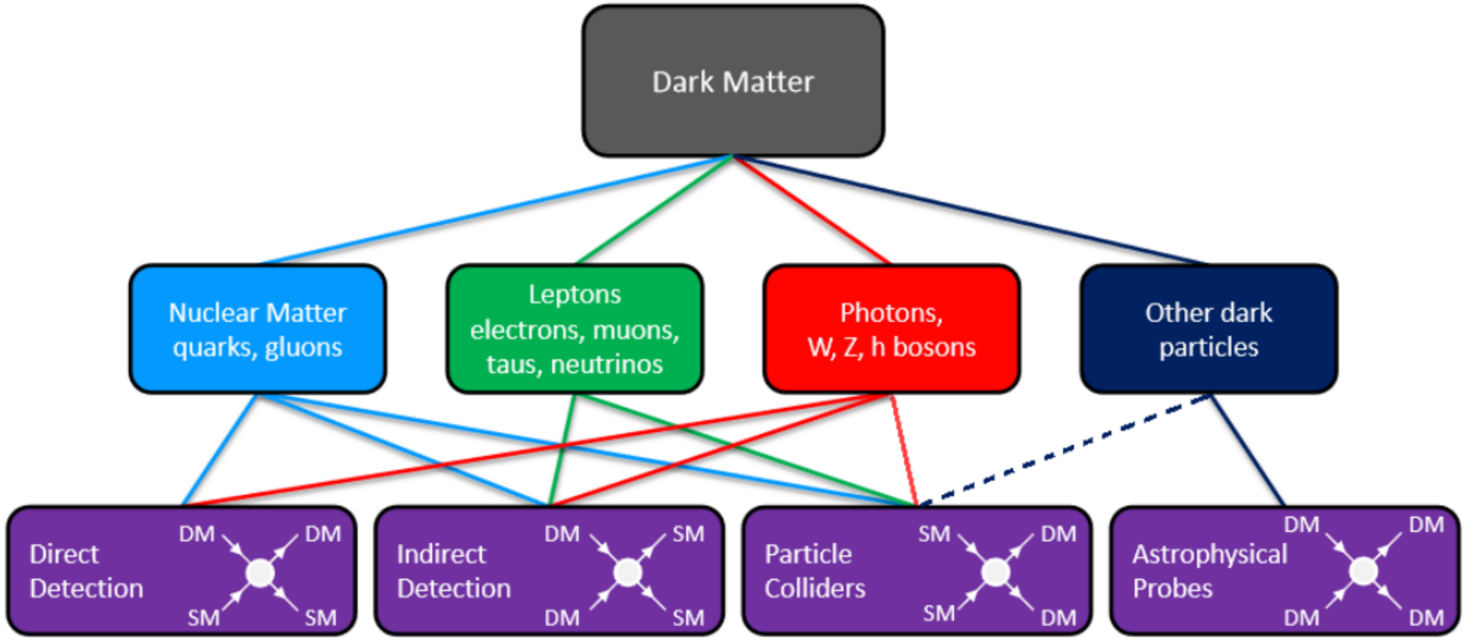
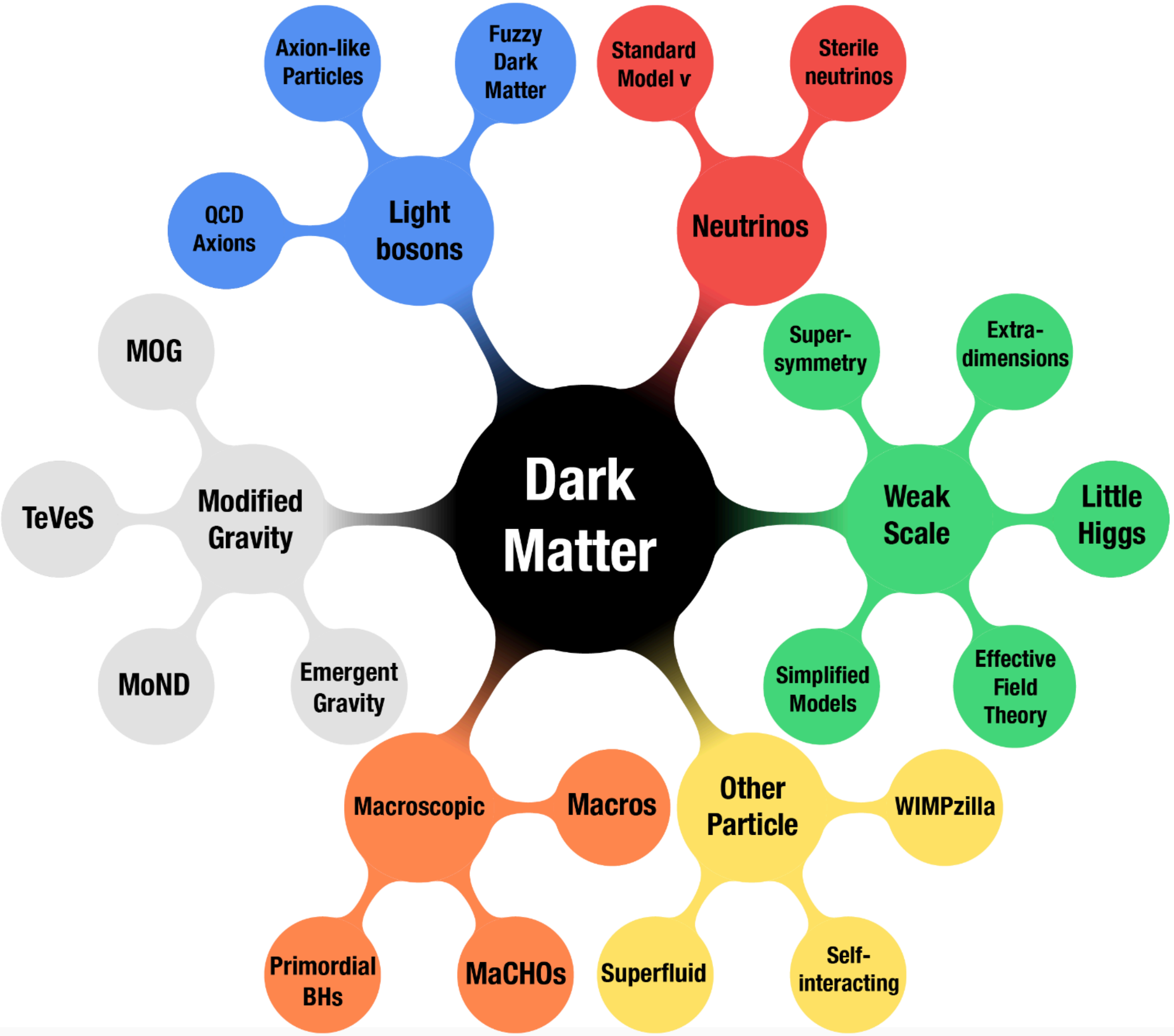




- DM evidence from astronomical observations and gravitational effects:
  - Galactic rotation curves, Gravitational lensing, Cosmic Microwave Background anisotropies, …
- Characteristics: Non-baryonic, massive, electrically neutral, gravitational, stable → WIMP context

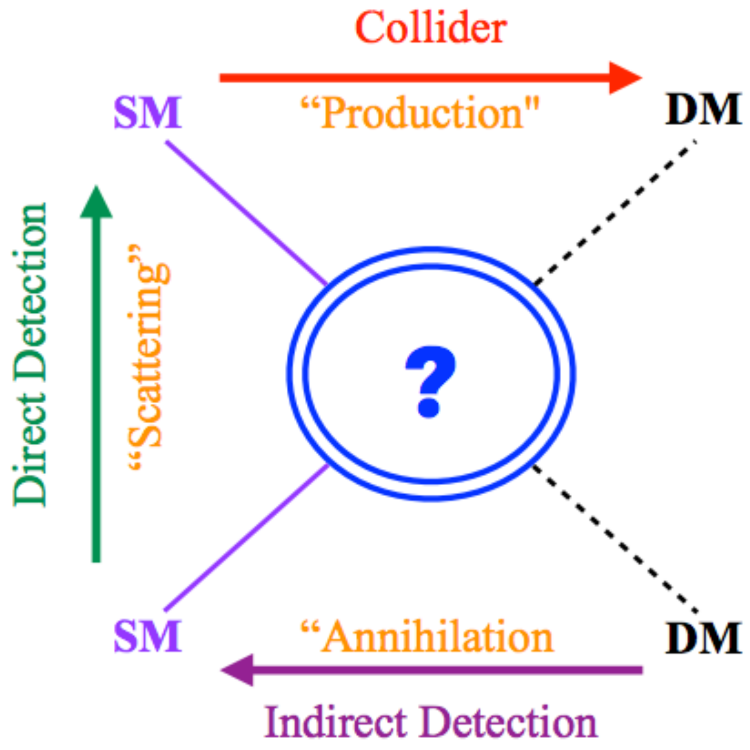
- BSM models predict weakly interacting massive particle (WIMP) -> Dark Matter Candidate. In SUSY models, the lightest SUSY particle LSP is a candidate for dark matter. Being LSP stable in most Models.
- Any WIMP DM produced at collider experiments will interact weakly and pass invisibly through detectors.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

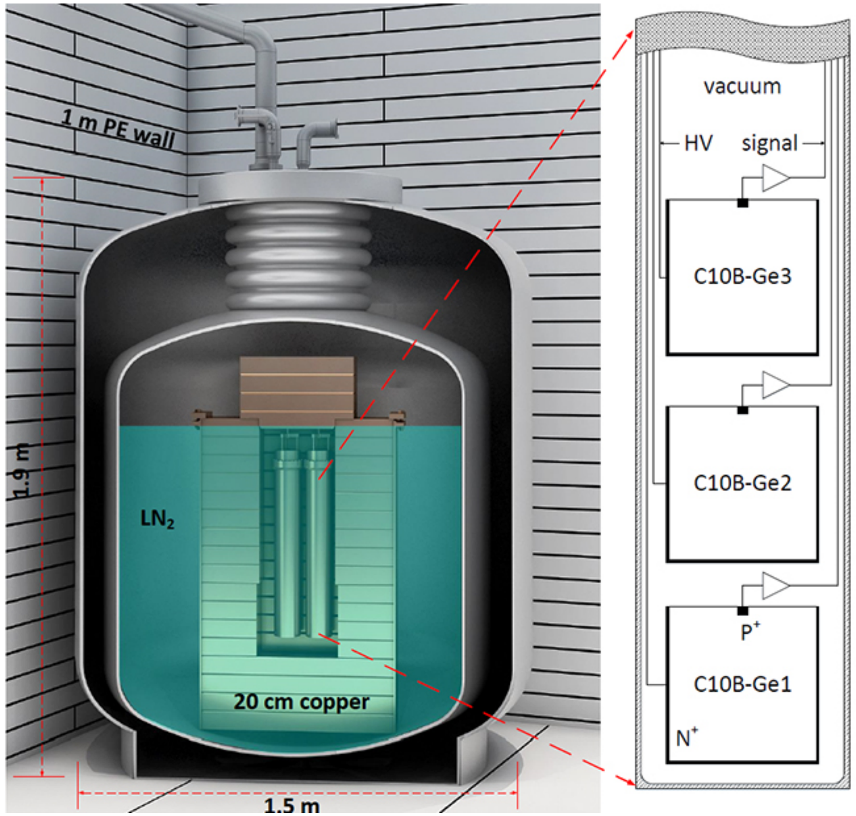
Frontiers that DM can reach out



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, ..)
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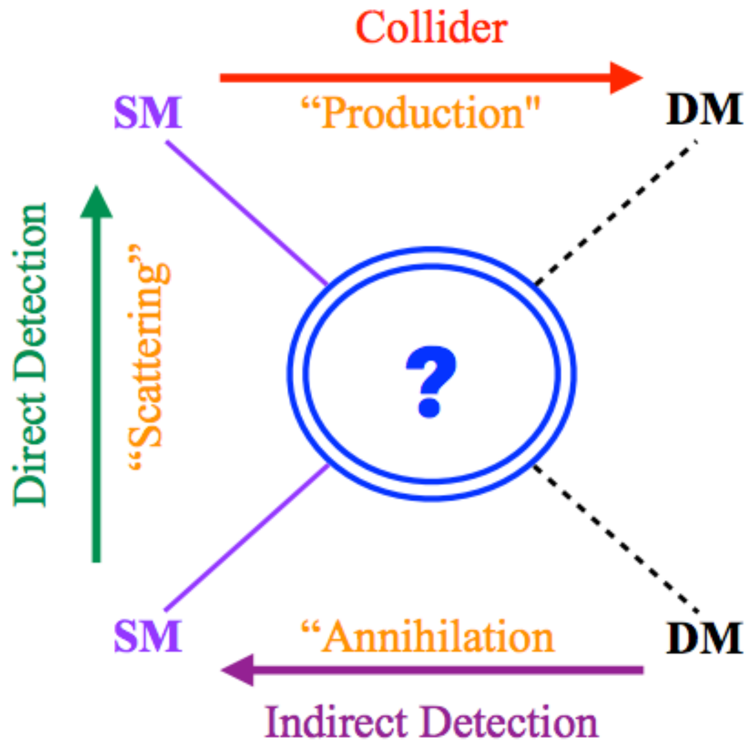
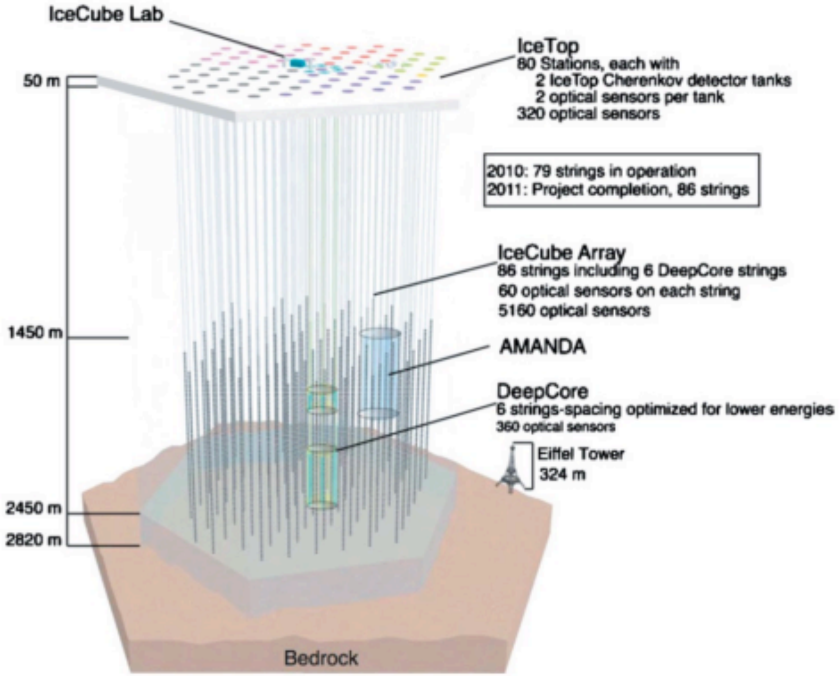
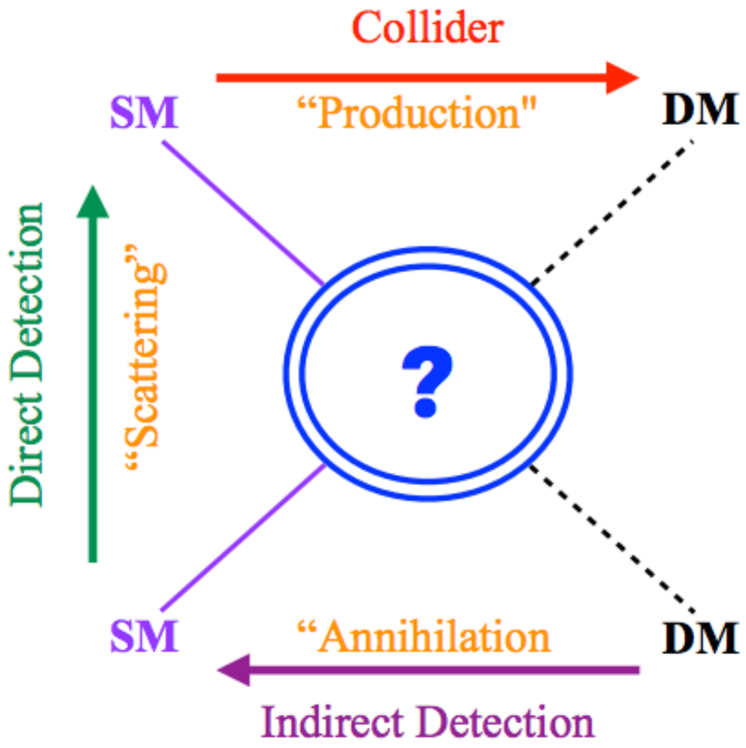
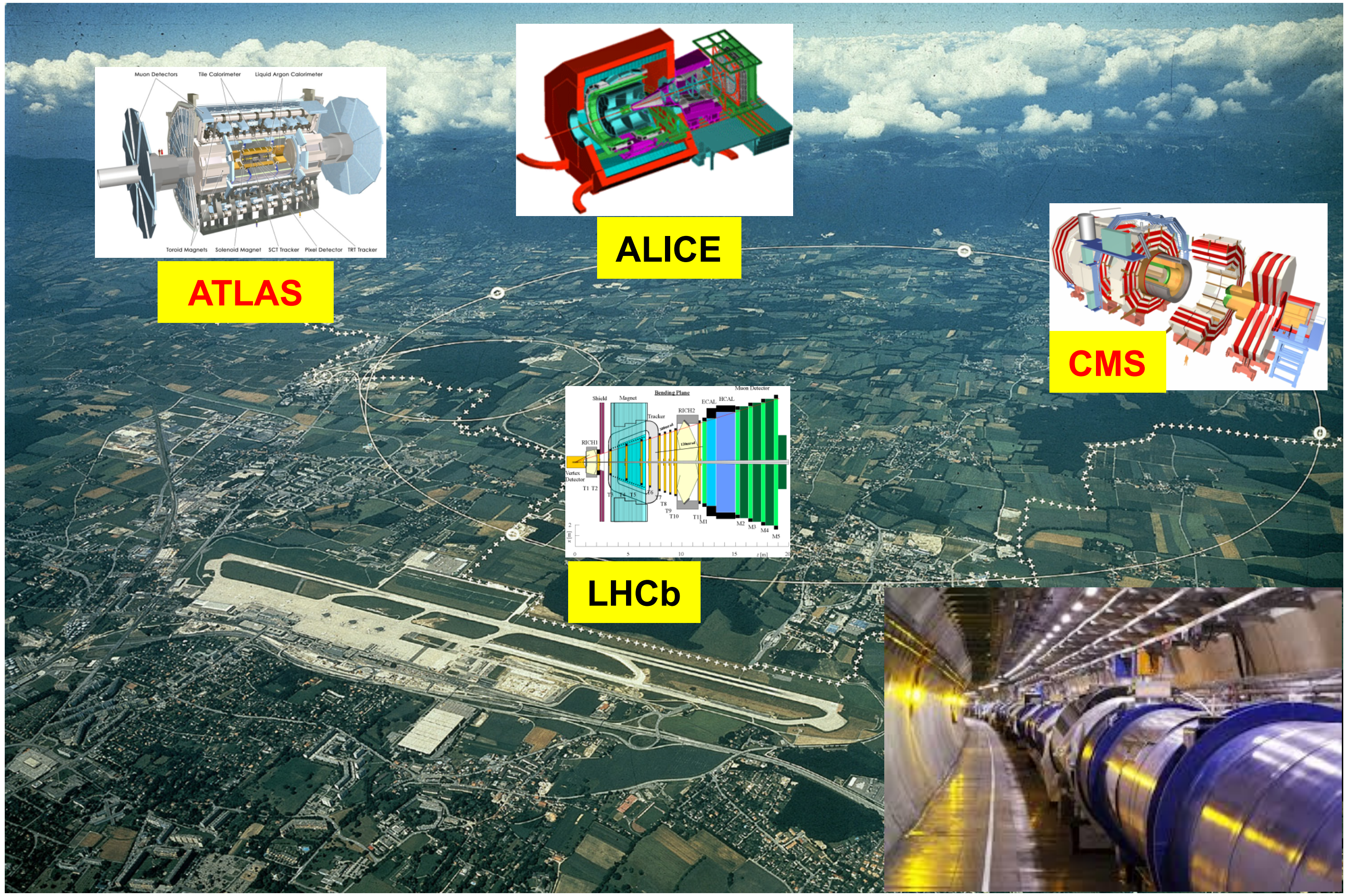




Dark Matter Collider productions

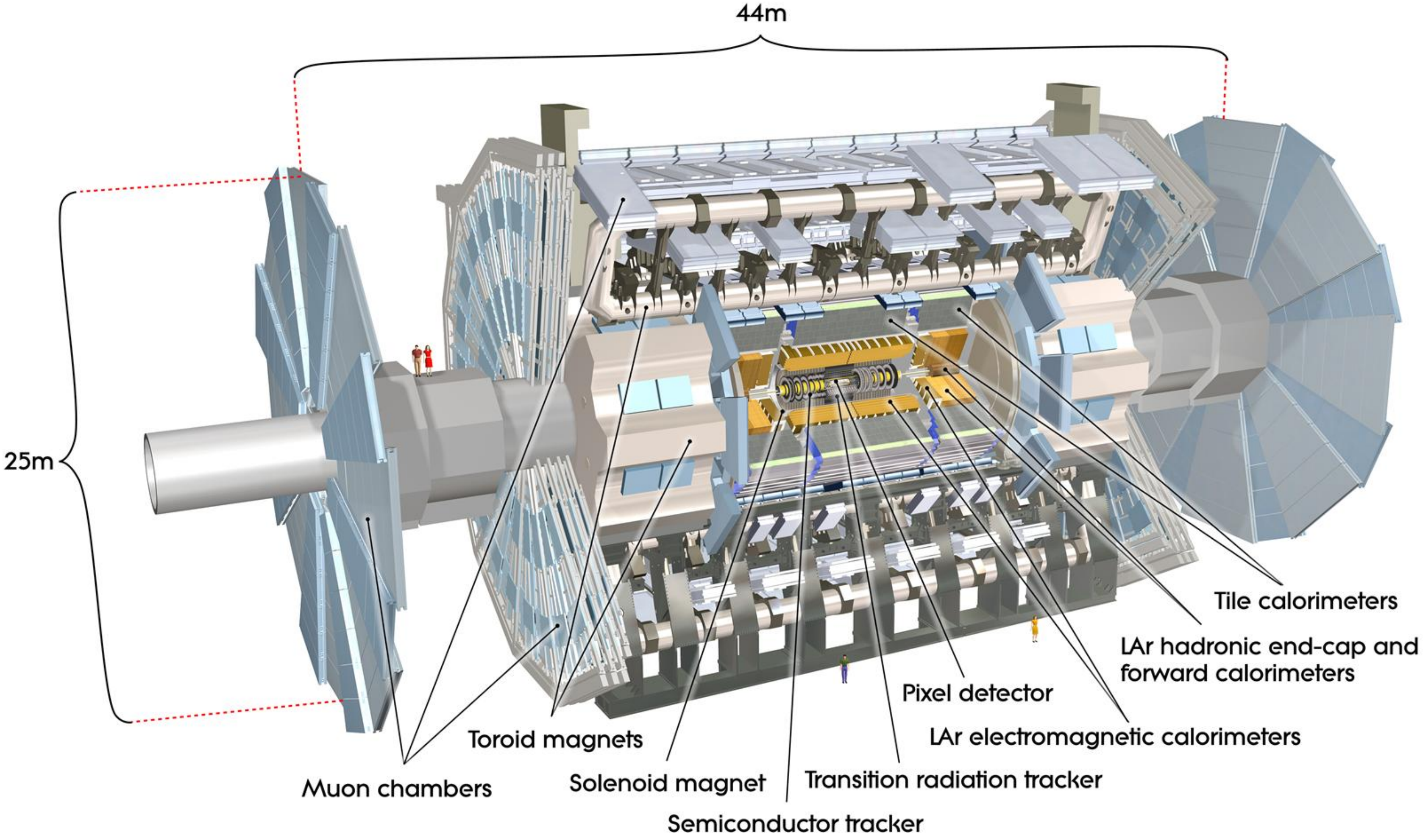
- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (CDEX, PandaX, LZ, XENONnT, ...)
- Indirect Detection (ID): products from DM annihilation (DAMPE, HESS, IceCube, ..)
- Colliders: DM production in high-energy collisions, focusing on the productions of a SM particle(s) (X) with large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



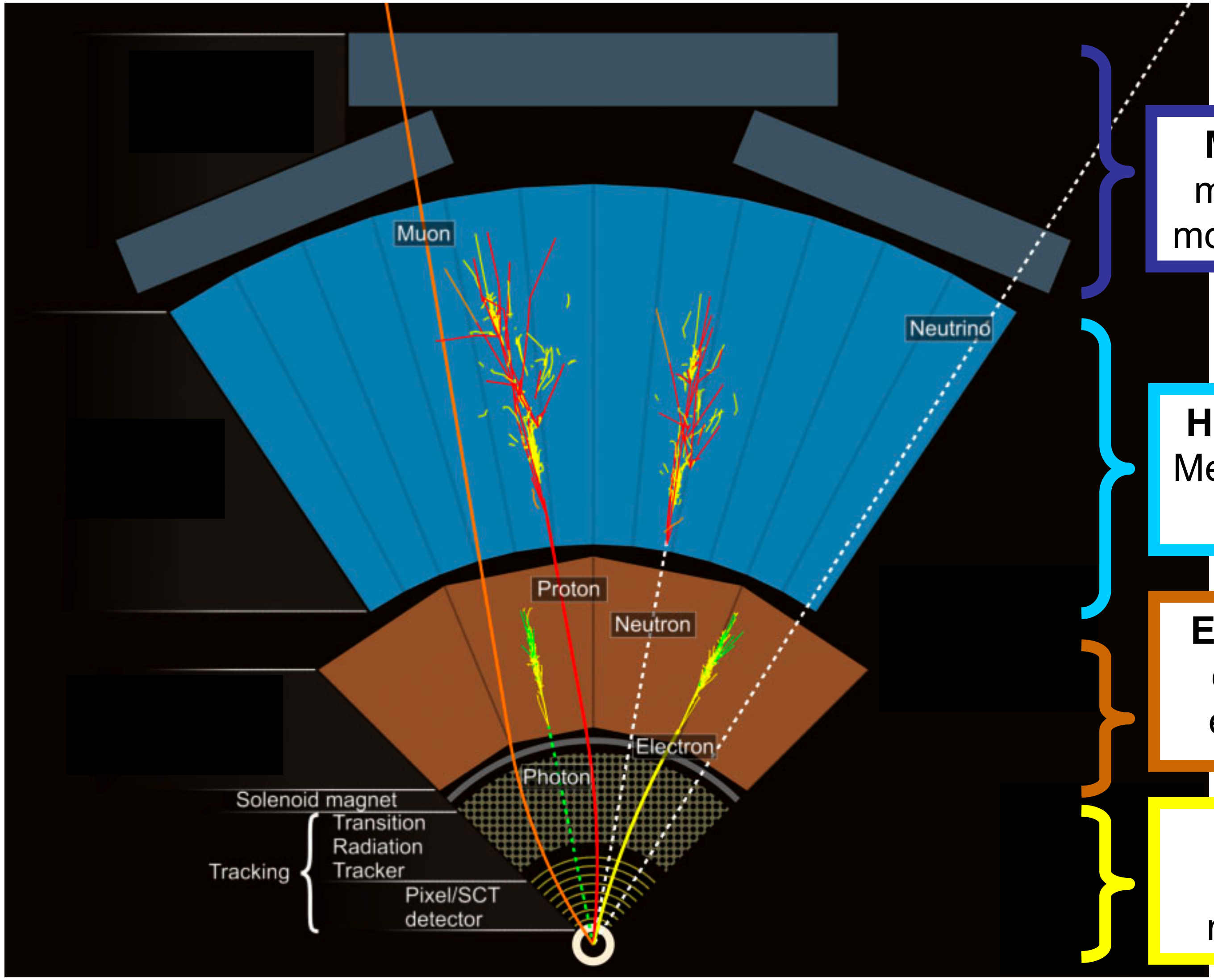


The ATLAS Experiment

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



ATLAS Detector System



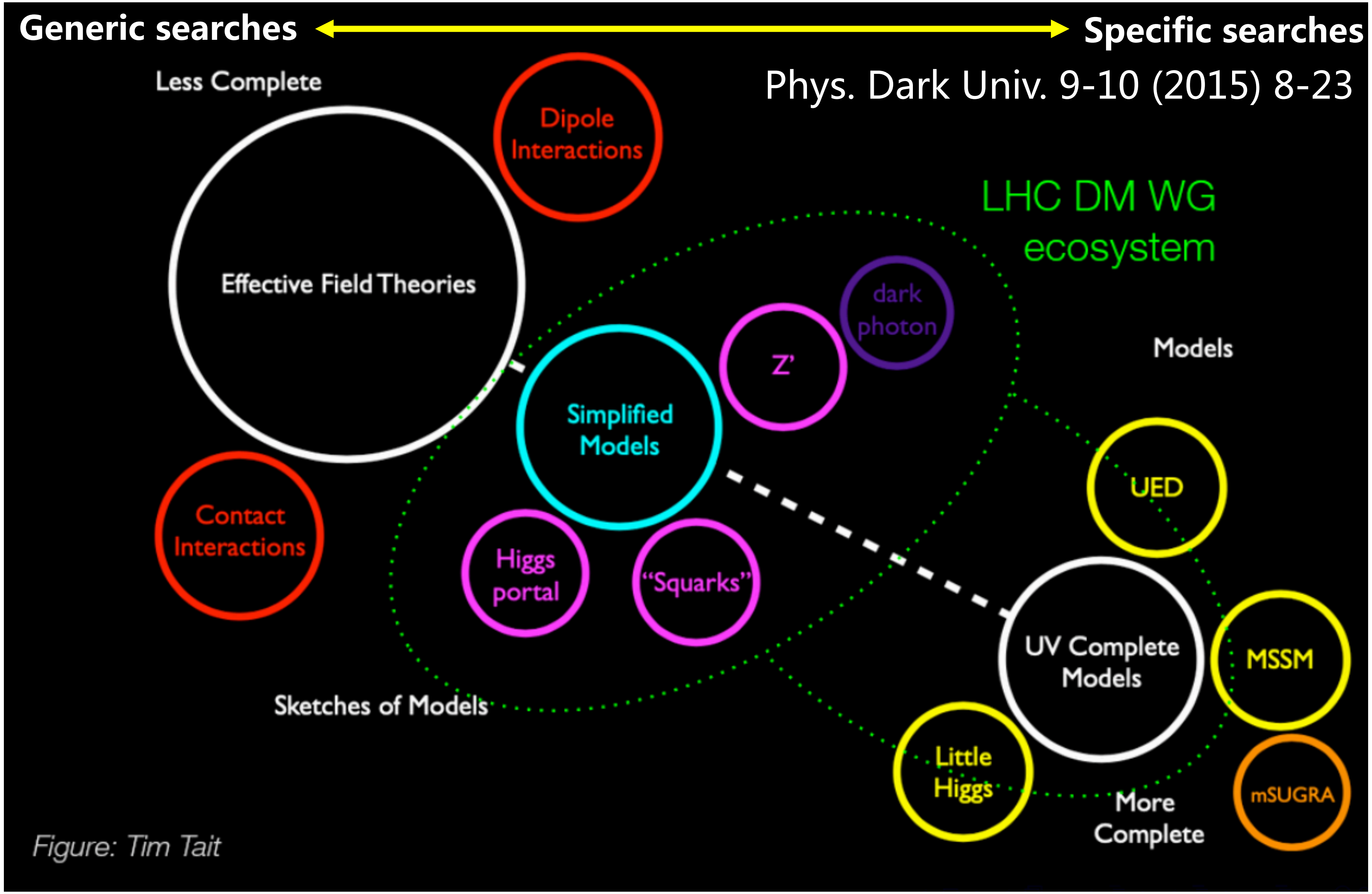
Muon Spectrometer:
muon identification and momentum measurement

Hadronic calorimeter:
Measurement of jets and missing energy

Electromagnetic calo:
e/γ identification and energy measurement

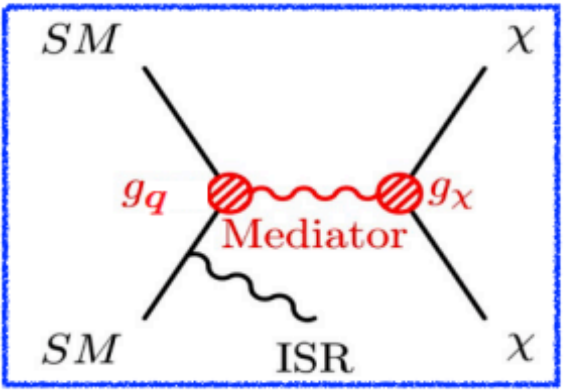
Tracking system:
Charged particle momentum, vertexing

Dark Matter Models for LHC



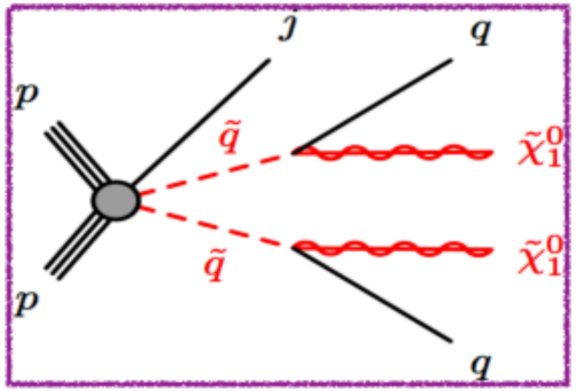
Dark Matter Search programs at LHC

Simplified models | **SUSY** | **Higgs portal** | **Extended Higgs sector**

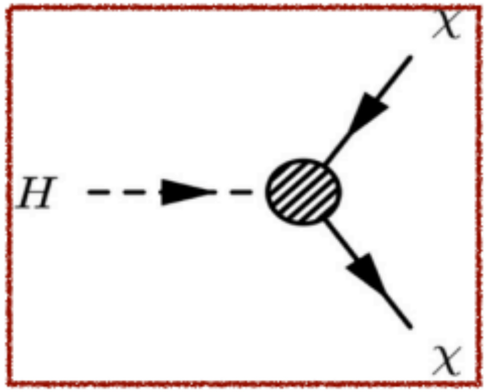


SM-DM boson mediator:

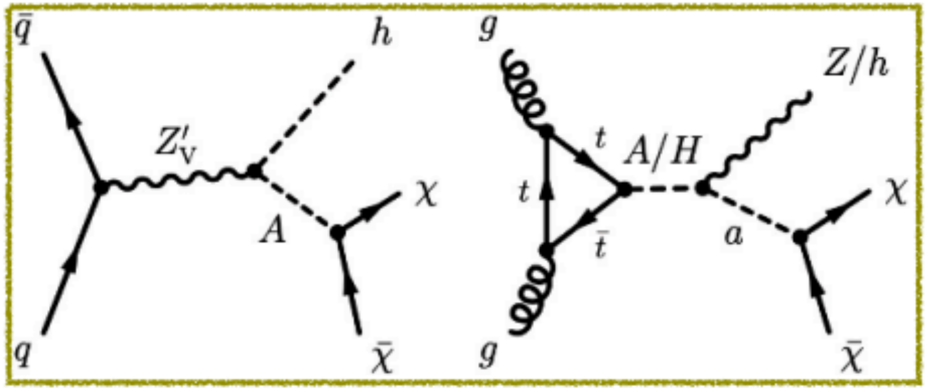
- Spin-0: Scalar (S) or pseudo-scalar (a)
- Spin-1: Vector (V/Z') or axial-vector (A)
- Minimal set of parameters: M_χ, $M_{mediator}$, g_χ, g_q, g_ℓ



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

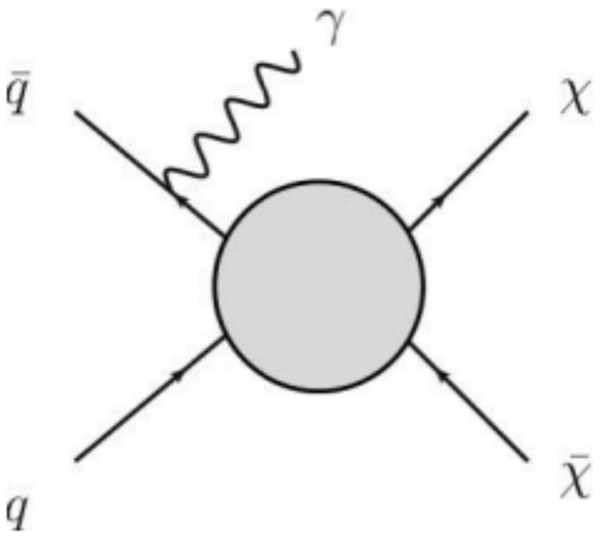


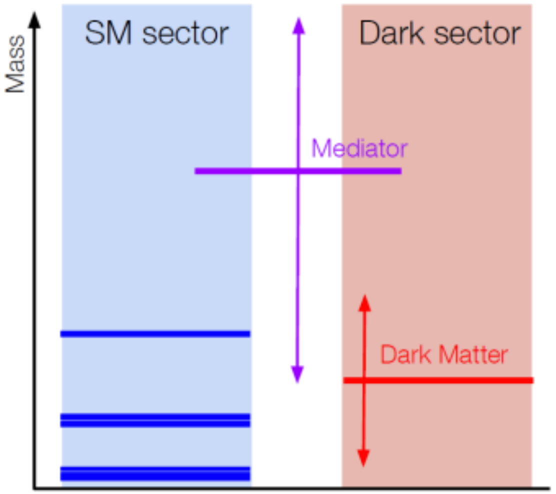
- Higgs boson mediates DM-SM interaction: $H \rightarrow invisible$
- Parameters: m_χ, χ spin

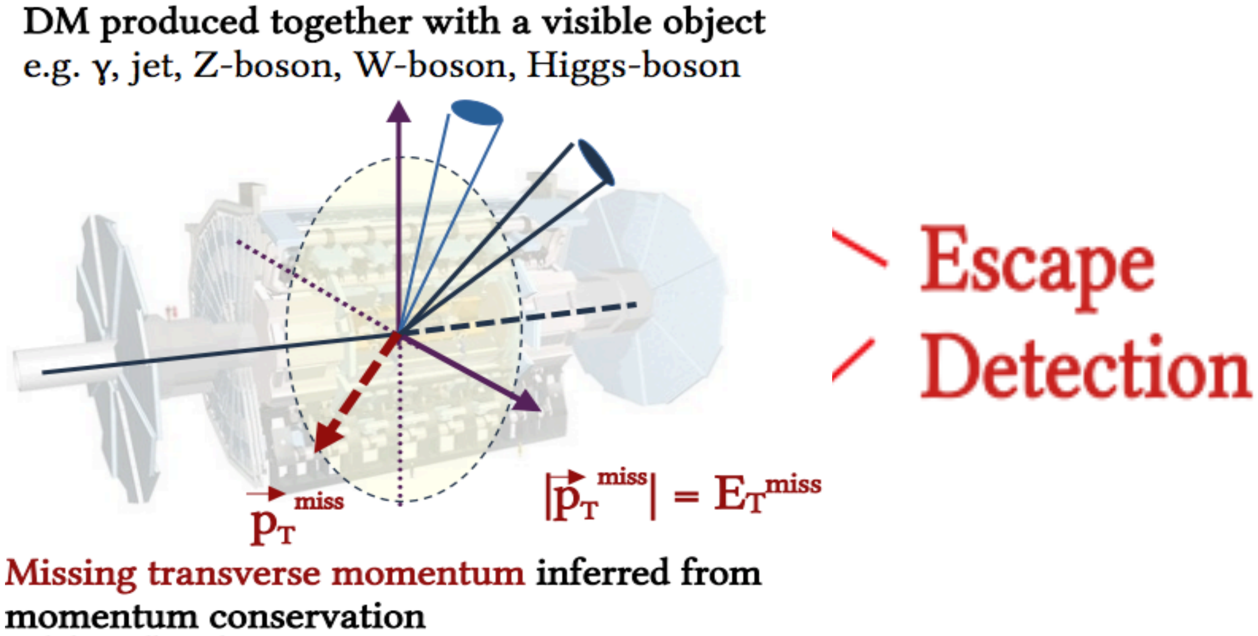


- More complete models (more free parameters and better sensitivity) involving several Higgs-like (or scalar) bosons: 2HDMa, Dark Higgs, ..

S-channel Mediator Simplified Models







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

Mono-Jet search (Jet + E_T^{miss})

Phys. Rev. D 103 (2021) 112006

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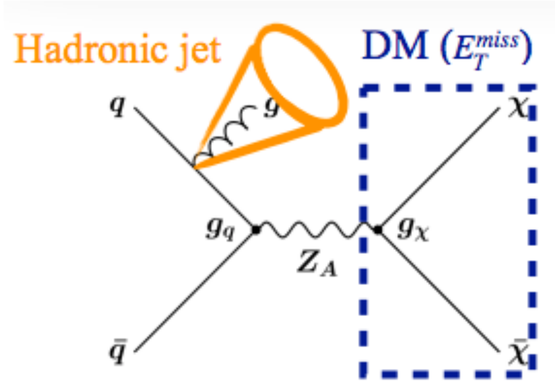
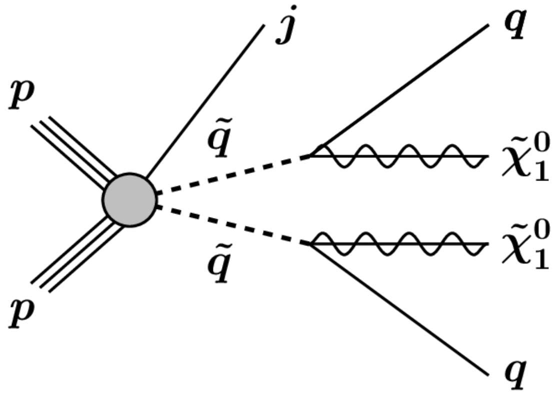
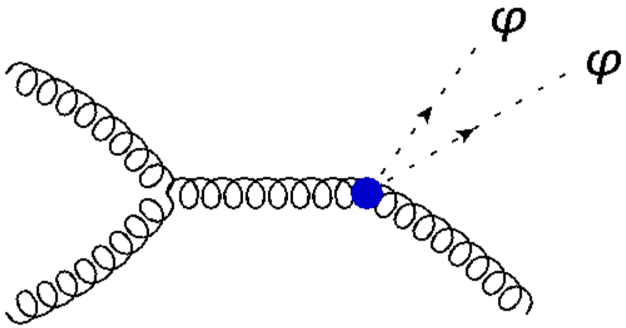
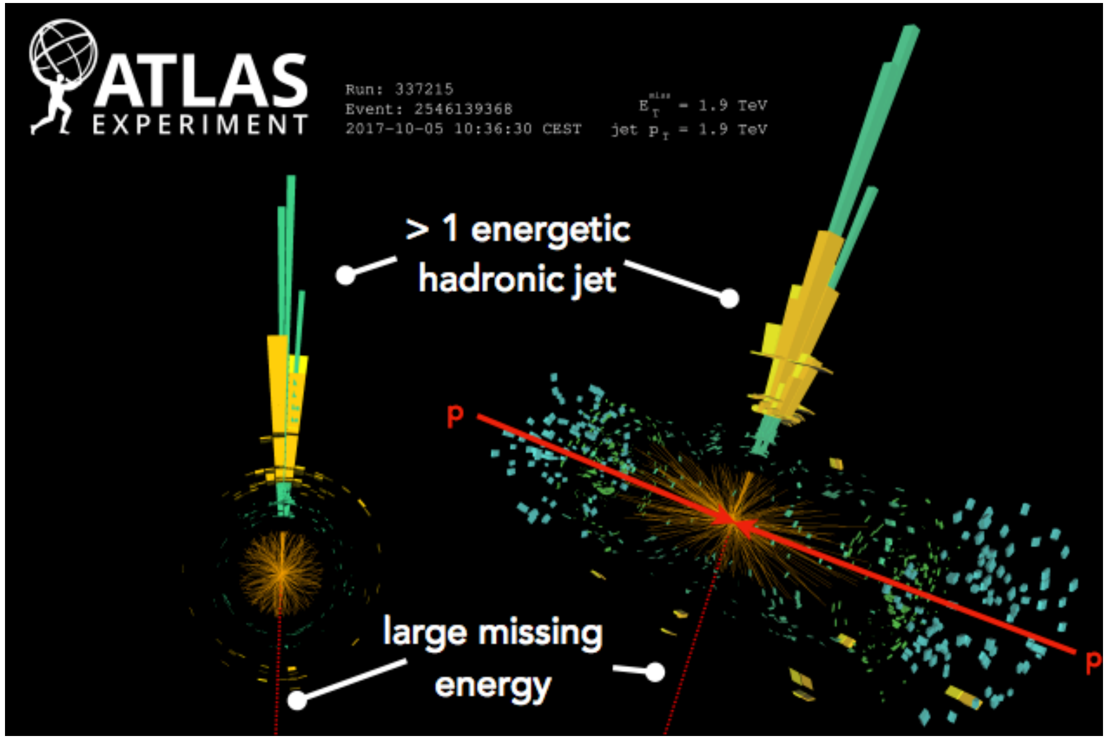
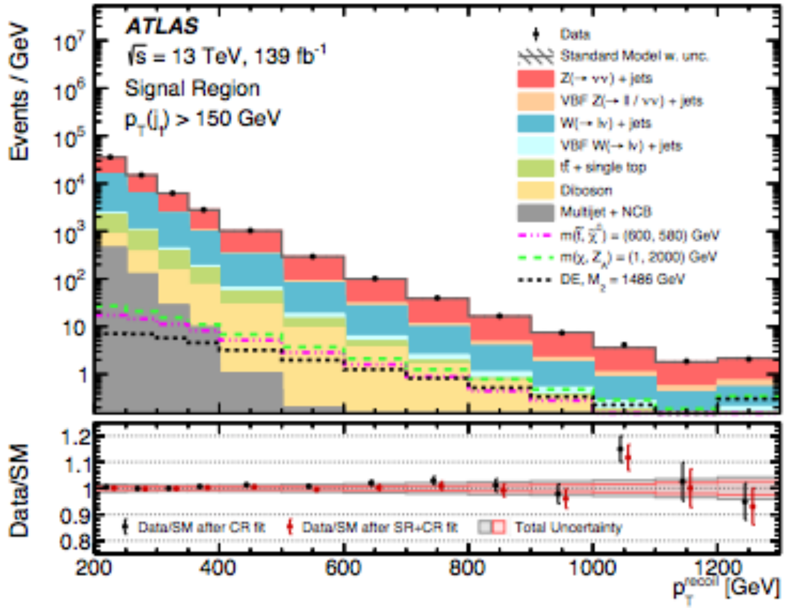


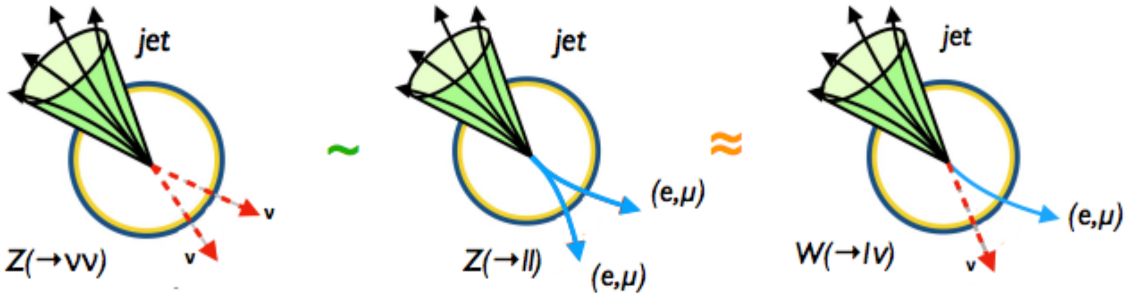








Signal region



Main backgrounds

Diverse Interpretations

- Simplified Models:
  - Fix coupling; Fix ratio
- T-channel models
- Generic sensitivity
  - SUSY, leptoquarks, extra dimensions, ...

Mono-Jet search (Jet + E_T^{miss})

Phys. Rev. D 103 (2021) 112006

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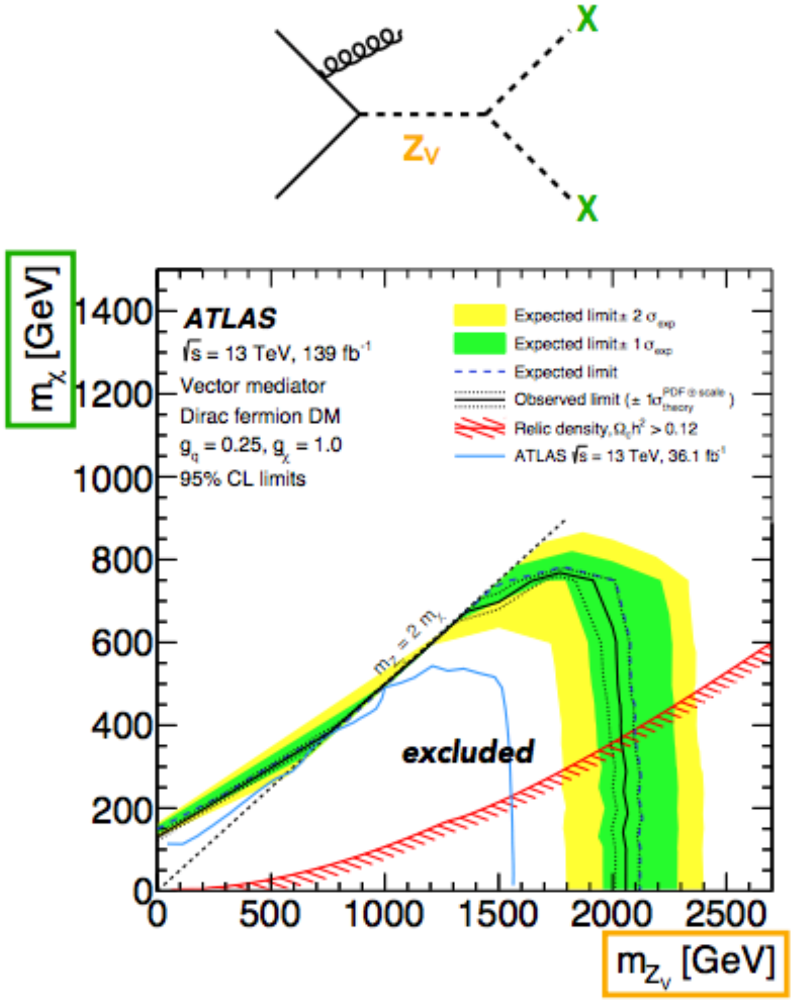
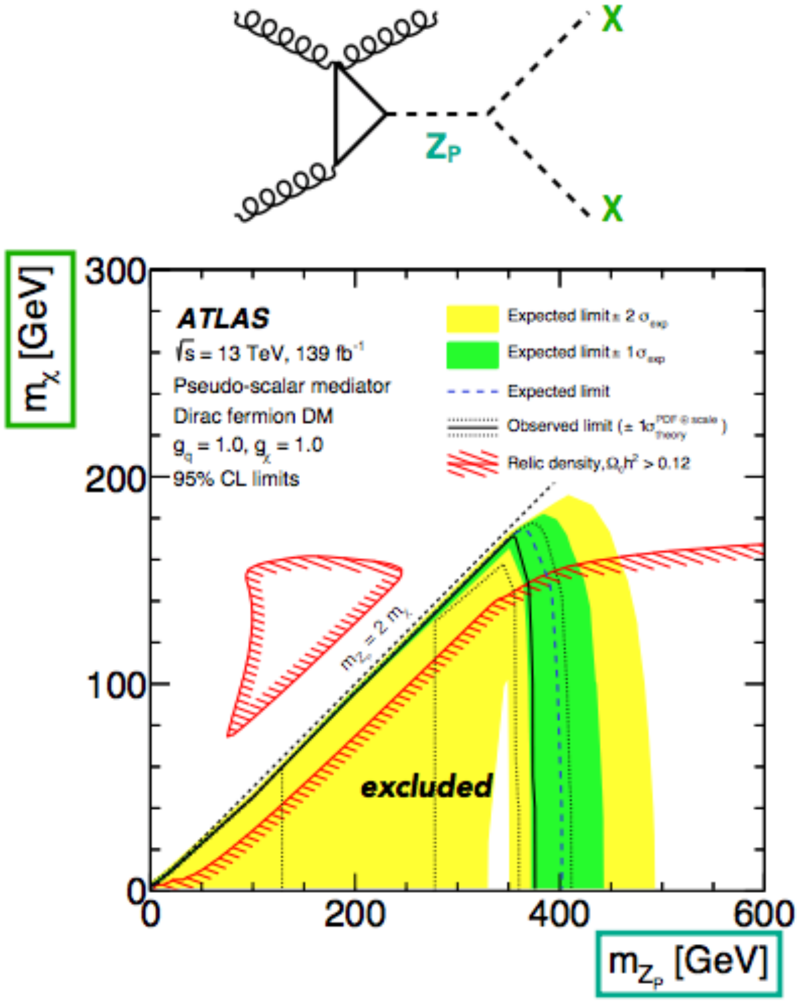
Spin 1



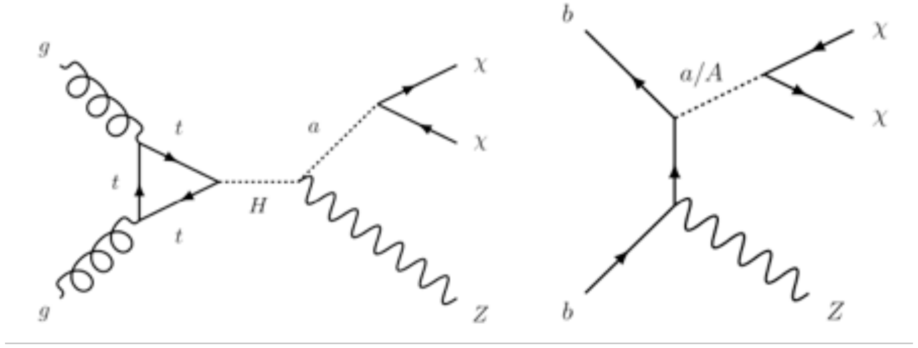
Spin 0

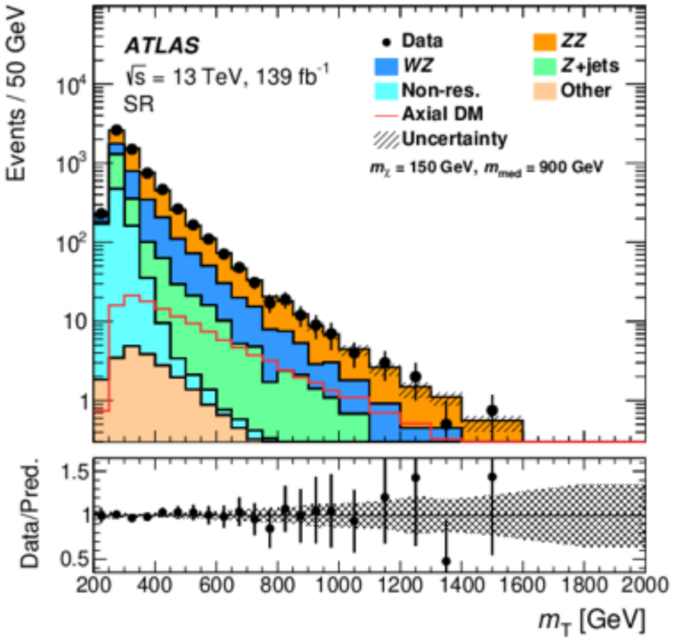


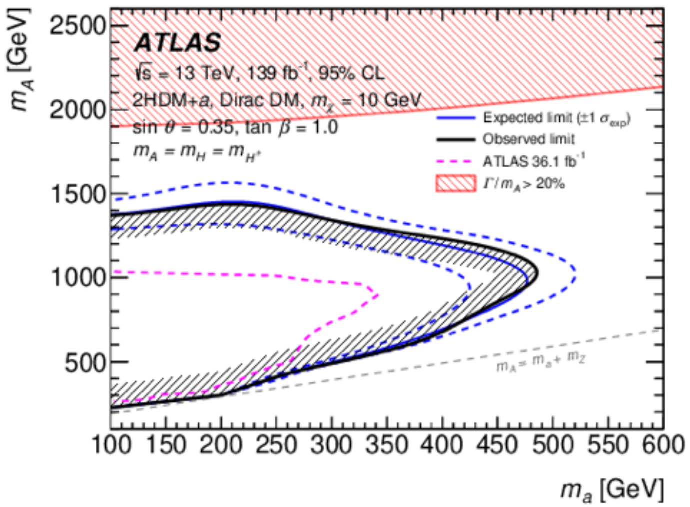
E_T^{miss}+Z(ll) signature

Phys. Lett. B 829 (2022) 137066

- **Signal region**:
  - Z boson recoiling against large E_T^{miss} > 90 GeV
  - Presence of a pair of high-p_T, same flavour, oppositely charged leptons with angular separation < 1.8
- Dominant bkgs ZZ, WZ and non-resonant bkgs estimated using **4l, 3l, and eμ Control Regions.**
- Fit to data is performed on m_T^{lep} (in SR and $e\mu$ CR) + E_T^{miss} (in 4l and 3l CRs).







Higgs portal to DM: invisible decays

Phys. Rev. D 105 (2022) 092007

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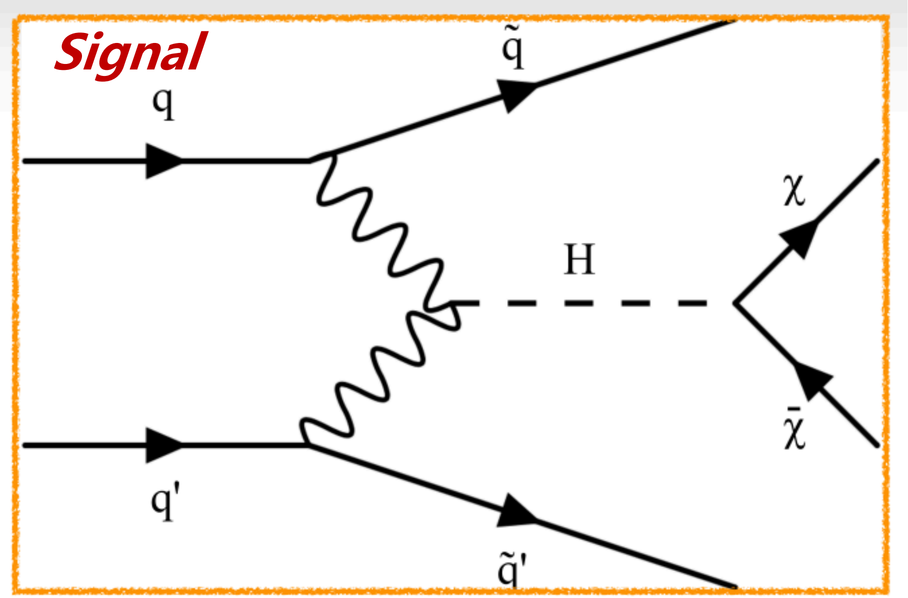
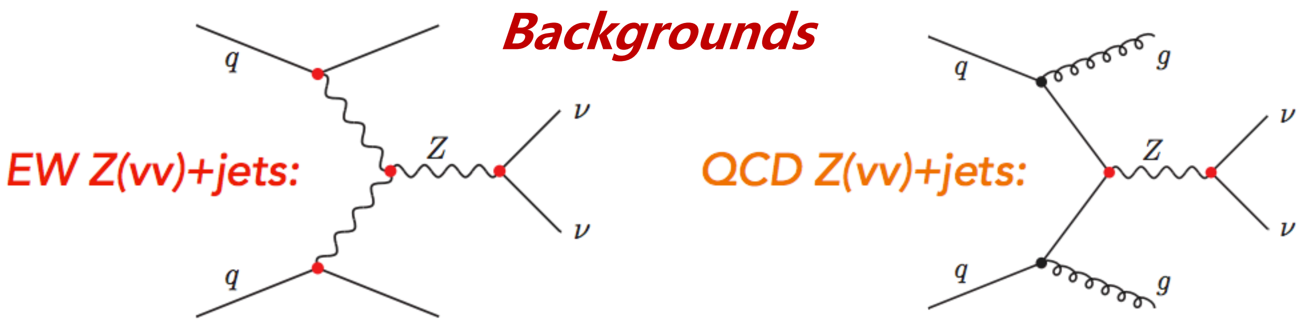
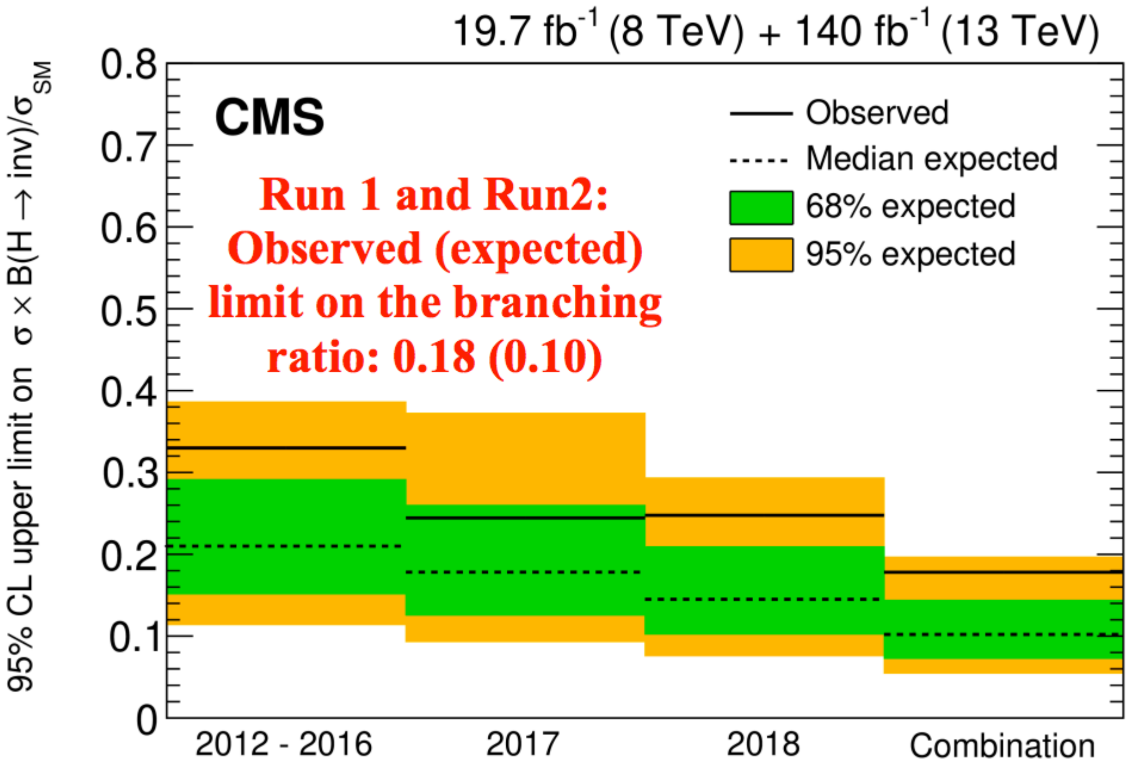




Observed Limit from the combination

$$\mathcal{B}(\mathrm{H} \to \mathrm{inv}) < 0.18\,(0.12) \text{ at the 95\% CL,}$$

- Signature: Vector-Boson Fusion
- Two SR triggers:
  - MTR with missing momentum trigger
  - VTR with VBF jet trigger



Phys. Lett. B 842 (2023) 137963

Higgs portal to DM: invisible decays

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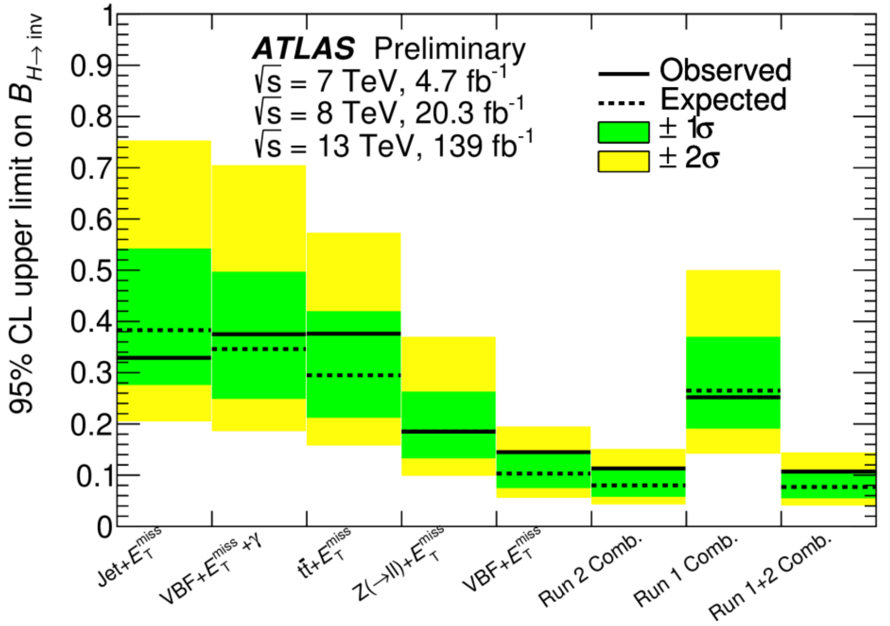
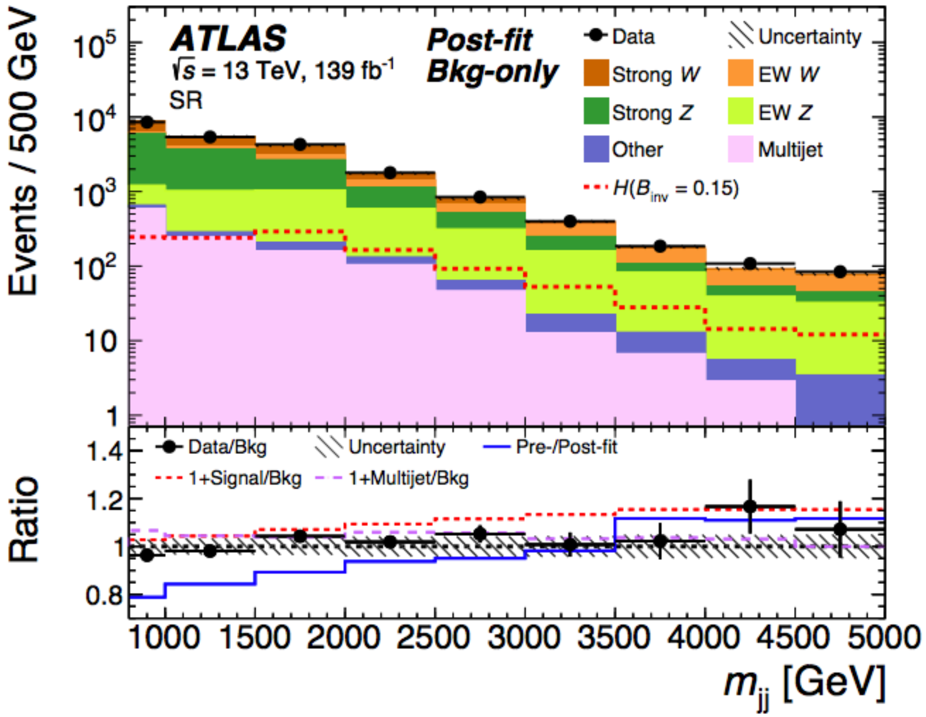
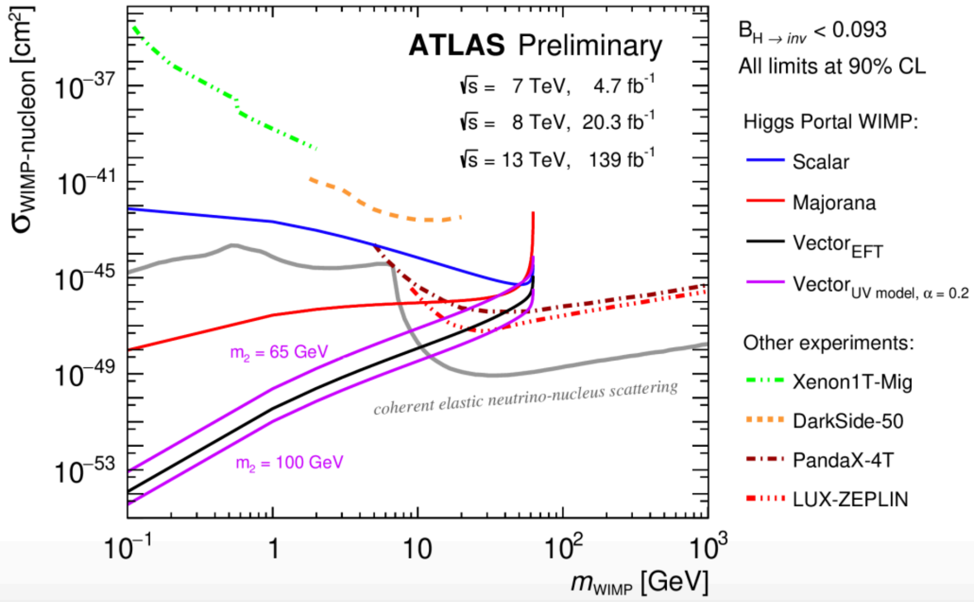
Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
Run 2 Comb.	0.04 ± 0.04	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	0.04 ± 0.04	0.107	$0.077^{+0.030}_{-0.022}$

- Z to W ratio predictions @NLO QCD, NLO EW - **arXiv:2204.07652** - used to constrain Zjets with Wjets
- Probing BR(H→ Inv) at 10% level







Higgs portal to DM: Mono-H($\gamma\gamma$)

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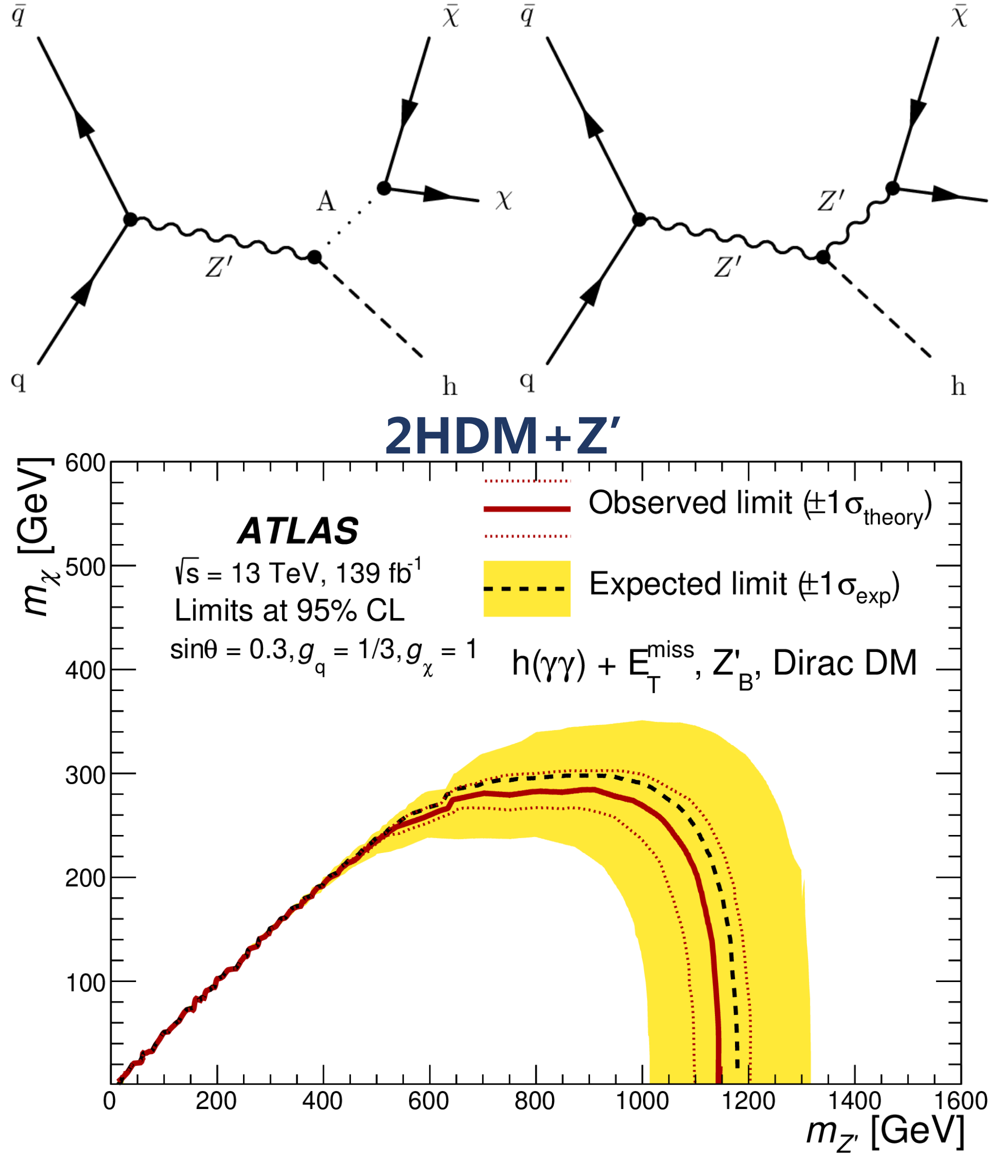

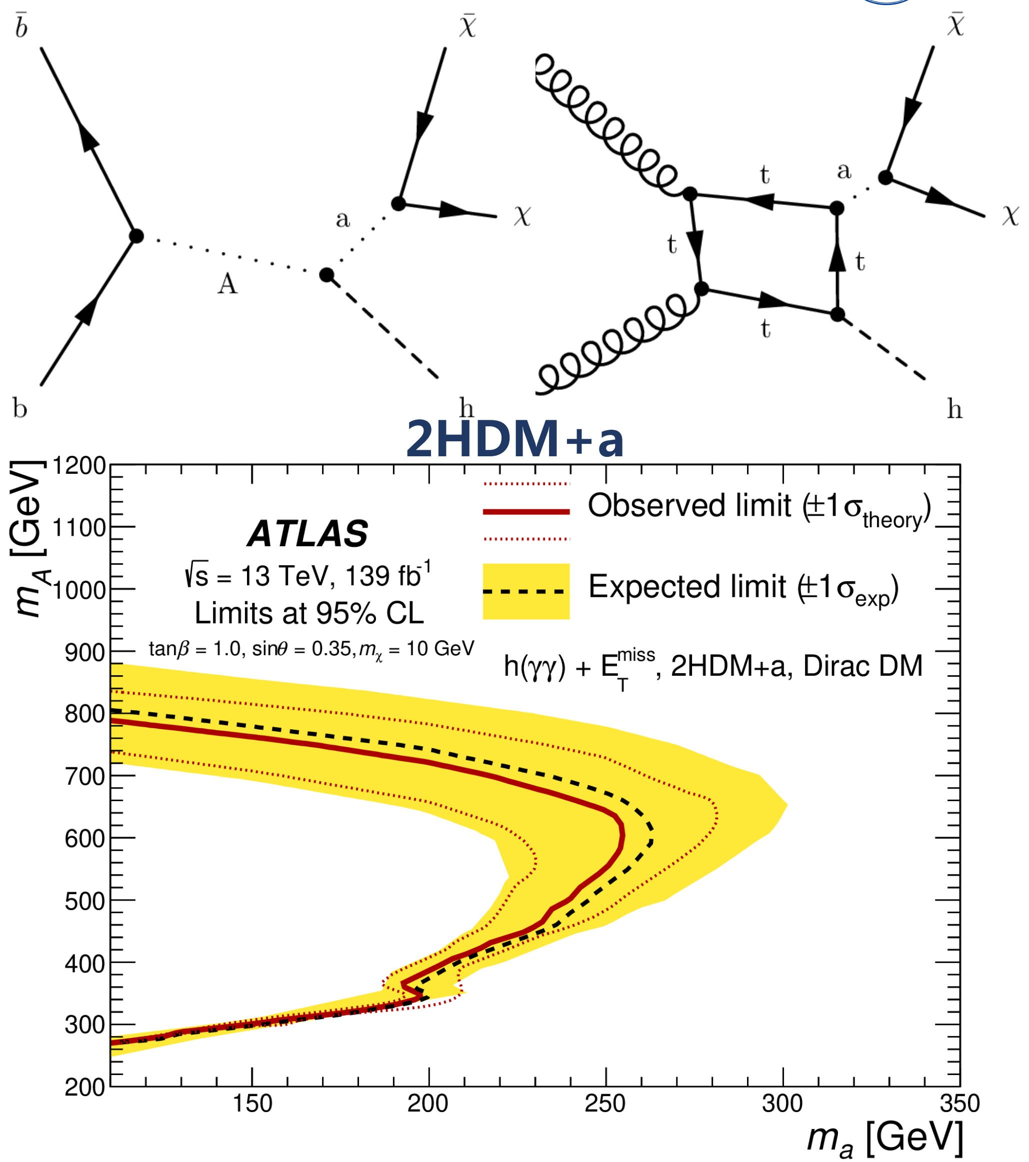

Higgs portal to DM: Mono-H(bb)

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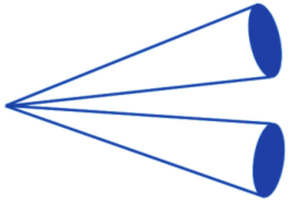
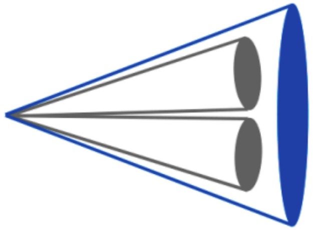
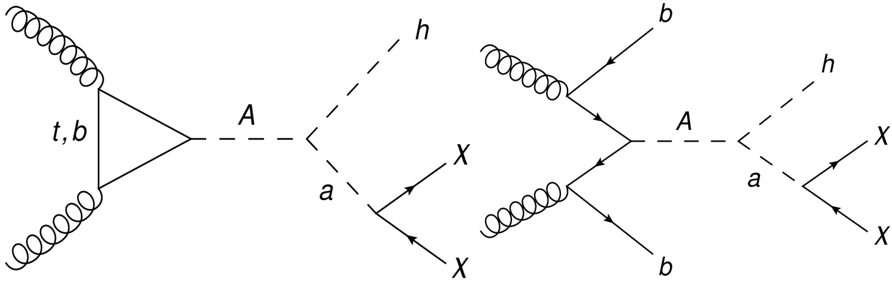
- Interpreted with 2HDM+Z′ , 2HDM+a in both ggF and bbH.
- Also Model-independent upper limits on the visible cross-section

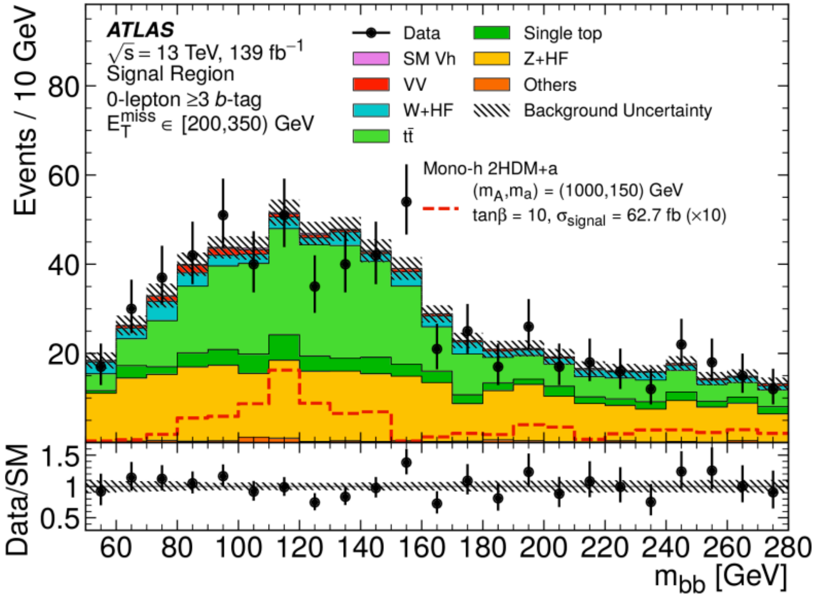
Resolved topology
$150 < E_T^{miss} < 500$ GeV
50 GeV $< m_h <$ 280 GeV
At least 2 small-R jets

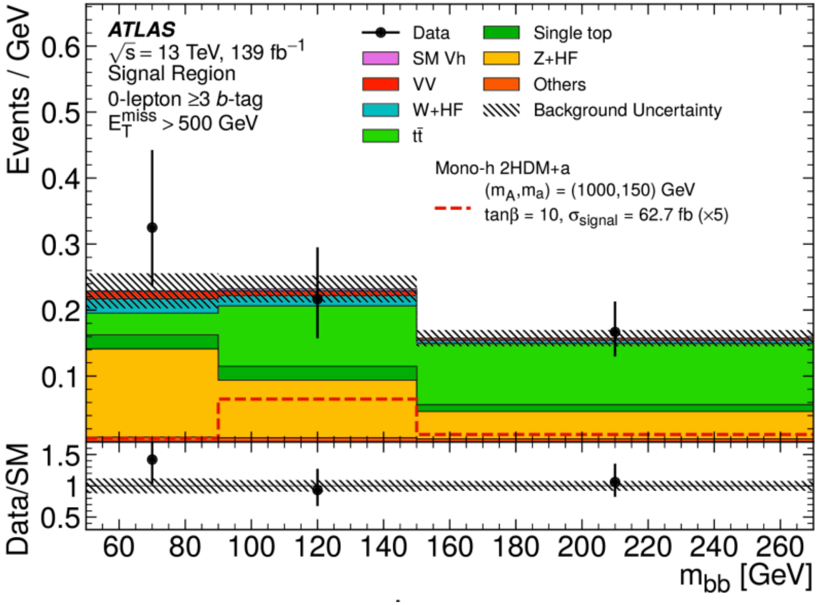


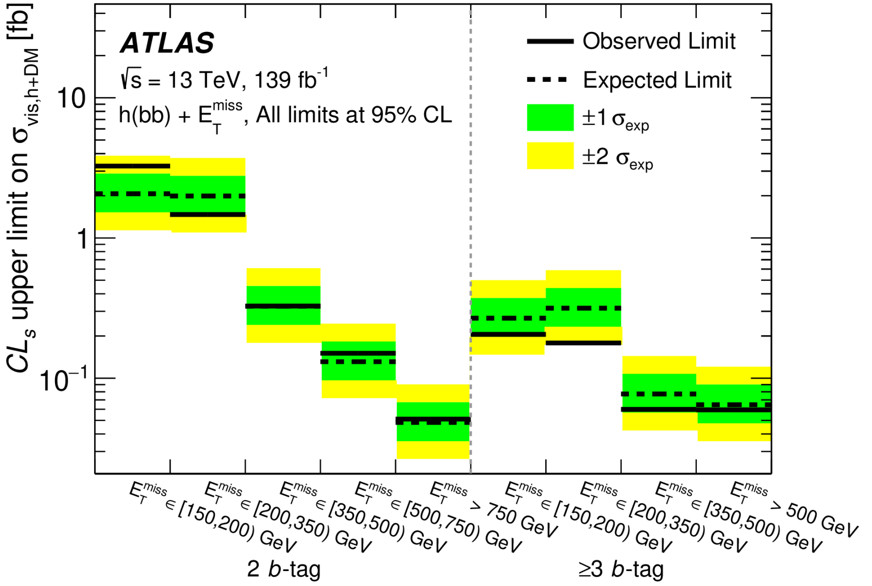
Merged topology
$E_T^{miss} > 500$ GeV
50 GeV $< m_h <$ 270 GeV
At least 1 large-R jet











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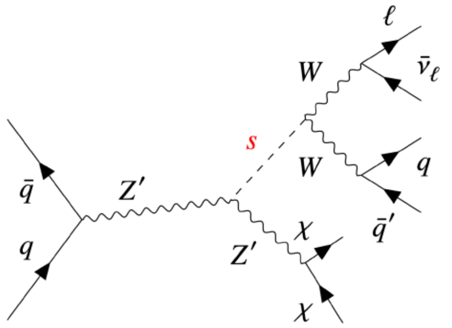
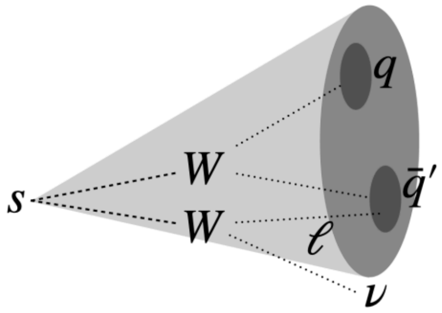
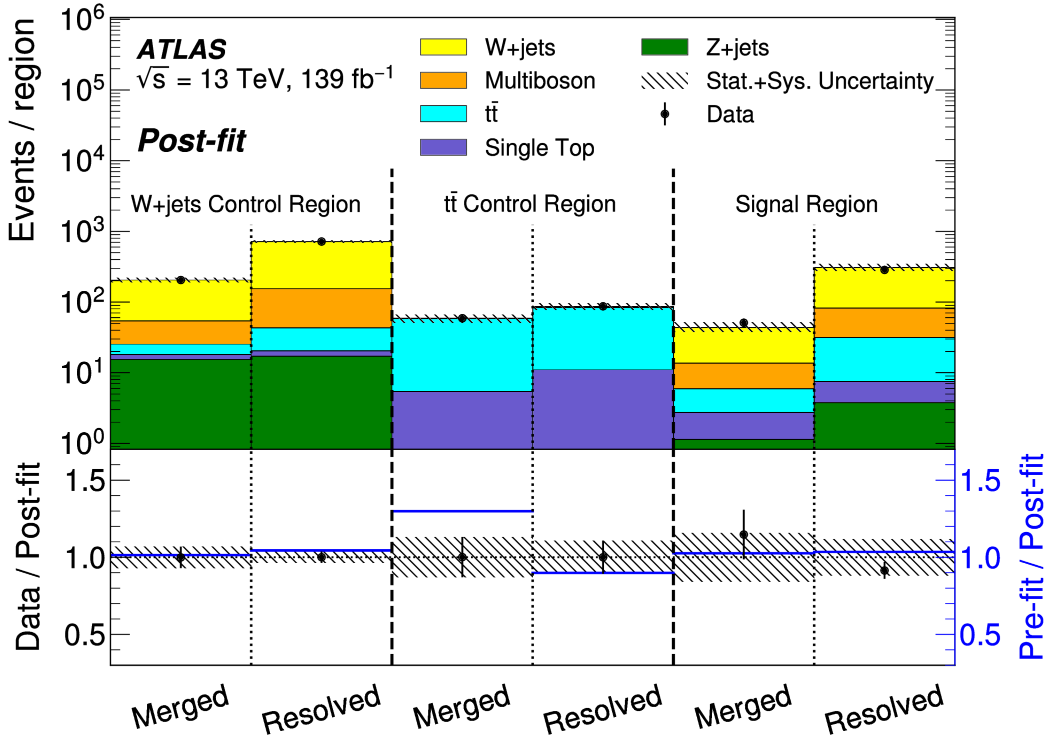
Dark Higgs Search: s→WW semileptonic

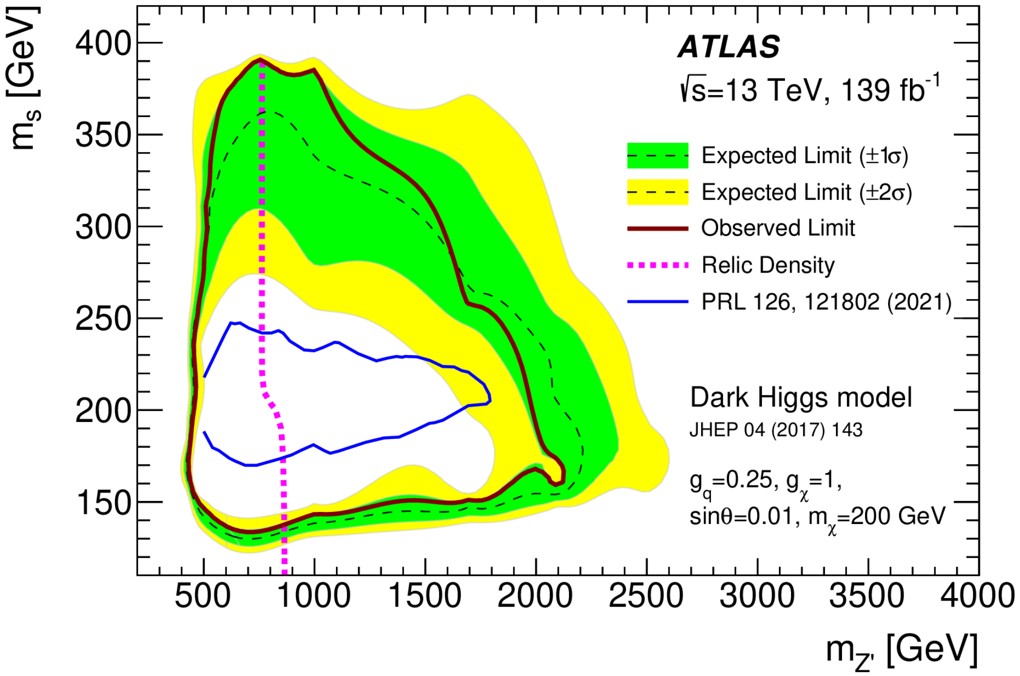




- Two mediator model: Z′ +Dark Higgs
- Utilize both resolved calorimeter-measured jet pair or merged from track-assisted reclustered jets

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





2HDM+a context

arXiv:2306.00641
[(Science Bulletin Accepted)]

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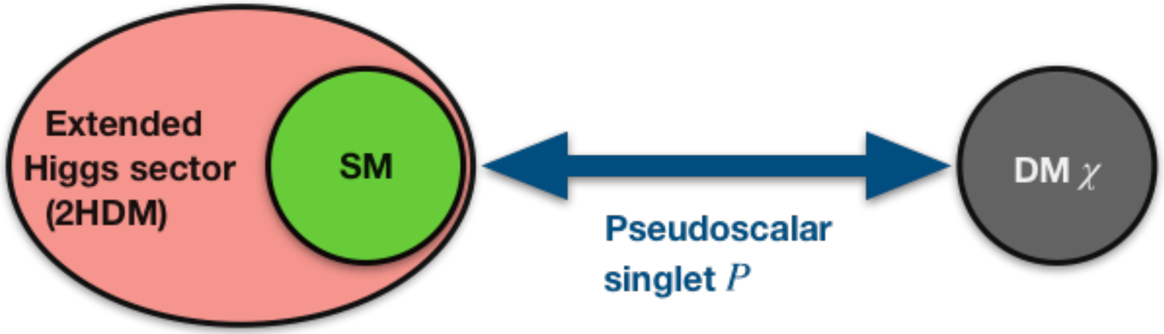
- One of the popular ATLAS DM benchmark context
  - Searches interpreted in Two-Higgs-Doublet Model plus a pseudo-scalar mediator (2HDM+a):
  - Minimal, UV-complete extension.
  - EWK Symmetry Breaking:
    - 5 Higgs: h, H, $H^{\pm}$, A
    - 1 light pseudo-scalar: a



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

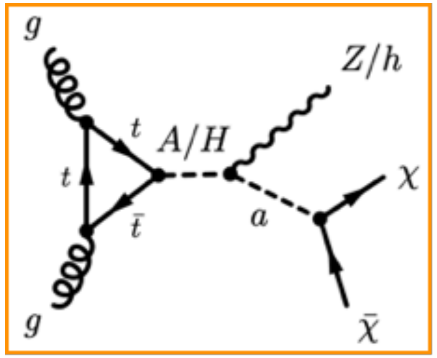
$m_A = m_H = m_{H^\pm}$	masses of heavy Higgs
m_a	mass of pseudo-scalar mediator
m_χ	DM mass
$\sin\theta$	mixing angle between CP-odd states a and A
$\tan\beta$	ratio of 2 Higgs doublet VEVs

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

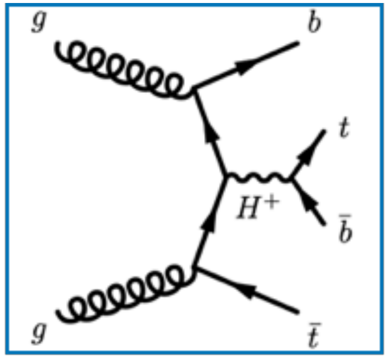
*h: SM-like CP-even Higgs with mass of 125 GeV

2HDM+a Experimental Signatures at ATLAS

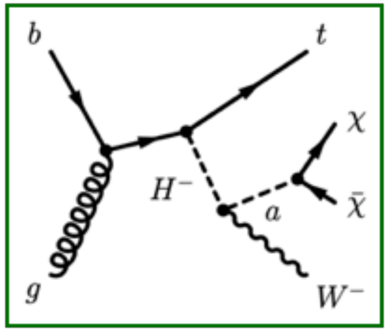
- 2HDM+a has rich phenomenology predicting wide range of signatures with both visible and invisible decays
  - resonantly production of E_T^{miss} +Z/h
  - additional (pseudo-)scalar bosons, e.g. tbH±(tb)
  - new signatures, e.g. E_T^{miss} +tW



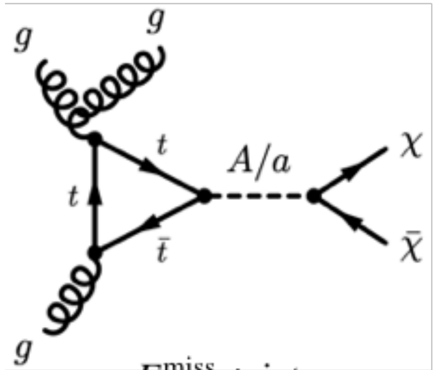
$E_T^{miss} + Z/h$



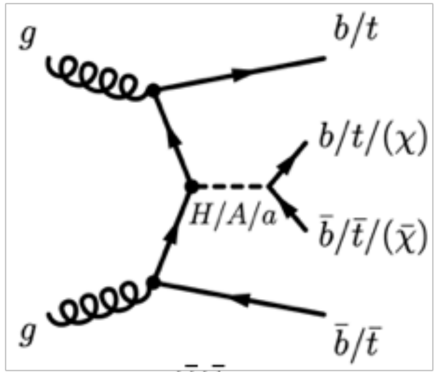
$tbH^{\pm}(tb)$



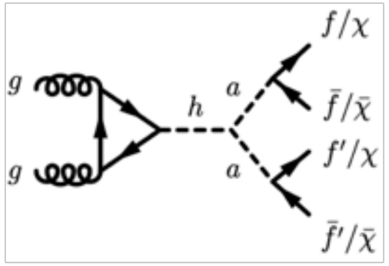
$E_T^{miss} + tW$



$E_T^{miss} + \mathrm{jet}$



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



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

Statistical Combination

arXiv:2306.00641
(Science Bulletin Accepted)

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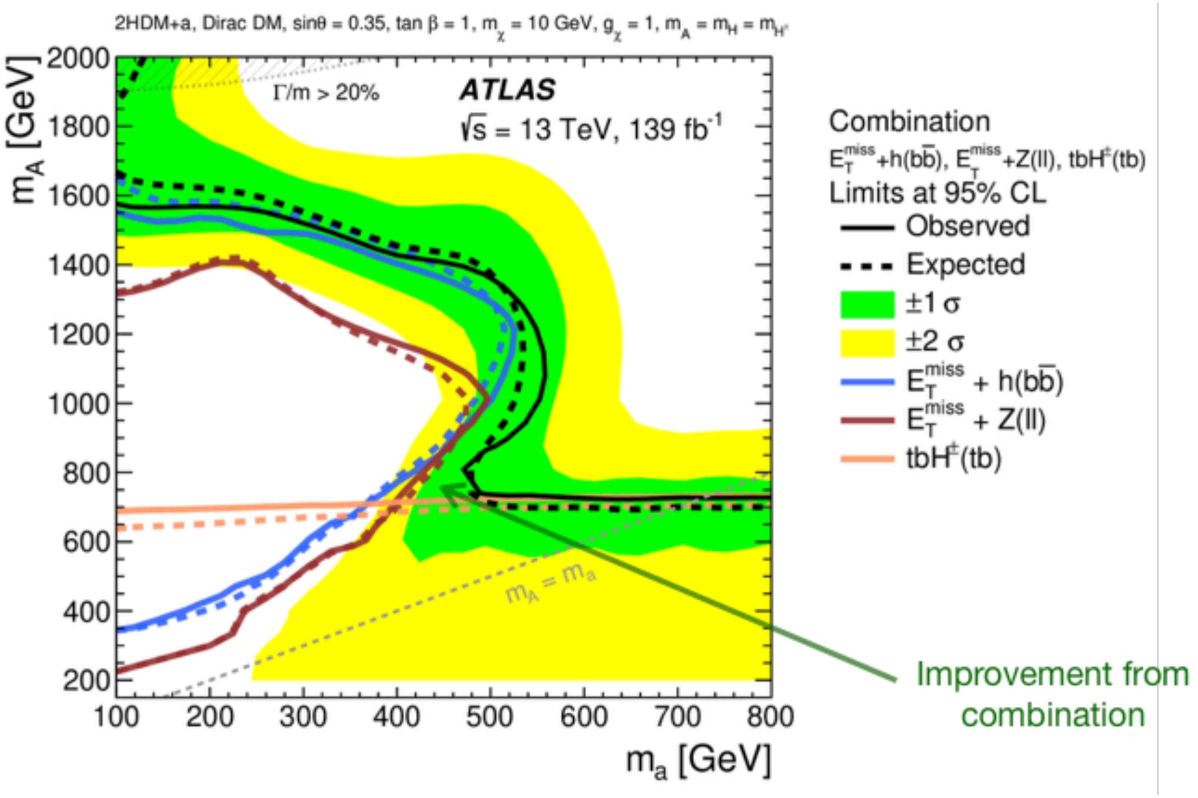
- $E_T^{miss} + h(bb)$, $E_T^{miss} + Z(ll)$ and $tbH^{\pm}(tb)$: Most constraining signatures of 2HDM+a.
  - $tbH^{\pm}(tb)$ gives significant complementarity to sensitivities of $E_T^{miss} + X$
  - stat. combination of 3 channels to maximize 2HDM+a constraints in parameter space.
- Combined exclusion 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_χ
6		0.35	1200	–	1.0	(m_a, m_χ)

shows interplay due to mass hierarchies (scenario 1)

motivated by similar scans done for general 2HDMs (scenarios 2 and 3)

illustration a-A mixing parameter effect (scenario 4)

connection with cosmological constraints and direct/indirect searches (scenarios 5 and 6)

showed for the 1st time (scenario 6)

m_χ set to 10 GeV in all scenarios, except 5 and 6

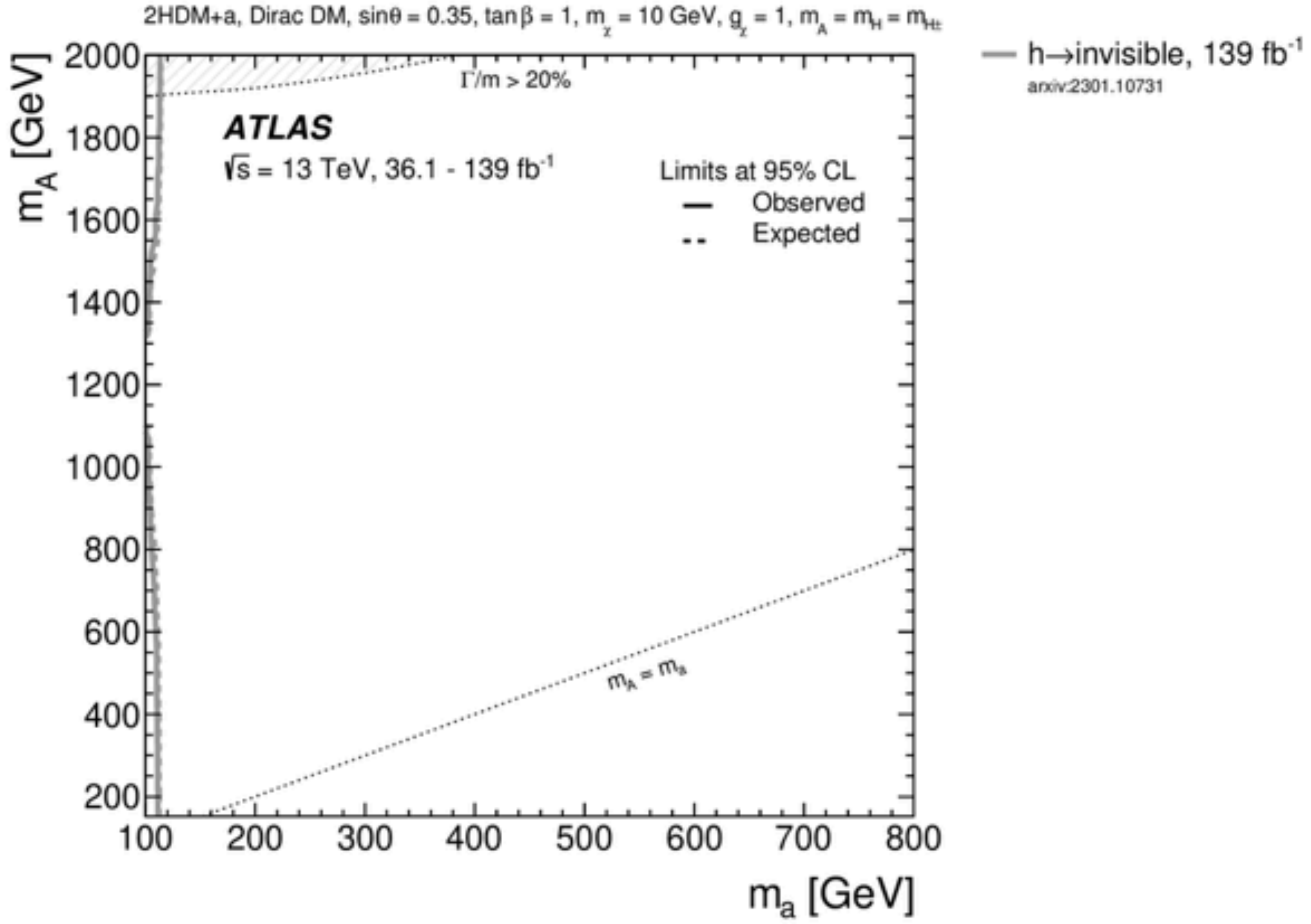
Summary of constraints on 2HDM+a

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
$E_T^{miss} + Z(\ell\ell)$ [74]	x	x	x	x	x	x	x	x	x	
$E_T^{miss} + h(b\bar{b})$ [75]	x	x	x	x	x	x	x	x	x	x
$E_T^{miss} + h(\gamma\gamma)$ [84]	x	x			x	x	x	x		
$E_T^{miss} + h(\tau\tau)$ [78]	x			x						
$E_T^{miss} + tW$ [77]	x	x	x	x	x	x	x	x		
$E_T^{miss} + j$ [45]	x	x			x	x	x	x		
$h \to$ invisible [86]	x	x			x					x
$E_T^{miss} + Z(q\bar{q})$ [127]	x						x	x		
$E_T^{miss} + b\bar{b}$ [128]							x	x		
$E_T^{miss} + t\bar{t}$ [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: sinθ=0.35, m_A - m_a plane

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



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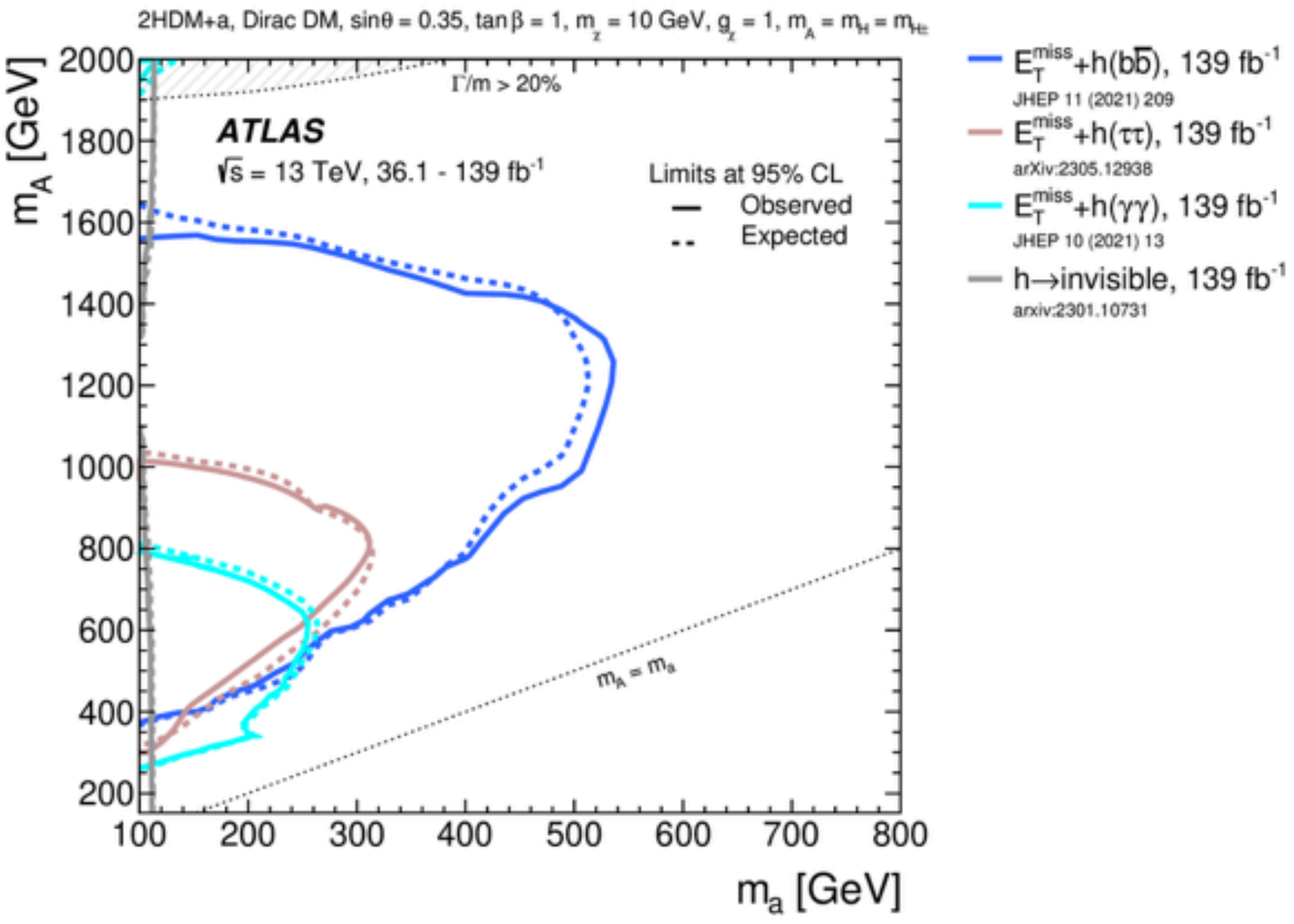
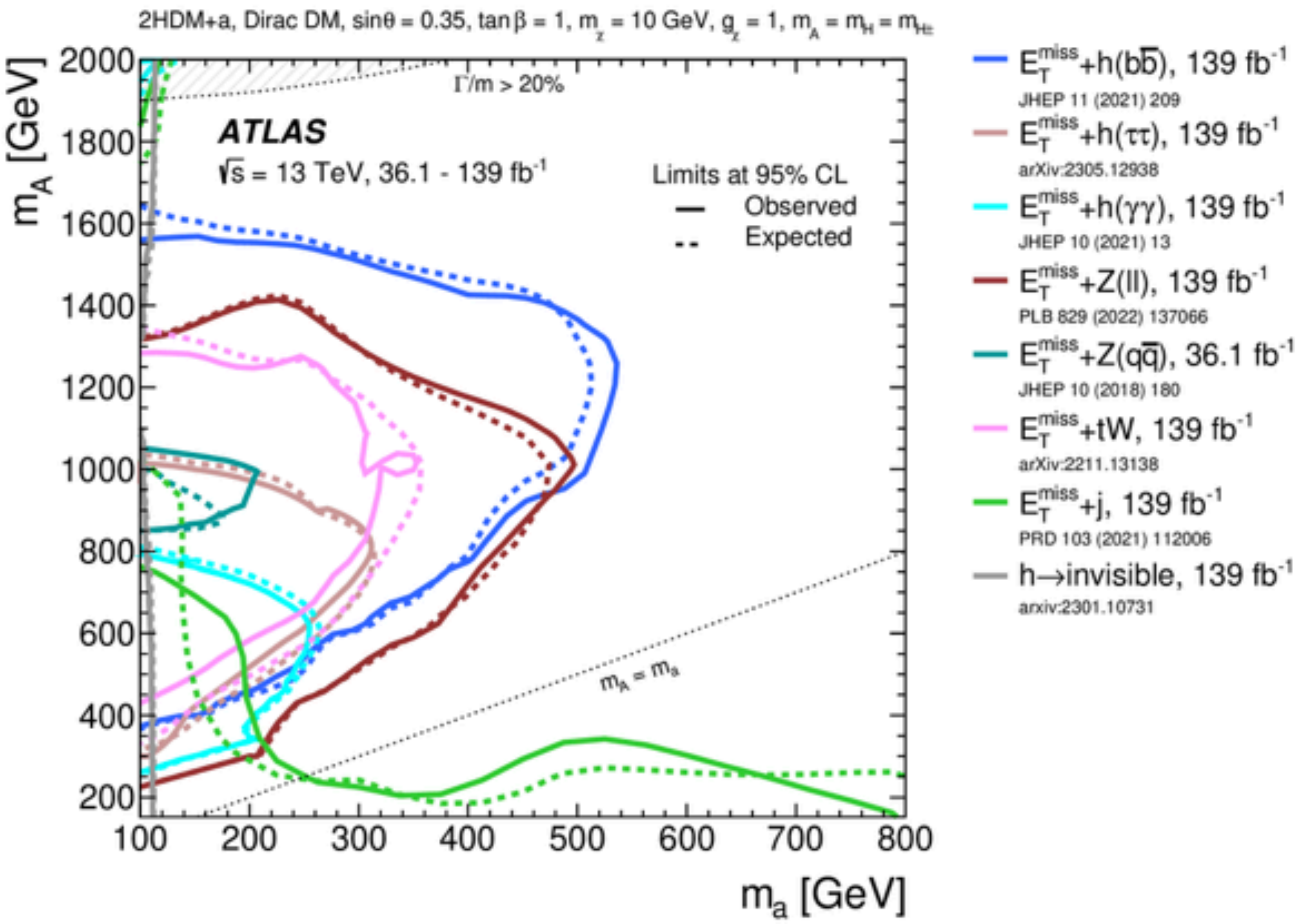
- constraints from $E_T^{\text{miss}} + h$ signatures: similar m_A-m_a dependence, with $h \to bb$ most sensitive.



Scenario 1a: sinθ=0.35, m_A - m_a plane

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



Scenario 1a: sinθ=0.35, m_A - m_a plane

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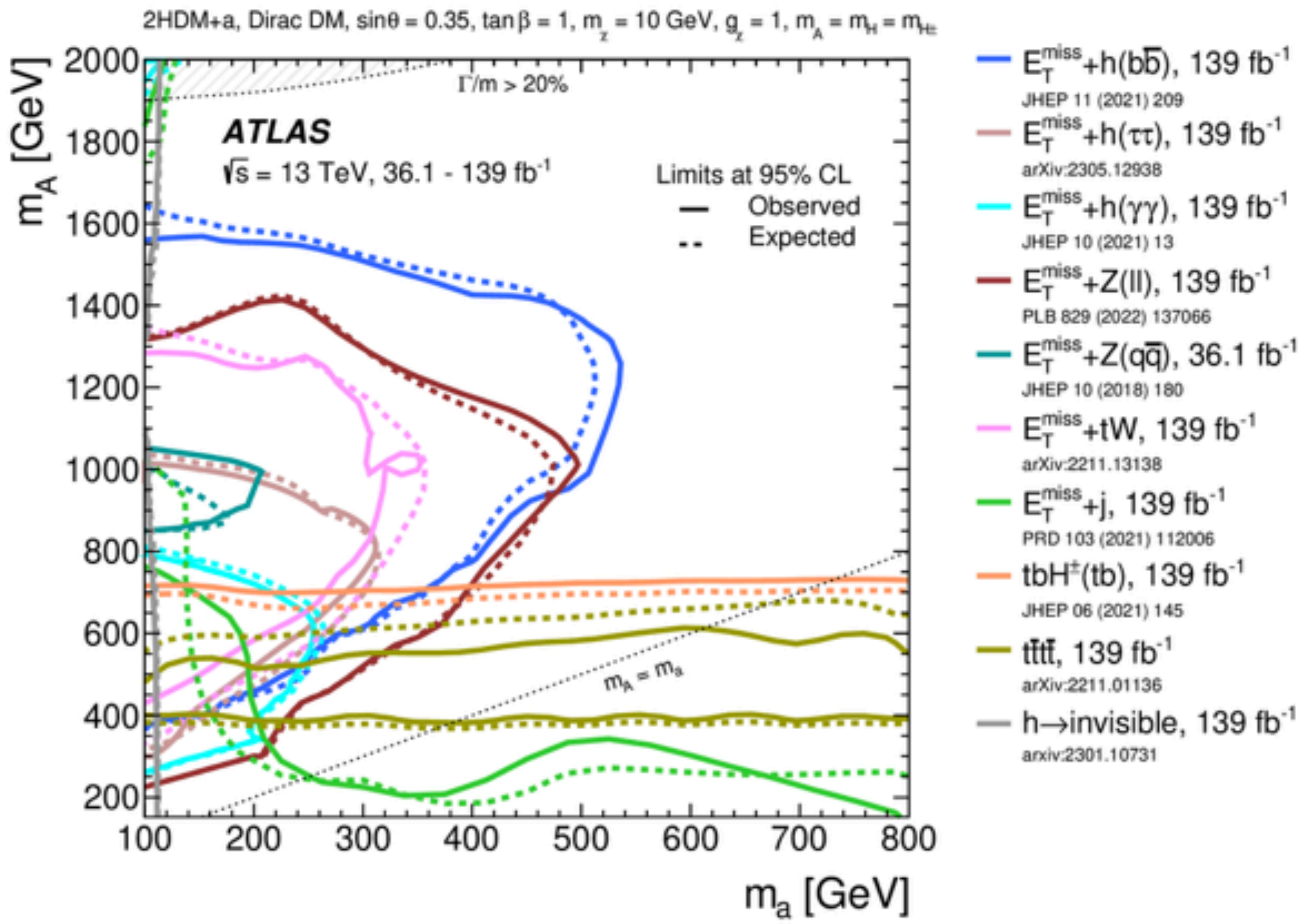
- Complementary constraints from searches not targeting DM.



Scenario 1a: sinθ=0.35, m_A - m_a plane

arXiv:2306.00641
(Science Bulletin Accepted)

- $h \to$ invisible constrains very low m_a.
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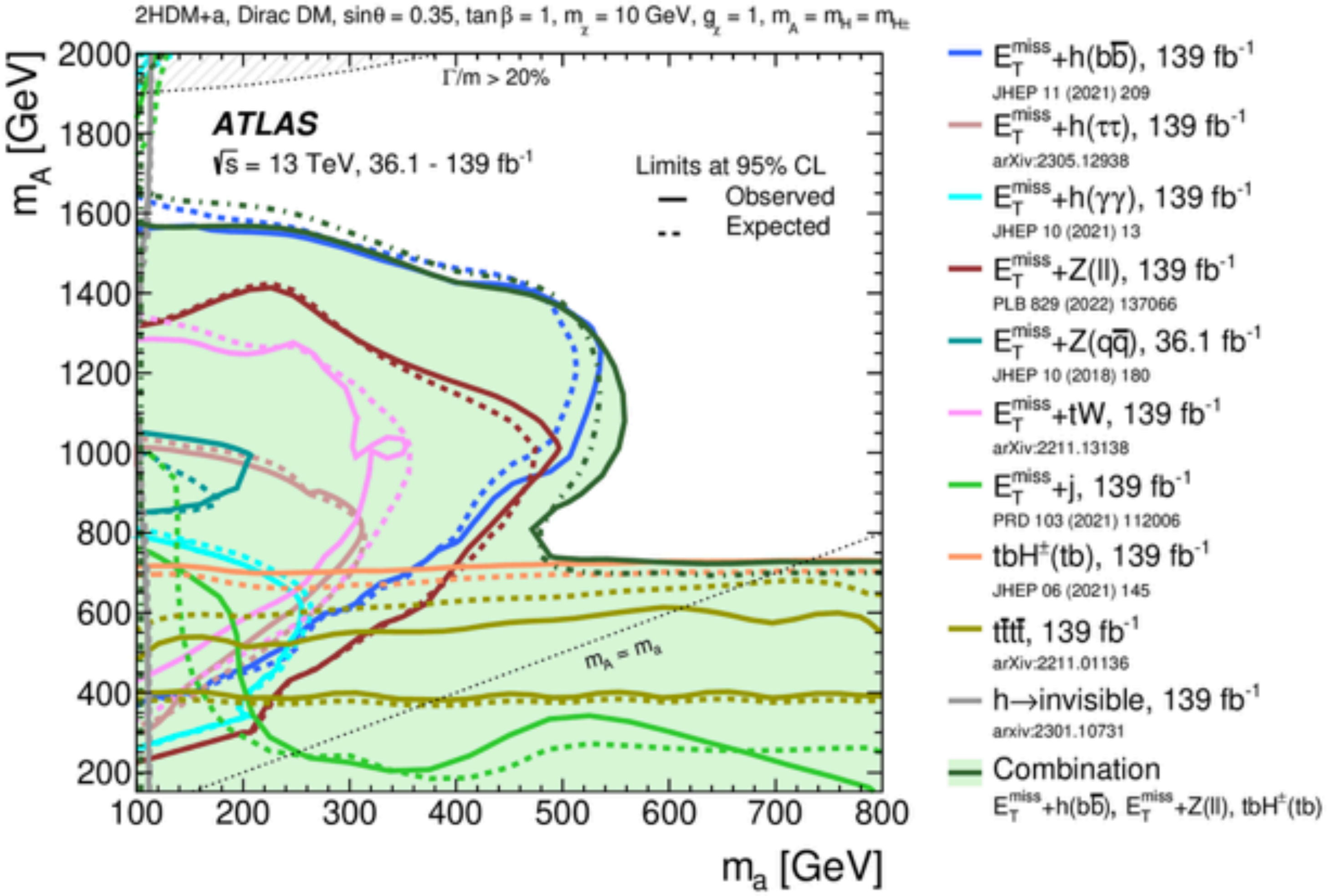
- E_T^{miss} + jet sensitivity notably different from those of $E_T^{miss} + Z$ and $E_T^{miss} + h$.
- Complementary constraints from searches not targeting DM.
- Sensitivity of 2HDM+a driven by the combination.



Scenario 6: m_a - m_χ plane

[arXiv:2306.00641](https://arxiv.org/abs/2306.00641)
(Science Bulletin Accepted)

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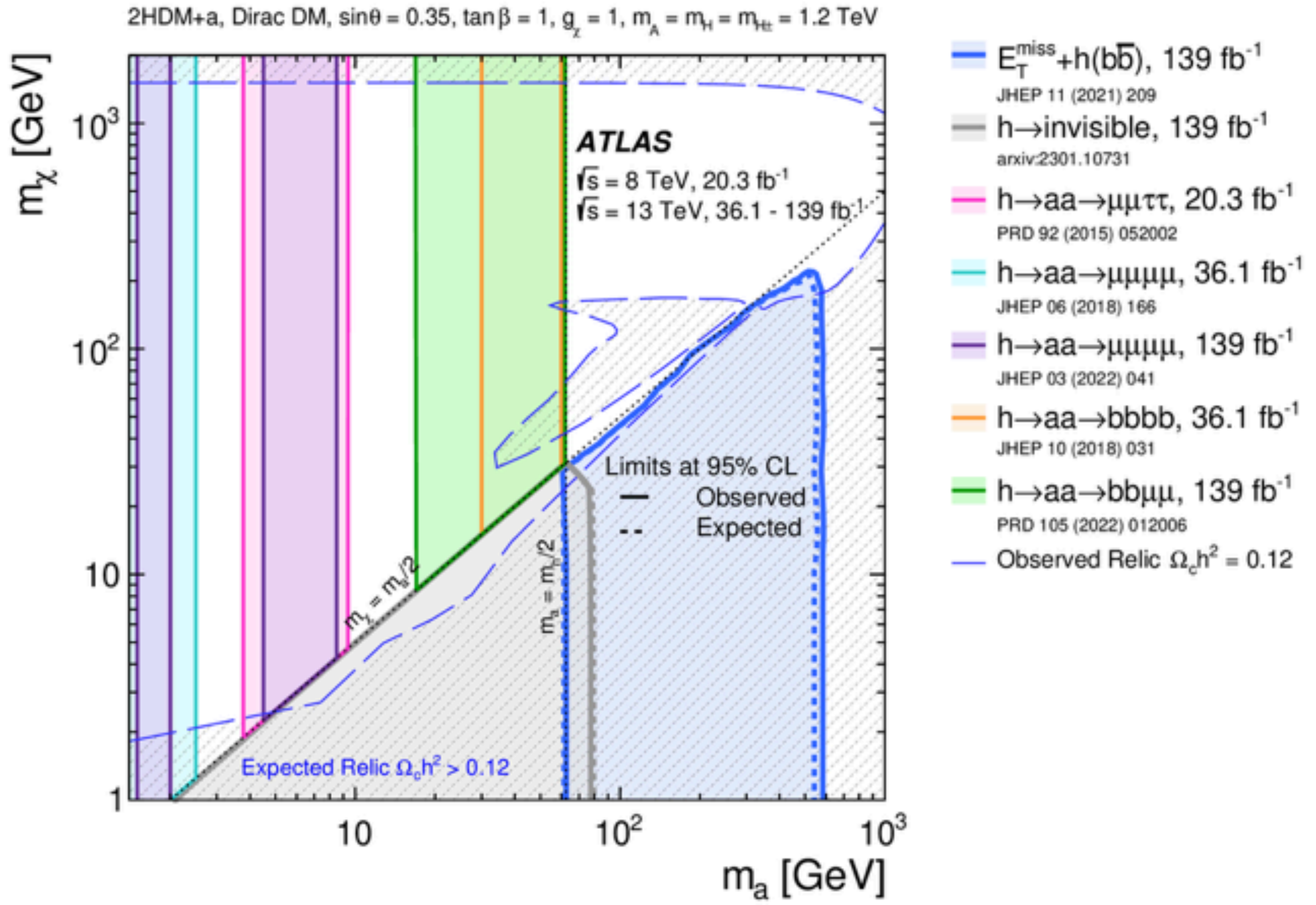
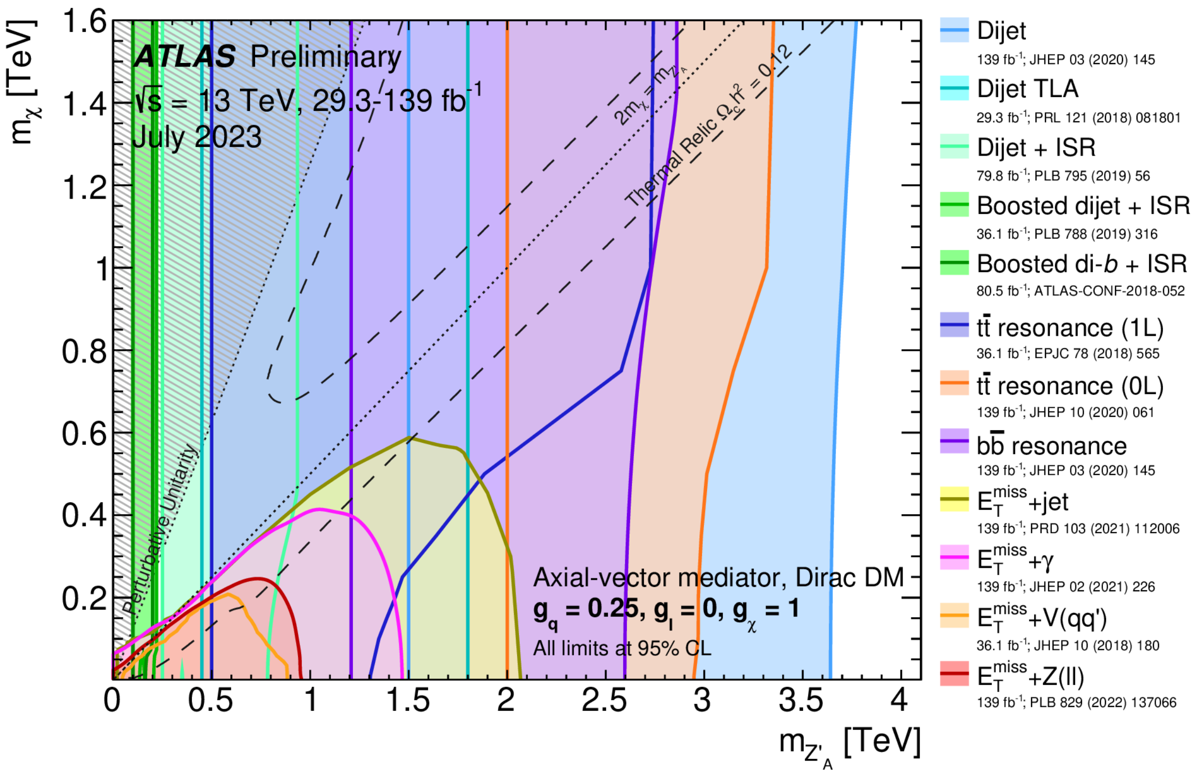
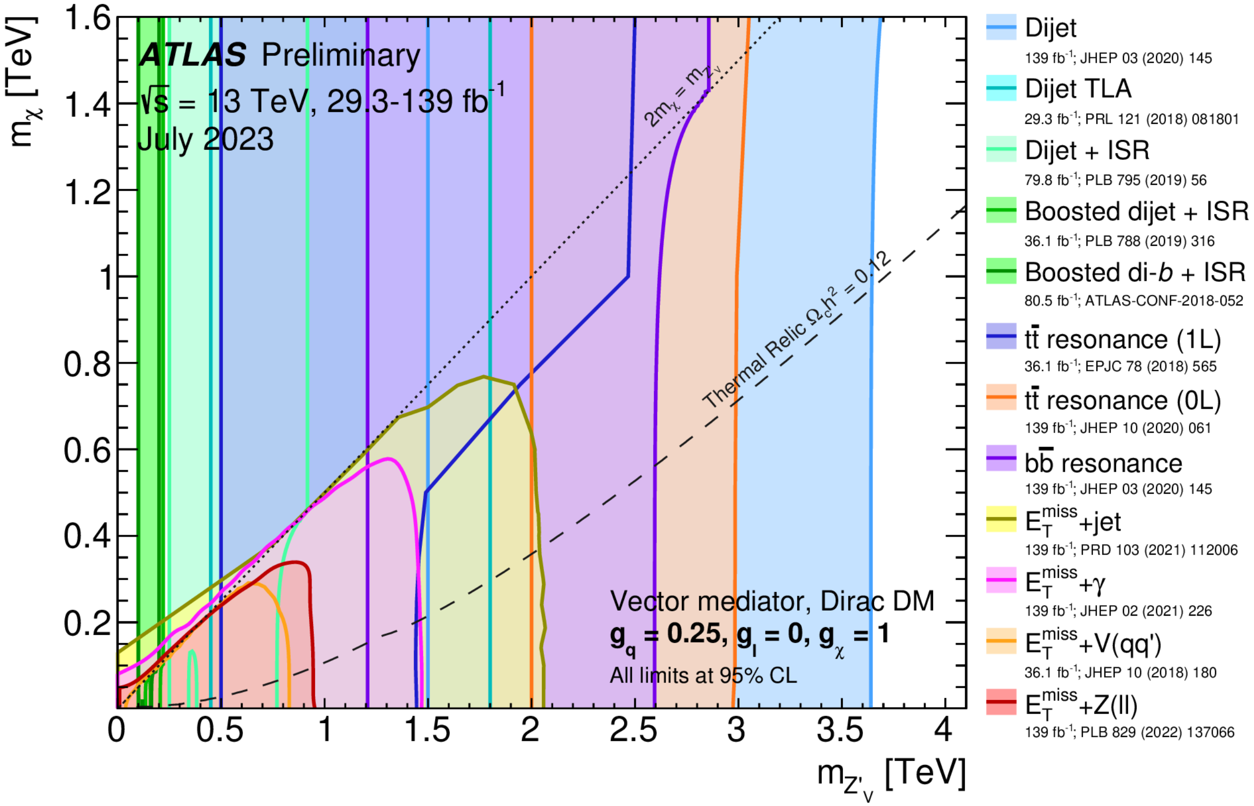
- New interpretation in m_a - m_χ plane:
- Searches for SM Higgs decaying to 4 fermions via constrain previously unprobed region of 2HDM+a.
- Complementarity to h→inv. and E_T^{miss}+h(bb) searches.



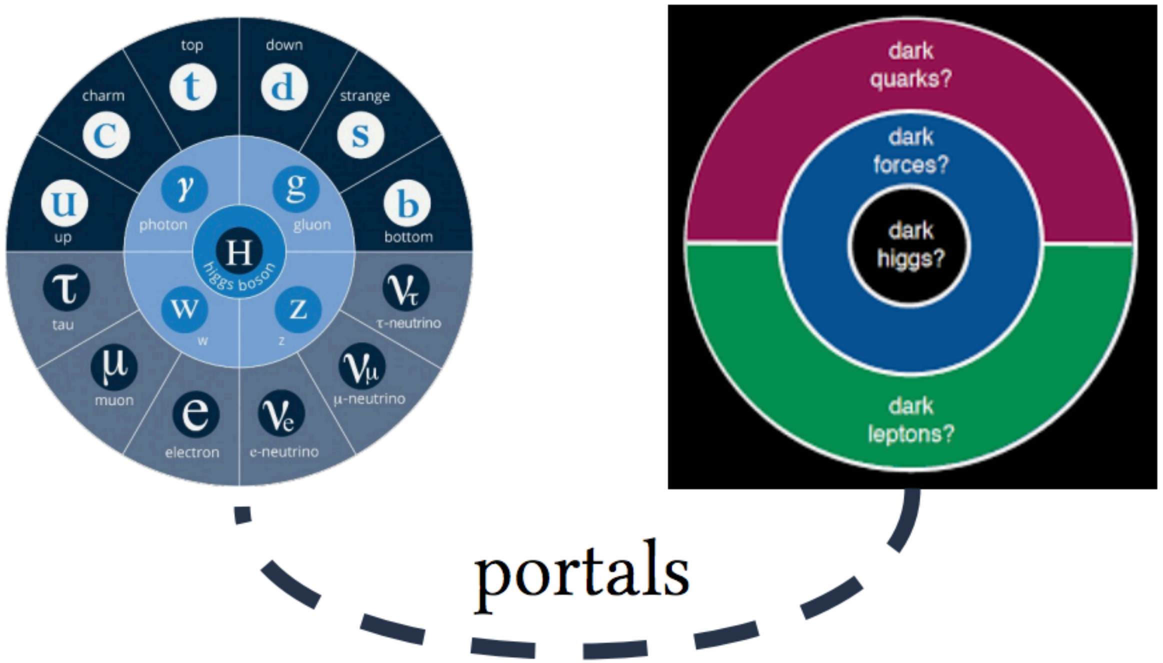
Auxiliary: (Axial-)Vector Mediator summary



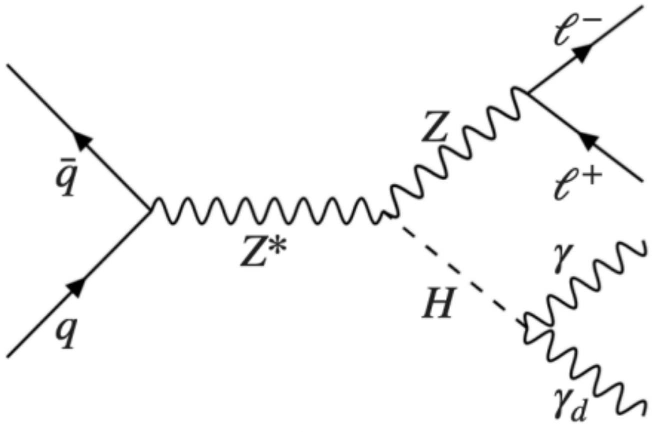


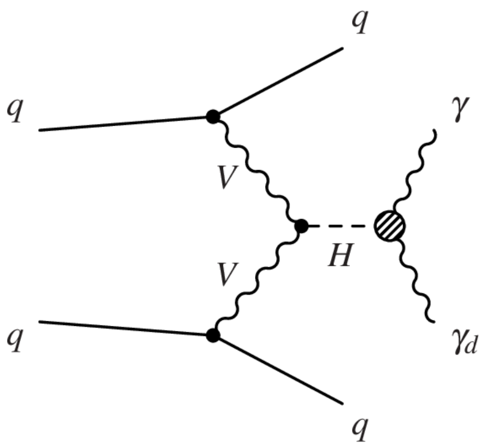
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2023-018/

Dark Higgs → more Dark Portals connecting hidden sectors



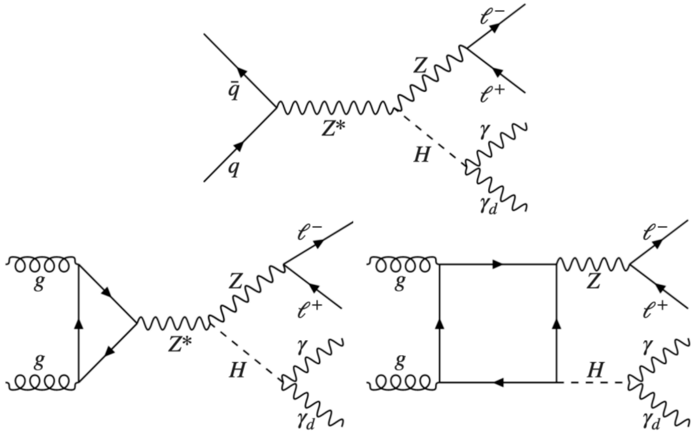
- Dark Photon BSM extensions:
  - U(1) extension of the SM
  - Hidden gauge boson A′ → kinetic mixing (ε) with the SM photon
  - the magnitude of ε affects production rate and lifetime





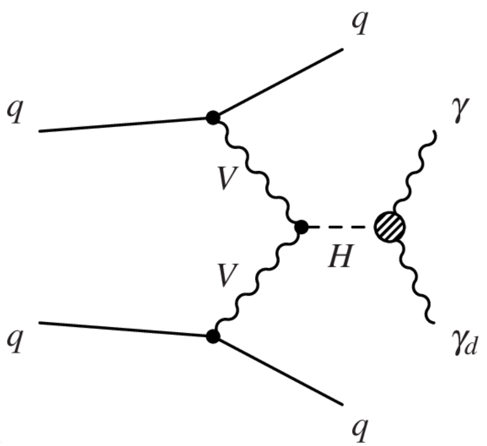
- Vector portal – dark photons
- Scalar portals - dark Higgs
- Neutrino portal
- Axion portal

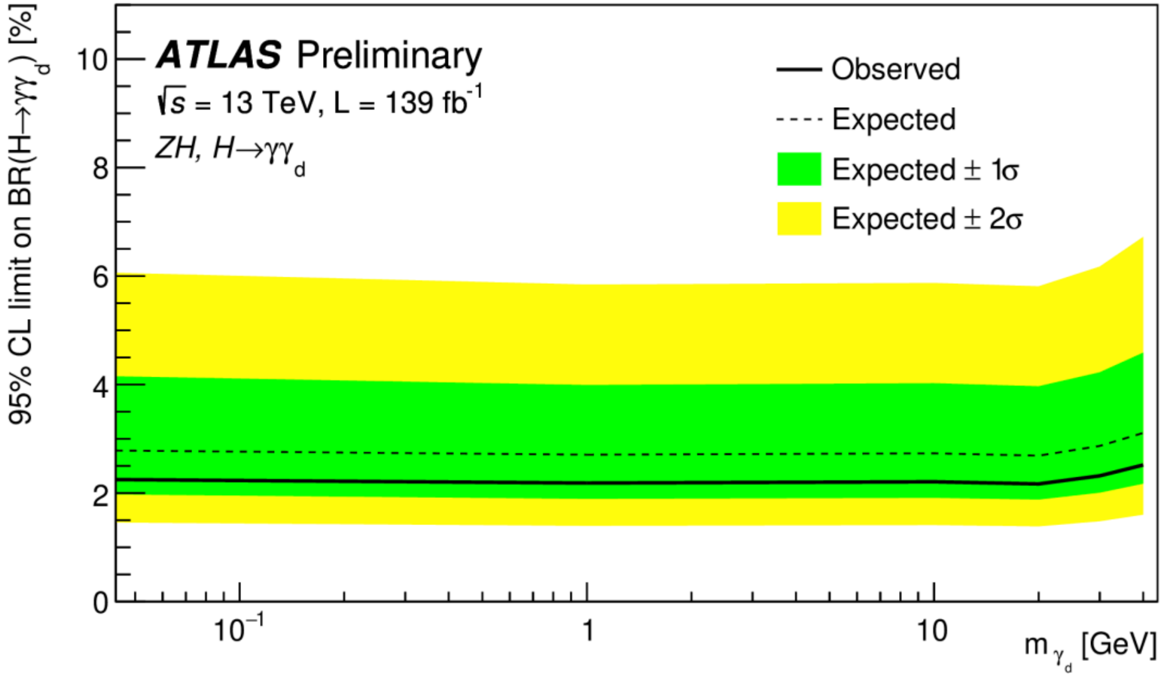
Dark Photon searches: ZH and VBF

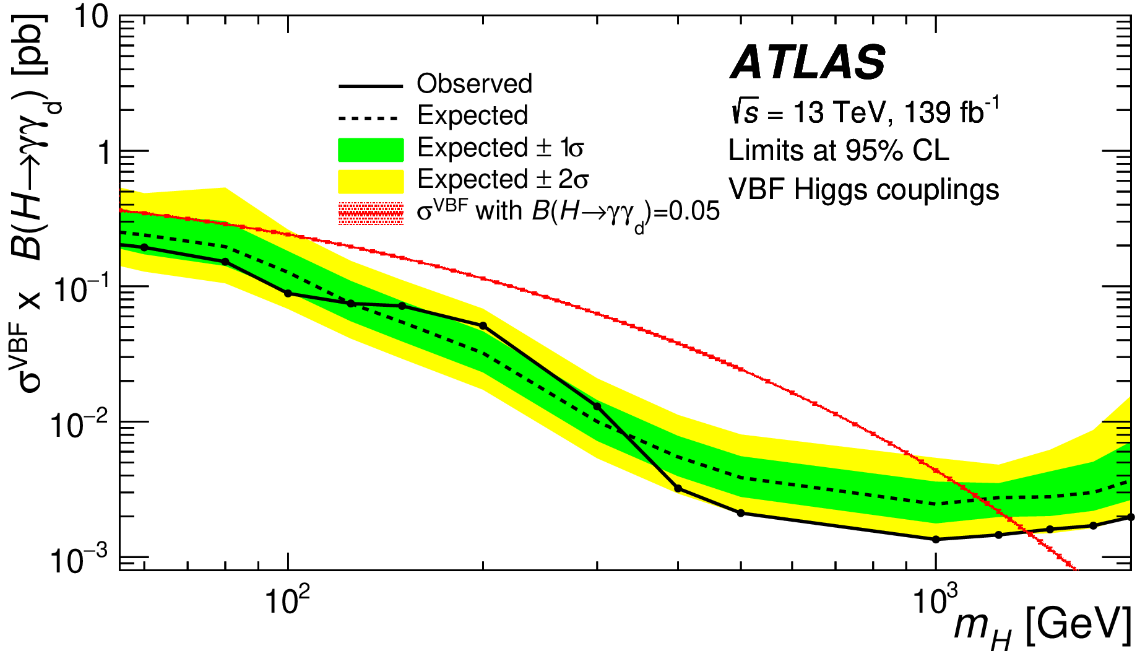


For massless γ_d

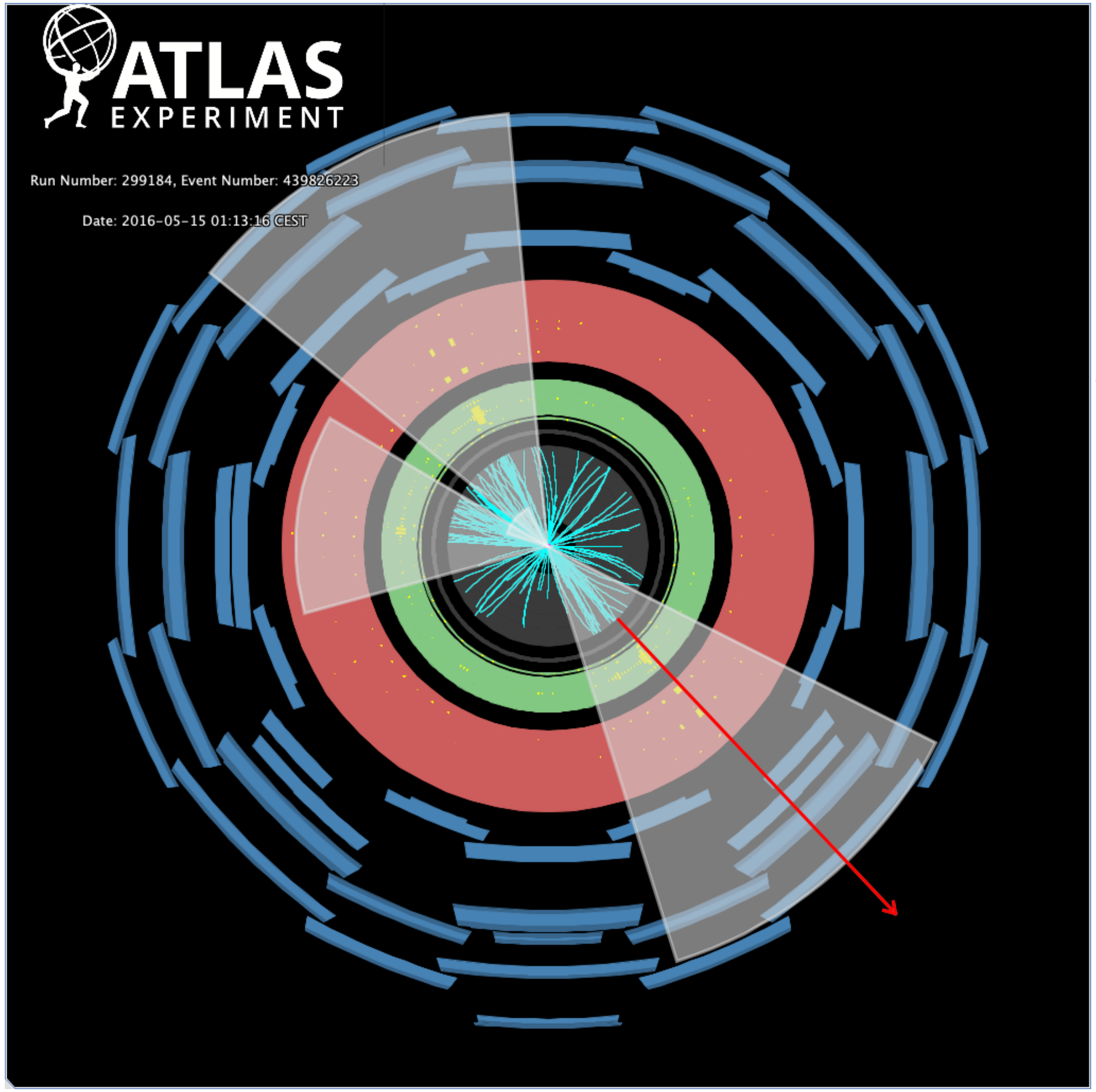
		Obs.	Exp.	
CMS	VBF	3.5%	2.8%	JHEP03(2021)011
CMS	ZH	4.6%	3.6%	JHEP10(2019)139
ATLAS	VBF	1.8%	1.7%	CERN-EP-2021-137
ATLAS	ZH	2.3%	2.8%	ATLAS-CONF-2022-064

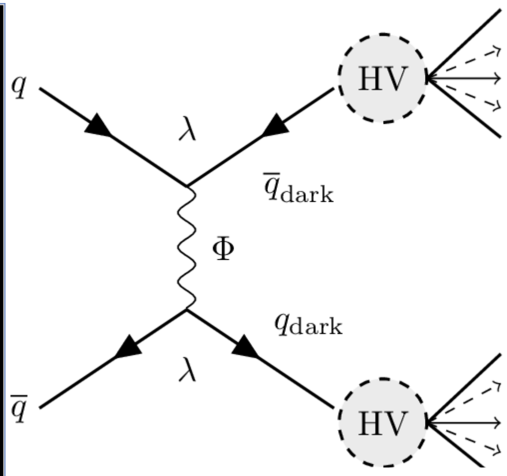




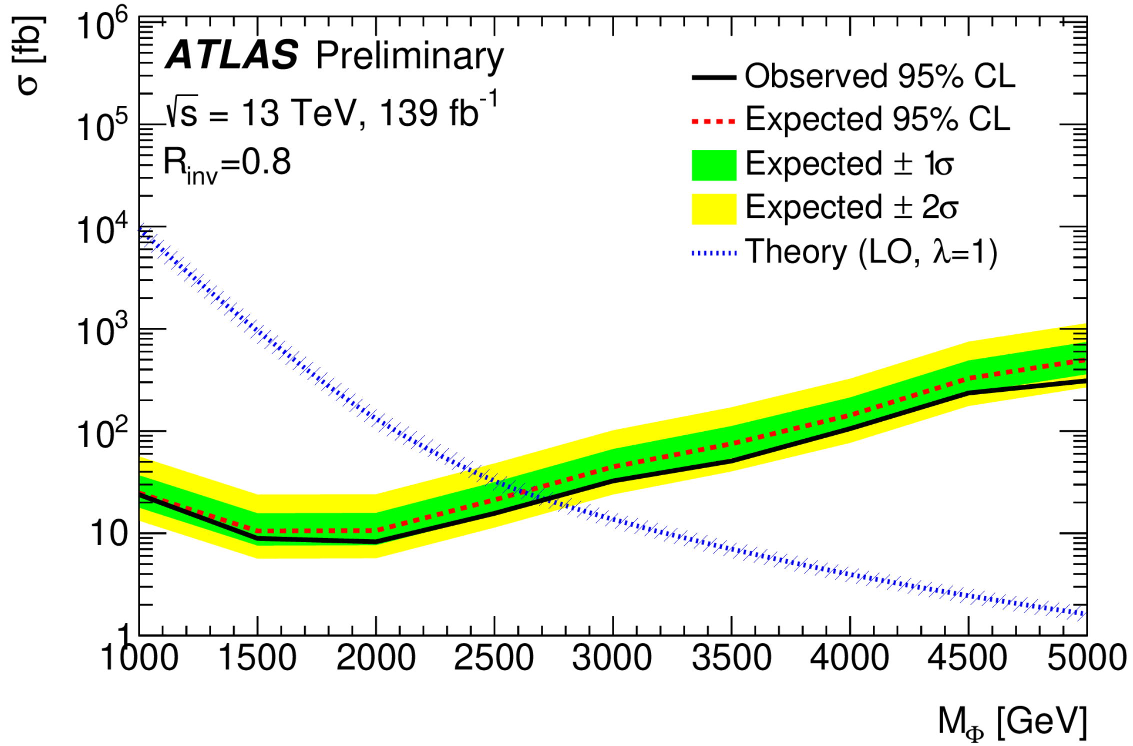


Unconventional searches with semi-visible jets





- Semi-visible jets arise in strongly-interacting dark sectors
- One of the jets is aligned with the missing transverse momentum direction: i.e. missing transverse momentum originates from the invisible components of the two semi-visible jets.



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Unconventional searches with semi-visible jets

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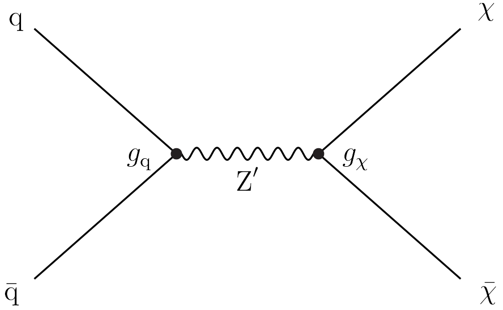
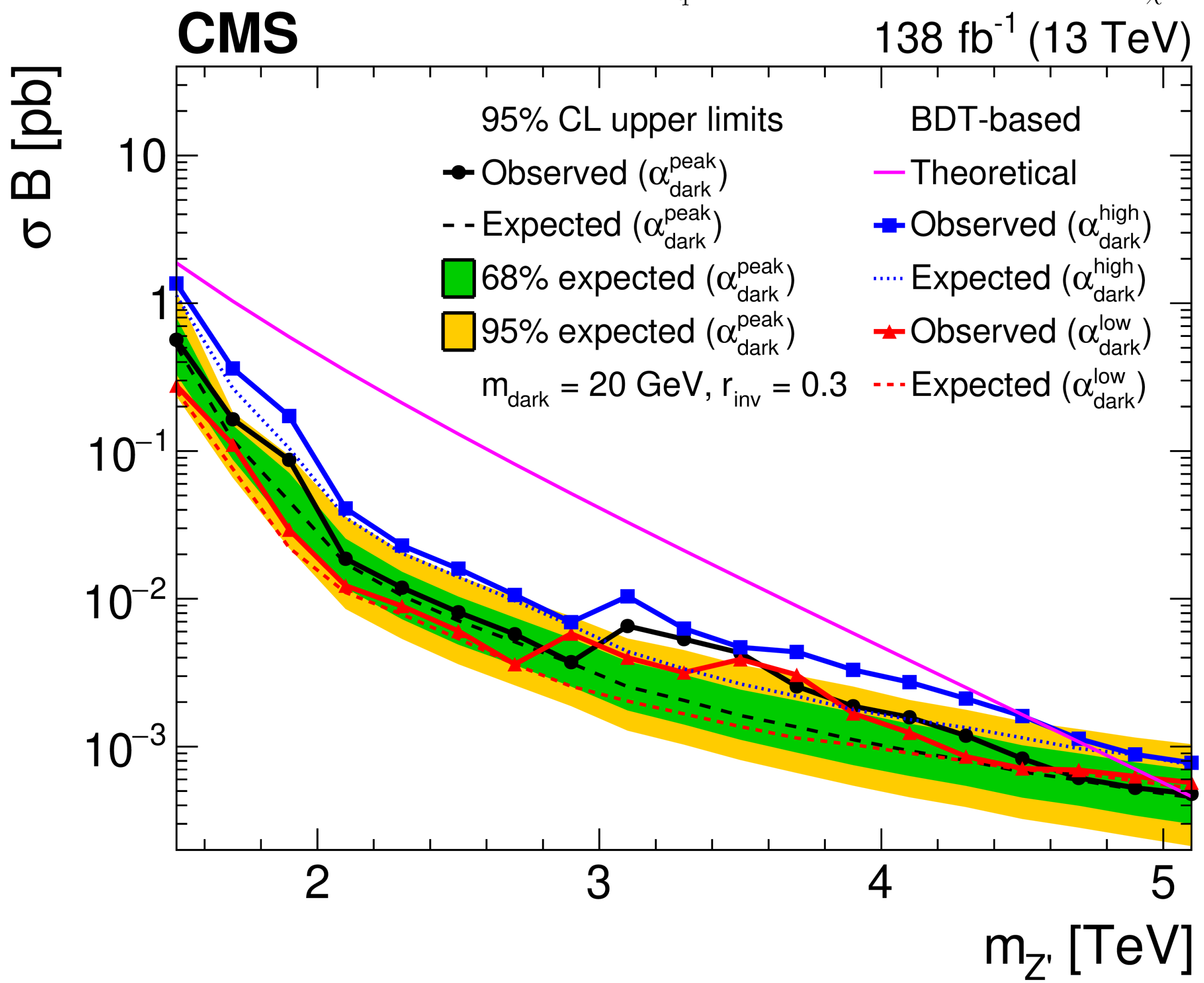
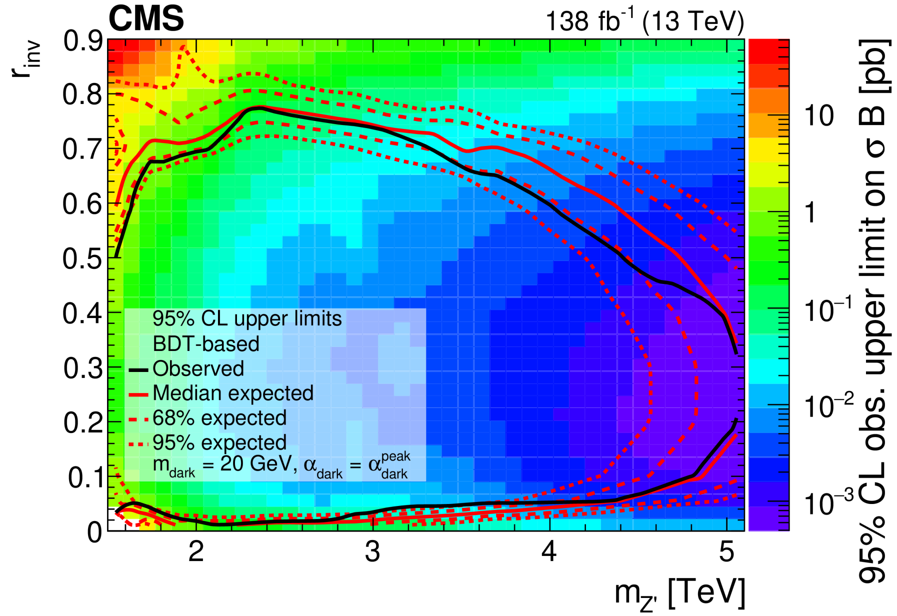
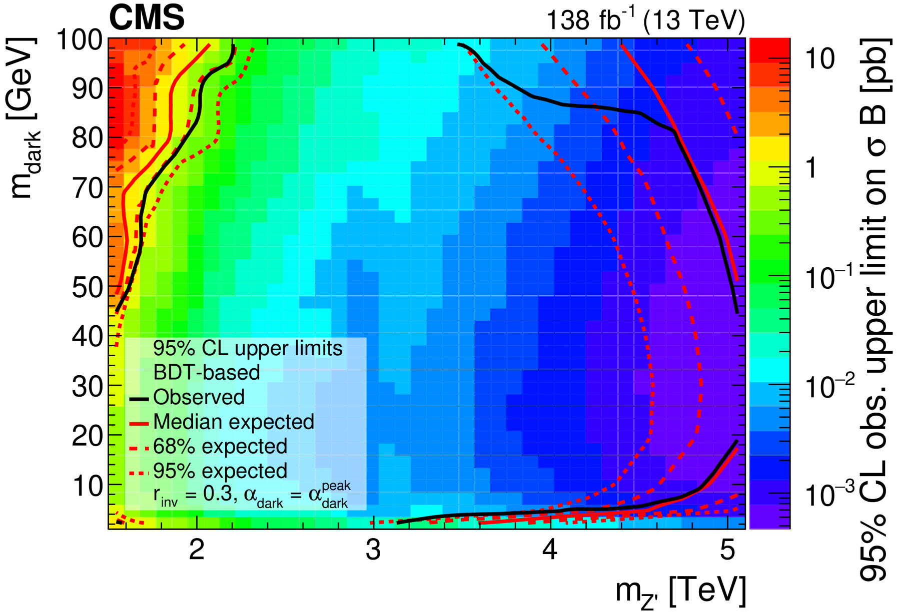
Search for s-channel resonant production of strongly coupled dark matter

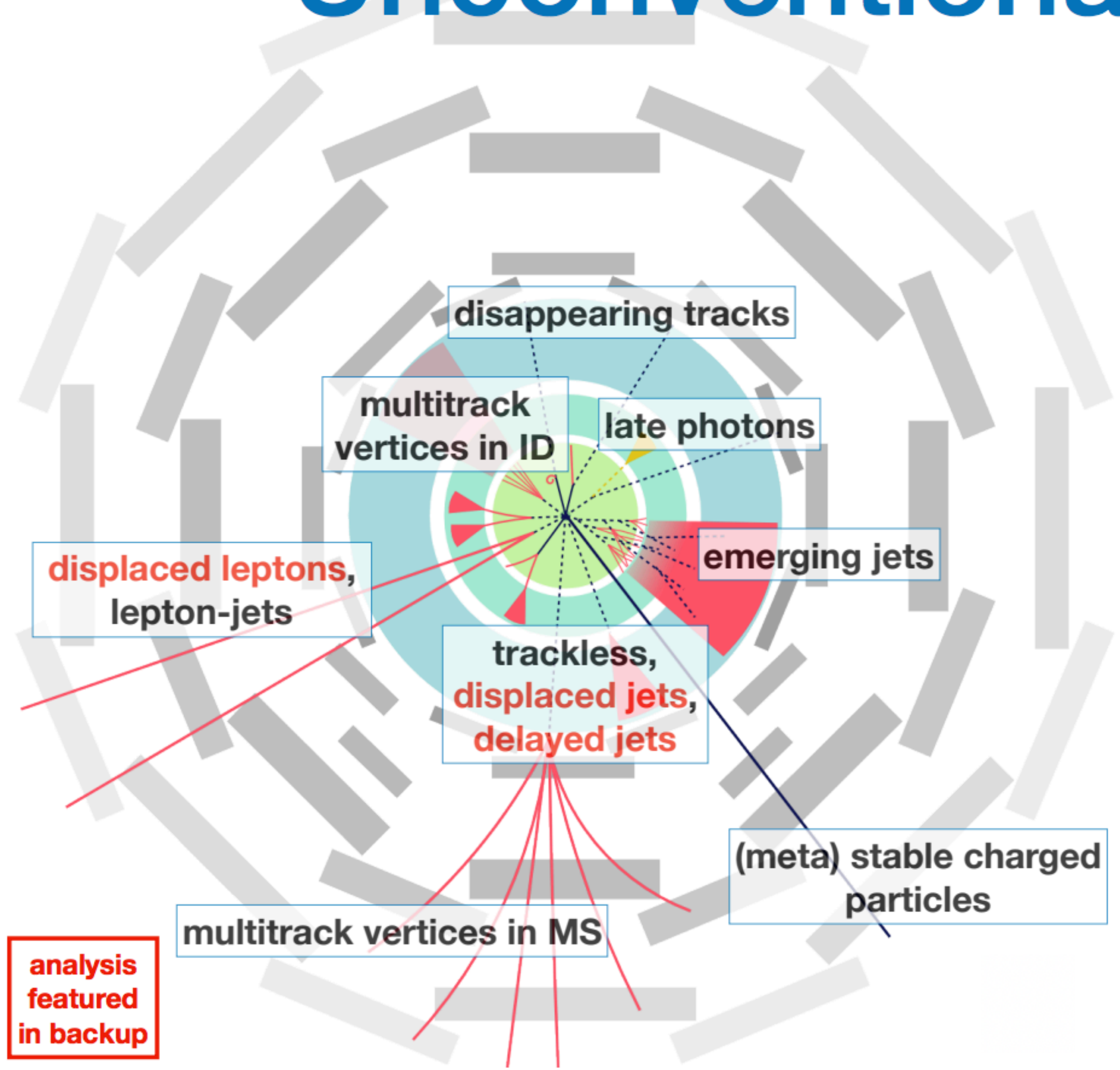




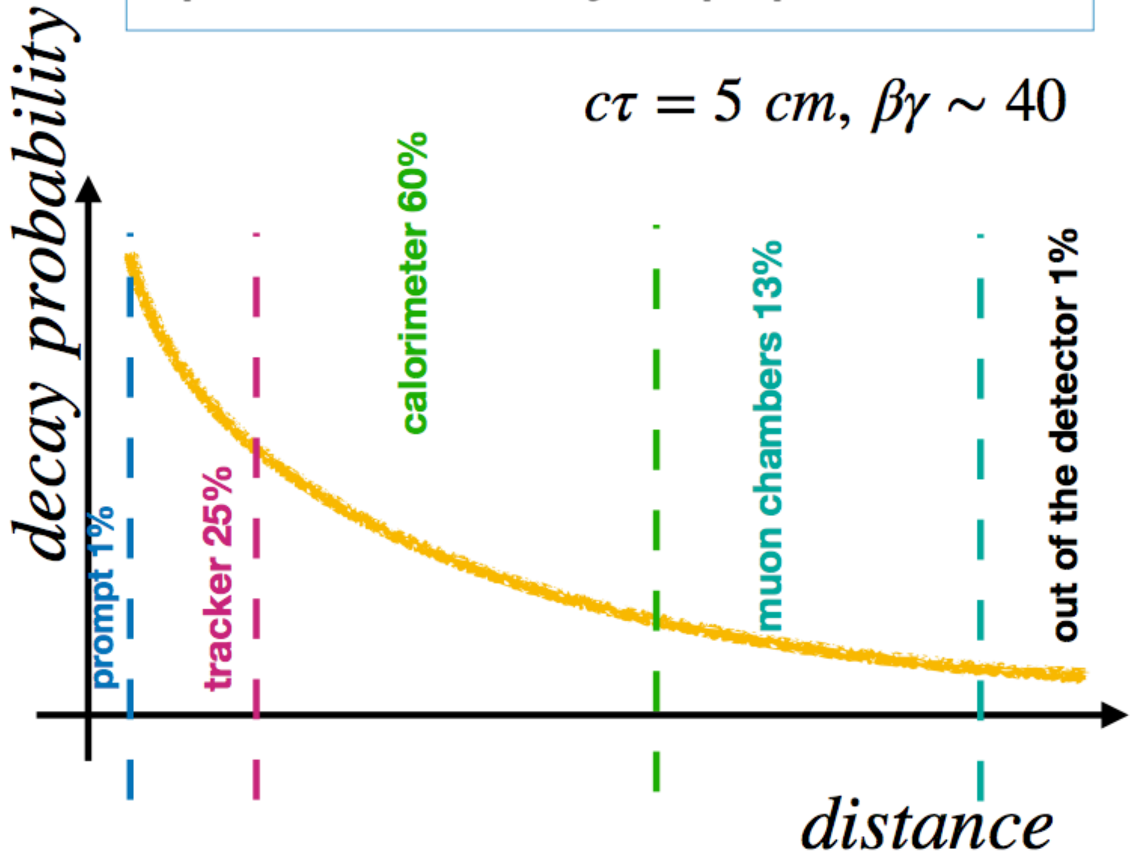




Unconventional signatures

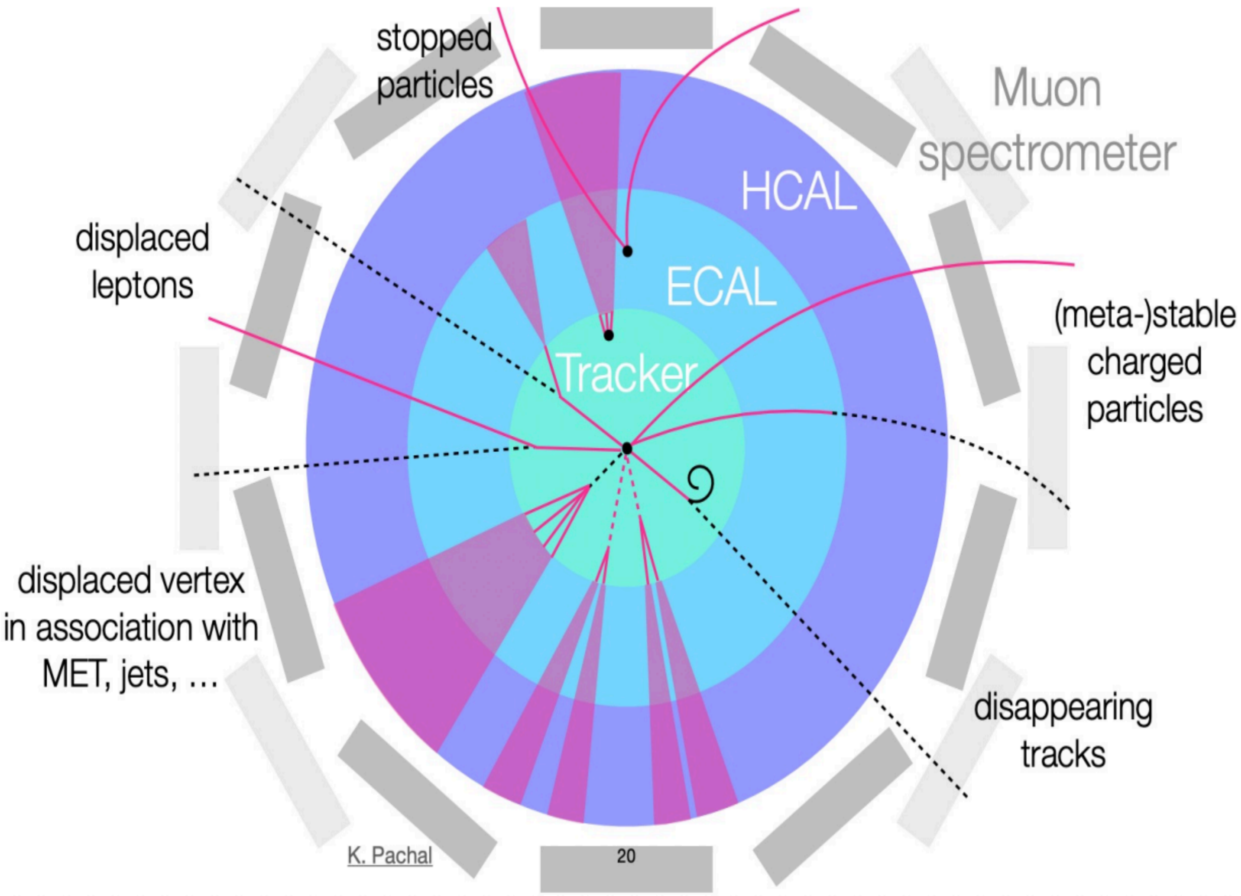


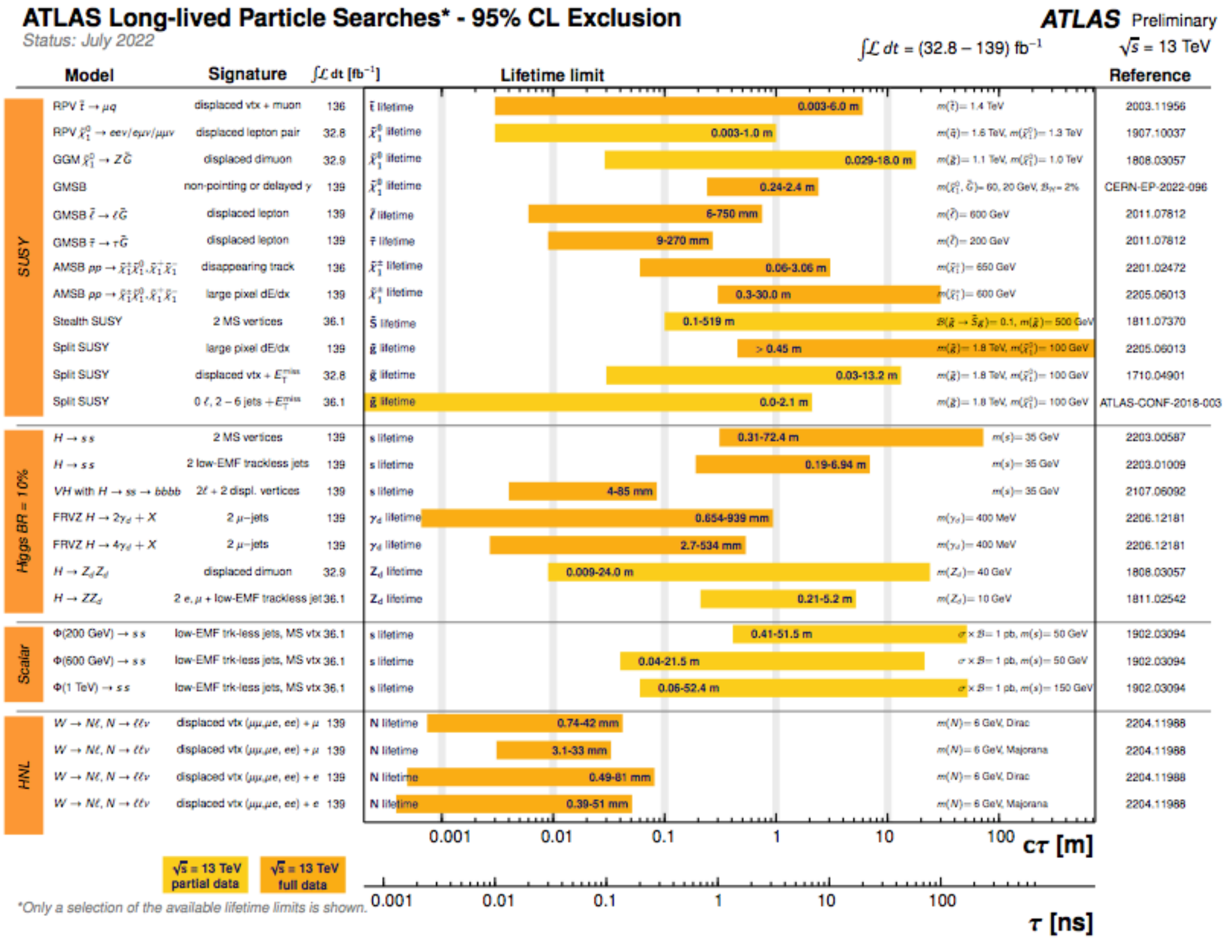
New particles can be long-lived: observed lifetime is governed by an exponential defined by the proper lifetime cτ



More unconventional searches

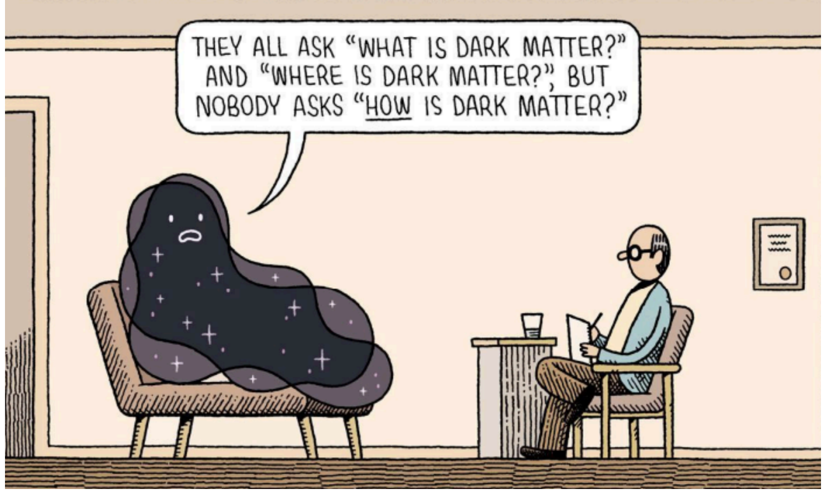
- LLP, displaced vertices, displaced leptons and jets, disappearing tracks, stopped particles
- Connecting more general untouched dark sector signatures, enlightening DM new prospects





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