



Illuminating the Dark

Dark matter searches at the LHC

中国物理学会高能物理分会
第十二届全国会员代表大会暨学术年会

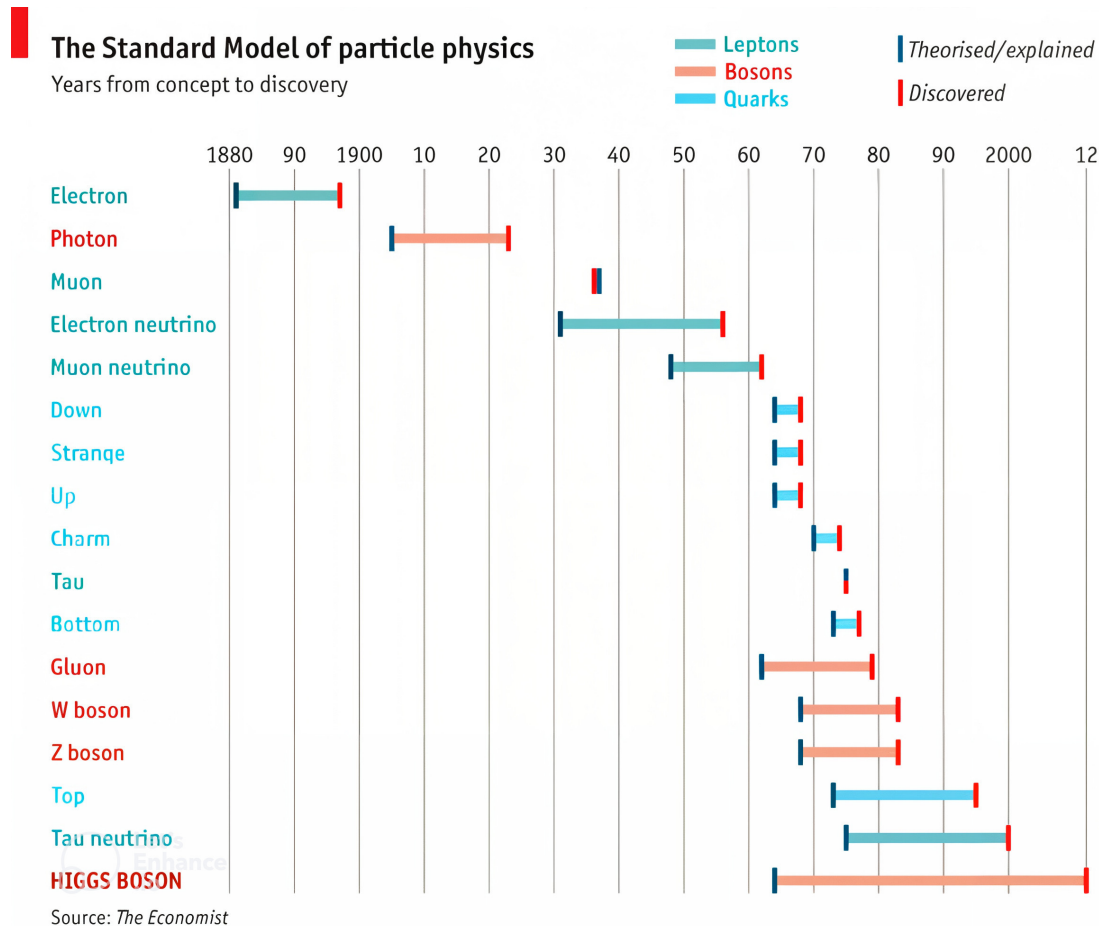
Zirui Wang

Guangzhou, China
2026-07-16



復旦大學
FUDAN UNIVERSITY

Theoretical and Experimental Particle Physics have revealed much about the nature of our universe



Economist

Higgs boson, with the existence predicted in 1964
 Discovered on July 4th, 2012, by **ATLAS** and **CMS** experiments on **LHC**

ALICE

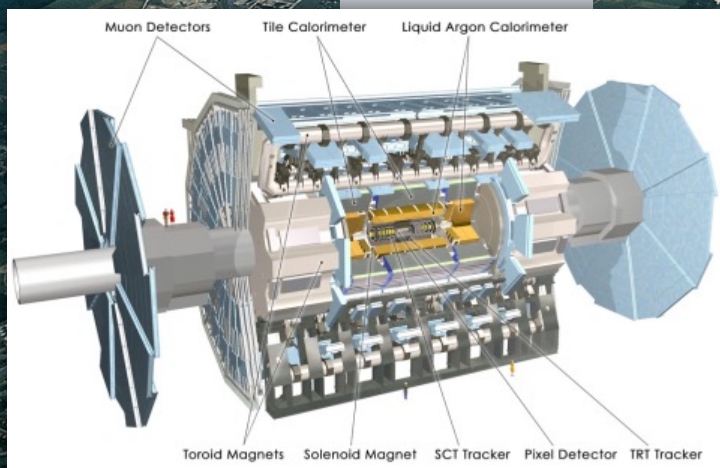
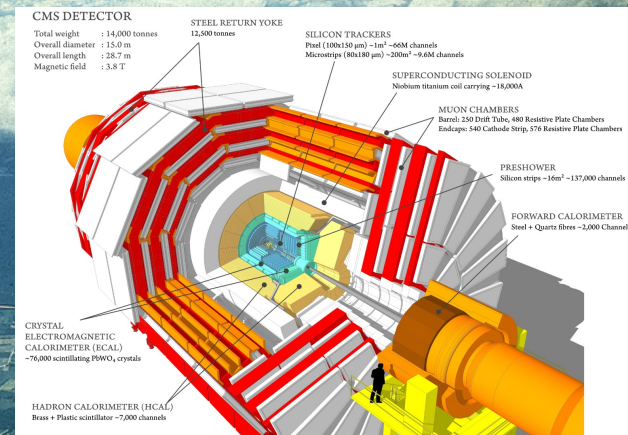
CERN

ATLAS

LHC: 27 km, the world's largest proton-proton collider (7-14 TeV)
 ~15% of planned total dataset collected so far.

CMS

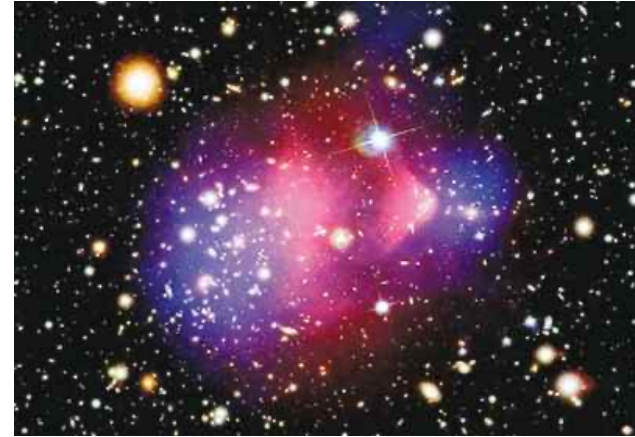
LHCb



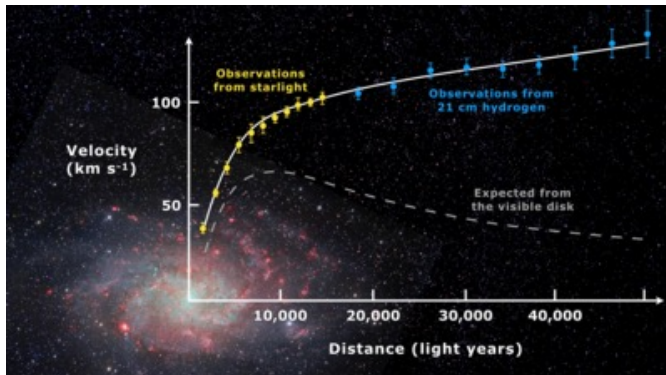
Gravitational Lensing



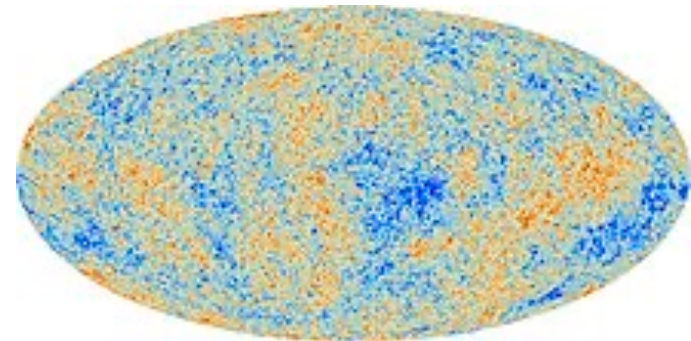
The Bullet Cluster



Rotation Curve



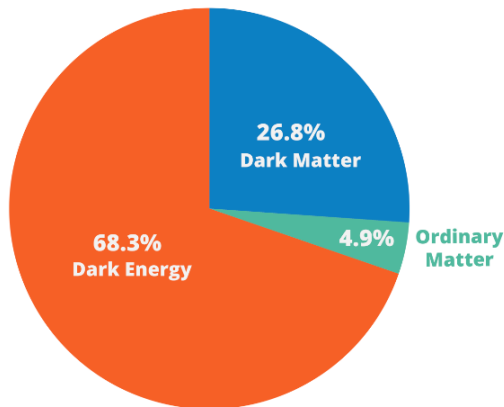
Cosmic Microwave Background



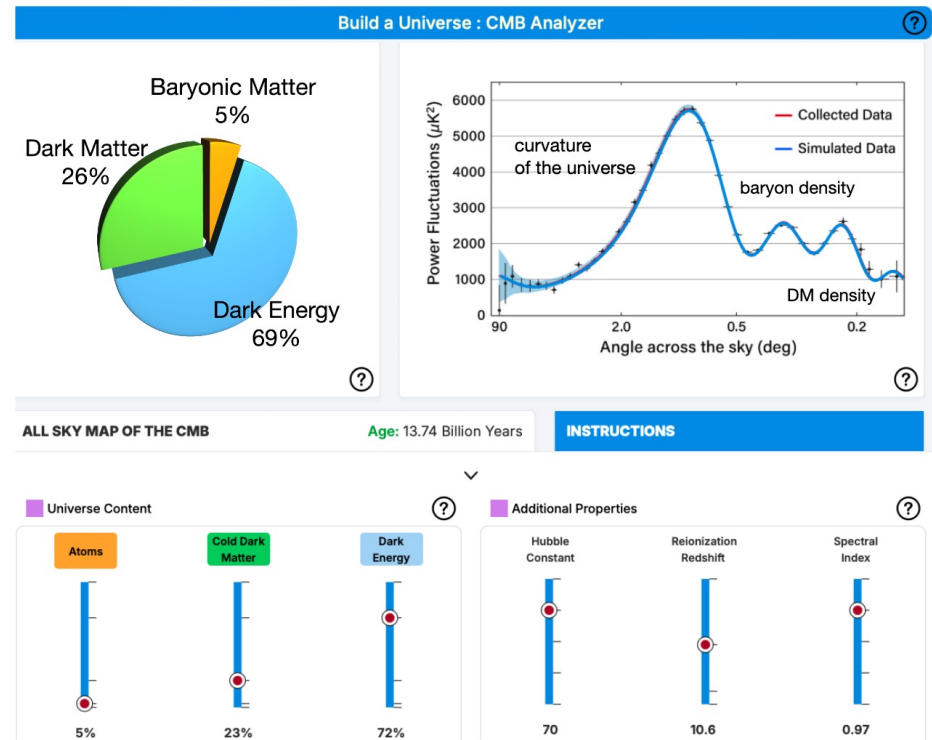
- **Empirical evidence of DM** from astrophysical observations at different scales, but only through gravitational effect.

- Astrophysical evidence for DM at every scale: rotation curves, lensing, CMB:
Most of the matter content in our universe is “transparent”.

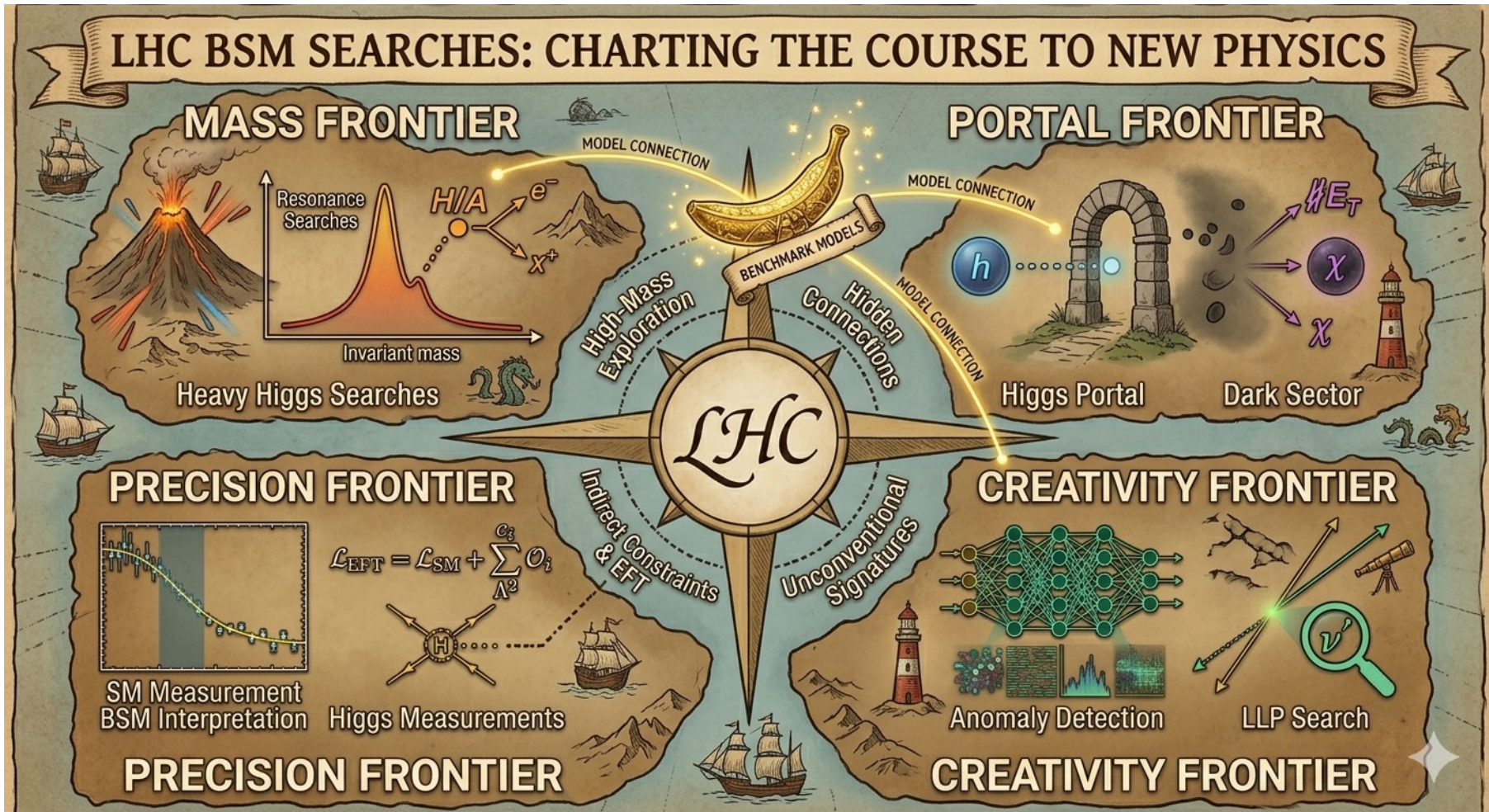
Estimated matter-energy content of the Universe



CMB game from NASA



Its relic density can be obtained by the CMB spectrum
DM's (particle) nature is unknown



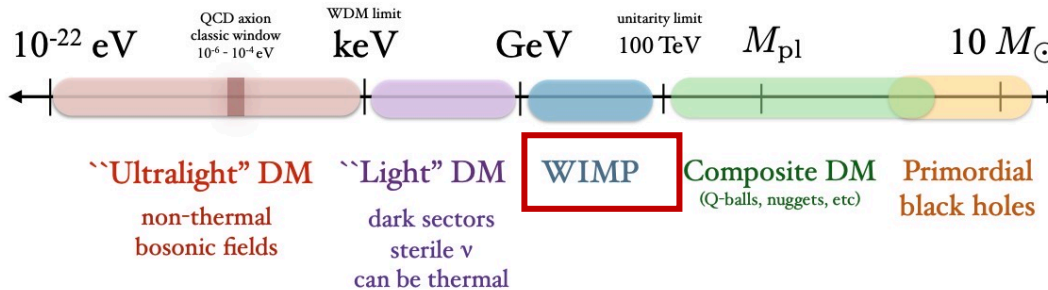
Benchmark DM models of different scenarios connect BSM search frontiers on LHC
(credit: Nano Banana)

The popular scenario: WIMP

Mass scale of dark matter

(not to scale)

[arXiv:1904.07915](https://arxiv.org/abs/1904.07915)

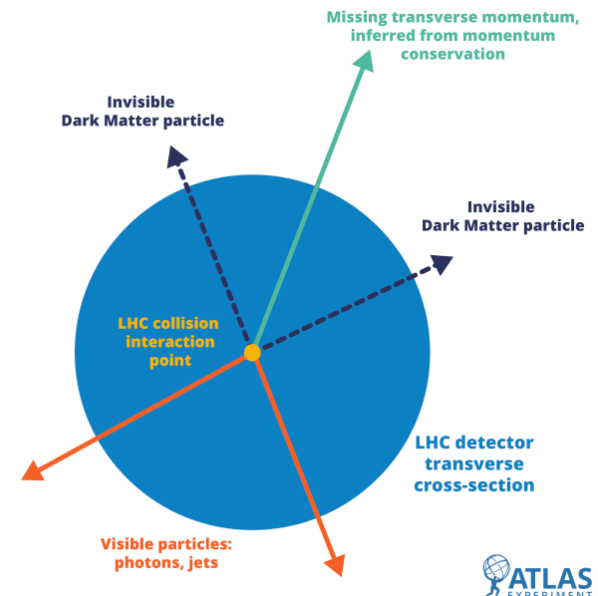
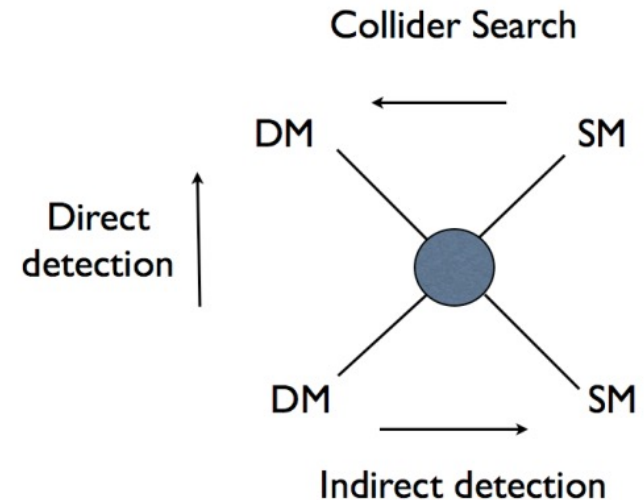


Candidate masses span 70+ orders of magnitude.

One most-popular scenario in the past 20 years:

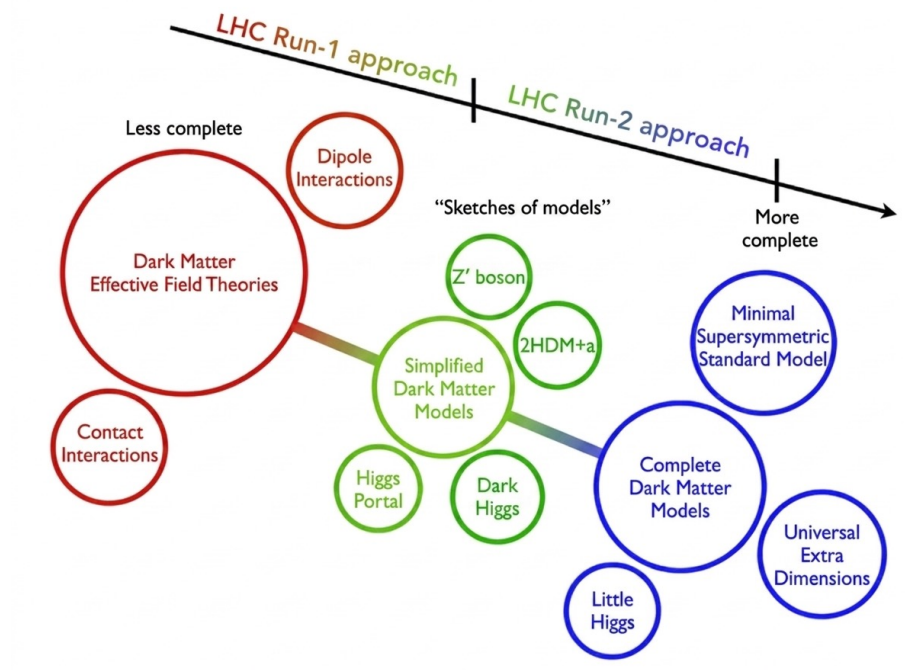
Assuming **DM-SM weak interaction**:

- **Direct detection:** LZ, PandaX, Xenon, ...
- **Indirect detection:** AMS, Fermi-LAT...
- **Colliders:** ATLAS, CMS ...
 - LHC could produce dark states directly.
 - Sensitive over **large kinematic range**
 - DM won't leave trace in the detector, but could create **MET**

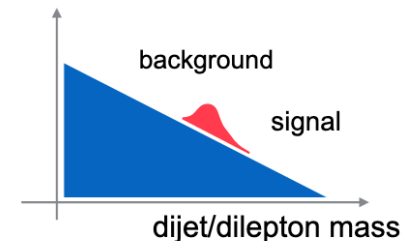
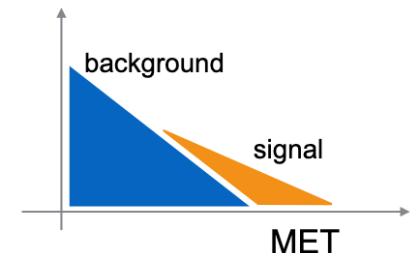


For WIMP searches, **theoretical benchmarks** are necessary to sharpen the regions of interest.

- **Optimize searches** and **characterize a possible discovery**
- Include **non-MET signatures** in DM searches
- Define a theoretical framework for **comparison with non-collider results**

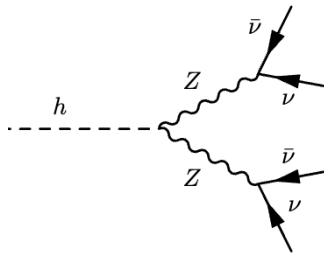


Revised figure from Tim Tait

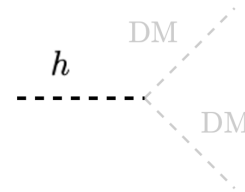


A unique gateway on LHC :

- H decays to a pair of stable WIMPs.



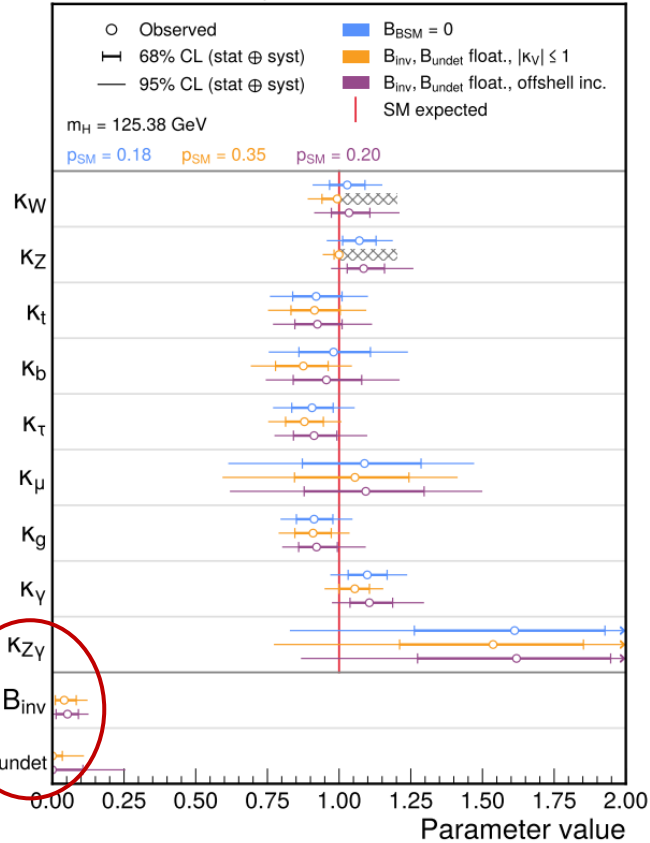
SM $\text{BR}(H \rightarrow \text{inv}) \sim 0.12\%$



DM will increase $\text{BR}(H \rightarrow \text{inv})$

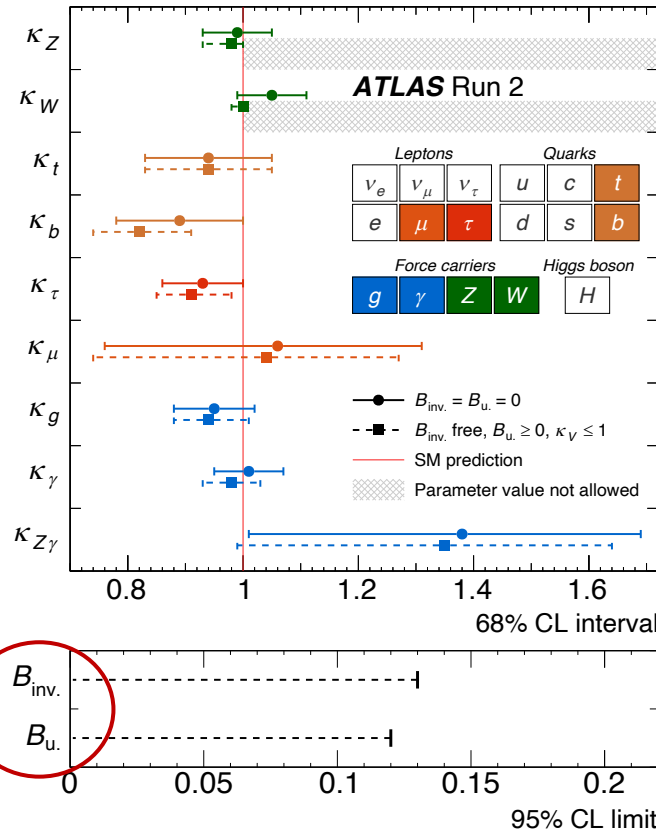
- **Large room left** (95% C.L. upper limit) for B_{inv}/B_u from the global fit.
- Important to explore exotic/invisible decays.

CMS Preliminary 138 fb⁻¹ (13 TeV)



CMS: $B_{\text{inv}} < 0.13$, $B_u < 0.25$

[CMS-PAS-HIG-21-018](#)



ATLAS: $B_{\text{inv}} < 0.13$, $B_u < 0.12$

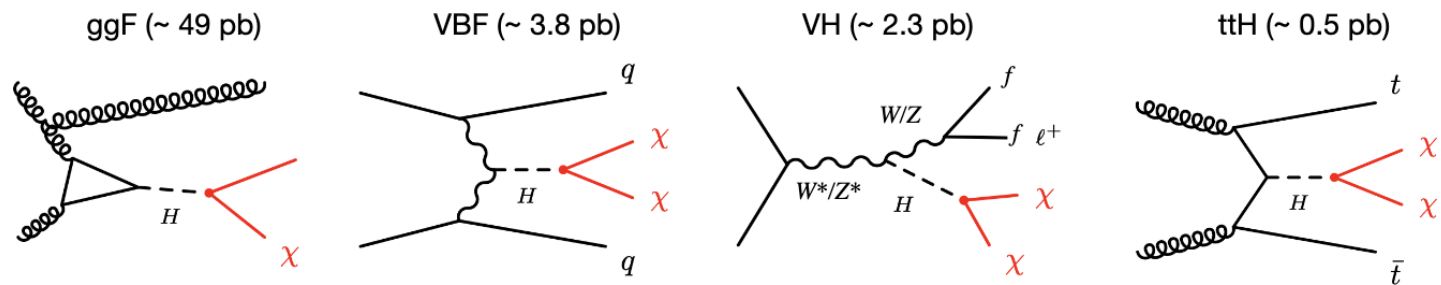
[Nature 607, 52–59 \(2022\)](#)



**HIGGS
INVISIBLE
DECAYS**



**HIGGS
EXOTIC
DECAYS**



Selection

high p_T ISR jet

2 forward jets
in opposite hemisphere

lepton or hadron decay
from W/Z

leptonic, semi-leptonic,
hadronic $t\bar{t}$

Final state

mono-jet

VBF + MET,
VBF + MET + γ

$Z(\ell\ell)$ + MET, mono-largeR jet

$t\bar{t}$ + MET

Sensitivity

Low

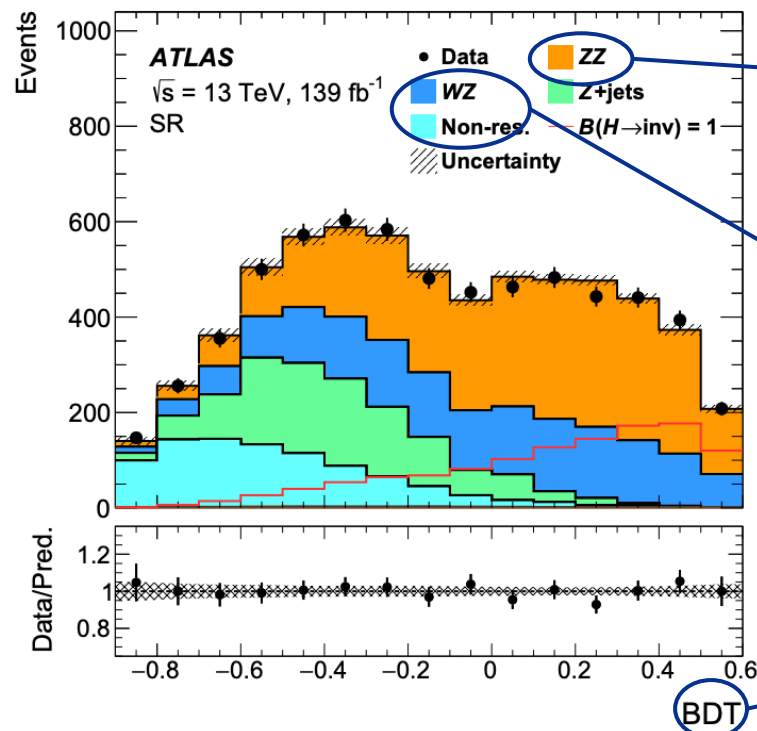
High

Intermediate

Intermediate

Hinv analyses have significantly optimized strategies at LHC, achieving **improvements beyond the increase in data size**.

For example, the ATLAS mono-Z [PLB, 2022, 829: 137066](#)



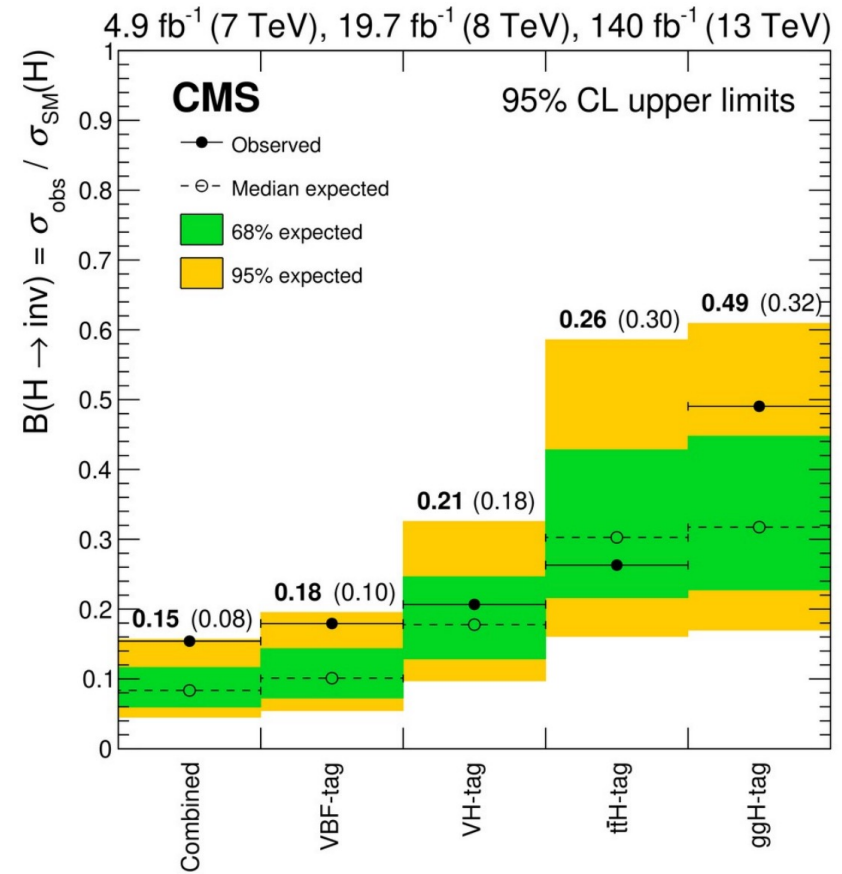
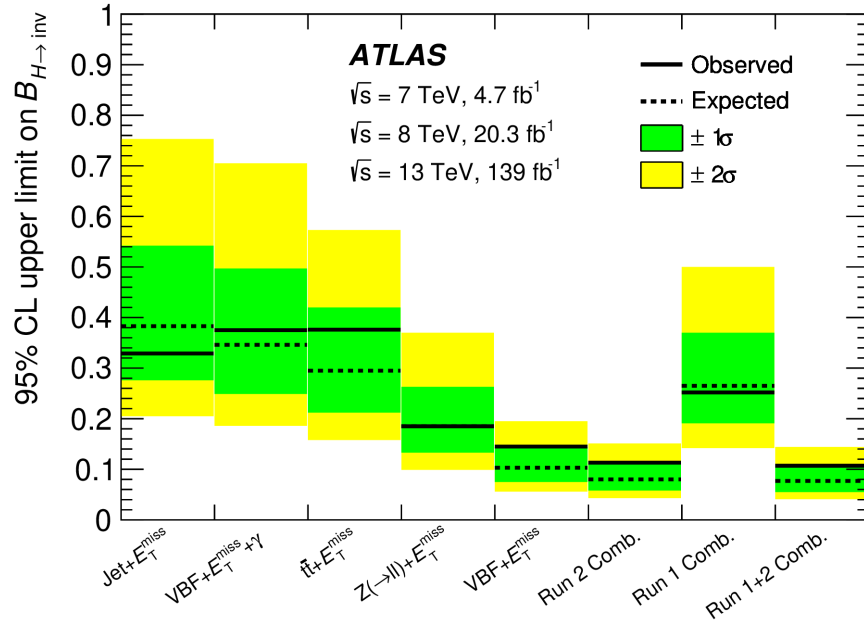
[PLB, 2022, 829: 137066](#)

Apply the latest theoretical calculation to correct the main backgrounds

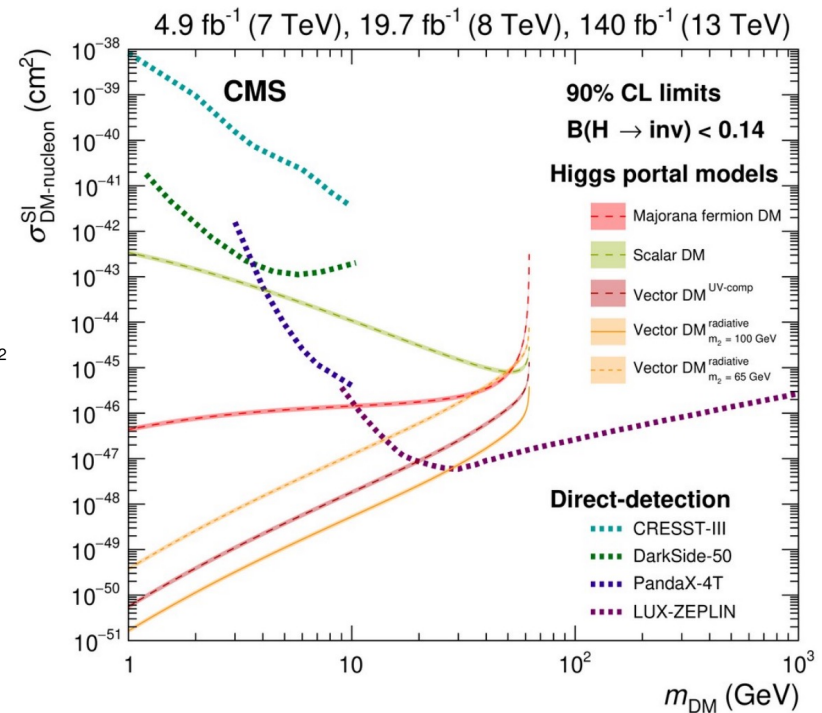
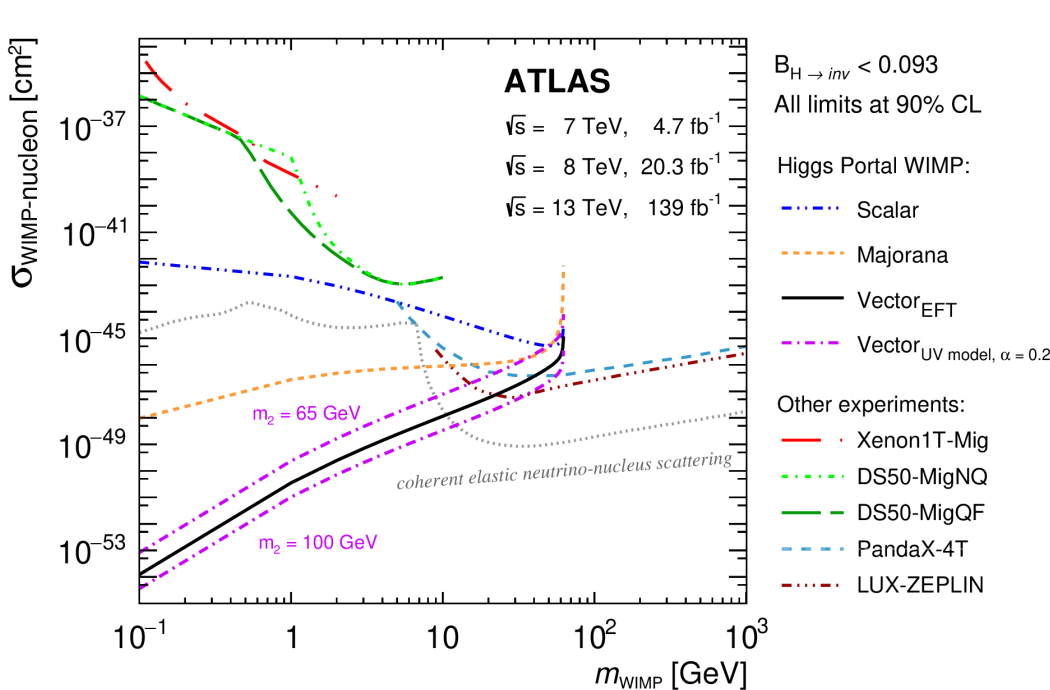
utilize data in control regions to reduce uncertainties

Use ML observables to distinguish between signal and background.

- $BR(H_{\text{inv}}) < 0.19$ @ 95% CL
- **Improvement of over 70%** compared to the previous result of 0.67.

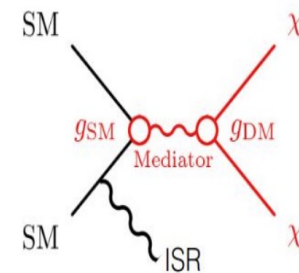


Further statistically combined All $H \rightarrow \text{inv}$ searches:
 ATLAS: $BR(H \rightarrow \text{inv}) < 10.7\% (7.7\%)$ [PLB 842 \(2023\) 137963](#)
 CMS: $BR(H \rightarrow \text{inv}) < 15\% (8\%)$ [EPJC 83 \(2023\) 933](#)

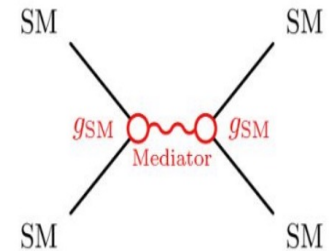


- **Significant complementarity** between LHC and direct detection experiments on DM-nucleon cross-section limits through the Higgs-portal model.

- Add a **s-channel spin-0** or **spin-1** mediator coupling to SM fermions and DM
 - Common ATLAS/CMS benchmark model since run 1 [[1507.00966](#)]

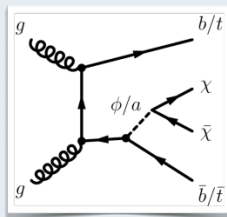
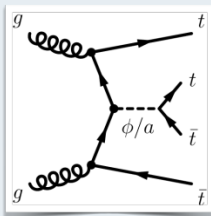
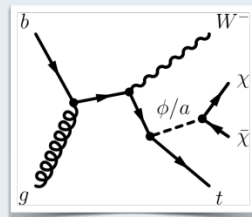
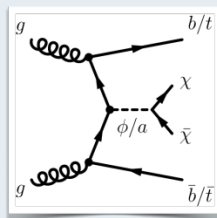
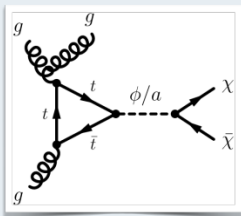


MonoX searches



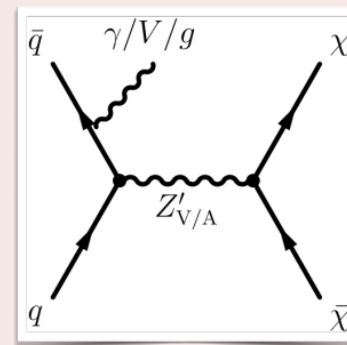
Resonance searches

Option 1: Spin-0 mediator Scalar/Pseudoscalar *Yukawa-like couplings*

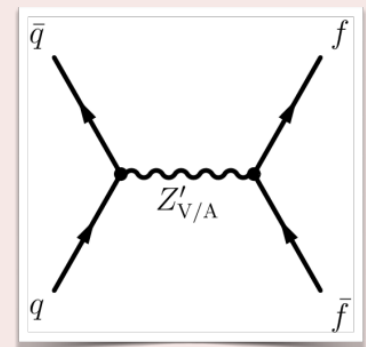


Free parameters: $g=g_u=g_d=g_l$, g_{DM} , m_{Med} , m_{DM}

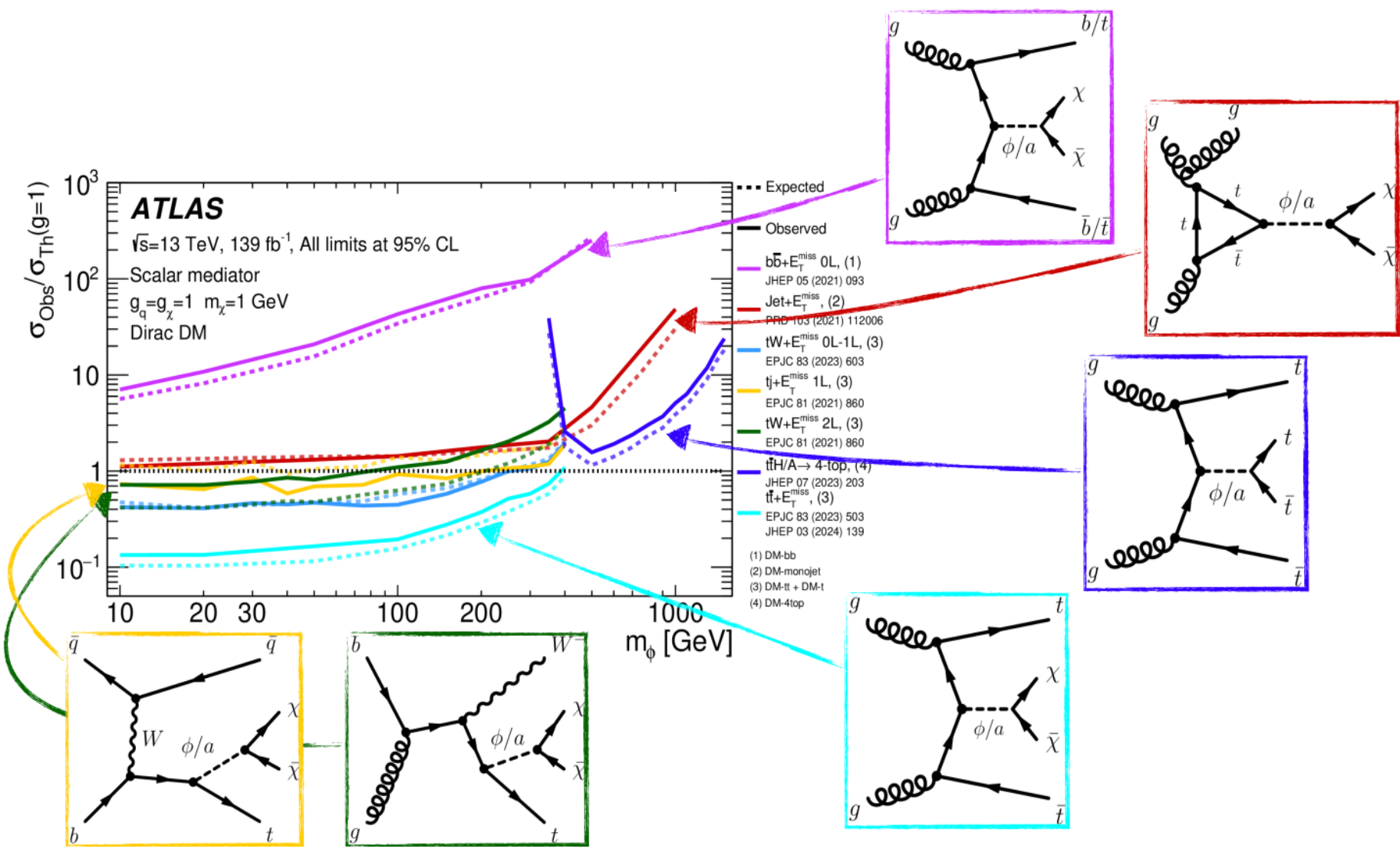
Option 2: Spin-1 mediator Vector/Axial-Vector *γ^μ/γ^5 couplings*

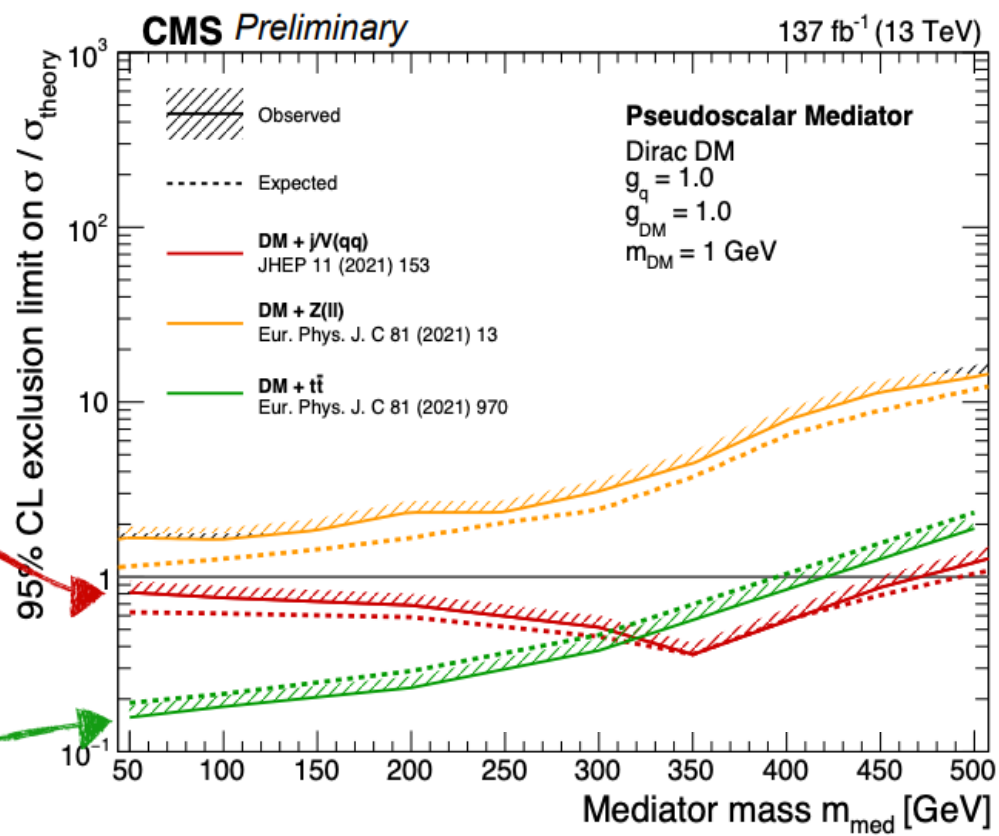
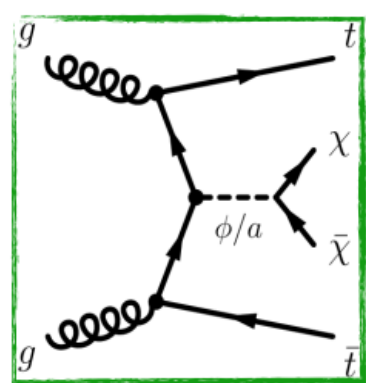
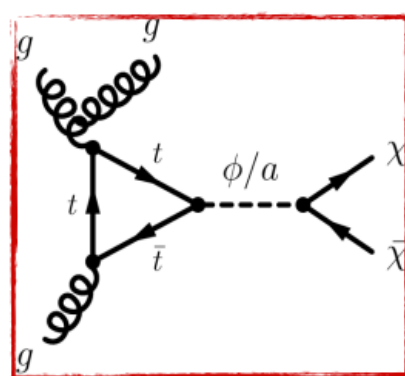


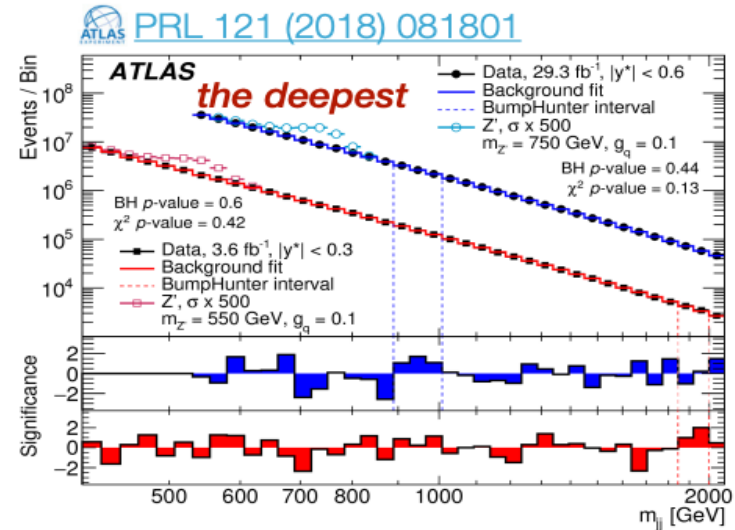
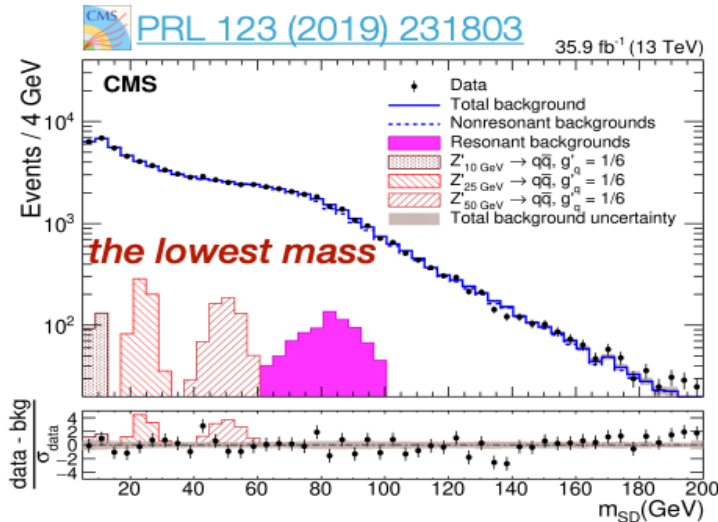
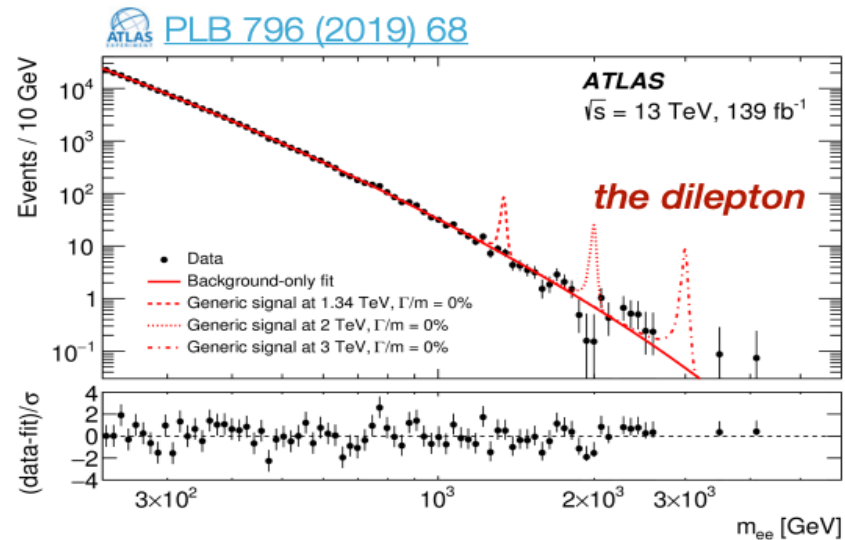
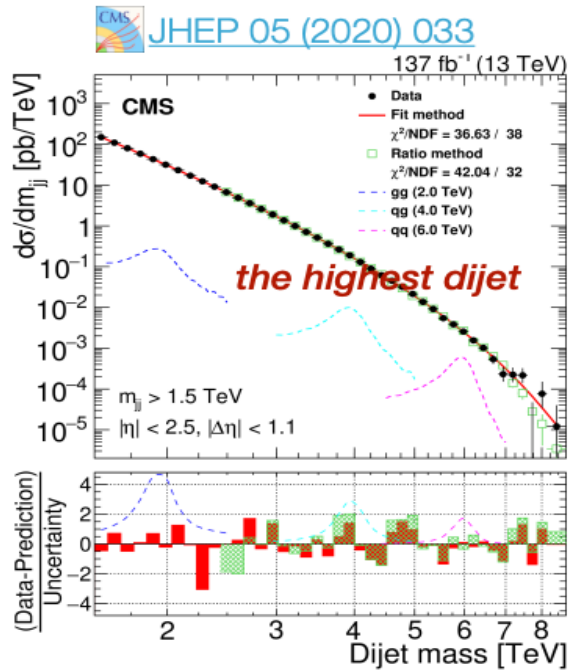
$$\mathcal{L} \simeq \mathcal{L}_{SM} + \sum_{i=part.} g_{p_i} M_\mu \bar{p}_i \gamma^{\mu/5} p_i$$

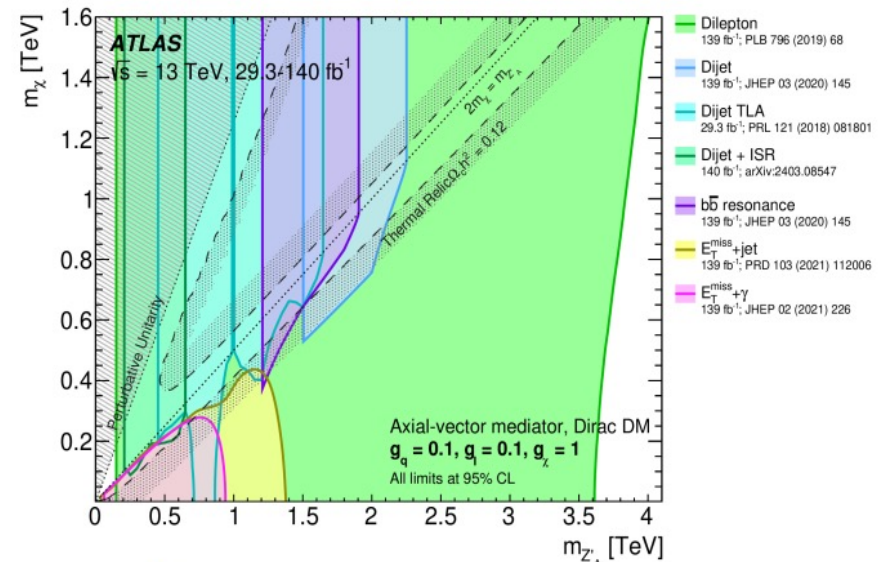
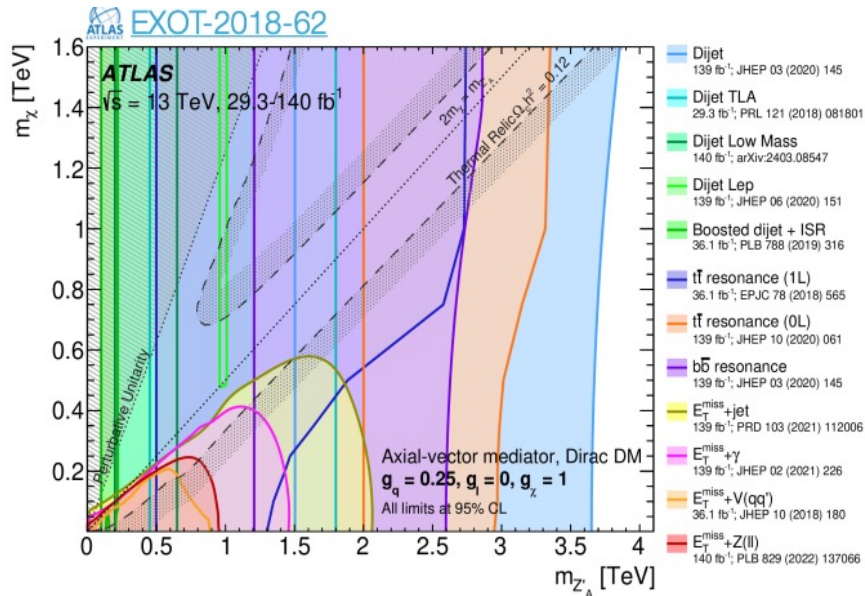


Free parameters: g_q , g_l , g_{DM} , m_{Med} , m_{DM}



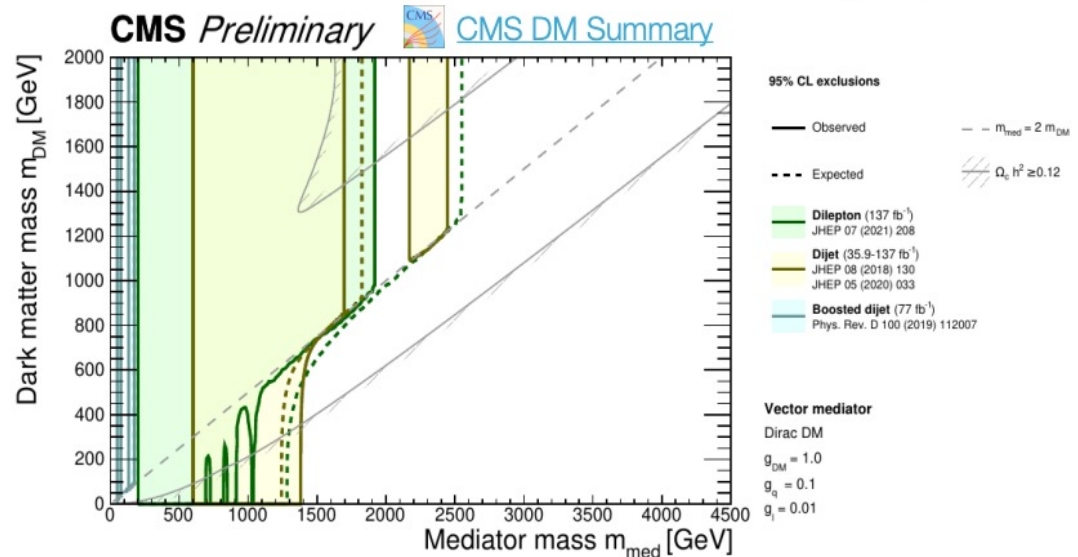






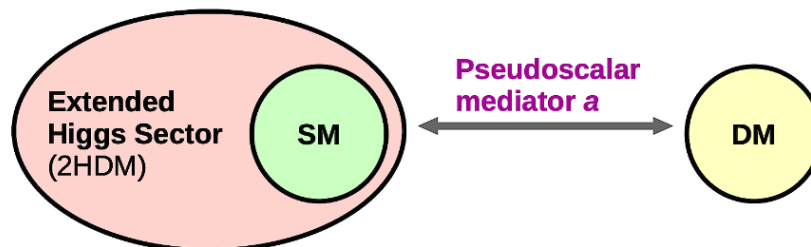
during the LHC Run 2 a large range of the m_χ - m_{Med} plane has been explored

things are changing, as soon as you change the coupling parameters



Two Higgs doublet model + pseudo-scalar

The simplest gauge-invariant and renormalisable extension of a simplified pseudoscalar model of DM.



6 new particles

- ▶ Neutral Higgs bosons: A, H
- ▶ Charged Higgs bosons: H^+, H^-
- ▶ Pseudoscalar mediator: a
- ▶ Dark matter: χ

5 free parameters (+ assumptions)

- ▶ $m_A = m_H = m_{H^+, H^-}$: heavy Higgs mass
- ▶ m_a : mediator mass
- ▶ m_χ : DM mass
- ▶ $\tan\beta$: ratio of VEVs of the two Higgs fields
- ▶ $\sin\theta$: mixing angle of the pseudoscalars

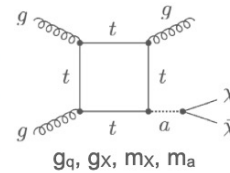
Rich phenomenology and great *signature interplay*

Re-interpretations

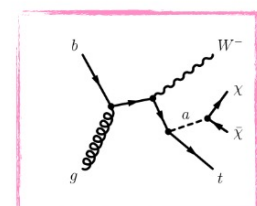
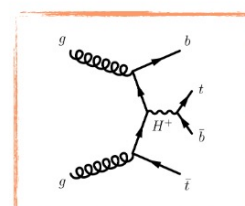
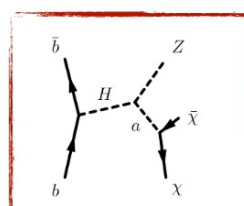
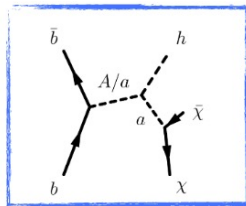
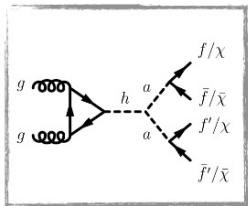
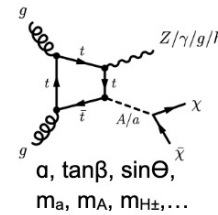
simplified model



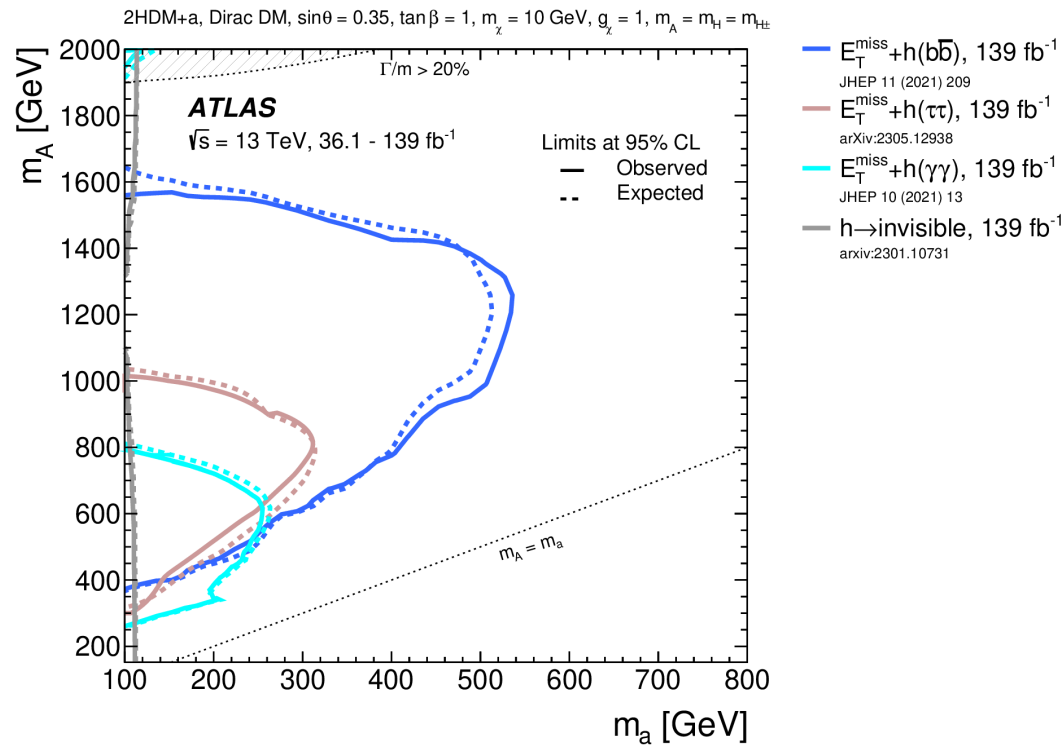
2HDM+a model



Dedicated searches

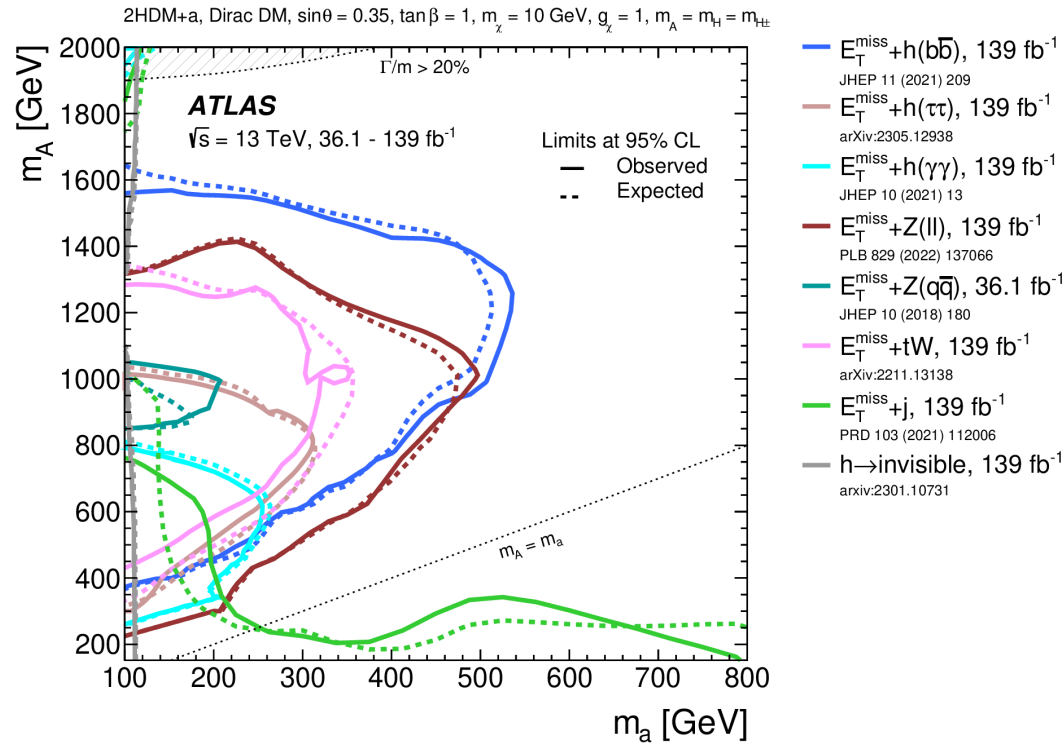


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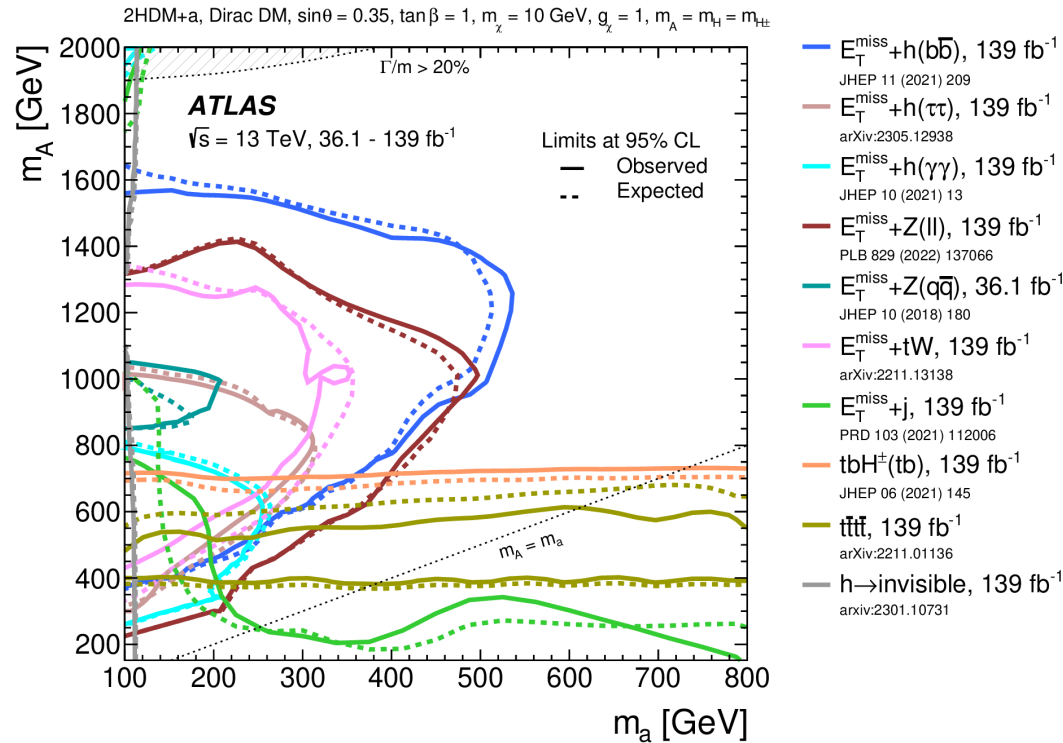
Higgs + DM signatures

DM appears in the final state together with Higgs



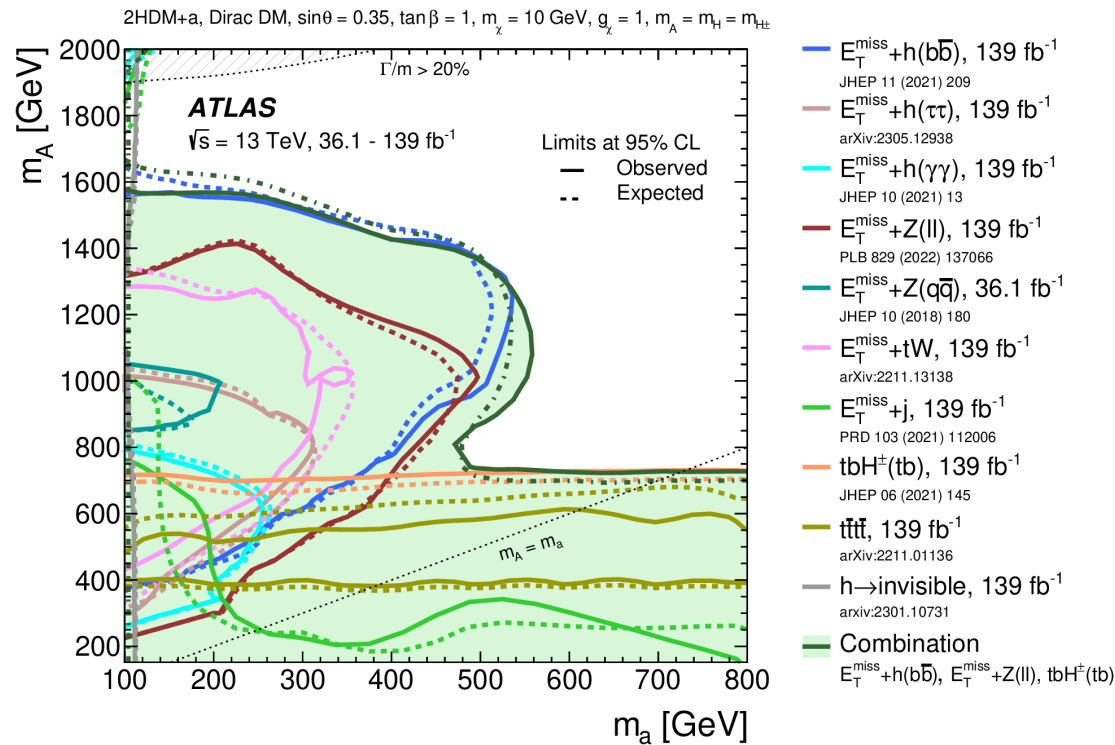
Add X + DM signatures, sensitivities largely improved at lower m_A

DM appears in the final state together with other SM particles



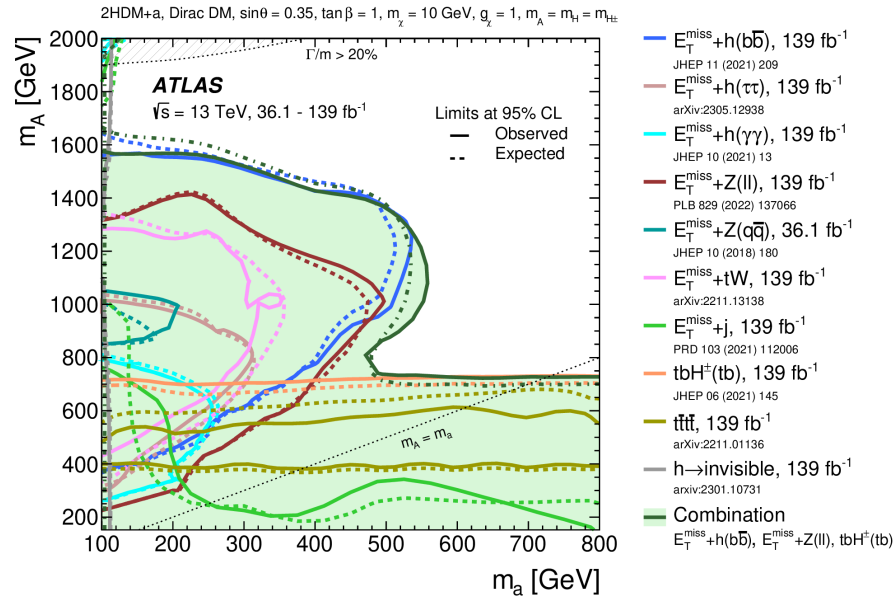
Add exotic Higgs boson signatures, complementarity obtained from resonant signatures.

DM doesn't need to appear in the final state

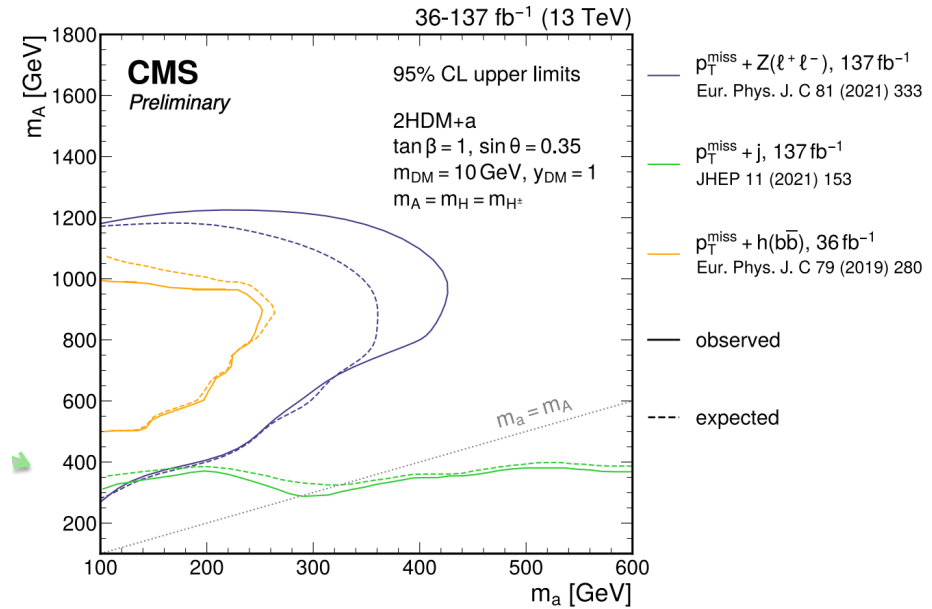


Combine analyses – reaching the best sensitivity!

Having three most sensitive channels combined

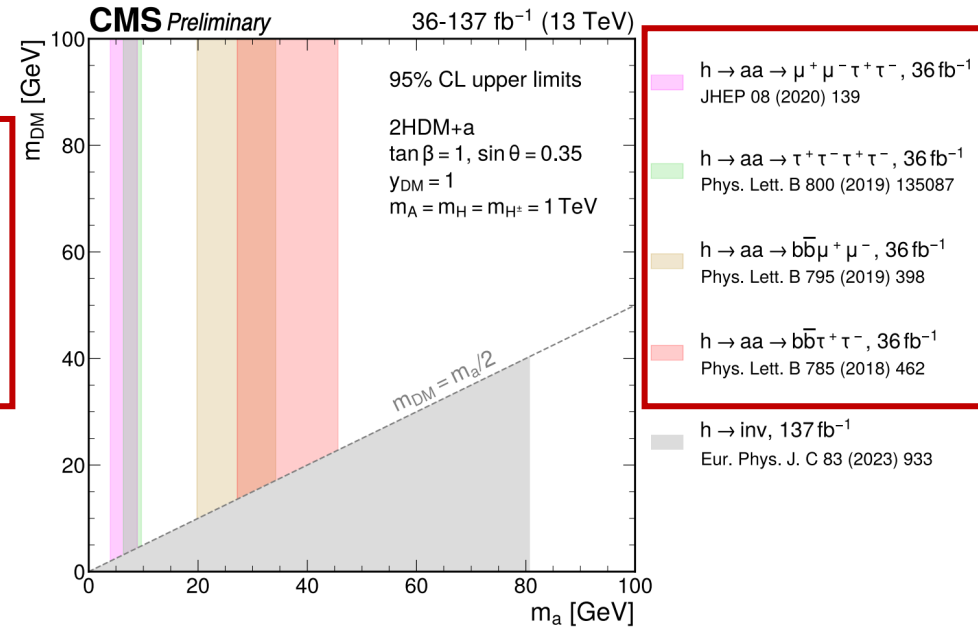
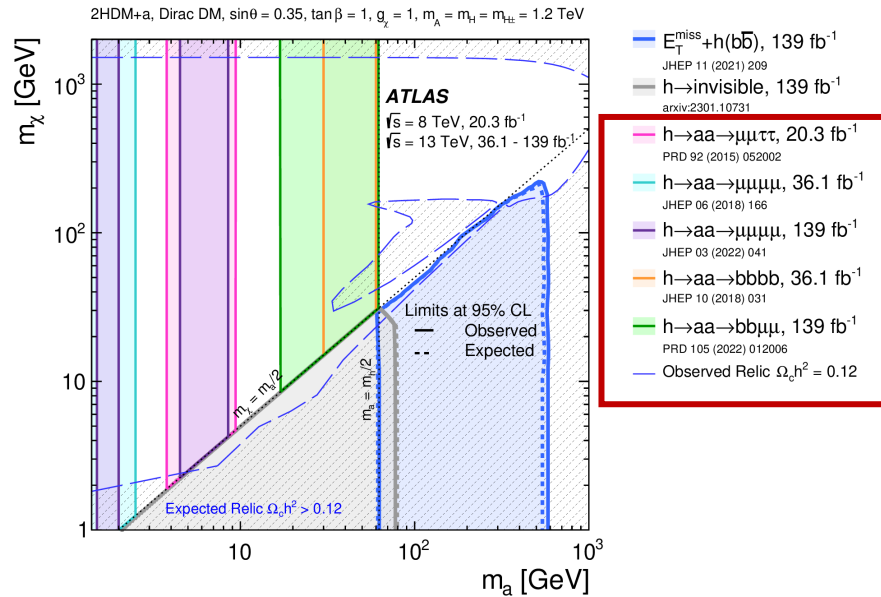


[Science Bulletin 69 \(2024\) 3005](#)



[CMS DM summary plot](#)

- $H \rightarrow aa \rightarrow 4f$ provides a **powerful** and **complementary** probe to **wider LHC search programs**—such as DM search projects in ATLAS and CMS



[Science Bulletin 69 \(2024\) 3005](#)

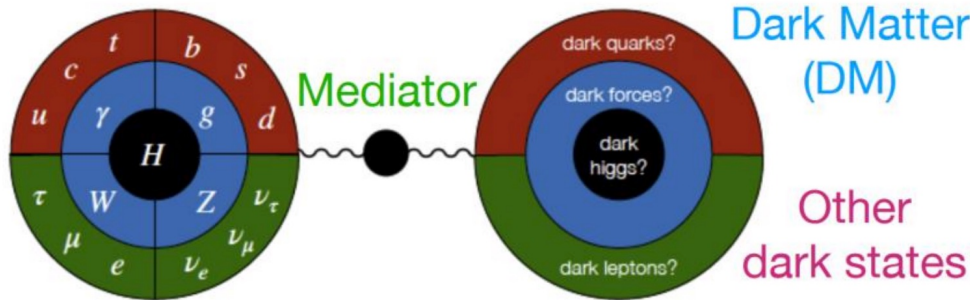
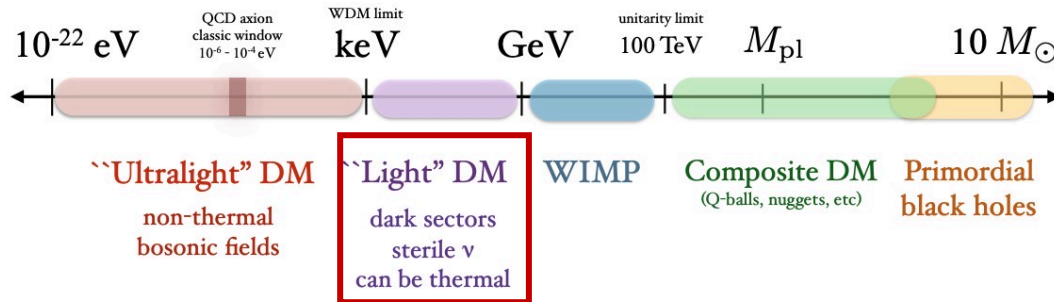
[CMS DM summary plot](#)

Beyond WIMP — dark sectors with their own dynamics

Mass scale of dark matter

(not to scale)

[arXiv:1904.07915](https://arxiv.org/abs/1904.07915)



The Standard Model (SM)

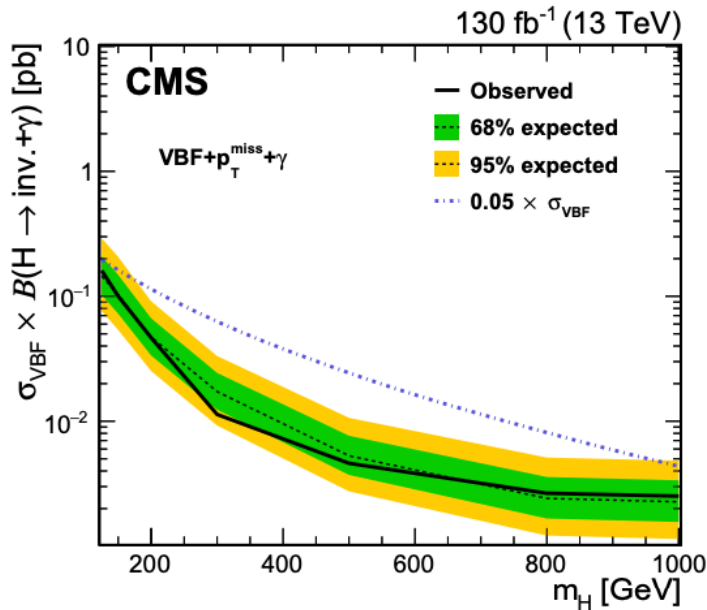
The dark sector
Particles neutral under the SM gauge symmetries

Dark sector portals

- * dark photon $\epsilon B^{\mu\nu} A'_{\mu\nu}$
- * dark scalar $\kappa |H|^2 |S|^2$
- * sterile neutrino $y H L N$
- * ALP $g_{a\gamma} \alpha \tilde{F}_{\mu\nu} F^{\mu\nu}$

... + strongly-coupled dark QCD

- Dark sector containing a **dark abelian gauge group $U(1)_D$**
- Massless (or ultra-light) **dark photon** leads to invisible signatures

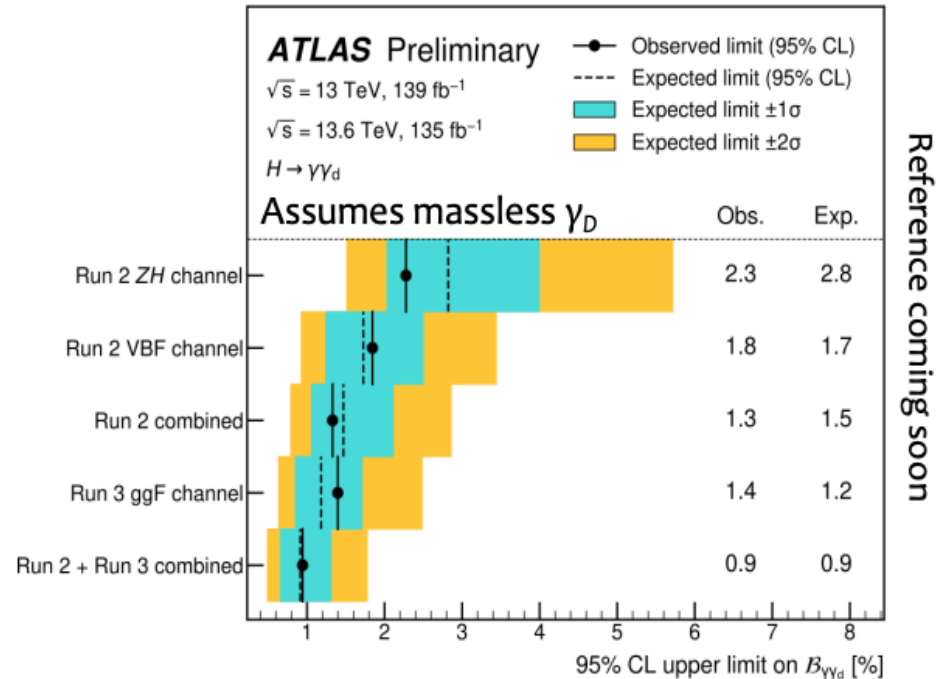


CMS 95% U.L. on BR(H125→γγ_D):

VBF channel: **3.5% (2.8%)** [JHEP 03 \(2021\) 011](#)

ZH channel: **4.6% (3.6%)** [JHEP 10 \(2019\) 139](#)

ZH+VBF: **2.9% (2.1%)** [JHEP 03 \(2021\) 011](#)



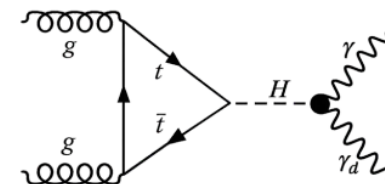
ATLAS 95% U.L. on BR(H125→γγ_D):

VBF channel: **1.8% (1.7%)** [EPJC 82 \(2022\) 105](#)

ZH channel: **2.3% (2.8%)** [JHEP 07 \(2023\) 133](#)

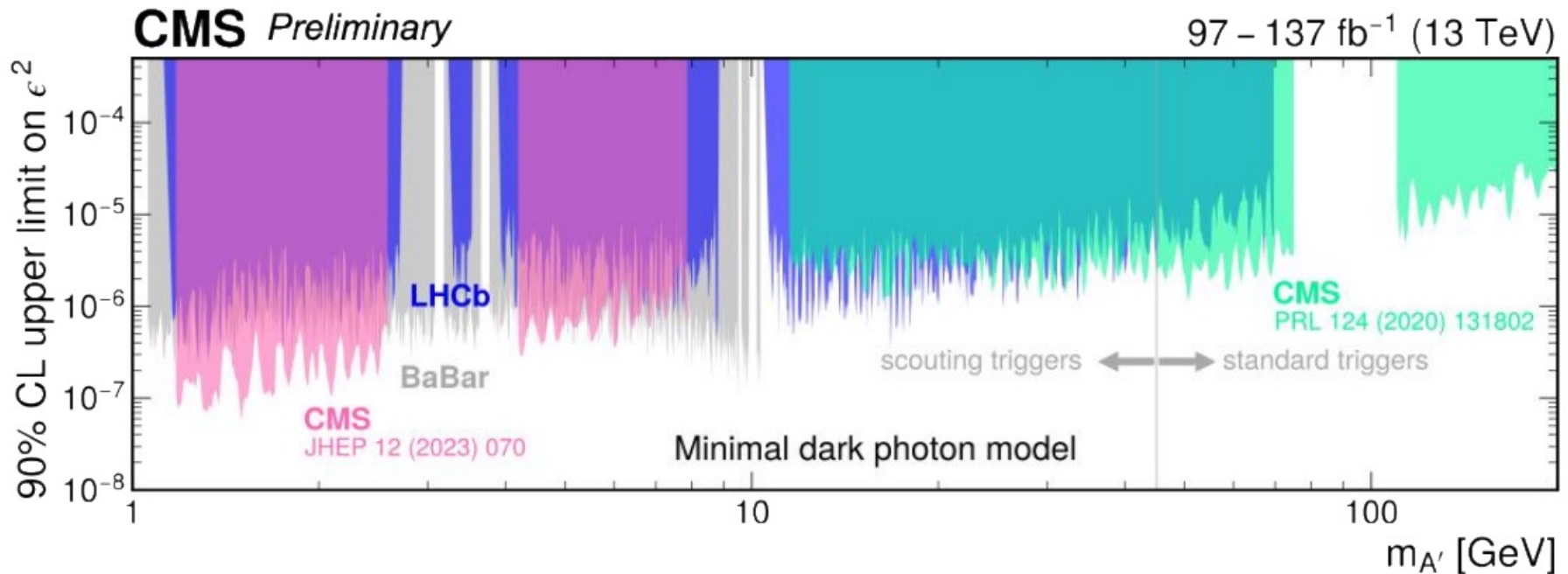
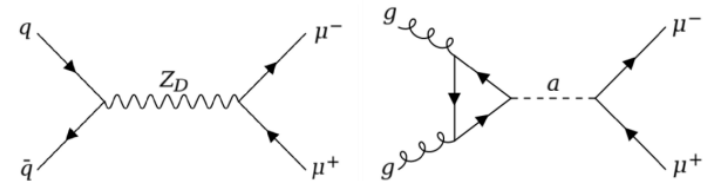
ZH+VBF: **1.3% (1.5%)** [JHEP 08 \(2024\) 153](#)

ZH+VBF+ggF: **0.9% (0.9%)** **New results** [link](#)



CMS experiment searched for dimuon resonances at **GeV scale up to 200 GeV**

Squared kinetic mixing coefficient:
above 10^{-6} are excluded over most of the
searched mass range

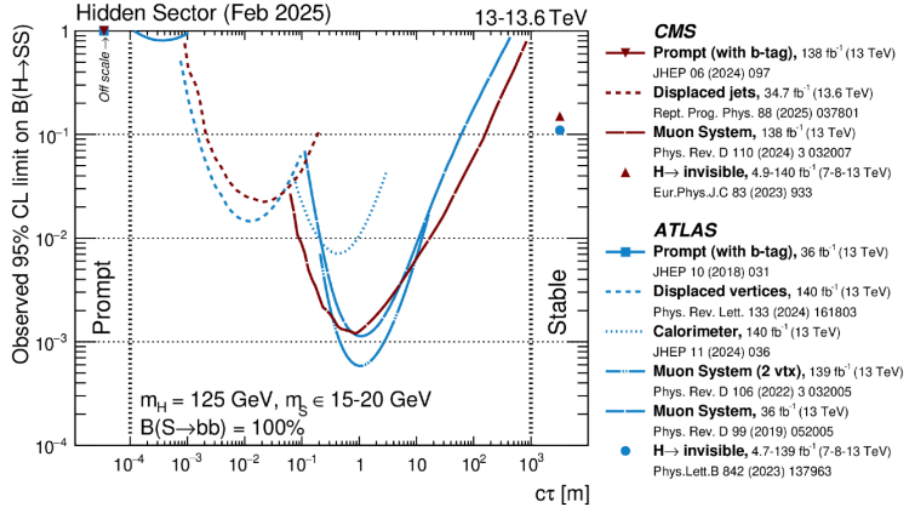


[CMS DM summary plot](#)

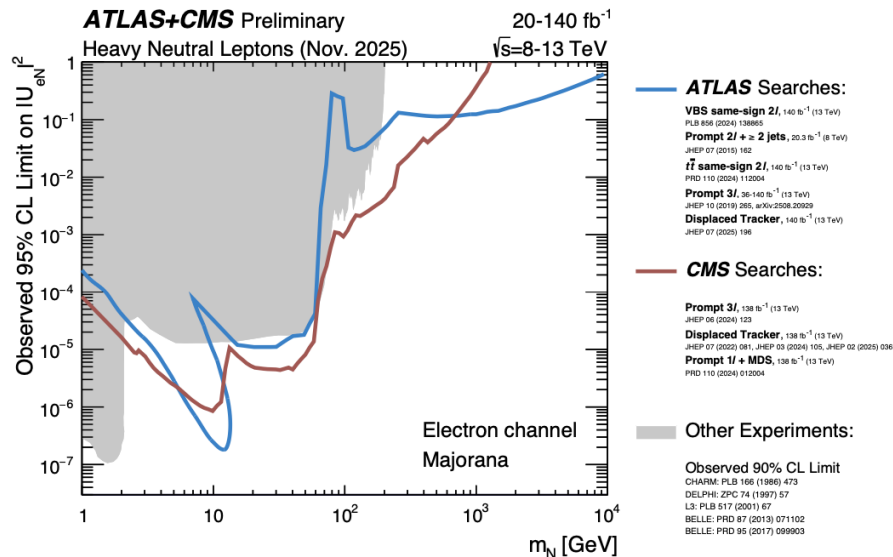
Hidden Sector $H \rightarrow SS$

m_S in [15-20] GeV

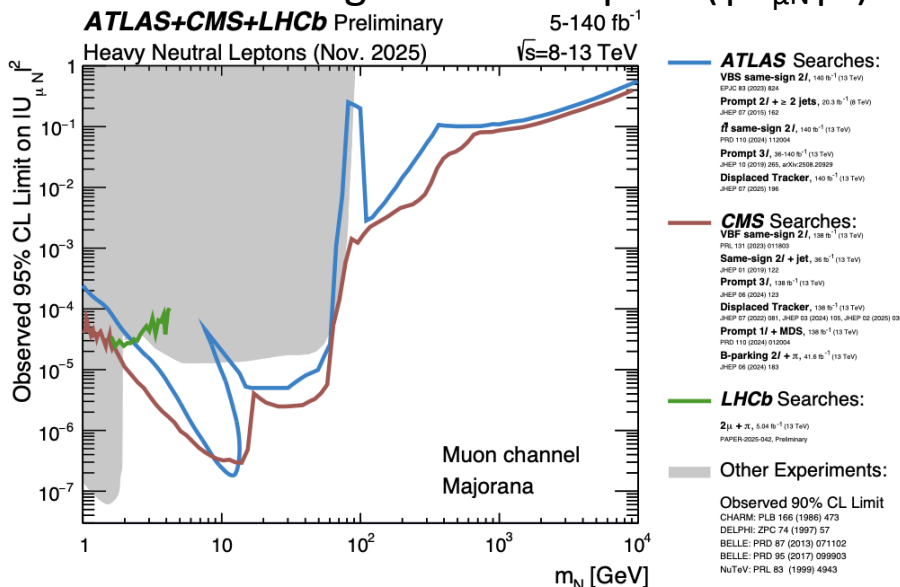
ATLAS+CMS Preliminary
Hidden Sector (Feb 2025)



HNL first generation lepton ($|U_{eN}|^2$)



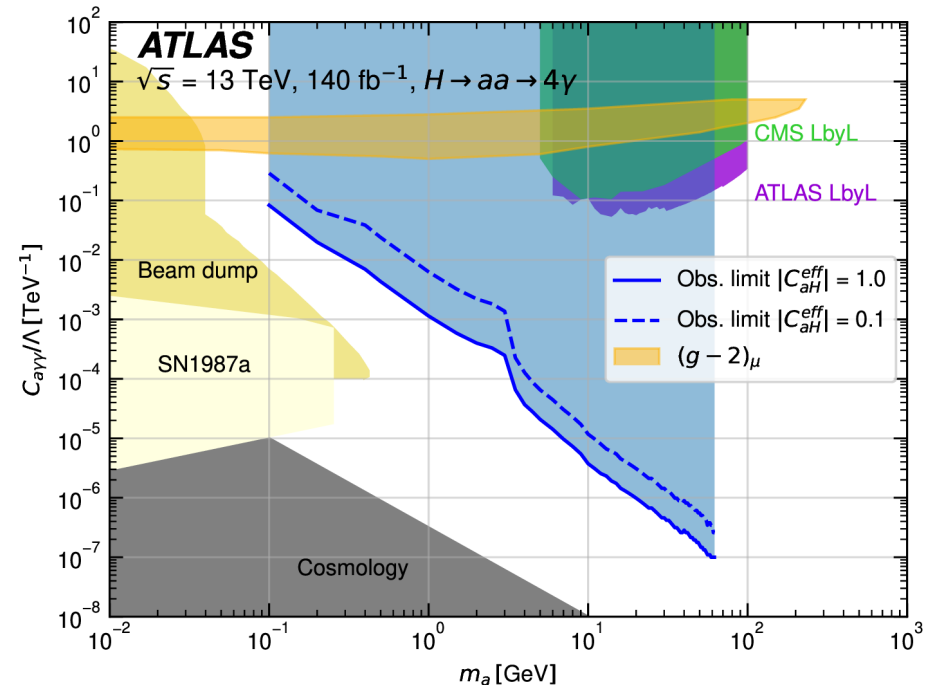
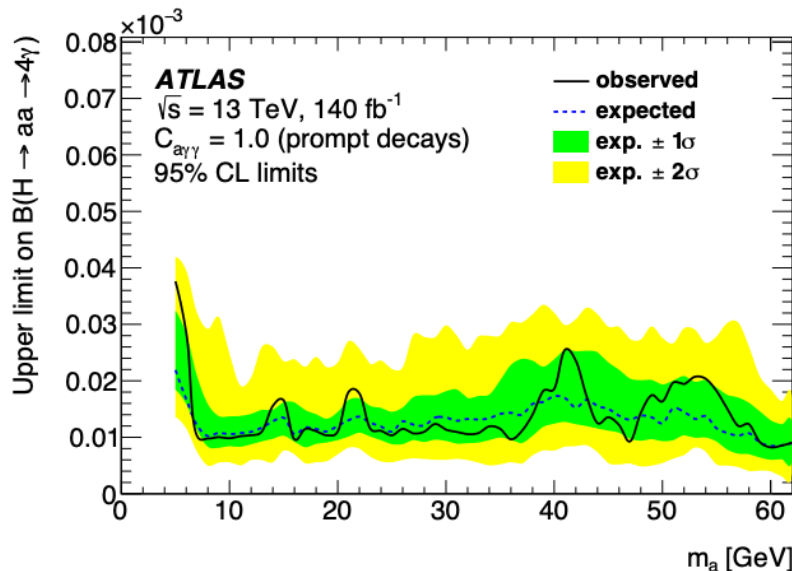
HNL second generation lepton ($|U_{\mu N}|^2$)



ALP mass range probed: $0.1 < m_a < 60$ GeV

[Eur. Phys. J. C 84 \(2024\) 742](#)

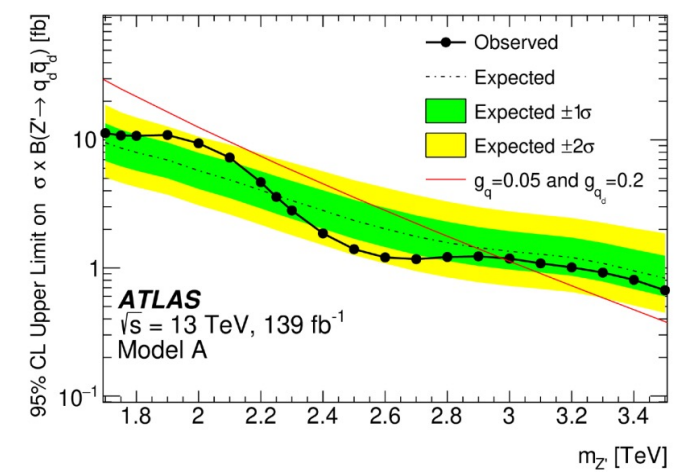
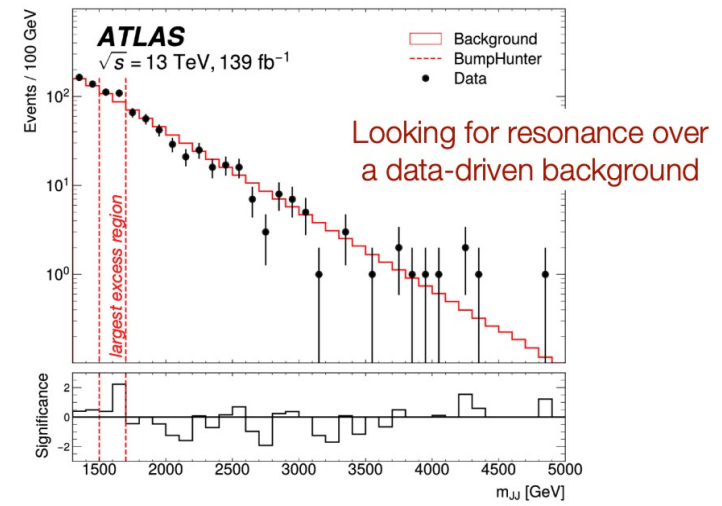
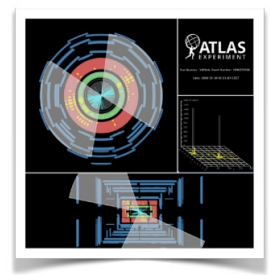
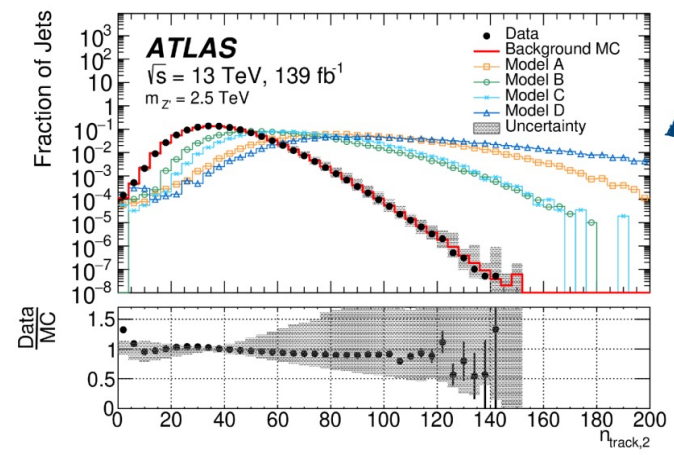
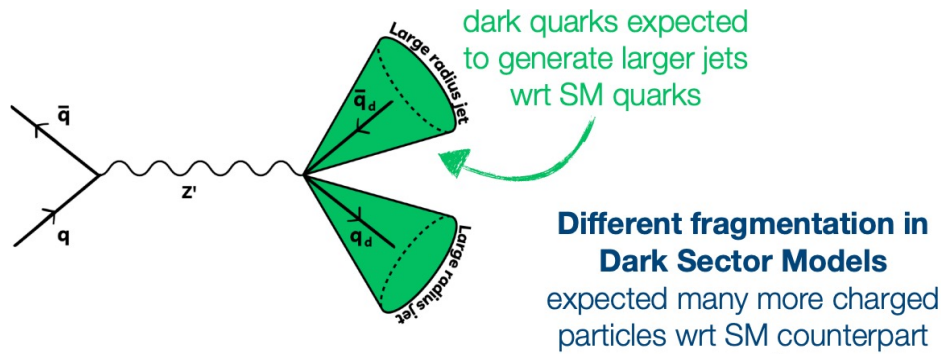
- **Collimated signature:** identified as single object when $m_a < 3.5$ GeV
- Both **Prompt (major sensitivity)** and **long-lived** signatures included



Limits on the ALP mass and coupling to photons at 95% CL, assuming $|C_{aH}^{eff}|/\Lambda^2 = 1 \text{ TeV}^{-2}$ (solid line) and $|C_{aH}^{eff}|/\Lambda^2 = 0.1 \text{ TeV}^{-2}$ (dashed line)

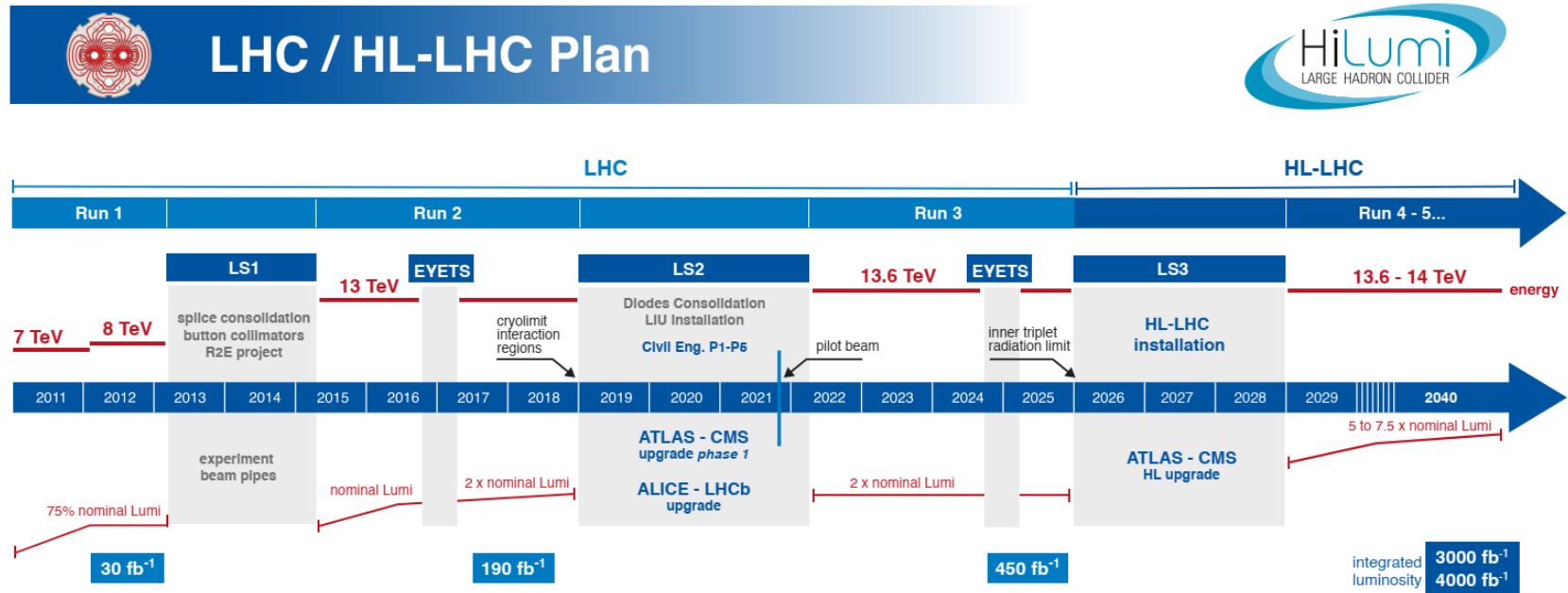
- **First time coverage of the full mass range** between 100 MeV and 62 GeV
- **Most stringent limits to date.**

Signature: larger, broader jets with more tracks



So far, the LHC has delivered **only around 15%** of its ultimate dataset, offering abundant opportunities for **high-precision measurements** and **explorations of new physics**.

- [List of excesses at the LHC](#)



- Ongoing effort to define **LHC Dark matter models for run 3 and HL-LHC**
 - Improve DM benchmarks
 - New benchmark models with unexplored signature.
 - Better connecting collider and other DM experiments

2024 LHC DM WG workshop LHC BSM WG Meeting

We warmly welcome our theory colleagues to contribute their expertise to the LHC dark matter search program!

Recent DM updates:

- **t-channel DM models:** [white paper](#)
- **New benchmark/white paper in preparation:**
 - **2HDM+a:**
 - Next Taskforce meeting [July 22nd](#)
 - **Dark QCD:** Taskforce meeting on [June 16th](#)



2024 LHC DM WG workshop
Roadmap of Dark Matter Models
for LHC Run 3

Topics include

- Uncovered signatures
- Simplified $s/\bar{s}$ -channel models
- Higgs to invisible
- Extended Higgs sectors
- Dark Higgs
- Dark showers
- Long-lived particle signatures
- Dark photons
- Axion Like Particles

13-17 May 2024
CERN
<http://cern.ch/lhcdm24>

Registration: 1/12/23 - 31/3/2024
Abstracts accepted: 1/12/23 - 1/3/24
Contact: lhcdm24-organisers@cern.ch

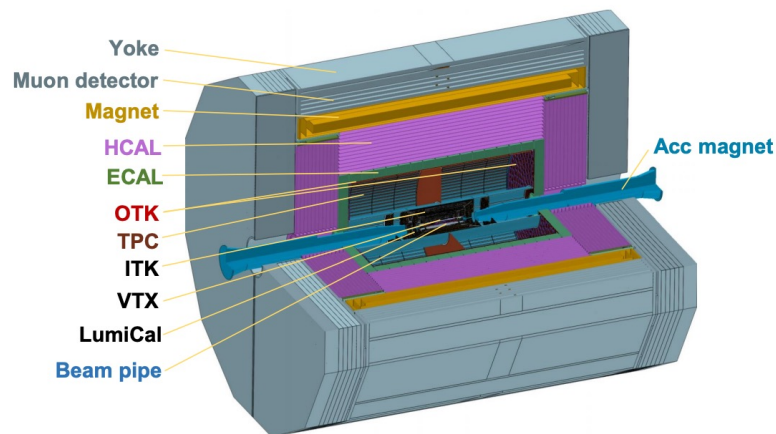
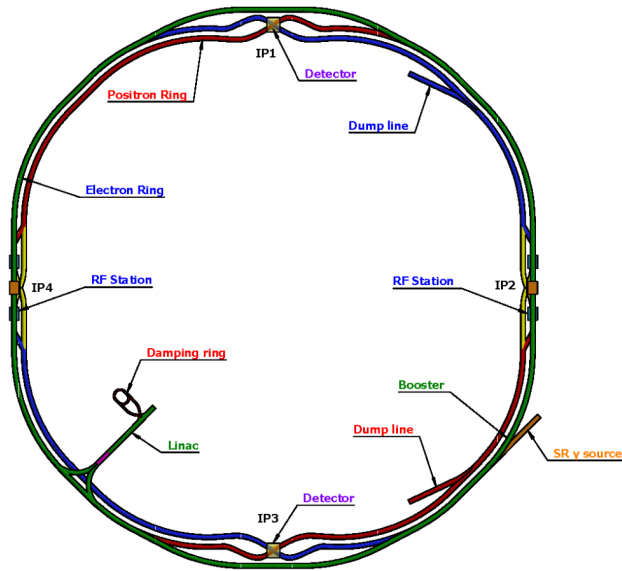
Organising committee

S. Argyropoulos	U. Haisch
X. Cid Vidal	D. Johnson
M. Cirelione	T. Tait
J. Frost	Z. Wang

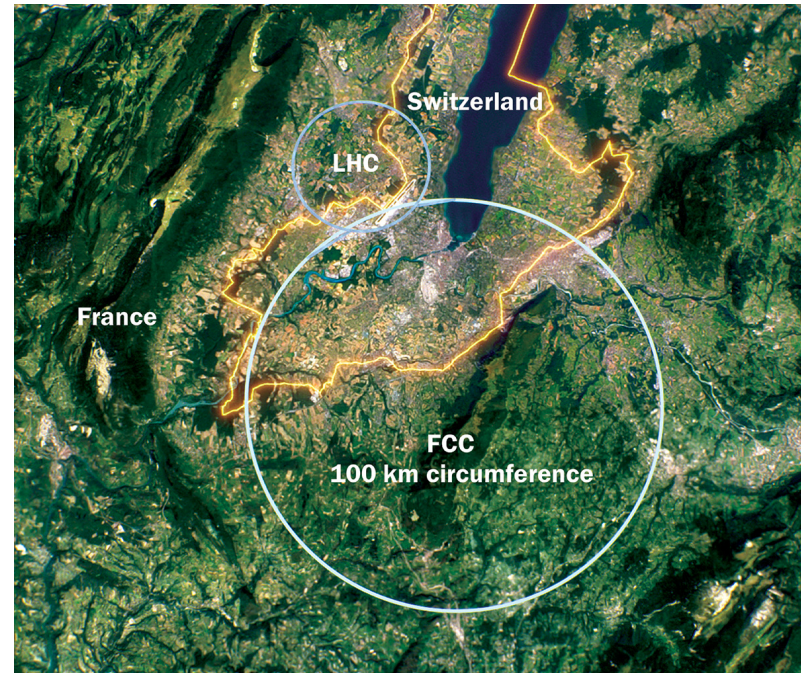
Programme committee

J. Alimena	P. Fox	P. Harris	B. Meier	S. Sinha
M. Blanke	B. Fuks	P. Hen	K. Reichert	M. Williams
L. Corpe	A. Gribajev	F. Kahlhoefer	P. Pani	
A. de Costa	G. Gustavino	S. Kulkarni	D. Robinson	

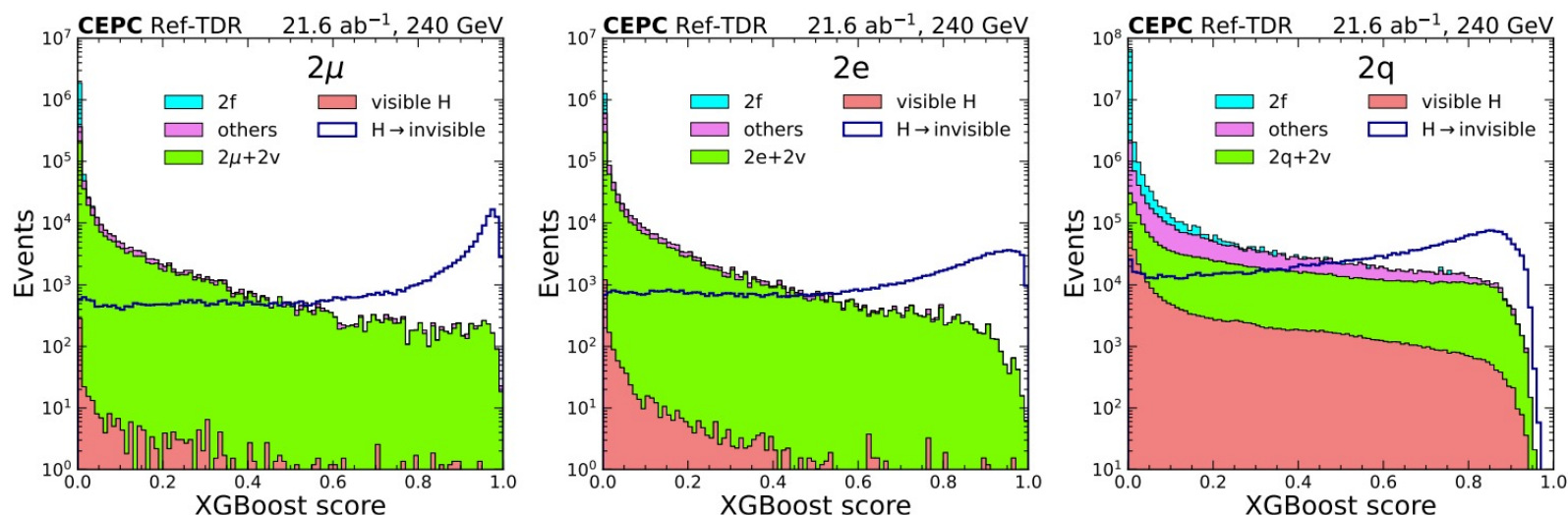




Meanwhile, future projects will provide **unprecedented precision**, opening new windows for exploring DM on collider.



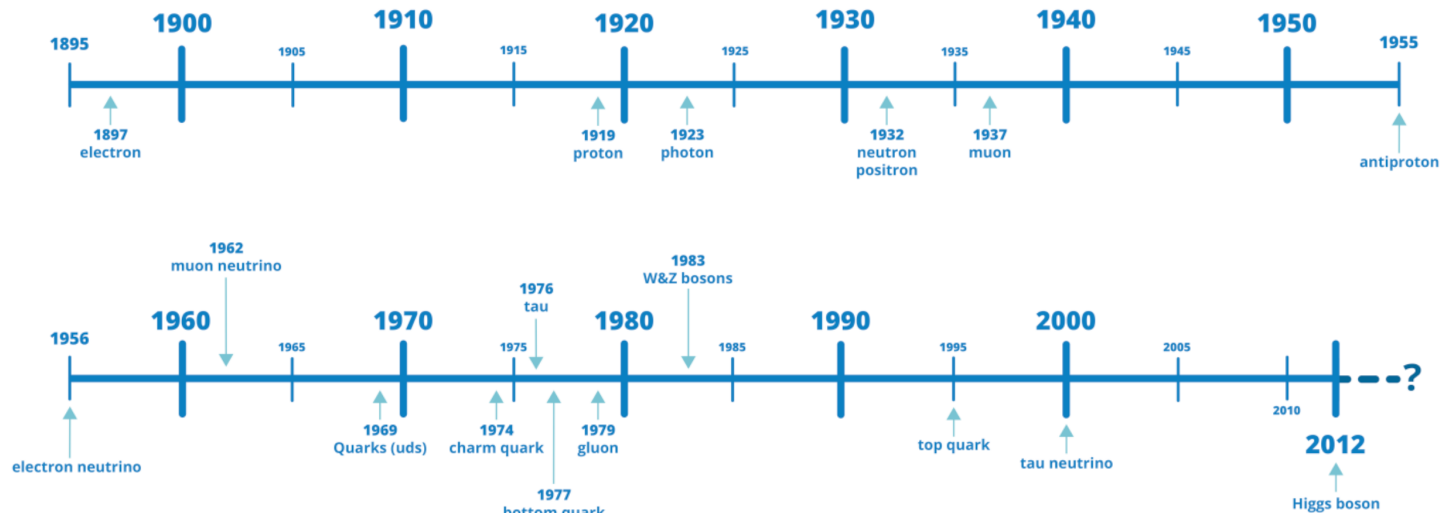
- The future higgs factory is expected to constrain $\text{BR}(H \rightarrow \text{inv})$ to the 0.05% level:
 - improvement in sensitivity by **two orders of magnitude!**



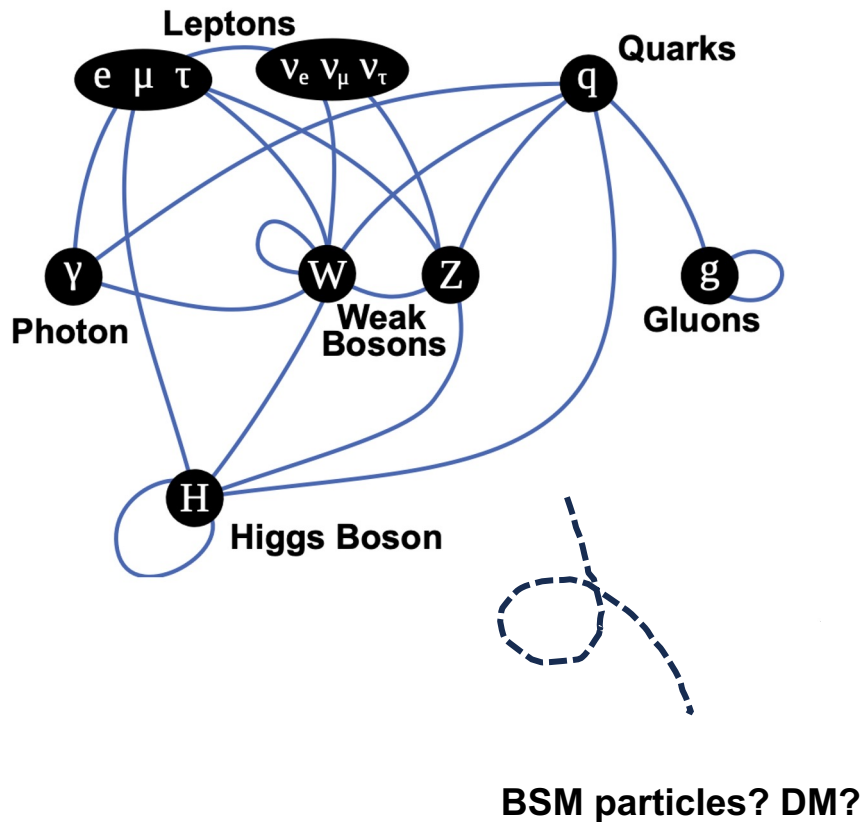
channel	uncertainties	significance of SM obs.	UL on BSM BR
2μ	$-42\%/+43\%$	2.5σ	0.089%
$2e$	$-60\%/+62\%$	1.7σ	0.13%
$2q$	$-29\%/+29\%$	3.4σ	0.061%
combine	$-22\%/+22\%$	4.5σ	0.047%

- Many theories, of various degrees of complexity, contain dark matter candidates.
- It is important to **cover all this ground** and also **prepare for unexpected, not-yet-theorised discoveries**.
- **No stone must be left unturned till probing the Dark Matter and New Physics!**

Key particle discoveries



Thanks

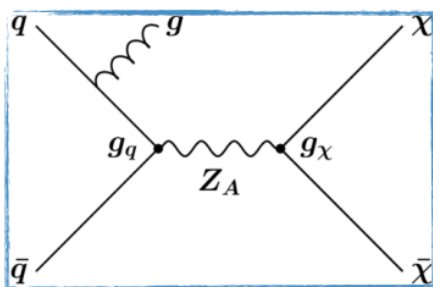
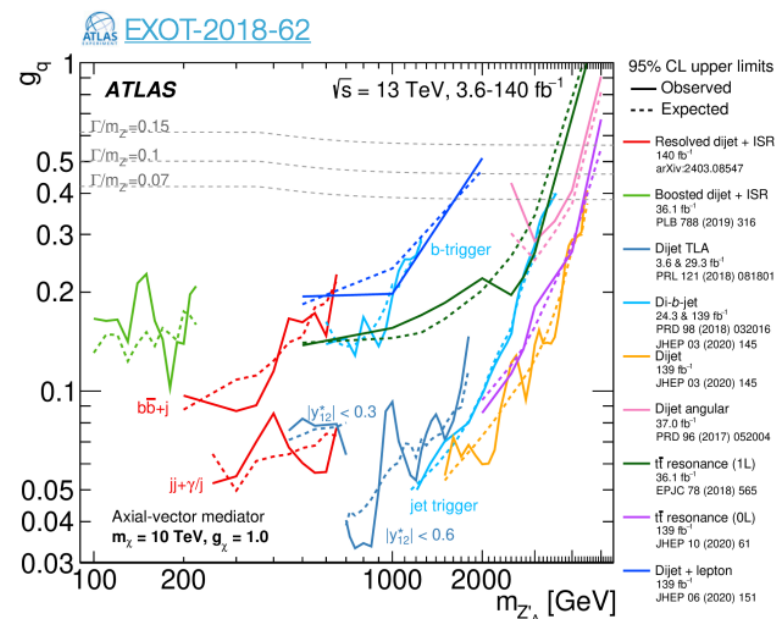


The discovery of Higgs boson completed the last piece of the SM particle content.

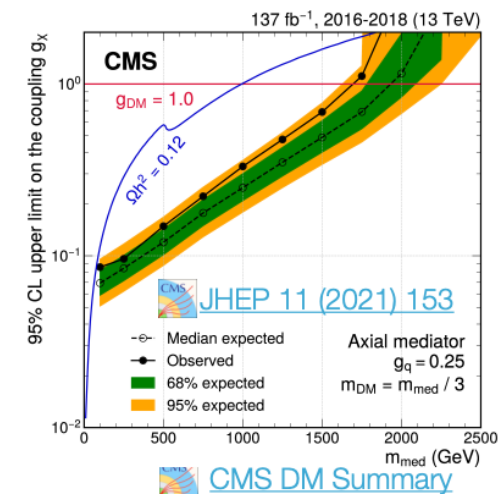
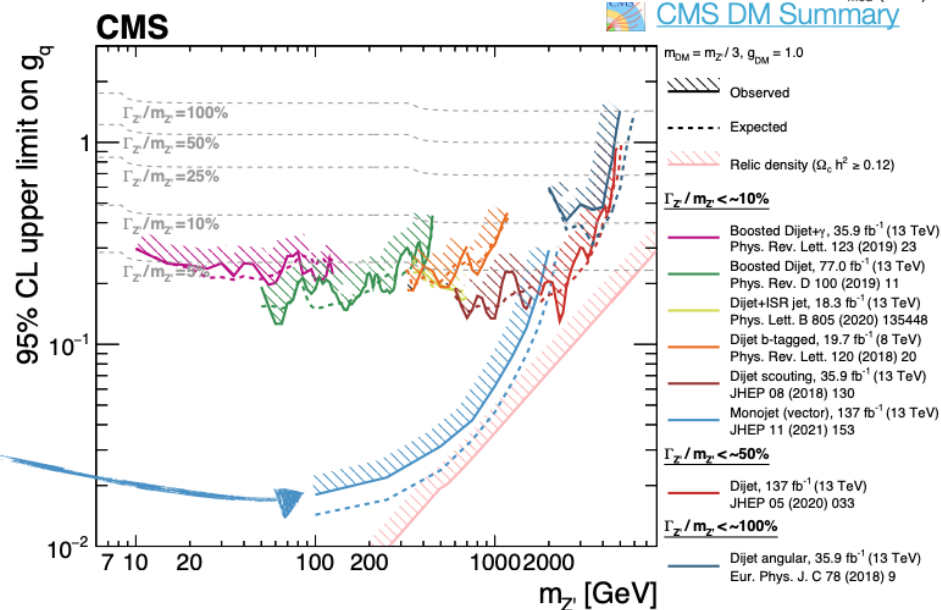


But the **SM** cannot explain:

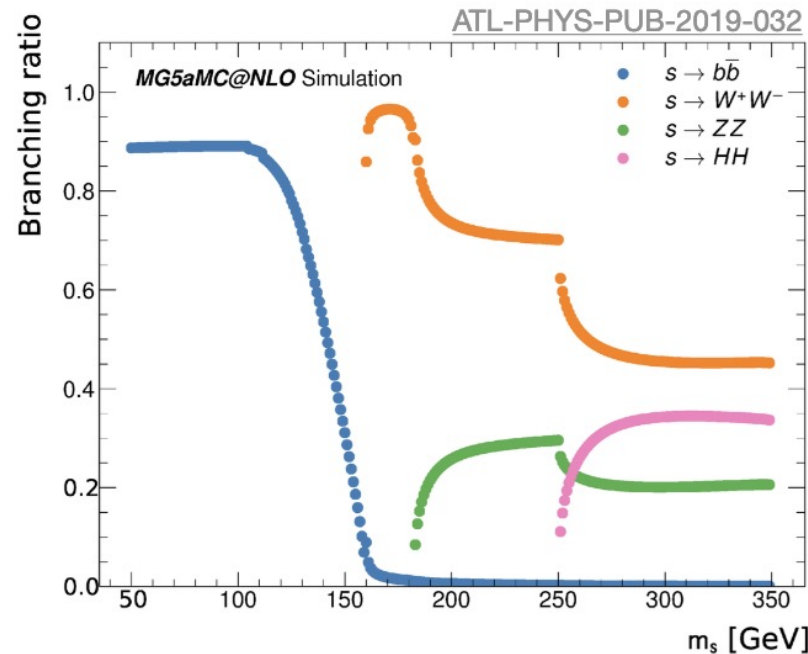
- What is the nature of dark matter and dark energy?
- How do neutrinos obtain their mass?
- What is the origin of matter-antimatter asymmetry
- ...



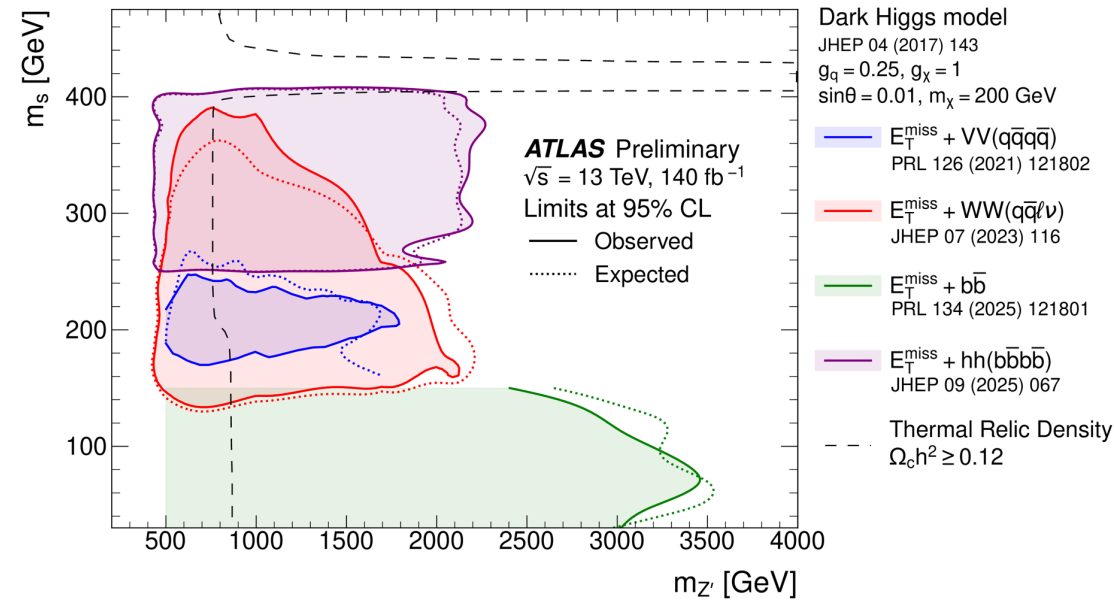
constraint also from monojet analysis



- **Dark sector model** with a scalar s (dark Higgs)
- Mediator Z' coupling to DM



Mases of BSM particles and couplings as new parameters
Yukawa-like couplings favours different final states for different mass scenarios.



$m_s \gtrsim 160 \text{ GeV}$

$s \rightarrow WW$ decays

Hadronic: $W(qq)W(qq)$

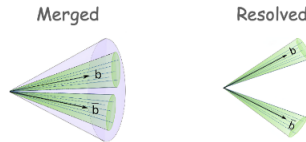
leptonic: $W(\ell\nu)W(\ell\nu)$

mixed: $W(qq)W(\ell\nu)$

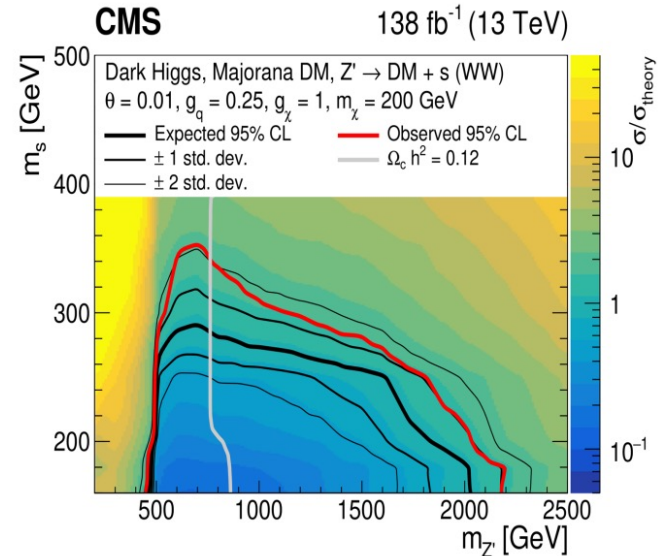
Lepton channels more sensitive

$m_s \lesssim 160 \text{ GeV}$

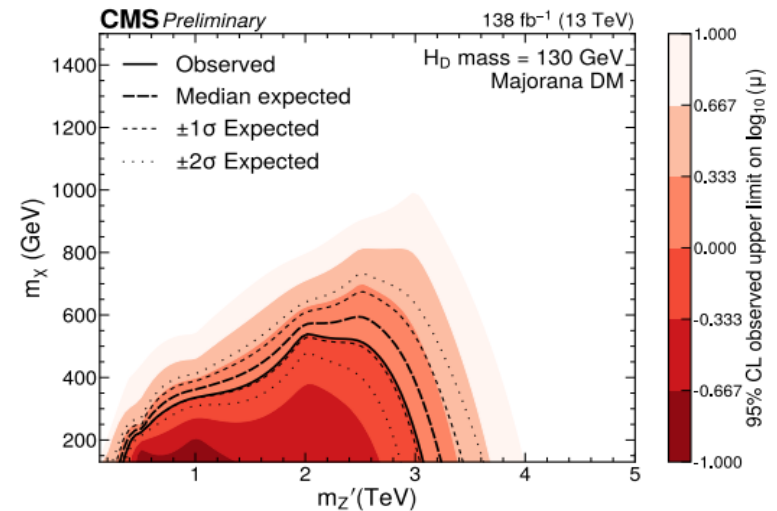
$s \rightarrow b\bar{b}$ decays



Large-R jets + Xbb tagger
to explore m_s down to 30 GeV



CMS $s \rightarrow WW \rightarrow 2\ell 2\nu/\ell\nu qq'$
 JHEP 03 (2024) 134

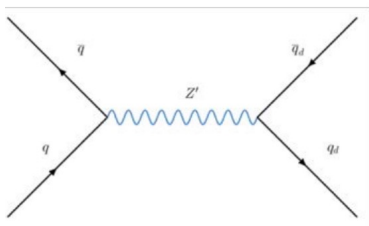
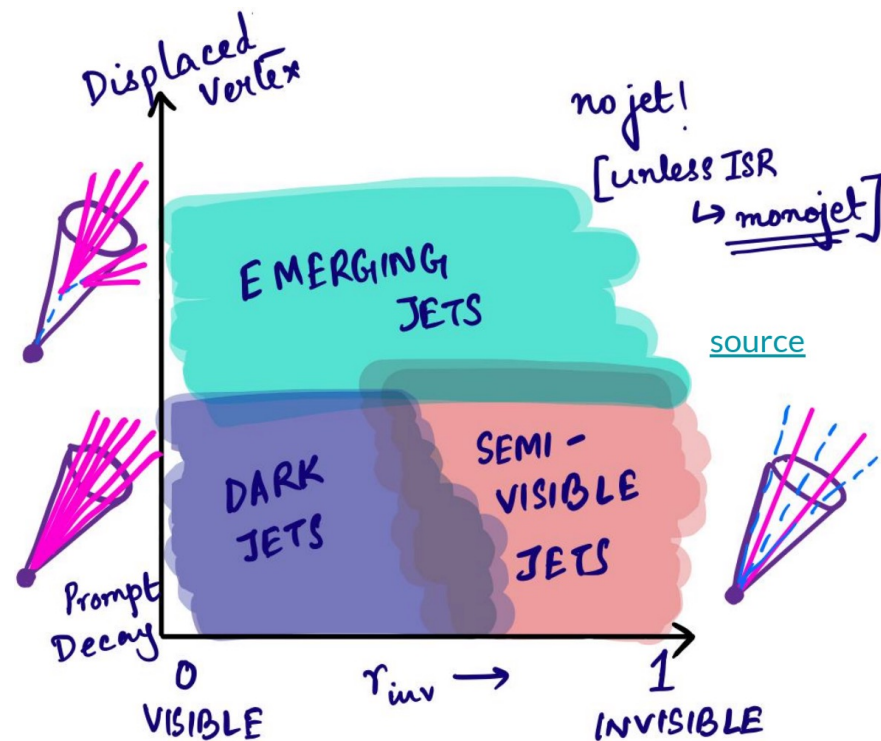


CMS $s \rightarrow b\bar{b}$

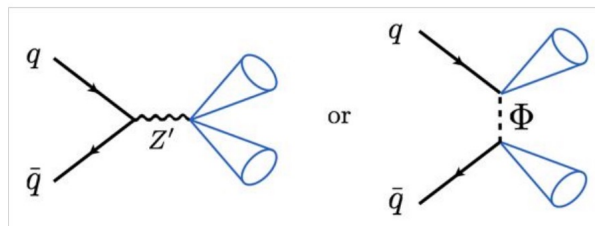
PAS-SUS-23-013

Signature based searches using benchmark models to look at unusual topologies and hidden corners of the phase space

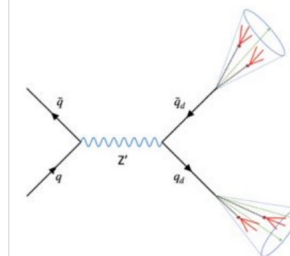
- Dark hadrons decaying PROMPTLY in a QCD-like fashion, fully (**dark jets**)
- or partially back to visible sector (**semi-visible jets**)
- Dark hadrons undergoing DISPLACED decays in a QCD-like fashion (**emerging jets**)



Dark jets



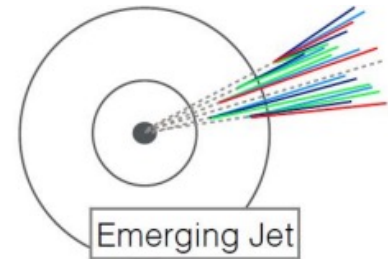
Semi-visible jets



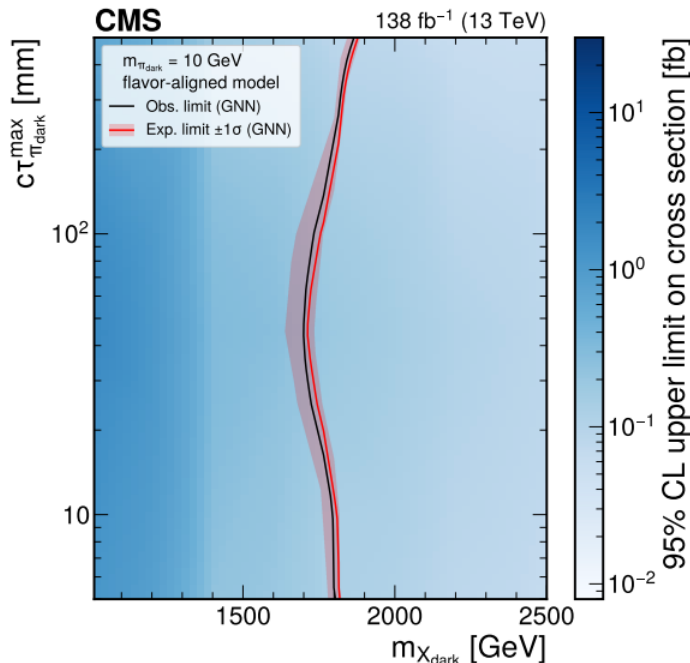
Emerging jets

Dark pions are long-lived, produced inside dark jets, and travel measurable distances before decaying to SM particles.

Signature: Sub-jets appear to **"emerge"** mid-flight from displaced secondary vertices.



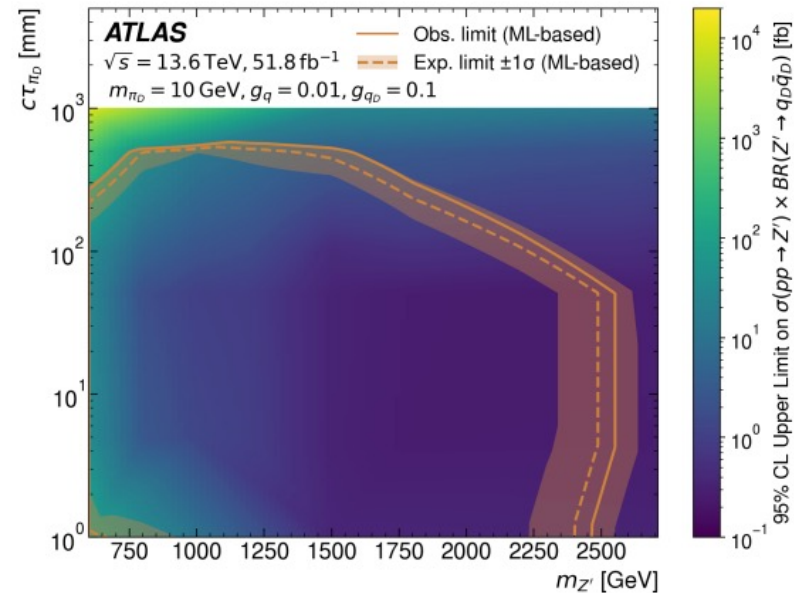
CMS Search



Excludes mediator up to **1950 GeV** ($\tau = 1\text{-}500$ mm).

[JHEP 07 \(2024\) 142](#)

ATLAS Search

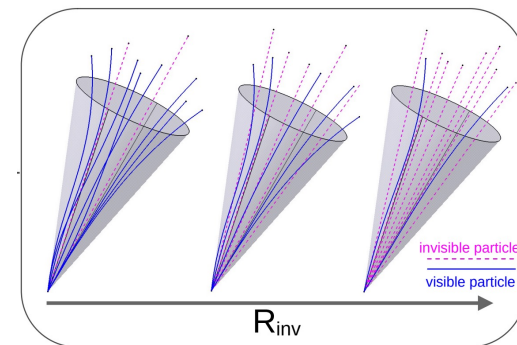


Excludes Z' up to **2559 GeV** ($\tau = 5\text{-}50$ mm).

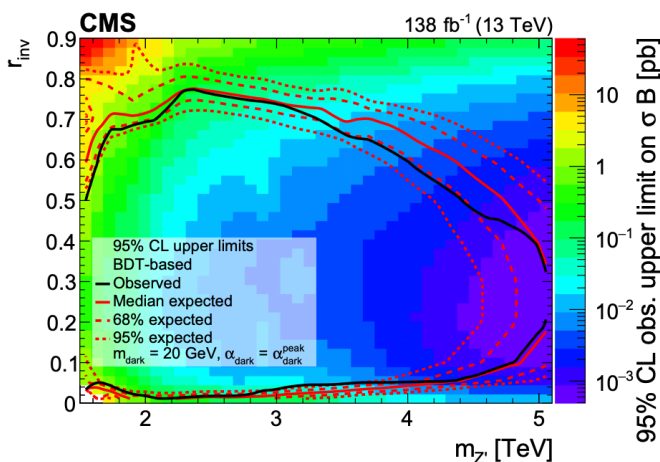
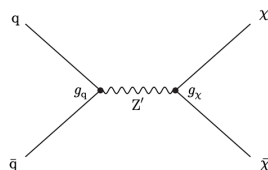
[Rep. Prog. Phys. 88 \(2025\) 097801](#)

Dark shower yields a mixture of stable and unstable dark hadrons.
Dark jet carries both visible and invisible energy.

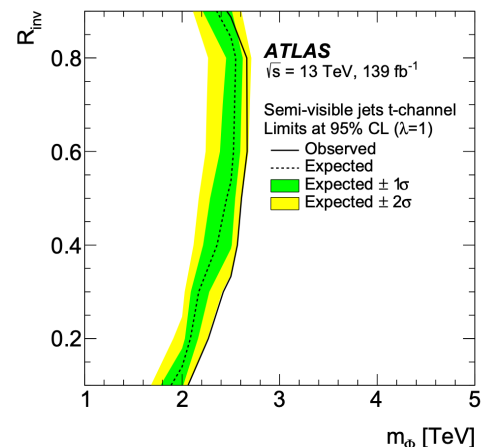
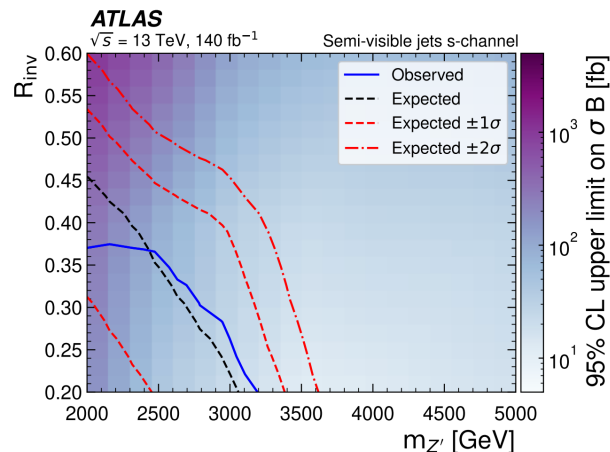
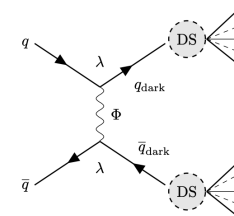
Signature: **Missing transverse momentum aligned with a jet.**



CMS Search (s-channel Z')



ATLAS Search (s- and t-channel)



Excludes Z' mass up to **5.1 TeV**
[JHEP 06 \(2022\) 156](#)

Excludes Z' mass up to **3.2 TeV**
[Phys. Rev. D 112 \(2025\) 012021](#)

Excludes ϕ mass up to **2.7 TeV**
[Phys. Lett. B 848 \(2024\) 138324](#)