Combination of ATLAS searches for Higgs boson decays into a photon and a massless dark photon

中国物理学会高能物理分会第十四届全国粒子物理学术会议

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Outline

1. Introduction
2. Overview of input $H \to \gamma\gamma_{\mathrm{d}}$ analyses
3. Statistical combination
4. Interpretation in Dark Photon Minimal Simplified Model

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

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

The ATLAS Collaboration

A combination of searches for Higgs boson decays into a visible photon and a massless dark photon ($H \to \gamma\gamma_{\mathrm{d}}$) is presented using 139 fb^{-1} of proton–proton collision data at a centre-of-mass energy of $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the Large Hadron Collider. The observed (expected) 95% confidence level upper limit on the Standard Model Higgs boson decay branching ratio is determined to be $\mathcal{B}(H \to \gamma\gamma_{\mathrm{d}}) < 1.3\,\%\ (1.5)\,\%$. The search is also sensitive to higher-mass Higgs bosons decaying into the same final state. The observed (expected) 95% confidence level limit on the cross-section times branching ratio ranges from 16 fb (26 fb) for $m_H = 400$ GeV to 1.0 fb (1.5 fb) for $m_H = 3$ TeV. Results are also interpreted in the context of a minimal simplified model.

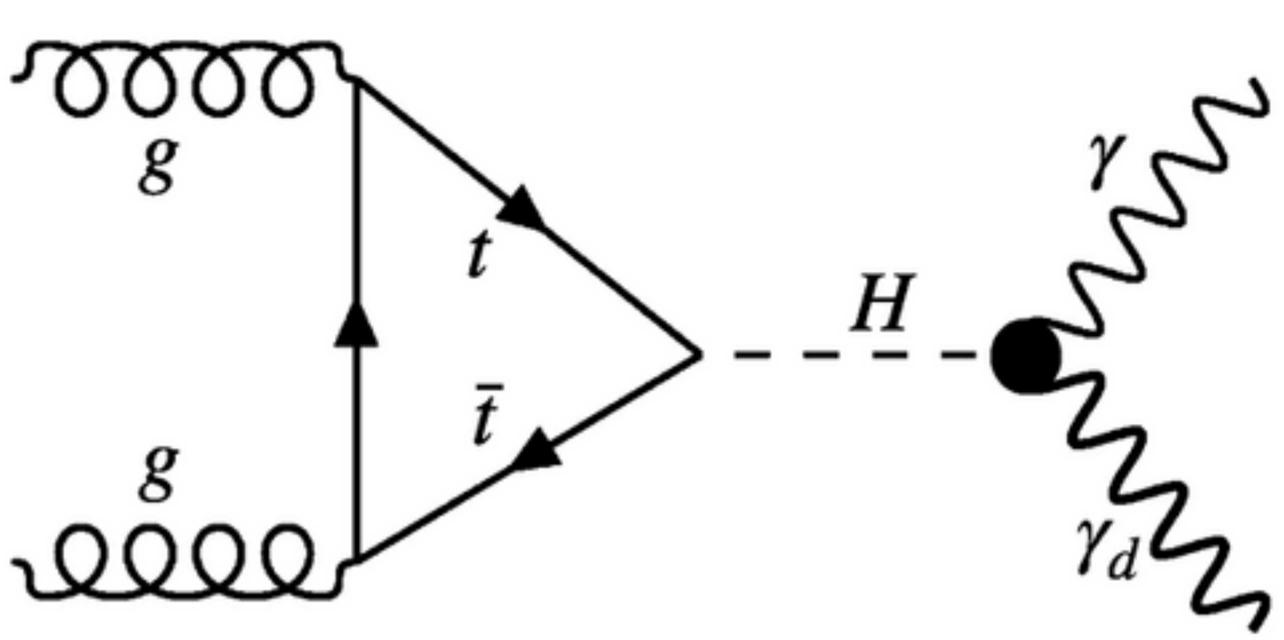
arXiv:2406.01656

accepted by JHEP

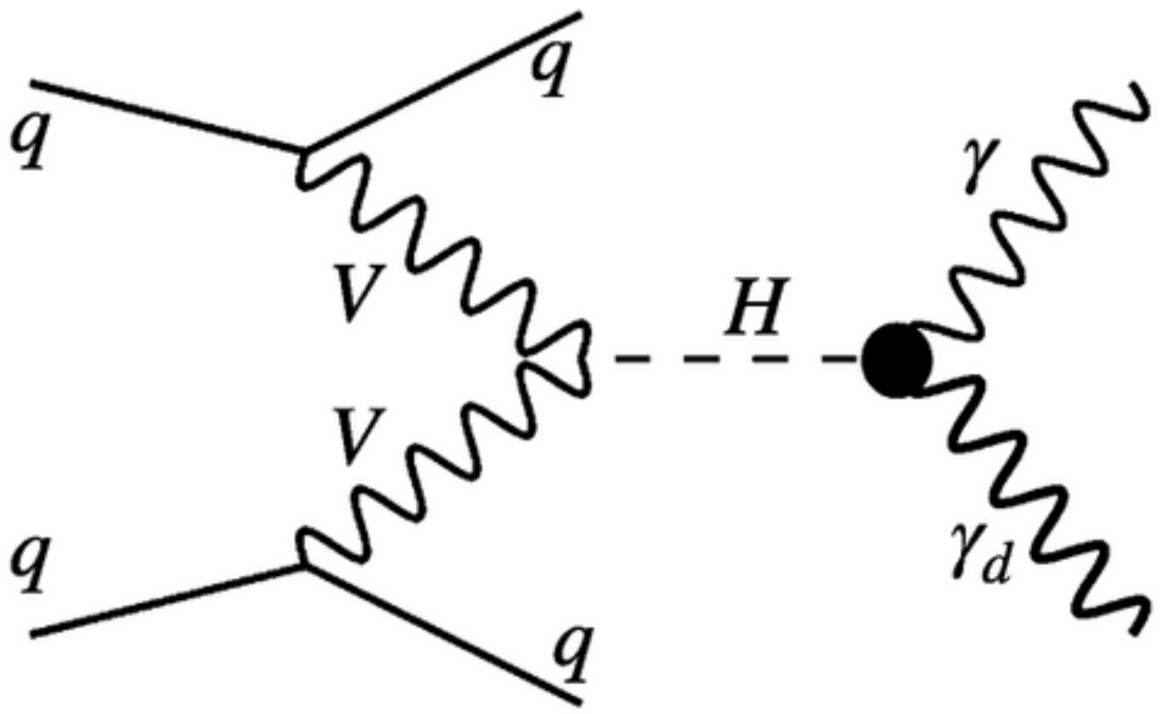
Introduction

- Undetected Higgs decay $\mathscr{B}_{\text{u.}} < \mathscr{O}(10\%)$ from *ATLAS* and *CMS* motivates searches for elusive BSM dark sector particles coupled to Higgs. One attractive candidate is undetectable, massless dark photon (γ_{d}).
  - Force carrier of extra $U(1)_{\text{d}}$ gauge symmetry of dark sector.
  - Introducing dark matter self-interactions for solving *small-scale structure formation problem* and *PAMELA-Fermi-AMS2 anomaly*.
  - Enhancing light DM annihilation rate, making *asymmetric DM scenarios* phenomenologically viable.

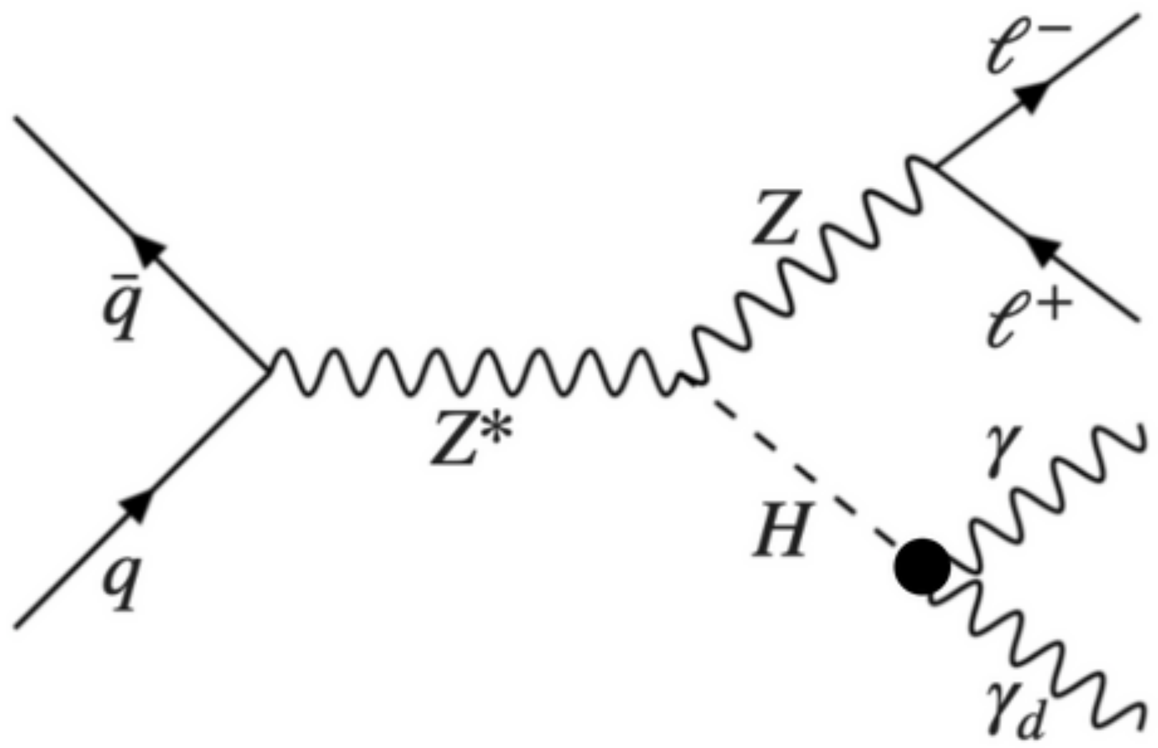
- Potential approach is search for $H \to \gamma\gamma_{\text{d}}$ in resonant $\gamma + E_{\text{T}}^{\text{miss}}$ signatures via three Higgs production modes



ggF process



VBF process



ZH process

Introduction

⭐ "Process" refers to production mode
⭐ "Channel" refers to selection topology

❖ Both ATLAS and CMS published various results for $H \to \gamma\gamma_d$ searches in distinct final states using LHC full Run 2 data:

<table>
<tr><th></th><th>$\gamma + E_T^{miss}$
(ggF channel)</th><th>$\gamma + E_T^{miss}$ + VBF jets
(VBF channel)</th><th>$\gamma + E_T^{miss} + Z(\to \ell\ell)$
(ZH channel)</th></tr>
<tr><td>ATLAS</td><td>reinterpretation of mono-γ</td><td>EPJC 82 (2022) 105</td><td>JHEP 07 (2023) 133</td></tr>
<tr><td rowspan="2">CMS</td><td rowspan="2">--</td><td></td><td>JHEP 10 (2019) 139</td></tr>
<tr><td colspan="2">JHEP 03 (2021) 011</td></tr>
</table>

$H_{125} \to \gamma\gamma_d$

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

95% CL limit on BR

$H_{BSM} \to \gamma\gamma_d$

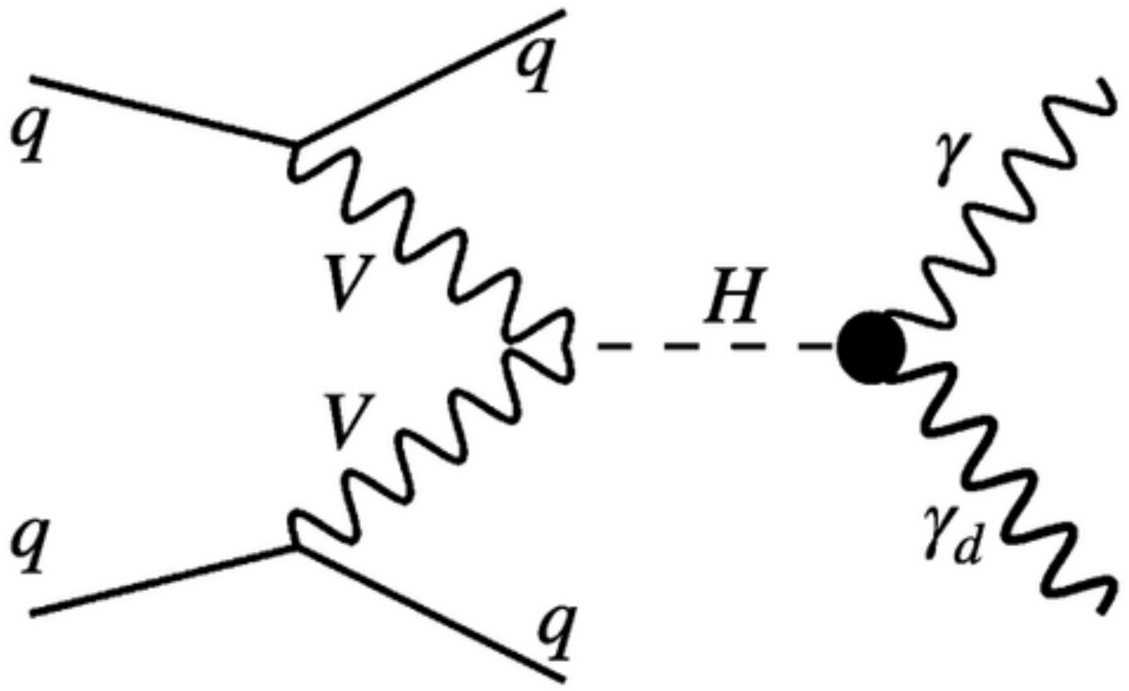
	VBF channel	ggF channel	Combined
ATLAS	Up to 2 TeV	Up to 3 TeV	This analysis
CMS	Up to 1 TeV	--	--

Mass range probed for *H*

❖ ATLAS provided competitive and complementary results, strong motivation for stat. combination to bring the best LHC constraint on $H_{125} \to \gamma\gamma_d$ and broadest search in terms of BSM *H* mass (400 - 3000 GeV).

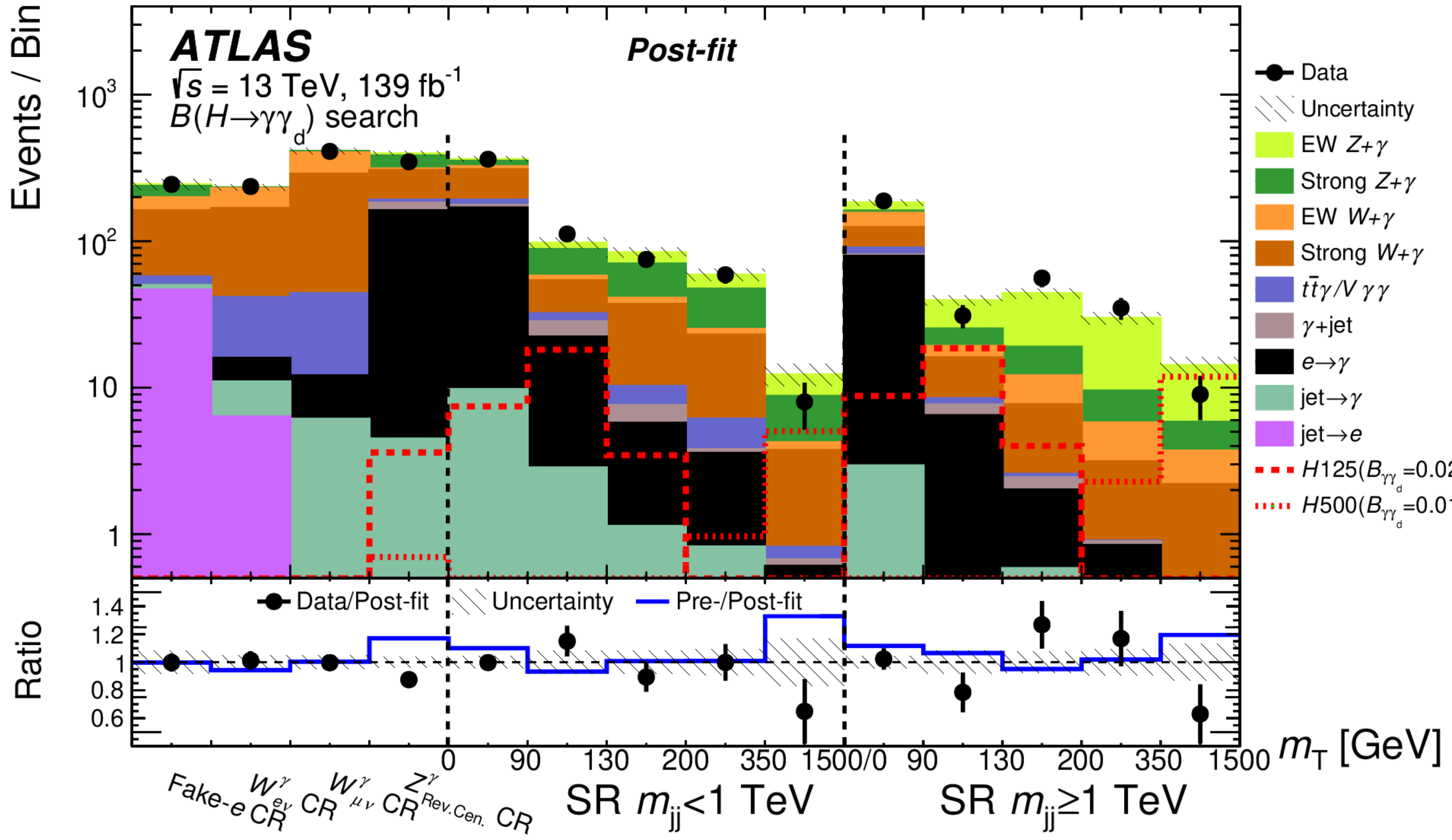
Input overview

VBF channel [EPJC 82 (2022) 105]



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

- Topology:
  - 1 photon, 2 or 3 VBF jets, E_T^{miss}
  - Lepton $(e,\ \mu)$ veto
- Background estimation
  - $W(\to \ell\nu)\gamma + \text{jets}$, $Z(\to \nu\nu)\gamma + \text{jets}$, and e-fake γ from control regions (CR).
  - jet-fake γ from data-driven.
- Fit to data on $m_{j_1 j_2}$, $m_{\mathrm{T}}(\gamma, E_{\mathrm{T}}^{\mathrm{miss}})$ bins in SR and 4 CRs.



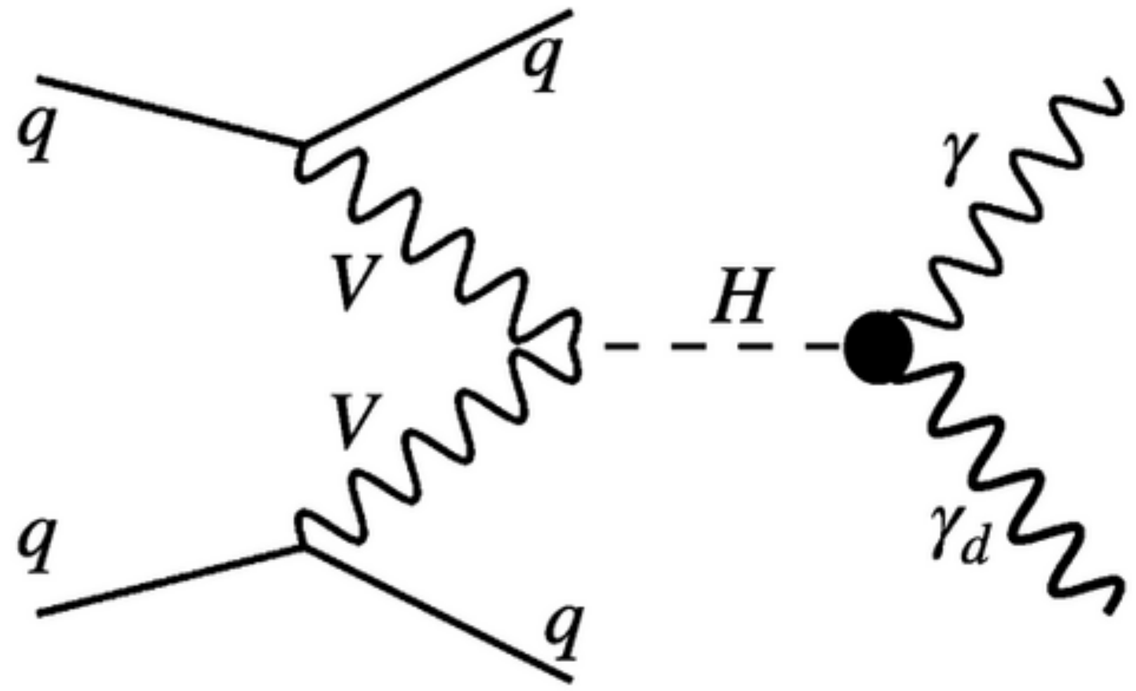
No significant deviation from SM prediction.

$$m_{\mathrm{T}}(\gamma, E_{\mathrm{T}}^{\mathrm{miss}}) = \sqrt{2 E_{\mathrm{T}}^{\gamma} E_{\mathrm{T}}^{\mathrm{miss}} \left[1 - \cos(\phi_\gamma - \phi_{E_{\mathrm{T}}^{\mathrm{miss}}})\right]}$$

$$C_i = \exp\left[-\frac{4}{(\eta_{j_1} - \eta_{j_2})^2}\left(\eta_i - \frac{\eta_{j_1} + \eta_{j_2}}{2}\right)^2\right]$$

Input overview

VBF channel EPJC 82 (2022) 105



- ❖ Topology:
  - ◉ 1 photon, 2 or 3 VBF jets, E_T^{miss}
  - ◉ Lepton $(e,\ \mu)$ veto
- ❖ Background estimation
  - ◉ $W(\to \ell\nu)\gamma + \text{jets}$, $Z(\to \nu\nu)\gamma + \text{jets}$, and e-fake γ from control regions (CR).
  - ◉ jet-fake γ from data-driven.
- ❖ Fit to data on $m_{j_1 j_2}$, $m_T(\gamma, E_T^{miss})$ bins in SR and 4 CRs.

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, $m_{j_1 j_2} > 250$ GeV, $\lvert\Delta\eta_{j_1 j_2}\rvert > 3$ $\eta_{j_1} \cdot \eta_{j_2} < 0$, $\Delta\phi_{j_1 j_2} < 2$, $C_{j_3} < 0.7$	≤ 2	≤ 1
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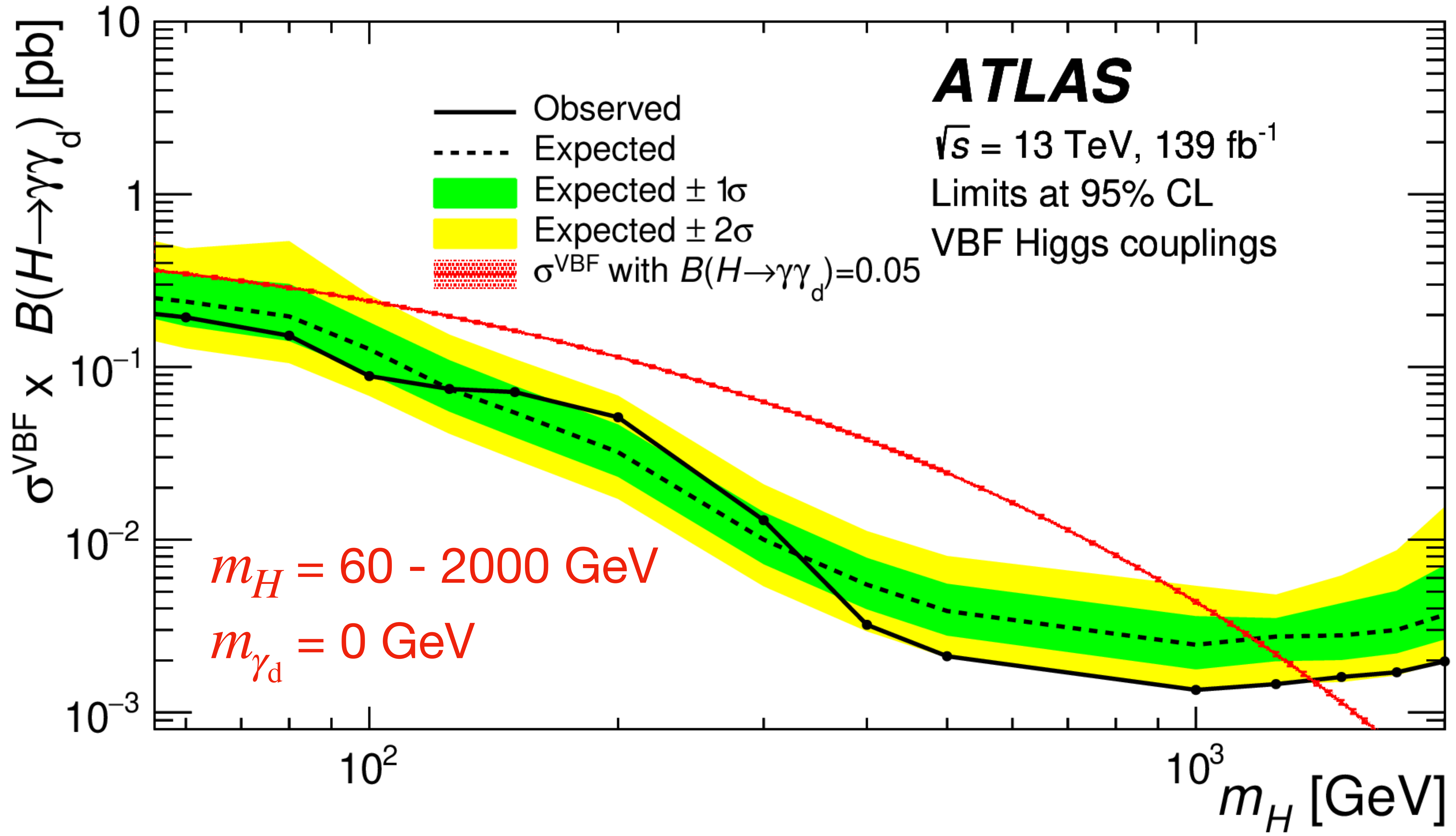

- ❖ For this combination,
  - ◉ ggF process contribution included for BSM Higgs decay search.
  - ◉ Extend H mass to 3 TeV.

Input overview

ZH channel JHEP 07 (2023) 133

Channels	VBF	ZH	ggF
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Lepton(s)	Photon
Photons	$= 1, C_{\gamma} > 0.4$	$= 1$	≥ 1
E_{T}^{γ} [GeV]	$\in (15, \max(110, 0.733 \times m_{\mathrm{T}}))$	> 25	> 150
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	> 60	> 200
Jets	2 or 3, $m_{j_1 j_2} > 250$ GeV, $\|\Delta\eta_{j_1 j_2}\| > 3$ $\eta_{j_1} \cdot \eta_{j_2} < 0, \Delta\phi_{j_1 j_2} < 2, C_{j_3} < 0.7$	≤ 2	≤ 1
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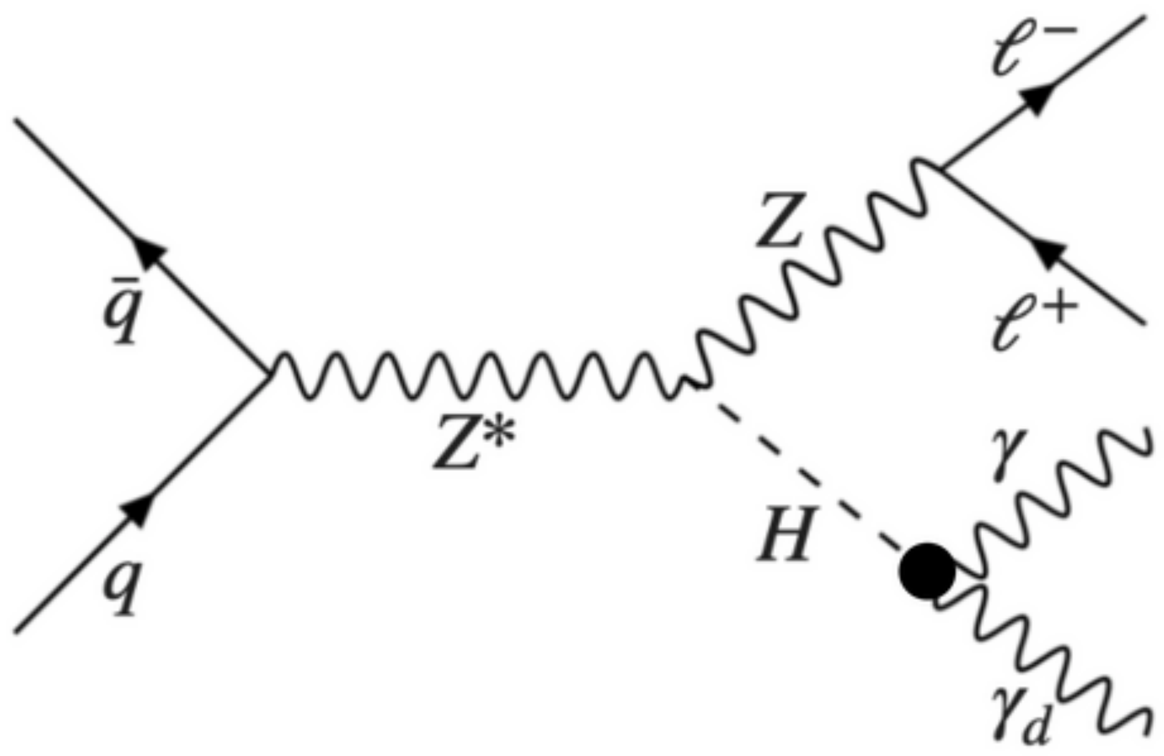
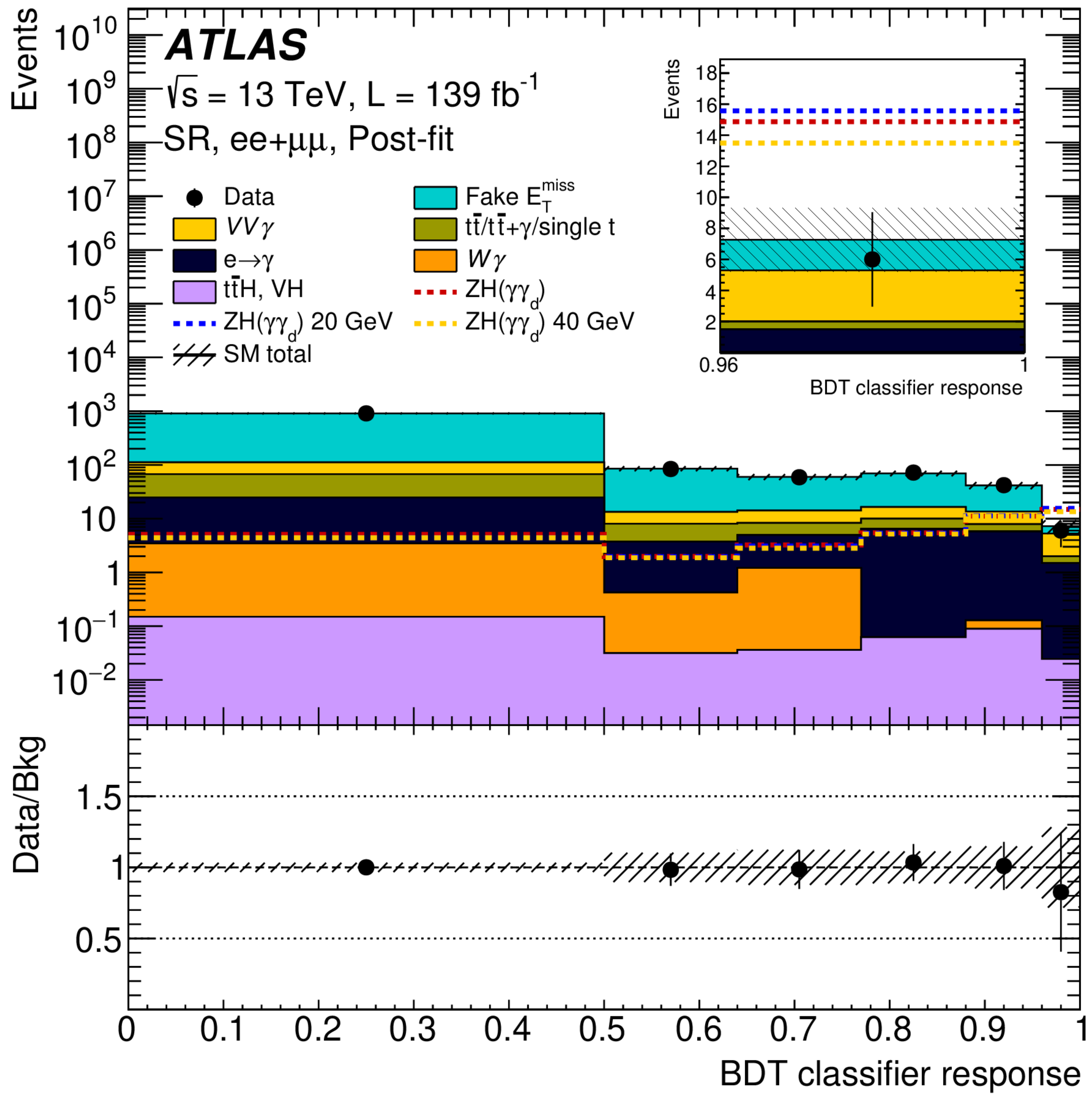


- Topology
  - 1 photon, no more than 2 jets, E_{T}^{miss}
  - 2 same-flavour, oppositely charged (SFOC) leptons within Z mass window
- BDT applied to enhance signal-bkg separation.
- Bkg estimation
  - Irreducible $VV\gamma$ from a dedicated CR.
  - Major $Z\gamma +$ jets, $Z +$ jets and e-fake γ from data-driven
- Fit to data performed including SR (binned by BDT) and $VV\gamma$ CR.



No significant deviation from SM prediction.

Input overview

ZH channel JHEP 07 (2023) 133

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, $m_{j_1 j_2} > 250$ GeV, $\lvert\Delta\eta_{j_1 j_2}\rvert > 3$ $\eta_{j_1} \cdot \eta_{j_2} < 0, \Delta\phi_{j_1 j_2} < 2, C_{j_3} < 0.7$	≤ 2	≤ 1
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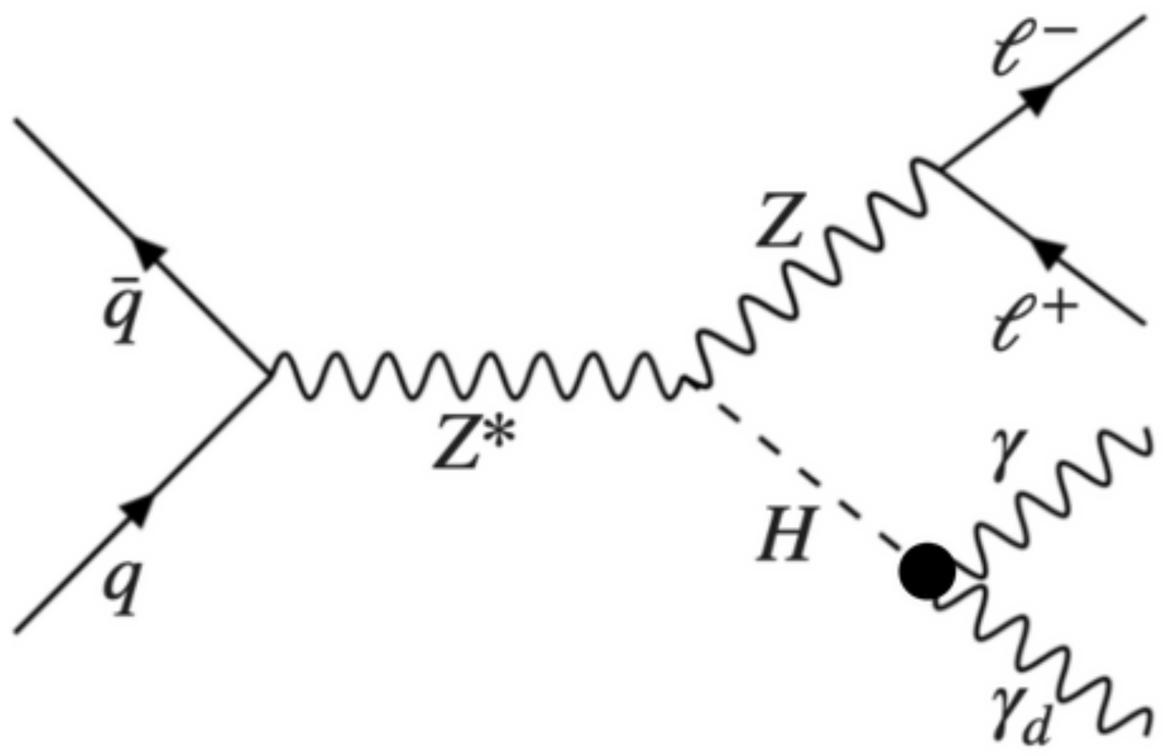

- Topology
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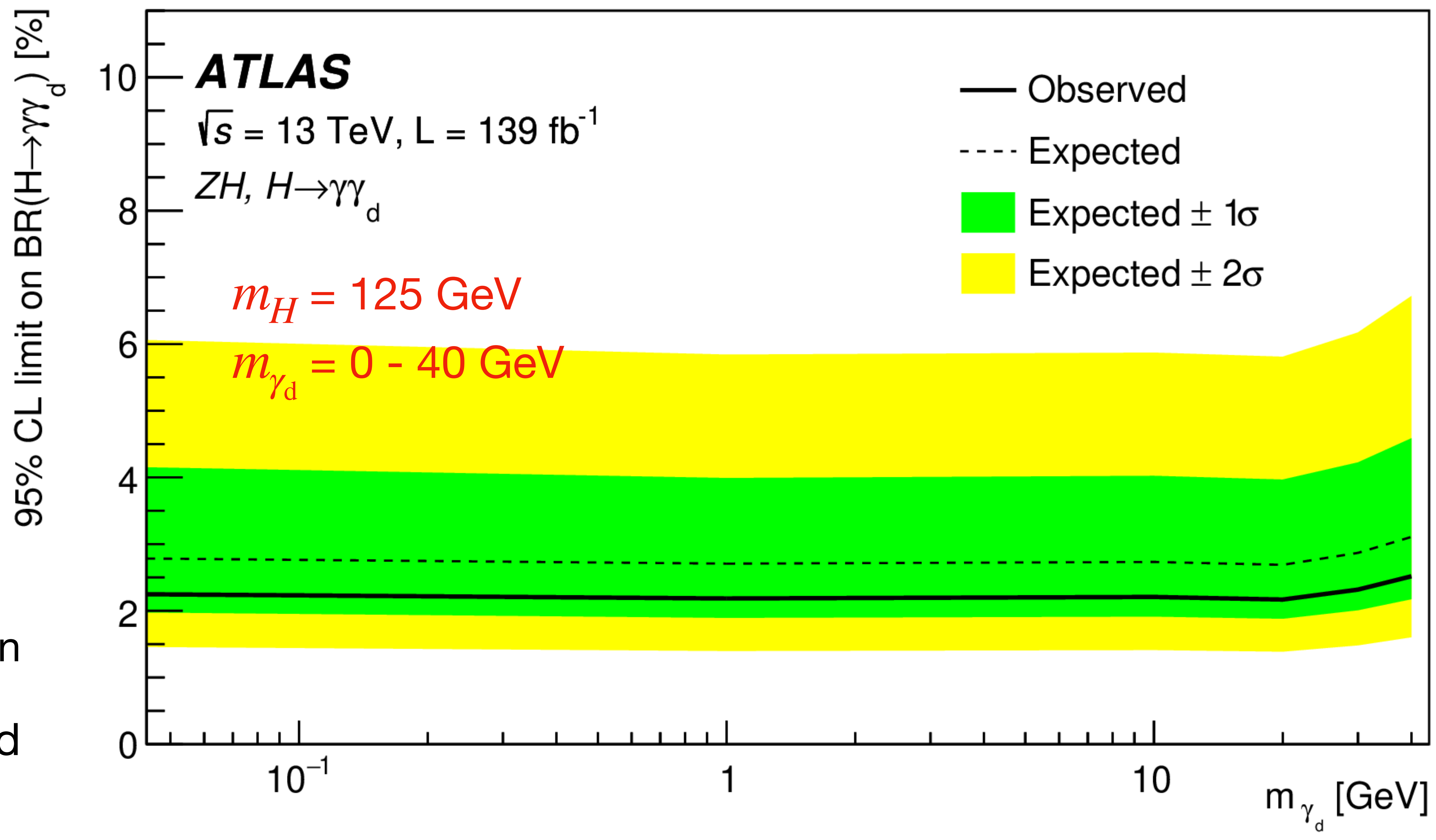
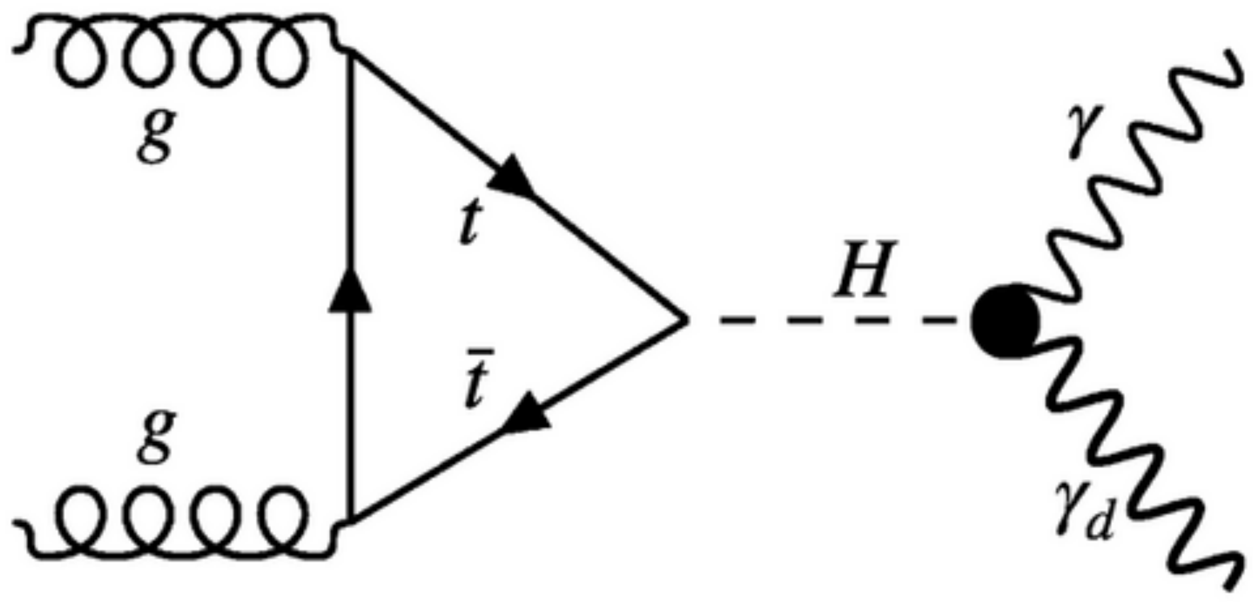
  - Major $Z\gamma + \text{jets}$, $Z + \text{jets}$ and e-fake γ from data-driven
- Fit to data performed including SR (binned by BDT) and $VV\gamma$ CR.



Input overview

ggF channel



- Topology
  - At least 1 photon, max 1 jet , large E_{T}^{miss}
  - Lepton $(e,\ \mu,\ \tau_{\mathrm{had}})$ veto
- Background estimation
  - True photon bkgs: $Z(\to \nu\nu)\gamma$, $W(\to \ell\nu)\gamma$ and $Z(\to \ell\ell)\gamma$ from dedicated CRs.
  - e-fake γ and jet-fake γ from data-driven.
- Fit to data performed including all SR (binned by E_{T}^{miss}) and CRs.
  - Including both VBF and ggF processes.

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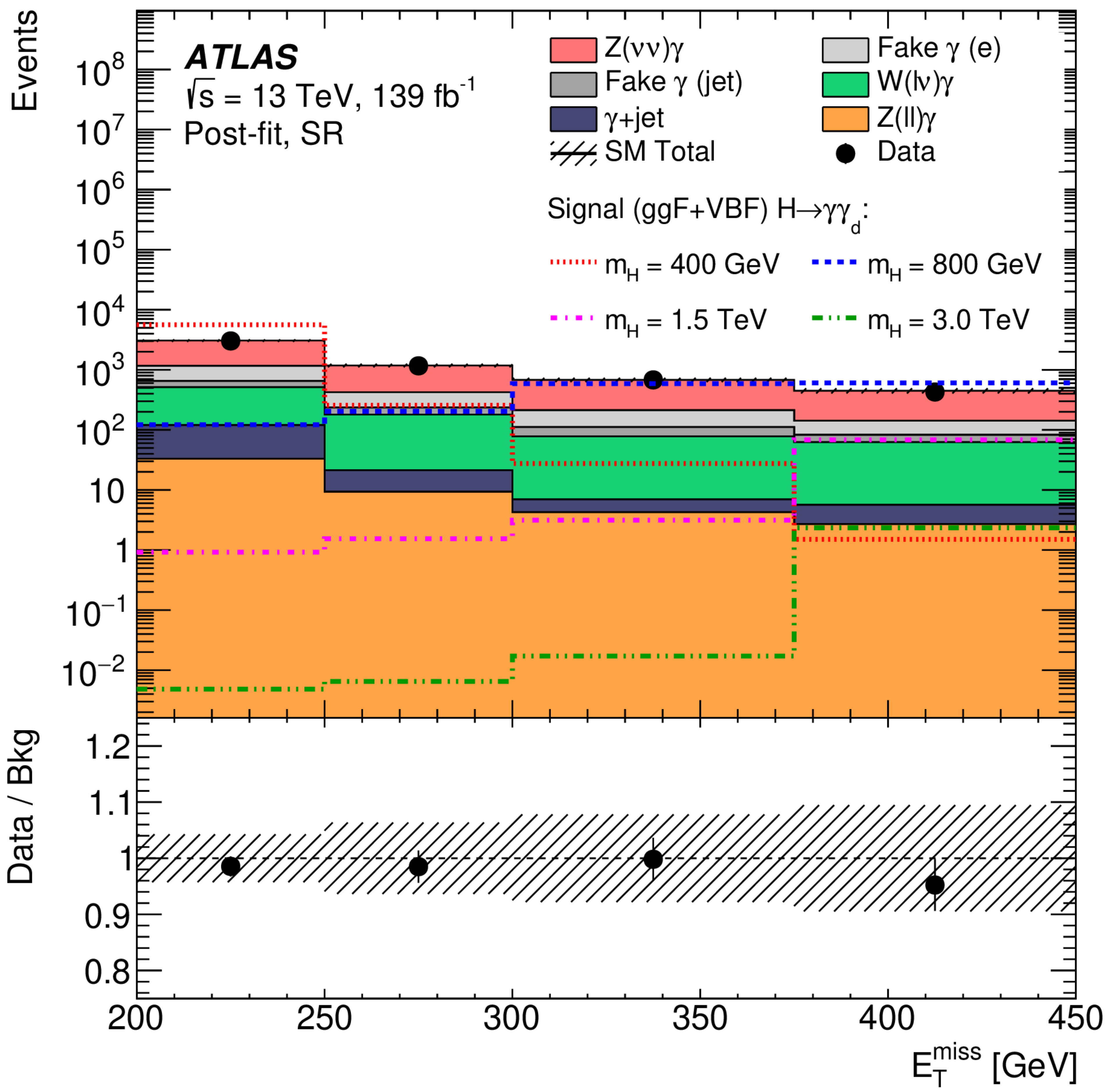
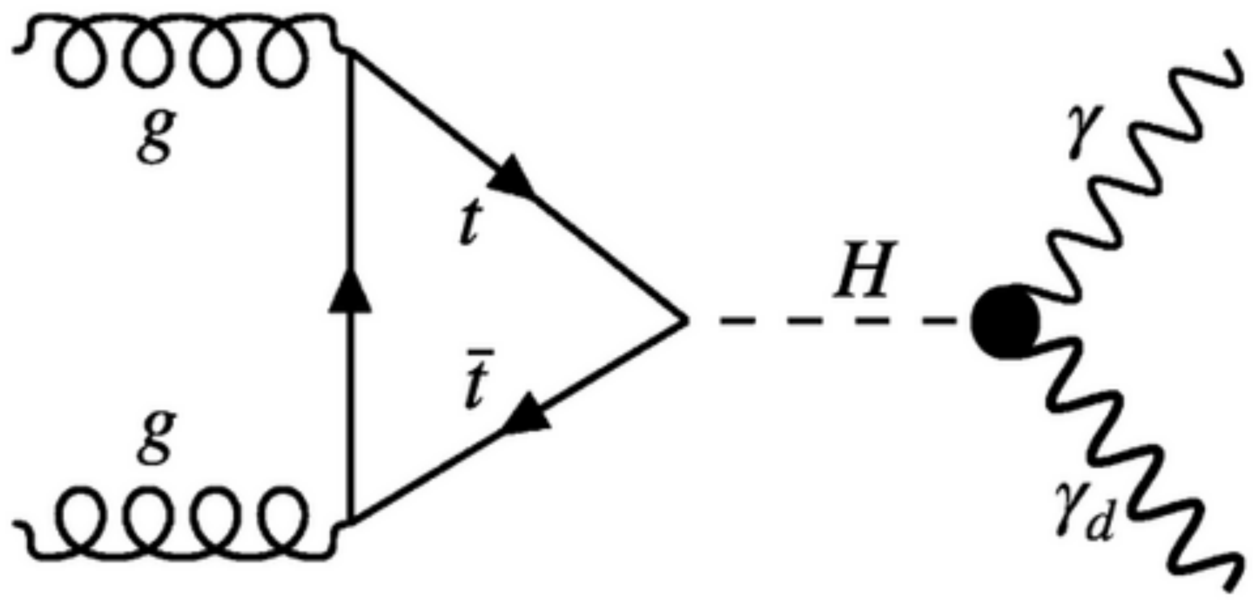


No significant deviation from SM prediction.

Input overview

ggF channel



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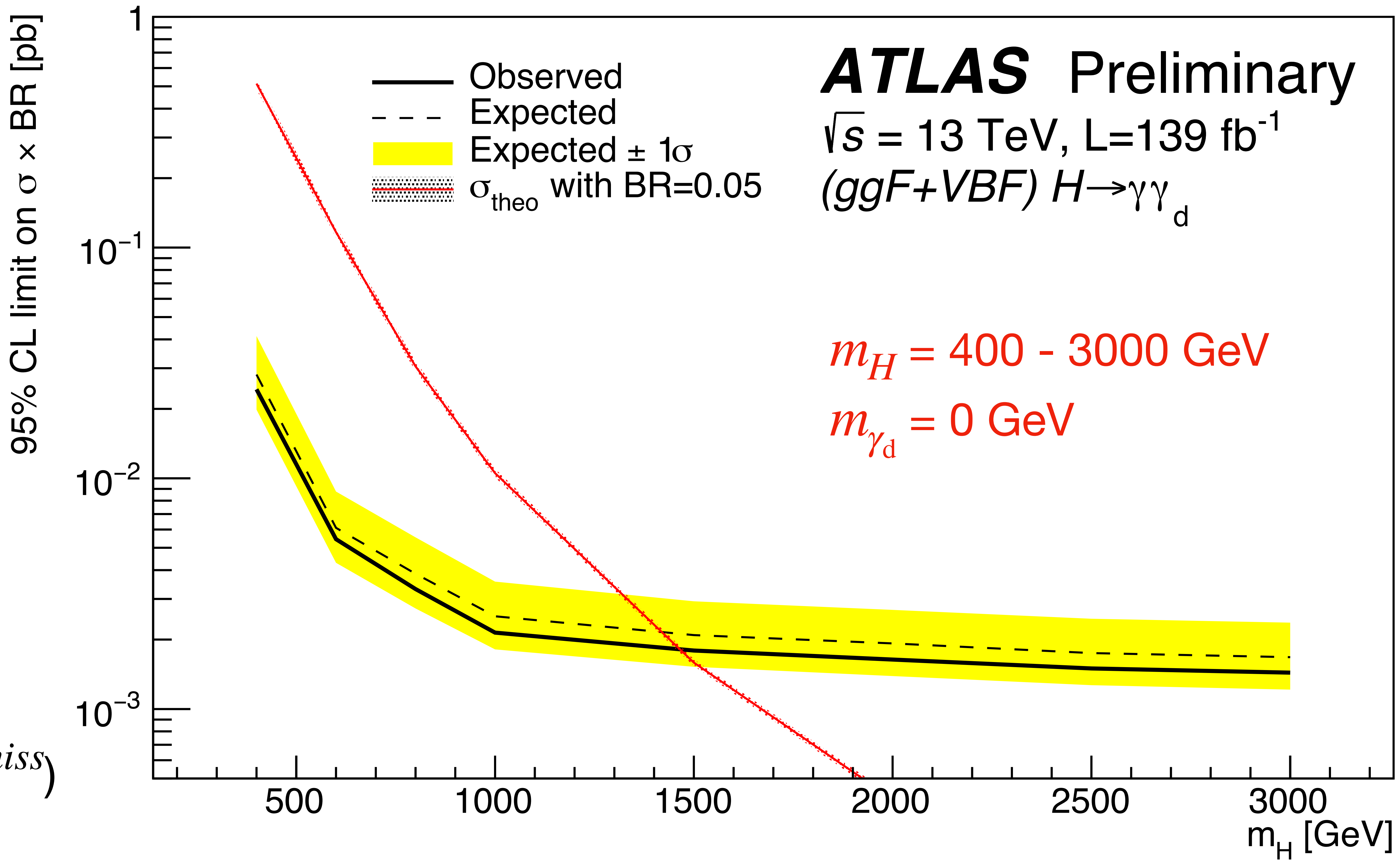
Leptons	$= 0$ (e, μ)	$= 2$, SFOC $m_{\ell\ell} \in (76, 116)$ GeV	$= 0$ (e, μ, τ)

- Topology
  - At least 1 photon, max 1 jet , large E_T^{miss}
  - Lepton (e, μ, τ_{had}) veto
- Background estimation
  - True photon bkgs: $Z(\to \nu\nu)\gamma$, $W(\to \ell\nu)\gamma$ and $Z(\to \ell\ell)\gamma$ from dedicated CRs.
  - e-fake γ and jet-fake γ from data-driven.
- Fit to data performed including all SR (binned by E_T^{miss}) and CRs.
  - Including both VBF and ggF processes.



Stat. combination

Systematic uncertainty correlation

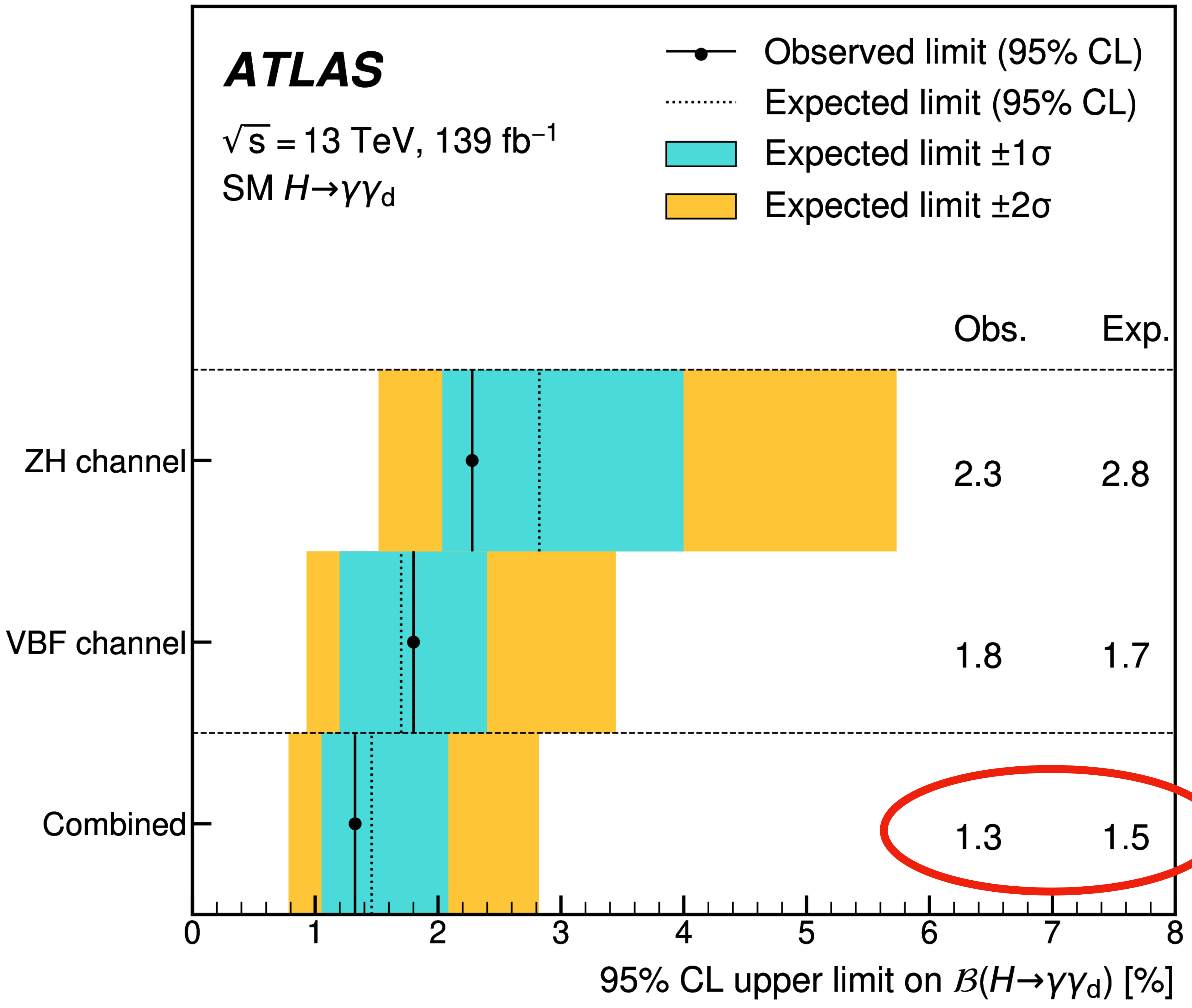
- Uncertainties from **luminosity**, **pile-up modelling** are correlated.

- **Experimental uncertainties**: correlated where appropriate, exceptions are:
  - Uncertainties related to same objects but **implemented with different schemes** among input channels (e.g 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.

Stat. combination -- SM Higgs

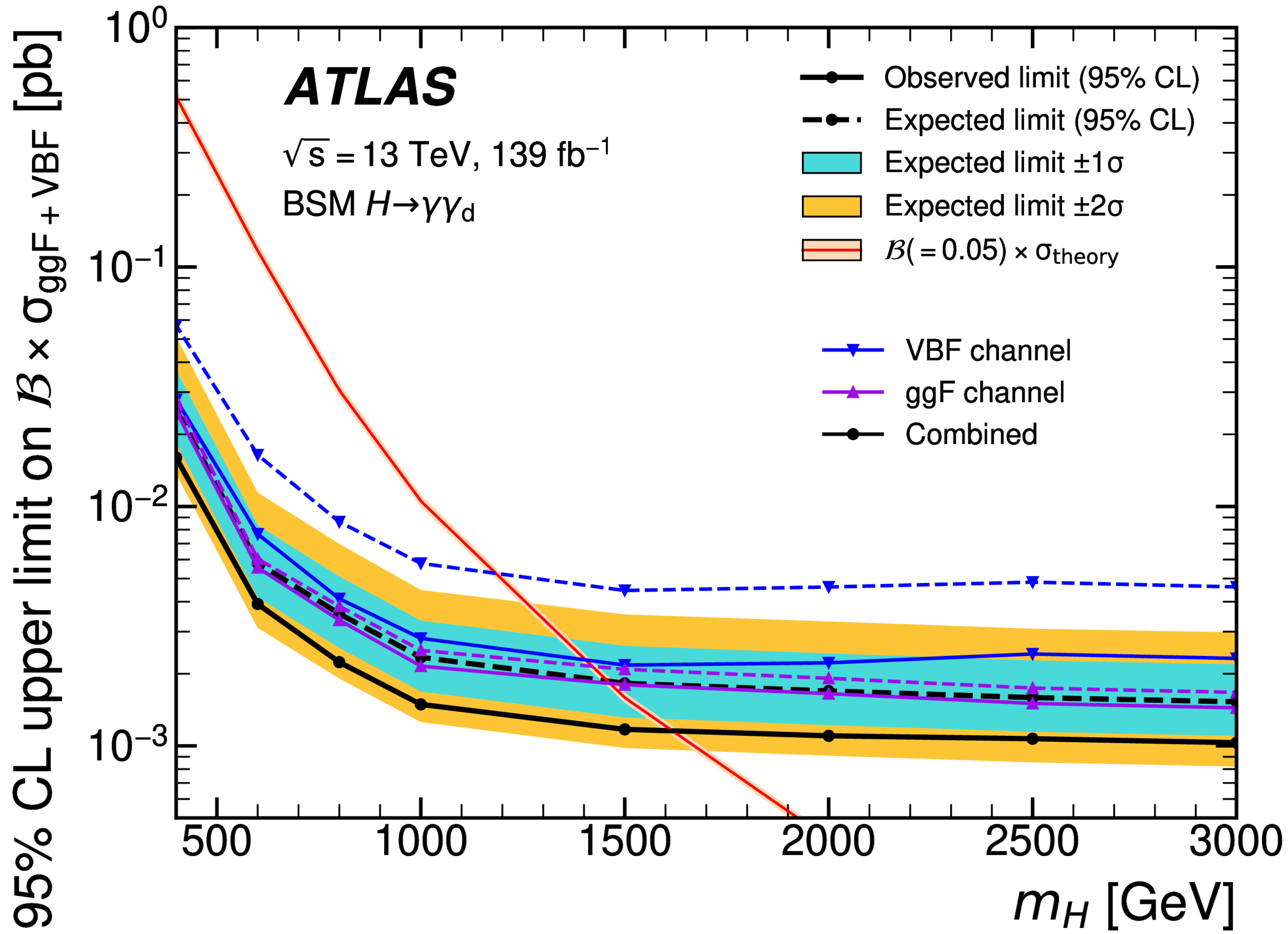


Uncertainty source	$\Delta\mathcal{B}_{\text{group}}/\Delta\mathcal{B}_{\text{total}}$ [%]
Theory uncertainties	49
Signal modelling	2.2
Background modelling	47
Experimental uncertainties	63
Luminosity, pile-up	< 0.1
Jets, E_T^{miss}	40
Electrons, muons	11
Fake background	35
MC statistical uncertainty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

- VBF-*ZH* combination set strongest limit on $\mathscr{B}(H_{125} \rightarrow \gamma\gamma_d)$ at LHC to date.
  - improved by 29% wrt VBF channel.

- Comparable impacts from Syst. and Stat. uncertainties.
- Leading syst. uncertainties from bkg modelling, Jets, E_T^{miss}, Fake bkg and MC stat.

Stat. combination -- BSM Higgs



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

- ❖ VBF-ggF combination set most comprehensive constraints on $\sigma_{ggF+VBF}\times\mathcal{B}(H_{BSM}\to\gamma\gamma_d)$ for H mass up to 3 TeV.
  - ◉ improved by 33% wrt ggF channel at $m_H = 1.5$ TeV.

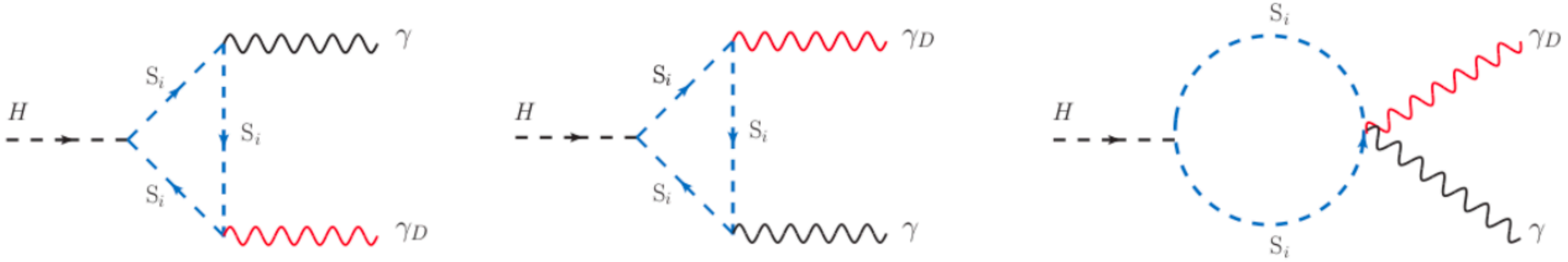
- ❖ Stat. uncertainty dominant at higher H masses.
- ❖ Leading syst. uncertainties from fake-bkg estimate and bkg modelling. Others share ~20% impact each.

Physics interpretation

- VBF-*ZH* combined limit on $\mathscr{B}(H_{125} \rightarrow \gamma\gamma_{\rm d})$ interpreted in a ***Minimal Simplified Model*** [1405.5196]
  - Generic Lagrangian: $\mathcal{L} \sim \mu \cdot H^{\dagger} S_L S_R + h.c. \xrightarrow{\text{EWSB}} \mathcal{L}_S^0 = \partial_\mu \hat{S}^{\dagger} \partial^{\mu} \hat{S} - \hat{S}^{\dagger} M_S^2 \hat{S}$
  - μ - mass parameter; S_L - $SU(2)_{\rm L}$ doublet; S_R - $SU(2)_{\rm L}$ singlet
  - Allowing $H_{125} \rightarrow \gamma\gamma_{\rm d}$ at 1-loop

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

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



- BR of $H \rightarrow \gamma\gamma_{\rm d}$ / $\gamma_{\rm d}\gamma_{\rm d}$ / $\gamma\gamma$ can be expressed as functions of $U(1)_{\rm d}$ fine-structure-constant $\alpha_{\rm d}$ and mixing parameter ξ

$$\mathrm{BR}_{\gamma\gamma_{\rm D}} = \mathrm{BR}_{\gamma\gamma}^{\rm SM} \frac{r_{\gamma\gamma_{\rm D}}}{1 + r_{\gamma_{\rm D}\gamma_{\rm D}} \mathrm{BR}_{\gamma\gamma}^{\rm SM}}$$

$$\mathrm{BR}_{\gamma_{\rm D}\gamma_{\rm D}} = \mathrm{BR}_{\gamma\gamma}^{\rm SM} \frac{r_{\gamma_{\rm D}\gamma_{\rm D}}}{1 + r_{\gamma_{\rm D}\gamma_{\rm D}} \mathrm{BR}_{\gamma\gamma}^{\rm SM}}$$

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

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

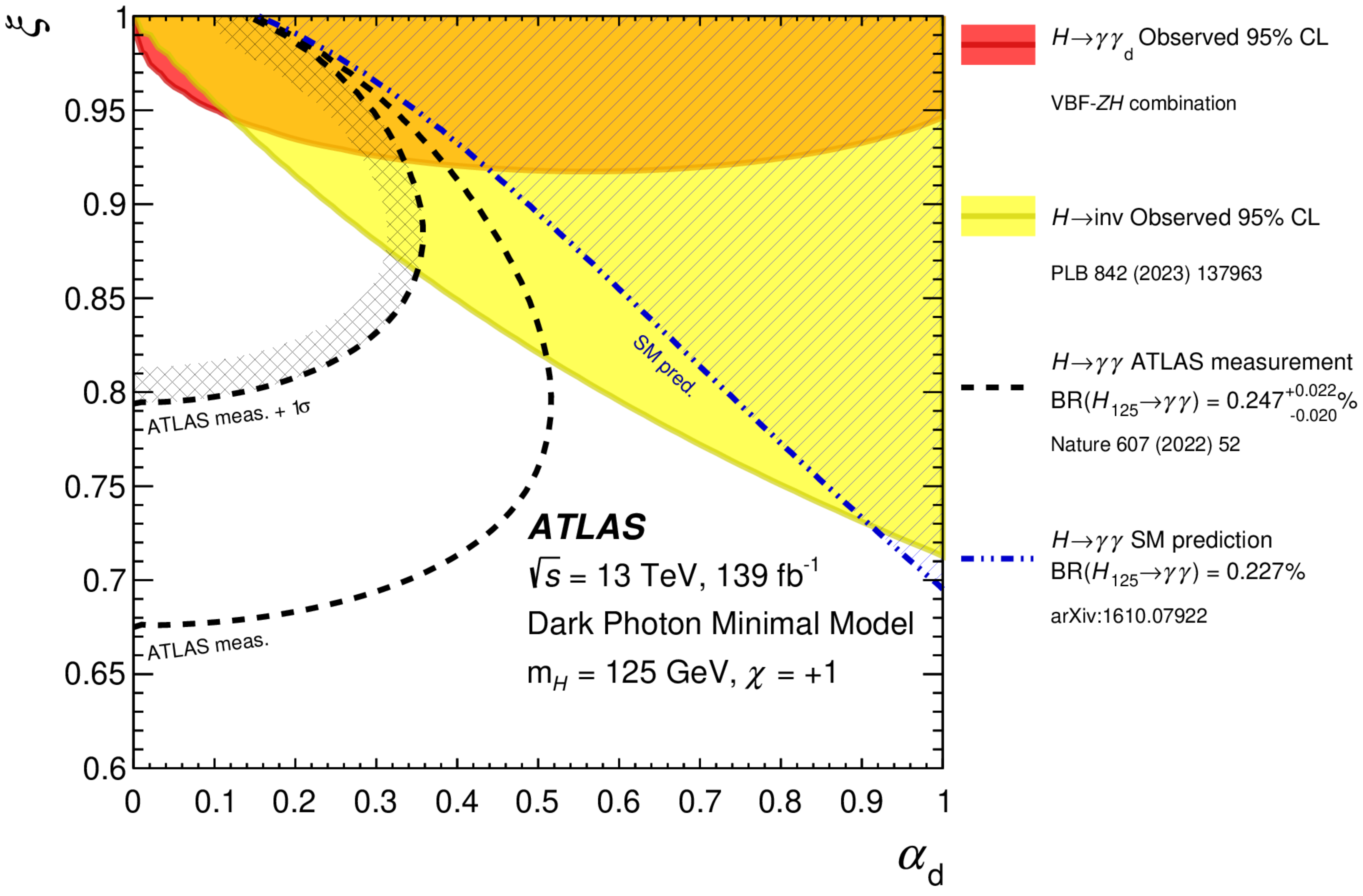
$$r_{\gamma_{\rm D}\gamma_{\rm D}} = X^2 \left(\frac{\alpha_D}{\alpha}\right)^2$$

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

$$X \equiv \frac{\xi^2}{3F(1-\xi^2)}$$

$$\xi = \frac{\Delta}{\bar{m}^2}$$

Physics interpretation



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

BR limits and measurements from this combination, $H \to \text{inv}$ or $H \to \gamma\gamma$ can be translated into constraints in (α_d, ξ).

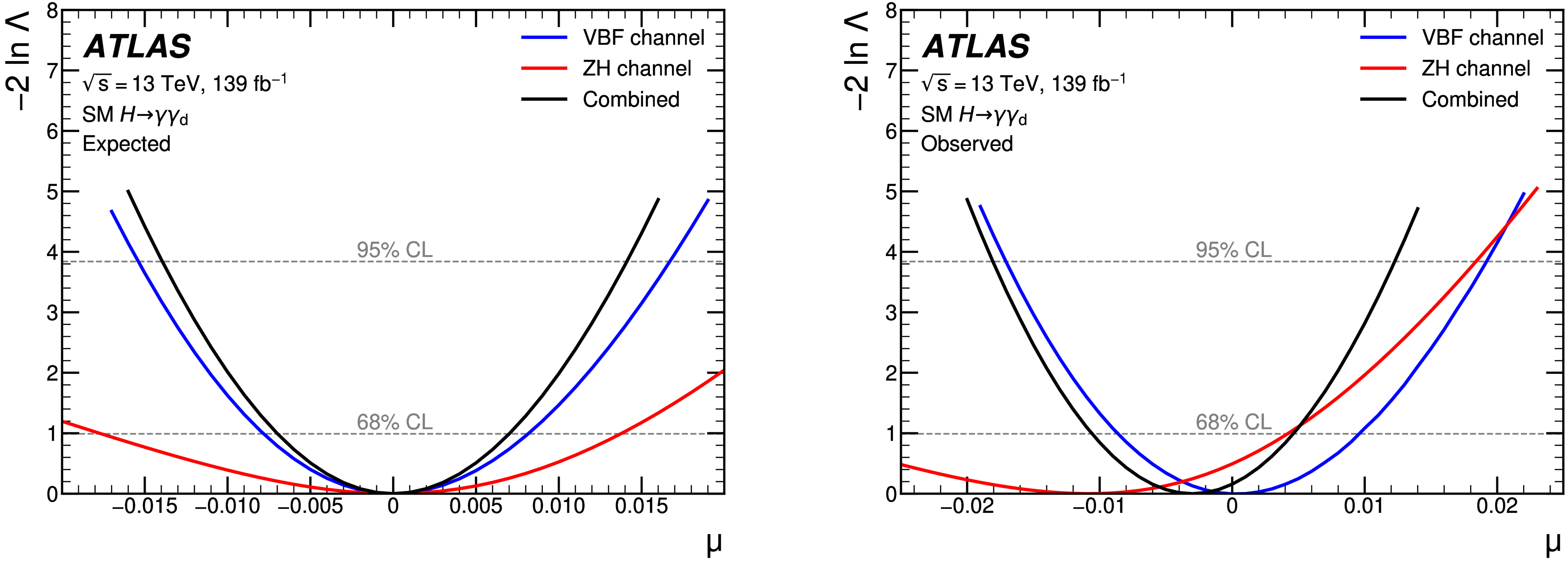
- $\xi \simeq 0.7$ at $\alpha_\mathrm{d} = 1$ excluded by $\mathscr{B}(H_{125} \to \text{inv})$ limit interpreted in terms of $H_{125} \to \gamma_\mathrm{d}\gamma_\mathrm{d}$ signal.
- $H_{125} \to \gamma\gamma_\mathrm{d}$ combination provides additional sensitivity in low-α_d region, which is disfavoured by ATLAS $\mathscr{B}(H_{125} \to \gamma\gamma)$ measurement.

Conclusion

- Combined search for $H \to \gamma\gamma_{\mathrm{d}}$ has been performed:
  - **SM Higgs**: VBF-*ZH* combination sets the most stringent limits on $\mathscr{B}(H_{125} \to \gamma\gamma_{\mathrm{d}})$ at LHC to date.
  - **BSM Higgs**: VBF-ggF combination provides most comprehensive constraint on $\sigma_{\mathrm{VBF+ggF}} \times \mathscr{B}(H_{125} \to \gamma\gamma_{\mathrm{d}})$ for Higgs mass up to 3 TeV.
- First physics interpretation of the $H_{125} \to \gamma\gamma_{\mathrm{d}}$, $H_{125} \to \mathrm{inv}$ and $H_{125} \to \gamma\gamma$ results in the Dark Photon Minimal Simplified Model with a generic messenger sector.

BACKUP

Auxiliary



ATLAS
$\sqrt{s} = 13$ TeV, 139 fb^{-1}
SM $H \to \gamma\gamma_d$
Expected
VBF channel
ZH channel
Combined
95% CL
68% CL
$-2 \ln \Lambda$
μ
ATLAS
$\sqrt{s} = 13$ TeV, 139 fb^{-1}
SM $H \to \gamma\gamma_d$
Observed
VBF channel
ZH channel
Combined
95% CL
68% CL
$-2 \ln \Lambda$
μ

Auxiliary

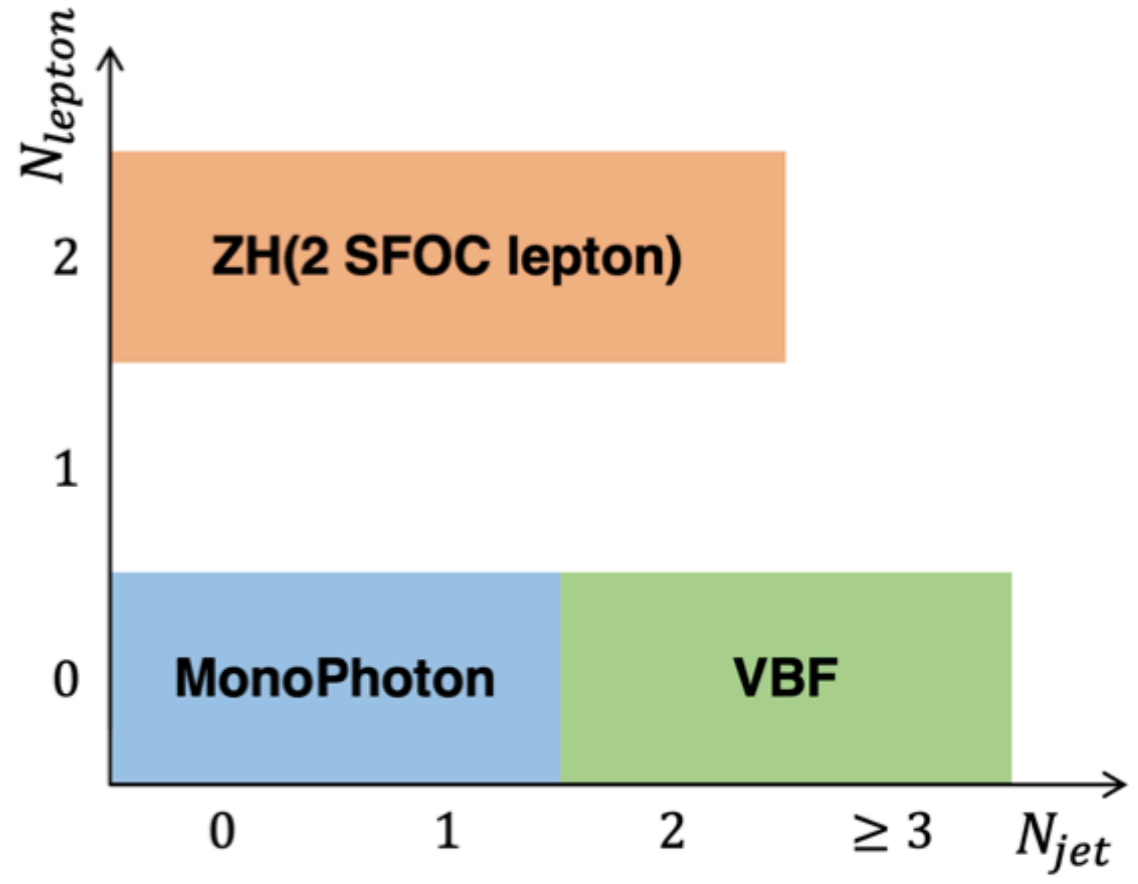
m_H [GeV]	$200 \leq E_T^{miss} < 250$ GeV ggF [%]	VBF [%]	$250 \leq E_T^{miss} < 300$ GeV ggF [%]	VBF [%]	$350 \leq E_T^{miss} < 375$ GeV ggF [%]	VBF [%]	$E_T^{miss} \geq 375$ GeV ggF [%]	VBF [%]
400	8.15	4.30	0.35	0.49	0.04	0.05	<0.01	<0.01
600	9.05	4.95	18.9	9.10	7.74	5.44	0.35	0.53
800	3.21	1.96	5.33	3.27	15.4	9.39	15.6	10.5
1000	1.63	1.24	2.50	1.72	5.92	4.01	29.4	21.2
1500	0.50	0.38	0.73	0.69	1.65	1.33	33.3	30.0
2000	0.22	0.21	0.35	0.33	0.67	0.69	32.7	34.3
2500	0.10	0.09	0.16	0.18	0.35	0.41	29.6	38.0
3000	0.04	0.08	0.08	0.11	0.19	0.29	28.9	39.6

Stat. combination

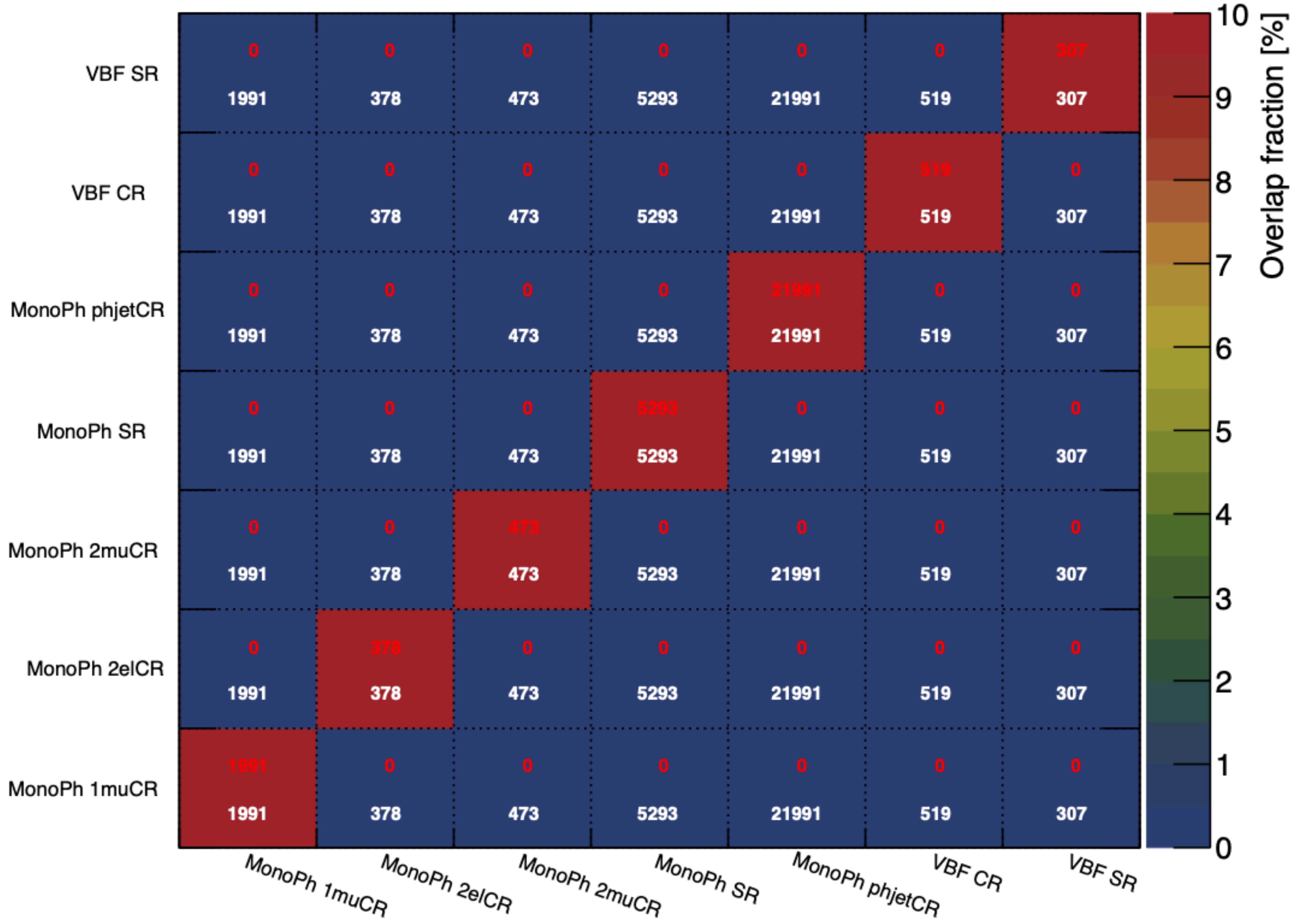
The results of the combination presented in this paper are obtained from a likelihood function $L(\mu, \vec{\theta})$, where μ denotes the parameter of interest (POI) of the model, and $\vec{\theta}$ constitutes a set of nuisance parameters, encoding the systematic uncertainty contributions and background normalisation factors that are constrained by CRs in data. The final likelihood function $L(\mu, \vec{\theta})$ is the product of the likelihoods from individual channels within the combination, which are themselves products of likelihoods computed from the final observables in various categories in a single analysis. To derive upper limits on the POI, the profile-likelihood-ratio test statistic is used with the CL_s method [74] following the asymptotic formulae [75].

Orthogonality 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