Hidden sectors at collider experiments and some prospects

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Synergy workshop between ep/eA and pp/pA/AA physics experiments

1/3/2024

Hidden sectors at colliders: a brief intro

- New physics models predicting long-lived particles gained lot of attention in the past few years
  - Hidden, dark sector (HS), are largely populated by feebly interacting particles (although prompt signatures arise as well!)
- Minimal benchmarks were established at the time of the **European Strategy** in 2019 for collider and non-collider experiments, privileging scenarios where comparisons could be made on equal grounds

Portal	Coupling
Vector (Dark Vector, A_μ)	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS}S^2)H^\dagger H$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Fermion (Sterile Neutrino, N)	$y_N LHN$

- HS can be minimal or non-minimal - i.e. new particles such as ALPs or dark photons arising in Higgs decays targeted by General Detector experiments (ATLAS/CMS) – Higgs as portal for new physics - as opposed to minimal models considered i.e. by LHCb, FASER, ALICE etc

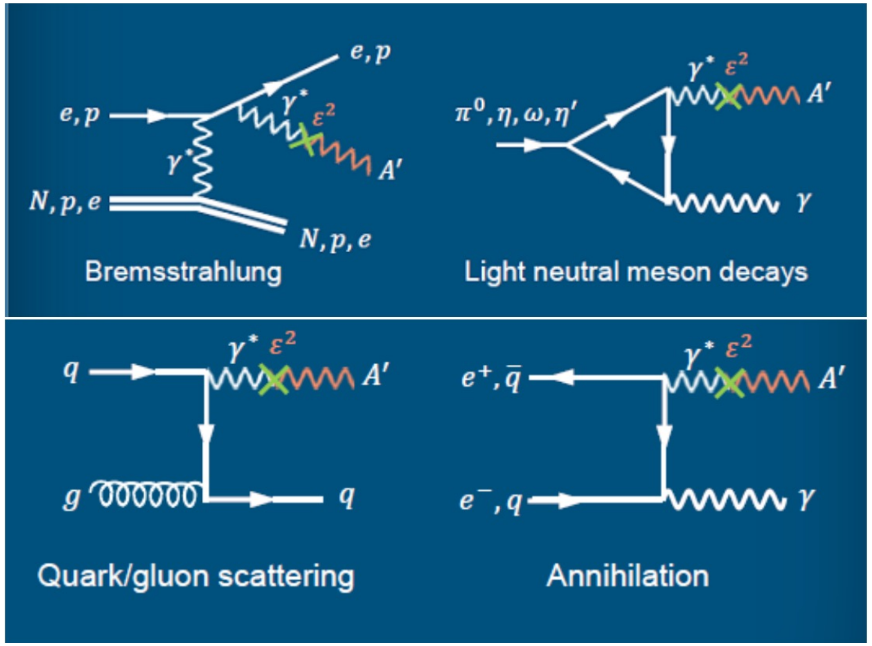
Hidden sectors at colliders: Outline

- Given the vastity of the HS programme at colliders, benchmarks considered so far will be highlighted in this talk, with emphasis on scenarios where complementarities of reach between LHeC/FCC-eh and experiments can be achieved and exploited – **I will use ES projections to set the stage (but also the more recent Snowmass21 report)**
- A brief list below:
  - Current ATLAS/CMS: **dark photon and ALPs from Higgs decays, HNL, dark higgses**
  - Current LHCb and FASER, and Heavy Ion prospects: **dark photons and ALPs**
  - (some) Prospects and feasibility studies for HL-LHC GDPs, LHCb, EIC and FASER-2
    - Comparisons of FASER-2 with Physics Beyond Collider experiments in Mario's talk
    - Focus on hh and not much on e+e- for lack of time, but to be explored further in future

Disclaimer: this is not meant to be a review talk on behalf of current/future experiments !

From European Strategy to nowadays: Dark Photons

- Vector portal minimal models: have masses around the GeV scale and their interactions are QED-like, scaled with the small mixing parameter ε.
- Quite versatile as can be produced in various ways
  - ep/eA/pp/pA/AA …



R. Jacobsson (CERN) LHC Operations Workshop, Evian, 2019

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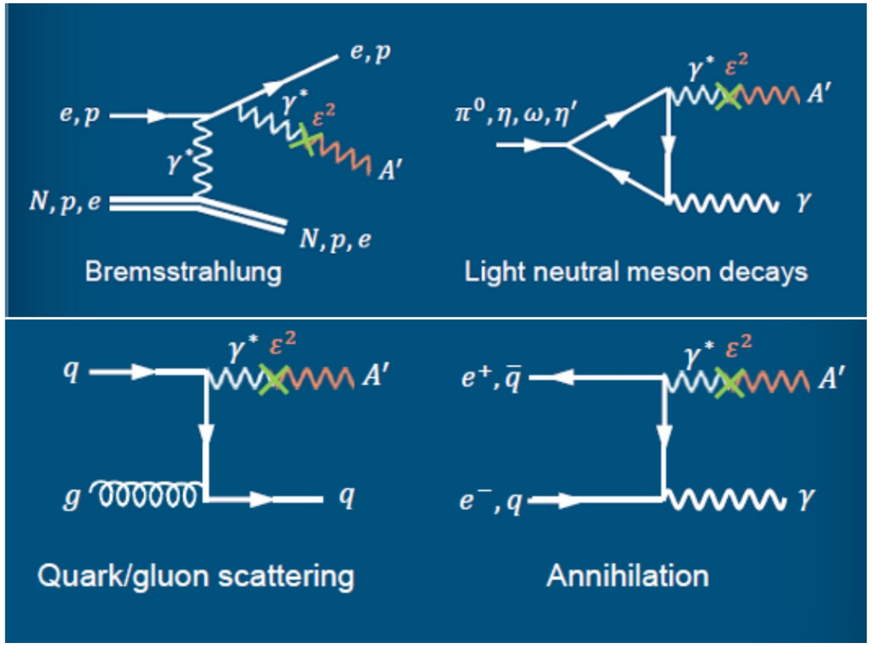

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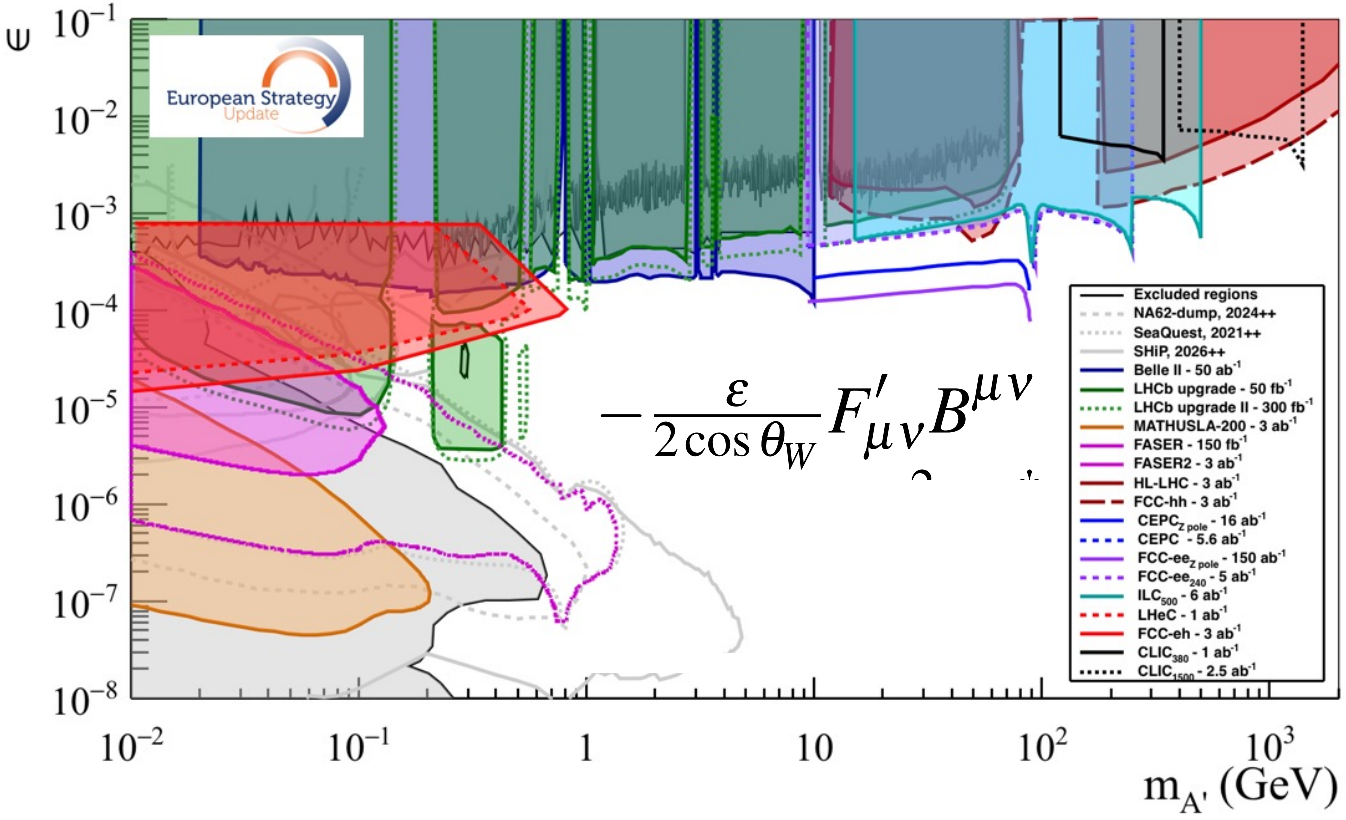
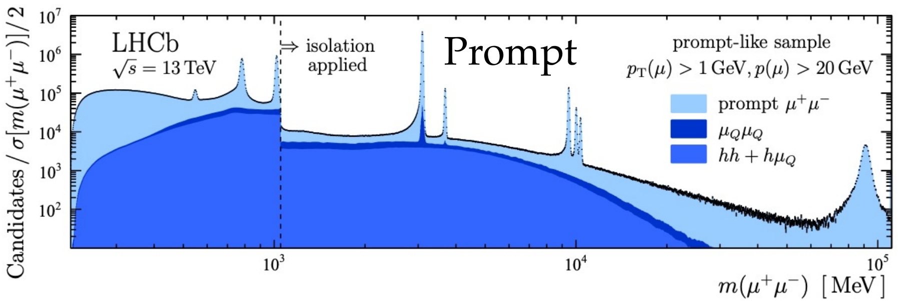


From European Strategy to nowadays: Dark Photons

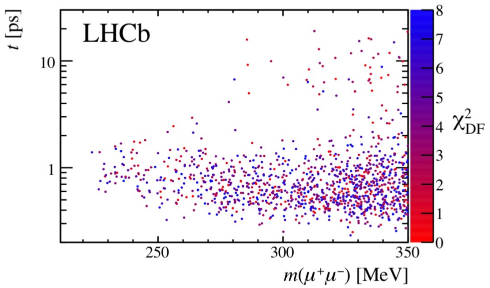
- Vector portal minimal models: have masses around the GeV scale and their interactions are QED-like, scaled with the small mixing parameter ε.

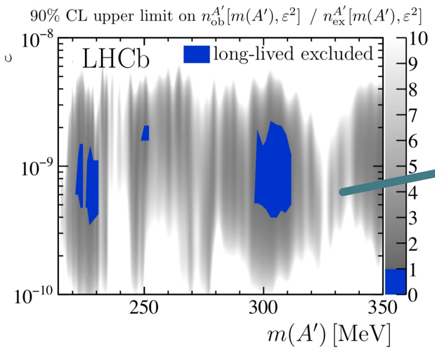
LHCb current results

dark photons decaying μ+μ-
→ **Prompt and displaced** (0.1 – 1cm)

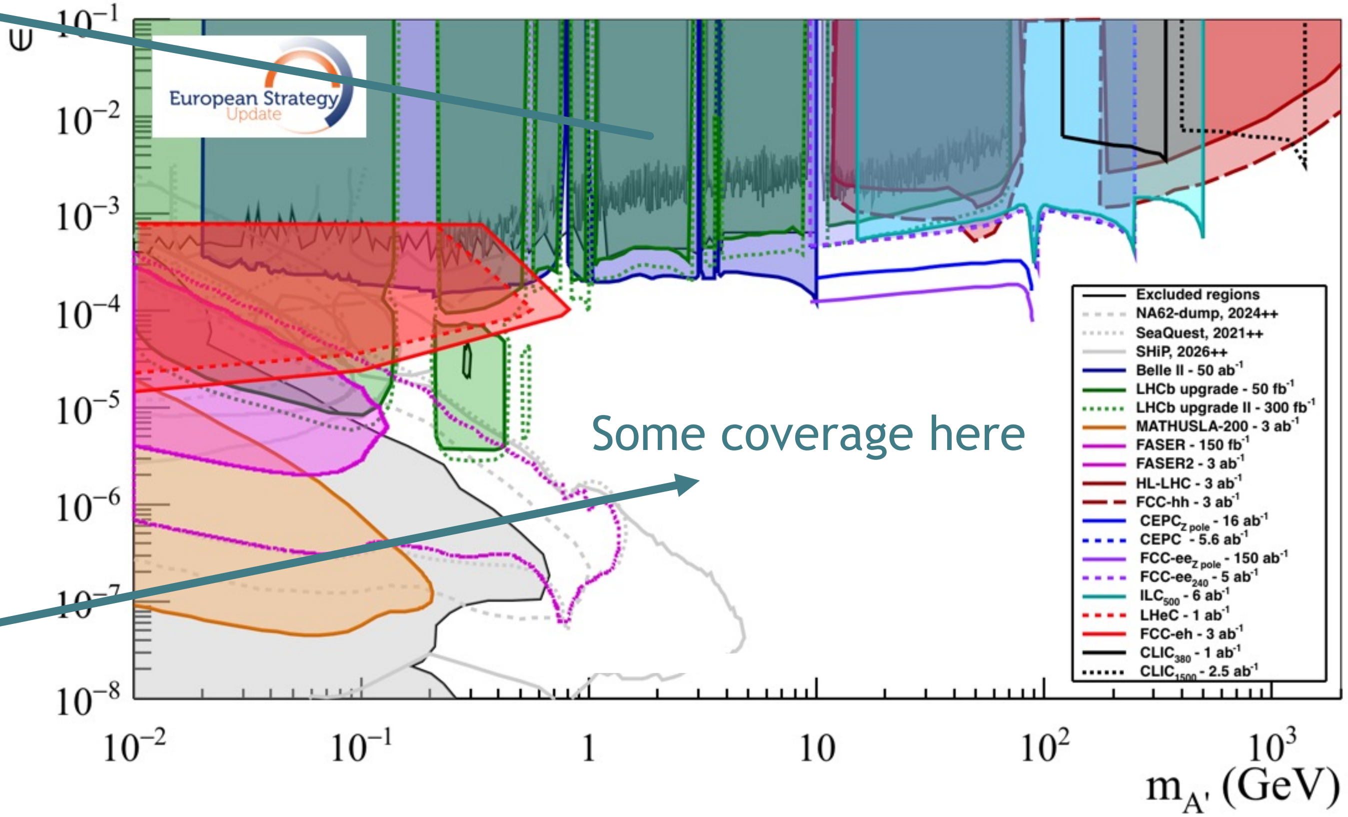


Displaced





Prompt searches sensitive to large couplings

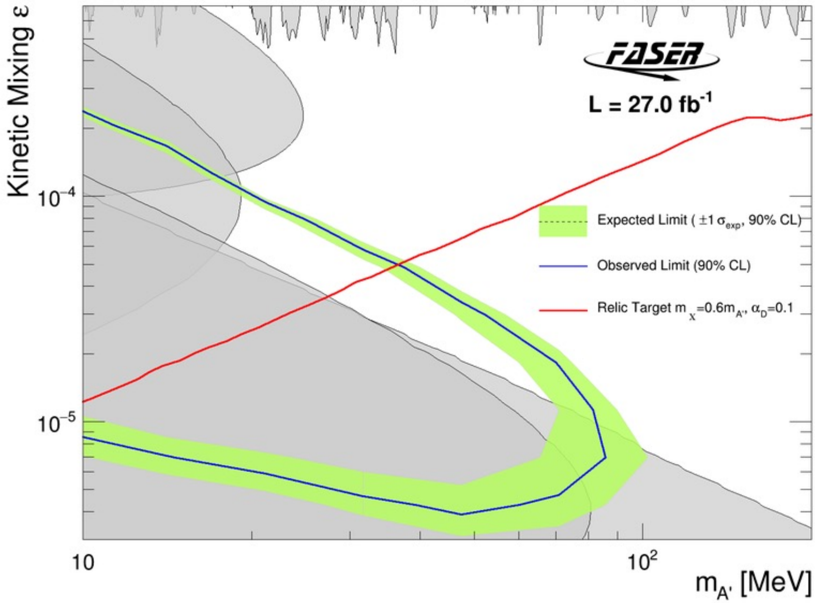


From European Strategy to nowadays: Dark Photons

- Vector portal minimal models: have masses around the GeV scale and their interactions are QED-like, scaled with the small mixing parameter ε.

FASER current results

dark photons decaying e+e-
→ **Very displaced**, background <10^{-3} events



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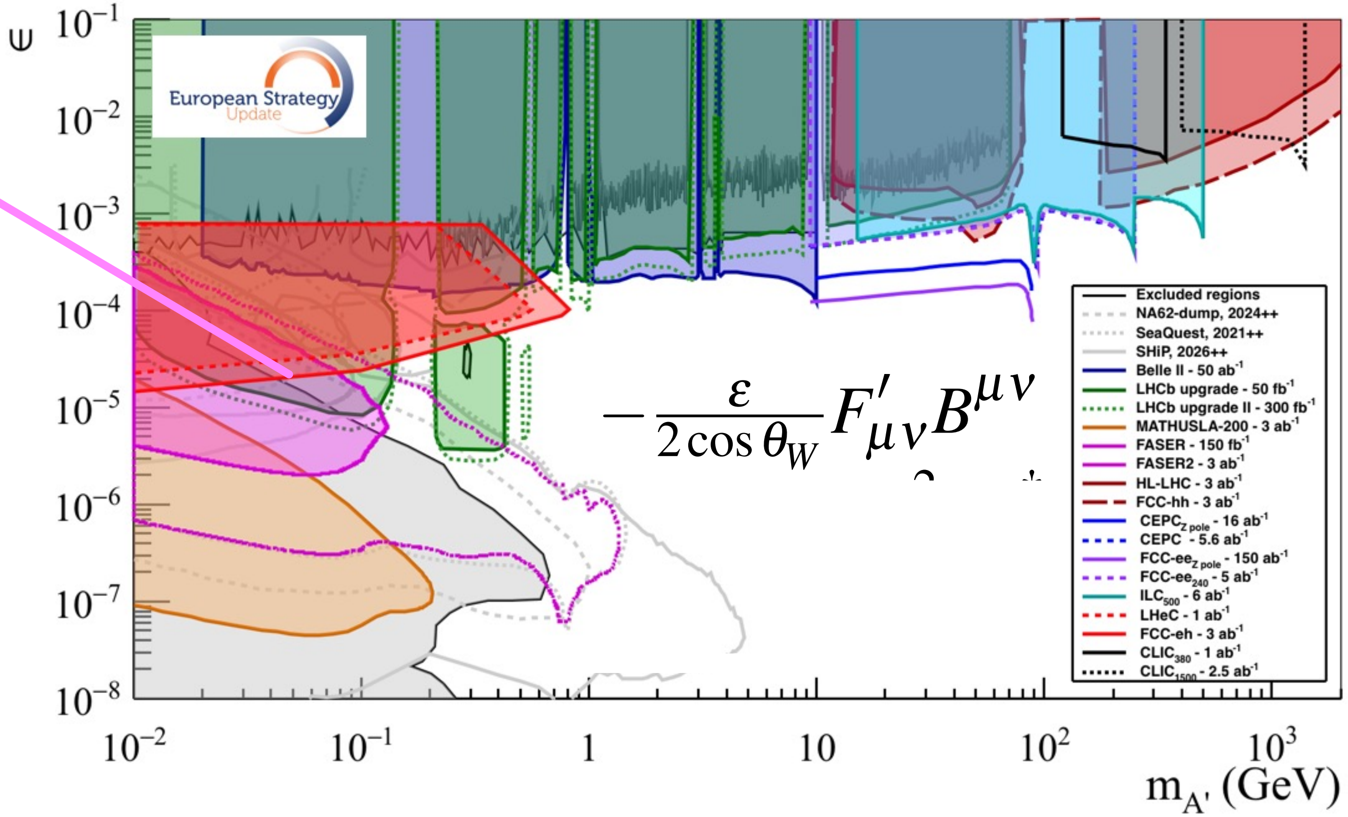
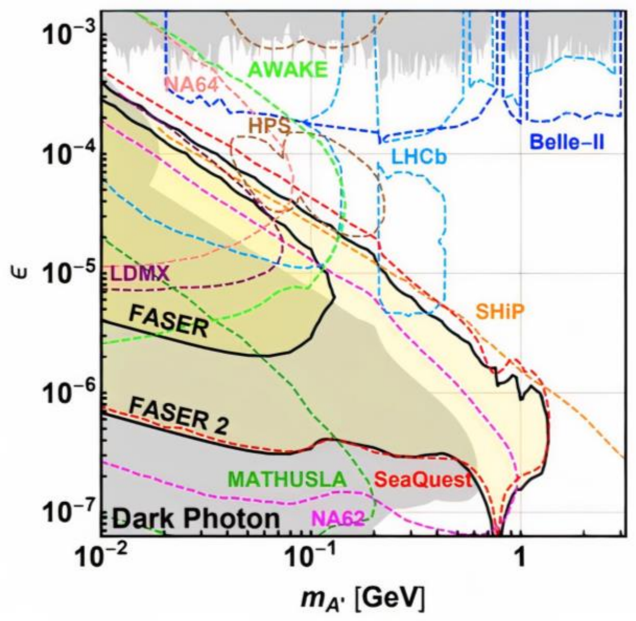


From European Strategy to nowadays: Dark Photons

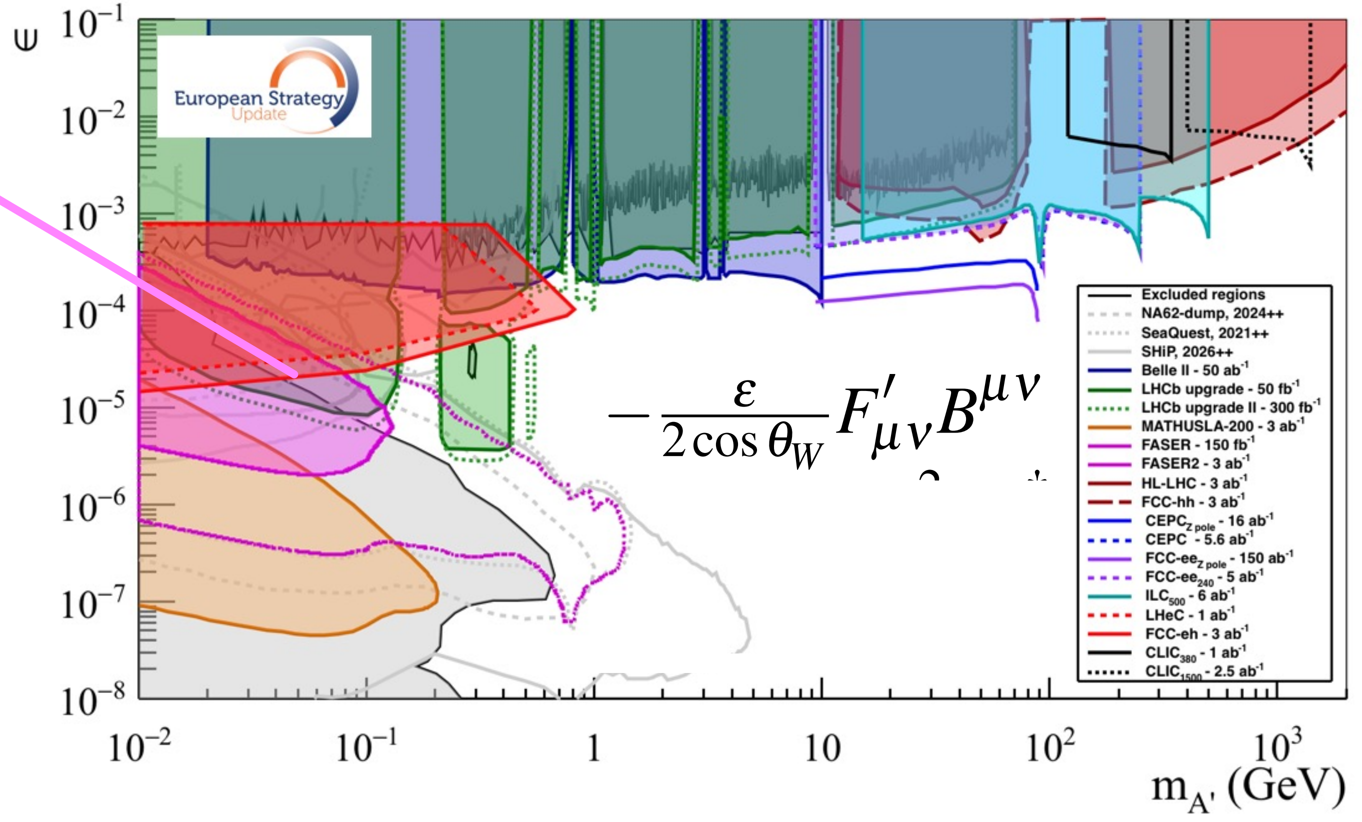
- Vector portal <u>minimal</u> models: have masses around the GeV scale and their interactions are QED-like, scaled with the small mixing parameter ε.

FASER prospects

dark photons decaying e+e- and $\mu^+\mu^-$
→ **Very d**isplaced, assume 0 background



Prompt searches sensitive to large couplings

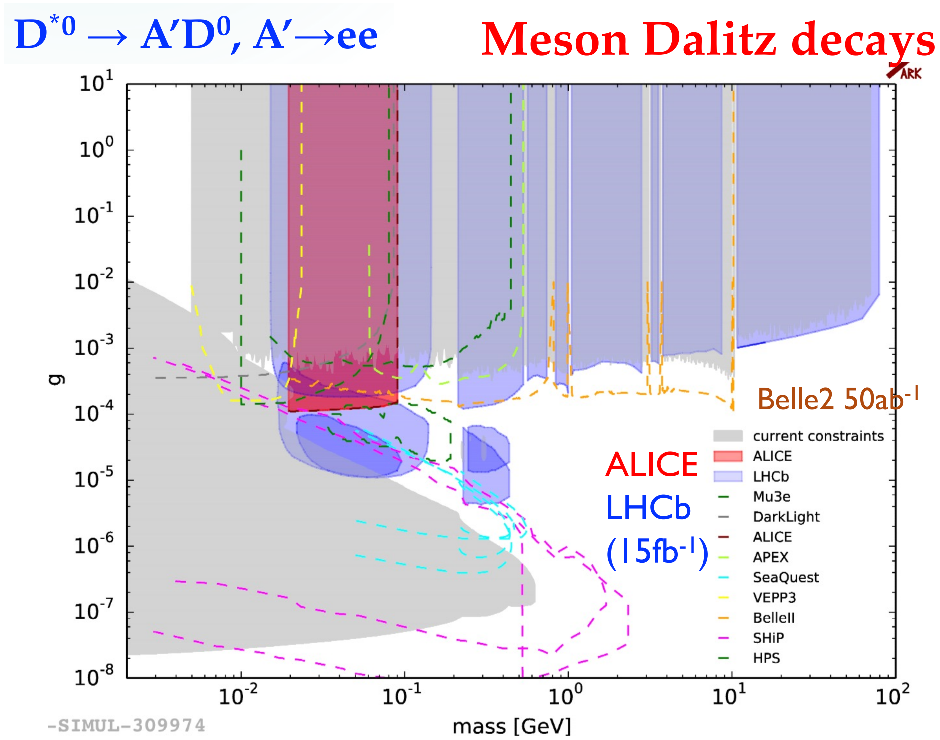


From European Strategy to nowadays: Dark Photons

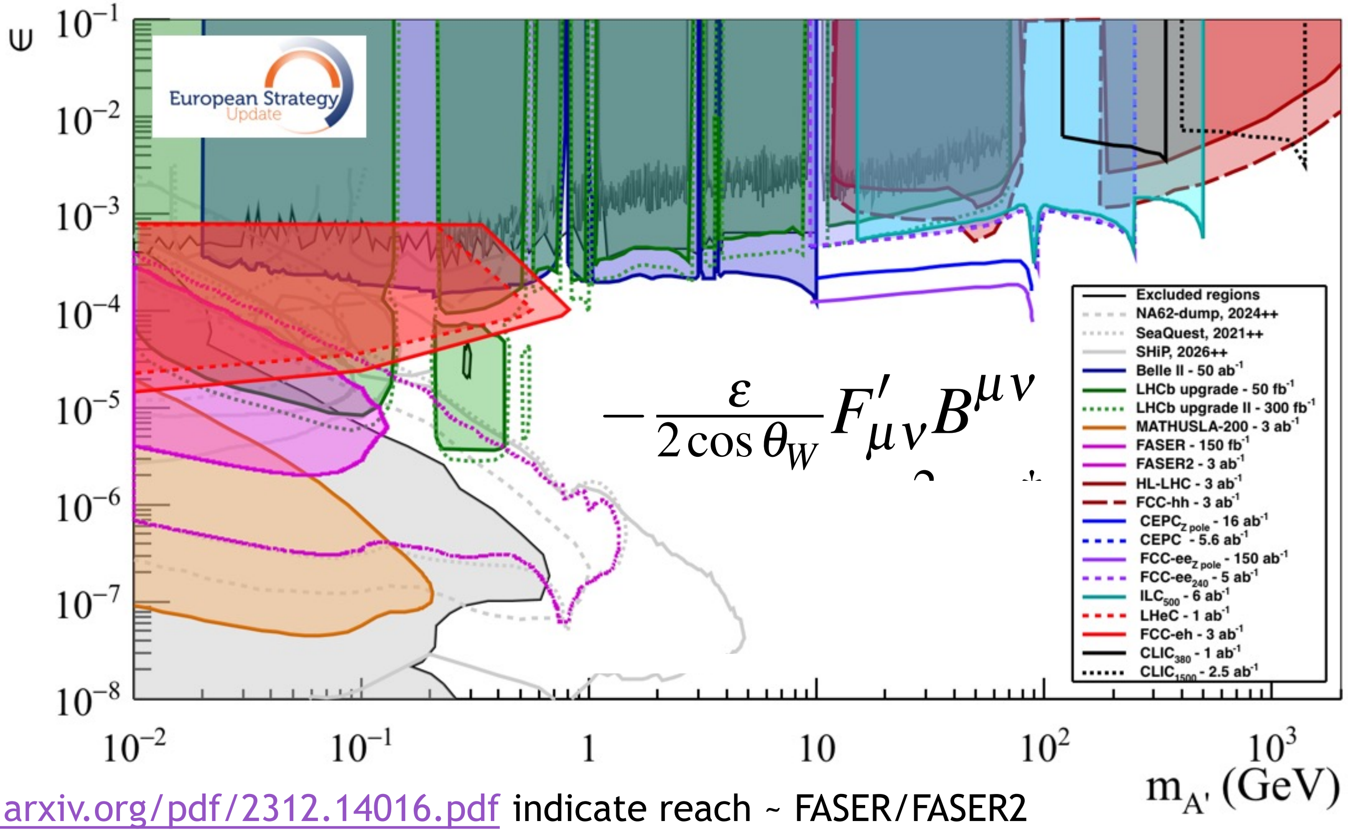
- Vector portal minimal models: have masses around the GeV scale and their interactions are QED-like, scaled with the small mixing parameter ε.

LHCb but also ALICE prospects

dark photons decaying e+e- or μ+μ-



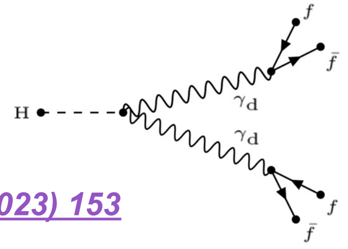
Prompt searches sensitive to large couplings

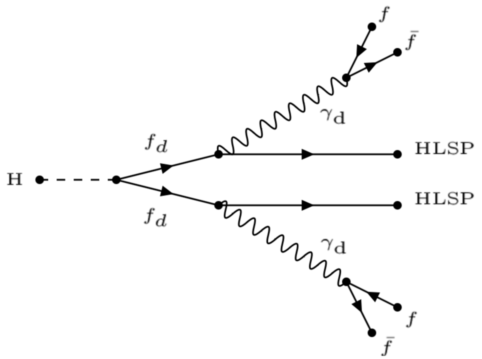


Other studies for LHCb potential for instance in https://arxiv.org/pdf/2312.14016.pdf indicate reach ~ FASER/FASER2

Non-minimal dark photons: a Higgs story

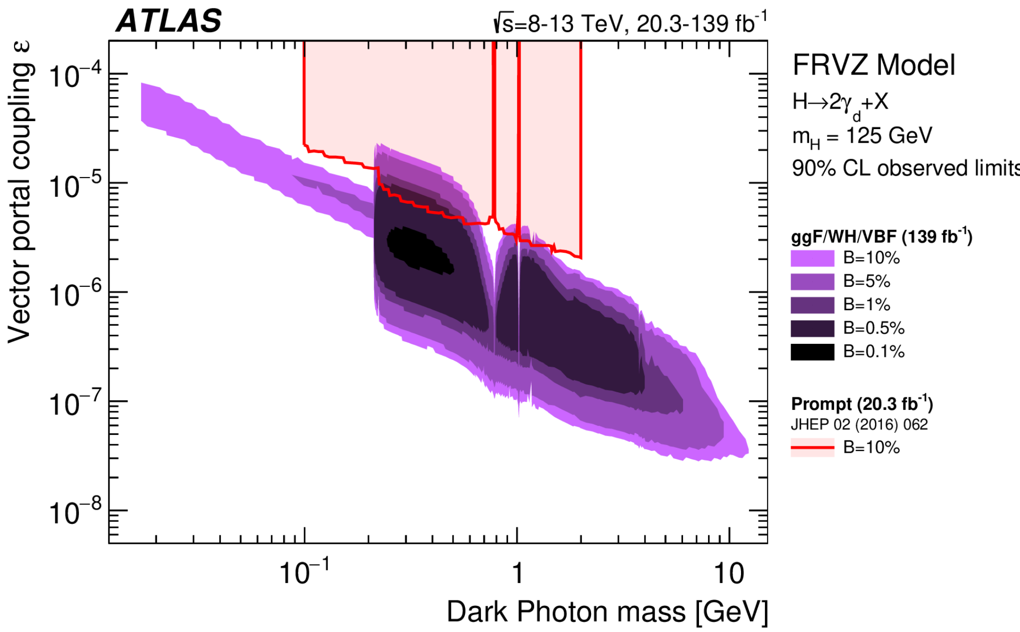
- Higgs boson might decay into **long-lived** dark photon (and possibly other dark particles). Constraints depend on mass and assumed Higgs BR



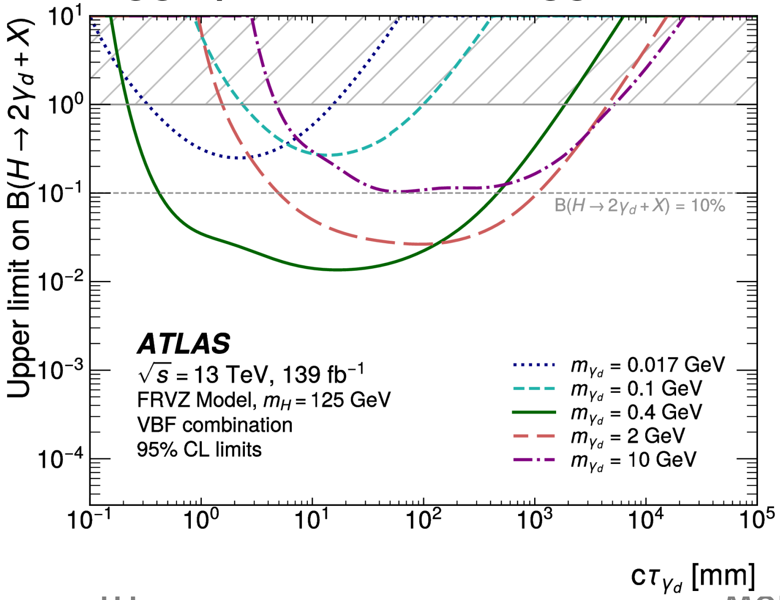


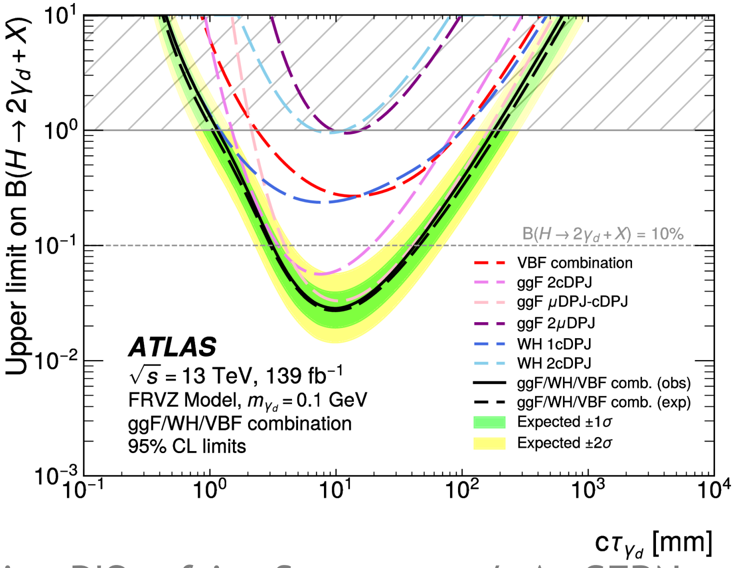
[JHEP 06 (2023) 153]

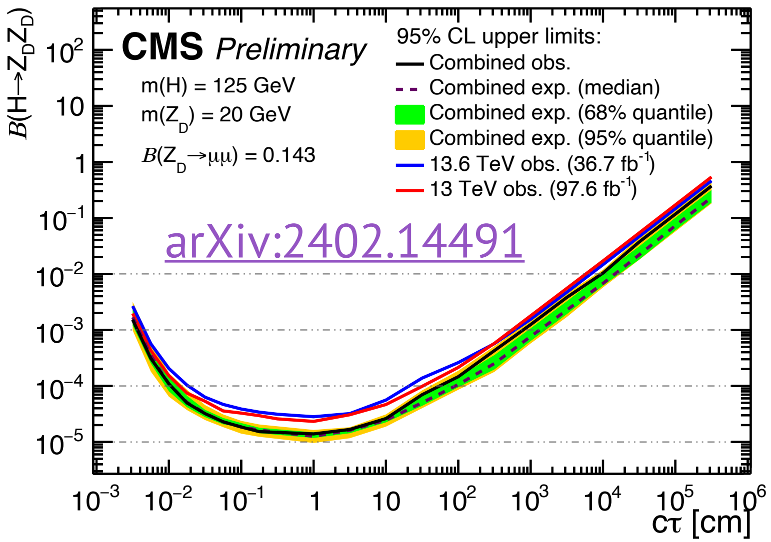
[2311.18298]



- Higgs produced via ggF, WH, VBF, CMS targets high masses



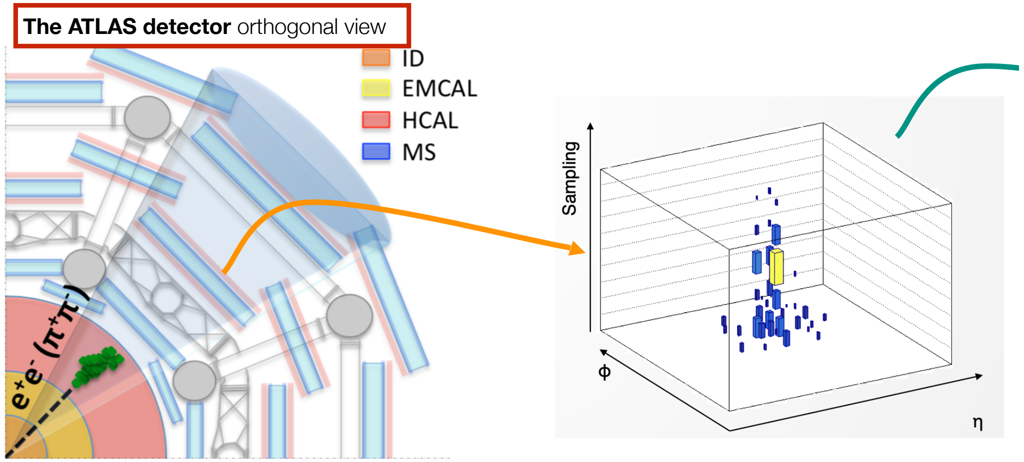


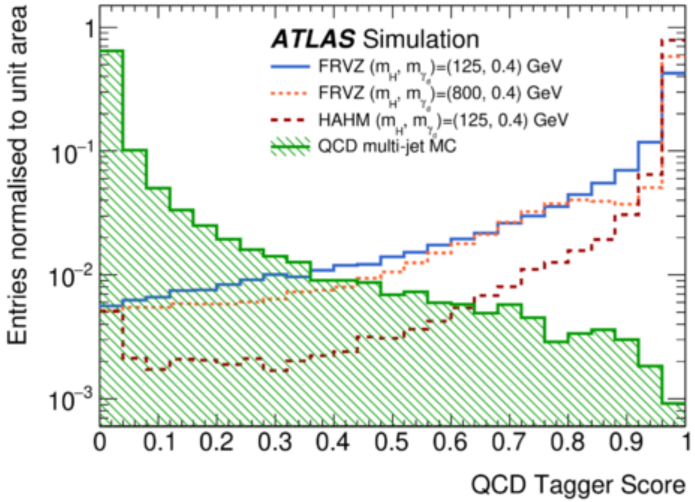


[arXiv:2402.14491]

Key features of signatures and challenges

- high couplings: mostly constrained already, prompt signatures dominant (i.e. $\mu^+\mu^-$)
- low couplings – the most difficult bit (10 MeV – GeV range in particular):
  - Dark photons decay to e+e- or $\mu^+\mu^-$, possibly soft-momenta i.e. at very light masses
  - At collider experiments, need low-pT thresholds trigger, good control of beam-induced and cosmic backgrounds, dedicated reconstruction of unconventional objects (non-standard tracks, non-standard energy deposits in calorimeters etc)
  - Example of narrow jets reconstruction for ATLAS search – use CNN to reject fake jets
    - Calorimeter-images used to identify signal clusters



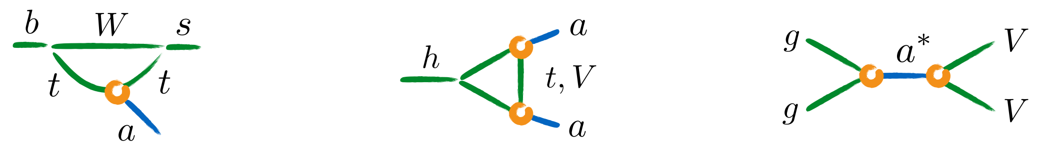


Such techniques could be used at ep as well!

Axion-Like Particles (ALPs)

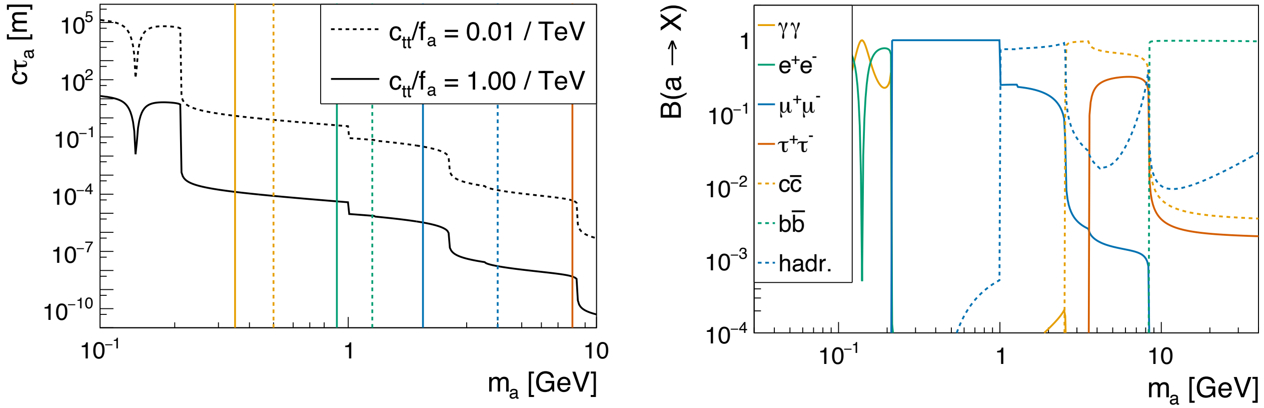
- Several production processes, decay lengths and decay modes to consider
  - At colliders:

meson decays — Higgs decays — virtual ALPs



(credit: [this talk]())

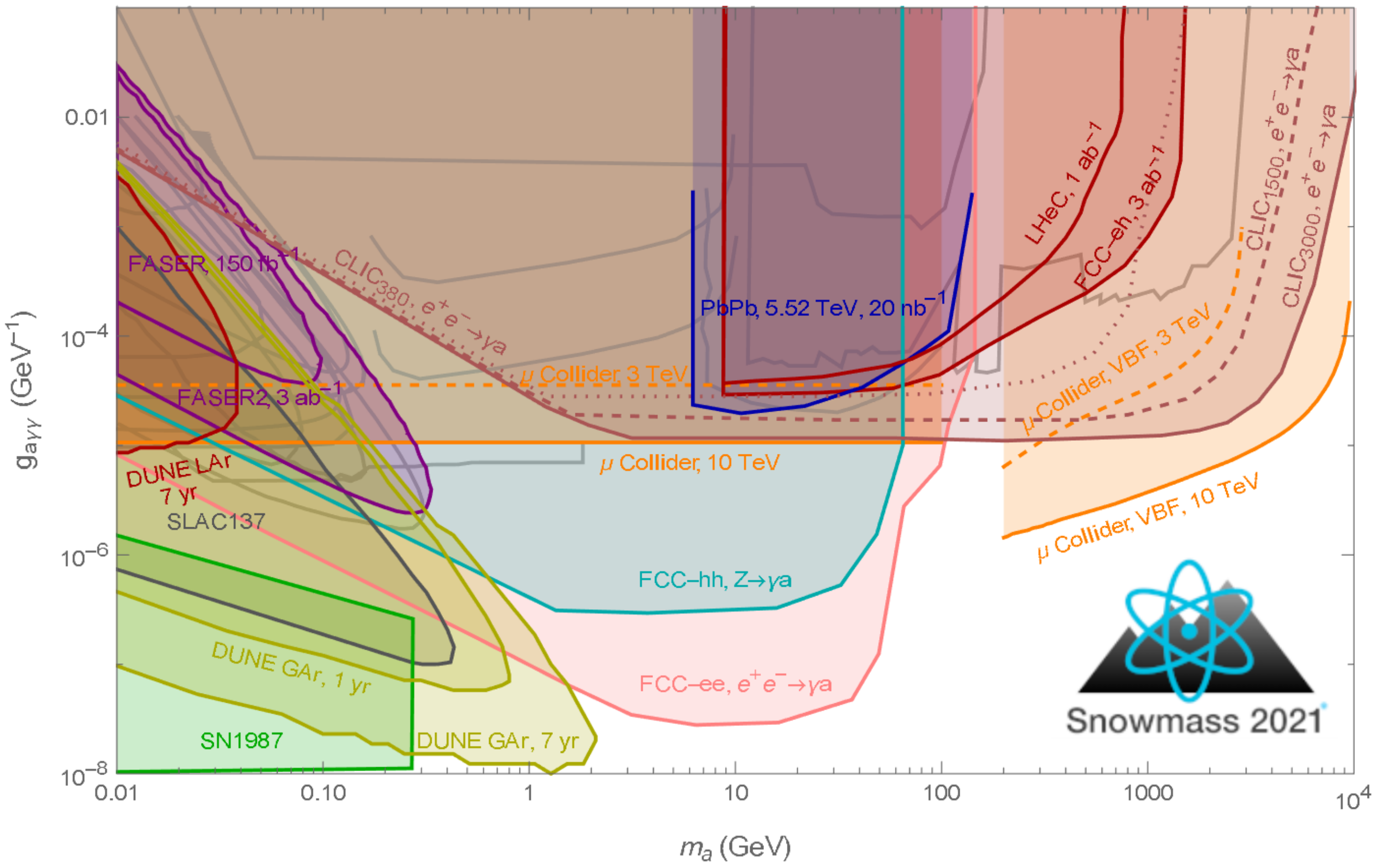
decay length — decay modes



- Minimal model from colliders:
  - ALPs decaying to photons (e.g. FASER (and FASER2) prospects) or muons (LHCb, EIC prospects)
  - Ultra-peripheral HI collisions study and prospects (ATLAS, CMS, ALICE 3)
- Non minimal from colliders
  - ATLAS/CMS searches from Higgs boson decays

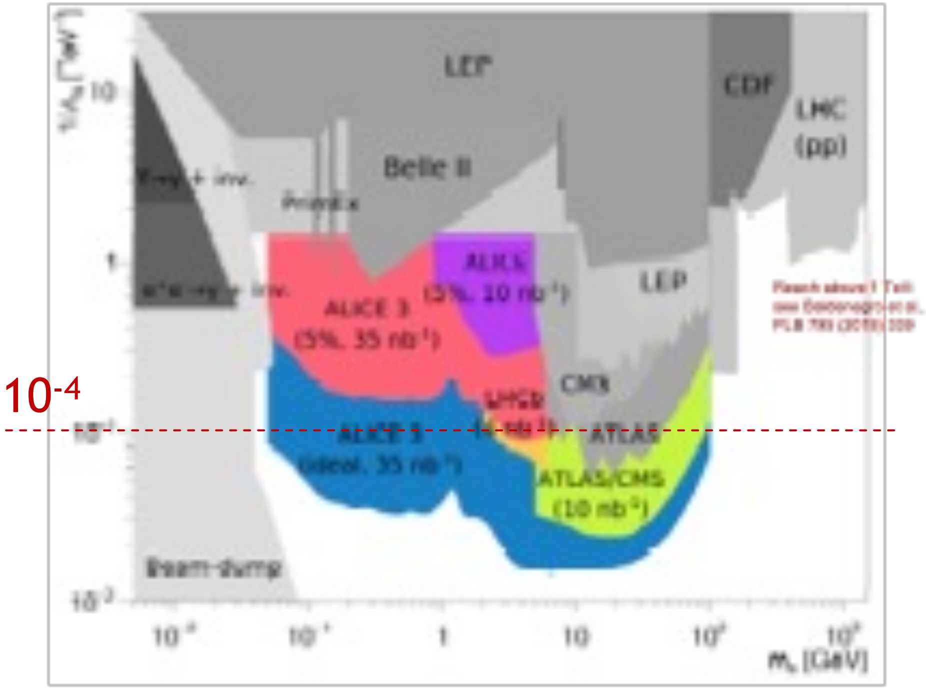
Axion-like particles (ALPs)

- Snowmass summary plot illustrates well the vast number of studies (long-term and medium-term) targeting axion-like particles – photon couplings here taken as benchmark
  - with LHeC/FCC-eh filling important gaps



Ultra-peripheral HI collisions – through $\gamma\gamma$ scattering offer interesting prospects (note different units! GeV vs TeV)

https://arxiv.org/pdf/2203.05939.pdf



Axion-like particles (ALPs): FASER

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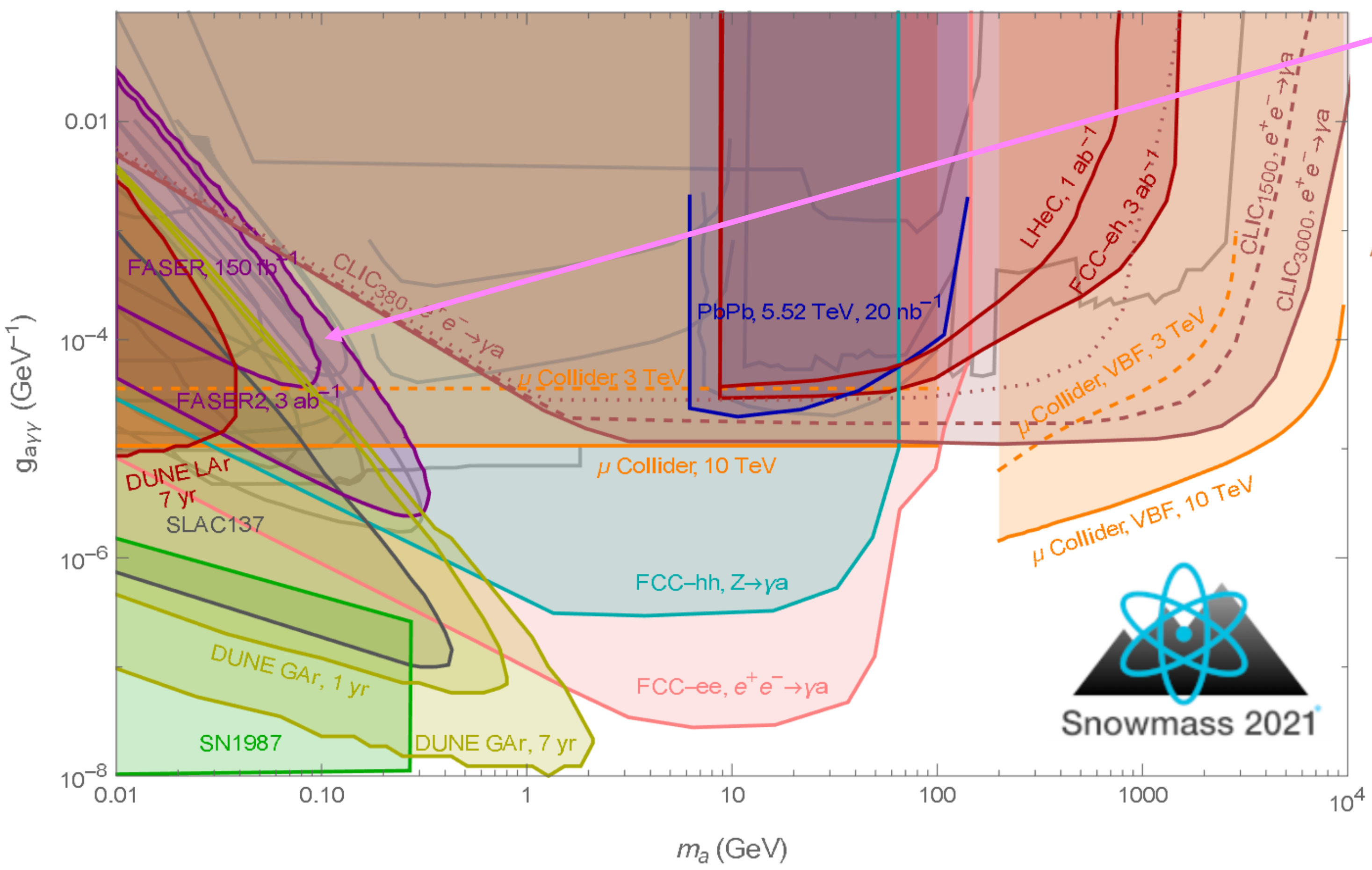
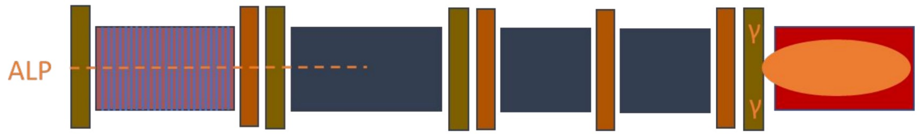
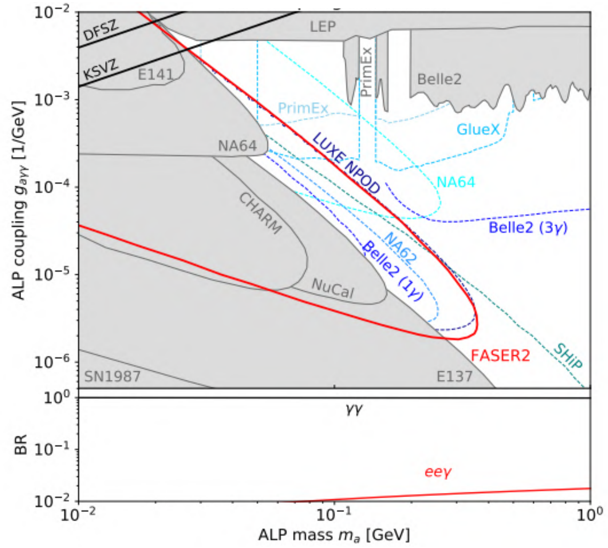


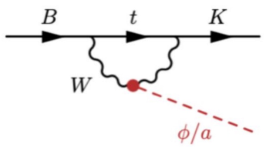
FASER and FASER-2 prospects

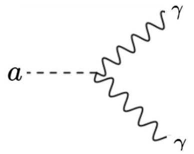
FASER analysis on-going, expected for Moriond24



ALP coupling to photon







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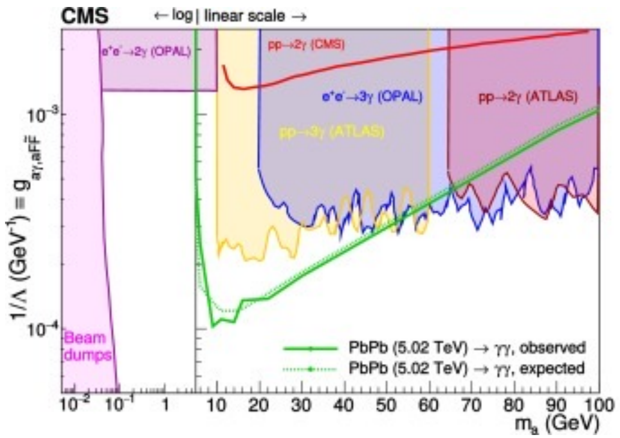
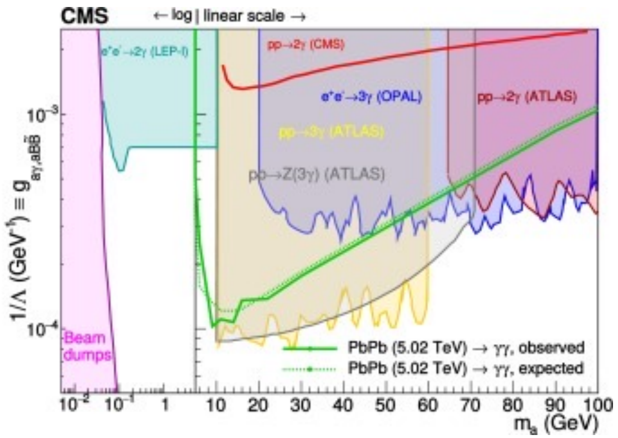
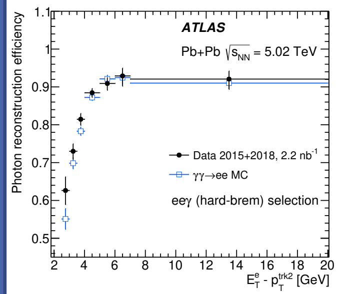
PLB Volume 797, 10 October 2019, 134826 (CMS)

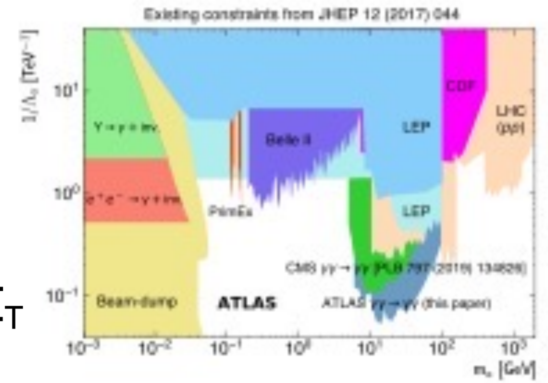


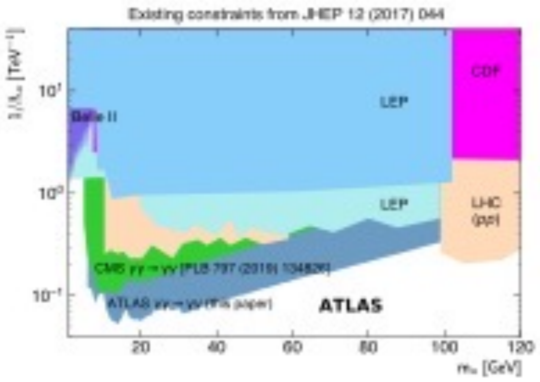




Very low photon E_T

*JHEP03(2021)243 (**ATLAS**)*

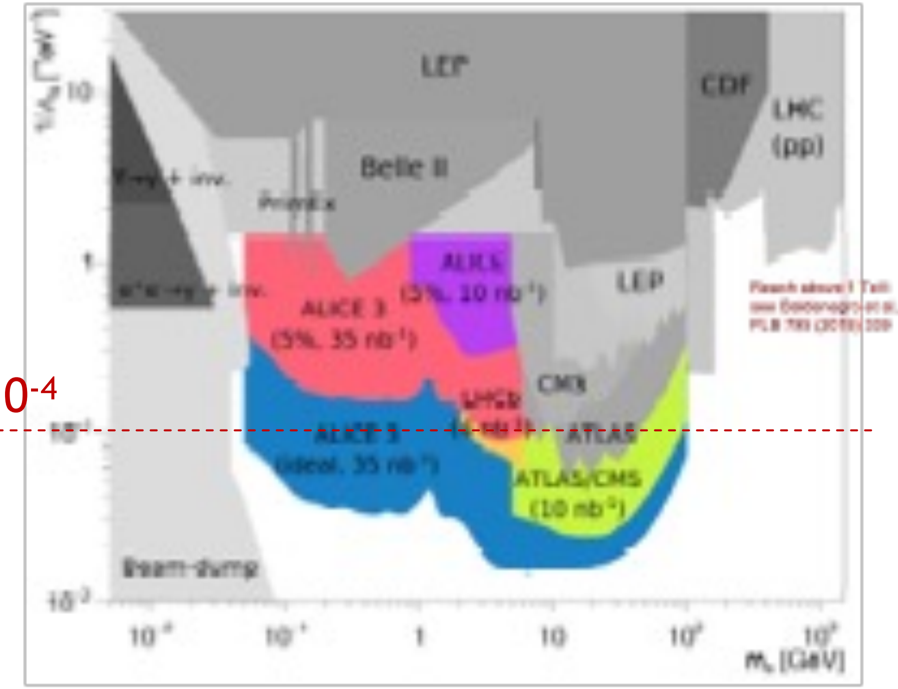




Ultra-peripheral HI collisions – through γγ scattering offer interesting prospects

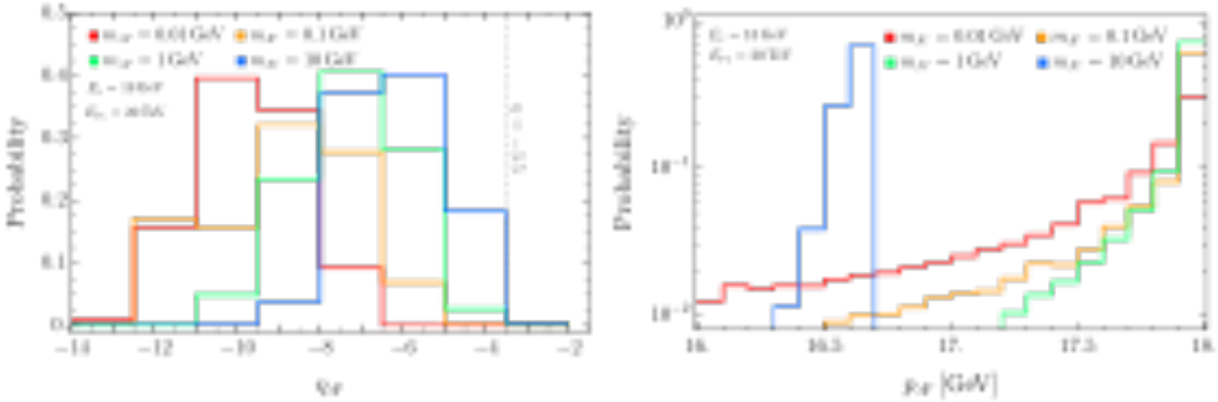
https://arxiv.org/pdf/2203.05939.pdf

10^{-4}



Axion-like particles (ALPs): other modes [prospects]

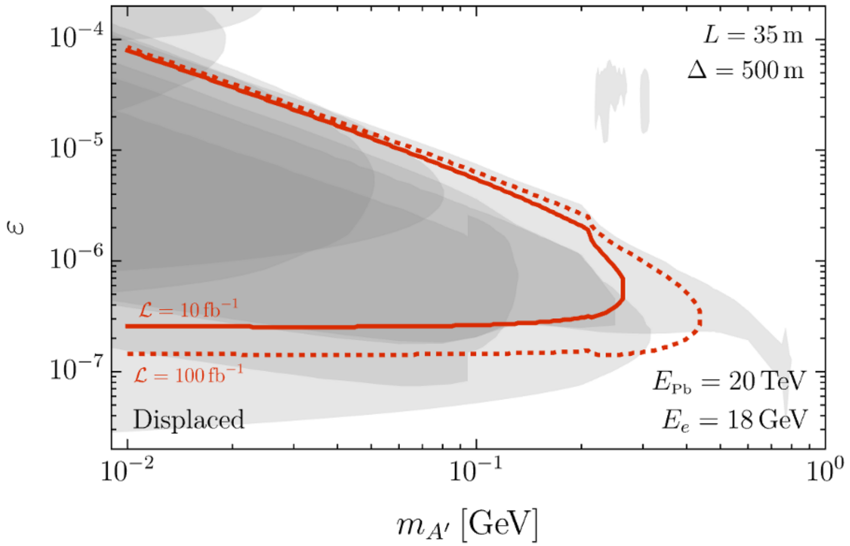
- Additional studies on prospects also consider other decay modes
  - For example: EIC (left) and LHCb (right)



$e^- N \to e^- N a$

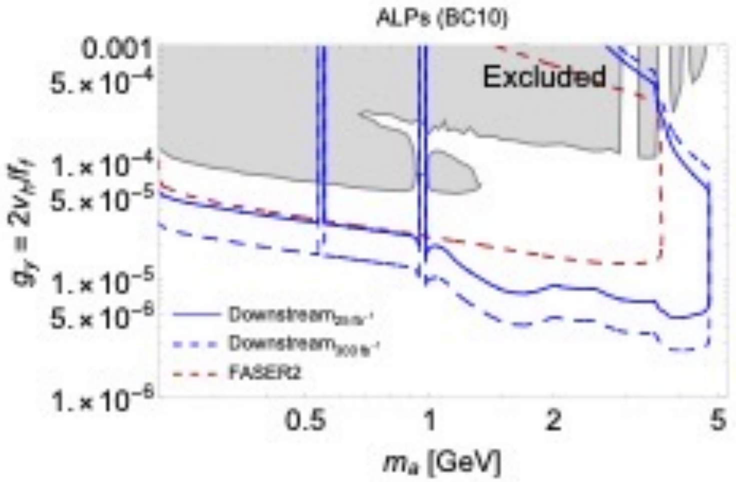
prompt $A' \to \mu^+\mu^-$

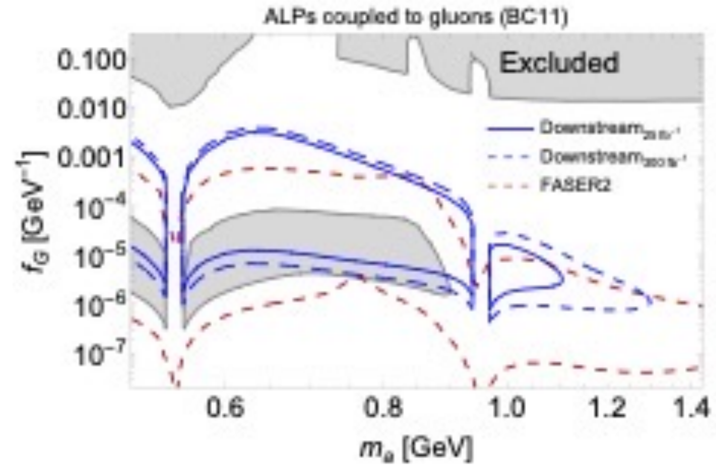
JHEP02(2024)123



https://arxiv.org/pdf/2312.14016

$B_{(s)} \to a X_s$ $\pi^0/\eta/\eta'$ mixing Drell-Yan	$\ell^+\ell^-, \eta 2\pi, 4\pi$ gg



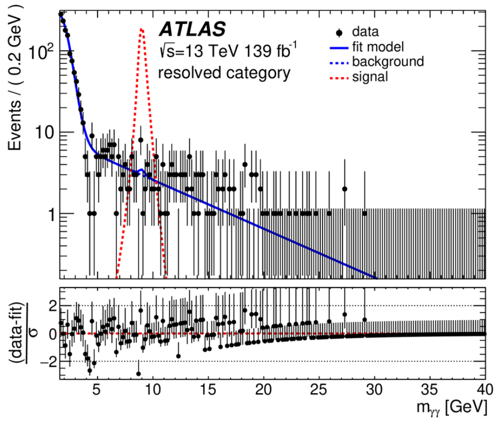


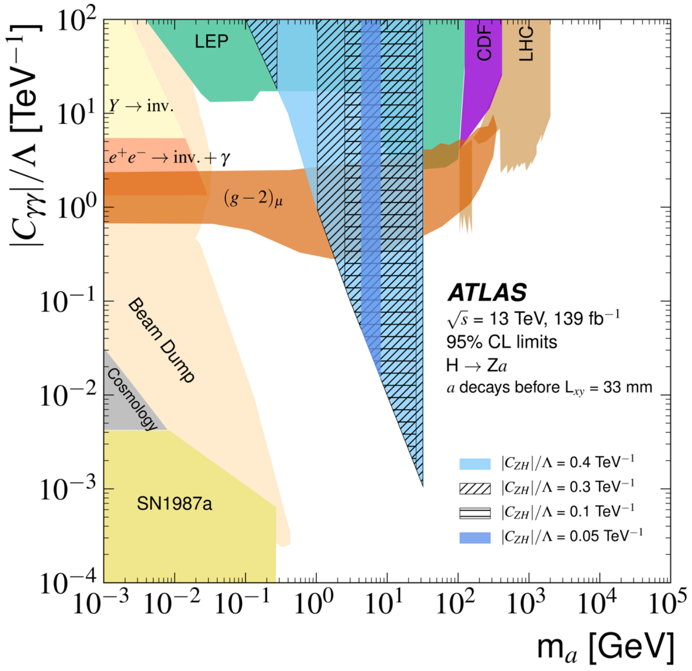
ATLAS/CMS search strategies: again, use the Higgs!

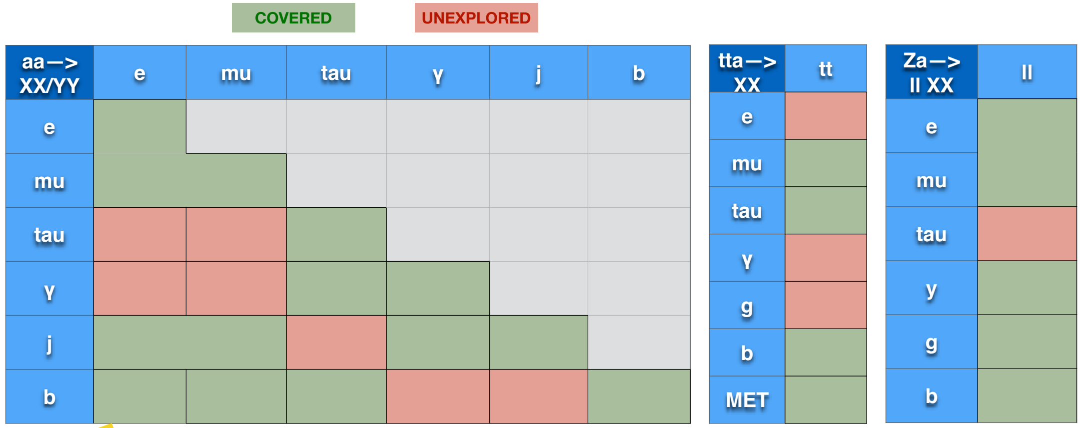
- Prompt and displaced - extensive programme on-going, with diverse analyses targeting various final states
  - but a lot of final states still unexplored!
- Example from ATLAS of ALPs in photons

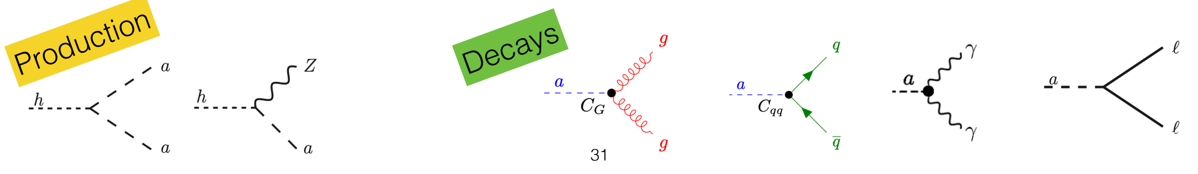
Phys. Lett. B 848 (2024) 138536

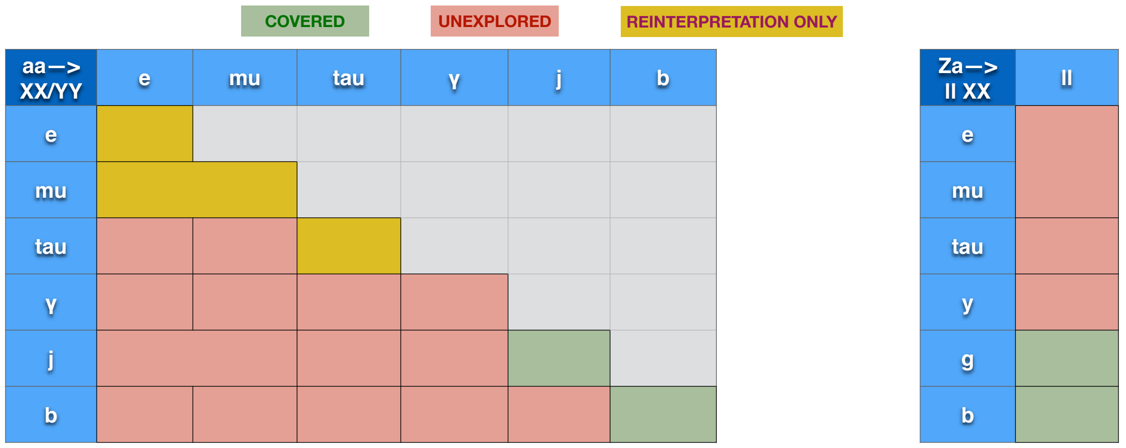
Prompt ALPs decays in $\gamma\gamma$











Credits: Cristiano Sebastiani

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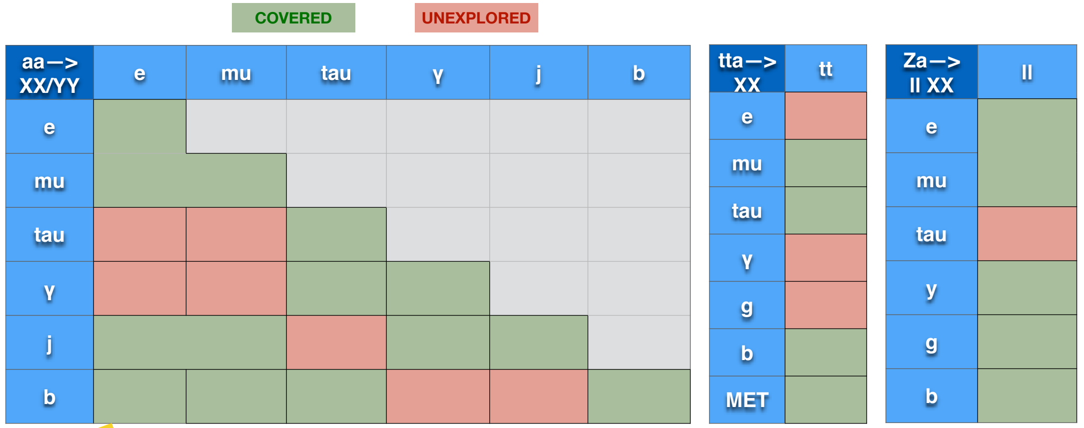
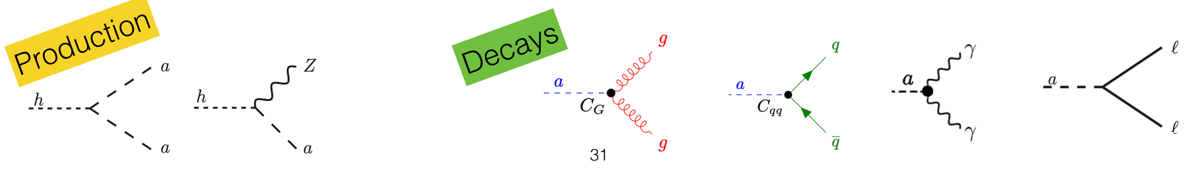
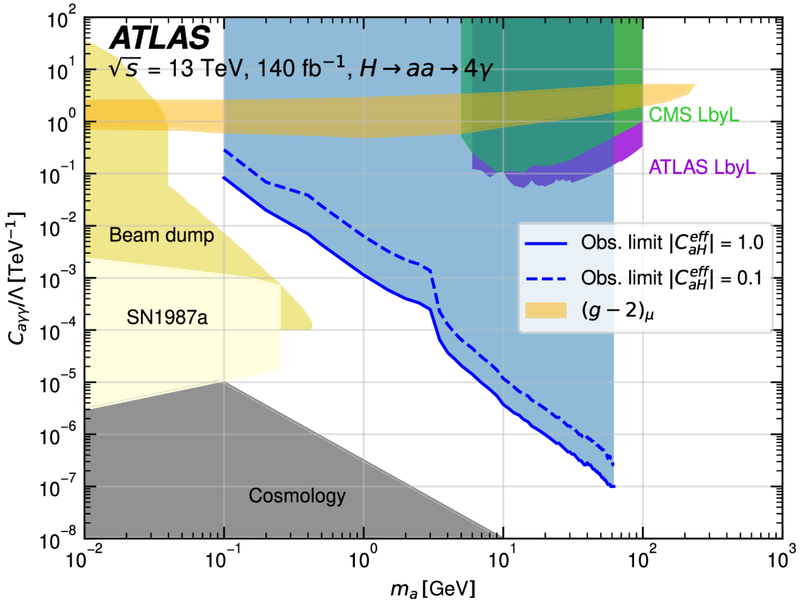
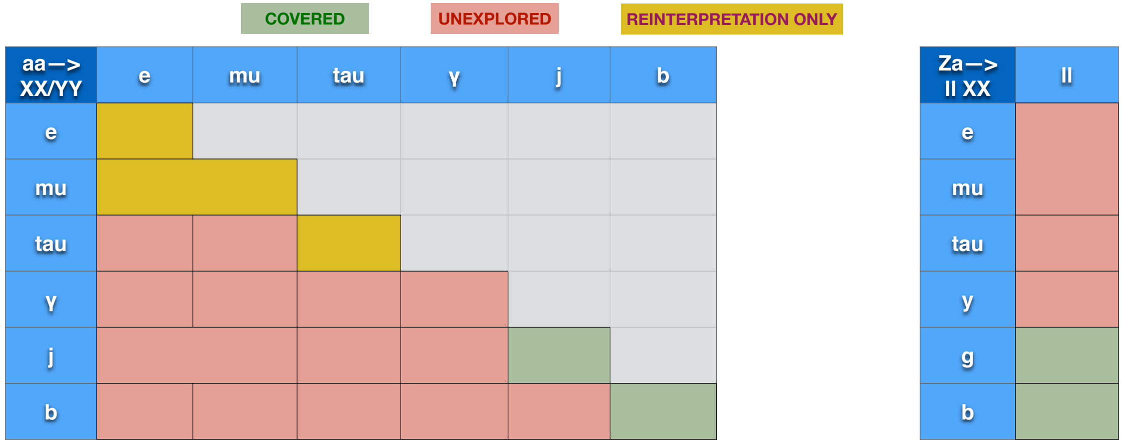




arXiv:2312.03306

Prompt and long-lived categories explored through different SRs





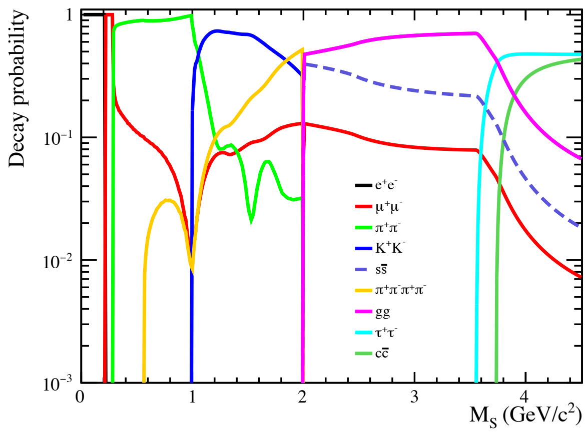
Credits: Cristiano Sebastiani

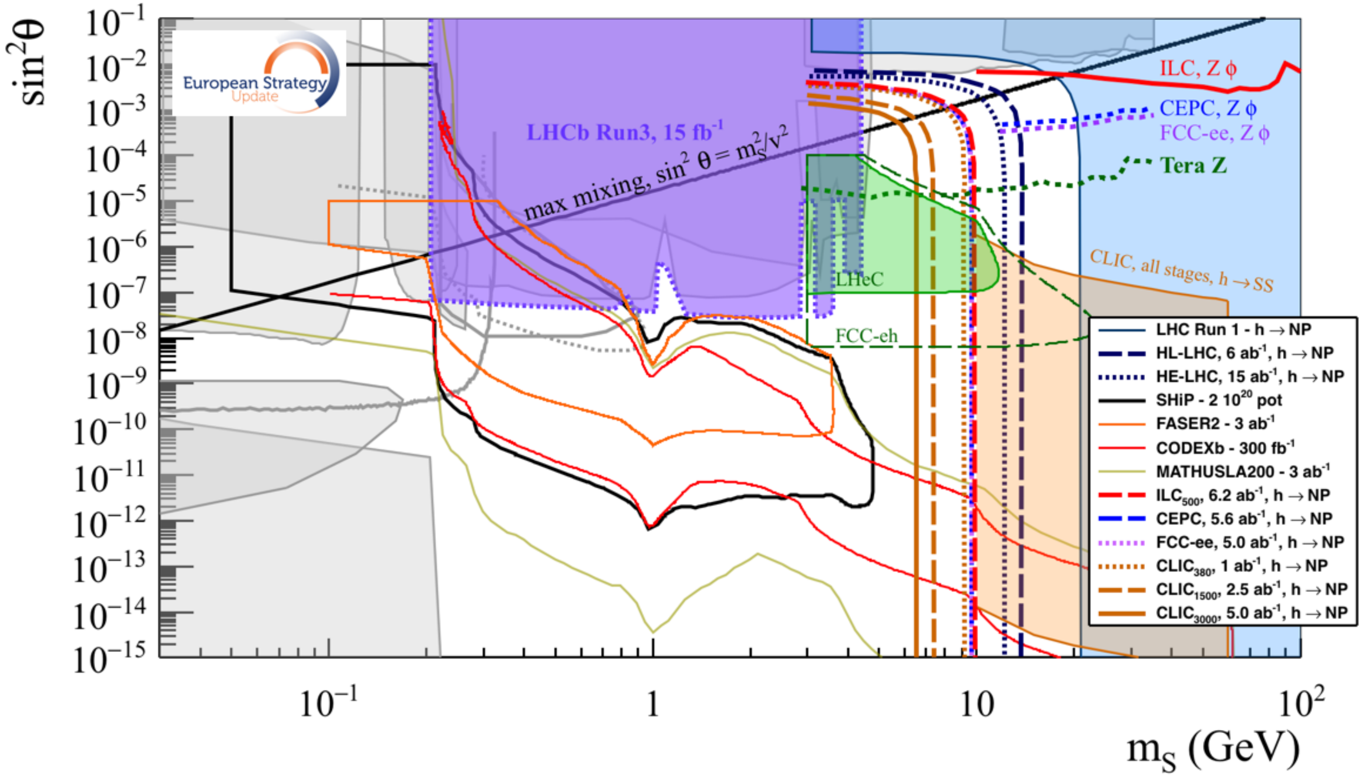
New (Dark) scalars

- New scalars can arise from many models. For HS, particles are again mostly long-lived
- Diverse signatures can be considered, interpreting the results for a specific model, where lifetime and production rate of the LLP are governed by a scalar mixing angle.
- In general:

$$(\mu S + \lambda_{HS} S^2) H^\dagger H$$

Production	Decay modes
$B_{(s)} \to S X_s$ $B \to SSX$ $h \to SS$	$\ell^+\ell^-, \pi^+\pi^-,$ $K^+K^-, c\bar{c}, gg\ldots$





the contours are for 3 events and consider displacements larger than 50 µm to be free of background

New (Dark) scalars

- New scalars can arise from many models. For HS, particles are again mostly long-lived
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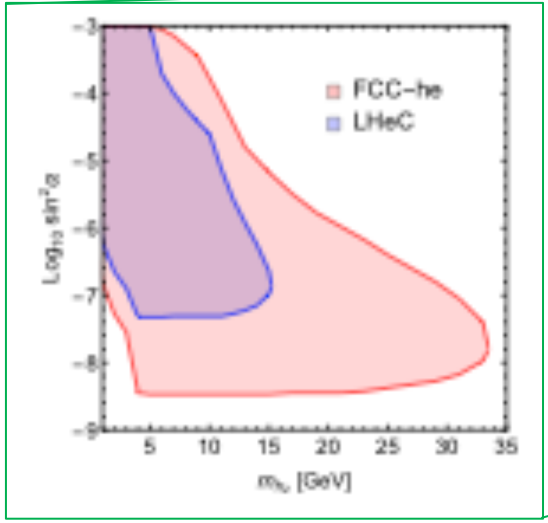
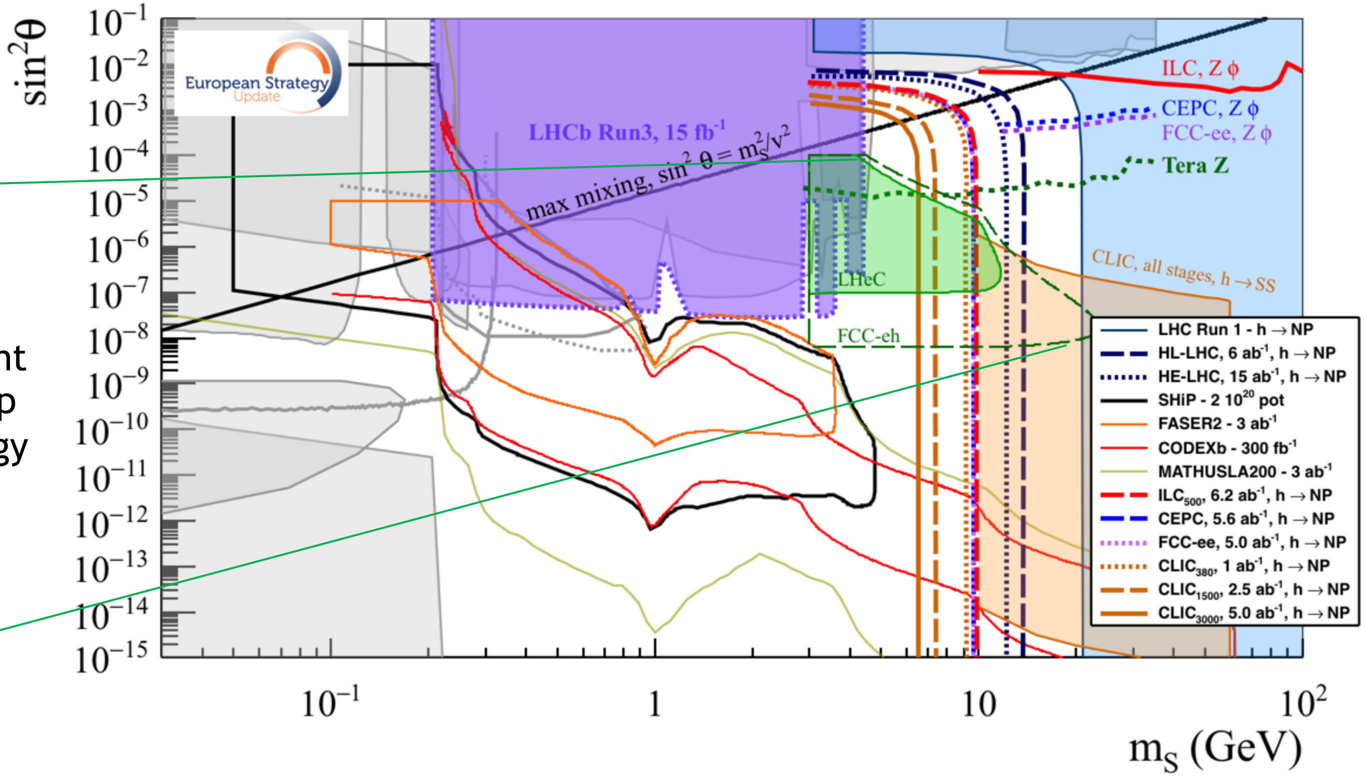
- At electron-proton:



ep covers important regions between pp and ee / low-energy experiments

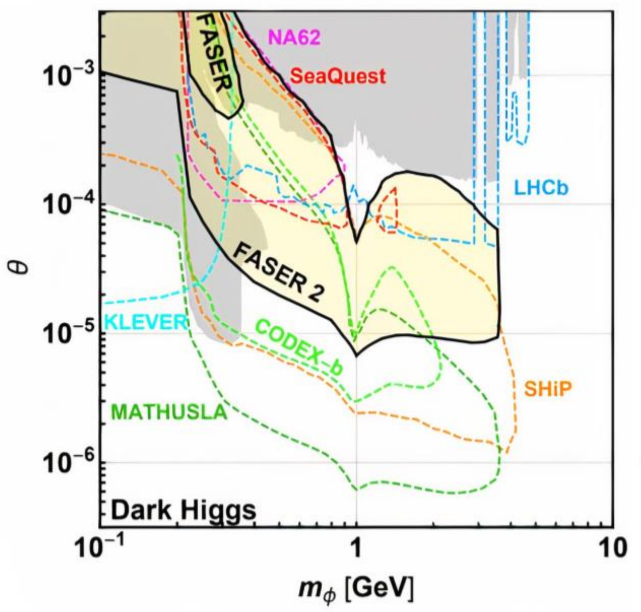


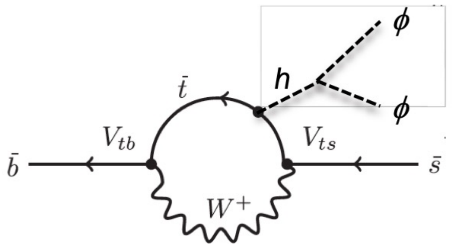
the contours are for 3 events and consider displacements larger than 50 µm to be free of background

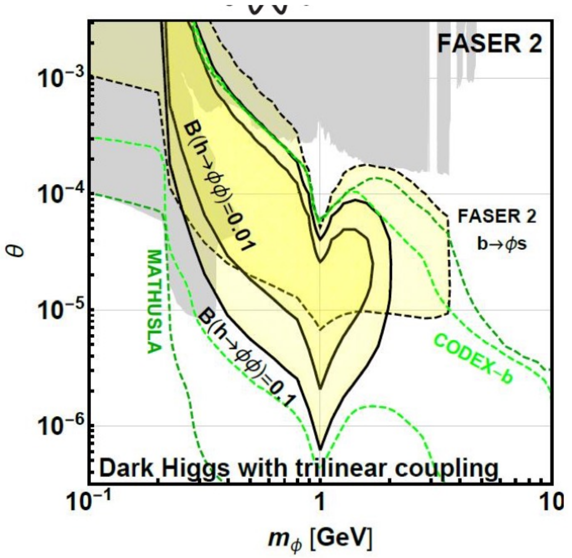
Constraints: mostly prospects!

➨ FASER-2 and LHCb as example: low production rates, mixed decay modes

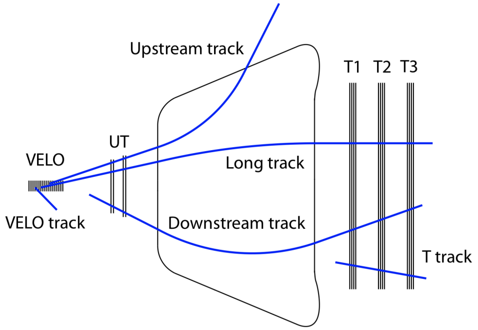
At FASER-2: consider benchmark with fixed BR or higgs invisible

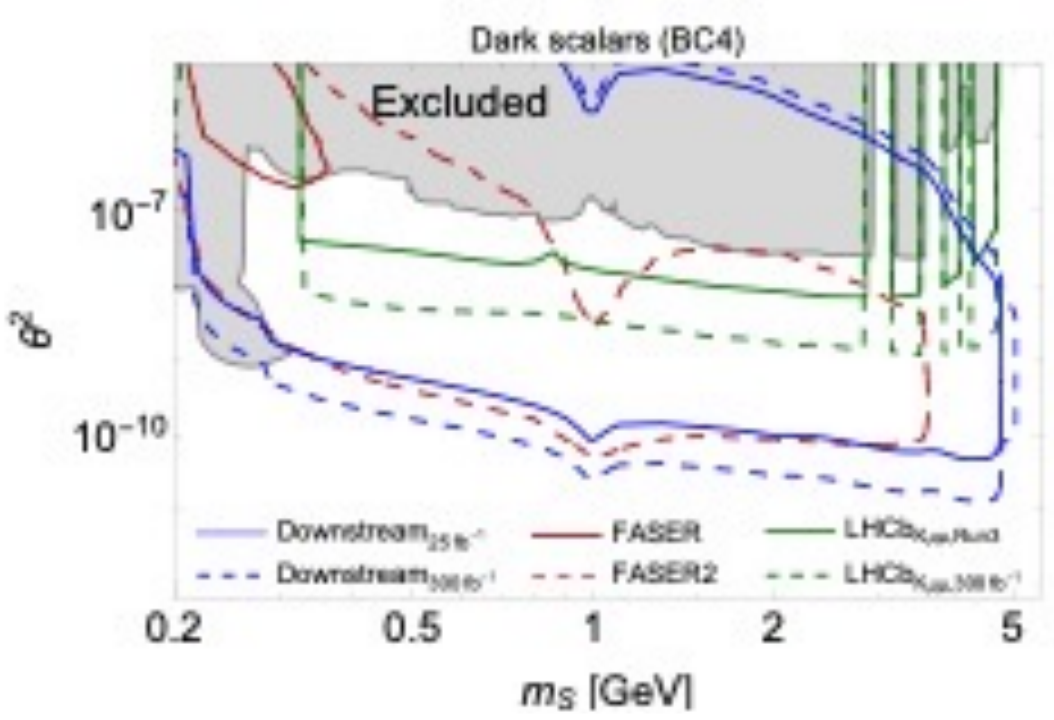






At LHCb: Improved prospects using new and more refined tracking algorithms



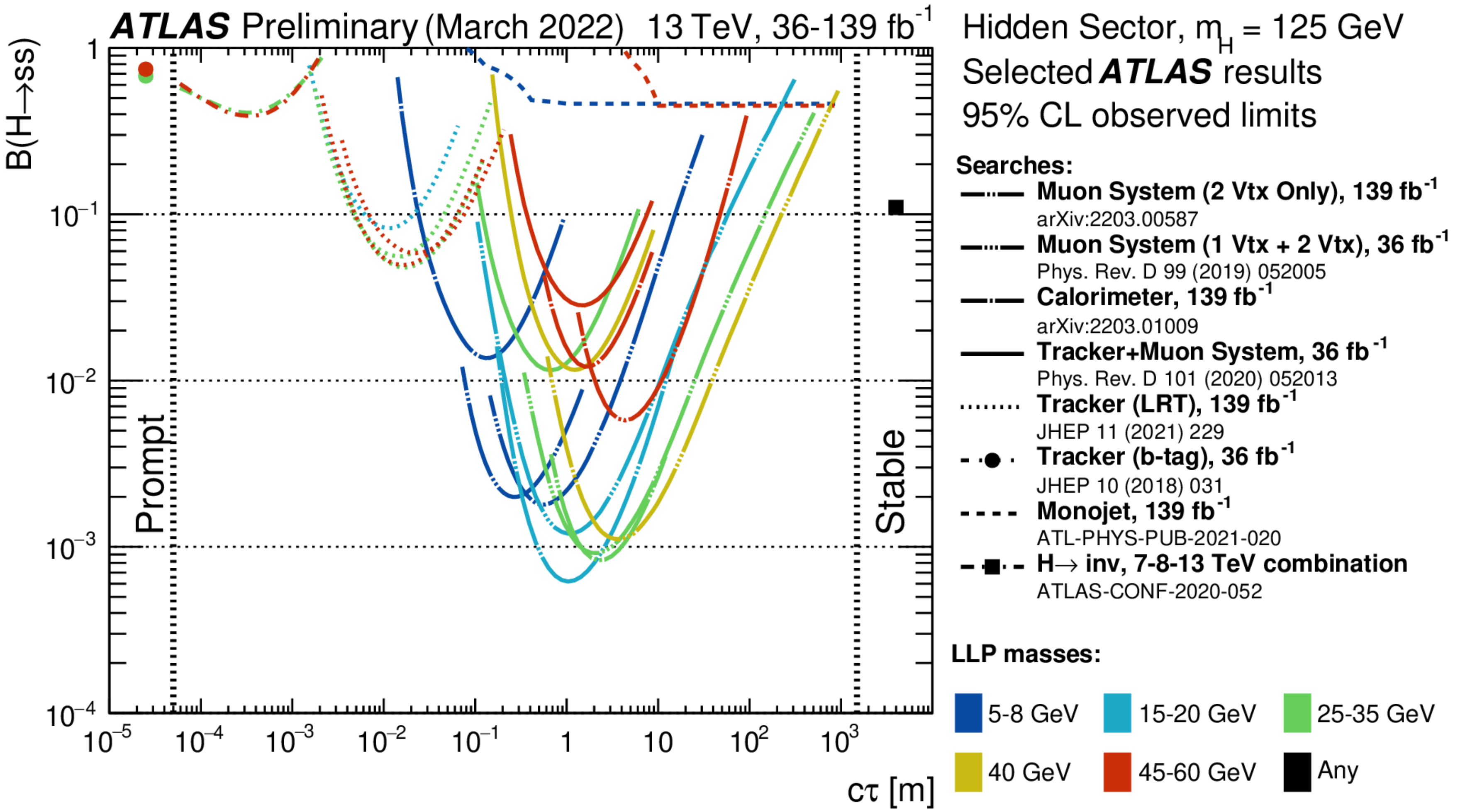


Constraints on new scalars from higgs decay

- At ATLAS and CMS: several searches that covers different and complementary decay lengths. Example: **h→ss**

Higgs BR versus cτ plane excluded at 95% CL, for a Hidden Sector model where a mediator Higgs boson of mass 125 GeV decays to a pair of long-lived neutral scalars (s).

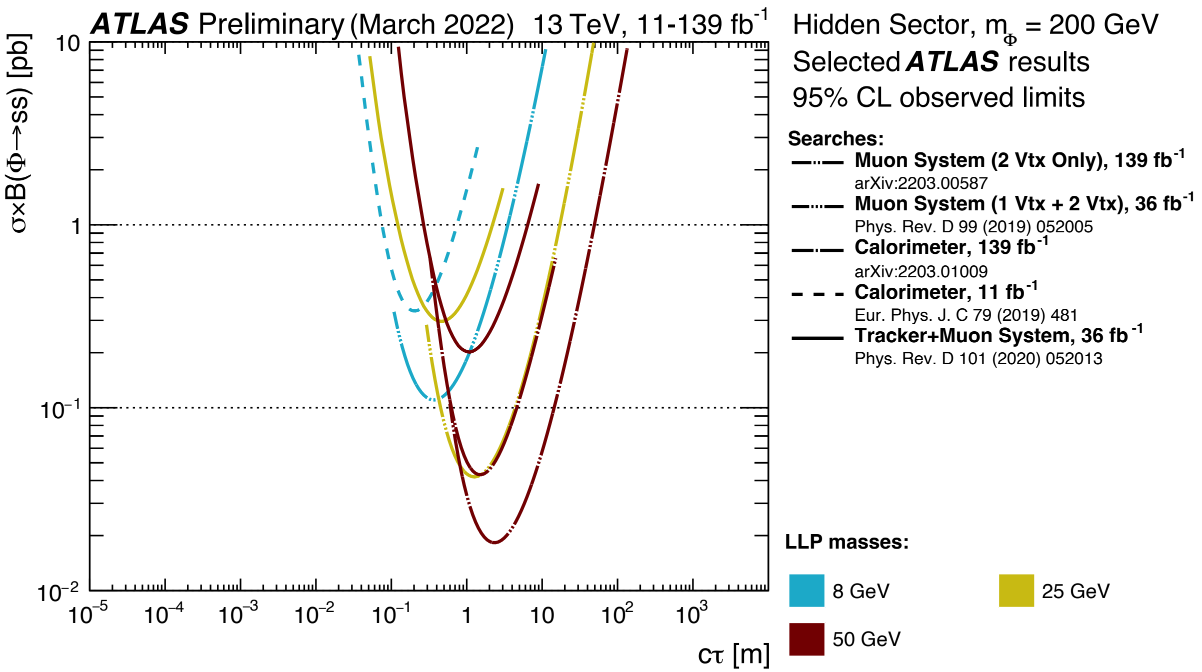
Considering current constrains on higgs invisible/untagged → region of interest for H→ss below 10%

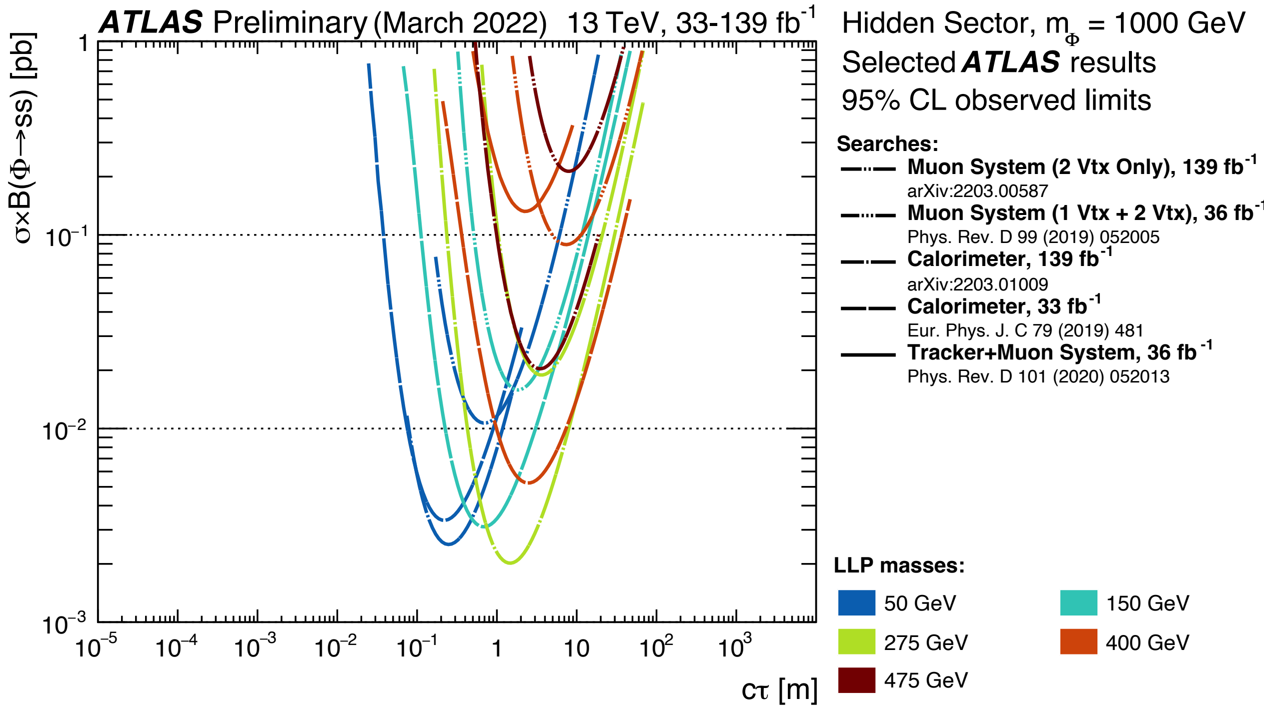


c is the speed of light and τ is the mean proper lifetime

New scalars from HS: more constraints

- Similarly, one can study the sensitivity for heavy scalar decaying into two LLP additional scalars. Constraints still in the region 10 cm – 10 m
  - Complementarities of other experiments and facilities for lower ctau?

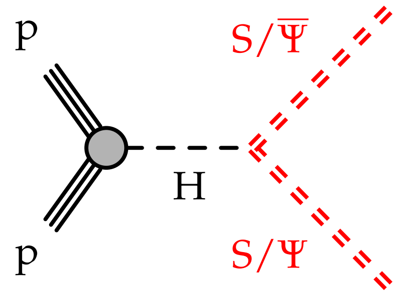




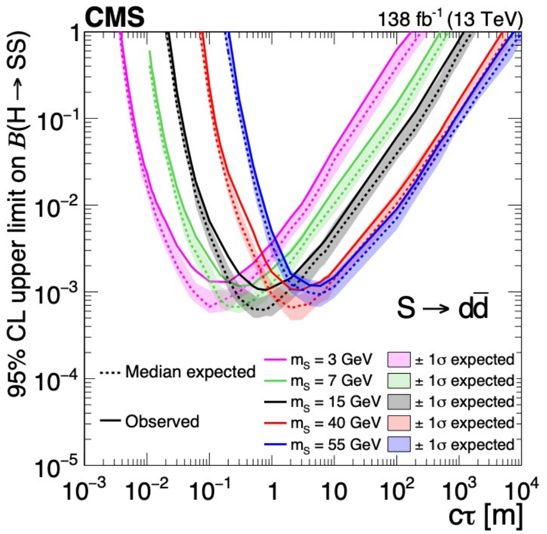
Additional hidden sectors and dark showers

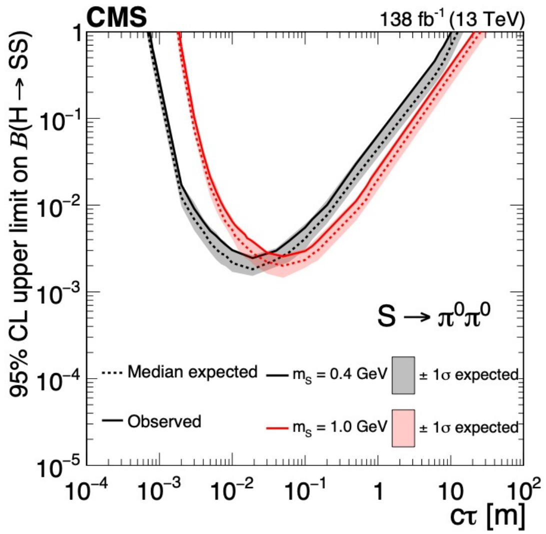
- Recent CMS result: targeting Higgs decaying into two new scalars OR two dark-sector quarks in the dark shower model

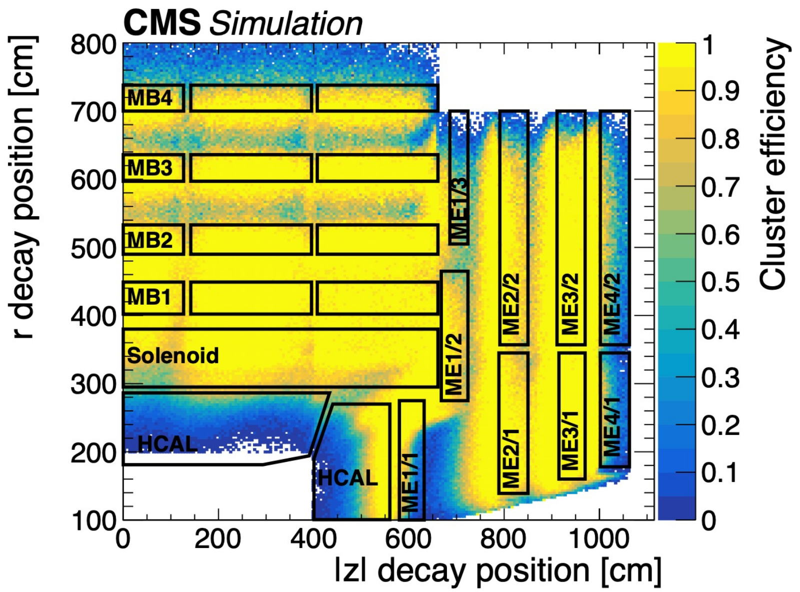
arXiv:2402.01898

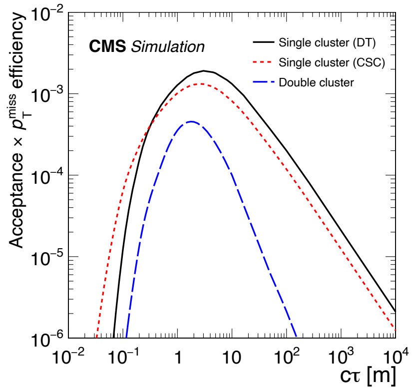


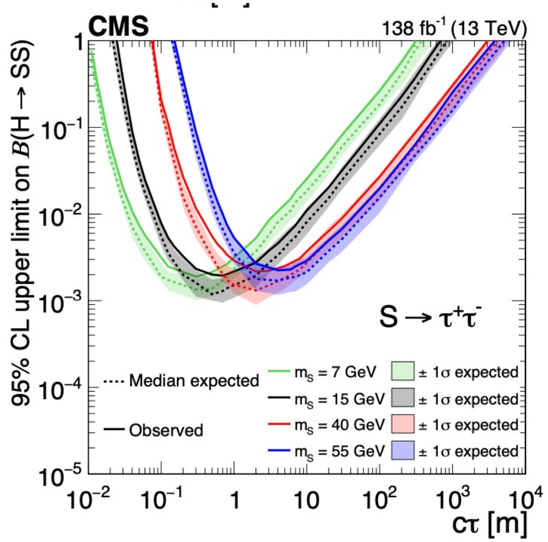
Hadronic and electromagnetic showers identified → background suppressed thanks to shielding provided by the inner detector and the CMS magnet return yoke











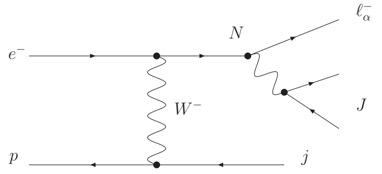
+ several interpretation in gluon-portal, Higgs portal, photon and dark-photon portal models

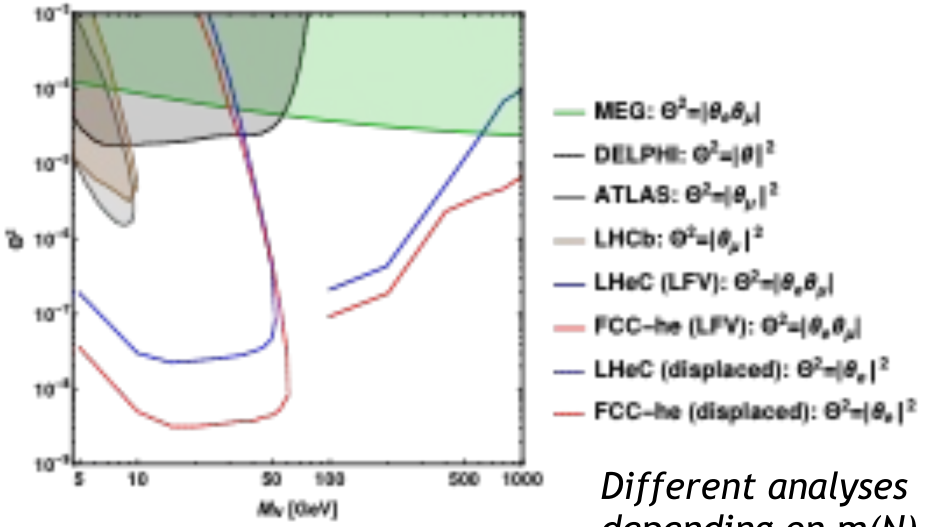
Sterile neutrinos (Heavy Neutral Leptons): an overview

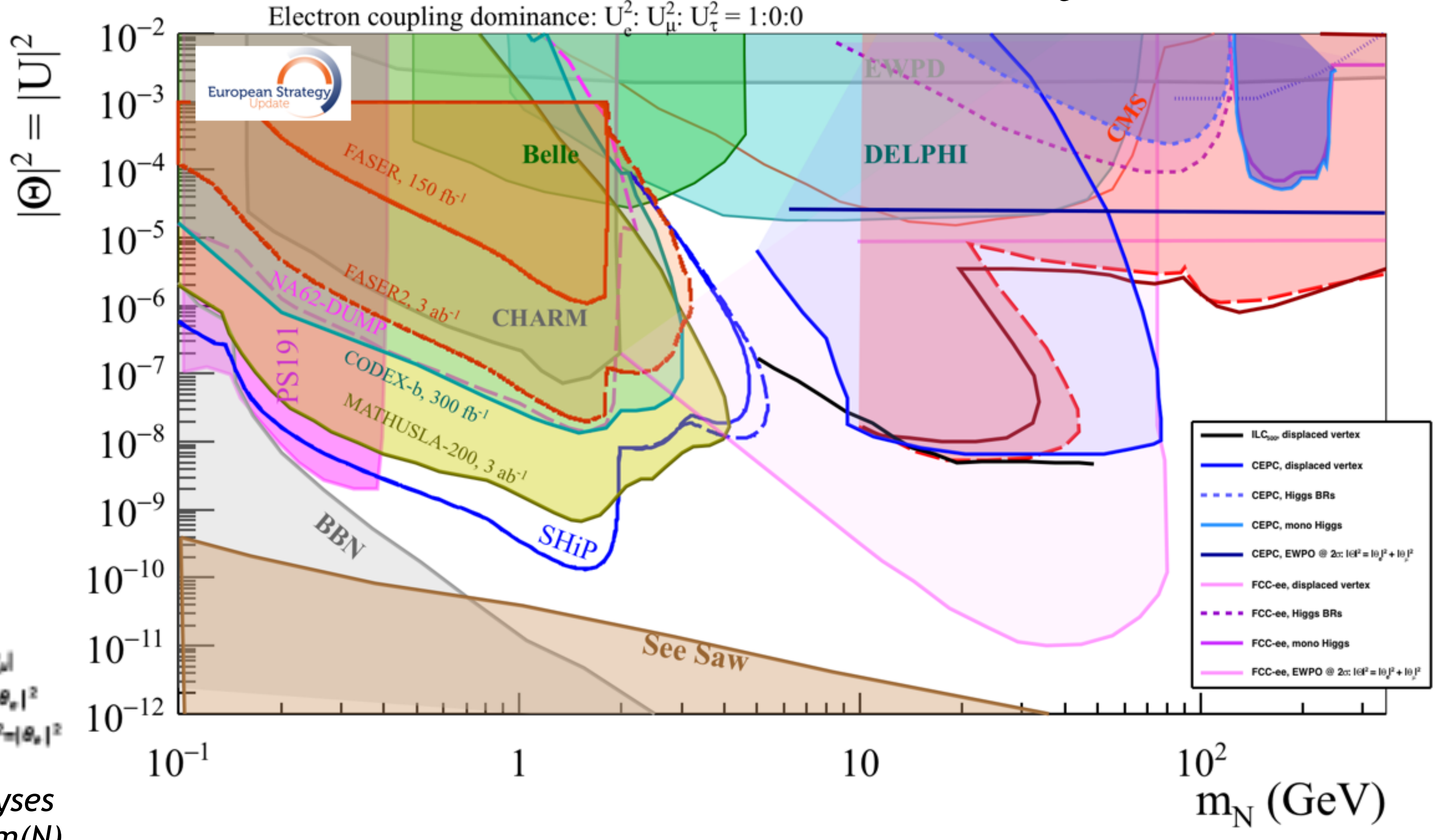
- From ES – colliders mostly sensitive in high theta regions

$$y_N L H N$$

ep results competitive but produced considering couplings to the second neutrino generation (not included in summary plot)







Different analyses depending on m(N) and m(W) relations

Sterile neutrino (Heavy Neutral Leptons)

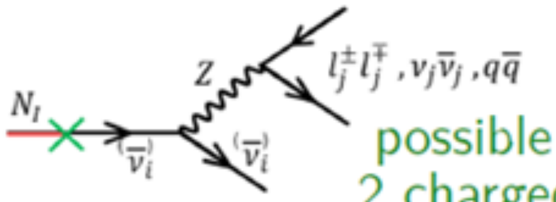
- Similarly to the case of the Higgs exotics decays:

FASER-2 prospects

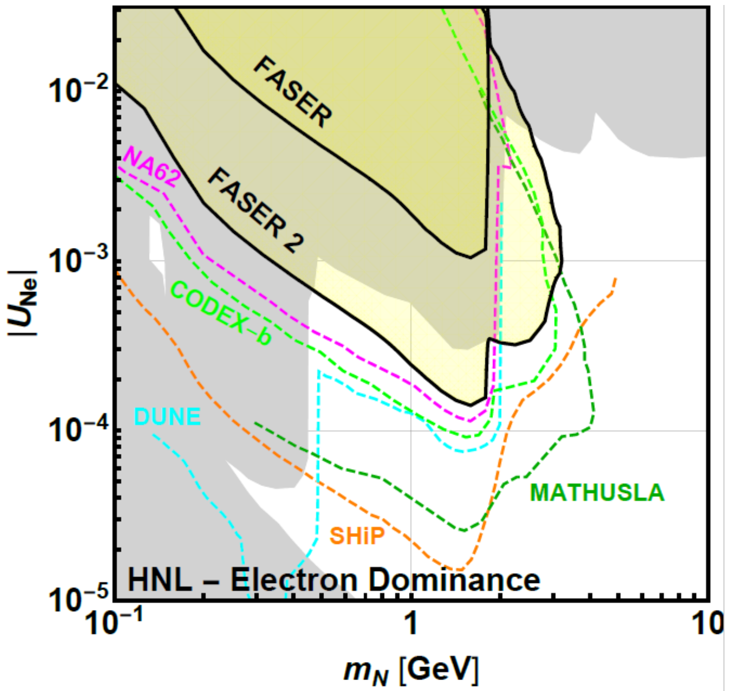
$m_N, \quad U_{eN}, \quad U_{\mu N}, \quad U_{\tau N}$ free parameters (only one U different from 0 at the time)

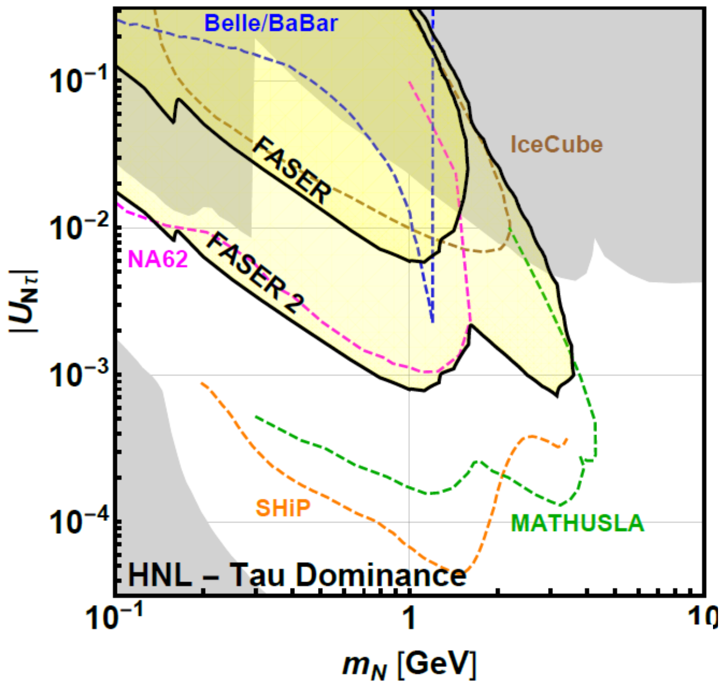
production $D^{0,\pm} \to N\, e^{\pm}\, K^{\mp,0,(*)},\ D_s^{\pm} \to N\, e^{\pm}, \ldots$
$B^{0,\pm} \to N\, e^{\pm}\, D^{\mp,0,(*)},\ B^{\pm} \to N\, e^{\pm},$

decay
$\mathrm{BR}(N \to 3\nu) \sim 10\% - 20\%$ invisible
$\mathrm{BR}(N \to \nu\, l_1^+\, l_2^-) \sim 20\%$ $(\mathrm{BR}(N \to \nu\, e^+\, e^-) \sim$ few percent)
$\mathrm{BR}(N \to \mathrm{hadrons}) \sim 60\% - 70\%$, various final states



possible
2 charged
tracks





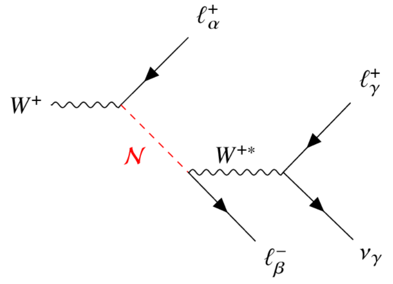
Sterile neutrino (Heavy Neutral Leptons): ATLAS

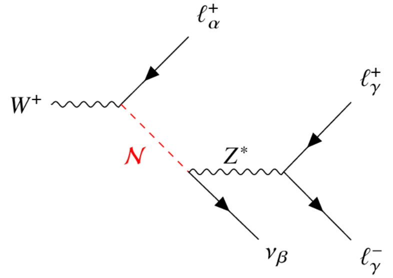
- Similar results and studies from CMS – two **ATLAS recent searches** as example

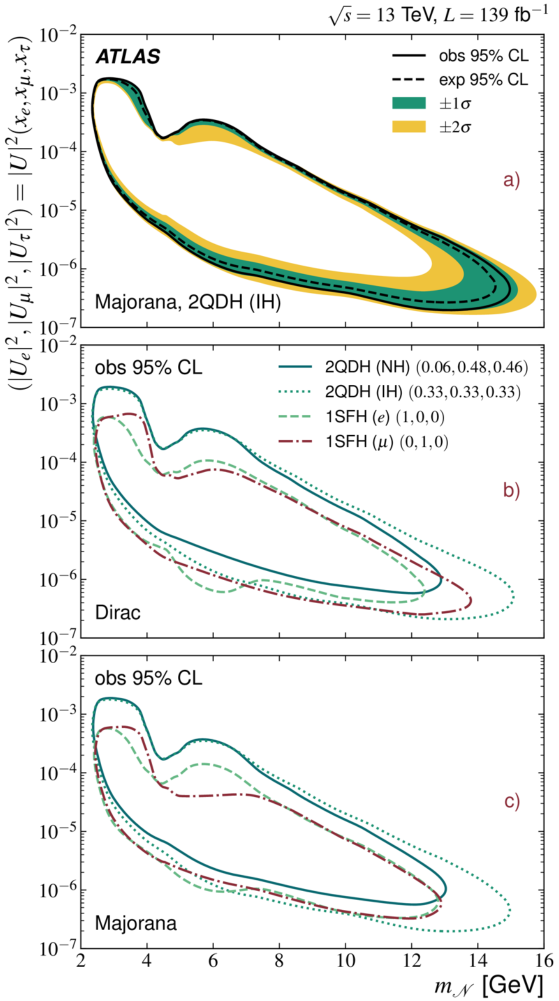
Eur. Phys. J. C 83 (2023) 1164

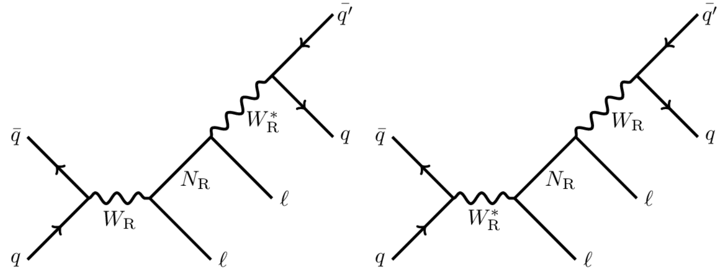
PhysRevLett.131.061803

HNL decays into two charged leptons and a neutrino, forming a displaced vertex



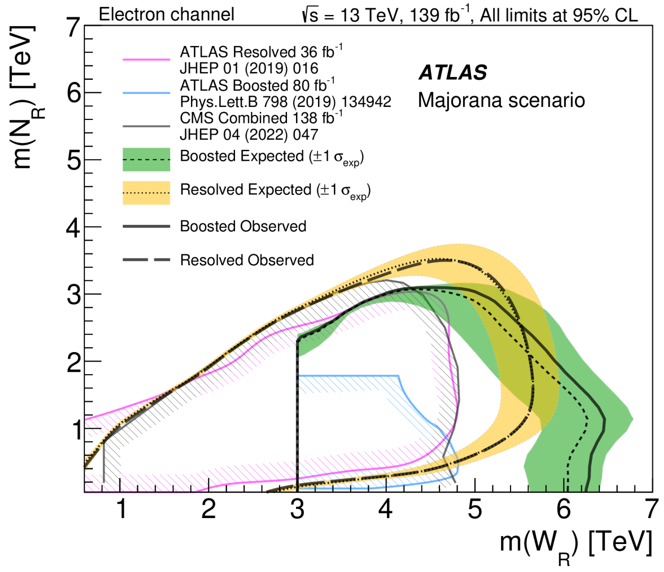


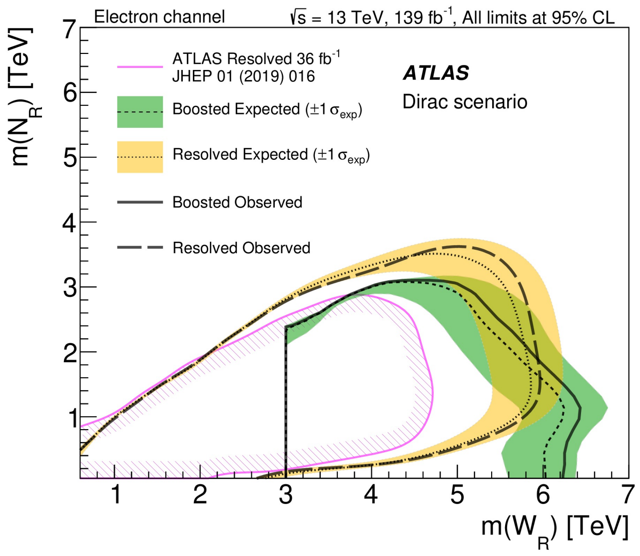




Prompt decays in leptons and jets, resolved or boosted SRs

Majorana and Dirac scenarios (muon-region constraints similar)





Conclusions

- Collider experiments have set a vast programme of searches focusing on hidden sectors and including dark photons, ALPs, new scalars and sterile neutrinos
  - Different and sometime complementary approaches and targets, i.e. minimal (FASER, LHCb) vs non-minimal (ATLAS, CMS), role of Higgs boson.
  - Approaches such as ultra-peripheral heavy ion collisions offer additional handles
- Usage of benchmark models agreed within the community facilitates comparisons, but more models are considered and specialised techniques developed (e.g. dark showers)
- Prospects from collider experiments include also additional possibilities not explicitly mentioned here but not to be forgotten (MATHUSLA, CODEXb etc.)
- **Complementarities in targeted scenarios and relevance for e-p**
  - Shorter lifetime are certainly an area where e-p can complement these searches
  - Techniques to reconstruct LLP can be re-utilised (e.g. narrow jets using calo-images)

More in Josè's discussion slides

Back up

ATLAS search example: only a small corner

- Prompt and displaced - extensive programme on-going, with most analysis covered but a lot of final states still unexplored (square indicate the ATLAS target)