Dark Matter and Dark Sectors at the LHC.

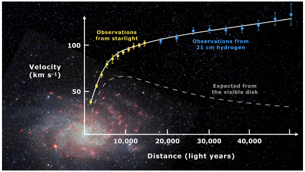
Diallo BOYE

Dark Interactions Workshop 2024
Simon Fraser University Harbour Centre (Vancouver)

[**On behalf of the ATLAS and CMS Collaboration**]

How do we know Dark Matter (DM) existence ?

- **Galaxy Rotation Curves**: **stars at the outer edges rotate faster than expected $\rightarrow$ presence of a large amount of unseen mass $\Rightarrow$ DM.**



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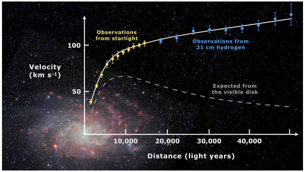
- **Gravitational Lensing**: bending of light from distant objects (gravitational lensing) stronger than what would be expected if only visible matter were present: DM ⇒ provides the extra gravitational influence.



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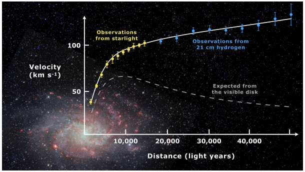
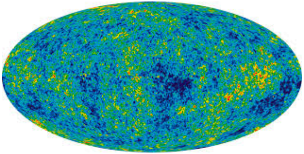
- **Cosmic Microwave Background (CMB)**: precise measurements of the CMB ⇒ 27% of the universe is composed of DM, far exceeding the amount of normal (baryonic) matter.





Why would Dark Matter matter?

DM $\rightarrow$ central to Structure Formation

- In the early universe, dark matter acted as the gravitational scaffolding for the formation of galaxies and large-scale structures. Without dark matter, the universe would not have had enough gravitational clumping to form galaxies and galaxy clusters as quickly as we observe today.

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Gaps in the Standard Model (SM)

- The SM of particle physics describes the known particles and forces very well, but it does not account for DM → there must be new physics beyond the SM that can explain DM.
- Discovering DM could help extend the SM, shedding light on new interactions or forces in nature.

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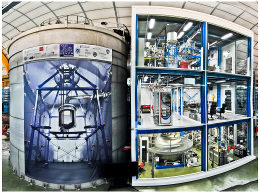
DM as a New Form of Matter

- If DM is made of WIMPs or other exotic particles, understanding it could revolutionize our knowledge of matter and the universe.
- This opens up the possibility of discovering dark sectors: hidden particles and forces that only weakly interact with the SM, introducing a whole new realm of physics.

How to search for Dark Matter?

Direct detection experiments

- **Attempt to observe DM particles interacting with ordinary matter on Earth (e.g., through nuclear recoil in detectors)E.g Xenon 1T experiment.** ☞



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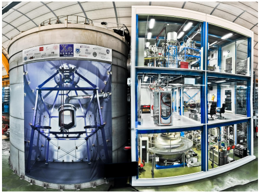

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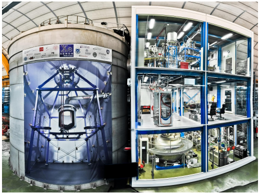

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Collider searches

- **Involve producing DM in high-energy collisions, which would escape detection and show up as missing transverse energy (MET). E.g LHC experiment ☞.**

Collider Searches for Dark Matter

DM as WIMPS → MET

- **WIMPs as DM remains an attractive option which can be directly produced at the LHC**.
- **It would interact weakly then pass invisibly through detectors**.
- **Consequently, collider searches focus on production of a SM particle(s) (X) with E_T^{miss} from the hypothetical WIMP**.
- **Initial state radiation (photons, jets, vector bosons) or associated production can tag DM pair production**.

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DM mediator - Dark sector

- **As a complementary approach, Dark Sector concept is used for the detection of a DM mediator that talk between SM and a Dark sector which then decay back to SM particles**.
- **As an example, the Higgs boson could decay to a dark photon mediator that decays to leptons. This process is also known as the Higgs portal**.

DM search at the LHC: outline

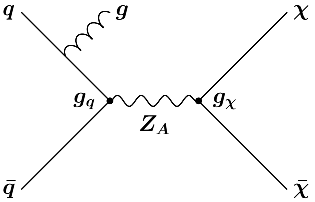
1. **MET-signature**
   - **General MET search: monojet**
   - **H to invisible (MET)**
2. Dark sector
   - Prompt DM mediator
   - Long Lived Particle as DM mediator
   - Semi-visible
3. Dark matter summary at the LHC
4. Conclusion

Monojet analysis ▸ PhysRevD.103.112006

- At least a high energetic jet & large E_T^{miss} and no leptons
  - Different interpretations including **DM simplified models**.

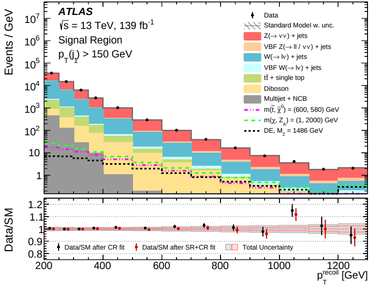
Summary selection

- SR selection:
  - no e, μ, τ & photons
  - $E_T^{\text{miss}} > 200$ GeV.
  - Leading jet $p_T > 150$ GeV
  - up to 3 jets



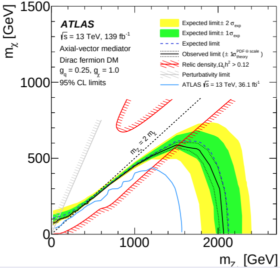
Bkg estimation

bkg	CR in smult. fit	Contribution
$Z(\to \nu\nu)$+jets	inferred from V+jets	Dominant bkg
$W(\to \ell\nu)$+jets	CR1ℓ0b	subdominant
tt single top	top CR	–
Dibosons	from MC	
$Z(\to \ell\ell)$+jets	CR2ℓ0b	–
Multi jets + NCB	data-driven methods	–



- No excess observed.

Mono-jet interpretation ▸ PhysRevD.103.112006



- **For $m_{Z_A} > 2 \times m_\chi$, mediator masses up to about 2.1 TeV are excluded for m_χ= 1 GeV.**

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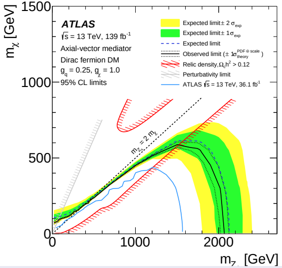

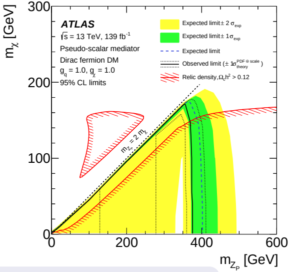

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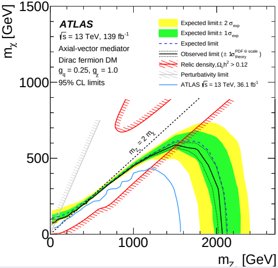
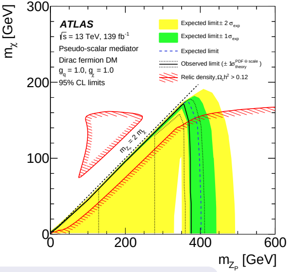
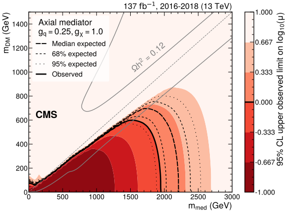
- **m_Z below 376 GeV are excluded for very light WIMP.**







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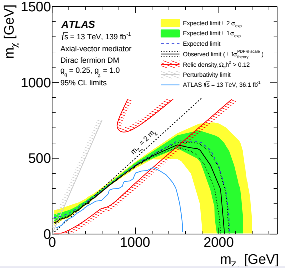
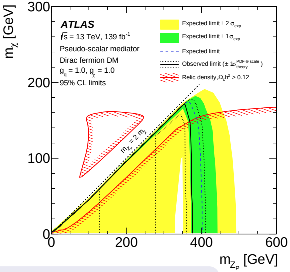
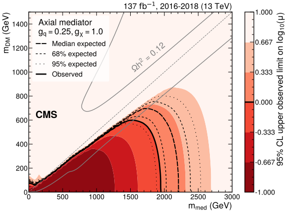
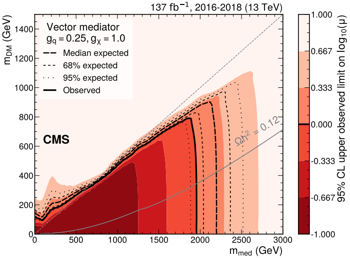
Mono-jet interpretation

PhysRevD.103.112006









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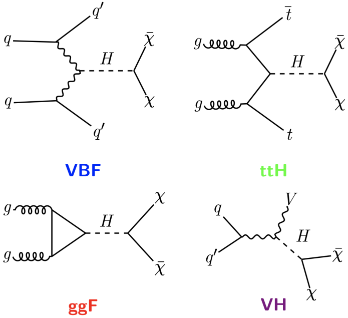
- **m_Z below 376 GeV are excluded for very light WIMP.**
- **The observed exclusion reaches up to m_{med} = 1.95 TeV (2.2 TeV expected) for m_{DM}= 1 GeV.**
- **Similar observation for the vector mediator**
- JHEP11(2021)153

Higgs to invisible search at the LHC

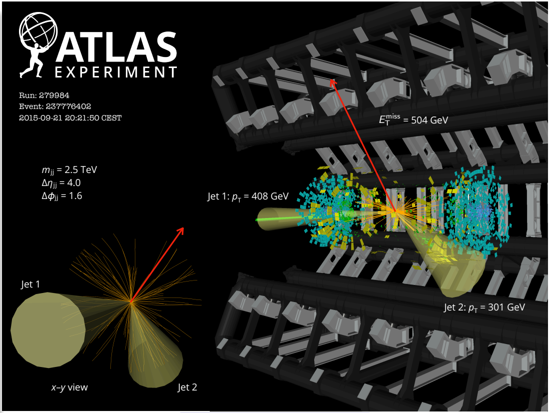
- **Invisible Higgs carries off momentum, characterised by large missing transverse momentum in the events**

- Four different channels for the Higgs to invisible search
- **Very unlikely process in Standard Model; branching ratio $\mathcal{B}_{H\to inv} \sim 1.05 \times 10^{-3}$ from $H \to ZZ^* \to 4\nu$**
- **Can be significantly enhanced in various BSM scenarios, including Higgs coupling to dark matter ("Higgs portal").**



Vector Boson Fusion: VBF

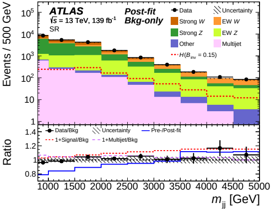
- Strong background rejection due to its distinct event topology.
- **The most sensitive mode for invisible decays of a Higgs boson at hadron colliders**
- Three mains backgrounds: Z strong, Z electroweak and di-boson production.



JHEP 08 (2022) 104

Event selection

- **At least two jets with** $p_T(j_1/j_2) > 80/50$ **GeV.**
- **Jets in opposite hemispheres:** $\Delta\eta_{jj} > 3.8$.
- $m_{jj} > 0.8$ TeV, Veto on e and μ



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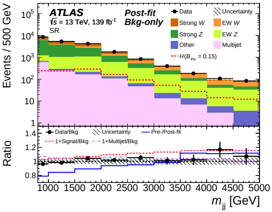
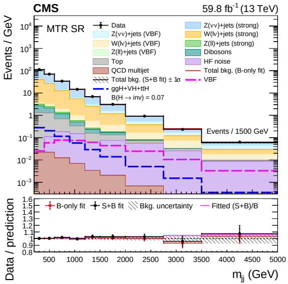
‣ JHEP 08 (2022) 104





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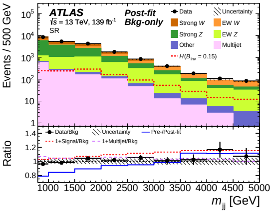

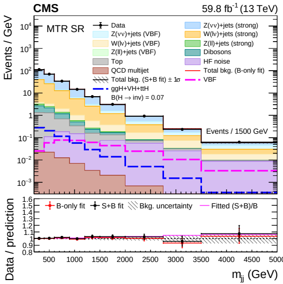

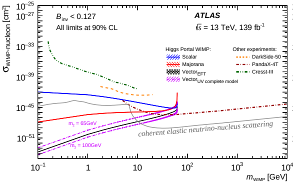

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VBF Higgs → inv interpretation

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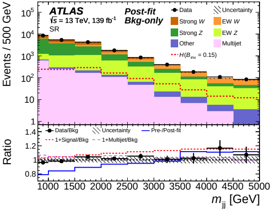

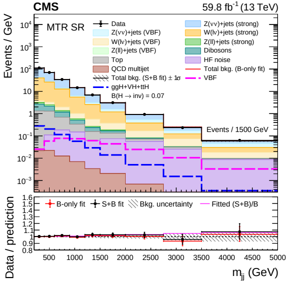

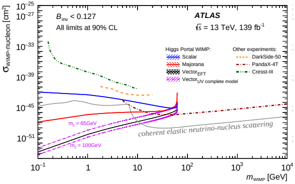

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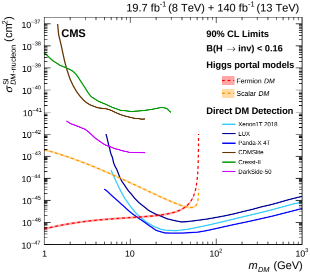
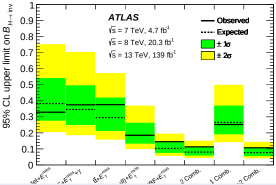
- **Limits set on the $\sigma_{\text{DM-nucleon}}$ vs m_{dm}**
- Phys. Rev. D 105 (2022) 092007
- **Complementary between collider and direct detection observed.**





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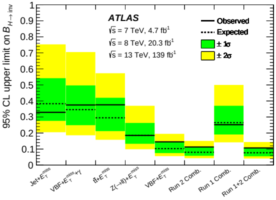

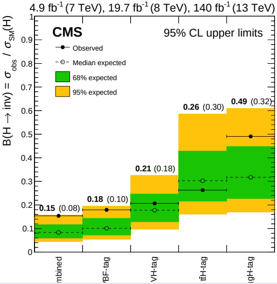

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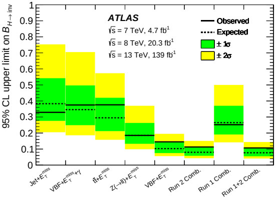

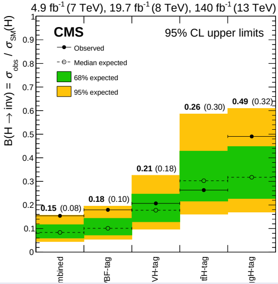

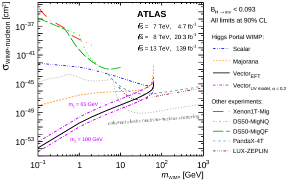

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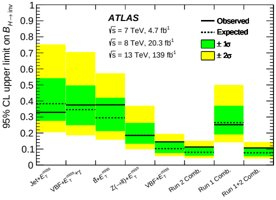
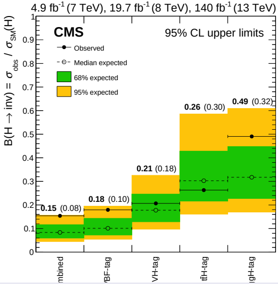
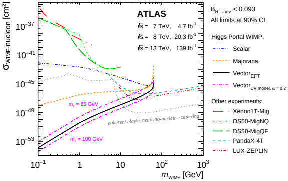
Higgs→inv combination

Phys. Lett. B 842 (2023) 137963







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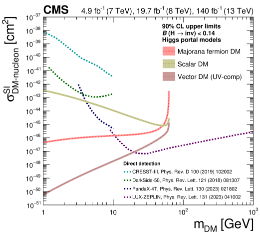
- **Powerful constraint at low mass for collider search vs to direct one**
- arXiv:2303.01214



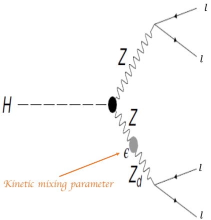
DM search at the LHC: outline

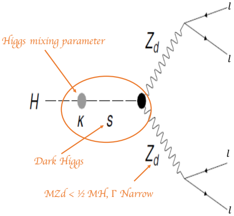
1. MET-signature
   - General MET search: monojet
   - H to invisible (MET)
2. **Dark sector**
   - **Prompt DM mediator**
   - **Long Lived Particle as DM mediator**
   - **Semi-visible**
3. Dark matter summary at the LHC
4. Conclusion

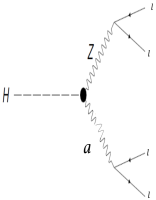
Dark sector: Dark photon search

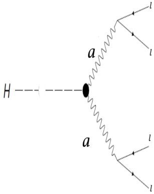
- **HAHM** (Hidden Abelian Higgs Model) → Curtin et al. (Phys.Rev.D90,075004(2014).), H. Davoudiasl et al Phys.Rev.D88.1(2013)015022
  - Predict a dark photon mediator Z_d that interacts with SM through kinetic mixing parameter ϵ.
  - Dark Higgs mechanism could spontaneously break the U(1) dark gauge symmetry (→ mixing between SM Higgs and dark Higgs → mixing parameter κ)

- **2HDM+S** Curtin et al. (Phys.Rev.D90, 075004(2014).), H. Davoudiasl et al Phys.Rev.D88.1(2013) 015022
  - It predicts the decay of the Higgs boson to 1 or 2 pseudo-scalar a determined by Yukawa couplings of a to fermions.

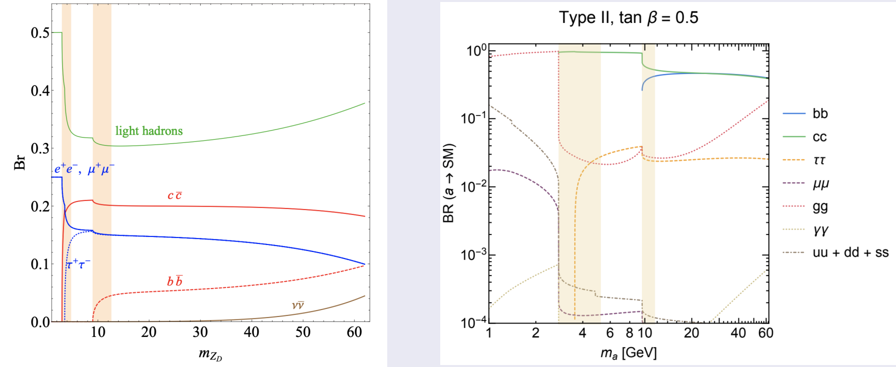








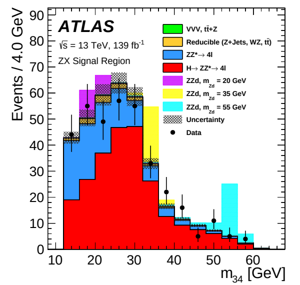
Dark photon and speudo scalar branching ratios

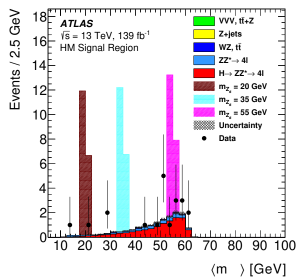


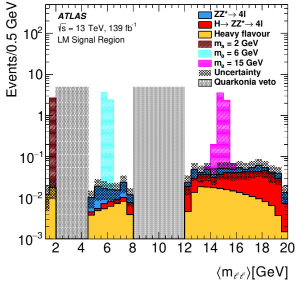
- **Left**: Branching ratios for Z_d decay, to lowest order and without QCD corrections, assuming decays to the dark sector are kinematically forbidden.
- **Right**: Branching ratios of a singlet-like pseudoscalar in the 2HDM+S for Type II Yukawa couplings.

Dark photon mediator in the Higgs portal

JHEP03(2022)041



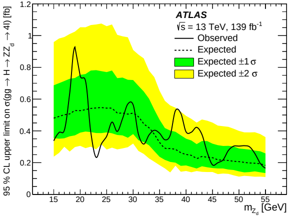


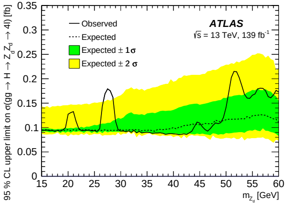


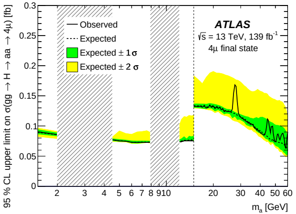
- Different analyses:
  - $H \to ZZ_d$, Z_dZ_d, $aa \to 4\ell$.
- Mass range:
  - $Z_d \in$ [15-60] GeV.
  - $a \in$ [1-20] GeV
- Observable:
  - m_{34} for ZZ_d channel → di-lepton mass most distant from the Z mass.
  - $\langle m_{\ell\ell} \rangle$ for Z_dZ_d and $aa \to$ average di-lepton mass.

- **No significant excess observed above the SM expectation.**
- **Results are interpreted in the HAHM and 2HDM+S models.**
- **Expected and Observed Limit is set at 95% CL on the branching ratio.**

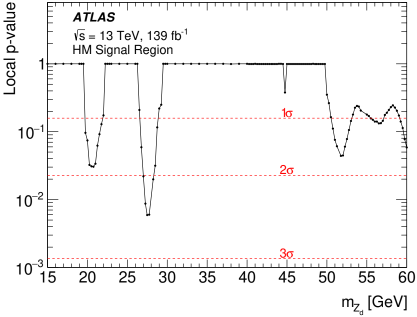
Dark photon mediator in the Higgs portal







- **The highest excess corresponds to a local significance of 2.5σ at m_{Z_d} = 28 GeV corresponding to $H \to Z_d Z_d \to 4\ell$ channel.**
- **This analysis is extended $S \to Z_d Z_d \to 4\ell$ where S is a scalar $m_S \neq m_{(H=125)}$.**



Dark photon mediator in the Higgs portal

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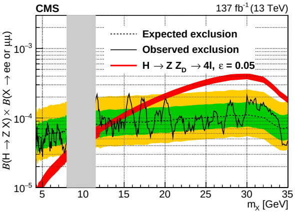
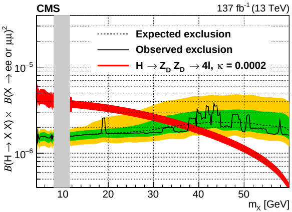
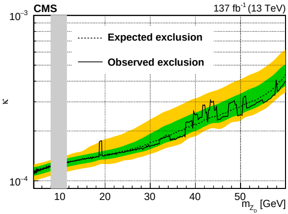
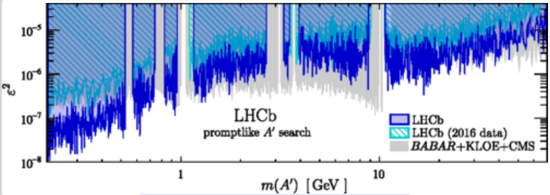






- CMS performed the same search.
- With no significant excess, limit was set on the Br and also on κ.
- A mediator decaying to di-muon is also performed in LHCb.
- Mass range below 1 GeV is probed, complementing ATLAS and CMS phase space.



Phys. Rev. Lett. 124, 041801

- Note that the model probe in LHCb is a minimal vector portal model that doesn't require a Higgs portal.

Prompt Lepton Jets ‣ EXOT-2018-55

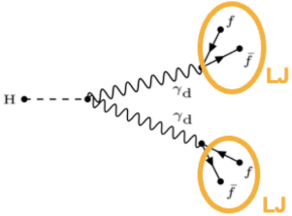
Experimental signature

- 2 benchmarks models: HAHM and FRVZ
- Final states: Lepton Jet (LJ) $\rightarrow$ collimated bundles of leptons.
- $m_{\gamma_d} \in$ [10 MeV - 10 GeV].
- 3 channels: 2eLJ, 2μLJ and eLJ+μLJ

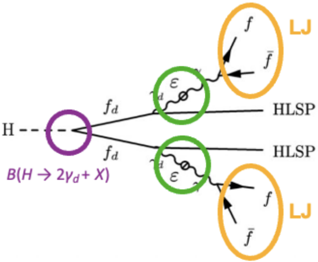
Analsysis strategy

- main bkg: Internal $\gamma*$, Z+jets and di-muon resonance.
- Triggers: single and di-electrons triggers for 2eLJ and di-muons trigger for 2μLJ.
- Bkg estimates: ABCD method for 2eLJ and Bump Hunting for 2μLJ.

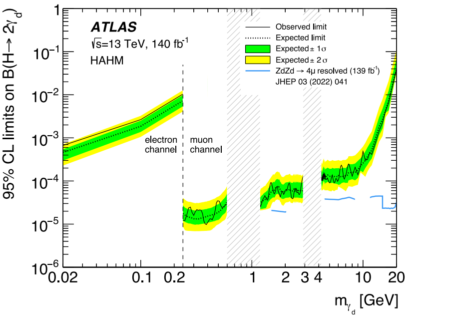
HAHM benchmark model

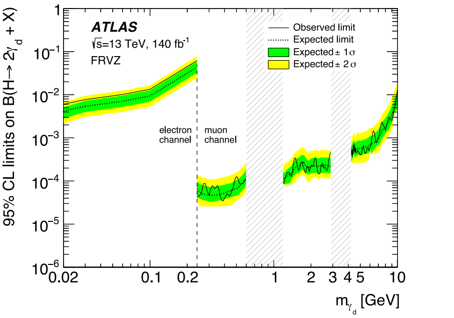


FRVZ benchmark model



Results



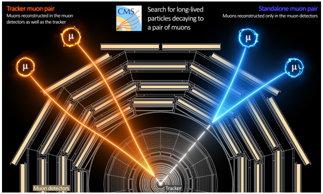


- **No significant excess in the data above the Standard Model background is observed.**
- **Left**: **95% CL limits on BR(H $\rightarrow 2\gamma_d$) w.r.t m_{γ_d} using the HAHM model.**
- **Right**: **95% CL limits on BR(H $\rightarrow 2\gamma_d + X$) w.r.t m_{γ_d} using the FRVZ model.**
- **Most stringent limits up to date probing for the first time γ_d mass down to $\sim$ 10 MeV.**

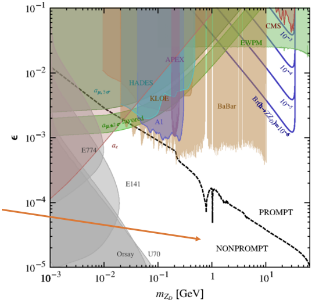
Unconventional signature: Long Lived Particles (LLP)

LLP is challenging

- Weak coupling to the SM leads to long-lived-particles (LLPs).
- challenges come from:
  - Decaying far from the primary vertex (PV), requiring special tracking.
  - Unusual shower shapes in calorimeters, unique fractions of ECal/HCal energy.
  - Need for timing information.



- The exclusion plot from the minimal vector portal dark-photon model shows an unexplored region of LLP of the dark photon.
- The very displaced area is accessible only via Higgs portal with ATLAS and CMS.



Phys. Rev. D 90, 075004

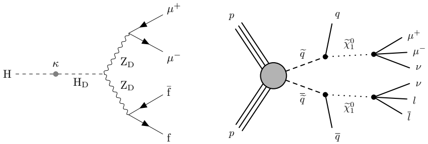
LLP decaying to a pairs of di-muons (NEW-Run 3)

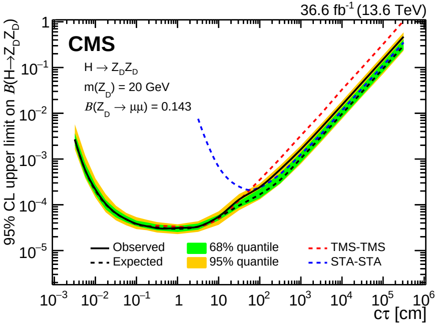
Experimental signature

- 2μ from a secondary vertex spatially separated from the IP by distances ranging from hundred μm to several meters.
- New triggers for displaced di-μ developed for Run 3.

Results and interpretation

- Results interpreted in the framework of the HAHM, in which $H \to ZdZd$ where Z_d is a long-lived dark photons.
- Most stringent limit to date in wide regions of lifetimes for LLPs with masses larger than 10 GeV.



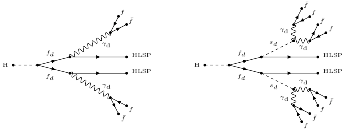


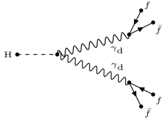
JHEP05(2024)047

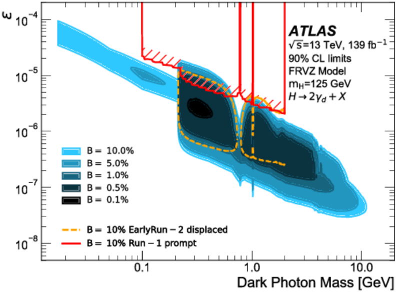
- R-parity violating SUSY model interpretation is also considered.

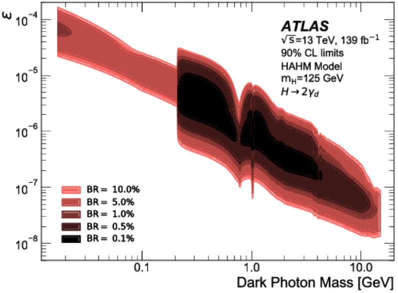
Displaced dark-photon jets ▸ JHEP06(2023)153

- LL dark photons in the decay of a Higgs boson produced via gluon–gluon fusion or in association with a W boson.
- Select events with displaced collimated SM fermions from the calorimeter muon spectrometer.
- FRVZ model and HAHM model considered.



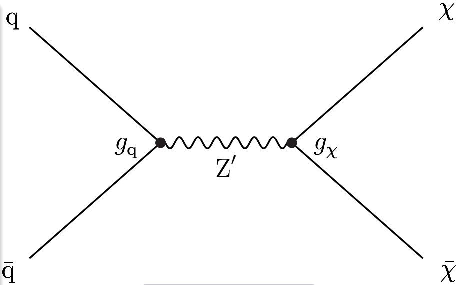






Search for strongly-coupled DM - semi visible jets

- Analogue to the SM, Dark Sector contains new confining force (dark QCD) → dark quarks → dark showers.
- Predicting a resonance production of a leptophobic Z' boson which decays into a pair of dark quarks generating dark shower as shown in the Feynman diagram.



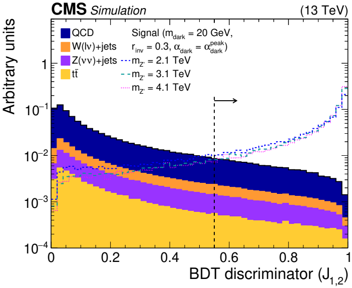
JHEP06(2022)156

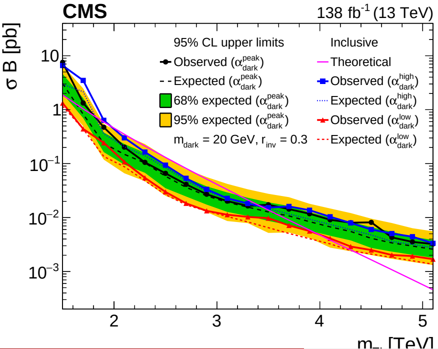
- Unstable dark hadrons $\xrightarrow[\text{decay}]{\text{promptly}}$ to SM quarks, while the stable dark hadrons are DM candidates (E_T^{miss}).
- Leading to two jets (decay products of the Z') in the final state.
- These jets contain quarks, gluons, and dark matter particles, and are therefore referred to as "semi-visible" jets.
- ATLAS and CMS performed such analyses presented in the next slides.

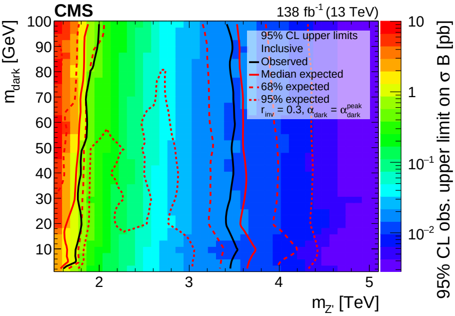
Strongly coupled dark matter search

JHEP06(2022)156

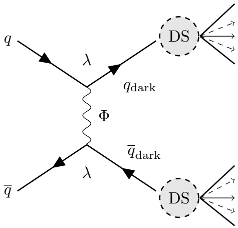
- Dijets transverse mass m_T used as discriminant.
- BDT to enhance the sensitivity.
- Look for new resonance as an excess in the m_T distribution.
- No structure in m_T compatible with the signal is observed.

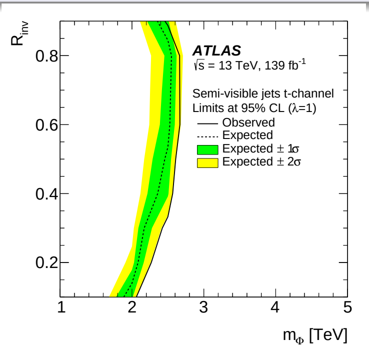


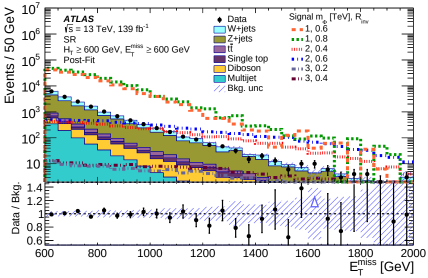




- In the t-channel production mode, a scalar mediator, ϕ, acts as a portal between the SM and dark sectors.
- λ is the coupling strength of $q - q_{\text{dark}} - \phi$ interaction.
- R_{inv} defined as the invisible fraction.
- E_T^{miss} and H_T(scalar sum of p_T of jets) > 600 GeV.



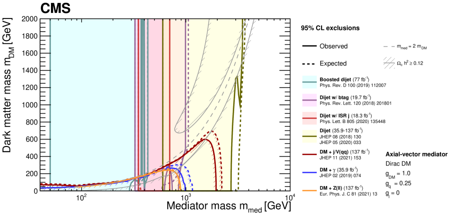


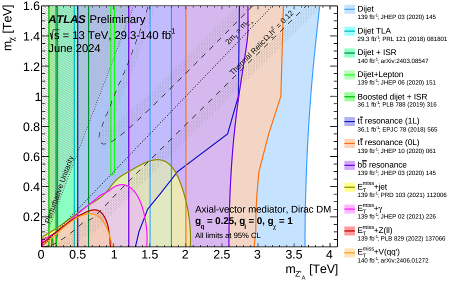


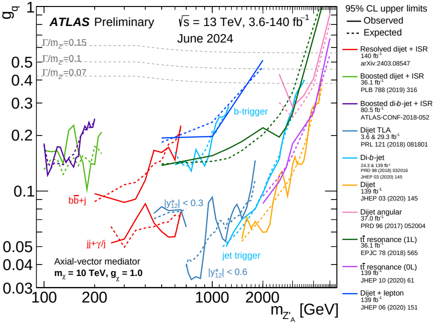
DM search at the LHC: outline

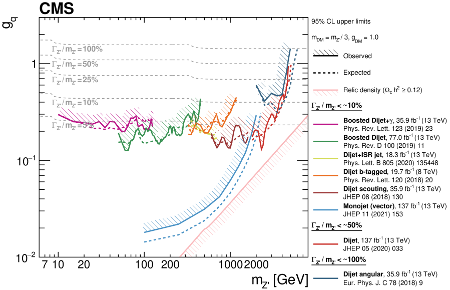
1. MET-signature
   - General MET search: monojet
   - H to invisible (MET)
2. Dark sector
   - Prompt DM mediator
   - Long Lived Particle as DM mediator
   - Semi-visible
3. **Dark matter summary at the LHC**
4. Conclusion

Quick summary: ▸ JHEP06(2022)156 ▸ CMS









Conclusion

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- **Experiments at the LHC, such as ATLAS, CMS, and LHCb, have developed extensive dark matter research programs**.
- **In close collaboration with theorists, different models have been tested, ranging from searches for Weakly Interacting Massive Particles (WIMPs) using missing energy signatures to probing dark matter mediators in the dark sector, as well as unconventional signatures like long-lived particles as potential dark matter candidates**.

Conclusion

- **Various methods for searching for dark matter are reviewed, with a focus on collider searches.**
- **Experiments at the LHC, such as ATLAS, CMS, and LHCb, have developed extensive dark matter research programs.**
- **In close collaboration with theorists, different models have been tested, ranging from searches for Weakly Interacting Massive Particles (WIMPs) using missing energy signatures to probing dark matter mediators in the dark sector, as well as unconventional signatures like long-lived particles as potential dark matter candidates.**
- **So far, none of these searches have led to a discovery, with the results being consistent with Standard Model predictions. As a result, exclusion limits have been set for various models.**

Conclusion

- **A brief comparison between collider and direct detection methods shows their complementarity: colliders provide better sensitivity in the low-mass region, while direct detection experiments are more sensitive at higher masses**.

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- **A brief comparison between collider and direct detection methods shows their complementarity: colliders provide better sensitivity in the low-mass region, while direct detection experiments are more sensitive at higher masses**.
- **The searches presented here are not exhaustive; more results can be found on the ATLAS and CMS results pages.**.
- **The LHC is entering a new phase of high luminosity, where exciting results are expected—so stay tuned**.

BACKUP

- LL dark photons in the decay of a Higgs boson produced via vector-boson-fusion.
- Select events with displaced collimated SM fermions in the calorimeter or muon spectrometer are probed.
- Only FRVZ model model is considered.