Combination of searches for the Higgs boson decaying into a photon and a massless dark photon using pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

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CLHCP 2024, Qingdao
November 15, 2024

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Outline

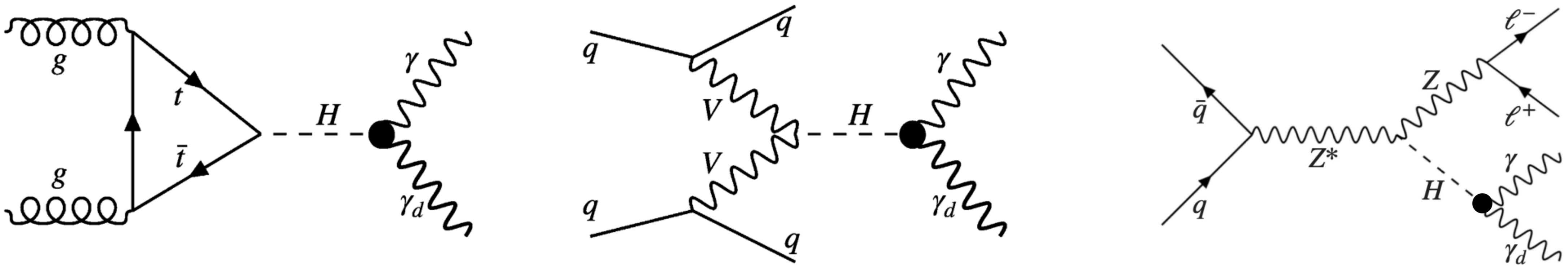
- Introduction
- Description of the input analyses
- Statistical combination
- Results
- Physics interpretation in Minimal simplified model
- Conclusion

Introduction

- Undetected Higgs decay $\mathcal{B}_{u.} < 10\%$ motivates searches for elusive BSM dark sector particles coupled to Higgs;
- One of the attractive candidates is undetectable, massless dark photon (γ_d).
  - Force carrier of $U(1)_D$ gauge group of dark sector.
  - Introduce dark matter self-interactions for solving *small-scale structure formation problems* and the *PAMELA-Fermi-AMS2 anomaly*
  - Enhancing the light dark matter annihilation rate, making asymmetric DM scenarios phenomenologically viable.

- Potential approach to search dark photon: through $\mathbf{H} \rightarrow \boldsymbol{\gamma\gamma_d}$
  - **Signature characterized by resonant $\boldsymbol{\gamma}$ + MET $\left(\boldsymbol{E_T^{miss}}\right)$**
  - Higgs is assumed to be produced via three Higgs production modes:

ggF process VBF process ZH process



Introduction

- Both ATLAS and CMS published various results for $\mathrm{H} \to \gamma\gamma_d$ searches with LHC full Run 2 data:

	$\gamma + E_T^{miss}$ (ggF channel)	$\gamma + E_T^{miss}$ + VBF jets (VBF channel)	$\gamma + E_T^{miss} + Z(\to ll)$ (ZH channel)
ATLAS	Reinterpretation of mono-γ	EPJC 82(2022) 105	JHEP 07 (2023) 133
CMS			JHEP 10(2019)139
		JHEP 03(2021)011	

$\mathrm{H}_{125} \to \gamma\gamma_d$

95% CL limit on BR

	VBF Channel	ZH Channel	Combined
ATLAS	1.8(1.7)%	2.3(2.8)%	This analysis
CMS	3.5(2.8)%	4.6(3.6)%	2.9(2.1)%

$\mathrm{H}_{\mathrm{BSM}} \to \gamma\gamma_d$

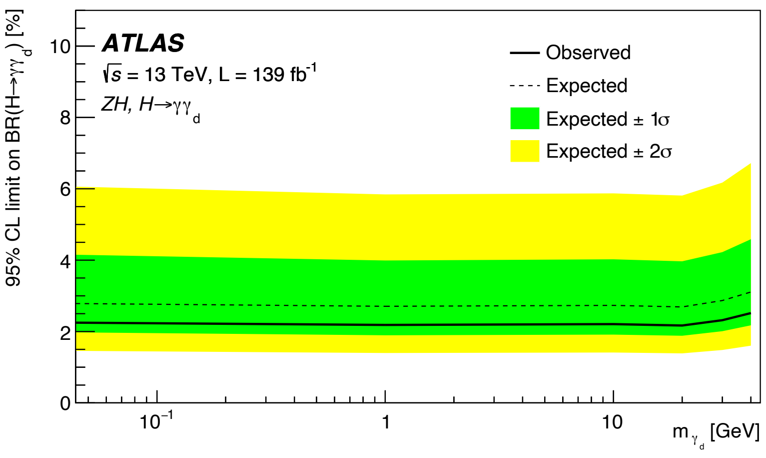
Mass range probed for H

	VBF Channel	ggF Channel	Combined
ATLAS	Up to 2 TeV	Up to 3 TeV	This analysis
CMS	Up to 1 TeV	-	-

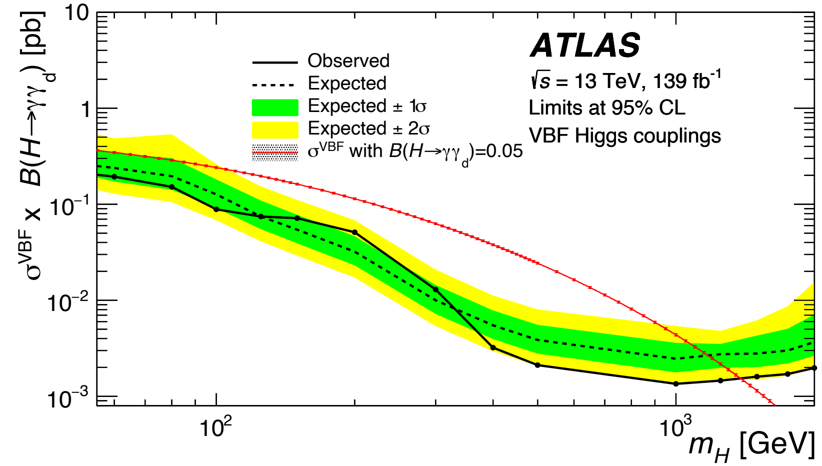
- ATLAS provided competitive and complementary result for $\mathrm{H} \to \gamma\gamma_d$ searches
  - Strong motivation for statistical combination to bring the most stringent LHC constraints for $\mathrm{H}_{125} \to \gamma\gamma_d$ and broadest search in BSM Higgs masses

Scenarios of combination

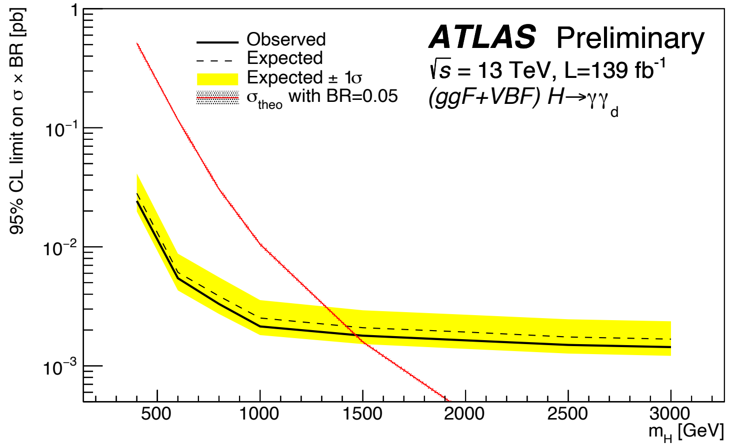
ZH Channel



VBF Channel



ggF Channel

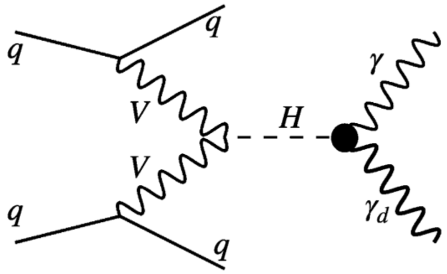


- Most straightforward and worthy scenarios for the statistical combination, based on 3 input analyses.

Input analysis	Signals	m_H	m_{γ_d}	Combination scenarios
ZH	SM $(\mathrm{ZH})\mathrm{H} \to \gamma\gamma_d$	125 GeV	[0, 40] GeV	**ZH + VBF** for **SM Higgs**, massless γ_d, targeting $\mathbf{BR(H125 \to \gamma\,\gamma_d)}$
VBF	SM $(\mathrm{ggF} + \mathrm{VBF})\mathrm{H} \to \gamma\gamma_d$	125 GeV	Massless γ_d	
	BSM $(\mathrm{VBF})\mathrm{H} \to \gamma\gamma_d$	[60, 2000] GeV	Massless γ_d	**ggF + VBF** for **Heavy Higgs**, massless γ_d, targeting $\boldsymbol{\sigma(\mathrm{ggF} + \mathrm{VBF}) \times \mathrm{BR}(\mathrm{H} \to \gamma\gamma_d)}$
ggF	BSM $(\mathrm{ggF} + \mathrm{VBF})\mathrm{H} \to \gamma\gamma_d$	[400, 3000] GeV	Massless γ_d	

- Signal grid for heavy Higgs combination
  - m_H = 400, 600, 800, 1000, 1500, 2000, 2500, 3000 GeV
    (blue masses added to VBF analysis to harmonize with ggF signal grid)

Input analysis: VBF channel



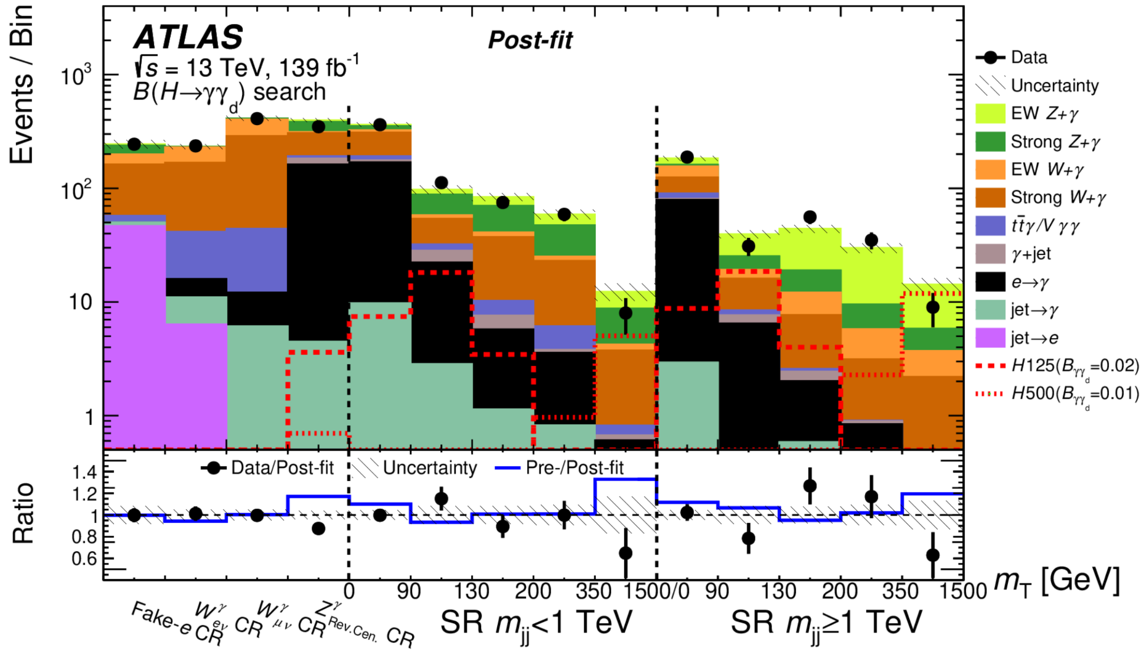
- **Topology:**
  - 1 photon, 2 or 3 VBF jet, E_T^{miss}
  - Lepton(e,μ) veto
- **Main background**
  - $W(\to l\nu)\gamma + jets$, $Z(\to \nu\nu)\gamma + jets$, $jet \to e$ from CRs.
  - $jet \to \gamma$ from data-driven.
- Simultaneous fit to data including SR and CRs divided into 2 bins of m_{jj}, each with 5 bins of $m_T(\gamma, E_T^{miss})$

$$m_T(\gamma, E_T^{miss}) = \sqrt{2p_T^{\gamma}E_T^{miss}[1-\cos(\phi_\gamma - \phi_{E_T^{miss}})]}$$

- **Dominant uncertainty**:
  - Data stats., fake bkg in syst.

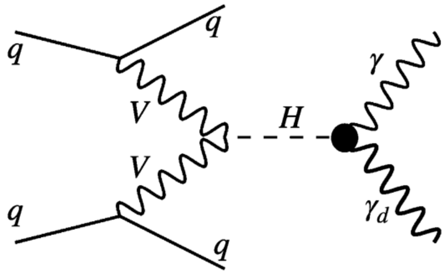
SM Higgs, massless dark photon
Observed (expected) limit at 95% CL on
BR$(\mathrm{H125} \to \gamma\gamma_d)$: 1.8(1.7)%

Channels	VBF	ZH	ggF
Trigger	E_T^{miss}	Lepton(s)	Photon
Photons	$= 1, C_\gamma > 0.4$	$= 1$	≥ 1
E_T^γ [GeV]	$\in (15, \max(110, 0.733 \times m_T))$	> 25	> 150
E_T^{miss} [GeV]	> 150	> 60	> 200
Jets	2 or 3, $m_{j_1j_2} > 250$ GeV, $\lvert\Delta\eta_{j_1j_2}\rvert > 3$ $\eta_{j_1}\cdot\eta_{j_2} < 0$, $\Delta\phi_{j_1j_2} < 2$, $C_{j_3} < 0.7$	≤ 2	≤ 1
Leptons	$= 0\ (e, \mu)$	$= 2$, SFOC $m_{\ell\ell} \in (76, 116)$ GeV	$= 0\ (e, \mu, \tau)$



No significant deviation from SM prediction

Input analysis: VBF channel



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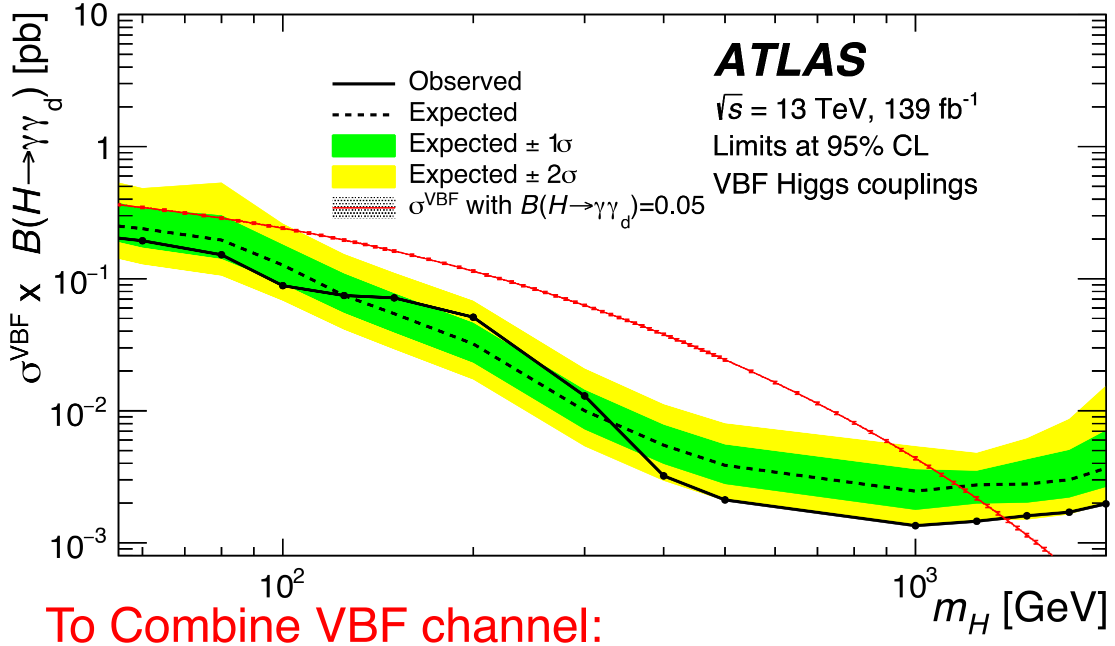
$$m_T(\gamma, E_T^{miss}) = \sqrt{2p_T^{\gamma} E_T^{miss}[1 - \cos(\phi_{\gamma} - \phi_{E_T^{miss}})]}$$

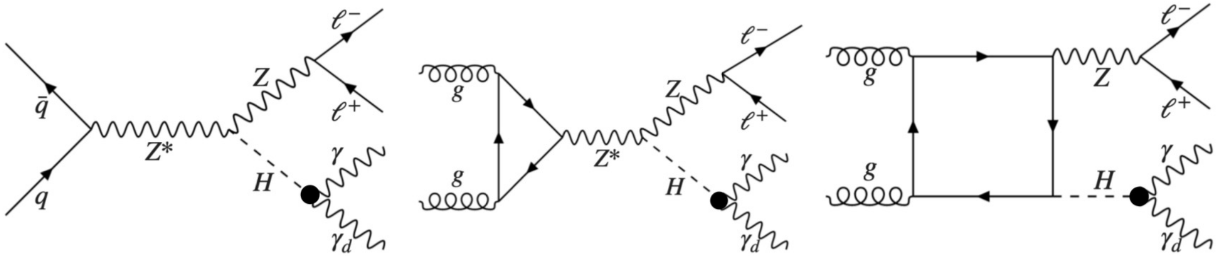
- **Dominant uncertainty**:
  - Data stats., fake bkg in syst.

BSM Higgs, massless dark photon
Probe H mass: [60, 2000] GeV



To Combine VBF channel:
- Add ggF contribution;
- Extend Higgs mass to 3 TeV for BSM scenario

Input analysis: ZH channel



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  - 2 SFOC leptons within Z mass window,
- **Main background**
  - Fake E_T^{miss} dominates and is estimated with data-driven.
  - $VV\gamma$ bkg estimated from CRs
- BDT (XGBoost) used to enhance the analysis sensitivity.
  - Binned maximum likelihood fit to data on BDT in SR and $VV\gamma$ CR
- **Dominant uncertainty**:
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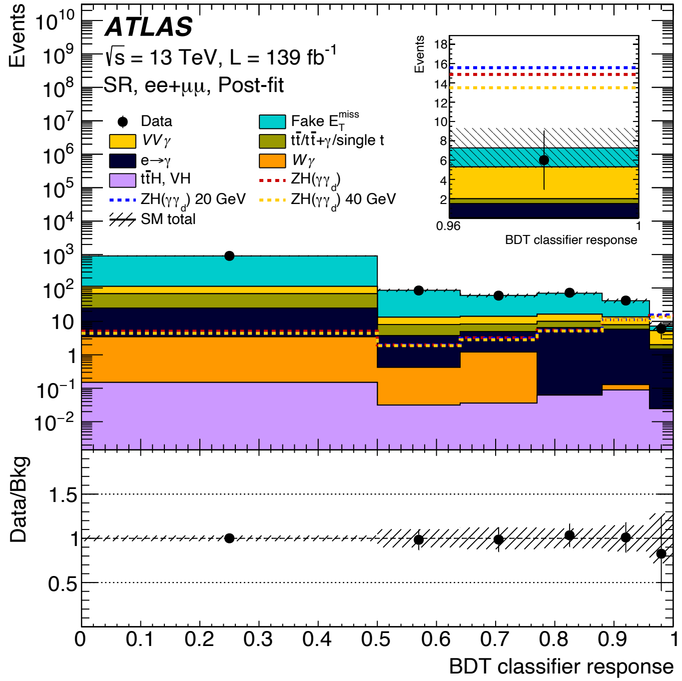
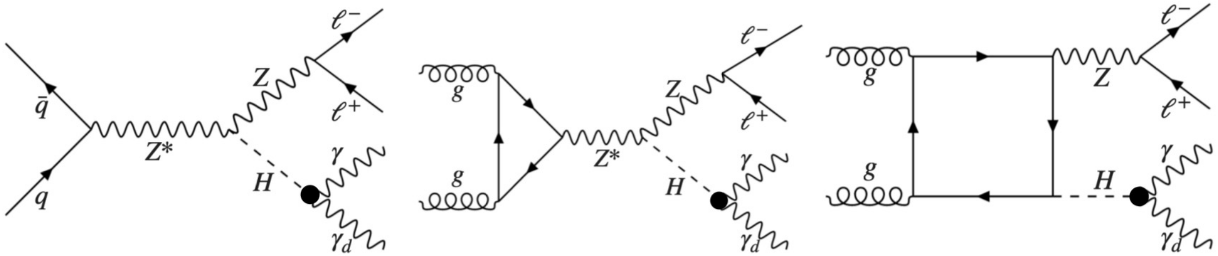


SM Higgs, massless dark photon
Observed (expected) limit at 95% CL
$\mathrm{BR}(H125 \rightarrow \gamma\gamma_d)$: 2.3(2.8)%

No significant deviation from SM prediction

Input analysis: ZH channel



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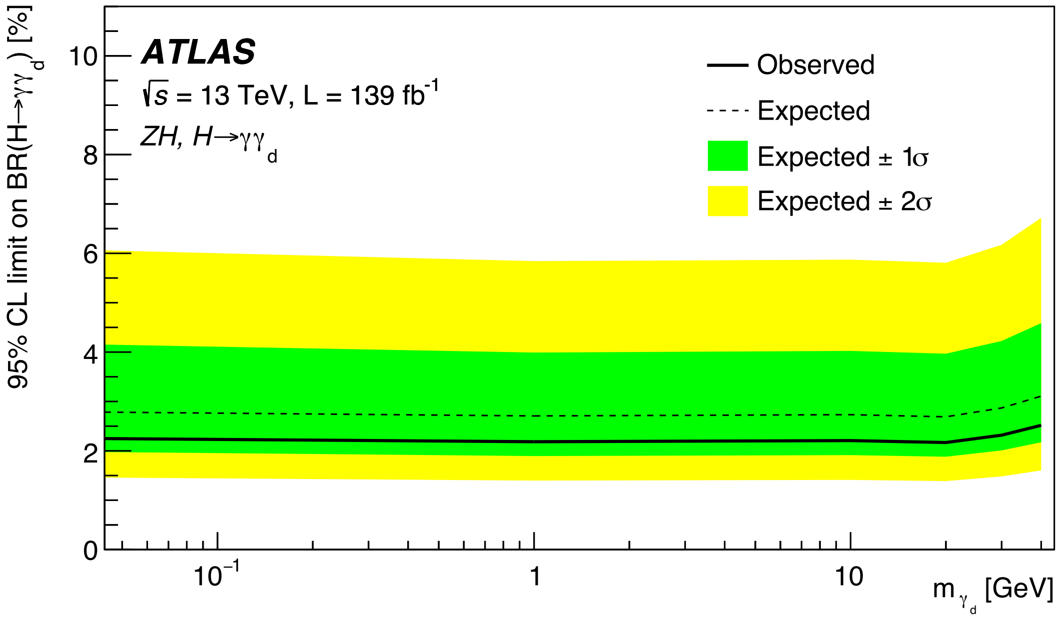
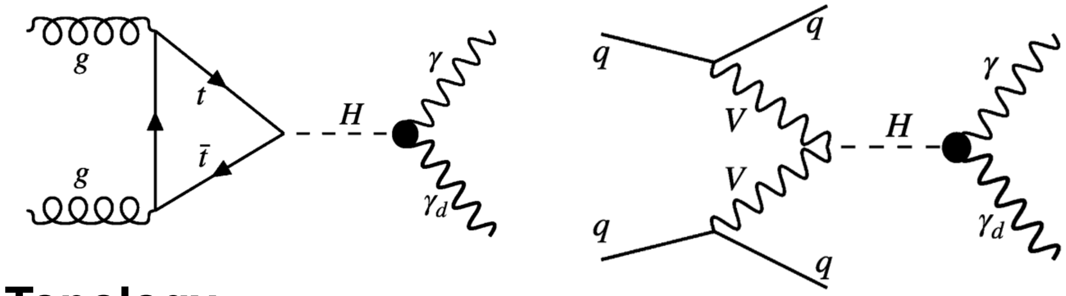


First limit on low mass dark photon up to 40 GeV from $H \to \gamma\gamma_d$ at LHC

Input analysis: ggF channel



- **Topology:**
  - >=1 photon, <=1 jet, E_T^{miss}
  - Lepton (e, μ, τ) veto
- **Main background**
  - $Z(\rightarrow \nu\nu)\gamma, W(\rightarrow l\nu)\gamma,\ \gamma + jets$ from CRs.
  - $jet \rightarrow \gamma$, $e \rightarrow \gamma$ from data-driven.
- Binned maximum likelihood fit to data on MET in SR
  - Including both VBF and ggF processes
- **Dominant uncertainty**:
  - Data stats., fake photons from jets in syst.

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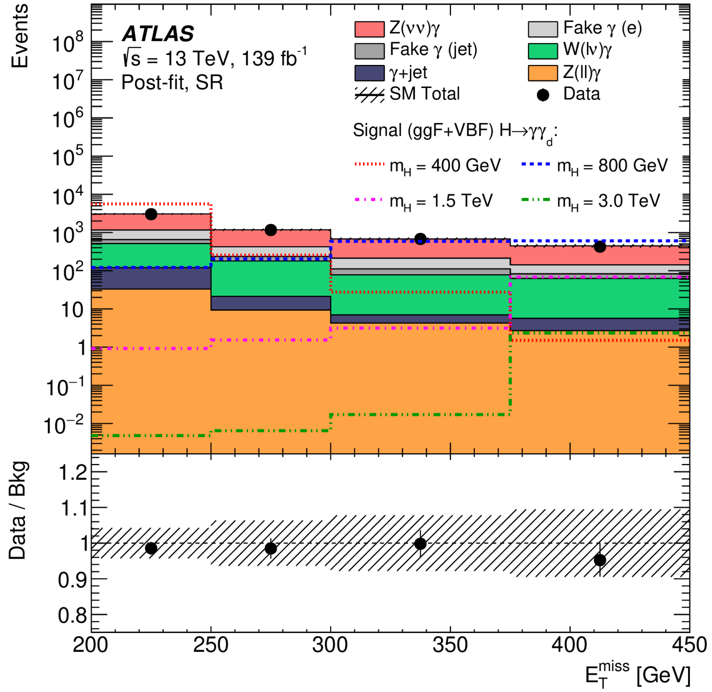

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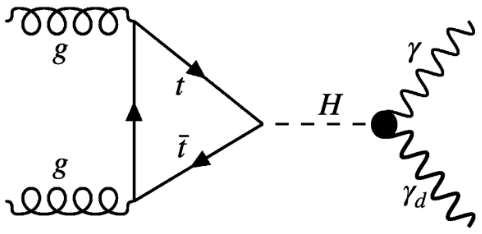

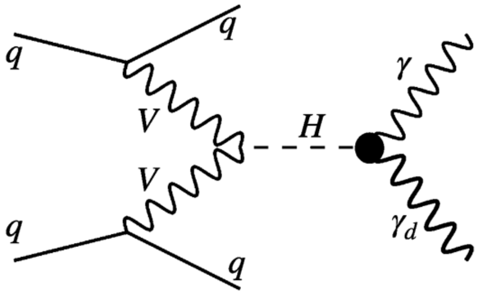

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BSM Higgs, massless dark photon
Probe H mass: [400, 3000] GeV

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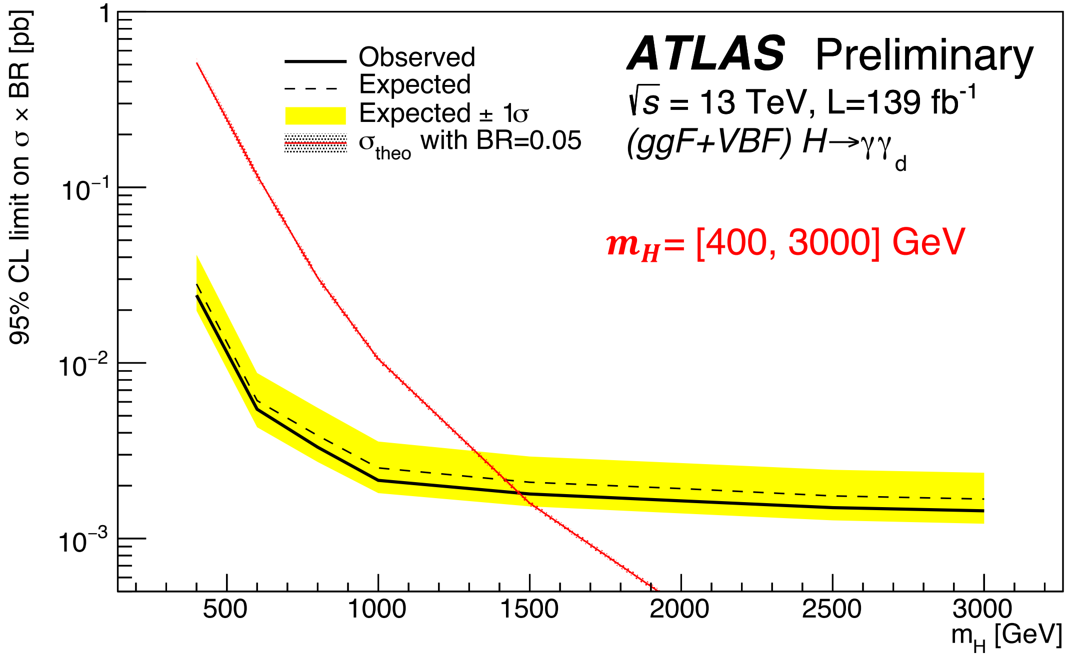


Combination strategy

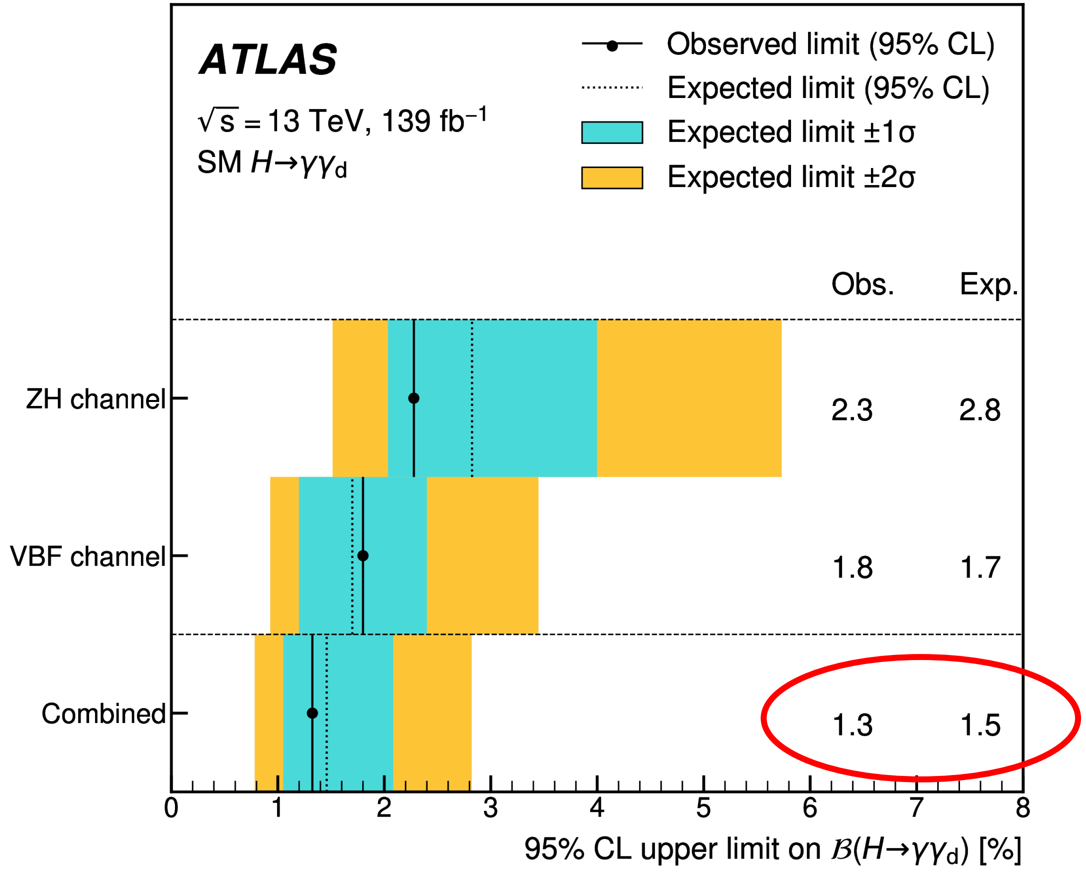
- **POI rescaling**

<table>
<tr><th>Input Analysis</th><th>Original POI</th><th colspan="2">Combination POI</th></tr>
<tr><td>ZH channel</td><td>signal strength, and scaled with BR = 5%</td><td rowspan="2">BR($H125 \rightarrow \gamma\gamma_d$)</td><td></td></tr>
<tr><td>VBF channel</td><td>BR($H \rightarrow \gamma\gamma_d$)</td><td rowspan="2">$\boldsymbol{\sigma}(\mathbf{VBF+ggF})\times$BR($H \rightarrow \gamma\gamma_d$)</td></tr>
<tr><td>ggF channel</td><td>$\sigma^{VBF+ggF}(m_H)\times BR(H \rightarrow \gamma\gamma_d)$</td><td></td></tr>
</table>

- **Systematic correlation:**
  - Uncertainties related to data-taking conditions are correlated:
    - **Luminosity, pile-up modelling**…
  - **Experimental uncertainties**: correlated where appropriate, exceptions are:
    - Uncertainties related to same objects but **implemented with different schemes** among input channels
      - Jet-Energy-Resolution…
    - Uncertainties **heavily constrained or pulled** in original input analyses.
  - **Background modelling uncertainties**
    - Uncorrelated since bkg composition and phase space are different
  - **Signal modelling uncertainties**
    - Stemming from choice of parton distribution functions and QCD calculations:
      - Minor impact on final results - uncorrelated

Results -- SM Higgs

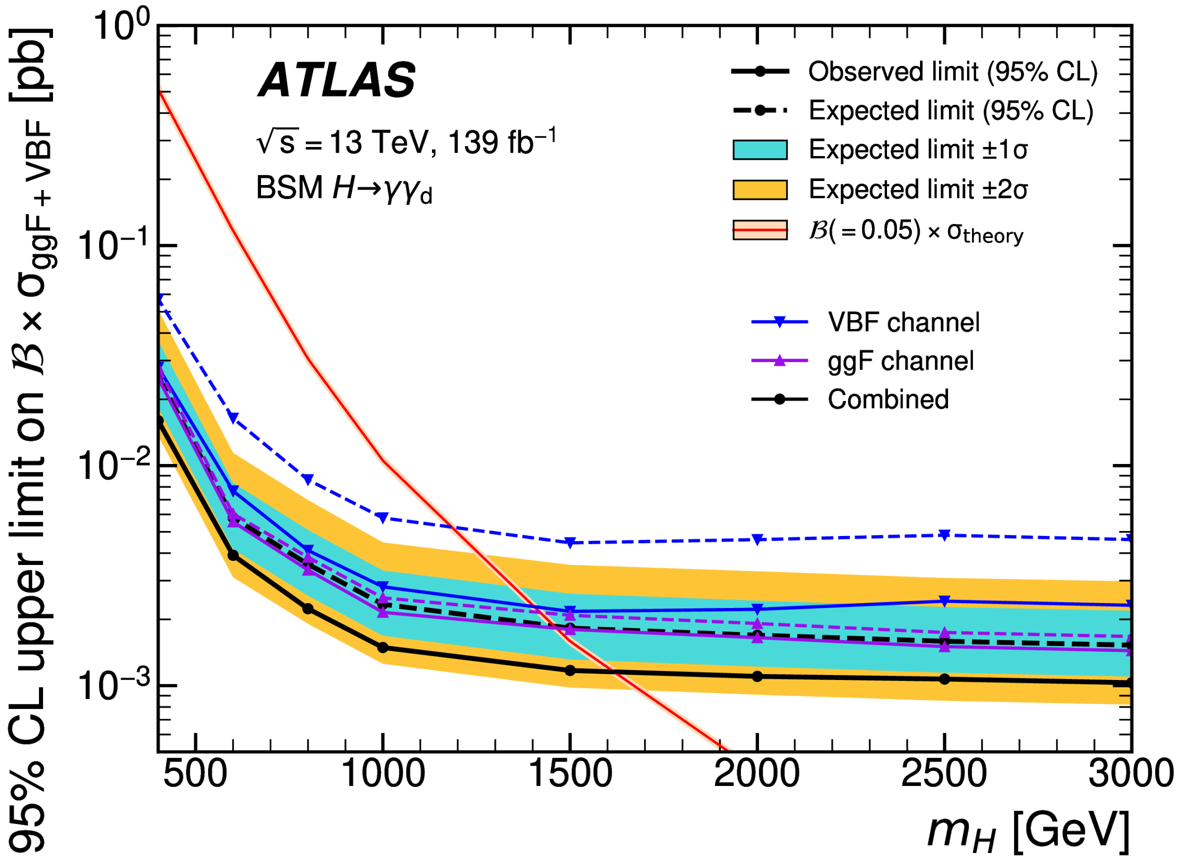
- VBF-ZH combined limits at 95% CL on BR($H \to \gamma\gamma_d$): 1.3 (1.5)%
  - Set the **most stringent limit** on BR($H \to \gamma\gamma_d$) of LHC results to date.
  - Improved by 29%(14%) w.r.t VBF channel.
- **Comparable impacts** from **statistical** and **systematic** uncertainties.
- Leading systematic uncertainties: bkg modelling, jet MET, fake estimation and MC stats.



Uncertainty source	$\Delta\mathcal{B}_{\text{group}}/\Delta\mathcal{B}_{\text{total}}$ [%]
Theory uncertainties	49
Signal modelling	2.2
Background modelling	47
Experimental uncertainties	63
Luminosity, pile-up	< 0.1
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	40
Electrons, muons	11
Fake background	35
MC statistical uncertainty	36
Systematic uncertainties	75
Statistical uncertainty	66
Total uncertainty	100

Results -- Heavy Higgs

- ggF+VBF combination produces combined limits on $\sigma(\mathrm{VBF}+\mathrm{ggF})\times\mathrm{BR}(H\rightarrow\gamma\gamma_d)$
  - Set the most comprehensive constraints.
  - Sensitivity improved by 33%(14%) w.r.t. ggF channel at m_H = 1500 GeV.
- **Statistical uncertainty dominant at Higher Higgs mass**
- Leading systematic uncertainties: fake estimation, bkg modelling, jet MET, MC stats and lepton reconstruction.



Uncertainty source	$\Delta\mathcal{B}_{group}/\Delta\mathcal{B}_{total}$ [%]				
m_H [GeV]	400	800	1000	2000	3000
Theory uncertainties	30	27	28	40	35
Signal modelling	2.2	4.6	5.2	6.9	2.0
Background modelling	30	27	27	38	34
Experimental uncertainties	64	51	45	37	41
Luminosity, pile-up	4.6	2.6	2.9	2.8	2.3
Jets, E_T^{miss}	22	12	11	13	14
Electrons, muons	20	23	18	13	14
Fake background	52	41	35	25	29
MC statistical uncertainty	20	17	19	19	23
Statistical uncertainty	75	84	87	85	86
Systematic uncertainties	67	55	49	53	52
Total uncertainty	100	100	100	100	100

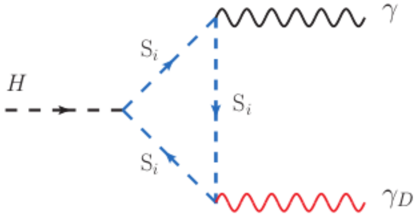
Physics interpretation

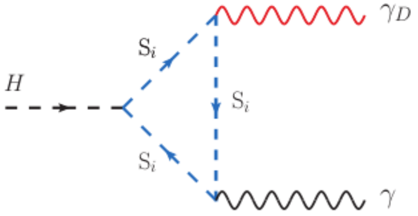
- Physics interpretation of ZH+VBF limits on BR($H125 \rightarrow \gamma\gamma_d$) in Minimal Model
- Minimal simplified model [arXiv:1405.5196].
  - Generic Lagrangian: $L \sim \mu(H^{\dagger} S_L S_R + h.c.)$
    - μ - mass parameter, S_L - $SU(2)_L$ doublet, S_R - $SU(2)_L$ singlet

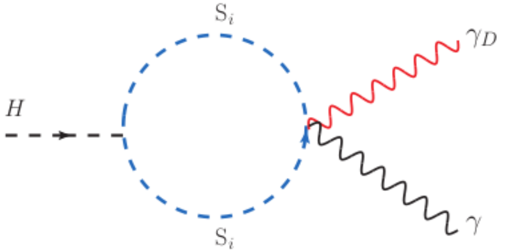
$\hat{S} = (S_L, S_R)$

  - With $U(1)_D$ and $U(1)_{em}$ interaction, the free kinetic Lagrangian: $L^0 = \partial_\mu \hat{S}^{\dagger} \partial^\mu \hat{S} - \hat{S}^{\dagger} M_S^2 \hat{S}$
  - 2 scalar messengers allow for $H125 \rightarrow \gamma\gamma_d$ at 1-loop

$$M_S^2 = \begin{pmatrix} m_L^2 & \Delta \\ \Delta & m_R^2 \end{pmatrix}$$







$\Delta = \lambda v$, parametrizes the scalar left-right mixing

  - BR of $H \rightarrow \gamma\gamma_d$ / $\gamma_d\gamma_d$ / $\gamma\gamma$ can be expressed as $U(1)_D$ fine-structure-constant α_D and mixing parameter ξ:

$$\mathrm{BR}_{\gamma\gamma_D} = \mathrm{BR}_{\gamma\gamma}^{\mathrm{SM}} \frac{r_{\gamma\gamma_D}}{1 + r_{\gamma_D\gamma_D}\mathrm{BR}_{\gamma\gamma}^{\mathrm{SM}}}$$

$$\mathrm{BR}_{\gamma_D\gamma_D} = \mathrm{BR}_{\gamma\gamma}^{\mathrm{SM}} \frac{r_{\gamma_D\gamma_D}}{1 + r_{\gamma_D\gamma_D}\mathrm{BR}_{\gamma\gamma}^{\mathrm{SM}}}$$

$$\mathrm{BR}_{\gamma\gamma} = \mathrm{BR}_{\gamma\gamma}^{\mathrm{SM}} \frac{(1 + \chi\sqrt{r_{\gamma\gamma}})^2}{1 + r_{\gamma_D\gamma_D}\mathrm{BR}_{\gamma\gamma}^{\mathrm{SM}}}$$

$$r_{\gamma\gamma_D} = 2X^2\left(\frac{\alpha_D}{\alpha}\right)$$

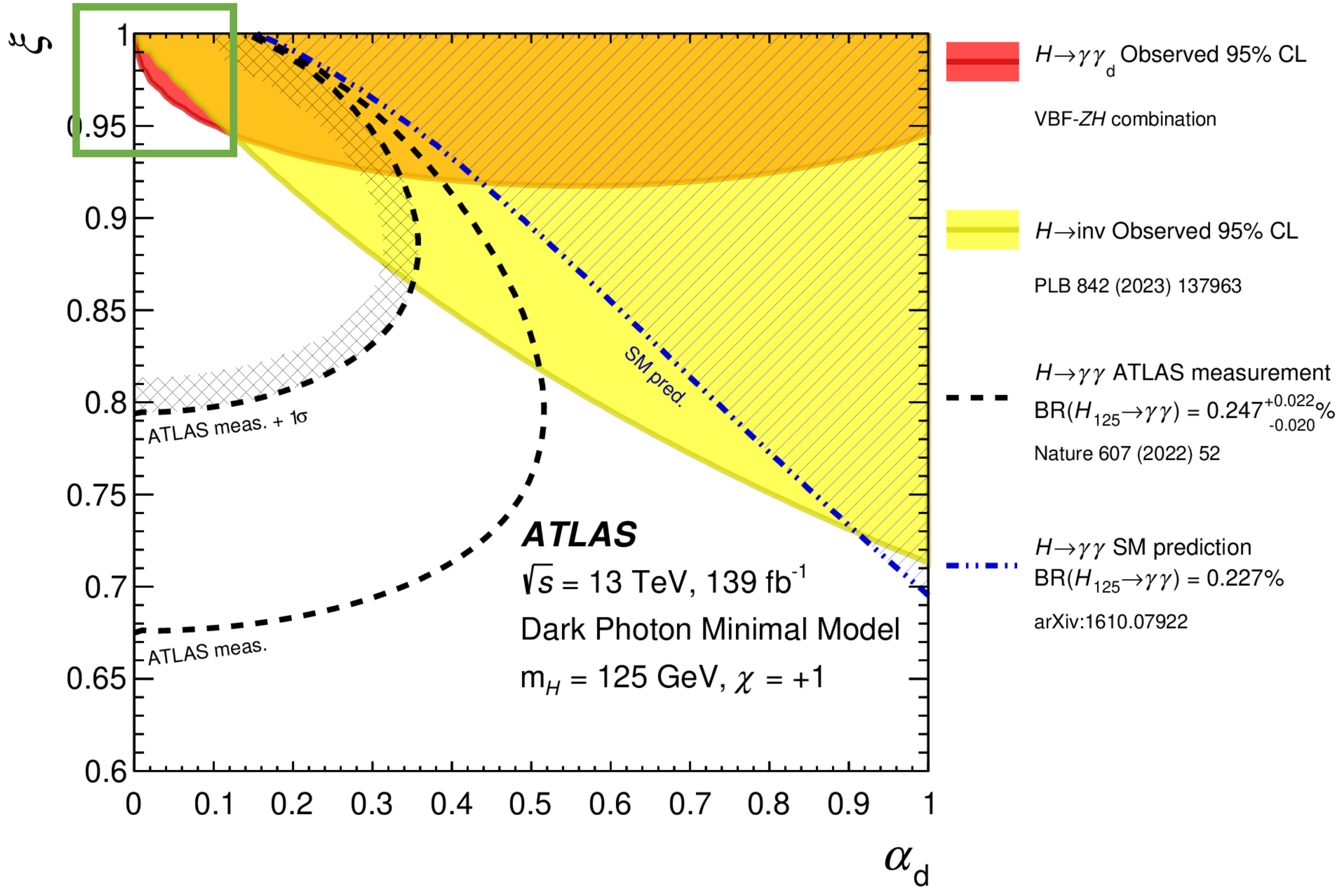
$$r_{\gamma_D\gamma_D} = X^2\left(\frac{\alpha_D}{\alpha}\right)^2$$

$$r_{\gamma\gamma} = X^2$$

$$X \equiv \frac{\xi^2}{3F(1-\xi^2)} \qquad \xi = \frac{\Delta}{\bar{m}^2}$$

- ZH+VBF combined limits on BR($H \rightarrow \gamma\gamma_d$) and other results from e.g. $H \rightarrow inv$, $H \rightarrow \gamma\gamma$ can be translated into restrictions on the allowed parameter space in the (ξ, α_D) plan.

Physics interpretation



$\chi = +1$: scenario with constructive interference from messenger sector in $H_{125} \to \gamma\gamma$

- $\xi \simeq 0.7$ at $\alpha_d = 1$ are excluded by BR($H \to inv$) limit interpreted in terms of $H_{125} \to \gamma_d \gamma_d$ signal.
- $H_{125} \to \gamma\gamma_d$ combination provides **additional sensitivity** in the low α_{d} region
  - Disfavoured by ATLAS BR($H_{125} \to \gamma\gamma$) measurement

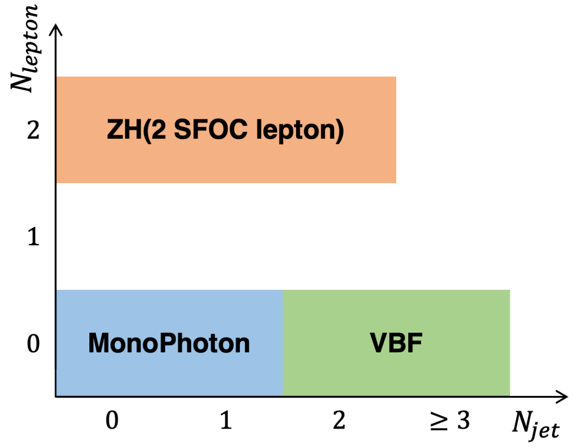
Conclusion

- 2 baseline scenarios have been studied for our combination effort:
  - **Scenario 1**: VBF+ZH combination for SM Higgs, massless dark photon sets
    the most stringent limits on BR($H \to \gamma\gamma_d$) at $m_H = 125\ \mathrm{GeV}$.
  - **Scenario 2**: VBF+monophoton-recast combination for heavy Higgs, massless dark photon
    provides a wider Higgs mass range on $\sigma(\mathrm{VBF} + \mathrm{ggF})\times$BR($H \to \gamma\gamma_d$).
- Provide the **first physics interpretation** of ZH+VBF limits on BR($H125 \to \gamma\gamma_d$) in Minimal model.
- Paper published by JHEP: JHEP08(2024)153

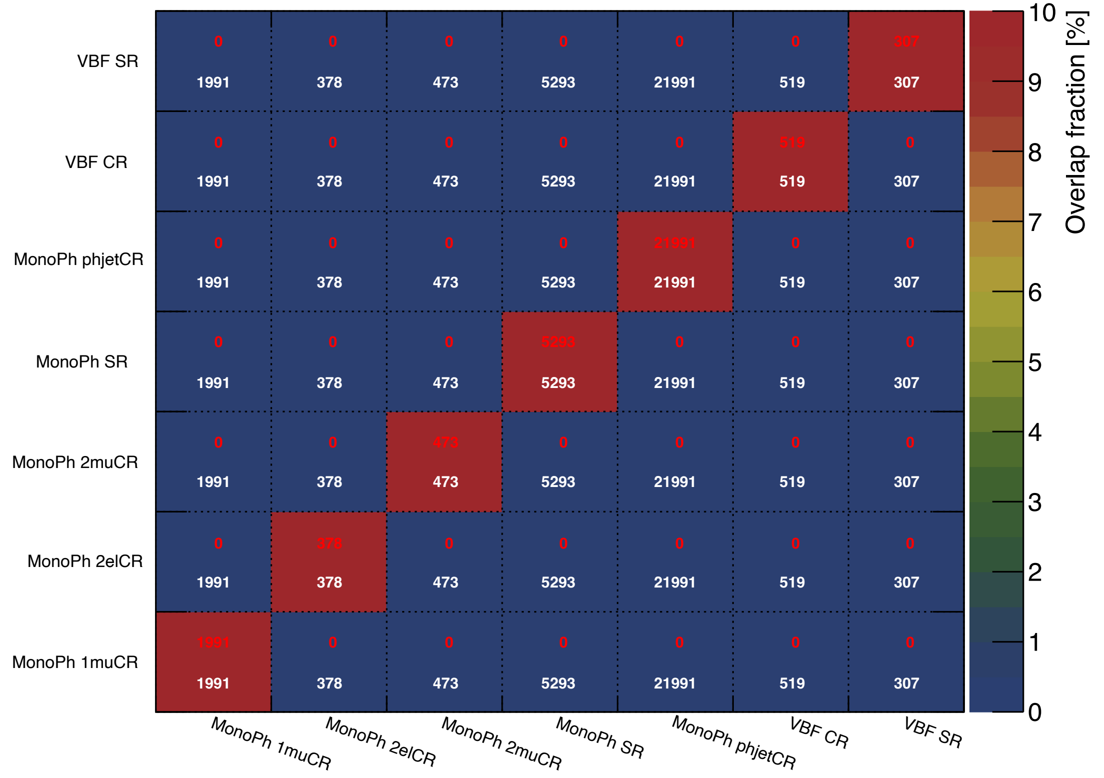
Backup

Combination: Overlap check

- No overlap expected due to **orthogonality** from Njet and Nlep definition.
  - **No overlap observed with Full run-2 data.**
- Little overlap(< 2%) found in VBF signal process on MC.
  - Reason for this overlap: Different jet reconstructions & pileup suppression
- Treated as statistically independent.



Heavy Higgs monophton-recast+VBF combination
Full run-2 data



7859 in MonoPh SR,
20 shared with VBF SR

mH = 1 TeV (largest overlap)
VBF production mode, MC