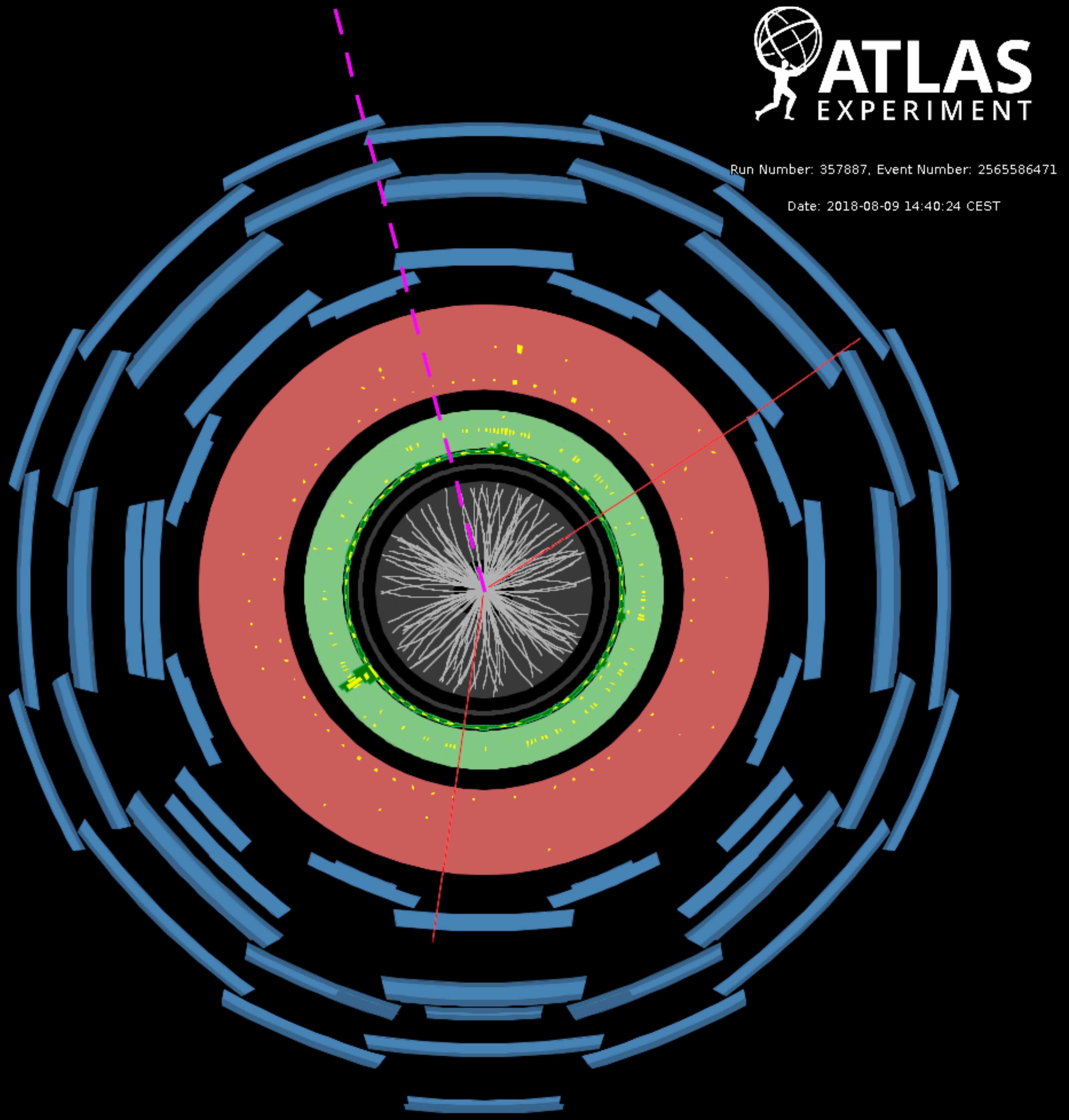


Search for a dark photon in resonant mono-photon signatures from Higgs boson decays

Higgs 2022, Pisa

Federica Piazza
on behalf of the **ATLAS** Collaboration

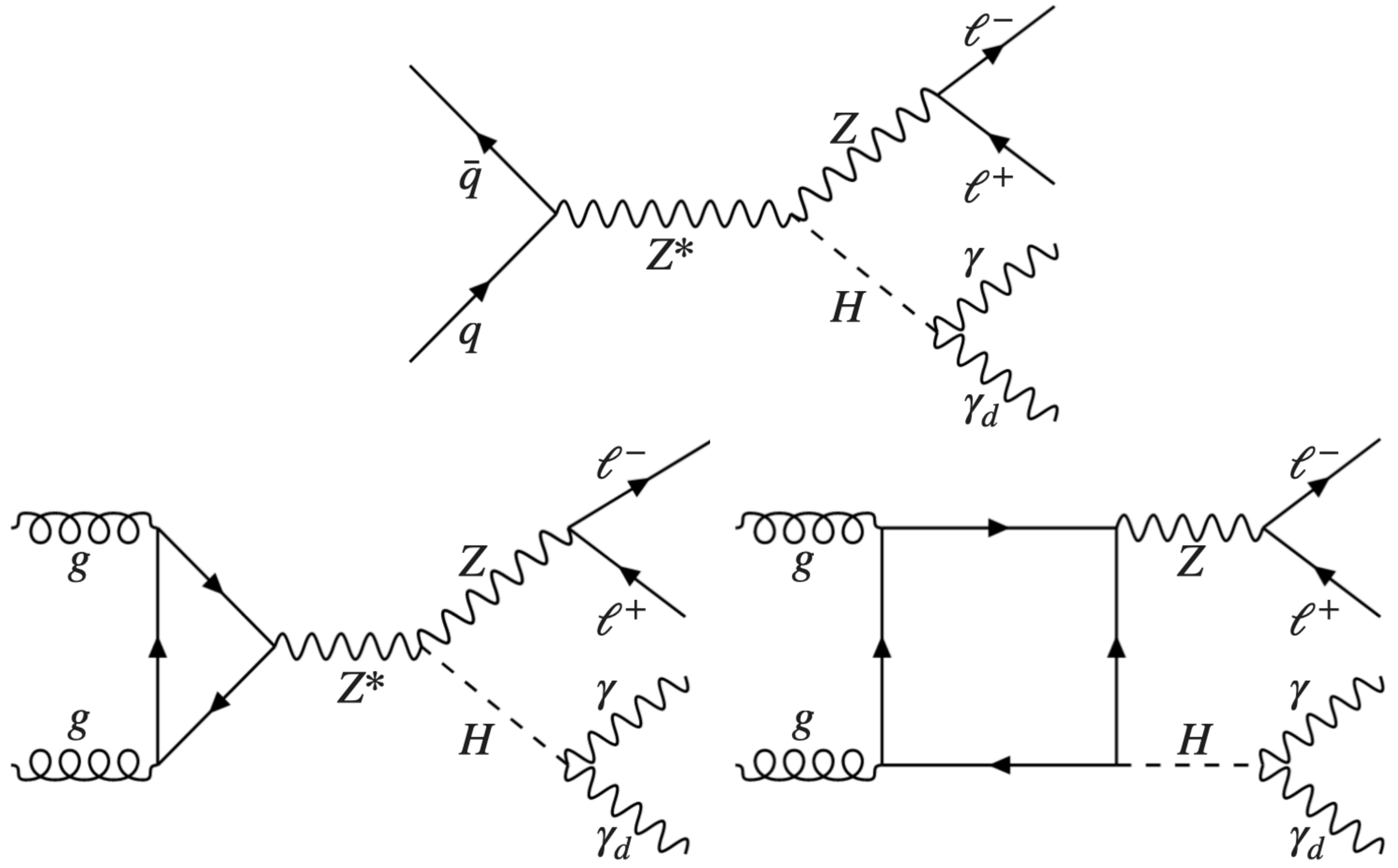
Motivations and analysis overview

Motivations

- Dark Matter can be part of a Dark Sector, potentially interacting with the Standard Model Sector through "portal" interactions
- Dark photon as the gauge boson of a new unbroken U(1) group of the Dark Sector (arxiv:2005.01515)
- It can interact with SM sector through higher than 4-dimensional operators via messenger exchange
  - Loop of messenger fields can allow $H \to \gamma\gamma_D$ or $H \to \gamma_D\gamma_D$ (Higgs portal)
  - BSM BR up to few % allowed by present constraints (arxiv:2206.05297)

This analysis:

- Dark-photon from (gg, qq) ZH, H $\to \gamma\gamma_d$
- Clean final state $\ell\ell + \gamma + E_T^{miss}$ (γ_d undetected)
- New analysis in ATLAS, using full Run 2 dataset
- γ_D masses: 0, 1, 10, 20, 30, 40 GeV



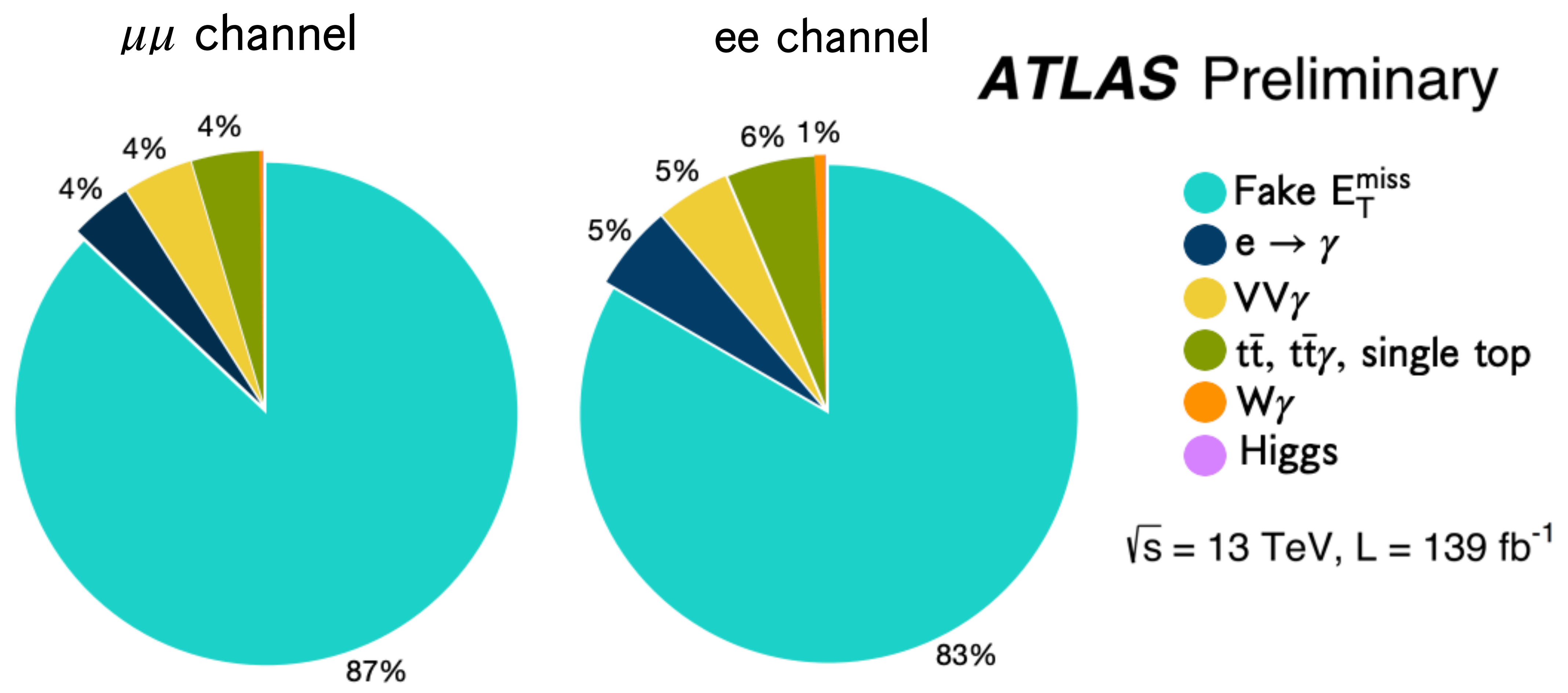
Analysis selections and strategy

- Discriminant variables: BDT output score
  Training input variables: E_T^{miss} significance, $m_T(\gamma, E_T^{miss})$, photon p_T, m_{ll}, $m_{ll\gamma}$, $\frac{|\vec{E}_T^{miss} + \vec{p}_T^{\gamma}| - p_T^{ll}}{p_T^{ll}}$
- Main backgrounds through data-driven techniques

Background	**Contributions**	**Estimate**
Fake E_T^{miss}	$Z\gamma$, $Z\gamma$ + jets, $Z\gamma\gamma$, $ZH(\gamma\gamma)$, gg/VBF $H(Z\gamma)$	Data-driven with ABCD Shape from MC
$e \rightarrow \gamma$	VV, VVV, $\ell^+\ell^-$Vt, $VVt\bar{t}$	Pure data-driven based on $e \rightarrow \gamma$ fake-rate
$VV\gamma$	$Z(\ell^+\ell^-)Z(\nu\bar{\nu})\gamma$, $W^+(\ell^+\nu)W^-(\ell^-\bar{\nu})\gamma$	MC rescaled by data in CR
Top	$tW\gamma$, $t\bar{t}\gamma$, $t\bar{t}$, single top	Pure MC, with 20% syst from data/bkg in top VR
$W\gamma$	$W\gamma$ with jet $\rightarrow \ell$	Pure MC
Higgs	$t\bar{t}H(Z\gamma)$, $VH(Z\gamma)$	Pure MC

SR selections

Medium ID, loose isolated muons. Medium ID, loose isolated electrons
Two same flavour, opposite sign leptons, with leading p_T > 27 GeV, sub-leading p_T > 20 GeV
Veto of any additional lepton with Loose ID and p_T > 10 GeV
76 GeV < $m_{\ell\ell}$ < 116 GeV
One Tight ID, Tight isolated photon with E_T^{γ} > 25 GeV
E_T^{miss} > 60 GeV with $\Delta\phi(\vec{E}_T^{miss}; \vec{p}_T^{\ell\ell\gamma})$ > 2.4 rad
$m_{\ell\ell\gamma}$ > 100 GeV
$N_{jet} \leq 2$, with p_T^{jet} > 30 GeV, $|\eta|$ < 4.5
Veto b-jet



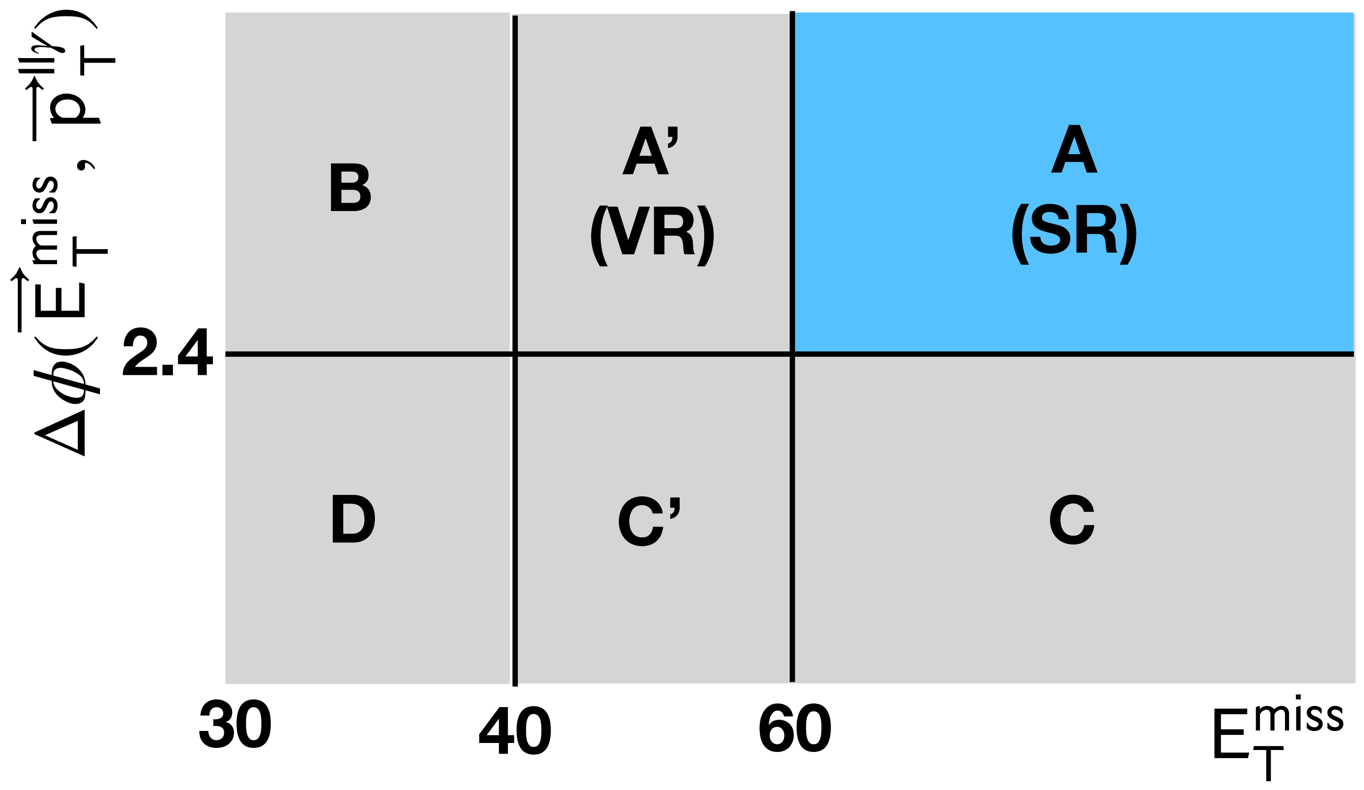
Data-driven estimates

Fake E_T^{miss}: ABCD method

$$N_A^{fakeMET} = R \times \frac{N_B N_C}{N_D},\ R = \frac{N^{MC}_{A+A'} N^{MC}_{D}}{N^{MC}_{C+C'} N^{MC}_{B}}$$

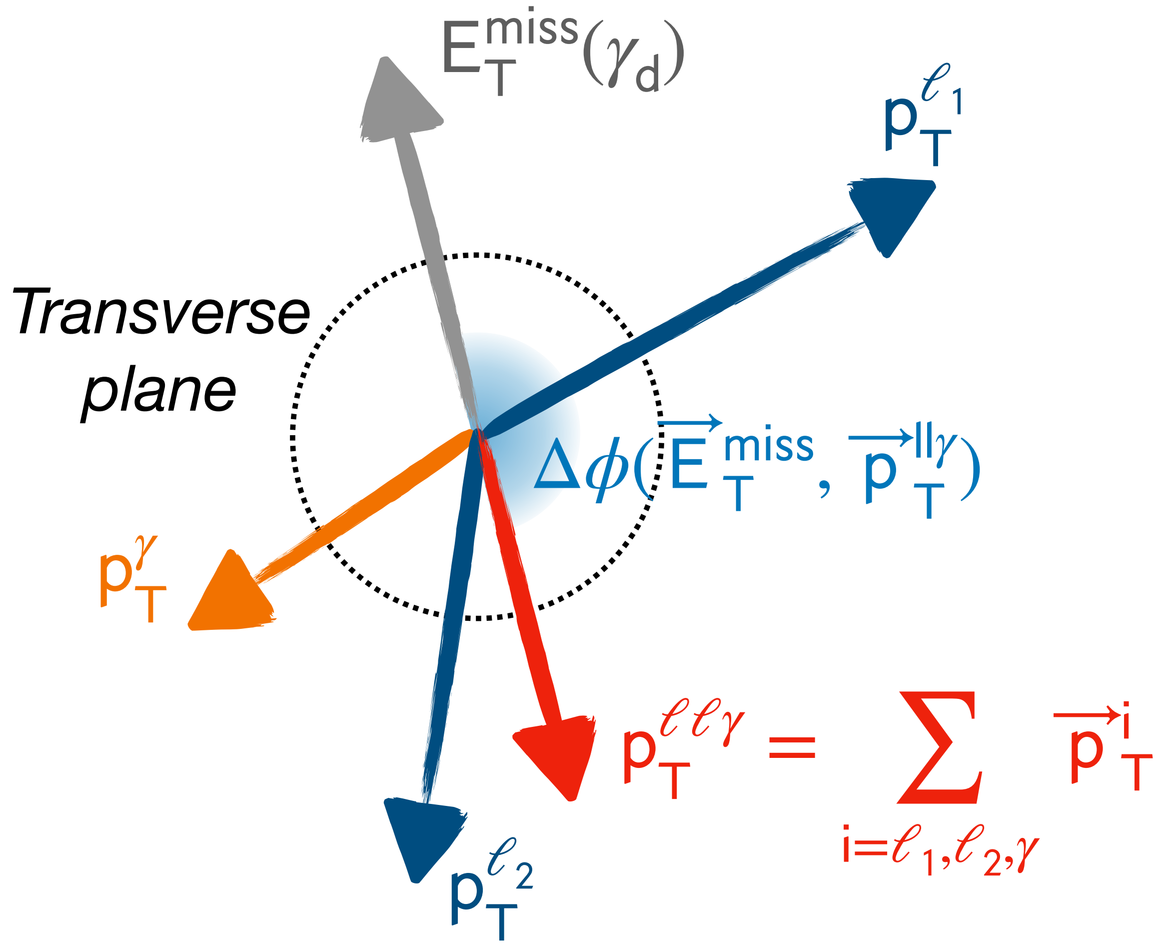
Closure in A' for R value

channel	R'	
	R'_{MC}	R'_{data}
ee	1.09 ± 0.11	1.16 ± 0.06
$\mu\mu$	1.15 ± 0.11	1.18 ± 0.05



- R from MC: takes into account possible correlation between the 2 variables
- N_X = observed data in region X, after subtraction of non-fake E_T^{miss} backgrounds
- Uncertainties: statistical uncertainty of data in the B, C and D regions and the uncertainty of R coefficient from MC statistics

Electrons faking photons: Yields in probe-e CRs rescaled by fake rate $F_{e\to\gamma} = \frac{N_{e\gamma}}{N_{ee}}$



- Probe-e CR : replace the photon with an electron in the analysis regions
- Fake rate from signal+bkg fit of invariant mass in ee and $e\gamma$ final states from Z decay
- Uncertainties: uncertainty on the fake-rate, statistics in probe-e CR, 100% uncertainty on $jet \to e$ subtraction

Data-driven estimates

Fake E_T^{miss}: ABCD method

$$N_A^{fakeMET} = R \times \frac{N_B N_C}{N_D}, \; R = \frac{N^{MC}_{A+A'} N^{MC}_D}{N^{MC}_{C+C'} N^{MC}_B}$$

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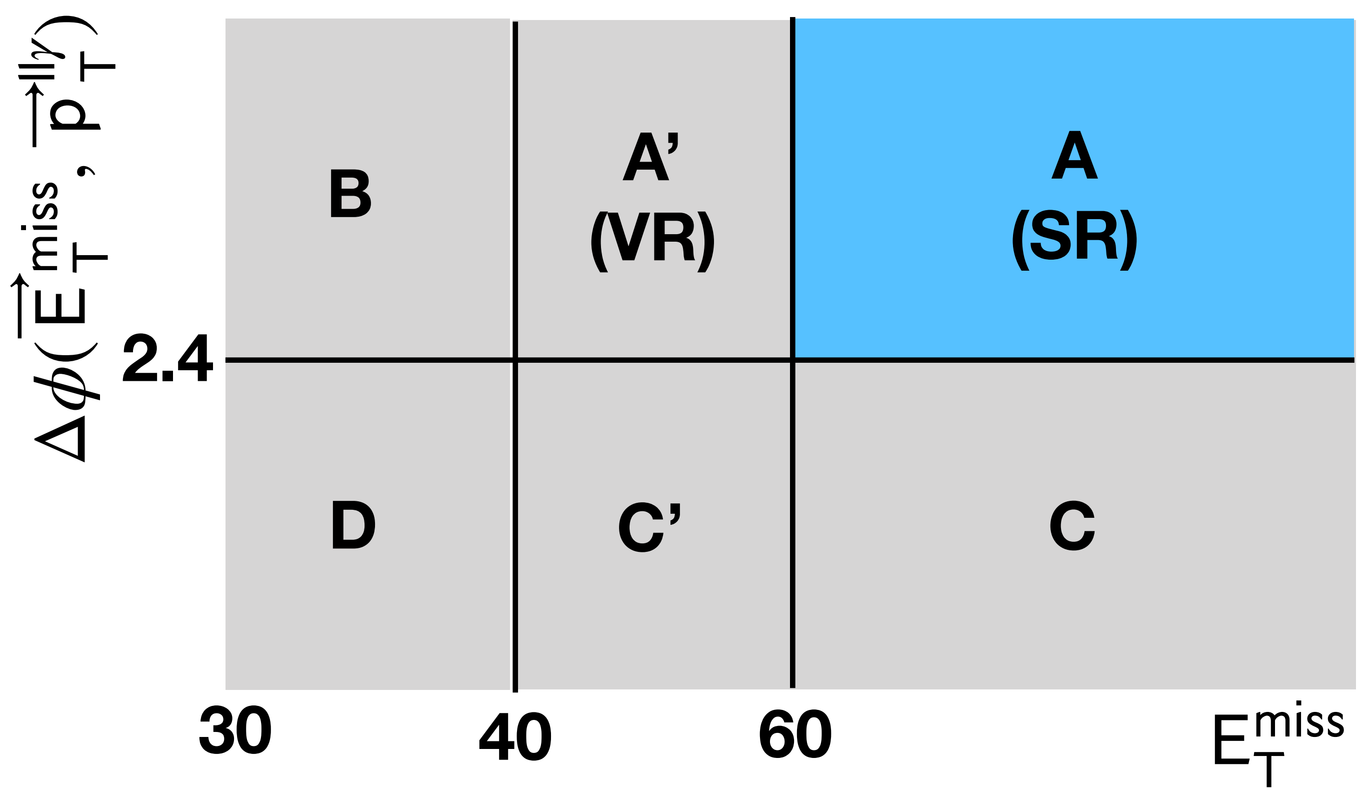

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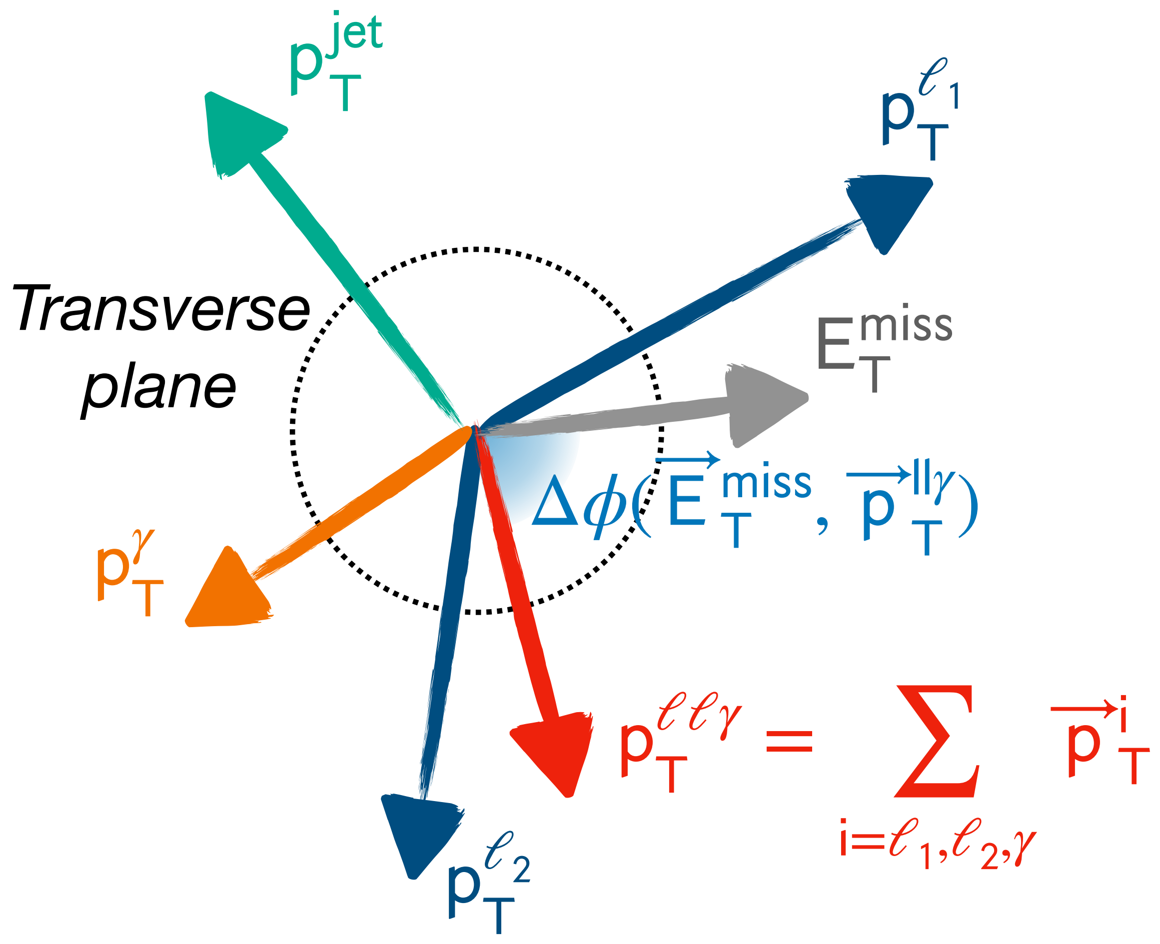

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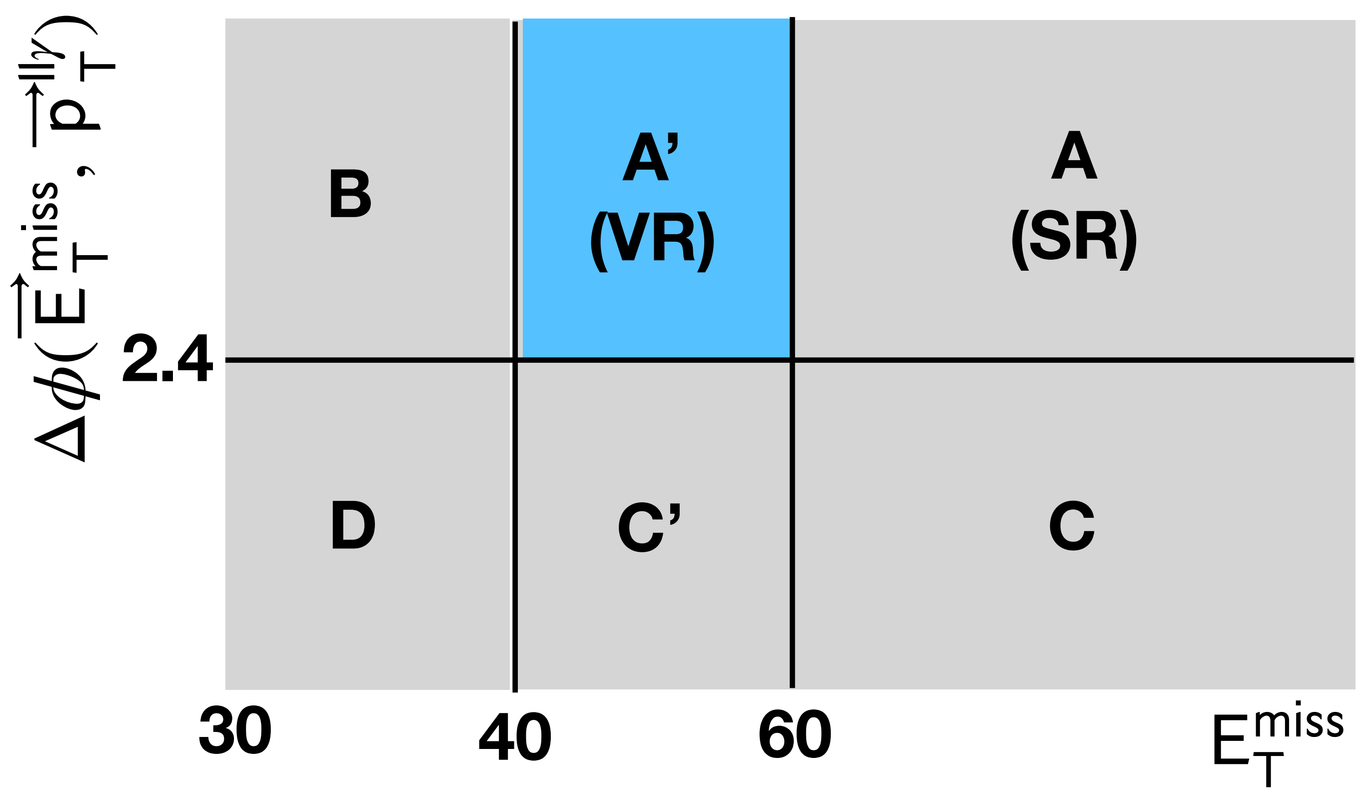
- Uncertainties: uncertainty on the fake-rate, statistics in probe-e CR, 100% uncertainty on $jet \to e$ subtraction

Validation of data-driven estimates

- Results obtained applying data-driven methods for $e \to \gamma$ and fake E_T^{miss} in the VR (A' region of the ABCD method)
- All other backgrounds from pure MC
- Statistical uncertainties only



Top and VVy backgrounds

Top VR:

- Same as SR, but at least 1 b-tagged jet, and $m_{\ell\ell}$ and $\Delta\phi(E_T^{miss}, ll\gamma)$ cuts removed to increase statistics
- 20% discrepancy between data and MC expectations included as a systematic uncertainty (subdominant background)

VVy CR:

- Same as SR, but with 3 muons and a photon, and removing $\Delta\phi(E_T^{miss}, ll\gamma)$ and E_T^{miss} cuts to increase statistics
- 3 muon-CR chosen to avoid high contamination from $e \rightarrow \gamma$ or contribution from $jet \rightarrow e$
- Due to poor statistics, CR included in the fit as a single-bin CR

Good data/background agreement observed in for the BDT input variables in both the top-VR and VVy-CR

Statistical analysis

- Binned maximum likelihood fit in SR + VVy CR on BDT score distributions
- Method validated in VR, and in low BDT SR (BDT < 0.5)

Free parameters

$[\mathrm{BR}(H \rightarrow \gamma\gamma_d), k_{VV\gamma}]$

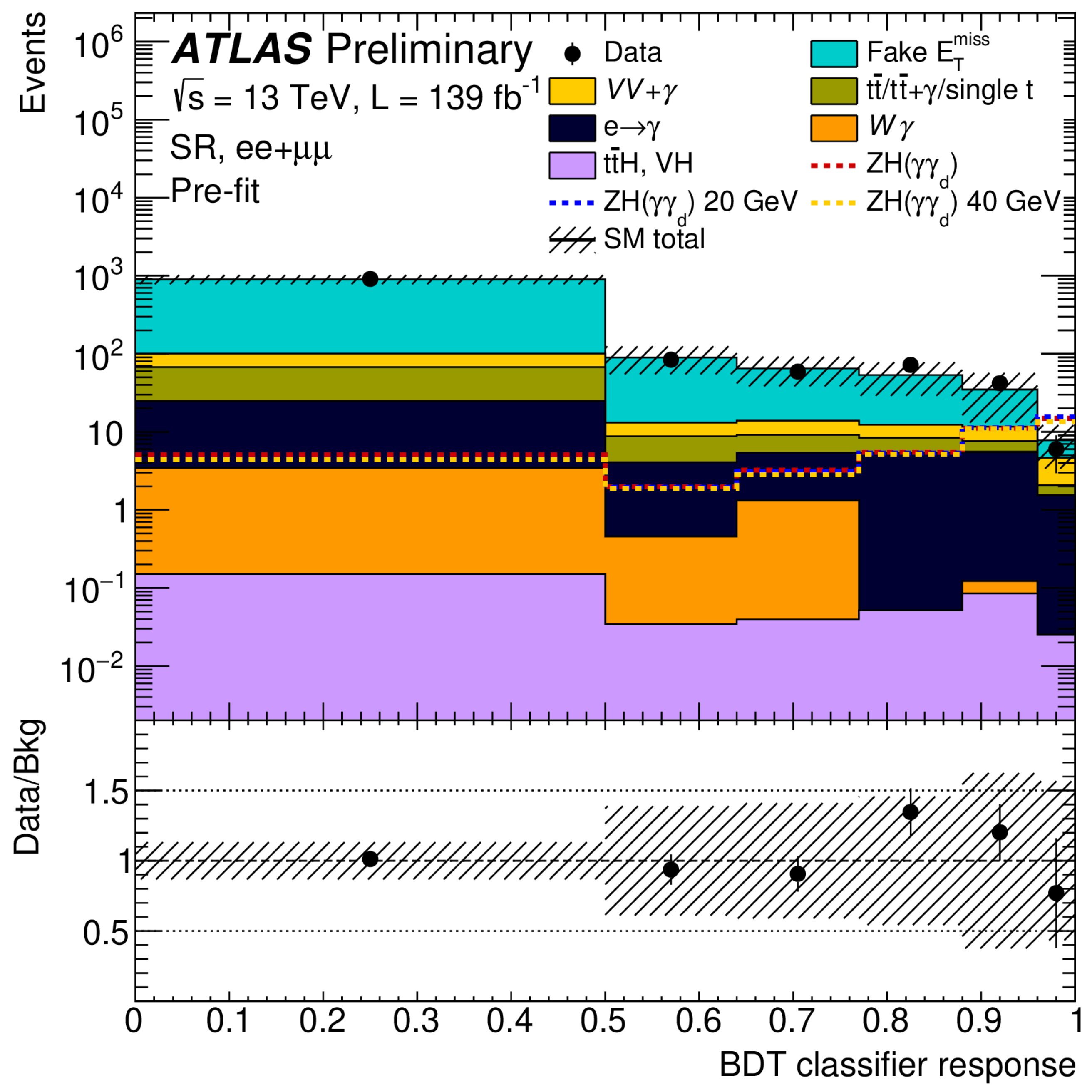
Constraint of systematics NPs: $G(x\,|\,0,1)$: gaussian with $\mu = 0$ and and $\sigma = 1$

$$\mathscr{L}(\text{data}\,|\,\mathbf{k}, \theta) = \prod_{i \in \{\text{BDT bins+CR}\}} \mathrm{Pois}(N_i^{\text{data}}\,|\,N_i^{\text{exp}}(\mathbf{k}, \theta)) \times \prod_{j \in \{\text{syst}\}} G(\theta_j\,|\,0,1)$$

$$N_i^{\text{exp}}(\boldsymbol{k}, \boldsymbol{\theta}) \propto \mathrm{BR}(H \rightarrow \gamma\gamma_d) N_i^{\text{sig}}(\boldsymbol{\theta}) + k_{VV\gamma} N_i^{VV\gamma}(\boldsymbol{\theta}) + \sum_{\text{bkg} \neq VV\gamma} N_i^{\text{bkg}}(\boldsymbol{\theta})$$

$$N_i^{\text{sig/bkg}}(\theta_j) = n_i^{\text{sig/bkg}} \times (1 + \theta_j \Delta_j)$$

with Δ_j the value of the j systematic uncertainty and $n_i^{\text{sig/bkg}}$ the central value

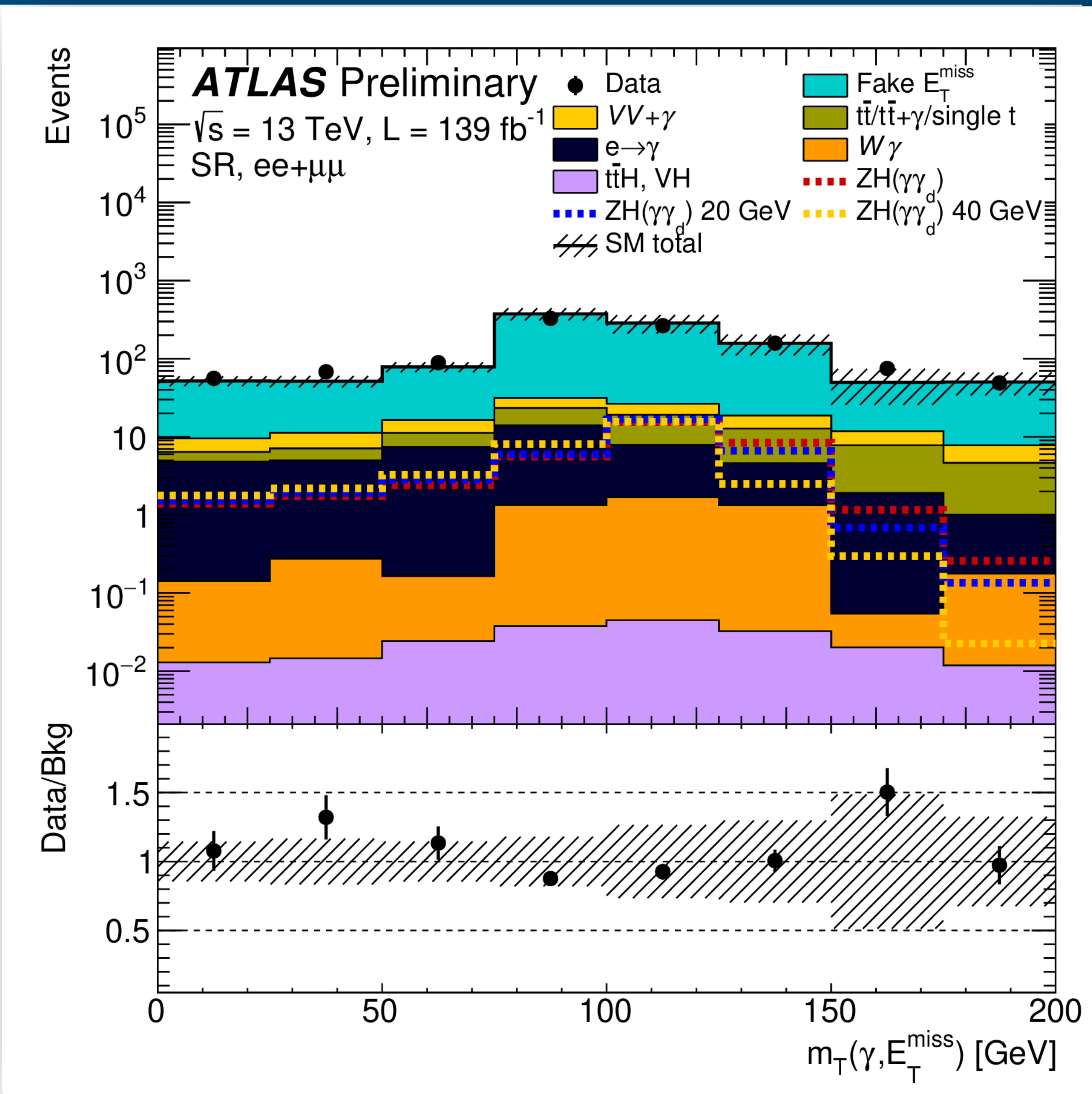


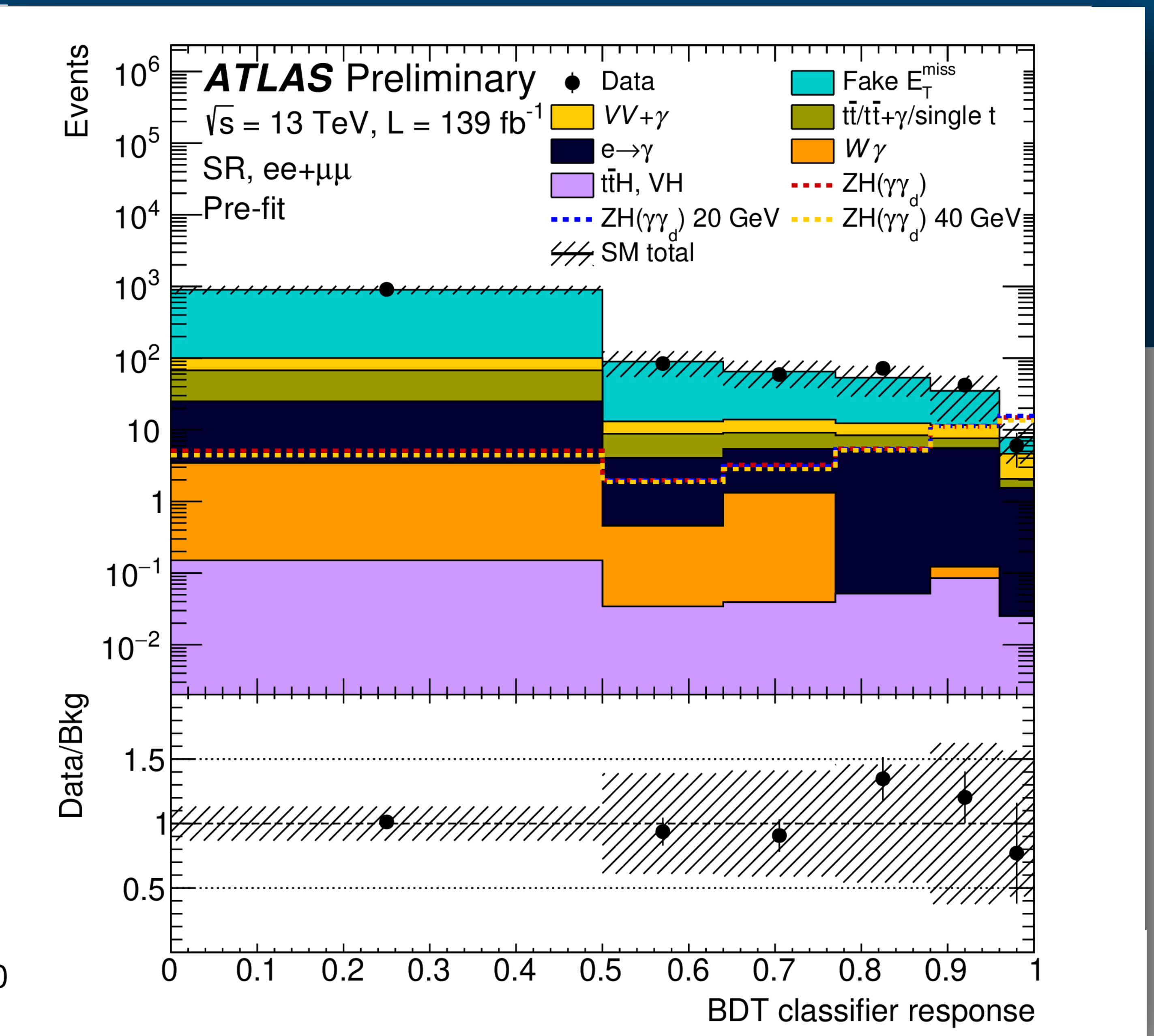
6 background templates + signal

- **Fake MET:** BDT shape from MC rescaled by data-driven estimate
- **VVy** : MC normalized to data in CR ($k_{VV\gamma}$)
- **Top**: pure MC
- **e→y** : BDT shape from data in probe-e CR rescaled by fake-rate
- **Wy** and **Higgs**: pure MC
- Signal: POI = $\mathrm{BR}(H \rightarrow \gamma\gamma_d)$

Background-only fit

- Good data/background agreement already before fit
- Binned maximum-likelihood fit on SR+CR, assuming no signal

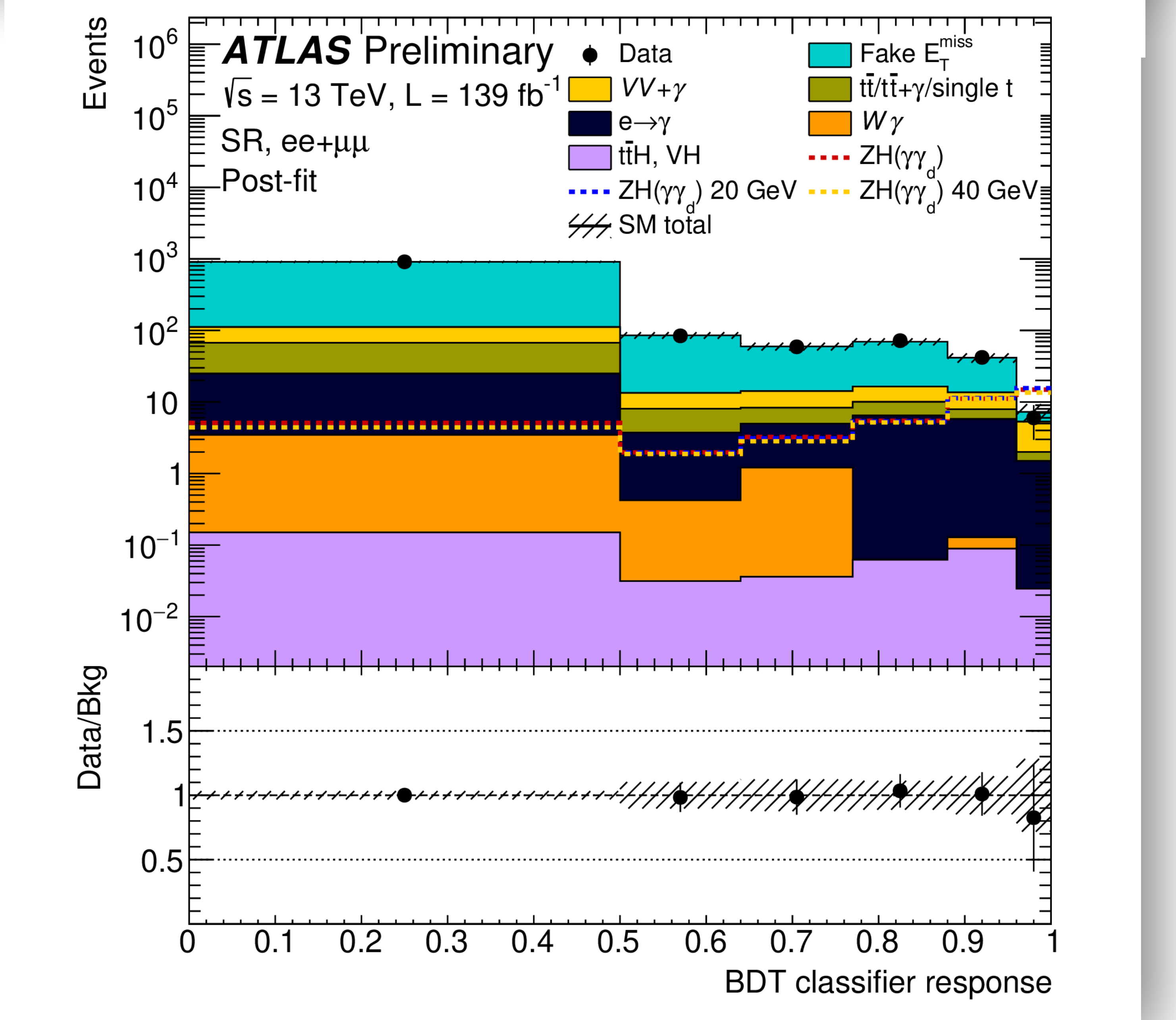




- Analysis dominated by statistical uncertainties

BDT bin	0 - 0.50	0.50 - 0.64	0.64 - 0.77	0.77- 0.88	0.88 - 0.96	0.96 - 1
Total(statistical+systematic) uncertainty	3.1%	10%	12%	11%	15%	28%
Statistical uncertainty	3.1%	9.9%	12%	11%	14%	16%

In last BDT bin, main systematic contributions from fake E_T^{miss} background modelling ($\sim 21\,\%$) and muons/electrons/photons/jets energy scale and resolution (ranging from $\sim 4\,\%$ to $\sim 16\,\%$)

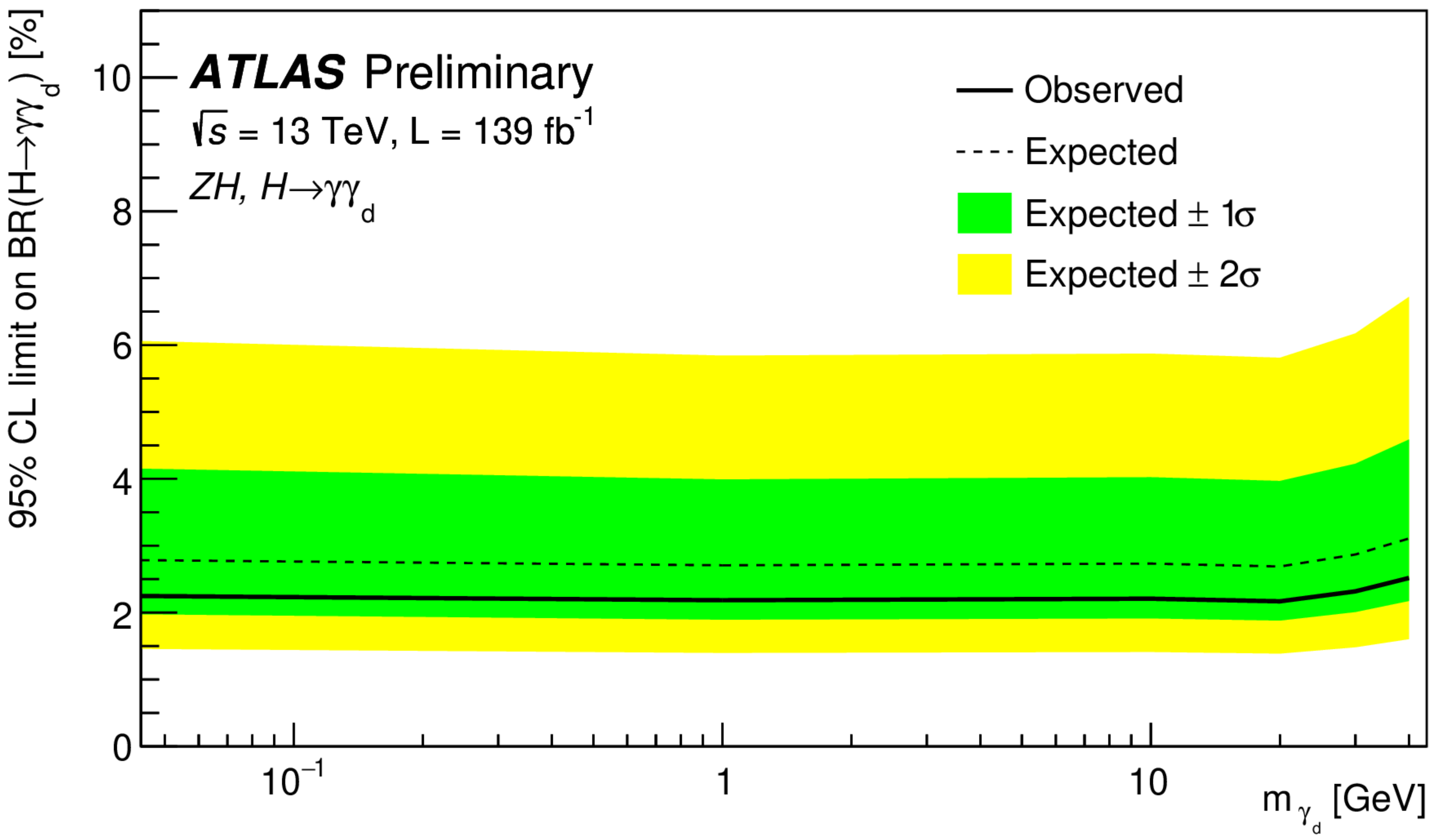


- No excess wrt SM expectations observed → exclusion limits can be set

Exclusion limit

- Binned maximum-likelihood fit on SR+CR, with BR($H \rightarrow \gamma\gamma_D$) as POI
- CLs scan to derive the 95% CL upper limit
- The exclusion limits are provided on the BR($H \rightarrow \gamma\gamma_D$), assuming the SM Higgs boson gg/qq ZH production cross section

m_{γ_d} [GeV]	$BR(H \to \gamma\gamma_d)^{95}_{obs}$	$BR(H \to \gamma\gamma_d)^{95}_{exp}$
0	2.28	$2.82^{+1.33}_{-0.84}$
1	2.19	$2.71^{+1.28}_{-0.81}$
10	2.21	$2.73^{+1.31}_{-0.82}$
20	2.17	$2.69^{+1.29}_{-0.81}$
30	2.32	$2.87^{+1.36}_{-0.86}$
40	2.52	$3.11^{+1.48}_{-0.93}$



For massless γ_d

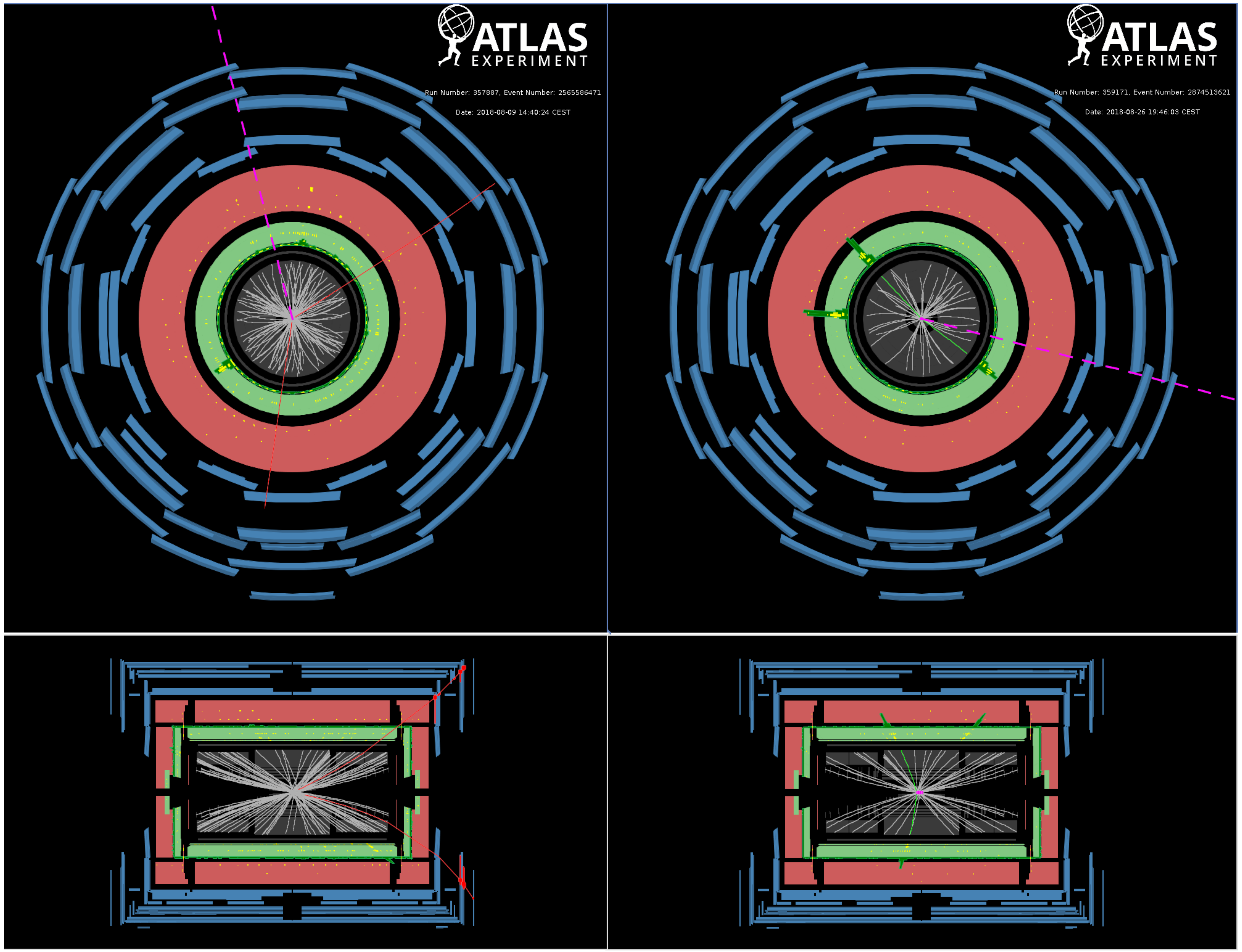
		Obs.	Exp.	
CMS	**VBF**	3.5%	2.8%	JHEP03(2021)011
CMS	**ZH**	4.6%	3.6%	JHEP10(2019)139
ATLAS	**VBF**	1.8%	1.7%	CERN-EP-2021-137
ATLAS	**ZH**	2.3%	2.8%	ATLAS-CONF-2022-064

Conclusions

- Search for dark photon in the $ZH, H \rightarrow \gamma\gamma_D$ process, using full Run 2 dataset
- New analysis in ATLAS
- No excess observed and 95% CL exclusion limits set on the $BR(H \rightarrow \gamma\gamma_D)$, for dark photon masses up to 40 GeV

For massless γ_d

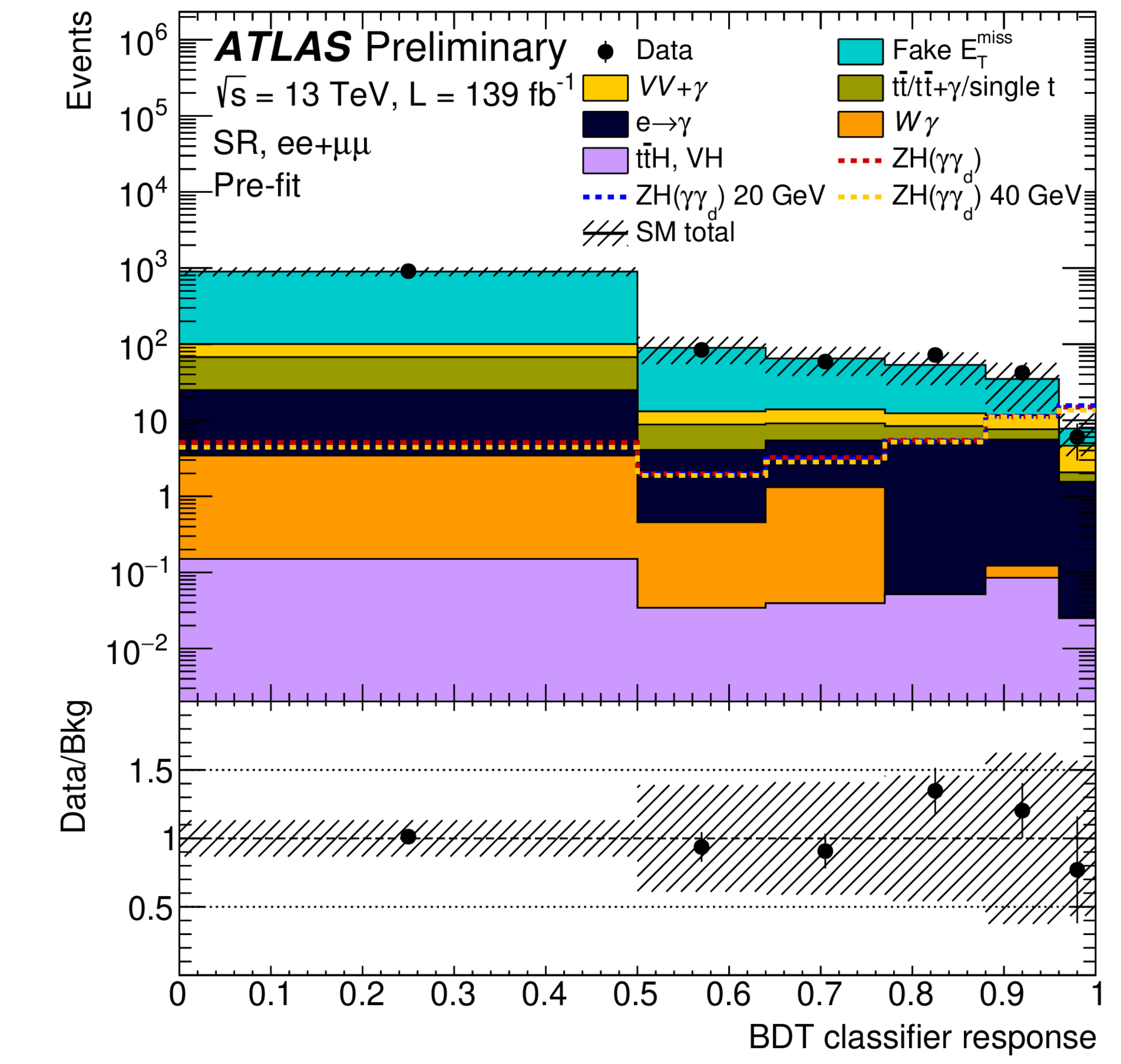
		Obs.	Exp.
CMS	**VBF**	3.5%	2.8%
CMS	**ZH**	4.6%	3.6%
ATLAS	**VBF**	1.8%	1.7%
ATLAS	**ZH**	2.3%	2.8%

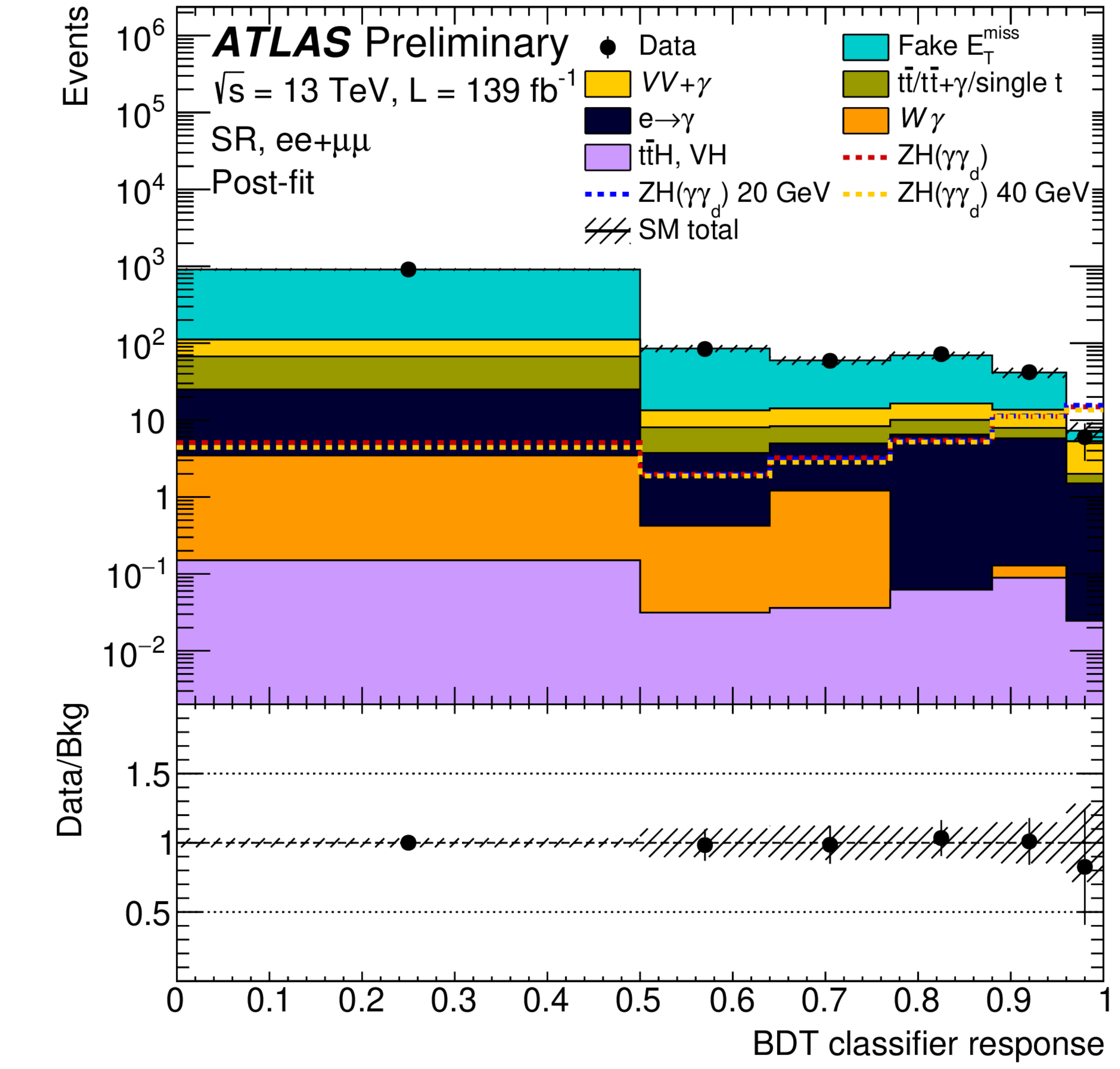


Background-only fit

$k_{VV\gamma} = 1.35 \pm 0.38$

BDT bin	SR 0 - 0.50	SR 0.50 - 0.64	SR 0.64 - 0.77	SR 0.77 - 0.88	SR 0.88 - 0.96	SR 0.96 - 1	CR 0 - 1
Observed	910	84	59	72	42	6	32
Exptected SM background	910 ± 29	85.5 ± 8.7	59.9 ± 7.3	69.7 ± 7.8	41.6 ± 6.1	7.3 ± 2.0	31.4 ± 5.4
Fake E_T^{miss}	800 ± 34	72.1 ± 8.3	45.7 ± 6.5	53.2 ± 7.1	27.9 ± 6.1	2.0 ± 1.9	$2.1^{+3.5}_{-2.1}$
$e \to \gamma$	21.5 ± 2.4	3.33 ± 0.65	3.75 ± 0.77	6.4 ± 1.2	5.7 ± 1.5	1.47 ± 0.26	1.24 ± 0.07
$VV\gamma$	44 ± 12	5.3 ± 1.6	5.8 ± 1.7	6.4 ± 1.8	5.7 ± 1.9	3.30 ± 0.97	27.3 ± 6.4
$t\bar{t}$, $t\bar{t}\gamma$, single t	42 ± 15	4.3 ± 1.5	3.4 ± 1.2	3.6 ± 1.2	2.13 ± 0.80	0.50 ± 0.18	0.63 ± 0.22
$W\gamma$	3.3 ± 1.5	0.39 ± 0.18	1.18 ± 0.55	–	0.04 ± 0.02	–	–
$t\bar{t}H,\ VH$	0.15 ± 0.02	0.03 ± 0.01	0.04 ± 0.01	0.06 ± 0.01	0.09 ± 0.03	0.02 ± 0.01	$0.17^{+0.18}_{-0.17}$
Pre-fit background	900 ± 120	90 ± 35	65 ± 27	53 ± 24	35 ± 22	7.8 ± 4.4	24 ± 4.7
Pre-fit Fake E_T^{miss}	800 ± 110	77 ± 33	51 ± 23	41 ± 21	23 ± 19	$3.2^{+4.0}_{-3.2}$	$1.8^{+3.2}_{-1.8}$
Pre-fit $e \to \gamma$	21.4 ± 2.6	3.62 ± 0.89	4.1 ± 1.3	5.3 ± 1.8	5.4 ± 1.9	1.52 ± 0.27	1.24 ± 0.07
Pre-fit $VV\gamma$	32.7 ± 6.8	4.3 ± 1.2	4.8 ± 1.7	3.9 ± 1.5	4.1 ± 1.6	2.56 ± 0.65	20.21 ± 3.29
Pre-fit $t\bar{t}$, $t\bar{t}\gamma$, single t	43 ± 17	4.7 ± 1.9	3.7 ± 1.7	3.0 ± 1.4	2.0 ± 1.0	0.52 ± 0.22	0.65 ± 0.23
Pre-fit $W\gamma$	3.3 ± 1.5	0.42 ± 0.21	1.28 ± 0.69	–	0.04 ± 0.02	–	–
Pre-fit $t\bar{t}H,\ VH$	0.15 ± 0.03	0.03 ± 0.01	0.04 ± 0.01	0.05 ± 0.02	0.08 ± 0.03	0.03 ± 0.01	$0.15^{+0.18}_{-0.15}$

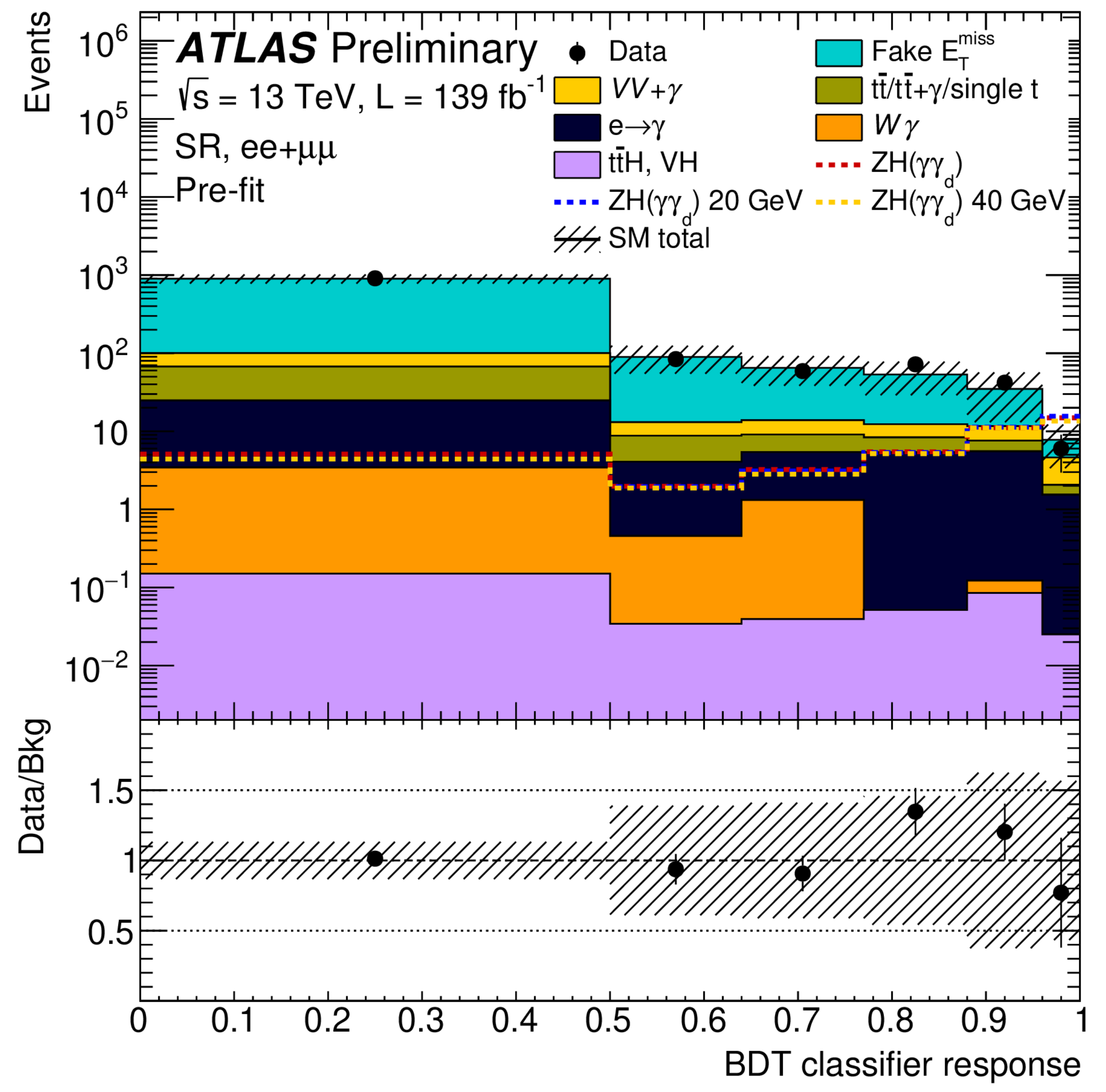


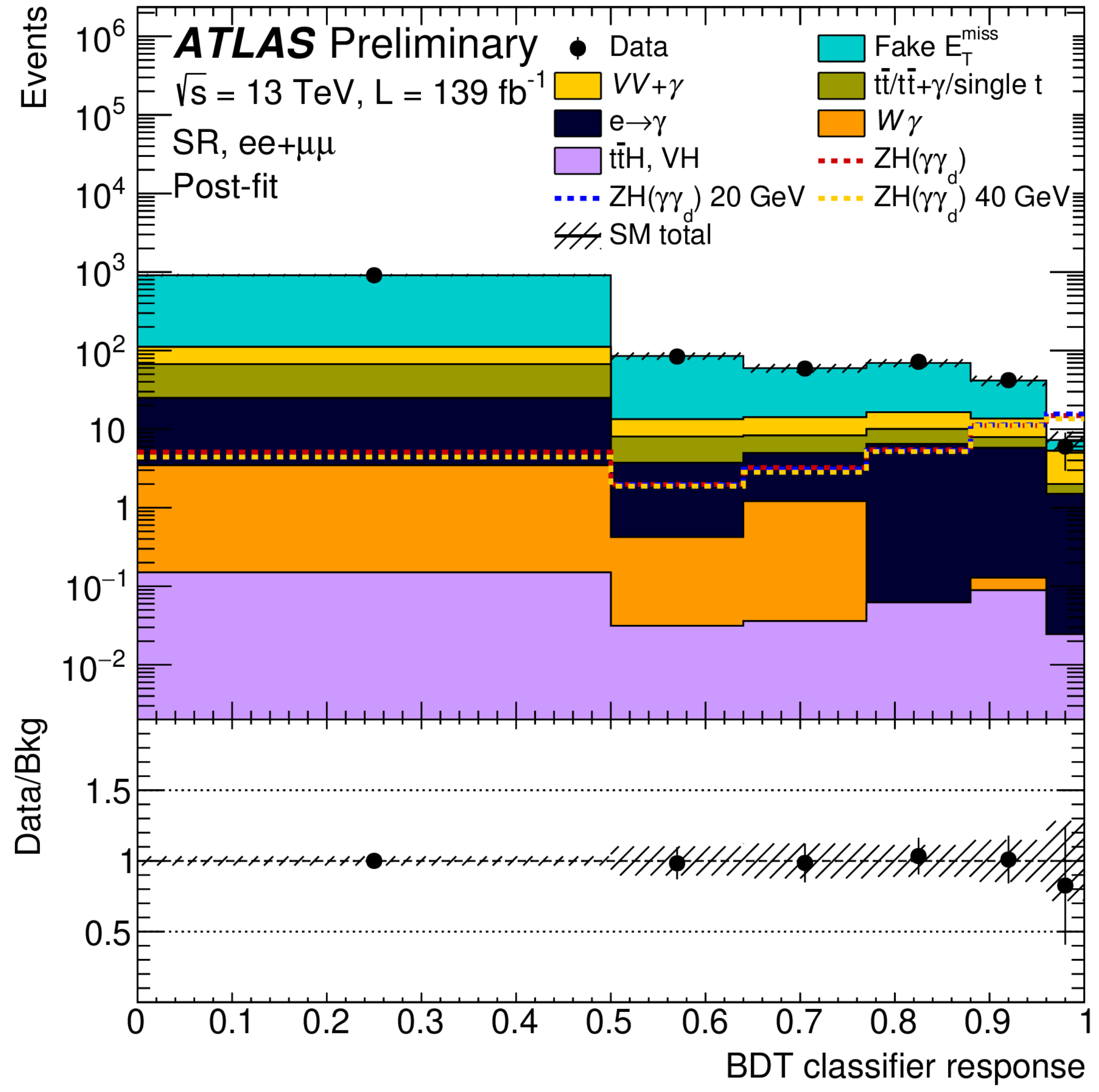


Background-only fit: post-fit uncertainties

Impact of grouped systematic uncertainties evaluated as the impact, on background yields, of refitting with the set of NPs associated to the systematics of interest set to constant values $\pm 1\sigma$

BDT bin	0 - 0.50	0.50 - 0.64	0.64 - 0.77	0.77- 0.88	0.88 - 0.96	0.96 - 1
Total(statistical+systematic) uncertainty	3.1%	10%	12%	11%	15%	28%
Statistical uncertainty	3.1%	9.9%	12%	11%	14%	16%
Fake $E_{\mathrm{T}}^{\mathrm{miss}}$ shape	0.17%	1.2%	0.15%	0.76%	2.4%	21%
Jet E scale and resolution	0.09%	4.3%	2.6%	1.1%	0.65%	16%
Electron, photon E scale and resolution	0.04%	0.60%	1.0%	0.21%	1.7%	7.4%
Muon E scale and resolution	0.08%	0.10%	0.28%	0.67%	1.3%	4.2%
Fake $E_{\mathrm{T}}^{\mathrm{miss}}$ data-driven	0.52%	0.29%	0.04%	0.04%	0.29%	3.3%
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale and resolution	0.27%	0.10%	0.50%	0.35%	0.33%	0.85%
Top normalization	0.07%	0.09%	0.14%	0.13%	0.07%	0.42%
Electrons faking photons data-driven	0.03%	0.10%	0.12%	0.12%	0.06%	0.34%
Reweighting of $\langle\mu\rangle$ in MC simulation	0.07%	0.09%	0.28%	0.33%	0.20%	0.23%
Flavour tagging eff.	0.02%	0.15%	0.13%	0.11%	0.07%	0.20%
Photon ID/iso/reco eff.	0.00%	0.10%	0.12%	0.11%	0.08%	0.17%
Muon trigger/ID/iso/reco eff.	0.01%	0.15%	0.10%	0.06%	0.07%	0.16%
Electron trigger/ID/iso/reco eff.	0.01%	0.18%	0.09%	0.13%	0.11%	0.15%
Theoretical top	0.09%	0.04%	0.03%	0.17%	0.17%	0.46%
Theoretical $W\gamma$	0.03%	0.13%	0.10%	0.15%	0.09%	0.44%
Theoretical $VV\gamma$	0.03%	0.10%	0.12%	0.08%	0.08%	0.35%
Theoretical Higgs	0.01%	0.10%	0.14%	0.08%	0.07%	0.22%
Theoretical fake $E_{\mathrm{T}}^{\mathrm{miss}}$	0.06%	0.13%	0.15%	0.28%	0.36%	0.31%





MC samples

Process	Generator	ME Order	PDF	Parton Shower	Tune
		Signal samples			
$ZH, H \rightarrow \gamma\gamma_d$	Powheg Box v2	NLO	NNPDF3.0nlo	Pythia 8.245	AZNLO
		SM background samples			
$V\gamma^{QCD}$	Sherpa v2.2.8	NLO (up to 2 jets), LO (up to 3 jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
$V\gamma^{EWK}$	MadGraph5_aMC@NLO [v2.6.5]	LO	NNPDF2.3lo	Pythia 8.240	A14
Z^{QCD}	Sherpa v2.2.1	NLO (up to 2 jets), LO (up to 4 jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
Z^{EWK}	Sherpa v2.2.1	NLO (up to 2 jets), LO (up to 4 jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
Single t-quark/$t\bar{t}$	Powheg Box v2	NLO	NNPDF2.3lo	Pythia 8.230	A14
$t\bar{t}\,(V, VV)$, $Wt\gamma$	MadGraph5_aMC@NLO [v2.2.3]	NLO	NNPDF2.3lo	Pythia 8.210	A14
SM Higgs	Powheg Box v2	NNLO	PDF4LHC15	Pythia 8.230	AZNLO
$VV\gamma$	Sherpa v2.2.11	NLO (0 jets), LO (up to 3 jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
VV/VVV	Sherpa v2.2.2	NLO (0 jets), LO (up to 3 jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa

Trigger & overlap removal

Period	Electron	Muon
Single-lepton		
2015	$p_T > 24, 60, 120$ GeV	$p_T > 20, 50$ GeV
2016-2018	$p_T > 26, 60, 140$ GeV	$p_T > 26, 50$ GeV
Di-lepton		
2015	$p_T^1, p_T^2 > 12$ GeV	$p_T^1 > 18$ GeV, $p_T^2 > 8$ GeV $p_T^1, p_T^2 > 10$ GeV
2016, 2018	$p_T^1, p_T^2 > 17$ GeV	$p_T^1 > 22$ GeV, $p_T^2 > 8$ GeV $p_T^1, p_T^2 > 14$ GeV
2017, 2018	$p_T^1, p_T^2 > 24$ GeV	$p_T^1 > 22$ GeV, $p_T^2 > 8$ GeV $p_T^1, p_T^2 > 14$ GeV

Remove	Keep	Matching criteria
jet	electron	$\Delta R < 0.2$
jet	muon	number of tracks < 3 and $\Delta R < 0.2$
jet	photon	$\Delta R < 0.4$
electron	jet	$0.2 < \Delta R < 0.4$
electron	muon	shared same ID track
electron	electron	shared same ID track, electron with lower p_T removed
muon	jet	$0.2 < \Delta R < 0.4$
muon	electron	muon with calorimeter deposits and shared ID track
photon	electron	$\Delta R < 0.4$
photon	muon	$\Delta R < 0.4$

Cutflow

Channel	ee		$\mu\mu$	
Selection	Yields	$\epsilon \times A$ [%]	Yields	$\epsilon \times A$ [%]
Filter efficiency	396.3	100	396.3	100
Preselections	101.1 ± 0.5	25.5	101.1 ± 0.5	25.5
Trigger	100.7 ± 0.5	25.4	100.7 ± 0.5	25.4
ee or $\mu\mu$ channel	38.0 ± 0.3	9.6	45.3 ± 0.3	11.4
Veto extra photons	37.9 ± 0.3	9.6	45.2 ± 0.3	11.4
Veto extra leptons	37.8 ± 0.3	9.5	45.2 ± 0.3	11.4
Leading lepton p_T	37.8 ± 0.3	9.5	45.2 ± 0.3	11.4
Photon p_T	36.8 ± 0.3	9.3	44.1 ± 0.3	11.1
E_T^{miss}	22.6 ± 0.2	5.7	26.5 ± 0.3	6.7
m_{ll}	21.7 ± 0.2	5.5	25.2 ± 0.2	6.3
$m_{ll\gamma}$	21.7 ± 0.2	5.5	25.1 ± 0.2	6.3
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\,\ell\ell\gamma})$	19.3 ± 0.2	4.9	22.4 ± 0.2	5.7

BDT

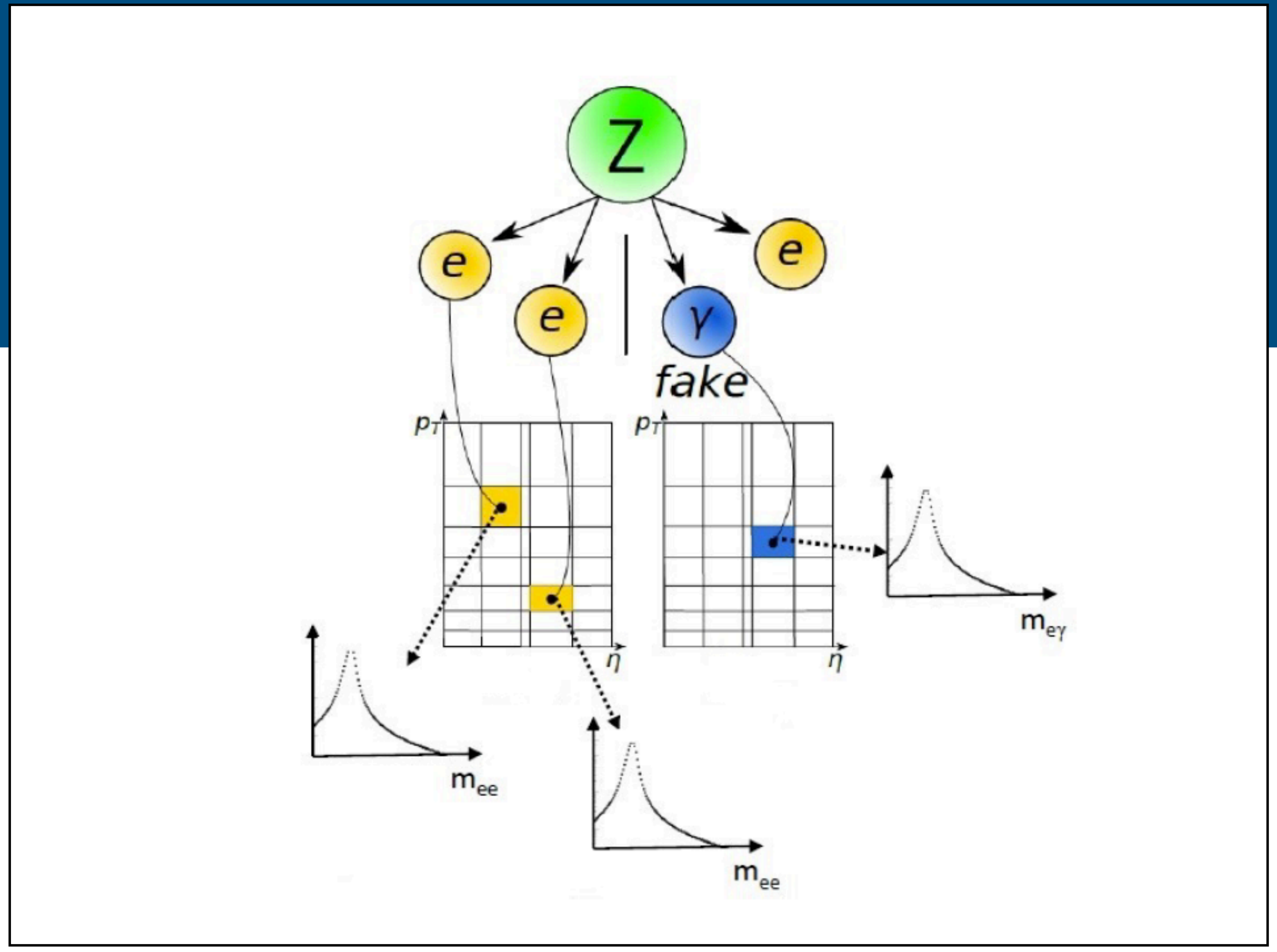
- Boosted Decision Tree (BDT) with XGBoost classifier:
  - Input variables in order of importance (no gain from including more variables)
    - $m_T(\gamma, E_T^{miss})$,
    - photon $p_{T,}$
    - $m_{ll\gamma,}$
    - $m_{ll},$
    - $\frac{|\vec{E}_T^{miss} + \vec{p}_T^{\gamma}| - p_T^{ll}}{p_T^{ll}},$
    - E_T^{miss} significance
  - Optimization of BDT hyperparameters based on Randomized + Grid search
  - 5-fold cross-validation (SKLearn::StratifiedKFold)

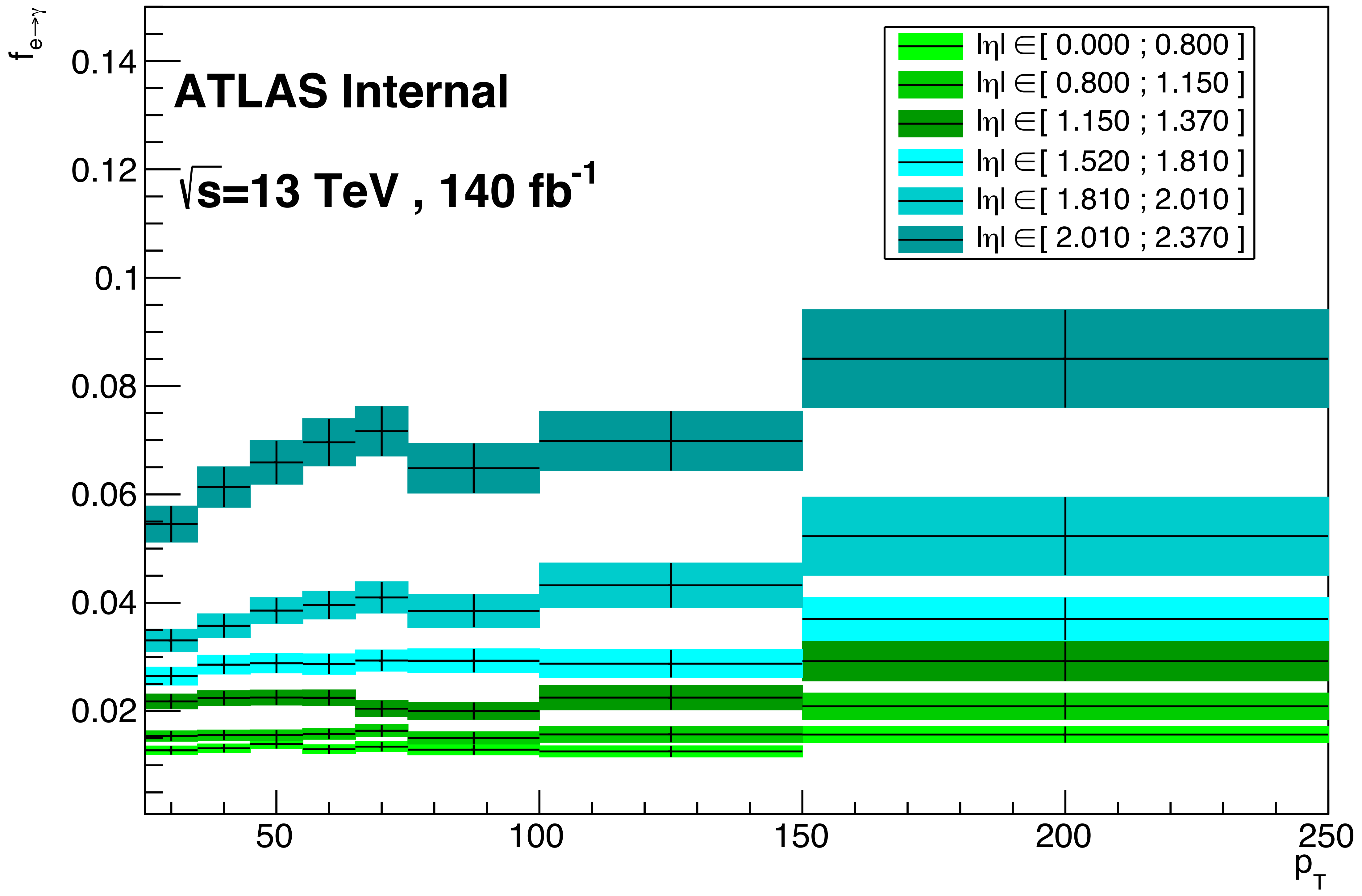
$$m_T = \sqrt{2E_T^{miss} p_T^{\gamma} [1 - \cos[\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{\gamma})]]}$$

- Kolmogorov-Smirnov test implemented: no overtraining observed
- BDT results consistent among different dark-photon masses

$e \rightarrow \gamma$ background

- Fake rate $F_{e\rightarrow\gamma} = \frac{N_{e\gamma}}{N_{ee}}$
  - obtained from signal+bkg fit in invariant mass using a Z(ee) data sample
  - Bkg modelled by DSCB+exp(pol3)





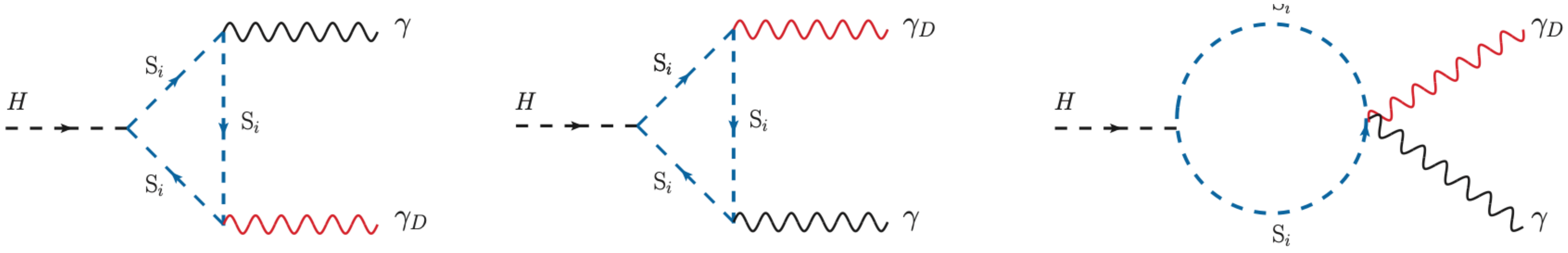
Uncertainties:

- For each N_Z, uncertainty to account for impact of "bad" fits: $\sigma_{fit} = |\Delta N_{peak}| - |\sigma_{N^{hist}_{peak}}|$ with $\Delta N_{peak} = N^{fit}_{peak} - N^{hist}_{peak}$
- Assign $\sigma_{N_Z} = \sqrt{\sigma^2_{fit} + N_Z}$ and propagate it to fake-rate
- Add in quadrature uncertainty from closure with MC:
  - $\delta^{rel}_{MC} = \frac{f^{truth}_{e\rightarrow\gamma}}{f^{fit}_{e\rightarrow\gamma}} - 1$ from MC
  - $\sigma^{rel}_{glob} = \sqrt{\langle(\delta^{MC}_{rel})^2\rangle}$

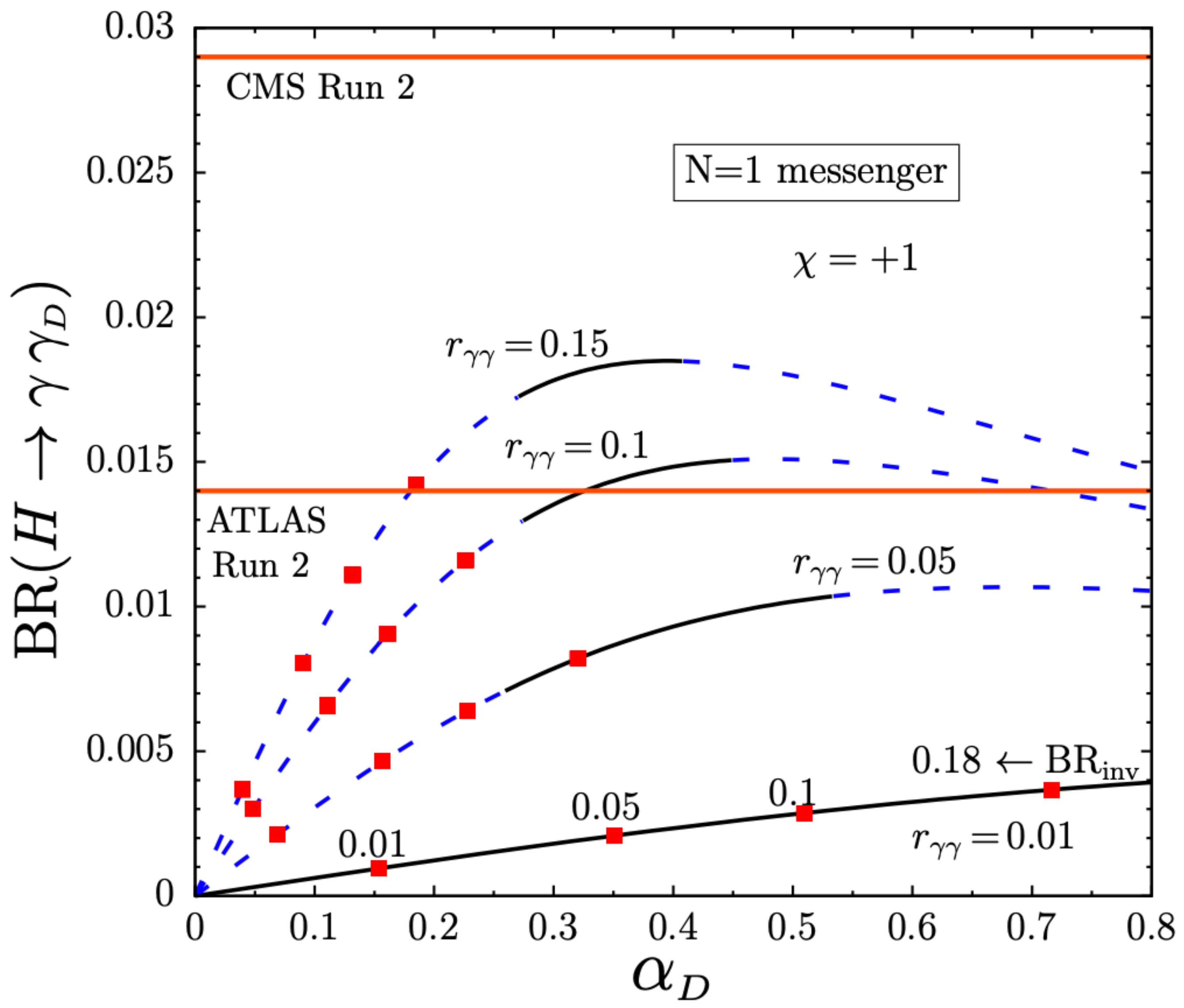
$$\mathcal{L}^{I}_{MS} = \lambda_S S_0 \left(\tilde{H}^\dagger S^U_L S^U_R + H^\dagger S^D_L S^D_R\right) + h.c.,$$

$$\Gamma(H \to \gamma\gamma_D) = \frac{m_H^3}{32\,\pi\,\Lambda^2_{\gamma\gamma_D}}$$

$$\Lambda_{\gamma\gamma_D} = \frac{6\pi v}{R\sqrt{\alpha\alpha_D}}\,\frac{1-\xi^2}{\xi^2}$$



=> Non-decoupling nature of $H \to \gamma\gamma_d$ => loop diagrams not suppressed by mass scales of messenger fields



$$r_{ij} \equiv \frac{\Gamma^{m}_{ij}}{\Gamma^{SM}_{\gamma\gamma}}$$

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

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

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

Figure 2: Predictions for $\mathrm{BR}(H \to \gamma\gamma_D)$ versus α_D for different $\mathrm{BR}_{\mathrm{inv}}$ and $r_{\gamma\gamma}$, for the minimal model of 1 (colorless) messenger with unit charges $e = q = 1$, and interference coefficient $\chi = +1$. Continuous (dashed) curves are allowed (excluded) by the $\mathrm{BR}(H \to \gamma\gamma)$ measurement at 2σ level. Horizontal lines indicate the corresponding ATLAS and CMS upper limits on $\mathrm{BR}(H \to \gamma\gamma_D)$ at 95% CL.

VBF+y+MET

Process	SR - $m_{jj} < 1$ TeV m_T [GeV]					SR - $m_{jj} \geq 1$ TeV m_T [GeV]				
	0-90	90-130	130-200	200-350	≥ 350	0-90	90-130	130-200	200-350	≥ 350
Strong $Z\gamma$ + jets	29 ± 7	30 ± 7	29 ± 7	22 ± 5	5 ± 1	6 ± 2	6 ± 2	7 ± 2	4 ± 1	2 ± 1
EW $Z\gamma$ + jets	10 ± 2	9 ± 1	14 ± 2	12 ± 2	4 ± 1	23 ± 3	14 ± 2	25 ± 3	20 ± 3	9 ± 2
Strong $W\gamma$ + jets	117 ± 15	22 ± 4	27 ± 5	17 ± 3	3 ± 1	34 ± 5	8 ± 1	5 ± 2	2 ± 1	2 ± 1
EW $W\gamma$ + jets	16 ± 3	4 ± 1	4 ± 1	2.1 ± 0.4	0.5 ± 0.2	31 ± 5	3 ± 1	4 ± 1	3 ± 1	1.5 ± 0.3
jet$\rightarrow \gamma$	10 ± 8	3 ± 2	1 ± 1	1 ± 1	0.1 ± 0.1	3 ± 3	0.5 ± 0.5	0.6 ± 0.5	0.1 ± 0.1	0.1 ± 0.1
jet$\rightarrow e$	–	–	–	–	–	–	–	–	–	–
$e \rightarrow \gamma$	179 ± 15	20 ± 2	5 ± 1	2.8 ± 0.3	0.5 ± 0.1	76 ± 6	6 ± 1	1.4 ± 0.1	0.8 ± 0.1	0.2 ± 0.1
γ + jet	7 ± 7	6 ± 6	2 ± 2	0.2 ± 0.2	0.1 ± 0.1	2 ± 1	1 ± 1	0.4 ± 0.4	0.1 ± 0.1	0.03 ± 0.02
$t\bar{t}\gamma/V\gamma\gamma$	15 ± 2	4 ± 1	2.7 ± 0.3	2.3 ± 0.3	0.1 ± 0.1	9 ± 1	0.8 ± 0.3	0.1 ± 0.1	0.04 ± 0.09	0.03 ± 0.01
Fitted Bkg	363 ± 15	97 ± 8	84 ± 7	59 ± 5	12 ± 2	184 ± 8	40 ± 3	44 ± 3	30 ± 3	14 ± 2
VBF $H125$ ($\mathcal{B}(H \rightarrow \gamma\gamma_d) = 0.02$)	3.6 ± 0.4	8.8 ± 1.1	1.7 ± 0.2	–	–	5.7 ± 0.7	12.2 ± 1.4	2.7 ± 0.3	–	–
ggF $H125$ ($\mathcal{B}(H \rightarrow \gamma\gamma_d) = 0.02$)	1.9 ± 0.6	4.3 ± 1.3	0.8 ± 0.3	–	–	0.7 ± 0.3	1.2 ± 0.4	0.2 ± 0.1	–	–
Data	362	112	75	59	8	188	31	56	35	9
Data/Fit	1.00 ± 0.07	1.15 ± 0.14	0.89 ± 0.13	1.00 ± 0.16	0.65 ± 0.25	1.02 ± 0.09	0.78 ± 0.15	1.27 ± 0.19	1.17 ± 0.23	0.63 ± 0.23