Illuminating the Dark

Review on the dark matter searches at the LHC

16th International Workshop on the Identification of Dark Matter

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Zaragoza, Spain
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IDM2026
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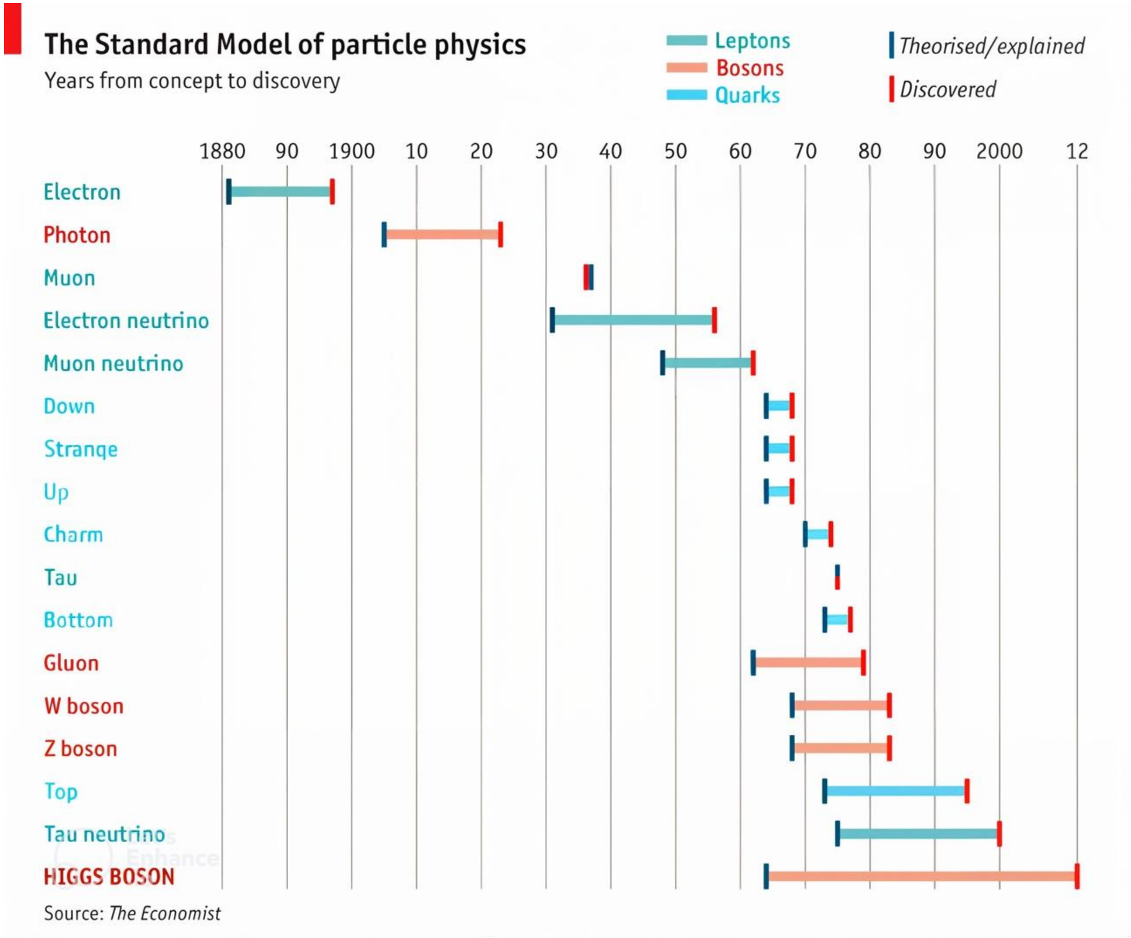
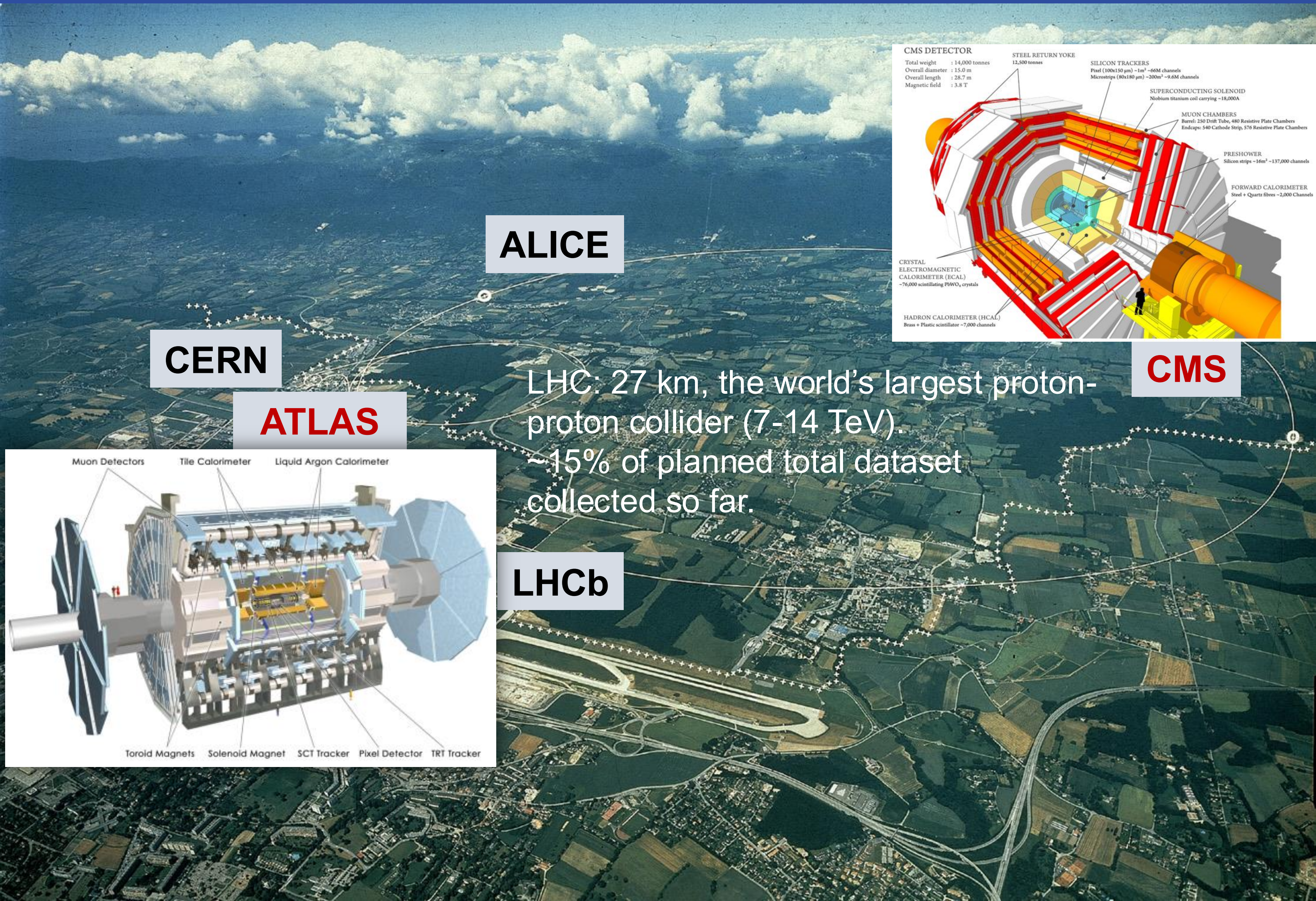
Theoretical and Experimental Particle Physics
have revealed much about the nature of our universe



[Economist]

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

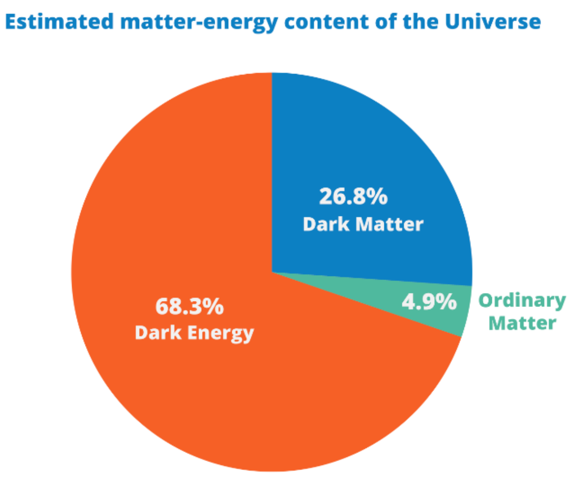
LHC



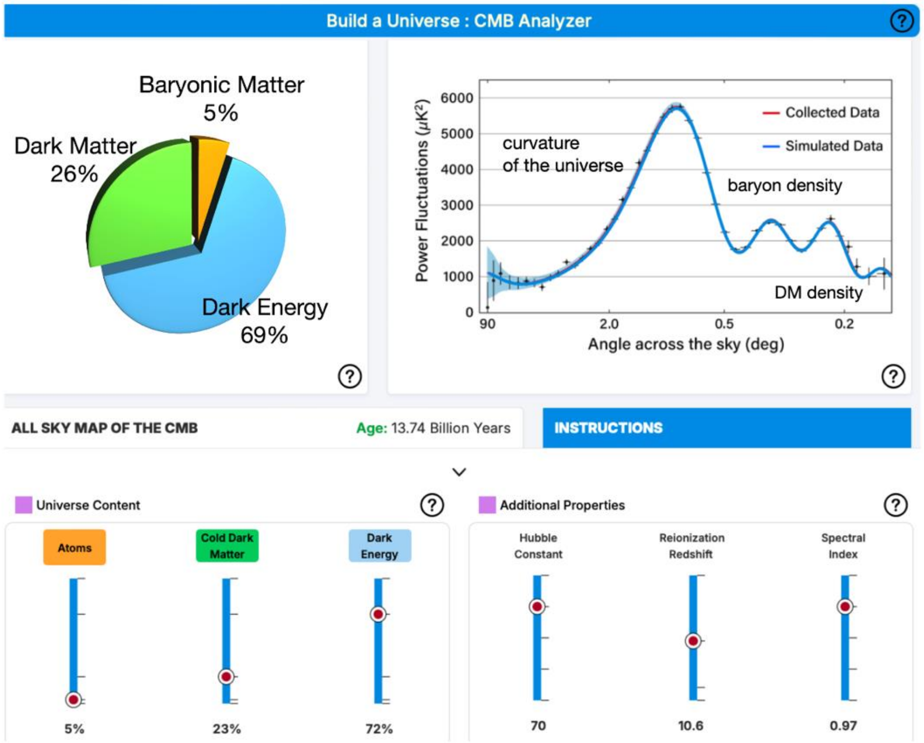
LHC: 27 km, the world's largest proton-proton collider (7-14 TeV).
~15% of planned total dataset collected so far.

Open questions beyond the SM

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

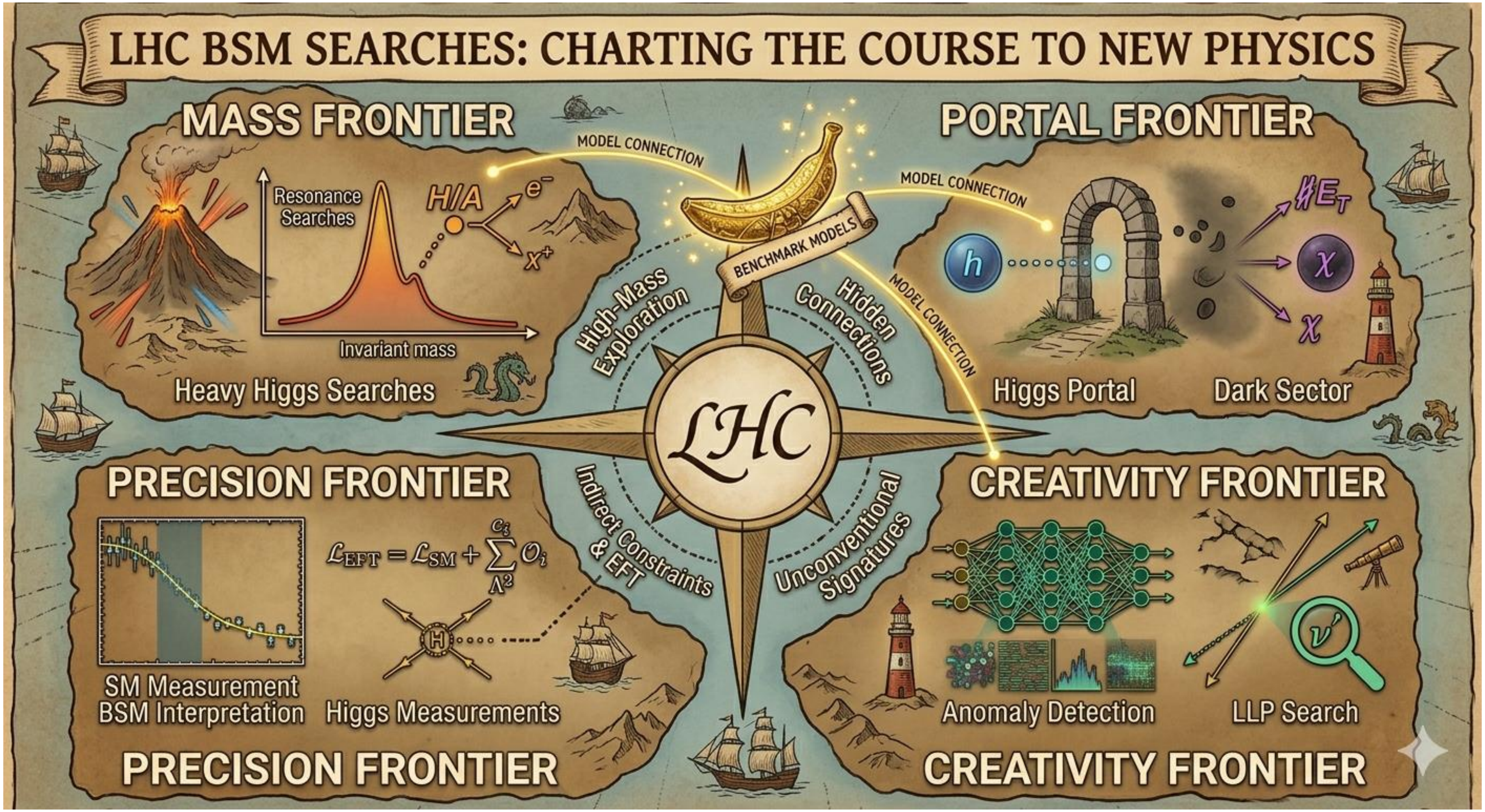


CMB game from NASA



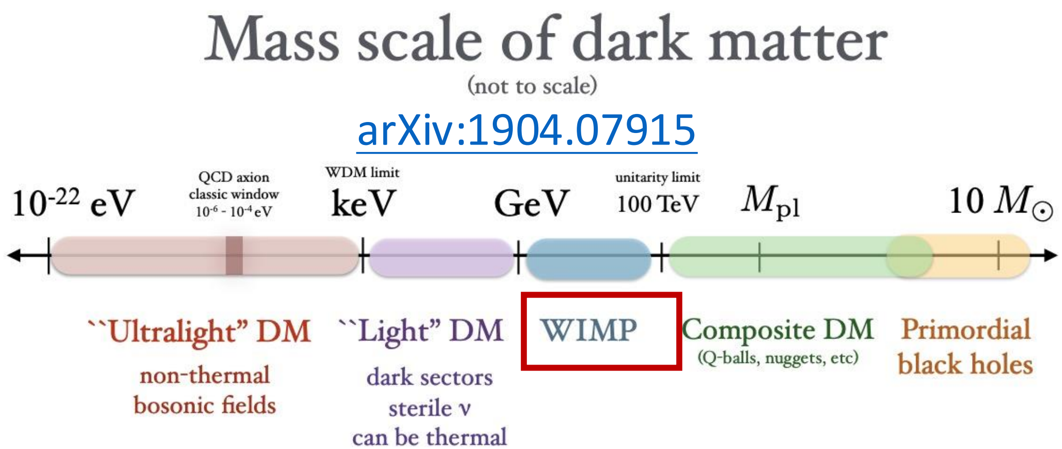
Its relic density can be obtained by the CMB spectrum

DM's (particle) nature is unknown



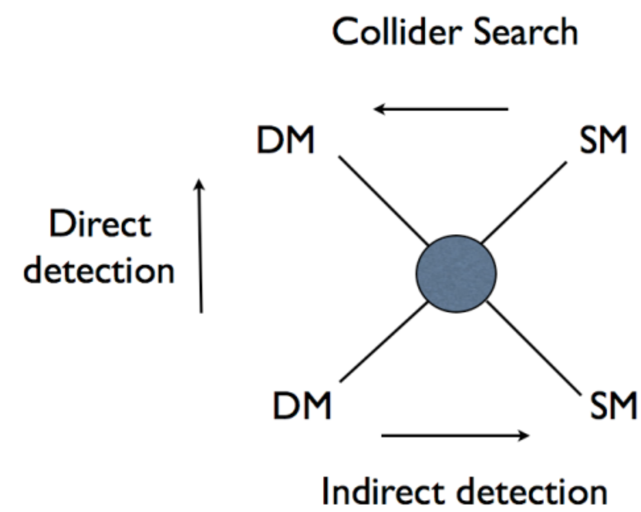
Benchmark DM models of different scenarios connect BSM search frontiers on LHC (credit: Nano Banana)

The popular scenario: WIMP



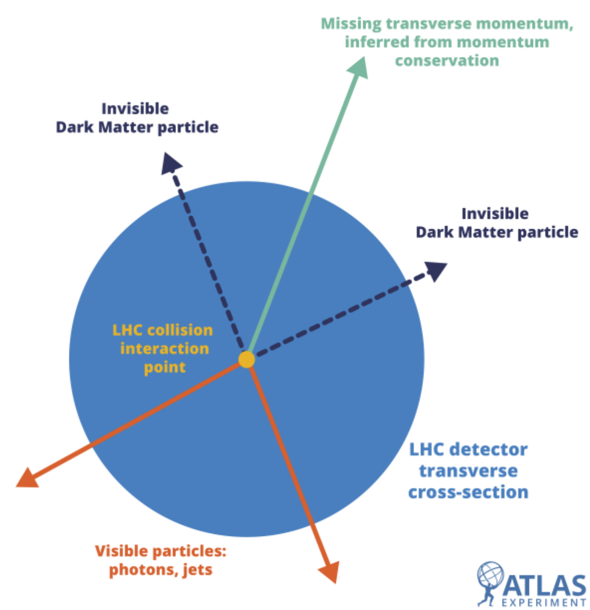
arXiv:1904.07915

Candidate masses span 70+ orders of magnitude.



One most-popular scenario in the past 20 years:
Assuming DM-SM weak interaction:

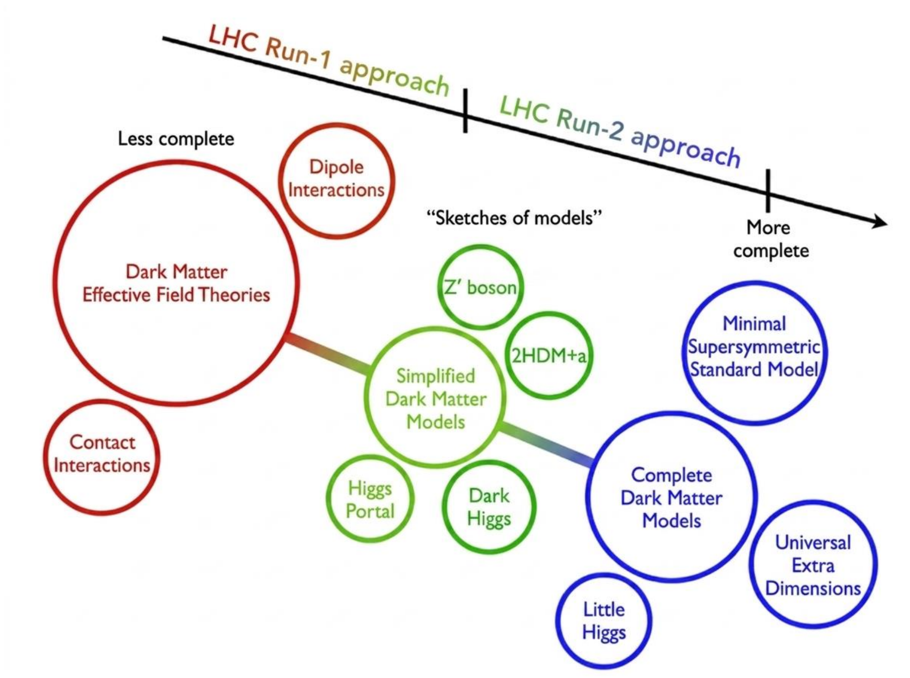
- **Direct detection:** LZ, PandaX, Xenon, …
- **Indirect detection:** AMS, Fermi-LAT…
- **Colliders:** ATLAS, CMS …
    - LHC could produces dark states directly.
    - Sensitive over **large kinematic range**
    - DM won't leave trace in the detector, but could create MET



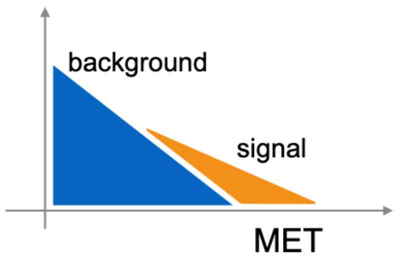
WIMP benchmark models

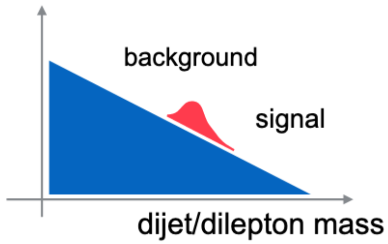
For WIMP searches, **theoretical benchmarks** are necessary to sharpen the regions of interest.

- **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

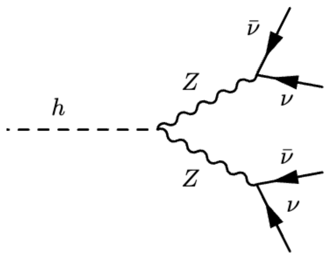




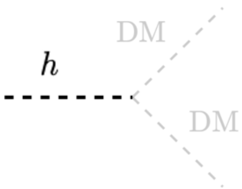
WIMP Model 1: Higgs portal

A unique gateway on LHC :

- H decays to a pair of stable WIMPs.



SM BR(H→inv) ~0.12%



DM will increase BR(H→inv)

Information from the global coupling fit

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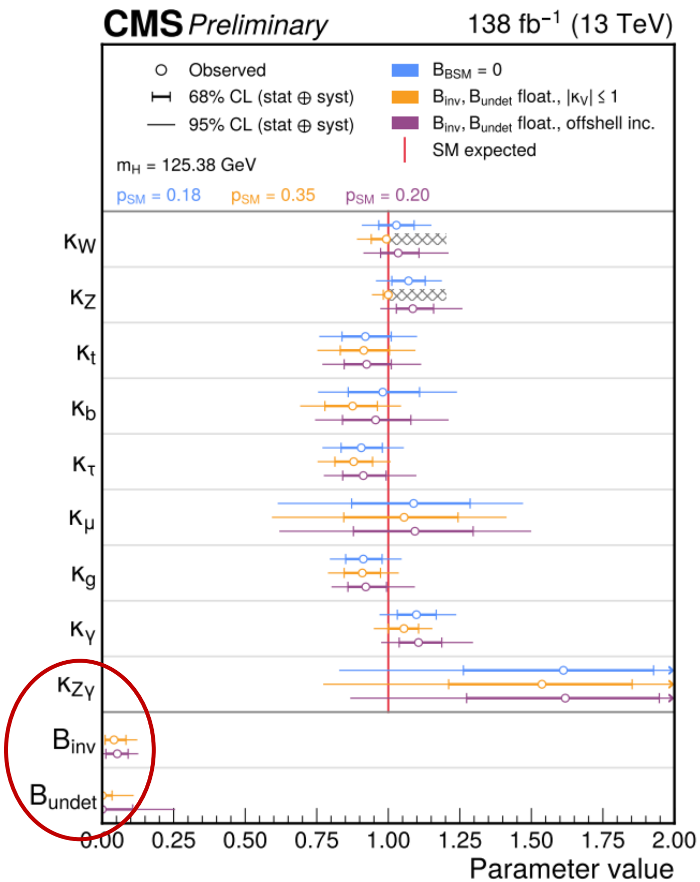
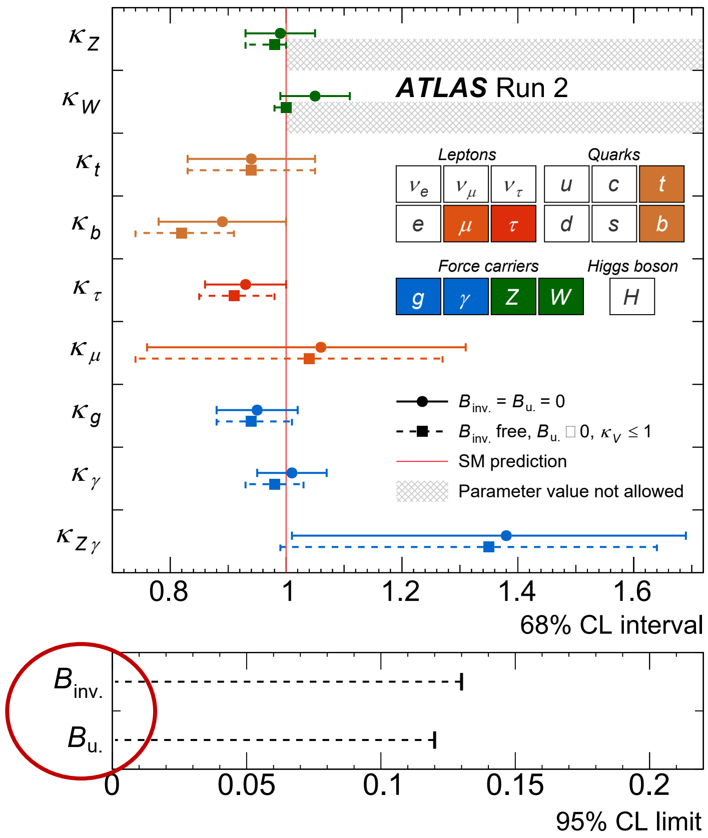
- Large room left (95% C.L. upper limit) for B_{inv}/B_u from the global fit.
- Important to explore exotic/invisible decays.





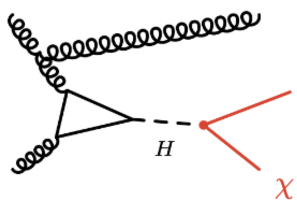
HIGGS INVISIBLE DECAYS

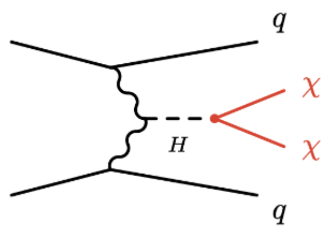
HIGGS EXOTIC DECAYS

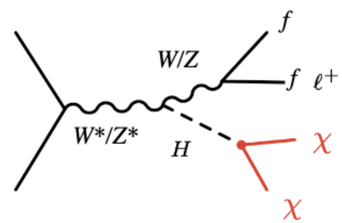
CMS: $B_{inv} < 0.13$, $B_u < 0.25$
[CMS-PAS-HIG-21-018]

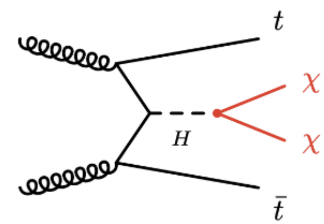
ATLAS: $B_{inv} < 0.13$, $B_u < 0.12$
[Nature 607, 52–59 (2022)]

Direct search channels





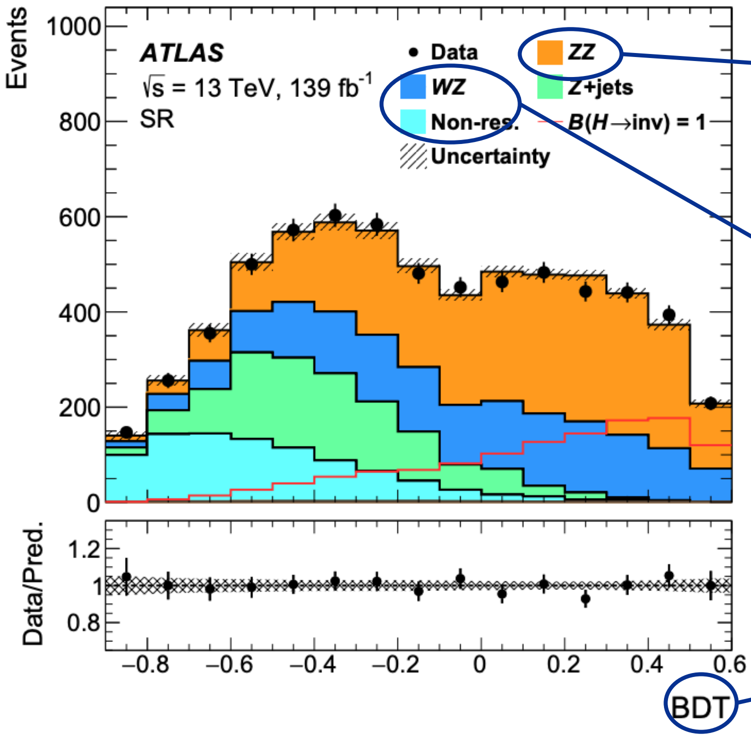




	ggF (~ 49 pb)	VBF (~ 3.8 pb)	VH (~ 2.3 pb)	ttH (~ 0.5 pb)
Selection	high p_T ISR jet	2 forward jets in opposite hemisphere	lepton or hadron decay from W/Z	leptonic, semi-leptonic, hadronic tt
Final state	mono-jet	**VBF + MET**, VBF + MET + γ	Z(ll) + MET, mono-largeR jet	tt + MET
Sensitivity	**Low**	**High**	**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

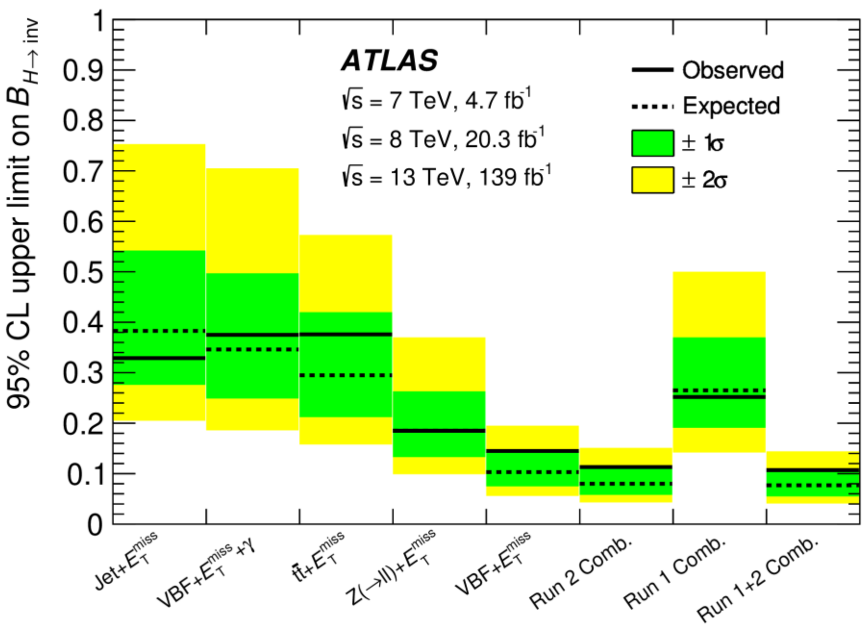
Apply the latest theoretical calculation to correct the main backgrounds

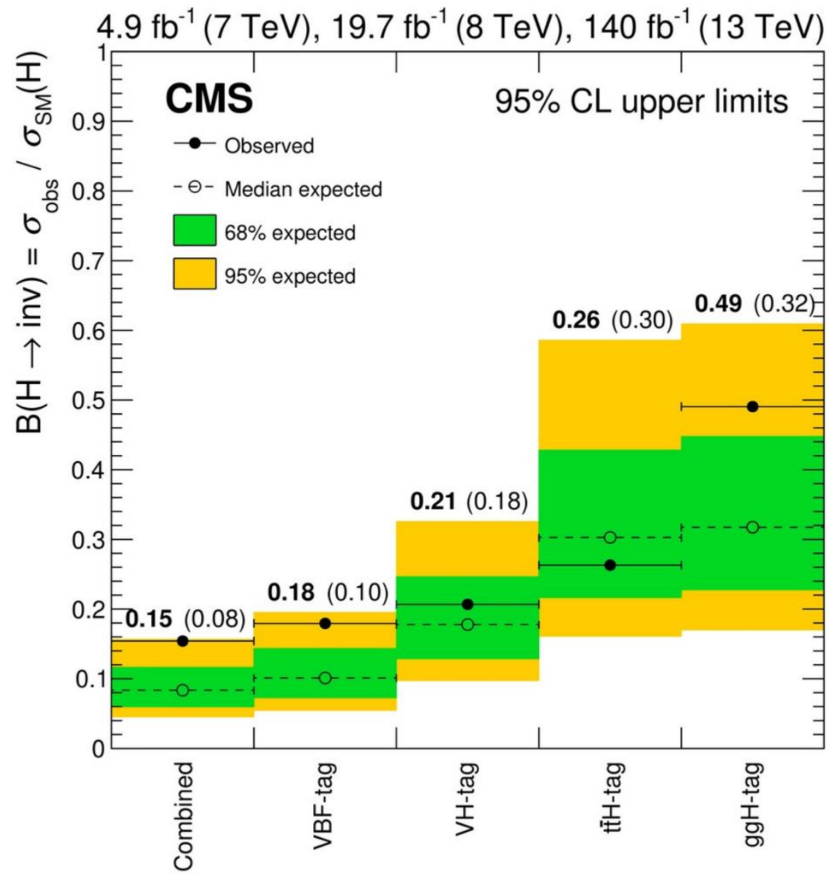
utilize data in control regions to reduce uncertainties

Use ML observables to distinguish between signal and background.

- BR(Hinv)<0.19 @ 95% CL
- Improvement of over 70% compared to the previous result of 0.67.

Put all the pieces together



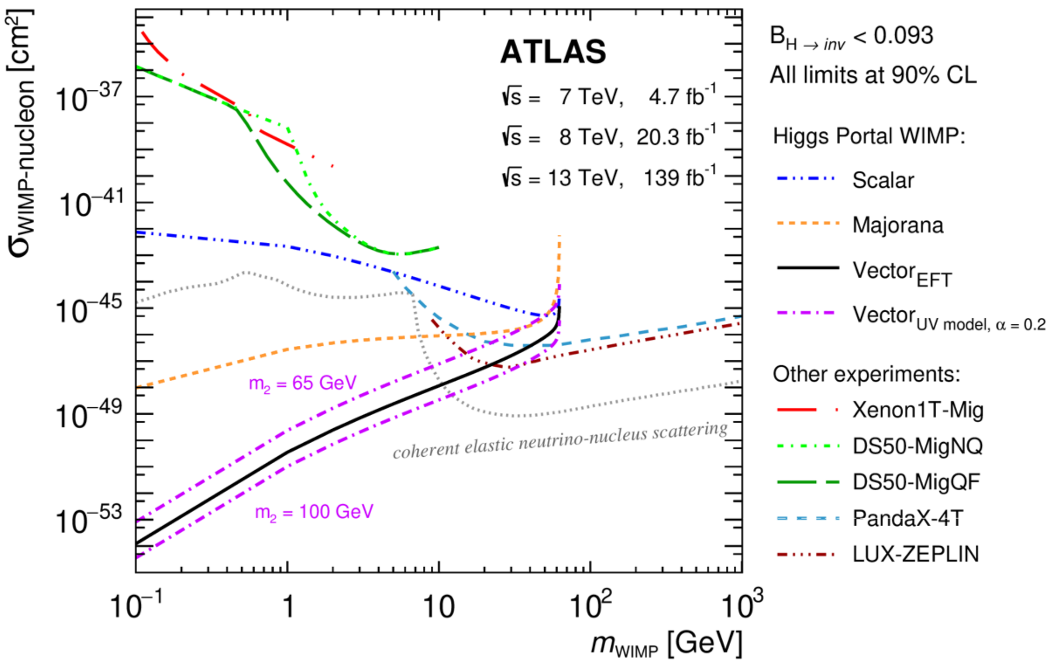


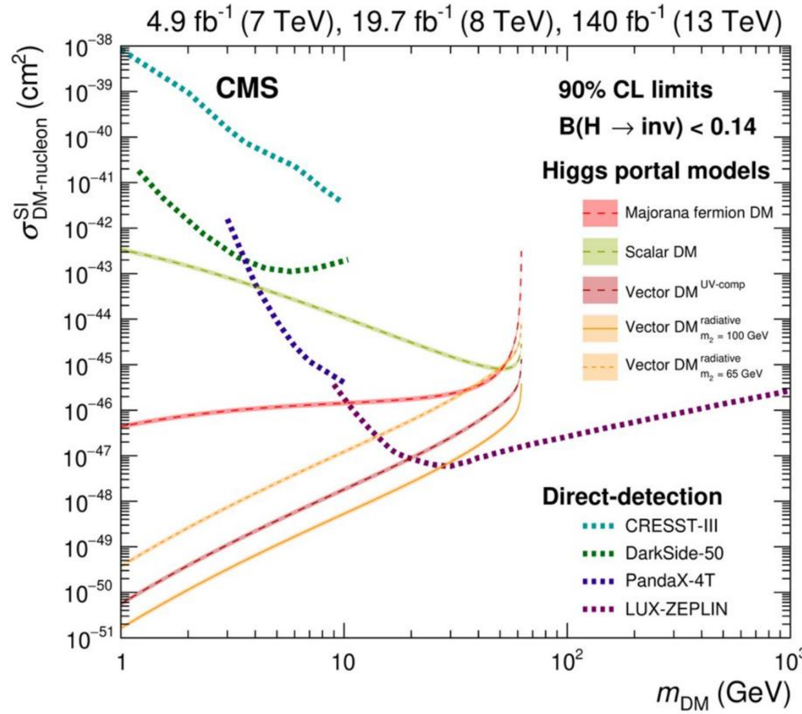
Further statistically combined All H→inv searches:

ATLAS: BR(H→inv) < 10.7% (7.7%) PLB 842 (2023) 137963

CMS: BR(H→inv) < 15% (8%) EPJC 83 (2023) 933

LHC vs Direct detection experiments

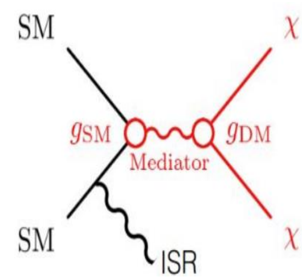




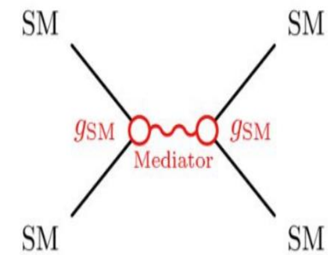
- **Significant complementarity** between LHC and direct detection experiments on DM-nucleon cross-section limits through the Higgs-portal model.

WIMP Model 2: Simplified s-channel DM 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](https://arxiv.org/abs/1507.00966)]



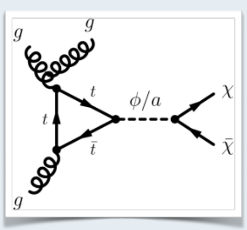
MonoX searches

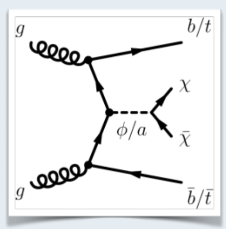


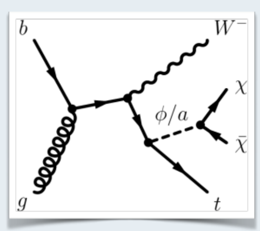
Resonance searches

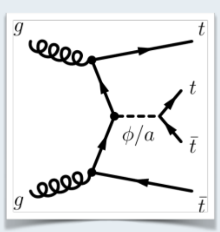
Option 1: Spin-0 mediator Scalar/Pseudoscalar

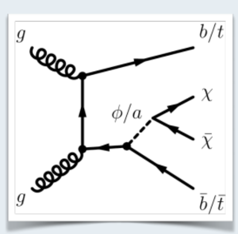
Yukawa-like couplings







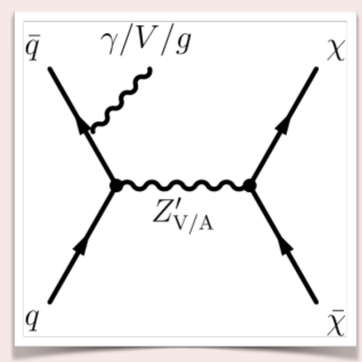




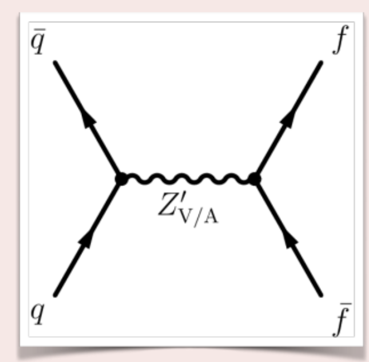
Free parameters: $g=g_u=g_d=g_l$, g_{DM}, m_{Med}, m_{DM}

Option 2: Spin-1 mediator Vector/Axial-Vector

γ^μ/γ^5 couplings

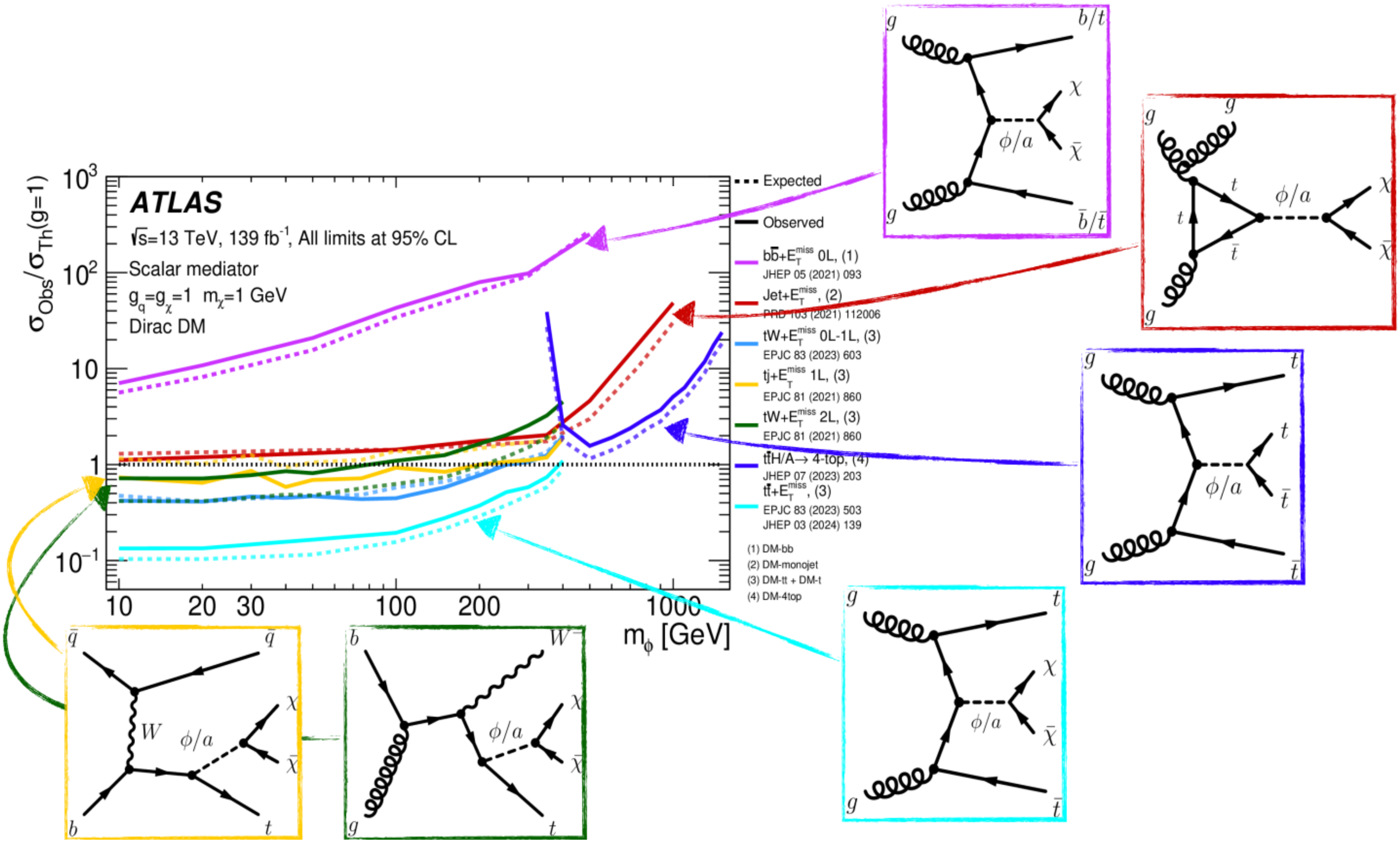


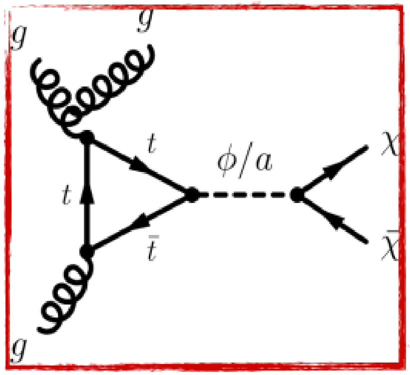
$$\mathscr{L} \simeq \mathscr{L}_{SM} + \sum_{i=part.} g_{p_i} M_\mu \bar{p}_i \gamma^{\mu/5} p_i$$

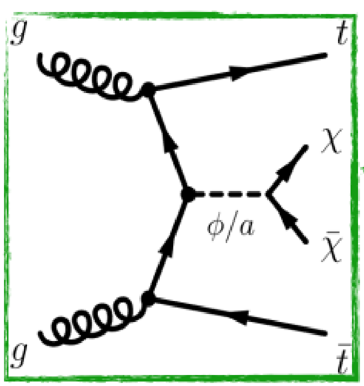


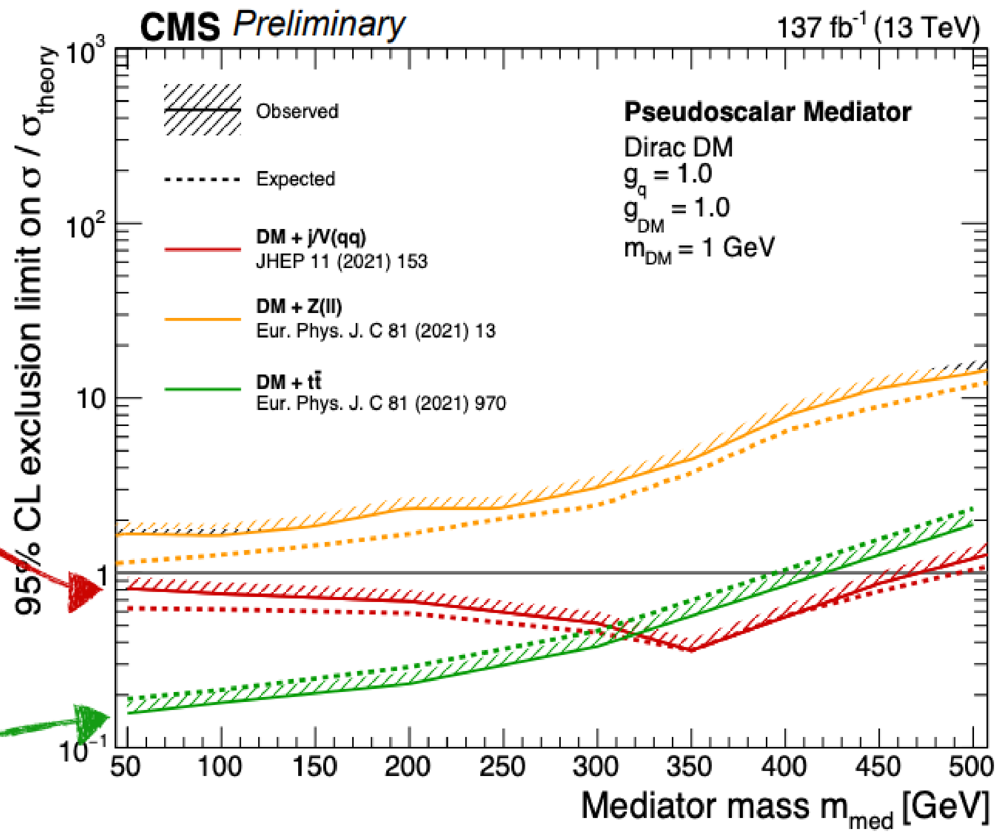
Free parameters: g_q, g_l, g_{DM}, m_{Med}, m_{DM}

Scalar mediator: signatures and results





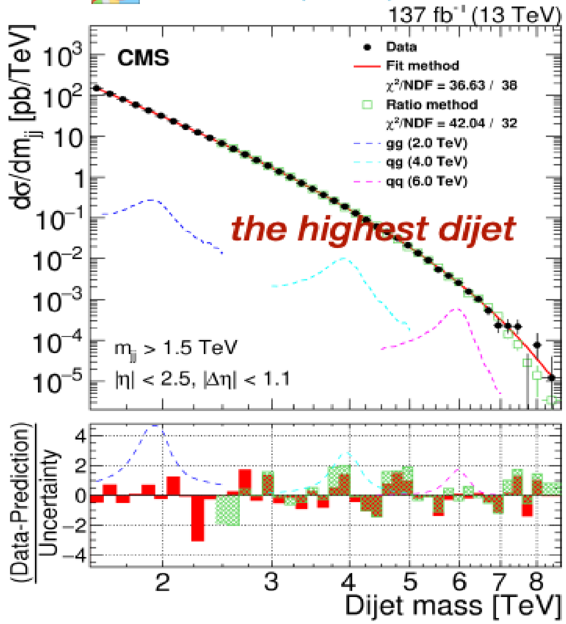




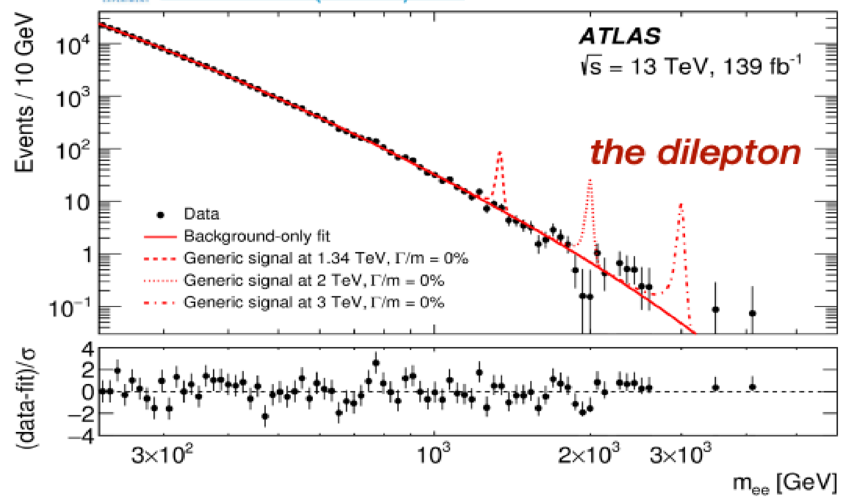
[CMS DM summary plot]

Vector mediator: resonance searches

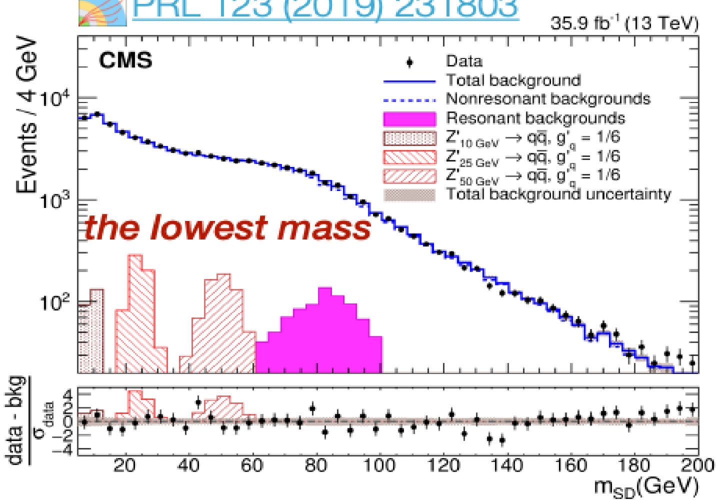
JHEP 05 (2020) 033



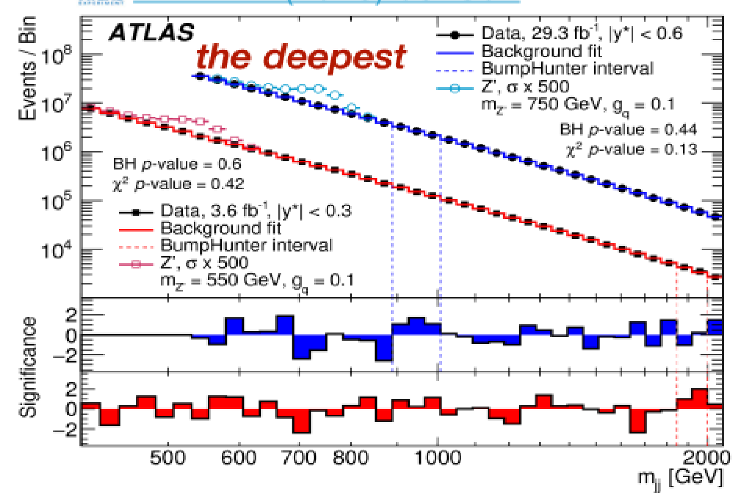
PLB 796 (2019) 68



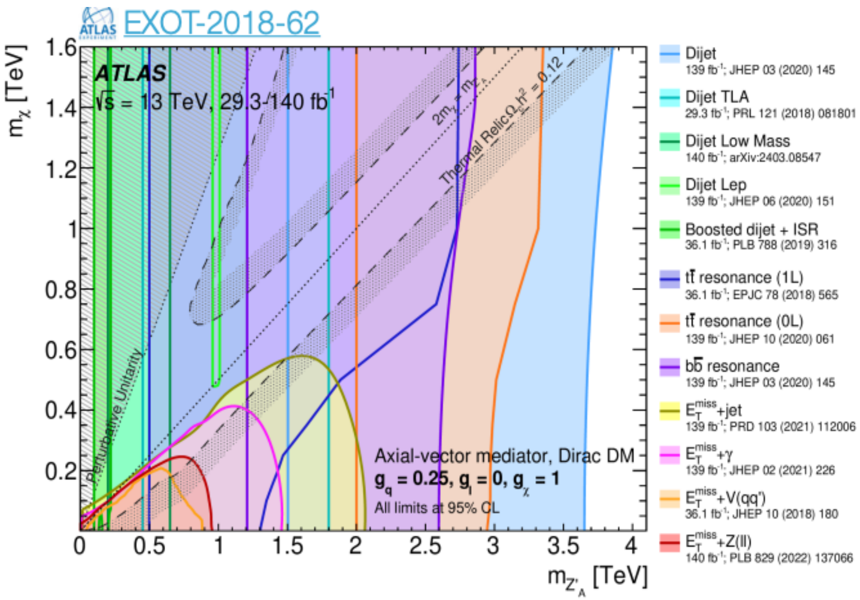
PRL 123 (2019) 231803

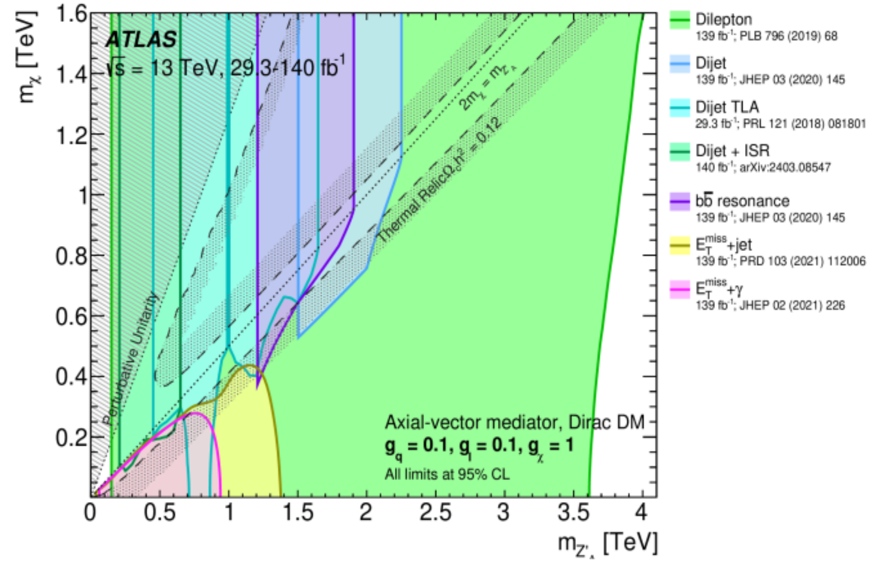


PRL 121 (2018) 081801



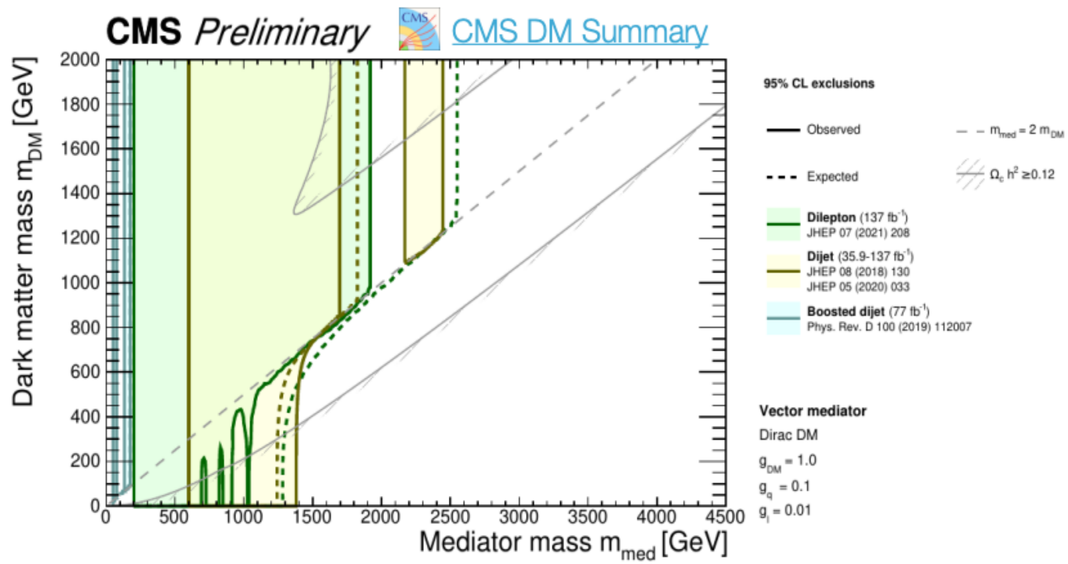
Vector mediator – m_χ -m_{Med} plane





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



WIMP Model 3: "Extended Higgs sector" 2HDM+a

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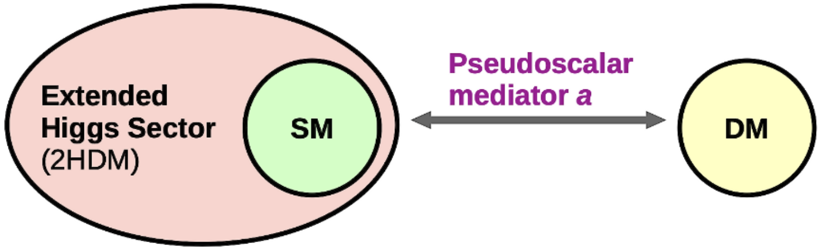
Two Higgs doublet model + pseudo-scalar

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 in 2HDM+a

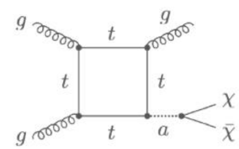
Rich phenomenology and great ***signature interplay***

Re-interpretations

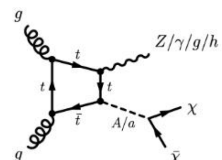
simplified model

↓

2HDM+a model

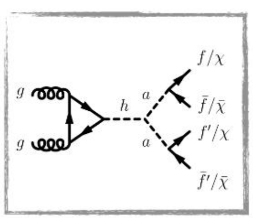


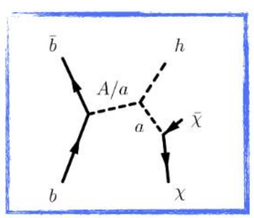
g_q, g_χ, m_χ, m_a

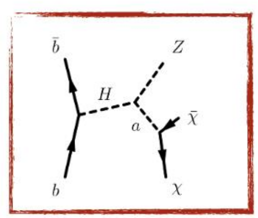


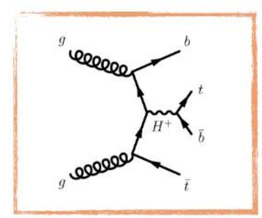
α, $\tan\beta$, $\sin\theta$, m_a, m_A, $m_{H\pm}$,…

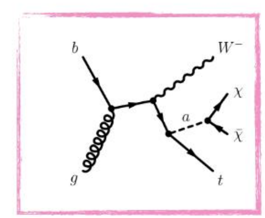
Dedicated searches





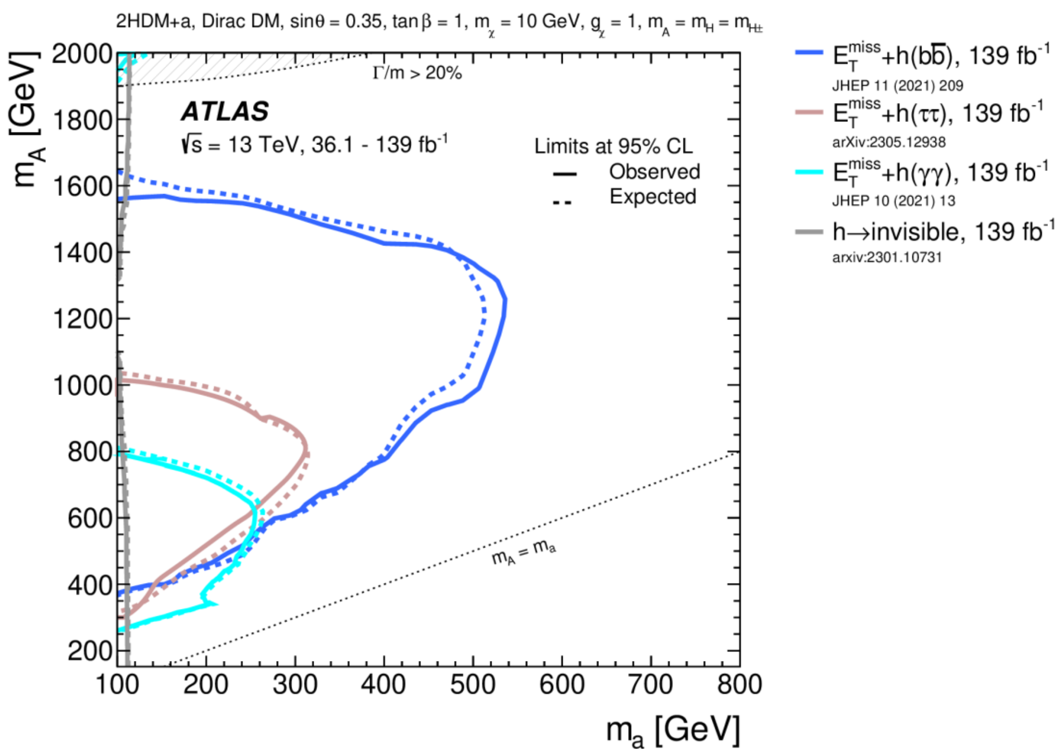






…

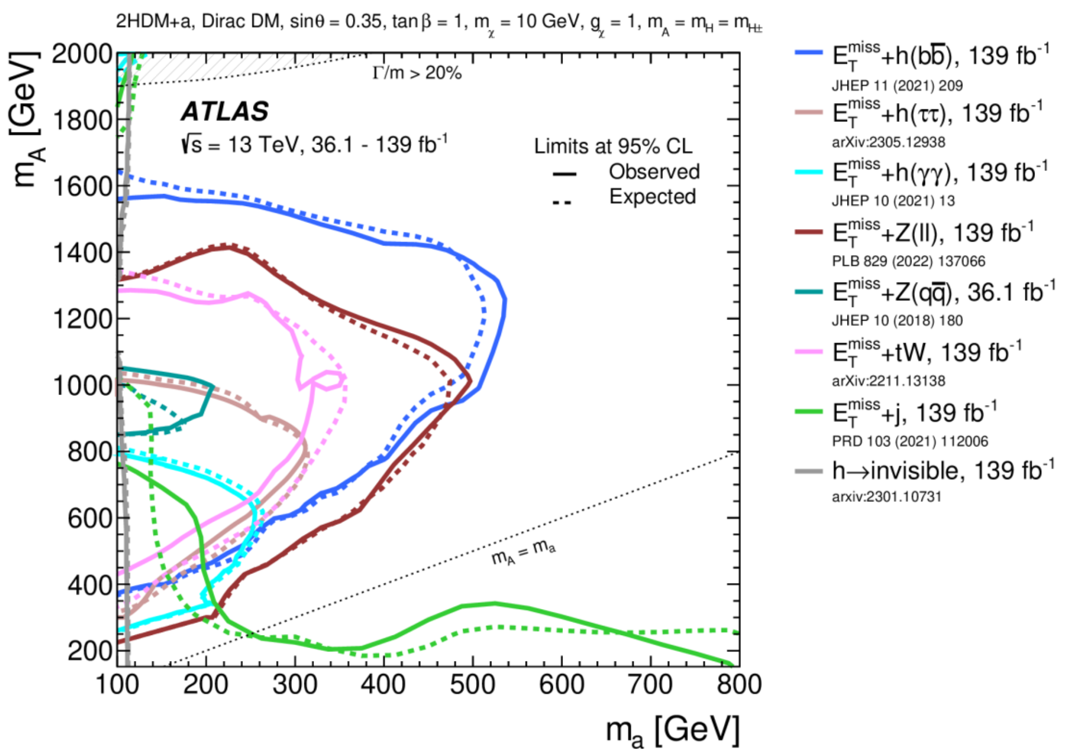
Evolution of sensitivity I



Higgs + DM signatures

DM appears in the final state together with Higgs

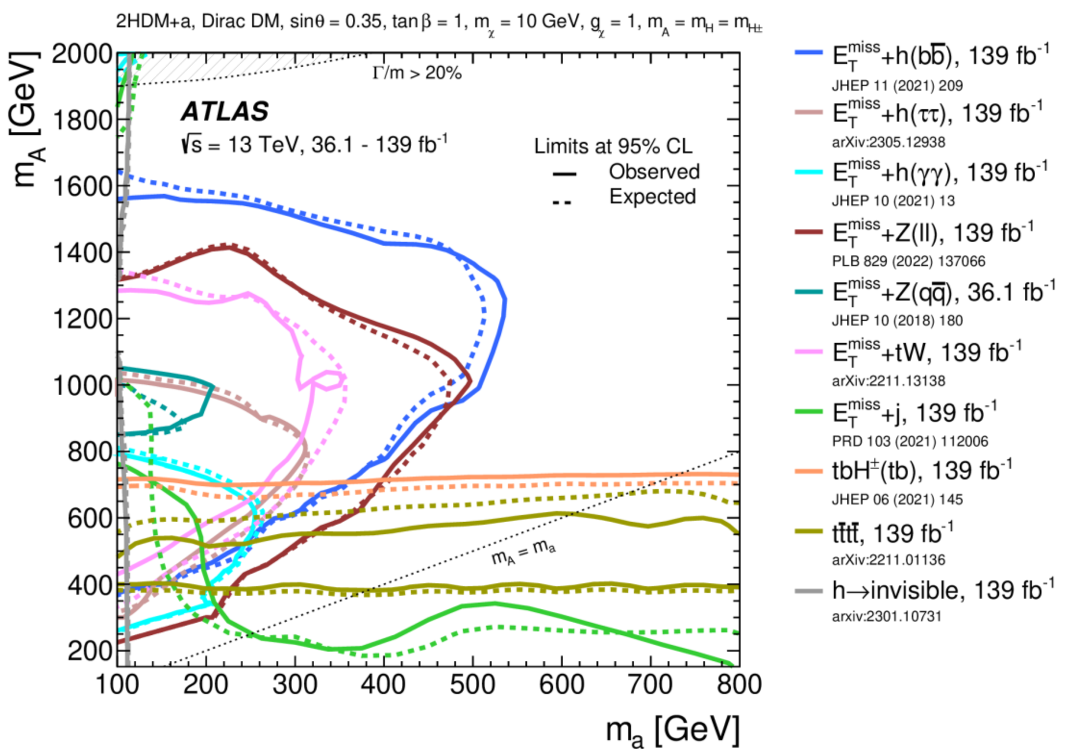
Evolution of sensitivity II



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

DM appears in the final state together with other SM particles

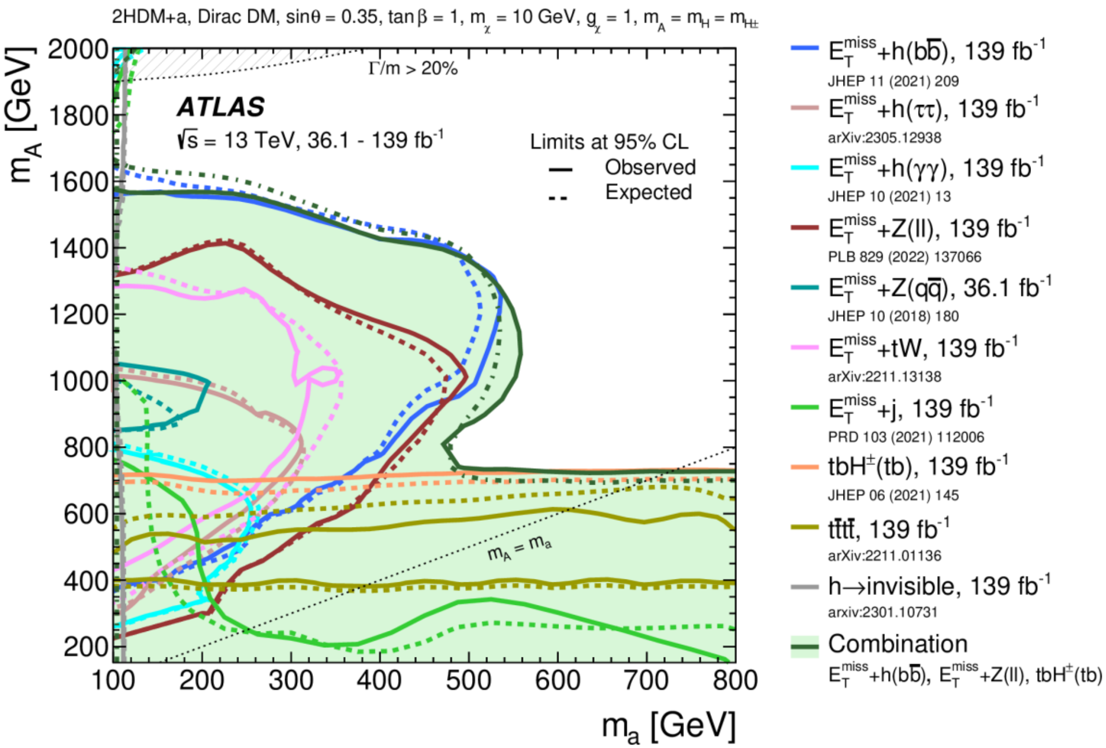
Evolution of sensitivity III



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

DM doesn't need to appear in the final state

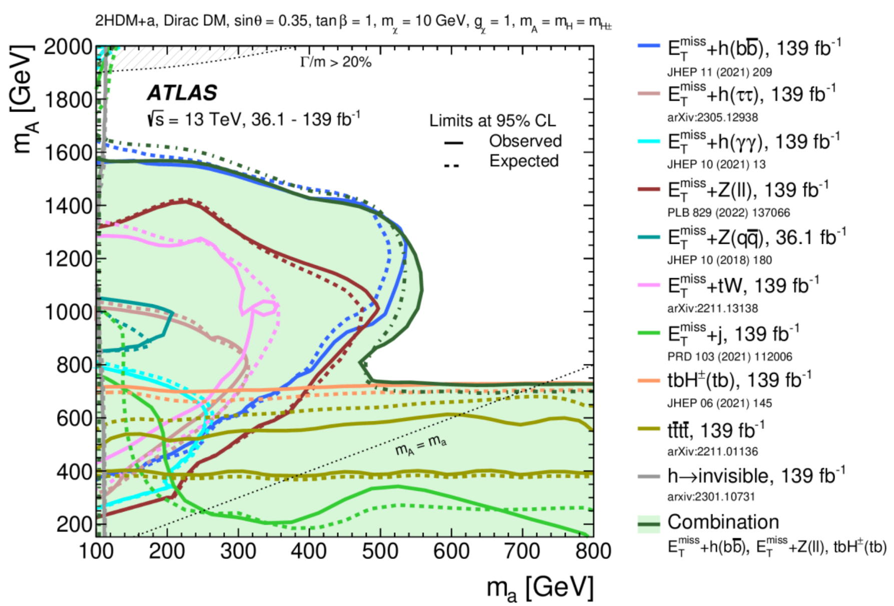
Evolution of sensitivity IV

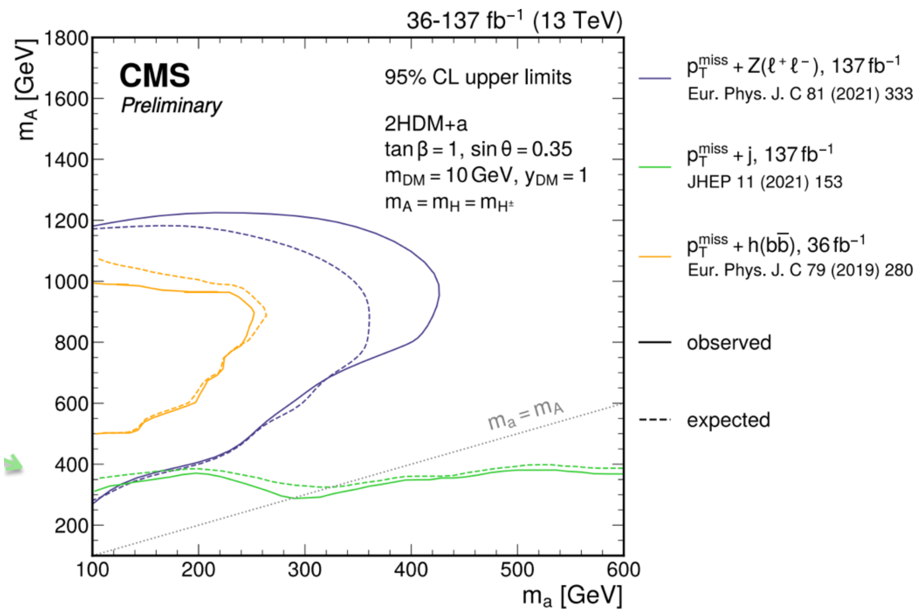


Combine analyses – reaching the best sensitivity!

Having three most sensitive channels combined

Complementarity across channels



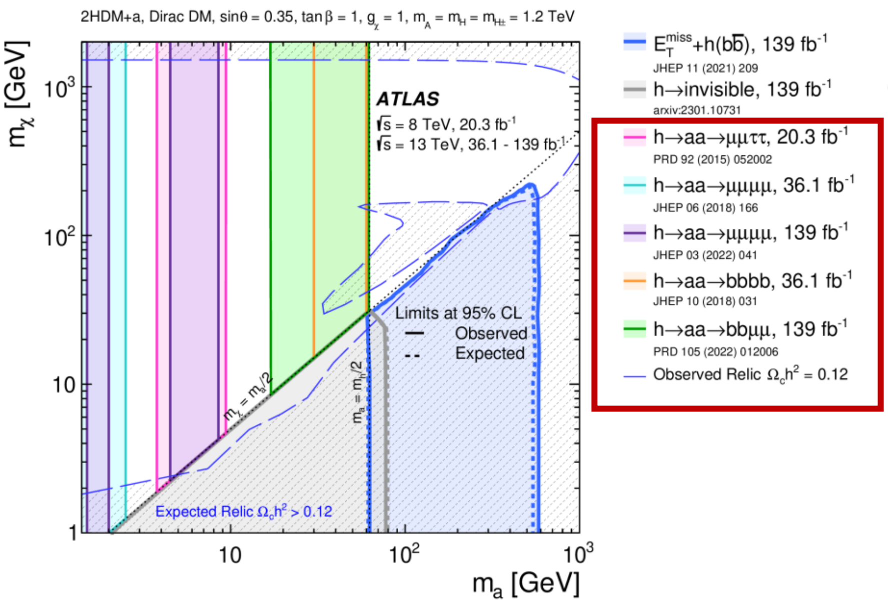


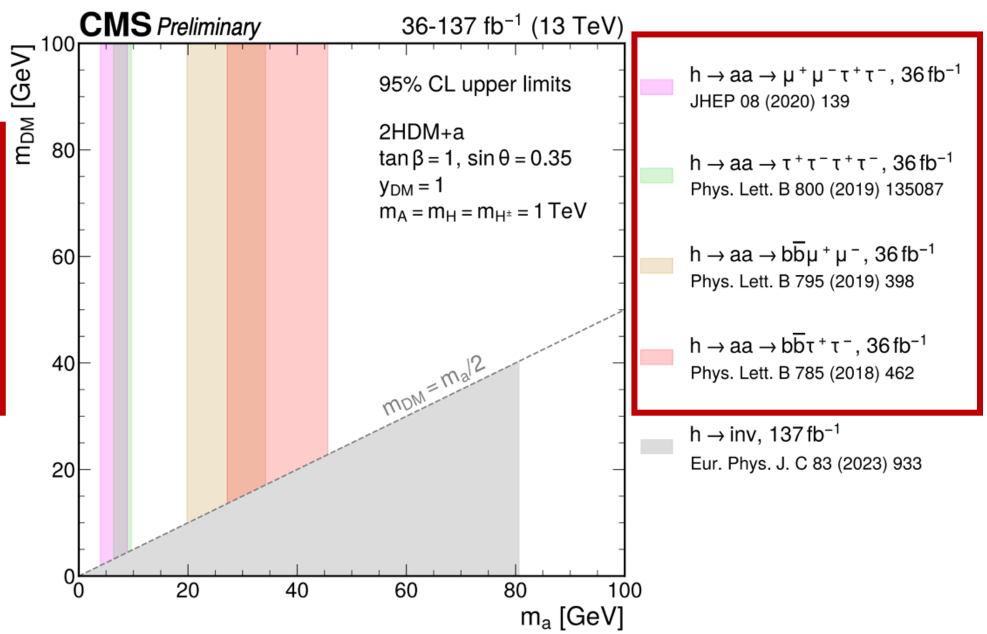
[Science Bulletin 69 (2024) 3005]

[CMS DM summary plot]

Exotic Higgs decay also contributes!

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



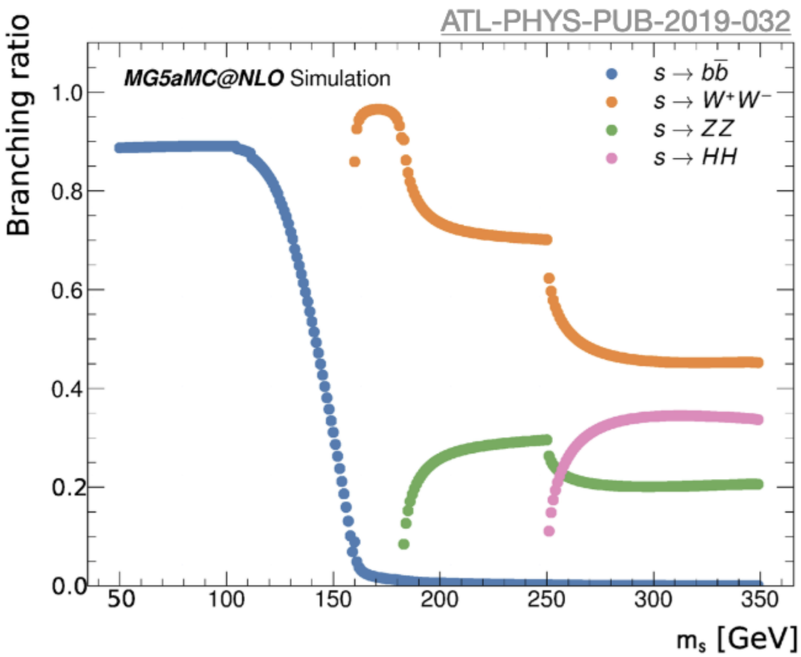


[Science Bulletin 69 (2024) 3005]

[CMS DM summary plot]

Model 4: Search for "Dark Higgs"

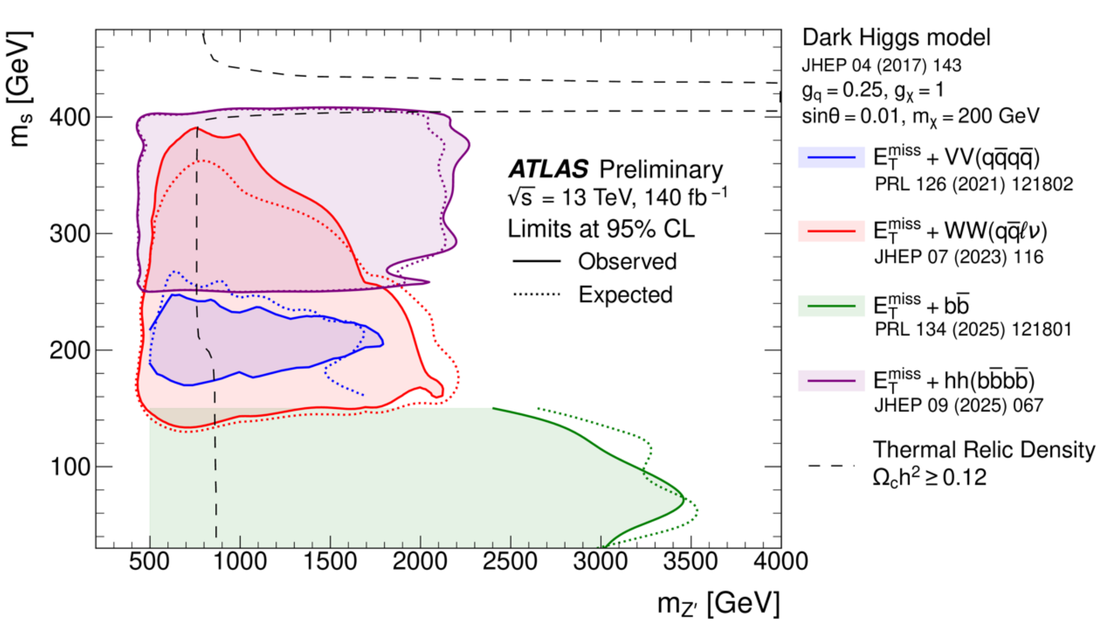
- **Dark sector model** with **a scalar *s*** (dark Higgs)
- Mediator Z' coupling to DM

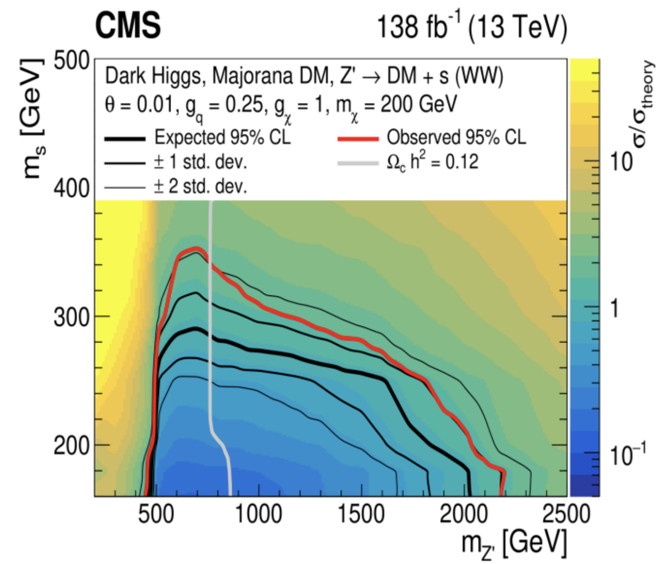


Mases of BSM particles and couplings as new parameters

Yukawa-like couplings favours different final states for different mass scenarios.

Search for "Dark Higgs"





CMS *s → WW→2l2ν/lνqq'*

JHEP 03 (2024) 134

$m_s \gtrsim 160$ GeV

s→WW decays

Hadronic: W(qq)W(qq)

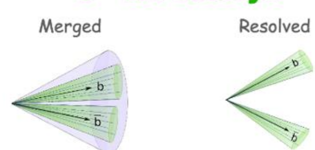
leptonic: W(lν)W(lν)

mixed: W(qq)W(lν)

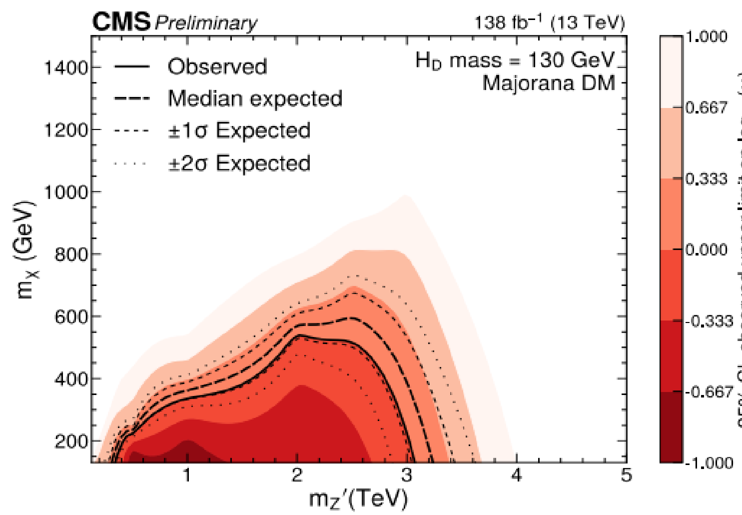
Lepton channels more sensitive

$m_s \lesssim 160$ GeV

s→bb decays



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

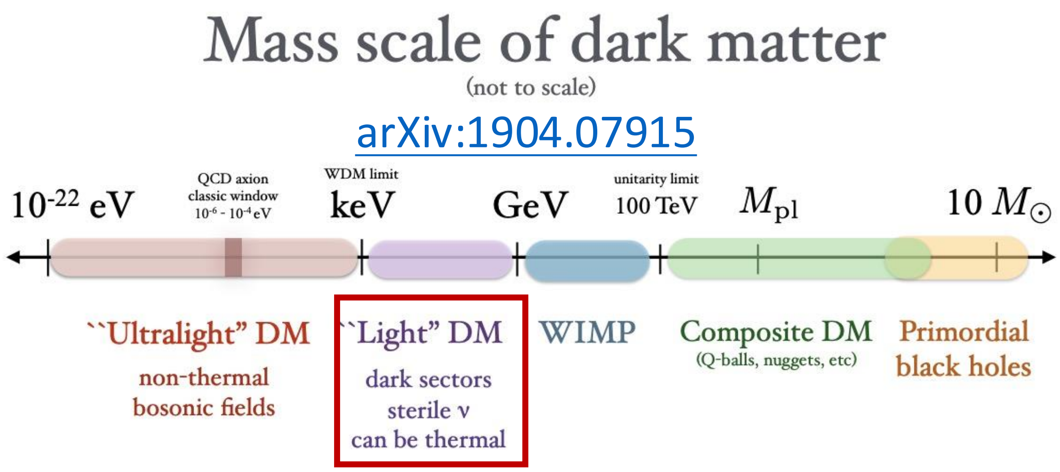


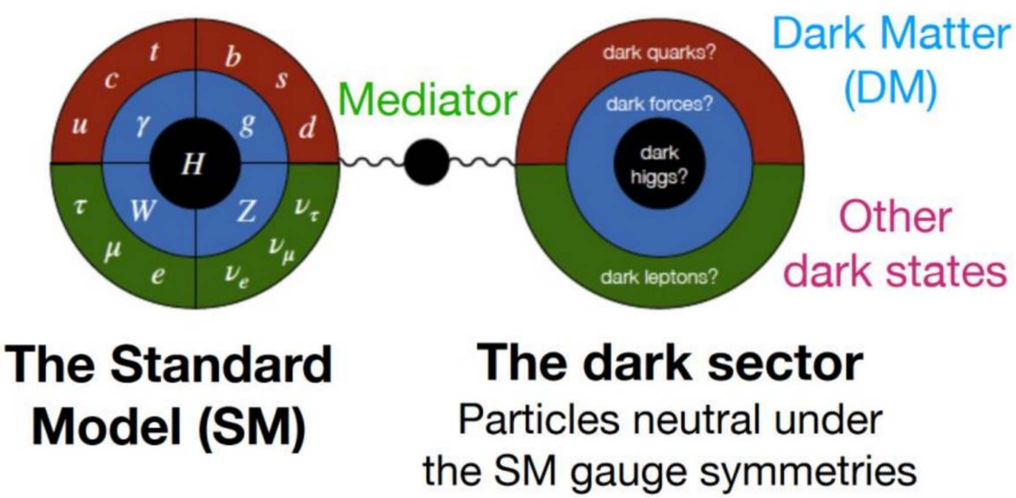
CMS *s → bb*

[ATLAS Dark Matter Summary Plots]

[PAS-SUS-23-013]

Beyond WIMP + Higgs portals — **dark sectors with their own dynamics**





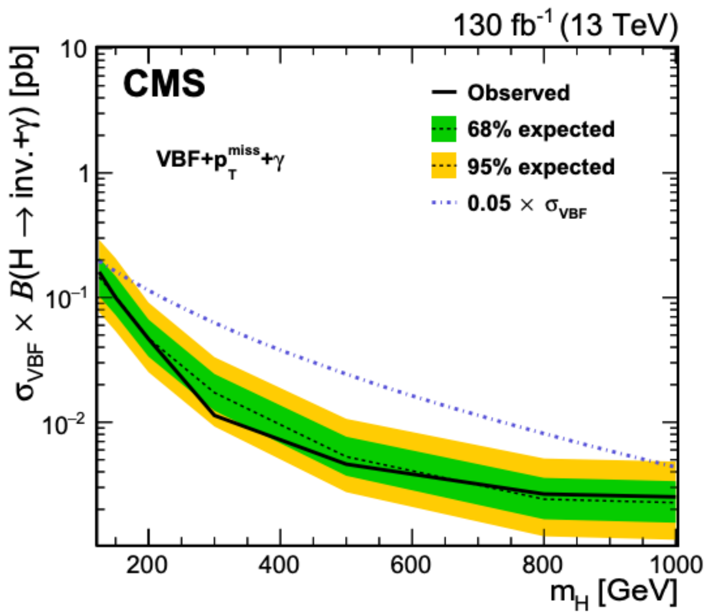
Dark sector portals

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

… + strongly-coupled **dark QCD**

Higgs decay to dark photons

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

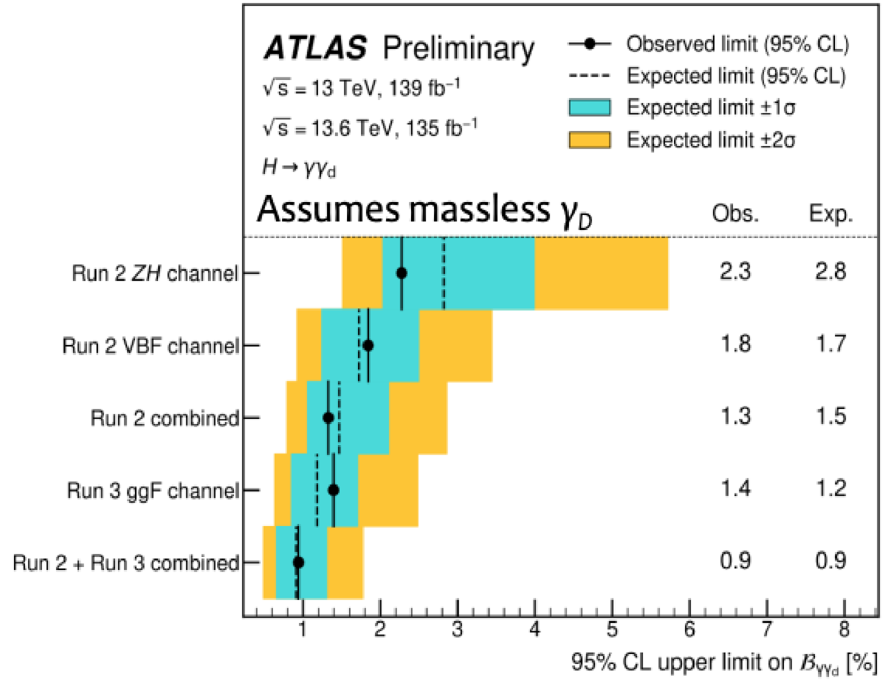


CMS 95% U.L. on BR(H125→γγ$_D$):

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]



Reference coming soon

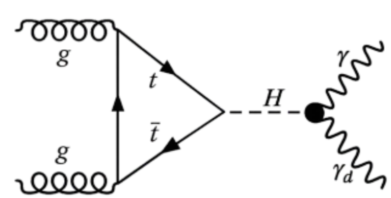
ATLAS 95% U.L. on BR(H125→γγ$_D$):

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]

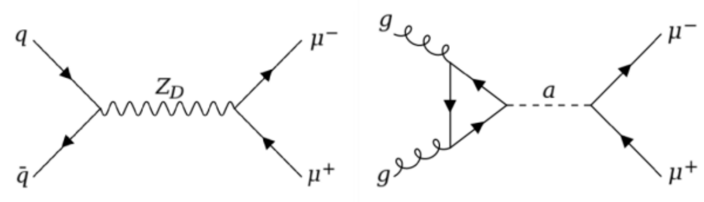
ZH+VBF+ggF: **0.9% (0.9%) New results** [link]

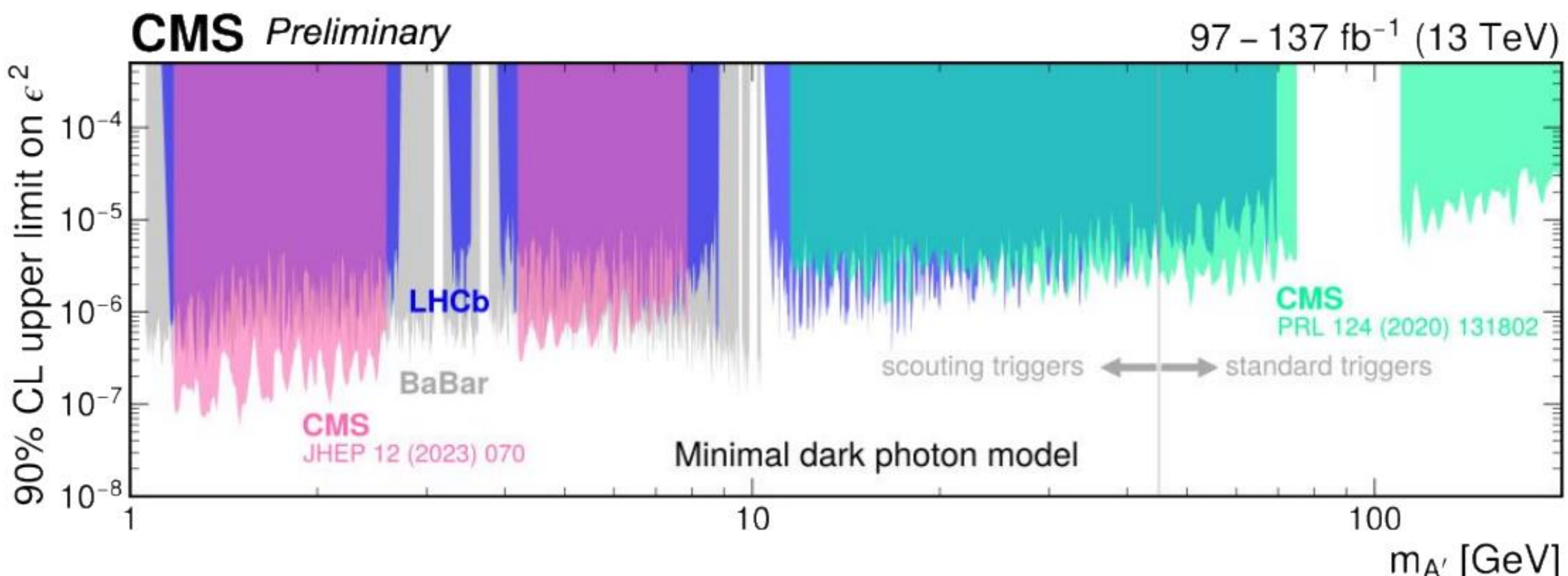


DY-like production of dark photons

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

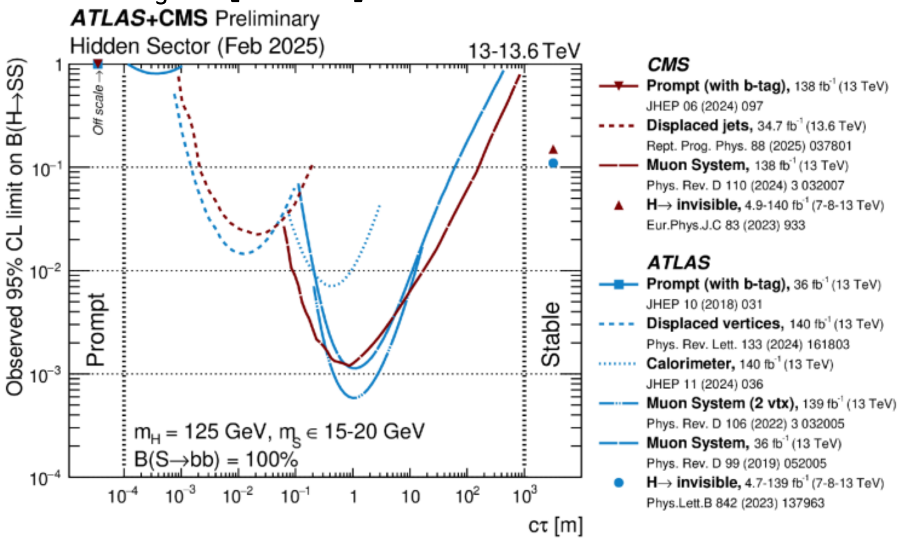


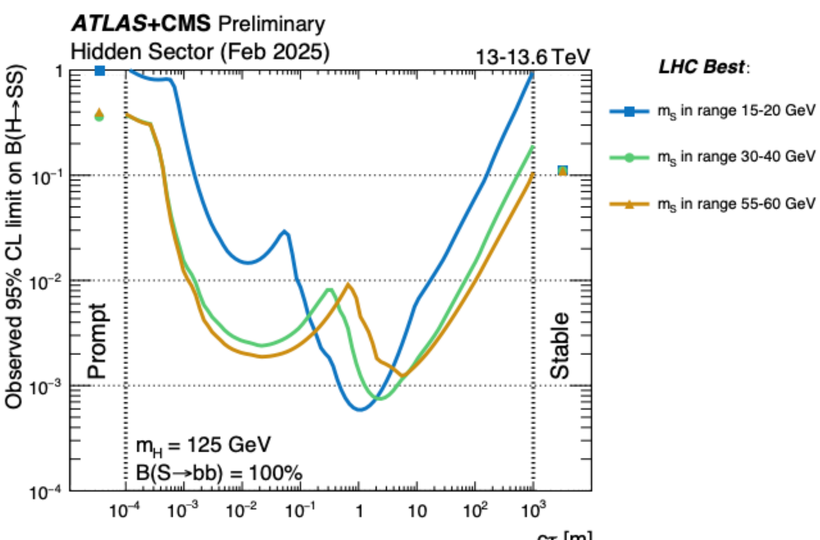


[CMS DM summary plot]

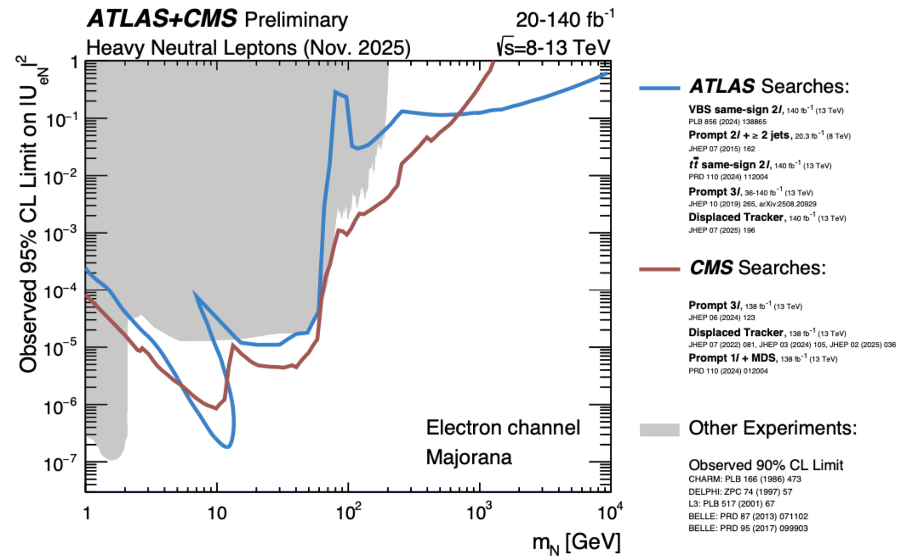
Hidden Sector H→SS

m_S in [15-20] GeV

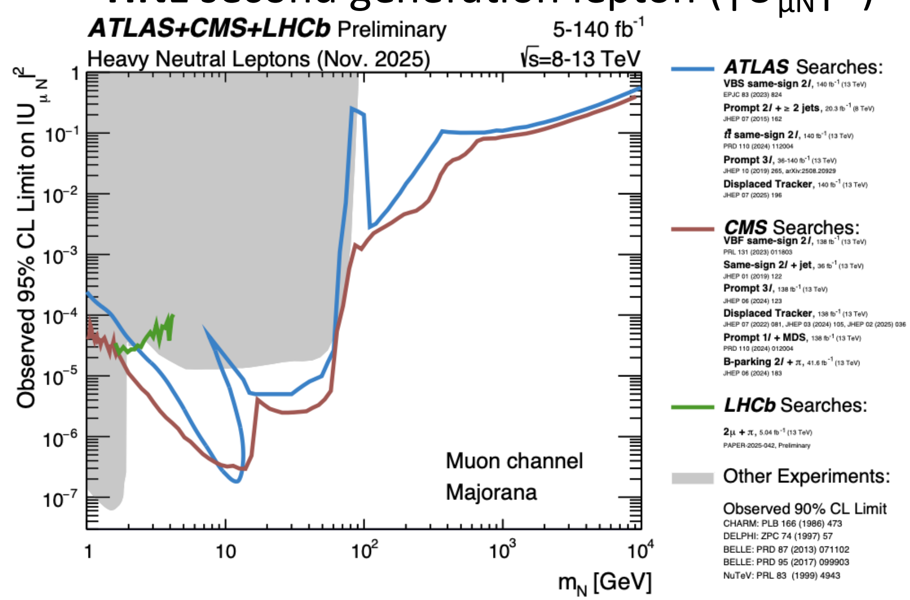




HNL first generation lepton ($|U_{eN}|^2$)



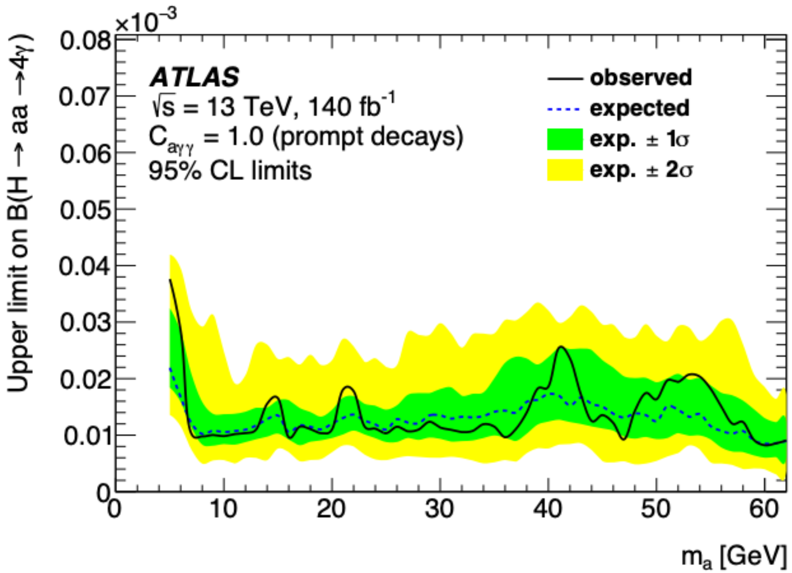
HNL second generation lepton ($|U_{\mu N}|^2$)

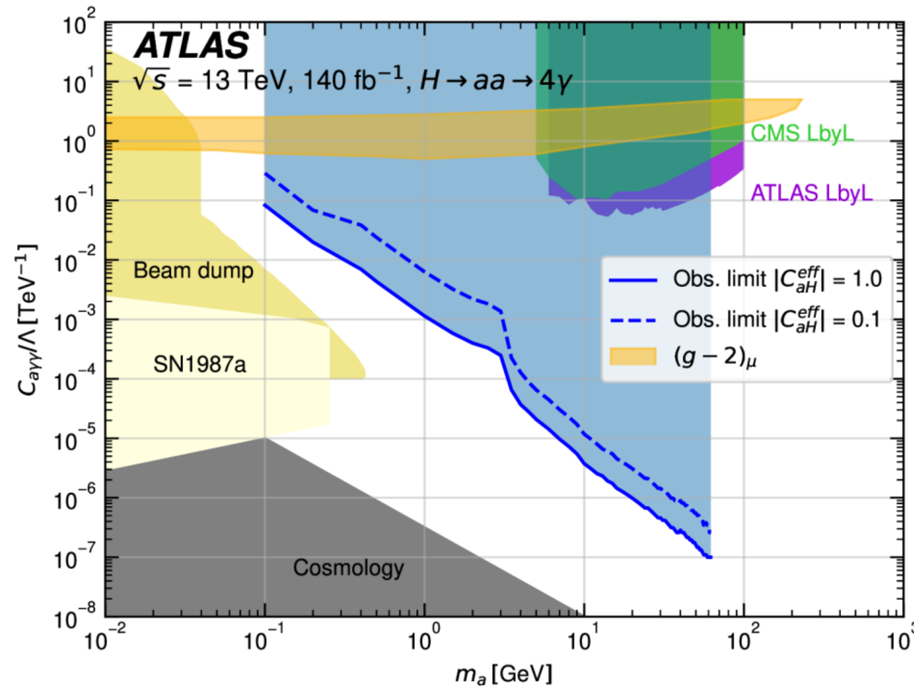


ALP mass range probed: $0.1 < m_a < 60$ GeV

[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





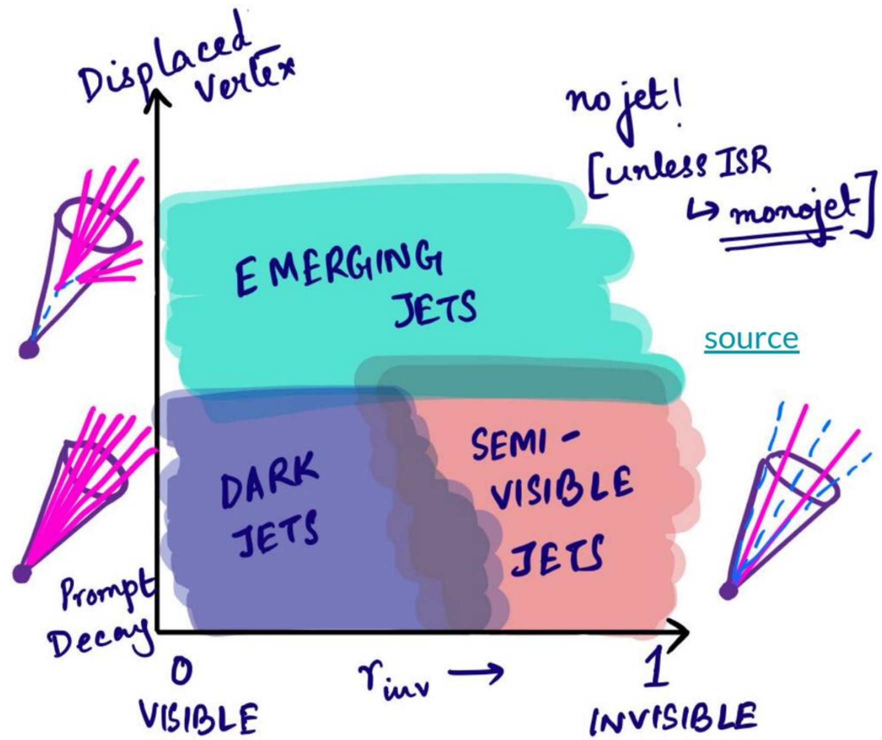
- **First time coverage of the full mass range** between 100 MeV and 62 GeV
- **Most stringent limits to date.**

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)

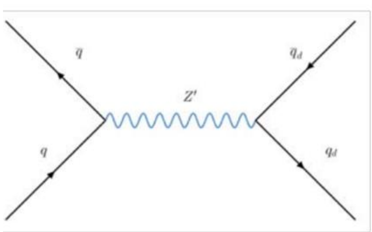
Dark QCD

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

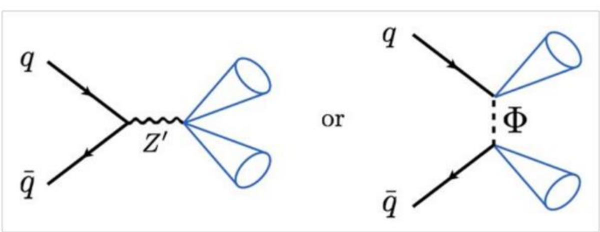
- Dark hadrons decaying PROMPTLY in a QCD-like fashion, fully (**dark jets**)
- or partially back to visible sector (**semi-visible jets**)
- Dark hadrons undergoing DISPLACED decays in a QCD-like fashion (**emerging jets**)



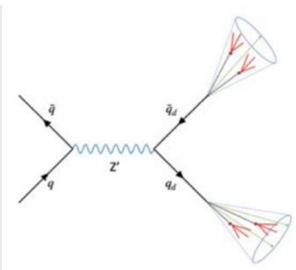
source



Dark jets



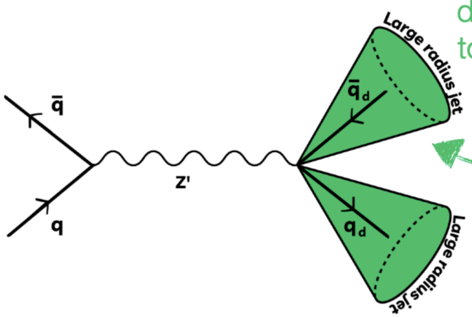
Semi-visible jets



Emerging jets

Prompt dark jets

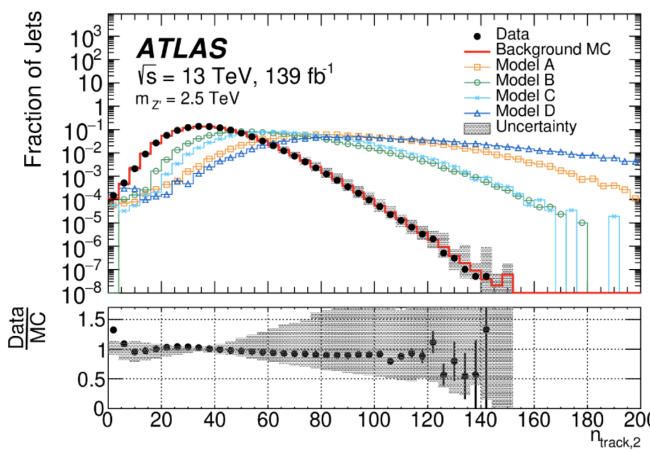
Signature: **larger, broader jets with more tracks**

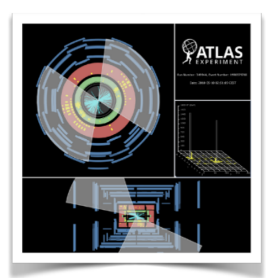


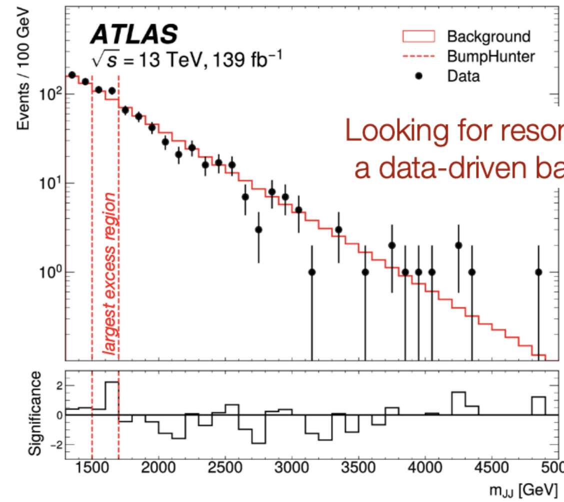
dark quarks expected to generate larger jets wrt SM quarks

Different fragmentation in Dark Sector Models

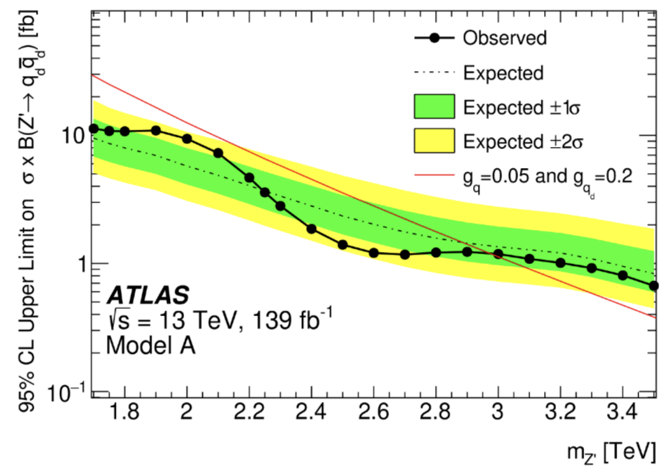
expected many more charged particles wrt SM counterpart







Looking for resonance over a data-driven background

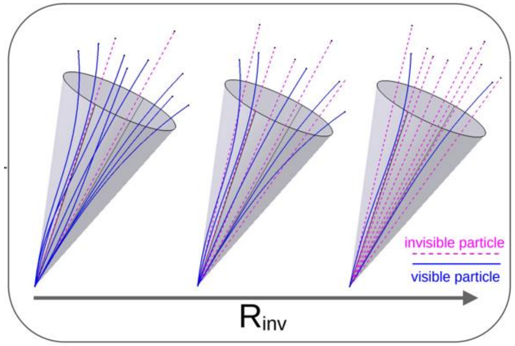


JHEP 02 (2024) 128

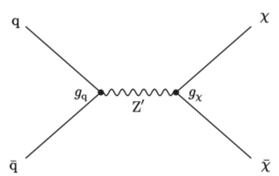
Semi-visible jets

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

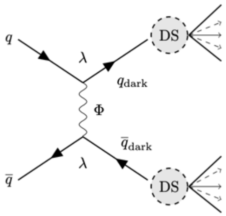
Signature: **Missing transverse momentum aligned with a jet.**

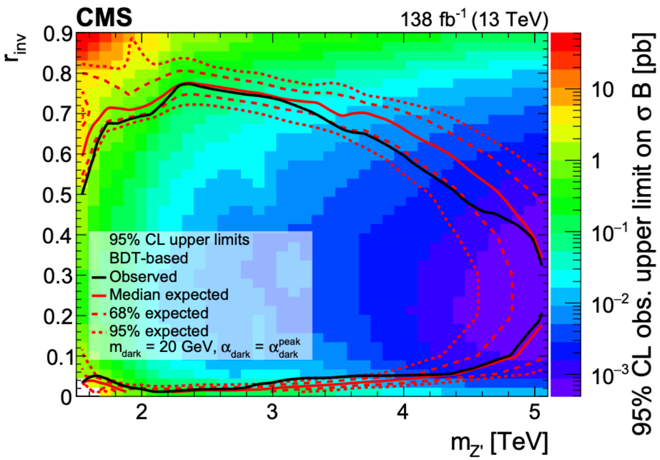


CMS Search (s-channel Z')

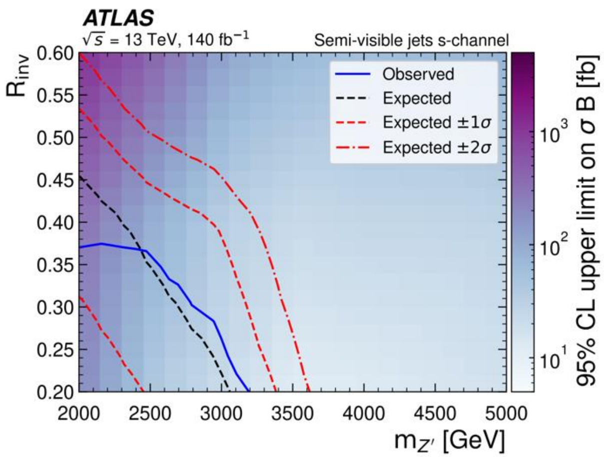


ATLAS Search (s- and t-channel)

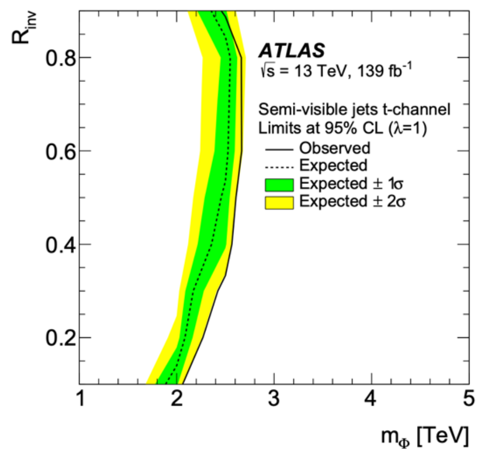




Excludes Z' mass up to **5.1TeV**
[JHEP 06 (2022) 156]



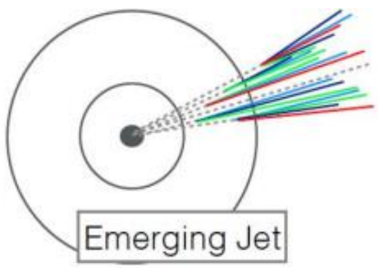
Excludes Z' mass up to **3.2 TeV**
[Phys. Rev. D 112 (2025) 012021]



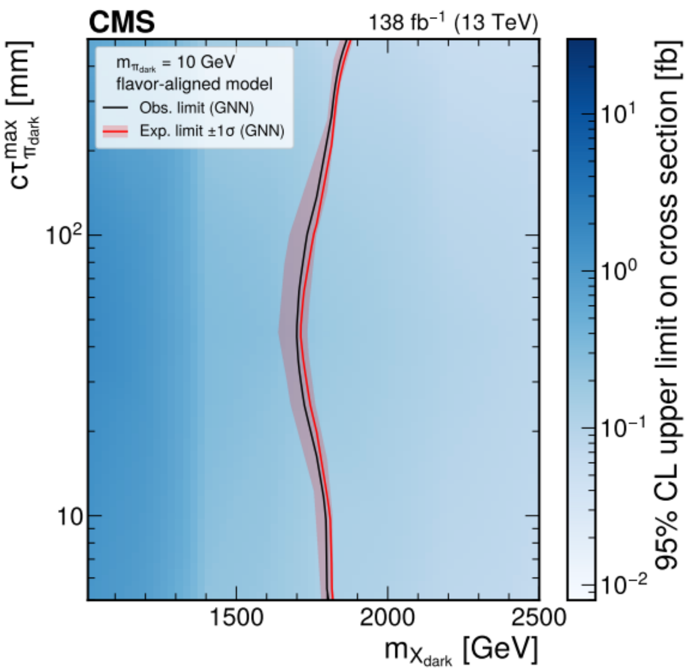
Excludes ϕ mass up to **2.7 TeV**
[Phys. Lett. B 848 (2024) 138324]

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.

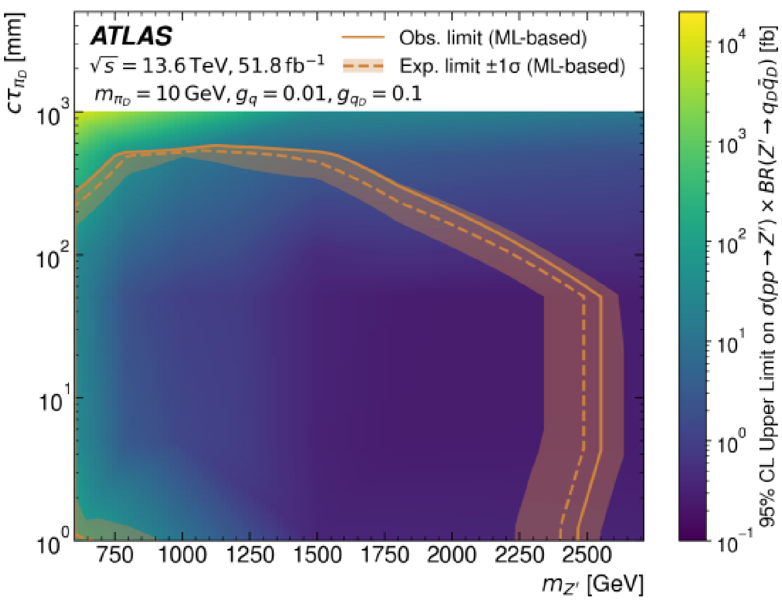


CMS Search



Excludes mediator up to **1950 GeV** (τ = 1-500 mm).
[JHEP 07 (2024) 142]

ATLAS Search

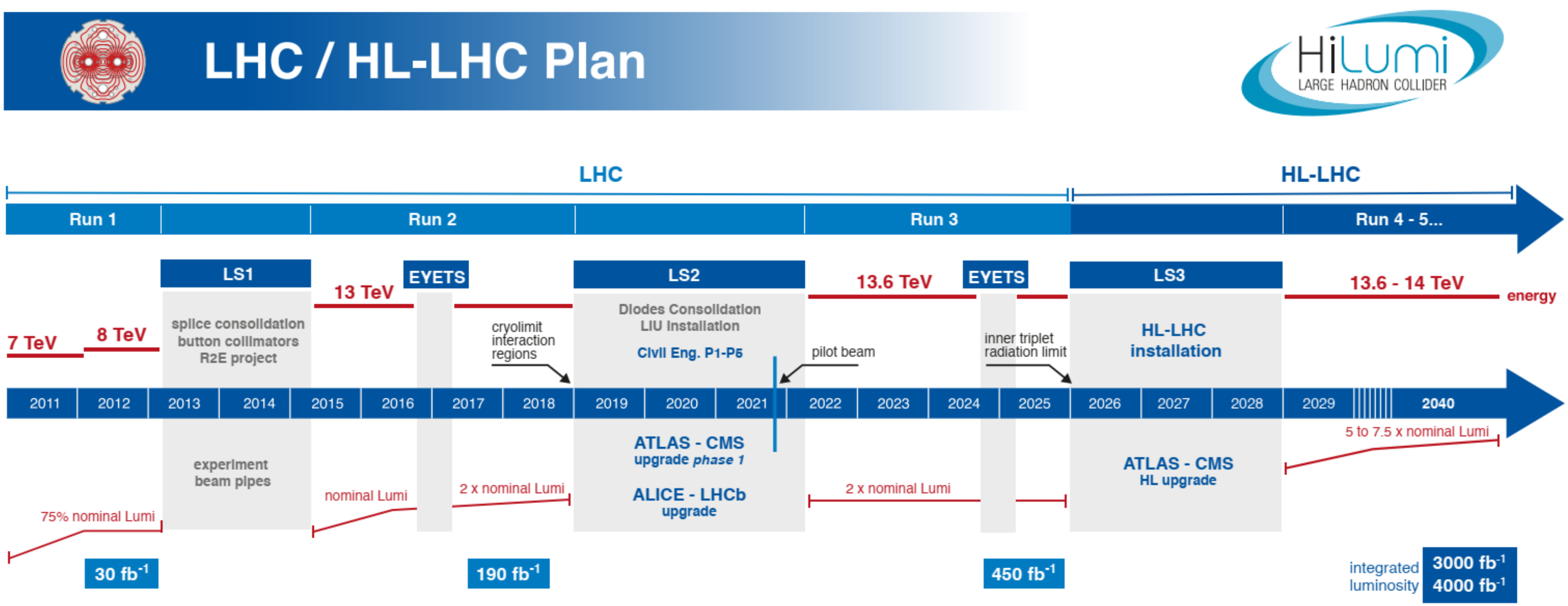


Excludes Z’ up to **2559 GeV** (τ = 5-50 mm).
[Rep. Prog. Phys. 88 (2025) 097801]

Outlook: LHC and HL-LHC

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]

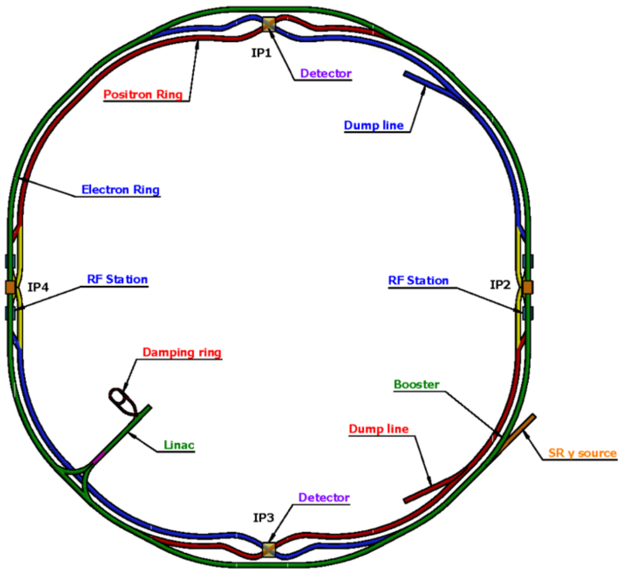
[LHC BSM WG Meeting]

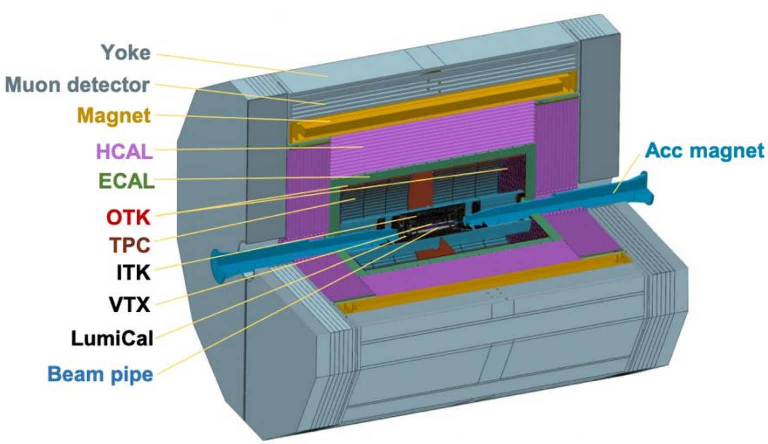
We warmly welcome our theory colleagues to contribute their expertise to the LHC dark matter search program!

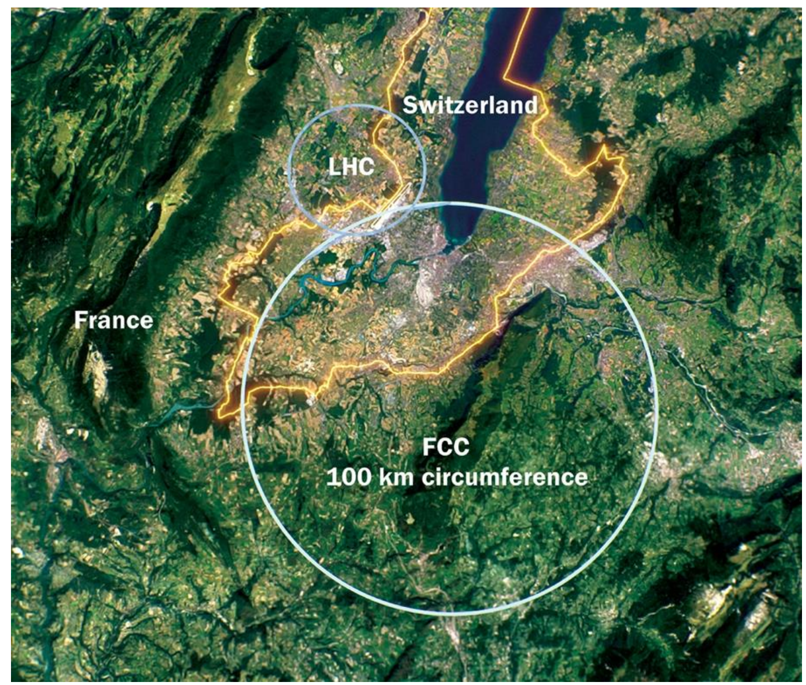
Recent DM updates:

- **t-channel DM models:** white paper
- **New benchmark/white paper in preparation:**
  - **2HDM+a:** Call for contributions: 1st Taskforce meeting on June 29th
  - **Dark QCD:** Taskforce meeting on June 16th

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

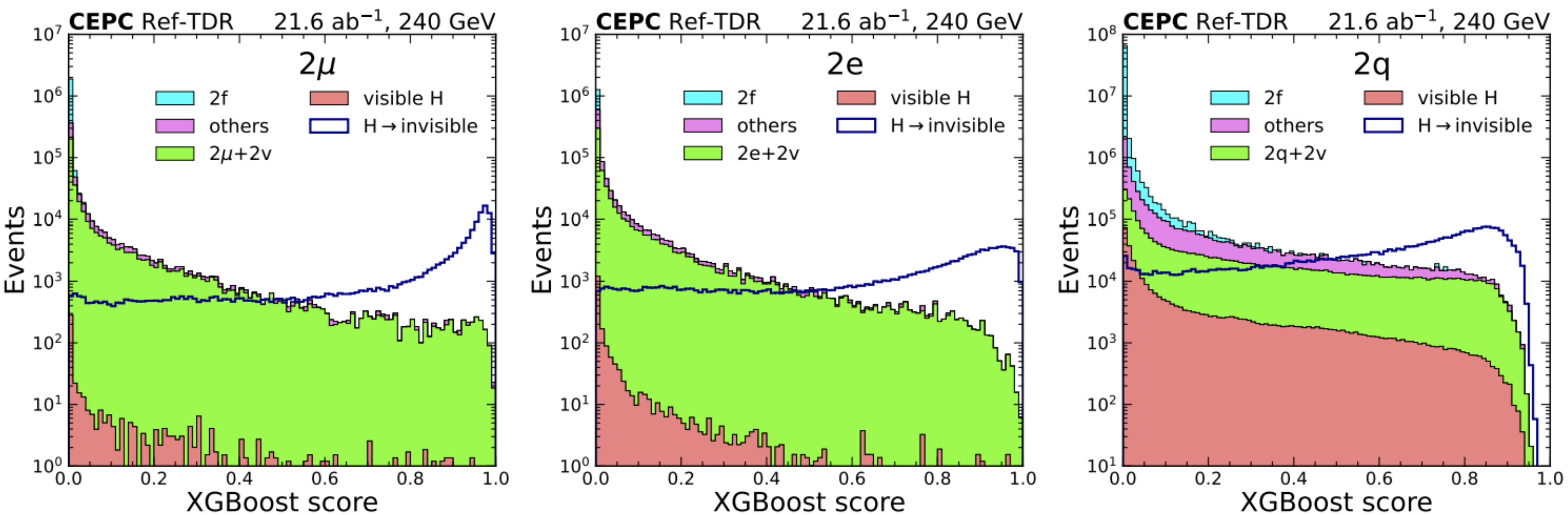






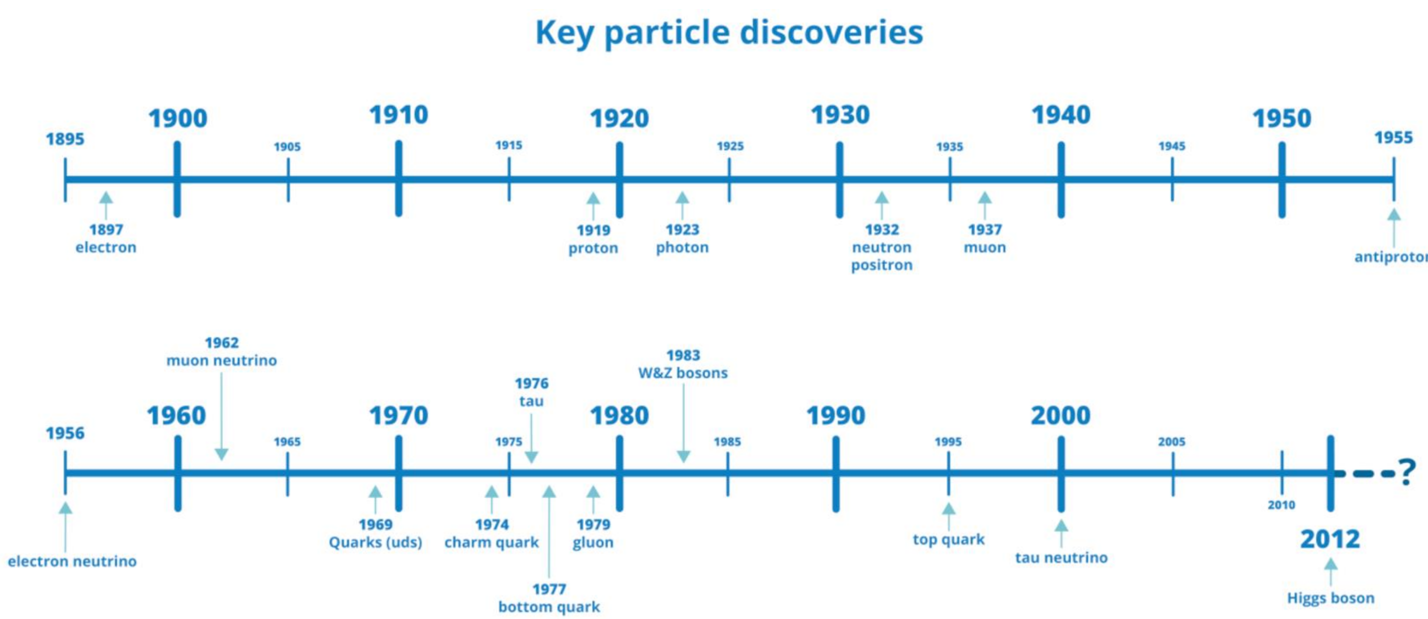
Outlook: Higgs invisible BR on FC

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



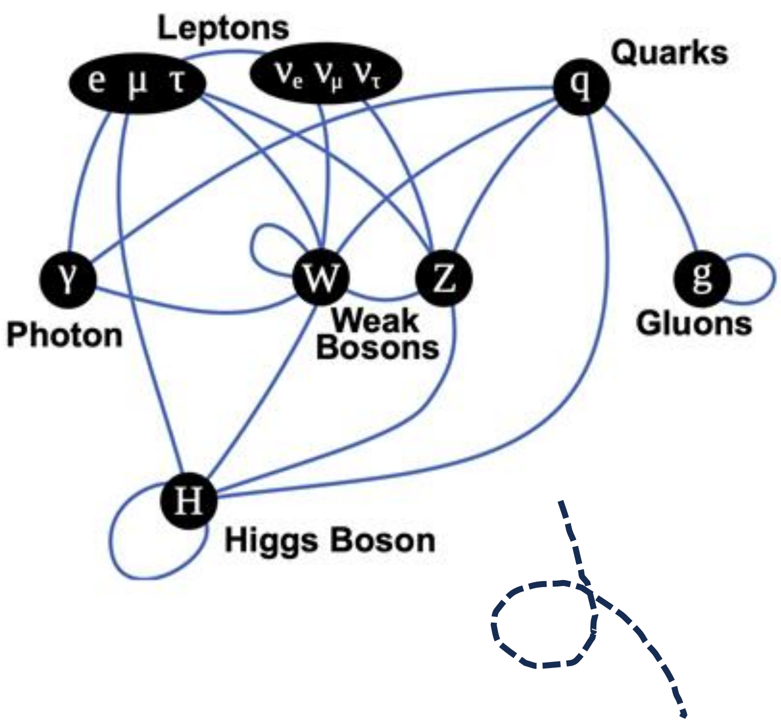
channel	uncertainties	significance of SM obs.	UL on BSM BR
2μ	$-42\%/+43\%$	2.5σ	0.089%
$2e$	$-60\%/+62\%$	1.7σ	0.13%
$2q$	$-29\%/+29\%$	3.4σ	0.061%
combine	$-22\%/+22\%$	4.5σ	0.047%

- 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!**



Thanks

Open questions beyond the SM



BSM particles? DM?

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

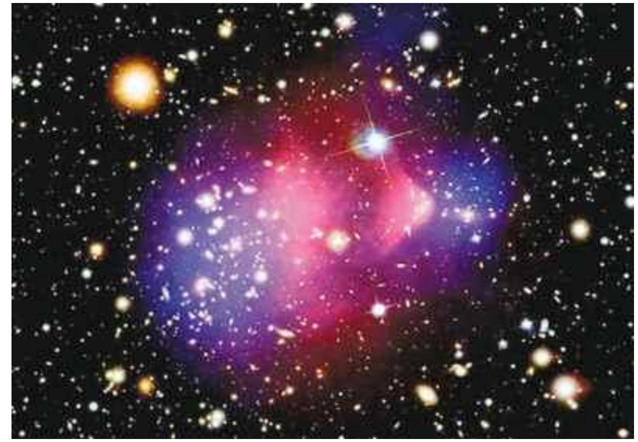
But the **SM cannot explain**:

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

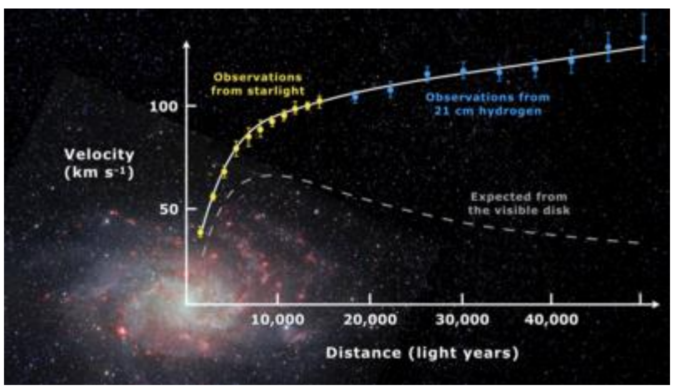
Evidence of Dark Matter

Gravitational Lensing

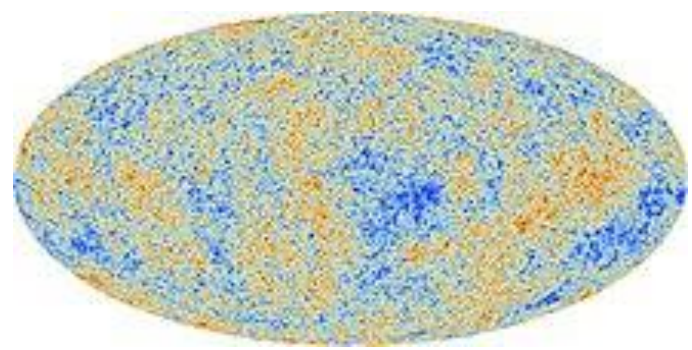
The Bullet Cluster



Rotation Curve

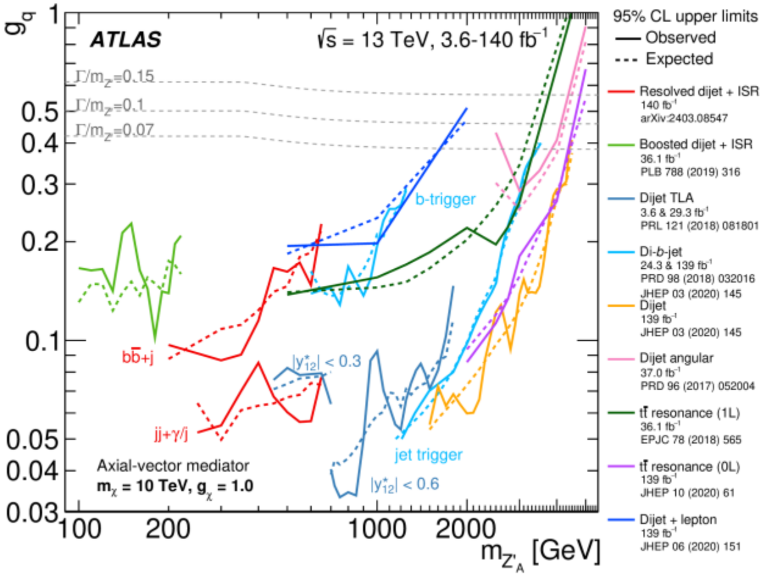


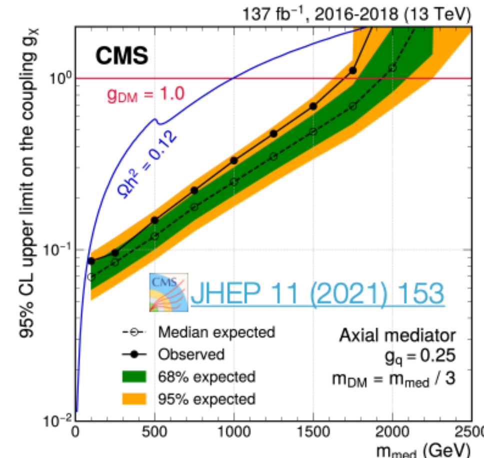
Cosmic Microwave Background



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

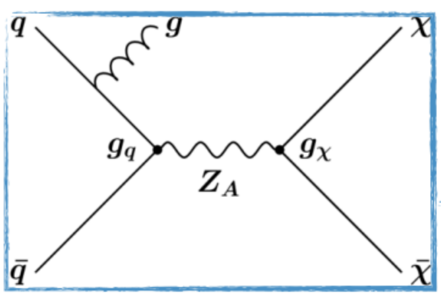
EXOT-2018-62





JHEP 11 (2021) 153

CMS DM Summary



constraint also from monojet analysis