Higgs Hidden/Dark Sector Physics

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ICNFP 2020

Overview

- Dark Matter (DM)
  - DM Experiments
  - DM Searches at LHC
- Hidden Dark Sector
  - Particles and Portals
  - Dark Photon and Dark Higgs
- Dark photon searches at Low Energy Experiments
  - Visible Photons Searches
  - Constraints & Future Prospects
- Hidden/Dark Sector at High Energy Colliders
  - Exotic Higgs and dark-Z boson
  - Constraints & Future Prospects
- Higgs & Hidden/Dark Sector Searches at LHC (Selected Examples)

Standard Model (SM)

- SM of elementary particle physics provides consistent description of Nature's fundamental constituents and their interactions.
- SM predictions tested and confirmed by numerous experiments.
  - Large Hadron Collider (LHC) runs culminated in the discovery of Higgs boson particle with mass of 125 GeV – the last critical SM component.
- In principle, all particles needed to explain results of previous accelerator experiments have been found.
- At the same time, no significant deviations from SM were found in direct or in indirect searches for New Physics (NP).
- However, SM is not a complete theory
  - Fails to explain several observed phenomena in particle physics, astrophysics and cosmology.

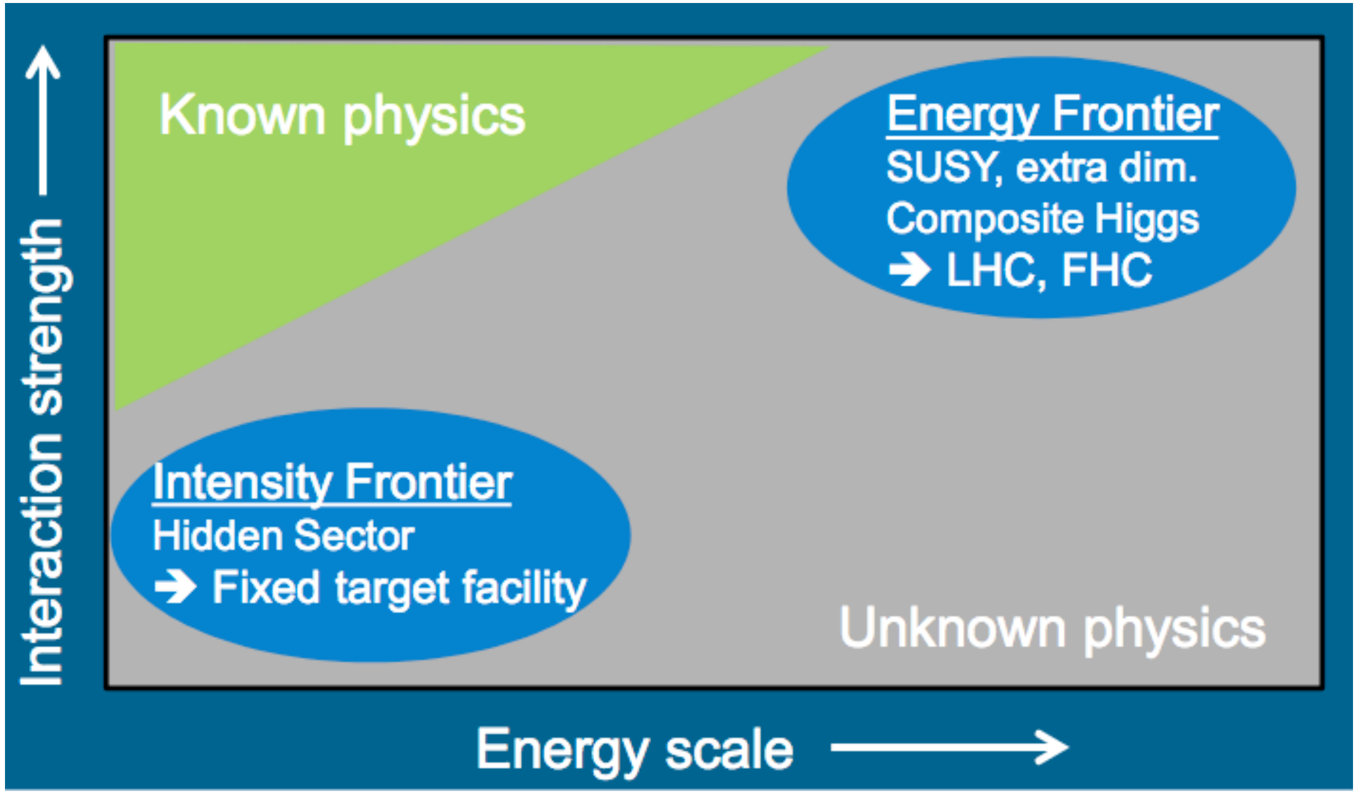
Beyond SM (BSM)

- Major unsolved challenges are commonly known as "Beyond-the-Standard Model" (BSM) problems:
  - <u>Neutrino masses and oscillations:</u> what makes neutrinos disappear and then re-appear in a different form? Why do neutrinos have mass?
  - <u>Baryon asymmetry of the Universe (BAU):</u> what mechanism created the tiny matter-antimatter imbalance in the early Universe?
  - <u>Dark Matter(DM):</u> what is the most prevalent kind of matter in our Universe?
  - <u>Dark Energy (DE):</u> what drives the accelerated expansion of the universe during the present stage of its evolution?

Energy and Intensity Frontier Research

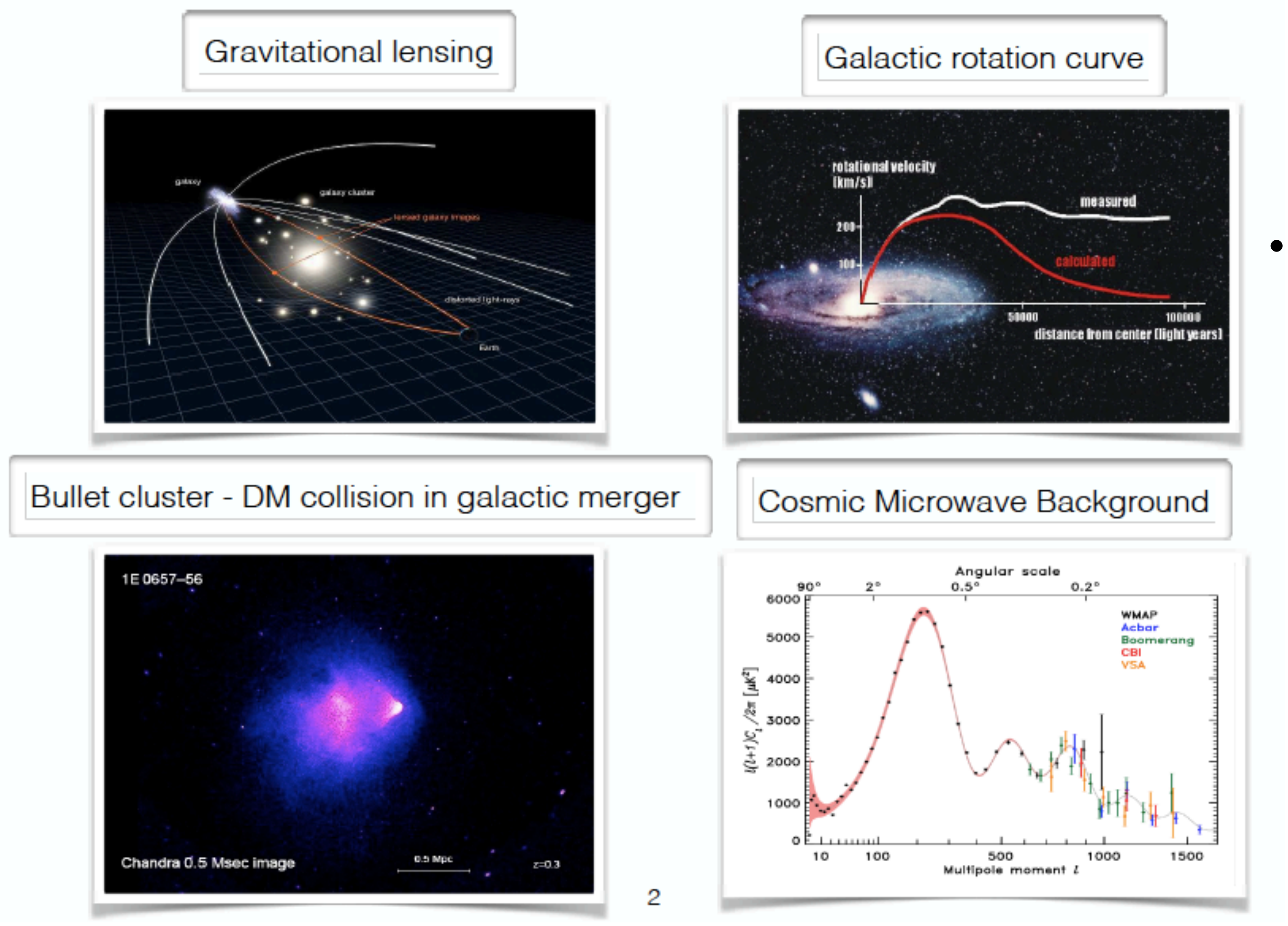
- Some yet unknown particles or interactions would be needed to explain these puzzles and to answer these questions.
- But in that case, why haven't new particles yet been observed?
- One possible answer is that hypothetical particles are heavy and require even higher collision energy to be observed
  - the so-called "Energy Frontier" (EF) research
- Major particle physics experiments of last few decades, including LEP and LHC at CERN, and Tevatron in US, have followed this path
- Another possibility is that our inability to observe new particles lies not in their heavy mass, but rather in their extremely feeble interactions.
- Different experimental approaches to detect them could be also used:
  - cross the "Intensity Frontier" (IF), rather than the "Energy Frontier (EF)"

Hidden Sector New Physics



- New Physics can be explored at Intensity Frontier experiments
- Complementarity with the Energy Frontier experiments

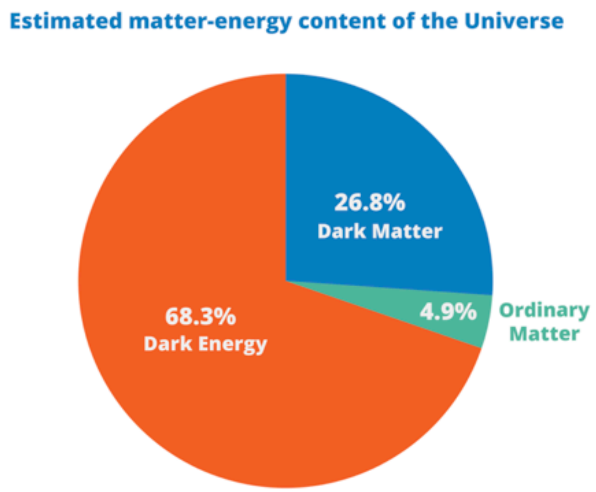
DM Astrophysical and Cosmological Evidence



- Observations of *galactic dynamics* and *Cosmic Microwave Background (CMB)* showed that the ordinary (SM) particles are not abundant enough to account for all matter in the universe

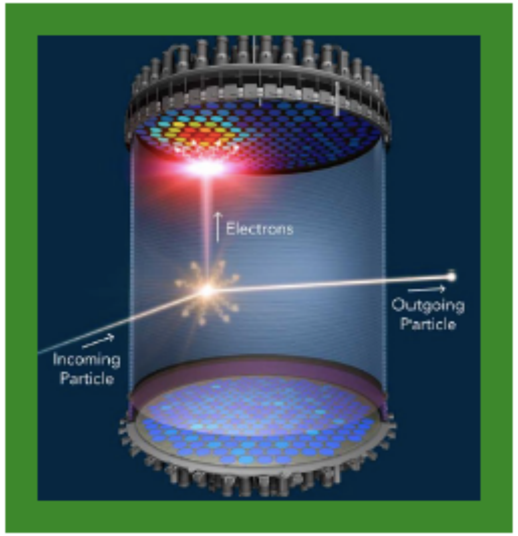
Dark Matter (DM) and Dark Energy (DE)

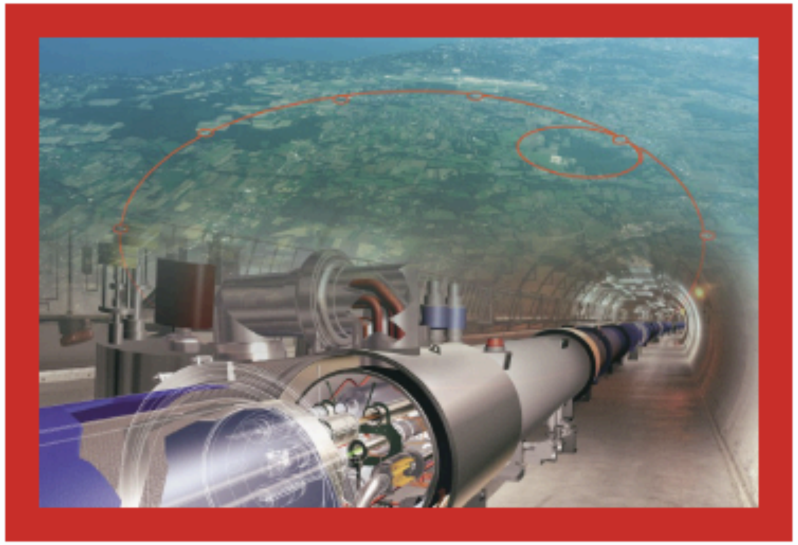
- Dark Matter, does not interact with strong, weak, or electromagnetic forces
  - does not absorb, reflect or emit light, making it extremely hard to spot
  - researchers able to infer the existence of DM only from gravitational effect on visible matter
- DM, outweigh visible matter (~6 to 1), making up ~27% of the universe
- Ordinary matter, makes up all stars and galaxies only accounts for ~5% of content of the universe!
- Dark Energy, makes up ~68% of the universe and appears to be associated with the vacuum in space
  - accelerate the expansion of the universe

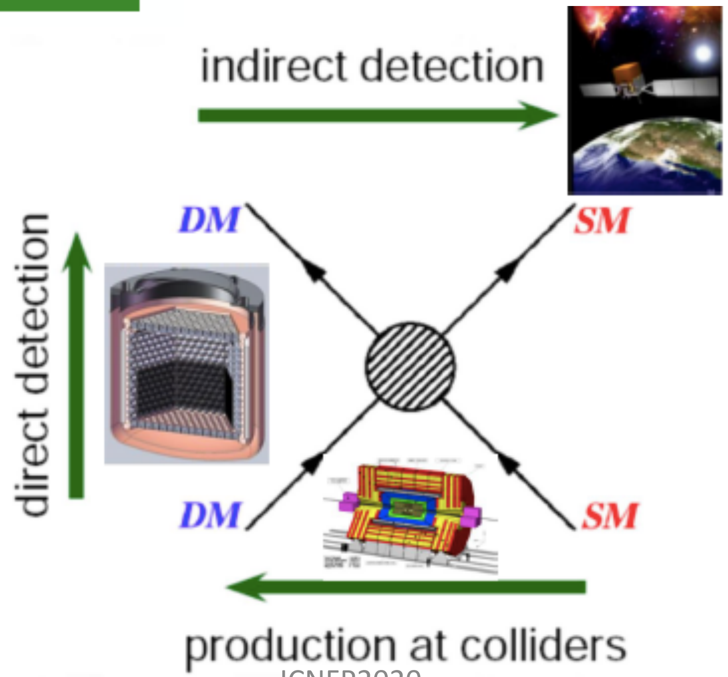


Percentage of ordinary matter, dark matter, dark energy (Image: CERN/ESA)

DM search strategies







DM Experiments in Astrophysics

- Direct Detection (DD) experiments, look for Galactic DM colliding with underground targets made of ordinary matter
  - by searching for kicks to atomic nuclei in underground detectors
    - XENON in Europe, LUX in North America and PANDA-X in China
- Indirect Detection (ID) experiments, search for products of annihilating DM concentrated within gravitational potential wells of Milky Way
  - by using telescopes in space and on ground to look for indirect signals of DM particles, as they collide and break themselves out in space
    - high-energy photons, observed by telescopes such as HESS, MAGIC and VERITAS
    - neutrinos, observed by neutrino telescopes such as IceCube
    - anti-particles, detected by space experiments such as AMS on International Space Station
- To succeed, both types of searches require that DM interact with ordinary matter:
  - DM–nucleon (or DM–electron) interactions in DD searches or DM annihilation to SM particles in ID searches.

DM Experiments at Colliders

- If experiments at Colliders detect a potential DM particle, it will require confirmation from the other experiments to prove that it is indeed a DM particle
- If the DD and ID experiments detect a signal from a DM particle interaction, experiments at Colliders could be designed to study the details of such an interaction
- Searches for DM at Colliders e.g. LHC guided so far by theoretical models that include DM particle which interacts weakly with ordinary particles – *Weakly Interacting Massive Particle (WIMP)*
    - WIMPs are one of the most captivating candidates for DM particle, could generate the current abundance of dark matter in cosmos
- DM is not described with a single particle and a single interaction, other possible theoretical models of DM used, to detect most prominent components and interactions of DM

DM searches at LHC – E_T^{miss}

- The main signature of the presence of a DM particle in pp collisions at LHC is the so-called *missing transverse momentum (E_T^{miss})*
- Two main types of this search at the LHC:
  - One type is guided by so-called *complete New Physics (NP) models*, such as SUSY models:
    - in SUSY models, the Lightest Supersymmetric Particle (LSP) is a WIMP
    - these searches look for E_T^{miss} from a pair of DM particles plus a spray, or "jet", of particles

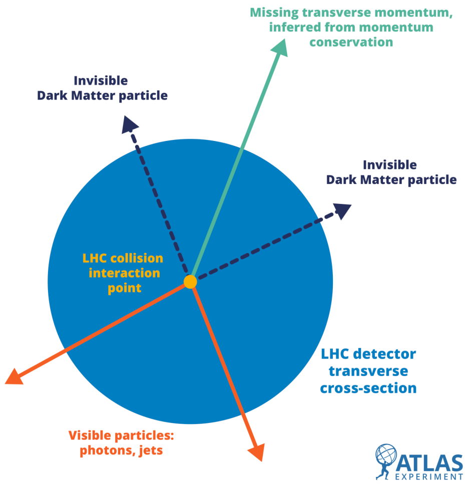
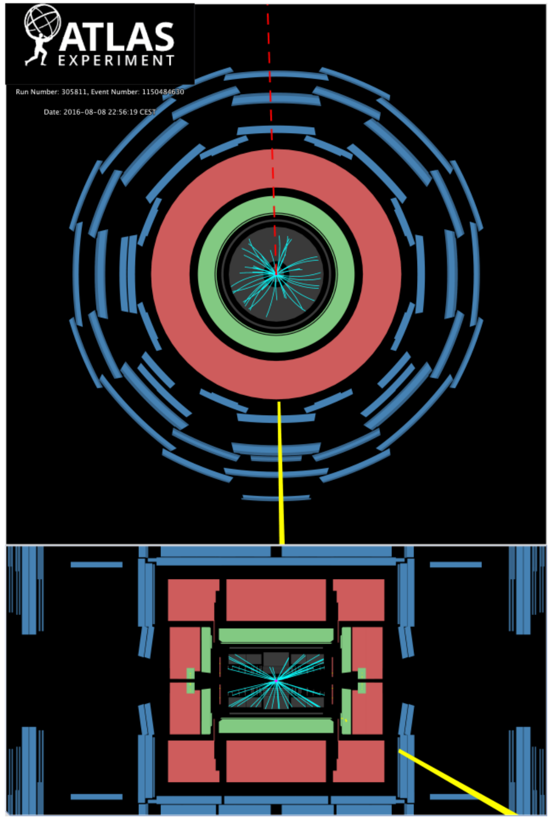


Diagram showing how E_T^{miss} is determined in the transverse cross-section of LHC detector. The LHC beams are entering/exiting through the plane (Image: ATLAS Collaboration)

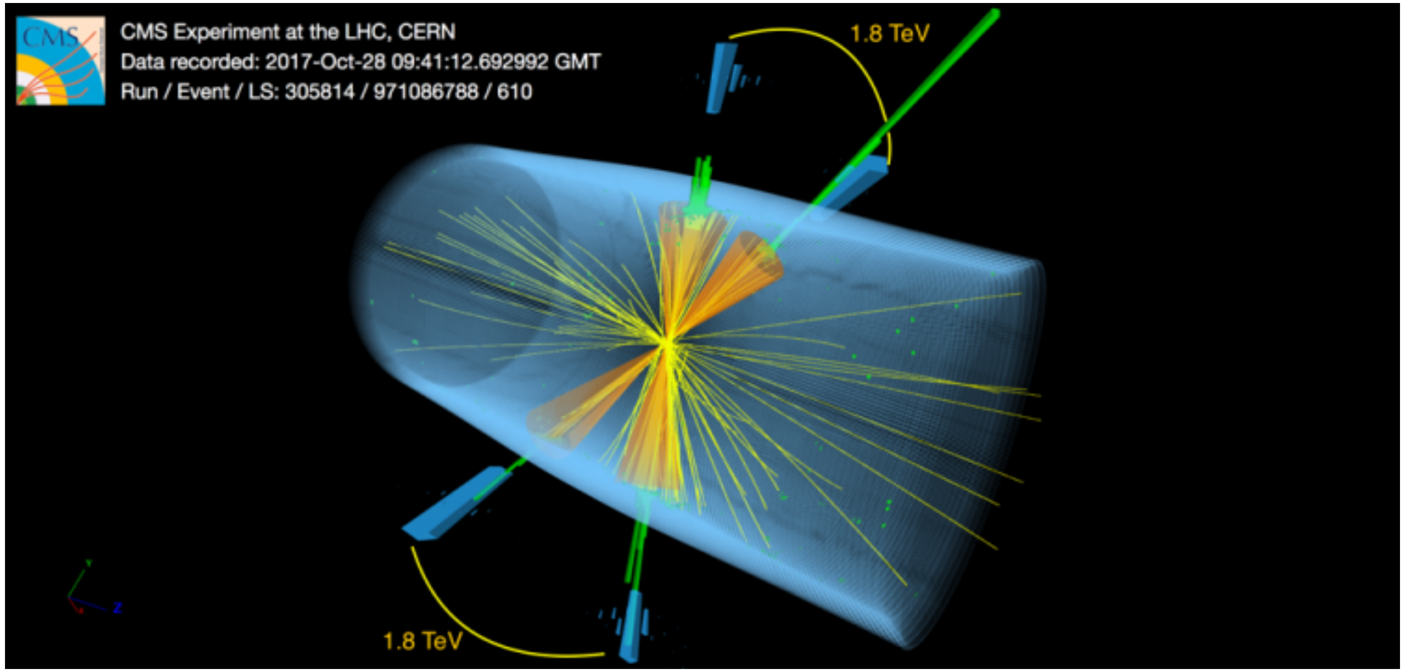
DM searches at LHC – dijets

- Another type of search, guided by *simplified models*, include a *WIMP-like* DM particle and *a mediator* particle that interact with known ordinary particles
  - the mediator can be either a known particle, such as Z boson or Higgs boson, or an unknown particle
  - in addition to E_T^{miss} from a pair of DM particles, looks for at least one highly energetic object such as a jet of particles or a photon
- An alternative to E_T^{miss} searches, looks not for the DM particle but for the *mediator* particle through its transformation, or “decay”, into ordinary particles.
  - it looks for a bump over a smooth background of events in collision data, such as a bump in the mass distribution of events with two jets or two leptons
  - the so-called *dijet searches* are very powerful because they can probe a large range of mediator masses and interaction strengths

DM candidate events at LHC



ATLAS 13 TeV event display
Search for DM in final states with an energetic photon and large E_T^{miss}



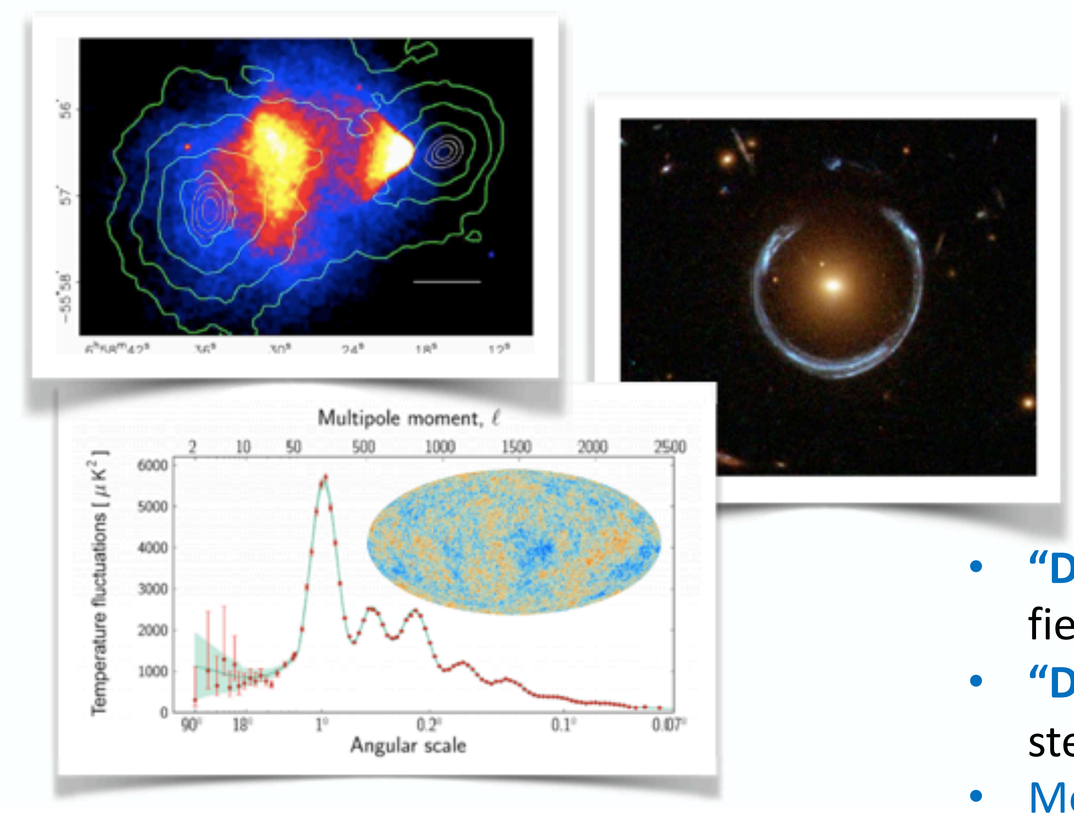
CMS 8 TeV event display
3-D display of the event with the second highest dijet invariant mass

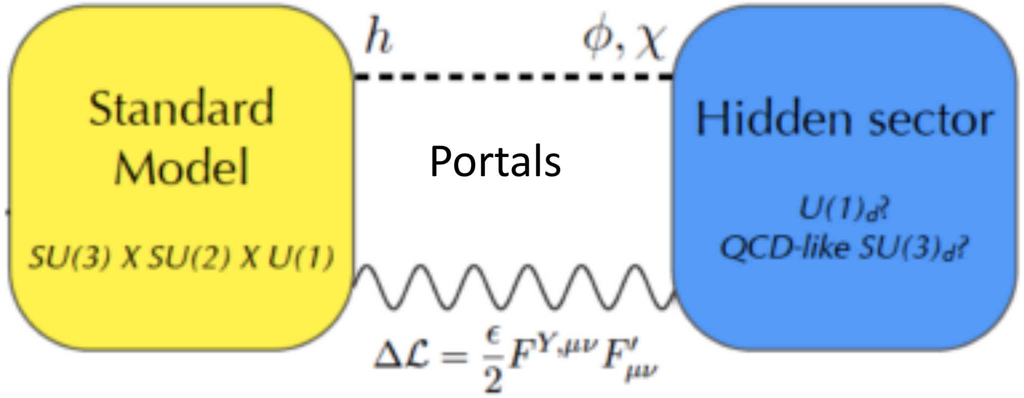
Hidden/Dark Sector

- Hypothesis that DM is part of a larger hidden/*dark sector* with several new types of dark particles
  - not charged directly under the SM, strong, weak, or electromagnetic forces
  - assumed to possess *gravitational* interactions
  - may also interact with ordinary matter through several *"portal"* interactions, constrained by the SM symmetries
- Motivation from astrophysics and theory of elementary particle physics
    - satellites, Fermi, AMS data
    - theoretical (extra U(1)'s, hidden sector, dark sector)
- Dark-sector particles could include a dark-matter equivalent of the photon - *the dark photon* - and *Long-Lived Particles (LLP)*
  - dark photon, would interact with other dark-sector particles as well as known particles
  - LLP, also predicted by Supersymmetry (SUSY) models

Hidden/Dark Sector

- Nature seems well described by SU(3)xSU(2)xU(1) gauge theory but
- We already know we are missing something…
- There is the Dark Sector…hidden





- **"Dark sector"** consists of particles that do not couple to known SM fields, but interact through a mediator:
- **"Dark photons"** (vector portal), dark scalars (Higgs portal), ALPs (axion), sterile neutrinos
- Mediators can provide **"portal"** to DM candidates or be the candidates

Hidden/Dark Sector Particles

- Dark sector typically include one or more *mediator* particles coupled to SM via a "portal"
- Portal relevant for dark sector-SM interactions depends on *mediator* spin and parity, and it it can be a:
  - **vector, A′ => Z_D, γ_D, A' (Dark Z, Dark photon)**
  - **scalar, ϕ => (h_D, s_D) (Dark Higgs)**
  - fermion, N => (sterile neutrino)
  - pseudo scalar, α => (α_D)
- SM gauge and Lorentz symmetries greatly restrict the ways in which mediator can couple to SM

Hidden/Dark Sector "Portals"

- Dominant interactions between SM and mediators are the following SM gauge singlet operators:

$$\mathcal{L} \supset \begin{cases} -\dfrac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}\,, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H\,, & \text{Higgs portal} \\ y_n L H N\,, & \text{neutrino portal} \\ \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}\,, & \text{axion portal.} \end{cases}$$

=> kinetic mixing with γ, Z^0

=> dark Higgs (mixes with SM Higgs)

=> sterile neutrino

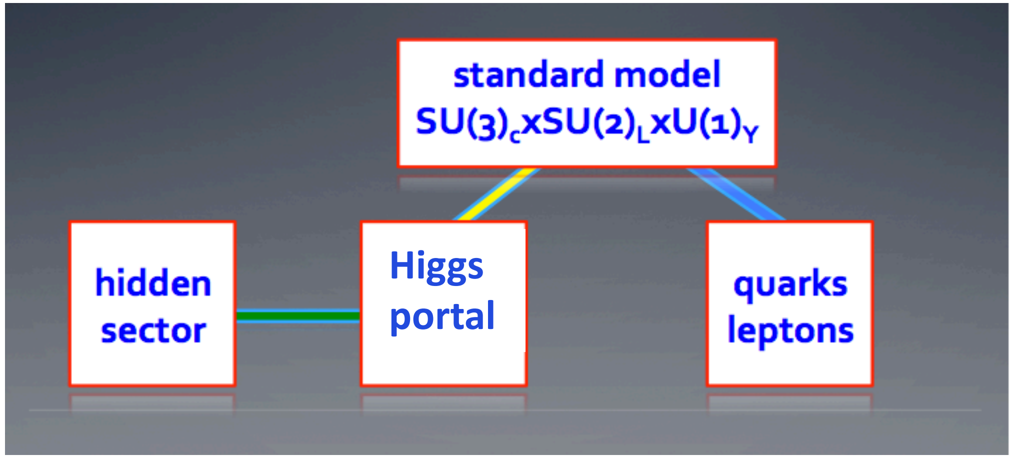
=> coupling through axion

- Focus will be given on the vector portal and
- If the mediator is a scalar, can interact via the Higgs portal (e.g. Exotic Higgs decays at LHC)

Higgs Hidden/Dark Sector "Portal"

- **Higgs as a Portal to the Hidden or "Dark" Sector**

  Higgs boson may connect the SM to other 'sectors'

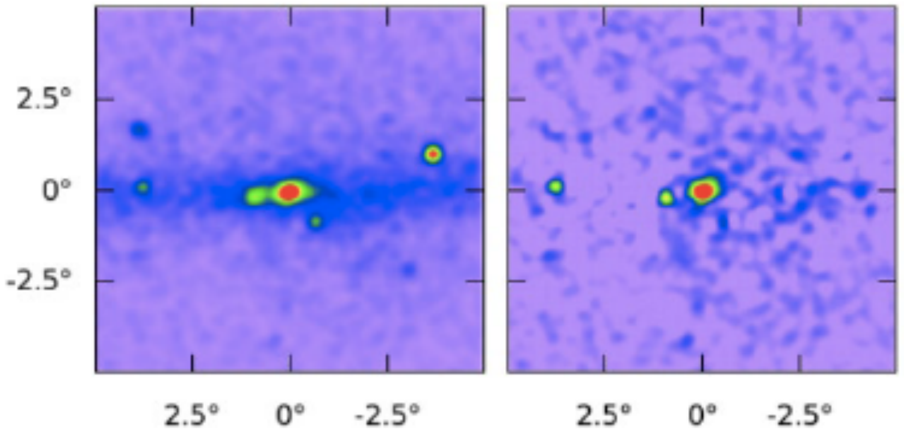


- Higgs production of dark photons
- Exotic rare Higgs decays

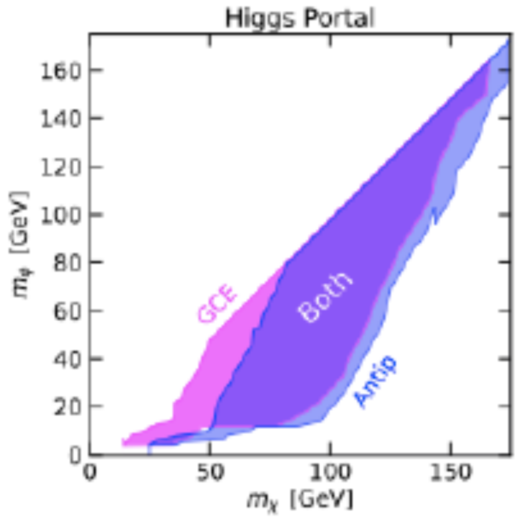
Dark Photons: Motivation

- Dark photons present in models for:
  - Naturalness
  - Thermal dark matter
  - Electroweak baryogenesis
  - Axions
- Various anomalies can be explained:
  - Gamma-ray excess at the center of the galaxy
  - Antiproton excess in cosmic rays
  - Excess in excited Beryllium decay

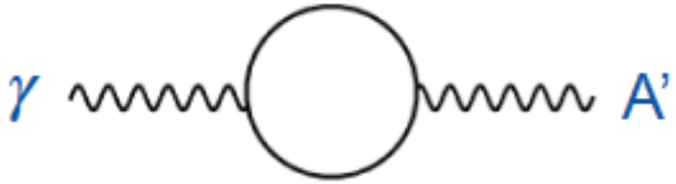
Fermi-LAT Collaboration, Phys. Rev. D 89, 042001

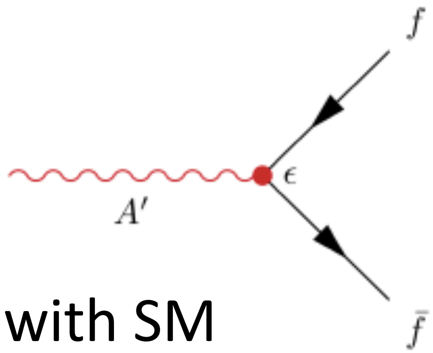


D. Hopper et al. arXiv:1912.08821



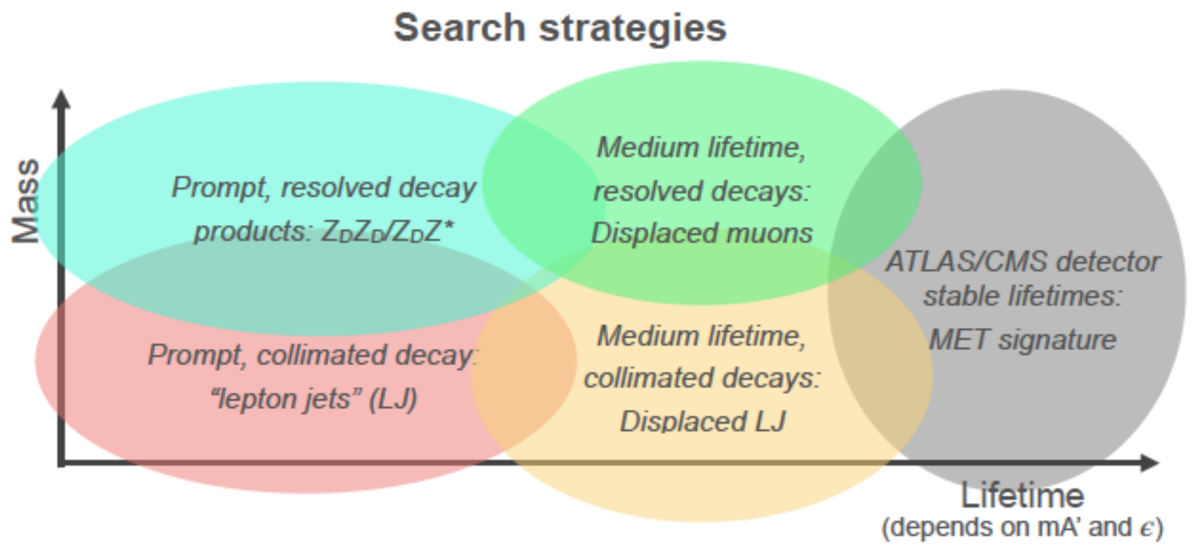
Dark Photon: A'

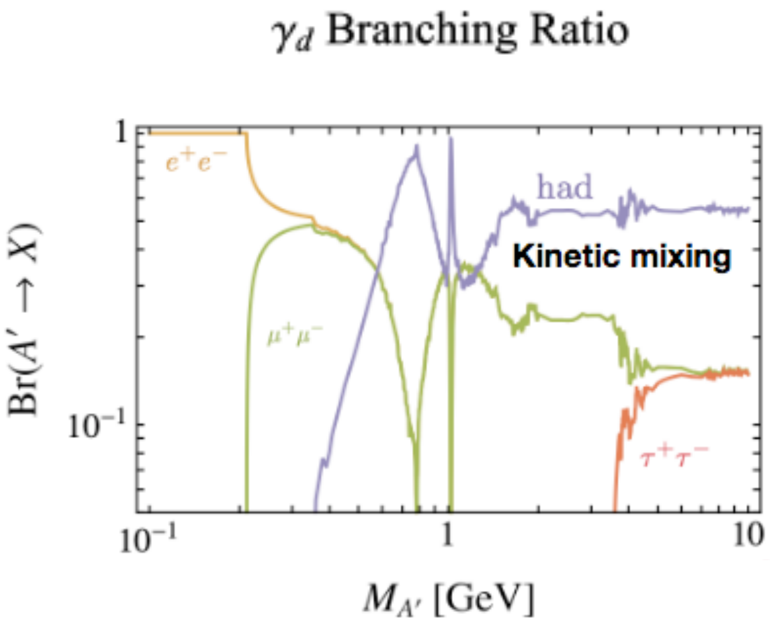




- Add a U(1)$_D$ where massive dark gauge boson (A'/Z_D/γ_D) kinetically mix with SM photon
- **Parameters**: **kinetic mixing term ε** and $m_{A'}$

arXiv:1803.05466



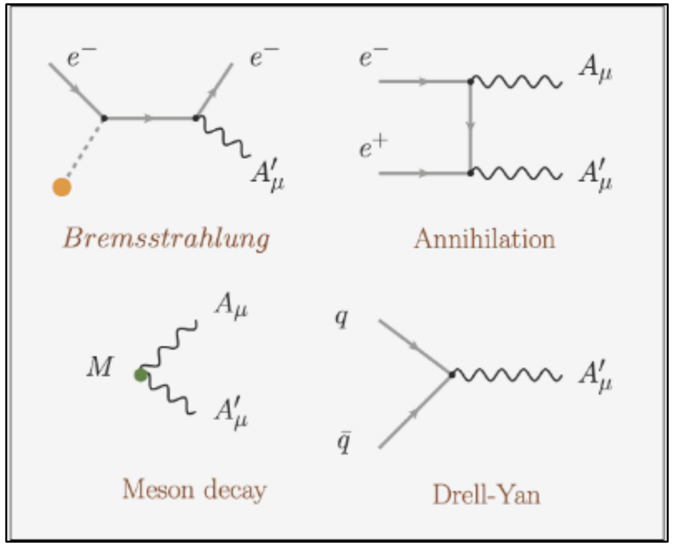


arXiv:1312.4992

‘Visible’ Dark Photon at Low Energy (1 MeV-10 GeV)

Production Modes

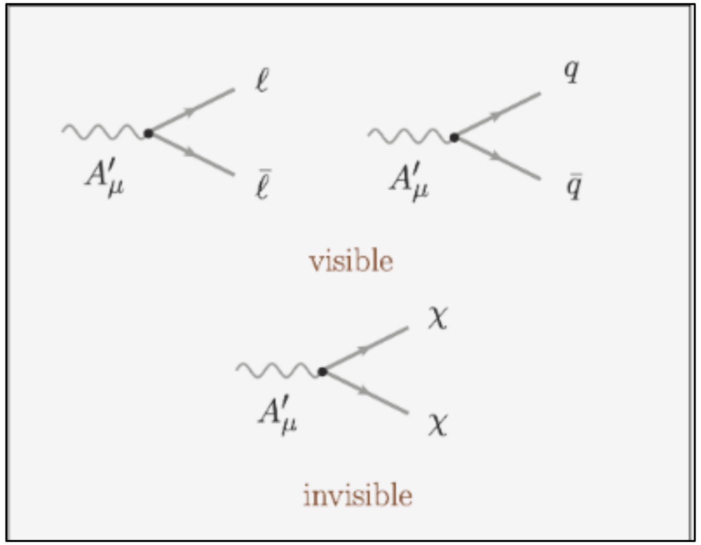
- Electron-positron annihilation
- Meson Decays
- Drell-Yan (collider or fixed target)
- Bremsstrahlung



- Production of dark photons: Bremsstrahlung, Annihilation, Meson decay and Drell-Yan

Detection Signatures

- Pair resonance
- Beam-dump late decay
- Inclusive missing mass
- Reconstructed displaced vertex



- Decay of massive dark photon into visible (SM leptons or hadrons) and invisible (DM) modes

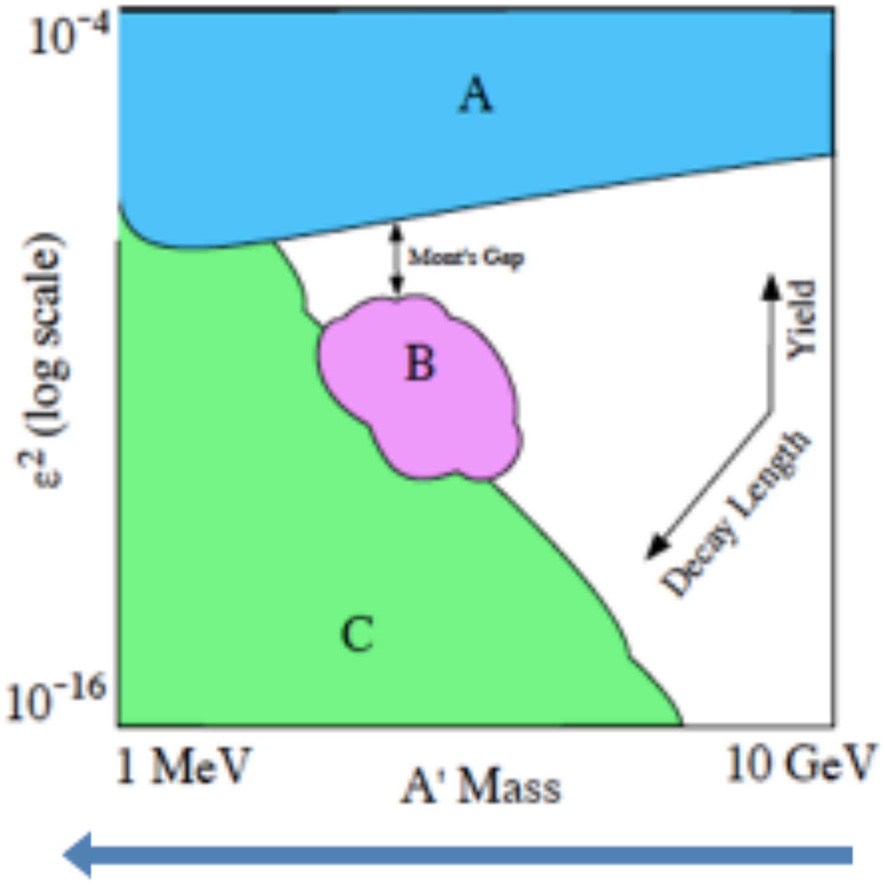
‘Visible’ Dark Photon Strategies

- Bremsstrahlung: $e^- Z \rightarrow e^- Z A'$
  - electrons incident on a nuclear target of charge Z
- Annihilation: $e^+ e^- \rightarrow \gamma A'$
  - invisible A’ decay modes (missing-mass), visible modes
  - annihilation channels in fixed-target experiments with e^+ beams and
  - e^+e^- collider experiments
- Meson decay:
  - Dalitz decays, $\pi^0/\eta/\eta' \rightarrow \gamma A'$, and rare meson decays $K \rightarrow \pi A'$, $\phi \rightarrow \eta A'$, $D^* \rightarrow D^0 A'$
  - hadronic environments, in colliders or fixed-target setups; e^+e^- colliders, (KLOE)
- Drell-Yan:
  - $q\bar{q} \Rightarrow A' \rightarrow (l^+l^-$ or $h^+h^-)$
  - hadron colliders and proton fixed-target experiments

“Visible” dark photons (1 MeV-10 GeV)

“ε^2 vs A’ mass (1 MeV-10 GeV) parameter plane

arXiv:1608.08632



more collimated decay products (lepton jets)

“Kinetic mixing parameter” ε^2 vs A’ mass (1 MeV-10 GeV):

- ***Region A:*** prompt decays to (in)visible particles, bump hunt for resonance (missing mass)
- ***Region B:*** displaced vertex searches, short decay lengths
- ***Region C:*** displaced vertex searches, long decay lengths

Closing “Mont’s” Vertexing Gap

- Closing from above (bump hunt) runs into systematics
- Closing from below requires great vertex resolution in high luminosity environment

Dark Sector Experiments

- High Energy Colliders, High Intensity Colliders, Fixed Target Experiments
- Broad worldwide effort to search for dark forces

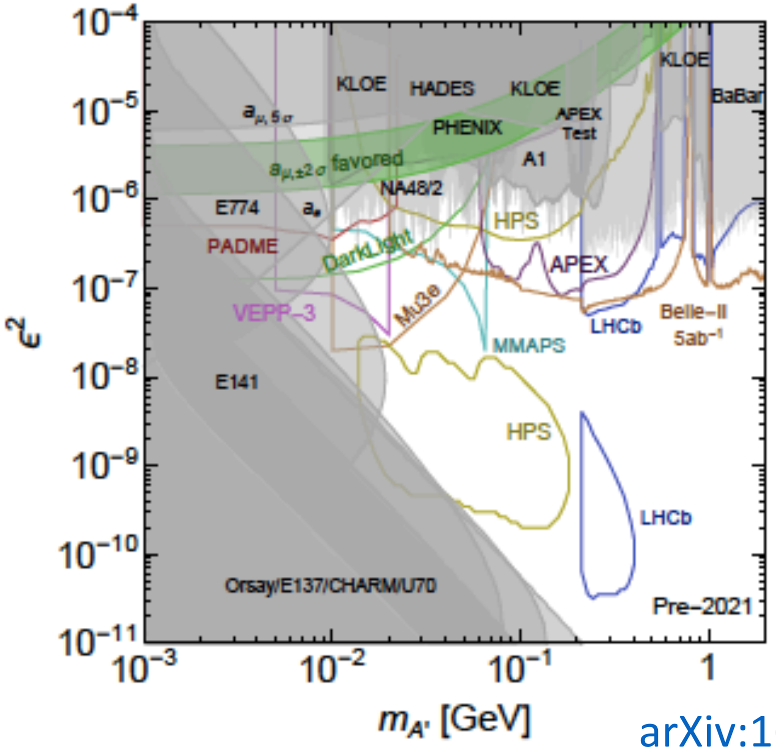
- Low Mass Dark Sector Experiments
  - High-luminosity e^+e^- colliders
    - e.g. BABAR, BELLE/BELLE II, KLOE/KLOE-2, BESIII
  - Beam Dump Experiments
    - e.g. CHARM, E137, BDX, SHiP
- Rich Dark Sector Experiments
  - High Energy Colliders – LHC
    - ATLAS, CMS, LHCb
    - Exotic Higgs Decays, Ljets, LLPs etc

- Other ongoing - future experiments
  - DarkLight
  - APEX
  - HPS
  - MMAPS
  - VEPP-3
  - MESA
  - MAMI-A1
  - SeaQuest
  - NA64 etc

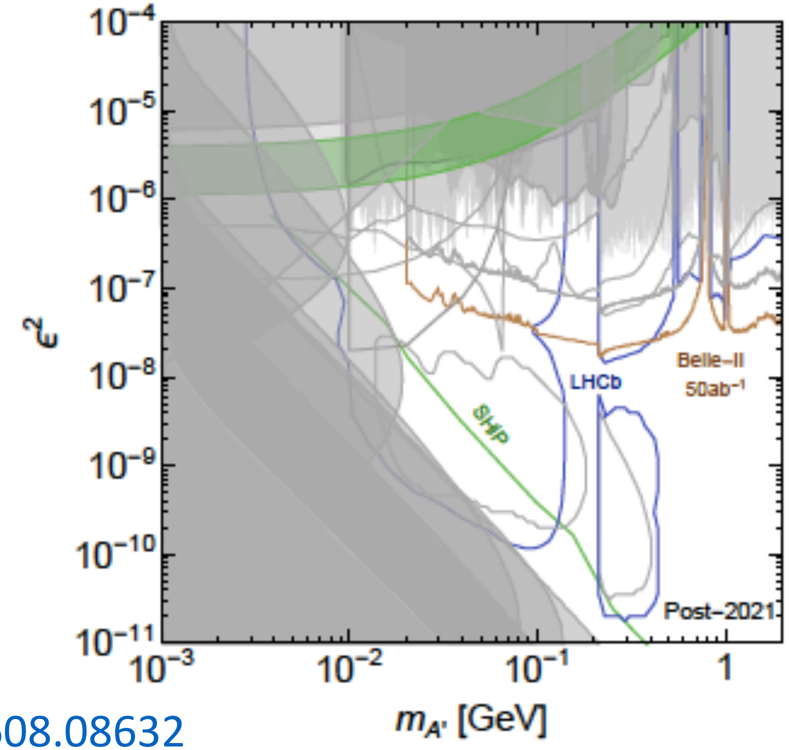
Dark photons (1 MeV-1 GeV): Constraints & Future Prospects

Experimental Sensitivity for visible decay modes A’ → l^+l^-

Experimental sensitivity up to 2021



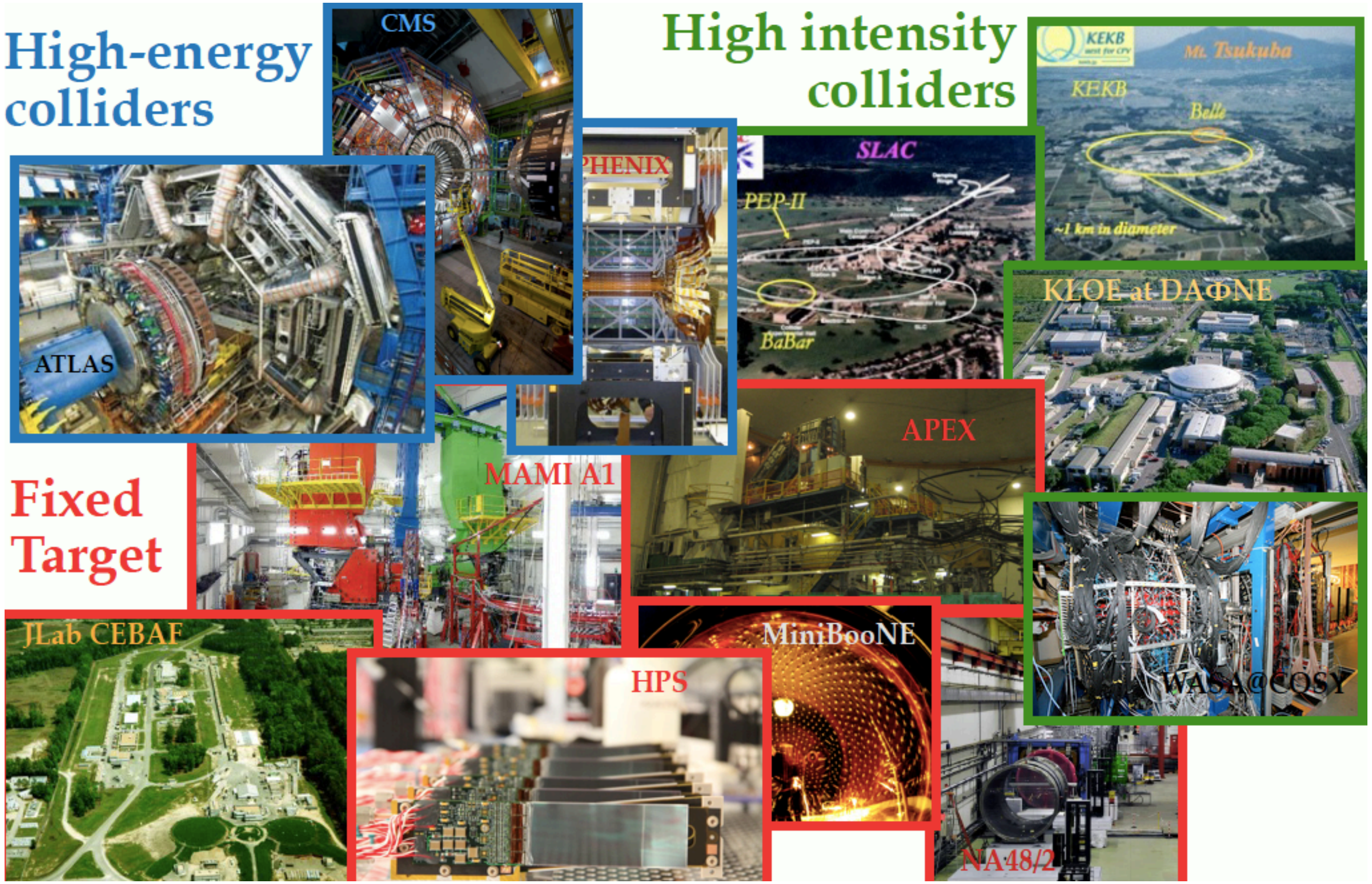
Prospects beyond 2021



arXiv:1608.08632

- Shaded regions: show ‘existing’ bounds.
- Green band: shows 2σ region in which A’ can explain discrepancy between calculated and measured value for muon g-2.
- Colored curves: anticipated exclusion reaches of planned experiments.

Dark photons: Ongoing Experiments



Hidden/Dark Sector at High Energy Colliders

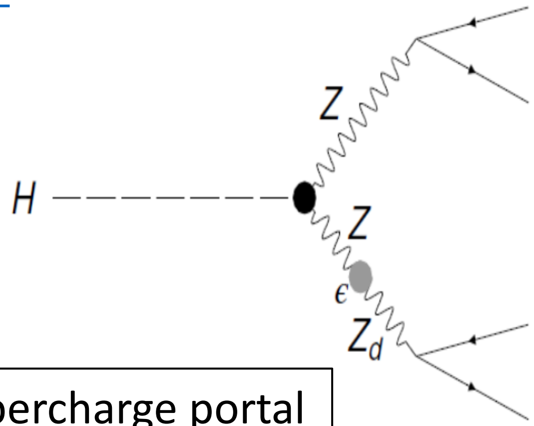
- Prototypical *hidden sector*, possibility of a spontaneously broken "dark" $U(1)_D$ gauge symmetry, mediated by a vector boson called the "*dark photon*", Z_D
- Dark photon's only renormalizable interaction with SM is through *kinetic mixing* with the hypercharge gauge boson
- In addition, if a *dark Higgs* mechanism is responsible for spontaneous breaking of $U(1)_D$ gauge symmetry, the dark Higgs boson will have a renormalizable coupling to 125 GeV SM-like Higgs, resulting in a mixing between two physical scalar states
- Hidden sector's leading interactions with SM may thus be through:
  - ***hypercharge portal:*** via *kinetic mixing coupling*, denoted as ε
  - ***Higgs portal:*** via *Higgs mixing*, denoted as κ

Exotic Higgs Decay and Dark-Z

- Hypercharge portal allows for direct production of dark photon in Drell-Yan (DY) events, pp → Z_D → l^+l^-
- Also, generates the exotic Higgs decay h → ZZ_D
- Higgs mixing allows for a different exotic Higgs decay, h → Z_DZ_D

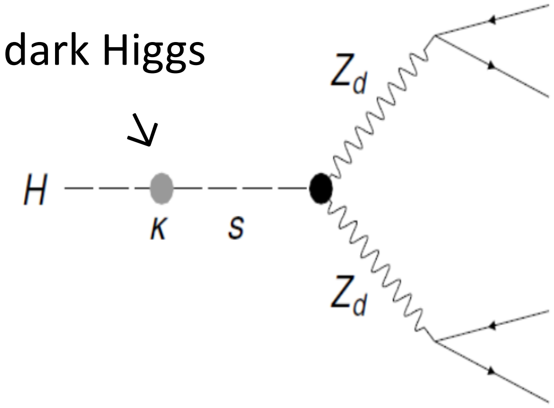
Massive dark photons in the "higgs-dark" $U(1)_D$ model
Search of Exotic Higgs decays to four leptons

arXiv:1312.4992



h → $Z_DZ^{(*)}$ → 4l via hypercharge portal

s: dark Higgs

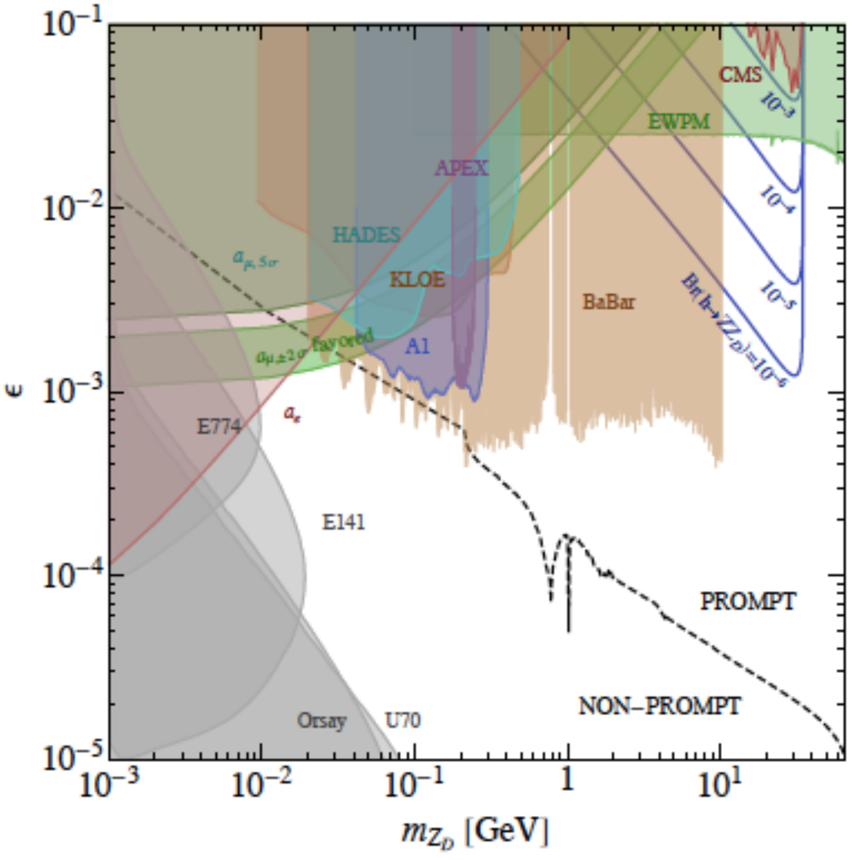


h → Z_DZ_D → 4l via Higgs portal

Dark-Z Regions of Interest (m_{ZD}<10 GeV)

Constraints on m_{ZD} for pure kinetic mixing (no additional source of Z-Z_D mass mixing), for mZ_D ~MeV-10 GeV

JHEP02(2015)157



D. Curtin et al. (Phys. Rev. D 90, 075004 (2014))

- Black dashed line: separates prompt ($c\tau$<1μm) from non-prompt Z_D decays
- Three blue lines: contours of Br(h → ZZ_D) of 10^{-4}, 10^{-5}, 10^{-6}
- Shaded regions: existing experimental constraints
- Red shaded region "CMS" limit derived by recasting the CMS Run-1 20+5 fb^{-1} h → ZZ* analysis
    - similar bound from ATLAS analysis
    - bound being optimized with new LHC measurements
- Green region labelled "EWPM": Electroweak Precision Measurement Bounds

- LHC experiments explore Z_D, below and above 10 GeV
- LHC searches on dark photons with sizable branching ratio to lepton pairs (ee, μμ)
    - prompt or displaced decays

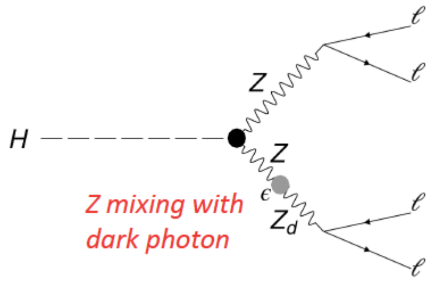
Exotic Higgs Decays and Dark Sector at LHC

- ATLAS and CMS discovery of neutral scalar particle of mass 125 GeV, H(125) at LHC, confirmed predicted electroweak symmetry breaking mechanism of SM
- Properties of new boson found consistent with SM Higgs boson
- Observed H(125) offers excellent opportunity to look for new physics at LHC
- Existing precision measurements of Higgs properties still allow up to ~10% branching fraction to BSM decays
- Since the SM predicts a very narrow decay width for the Higgs, even a small coupling to a new light state could result in a significant branching fraction to that state
- This opens a new and rich experimental program that includes the search for Exotic Higgs decays to light BSM bosons, “light” means lighter than the SM *Z* boson
- Explicit search for (BSM) Exotic Higgs boson decays presents an alternative opportunity for discovery of BSM physics and provide the best window on dark matter

Phys. Rev. D 90, 075004 (2014)

Phys.Rev.D 92 (2015) 092001

$H \to ZZ_d \to 4l$



Exotic Higgs boson decays to four leptons induced by intermediate dark vector bosons via the hypercharge portal

Z_d: on-shell, mass < Z-mass, prompt decay

- Benchmark model studied: Hidden Abelian Higgs Model (HAHM) for vector Z_d bosons
  - Comprising a BSM vector boson, Z_d, predicted in $U(1)_d$ dark-sector extensions of SM

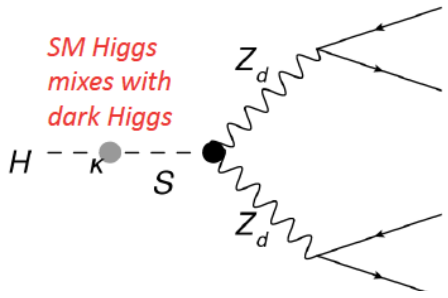
- Z_d gauge boson decays to SM particles through kinetic mixing, ε, with the hypercharge field (or through mass mixing, δ), with the Z boson
- HZZ_d vertex factor is proportional to ε

- For Z_d mass range $1 < m_{Zd} < 60$ GeV, the branching ratio for decays to electron or muon pairs can be 10-15%
- For Z_d masses 1 GeV - 60 GeV, the decay will be *prompt for $\varepsilon > 10^{-5}$*
- For *smaller values of ε, displaced decays* provide a unique signature
- For Z_d masses < a few GeV and small values of ε, the decay products will be *highly collimated leptons-jets (LJ)* and require a special analysis

Phys. Rev. D 90, 075004 (2014)

$H \rightarrow Z_{(d)}Z_d \rightarrow 4l$

Phys.Rev.D 92 (2015) 092001



- Presence of dark sector inferred from deviations from:
  - SM-predicted rates of Drell-Yan (DY) events
  - Higgs boson decays through exotic intermediate states

- If $U(1)_d$ symmetry is broken by additional dark Higgs, there could be a mixing with strength κ
- $H \rightarrow Z_dZ_d$ sensitive to small ε, required to be large enough for Z_d to decay promptly
- $H \rightarrow Z_dZ_d$ search constrains the Higgs mixing parameter κ

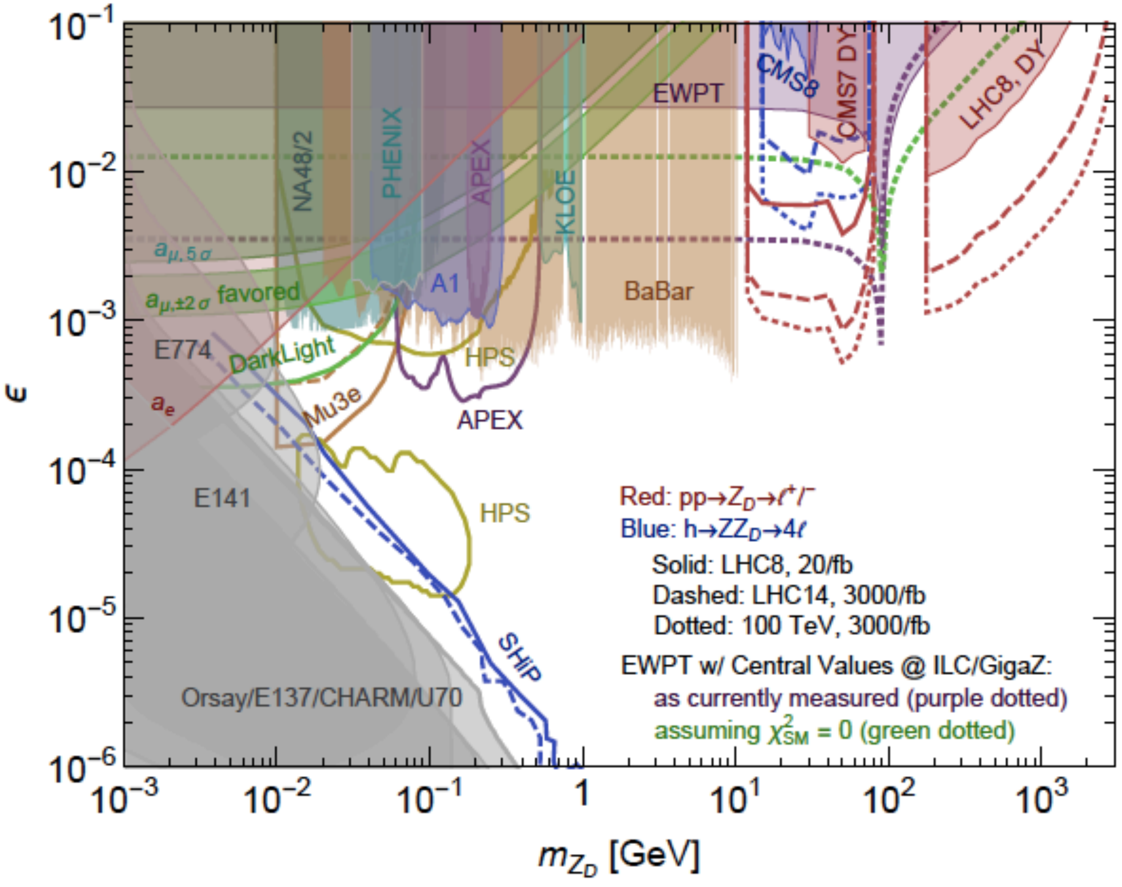
- Model-independent upper bounds from *electroweak constraints* on kinetic mixing parameter ε:
  - $\varepsilon < 0.03$, for Z_d masses: 1 GeV-200 GeV
- Upper bounds on ε, based on searches for *di-lepton resonances, $pp \rightarrow Z_d \rightarrow ll$*, below the Z-mass
  - $\varepsilon < 0.005–0.020$, for Z_d masses: 20 GeV-80 GeV
- In the mass range of 10 MeV-10 GeV, $\varepsilon > \sim 10^{-3}$ ruled out

Higgs Hidden/Dark Sector Future Collider Searches

- The high-luminosity run (HL- LHC), a possible future 100 TeV p-p collider, and future electron-positron colliders, give the exciting opportunity to probe dark photons well above 10 GeV
- These experiments are the only known probe of dark photons above 10 GeV that explore ε values not disfavored by current EWPT
- The Higgs portal can give experimental sensitivity to values of ε far below the reach of searches that only rely on the hypercharge portal, allowing to peer deeply into the hidden sector.

Dark-Z Future Colliders Prospects (1 MeV-1 TeV)

Summary of dark photon constraints and prospects



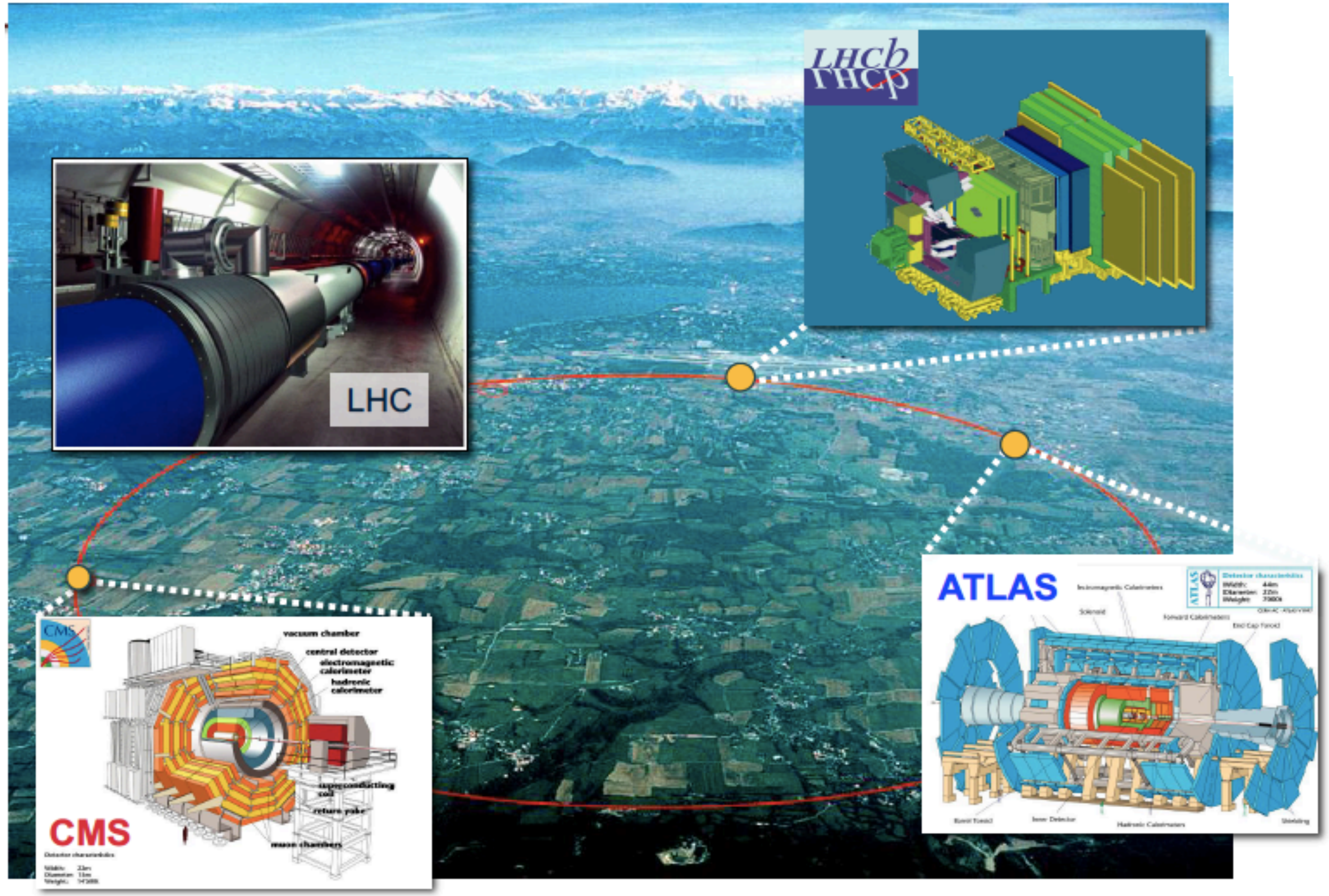
- High-energy colliders (HL-LHC, 100 TeV, ILC) are sensitive to dark photons with $m_{ZD} > 10$ GeV
- Precision QED observables and searches at B- and Φ-factories, beam dump experiments, and fixed target-experiments probe lower masses

- Dark photons can be detected at high-energy colliders
  - blue curves: exotic decay of 125 GeV Higgs, $h \to ZZ_D \to 4l$
  - red curves: Drell-Yan events, $pp \to Z_D \to ll$
  - green/purple dashed curves: improved measurements of electroweak precision observables

- If, in addition to kinetic mixing, the 125 GeV Higgs mixes with the dark Higgs that breaks the dark U(1), then
  - $h \to Z_D Z_D$ decay would set constraints on ε, orders of magnitude more powerful than other searches, down to dark photon masses of ~100 MeV.

D. Curtin et al. JHEP02(2015)157

ATLAS, CMS, LHCb Experiments at LHC



Selected Dark Photon Studies at LHC

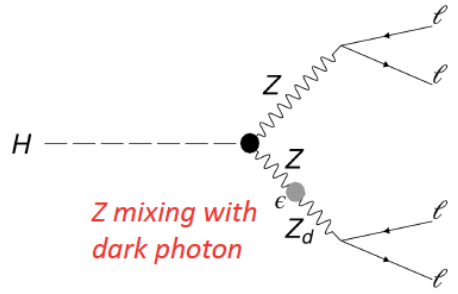
- Dark photon from Higgs decay (ATLAS, CMS):
  - massive dark photon
  - massless dark photon
- Dark photon from Higgs decay (ATLAS, CMS):
  - displaced leptons , LLPs
  - lepton-jets, prompt and displaced, LLPs
- Low-mass dimuon resonance search (LHCb, CMS)

JHEP 06 (2018) 166

Exotic Higgs decay at ATLAS: Hypercharge Portal

13 TeV, 36.1 fb^{-1}

$H \to ZZ_D \to 4\ell$



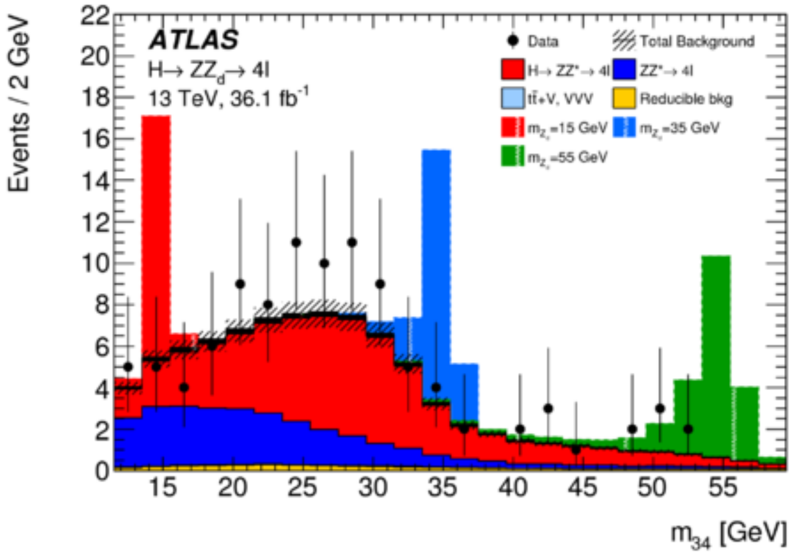
H → ZX, 4e, 4μ, 2μ2e, 2e2μ

- Three leading leptons p_T>20, 15, 10 GeV
- Dark photon (X) mass: 15 - 55 GeV

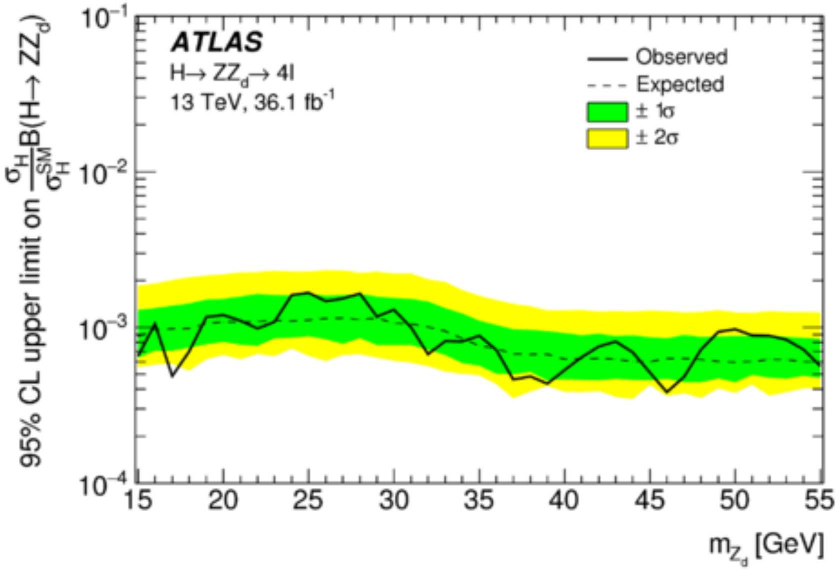
Main backgrounds

H → ZZ* → 4l, SM ZZ* non-resonance

Signal region $m_{4\ell} \in [115,130]$ GeV



ATLAS-EXOT-2016-22



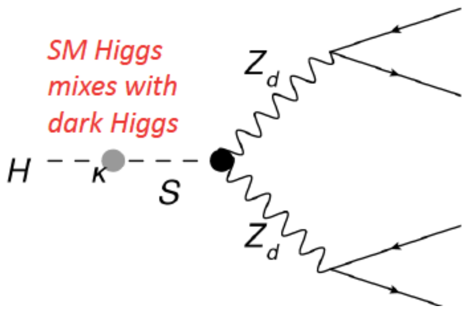
m_{12} dilepton mass closest to Z mass
m_{34} mass of the other pair

Exotic Higgs decay at ATLAS: Higgs Portal

JHEP 06 (2018) 166

13 TeV , 36.1 fb^{-1}

$H \rightarrow Z_D Z_D \rightarrow 4\ell$

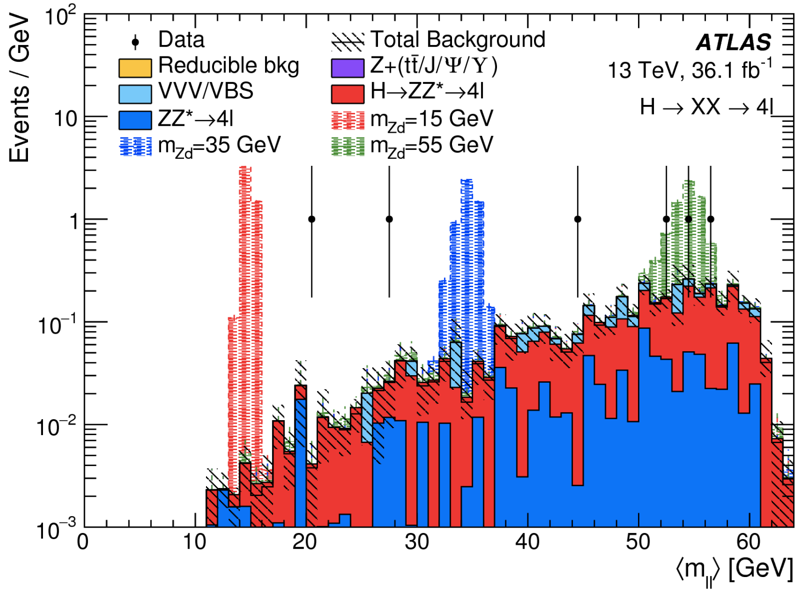


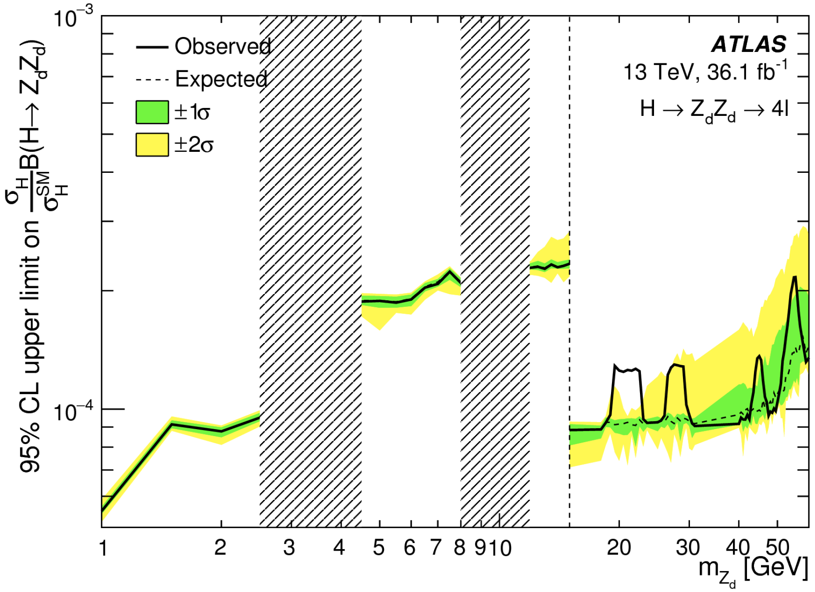
- High mass: $H \rightarrow XX \rightarrow 4e, 4\mu, 2\mu 2e$
  - $15 \text{ GeV} < m_X < 60 \text{ GeV}$
- Low mass: $H \rightarrow XX \rightarrow 4\mu$
  - $1 \text{ GeV} < m_X < 15 \text{ GeV}$
- Select quadruplet with smallest |m12 - m34|

Main backgrounds

- $H \rightarrow ZZ^* \rightarrow 4l$; SM ZZ^* non-resonance

Signal region





ATLAS-EXOT-2016-22

Exotic Higgs decay at ATLAS: Hypercharge & Higgs Portal

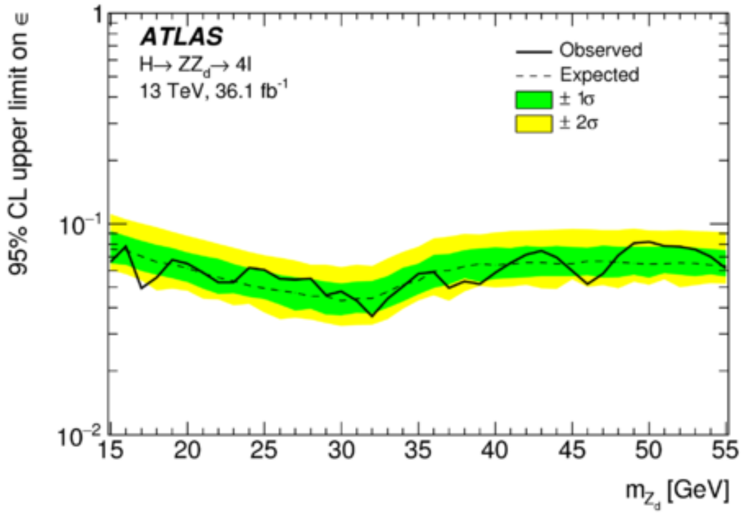
13 TeV, 36.1 fb^{-1}

$H \to Z/Z_D Z_D \to 4\ell$

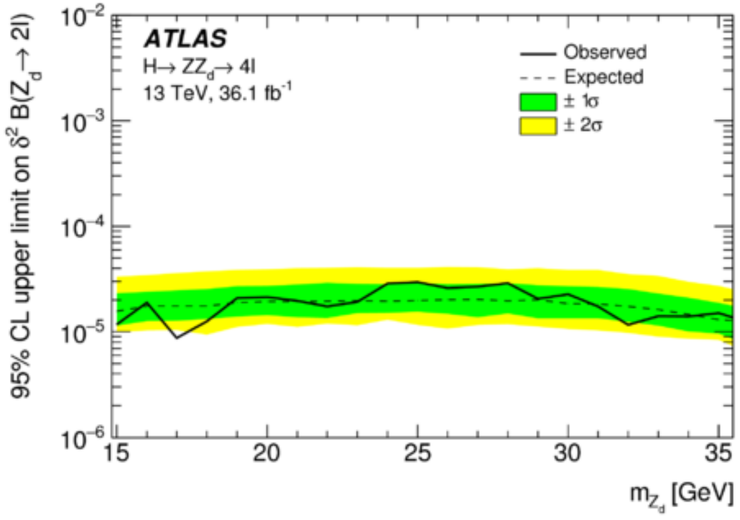
- **Hypercharge portal**: related to kinetic mixing, ε, and mass-mixing, δ, parameters
- **Higgs portal model**: related to Higgs mixing parameter, κ

$H \to ZZ_D \to 4\ell$

$m_{Zd} < m_H - m_Z$



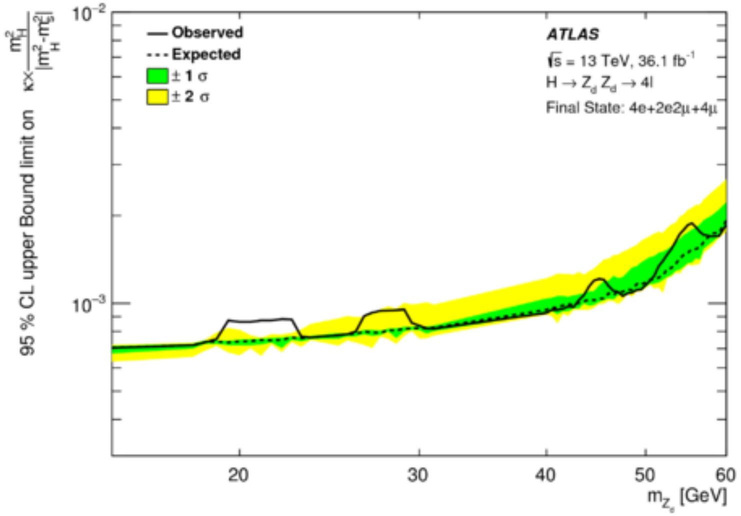
Upper bound on ε ~ (4-8) x 10^{-2}



ATLAS-EXOT-2016-22

$H \to Z_D Z_D \to 4\ell$

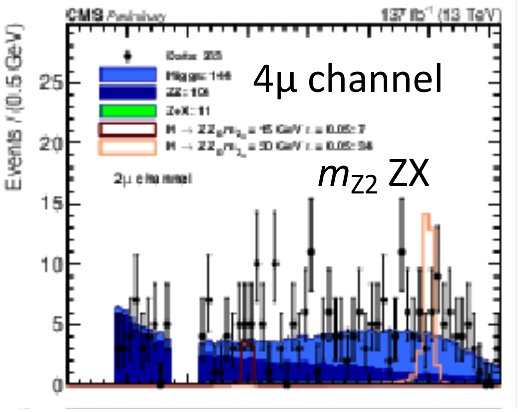
(κ >> ε), $m_S > m_H/2$, $m_{Zd} < m_H/2$

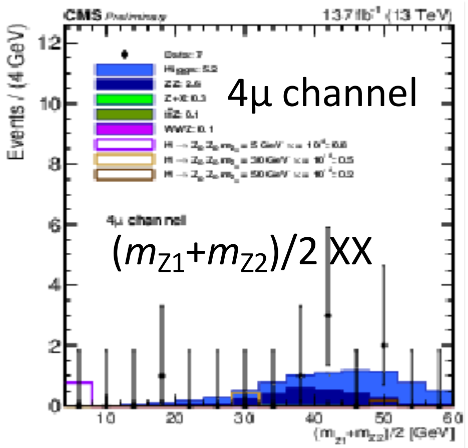


upper bound on κ ~ (1–10)×10^{-4}

Exotic Higgs Decay in $H \to ZZ_D$, $H \to Z_D Z_D$ at CMS

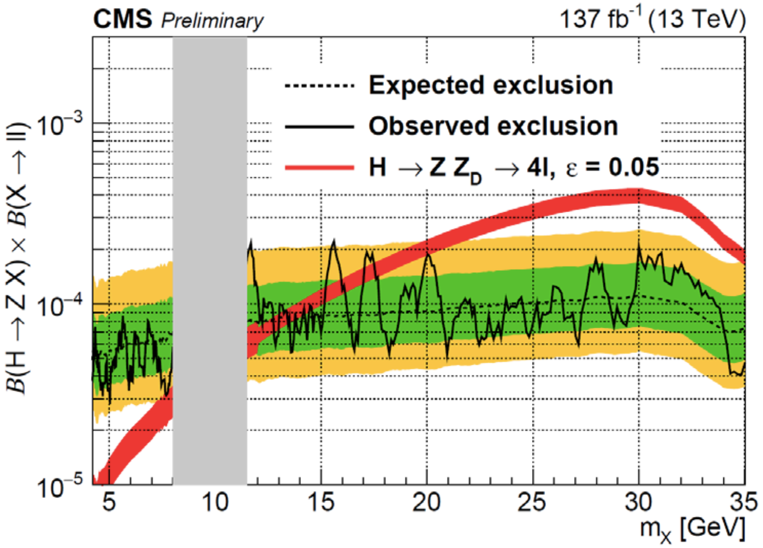
CMS-PAS-HIG-19-007
13 TeV, 137 fb^{-1}



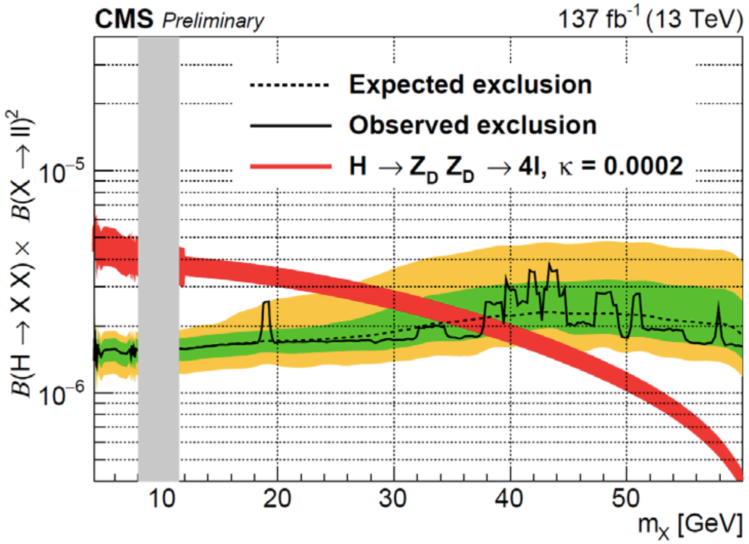


- Search for decays in $4e$, $2e2\mu$, 4μ
- Searches for masses
  - $4 < m_{ZD} < 35(60)$ GeV in ZX (XX)

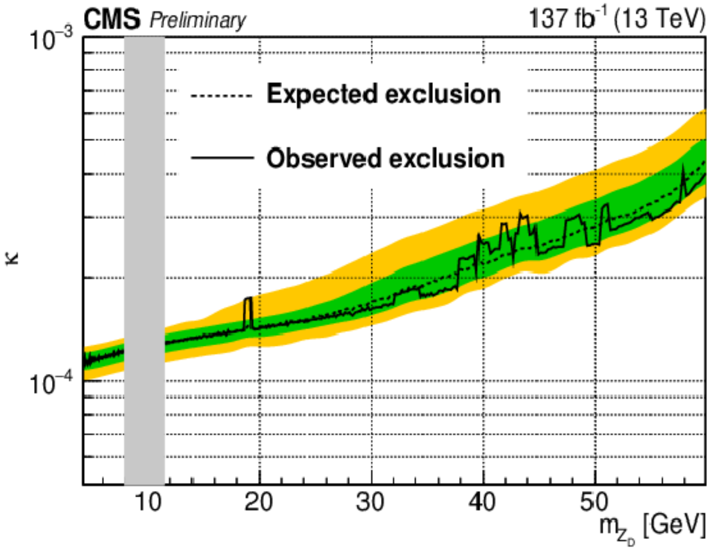
B(H→ZX)×B(X→ee or $\mu\mu$)



B(H→XX)×B(X→ee or $\mu\mu$)^2



Higgs-mixing parameter $\kappa < 3\text{x}10^{-3}$

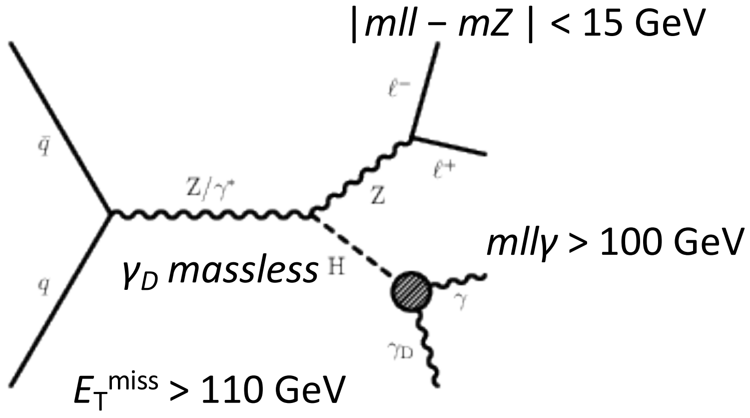


Dark Photon in ZH at CMS: Massless

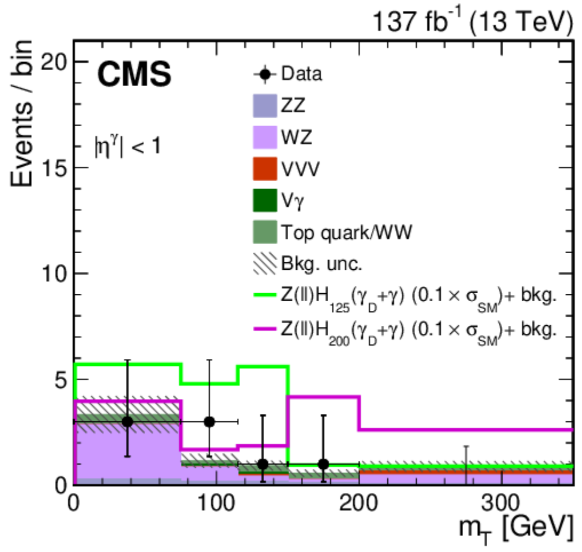
JHEP10(2019)139

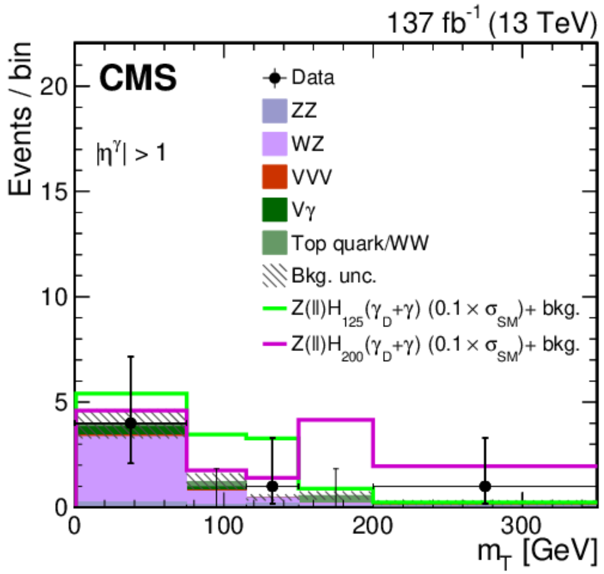
13 TeV, 137 fb^{-1}

$Z(\rightarrow \ell\ell)H(\rightarrow \gamma\gamma_D)$

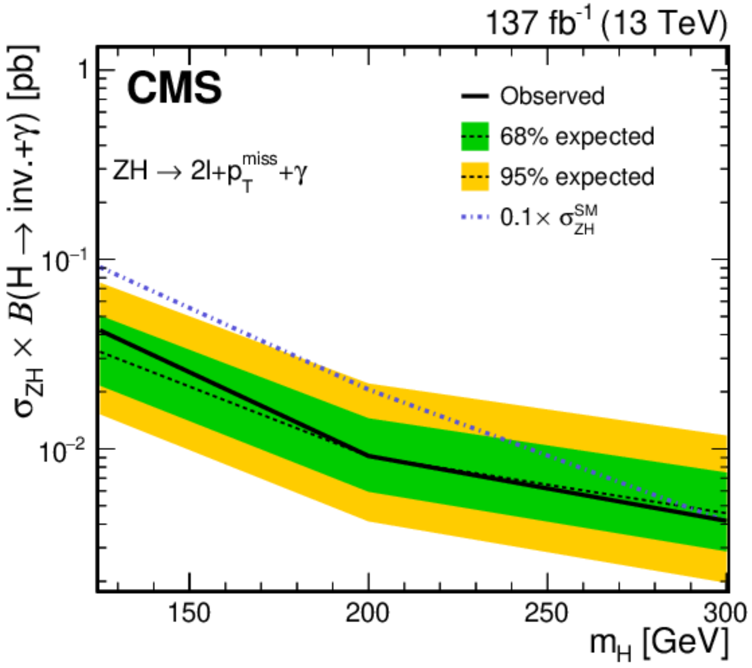


- Signal region
  - SFOS high-p_T isolated lepton pair, one high p_T photon + large p_T^{miss}
- Main backgrounds:
  - non-resonant dilepton, resonant w/γ mis-ID, fake p_T^{mis}
- Signal extraction from transverse mass of $\gamma + p_T^{miss}$





$B(H \rightarrow \text{inv.} + \gamma)$

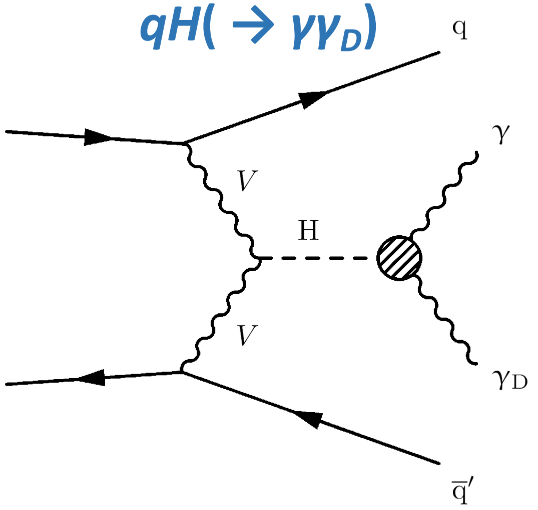


Dark Photon in VBF Higgs at CMS: Massless

CMS-PAS-EXO-20-005

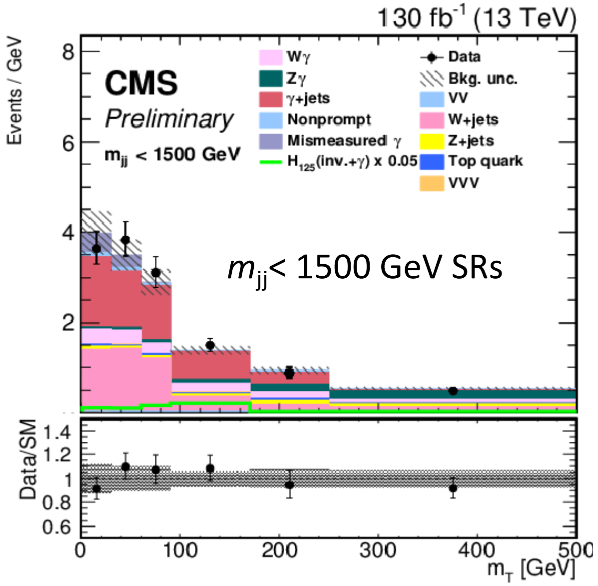
13 TeV, 130 fb^{-1}

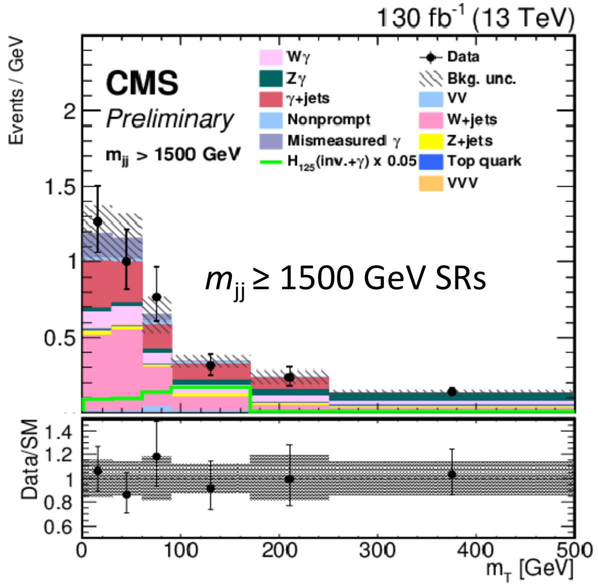
$qH(\rightarrow \gamma\gamma_D)$



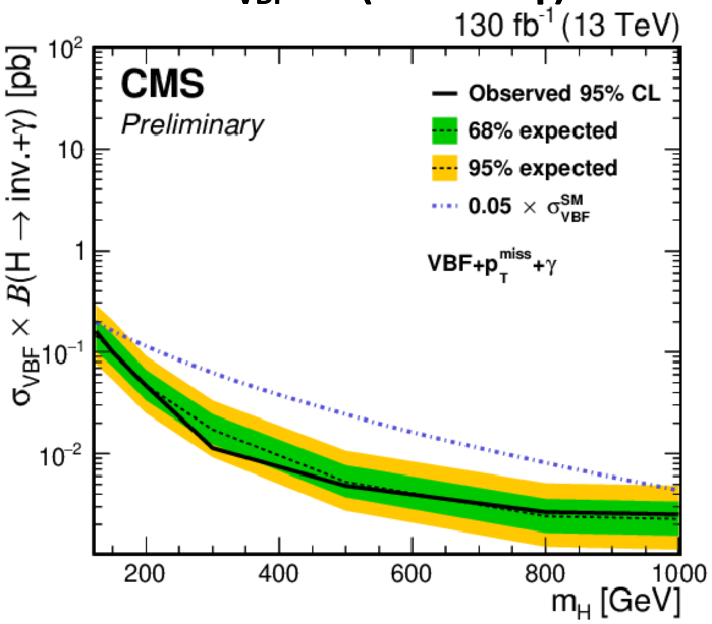
- **Signal region**
  - VBF H + high p_T γ+ large p_T^{miss}
- Backgrounds:
  - W+jets, Z(ll) +γ, W(→lν)+γ, γ+jets

Combining ZH(H→inv+γ) + B(H→inv+γ) at m_H=125 GeV limits are 2.9 (2.1)%





σ_{VBF} x B(H→inv+γ)



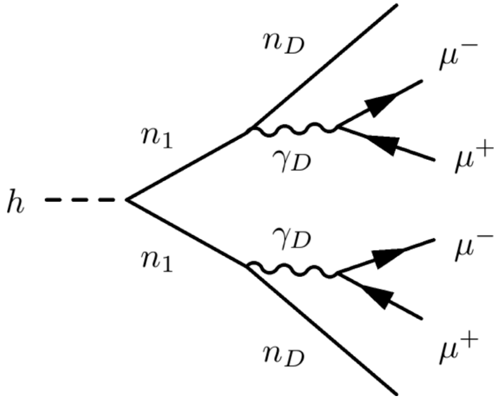
Excluded>150-2 fb, m_H:125-1000 GeV

Dark photon at CMS: Displaced vertex

[Phys. Lett. B 796 (2019) 131](#)

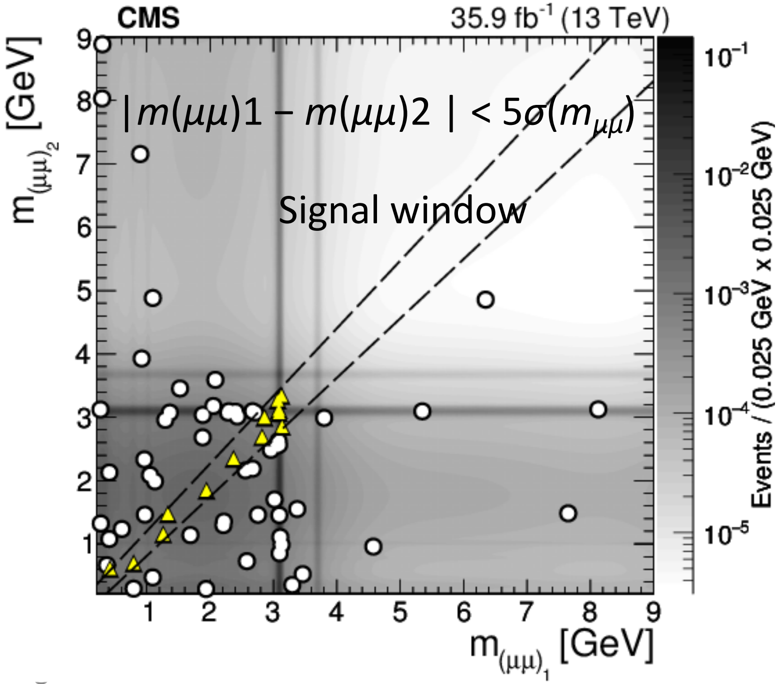
13 TeV, 35.9 fb^{-1}

$H \rightarrow 4\mu + X$

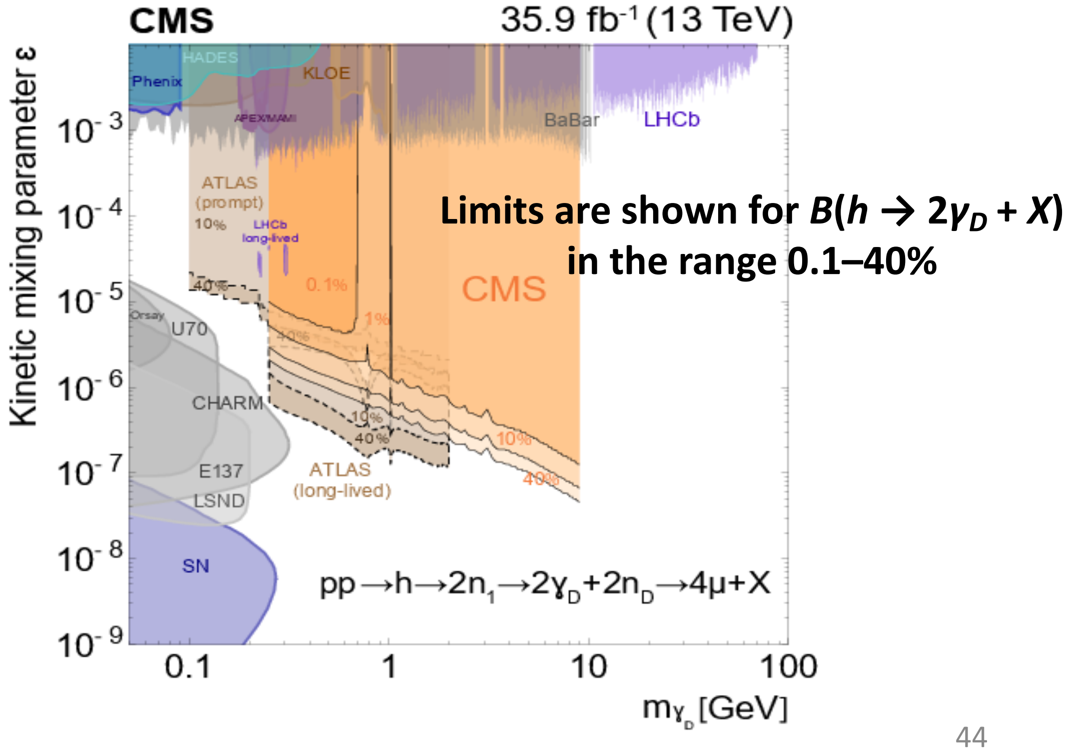


- Dark photon from lightest neutralino decay
  - O(1) GeV, ε~10^{-6} => *displaced muon pair*
- **Isolated dimuon pair** from same PV, dimuon invM< 9 GeV
- Low background from bb, J/ψ

n_1: lightest non-dark neutralino
n_D : dark neutralino undetected



$\sigma(pp \rightarrow h \rightarrow 2n_1 \rightarrow 2\gamma_D + 2n_D) \times B(\gamma_D \rightarrow 2\mu)$

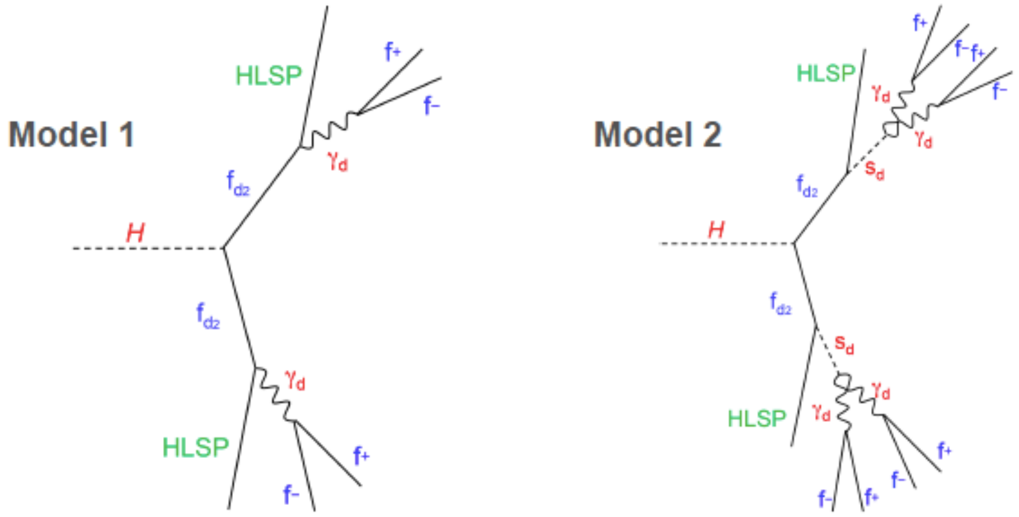


Lepton Jets (LJ)-LLPs at ATLAS

[Eur. Phys. J. C 80 (2020) 450](), [JHEP02(2016)062]()
13 TeV, 36.1 fb^{-1} 8 TeV 20.3 fb-1

- Search for collimated production of leptons: "lepton-jets"
- Benchmark model(s): Higgs portal production and vector portal decay (FRVZ model)

Dark fermions (f_{d2}) produced in H decays => decay to γ_D, (via dark scalar (s_d)) and HLSP



- **Prompt and displaced lepton jet signatures**
  - Depend on lifetime of dark photon

- FRVZ model: 2 or 4 dark photons
  - boosted dark photon
  - long-lived collimated dark photon decay products
    - dark photon jets (DPJ) with displacement

HLSP = hidden lightest stable particle (fermion)

Lepton Jets (LJ)-LLPs at ATLAS

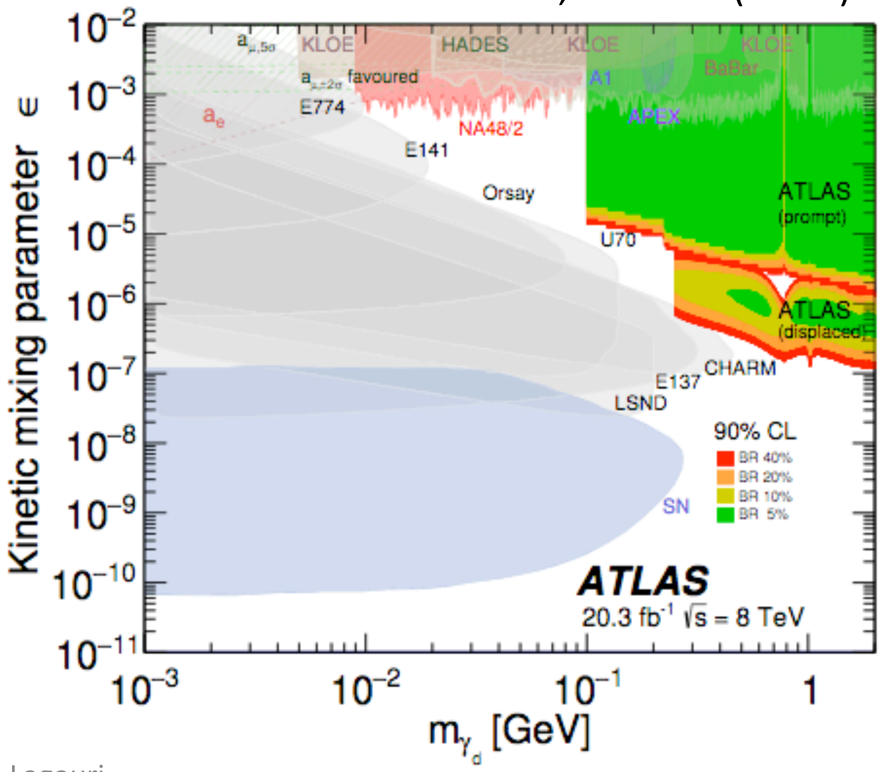
[Eur. Phys. J. C 80 (2020) 450](), [JHEP02(2016)062]()
13 TeV, 36.1 fb^{-1} 8 TeV 20.3 fb-1

Prompt decays

- Exclusion plot $m_{\gamma d}$ – ε kinetic mixing parameter
- H→$2_{\gamma d}$+ X decays

JHEP02(2016)062, JHEP11(2014) 088

ATLAS, 20.3 fb^{-1} (8 TeV)

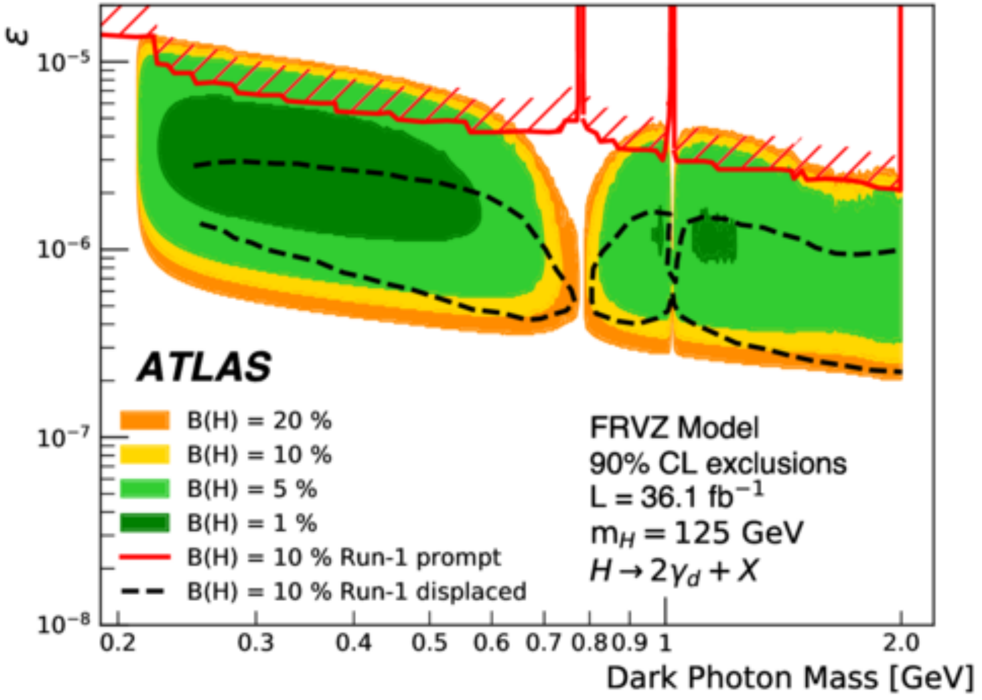


Displaced decays

- Limits on kinetic mixing parameter ε, and $m_{A'}$
- Limits shown for ε in B(H) range 1-20%, H→$2_{\gamma d}$+ X

Eur. Phys. J. C 80 (2020) 450

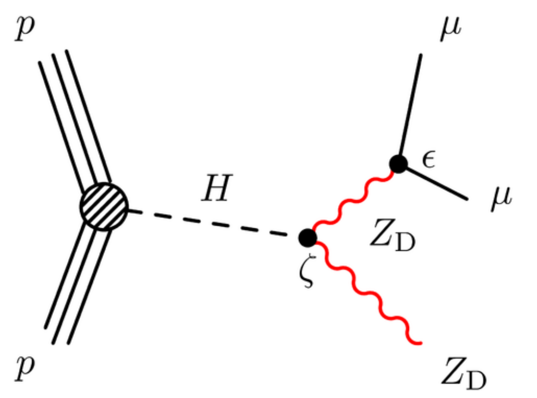
ATLAS, 36.1 fb^{-1} (13 TeV)



Higgs Decay: Displaced Muons at ATLAS

Phys. Rev. D 99 (2019) 012001
13 TeV, 32.9 fb^{-1}

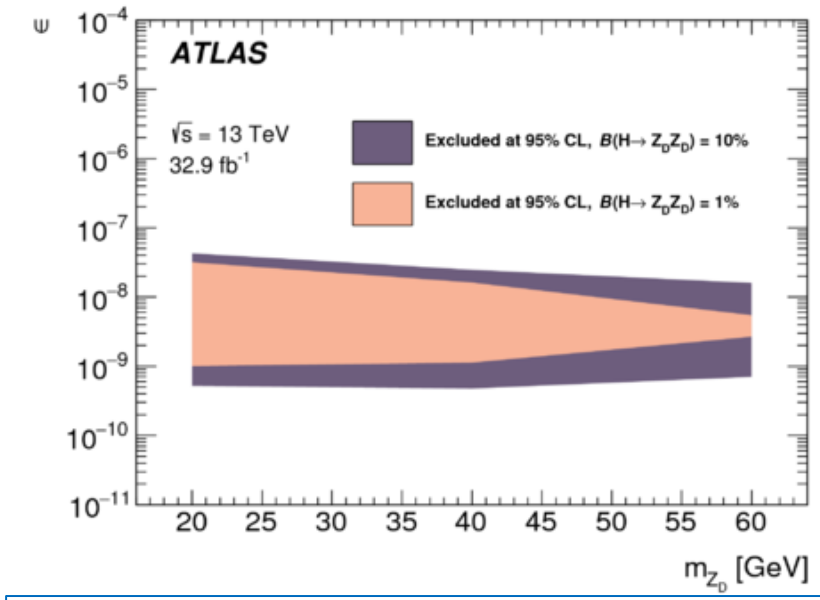
Long-lived dark photons $Z_D \rightarrow \mu^+\mu^-$ produced from Higgs decay



- B($H \rightarrow Z_D Z_D$)=1%, 10%, and m_{HD} = 300 GeV
- B($Z_D \rightarrow \mu^+\mu^-$): 0.1475 - 0.1066 for m_{ZD} = 20–60 GeV

- Low mass search for OS dimuon not originating from IP: 0.5-5 m
- Backgrounds:
  - non-prompt: cosmic/beam/pion/kaon
  - prompt: jet mis-ID or punch through, $m_{\mu\mu}$>15GeV

Excluded regions: Z_D–Z kinetic mixing parameter, ε, vs Z_D mass



ε <10^{-8} excluded for 20 GeV <m_{ZD} < 60 GeV

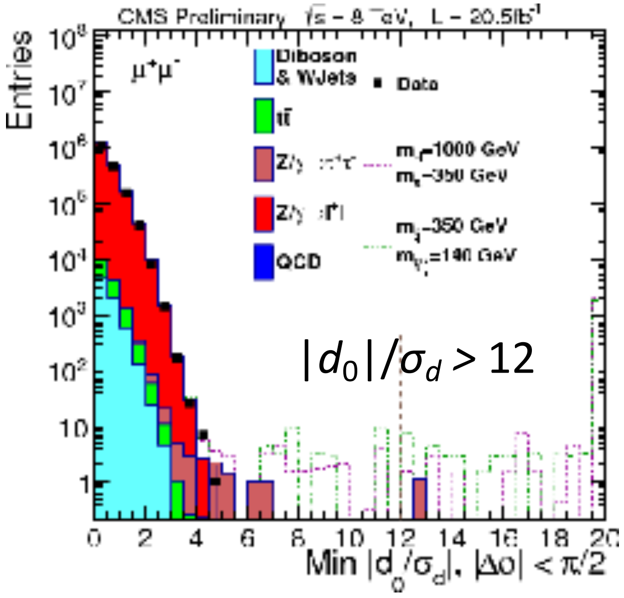
Higgs Decay: Displaced Leptons at CMS

PhysRevD.91.052012
8 TeV, 19.6 fb^{-1}

- Massive, long-lived exotic particles decay to a pair of charged leptons ($e^+e^-/\mu^+\mu^-$), originating from a common secondary vertex
- **Model: $H^0 \rightarrow XX$, $X \rightarrow l^+l^-$**, X: long-lived particle spinless boson, with BR to dileptons and H^0 (non-SM) Higgs

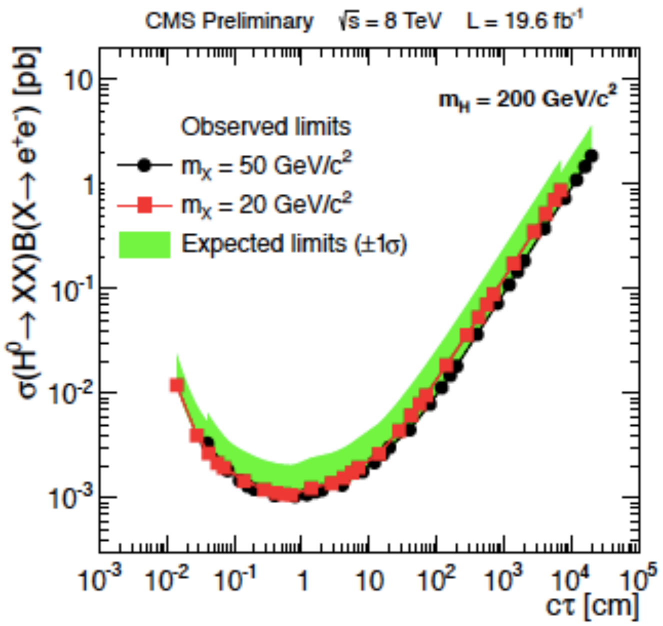
Upper limits on $\sigma(H^0 \rightarrow XX)B(X \rightarrow l^+l^-)$ for a H^0 mass of 200 GeV

$|d_0|/\sigma_d$ ($|\Delta\Phi| < \pi/2$) for dimuons

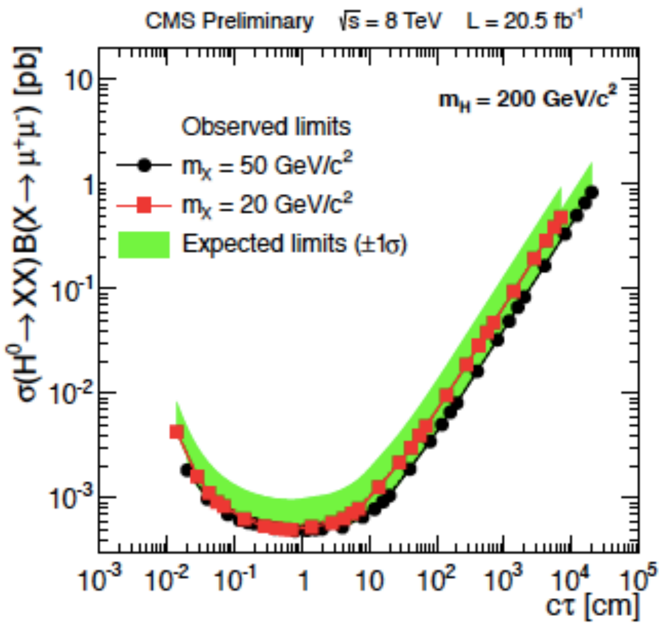


$|d_0|/\sigma_d > 12$

electron channel



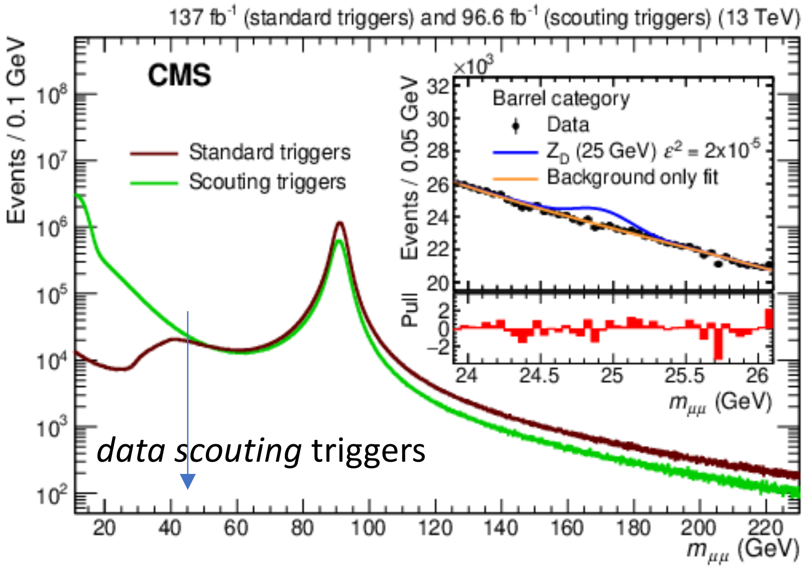
muon channel



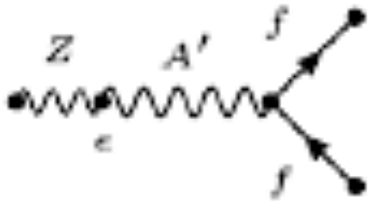
Dimuon Resonance at CMS

[Phys. Rev. Lett. 124 , 13 (2020) 131802]()

13 TeV, 137 fb^{-1}

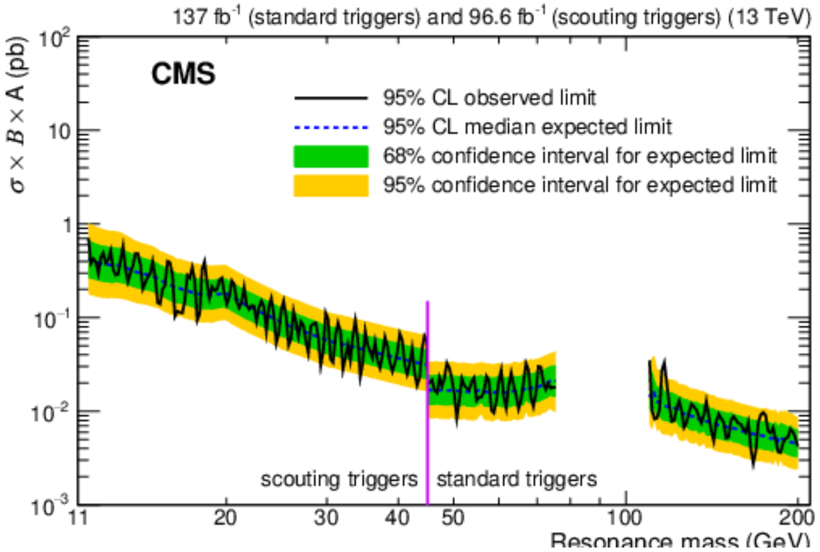


- Bump-hunt in $m_{\mu\mu}$
  - p_T >20 (10) GeV, |η|<1.9
- Probing large kinematic mixing ε~ 10^{-3}
- Main background: DY

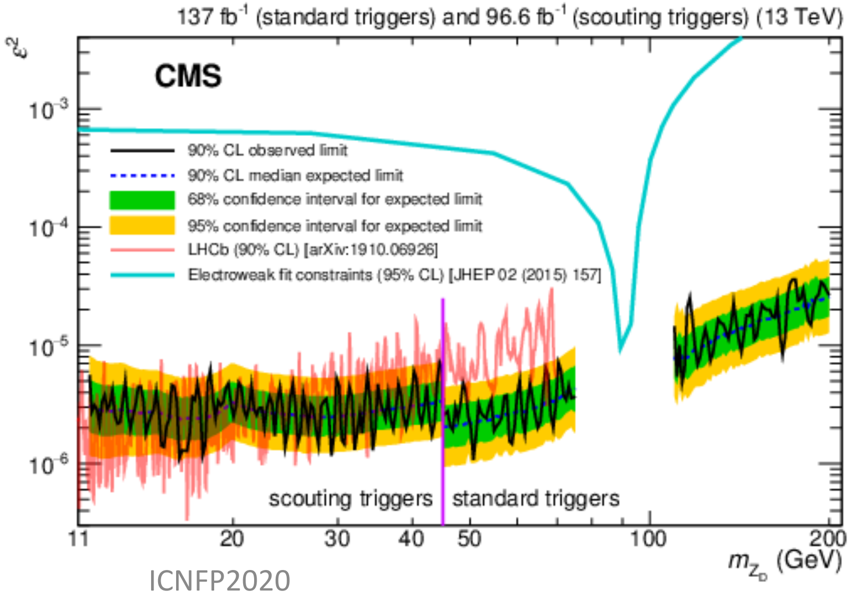


- Scouting (HLT-level) stream: data (96.6 fb^{-1})
  - events with lower thresholds (>4 GeV for invM< 7-18 GeV)
- Improved acceptance for **$m_{\mu\mu}$ < 45 GeV** (11.5-45 GeV)

Model-independent limits



Dark photon model limits



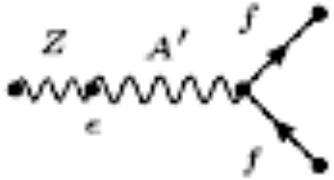
11.5 < $m_{A'}$< 200 GeV
45-75 & 110-200 GeV

(Omitting Z: 75-110 GeV)

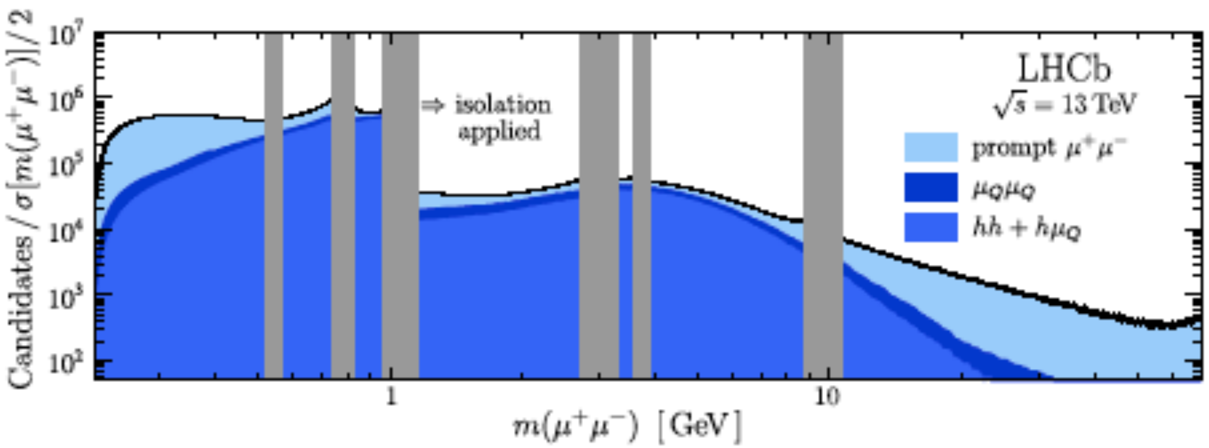
Phys. Rev. Lett. 124 (2020) 041801

Dimuon Resonance at LHCb: prompt muons

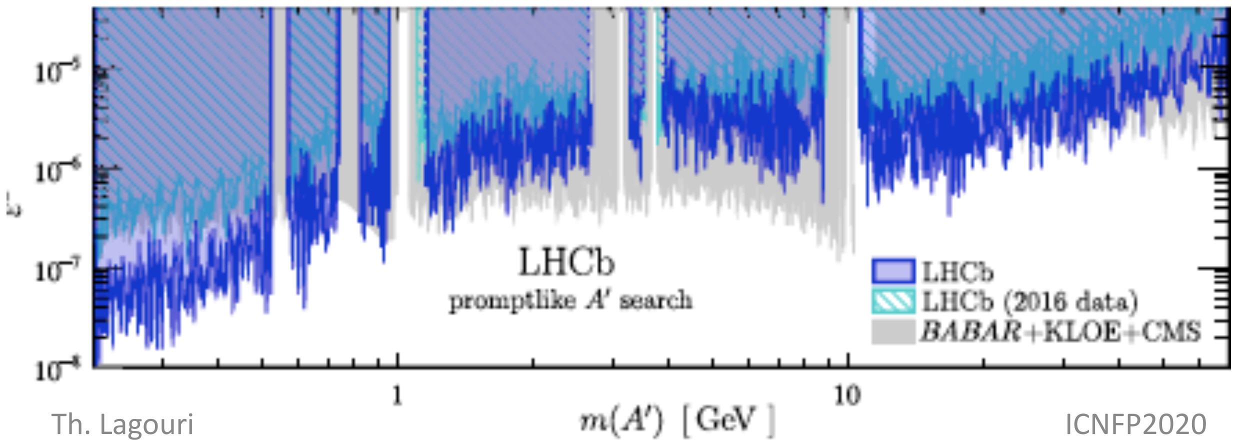
13 TeV, 5.5 fb^{-1}



$A' \to \mu\mu$ 214 MeV < $m_{A'}$ < 740 MeV and 10.6 GeV < $m_{A'}$ < 30 GeV



LHCb results compared with other experiments



Inclusive di-muon search

Prompt-muons strategy

- Look for low p_T >1 GeV, forward muons
- Consistent with light, DY production
- Require $\mu^+\mu^-$ pairs consistent with PV

Selection

- No isolation applied for < 1 GeV
  - meson decay dominates
- Background
  - prompt $\gamma^* \to \mu^+\mu^-$ (irreducible)
  - resonant (look around)
- Mis-ID of prompt hadrons (h) as μ ($h_{\mu Q}$) or
- μ from HF decay (μ_Q)

Tightest limits on ε
10.6 GeV < mass dark photon < 70 GeV

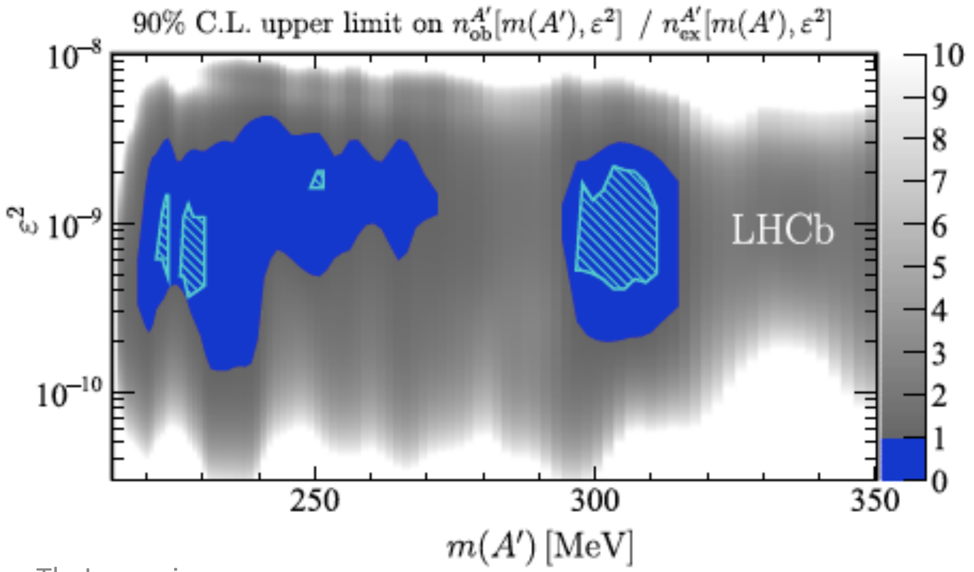
Phys. Rev. Lett. 124 (2020) 041801

Dimuon Resonance at LHCb: displaced muons

13 TeV, 5.5 fb^{-1}

Long-lived A′ search 214 MeV < $m_{A'}$ < 350 MeV

- **Signature:** di-muon OS pair in mass range 214 - 350 MeV
  - Muons inconsistent with coming from PV
  - Required to be consistent with coming from single, prompt, resonance
- **Search strategy**
  - Reject muons from B-hadron decays (BDT)
  - Reject photon conversions to muons in material



Long-lived A′ → $\mu^+\mu^-$ search

- large regions of [mA′, ε^2] parameter space
- world-leading constraints on **low-mass dark photons** with lifetimes **O(1) ps**

Summary

- Dark photons are well-motivated and can be the mediator between SM and dark sector
- Rich landscape of dark photon searches at LHC production from Higgs decay and other dark sector models
  - Prompt decay, displaced decay, missing momentum (invisible/very long-lived)
- Different search strategies based on mass, mixing, production and decay modes
  - Limited reach to lower mass due to trigger and other constraints

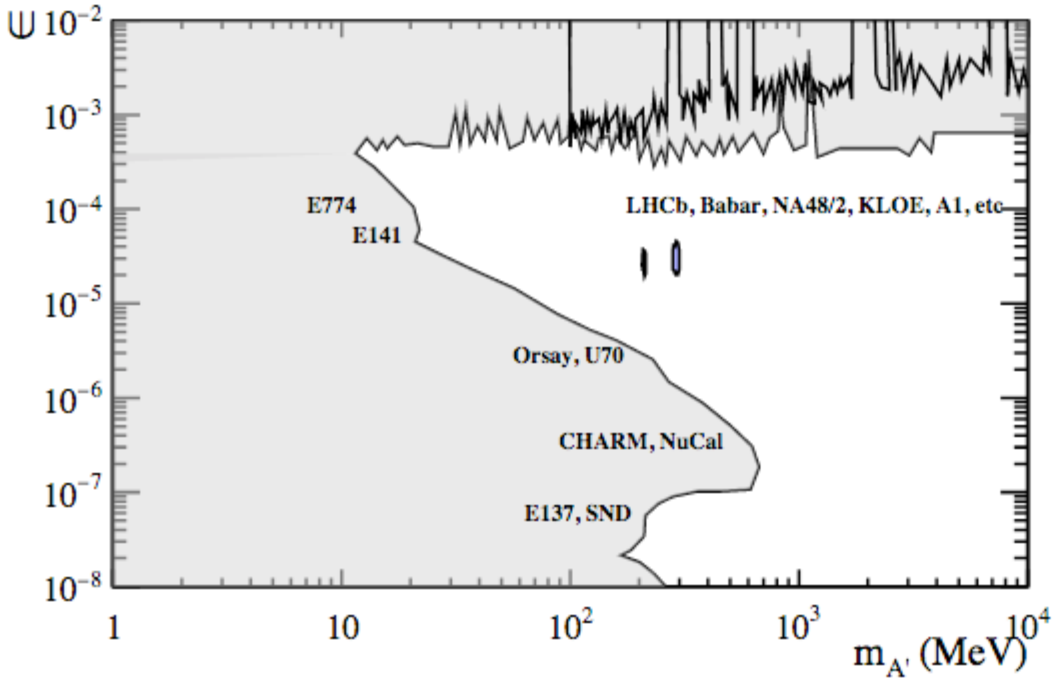
Conclusions and Future Prospects

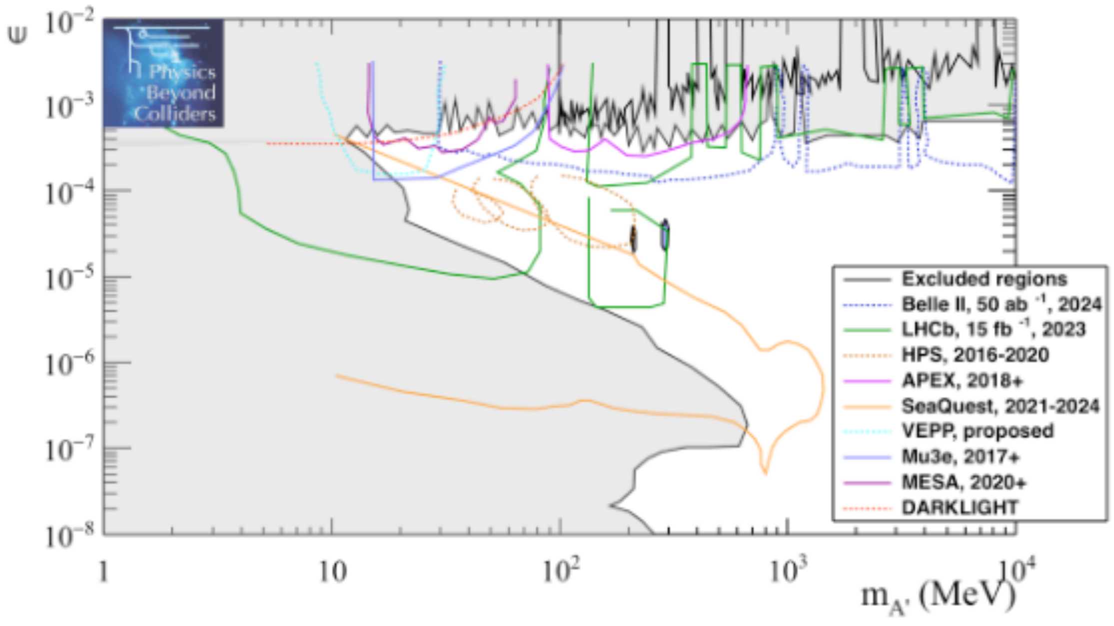
- Exploring Hidden/Dark Sectors is important and growing element of physics BSM
- Requires searching for several complementary signatures
- A wealth of exciting ongoing experiments exist
  - High Energy Colliders, High Intensity Colliders and Fixed Target Experiments
- Complementary searches from different experiments exist
  - ATLAS, CMS, LHCb at LHC: larger mass range, smaller couplings
  - B-factories, fixed target, heavy ions, also future LLP experiments
- Exciting prospects for future dark photon searches at HL-LHC
  - Major upgrades of ATLAS and CMS detectors with the ultimate aim to reach an integrated luminosity of ~3000 fb^{-1} by around 2035
  - Improved detectors and triggers: better vertexing/lower p_T threshold
- Future experiments at CERN and outside target complementary phase spaces for NP

Additional Slides

Dark (visible) photons (1 MeV-10 GeV)

arXiv:1901.09966

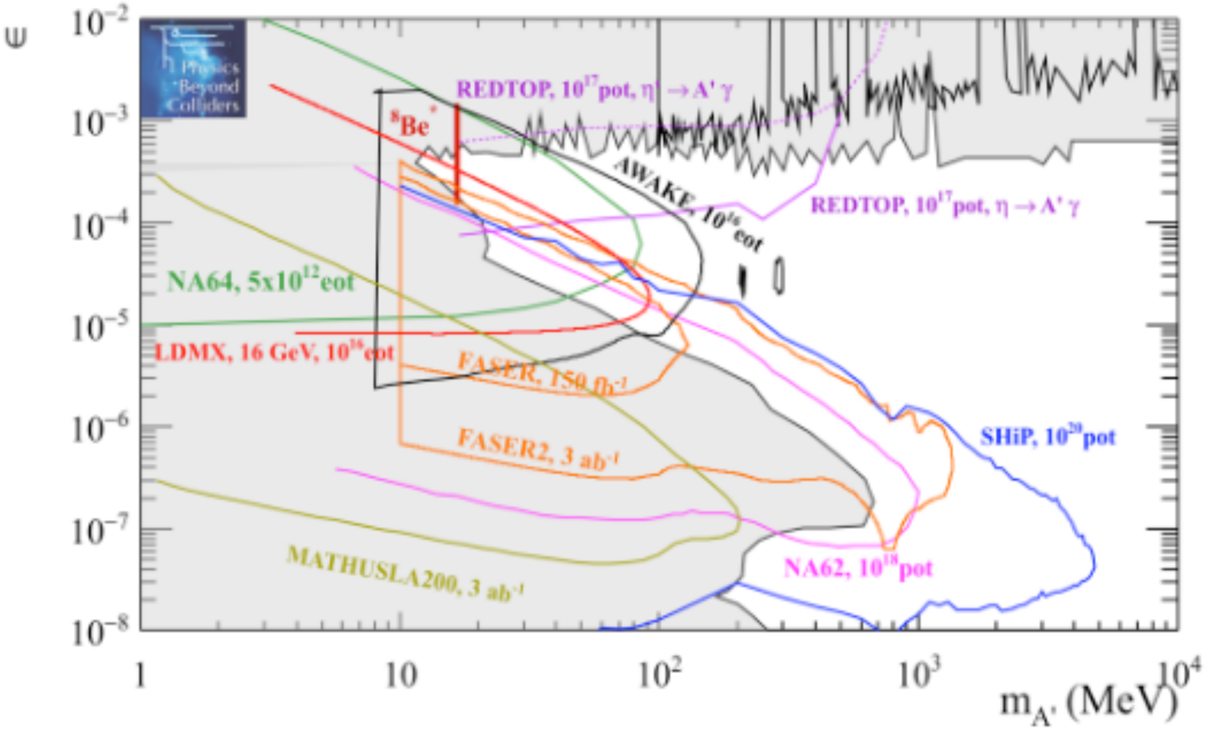




- Current limits for Dark Photon in visible decays in the plane mixing strength ε versus mass of the Dark Photon $m_{A'}$
- Future upper limits at 90 % CL for dark photons in visible decays in the plane mixing strength ε versus mass $m_{A'}$

Dark photons (1 MeV-10 GeV): Future Experiments Prospects

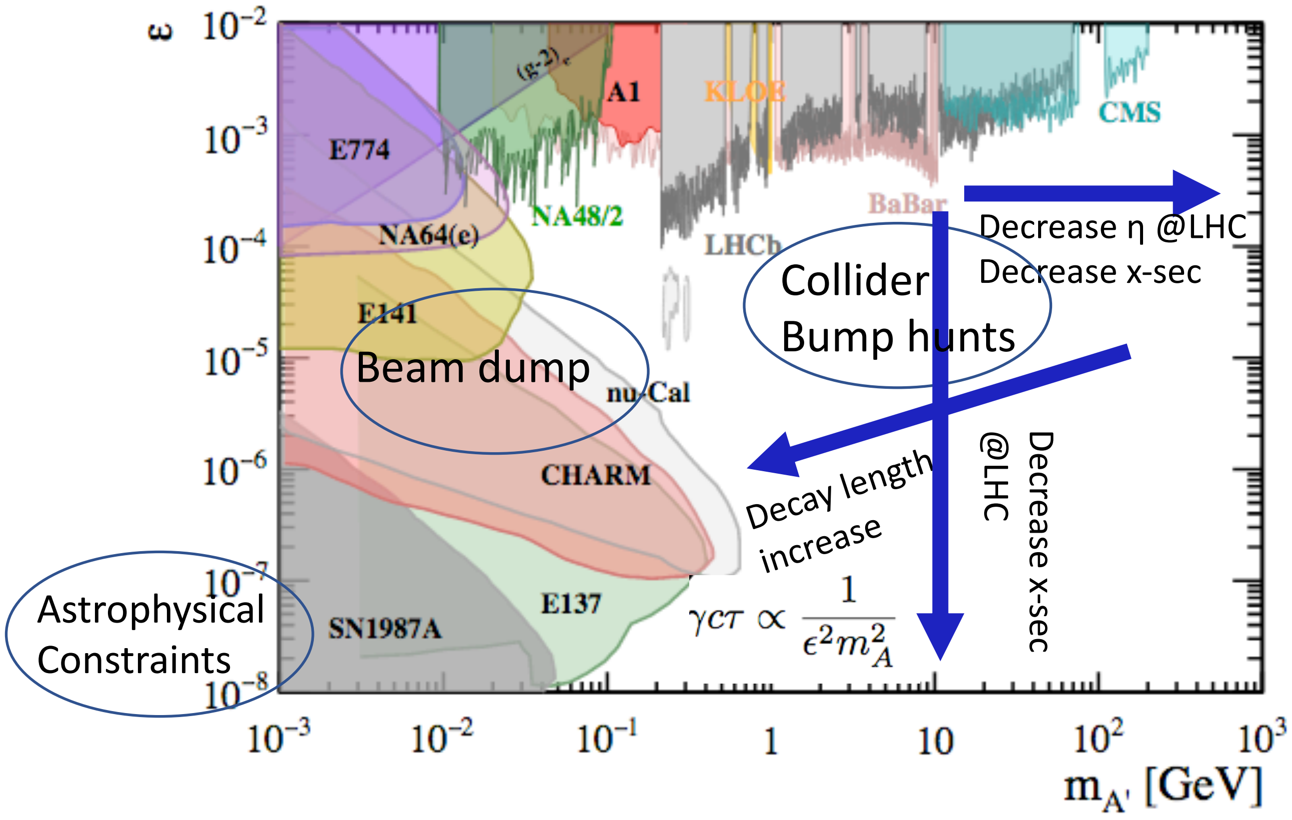
arXiv:1901.09966



- Future upper limits at 90 % CL for Dark Photon in visible decays in the plane mixing strength ε versus mass $m_{A'}$ for PBC projects on a ~10-15 years timescale.
- The vertical red line shows the allowed range of e−X couplings of a new gauge boson X coupled to electrons that could explain the ^{8}Be anomaly

Dark Photon Parameter Plane (1 MeV-1 TeV)

Current status of 90% CL exclusion limits (via visible decay)

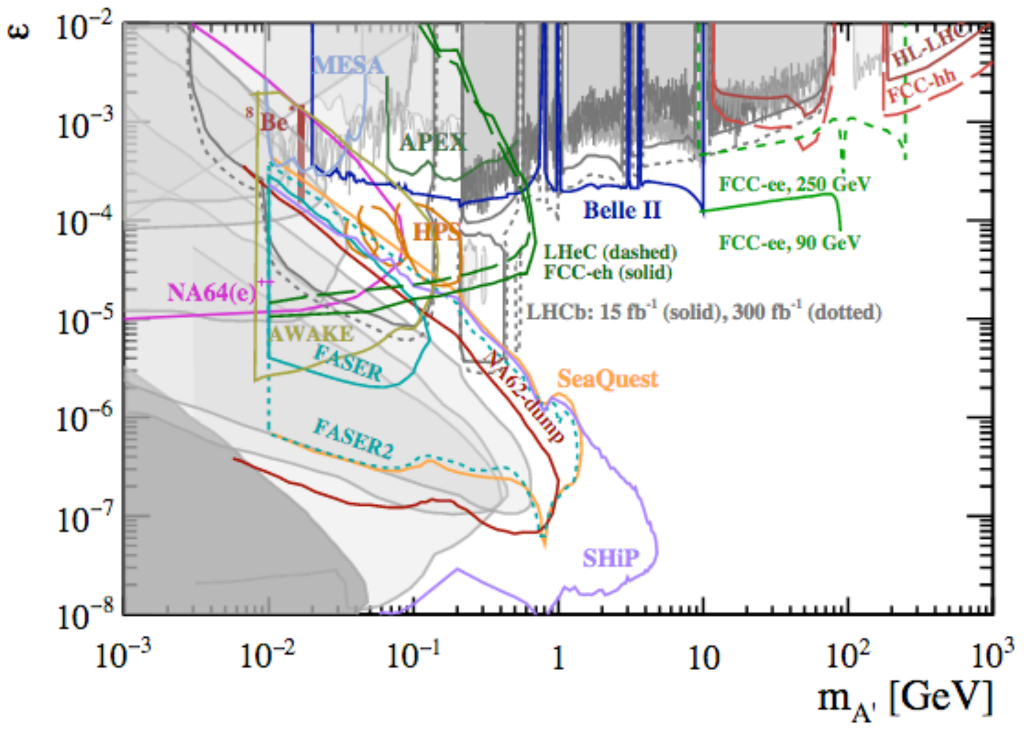


arxiv:2005.01515

- Existing limits on massive dark photon for $m_{A'}$>1 MeV from di-lepton searches at experiments
  - At collider/fixed target (A1 (Merkelet al., 2014), LHCb (Aaijet al., 2020), CMS (Sirunyan et al., 2019a), BaBar (Lees et al.,2014), KLOE (Anastasi et al., 2016; Archilli et al., 2012; Babusciet al., 2013, 2014), and NA48/2 (Batleyet al., 2015))
  - Old beam dump: E774 (Bross et al., 1991), E141 (Riordanet al., 1987), E137 (Batell et al., 2014; Bjorken et al., 1988; Marsicano et al., 2018)), ν-Cal (Blumlein and Brunner, 2011, 2014), and CHARM (from (Gninenko, 2012).
  - Bounds from supernovae (Dent et al., 2012; Dreiner et al., 2014) and (g−2)e (Pospelov, 2009) are also included

Dark Photon Parameter Plane Prospects (1 MeV-1 TeV)

90% CL projected exclusion limits (via visible decay)

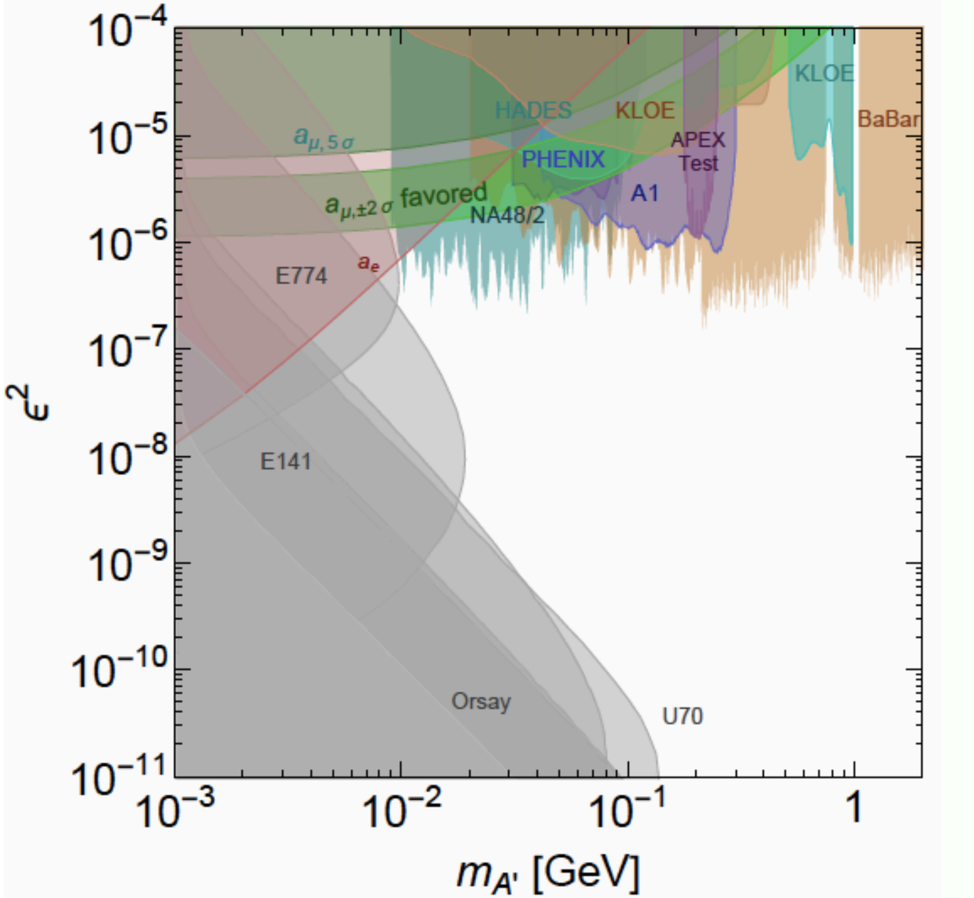


arxiv:2005.01515

- Colored curves are projections for existing and proposed experiments:
  - Belle-II (Altmannshofer et al., 2019) at SuperKEKb; LHCb upgrade (Ilten et al., 2016, 2015) at LHC; NA62 in dump mode (Cortina Gilet al., 2019a) and NA64(e)++ (Banerjee et al., 2018a) at the SPS; FASER and FASER2 (Feng et al., 2018) at LHC; SeaQuest (Berlin et al., 2018) at Fermilab; HPS (Adrian et al., 2018) at JLAB; an NA64-like experiment at AWAKE (Caldwell et al., 2018), and an experiment dedicated to dark photon searches at MESA (Doria et al., 2018, 2019).
  - For masses above 10 GeV projections obtained for ATLAS/CMS during the high luminosity phase of the LHC (HL-LHC (Curtin et al., 2015)) and for experiments running at a future FCC-ee (Karliner et al., 2015), LHeC/FCC-eh (D'Onofrio et al., 2020), and FCC-hh (Curtin et al., 2015) are also shown.
  - The vertical red line shows the allowed range of couplings of a new gauge boson X to electrons that could explain the ^{8}Be anomaly (Feng et al., 2016, 2017). The existing limits are shown as gray areas.

Dark photons (1 MeV-1 GeV): Existing Constraints

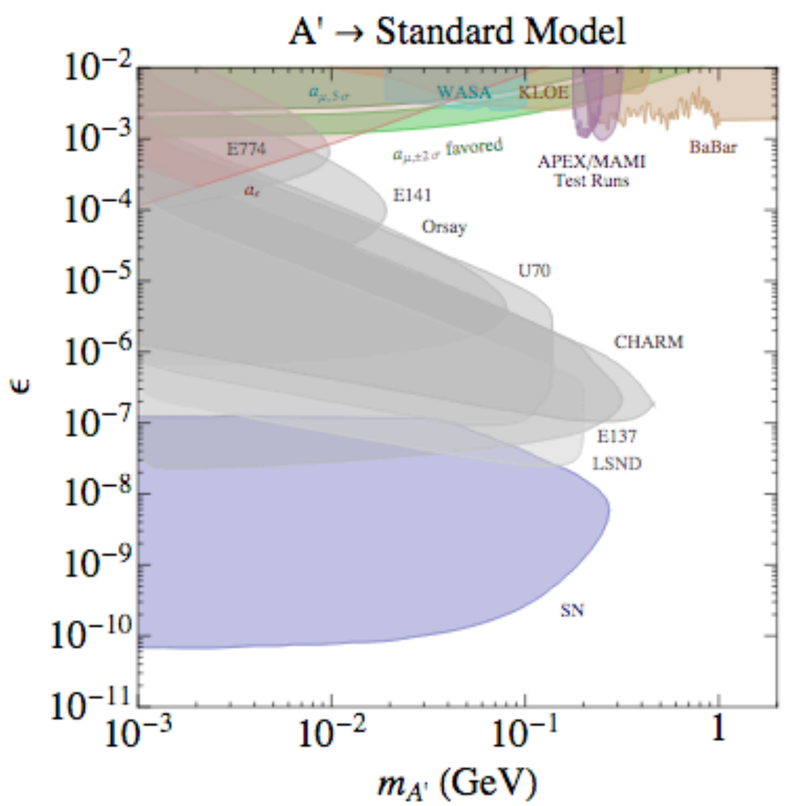
arXiv:1608.08632

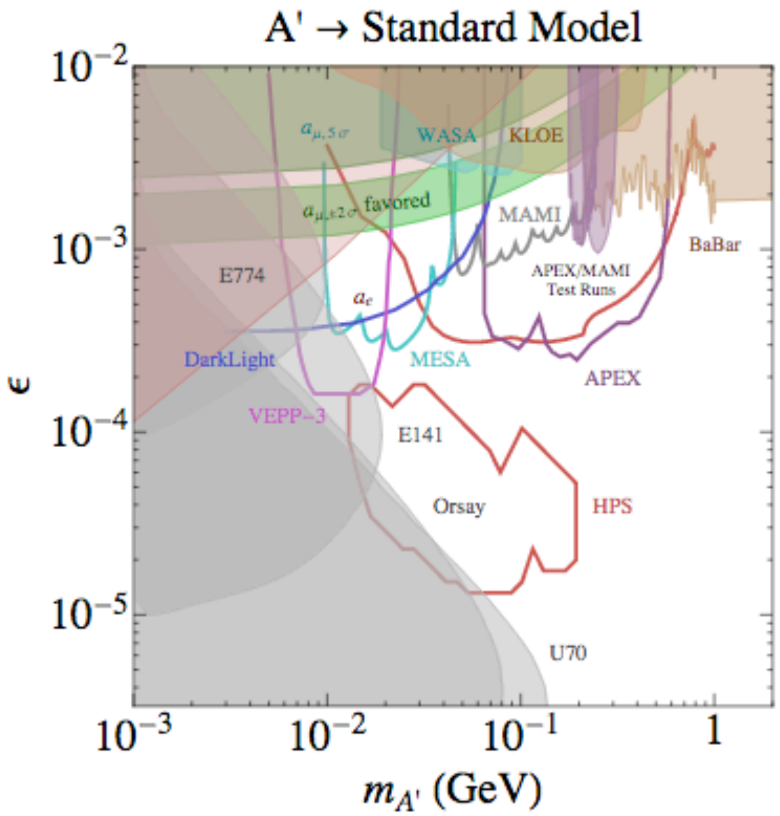


- Red/green: e, μ anomalous dipole moments
- All other colors: Pair resonance searches
- Gray: Beam Dump

Dark photons (1 MeV-1 GeV): Existing Constraints

Parameter space for dark photons (A′) with mass $m_{A'}$ >1 MeV





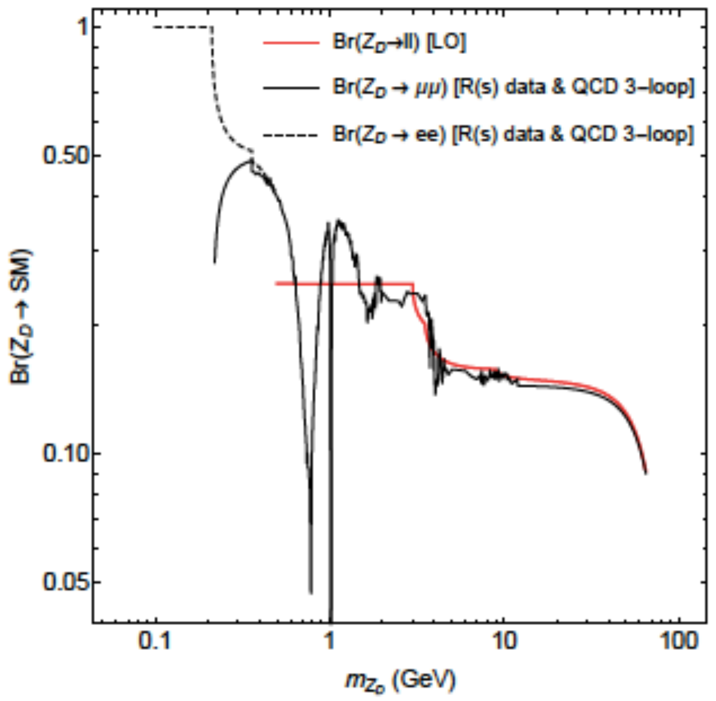
arXiv:1311.0029

- 90% CL from SLAC and Fermilab beam dump experiments E137, E141, and E774, the electron and muon anomalous magnetic momenta α_{μ}, KLOE, WASA-at-COSY, test run results reported by APEX and MAMI, estimate using a BABAR result, and constraint from supernova cooling.
- In the green band, the A′ can explain the observed discrepancy between calculated and measured muon anomalous magnetic moment at 90% CL.
- On the right, in more detail the parameter space for larger values of ε, probed by several proposed experiments, including APEX, HPS, DarkLight, VEPP-3, MAMI, and MESA. Existing and future e^+e^- colliders such as BABAR, BELLE, KLOE, SuperB, BELLE-2, and KLOE-2 can also probe large parts of the parameter space for $\varepsilon > 10^{-4}$–10^{-3}

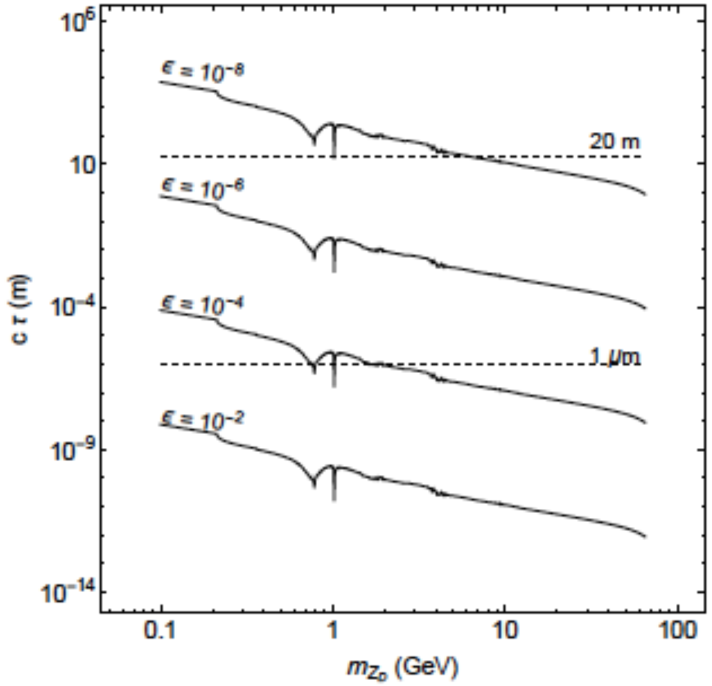
Dark-Z Br and decay length (ε)

Phys. Rev. D 90, 075004 (2014)
arXiv:1312.4992

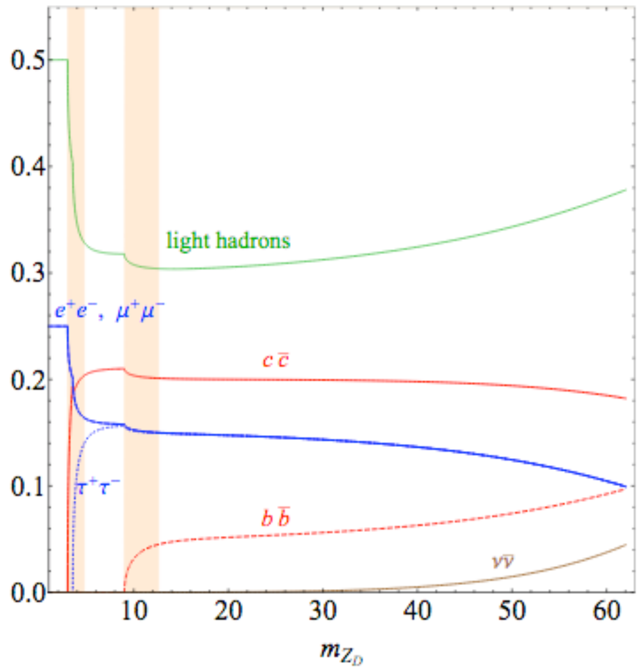
Leptonic branching fraction of Z_D



Decay length of Z_D for different ε



Br for Z_d decays

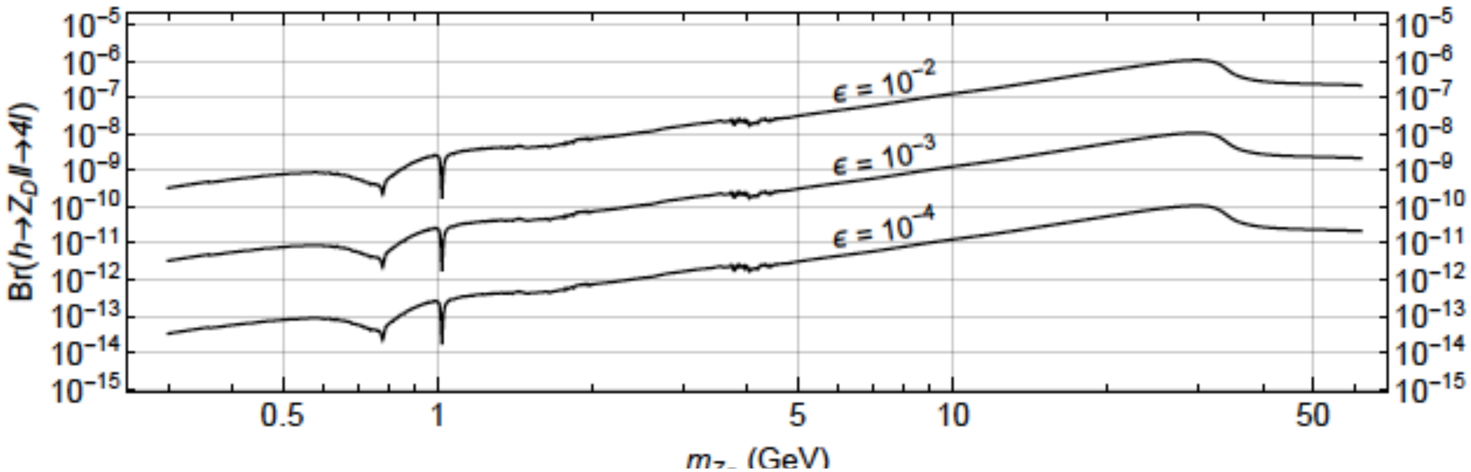


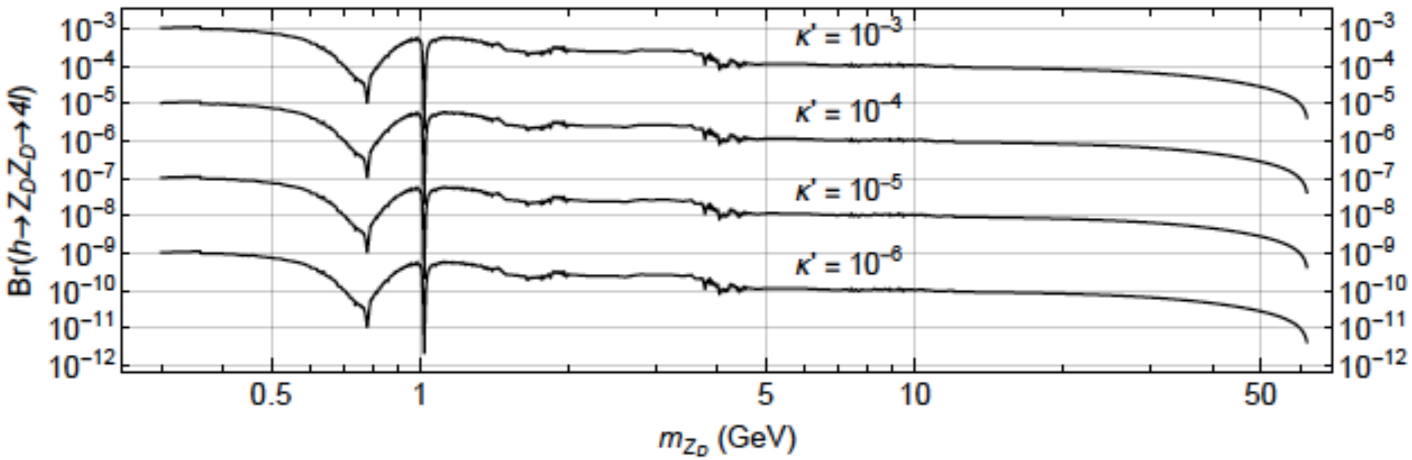
- LHC searches on dark photons
  - sizable branching ratio to lepton pairs (ee, μμ)
  - prompt or displaced decays

D. Curtin et al. JHEP02(2015)157

- The dashed lines indicate boundaries between qualitatively different experimental regimes:
  - prompt decay for cτ < 1μm and
  - likely escape from an ATLAS-size detector for cτ > 20m.

BR for ε-κ

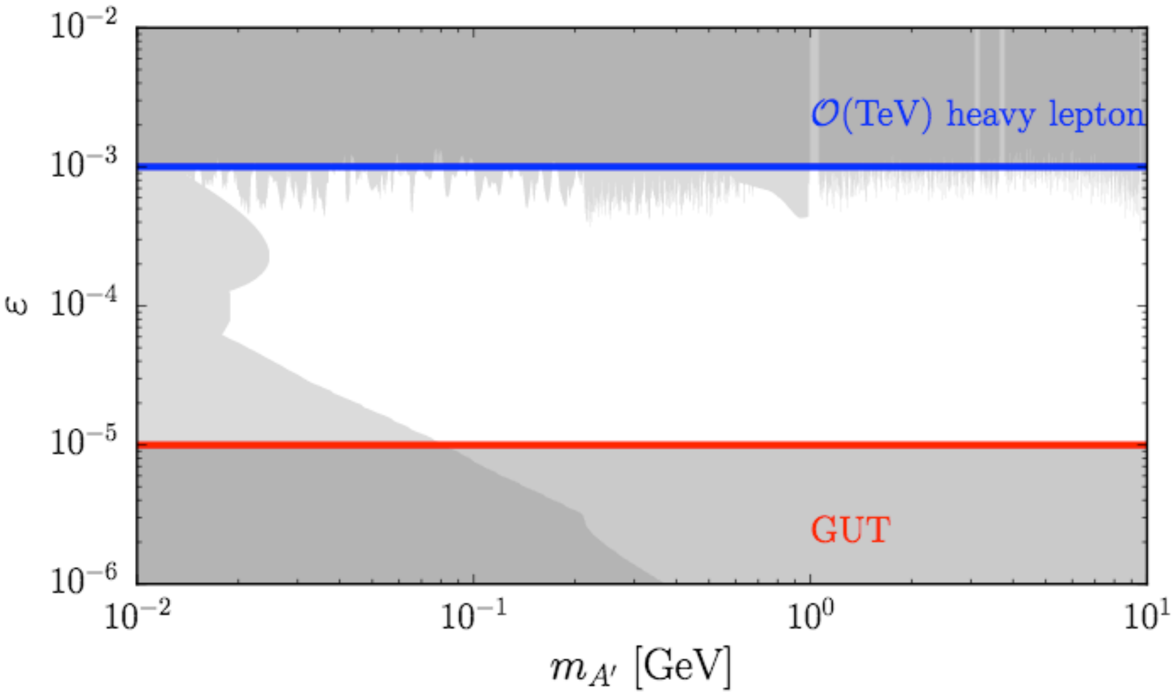


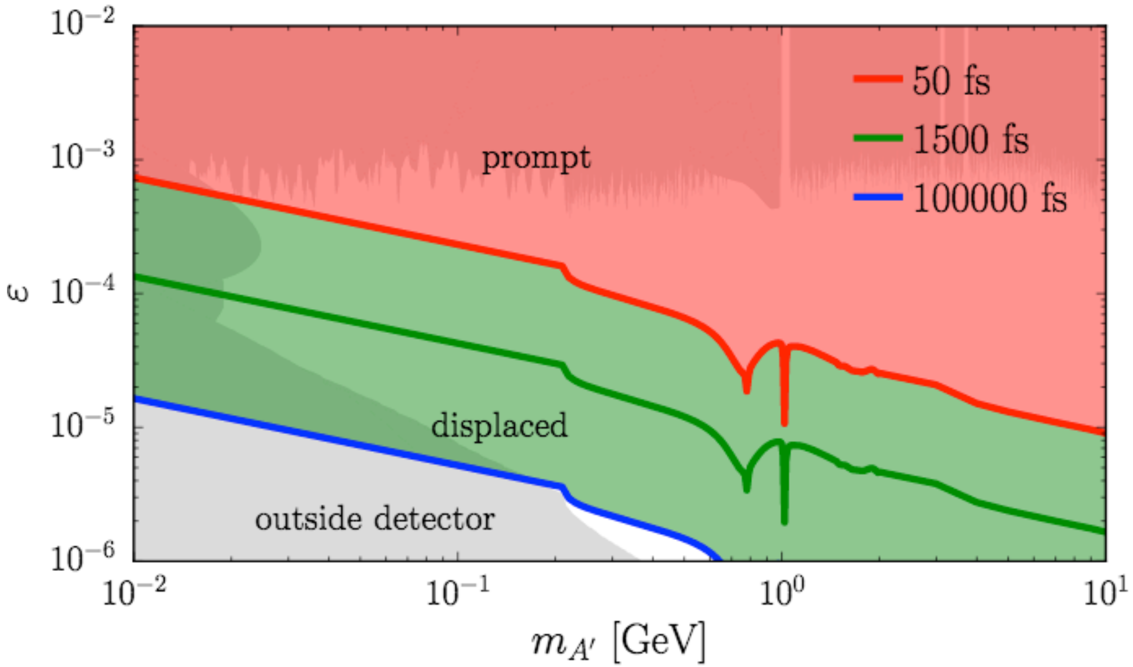


Br($h \to ZZ_D \to 4l$) (top) and Br($h \to Z_D Z_D \to 4l$) (bottom) for different values of ε and κ

D. Curtin et al. [JHEP02(2015)157]

Parameters & Lifetime





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