Dark photon searches with the ATLAS Detector at the LHC

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On behalf of the ATLAS collaboration

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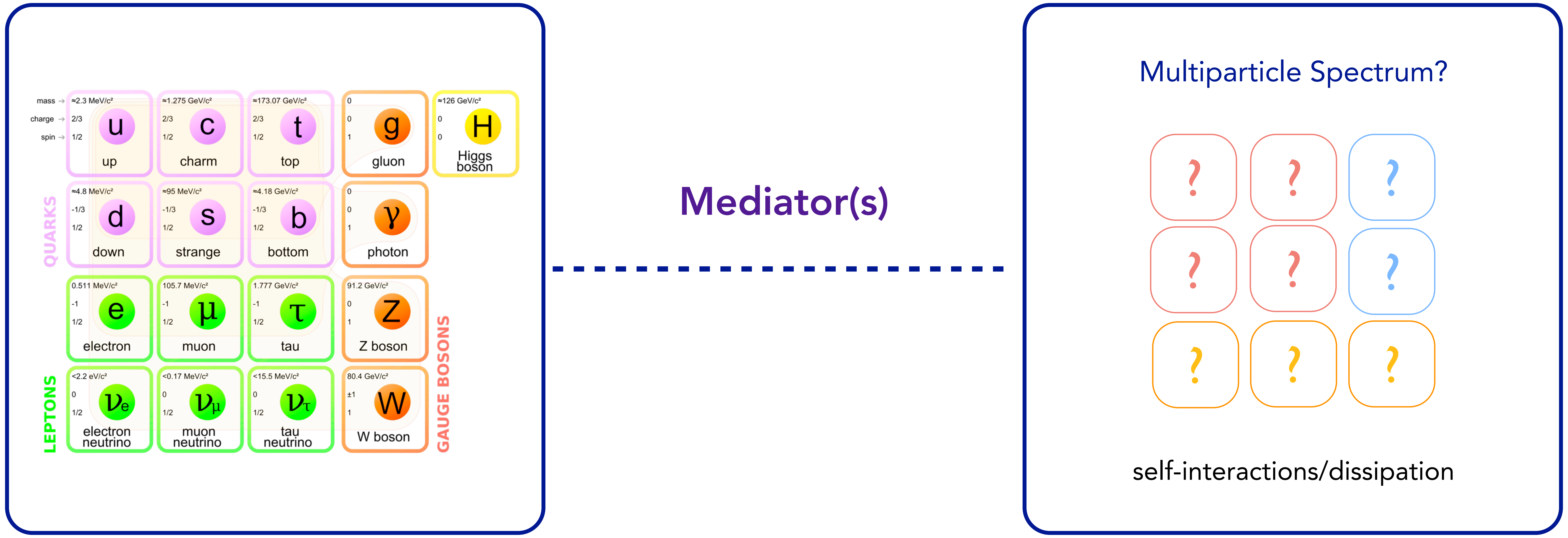
Hidden Dark Sector

Attractive BSM scenarios predict **existence of a Dark Sector (DS)** allowing a wide variety of unexplored signatures at the LHC.

- DS is a hypothetical collection of fields and particles predicted as a possible SM extensions with no direct interactions.
  - Couples extremely weakly to the SM through mediating particles such as **Dark photons** (“portal” interactions)

Visible Sector **Hidden Sector**



Dark Photon

- Predicted in models with an additional dark U(1) gauge symmetry in the hidden sector (arxiv:2005.01515).
- Either kinetically mixes with the SM photon or couples to the Higgs sector via mediators and could be produced through portals:

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

Vector portal [Okun; Galison & Manohar; Holdom; Foot et al]

Higgs portal [Patt & Wilczek]

Neutrino portal [Patt & Wilczek]

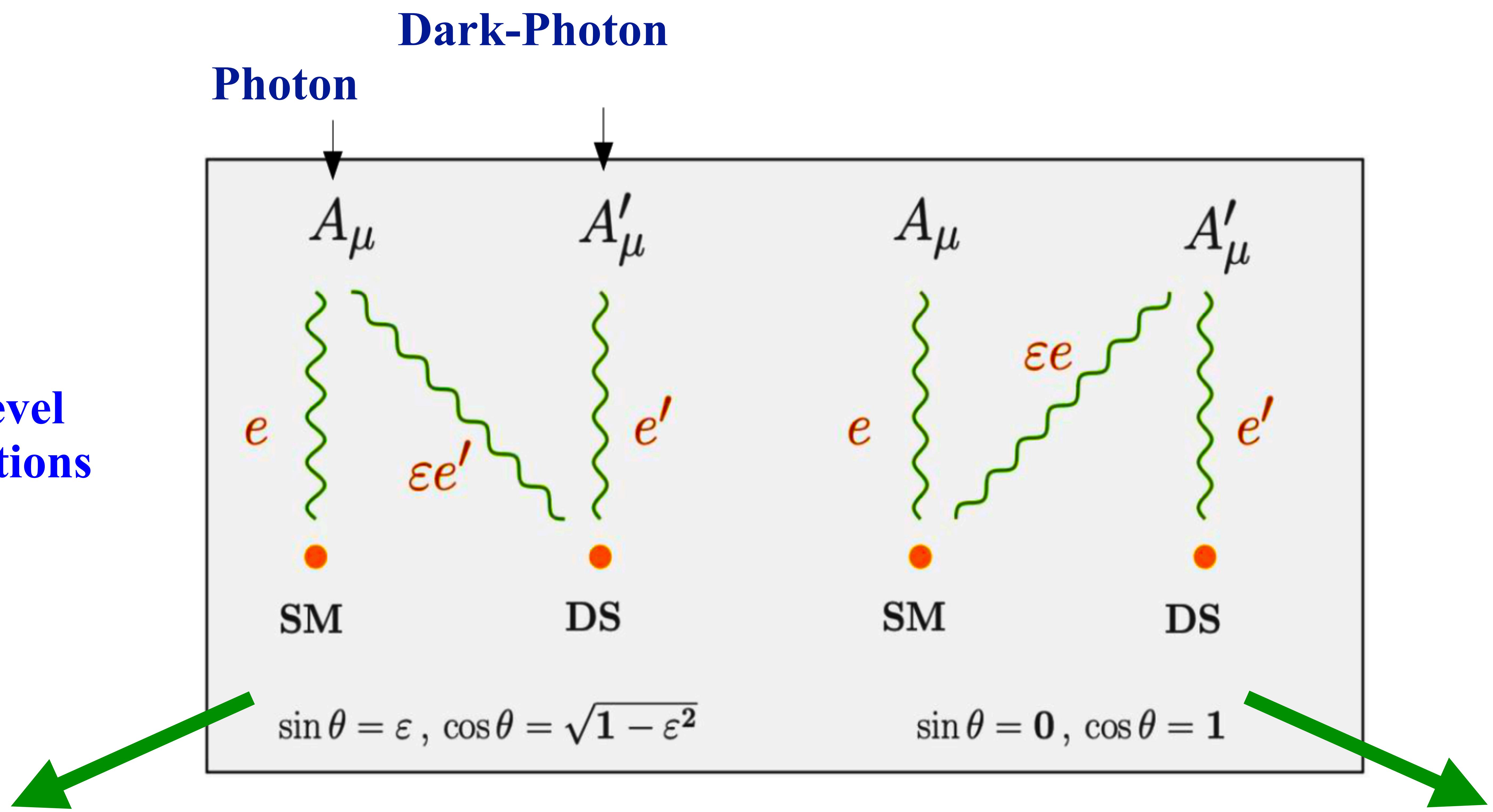
Axion portal [Weinberg; Wilczek; KSVS; DFSZ]

- **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

Massive vs massless

Summary of tree-level dark photon interactions

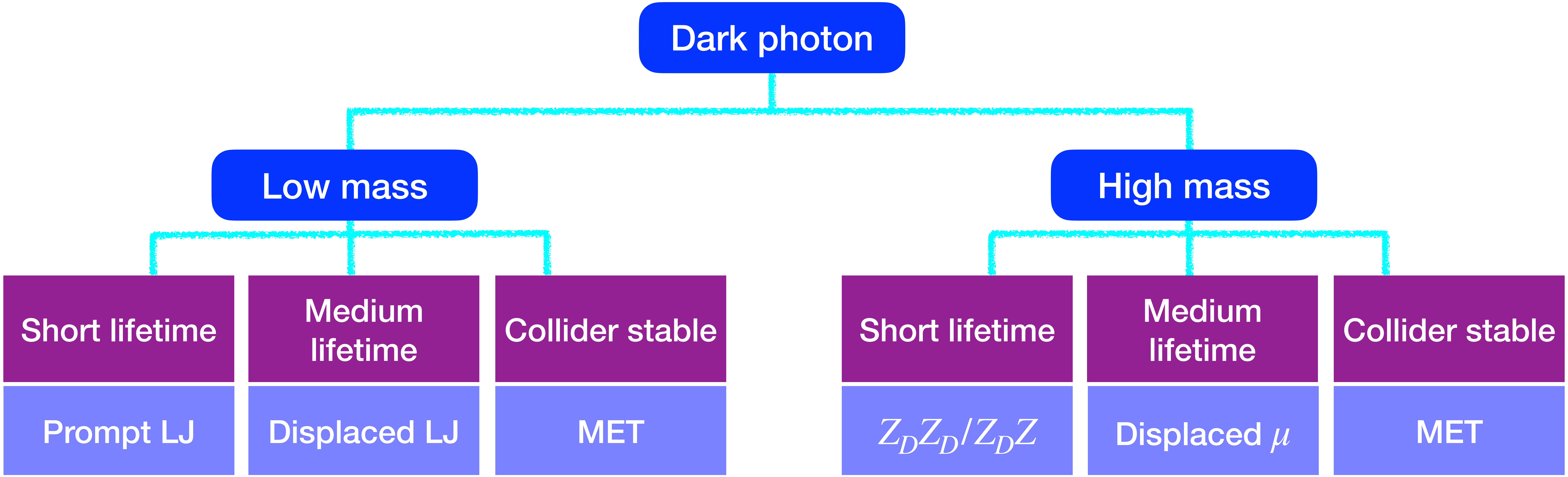


Massless Dark-Photon: less explored scenario (No tree-level couplings with SM) => effective (higher-dimensional operators induced at 1-loop).

Massive Dark-Photon: most searched for (tree-level coupling with SM fermions via kinetic mixing).

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



Summary of ATLAS dark photon results between 2020 - 2024

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

PhysRevD.99.012001

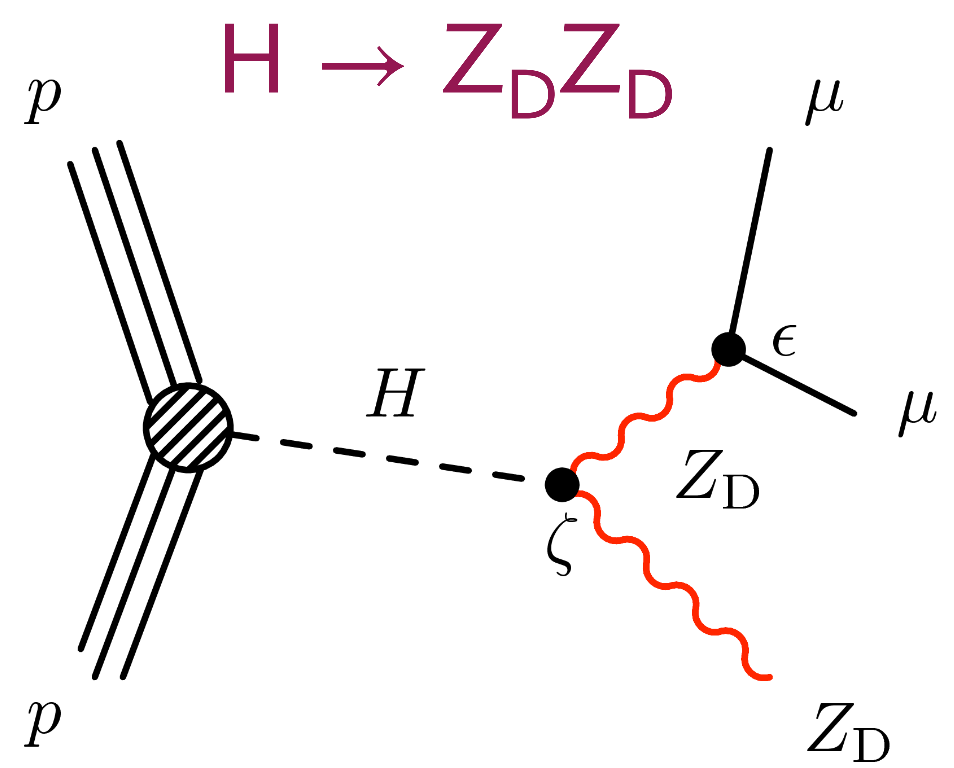
- ggF Higgs production: 44.1 pb.
- m_H= 125 GeV, m_{H_D}= 300 GeV
- Main background: low-mass Drell–Yan, Z+jets and cosmic-muons.
- m_{Z_D}= 20–60 GeV => $Br(Z_D \to \mu^+\mu^-)$ = 0.1475 - 0.1066.

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

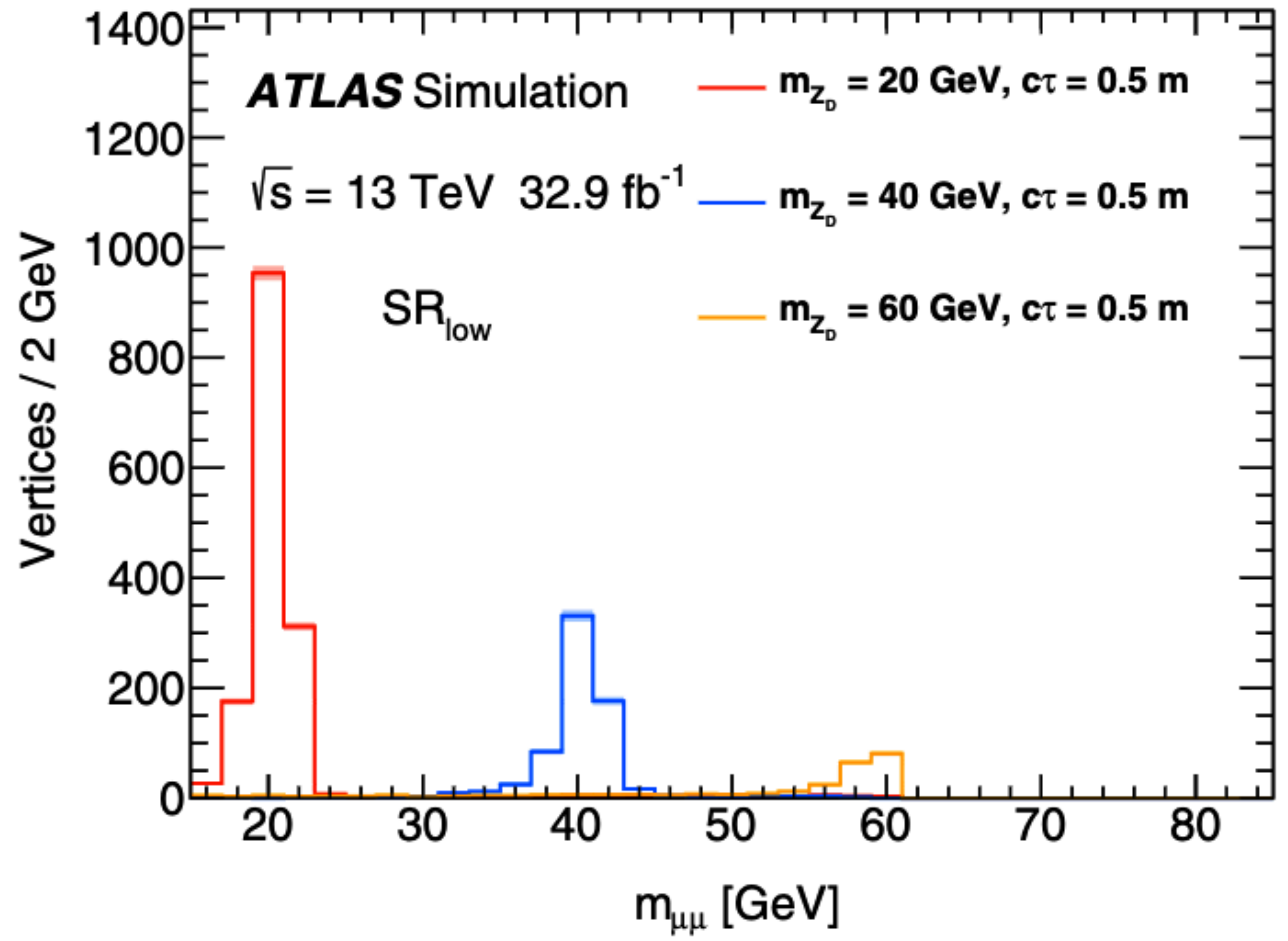
$$\sigma(pp \to H) \times B(H \to Z_D Z_D) \times B(Z_D \to \mu^+\mu^-)$$

m_{Z_D} [GeV]	$c\tau_{Z_D}$ [cm]	$B(Z_D \to \mu^+\mu^-)$
20	50	0.1475
40	50	0.1370
40	500	0.1370
60	50	0.1066
60	500	0.1066

Higgs to long-lived dark photons



Di-muon invariant mass

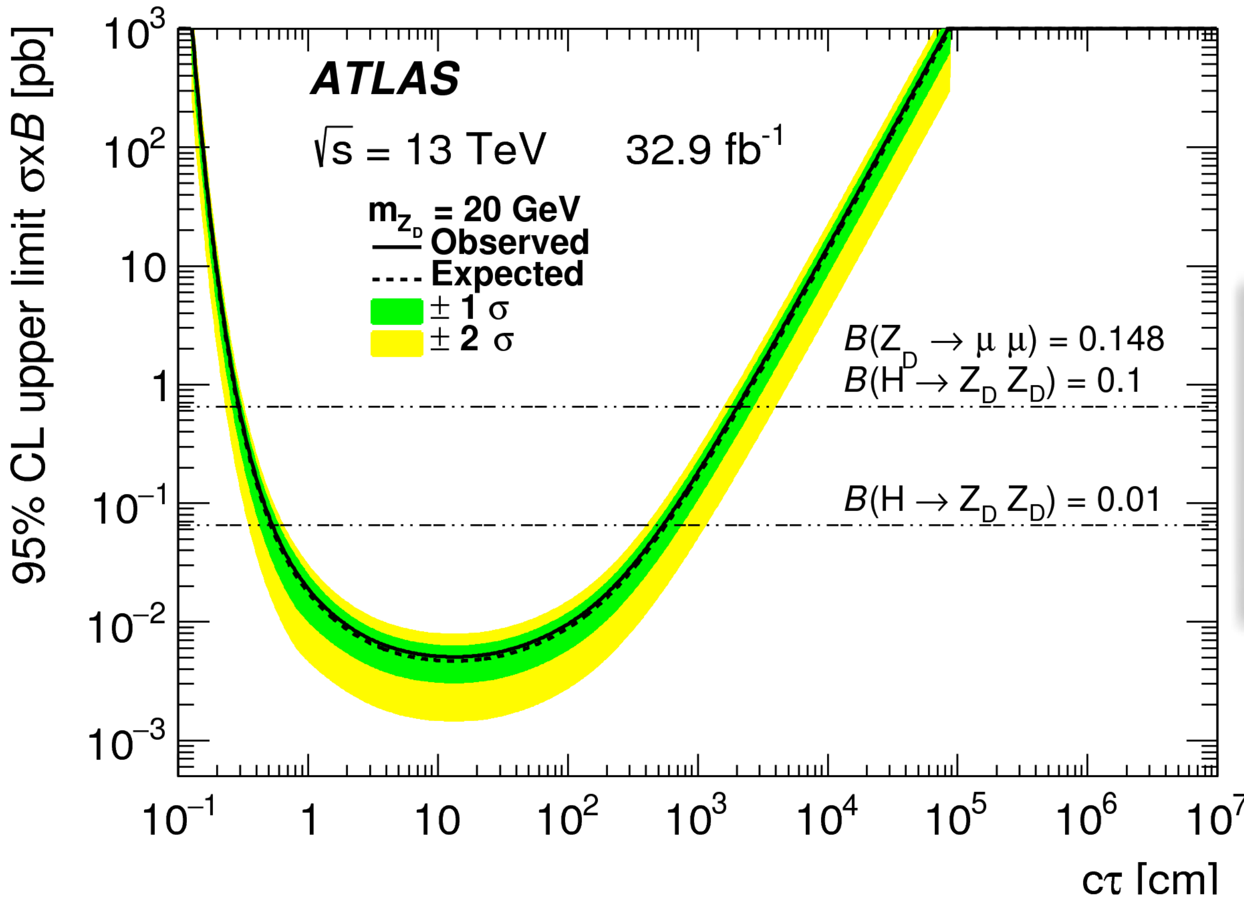


Long-lived particles in displaced di-muon vertices

PhysRevD.99.012001

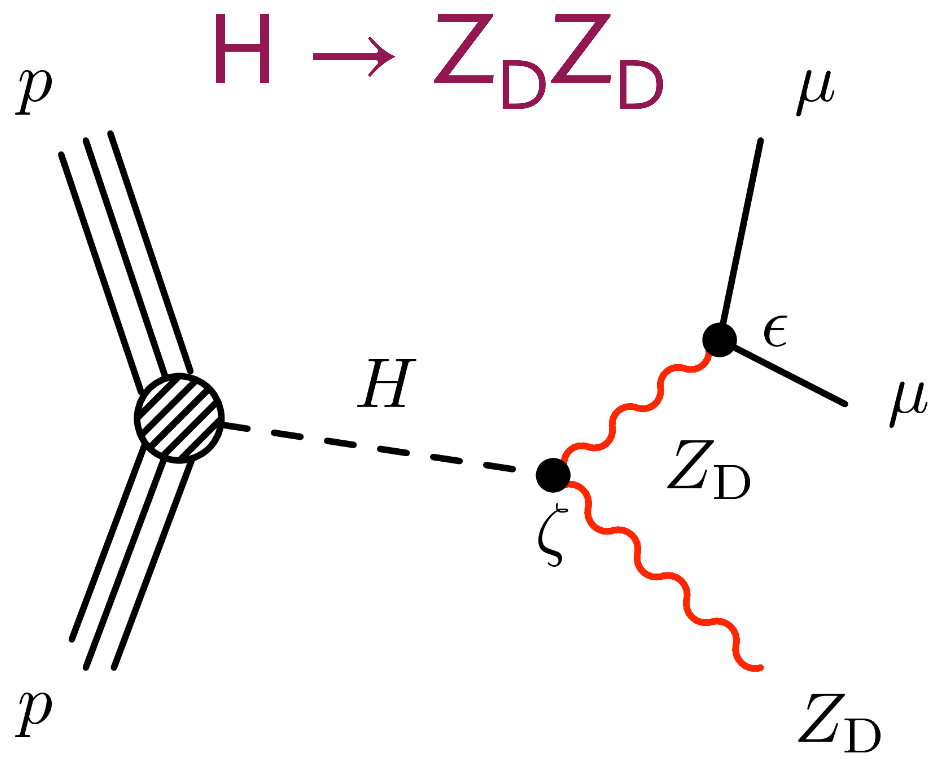
$$\sigma(pp \to H) \times B(H \to Z_D Z_D) \times B(Z_D \to \mu^+\mu^-)$$

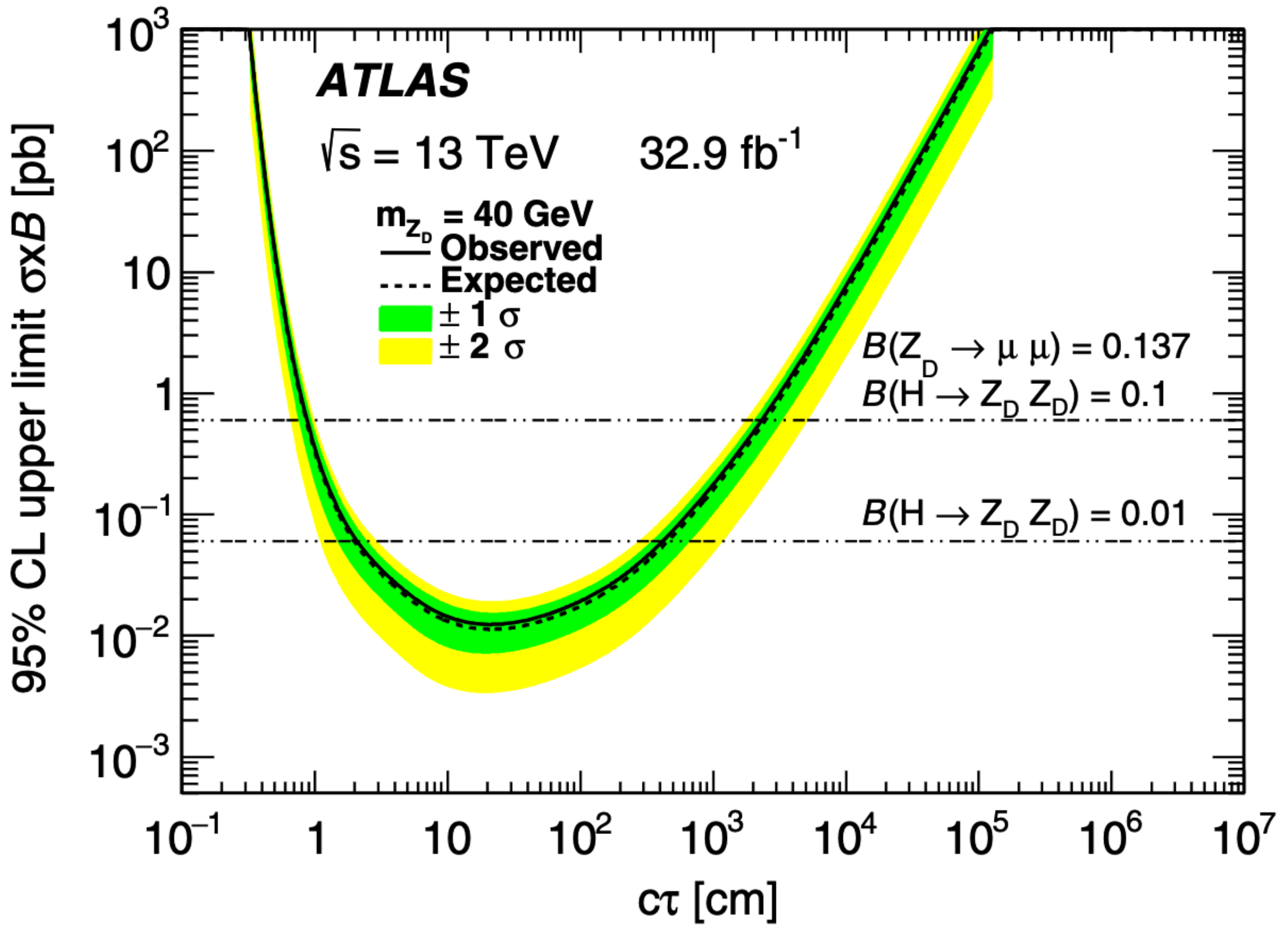
various assumptions on Br($H \to Z_D Z_D$), 1 and 10 %

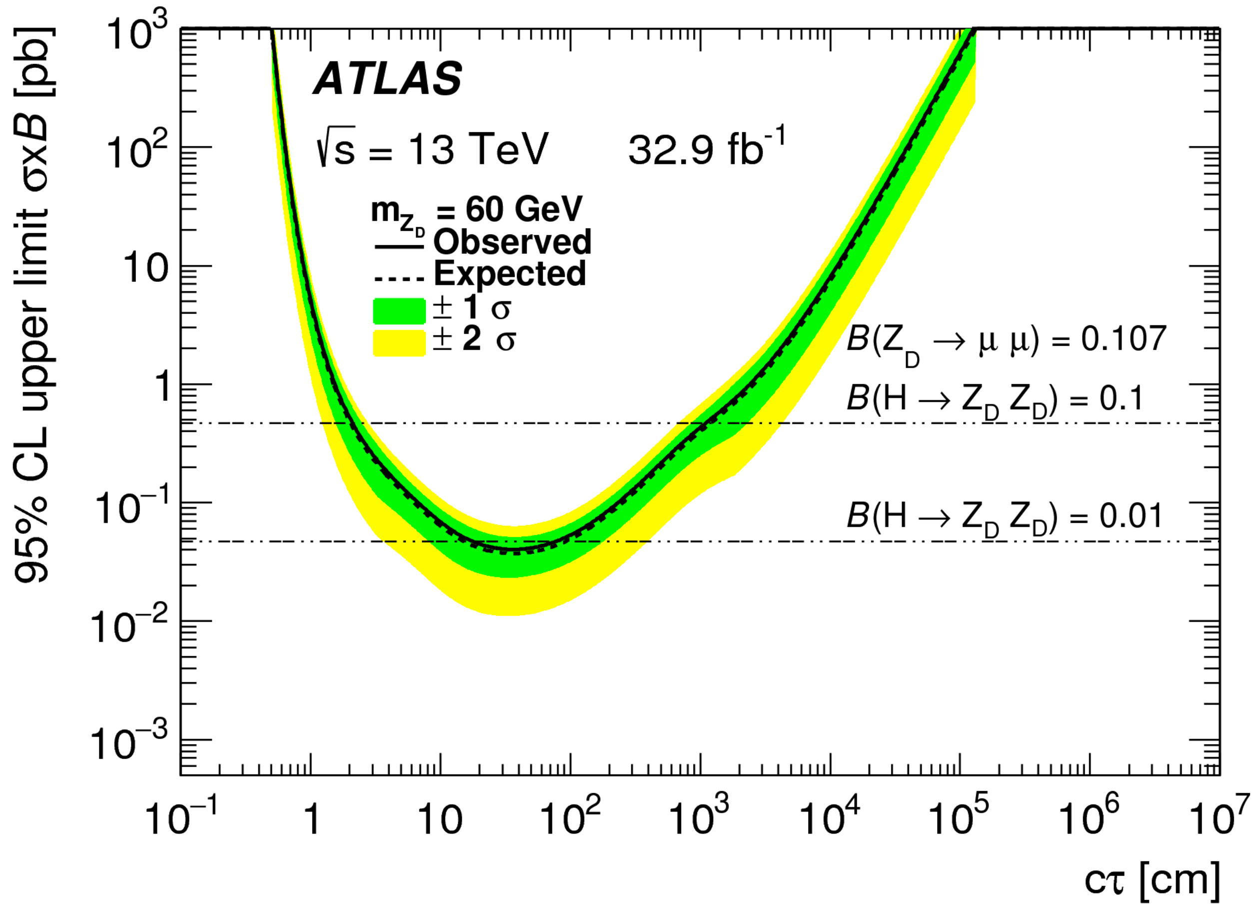


Br=10 %,
cτ = 0.3–2000 cm
excluded

Higgs to long-lived dark photons



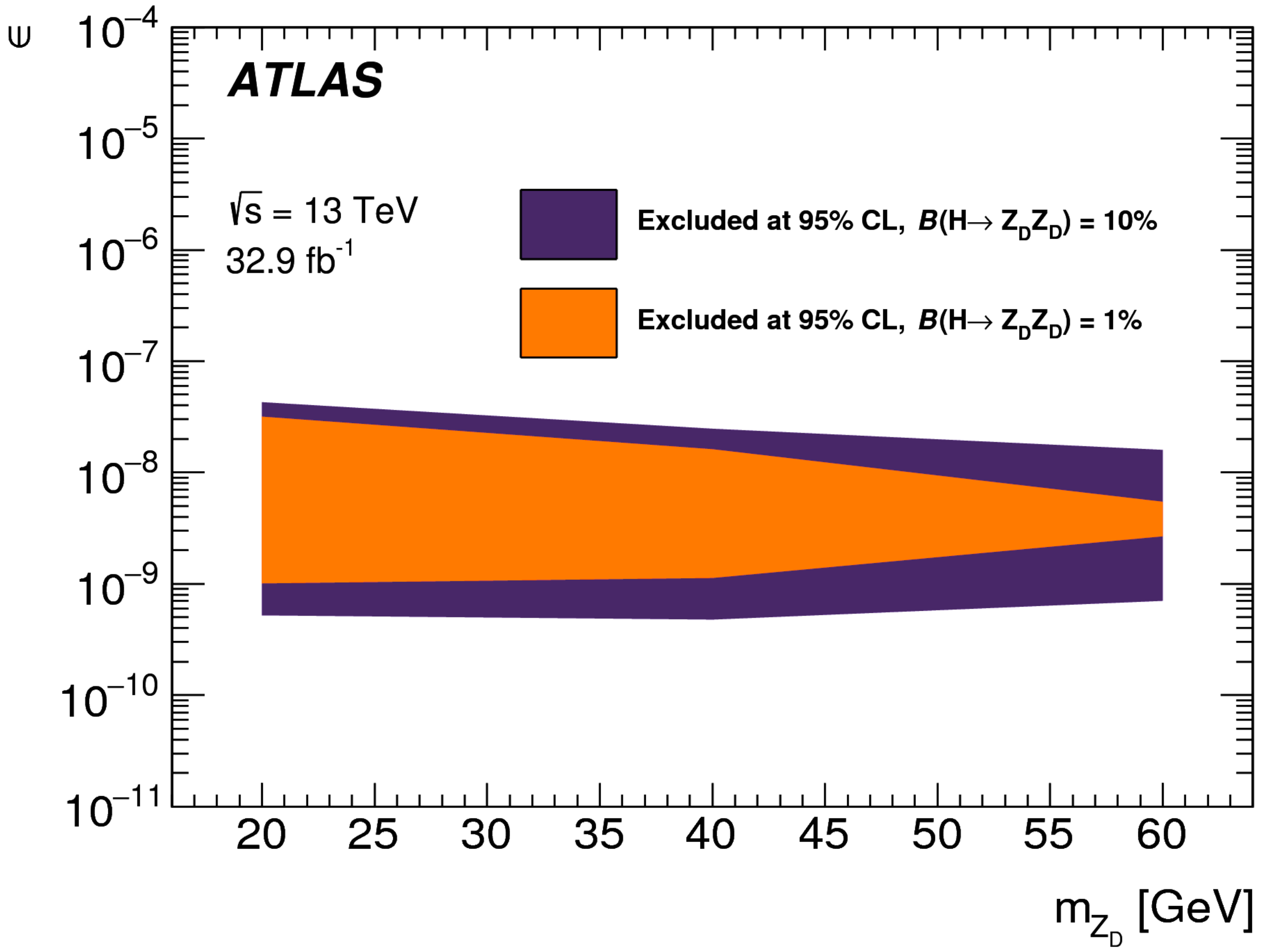




Br=10 %,
cτ = 0.9–2400 cm
excluded

Br=10 %,
cτ = 2.1–1100 cm
excluded

Exclusion contour on the kinetic mixing



Lifetimes in the range cτ = 1–2400 cm are excluded

Displaced Hadronic Jets

ATL-PHYS-PUB-2020-007

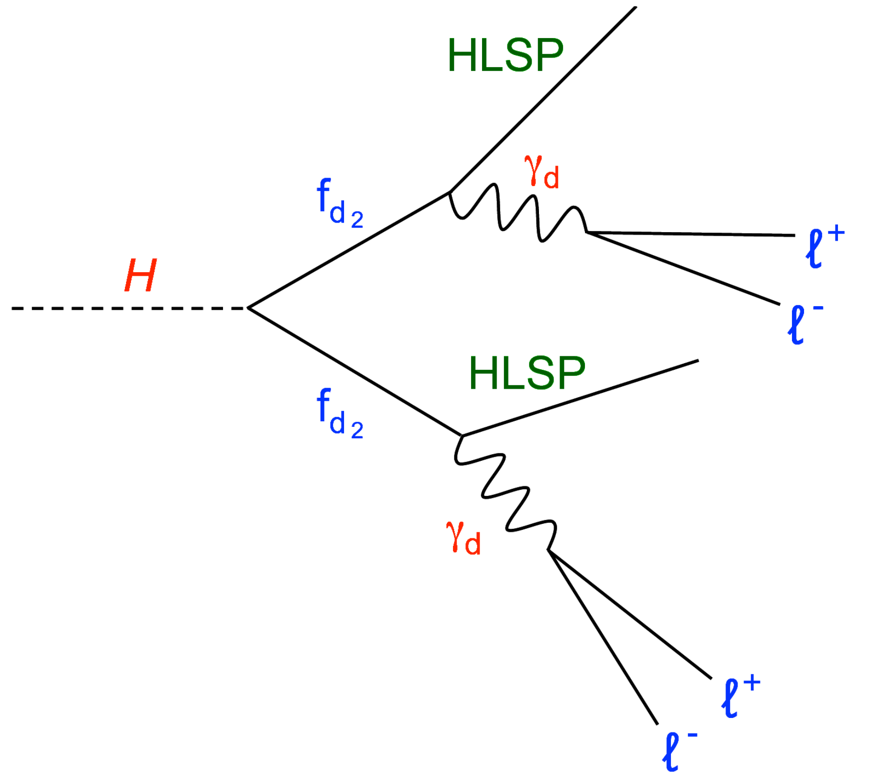
- Higgs and heavy boson decay to collimated hadrons via long-lived dark photons: $m_H = 125, 800$ GeV, $m_{\gamma_d} = 0.4$ GeV.
- Main background: SM multijet production.
- First limit on the SM Higgs channel in this model by ATLAS.

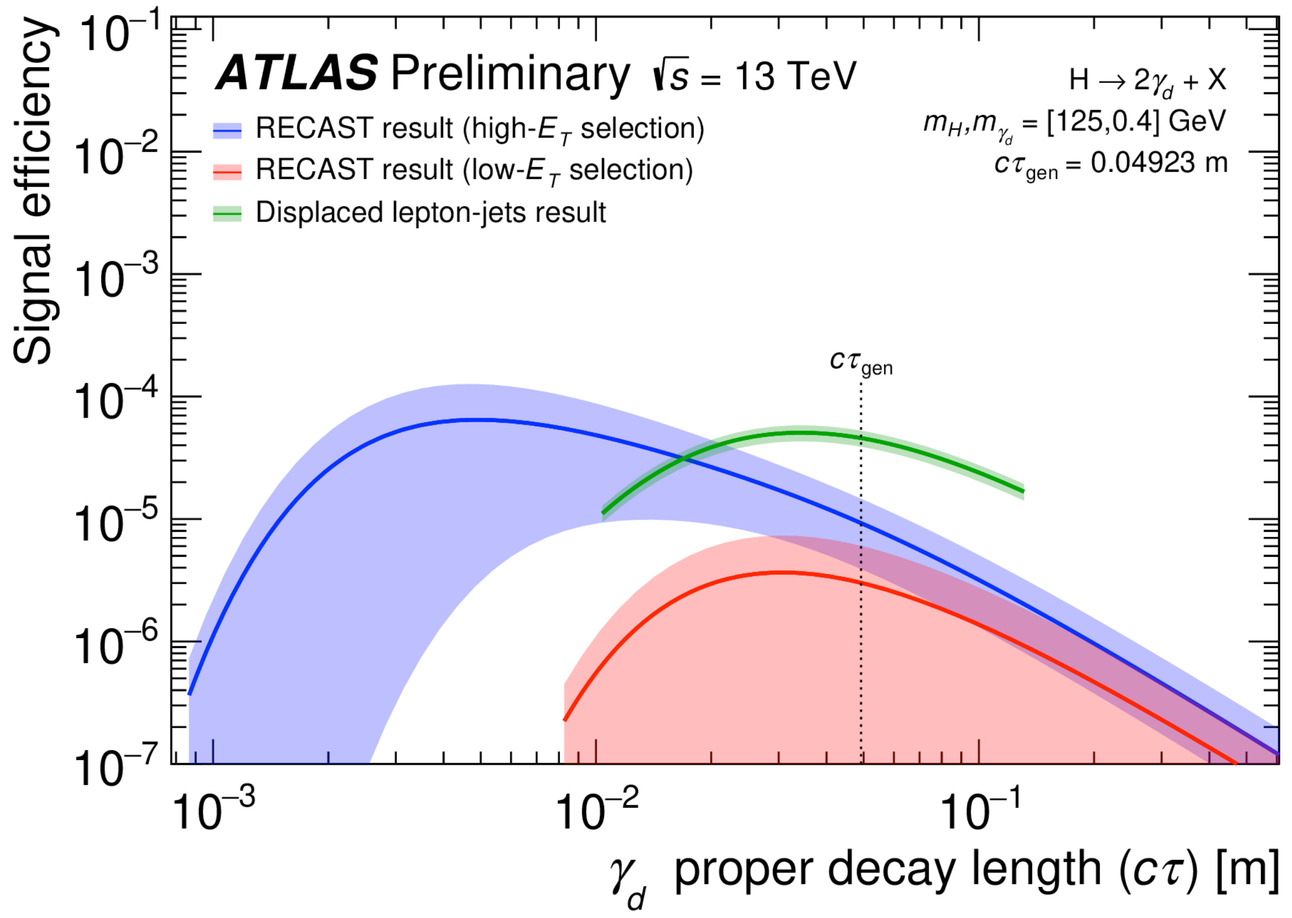
FRVZ model

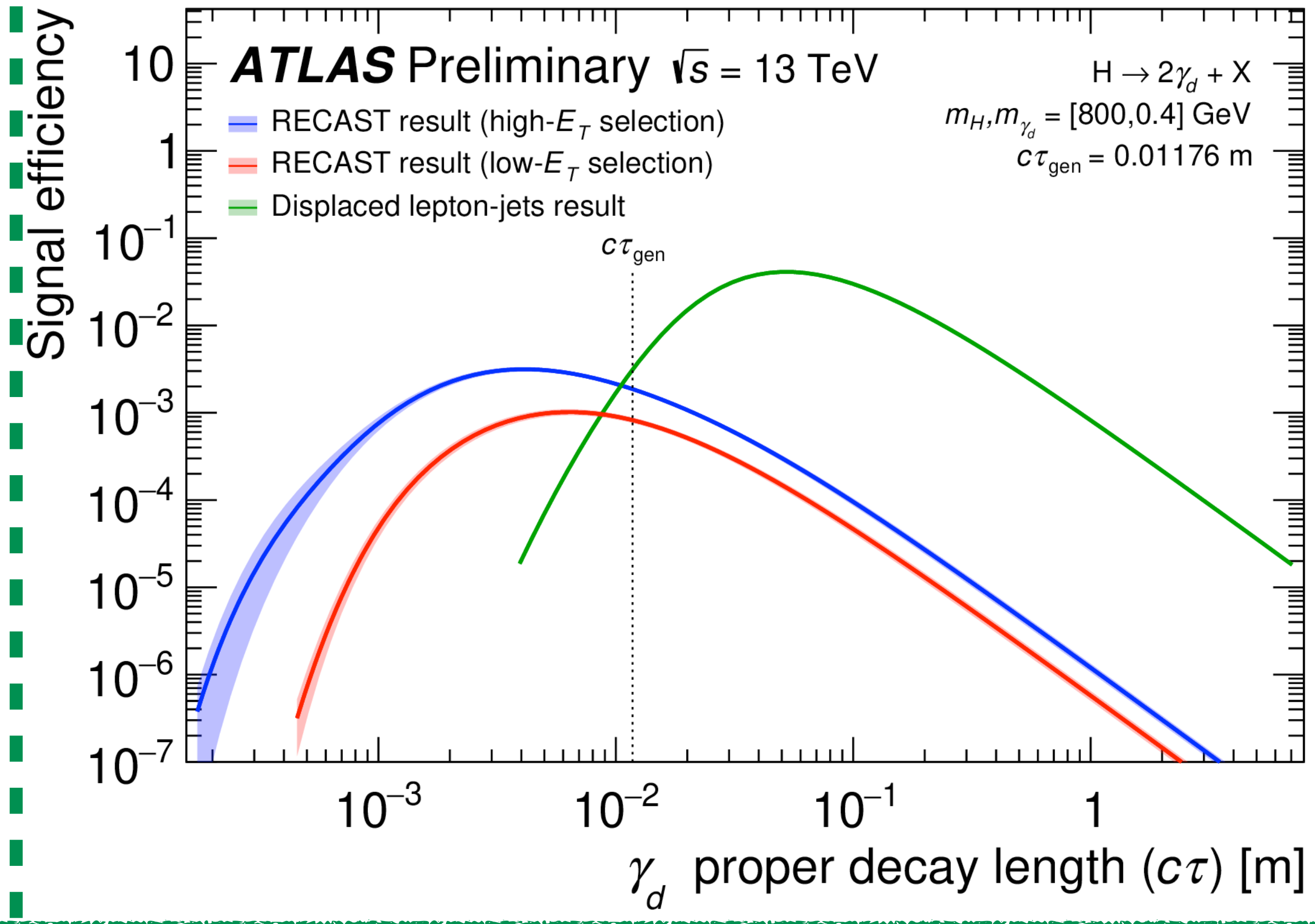
(Falkowski–Ruderman–Volansky–Zupan)

$m_H = 125$ GeV | $m_H = 800$ GeV

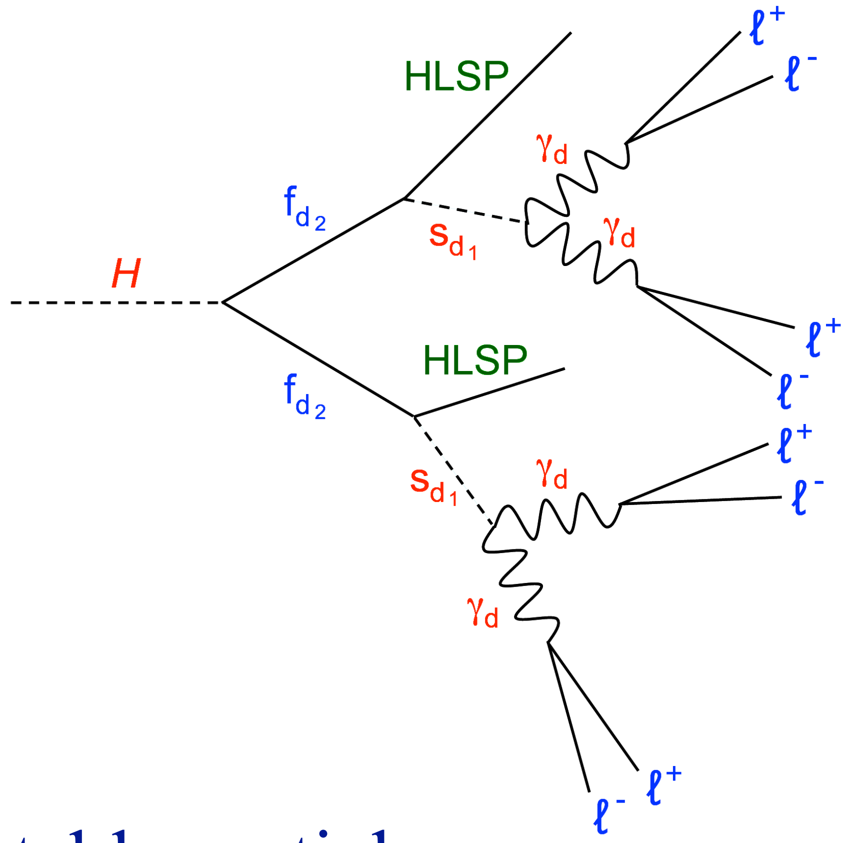
$H \rightarrow 2\gamma_d + X$

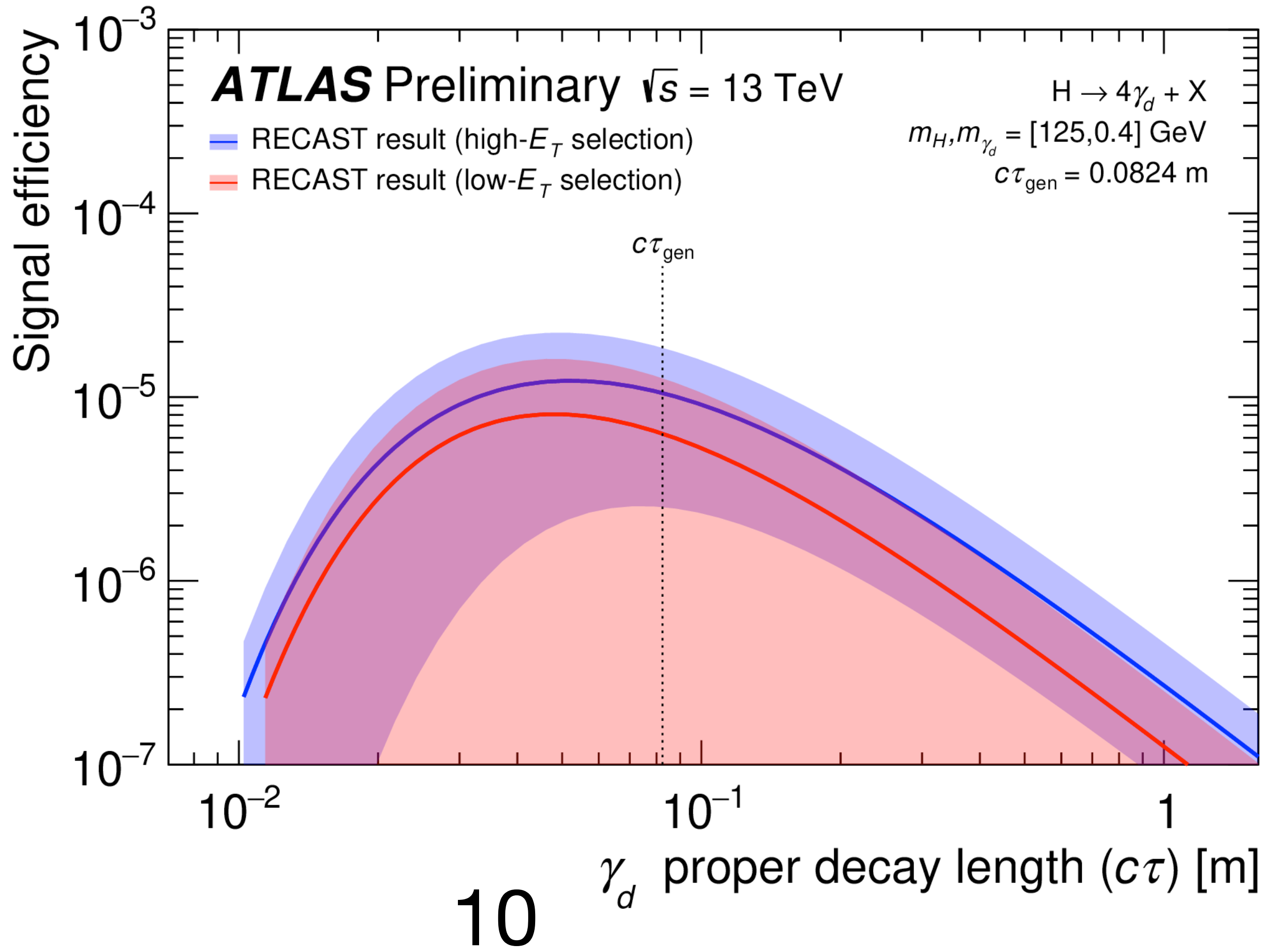


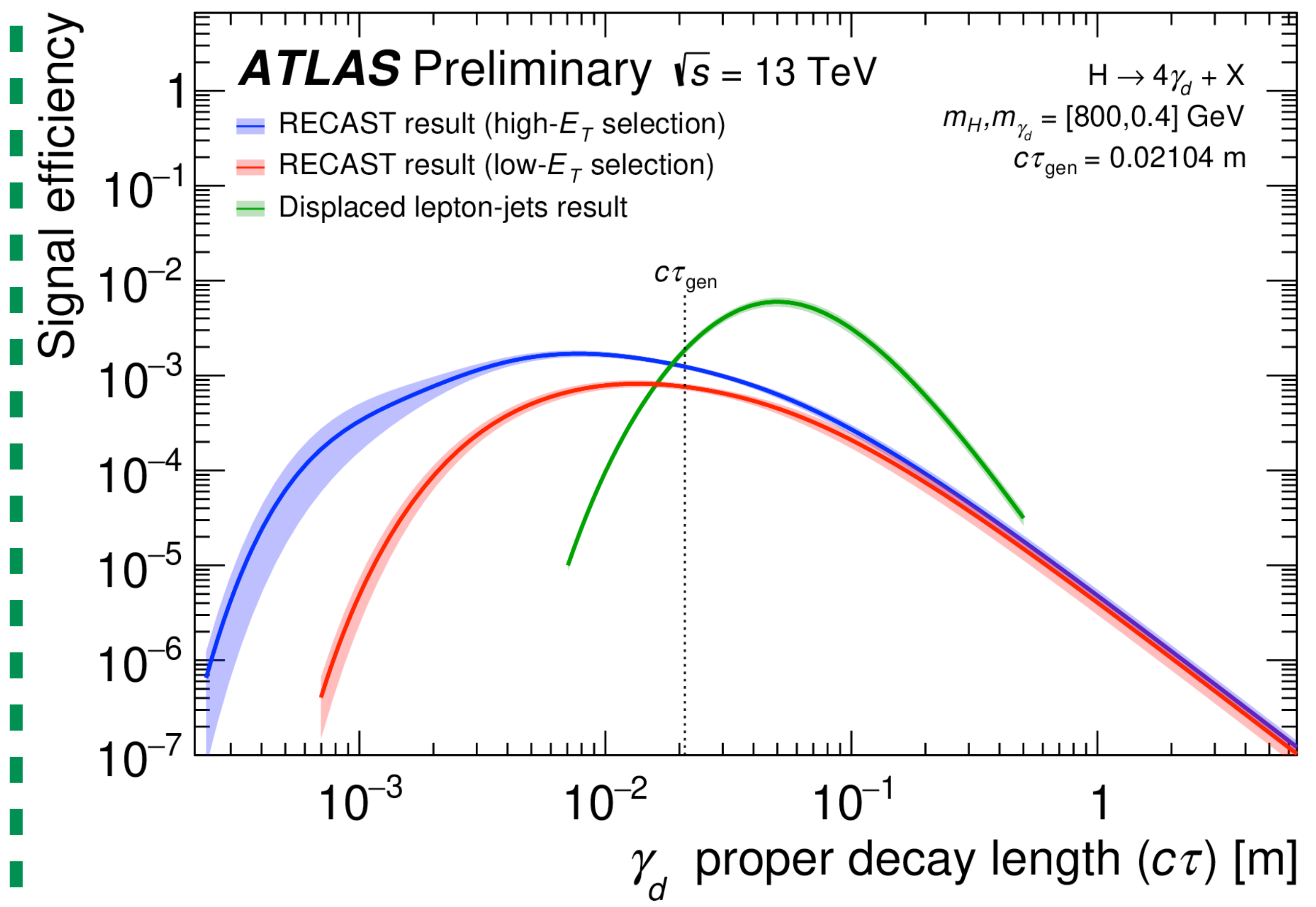




$H \rightarrow 4\gamma_d + X$







- HLSP: hidden lightest stable particle
- cτgen = generated LLP decay length

Displaced Hadronic Jets

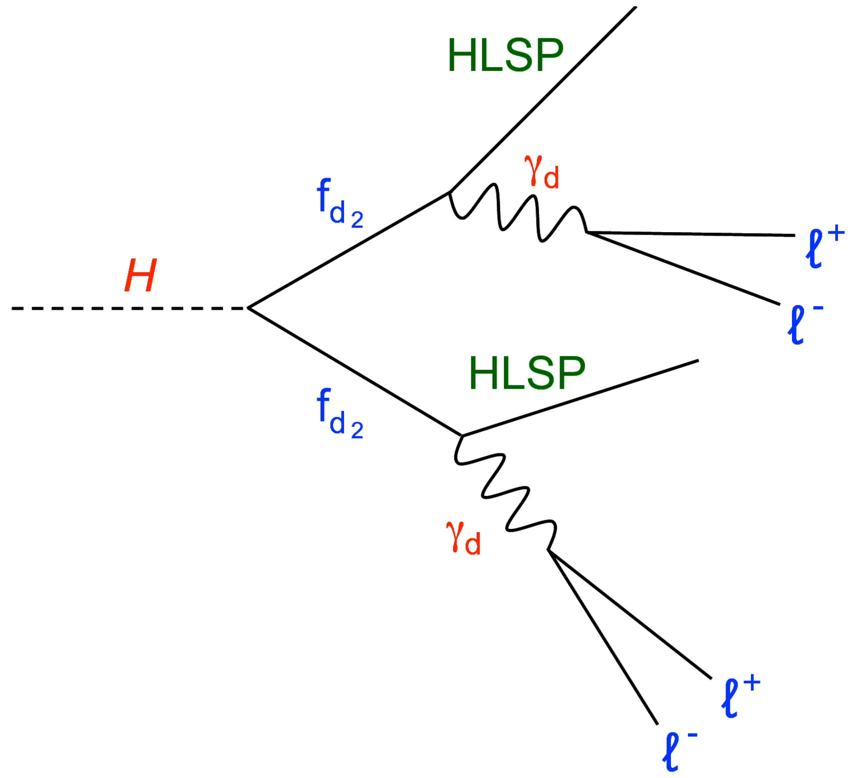
ATL-PHYS-PUB-2020-007

- 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.

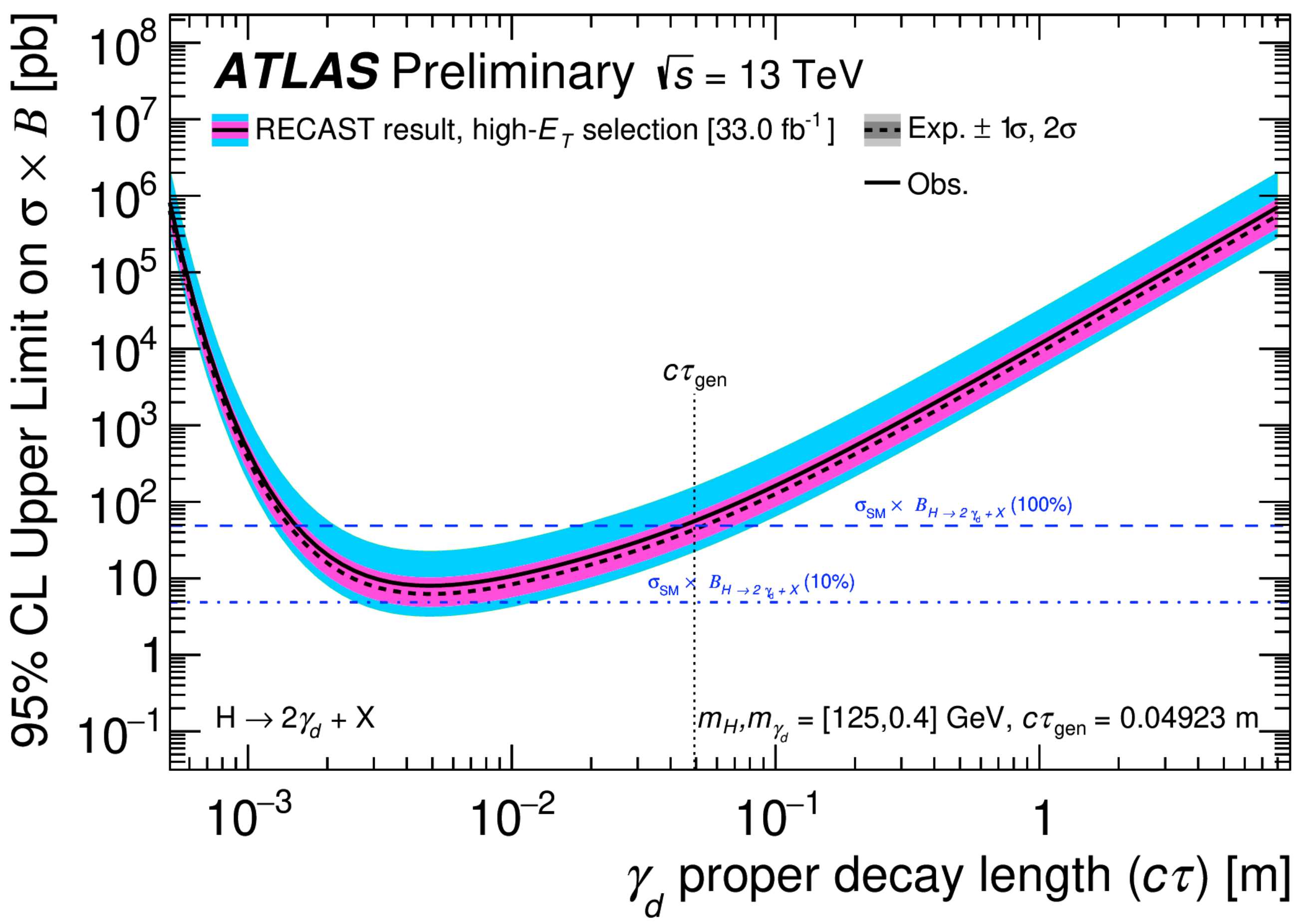
FRVZ model

(Falkowski–Ruderman–Volansky–Zupan)

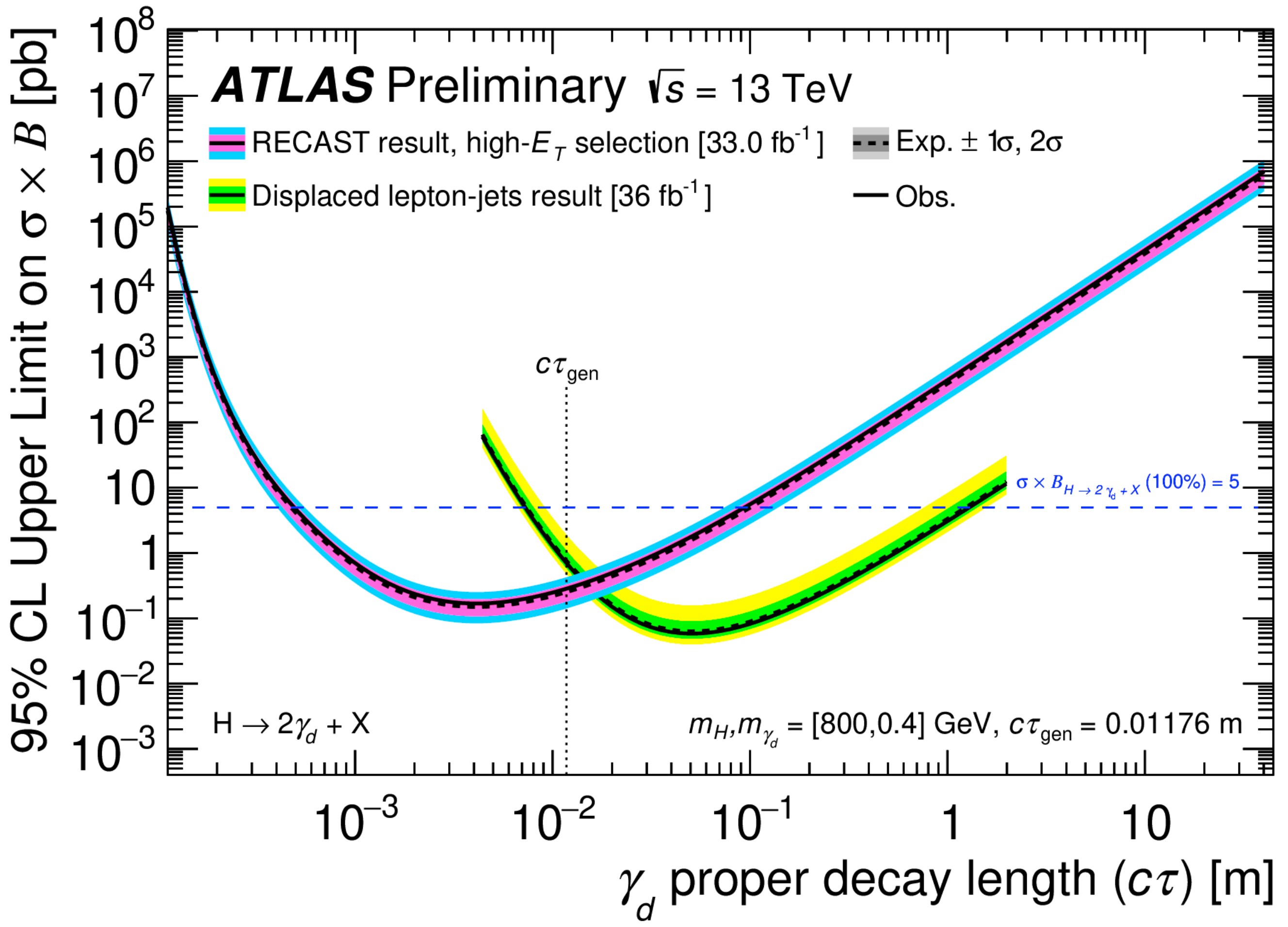
$H \to 2\gamma_d + X$



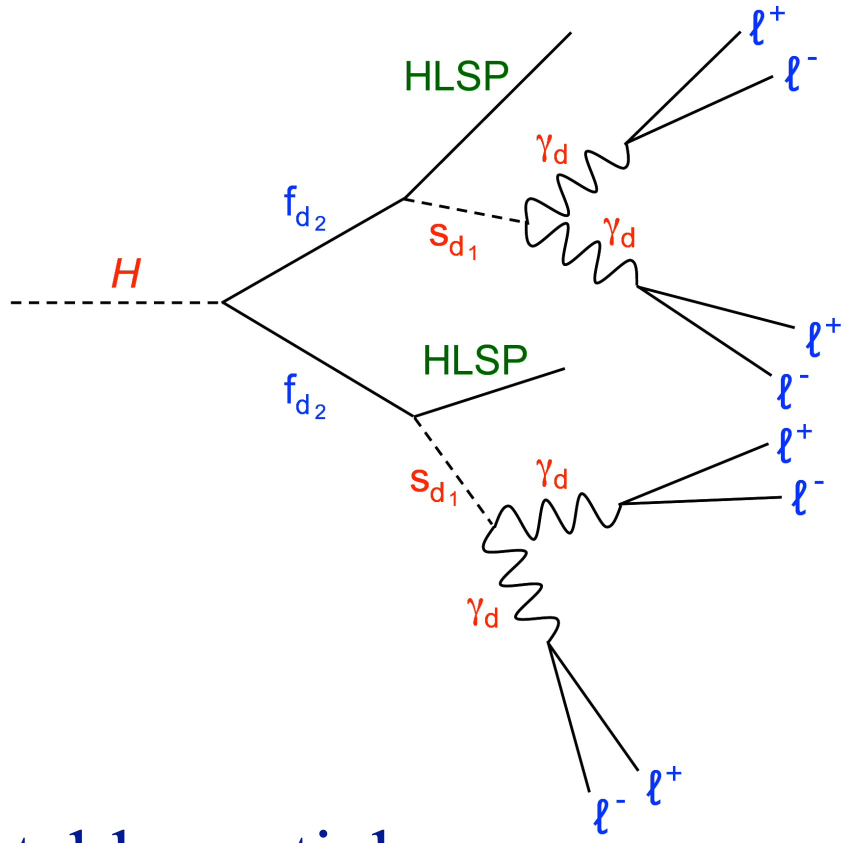
$m_H = 125$ GeV

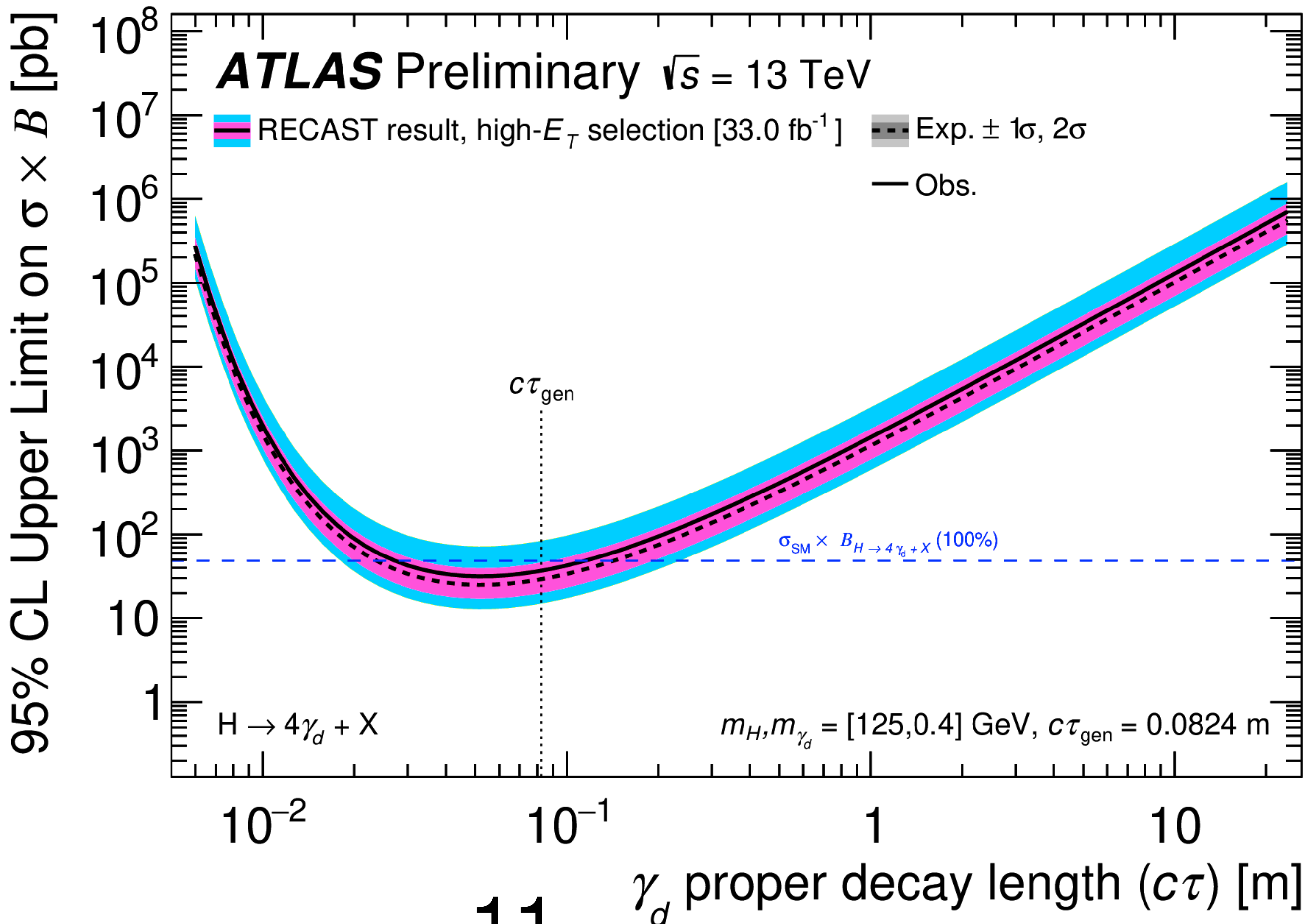


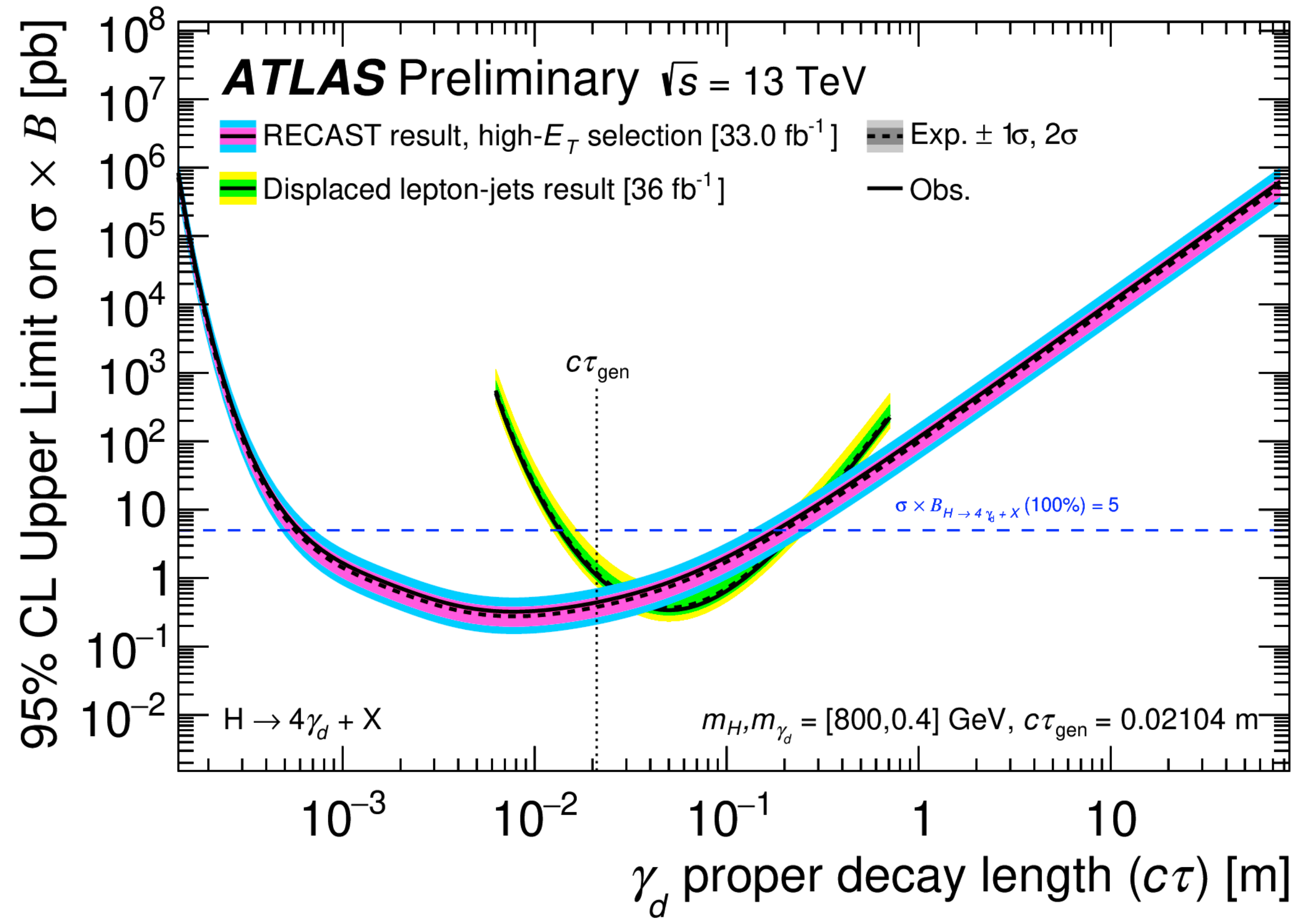
$m_H = 800$ GeV



$H \to 4\gamma_d + X$







- HLSP: hidden lightest stable particle
- cτgen = generated LLP decay length

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

- **Dark Photon from Higgs Boson decay:**

  ➡$H \to Z_d Z_d$, (or ZZ_d) $\to 4\ell$.

  ➡(VBF, ZH and ggF) $H \to \gamma\gamma_d$.

  ➡(VBF, ggF and WH) light LLP $H \to 2\gamma_d + X$.

- **Dark Photon in rare *Z* boson decays.**

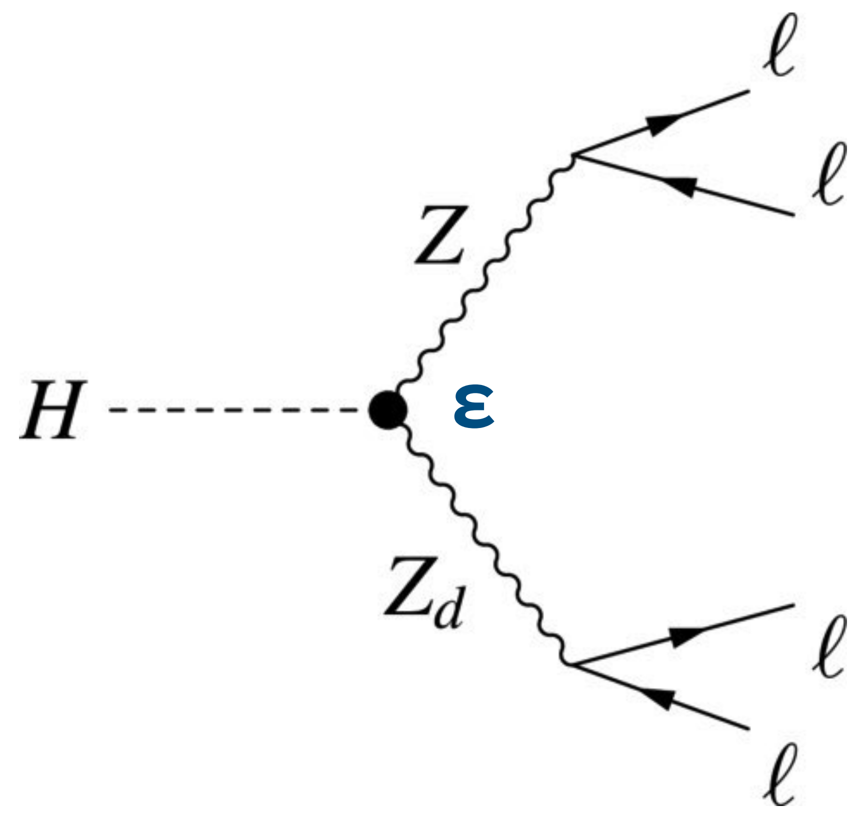
$H \to Z_d Z_d$, (or ZZ_d) $\to 4\ell$

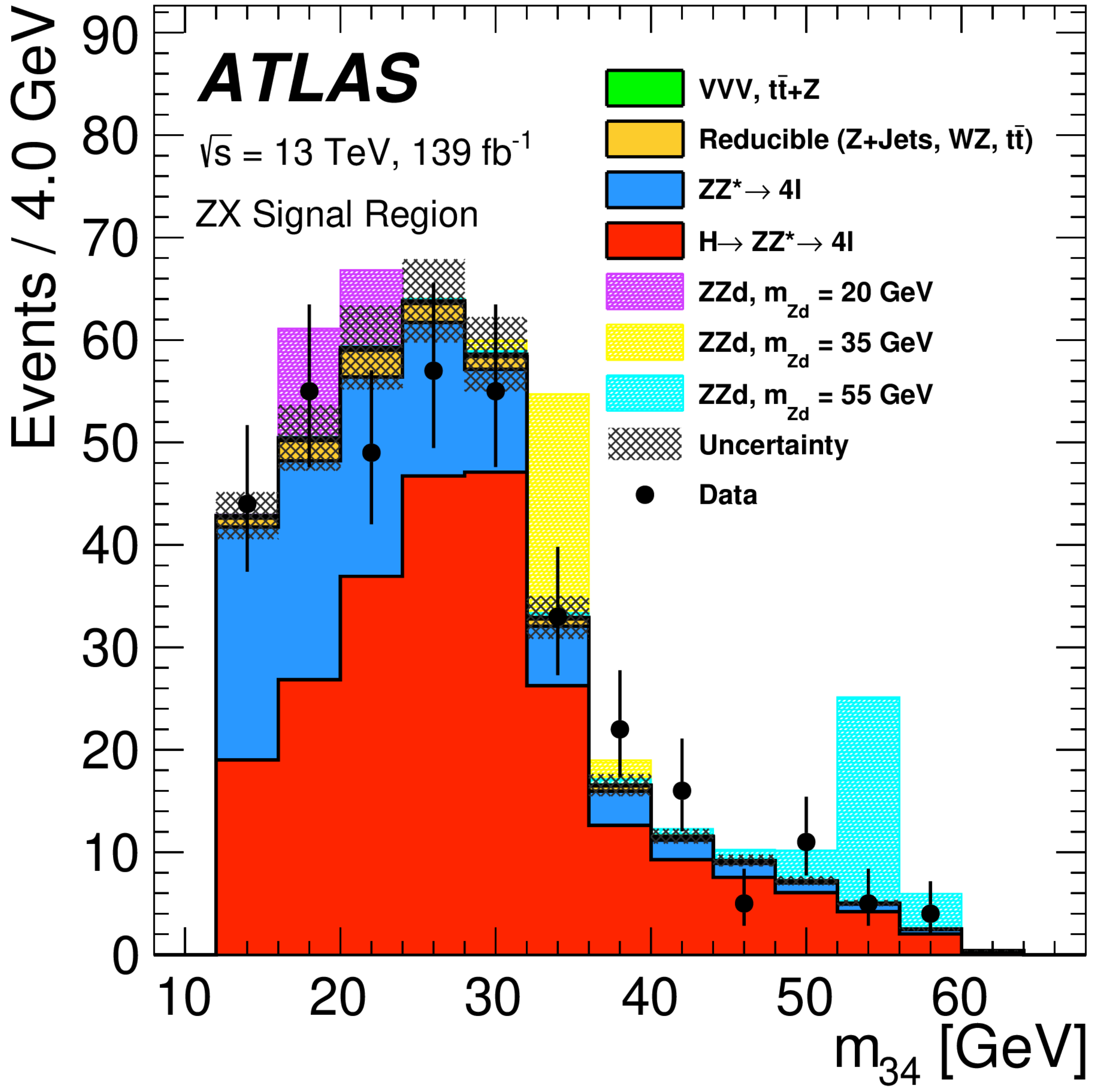
JHEP 03 (2022) 041

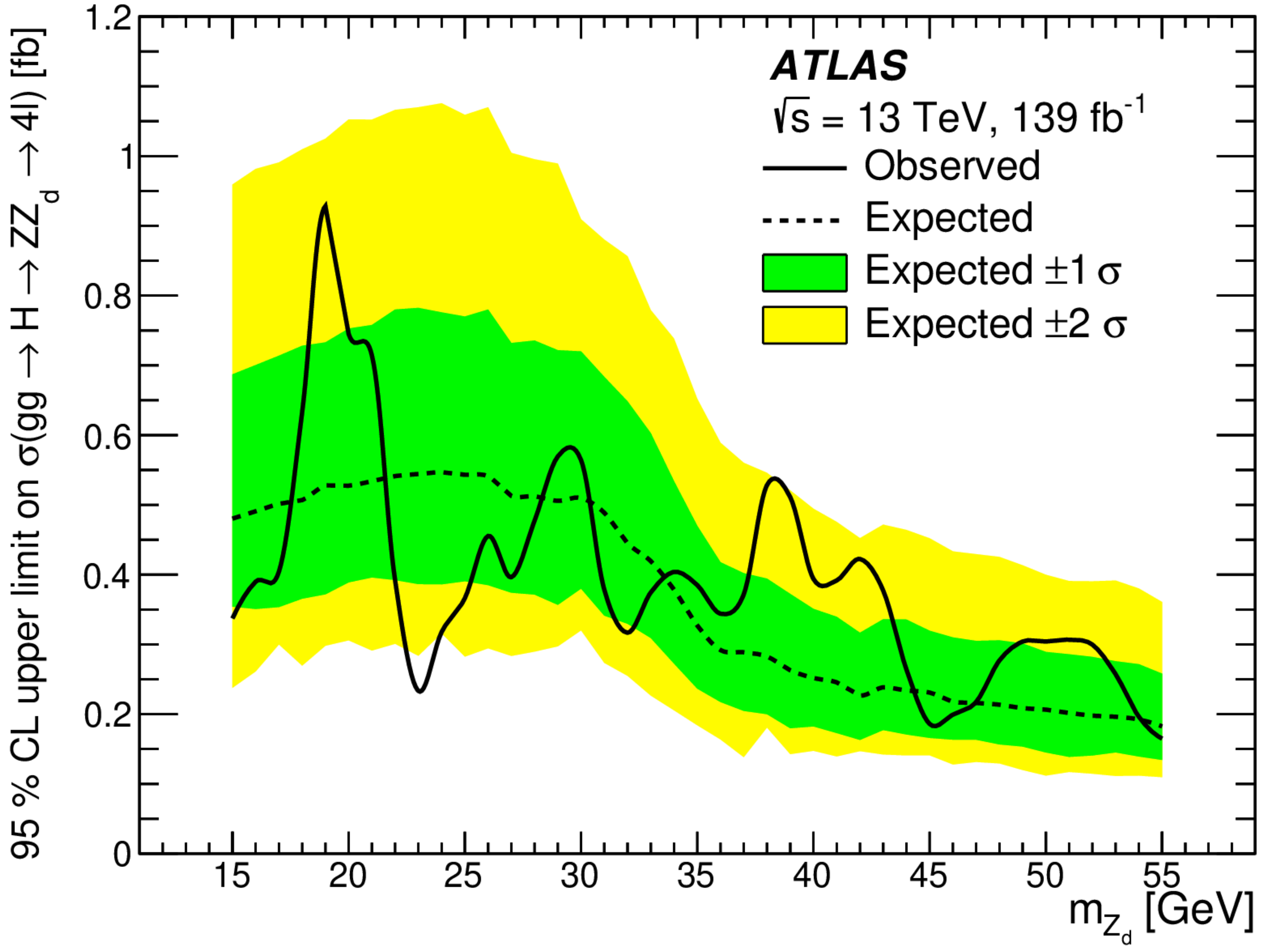
$H \rightarrow ZZ_d \rightarrow 4\ell$

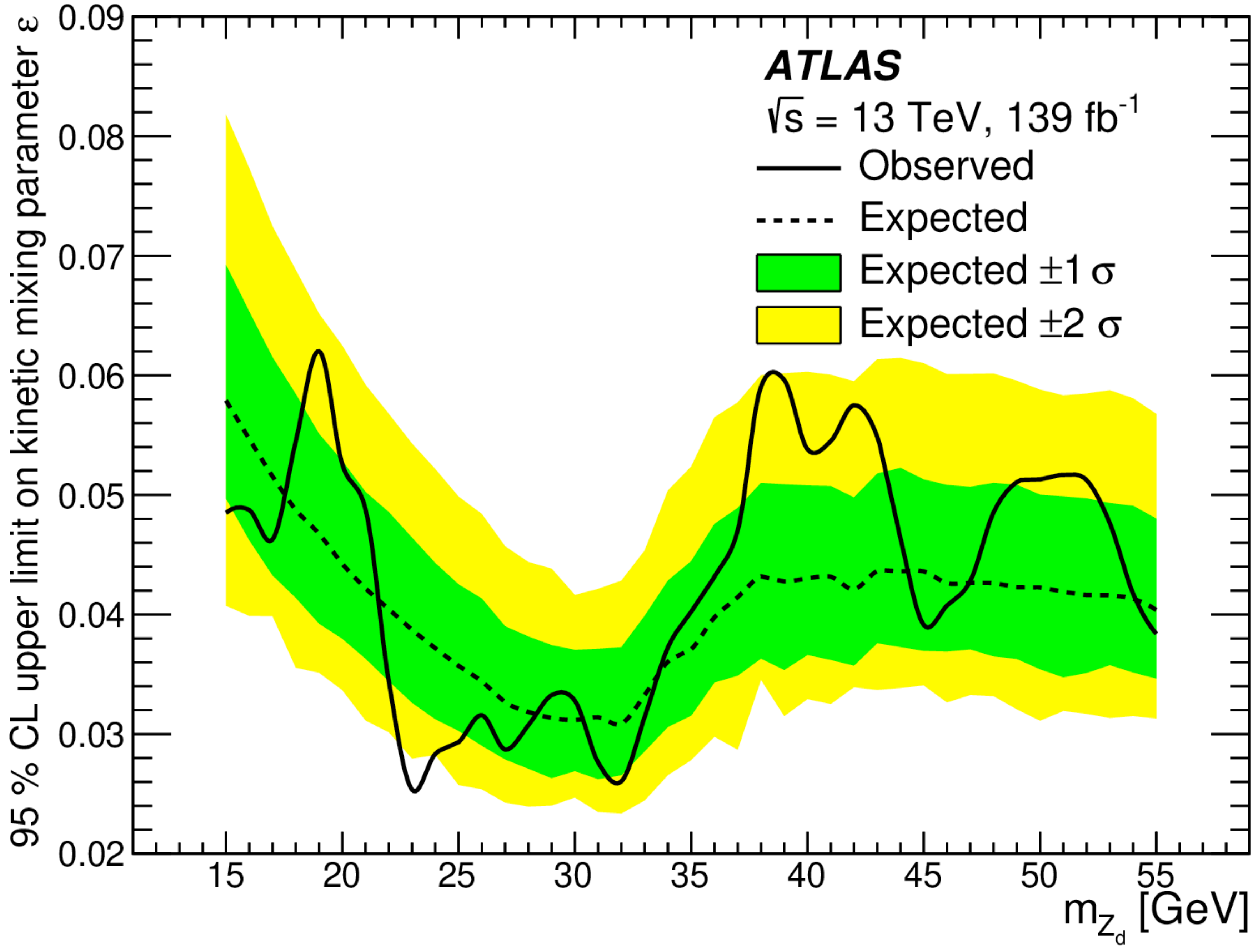
JHEP 03 (2022) 041

- **Massive** Dark-Photon: ggF production, prompt decay of Z_d and m_{4L} consistent with 125 GeV.
- $H \rightarrow ZZ_d \rightarrow 4\ell$ channel is sensitive to the hypercharge portal through ϵ.
- Dark Photon mass range: $15 \text{ GeV} < m_{Z_d} < 55 \text{ GeV}$
- The $H \rightarrow ZZ_d$ vertex factor is proportional to ε.





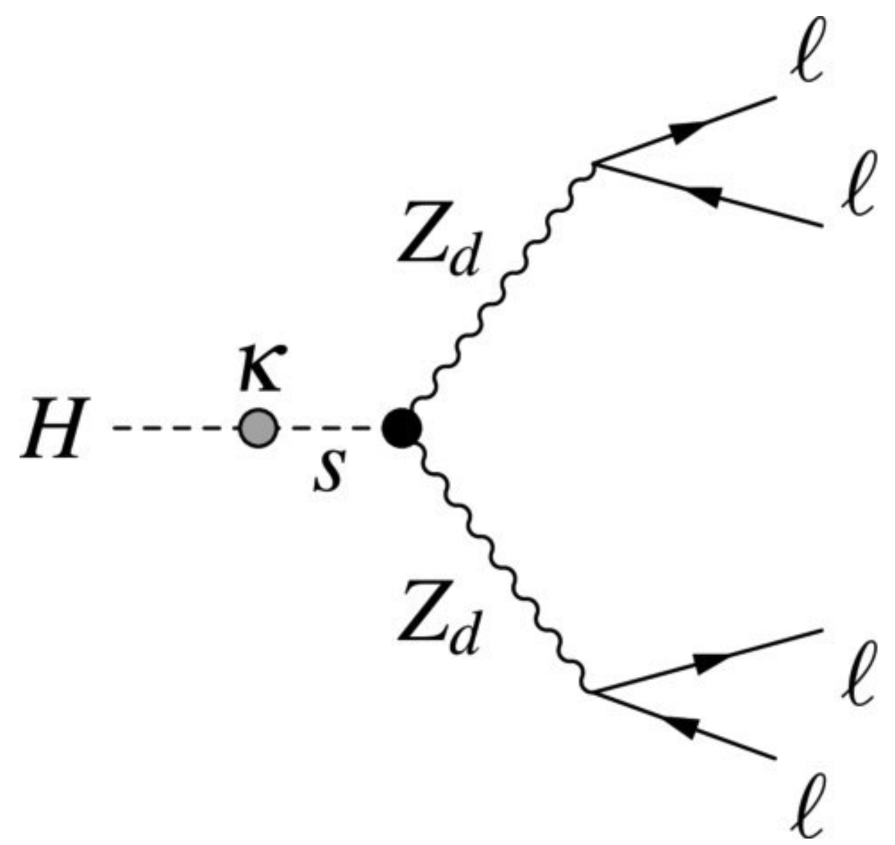


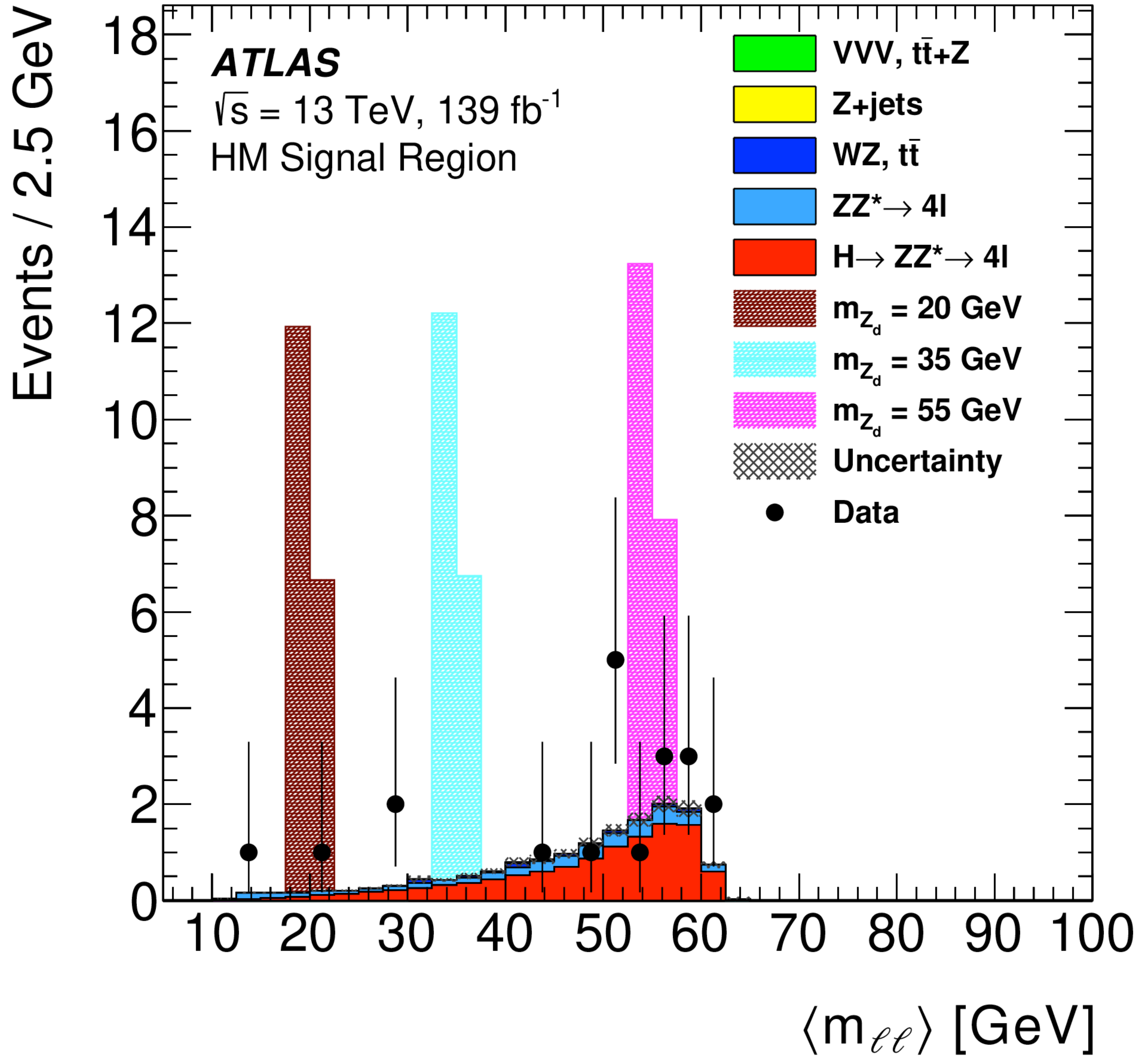


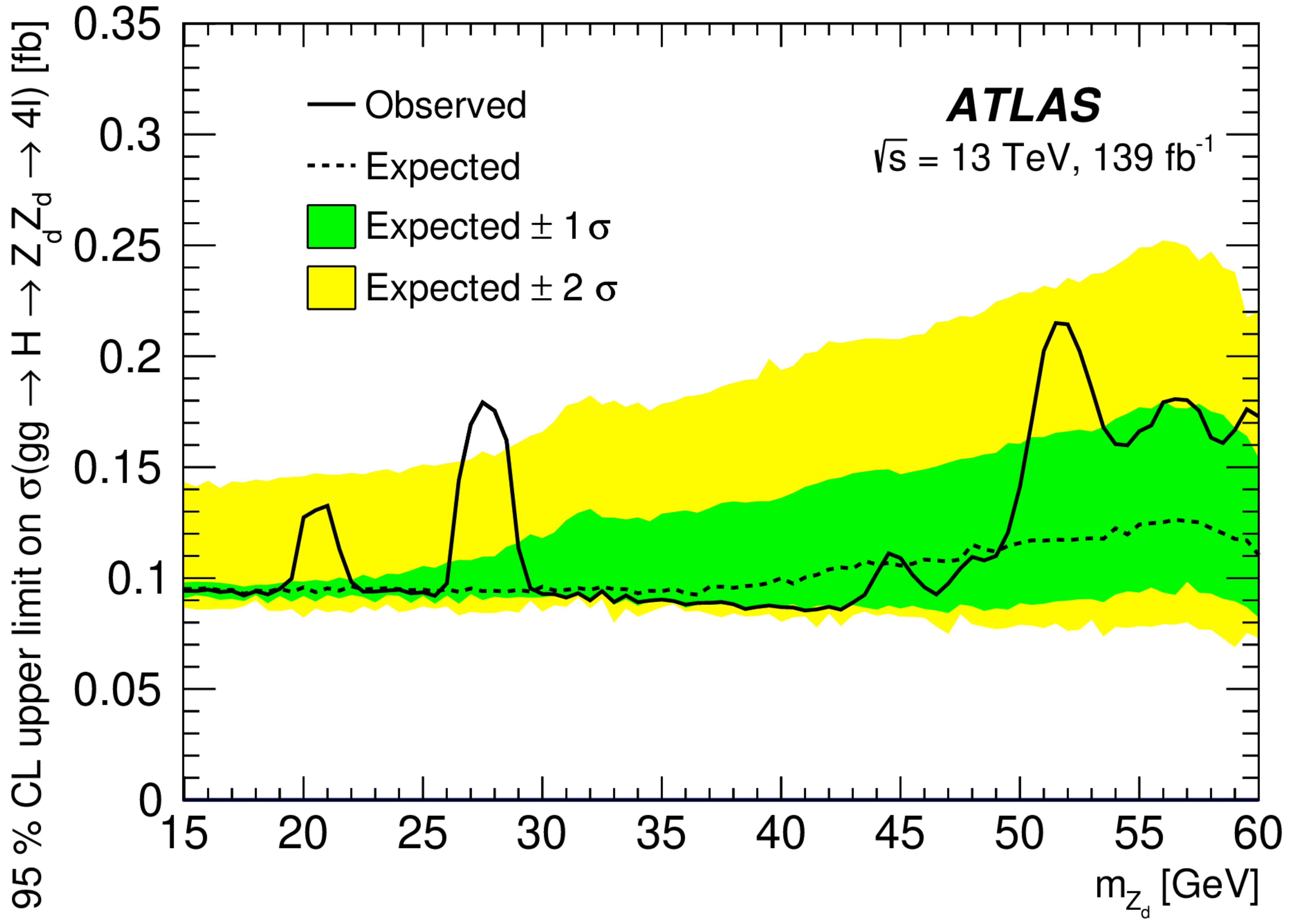
$H \rightarrow Z_d Z_d \rightarrow 4\ell$

JHEP 03 (2022) 041

- **Massive** Dark-Photon: ggF production, prompt decay of Z_d and m_{4L} consistent with 125 GeV.
- $H \rightarrow Z_d Z_d \rightarrow 4\ell$ channel is sensitive to the Higgs portal through k (mixing of H and s (dark H))
- Two Dark Photon mass ranges: LM ($1\ \text{GeV} < m_{Z_d} < 15\ \text{GeV}$) and HM ($15\ \text{GeV} < m_{Z_d} < 60\ \text{GeV}$).
- The $H \rightarrow Z_d Z_d$ vertex factor is proportional to κ.







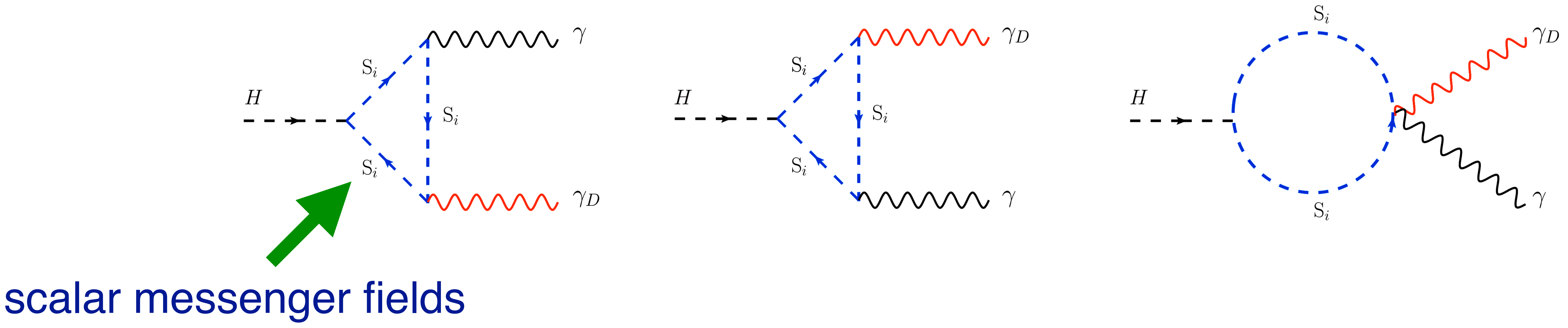
The most significant excess corresponds to a local significance of 2.5σ at m_{Z_d} = 28 GeV

Dark Photon in $H \to \gamma\gamma_d$

Dark Photon in $H \to \gamma\gamma_d$

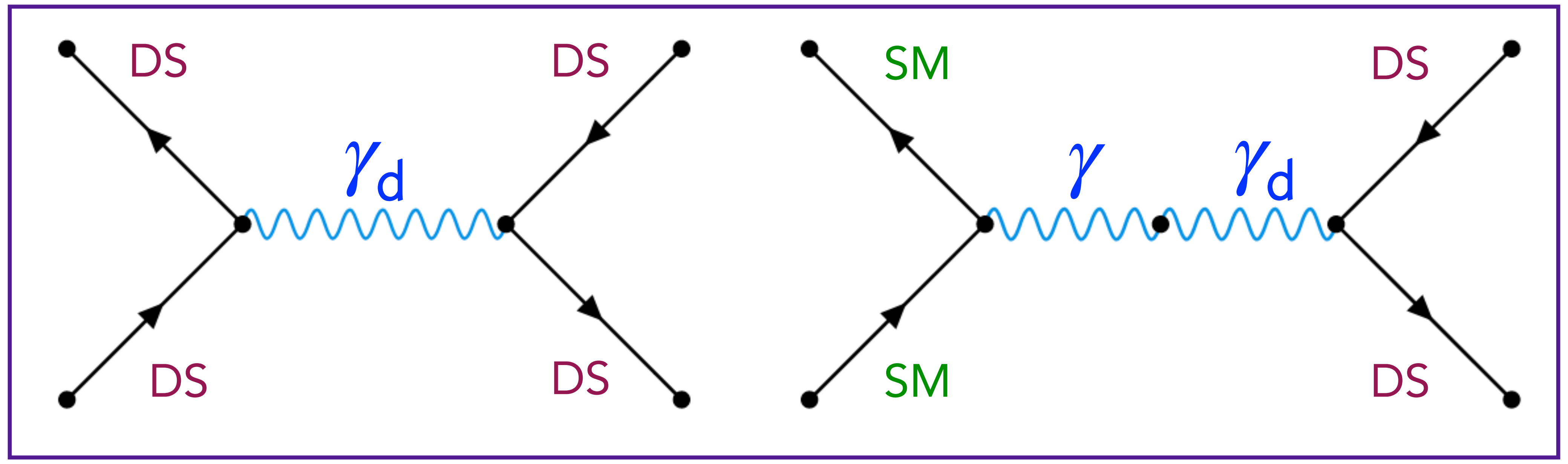
- Both massless and massive dark photons could give rise to same signature: resonant $\gamma + E_T^{miss}$ signature

$H \to \gamma\gamma_d$ massless dark photon production mechanism



arxiv:2206.05297

- The discovery of $H \to \gamma\gamma_d$ signature would be a direct observation of long-range forces in the DS and an indirect evidence of new physics coupled to both the SM and DS.

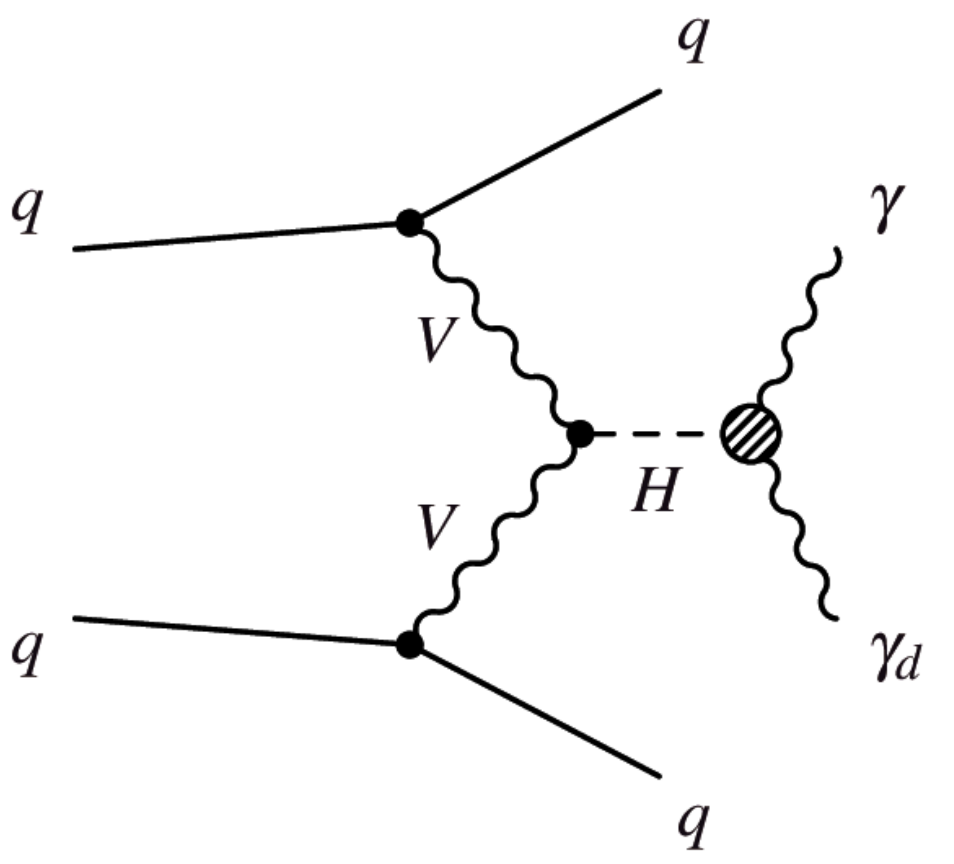


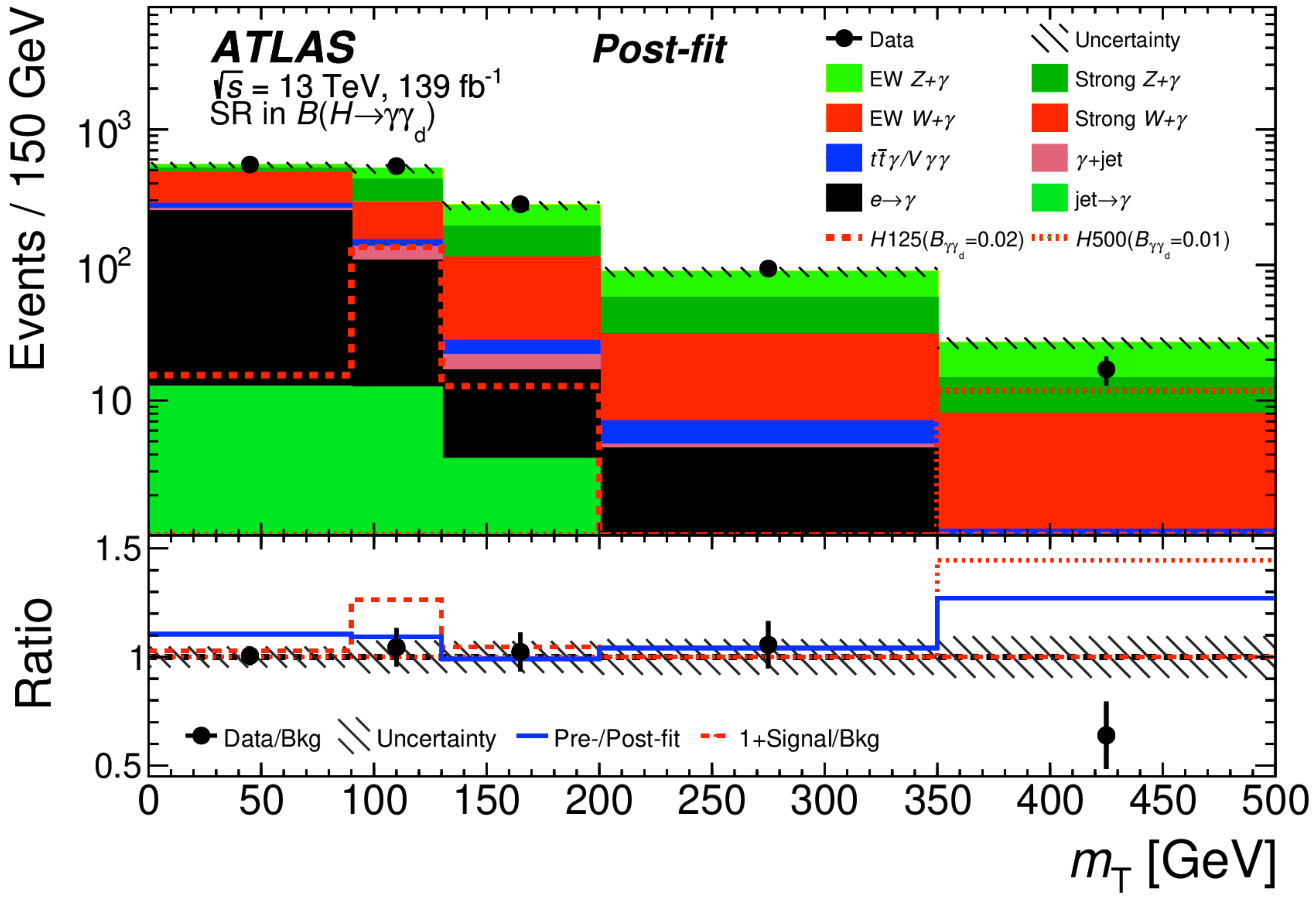
- Could provide a potential explanation for astrophysical positron excess and small-scale structure formation problems.

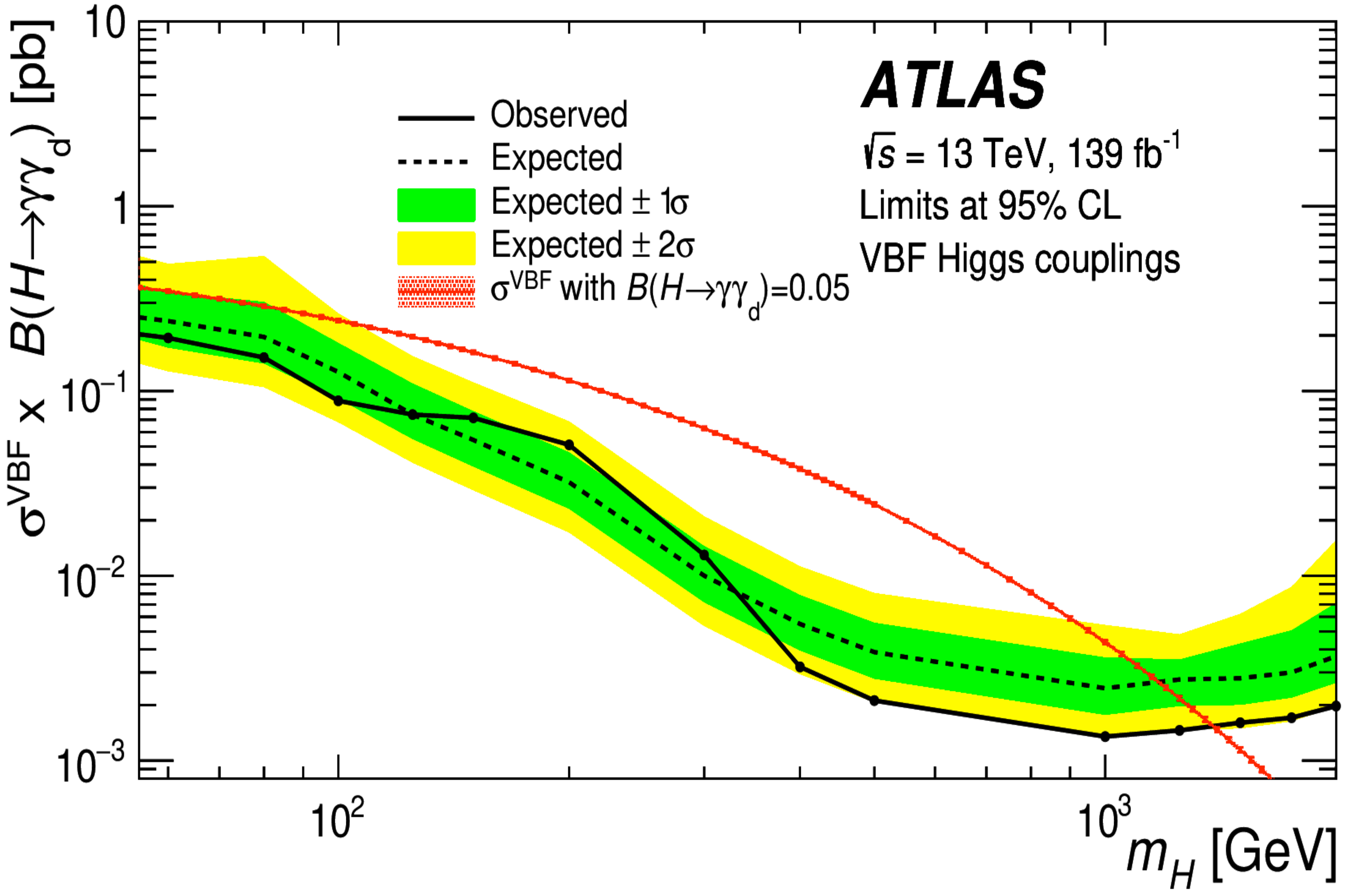
VBF H → $\gamma\gamma_d$

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

- Trigger: single-photon
- Dominant background: $V\gamma$ + jets ($W(\rightarrow \ell\nu)(+\gamma) + jets$ 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: $m_T(\gamma, E_T^{miss}) = \sqrt{2\ p_T\ E_T^{miss}\ [1 - \cos(\phi_\gamma - \phi_{E_T^{miss}})]}$
- $m_\gamma = 0$ GeV, $m_H = 60$ Gev – 2 TeV



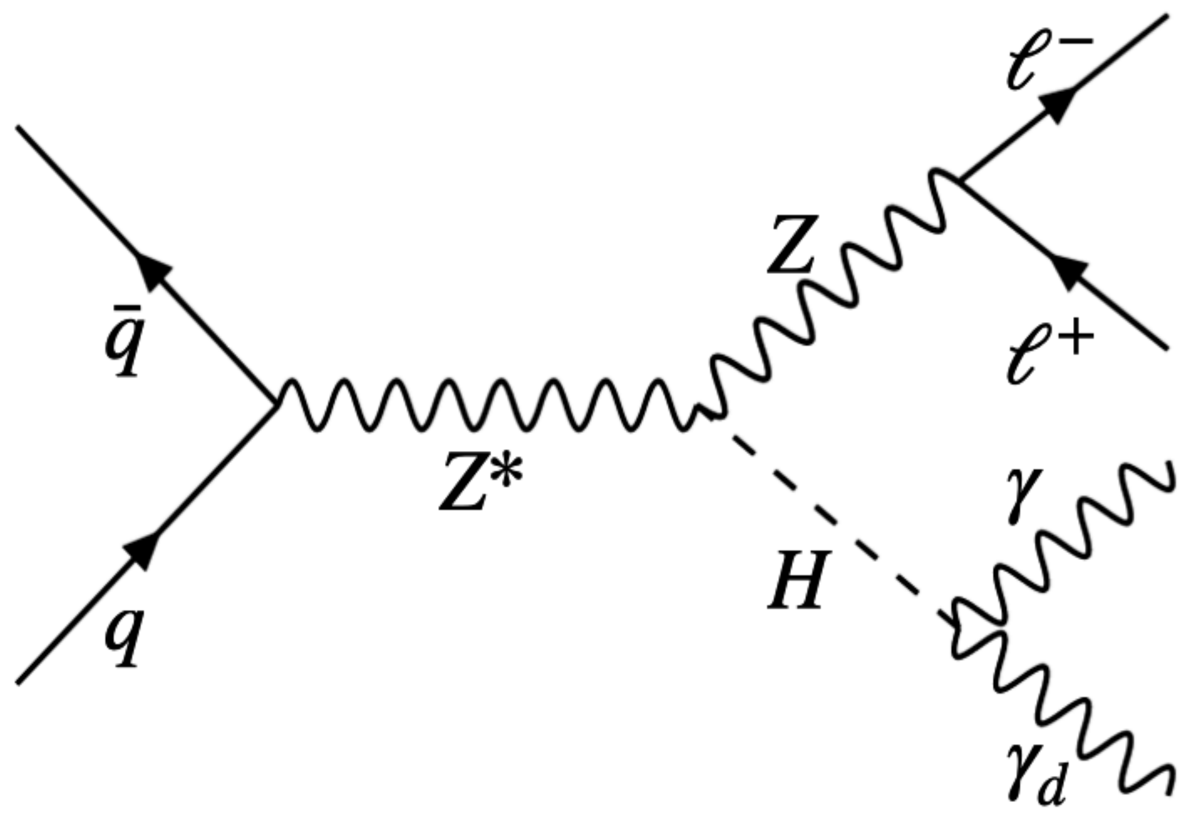


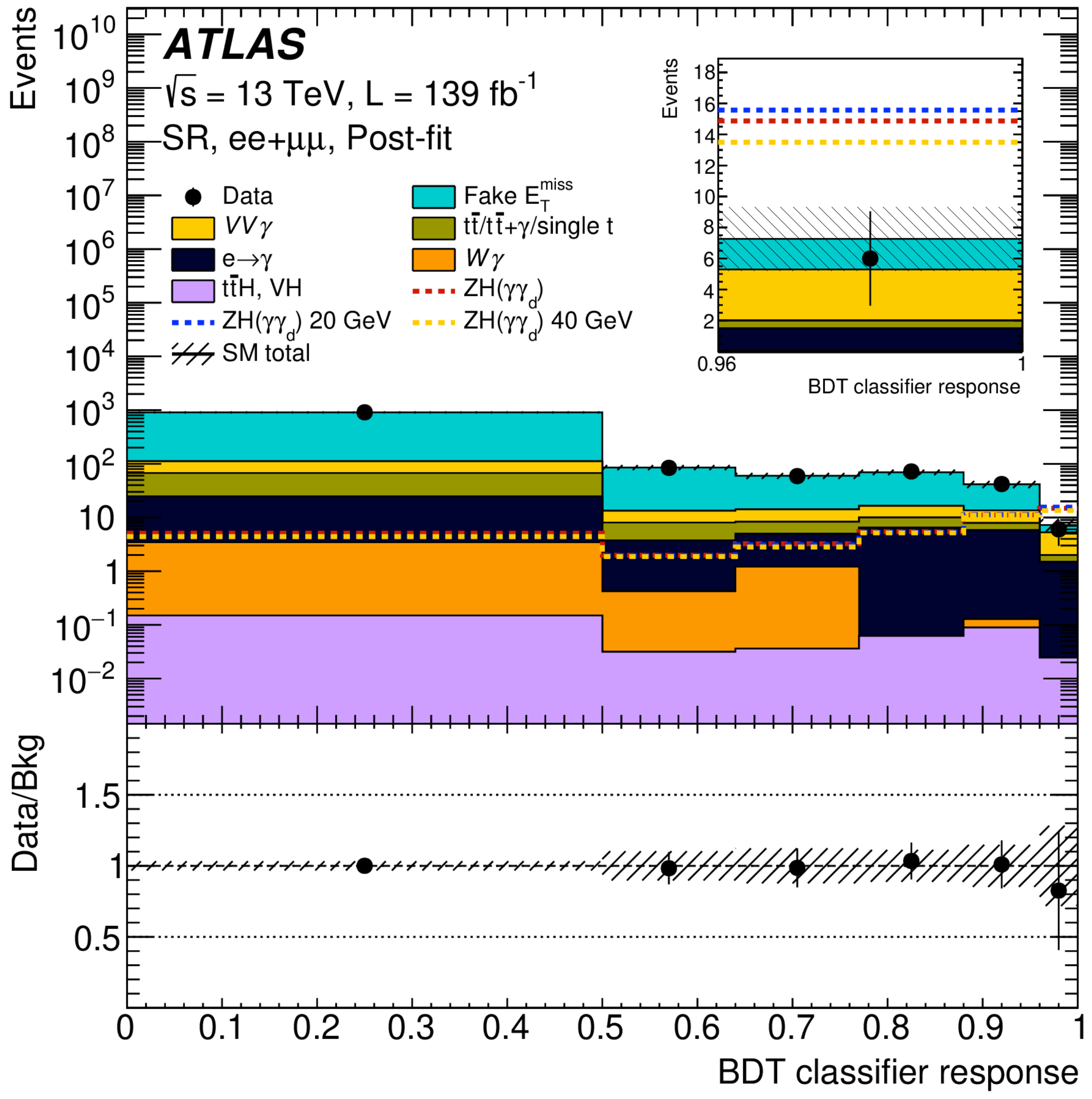


SM 125 GeV Higgs boson: observed (expected) 95% CL upper limit on Br(H → $\gamma\gamma_d$) is set at 0.018 ($0.017_{+0.007-0.005}$)

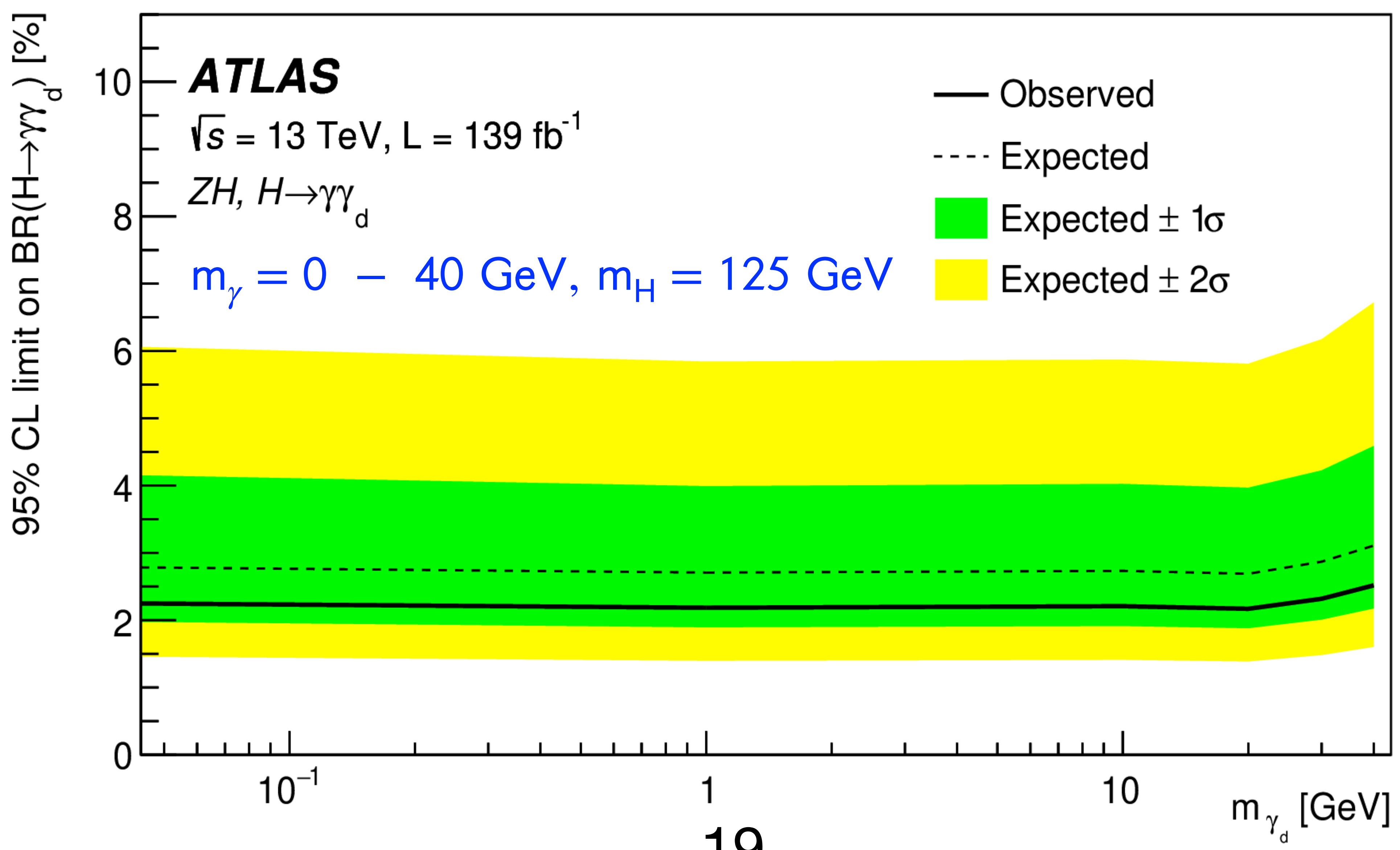
ZH $H \to \gamma\gamma_d$

- ✓ Signal: $ZH, Z \to \ell^+\ell^-$ and $H \to \gamma\gamma_d$ (undetected dark photon $\to E_T^{miss}$).
- ✓ Trigger: single and dilepton
- ✓ BDT (XGBoost) is used as discriminator 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.





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



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

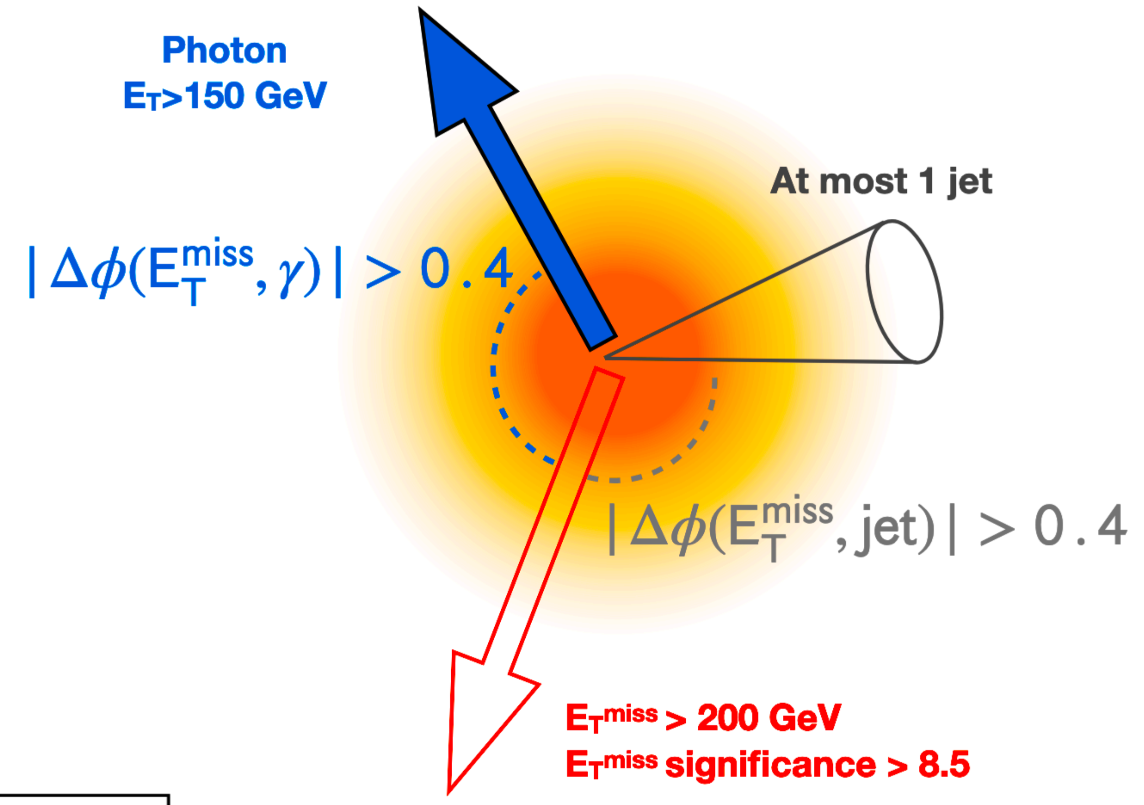
Production	ZH	VBF
ATLAS	2.3 (2.8)%	1.8 (1.7)%
CMS	4.6 (3.6)%	3.5 (2.8)%

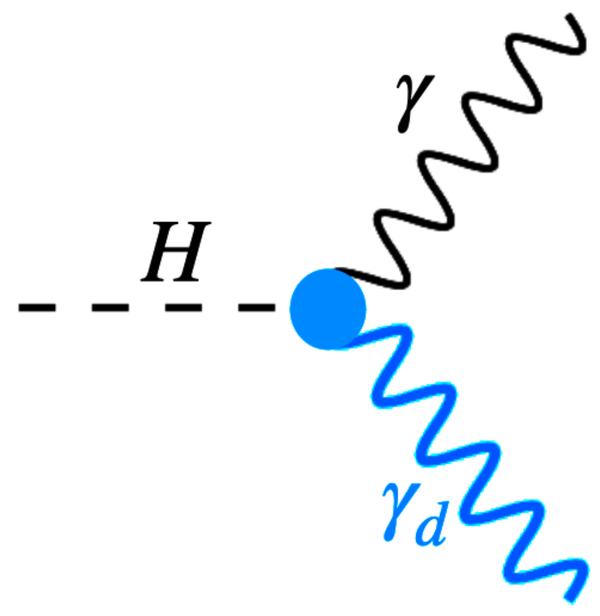
ggF and new VBF $H \to \gamma\gamma_d$

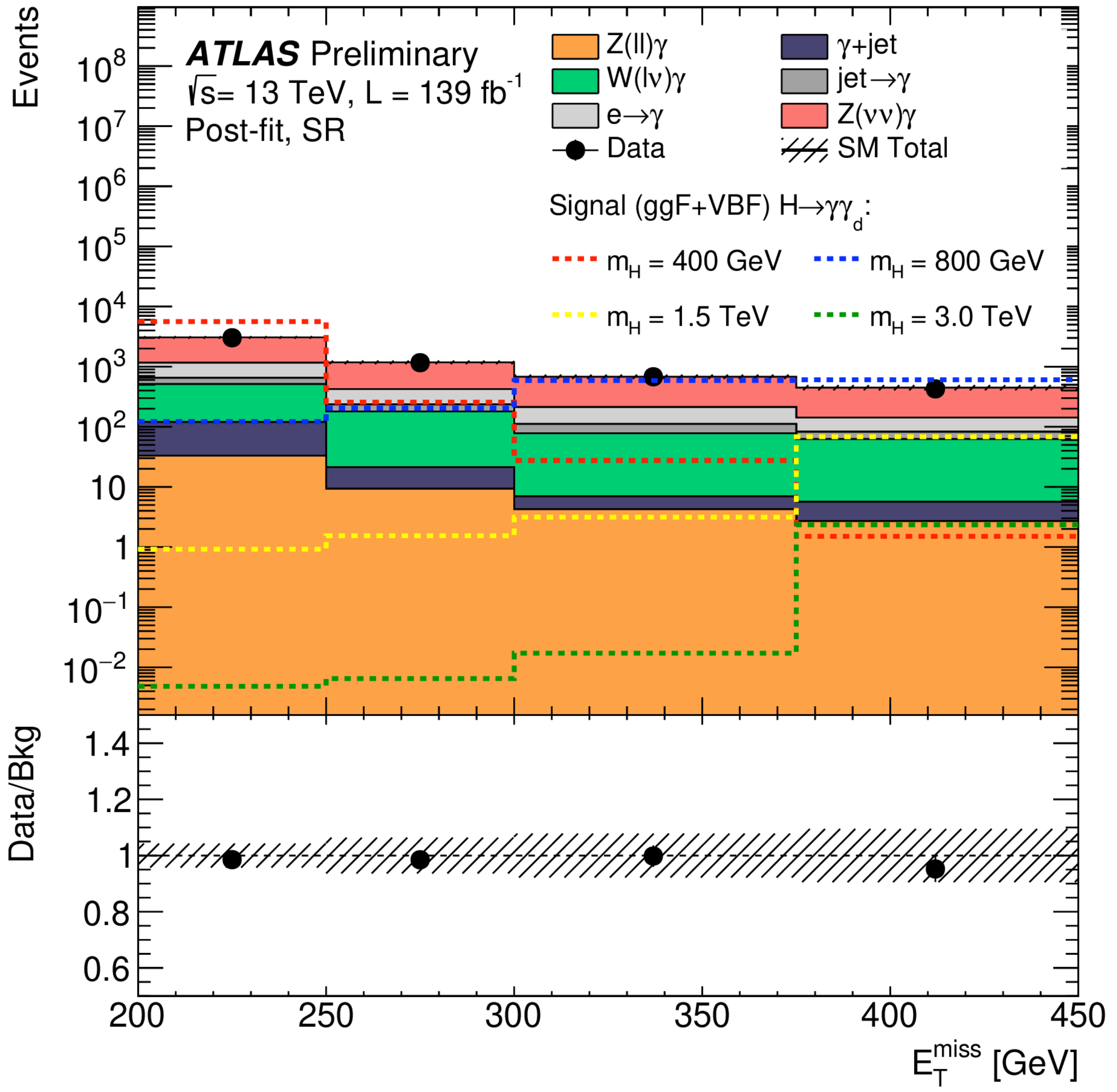
ATL-PHYS-PUB-2023-003

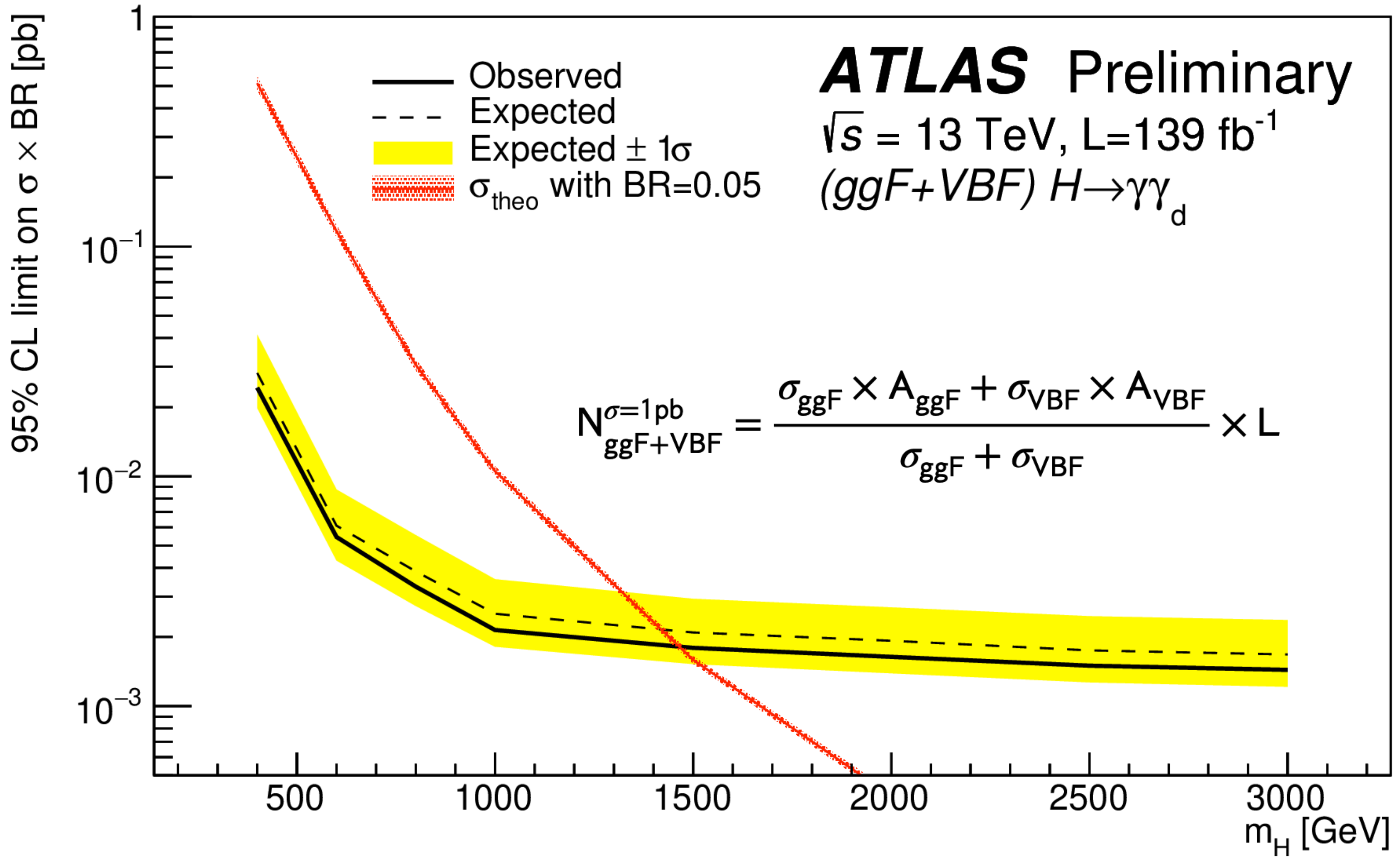
Reinterpretation of the ATLAS mono-photon ($\gamma + E_T^{miss}$) to search for dark photons in high-mass resonances.

- E_T^{miss} trigger limits the reach for low masses.
- $m_\gamma = 0$ Gev, 8 $m_H = 400$ GeV – 3 TeV
- Considering ggF and VBF production modes.
- 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.
- Discriminant variable: E_T^{miss}









$$N^{\sigma=1pb}_{ggF+VBF} = \frac{\sigma_{ggF} \times A_{ggF} + \sigma_{VBF} \times A_{VBF}}{\sigma_{ggF} + \sigma_{VBF}} \times L$$

ggF + VBF combined with relative contribution from theoretical cross-section

- 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)
- Observed (expected) exclusion limits at 95% CL on the $\sigma \times BR(H \to \gamma\gamma_d)$ as a **[1.44-24.2]fb ([1.68-28.1]fb)** range.

Light LLP $H \to 2\gamma_d + X$.

WH and ggF light LLP in $H \to 2\gamma_d + X$

JHEP06(2023)153

- Small values of the kinetic mixing parameter: $\epsilon < 10^{-5} \to$ long-lived γ_d, m(γd) ∈ [0.4, 2] GeV
- Resulting fermions may be electrons, muons, hadrons depending on the dark photon mass.
- Two production modes ggF and WH.

WH channel:

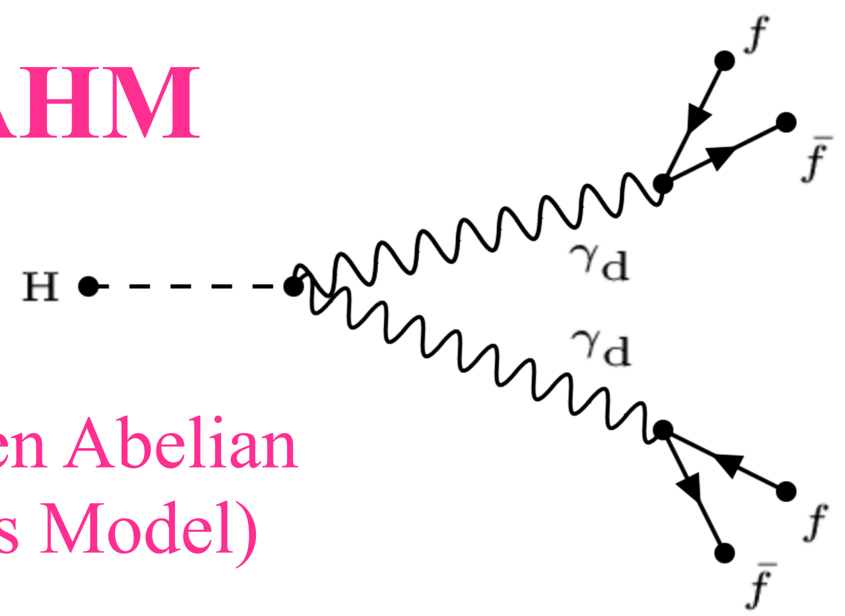
- Signature: at least one dark-photon jets (DPJs) (collimated group of fermions) and 1 charged lepton
- Background from W+jets and punch-through jet.
- Single-lepton trigger.

ggF channel:

- Signature: at least two dark-photon jets (DPJs) (collimated group of fermions) and no charged leptons
- Background from multi-jet production, cosmic-ray muons.
- MS and calorimeter-based trigger

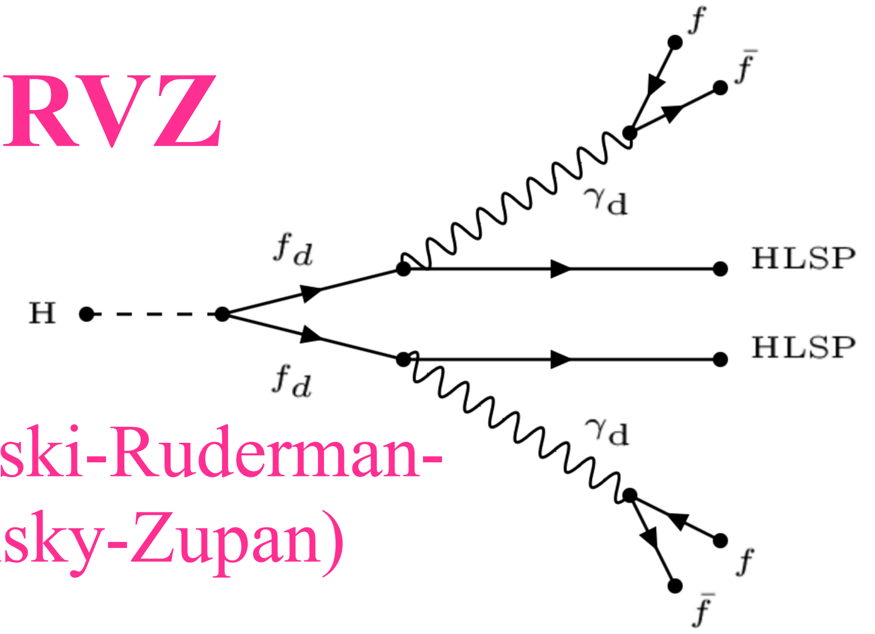
Two considered models: HAHM and FRVZ.

HAHM



(Hidden Abelian Higgs Model)

FRVZ



(Falkowski-Ruderman-Volansky-Zupan)

WH and ggF light LLP in $H \to 2\gamma_d + X$

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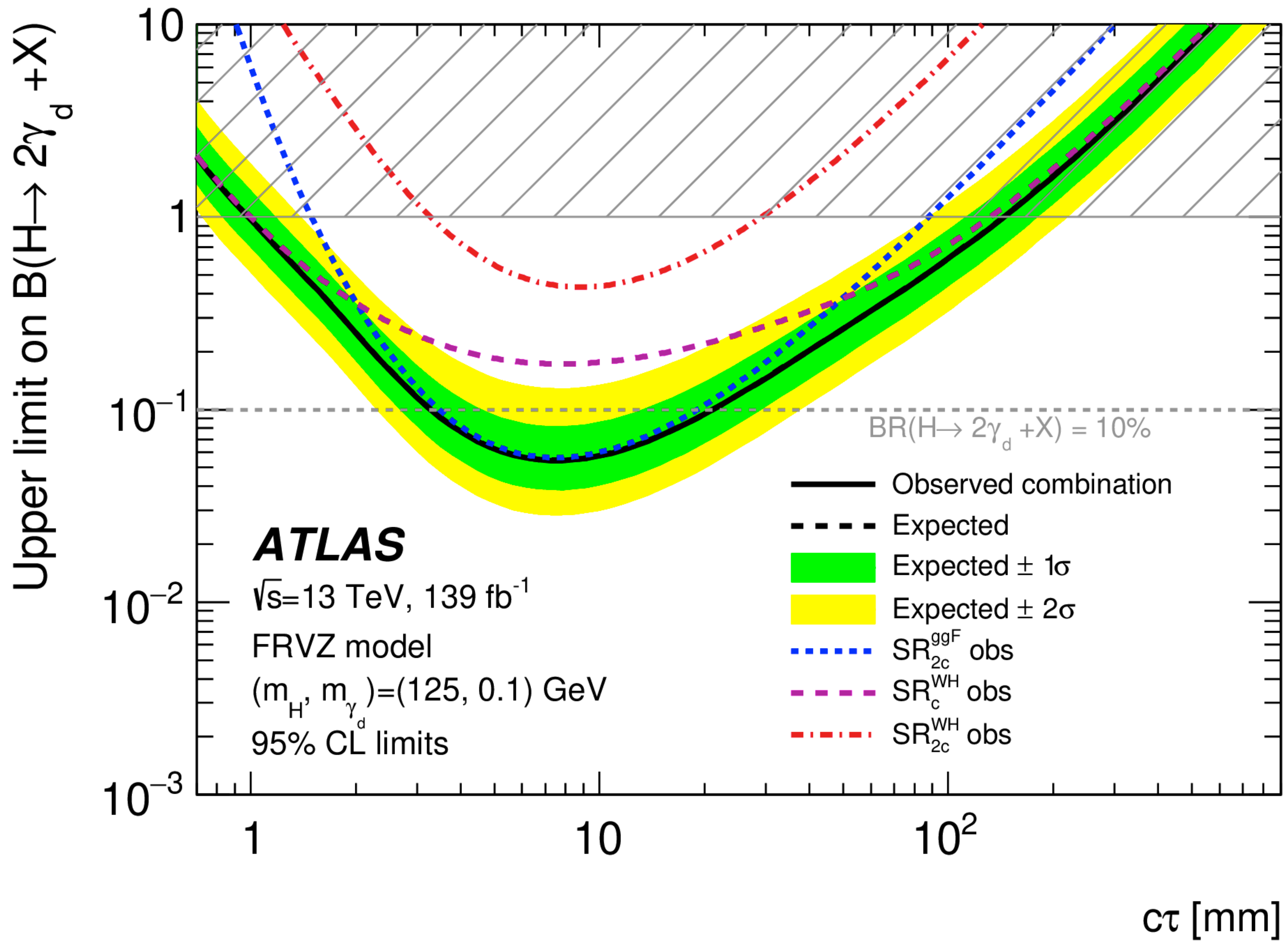
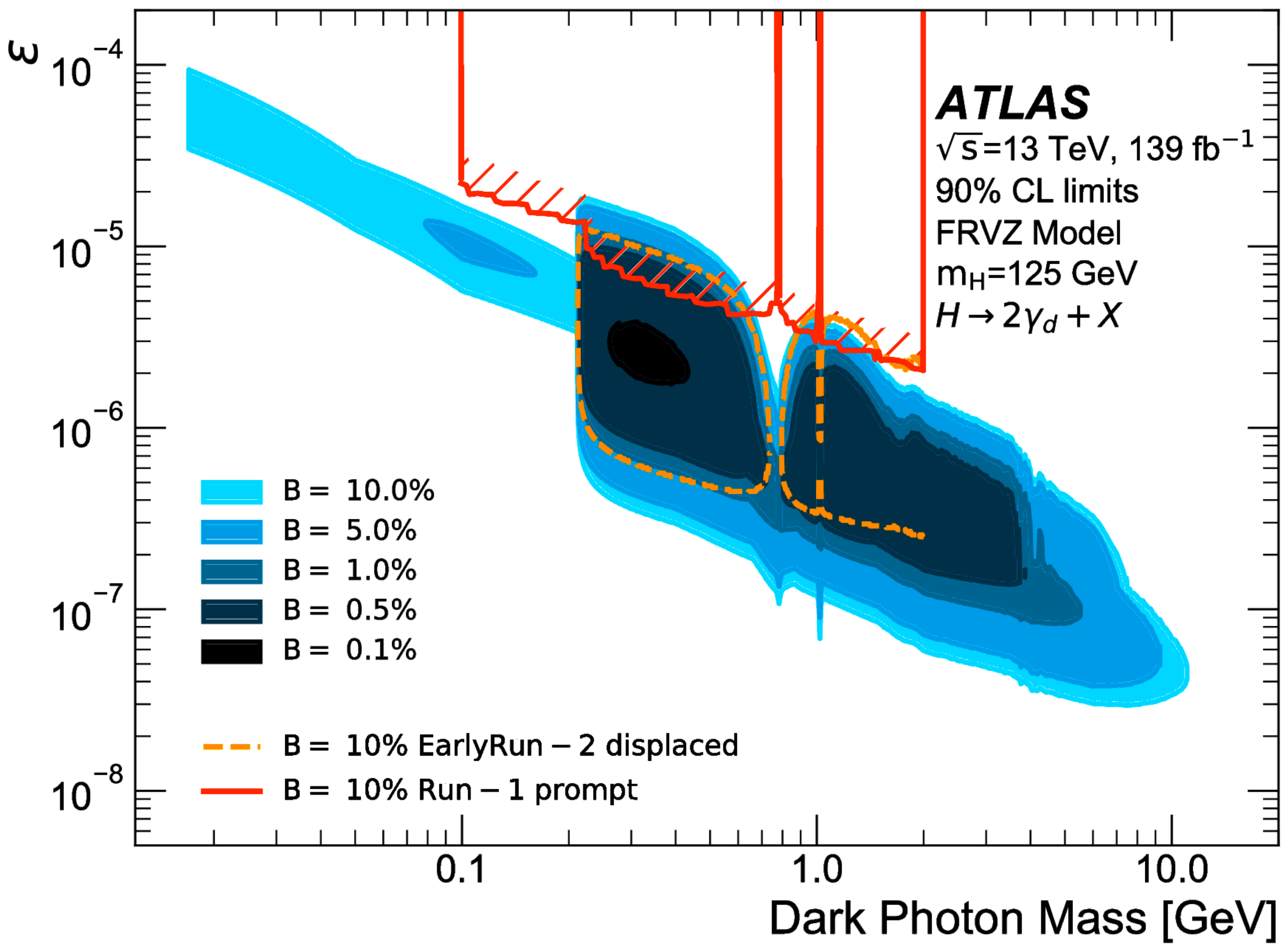
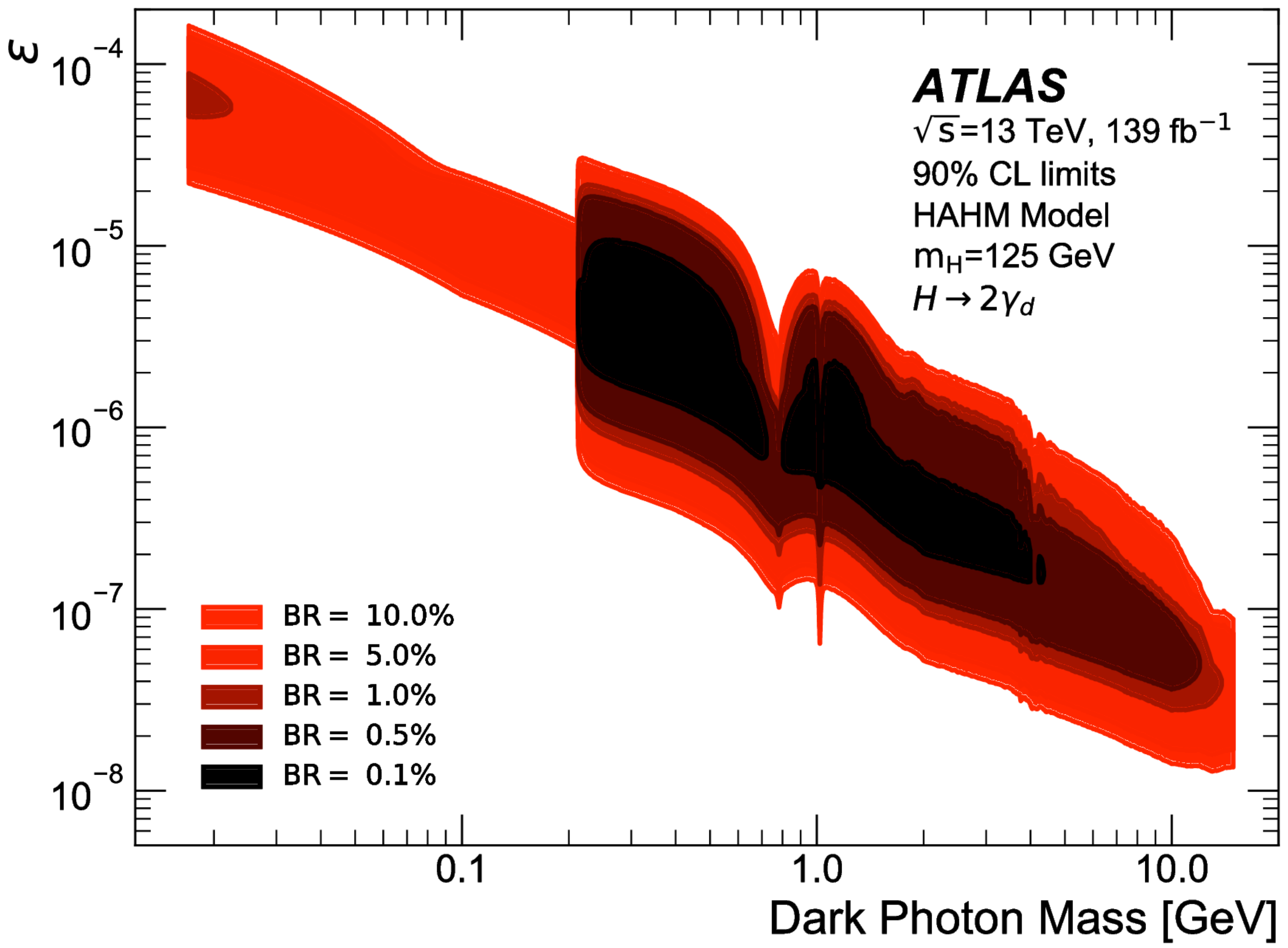






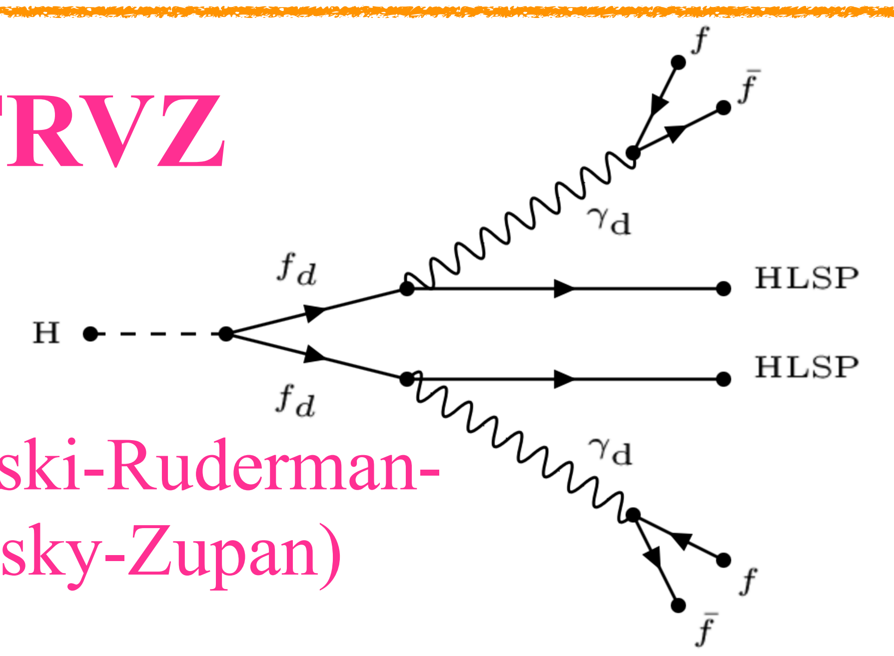
Br > 1% is excluded for 10 mm < $c\tau$ < 250 mm and 0.4 GeV < m_{γ_d} < 2 GeV

- **Signature**: at least one dark-photon jets (DPJs) (collimated group of fermions)
- A dark coupling equal to $\alpha d \lesssim 0.01$ and Small values of the kinetic mixing parameter,

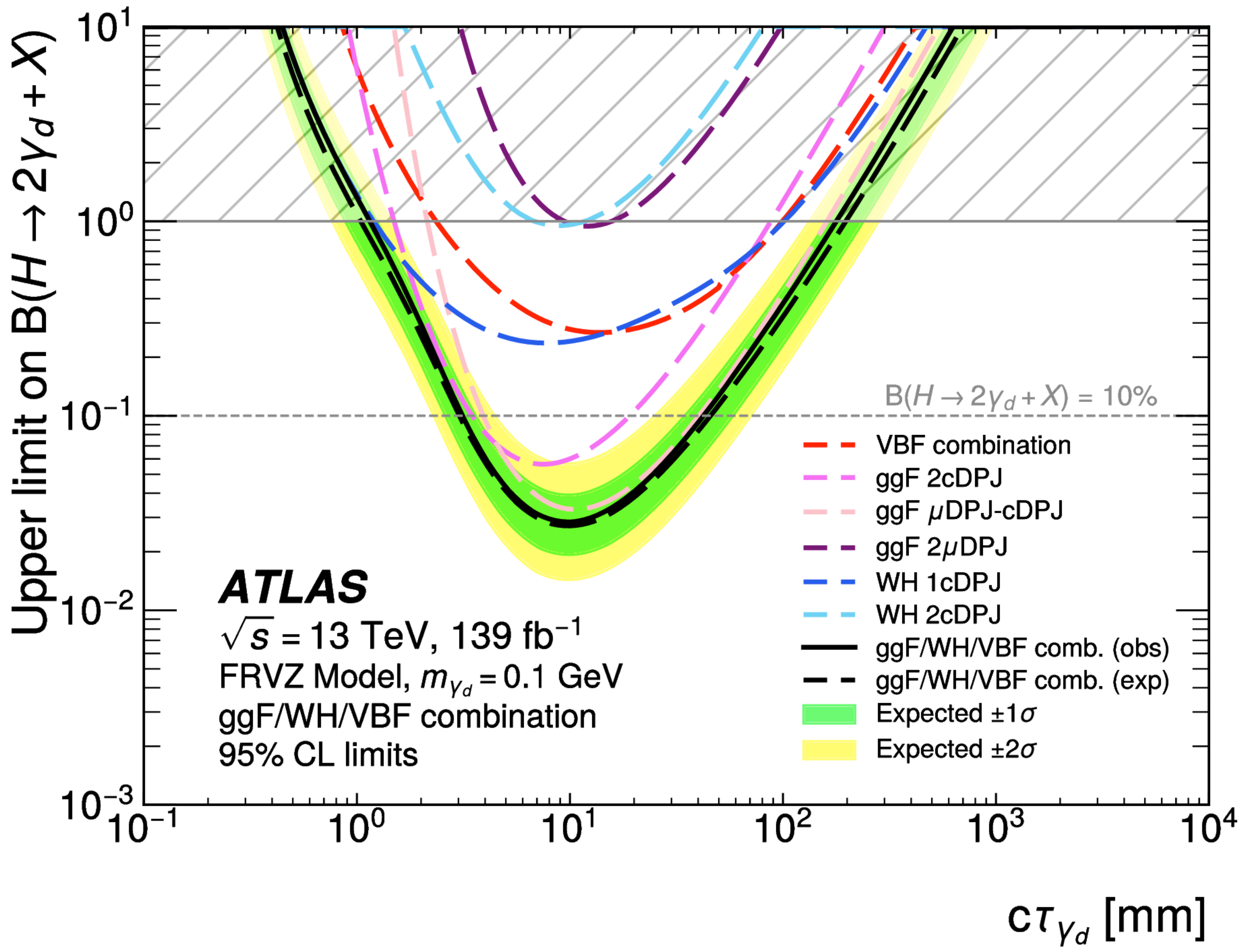
$$\epsilon < 10^{-5} \to \text{long-lived } \gamma_d,\ m(\gamma d) \in [0.1, 15]\ \text{GeV}$$

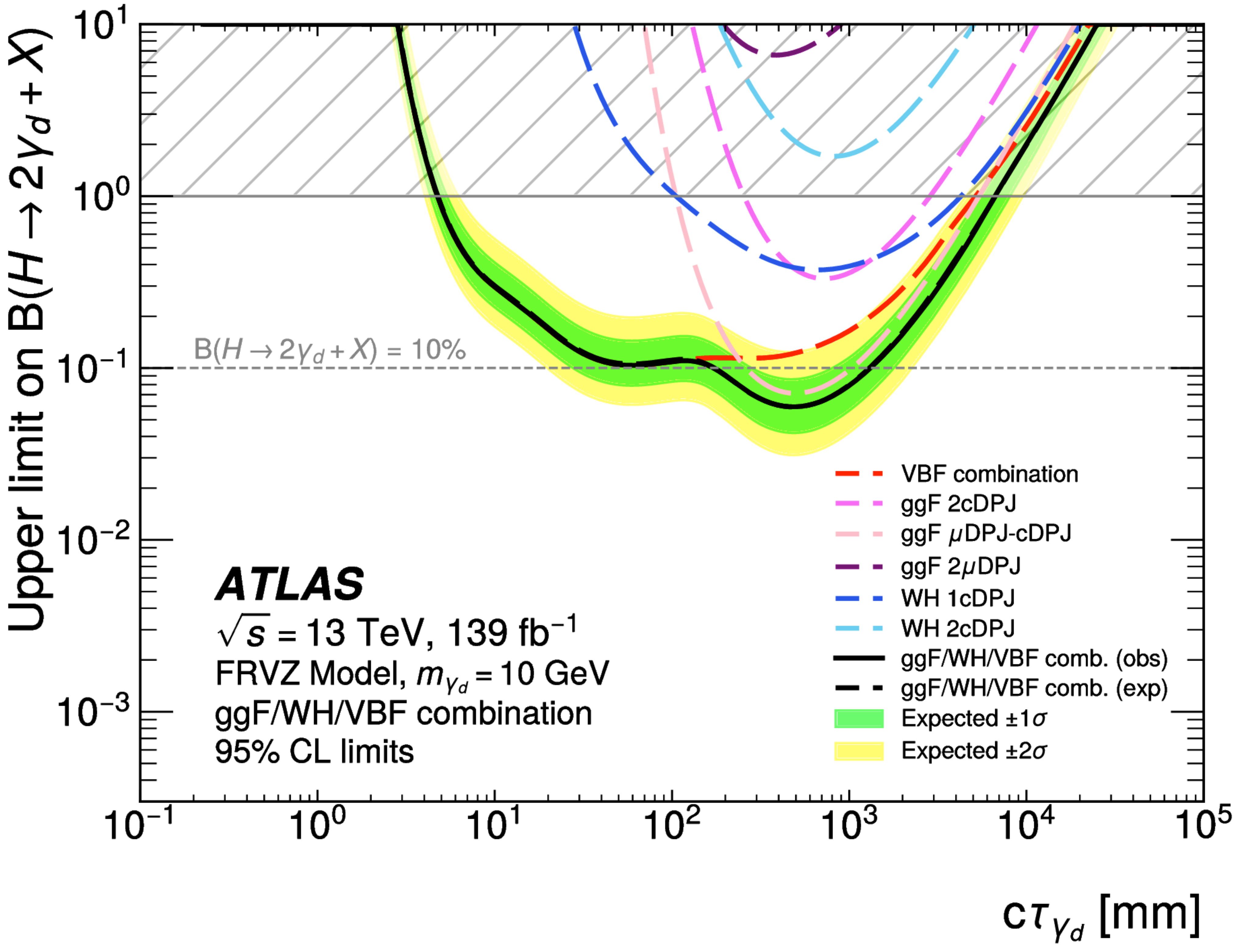
- Resulting fermions may be electrons, muons, hadrons depending on the dark photon mass.
- MS and calorimeter-based trigger
- Background from multi-jet, V + jets and cosmic-ray muons estimated using D-D techniques.

FRVZ



(Falkowski-Ruderman-Volansky-Zupan)

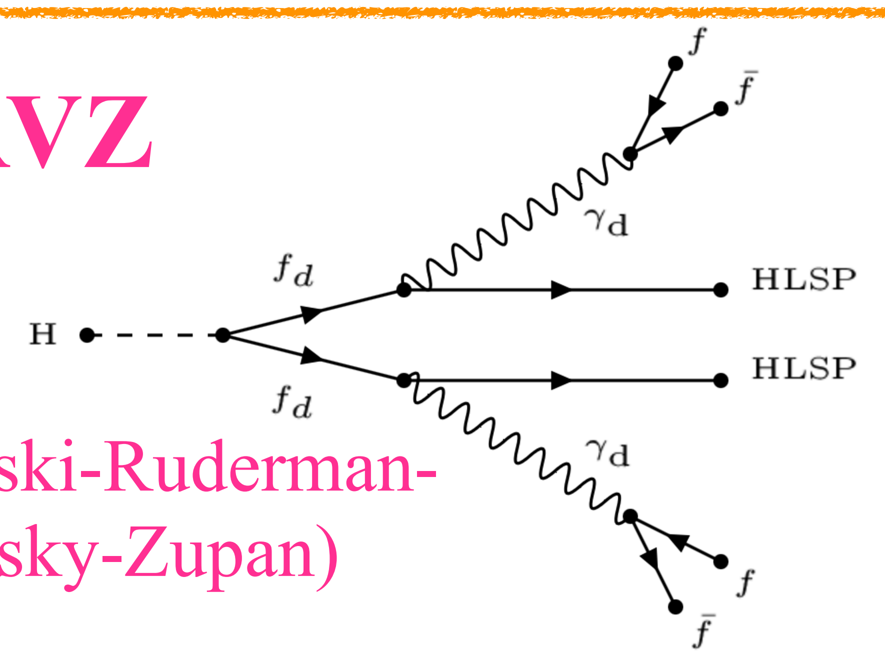




VBF light LLP in $H \rightarrow 2\gamma_d + X$

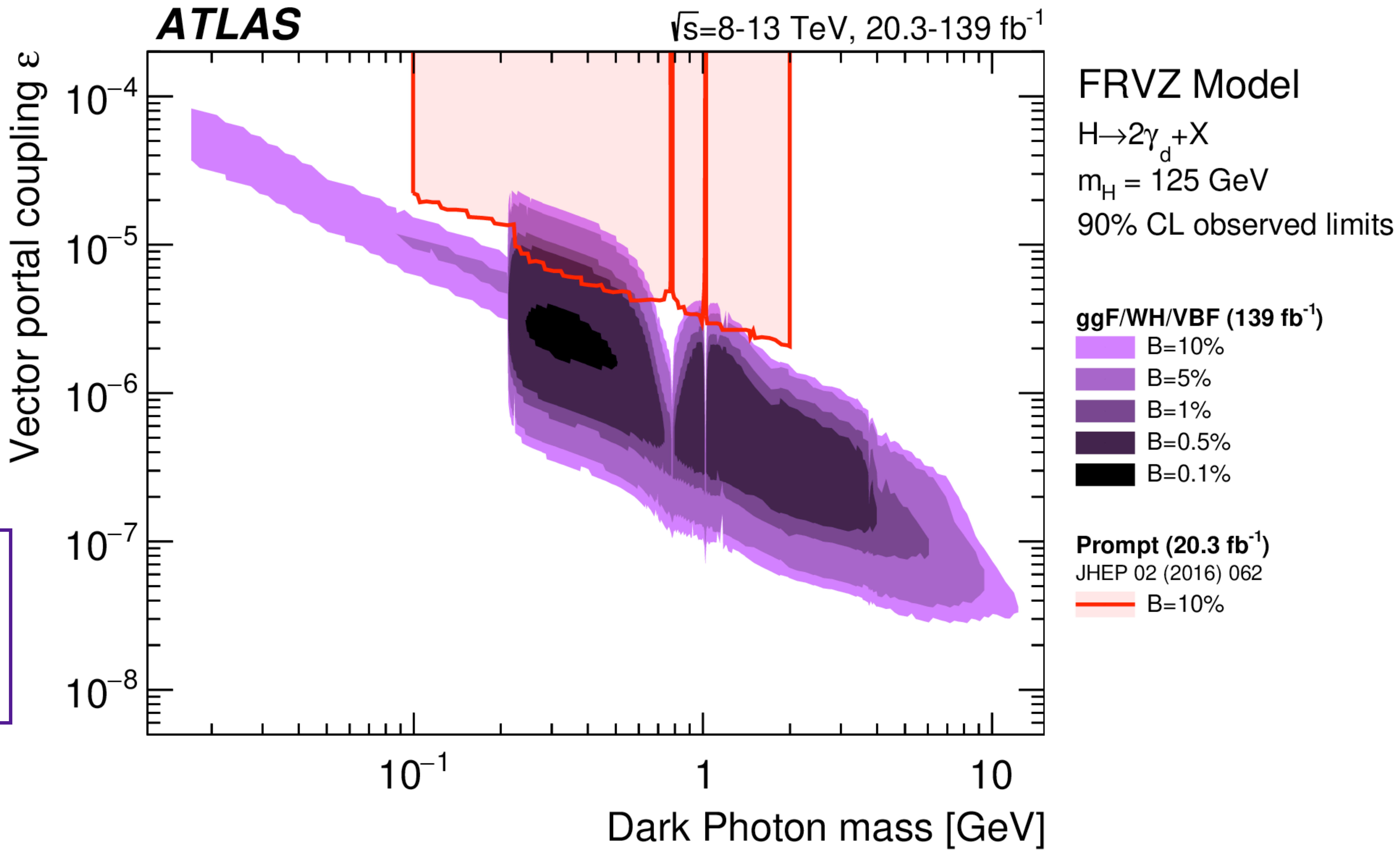
2311.18298
Submitted to: EPJC

FRVZ



(Falkowski-Ruderman-Volansky-Zupan)

Br > 10% is excluded at 95% CL for 173 mm < $c\tau$ < 1296 mm and m_{γ_d} = 10 GeV



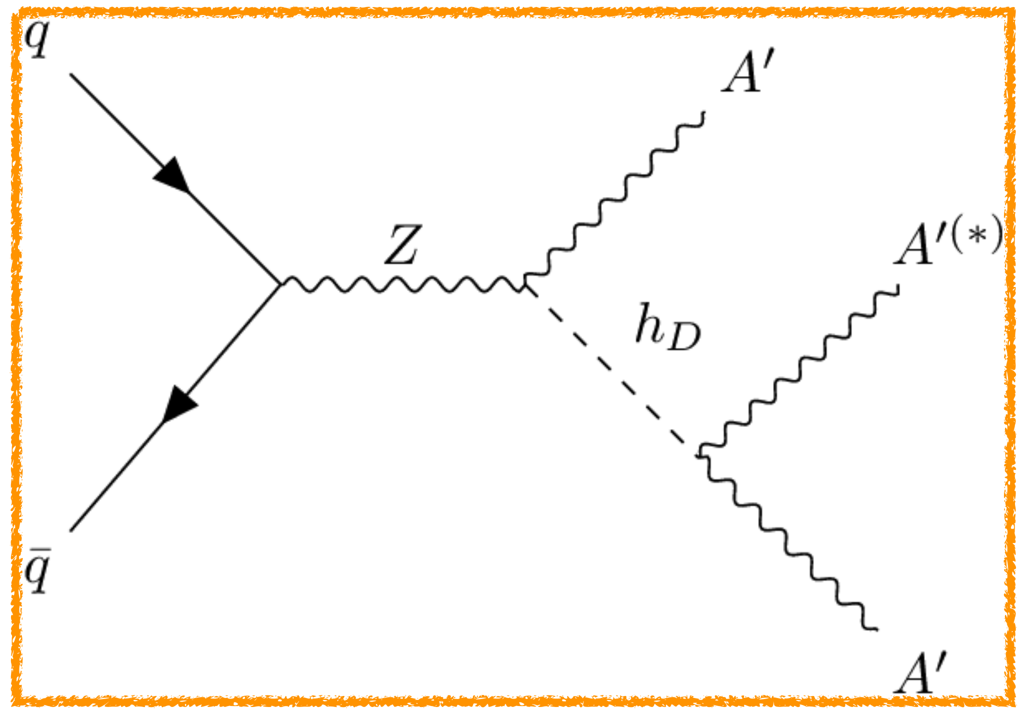
- Combination results with previous ggF and WH results.
- Displaced DPJ complementary to those from related ATLAS searches for prompt DPJs

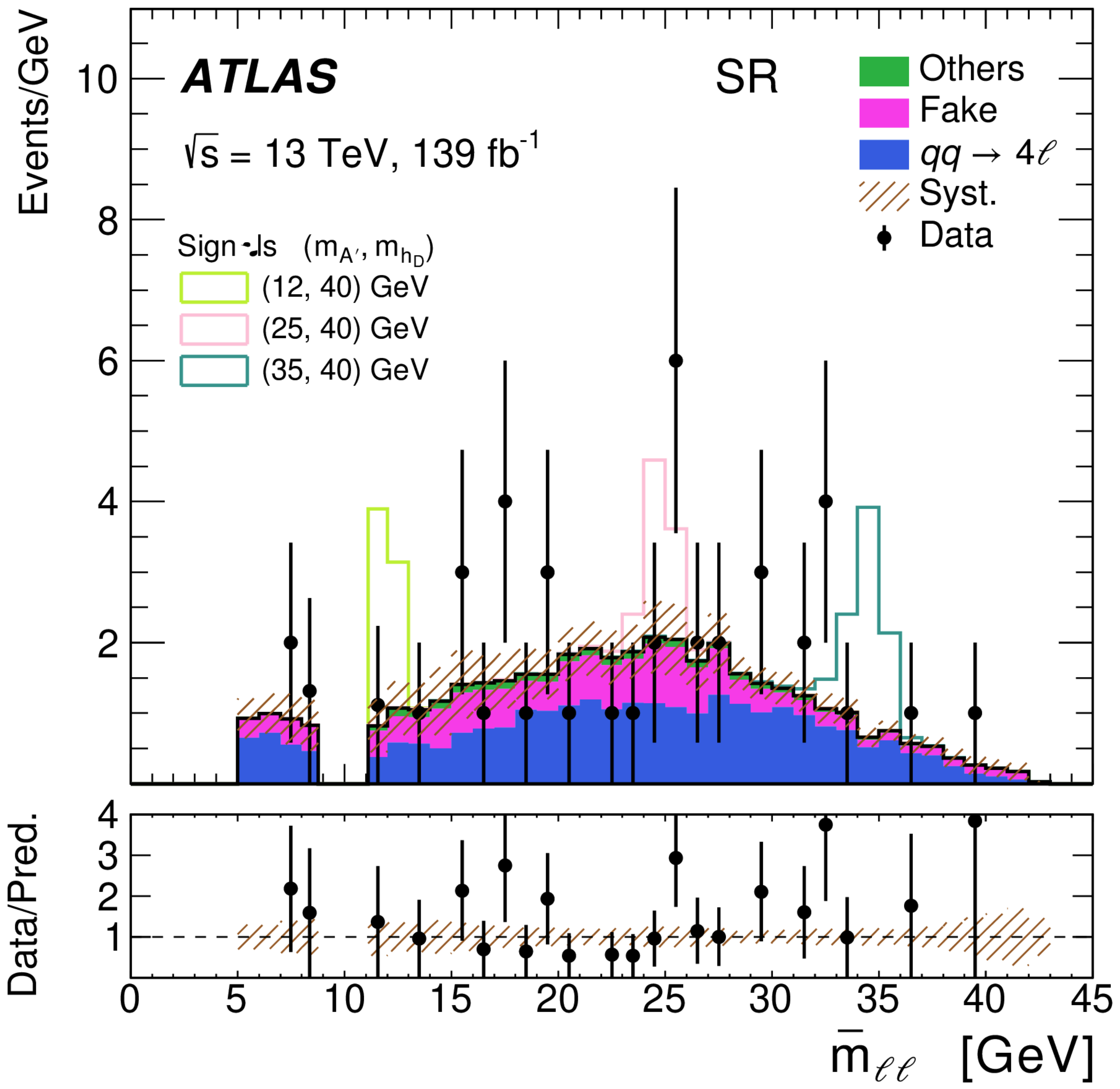
Dark Photon in rare Z boson decays.

Dark photons in rare Z boson decays

PhysRevLett.131.251801

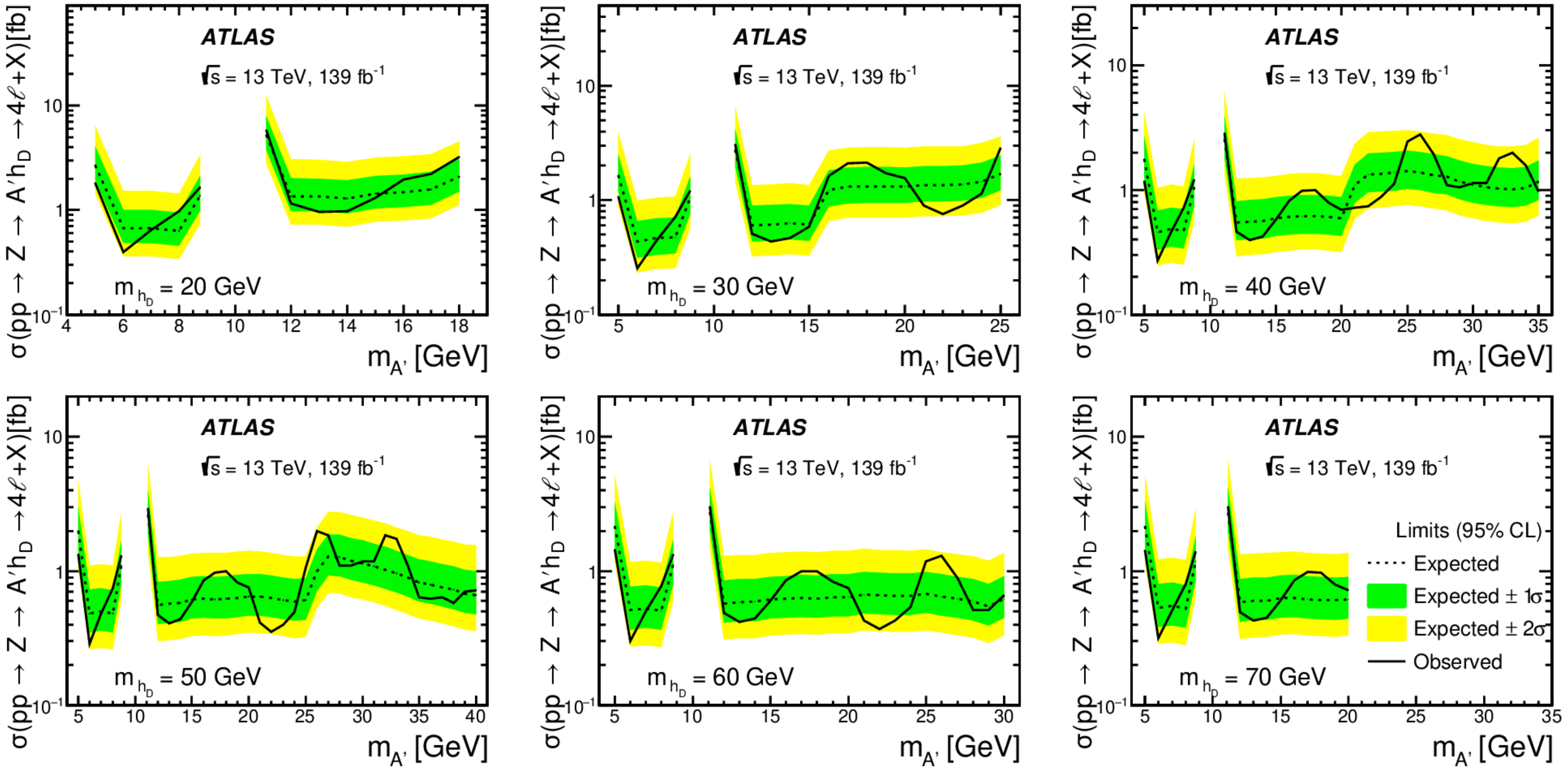
- First search for a dark photon and dark Higgs boson produced via the dark Higgs-strahlung process in rare Z boson decays at the LHC: $Z \rightarrow A' h_D$ with $m_{A'} + m_{h_D} < m_Z$.
- Model parameter: ϵ, α_D, $M_{A'}$, M_{h_D}
- Dark photon A' is the lightest particle in the DS, $A' \rightarrow f\bar{f}$ (SM)
- $pp \rightarrow Z \rightarrow A' h_D \rightarrow A'A'A'^{(*)} \rightarrow 4l + X$ (at least two SFOS lepton pairs)
- Sensitive to $\alpha_d \epsilon^2$, the coupling of A' to h_D times the effective coupling of A' to SM particles .
- Dominant background: $qq \rightarrow 4l$ estimated in a dedicated control region.
- Minimum likelihood fit to the average $\bar{m}_{ll}$, with no excess over SM predictions.





Upper limits on $\sigma \times$ Br for

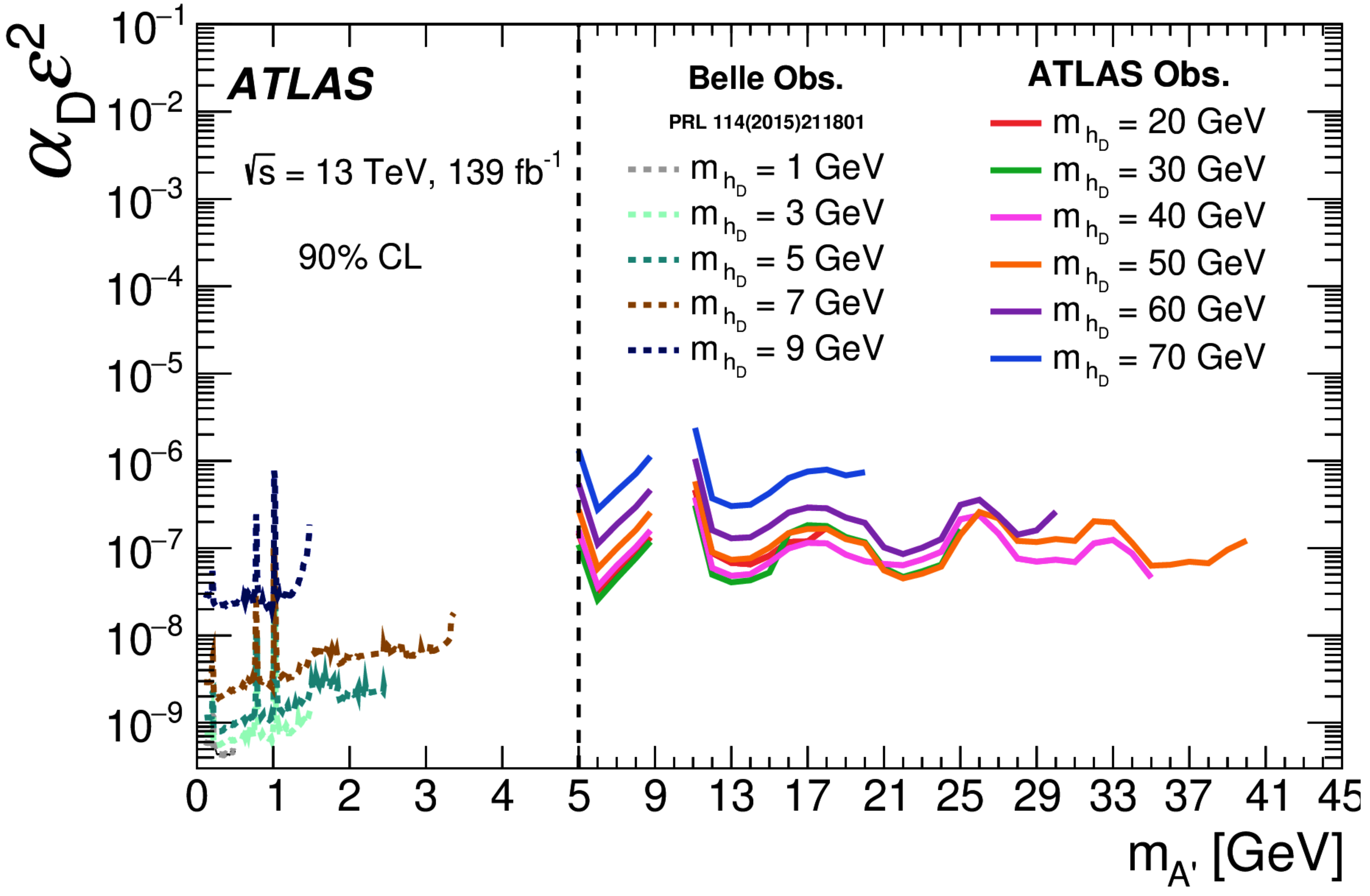
5 GeV < $m_{A'}$ < 40 GeV and 20 GeV < m_h < 70 GeV with $m_{A'} < m_{h_D}$



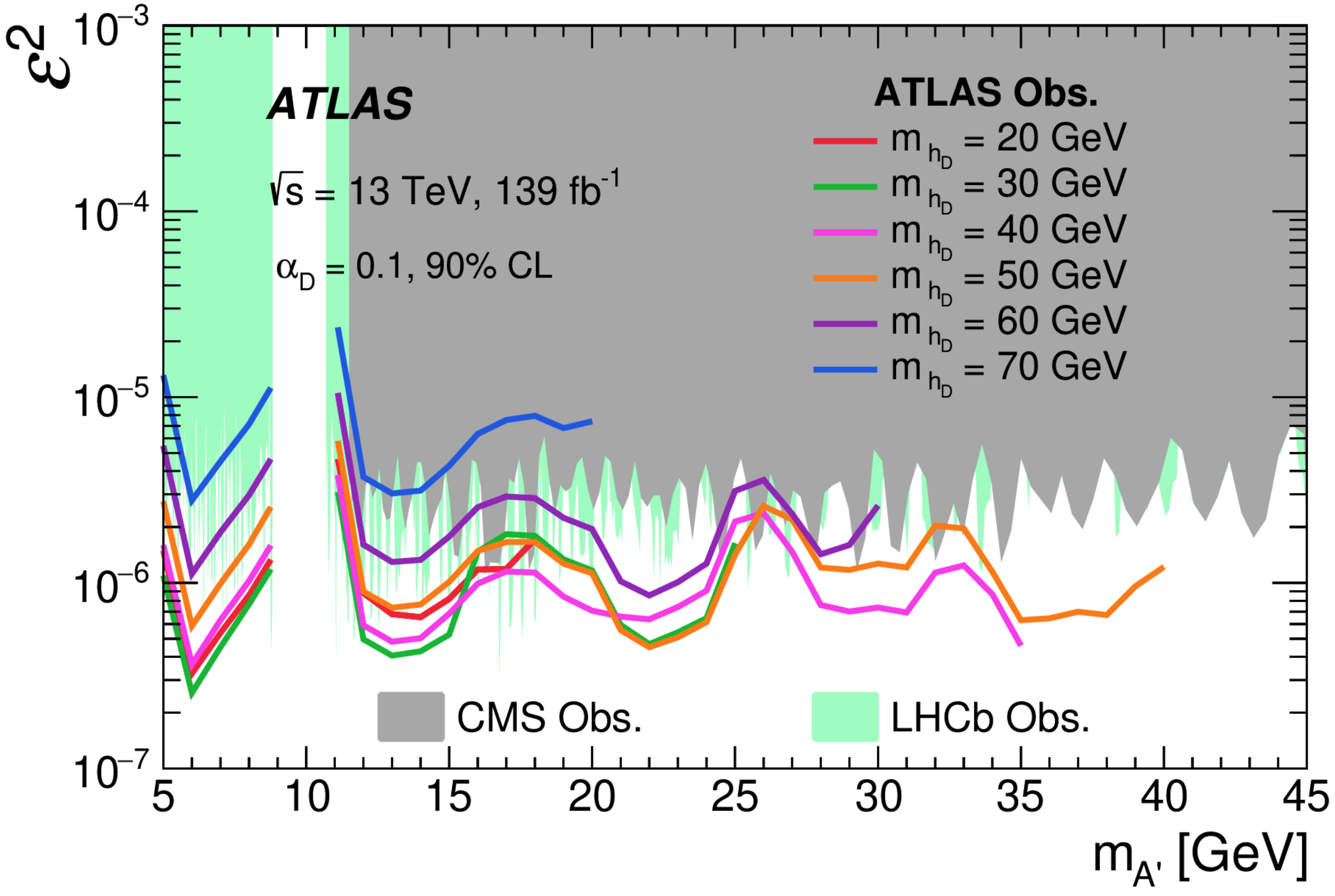
Dark photons in rare Z boson decays

PhysRevLett.131.251801

Observed 90% CL upper limits on $\alpha_d \epsilon^2$, as a function of mA′, compared to the results from Belle.



Observed 90% CL upper limits on $\epsilon^2(\alpha_d = 0.1)$, as a function of mA′. Compared to the LHCb and CMS results.



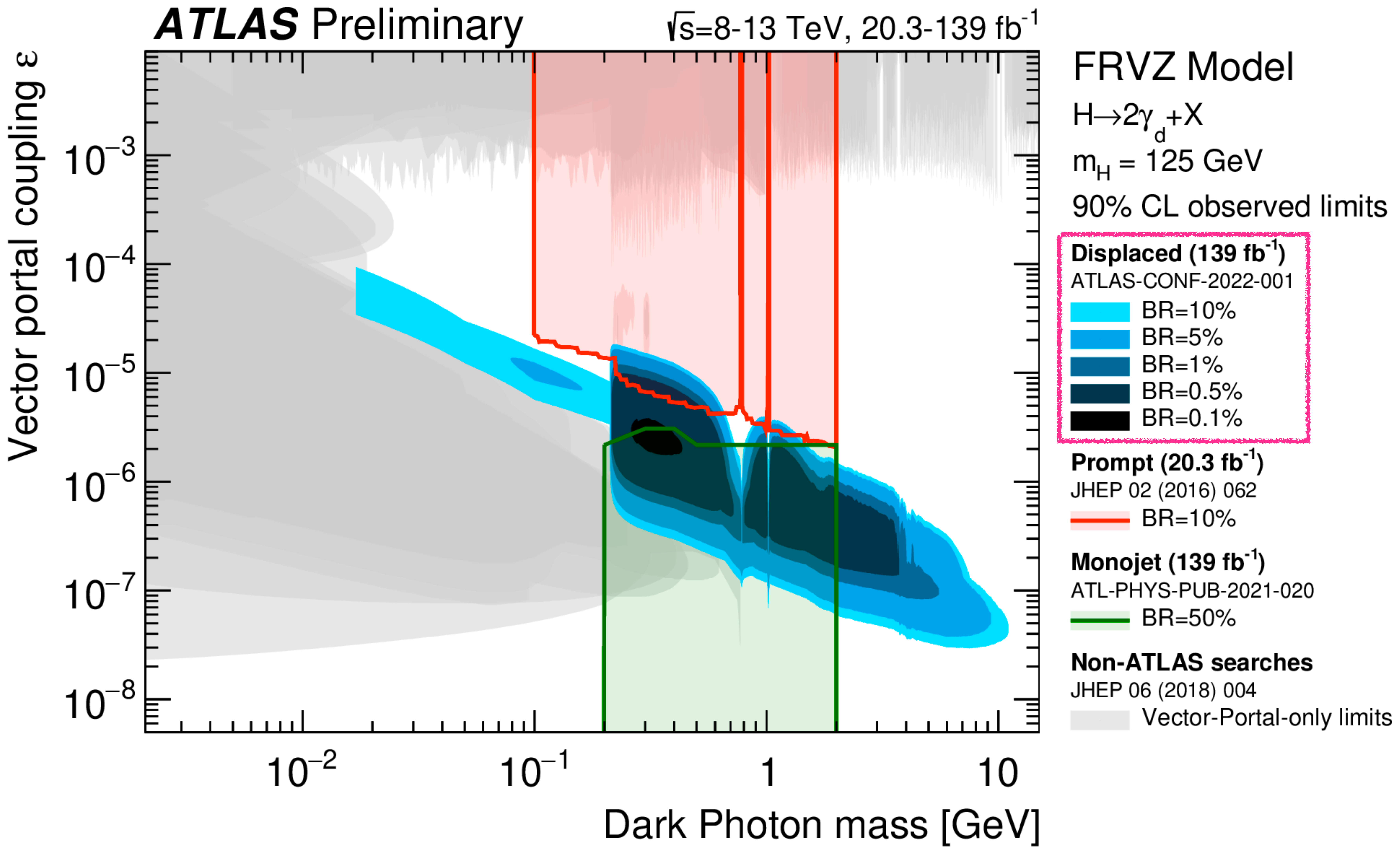
$\sqrt{s} = 8 - 13$ TeV, $20.3 - 139$ fb^{-1} **dark photon summary plot**

Dark photon summary

ATL-PHYS-PUB-2022-007

Three different ATLAS analyses are shown for different assumptions on the H→ 2γd+X (0.1% - 50%).

The masses of the intermediate dark fermions predicted by the model are chosen to be lighter w-r-t 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.
- Upper limits at 95% CL are set on branching ratios and model parameters (coupling, mass, lifetime).
- More efforts are ongoing with extended datasets (Run2 + Run 3), new signatures/ideas and more combinations.
- No significant excess of events above SM background prediction with the LHC Run 2 data.
- Stay tuned for new Run 3 ATLAS dark photon results and Run 2 combinations.

Thank you