Review on the Dark Matter Searches at the LHC: non-WIMP Scenarios

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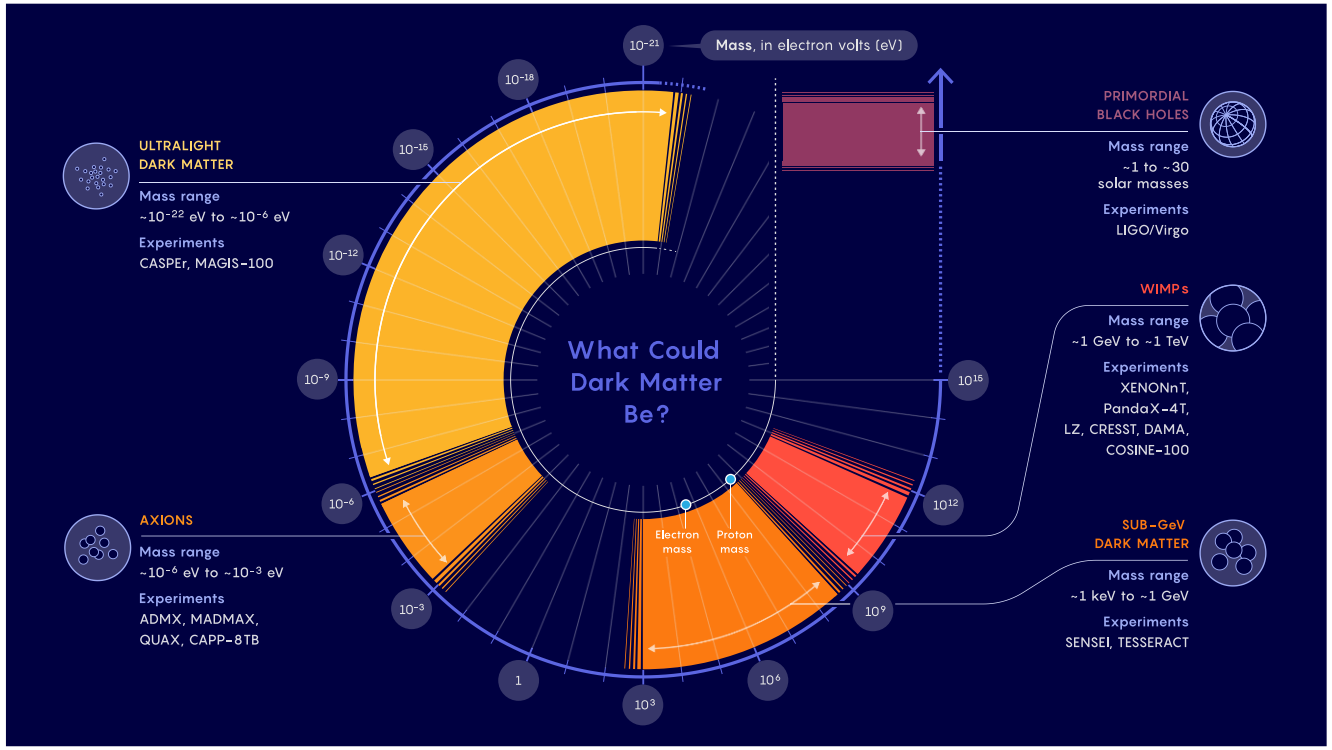
April 17, 2026

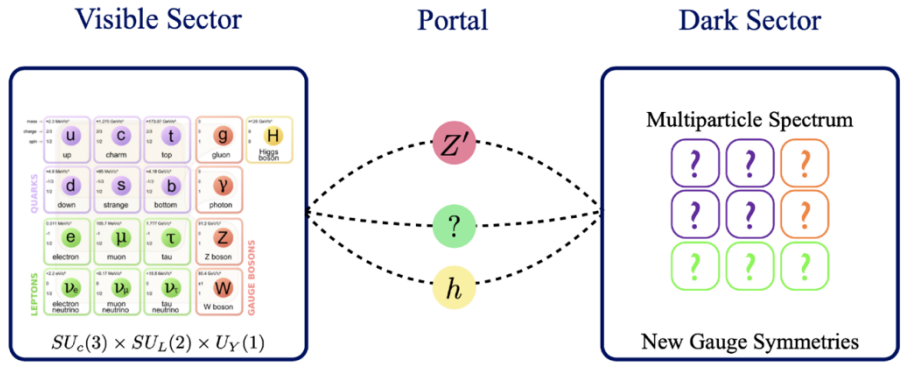
Search for New Physics at Colliders @ NJU, Suzhou

Preamble

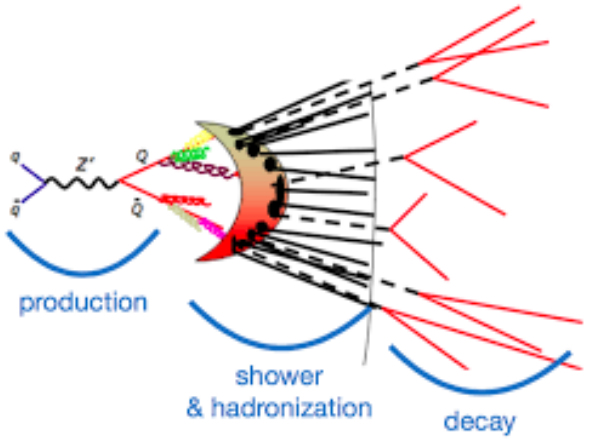
- **The “WIMP miracle” is attracting as it naturally achieves the observed relic DM density through thermal freeze-out in early universe**
- **Absence of observation lead to increasing consensus that DM has its own complex sector**
- **Non-WIMP landscape heavily relies on the categorization of potential portal interactions**
  - Dark QCD, SIMPs
  - Dark photons
  - Axion-Like Particles
  - Inelastic DM
  - Fractionally charged particles
- **Unconventional collider topologies:**
  - semi-visible jets, emerging jets, trackless jets, highly displaced vertices, soft displaced lepton pairs associated with LLPs, etc.



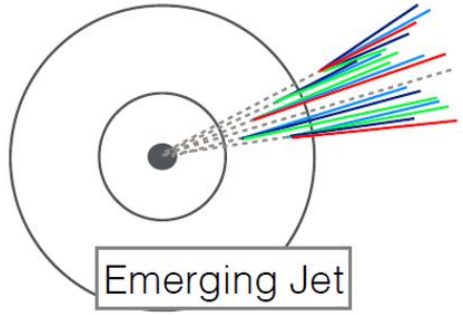
1. Strongly coupled dark sector/Dark QCD



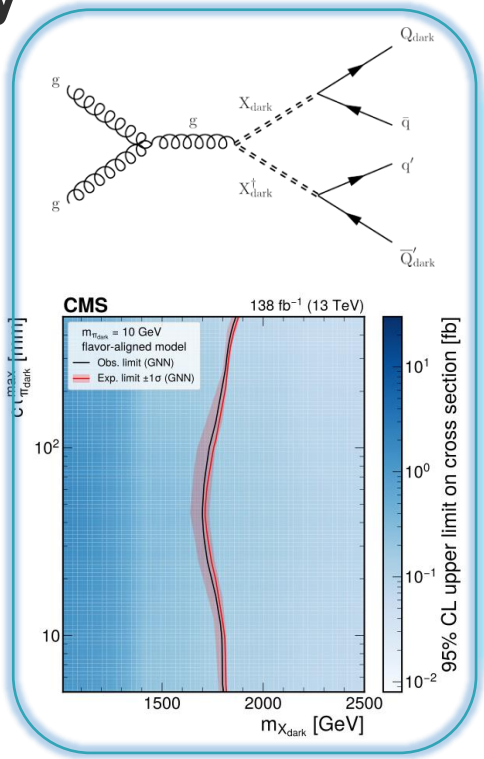
- **Hypothesizes a hidden sector that mirrors QCD**
- **Communicates with SM through heavy mediators**
- **Dark quarks shower and hadronize into dark jets. The phenomenology splits into several sub-category depending on the lifetime and decay modes of dark hadrons**
  - Stable dark hadrons → invisible (dark matter)
  - Long-lived dark hadrons → delayed SM decays (displaced vertices)
  - Promptly decaying dark hadrons → visible SM particles
- **Lightest stable dark hadron serves as the DM candidate**
- **One of the richest new paradigms at the LHC**
  - Emerging jets, semi-visible jets, prompt dark jets, soft unclustered energy patterns, composite DM, low-mass hidden valley dark showers, SIMP trackless jets.



1.1 Emerging jets



- **Dark pions are long lived, produced inside dark jets and travel measurable distances before decaying to SM particles**
- **The sub-jets appear to “emerge” mid-flight from displaced secondary vertices**
- **CMS searched for the pair production of heavy mediators decaying to a quark and dark quark**
  - Also probed the postulated flavor structure of the dark sector
  - Excludes mediator mass up to 1950 GeV for dark pion lifetime of 1 to 500 mm
- **ATLAS searched for the pair production of emerging jets via s-channel Z’ & t-channel Φ**
  - Run3 data at 13.6 TeV
  - Excludes Z’ up to 2559 TeV, Φ up to 1375 TeV for dark pion lifetime of 5-50 mm



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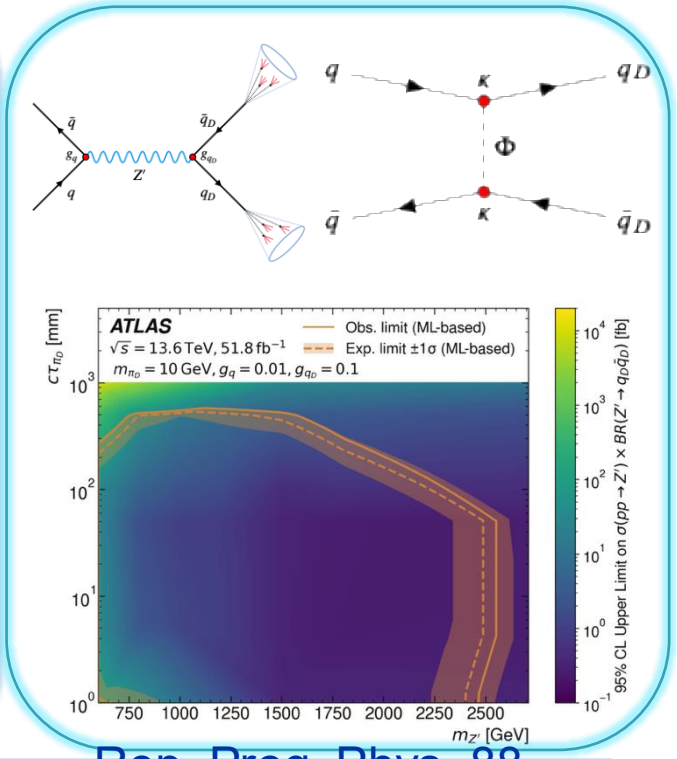

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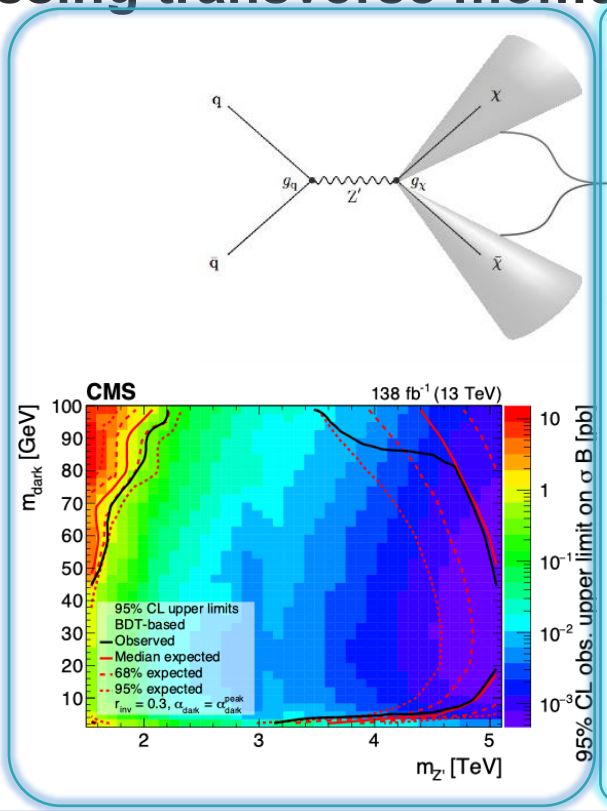
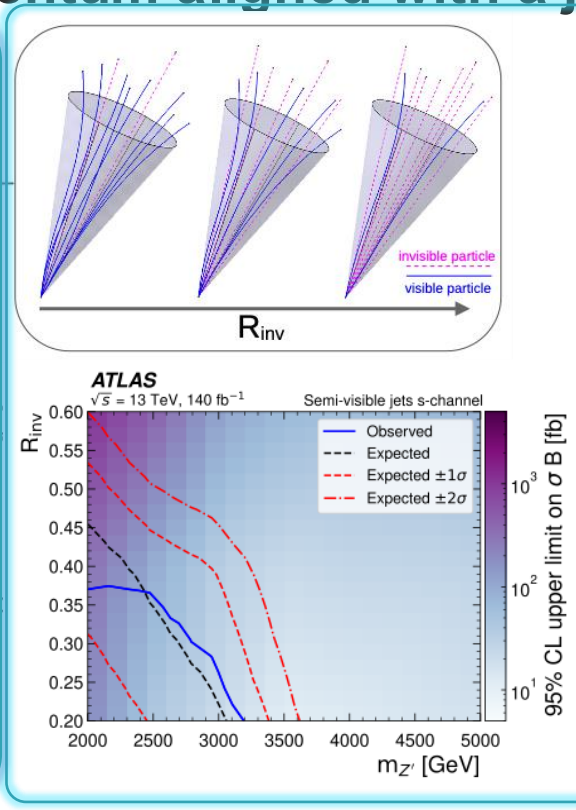
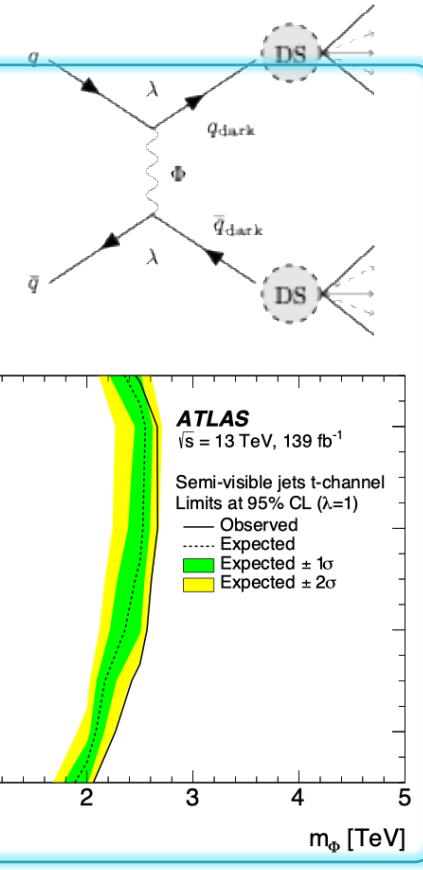
1.2 Semi-visible jets

- **Dark shower yields a mixture of stable and unstable dark hadrons, resulting in dark jet carries both visible and invisible energies.**
- **A striking signature of missing transverse momentum aligned with a jet.**
- **CMS searched for s-channel Z'**
  - Excludes Z' mass up to 5.1 GeV
- **ATLAS searched for s-channel Z' and t-channel Φ**
  - Excludes Z' mass up to 3.2 GeV
  - Excludes Φ up to 2.7 GeV







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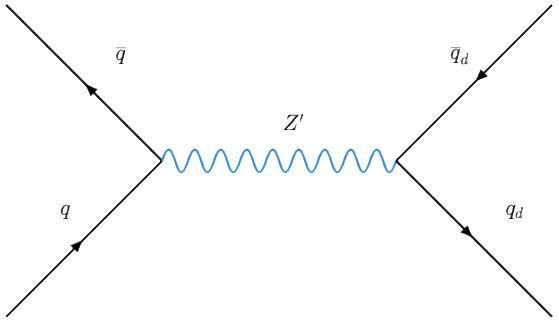
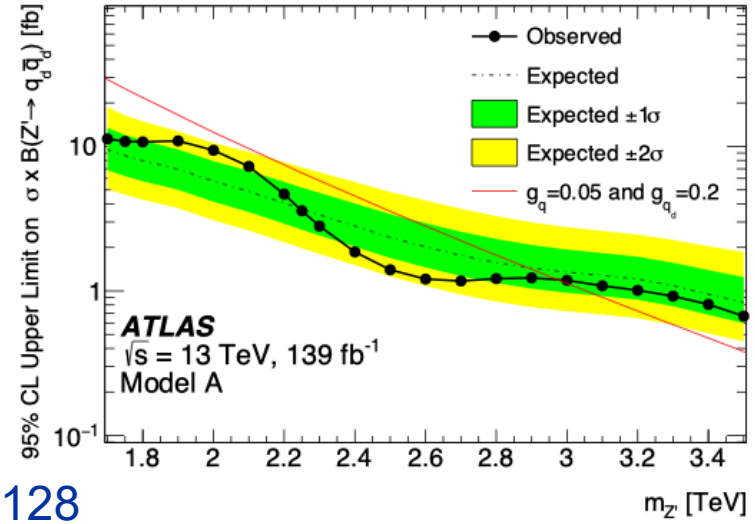
1.3 Prompt dark jets

- **All dark hadrons decay promptly to SM particles**
- **Visually like ordinary QCD jets, but broader and exhibit higher charged-particle multiplicity**
- **ATLAS searched for resonant dark quark production in the dijet final state**
  - No significant excess of events observed
  - Upper limits at 95% CL set on Z' production cross section times branching ratio





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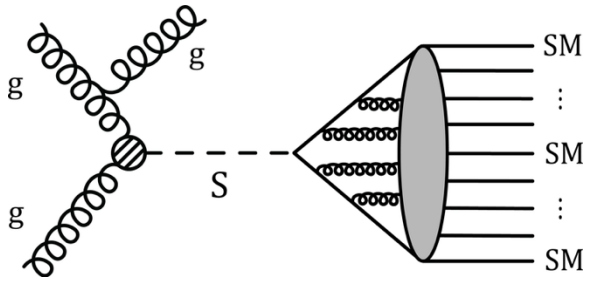
1.4 Soft unclustered energy patterns



- **Very large dark sector gauge coupling, dark mediator thermalizes before decaying, releasing many soft dark mesons distributed nearly isotropically**
- **Events with anomalously high-multiplicity of soft, nearly spherically distributed charged tracks**
- **CMS published searches of SUEPs in many production modes**
  - Gluon fusion, Z/W associated, VH production modes
  - No access observed

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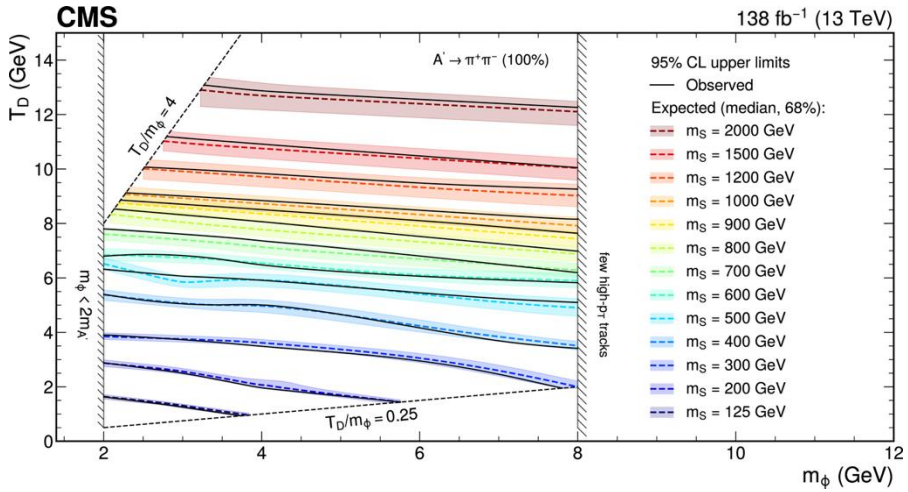
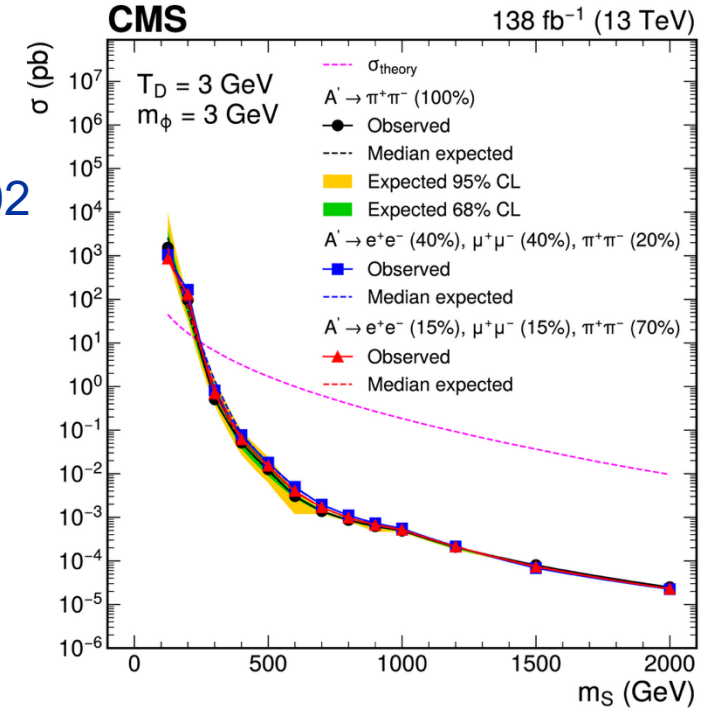
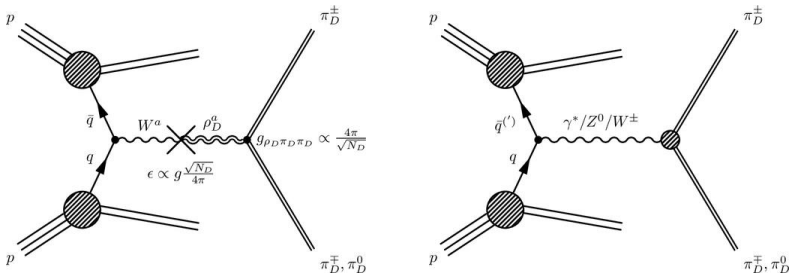
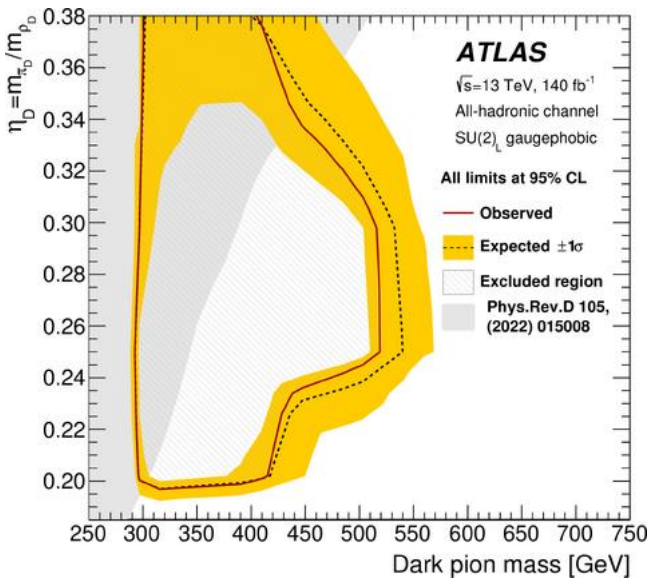


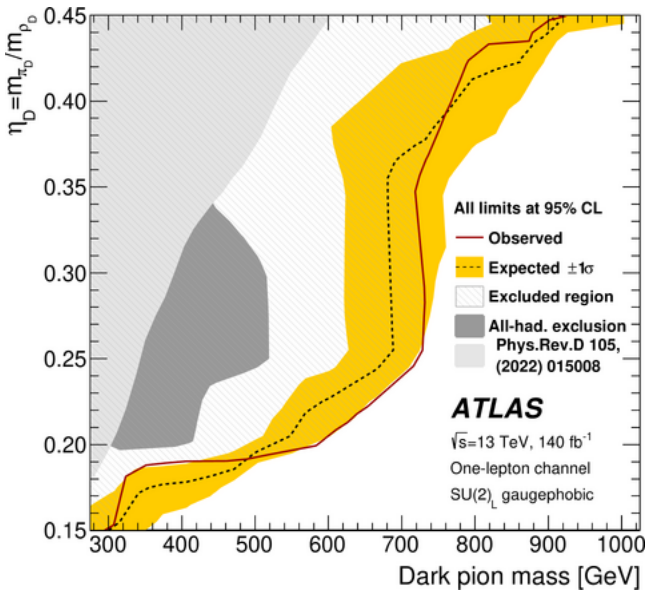


1.5 Composite Dark Matter

- **Strongly-coupled SU(2) dark flavor symmetry conserving models and decaying gaugephobically to pure SM final states containing top and bottom quarks**
- **Dark pion pair production via kinetic mixing with W-field or B-field**
- **ATLAS presented a first direct search of these composite dark particles**
  - 2D signal space of dark pion and dark rho masses scanned
  - Dark pion asses excluded up to ~1 TeV







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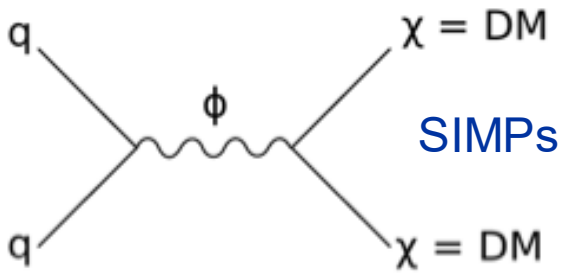
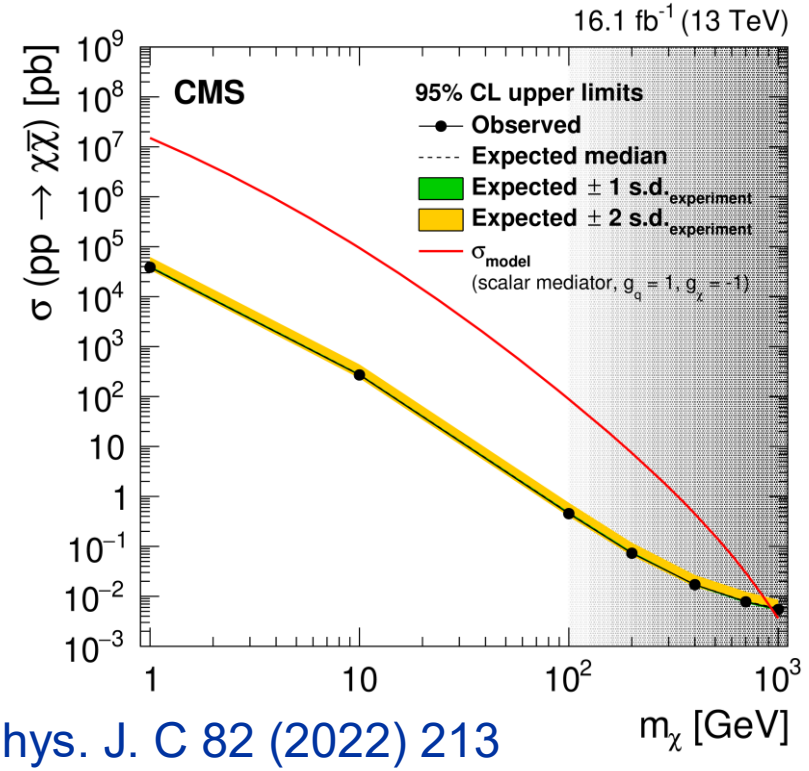
1.6 SIMP trackless jets

- **A simplified model that postulates SIMPs produces in pairs via s-channel scalar mediator at the LHC**
- **DM relic density realized via self annihilation processes**
- **SIMPs bypass tracker but deposit energy in the hadron calorimeter -- jets without associated tracks**
- **CMS presented a search for such models**
  - Excluded SIMP masses up to 100 GeV



SIMPs only interact in calorimeter



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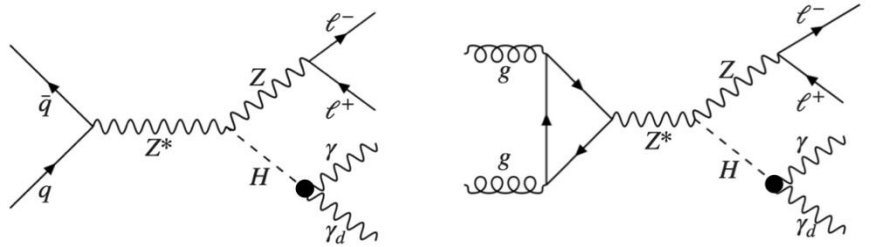
2. Dark photons/hidden U(1) symmetry

- **The vector portal extends the SM with a new broken $U(1)_D$ gauge symmetry. The dark photon acquires mass via a dark Higgs mechanism**
- **The dark photon couples to the SM exclusively through kinetic mixing with the SM hypercharge gauge boson**
- **The dark photon can be dark matter mediators (vector portal dark matter) or as dark matter candidates themselves (at very low mass)**
- **Key production modes at the LHC:**
  - Higgs boson exotic decays
  - Direct Drell-Yan-like production
  - Associated production with W/Z bosons

2.1 Higgs decays to dark photons



- **CMS searched for dark photons in the ZH production mode and VBF mode**
  - Full Run 2 dataset
  - An observed upper limit of 4.6% and 3.4% on H decay branching fraction in the two modes

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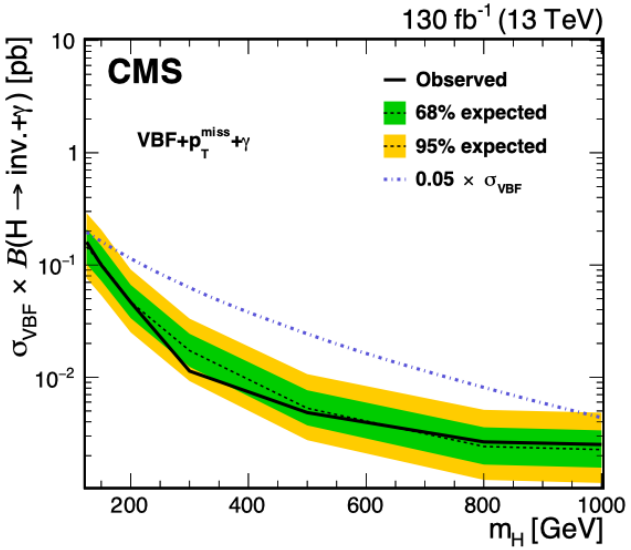
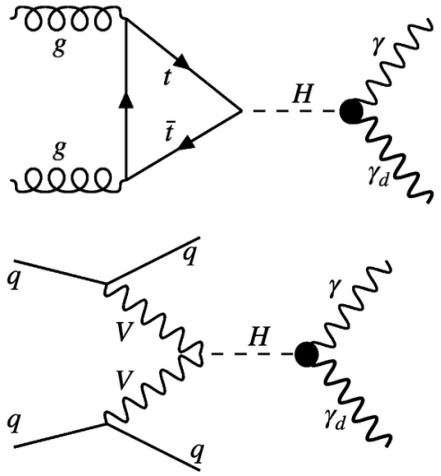
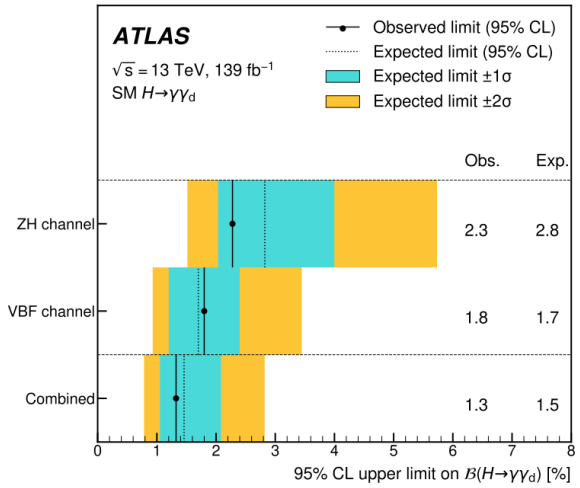
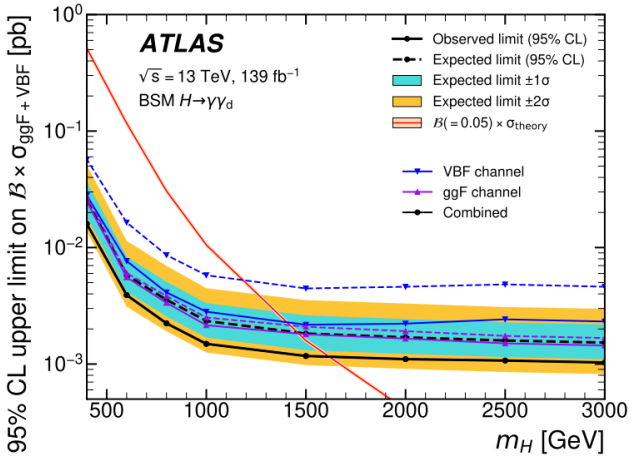


- **ATLAS presented a combination of searches for H decay to a photon and a massless dark photon**







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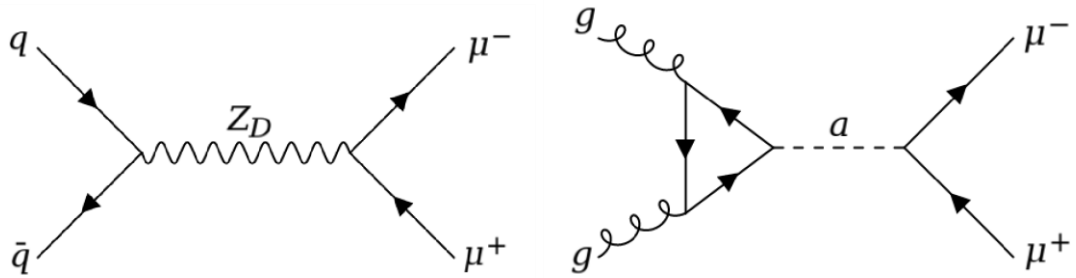
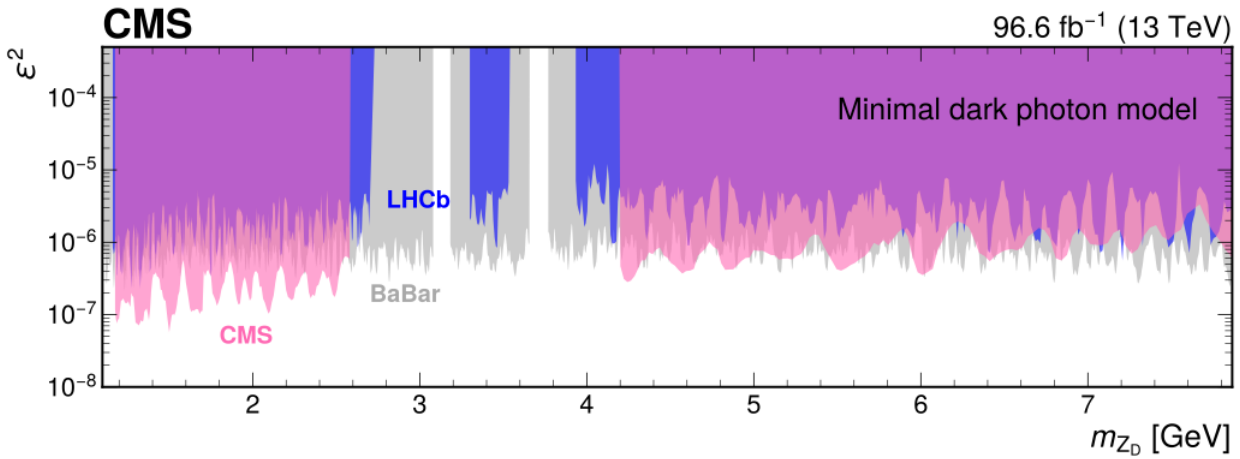
2.2 DY-like production of dark photons

- **CMS experiment searched for dimuon resonances at GeV scale up to 200 GeV**
  - Dark photon models with squared kinetic mixing coefficient above 10^{-6} are excluded over most of the searched mass range





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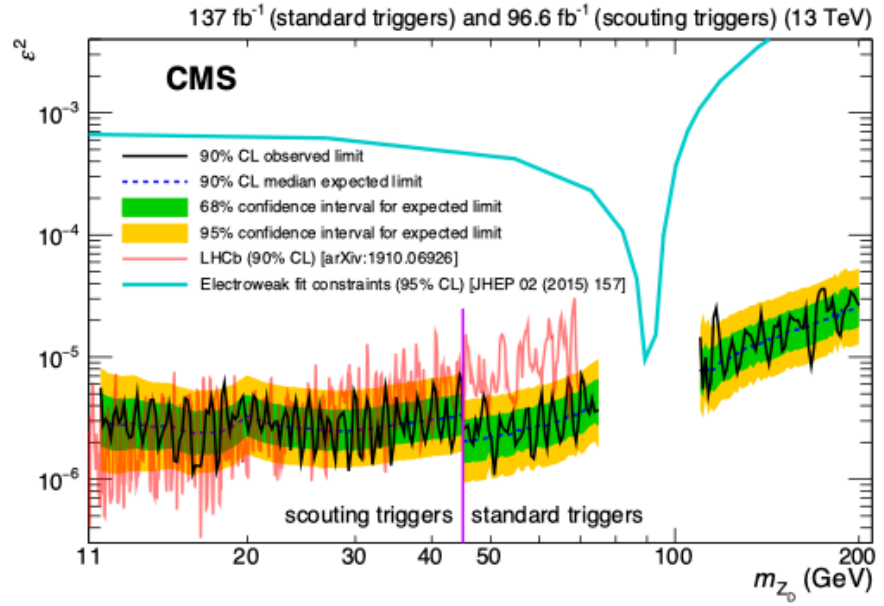
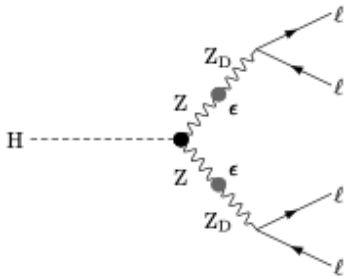
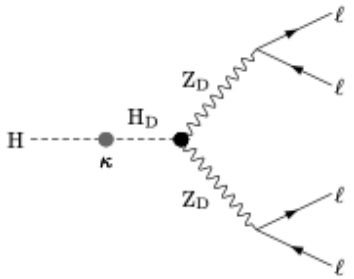


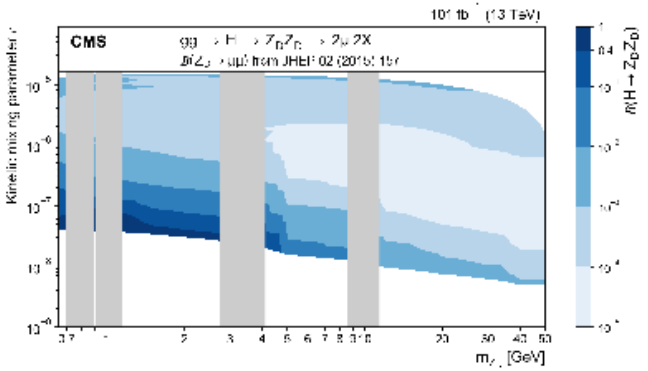
Phys. Rev. Lett. 124 (2020) 131802

2.3 Displaced dark photons





- **CMS searched for long-lived particles decaying to muon pairs in both Run2 and Run3**
  - Set exclusion limit on dark photon mass and lifetime



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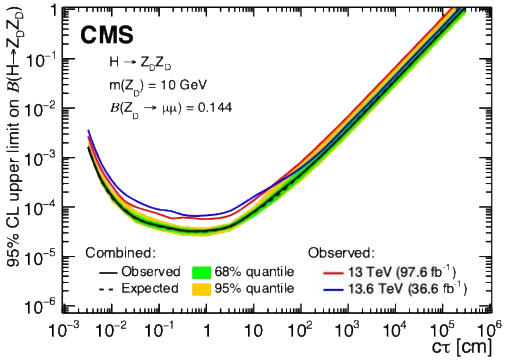

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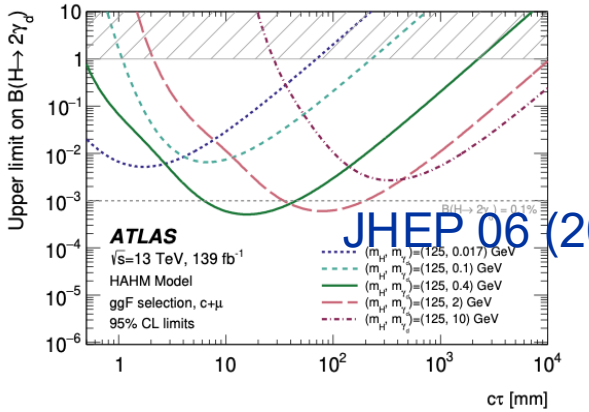
- **ATLAS searched for long-lived particles that decay into collimated pairs of leptons or light hadrons or displaced jets**
  - Exclusion limits on dark photon production branching fraction



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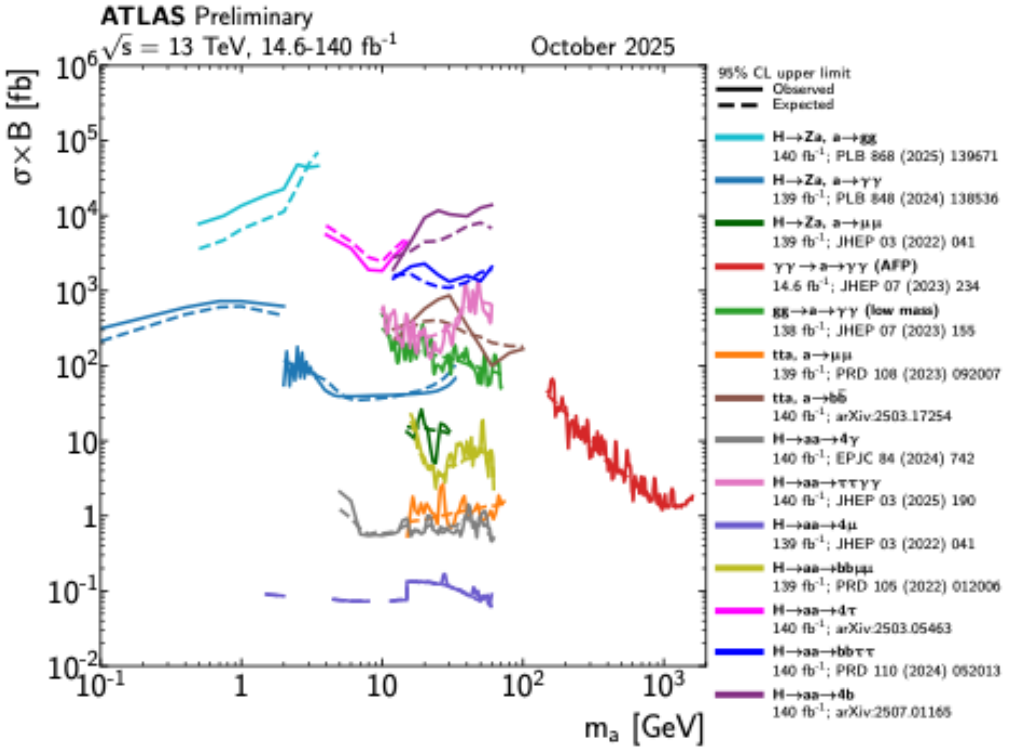
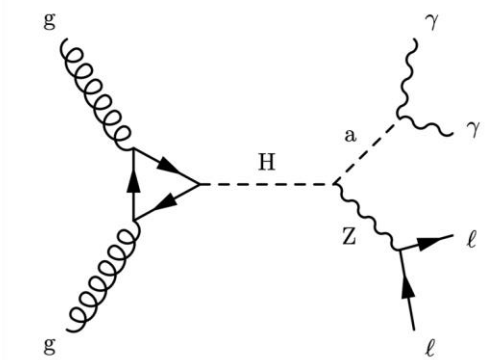
3. Axion-Like Particles (ALPs)

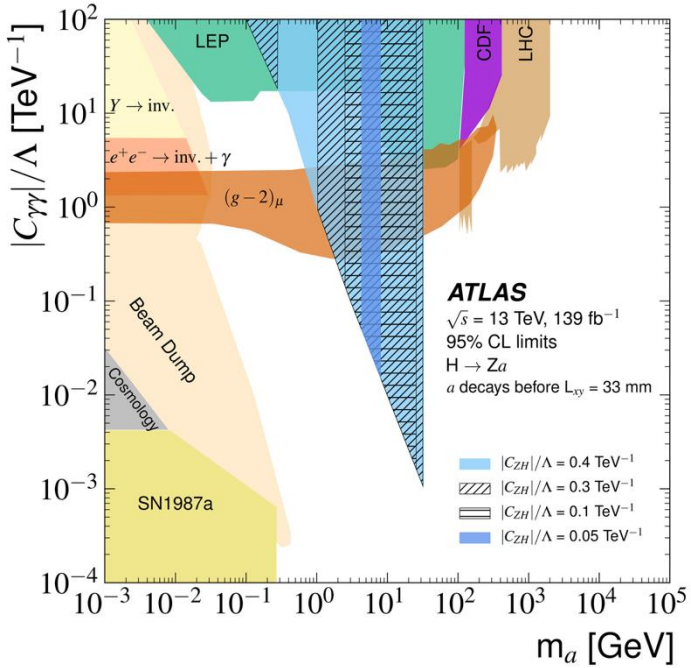
- **Generic class of pseudoscalar bosons that naturally emerge in numerous extensions of the SM featuring spontaneously broken global symmetries.**
- **Generally, no fixed mass-coupling relationship and span a vast parameter space**
- **Non-thermal DM candidates with relic density set by the misalignment mechanism**
- **ALPs can be produced at LHC via:**
  - Exotic Higgs decays
  - Gluon fusion
  - DY-like production
  - Forward proton scattering
  - light-by-light scattering in ultraperipheral HI collisions
- **Can be prompt or LLP**



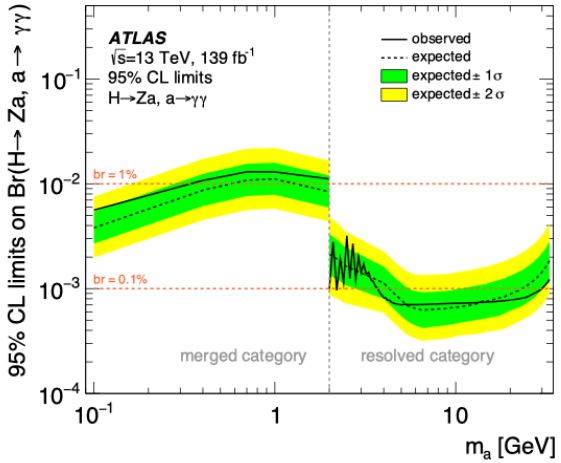
3.1 Exotic Higgs decays

- **ATLAS and CMS both searched for H->Za->llγγ**
  - m_a~0.1/1-30 GeV
  - CMS observed an excess with local (global) significance of 2.6 (1.3) σ for m_a=3 GeV





- **Overview of LHC excesses**
  - https://indico.cern.ch/event/1651921/



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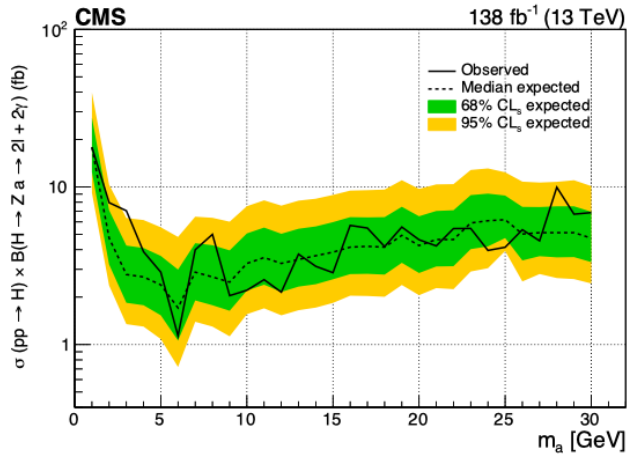
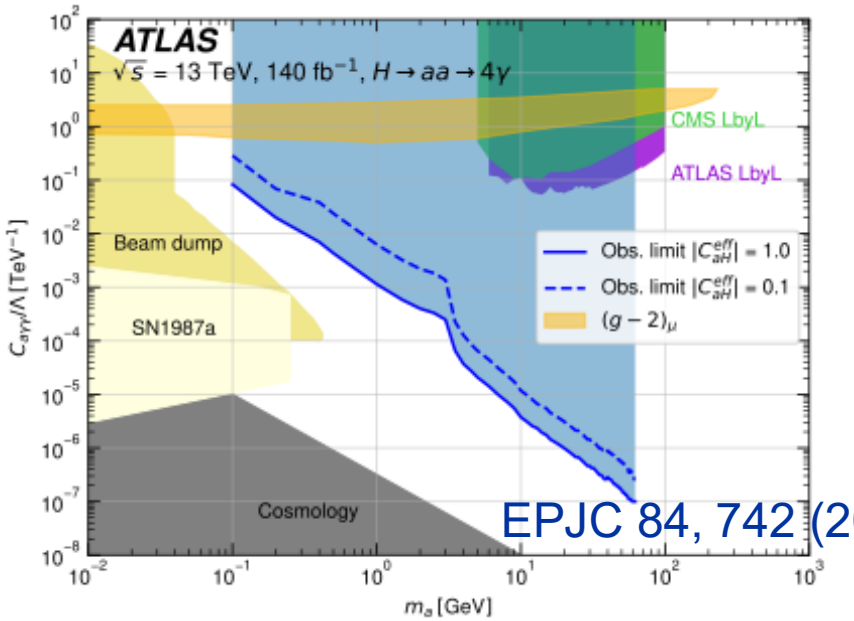


Phys. Lett. B 852 (2024) 138582

3.1 Exotic Higgs decays

- **ATLAS searched for H->aa->4γ**
  - Covers ALP mass 100 MeV-62 GeV and couplings 10^{-5}/TeV-1/TeV
  - Upper limits set at 10^{-5}-10^{-2}



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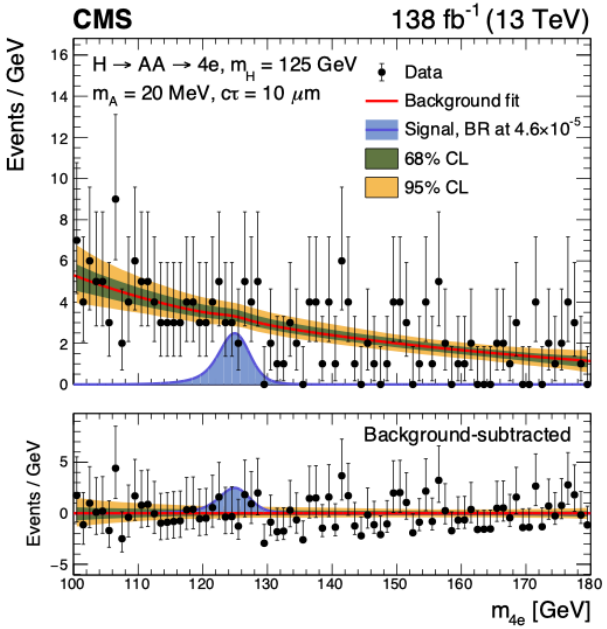
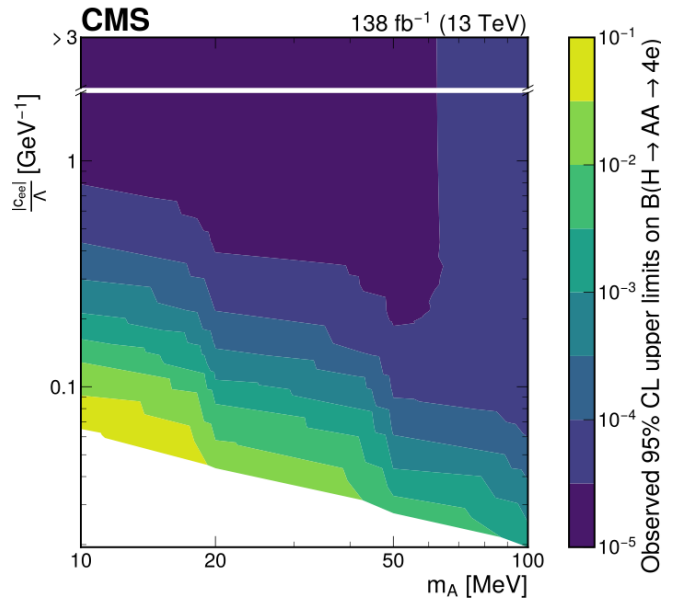
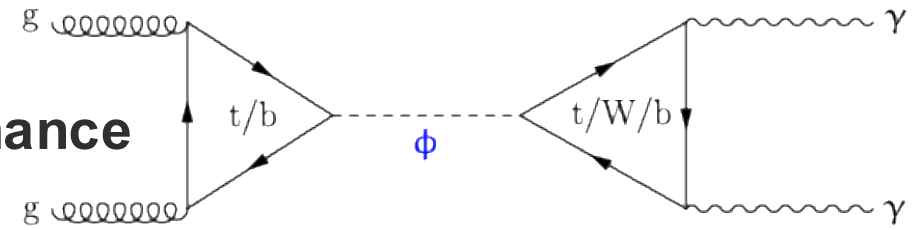
- **CMS searched for H->aa->4e via very light axions**
  - Axions mass between 10 and 100 MeV
  - Axions proper decay length below 100 m
  - Branching fraction sensitivity as low as 10^{-5}



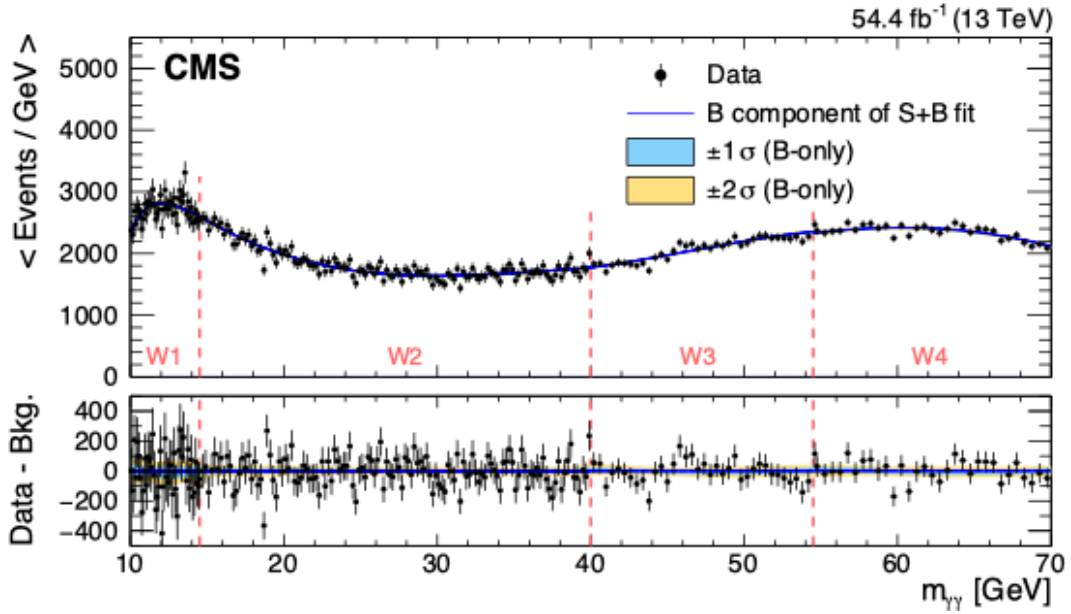


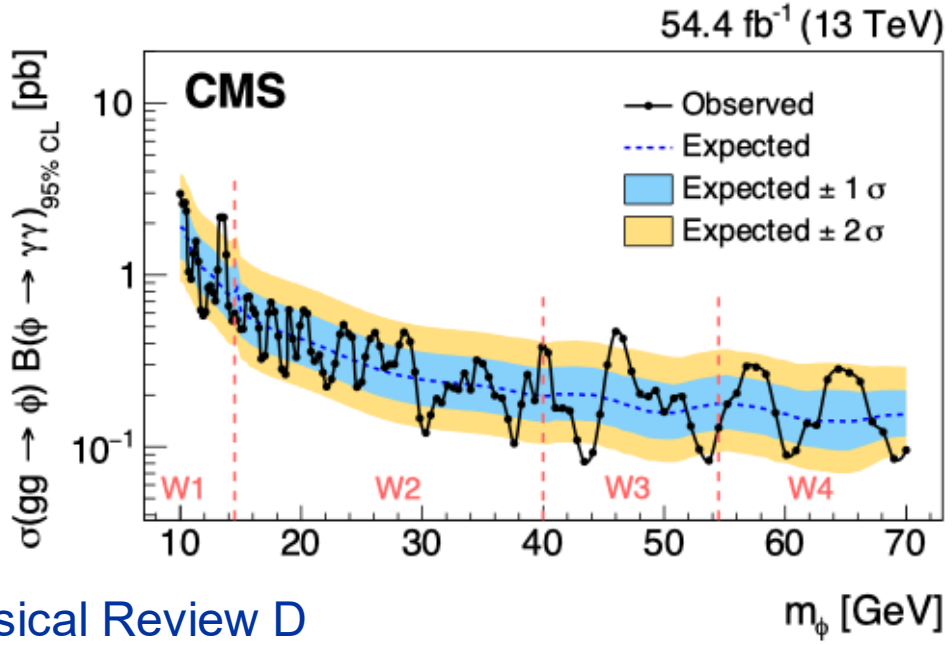
Accepted for publication in Phys. Rev. Lett.

3.2 Direct ALP search from diphoton resonance



- CMS presented a search for narrow diphoton resonance in the range of 10-70 GeV
- Probed models with gg->a->$\gamma\gamma$
- Most significant excess in the SR at a mass hypothesis of 13.6 GeV, slightly over 2σ



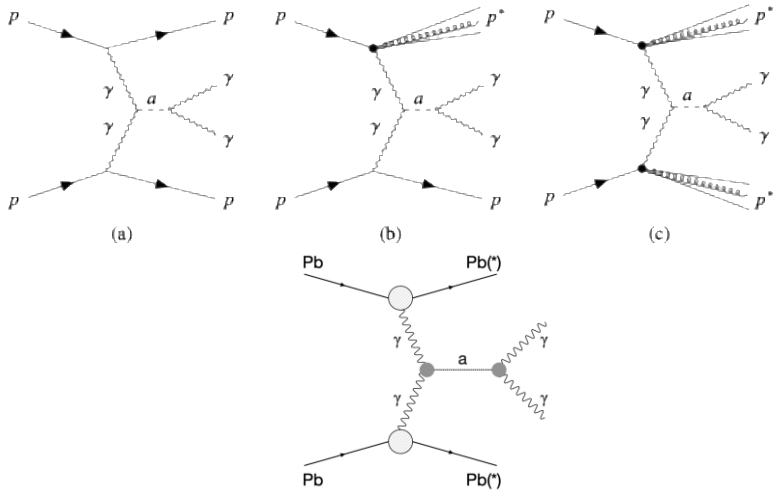


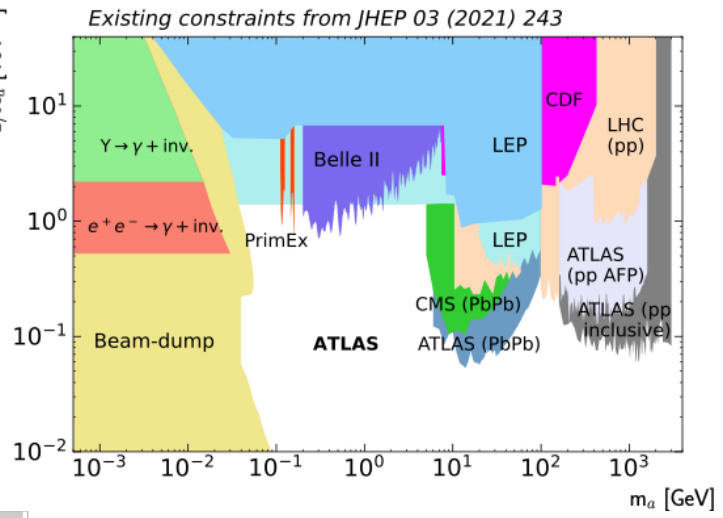
Submitted to Physical Review D

3.3 Light-by-light scattering induced ALPs

- **ATLAS searched for ALPs from forward proton scattering**
  - ALP mass 150-1600 GeV
  - Coupling limits ~0.04-0.09 TeV^{-1}

- **CMS and ATLAS both searched for ALPs from ultraperipheral Pb-Pb collisions**
  - ALP mass 5-100 GeV
  - Run2 data with $\sqrt{s_{NN}}$=5.2 TeV





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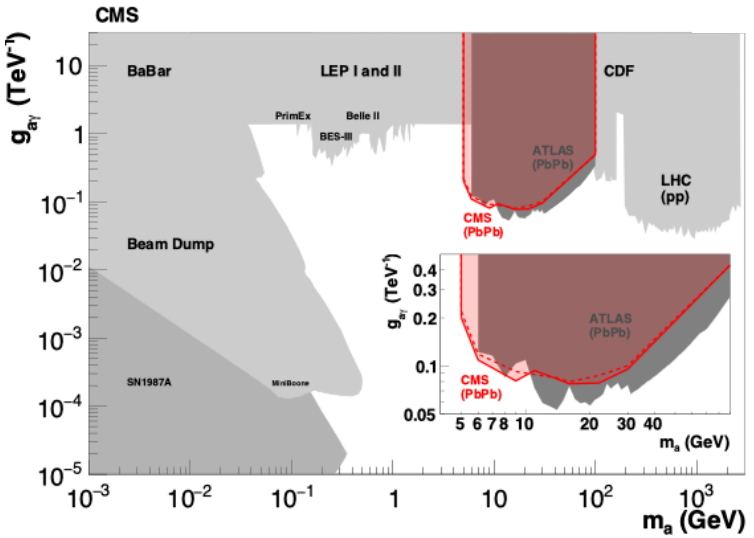

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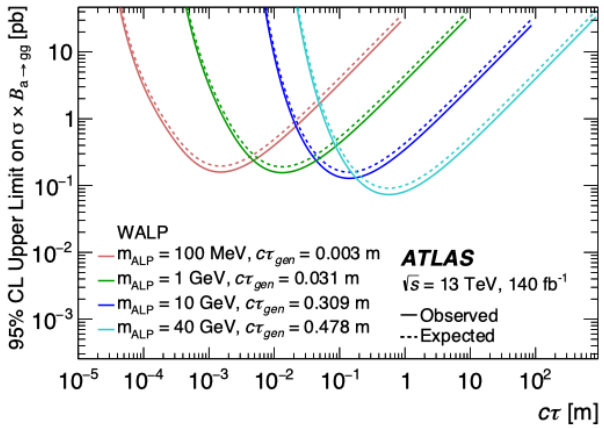
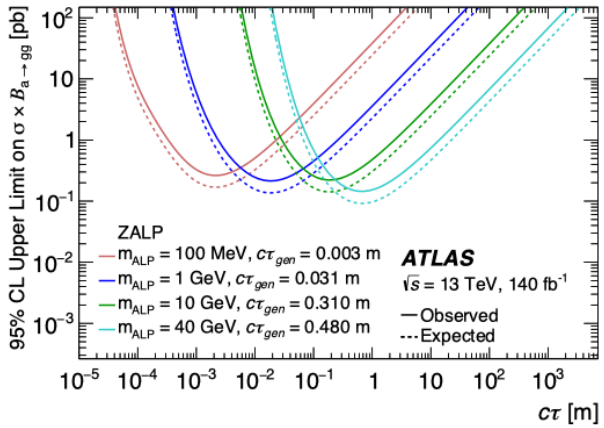
3.4 Long-Lived/Displaced ALPs

- **Long-lived photophobic ALPs via displaced vertices in the muon spectrometer**
  - Considered both W and Z associated production
  - Produces the strongest limits to date for proper decay lengths greater than O(10) cm





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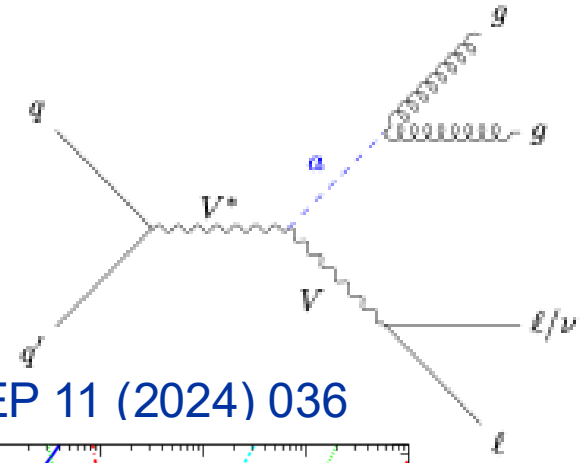

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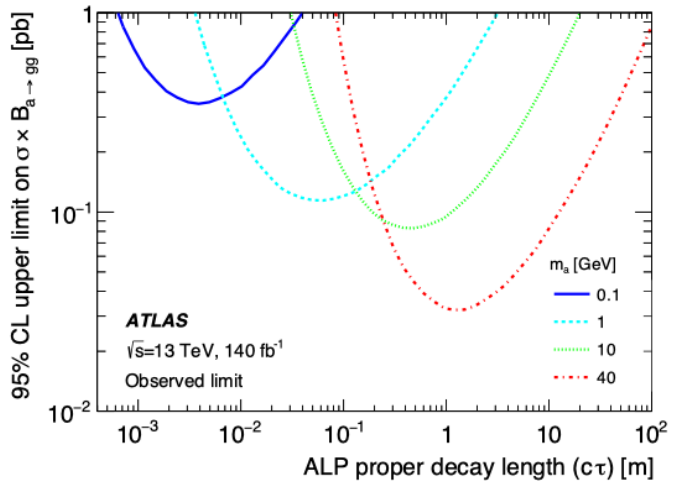
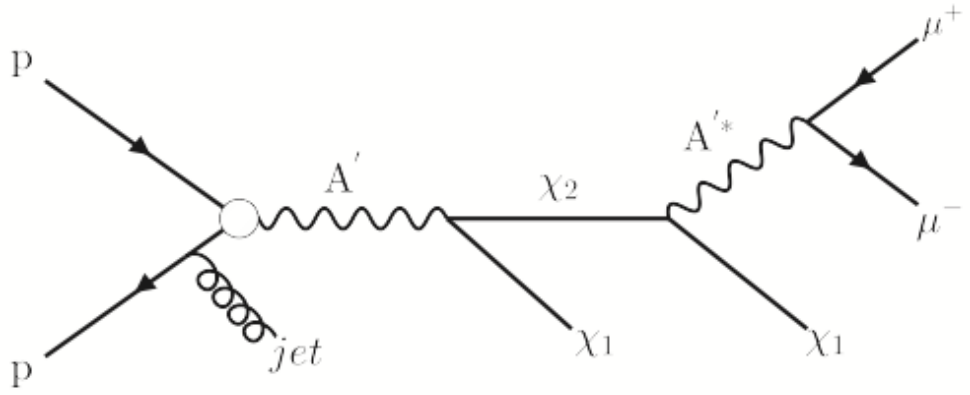


- **Long-lived photophobic ALPs via calorimeter displaced jets**
  - Z associated mode
  - Production cross-sections above 0.1 pb excluded in the 0.1 mm to 10 m range

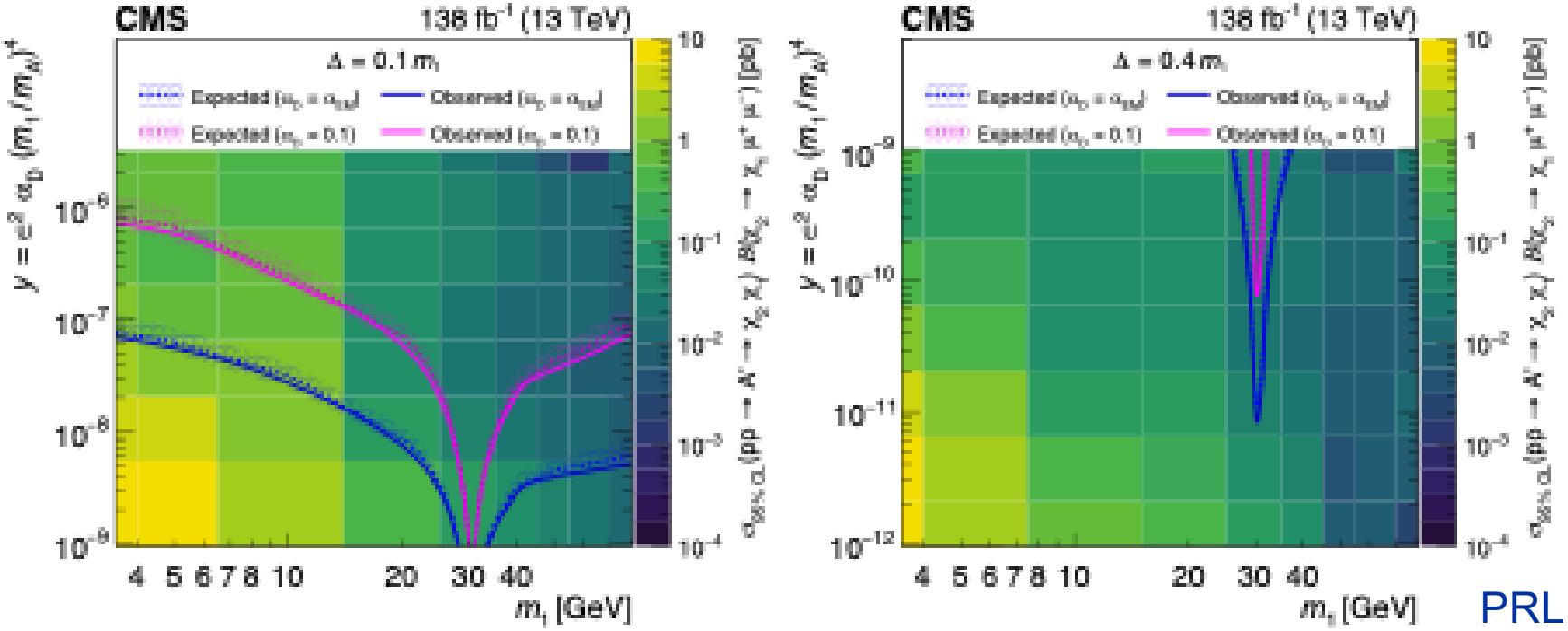
4. Inelastic Dark Matter (iDM)

- This dark sector has at least two nearly degenerate mass eigenstates χ_1 and χ_2, with small mass difference δ
- Gauge symmetry in the dark sector forces off-diagonal coupling: χ_1 must up-scatter to χ_2 to interact with SM particles
- Local galactic DM velocity too small to supply the energy needed for up-scattering -> invisible to direct detection
- Collider production involves a dark photon mediator that decays into $\chi_1\chi_2$, the heavier χ_2 subsequently decays to χ_1 and a pair of leptons.



4. Inelastic Dark Matter (iDM)

- **CMS searched for iDM in events with a displaced non-resonant muon pair and missing transverse momentum**



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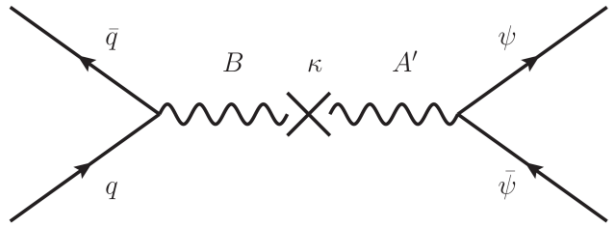
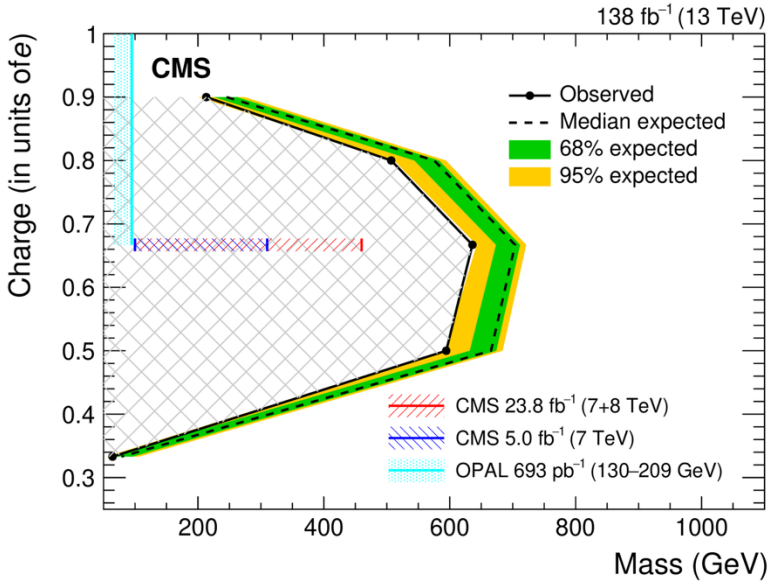
- **2-dimention upper limit as a function of DM mass and interaction strength**
- **Regions above the curve are excluded**

5. Millicharged/Fractionally charged Particles

- **These particles arise in dark photon models via kinetic mixing or in models with extra U(1) gauge group**
- **They interact purely electromagnetically with suppressed coupling**
- **Not dark matter in the traditional sense but are important dark sector states**
- **Can be produced via DY process at the LHC, and leave anomalously small ionization signals**

- **CMS presented a search for new particles with charge between e/3 and 0.9e**
  - Masses up to 640 GeV and charges as low as e/3 are excluded at 95% CL





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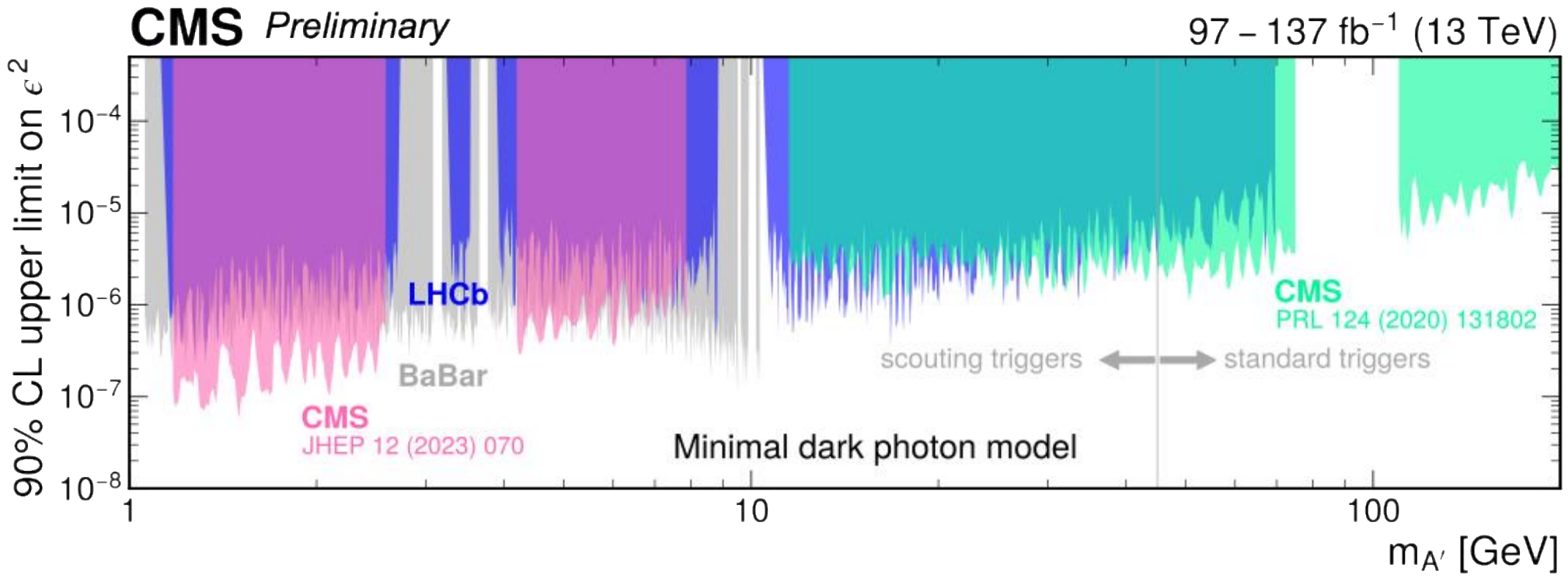
Summary

- Null results from Run2 comprehensive WIMP searches have redirected the community toward alternative theories
- Machine learning is now essential in collider search methods
- The lifetime frontier is expanding, long-lived and displaced signatures are reshaping the detector designs
- HL-LHC data with 3000/fb will drastically extend sensitivity to small couplings, compressed spectra, and ultra-rare exotic Higgs decays
- The parameter space for non-WIMP dark matter remains vast, calling for sustained theory-experiment collaboration
- No signals yet, but leave no stones unturned

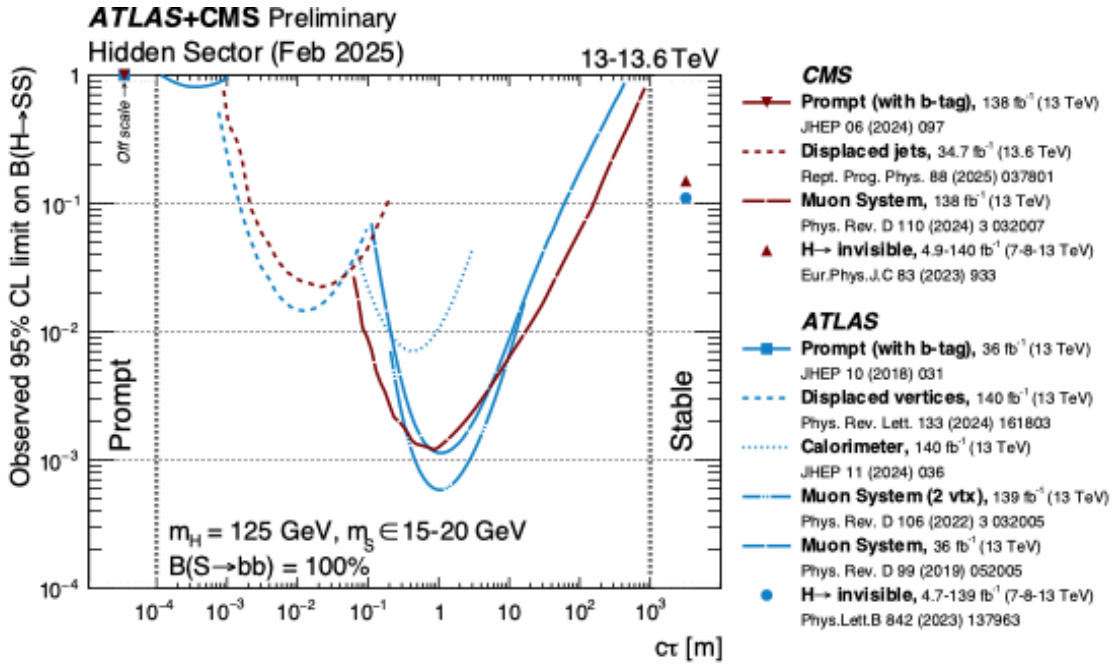
Backups

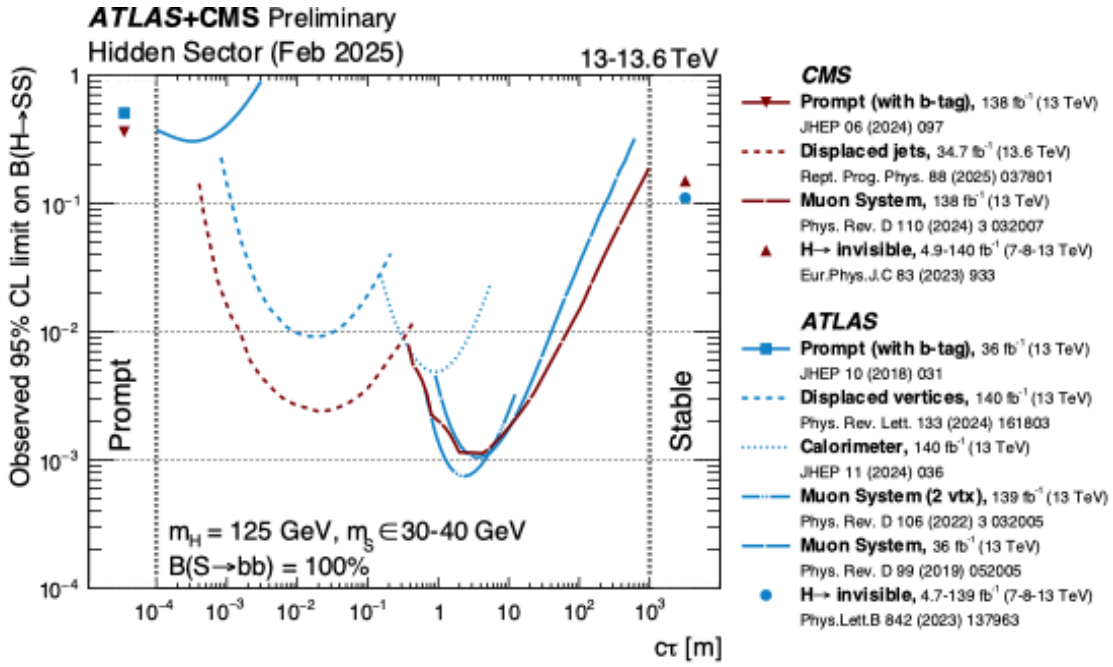
Dark photon summary



Observed upper limits at 90% CL on the square of the kinetic mixing coefficient ε in the minimal model of a dark photon from a CMS search [arXiv:2309.16003] in the mass ranges of 1.1–2.6 GeV and 4.2–7.9 GeV (pink) and from another CMS search [arXiv:1912.04776] at higher masses (green). The limits are compared with the existing limits at 90% CL provided by LHCb (blue) [arXiv:1710.02867, arXiv:1910.06926] and BaBar (gray) [arXiv:1406.2980].

LLP summary





95% confidence level upper limits on the Higgs boson branching to a pair of long-lived neutral scalars