ATLAS Dark Photon Results

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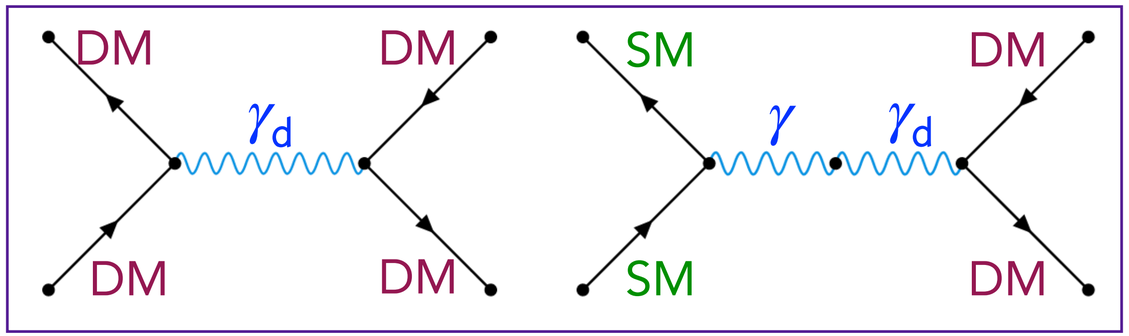
Dark Photon

Predicted in hidden-sector models with an extra dark U(1) gauge symmetry (arxiv:2005.01515).

- Dark photon either kinetically mixes with the SM photon or couple to the Higgs sector via some mediator.
- Could be produced through:
  - **Vector portal**: Kinetic mixing of γ_D with the SM photon (ϵ) by adding a $U(1)_{Dark}$.
  - **Higgs portal**: Add dark scalar singlet (S) that spontaneously breaks U(1) and mixes with SM Higgs.

$$L \supset \underbrace{-\frac{\epsilon}{2}B^{\mu\nu}A'_{\mu\nu}}_{\text{Vector portal}} \underbrace{- H^{+}H(AS + \lambda S^{2})}_{\text{Higgs portal}} \underbrace{- Y_{N}^{ij}L_{i}HN}_{\text{Neutrino portal}} + \underbrace{\frac{1}{f_a}(tr(G\tilde{G}) + c_F F\tilde{F})a}_{\text{Axion portal}} + o(dim \geq 5)$$

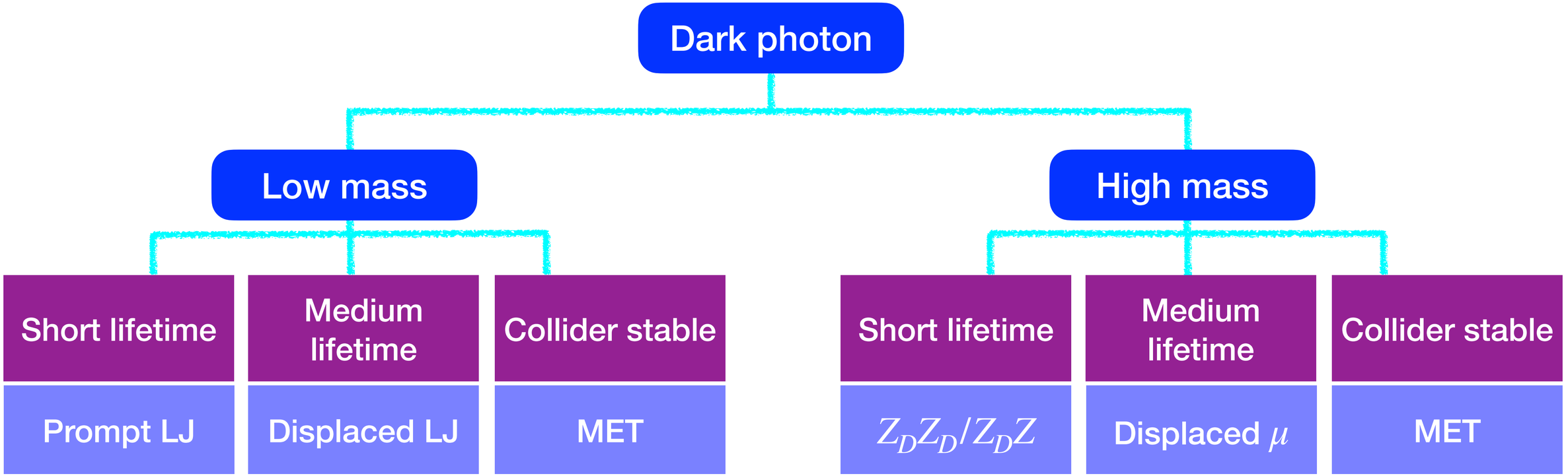
[Okun; Galison & Manohar; Holdom; Foot et al] — [Patt & Wilczek] — [Patt & Wilczek] — [Weinberg; Wilczek; KSVS; DFSZ]



- **Kinetic mixing**: $\epsilon \sim 10^{-3} - 10^{-1}$ (1 loop correction), $\epsilon \sim 10^{-7} - 10^{-3}$ (2 loop corrections)
- **Lifetime**: $\tau(\gamma_D) \propto \frac{1}{m(\gamma_D)\epsilon^2}$ (Small ϵ value => long γ_D)

Dark Photon ATLAS signatures

- ATLAS is searching for dark photons in various experimental signatures
- A wide range of dark photon masses is considered: from 0 to 200 GeV



Dark Photon ATLAS results

This talk includes results published between 2020-2023 using partial and total Run 2 luminosity:

➡ 33 fb^{-1}:

- Displaced Hadronic Jets
- Long-lived particles in final states with displaced di-muon vertices

➡ 139 fb^{-1}:

- Light long-lived neutral particles decaying into displaced collimated leptons or light hadrons.
- Higgs boson decay into new spin-0 or spin-1 particles in four-lepton states
- (VBF, ZH and ggF) $H \rightarrow \gamma\gamma_d$
- Dark photons in rare Z boson decays

➡ $\sqrt{s} = 8 - 13$ TeV, $20.3 - 139$ fb^{-1} dark photon summary plot

2020 Results using 33 fb^{-1} collected in 2016:

- **Long-lived particles in displaced di-muon vertices**
- **Displaced Hadronic Jets**

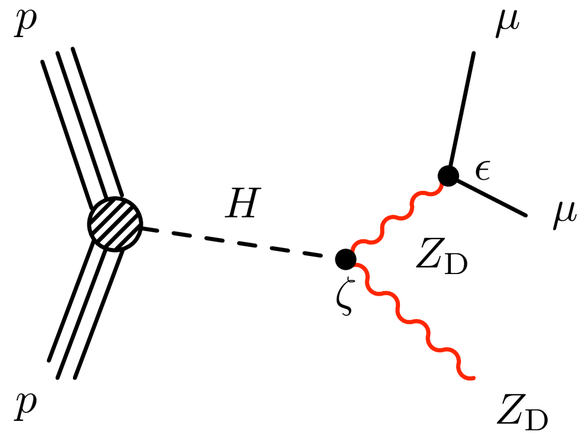
Long-lived particles in displaced di-muon vertices [1808.03057.pdf]

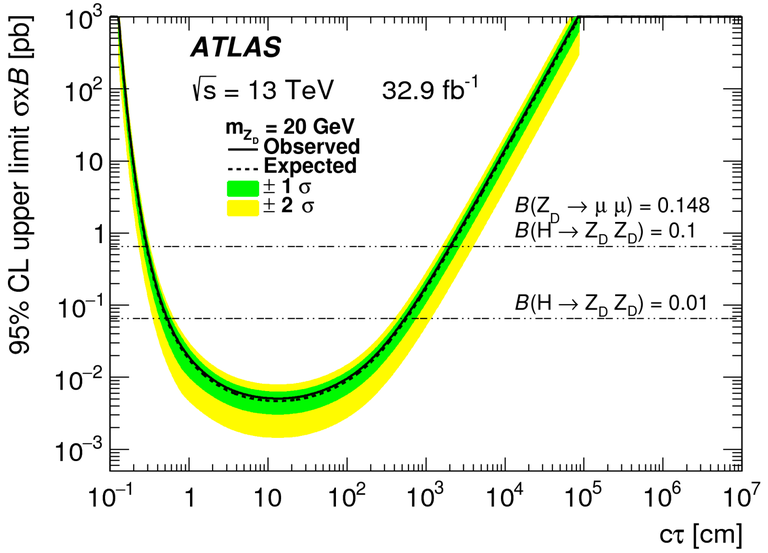
- m_H= 125 GeV, m_{H_D}= 300 GeV and m_{Z_D}= 20–60 GeV, Br($Z_D \to \mu^+\mu^-$) = 0.1475 - 0.1066.
- Main background: low-mass Drell–Yan, Z+jets and cosmic-muons.
- Lifetimes in the range cτ = 1–2400 cm are excluded, 20–60 GeV.

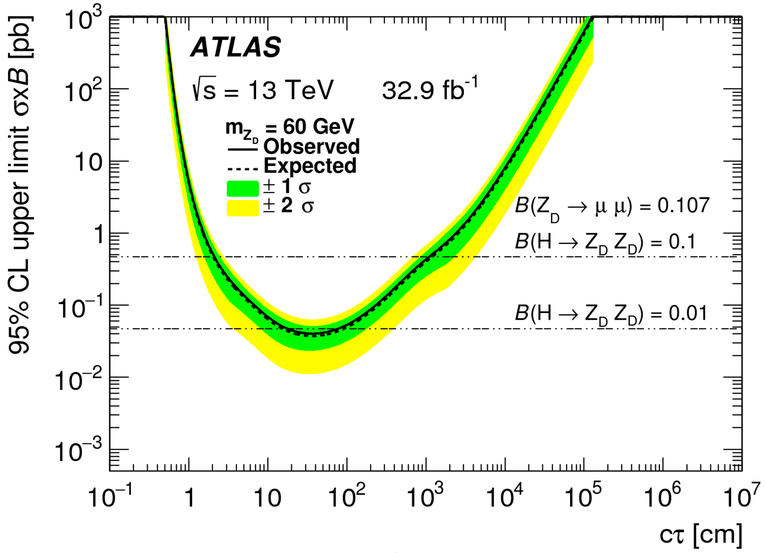
$$B\,(H \to Z_D Z_D) \propto \zeta \frac{m_H^2}{|m_{H_D}^2 - m_H^2|}$$

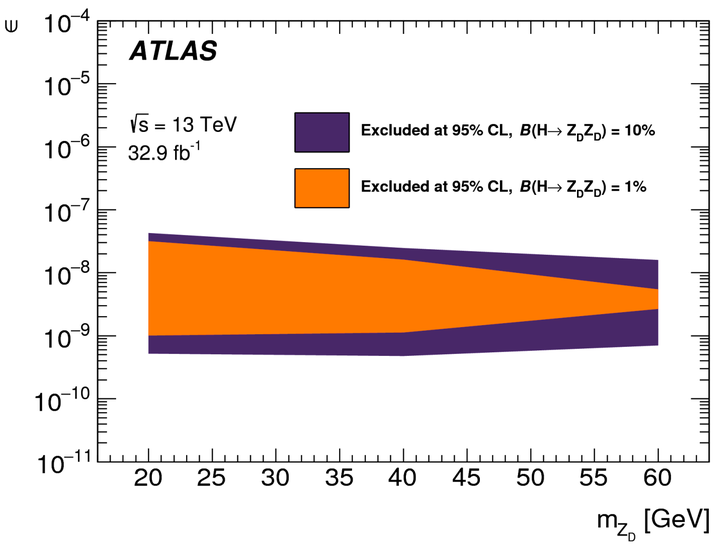
$$\sigma(pp \to H) \times B(H \to Z_D Z_D) \times B(Z_D \to \mu^+\mu^-)$$

$H \to Z_D Z_D$







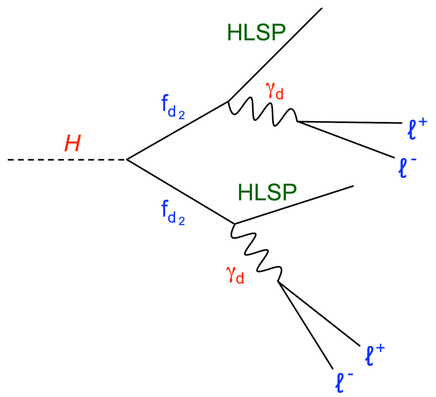


Displaced Hadronic Jets

https://cds.cern.ch/record/2714064/

- Higgs and heavy boson decay to collimated hadrons via long-lived dark photons: m_H = 125, 800 GeV.
- Main background: SM multijet production.
- First limit on the SM Higgs channel by ATLAS.

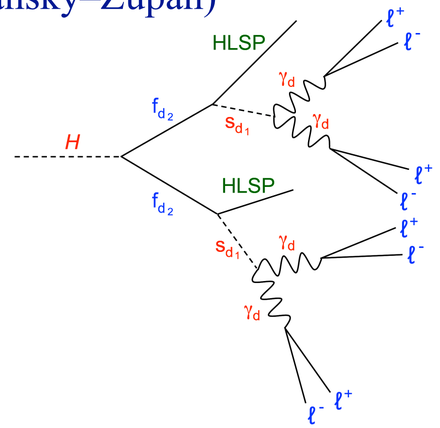
$H \to 2\gamma_d + X$



FRVZ model

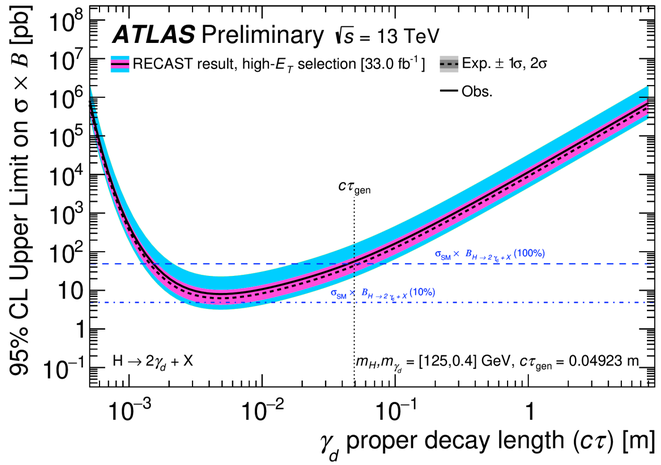
(Falkowski–Ruderman–Volansky–Zupan)

$H \to 4\gamma_d + X$

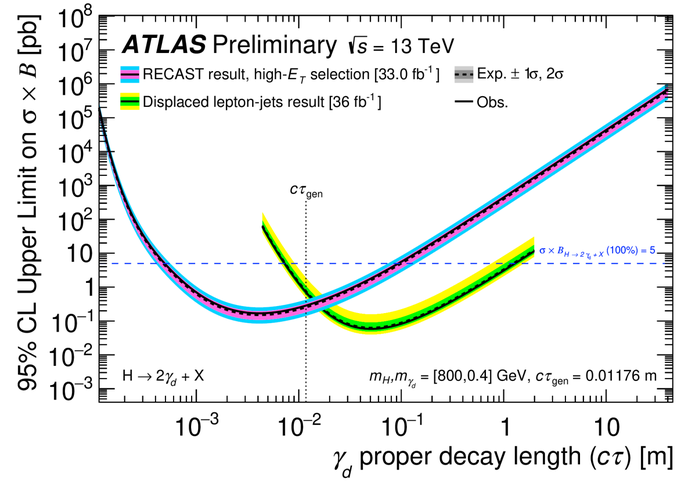


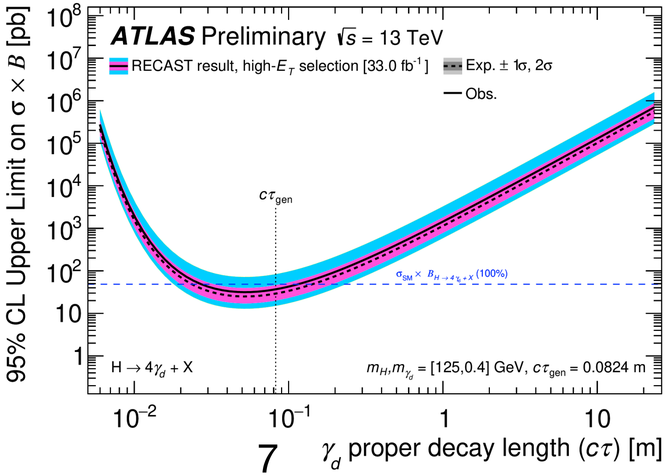
- HLSP: hidden lightest stable particle

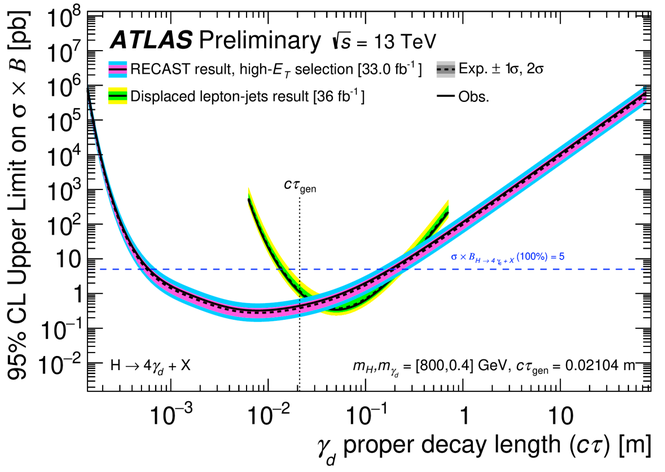
m_H = 125 GeV



m_H = 800 GeV







2022-2023 Results using full Run 2 139 fb^{-1}:

- **Light long-lived neutral particles decaying into displaced collimated leptons or light hadrons.**
- **Higgs boson decay into new spin-0 or spin-1 particles in four-lepton states**
- **(VBF, ZH and ggF)** $H \rightarrow \gamma\gamma_d$
- **Dark photons in rare *Z* boson decays**

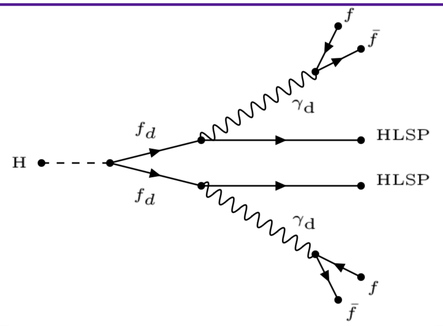
Light long-lived neutral particles in displaced collimated leptons or light hadrons

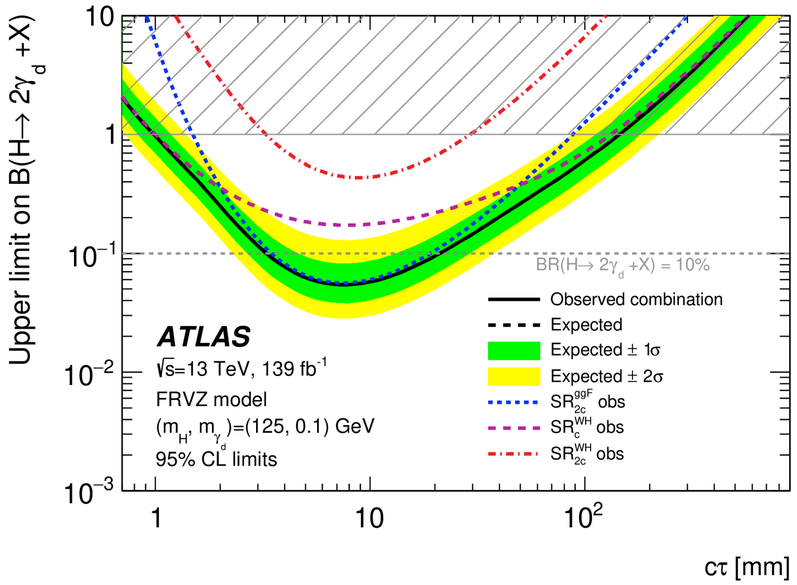
2206.12181

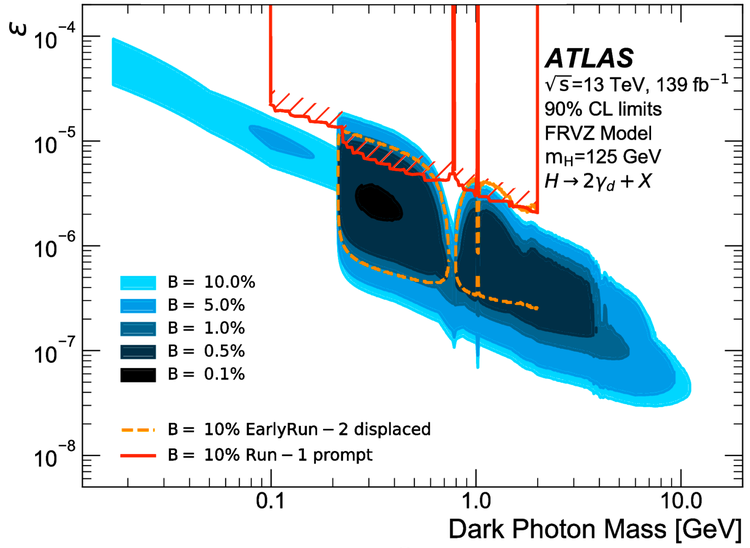
- **Signature**: at least two dark-photon jets (DPJs) $H \to 2\gamma_d + X$
  - ggF→ MS and calorimeter-based trigger, background from multi-jet production, cosmic-ray muons.
  - WH→ single-electron or single-muon trigger, background from W+jets events and punch-through jets.
- Models: **FRVZ** and **HAHM** (Hidden Abelian Higgs Model)
- Small values of the kinetic mixing parameter, $\epsilon < 10^{-5}$ → long-lived γ_d with m(γd) ∈ [0.4, 2] GeV

FRVZ

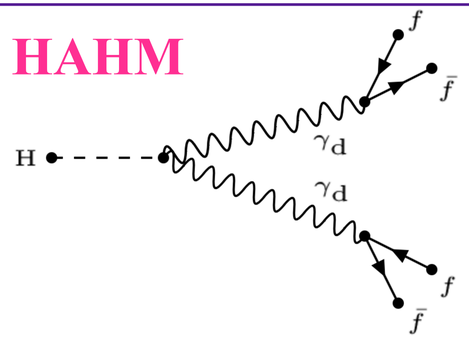
Br > 0.1% is excluded for
10 mm < cτ < 250 mm

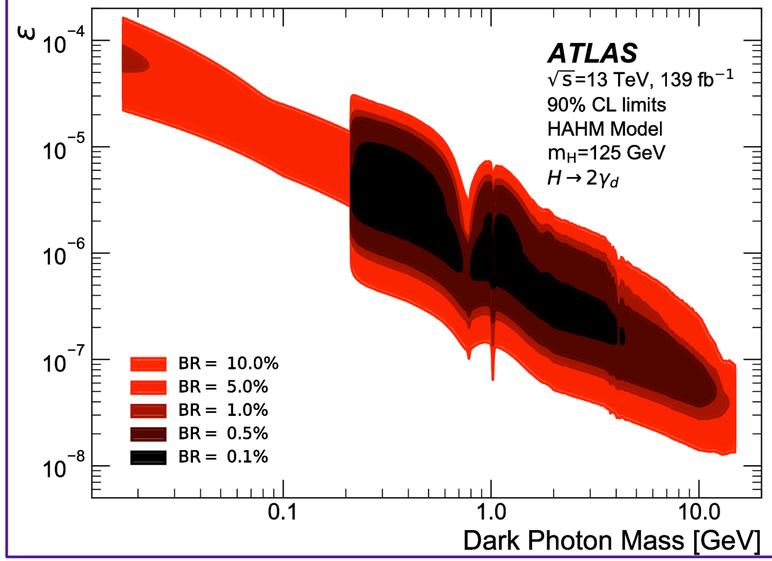






HAHM





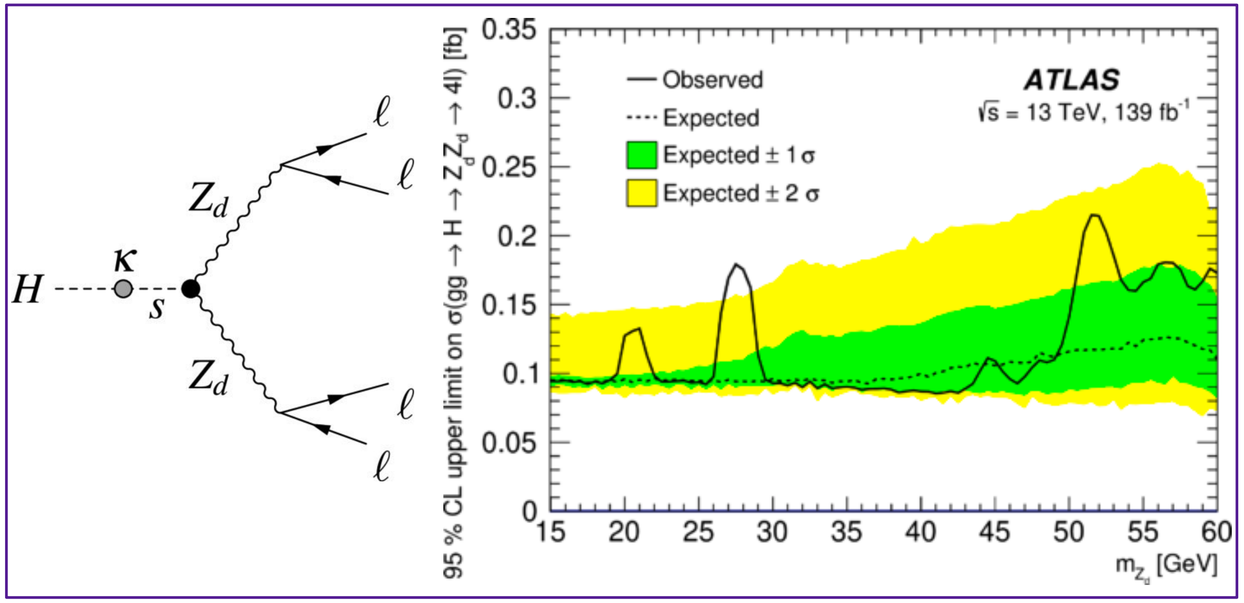
Higgs boson decay into new spin-0 or spin-1 particles in four-lepton states

JHEP 03 (2022) 041

- ggF Higgs production and prompt decay of Z_d.
- 4 lepton signatures, require m_{4L} consistent with 125 GeV.
- Photon portal (Z mixing with Z_d): m_{12} consistent with Z, di-lepton resonance above H—> ZZ* background
- Higgs portal (mixing of SM H with dark H (S) via mixing parameter): consistent mass for two di-lepton pairs.
- Limits are set on branching ratios and mixing parameters.
- **The most significant excess corresponds to a local significance of 2.5σ at m_{Z_d} = 28 GeV**

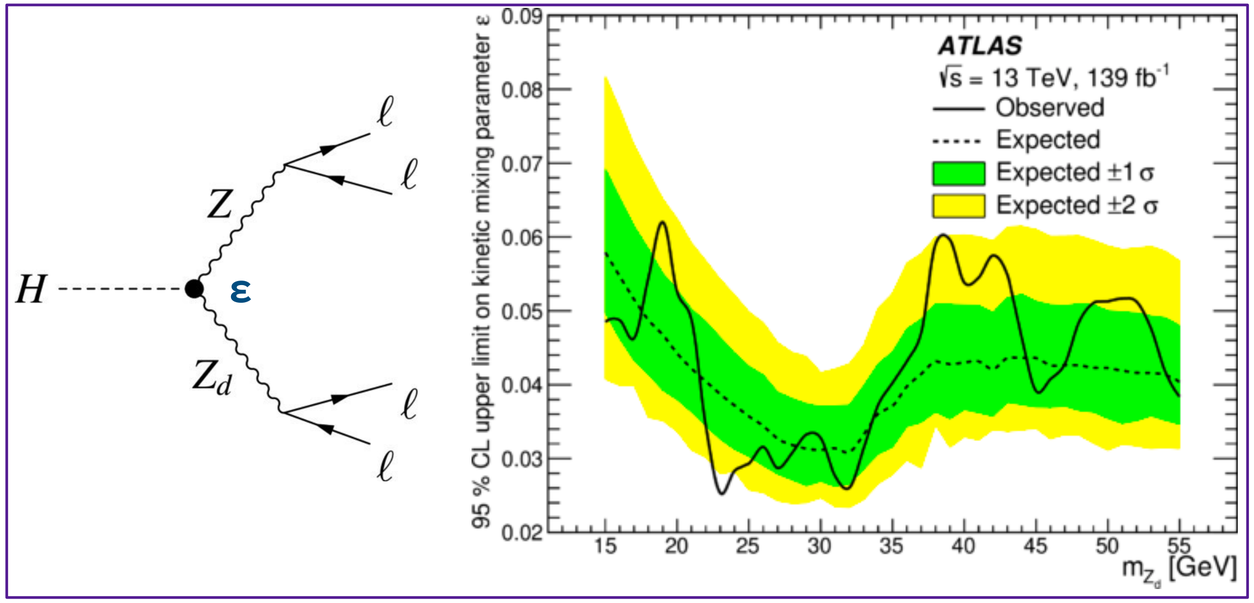
$H \to Z_d Z_d \to 4\ell$

Higgs portal through k:
HM (15 GeV < m_{Z_d} < 60 GeV) and LM (1 GeV < m_{Z_d} < 15 GeV)



$H \to ZZ_d \to 4\ell$

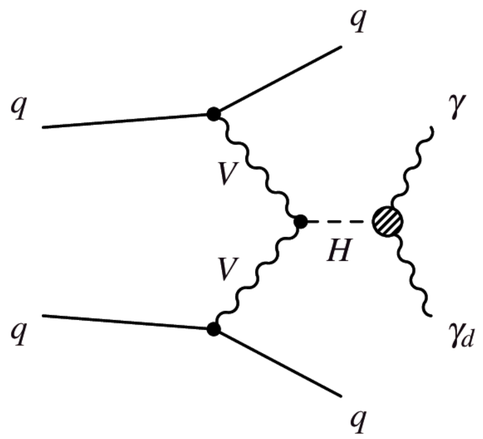
Hypercharge portal through ϵ: 15 GeV < m_{Z_d} < 55 GeV

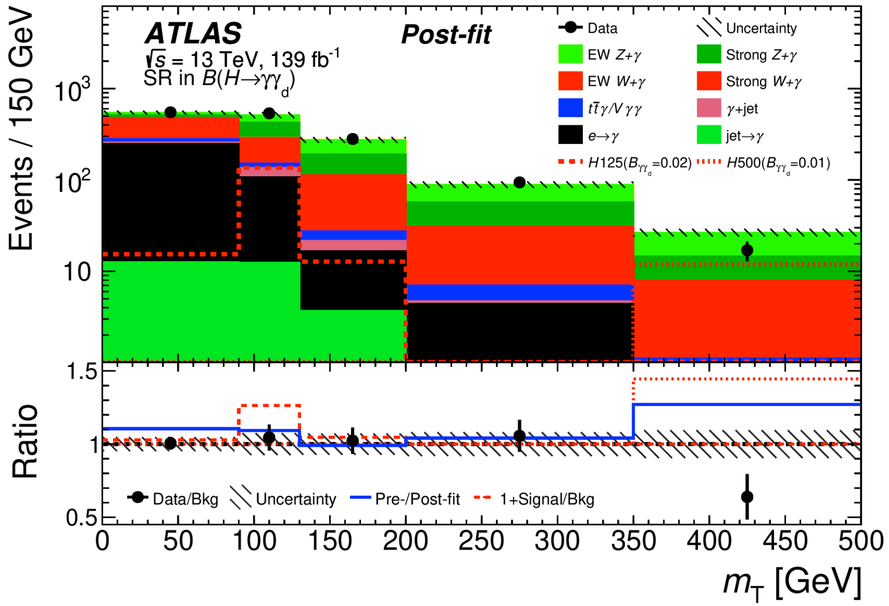


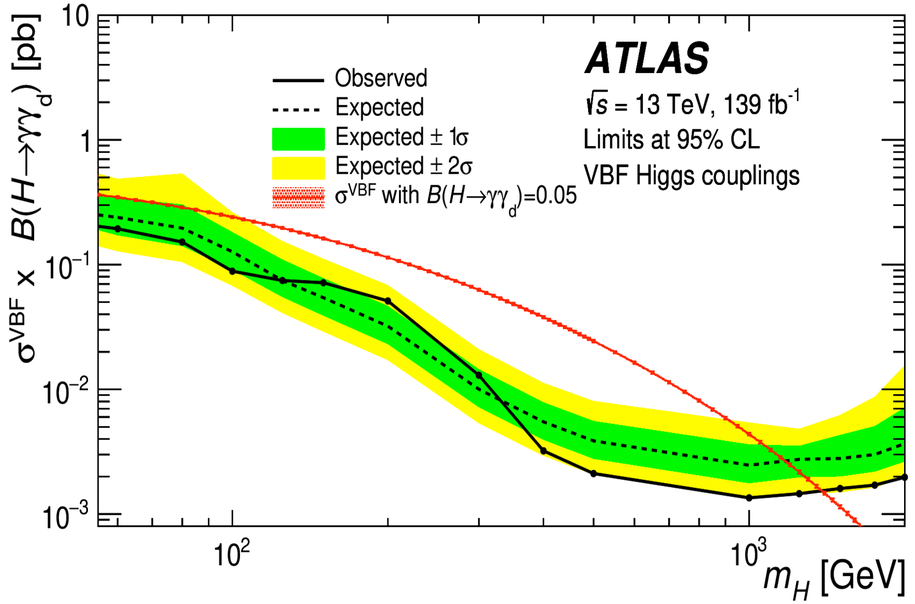
VBF H → $\gamma\gamma_d$

Eur. Phys. J. C 82 (2022) 105

- Trigger: single-photon
- Dominant background: $W(\rightarrow \ell\nu)(+\gamma)+jets$ and $Z(\rightarrow \nu\nu)(+\gamma)+jets$
- SR: isolated photon, two forward jets with $|\Delta\eta_{jj}|>2.5$ and high E_T^{miss}
- The most powerful discriminating variable: $m_T(\gamma, E_T^{miss}) = \sqrt{2\ p_T\ E_T^{miss}\ [1-\cos(\phi_\gamma - \phi_{E_T^{miss}})]}$





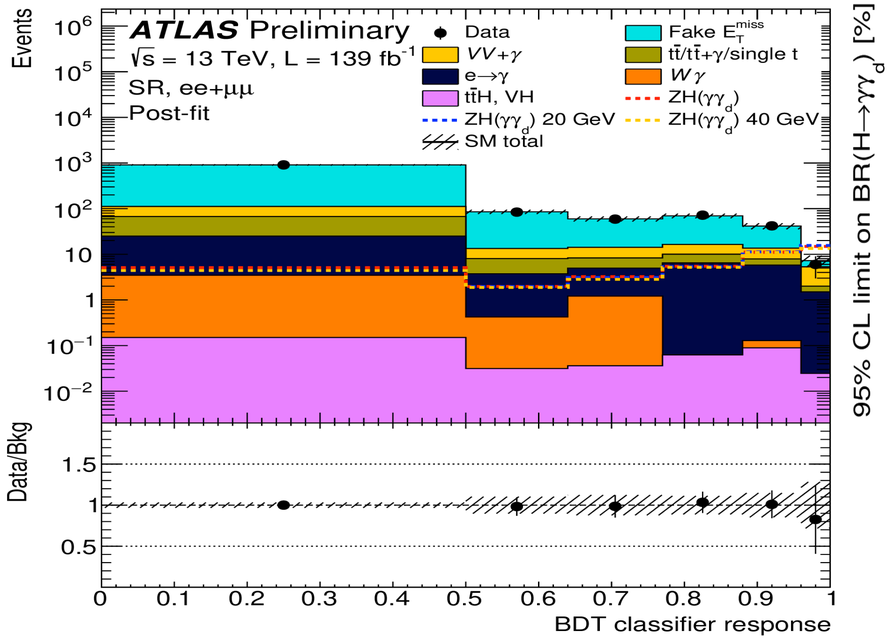


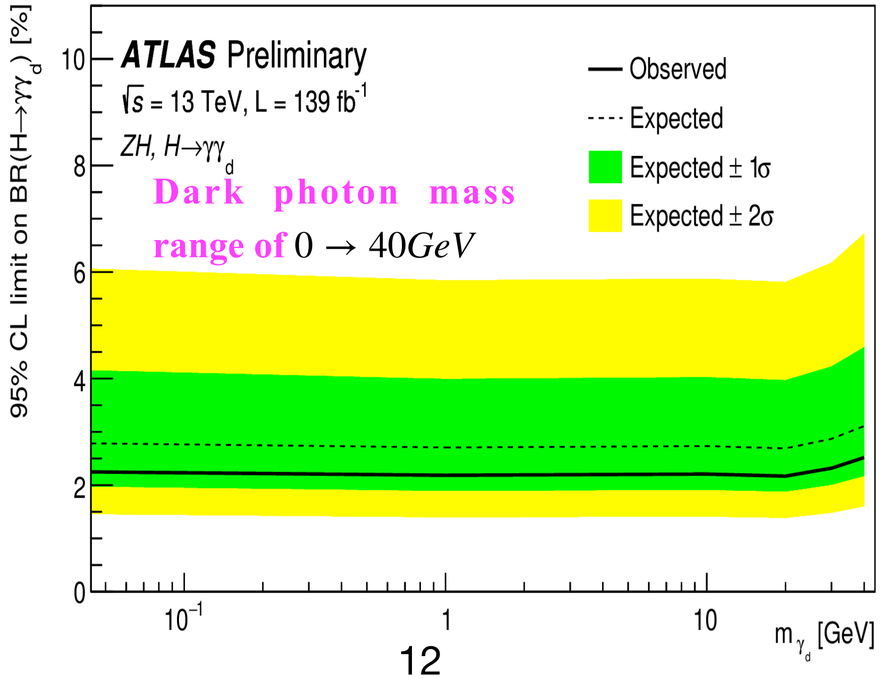
An observed (expected) 95% CL upper limit on the branching ratio for this decay is set at 0.018 ($0.017_{+0.007-0.005}$), assuming the SM 125 GeV Higgs boson.

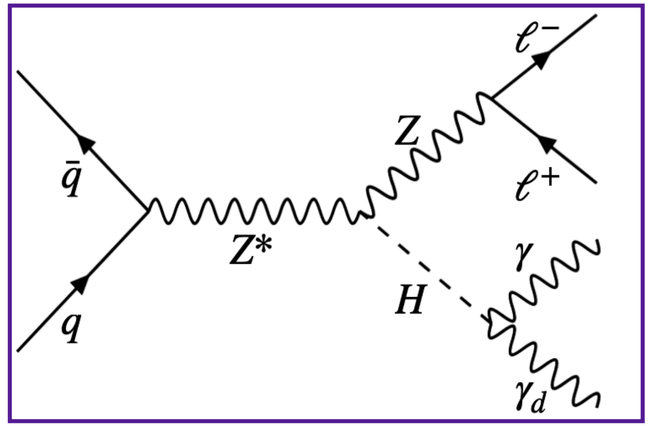
ZH $H \to \gamma\gamma_d$

https://arxiv.org/abs/2212.09649

- ✓ Signal: $ZH, Z \to \ell^+\ell^-$ and $H \to \gamma\gamma_d$ (undetected dark photon $\to E_T^{miss}$).
- ✓ BDT (XGBoost) is used to enhance the analysis sensitivity.
- ✓ Background estimation:
  - ✳ Fake E_T^{miss}: $Z\gamma + jets, Z + jets \Rightarrow$ Data-driven ABCD
  - ✳ $e \to \gamma$ fake: $VV, VVV \Rightarrow$ Data-driven fake rate and probe-electron CR
  - ✳ top, $VV\gamma$, $W\gamma$, Higgs: MC estimated with validations in CR, VR.







Observed (expected) exclusion limits at 95% CL on the BR(H → $\gamma\gamma_d$) as a function of the dark photon mass: are found to be within the [2.19-2.52]% ([2.71-3.11]%) range.

Production	ZH	VBF
ATLAS	**2.3 (2.8)%**	1.8 (1.7)%
CMS	4.6 (3.6)%	3.5 (2.8)%

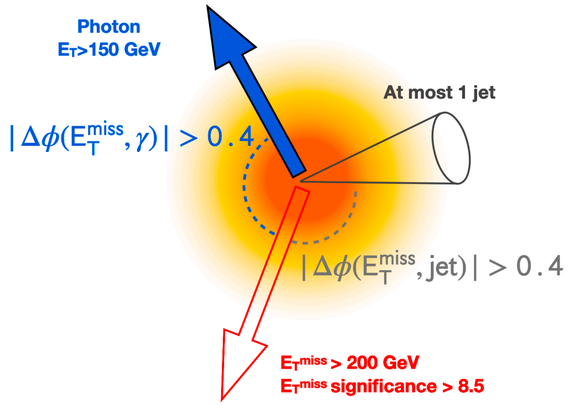
First limit on low mass γ_d from H → $\gamma\gamma_d$ at the LHC

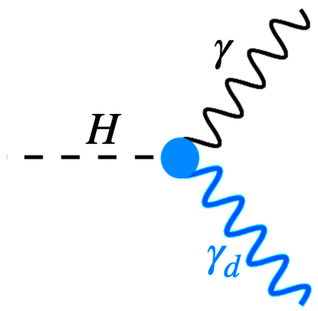
ggF and new VBF $H \to \gamma\gamma_d$

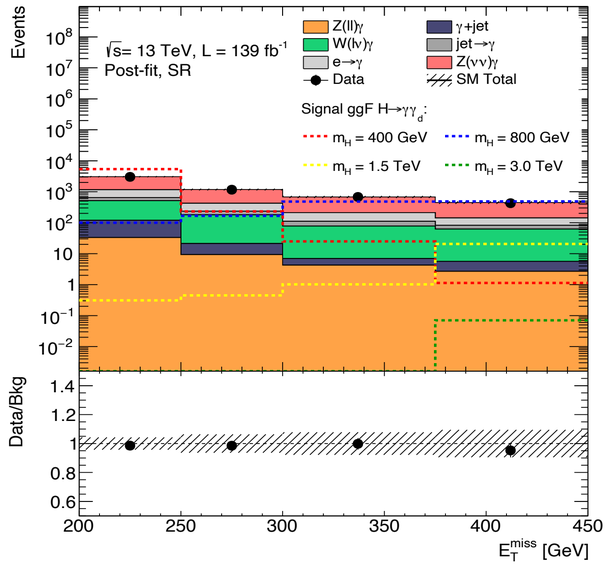
https://cds.cern.ch/record/2851415/

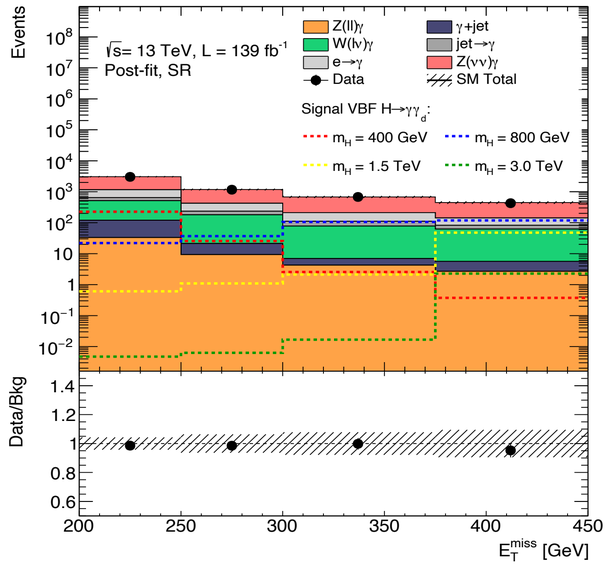
Reinterpretation of the ATLAS mono-photon ($\gamma + E_T^{miss}$) to search for dark photons in high-mass resonances.

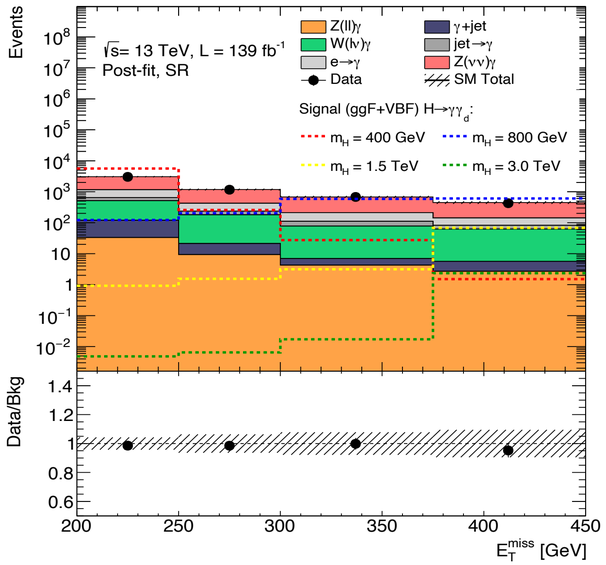
- E_T^{miss} trigger limits the reach for low masses.
- Analysis optimised in E_T^{miss} bins defining 4 SRs for maximum sensitivity.
- Main background: $Z(\to \nu\nu)\gamma$, $W(\to \ell\nu)\gamma$ and Fake objects.
- Massless γ_d and 8 heavy Higgs boson mass points: 400-3000 GeV.
- Considering ggF and VBF production modes.
- Discriminant variable: E_T^{miss}







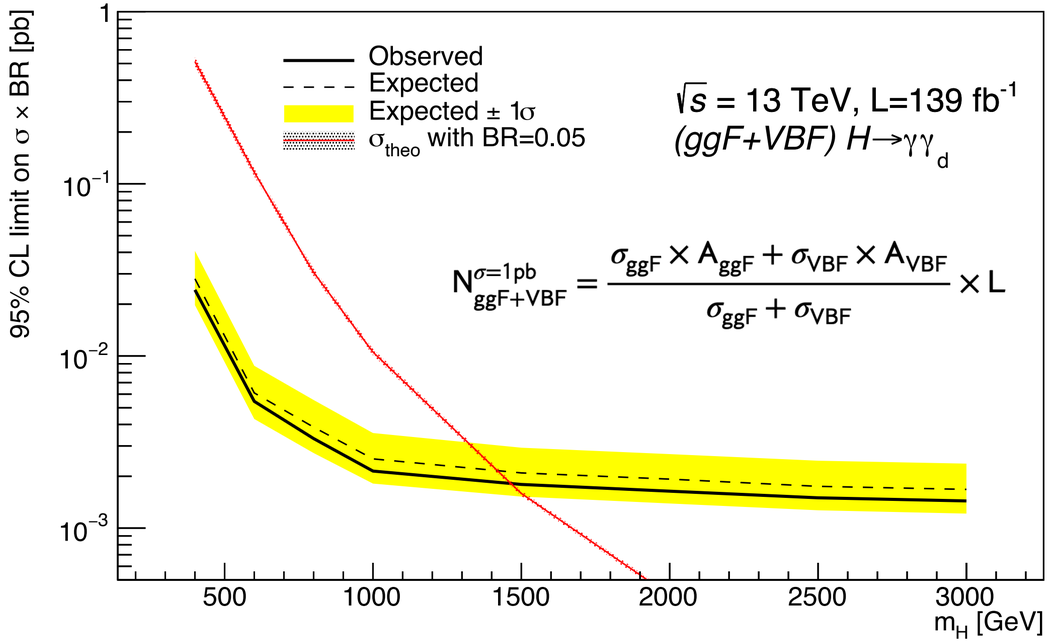




ggF and new VBF H → $\gamma\gamma_d$

https://cds.cern.ch/record/2851415/

- Independent results for ggF (**first at the LHC**) and VBF (**Improved results** w-r-t existing analysis, most stringent exclusion at high mass $\gamma + E_T^{miss}$ resonances), + **combination.**
- Observed (expected) exclusion limits at 95% CL on the $\sigma \times BR(H \rightarrow \gamma\gamma_d)$ as a function of the heavy Higgs boson mass for separate and combined production modes are found to be within the **[1.44-24.2]fb ([1.68-28.1]fb)** range.



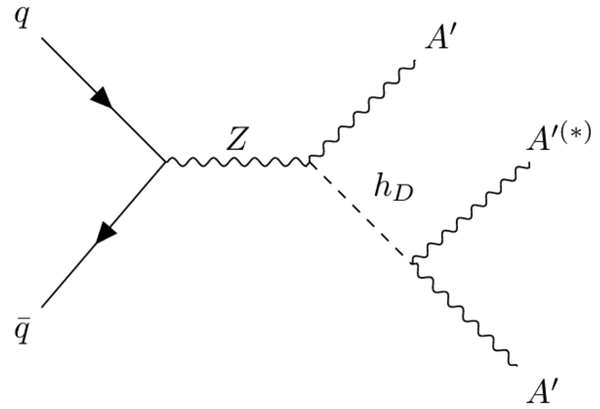
ggF and VBF production modes combined with relative contribution from theoretical cross-section

95% CL Limits	$\sigma_{ggF} \times BR$		$\sigma_{VBF} \times BR$		$\sigma_{(ggF+VBF)} \times BR$	
m_H	Obs. (fb)	Exp.$^{+1\sigma}_{-1\sigma}$ (fb)	Obs. (fb)	Exp.$^{+1\sigma}_{-1\sigma}$ (fb)	Obs. (fb)	Exp.$^{+1\sigma}_{-1\sigma}$ (fb)
400 GeV	23.9	$27.3\ ^{+12.7}_{-7.80}$	44.4	$51.4\ ^{+23.1}_{-15.2}$	24.2	$28.1\ ^{+12.7}_{-8.30}$
600 GeV	5.08	$5.72\ ^{+2.60}_{-1.65}$	9.30	$10.43\ ^{+4.35}_{-2.94}$	5.45	$6.10\ ^{+2.66}_{-1.80}$
800 GeV	3.04	$3.56\ ^{+1.63}_{-1.05}$	4.54	$5.28\ ^{+2.17}_{-1.46}$	3.31	$3.86\ ^{+1.69}_{-1.13}$
1 TeV	1.93	$2.30\ ^{+1.02}_{-0.67}$	2.62	$3.08\ ^{+1.21}_{-0.85}$	2.14	$2.52\ ^{+1.04}_{-0.71}$
1.5 TeV	1.73	$2.05\ ^{+0.92}_{-0.60}$	1.86	$2.17\ ^{+0.87}_{-0.59}$	1.79	$2.09\ ^{+0.84}_{-0.57}$
2 TeV	1.74	$2.05\ ^{+0.88}_{-0.59}$	1.64	$1.92\ ^{+0.78}_{-0.52}$	1.64	$1.93\ ^{+0.76}_{-0.54}$
2.5 TeV	2.06	$2.44\ ^{+1.24}_{-0.77}$	1.48	$1.73\ ^{+0.70}_{-0.49}$	1.50	$1.75\ ^{+0.71}_{-0.48}$
3 TeV	2.11	$2.50\ ^{+1.27}_{-0.79}$	1.42	$1.66\ ^{+0.69}_{-0.46}$	1.44	$1.68\ ^{+0.69}_{-0.46}$

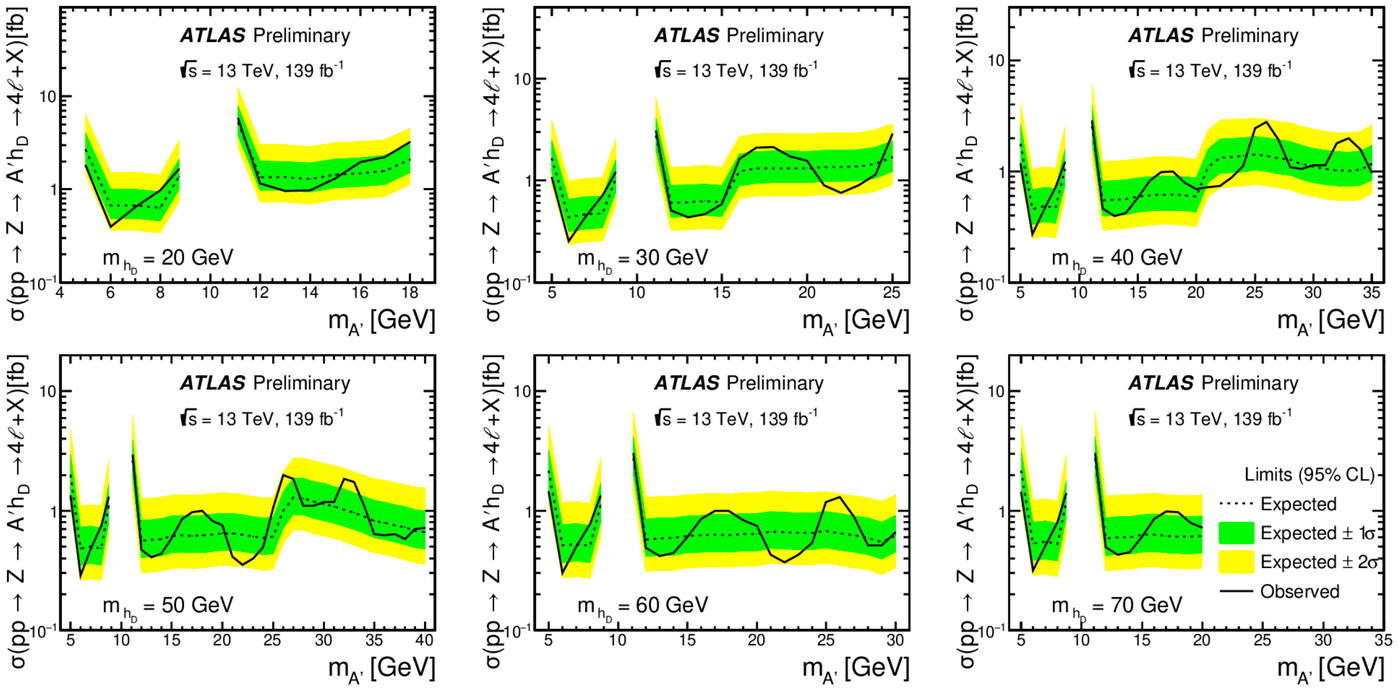
Dark photons in rare Z boson decays

https://cds.cern.ch/record/2855334

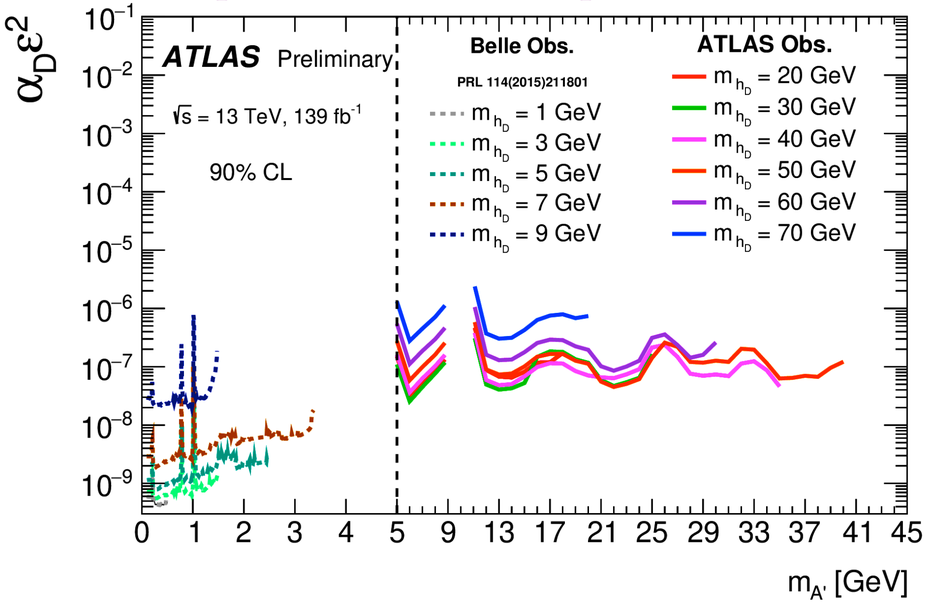
- First search for a dark photon and dark Higgs boson produced via the dark Higgs-strahlung process in rare Z boson decays at the LHC, with a final state of at least four charged (from dark photon decay).



Upper limits on the production cross-section times branching fraction for
5 GeV < mA' < 40 GeV and 20 GeV < m_h < 70 GeV



Upper limits on the dark photon coupling to the dark Higgs boson times the kinetic mixing between the SM photon and the dark photon, $\alpha D\epsilon^2$



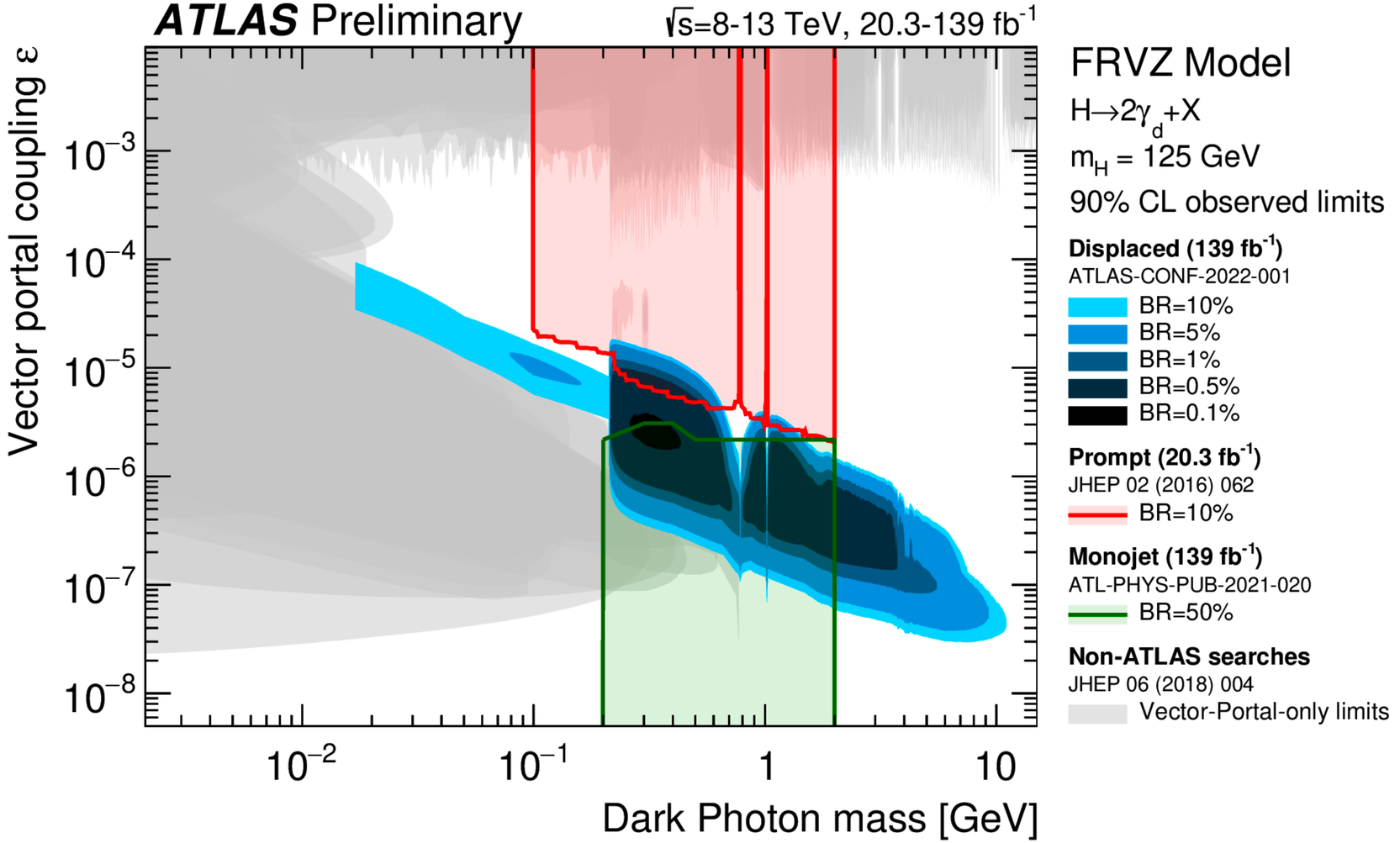
$\sqrt{s} = 8 - 13$ TeV, $20.3 - 139$ fb^{-1} dark photon summary plot

Summary plot

http://cds.cern.ch/record/2803320

Results from three different ATLAS analyses are shown for different assumptions on the H→ 2γd+X branching ratio, ranging between 0.1% and 50%.

The masses of the intermediate dark fermions predicted by the model are chosen to be light relative to the Higgs boson mass and far from the kinematic threshold for the production of the γd and the HLSP.



Summary

- Many signatures were explored thanks to excellent detector performance
- Massless and massive dark photons both are considered in ATLAS searches.
- Wide range of parameter space and models covered by ATLAS, but no hint so far
- No significant excess of events above SM background prediction with the LHC Run 2 data.
- Upper limits at 95% CL are set on branching ratios and model parameters (coupling, mass, lifetime)
- Stay tuned for new Run 3 ATLAS dark photon results.