Light dark matter searches at ATLAS

Cristiano Sebastiani (CERN)

Intro

- New Physics can be decoupled from electroweak scale in Dark Sector models, requiring additional low-mass mediators to explain the observed relic density with light DM (sub-GeV)

- Dark sectors present a huge model-space: identification of general enough benchmarks allow for a systematic programme of searches (at colliders and elsewhere)

- Collider searches have complementary reach to beam dumps and non-accelerator searches

ATLAS has a great potential to discover dark sectors and unveil their structure with new searches in Run3

Dark Sector portals

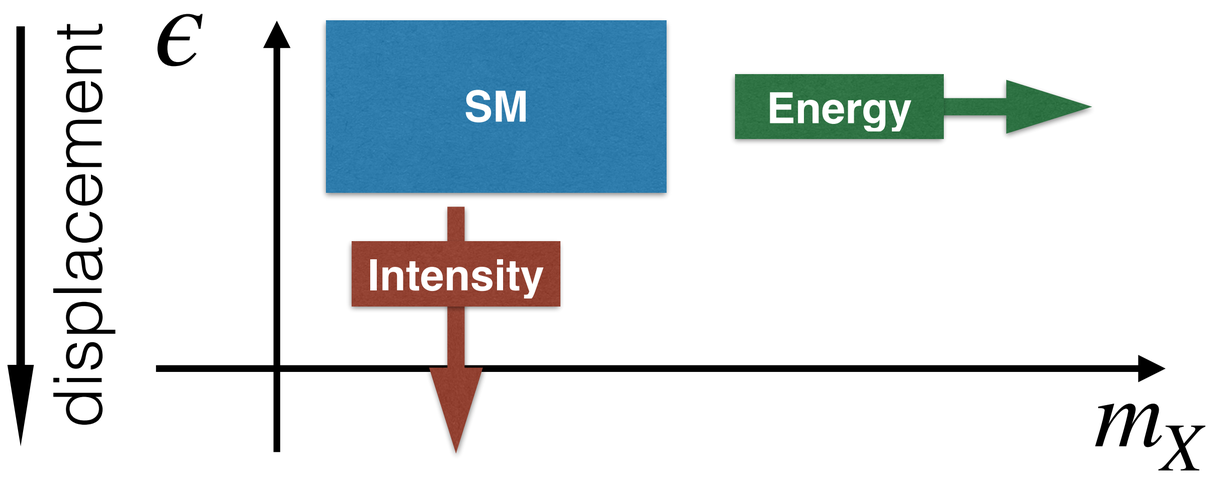
Only a finite number of portal which can link to the dark sector to the SM

Pseudoscalar portal: $\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma^5\psi$ **axions/ALPs**

Vector portal: $\epsilon F'_{\mu\nu}F^{\mu\nu}$ **'dark' vector boson (A', γ_d, Z_d) which mixes with SM photon**

Higgs portal: $\kappa H^2 S^2 + \mu H^2 S$ **'dark' scalar boson (S) —> exotic Higgs decays**

Neutrino portal: $\kappa(LH)N$ **no more sterile neutrino**



Feebly interacting particles are well motivated but their mass scale is unknown and are very difficult to probe at particle colliders, often lead to unconventional signatures!

Dark Sector portals

Light mediators, HNL and ALPs must be SM singlets: options limited by SM gauge invariance

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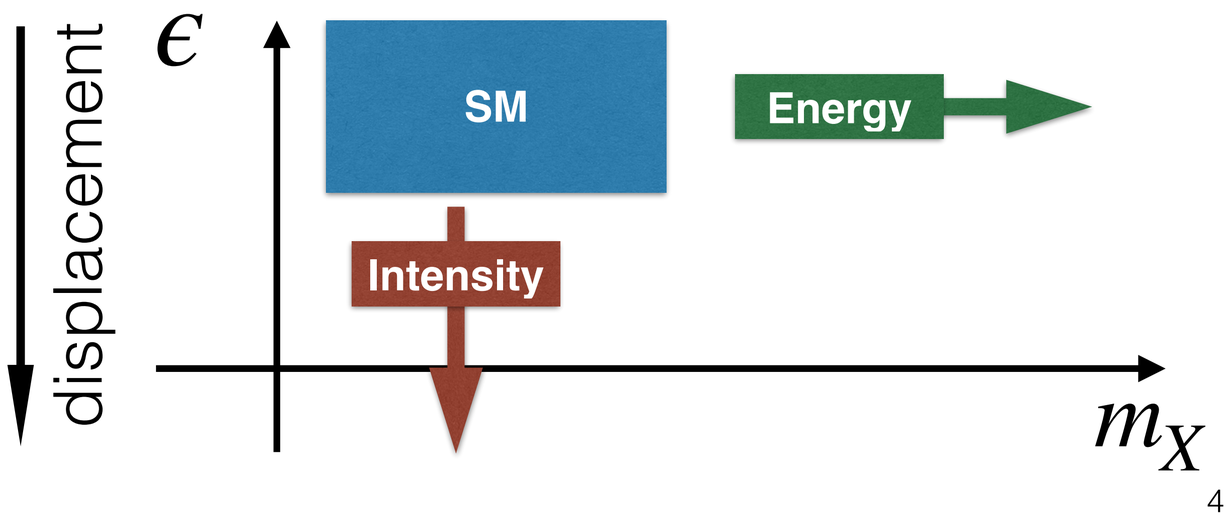
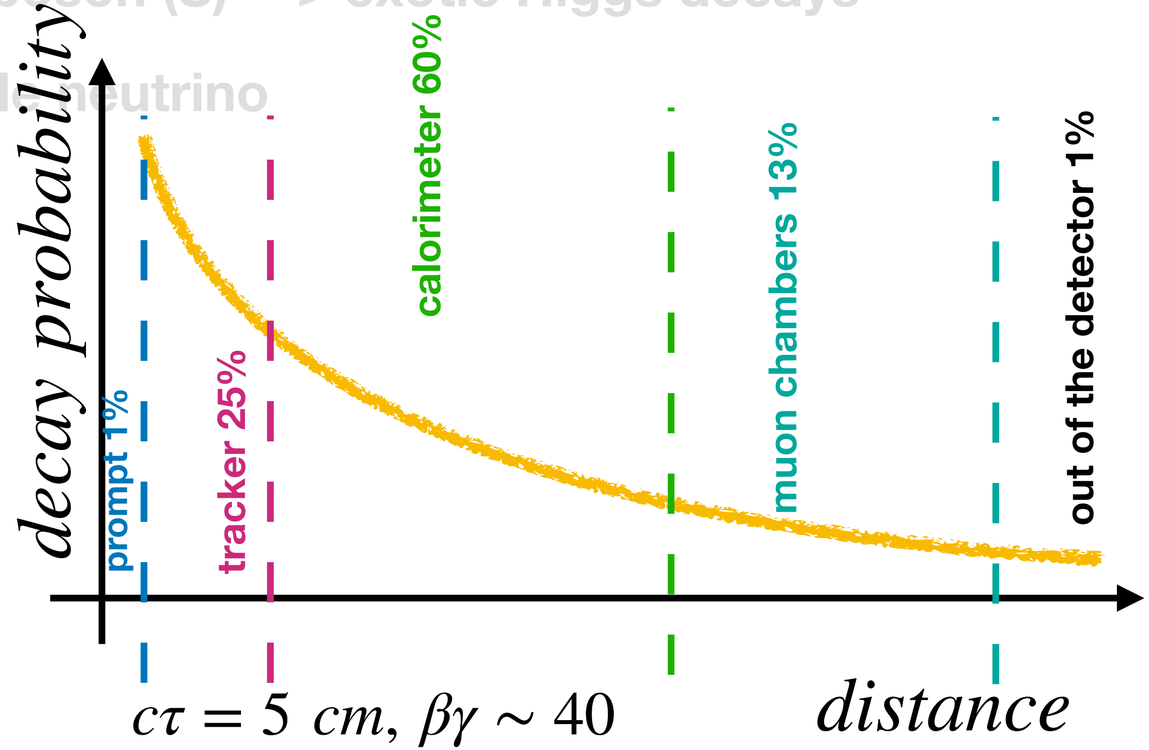
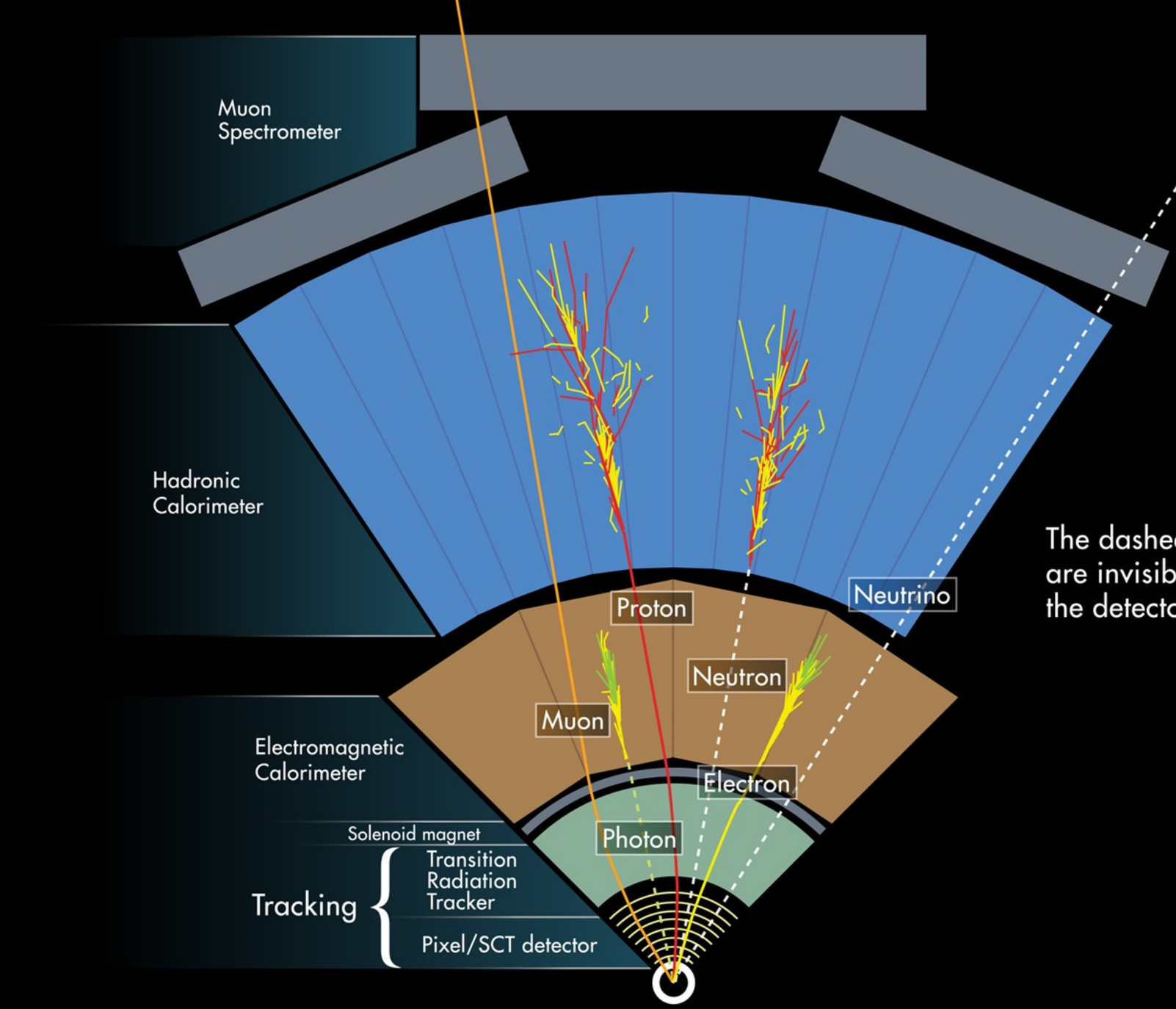
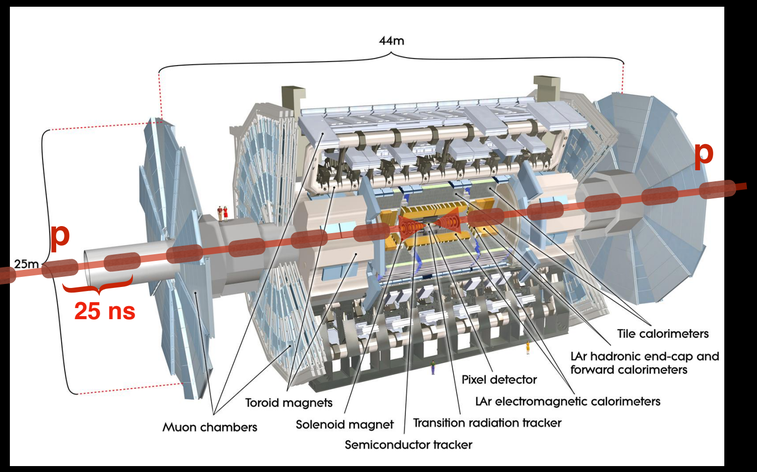




ATLAS@LHC



The dashed tracks are invisible to the detector



Unconventional signatures

Unusual and unique signatures are extremely challenging to probe:

TRIGGER

Anomalous signatures not associated with standard activity in the detector require the development of dedicated triggers!

RECONSTRUCTION

Object identification and reconstruction algorithms are to be updated to include non-standard tracks and energy deposits

NON-COLLISION BACKGROUND

Unconventional signatures have unconventional backgrounds, from detector noise to non-collision physics events

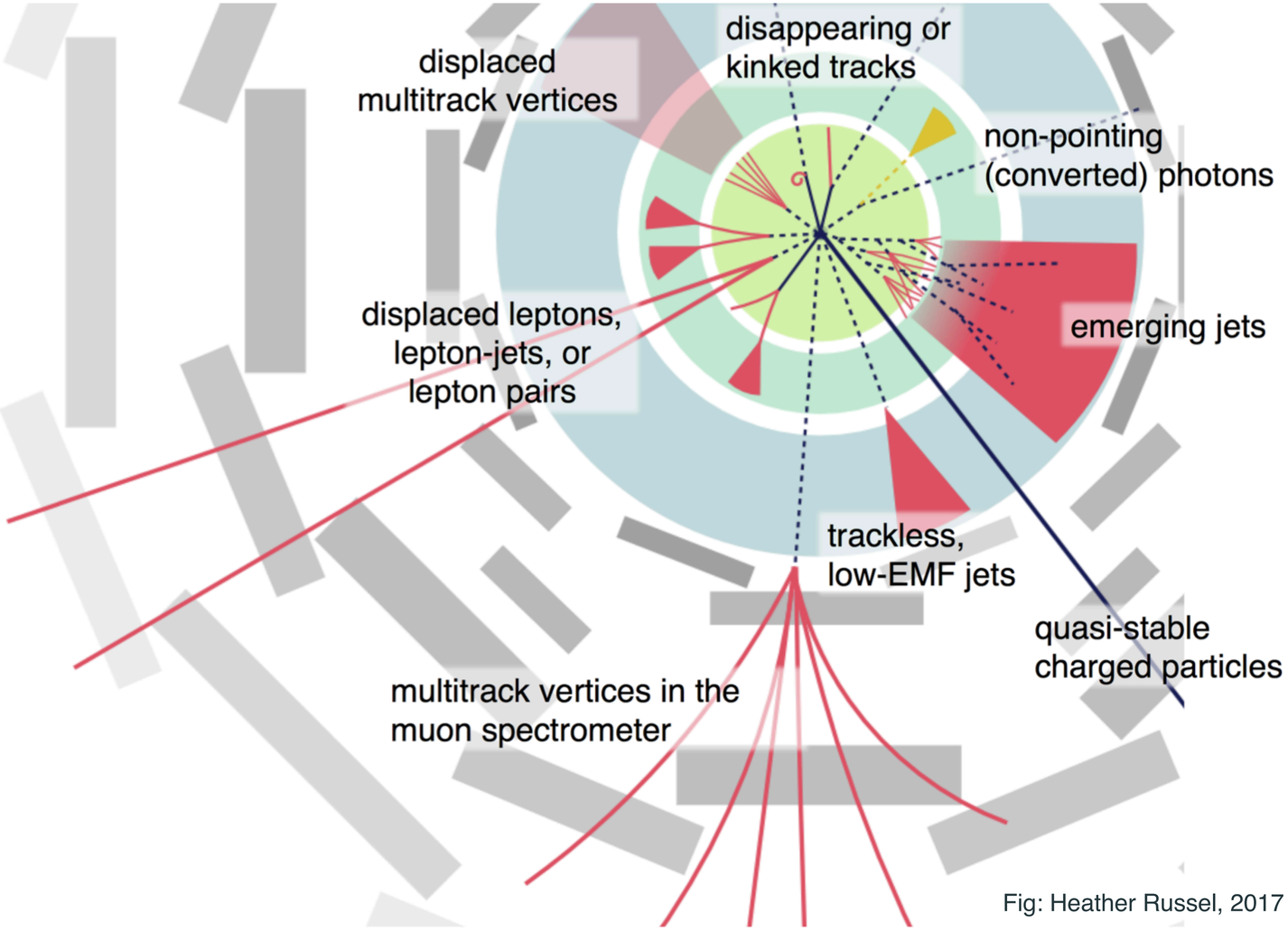
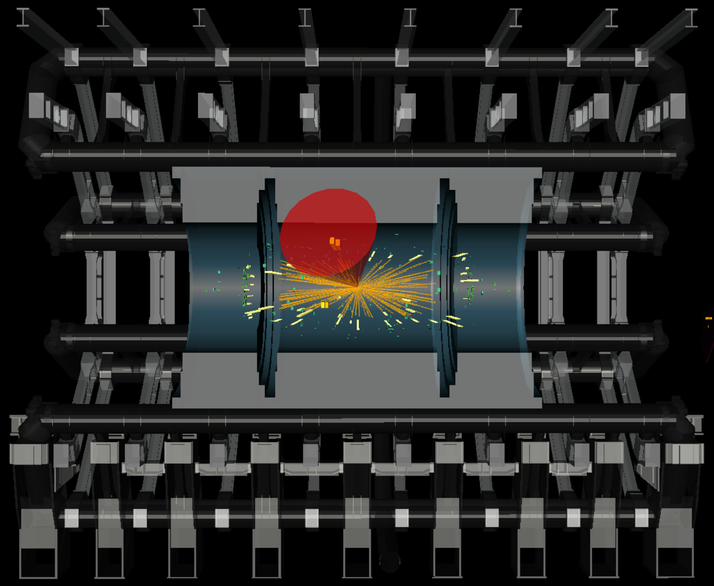
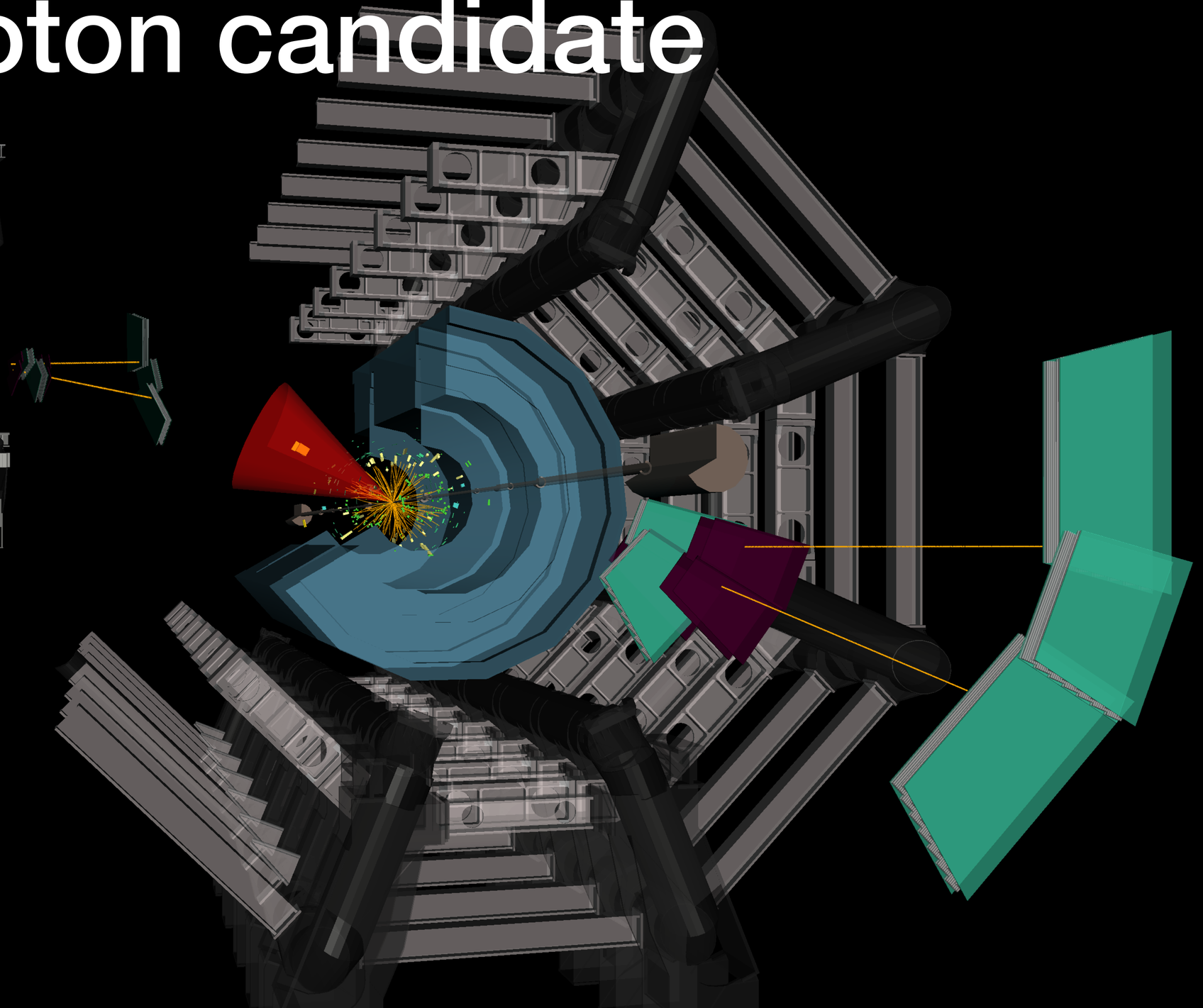


Fig: Heather Russel, 2017

LL dark-photon candidate





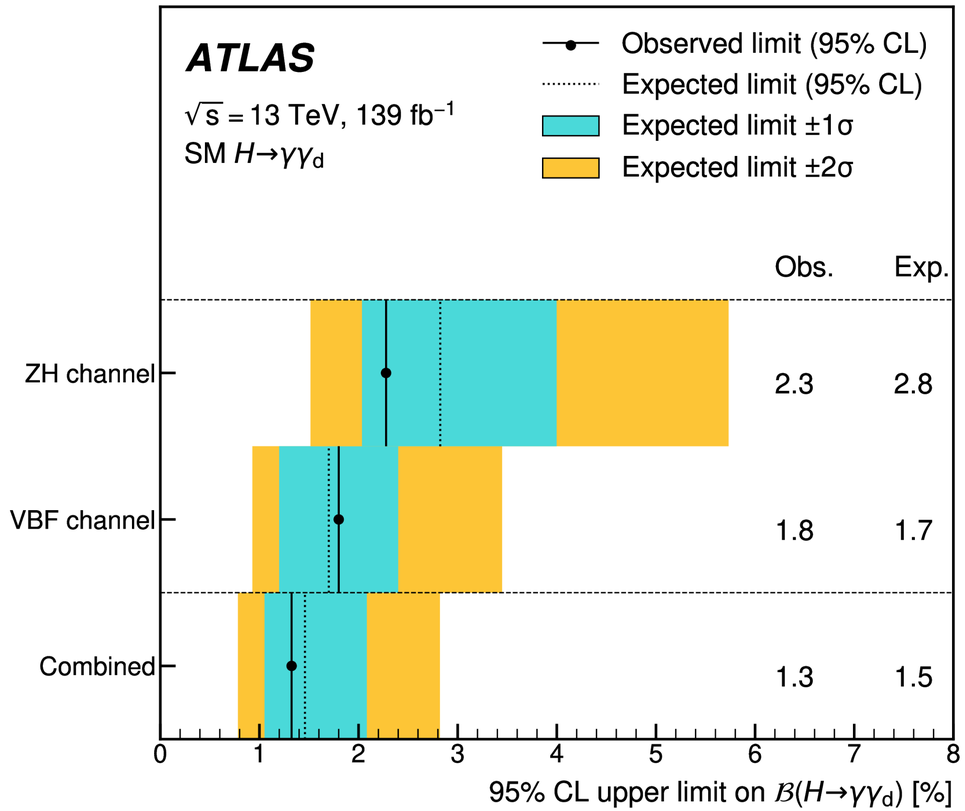
ATLAS EXPERIMENT

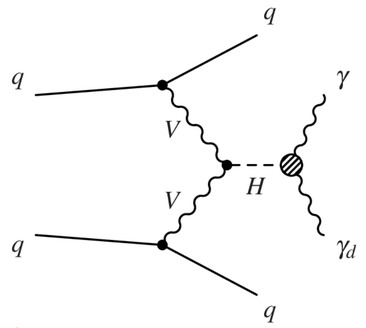
Run: 303266
Event: 1584619053
2016-07-04 04:57:58 CEST
EXOT-2019-05

Vector portal (dark photon)

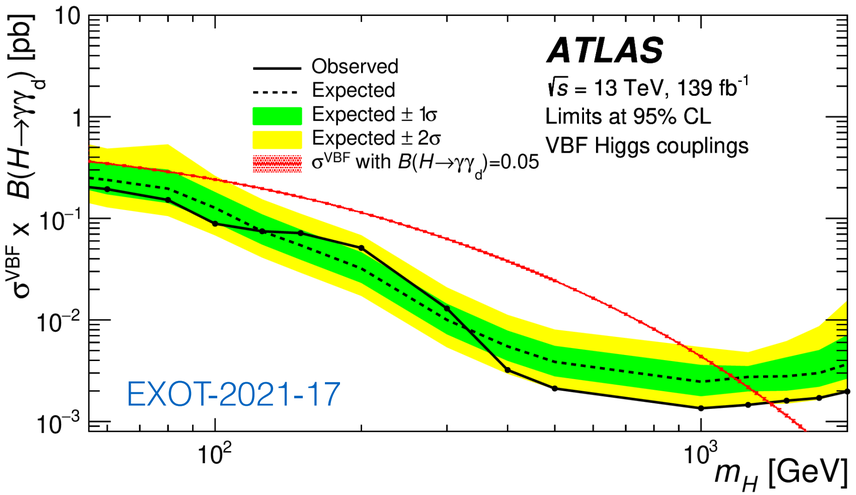
Higgs to invisible dark photons

Exploit open room in Higgs invisible decay to constraint BSM Higgs invisible decay
SM invisible decay(Br ~0.1%)

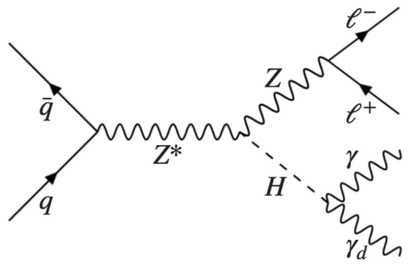


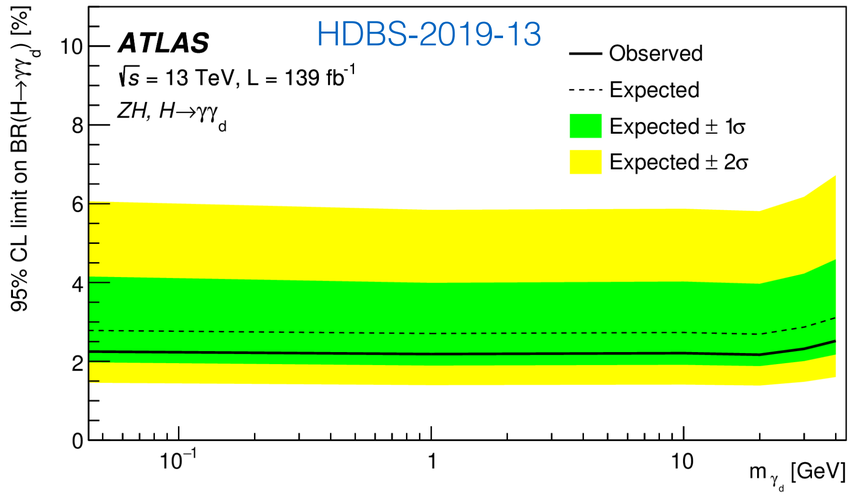


VBF



ZH



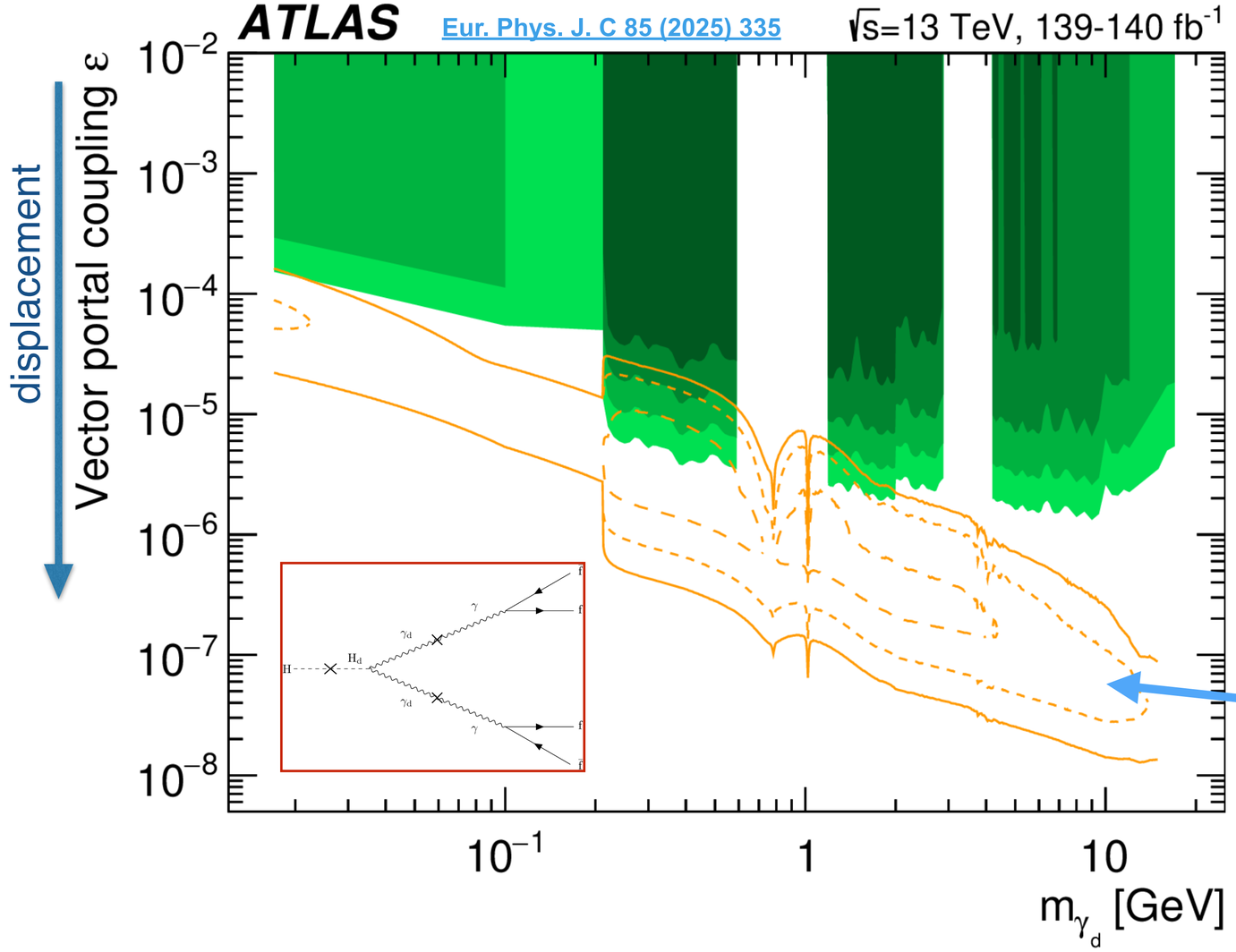


Higgs to invisible (Nature 607 (2022)52):
BR(h→inv) < 0.11 @ 95% CL

Higgs to undetected (Phys.Lett. B842 (2023)137963):
BR(h→und) < 0.13 @ 95% CL

Higgs to visible dark photon

Search for BSM Higgs decays into (long-lived) light dark photons
Very unconventional topology: collimated structures of leptons or light hadrons (lepton-jet, LJ, DPJ)



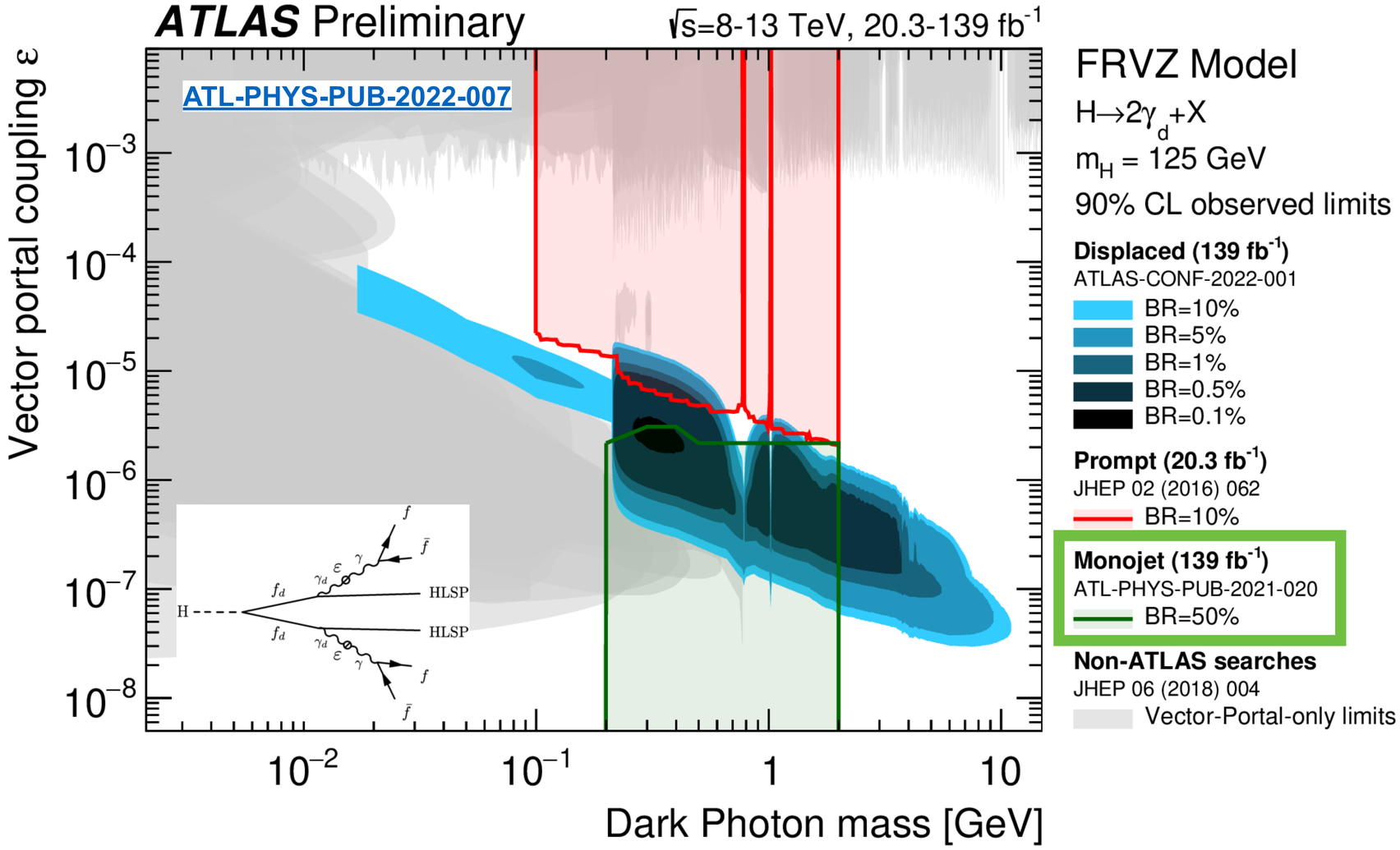
New result!

Full Run2 prompt analysis probe for the first time electron decays

Combination of ggH + VH + VBF displaced analyses (EPJC 84 (2024) 719)

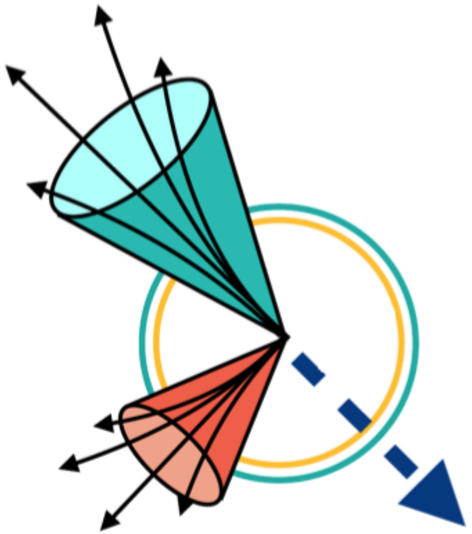
From visible to invisible

Probe ultra long-lived decays where both LLPs decay outside ATLAS!



Monojet UL on Br(H->inv) ~ 0.50

- Not very competitive…
- Opens wide range of reinterpretation of invisible searches for visible LLPs

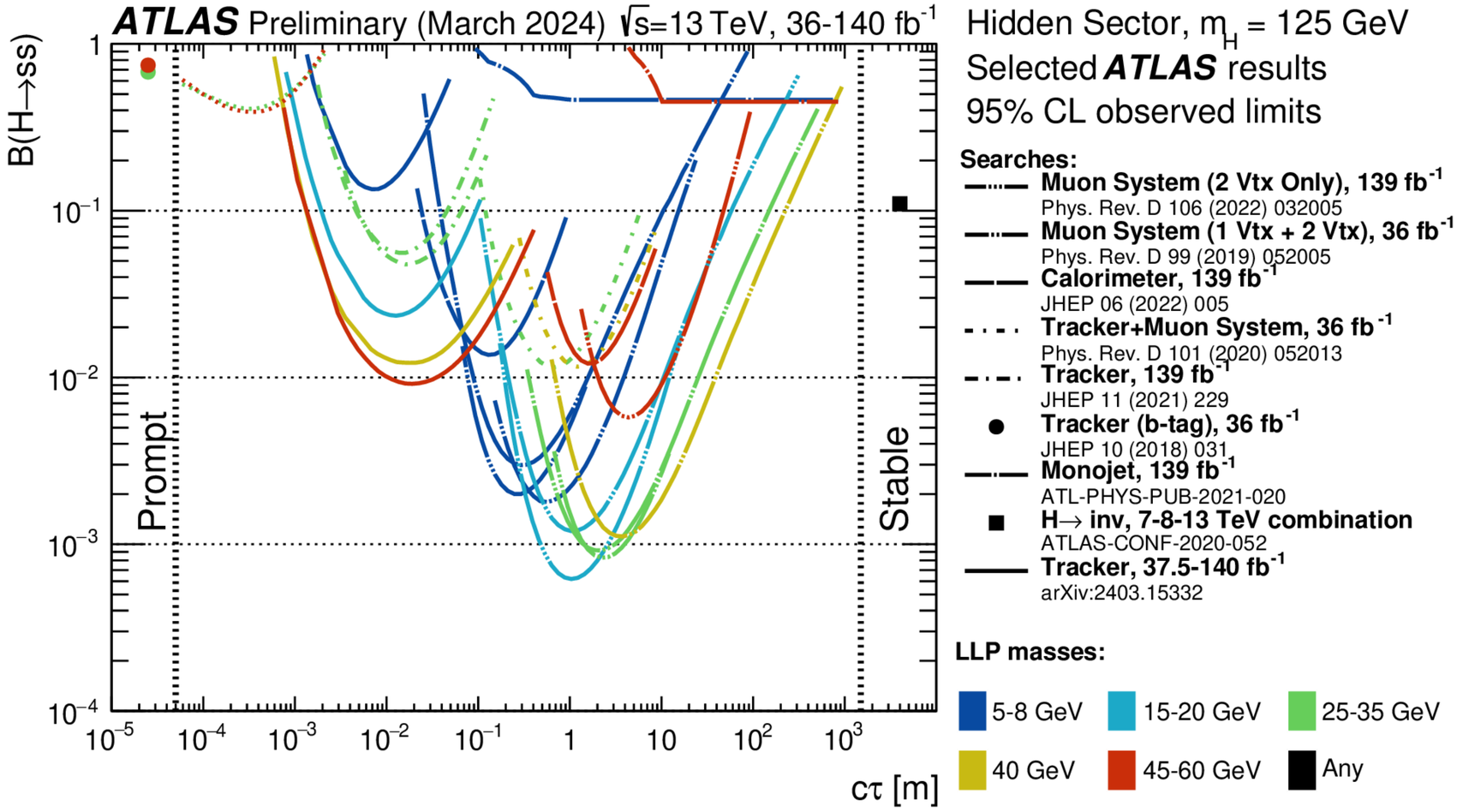


mono-jet signature

Scalar portal

Higgs to spin-0

Higgs boson mediated hidden sector summary: quite few analysis contribute to an impressive level of excluded parameter space!



- Long lifetimes often lead to very small couplings
- Longer Lifetime: Higgs to invisible bounds dominate

Higgs to spin-0

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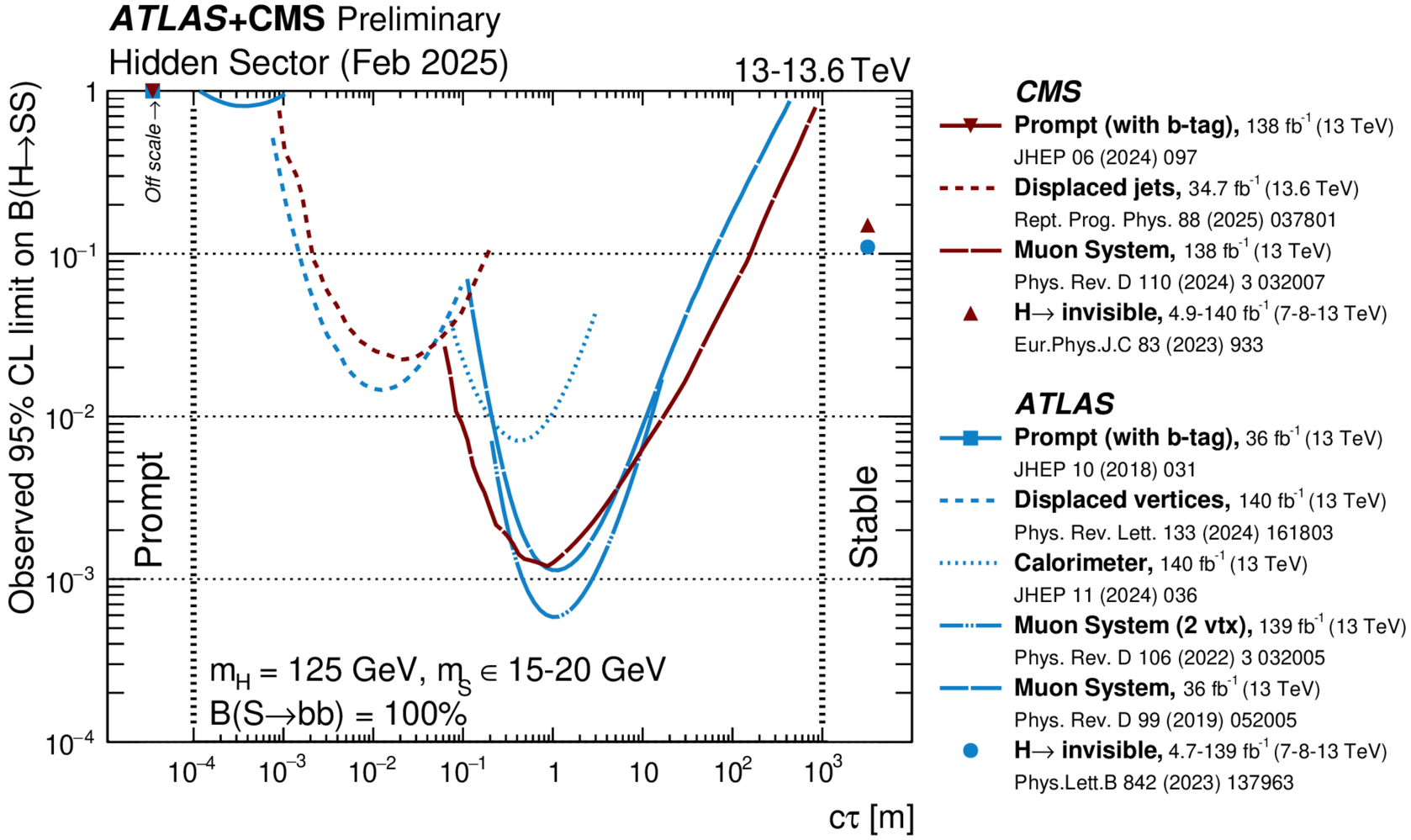
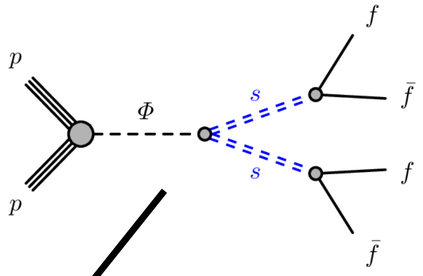


New ATLAS+CMS summary plot!
Prepared within the LLP LHC WG

New result!

Higgs to spin-0

Search for displaced jets in the muon spectrometer



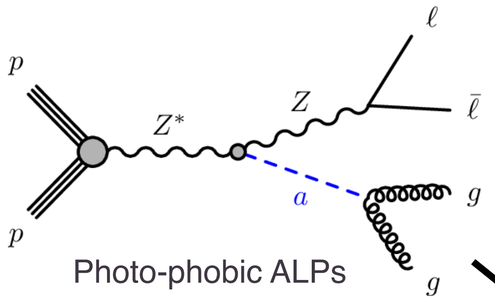
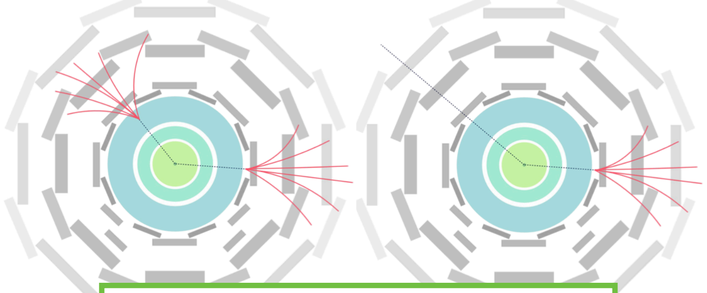
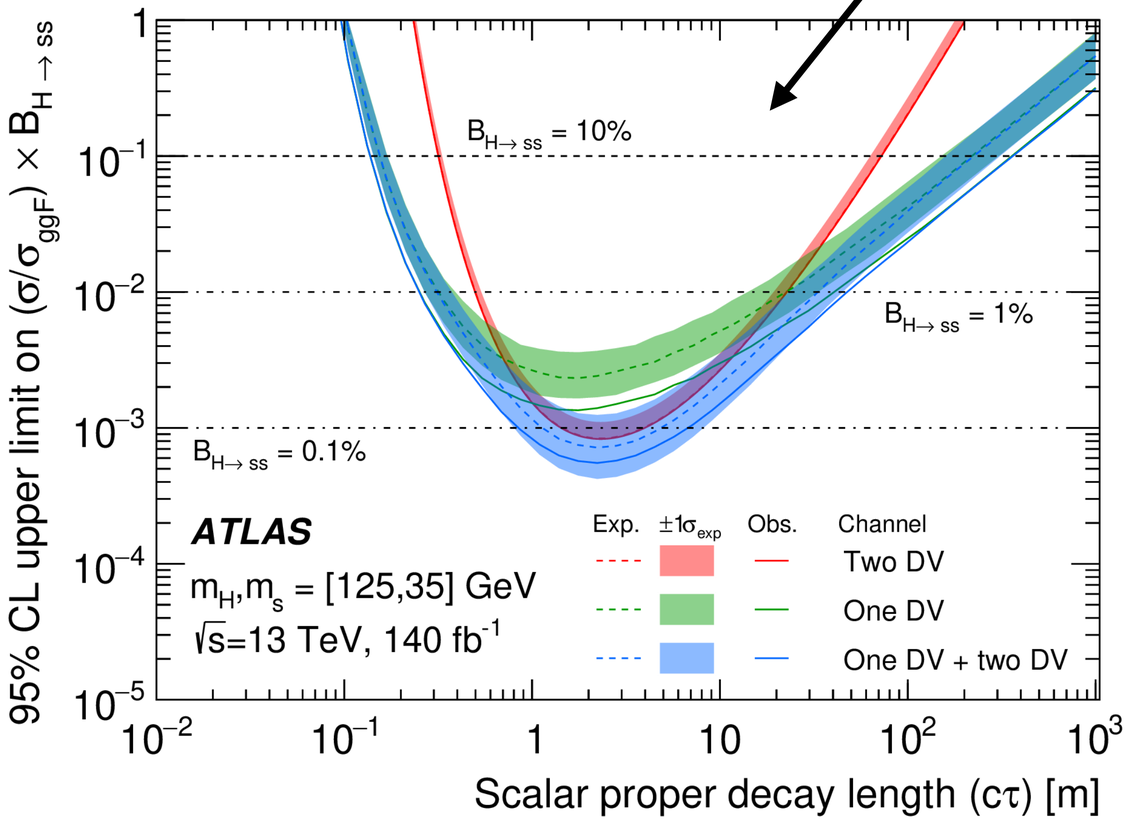


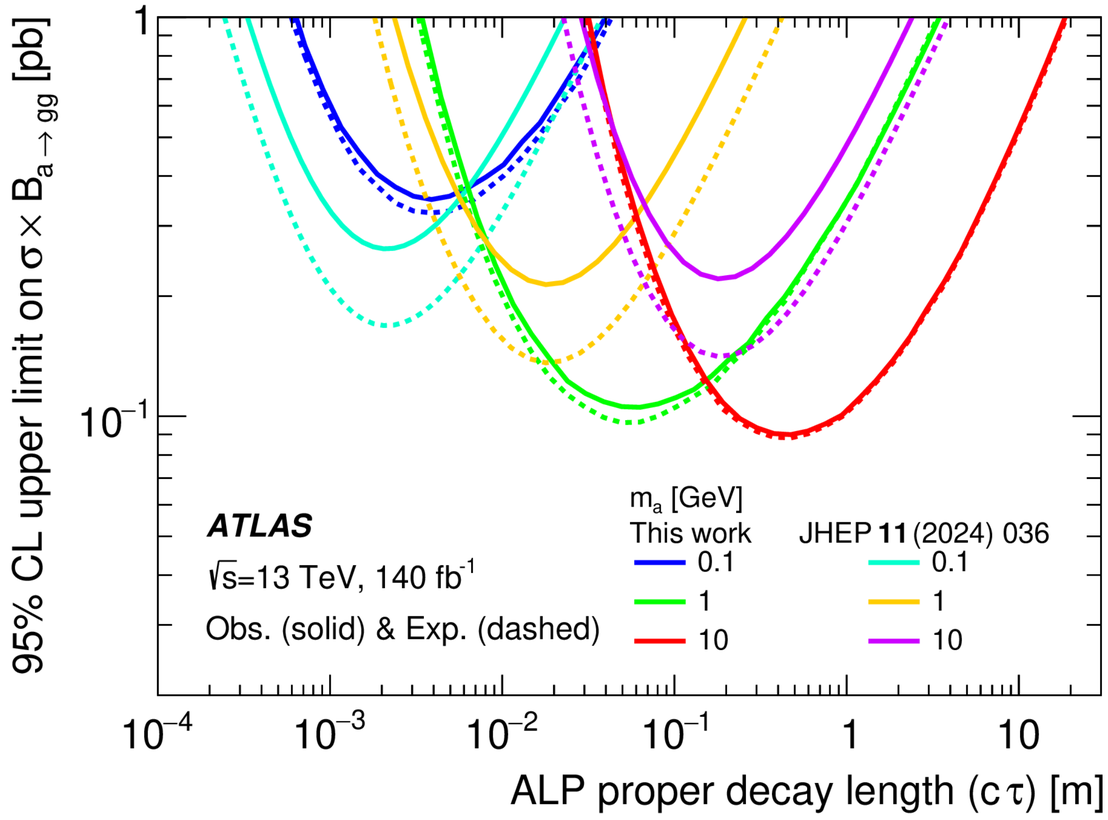
Photo-phobic ALPs



Combination of 1DV + 2DV searches

arXiv:2503.20445



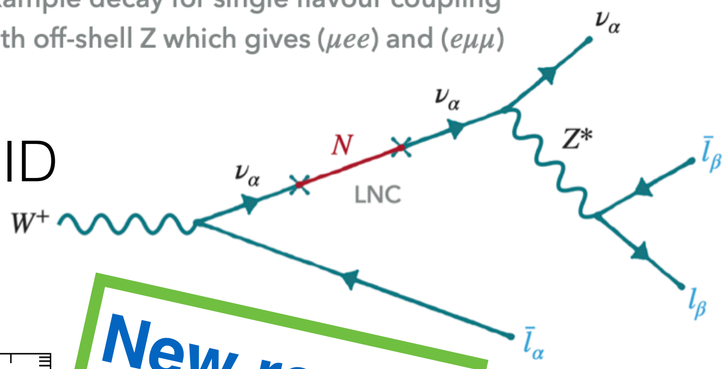


Neutrino portal

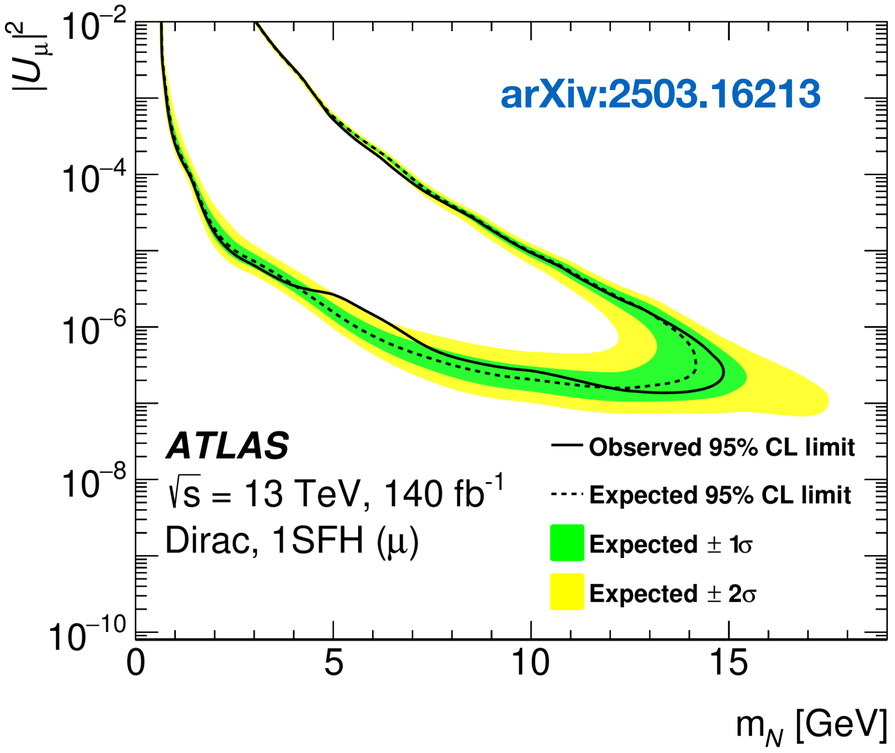
Displaced HNL

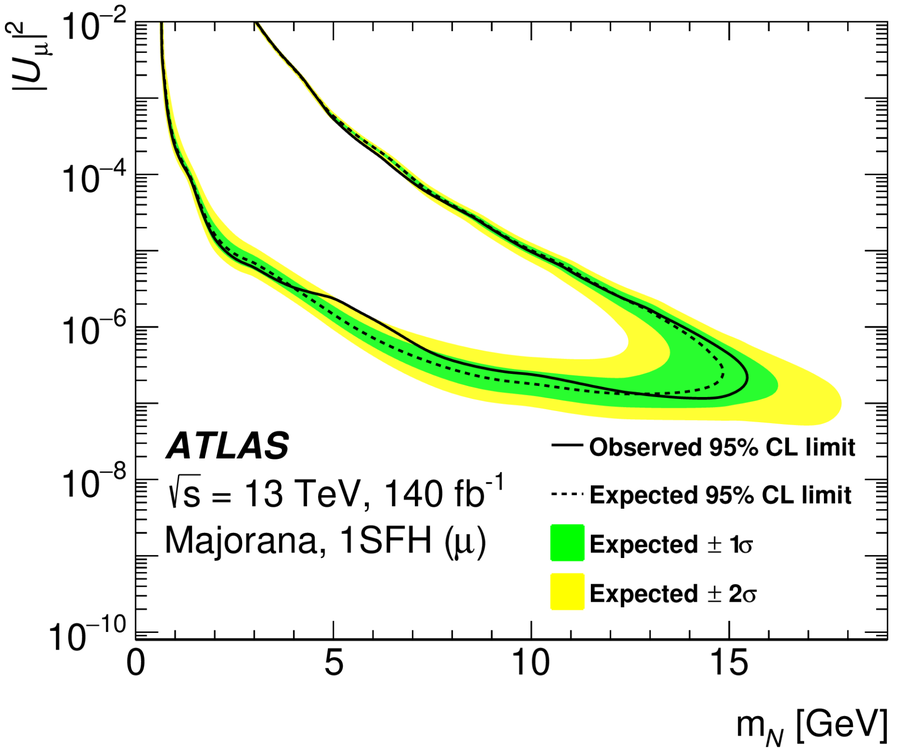
Full Run2 search for displaced HNL decaying (semi-)leptonically in the ID

example decay for single flavour coupling with off-shell Z which gives (μee) and ($e\mu\mu$)

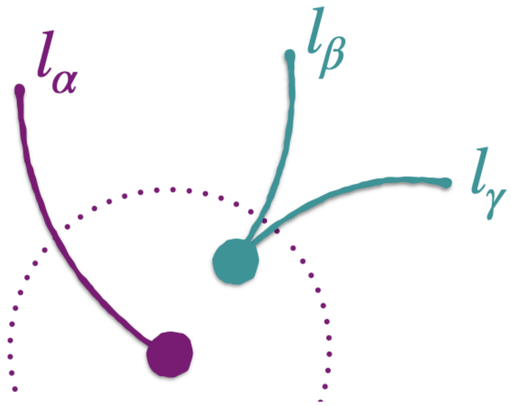


New result!





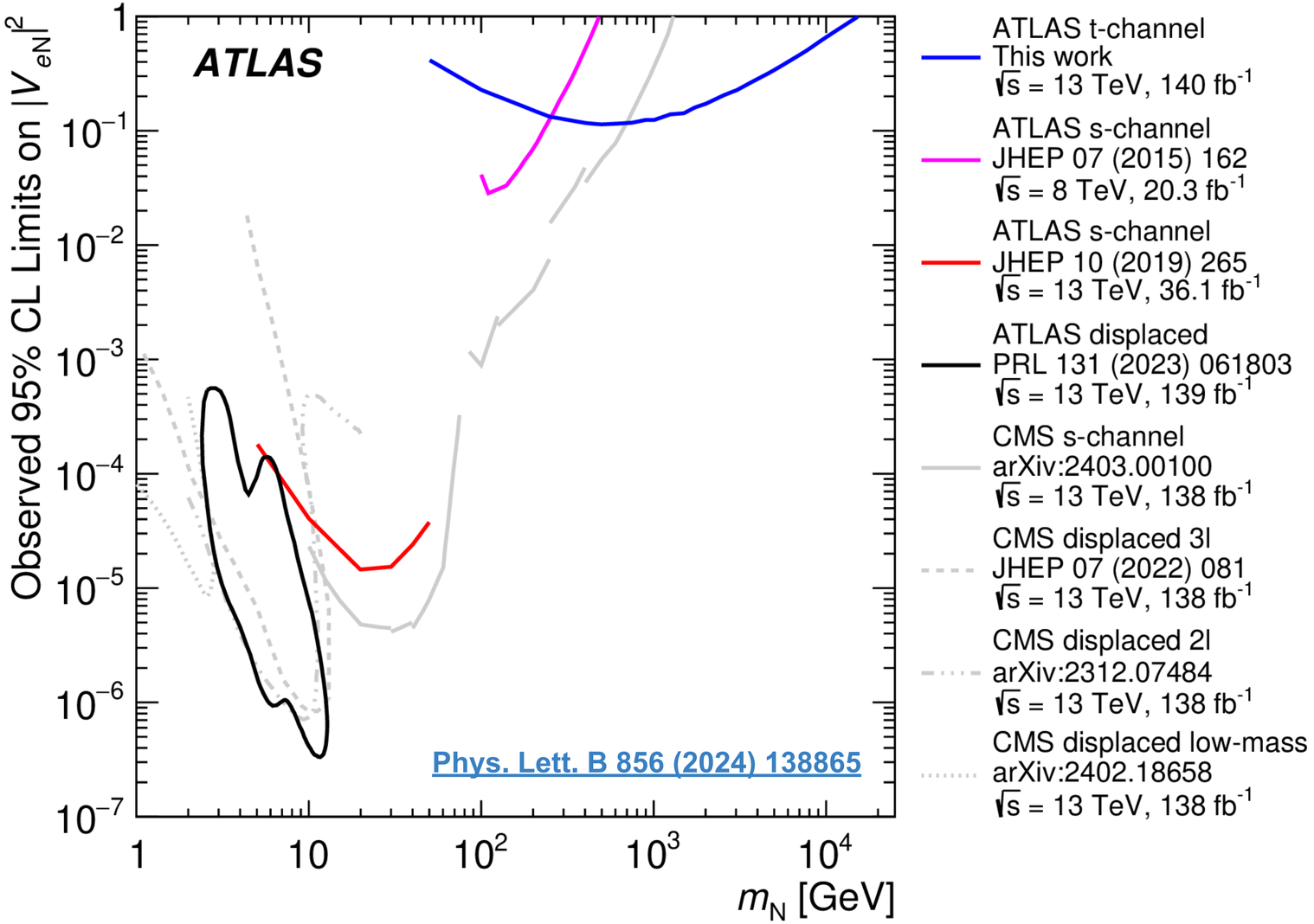
Signal:

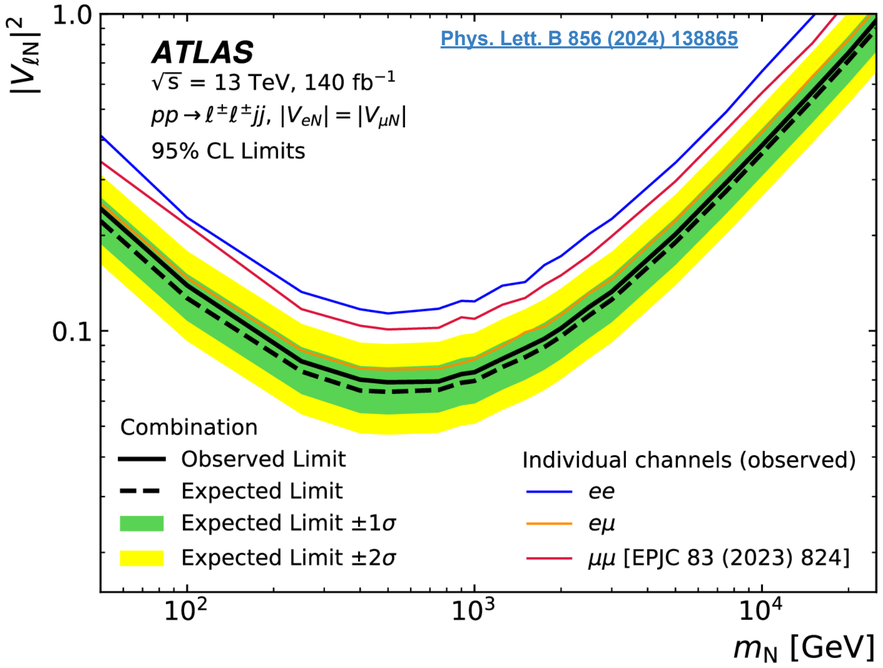


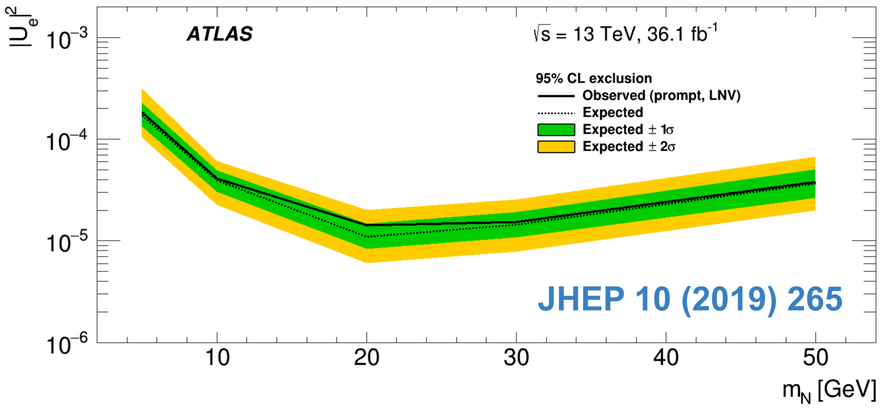
Prompt lepton with opposite-sign displaced vertices.

Improvement by a factor x15 over old full Run2 result with same dataset!

Prompt HNL


ATLAS
Observed 95% CL Limits on $|V_{eN}|^2$
m_N [GeV]
Phys. Lett. B 856 (2024) 138865
ATLAS t-channel
This work
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
ATLAS s-channel
JHEP 07 (2015) 162
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
ATLAS s-channel
JHEP 10 (2019) 265
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS displaced
PRL 131 (2023) 061803
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
CMS s-channel
arXiv:2403.00100
$\sqrt{s}$ = 13 TeV, 138 fb^{-1}
CMS displaced 3l
JHEP 07 (2022) 081
$\sqrt{s}$ = 13 TeV, 138 fb^{-1}
CMS displaced 2l
arXiv:2312.07484
$\sqrt{s}$ = 13 TeV, 138 fb^{-1}
CMS displaced low-mass
arXiv:2402.18658
$\sqrt{s}$ = 13 TeV, 138 fb^{-1}

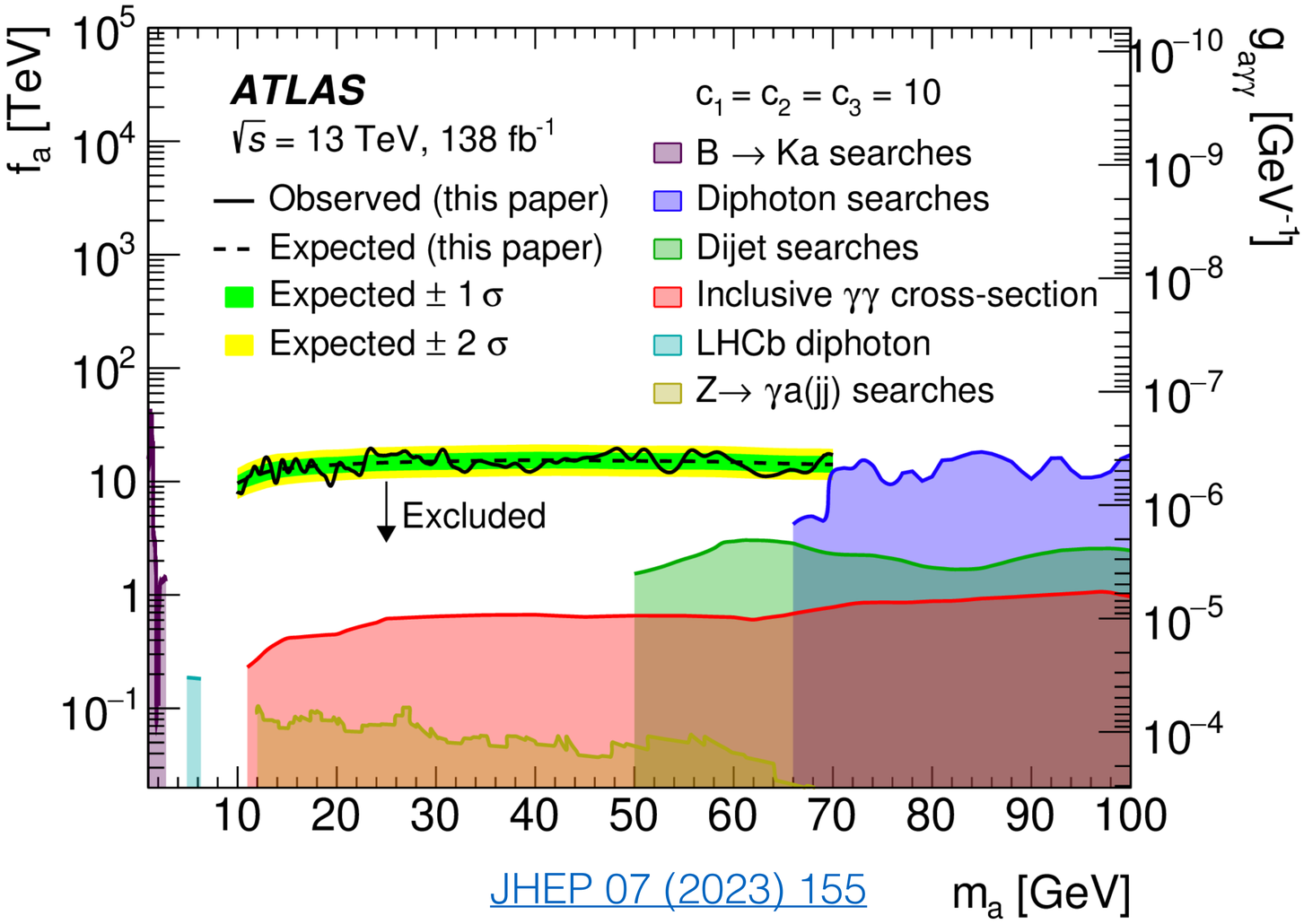

ATLAS
Phys. Lett. B 856 (2024) 138865
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
$pp \to \ell^{\pm}\ell^{\pm}jj$, $|V_{eN}| = |V_{\mu N}|$
95% CL Limits
$|V_{\ell N}|^2$
m_N [GeV]
Combination
Observed Limit
Expected Limit
Expected Limit ±1σ
Expected Limit ±2σ
Individual channels (observed)
ee
eμ
μμ [EPJC 83 (2023) 824]


ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
95% CL exclusion
Observed (prompt, LNV)
Expected
Expected ± 1σ
Expected ± 2σ
$|U_e|^2$
m_N [GeV]
JHEP 10 (2019) 265

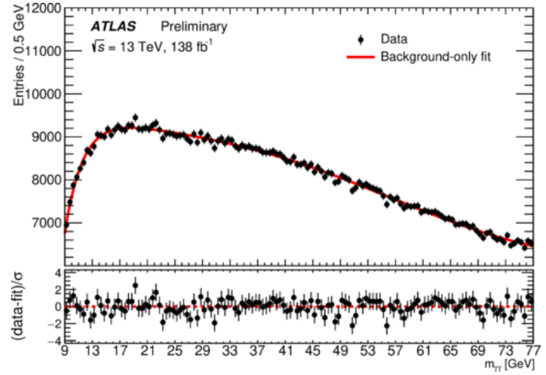
Pseudo-scalar portal (ALPs…)

Low-mass di-photon

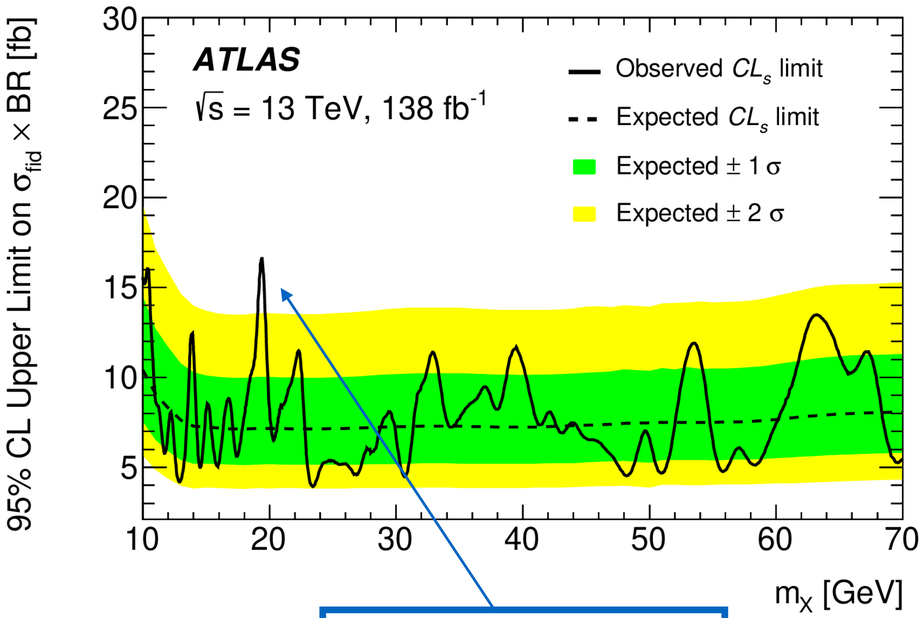
Diphoton resonance search (gg -> X -> γγ) in low-mass region



JHEP 07 (2023) 155



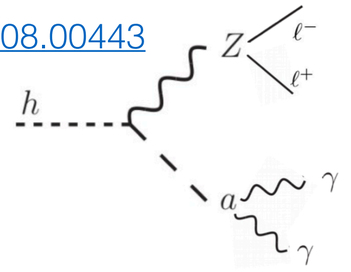
background shape due to trigger



excess at 19 GeV
3.1σ local (1.4σ global)

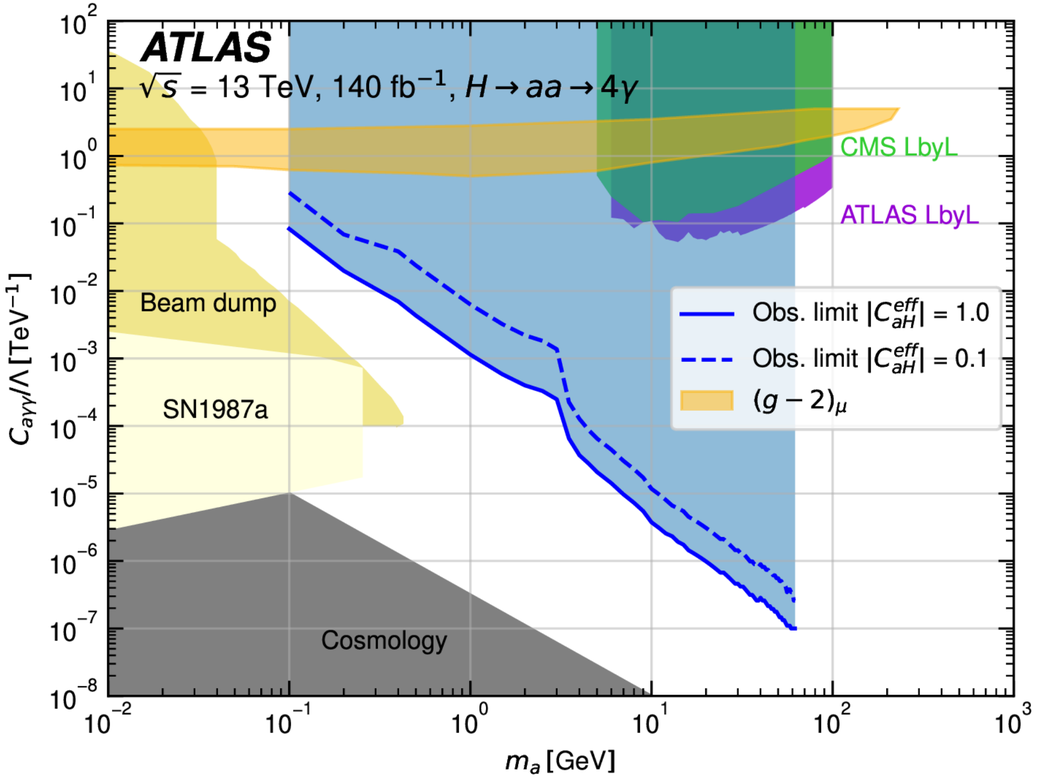
ALP in yy channel

arXiv:1708.00443



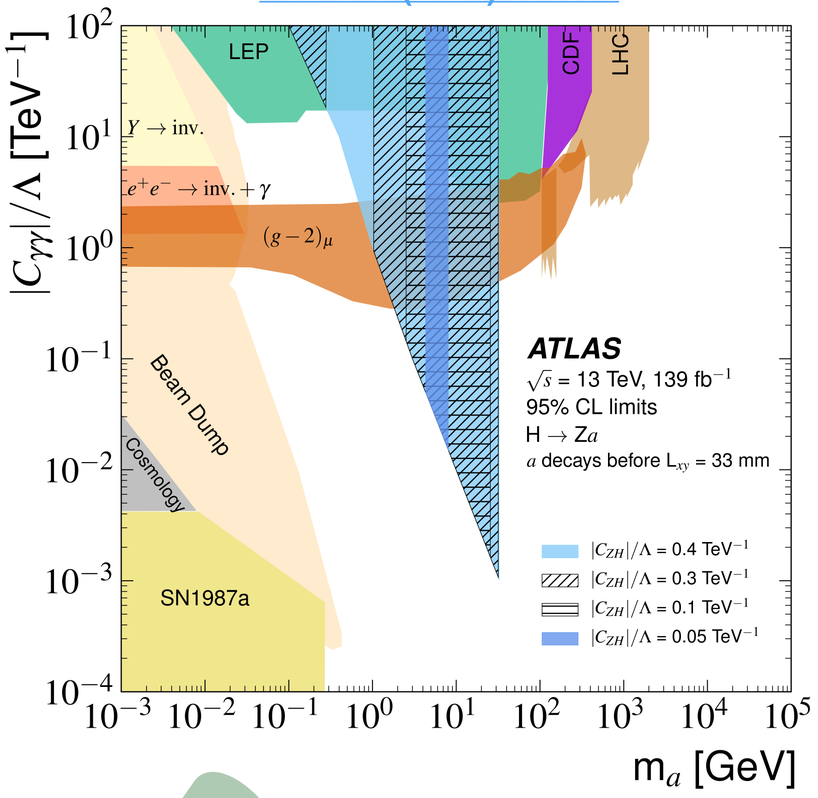
h—> aa, a->γγ

EPJC 84 (2024) 742



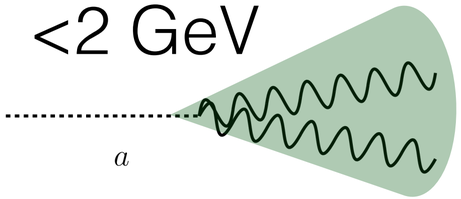
h—> Za, a->γγ

PLB 848 (2024) 138536

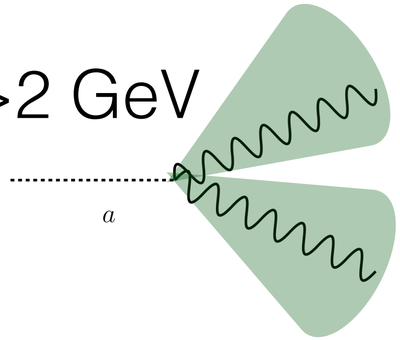


Excluded m ∈ [0.01,0.1] GeV and coupling up to 0.1 TeV-1

<2 GeV



>2 GeV



Excluded m ∈ [2,33] GeV and coupling |Cγγ|/Λ up to 3 10-6 TeV-1

not finding a signal in h → aa would not necessarily exclude h → Za

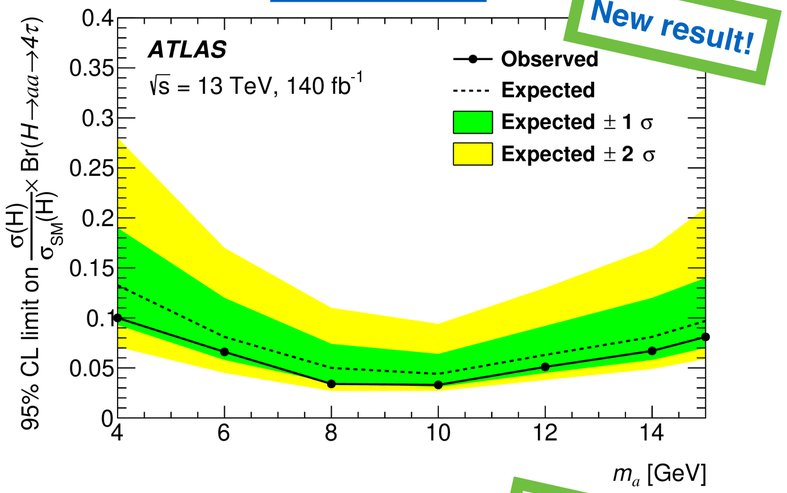
Many more…alps searches

Many Run2 searches looking for ALPs to systematically cover all production and decay channels!

H->Za/aa ; Z*->Za ; diphoton	
h->Za->$\ell\ell\ \gamma\gamma$	PLB 848 (2024) 138536
h->Za->$\ell\ell$ jj	arviv:2411.16361
H->aa->4m	JHEP 03 (2022) 041
h->aa->$\gamma\gamma\ \tau\tau$	JHEP 03 (2025) 190
h->aa->4τ	arXiv:2503.05463
V*->Va	JHEP 11 (2024) 126
$\gamma\gamma$ →a →$\gamma\gamma$	JHEP 07 (2023) 234
h→aa; a→$\gamma\gamma$	EPJC 84 (2024) 742
V*→Va; a→gg V→$\ell\ell/\ell\nu$	**dVtx in ID:** PRL 133 (2024) 161803 **CalRatio+X:** JHEP 11 (2024) 036 **1MVtx+Z:** arXiv:2503.20445

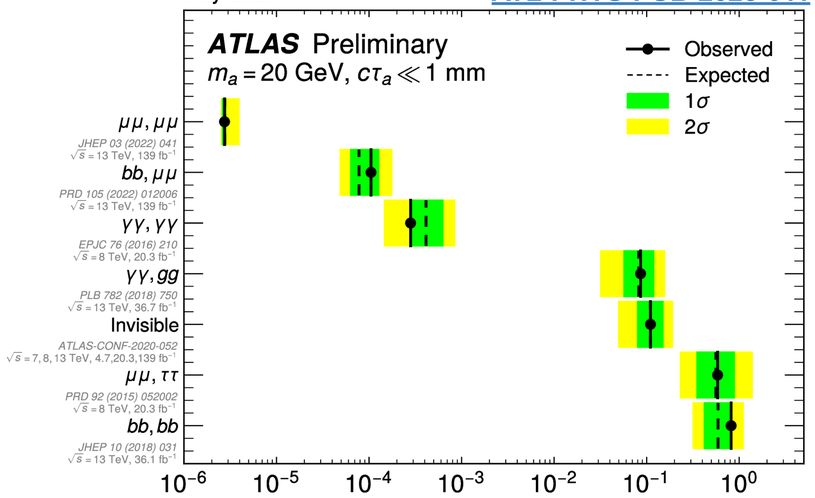
arXiv:2503.05463

New result!

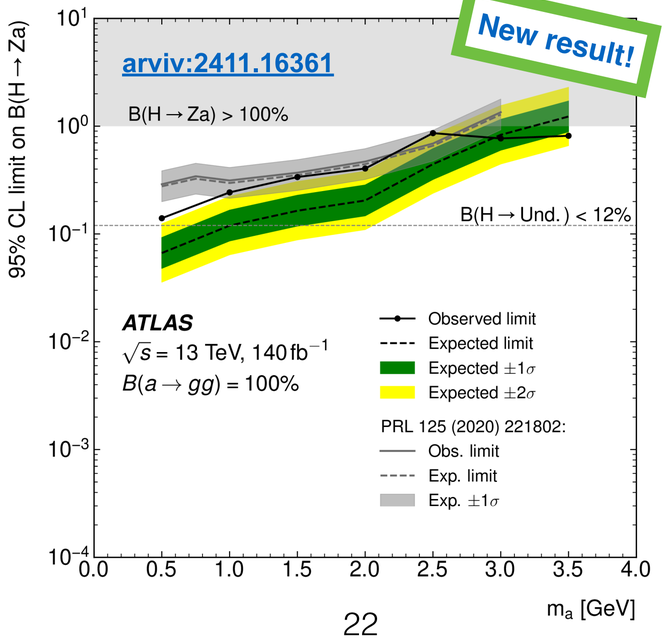


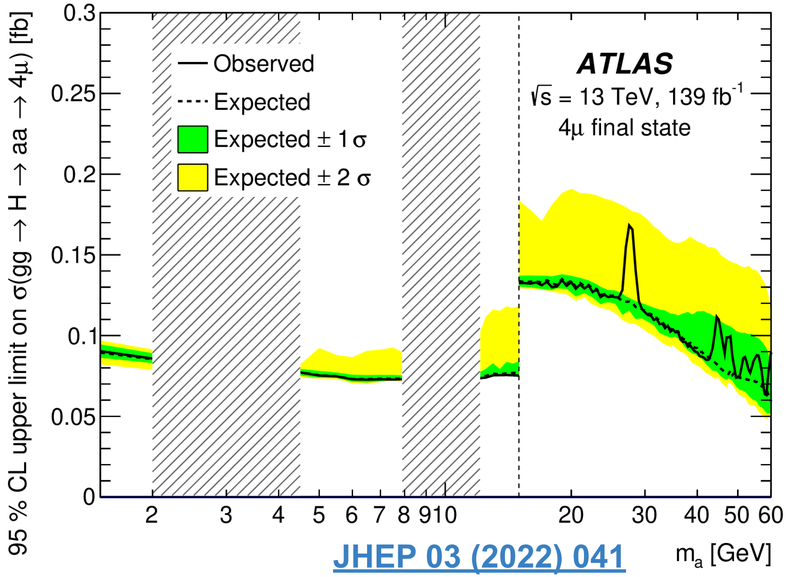
July 2022

ATL-PHYS-PUB-2025-011



New result!

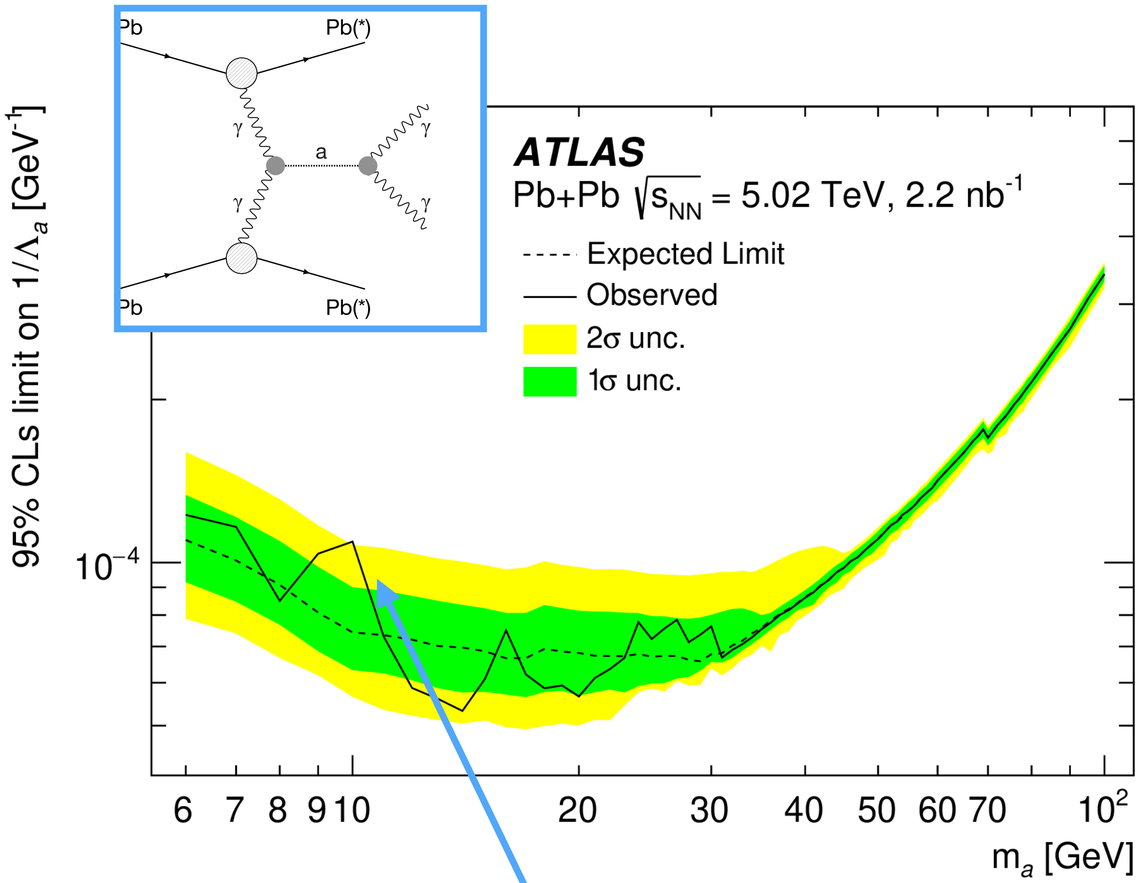




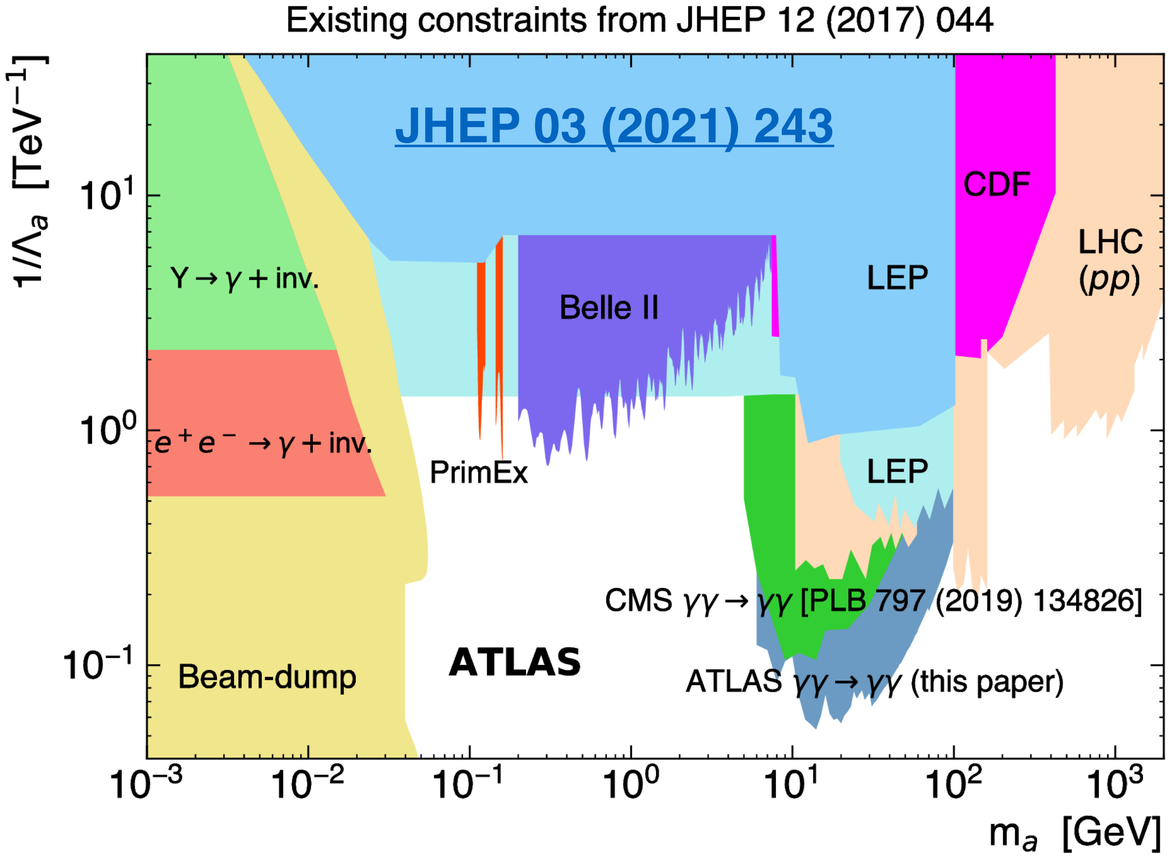
JHEP 03 (2022) 041

Light-by-light scattering

search for resonance in diphoton invariant mass spectrum from photon-photon interactions in UPC HI collisions



2.1 sigma



So far best over mass range of 6-100 GeV (assuming 100% BR to photons)

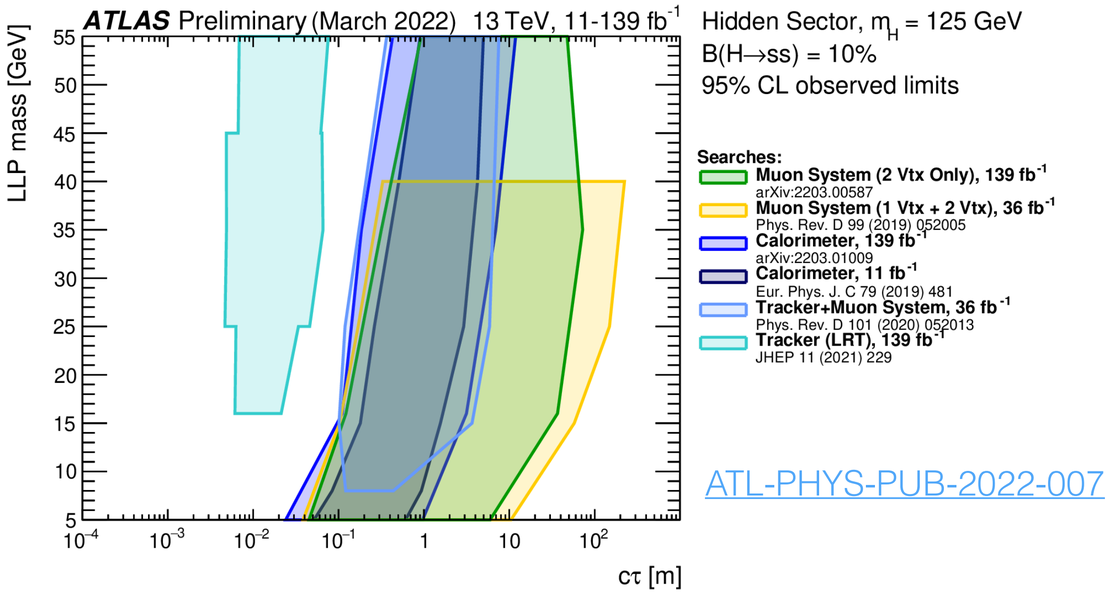
Takeaways

- Dark Sectors searches have been so far discontinuous in ATLAS: from the portal framework we can identify benchmark models for a systematic investigation

- A snapshot of the most recent results from ATLAS have been shown, but many more analyses in progress using the Run3 dataset

- Run3 larger dataset with new exciting improvements will enhance the discovery potential for dark sector signatures

- Many unexplored synergies and overlaps across searches that could be exploited
  - Harmonise common models where possible or promote multiple interpretations
  - Encourage combinations and summary plots to spot uncovered regions



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BACKUPS