Higgs Hidden/Dark Sector Physics

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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:
  • Neutrino masses and oscillations: what makes neutrinos disappear and then re-appear in a different form? Why do neutrinos have mass?
  • Baryon asymmetry of the Universe (BAU): what mechanism created the tiny matter-antimatter imbalance in the early Universe?
  • Dark Matter (DM): what is the most prevalent kind of matter in our Universe?
  • Dark Energy (DE): 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
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 – $E_T^{\text{miss}}$

• The main signature of the presence of a DM particle in pp collisions at LHC is the so-called *missing transverse momentum* ($E_T^{\text{miss}}$)

• 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 $E_T^{\text{miss}}$ from a pair of DM particles plus a spray, or “jet”, of particles

Diagram showing how $E_T^{\text{miss}}$ 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 $E_T^{\text{miss}}$ 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 $E_T^{\text{miss}}$ 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 $E_T^{\text{miss}}$

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, $A'$ => $Z_D$, $\gamma_D$, $A'$ (Dark Z, Dark photon)
  • scalar, $\phi$ => $(h_D, s_D)$ (Dark Higgs)
  • fermion, $N$ => (sterile neutrino)
  • pseudo scalar, $\alpha$ => $(\alpha_D)$

• 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:

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

=> kinetic mixing with $\gamma, Z^0$

=> 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
Dark Photon: $A'$

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

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Search strategies

- **Prompt, resolved decay**
  - Mass: $Z_0 Z_0 Z_0^*$
  - Resolved decays: Displaced muons
- **Prompt, collimated decay**
  - “Lepton jets” (LJ)

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Branching Ratio $\gamma_d$

- ATLAS/CMS detector stable lifetimes: MET signature
- Medium lifetime, collimated decays: Displaced LJ

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$\gamma$ Branching Ratio

- $e^+e^-$
- $\mu^+\mu^-$
- $\tau^+\tau^-$
- Hadronic

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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

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

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

- 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**:
  - $q \bar{q} \rightarrow A' \rightarrow (l^+ l^- \text{ or } h^+ h^-)$
  - hadron colliders and proton fixed-target experiments
“Visible” dark photons (1 MeV-10 GeV)

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

arXiv:1608.08632

“Kinetic mixing parameter” $\varepsilon^2$ 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

more collimated decay products (lepton jets)
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 $A' \rightarrow l^+l^-$

- **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.

Experimental sensitivity up to 2021

Prospects beyond 2021

arXiv:1608.08632
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 $\varepsilon$
  - *Higgs portal*: via *Higgs mixing*, denoted as $\kappa$
Exotic Higgs Decay and Dark-Z

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

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

arXiv:1312.4992
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 m_{ZD} \sim \text{MeV}-10 \text{ GeV}

- **Black dashed line:** separates prompt (c\tau<1\mu m) from non-prompt Z_D decays
- **Three blue lines:** contours of Br(h \rightarrow 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 \rightarrow ZZ^* analysis
  - similar bound from ATLAS analysis
  - bound being optimized with new LHC measurements
- **Green region** labelled “EWPM”: Electroweak Precision Measurement Bounds

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

JHEP02(2015)157

- LHC experiments explore Z_D, below and above 10 GeV
- LHC searches on dark photons with sizable branching ratio to lepton pairs (ee, \mu\mu)
  - 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
Exotic Higgs boson decays to four leptons induced by intermediate dark vector bosons via the hypercharge portal

- 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, $\epsilon$, with the hypercharge field (or through mass mixing, $\delta$), with the Z boson
  - HZZ$_d$ vertex factor is proportional to $\epsilon$

- For $Z_d$ mass range $1 < m_{Z_d} < 60$ 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 $\epsilon > 10^{-5}$
- For smaller values of $\epsilon$, displaced decays provide a unique signature
- For $Z_d$ masses < a few GeV and small values of $\epsilon$, the decay products will be highly collimated leptons-jets (LJ) and require a special analysis
H → Z_(d) Z_d → 4l

• 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 → Z_d Z_d sensitive to small ε, required to be large enough for Z_d to decay promptly
• H → Z_d Z_d search constrains the Higgs mixing parameter κ

• Model-independent upper bounds from electroweak constraints on kinetic mixing parameter ε:
  • ε < 0.03, for Z_d masses: 1 GeV-200 GeV
  • Upper bounds on ε, based on searches for di-lepton resonances, pp → Z_d → ll, below the Z-mass
    • ε < 0.005–0.020, for Z_d masses: 20 GeV-80 GeV
  • In the mass range of 10 MeV-10 GeV, ε > ~ 10^{-3} ruled out
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 $\varepsilon$ values not disfavored by current EWPT. The Higgs portal can give experimental sensitivity to values of $\varepsilon$ 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)

- High-energy colliders (HL-LHC, 100 TeV, ILC) are sensitive to dark photons with $m_{Z^D} > 10$ 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, $h \rightarrow ZZ^D \rightarrow 4l$
  - red curves: Drell-Yan events, $pp \rightarrow Z_D \rightarrow ll$
  - 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
  - $h \rightarrow Z_D Z^D$ decay would set constraints on $\epsilon$, orders of magnitude more powerful than other searches, down to dark photon masses of $\sim 100$ MeV.
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)
Exotic Higgs decay at ATLAS: Hypercharge Portal

$H \rightarrow ZZ_D \rightarrow 4\ell$

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

$13$ TeV, $36.1$ fb$^{-1}$

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

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

- **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 $|m_{12} - m_{34}|$

**Main backgrounds**
- $H \rightarrow ZZ^* \rightarrow 4\ell$; SM ZZ* non-resonance

**Signal region**

**Main backgrounds**
- $H \rightarrow ZZ^* \rightarrow 4\ell$; SM ZZ* non-resonance
Exotic Higgs decay at ATLAS: Hypercharge & Higgs Portal

\[ H \rightarrow Z/Z_Z \rightarrow 4\ell \]

- **Hypercharge portal**: related to kinetic mixing, \( \varepsilon \), and mass-mixing, \( \delta \), parameters
- **Higgs portal model**: related to Higgs mixing parameter, \( \kappa \)

\[ H \rightarrow ZZ_D \rightarrow 4\ell \]

\[ m_{Zd} < m_H - m_Z \]

\[ H \rightarrow ZD \rightarrow 4\ell \]

\( (\kappa >> \varepsilon) \), \( m_S > m_H/2 \), \( m_{Zd} < m_H/2 \)

Upper bound on \( \varepsilon \sim (4-8) \times 10^{-2} \)

Upper bound on \( \kappa \sim (1-10) \times 10^{-4} \)

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Exotic Higgs Decay in $H \rightarrow ZZ_D$, $H \rightarrow Z_DZ_D$ at CMS

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

**$B(H \rightarrow ZX) \times B(X \rightarrow ee$ or $\mu\mu$)**

**$B(H \rightarrow XX) \times B(X \rightarrow ee$ or $\mu\mu)^2$**

Higgs-mixing parameter $\kappa < 3 \times 10^{-3}$
Dark Photon in ZH at CMS: Massless

$Z(\rightarrow \ell\ell)H(\rightarrow \gamma_{D})$

- **Signal region**
  - SFOS high-$p_T$ isolated lepton pair, one high $p_T$ photon + large $p_T^{\text{miss}}$

- **Main backgrounds:**
  - non-resonant dilepton, resonant w/γ mis-ID, fake $p_T^{\text{miss}}$

- **Signal extraction from** transverse mass of $γ+p_T^{\text{miss}}$

$|m_{\ell\ell} - m_Z| < 15$ GeV

$m_{\ell\ell} > 100$ GeV

$E_T^{\text{miss}} > 110$ GeV

$\gamma_D$ massless

$m_H > 100$ GeV

$M_{\gamma_1} > 100$ GeV

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13 TeV, 137 fb$^{-1}$

$B(H \rightarrow \text{inv.} + γ)$
Dark Photon in VBF Higgs at CMS: Massless

- **Signal region**
  - VBF H + high $p_T\gamma$ + large $p_T^{miss}$
- **Backgrounds:**
  - $W$+jets, $Z$(ll) +$\gamma$, $W$($\rightarrow$l$\nu$)+$\gamma$, $\gamma$+jets

Combining $ZH(H\rightarrow{inv}\gamma)+B(H\rightarrow{inv}\gamma)$ at $m_H=125$ GeV limits are 2.9 (2.1)%

CMS-PAS-EXO-20-005
13 TeV, 130 fb$^{-1}$

Excluded $>150$-2 fb, $m_H$:125-1000 GeV
Dark photon at CMS: Displaced vertex

- Dark photon from lightest neutralino decay
  - $O(1) \text{ GeV}, \varepsilon \sim 10^{-6} \Rightarrow \text{displaced muon pair}$
- Isolated dimuon pair from same PV, dimuon $\text{invM} < 9 \text{ GeV}$
- Low background from $b\bar{b}$, $J/\psi$

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

$H \rightarrow 4\mu + X$

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

Limits are shown for $B(h \rightarrow 2\gamma_D + X)$ in the range $0.1$–$40\%$
Lepton Jets (LJ)-LLPs at ATLAS

• 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 \( \gamma_D \) (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

Prompt decays
- Exclusion plot $m_{\gamma d} - \varepsilon$ kinetic mixing parameter
- $H \to 2\gamma d + X$ decays

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

13 TeV, 36.1 fb$^{-1}$

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

JHEP02(2016)062, JHEP11(2014) 088
ATLAS, 20.3 fb$^{-1}$ (8 TeV)

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Higgs Decay: Displaced Muons at ATLAS

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

- 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, $m_{\mu\mu} > 15$ GeV

Excluded regions: $Z_D$–$Z$ kinetic mixing parameter, $\varepsilon$, vs $Z_D$ mass

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

$\varepsilon < 10^{-8}$ excluded for $20$ GeV $< m_{ZD} < 60$ GeV
Higgs Decay: Displaced Leptons at CMS

- 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

**electron channel**

**muon channel**

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Dimuon Resonance at CMS

13 TeV, 137 fb⁻¹

- Bump-hunt in $m_{\mu\mu}$
  - $p_T > 20$ (10) GeV, $|\eta| < 1.9$
  - Probing large kinematic mixing $\varepsilon \sim 10^{-3}$
  - 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)
**Dimuon Resonance at LHCb: prompt muons**

\[ A' \rightarrow \mu^+\mu^- \quad 214 \text{ MeV} < m_{A'} < 740 \text{ MeV} \text{ and } 10.6 \text{ GeV} < m_{A'} < 30 \text{ GeV} \]

**Inclusive di-muon search**

**Prompt-muons strategy**
- Look for low \( p_T > 1 \text{ GeV} \), 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 \( \gamma^* \rightarrow \mu^+\mu^- \) (irreducible)
  - resonant (look around)
- Mis-ID of prompt hadrons (h) as \( \mu \) (h_{\mu Q}) or
  - \( \mu \) from HF decay (\( \mu_Q \))

**Tightest limits on \( \varepsilon \)**

\[ 10.6 \text{ GeV} < \text{mass dark photon} < 70 \text{ GeV} \]
Dimuon Resonance at LHCb: displaced muons

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

- **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 $A' \rightarrow \mu^+\mu^-$ search

- large regions of $[m_{A'}, \varepsilon^2]$ parameter space
- world-leading constraints on low-mass dark photons with lifetimes $\mathcal{O}(1)$ 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)

• Current limits for Dark Photon in visible decays in the plane mixing strength $\epsilon$ 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 $\epsilon$ 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 $\varepsilon$ versus mass $m_{A'}$ for PBC projects on a $\sim$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
Current status of 90% CL exclusion limits (via visible decay)

- 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 et 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), $\nu$-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

**arxiv:2005.01515**
Dark Photon Parameter Plane Prospects (1 MeV-1 TeV)

90% CL projected exclusion limits (via visible decay)

- 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 $^8\text{Be}$ anomaly (Feng et al., 2016, 2017). The existing limits are shown as gray areas.

arxiv:2005.01515
Dark photons (1 MeV-1 GeV): Existing Constraints

- Red/green: e, \( \mu \) anomalous dipole moments
- All other colors: Pair resonance searches
- Gray: Beam Dump

arXiv:1608.08632
Dark photons (1 MeV-1 GeV): Existing Constraints

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

- $90\%$ CL from SLAC and Fermilab beam dump experiments E137, E141, and E774, the electron and muon anomalous magnetic momenta $\alpha_\mu$, 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 $\epsilon$, 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 $\epsilon > 10^{-4}-10^{-3}$

arXiv:1311.0029
Leptonic branching fraction of $Z_d$

![Graph showing the leptonic branching fraction of $Z_d$ vs $m_{Z_d}$ (GeV).]

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

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

Decay length of $Z_d$ for different $\varepsilon$

![Graph showing decay length of $Z_d$ for different $\varepsilon$.]

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

Br for $Z_d$ decays

![Graph showing branching ratio for $Z_d$ decays.]

arXiv:1312.4992
BR for $\epsilon$-$\kappa$

Br($h \rightarrow ZZ_D \rightarrow 4l$) (top) and Br($h \rightarrow Z_DZ_D \rightarrow 4l$) (bottom) for different values of $\epsilon$ and $\kappa$

D. Curtin et al.  JHEP02(2015)157
Parameters & Lifetime

$O(\text{TeV})$ heavy lepton

GUT

$\omega$ vs $m_{A'}$ [GeV]

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