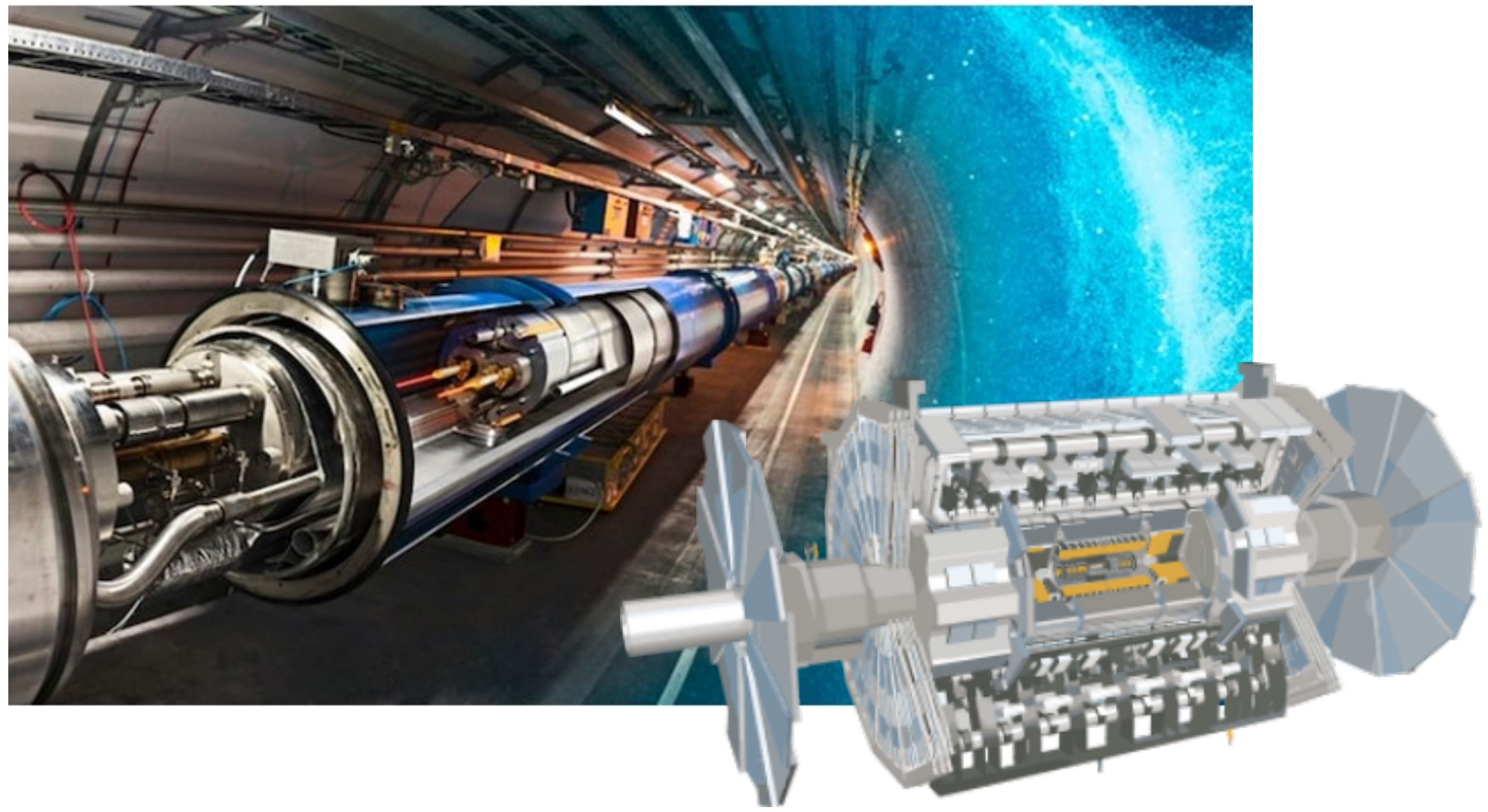
李政道研究所
Tsung-Dao Lee Institute

ATLAS EXPERIMENT

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

Workshop on Multi-front Exotic phenomena in Particle and Astrophysics
(MEPA 2024)

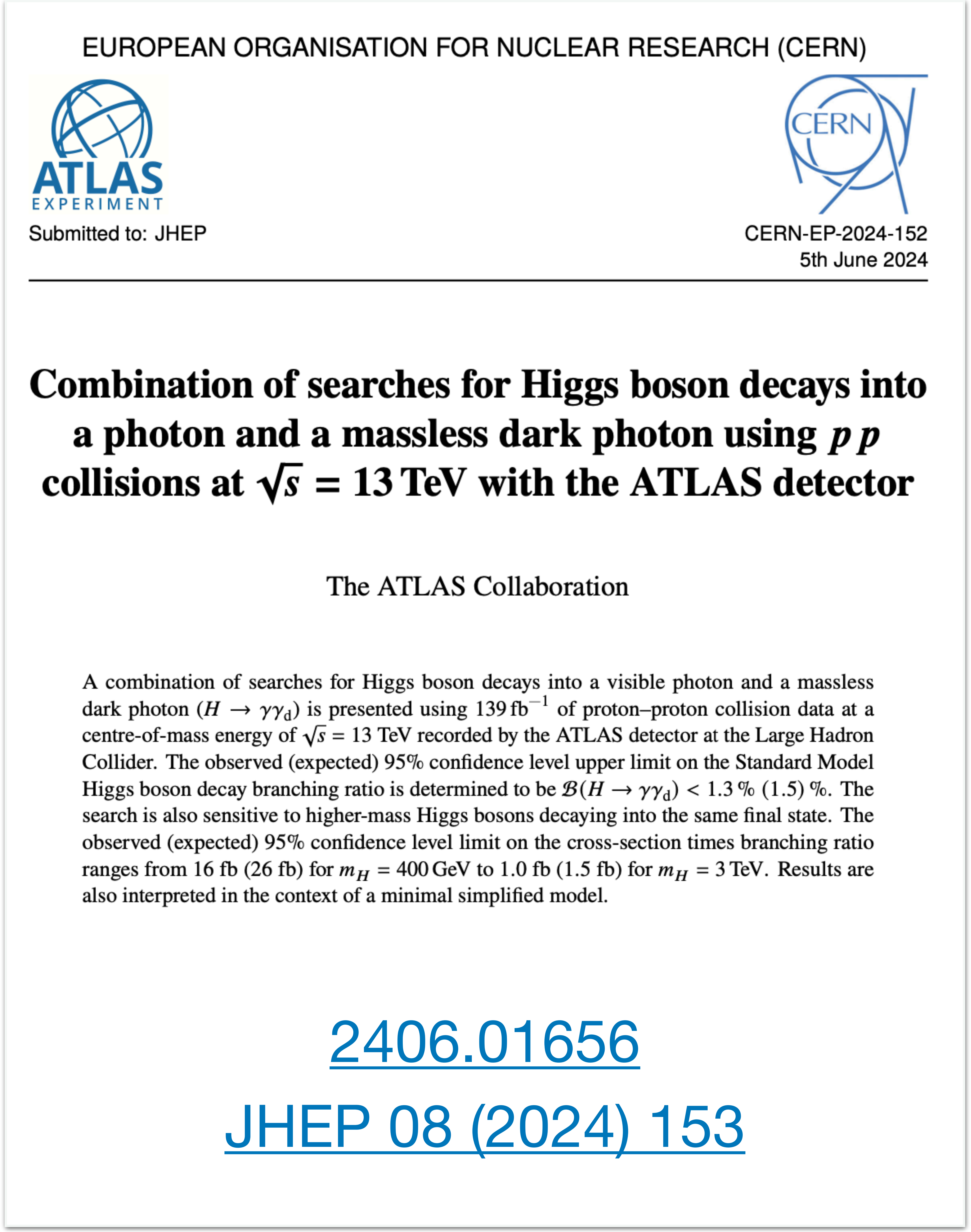


Khanh N. Vu

Yunnan, 25/08/2024

Today’s talk

- Thanks and credits to the Chinese ATLAS collaborators:
  - **Michigan**: Zirui Wang
  - **Wisconsin**: Rui Zhang
  - **IHEP**: Xinhui Huang, Zhijun Liang
  - **TDLI/SJTU**: Khanh N. Vu, Qibin Liu, Shu Li, Changqiao Li



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: JHEP

CERN-EP-2024-152
5th June 2024

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

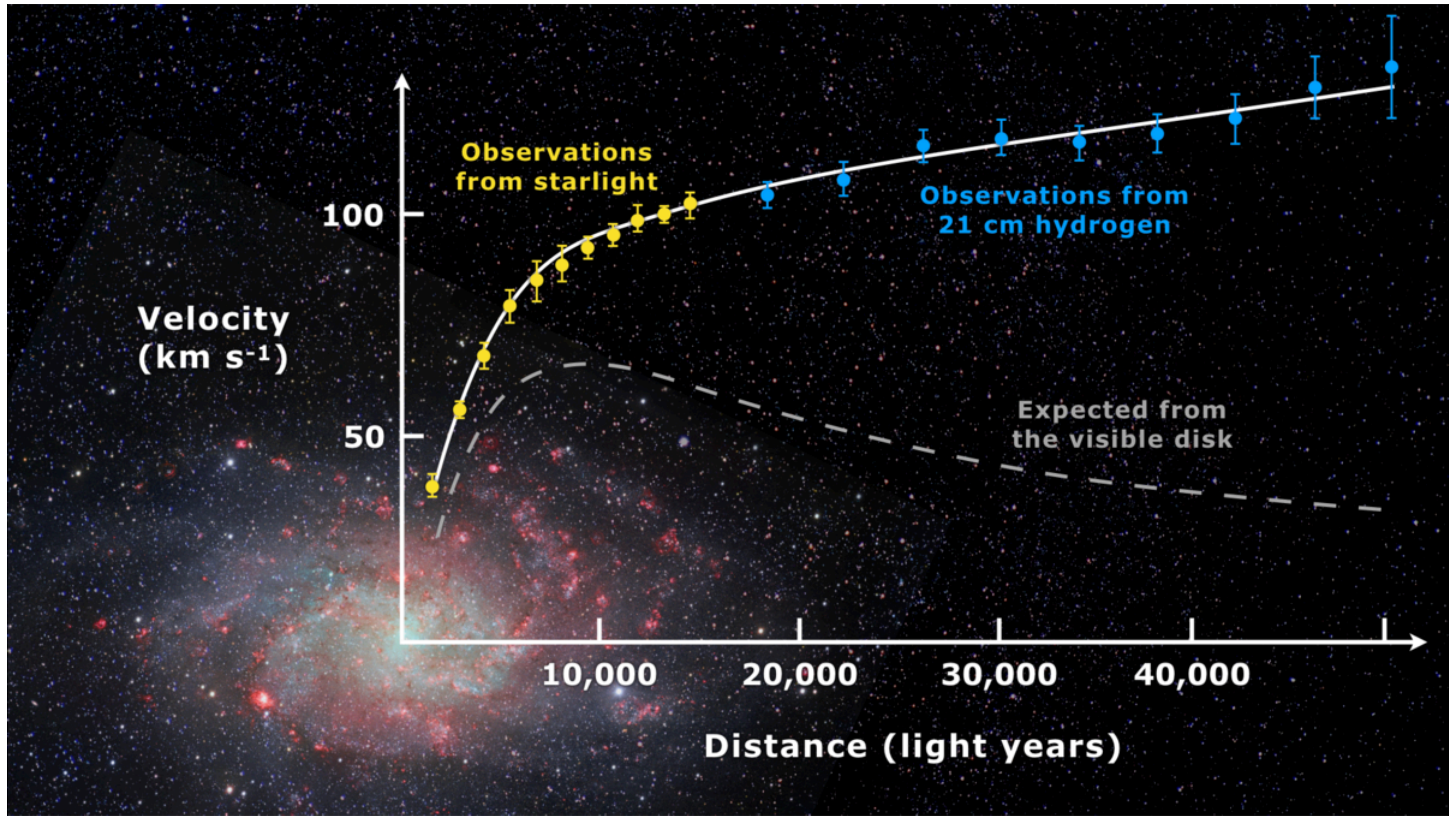
A combination of searches for Higgs boson decays into a visible photon and a massless dark photon ($H \to \gamma\gamma_d$) is presented using 139 fb^{-1} of proton–proton collision data at a centre-of-mass energy of $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the Large Hadron Collider. The observed (expected) 95% confidence level upper limit on the Standard Model Higgs boson decay branching ratio is determined to be $\mathcal{B}(H \to \gamma\gamma_d) < 1.3\,\%\ (1.5)\,\%$. 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.

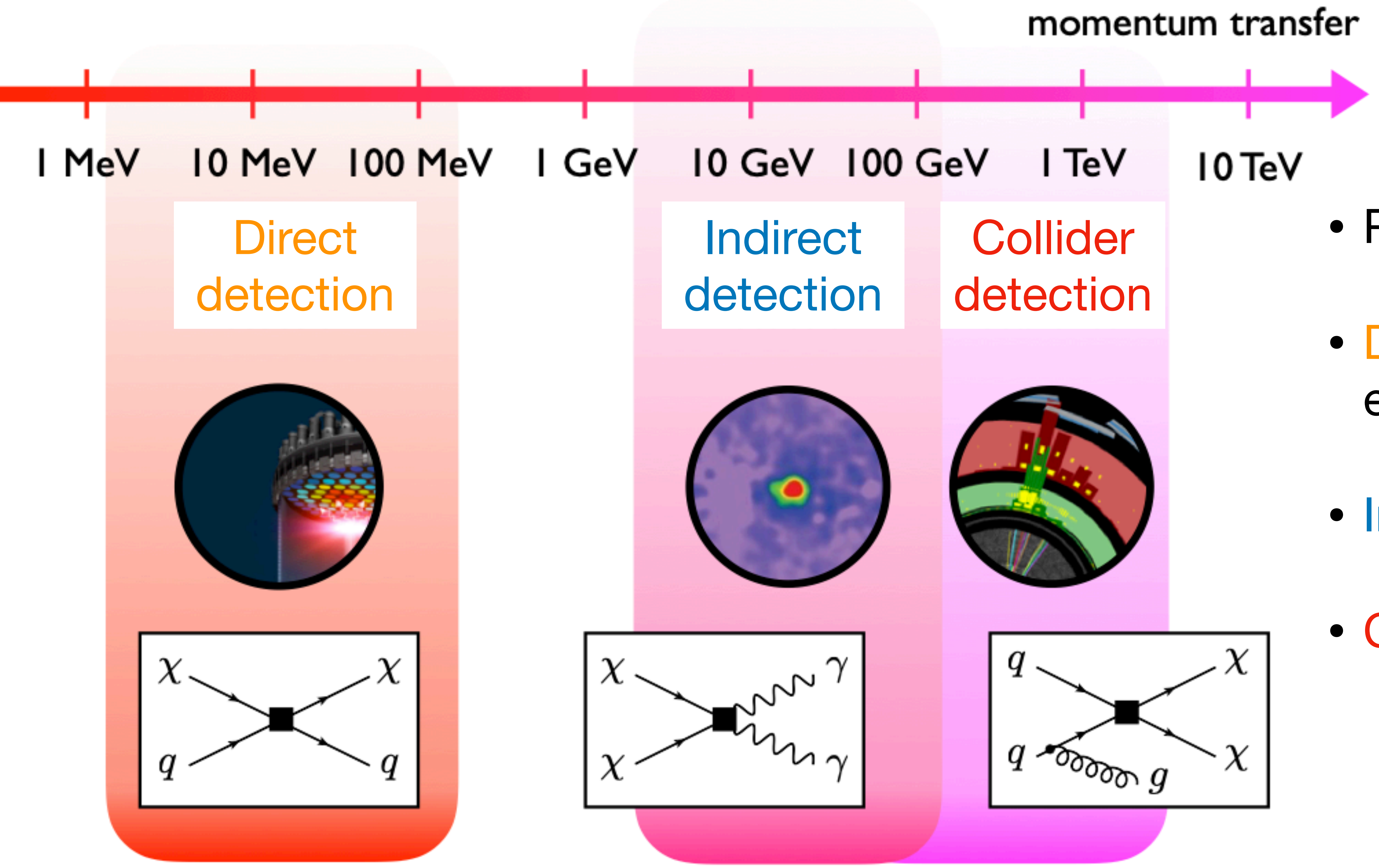
2406.01656

JHEP 08 (2024) 153

Dark Matter

- Dark Matter existence supported by plethora of astrophysical measurements.
  - NOT sufficiently explained by Standard Model, making DM nature a central question in particle physics.
  - ***DM candidate***: a strong consideration in many beyond-the-SM models.





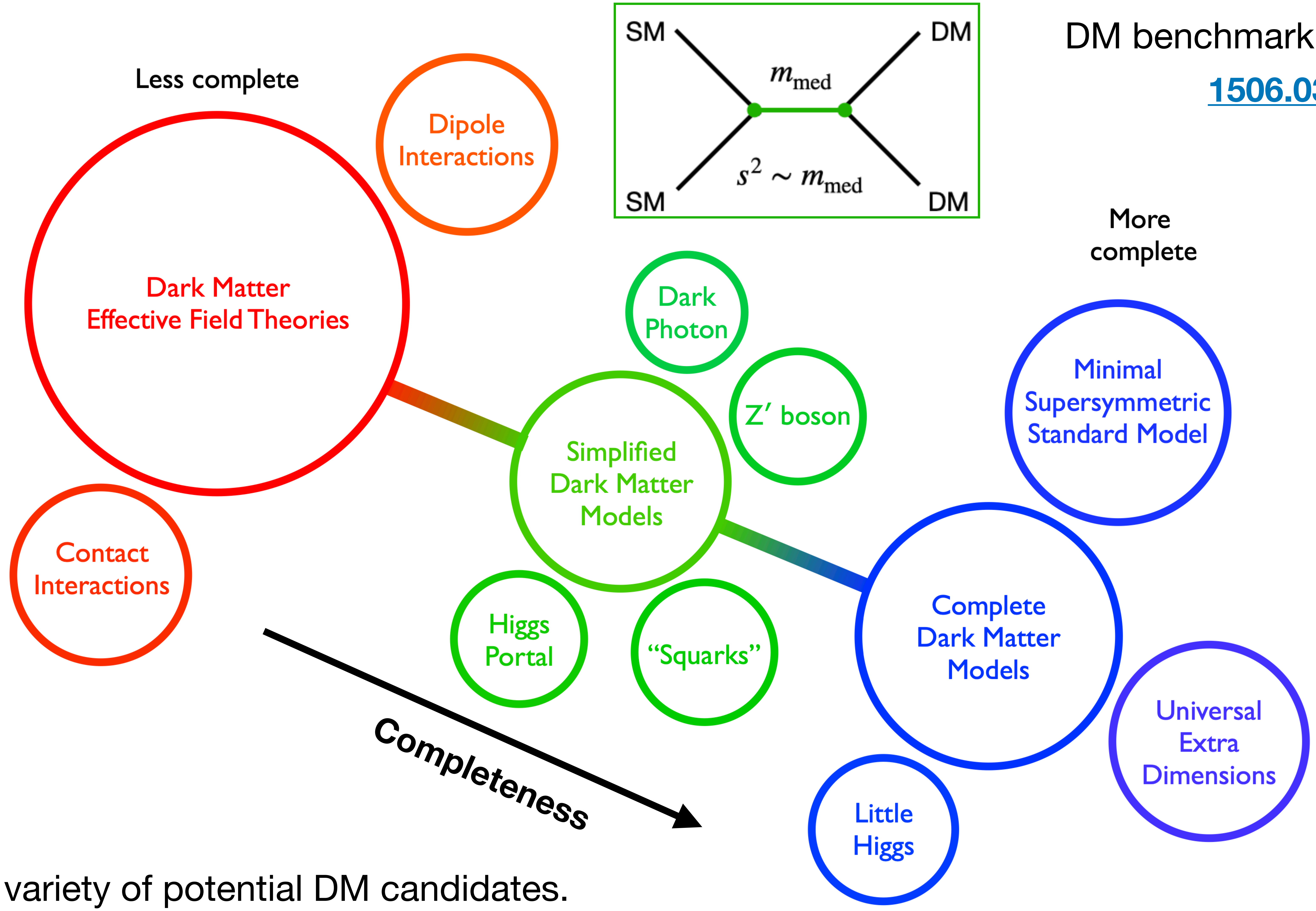
[1810.09420](https://arxiv.org/abs/1810.09420)

- Probes of DM underway in several areas.
- Direct searches for elastic scattering between DM and nuclei or electrons.
- Indirect searches for products of DM annihilation or decay.
- Collider searches for production of DM from collisions of SM particles
  - complementarity to other detections at GeV-TeV scale.
  - provide access to particles mediating interactions between DM and SM sector.

Dark Matter probes at ATLAS

DM benchmark models at LHC

[1506.03116v3](1506.03116v3)



Less complete

Dipole Interactions

Dark Matter Effective Field Theories

Contact Interactions

Dark Photon

Z′ boson

Simplified Dark Matter Models

Higgs Portal

“Squarks”

Completeness

More complete

Minimal Supersymmetric Standard Model

Complete Dark Matter Models

Universal Extra Dimensions

Little Higgs

- ATLAS sensitive to wide variety of potential DM candidates.
- Most of DM searches at the LHC focus on ***Weakly Interacting Massive Particles*** (***WIMPs)*** in ***simplified models or extended Higgs sectors.***
- Also strong consideration in other ***Dark Sector particles*** such as Dark Photon, Dark Higgs, Dark QCD, and so on.

Dark Photon scenario

- $\mathscr{B}(H \to \text{und}) < \mathcal{O}(10\%)$ motivates searches for DS particles coupled to Higgs. One attractive candidate is dark photon (γ_d).
  - Force carrier of extra $U(1)_\text{d}$, providing portal between DS and SM via kinetic mixing with visible $U(1)$.
  - 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.

- Massive γ_d couples directly to SM, more accessible and consideration in experiment searches.

- Massless γ_d NO direct couplings with SM, less attention but can provide comparably rich experimental target.

- In this talk, γ_d is collider-stable, resulting in Missing Transverse Momentum (E_T^miss) in event final-state.

Kinetic mixing $U(1)_a \times U(1)_b$ [2005.01515]

Kinetic part: $\mathcal{L}_0 = -\frac{1}{4}F_{a\mu\nu}F_a^{\mu\nu} - \frac{1}{4}F_{b\mu\nu}F_b^{\mu\nu} - \frac{\varepsilon}{2}F_{a\mu\nu}F_b^{\mu\nu}$

Interaction with matter fields: $\mathcal{L} = e\,J_\mu A_b^\mu + e' J'_\mu A_a^\mu$

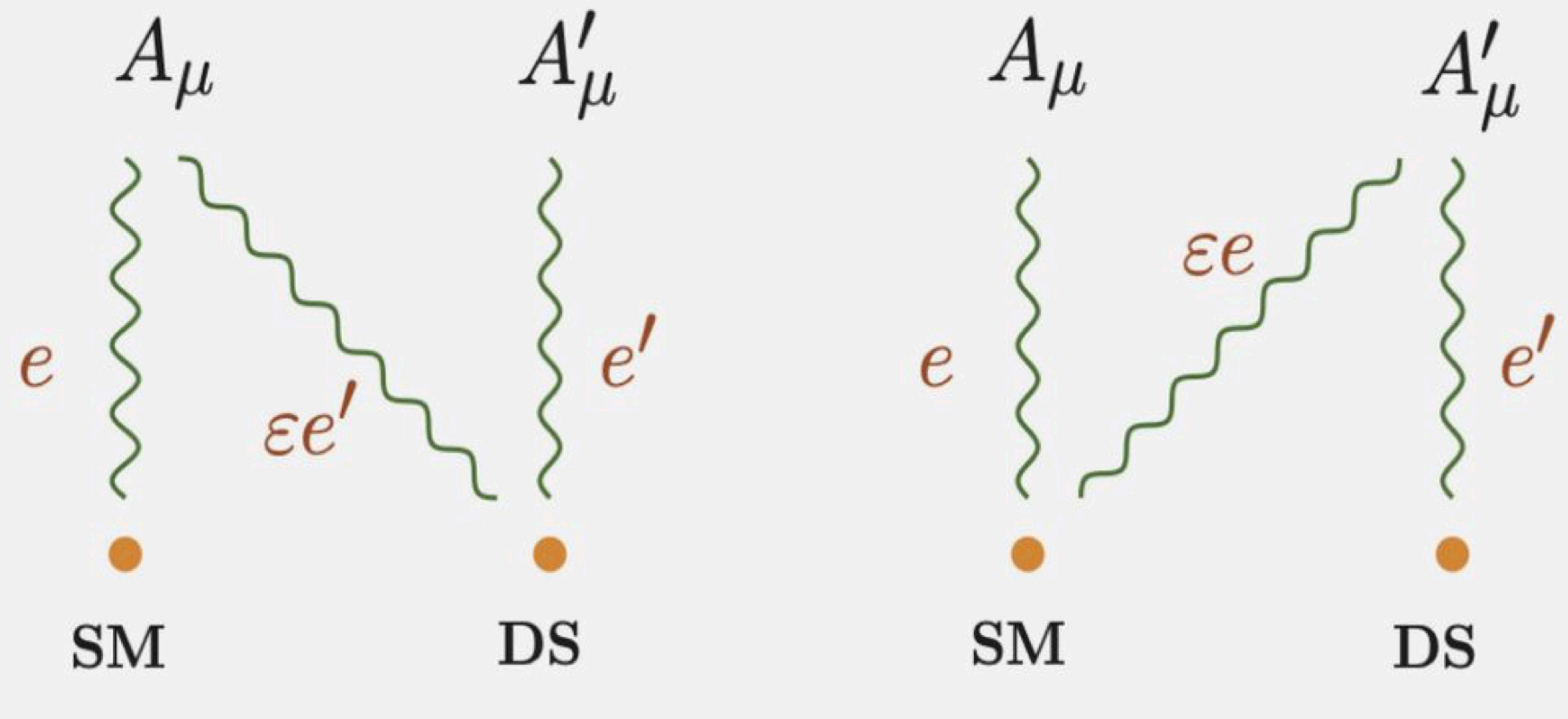
SM DS

Diagonalized up to a rotation:

$$\begin{pmatrix} A_a^\mu \\ A_b^\mu \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{1-\varepsilon^2}} & 0 \\ -\frac{\varepsilon}{\sqrt{1-\varepsilon^2}} & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A'^\mu \\ A^\mu \end{pmatrix}$$

Dark photon

Photon



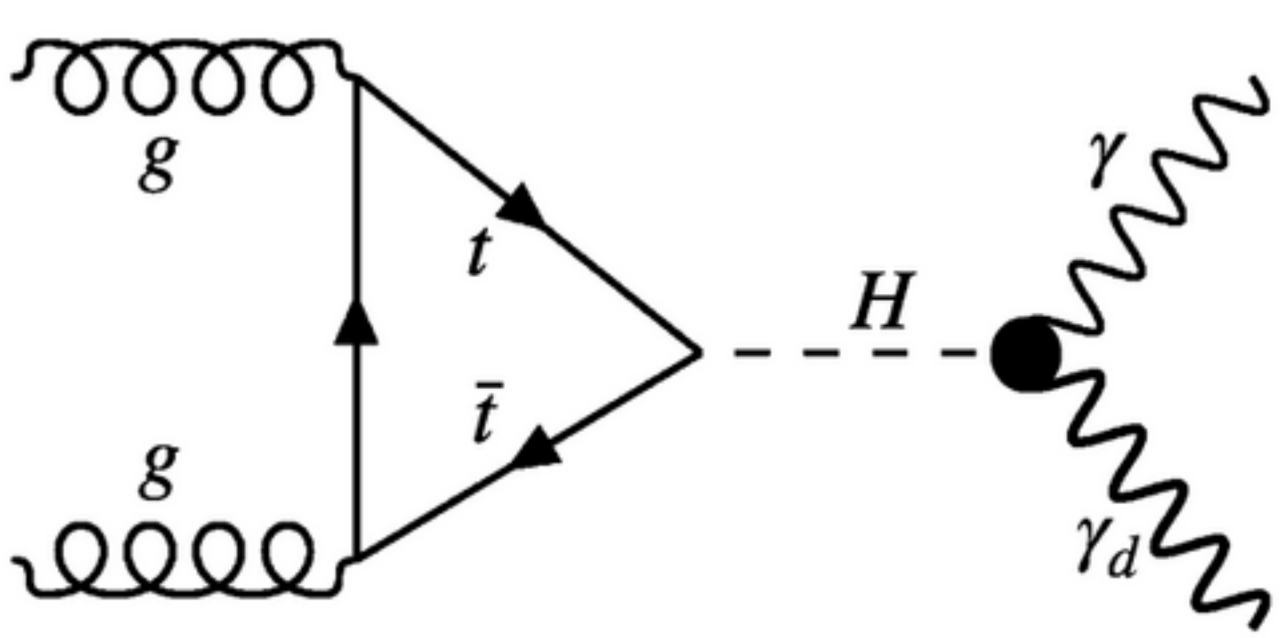
Massless
Dark photon

Massive
Dark photon

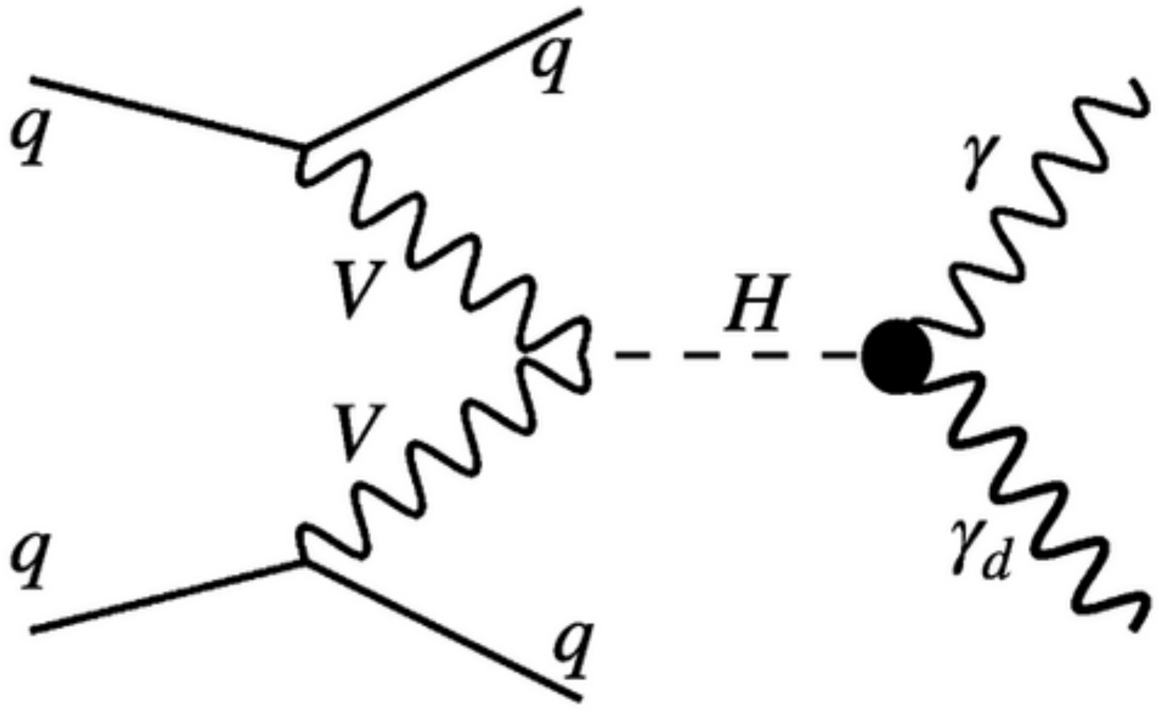
Dark Photon search using Higgs

- ☆ "Process" refers to production mode
- ☆ "Channel" refers to selection topology

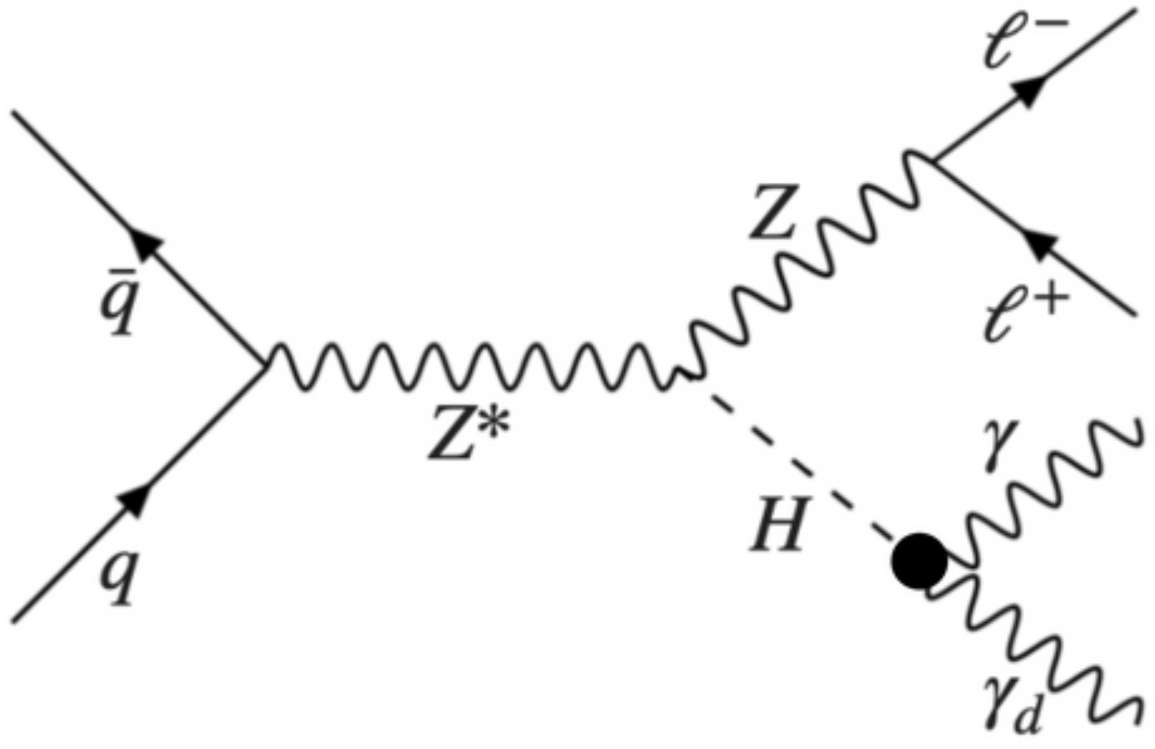
❖ Potential approach is search for $H \rightarrow \gamma\gamma_\mathrm{d}$ in resonant $\gamma + E_\mathrm{T}^\mathrm{miss}$ signatures via three Higgs production modes



ggF process



VBF process



ZH process

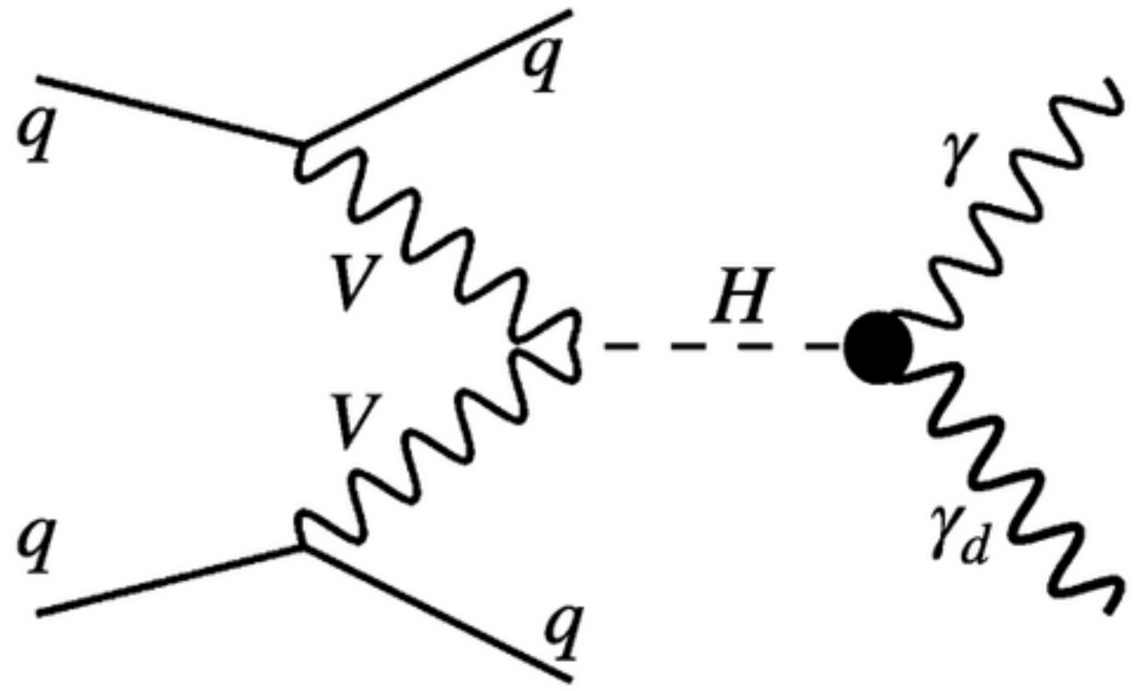
❖ Both ATLAS and CMS published various results for $H \rightarrow \gamma\gamma_\mathrm{d}$ searches in distinct final states using LHC full Run 2 data:

<table>
<tr><th></th><th>$\gamma + E_\mathrm{T}^\mathrm{miss}$
(ggF channel)</th><th>$\gamma + E_\mathrm{T}^\mathrm{miss}$ + VBF jets
(VBF channel)</th><th>$\gamma + E_\mathrm{T}^\mathrm{miss} + Z(\rightarrow \ell\ell)$
(<i>ZH</i> 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>

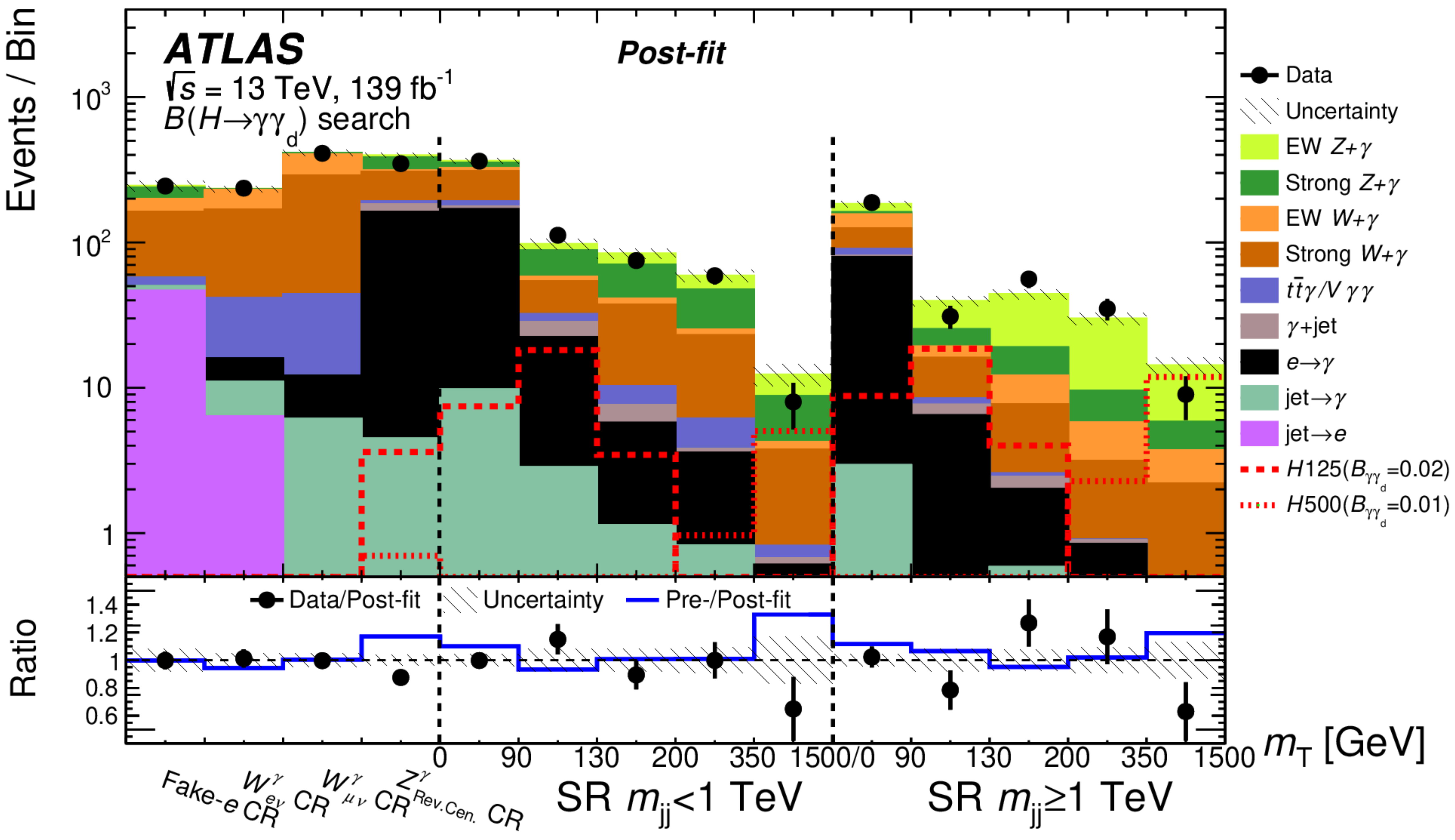
VBF channel

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.

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

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

VBF channel

EPJC 82 (2022) 105

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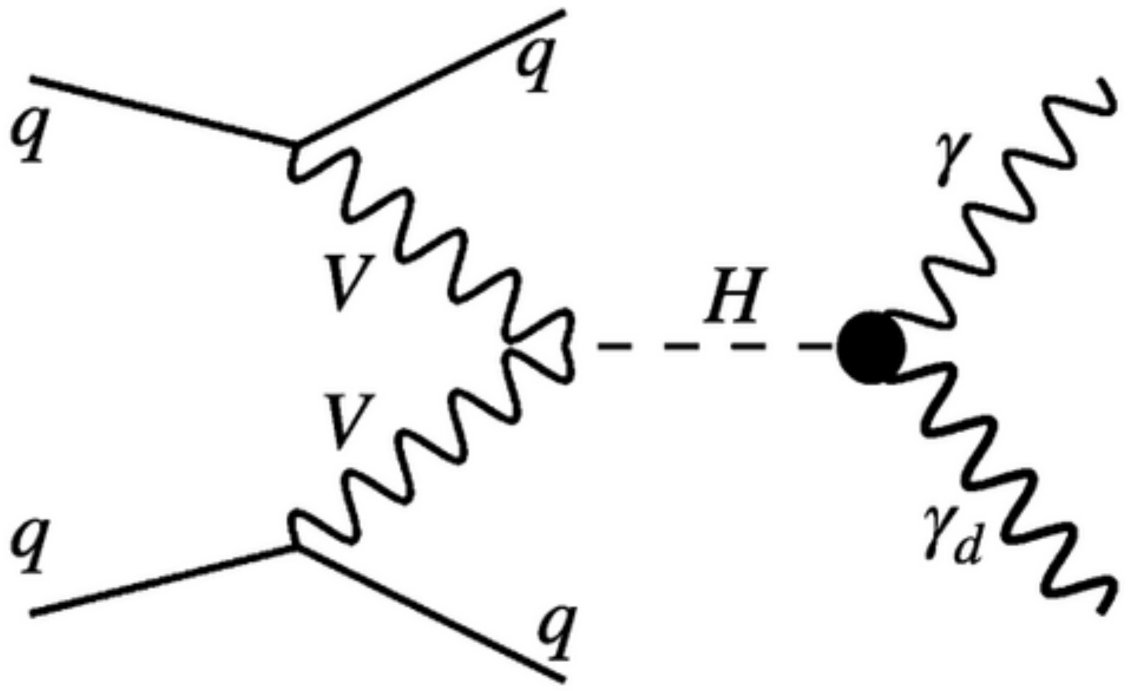

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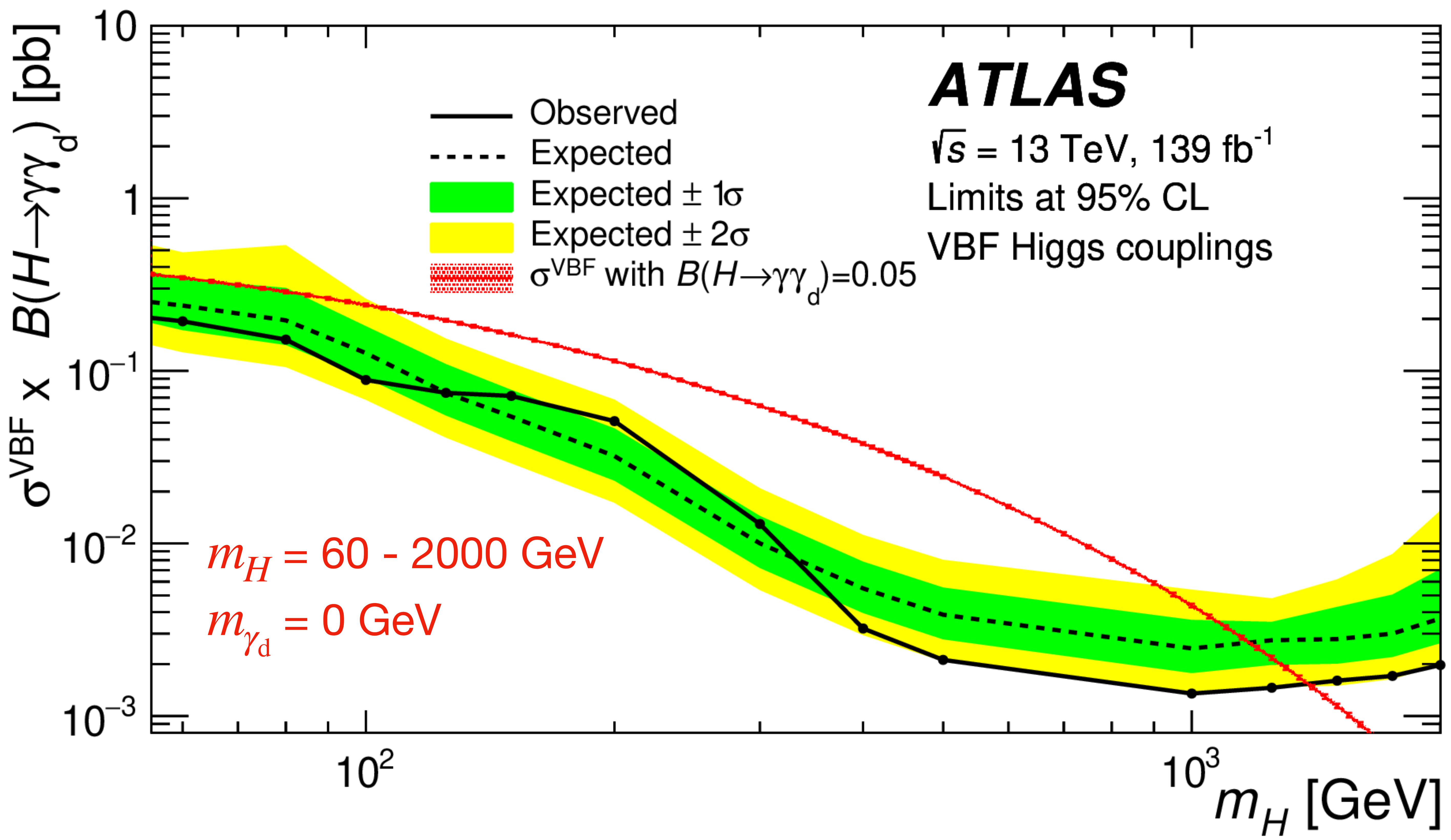
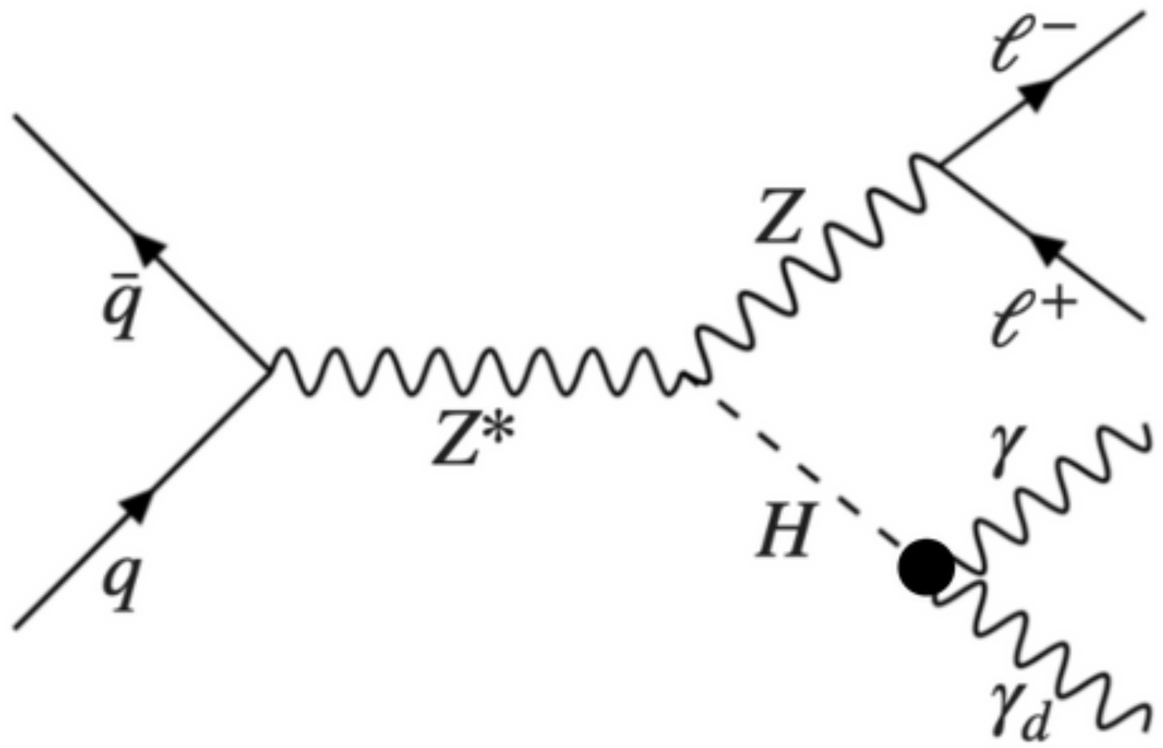


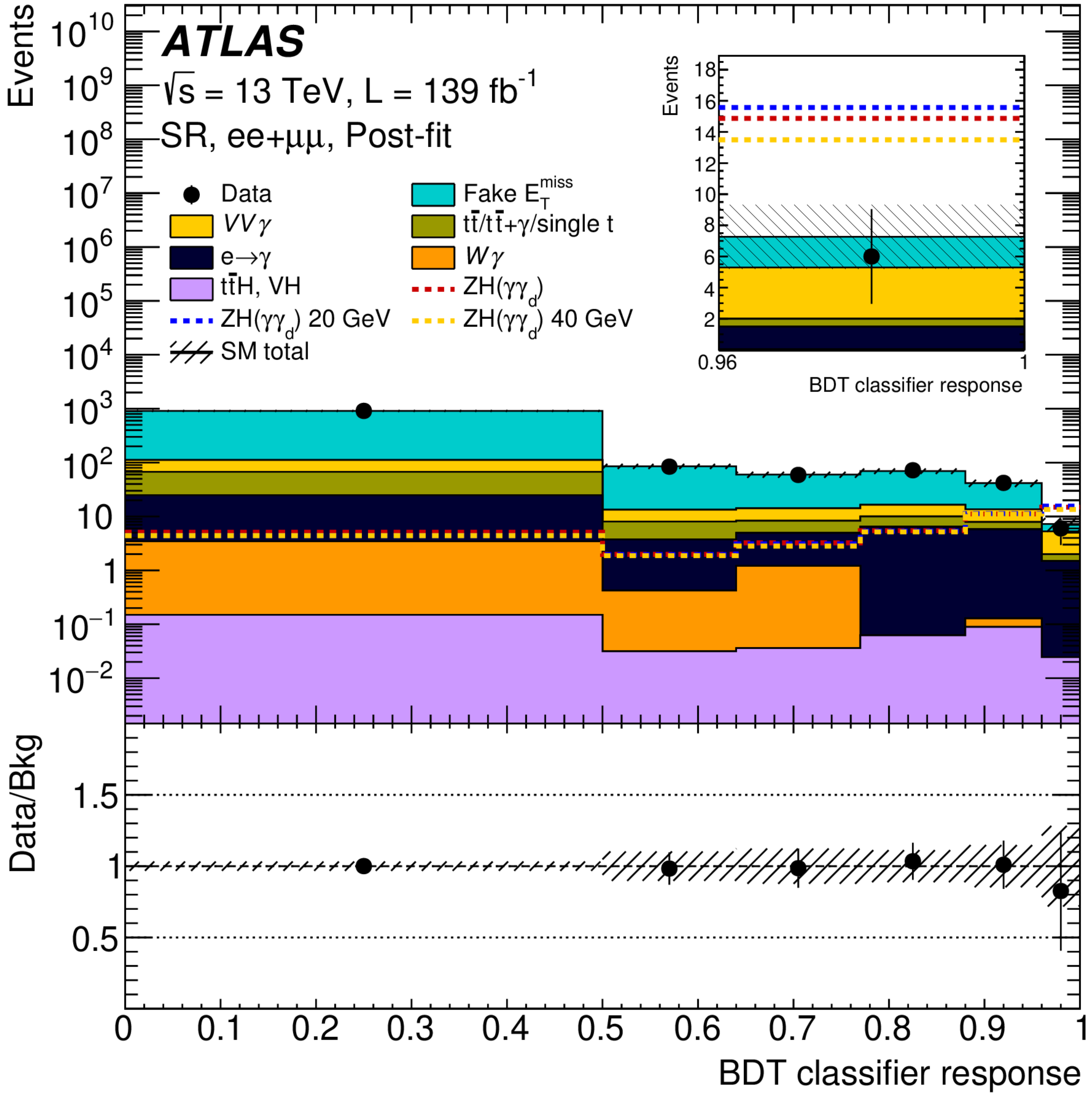
ZH channel

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, $m_{j_1 j_2} > 250\,\mathrm{GeV}, \lvert\Delta\eta_{j_1 j_2}\rvert > 3$ $\eta_{j_1} \cdot \eta_{j_2} < 0, \Delta\phi_{j_1 j_2} < 2, C_{j_3} < 0.7$	≤ 2	≤ 1
Leptons	$= 0\ (e, \mu)$	$= 2$, SFOC $m_{\ell\ell} \in (76, 116)$ GeV	$= 0\ (e, \mu, \tau)$



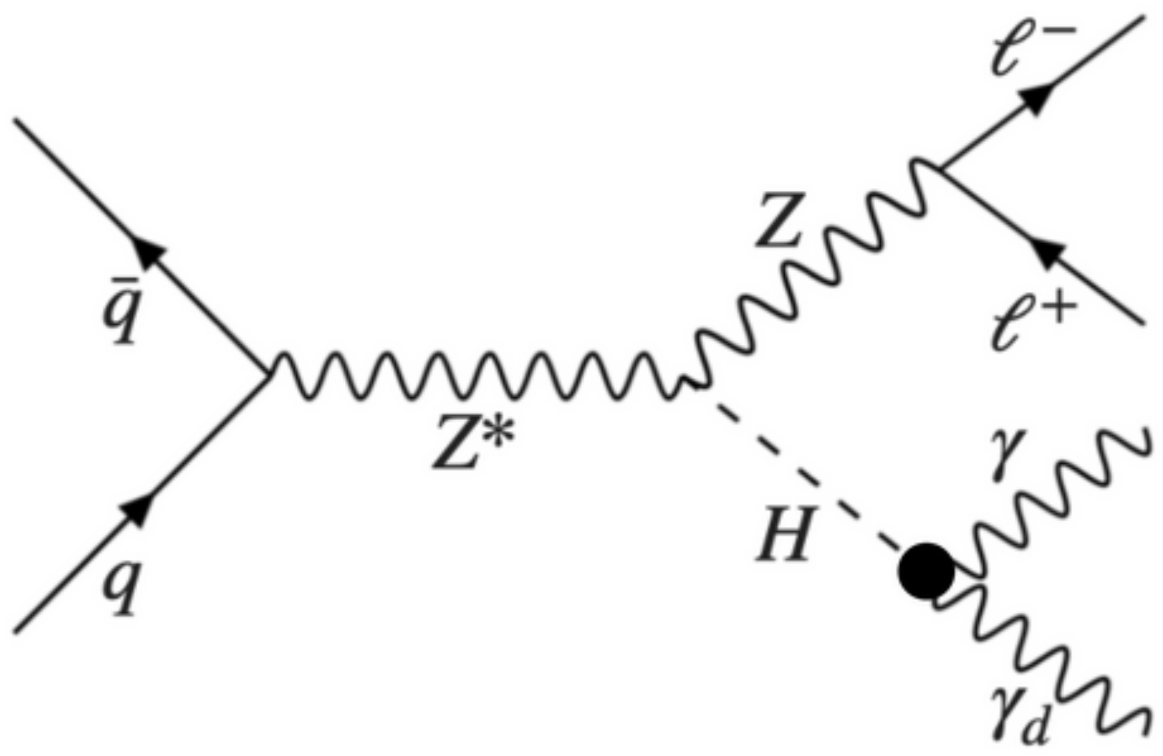
- Topology
  - 1 photon, no more than 2 jets, E_{T}^{miss}
  - 2 same-flavour, oppositely charged (SFOC) leptons within Z mass window
- BDT applied to enhance signal-bkg separation.
- Bkg estimation
  - Irreducible $VV\gamma$ from a dedicated CR.
  - Major $Z\gamma + $ jets, $Z + $ jets and e-fake γ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



No significant deviation from SM prediction.

ZH channel

JHEP 07 (2023) 133



- Topology
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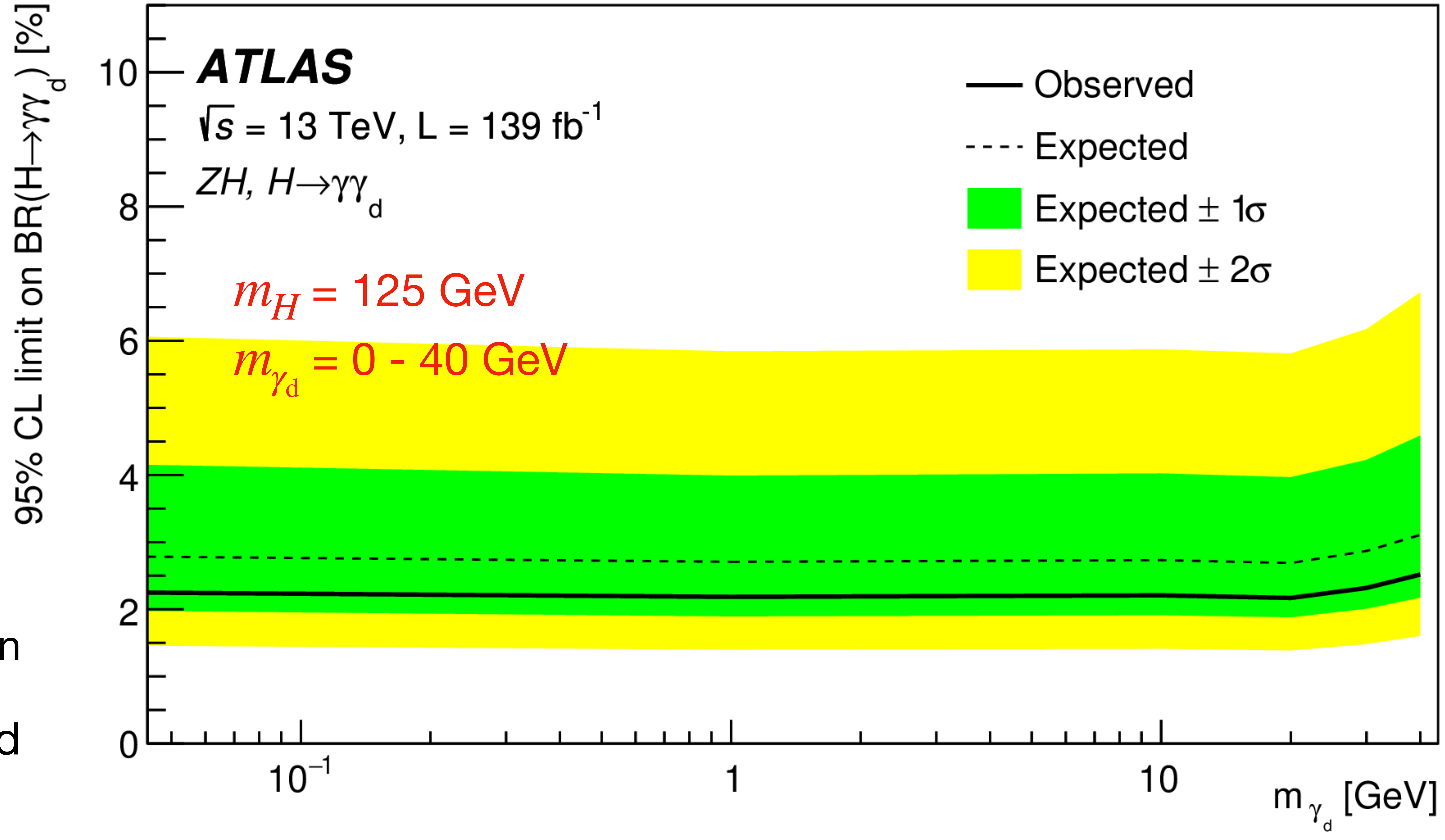
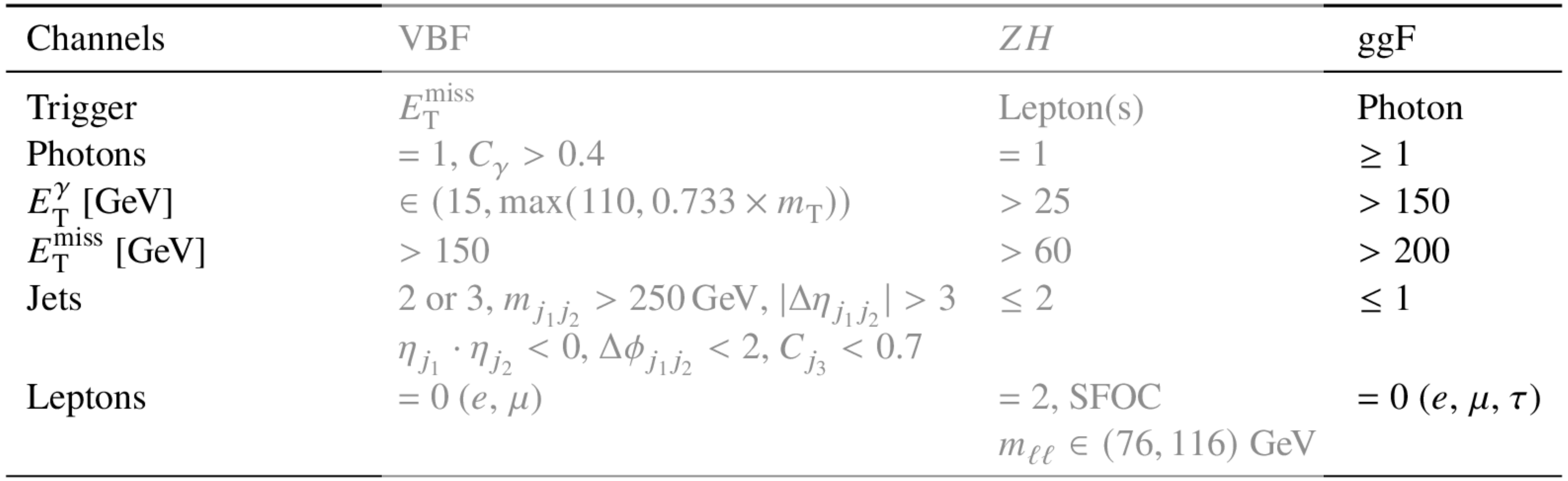


ggF channel

reinterpretation from JHEP 02 (2021) 226



Channels	VBF	ZH	ggF
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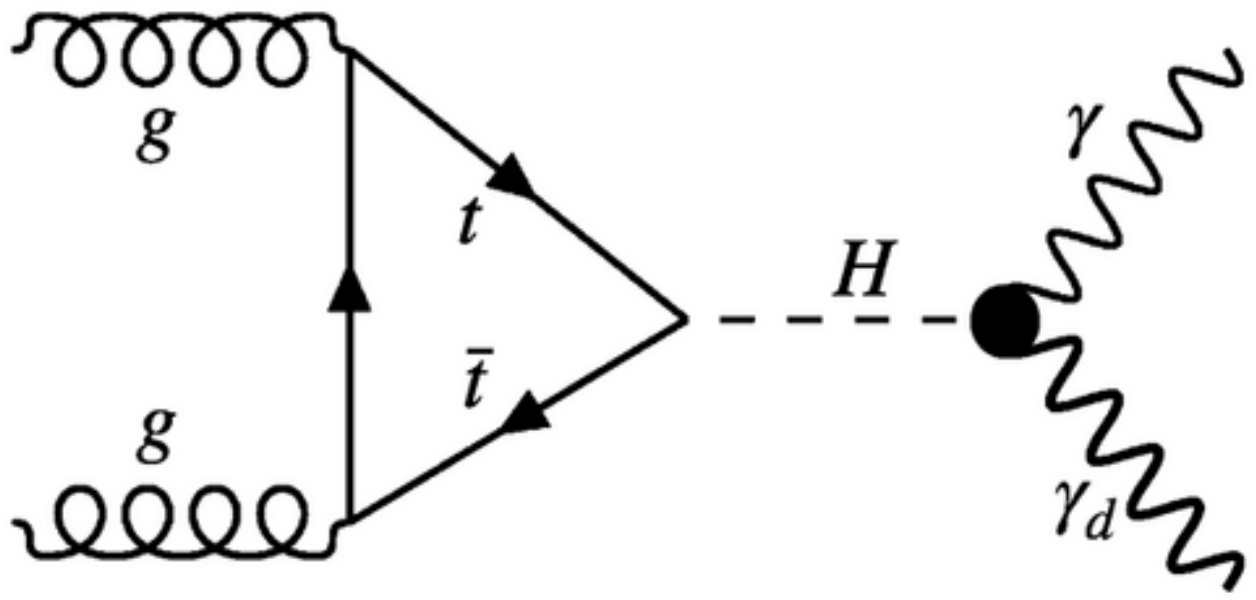
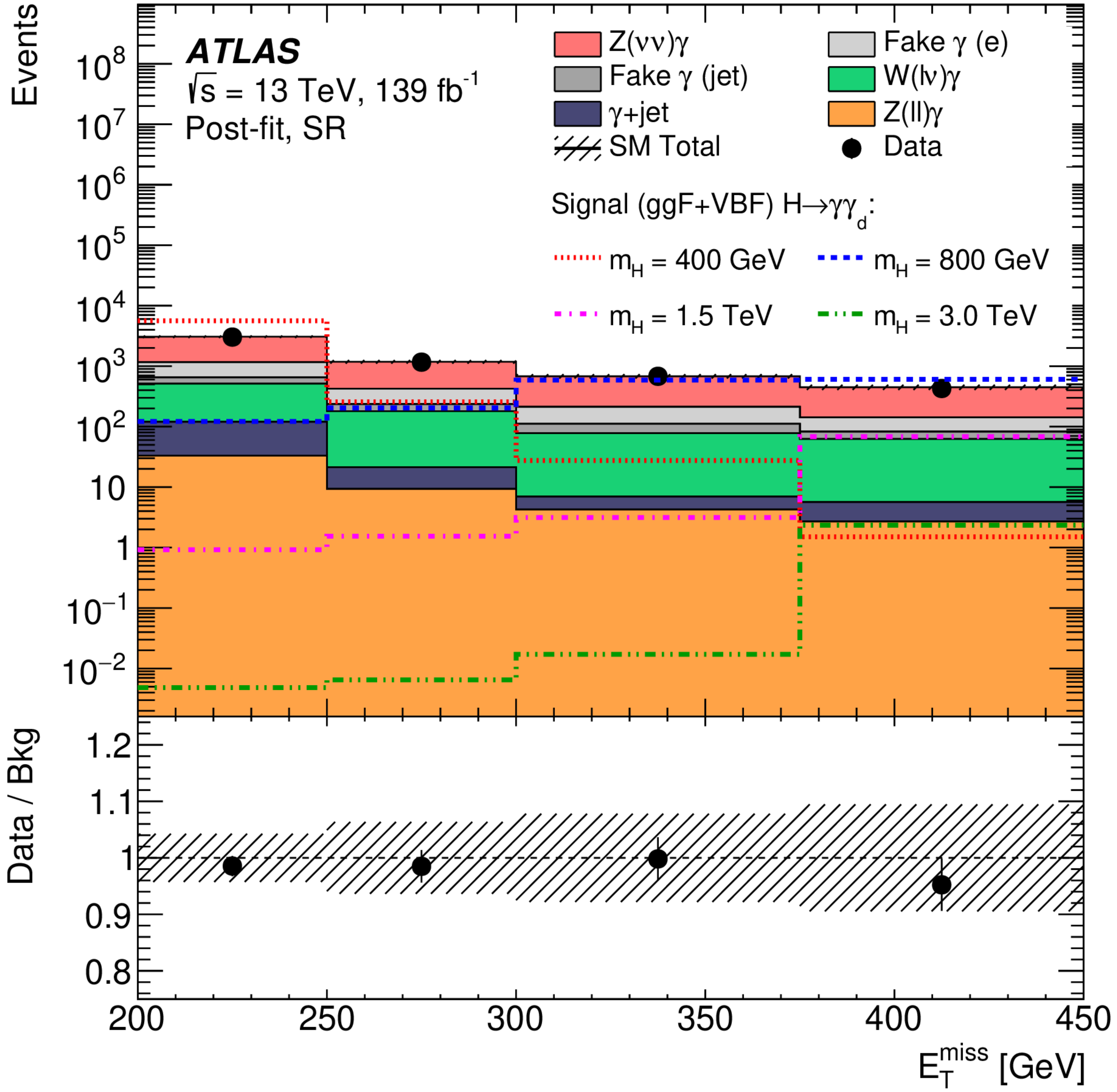


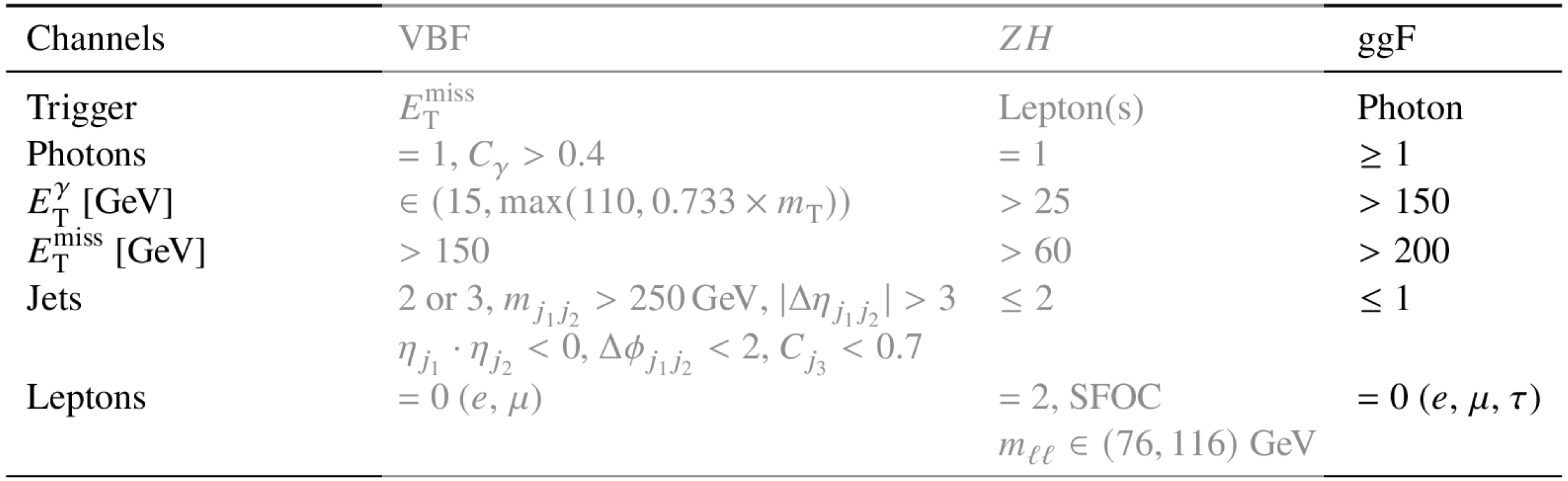
- ❖ Topology
  - ◉ At least 1 photon, max 1 jet , large E_{T}^{miss}
  - ◉ Lepton $(e,\ \mu,\ \tau_{\mathrm{had}})$ veto
- ❖ Background estimation
  - ◉ True photon bkgs: $Z(\to \nu\nu)\gamma$, $W(\to \ell\nu)\gamma$ and $Z(\to \ell\ell)\gamma$ from dedicated CRs.
  - ◉ e-fake γ and jet-fake γ from data-driven.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



No significant deviation from SM prediction.

ggF channel

reinterpretation from JHEP 02 (2021) 226



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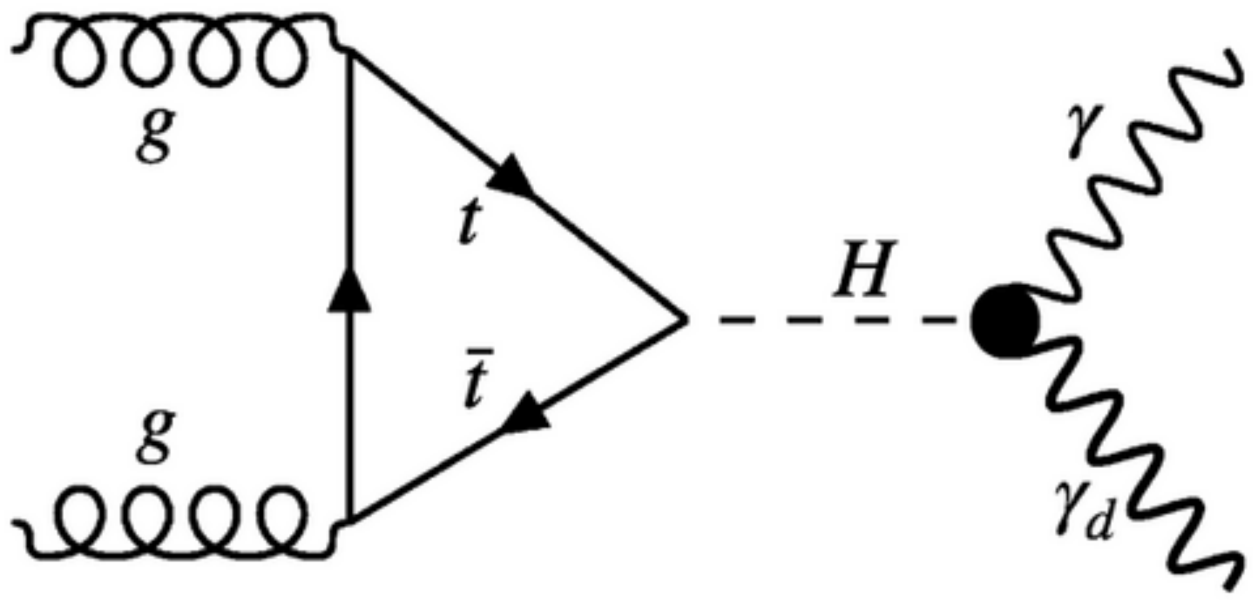

- Topology
  - At least 1 photon, max 1 jet , large E_T^{miss}
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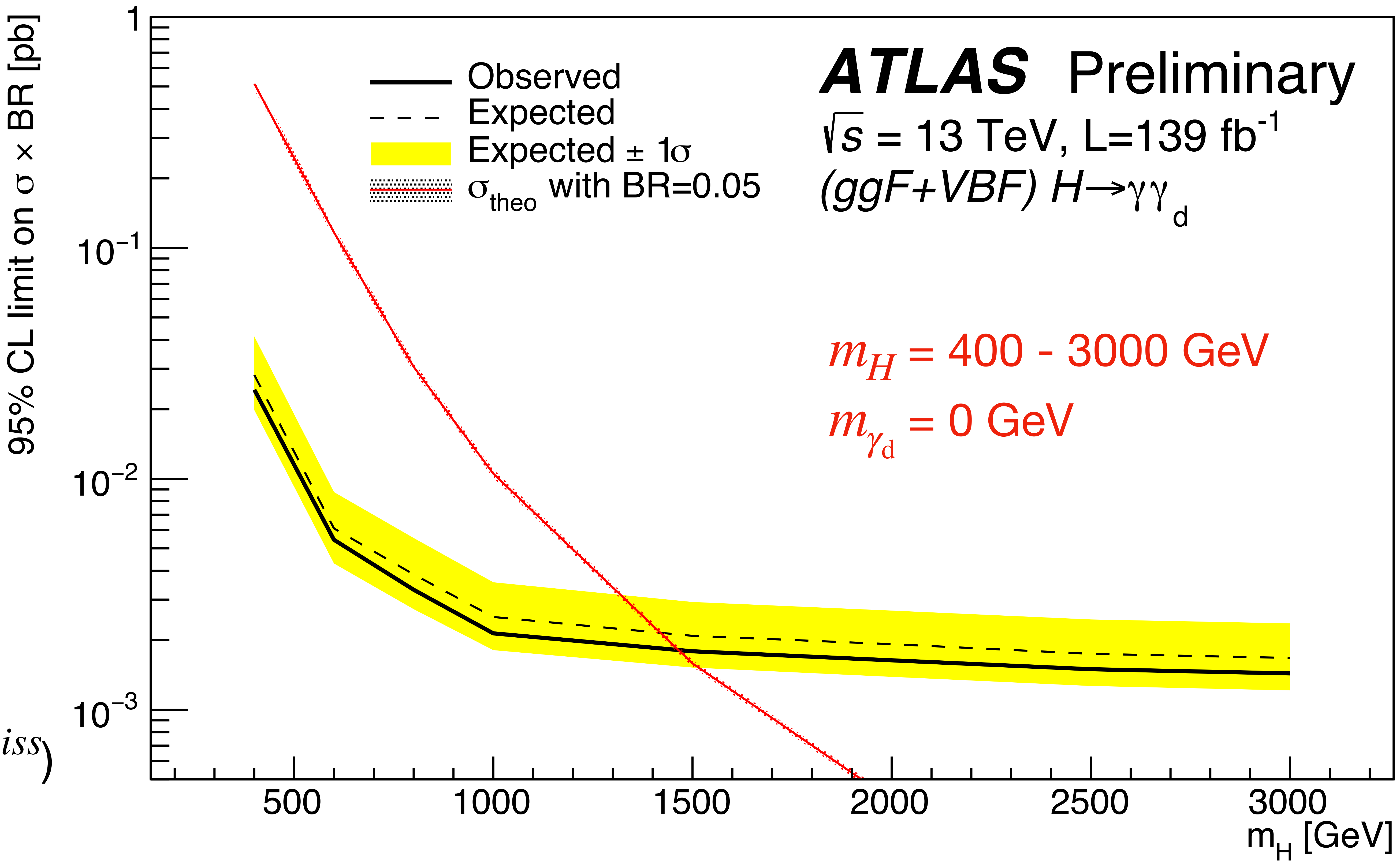
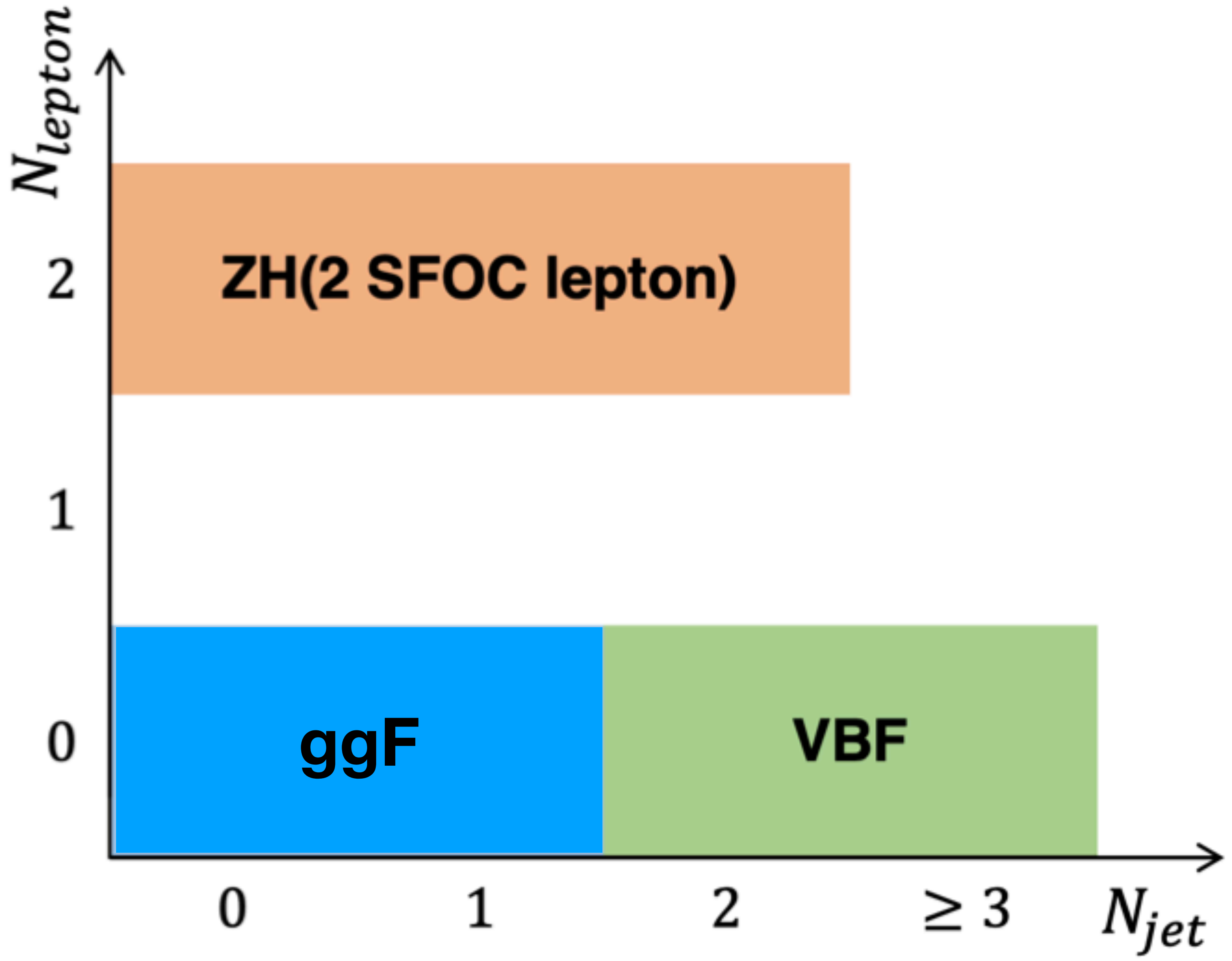


Motivation for combination



- 3 ATLAS channels probe complementary phase spaces in terms of jet and lepton multiplicities.

- Also provided very competitive results compared to CMS in terms of limits on $\mathscr{B}(H_{125} \to \gamma\gamma_{\rm d})$ and probed *H* mass range.

$H_{125} \to \gamma\gamma_{\rm d}$

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

95% CL limit on BR

$H_{\rm BSM} \to \gamma\gamma_{\rm d}$

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

Mass range probed for *H*

- Strong motivation for stat. combination to bring the best LHC constraint on $H_{125} \to \gamma\gamma_{\rm d}$ and the most comprehensive search in terms of BSM *H* mass.

Combination scenarios

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

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

❖ For this combination, adjustments wrt original VBF channel
  - ◉ ggF process contribution included for BSM Higgs decay search.
  - ◉ Extend *H* mass to 3 TeV.

Stat. combination

Statistical method

- Combination results obtained from a combined Likelihood function:
    - Product of likelihoods from individual channels within the combination.
    - These channel likelihoods themselves products of likelihoods computed from final observables in various categories in a single analysis.
- Upper limits on POI derived using profile-likelihood-ratio test statistic with [***CLs method***]() following [***asymptotic formulae***]().

Likelihood function

$$\mathcal{L}(\mathcal{D},\mathcal{G}|\mu,\alpha) = \prod_{c\in\mathbb{C}} \mathrm{Pois}(n_c|\nu_c(\mu,\alpha)) \prod_{e=1}^{n_c} f_c(x_{ce}|\mu,\alpha) \times \prod_{p\in\mathbb{S}} f_p(a_p|\alpha_p)$$

Parameter of interest

Nuisance parameters

Profile likelihood ratio

$$\tilde{\lambda}(\mu) = \begin{cases} \frac{\mathcal{L}(\mu,\hat{\hat{\theta}}(\mu))}{\mathcal{L}(0,\hat{\theta}(0))} & \hat{\mu} < 0, \\ \frac{\mathcal{L}(\mu,\hat{\hat{\theta}}(\mu))}{\mathcal{L}(\hat{\mu},\hat{\theta})} & \hat{\mu} \geq 0. \end{cases}$$

Test statistic

$$\tilde{q}_\mu = \begin{cases} -2\ln\tilde{\lambda}(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases} = \begin{cases} -2\ln\frac{\mathcal{L}(\mu,\hat{\hat{\theta}}(\mu))}{\mathcal{L}(0,\hat{\theta}(0))} & \hat{\mu} < 0, \\ -2\ln\frac{\mathcal{L}(\mu,\hat{\hat{\theta}}(\mu))}{\mathcal{L}(\hat{\mu},\hat{\theta})} & 0 \leq \hat{\mu} \leq \mu, \\ 0 & \hat{\mu} > \mu. \end{cases}$$

Stat. combination

Systematic uncertainty correlation

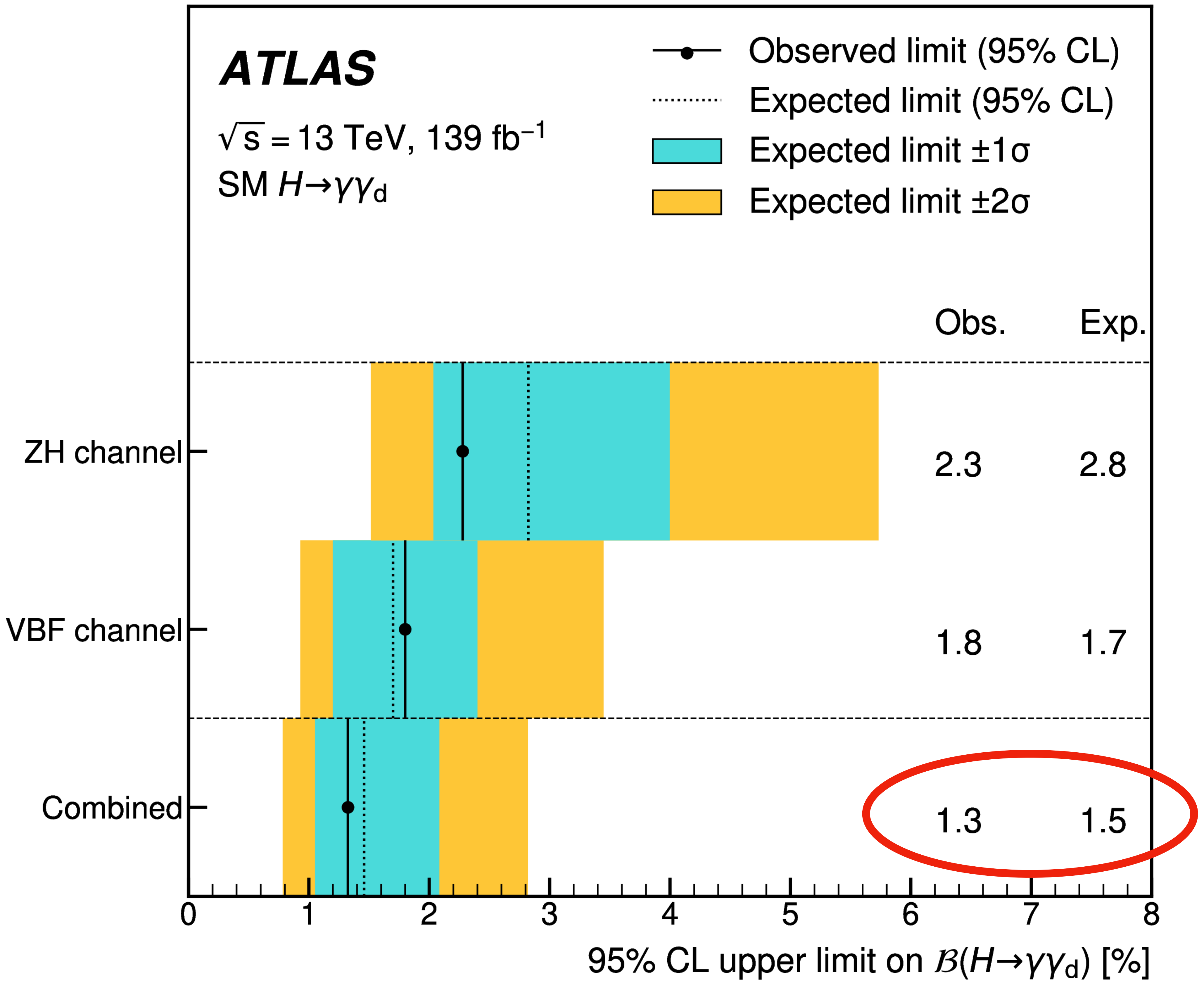
- Uncertainties from **luminosity**, **pile-up modelling** are correlated.

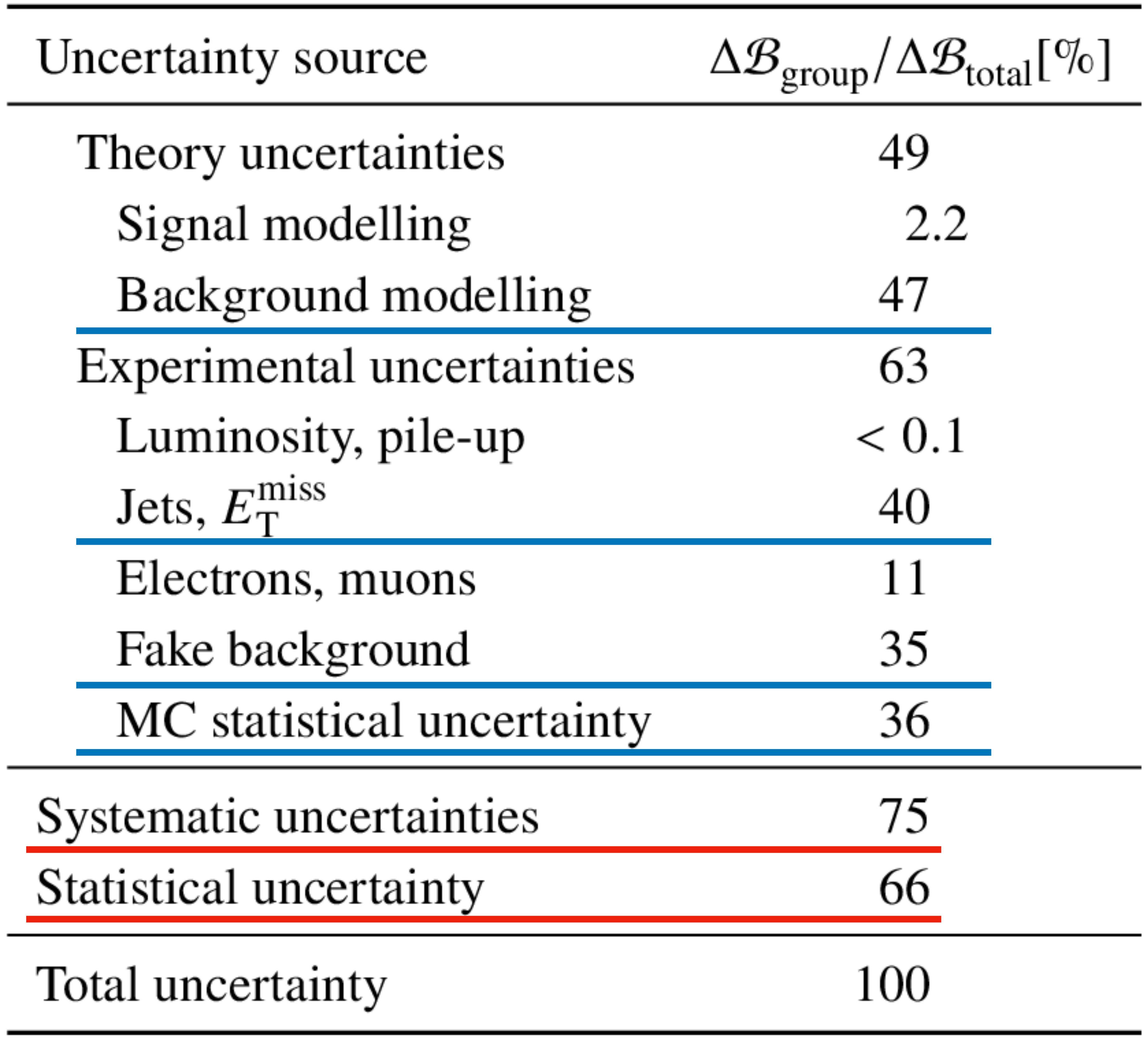
- **Experimental uncertainties**: correlated where appropriate, exceptions are:
  - Uncertainties related to same objects but **implemented with different schemes** among input channels (e.g Jet-Energy-Resolution).
  - Uncertainties **heavily constrained or pulled** in original input analyses.

- **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.

Results -- SM Higgs



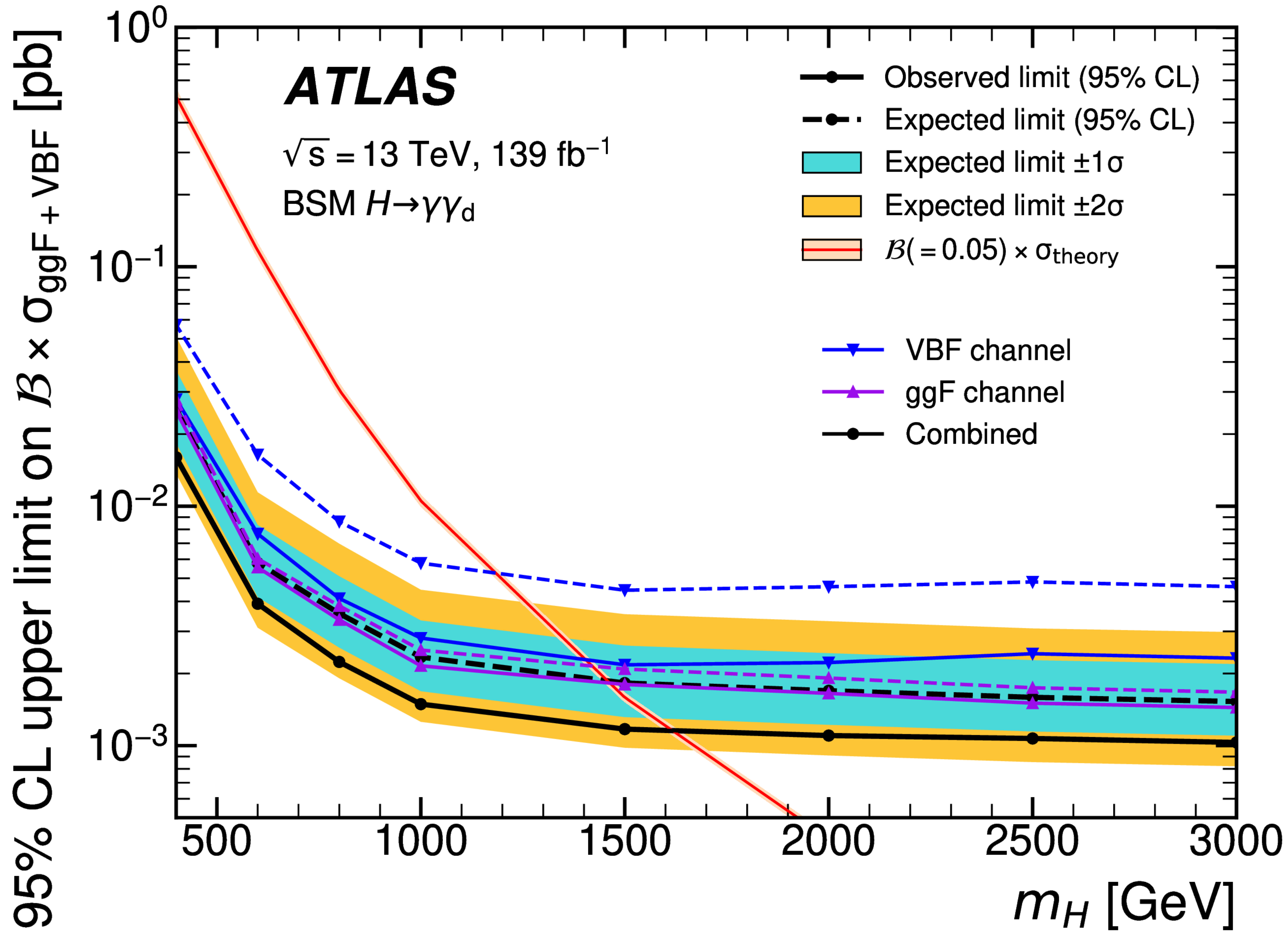


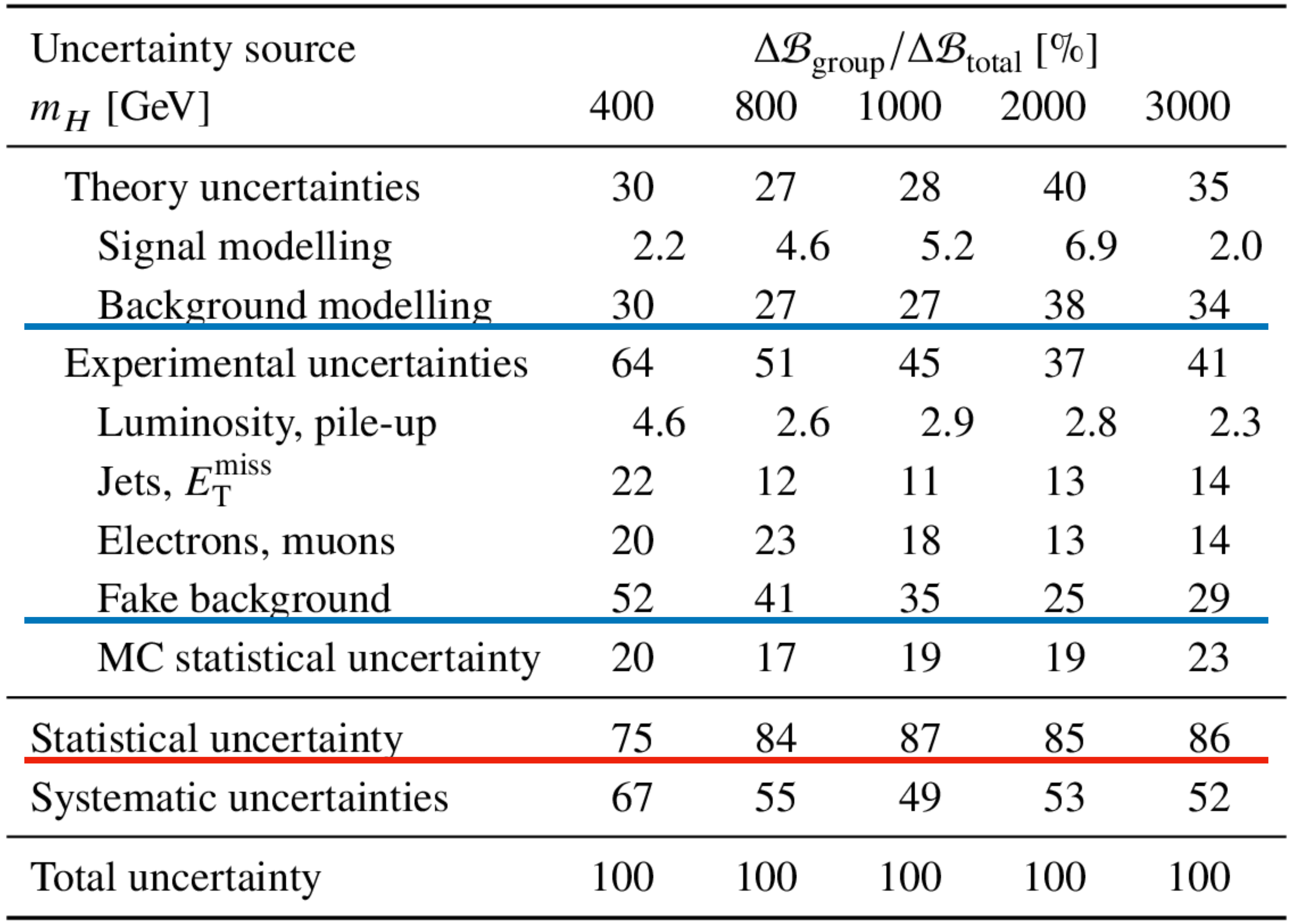
Uncertainty source	$\Delta\mathcal{B}_{\text{group}}/\Delta\mathcal{B}_{\text{total}}$ [%]
Theory uncertainties	49
Signal modelling	2.2
Background modelling	47
Experimental uncertainties	63
Luminosity, pile-up	< 0.1
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	40
Electrons, muons	11
Fake background	35
MC statistical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

- VBF-*ZH* combination set strongest limit on $\mathscr{B}(H_{125} \to \gamma\gamma_d)$ 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.

Results -- BSM Higgs





Uncertainty source	$\Delta\mathcal{B}_{\mathrm{group}}/\Delta\mathcal{B}_{\mathrm{total}}$ [%]				
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, $E_{\mathrm{T}}^{\mathrm{miss}}$	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 $\sigma_{\mathrm{ggF+VBF}} \times \mathcal{B}(H_{\mathrm{BSM}} \rightarrow \gamma\gamma_{\mathrm{d}})$ 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 for SM Higgs results

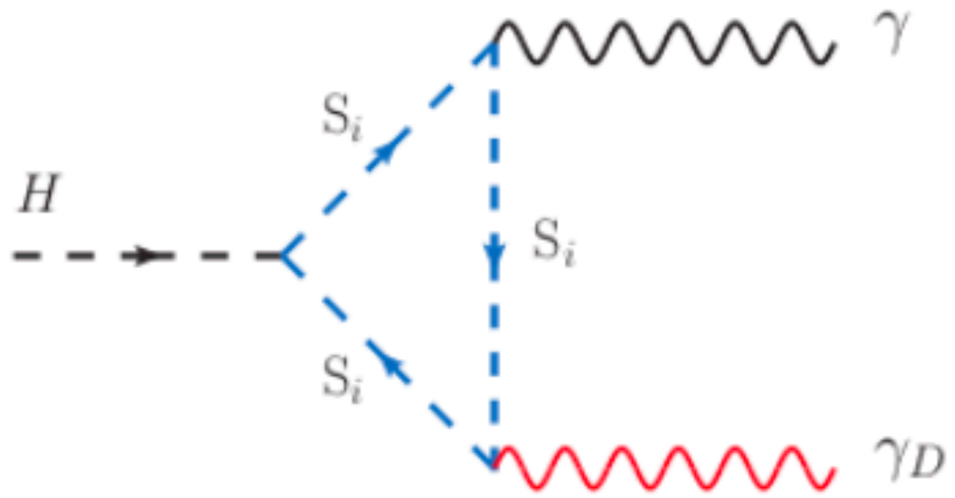
- VBF-*ZH* combined limit on $\mathscr{B}(H_{125} \to \gamma\gamma_{\rm d})$ interpreted in a ***Minimal Simplified Model*** [1405.5196]

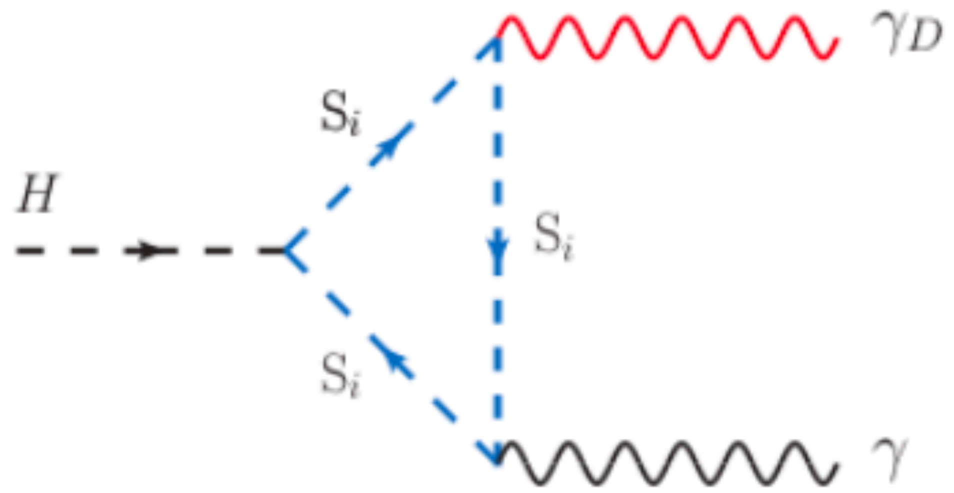
$$\hat{S} = (S_L, S_R)$$

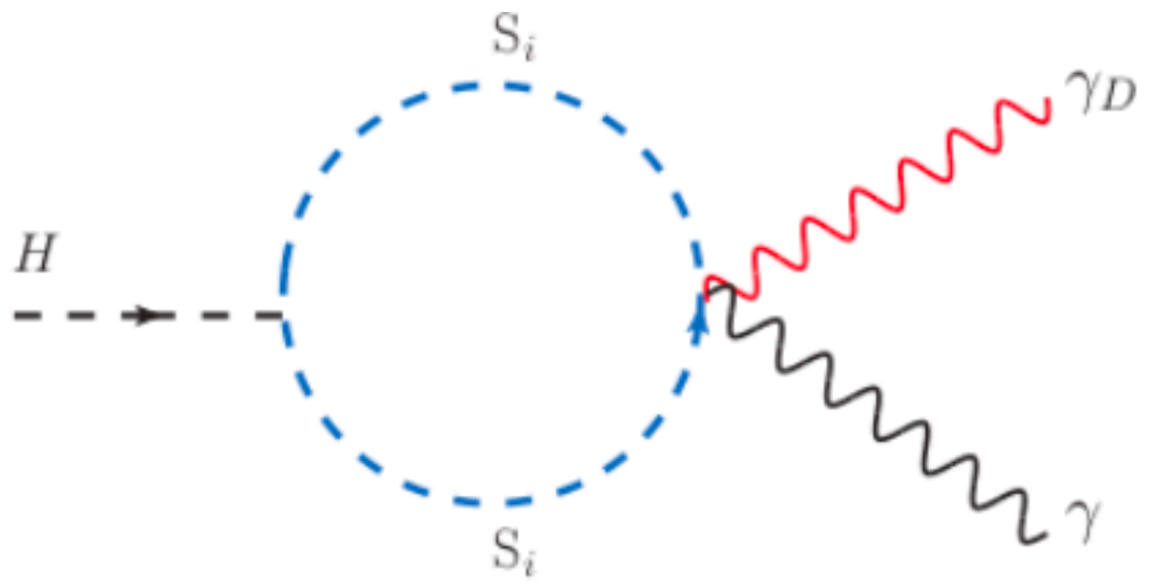
  - Generic Lagrangian: $\mathcal{L} \sim \mu \cdot H^\dagger S_L S_R + h.c. \xrightarrow{\text{EWSB}} \mathcal{L}_S^0 = \partial_\mu \hat{S}^\dagger \partial^\mu \hat{S} - \hat{S}^\dagger M_S^2 \hat{S}$

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

  - μ - mass parameter; S_L - $SU(2)_{\rm L}$ doublet; S_R - $SU(2)_{\rm L}$ singlet
  - Allowing $H_{125} \to \gamma\gamma_{\rm d}$ at 1-loop







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

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

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

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

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

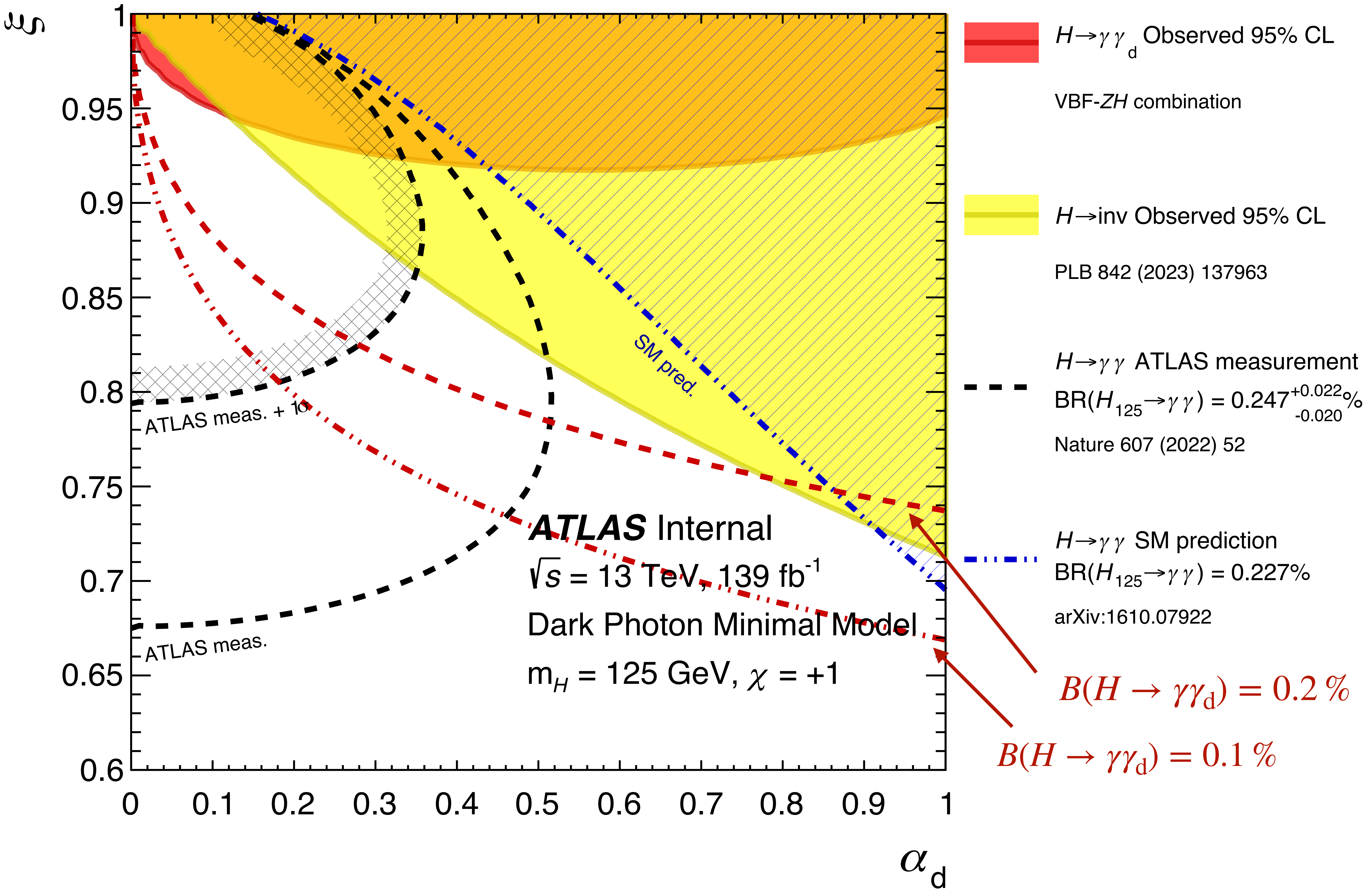
$$r_{\gamma_{\rm D}\gamma_{\rm D}} = X^2\left(\frac{\alpha_D}{\alpha}\right)^2$$

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

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

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

Physics interpretation for SM Higgs results



$B(H \to \gamma\gamma_d) = 0.2\,\%$

$B(H \to \gamma\gamma_d) = 0.1\,\%$

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

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

- ❖ $\xi \simeq 0.7$ at $\alpha_d = 1$ excluded by $\mathscr{B}(H_{125} \to \mathrm{inv})$ limit interpreted in terms of $H_{125} \to \gamma_d\gamma_d$ signal.
- ❖ $H_{125} \to \gamma\gamma_d$ combination provides additional sensitivity in low-α_d region, which is disfavoured by ATLAS $\mathscr{B}(H_{125} \to \gamma\gamma)$ measurement.
- ❖ Still need ~$\mathscr{O}(1)$ better in sensitivity for $H_{125} \to \gamma\gamma_d$ search.

Conclusion

- Combined search for Higgs decays into photon and massless dark photon has been performed:
  - **SM Higgs**: VBF-*ZH* combination sets the most stringent limits on $\mathscr{B}(H_{125} \to \gamma\gamma_{\rm d})$ at LHC to date.
  - **BSM Higgs**: VBF-ggF combination provides most comprehensive constraint on $\sigma_{\rm VBF+ggF} \times \mathscr{B}(H_{125} \to \gamma\gamma_{\rm d})$ for Higgs mass up to 3 TeV.

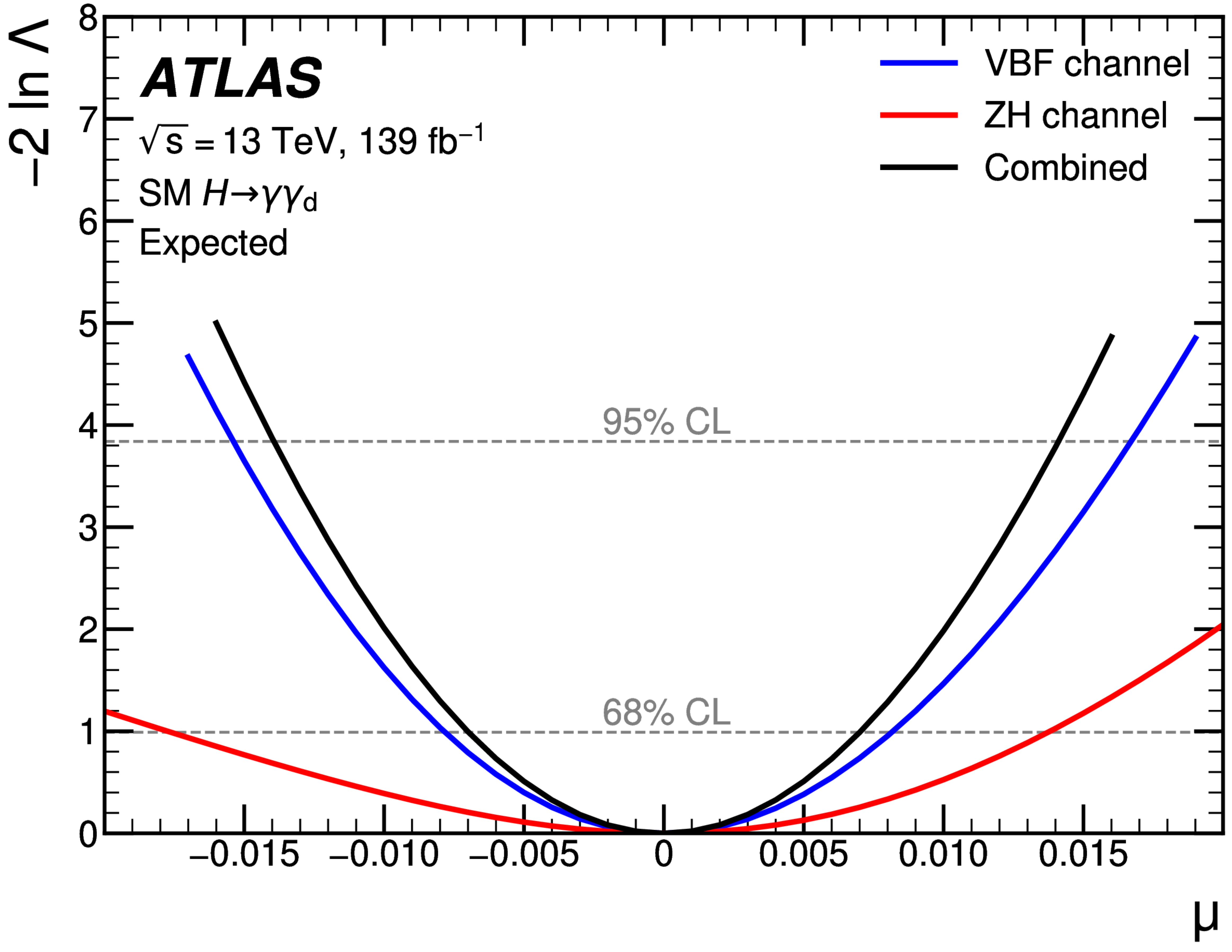
- First physics interpretation of the $H_{125} \to \gamma\gamma_{\rm d}$, $H_{125} \to {\rm inv}$ and $H_{125} \to \gamma\gamma$ results in the Dark Photon Minimal Simplified Model with a generic messenger sector.

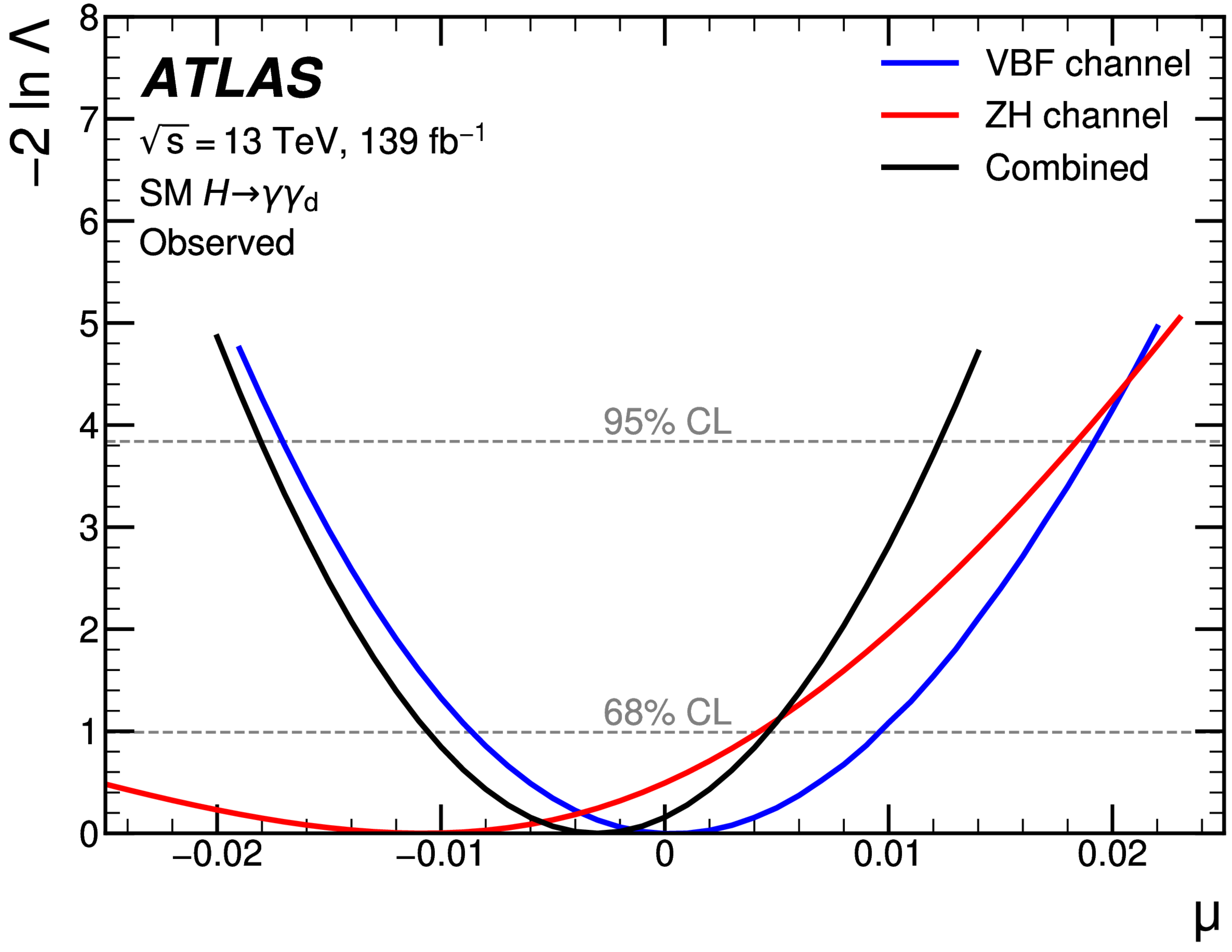
- See Lailin XU's talk for more results on Dark Photon searches at LHC.

Thank you for attention

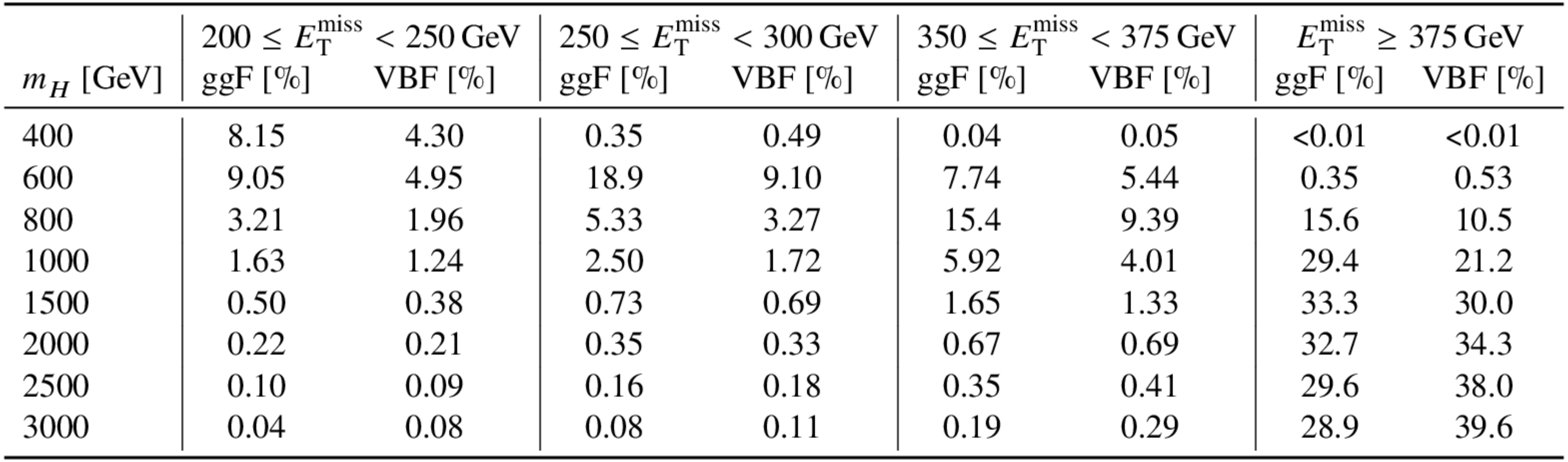
Backup

Auxiliary


ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
SM $H \rightarrow \gamma\gamma_d$
Expected
VBF channel
ZH channel
Combined
95% CL
68% CL
−2 ln Λ
μ
0
1
2
3
4
5
6
7
8
−0.015
−0.010
−0.005
0
0.005
0.010
0.015

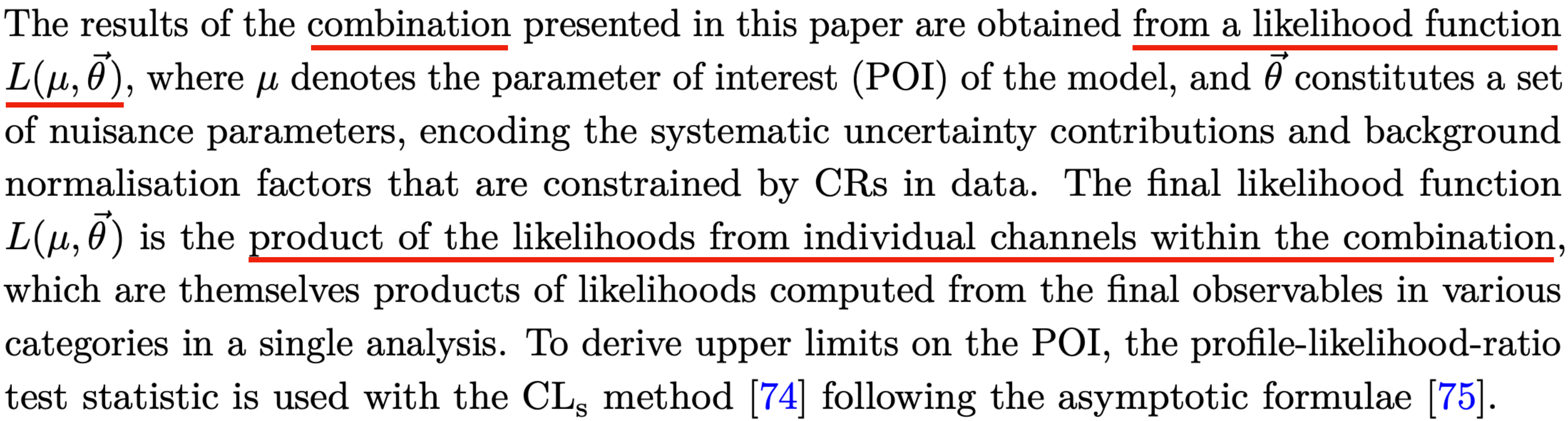

ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
SM $H \rightarrow \gamma\gamma_d$
Observed
VBF channel
ZH channel
Combined
95% CL
68% CL
−2 ln Λ
μ
0
1
2
3
4
5
6
7
8
−0.02
−0.01
0
0.01
0.02

Auxiliary



	$200 \leq E_{\mathrm{T}}^{\mathrm{miss}} < 250$ GeV		$250 \leq E_{\mathrm{T}}^{\mathrm{miss}} < 300$ GeV		$350 \leq E_{\mathrm{T}}^{\mathrm{miss}} < 375$ GeV		$E_{\mathrm{T}}^{\mathrm{miss}} \geq 375$ GeV	
m_H [GeV]	ggF [%]	VBF [%]	ggF [%]	VBF [%]	ggF [%]	VBF [%]	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

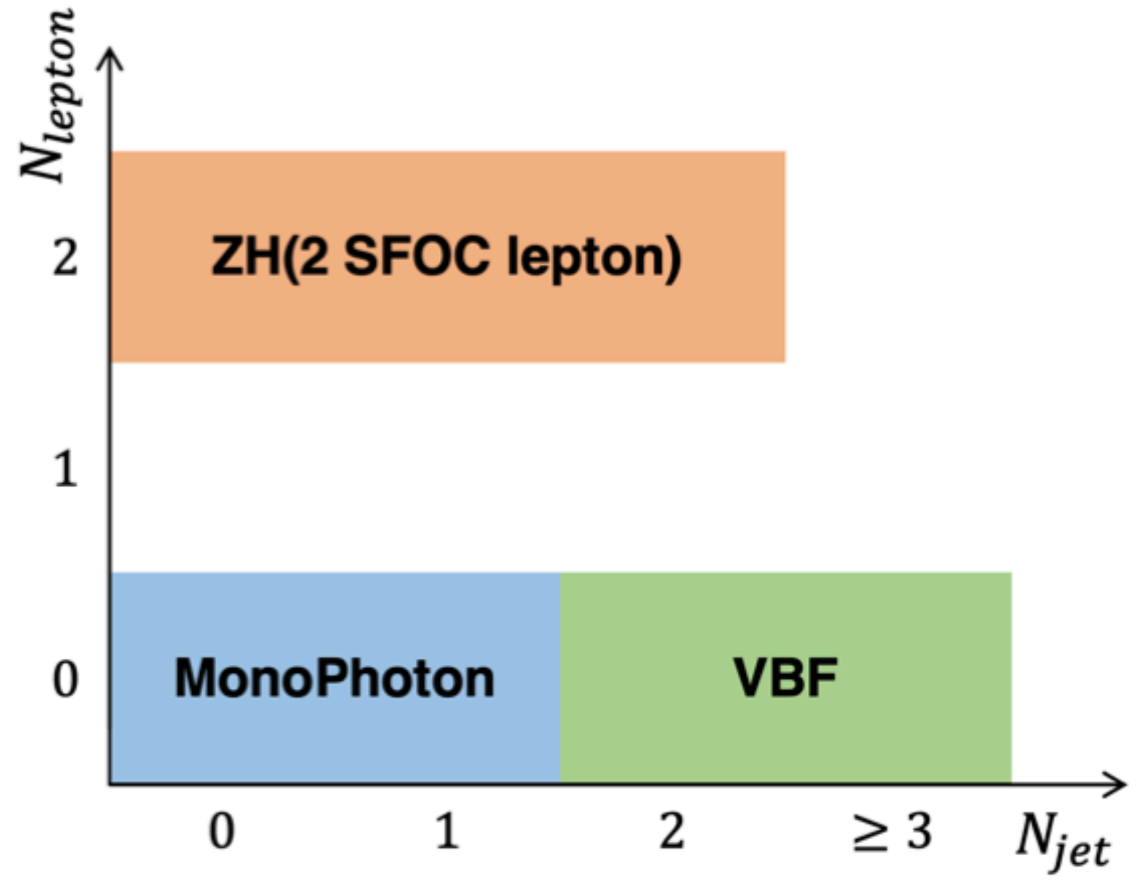
Stat. combination



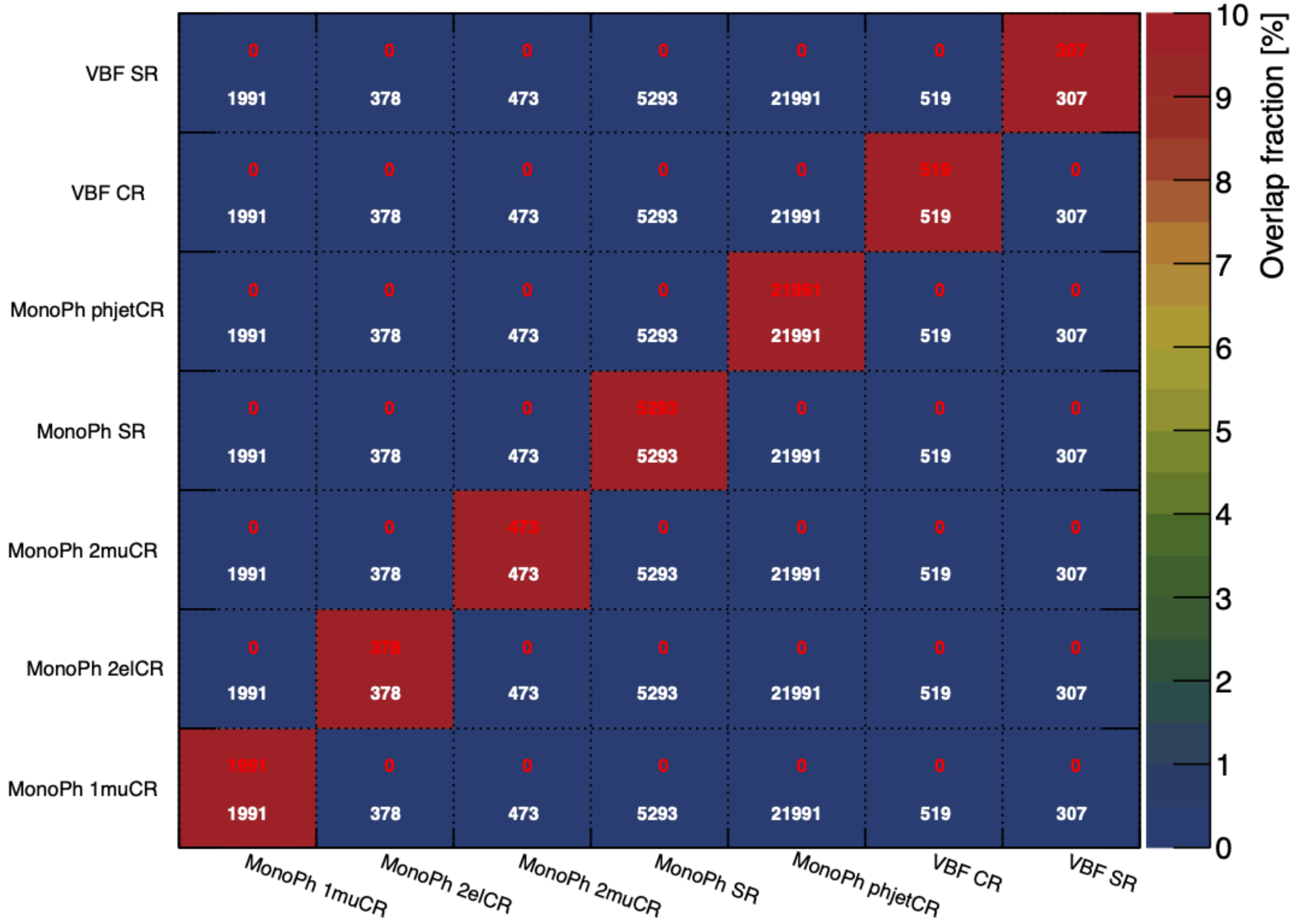
The results of the combination presented in this paper are obtained from a likelihood function $L(\mu, \vec{\theta})$, where μ denotes the parameter of interest (POI) of the model, and $\vec{\theta}$ constitutes a set of nuisance parameters, encoding the systematic uncertainty contributions and background 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 $\mathrm{CL_s}$ 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.



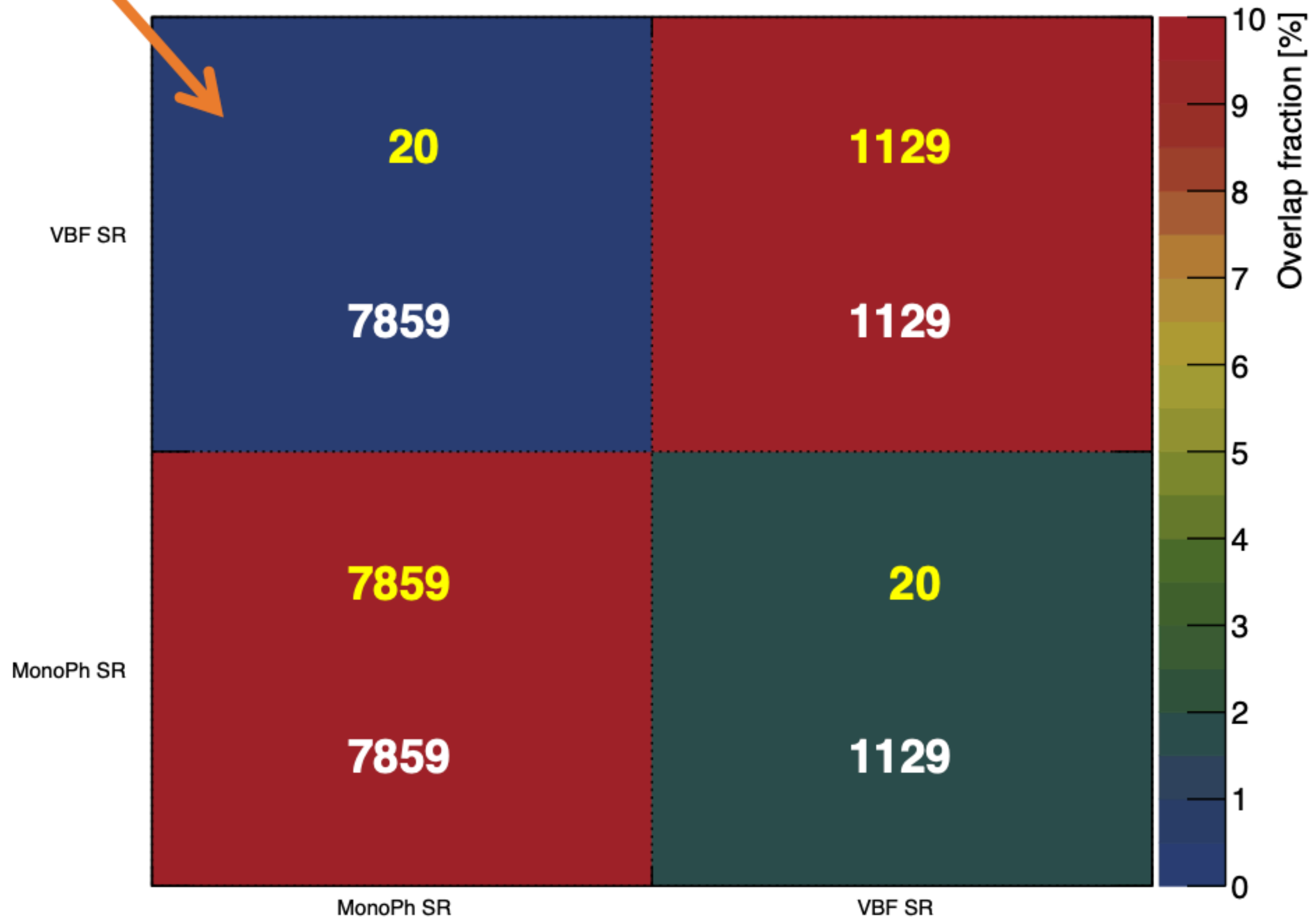
Heavy Higgs monophton-recast+VBF combination
Full run-2 data



	MonoPh 1muCR	MonoPh 2elCR	MonoPh 2muCR	MonoPh SR	MonoPh phjetCR	VBF CR	VBF SR
VBF SR	0 1991	0 378	0 473	0 5293	0 21991	0 519	307 307
VBF CR	0 1991	0 378	0 473	0 5293	0 21991	519 519	0 307
MonoPh phjetCR	0 1991	0 378	0 473	0 5293	21991 21991	0 519	0 307
MonoPh SR	0 1991	0 378	0 473	5293 5293	0 21991	0 519	0 307
MonoPh 2muCR	0 1991	0 378	473 473	0 5293	0 21991	0 519	0 307
MonoPh 2elCR	0 1991	378 378	0 473	0 5293	0 21991	0 519	0 307
MonoPh 1muCR	1991 1991	0 378	0 473	0 5293	0 21991	0 519	0 307

7859 in MonoPh SR,
20 shared with VBF SR

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



	MonoPh SR	VBF SR
VBF SR	20 7859	1129 1129
MonoPh SR	7859 7859	20 1129