VBF + E_T^{miss} + γ

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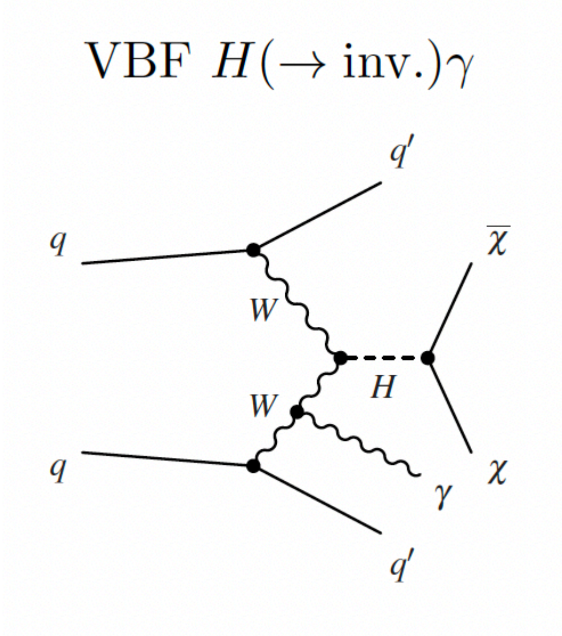
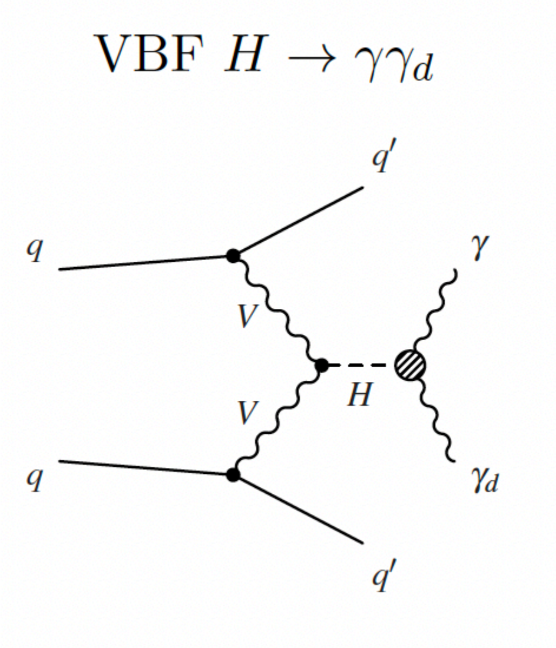
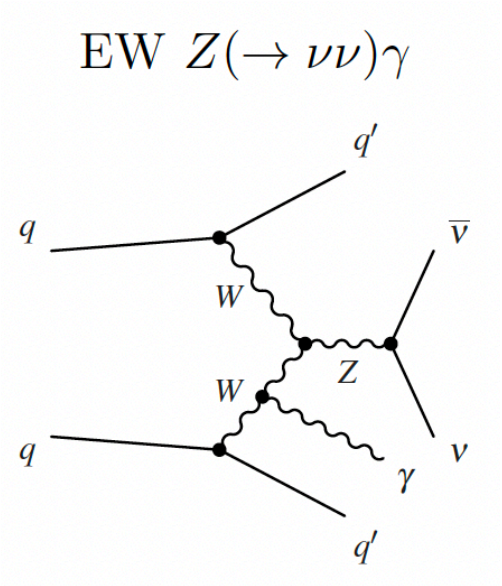
Introduction

- **Moriond Conference** : ATLAS-CONF-2021-004
- **EPJC (under review)** : arXiv:2109.00925
- **Three signal process** have the VBF+E_T^{miss}+γ final state
  - **VBF H(->invisible)γ**
    - Higgs portal of dark matter
    - First analysis of the process
  - **VBF H($\rightarrow \gamma\gamma_d$)**
    - Higgs portal of dark photon
    - First analysis ATLAS search
    - CMS publication
  - **SM EW Z($\rightarrow \nu\nu$)γ**
    - First observation > 5σ
    - One of the major backgrounds for H(->invisible)γ and H($\rightarrow \gamma\gamma_d$)

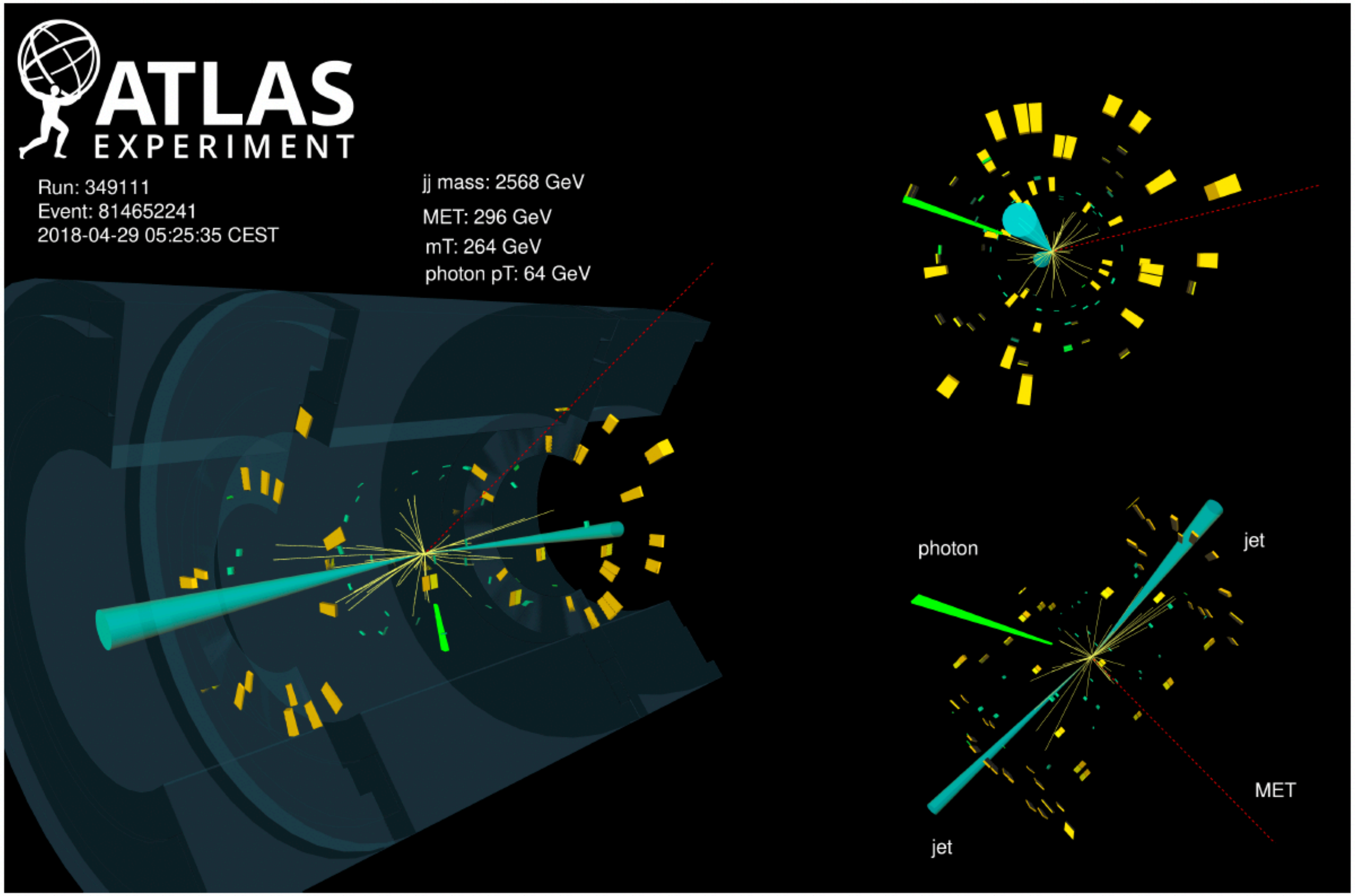






Signal Signature for VBF+E_T^{miss}+γ

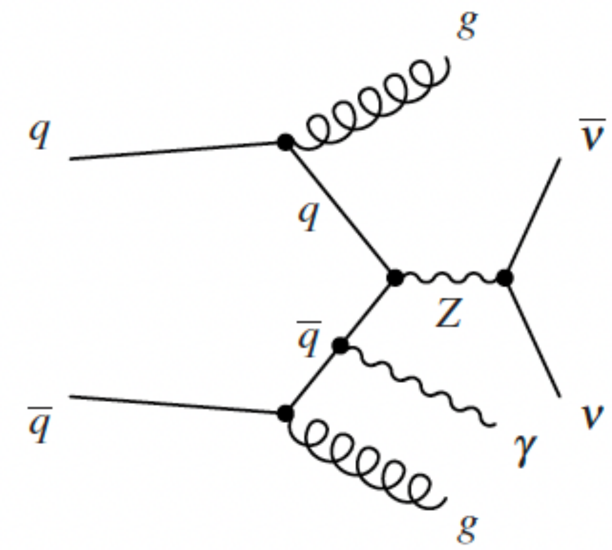
- VBF topologies
  - 2 foward jets
  - high m_{jj} (>0.25 TeV)
  - large separation in η ($\Delta\eta > 3.0$)
  - Not back to back in ϕ ($\Delta\phi < 2.5$)
- Large E_T^{miss} (>150 GeV)
- Single photon
  - high p_T ([15GeV, 110GeV])
  - centered between jets in η ($C_\gamma > 0.4$)



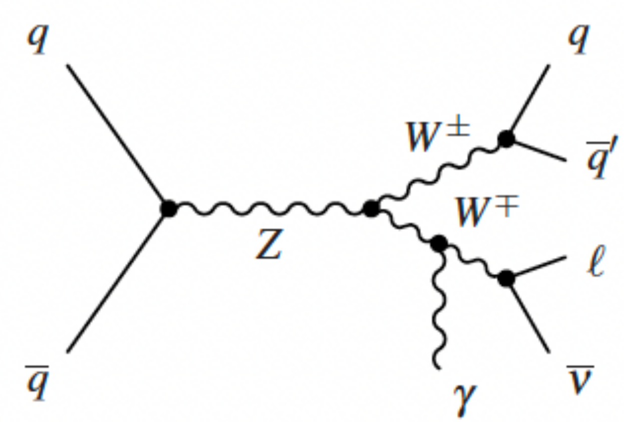
- E_T^{miss} Definition: negative vectorial sum of transverse momenta of all selected objects
- C_γ — photon centrality: $C_\gamma = \exp\left[-\frac{4}{(\eta_1-\eta_2)^2}\left(\eta_\gamma - \frac{\eta_1+\eta_2}{2}\right)^2\right]$

Backgrounds

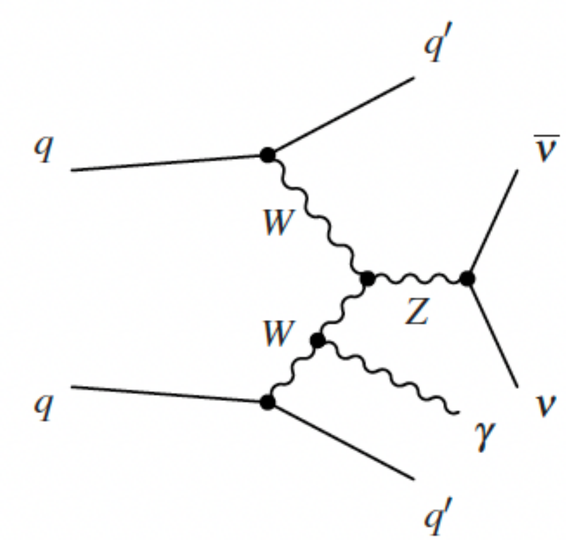
- $V\gamma$+jets (dominant)
  - $W(\to \ell\nu)\gamma$+jets and $Z(\to \nu\nu)\gamma$+jets
  - strong and EW (inc. triboson) contributions
- Other backgrounds
  - Jet faking photon (e.g. V+jets)
  - Electron faking photon (e.g. W+jets)
  - Jet faking electron (in $W^{\gamma}_{e\nu}$ CR)
  - γ+jet (QCD multijets)
  - …



Strong $Z(\to \nu\nu)\gamma + \mathrm{jets}$



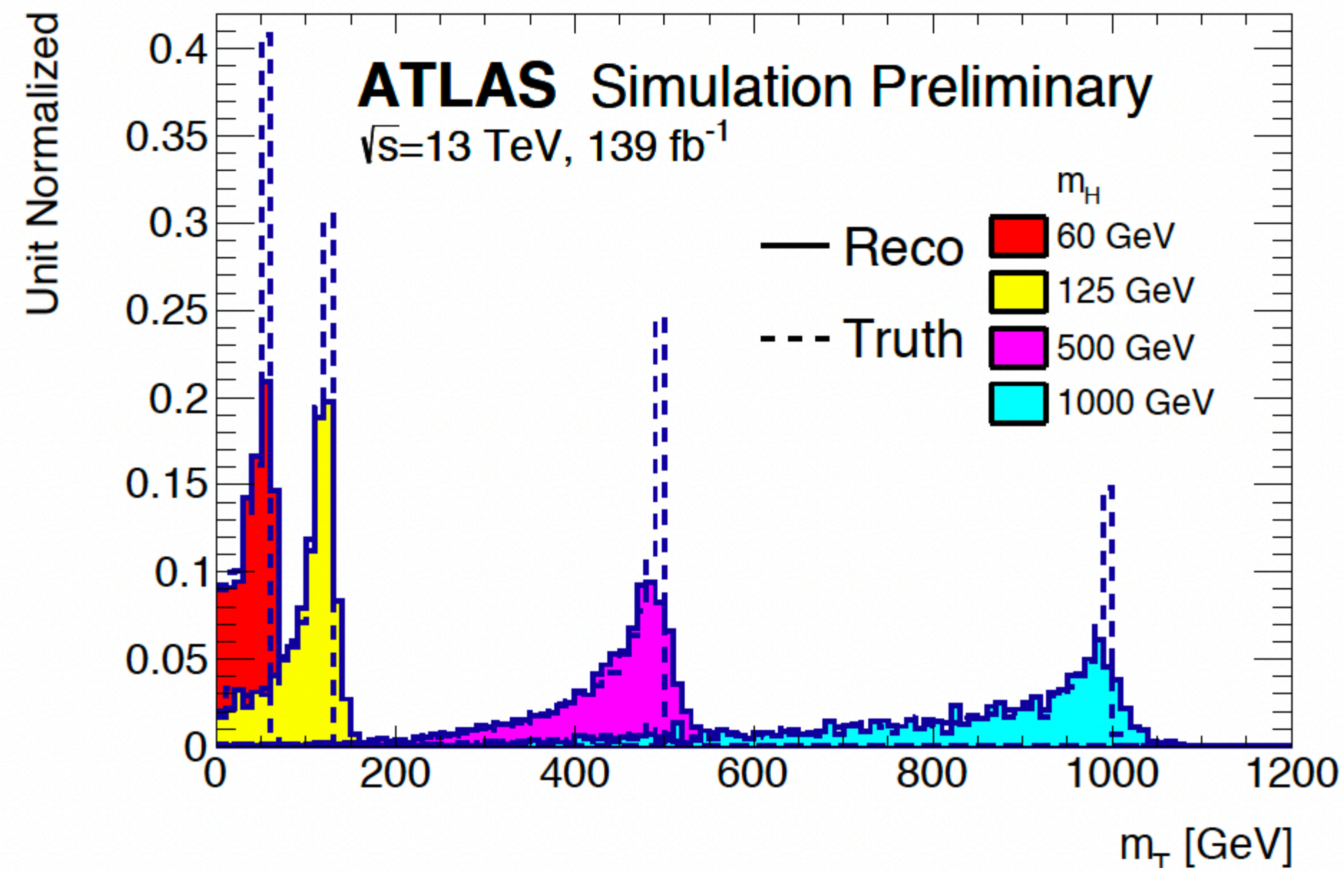
Triboson (EW)



EW $Z(\to \nu\nu)\gamma + \mathrm{jets}$

Event Selection

- **Signal region:**
  - $H \to$ inv. , $Z(\to \nu\nu)\gamma$
    - $H \to$ inv.: 4 SR bins in DNN score
    - $Z(\to \nu\nu)\gamma$: 4 SR bins in m_{jj}
  - $H \to \gamma\gamma_d$
    - Higgs-like mediators with mass in [60GeV, 2TeV]
    - Few differences from $H \to$ inv. SR
    - 10 SR bins in $m_T(E_T^{miss}, \gamma)$
- **Control region:**
  - 4 CRs are used to constrain background normalization in the fit
  - $W^{\gamma}_{\mu\nu}$ and $W^{\gamma}_{e\nu}$ CRs
    - $W(\to \ell\nu)\gamma$ events in SR have lost lepton
  - $Z^{\gamma}_{\text{Rev.Cen.}}$ CR
    - Strong $Z(\to \nu\nu)\gamma$ events in SR have central photon
  - Fake-e CR
    - jet/$\gamma \to e$ background in $W^{\gamma}_{e\nu}$ CR



Variable	SR	$W^{\gamma}_{\mu\nu}$ CR	$W^{\gamma}_{e\nu}$ CR	$Z^{\gamma}_{\text{Rev.Cen.}}$ CR	Fake$-e$ CR
p_T (j_1) [GeV]	> 60				
p_T (j_2) [GeV]	> 50				
N_{jet}	2,3				
$N_{\text{b-jet}}$	< 2				
$\Delta\phi_{jj}$	< 2.5 [2.0]				
$\|\Delta\eta_{jj}\|$	> 3.0				
$\eta(j_1) \times \eta(j_2)$	< 0				
C_3	< 0.7				
m_{jj} [TeV]	> 0.25				
E_T^{miss} [GeV]	> 150	–	> 80	> 150	< 80
$E_T^{\text{miss,lep-rm}}$ [GeV]	–	> 150	> 150	–	> 150
$E_T^{\text{jets,no-jvt}}$ [GeV]	> 130				
$\Delta\phi(j_i, E_T^{\text{miss,lep-rm}})$	> 1.0				
N_{γ}	1				
p_T (γ) [GeV]	> 15, < 110 [> 15, $<$max(110,0.733 $\times$ m_T)]				
C_{γ}	> 0.4	> 0.4	> 0.4	< 0.4	> 0.4
$\Delta\phi(\gamma, E_T^{\text{miss,lep-rm}})$	> 1.8 [–]				
N_{ℓ}	0	1 μ	1 e	0	1 e
p_T (ℓ) [GeV]	> 30				

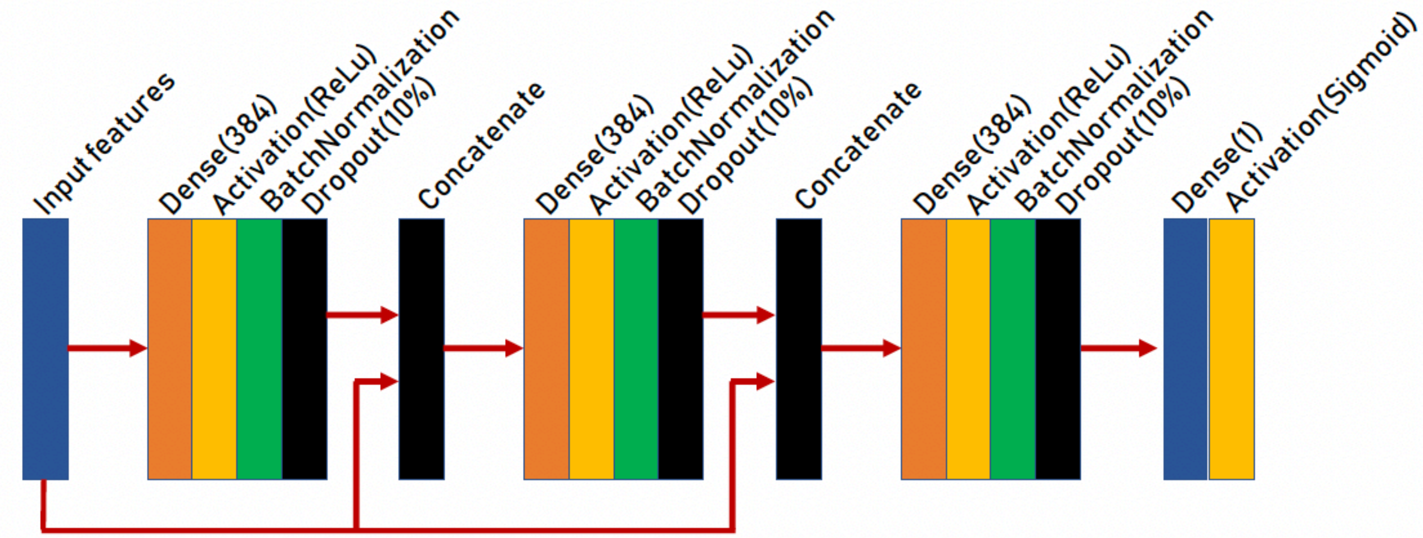
Fiducial Volume

- EW $Z(\rightarrow \nu\nu)\gamma$ + jets cross section measurement
- Very similar to the SR definition
- Particle-level requirements for stable particles before interaction with the detector but after hadronization
  - Dressed leptons are vetoed
  - Separated photon and Jets/lepton of $\Delta R > 0.4$
  - Truth-E_T^{miss}: vector sum of transverse momentum of all final state neutrinos

Observable	Requirements
N_{jet} with $p_{\text{T}} > 25$ GeV	≥ 2
$\lvert\eta(j_{1,2})\rvert$	< 4.5
$p_{\text{T}}(j_1)$ [GeV]	> 60
$p_{\text{T}}(j_2)$ [GeV]	> 50
$\Delta R(j, \ell)$	> 0.4
$\lvert\Delta\eta_{\text{jj}}\rvert$	> 3.0
C_3	< 0.7
m_{jj} [TeV]	> 0.5
truth-$E_{\text{T}}^{\text{miss}}$ [GeV]	> 150
$\Delta\phi(\text{truth-}\vec{E}_{\text{T}}^{\text{miss}}, j_i)$	> 1.0
$p_{\text{T}}(\gamma)$ [GeV]	$> 15, < 110$
$\lvert\eta(\gamma)\rvert$	< 2.37
$E_{\text{T}}^{\text{cone20}}/E_{\text{T}}^{\gamma}$	< 0.07
$\Delta R(\gamma, \text{jet-or-}\ell)$	> 0.4
C_γ	> 0.4
$\Delta\phi(\text{truth-}\vec{E}_{\text{T}}^{\text{miss}}, \gamma)$	> 1.8
N_ℓ with $p_{\text{T}} > 4$ GeV and $\lvert\eta\rvert < 2.47$	0

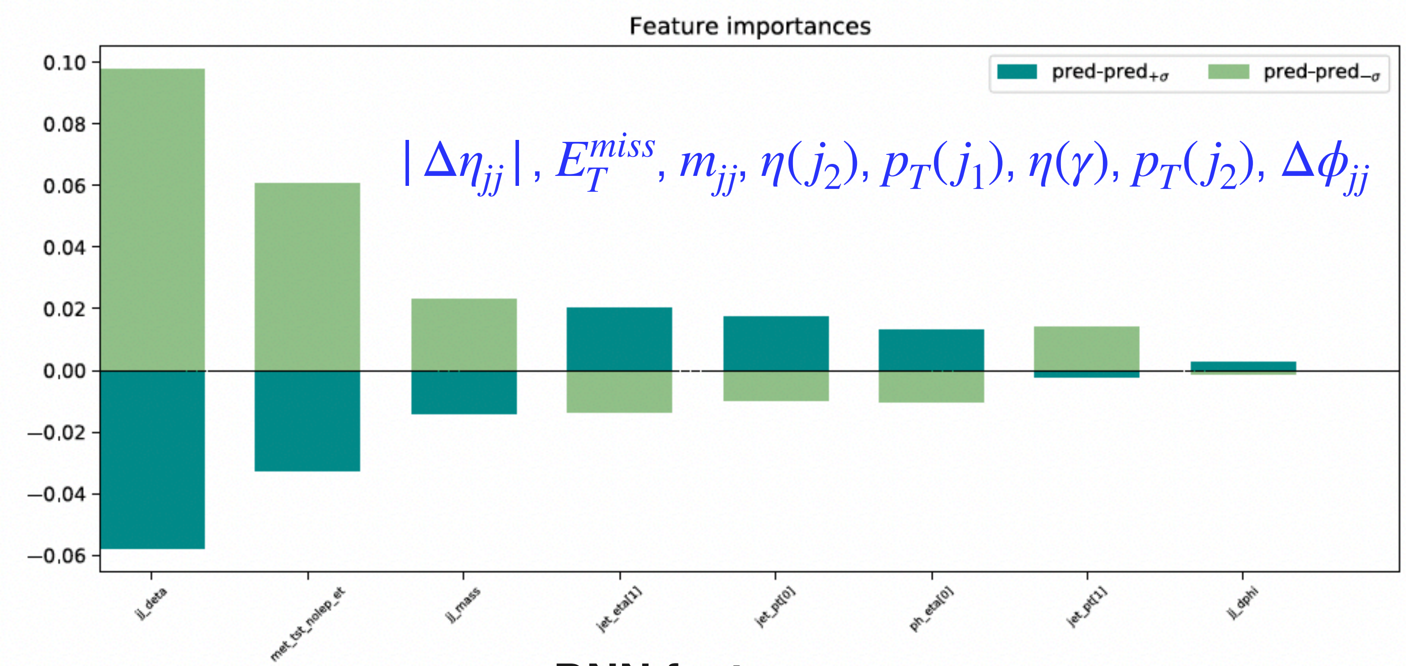
DNN Classification

- A Dense Neutral Network (DNN) is used for the $H \rightarrow$ inv. search
- DNN architecture: 3 blocks, each composed of: 1.dense layer, 2. ReLU activation function, 3. Batch Normalization, and 4. Droupout rate.



DNN architecture

- DNN feature selection with **backward elimination procedure**
- 8 features selected



DNN features

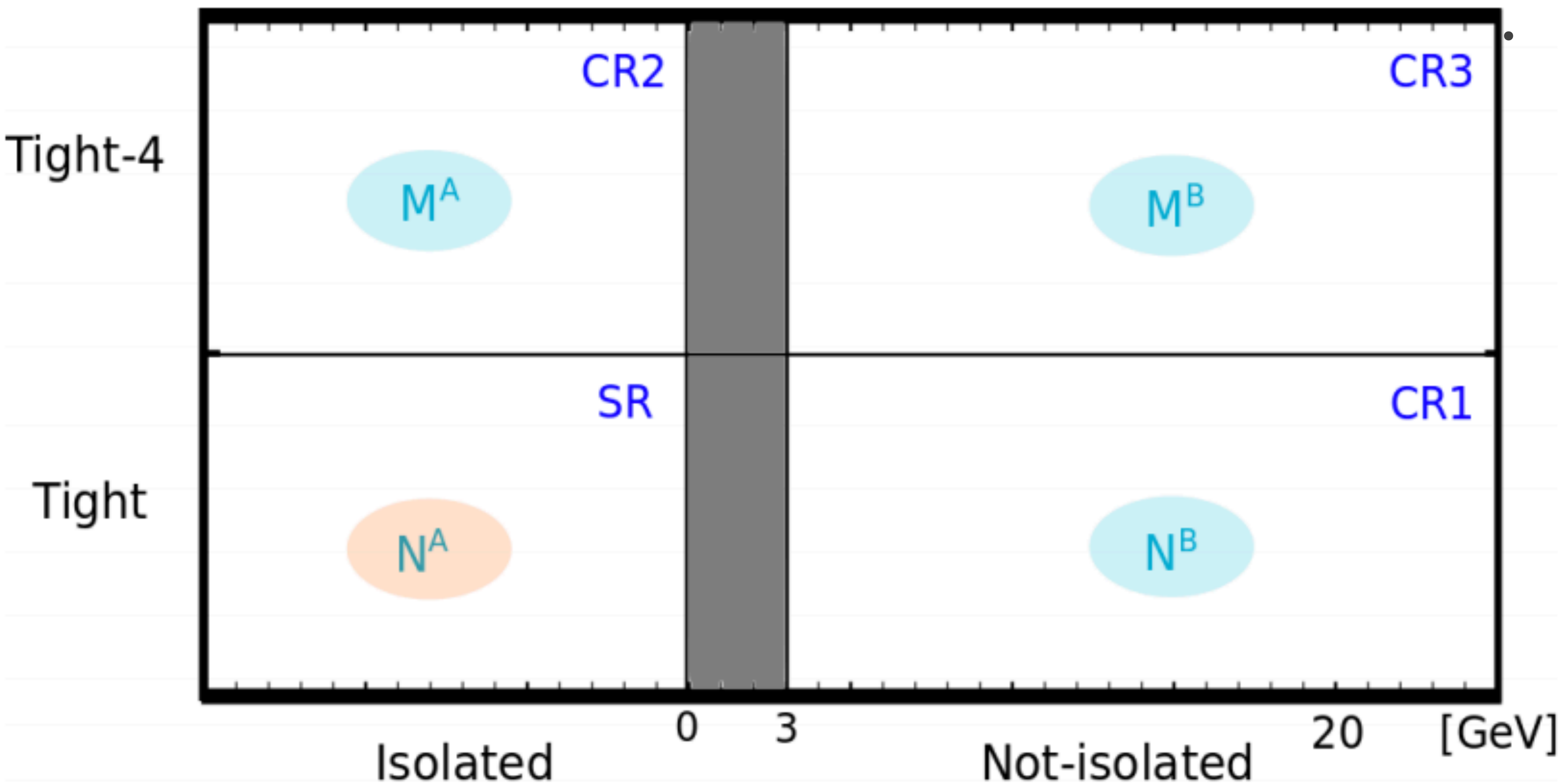
Feature importance is quantified by the average variation in DNN output caused by a 10% upward/downward variation of the feature

- DNN score ranges from 0 (background) to 1 (signal)
- ~ 20% improvement in sensitivity over cut-based approach

Jet faking Photon

- W/Z+jets have contribution may due to the mis-identified of jets as photons.
  - Estimated by the **ABCD method**
  - Comprises ~1% of SRs

1 SR: isolated-tight photon; 3 CRs: photon failed isolation or tightness



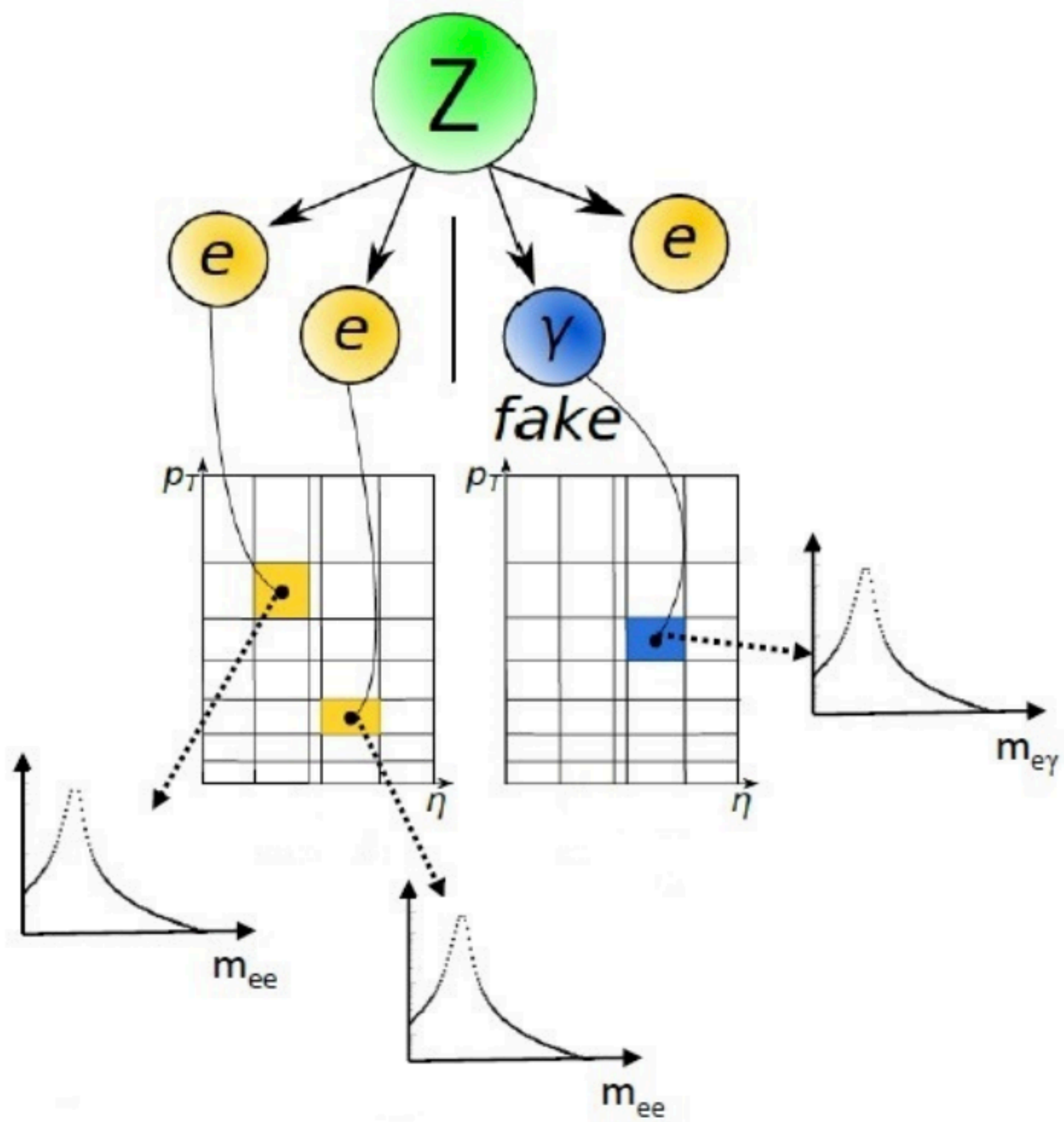
- 2 Model assumptions:
  - 1). No correlation between photon isolation and tightness
  - 2). Negligible signal photon in CRs
  - $N_A/N_B = M_A/M_B$
  - Released by extracting correlation (R_{MC}) and signal leakage ($c_{1,2,3}$) from MC

Data driven technique applied to get SR photon purity: →

$$P = \frac{(M^B + N^A c_3 - N^B c_2 R_{MC} - M^A c_1 R_{MC})}{2N^A(c_1 c_2 R_{MC} - c_3)} \cdot \left(-1 + \sqrt{1 + \frac{4(c_1 c_2 R_{MC} - c_3)(N^A M^B - N^B M^A R_{MC})}{(M^B + N^A c_3 - N^B c_2 R_{MC} - M^A c_1 R_{MC})^2}}\right)$$

Electrons Faking Photons

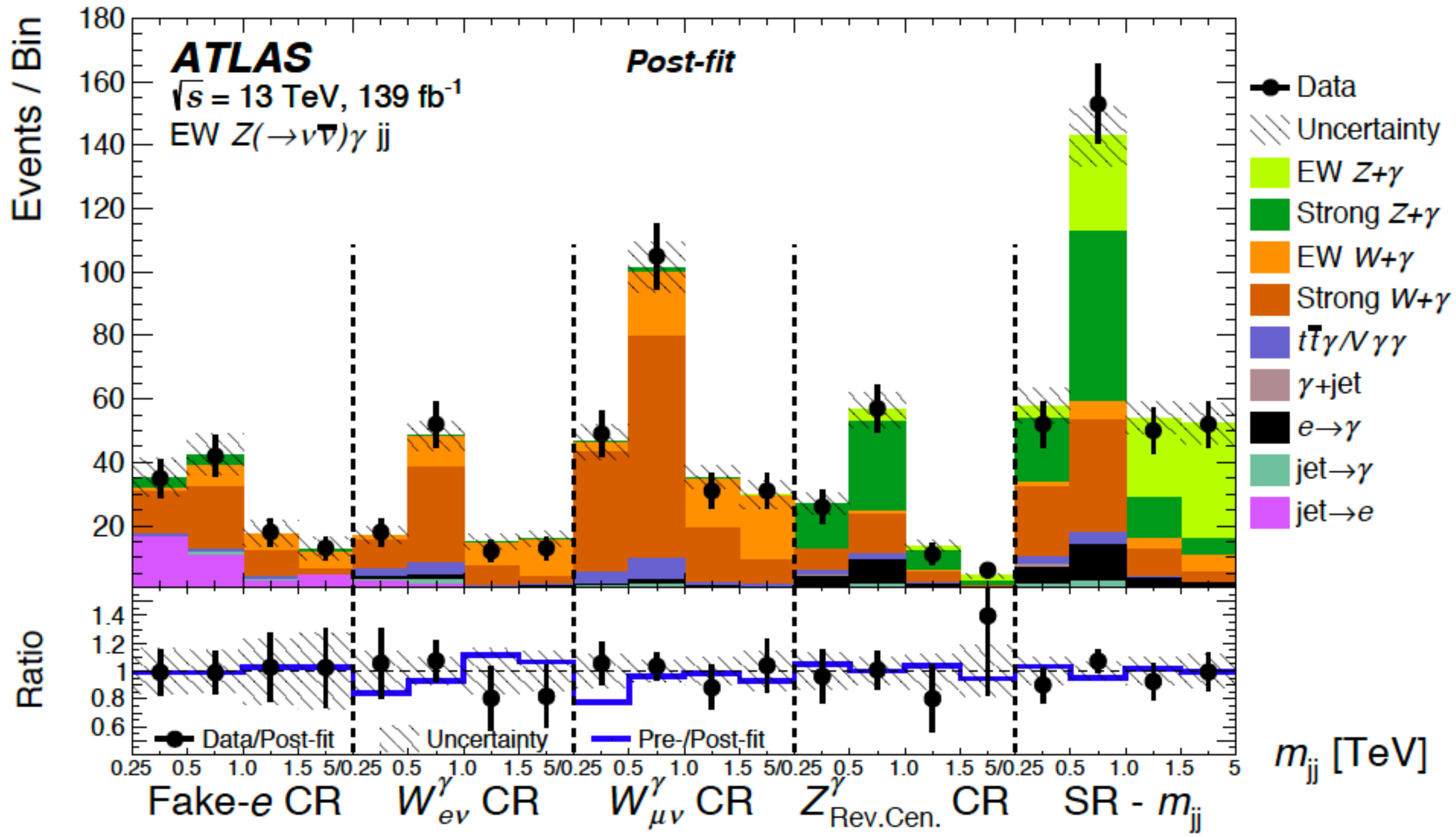
- V+jets gives contribution also due to misidentified electrons as photons.
- Comprised ~6% of $H \to$ inv. and $Z(\to \nu\nu)\gamma$ SRs, ~35% of $H \to \gamma\gamma_d$ SR
- Measured the fake rate of electrons being reconstructed as photons in the Z mass peak.
- $$F_{e\to\gamma} = \frac{\epsilon(e^{true} \to \gamma^{reco})\epsilon_\gamma}{\epsilon(e^{true} \to e^{reco})\epsilon_e}$$
- Measurement in Z(->ee)+jet to determine the mis-construction rate by comparing the rate of Z reconstruction in $e^{\pm}\gamma$ and e^+e^-
  - $$F_{e\to\gamma} = \frac{N_{e\gamma}}{2N_{ee}}$$
  - All e and γ from the ee/$e\gamma$/$\gamma\gamma$ pairs are classified in η and pT bins and invariant mass spectra are built.



Results

EW $Z(\to \nu\nu)\gamma$ + jets Measurement

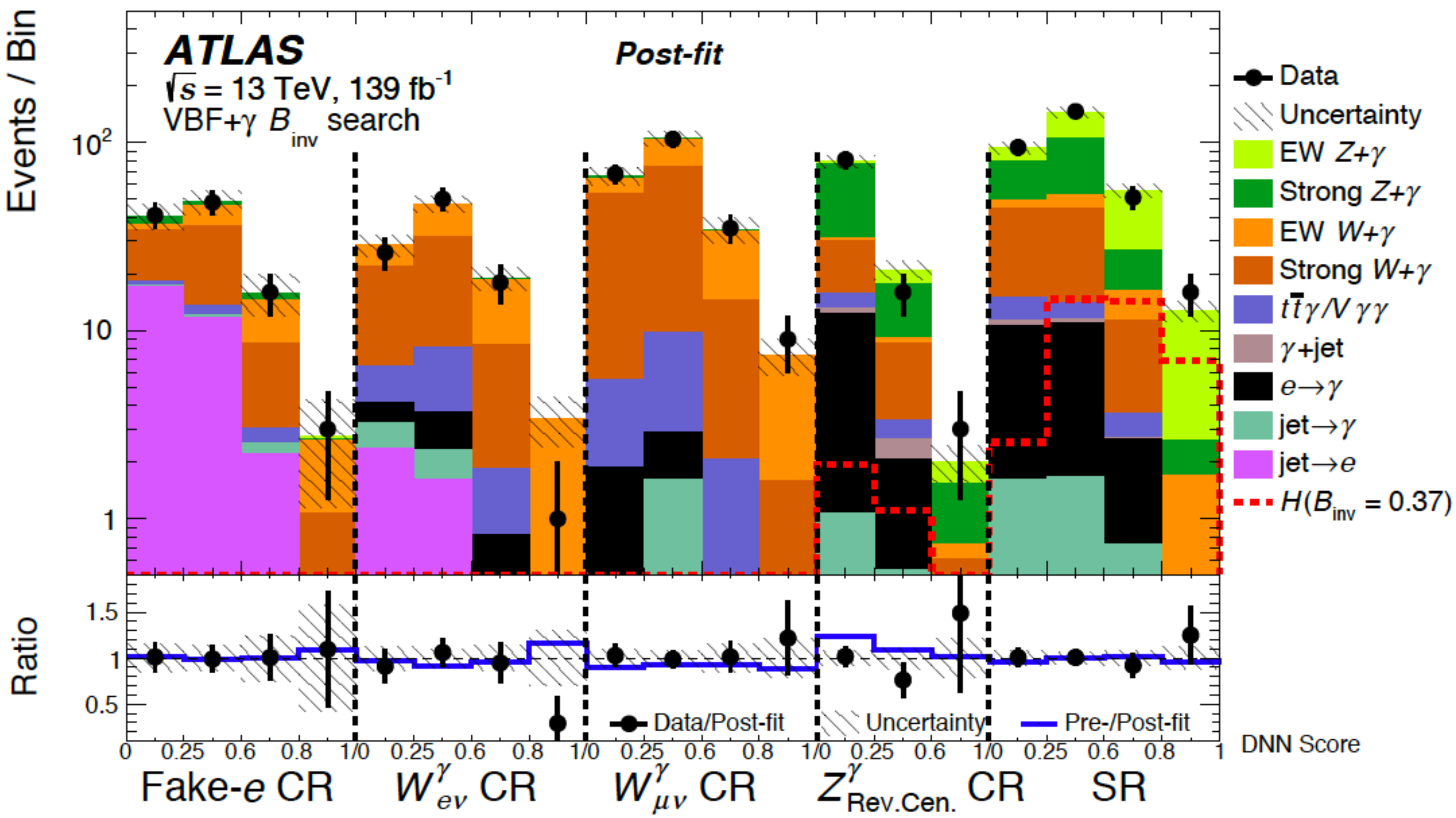
- SR and CRs are binned in m_{jj}
  - 4 SR bins and 16 CR bins
  - 5.2σ observation (5.1σ exp.) of EW $Z(\to \nu\nu)\gamma$ + jets process
  - Signal strength $\mu_{Z\gamma}$ extraction
- Measure fiducial cross section of 1.31 ± 0.29 fb



$\mu_{Z\gamma_{\text{EW}}}$	$\beta_{Z\gamma_{\text{strong}}}$	$\beta_{W\gamma}$
1.03 ± 0.25	1.02 ± 0.41	1.01 ± 0.20

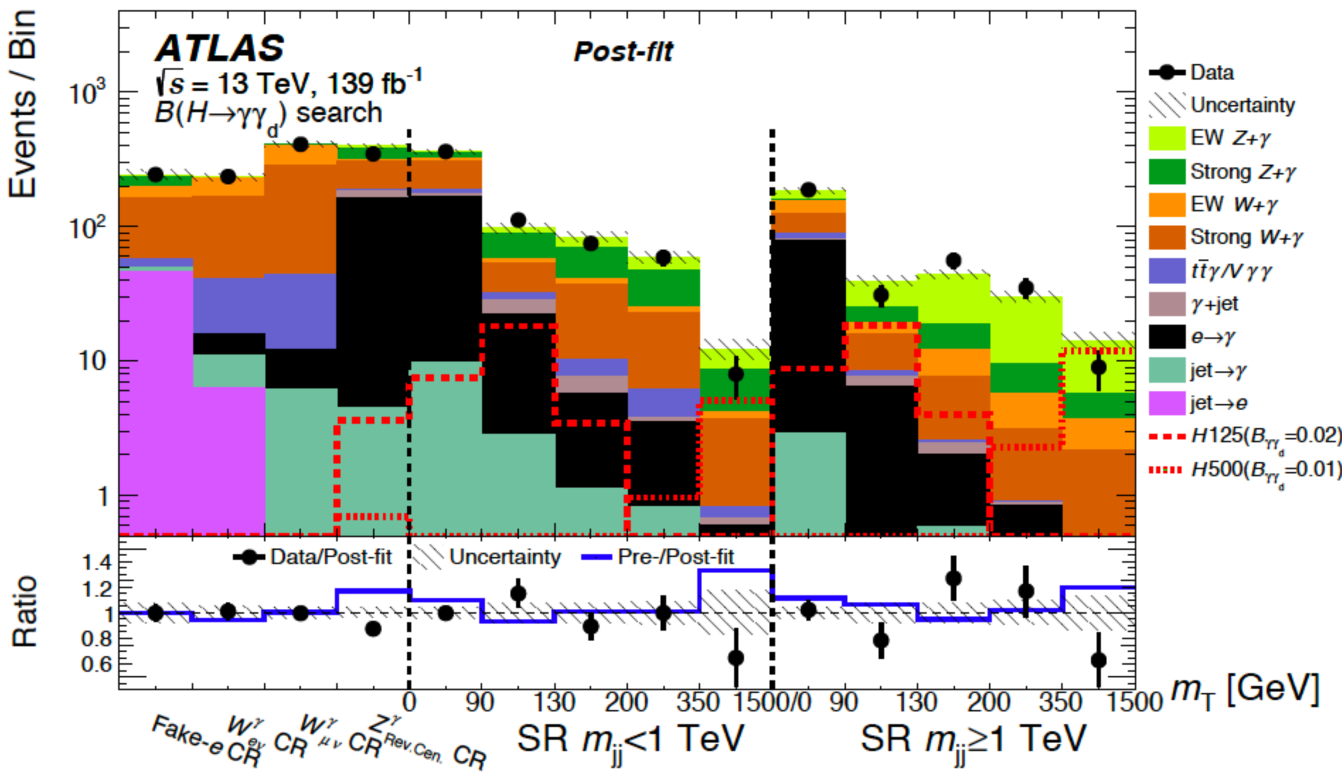
$H \to$ inv. Search

- SR and CRs are binned in DNN score
  - 4 SR bins and 15 CR bins
  - DNN [0, 0.25, 0.6, 0.8, 1]
- No evidence of a new physics contribution is observed
- Set upper limit on B_{inv} of 0.37 (0.35 expected)

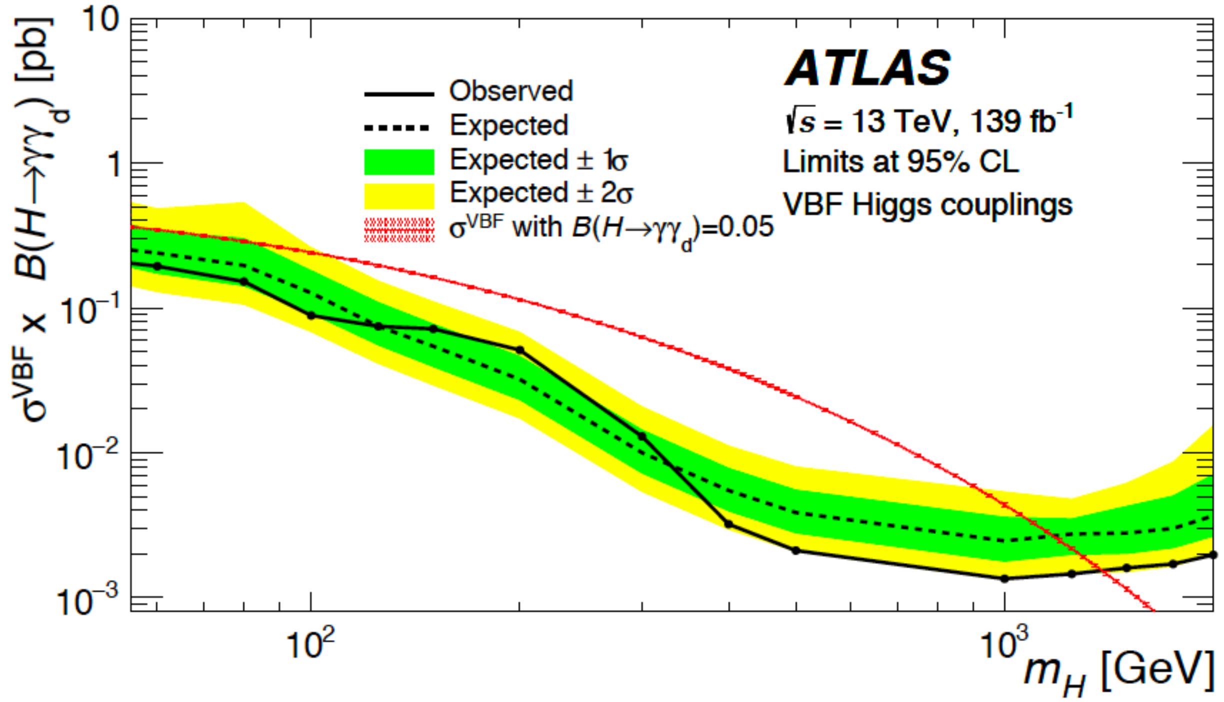


$H \to \gamma\gamma_d$ Search

- 2 SRs: $m_{jj} < 1$ TeV, $m_{jj} > 1$ TeV
  - Different sensitivities to ggF/VBF production
- SRs are binned in $m_T(\gamma, E_T^{\text{miss}})$
  - 10 SR bins and 20 CR bins
- Set upper limit on $B(H \to \gamma\gamma_d)$ of 0.018 (0.017 expected)



- Set limits on cross section times branching fraction for Higgs-like mediator, which from 0.15 pb to 3fb for 60 GeV $< m_H < 2$ TeV



Summary

- Analysis of VBF $H(\rightarrow \text{inv.})\gamma$, $H \rightarrow \gamma\gamma_d$, and EW $Z(\rightarrow \nu\nu)\gamma$ process in VBF+MET+γ final state
- First search for VBF $H(\rightarrow \text{inv.})\gamma$
  - DNN classification
  - Set upper limit on $B(H \rightarrow \text{inv.})$ of 0.37 (0.35 expected)
- First ATLAS search for $H \rightarrow \gamma\gamma_d$
  - Improved $B(H \rightarrow \gamma\gamma_d)$ limit compared to CMS combined result (1.8% vs. 2.9%)
- First observation of EW $Z(\rightarrow \nu\nu)\gamma +$ jets process with 5.2σ significance
  - Fiducial cross section measurement: 1.31 ± 0.29 fb
  - Will combine with SM VBS analysis for ~6.7σ expected significance

Back Up

Back Up

Data yields and fitted predictions for EWK Zg

Process	Fake-e CR	$W^{\gamma}_{e\nu}$ CR	$W^{\gamma}_{\mu\nu}$ CR	$Z^{\gamma}_{\text{Rev.Cen.}}$ CR	SR - m_{jj} [TeV]			
					0.25-0.5	0.5-1.0	1.0-1.5	$\geq$ 1.5
Strong $Z\gamma+$jets	8 ± 8	0 ± 1	3 ± 2	50 ± 12	20 ± 6	54 ± 12	13 ± 5	5 ± 2
EW $Z\gamma+$jets	0.6 ± 0.2	0.3 ± 0.2	0.4 ± 0.2	7 ± 2	4 ± 1	30 ± 7	25 ± 5	36 ± 7
Strong $W\gamma+$jets	43 ± 9	47 ± 9	133 ± 21	24 ± 6	22 ± 6	35 ± 10	9 ± 3	3 ± 1
EW $W\gamma+$jets	19 ± 6	31 ± 7	59 ± 13	1.4 ± 0.5	2 ± 1	6 ± 1	4 ± 1	5 ± 1
jet$\rightarrow \gamma$	1 ± 1	2 ± 2	3 ± 2	2 ± 2	1 ± 1	2 ± 2	1 ± 1	0.4 ± 0.3
jet$\rightarrow e$	34 ± 17	5 ± 3	–	–	–	–	–	–
$e \rightarrow \gamma$	–	2.7 ± 0.4	2.9 ± 0.4	13 ± 1	6 ± 1	11 ± 1	2.6 ± 0.4	1.4 ± 0.3
$\gamma+$jet	–	–	–	0.7 ± 0.5	0.7 ± 0.5	0.4 ± 0.3	0.1 ± 0.1	0.1 ± 0.1
$t\bar{t}\gamma/V\gamma\gamma$	3 ± 1	9 ± 2	13 ± 2	3 ± 1	2 ± 1	4 ± 1	0.4 ± 0.2	0.1 ± 0.1
Fitted Yields	108 ± 10	96 ± 8	213 ± 14	102 ± 9	58 ± 6	143 ± 12	54 ± 5	52 ± 6
Data	108	95	216	100	52	153	50	52
Data/Fit	1.00 ± 0.14	0.99 ± 0.12	1.01 ± 0.09	0.98 ± 0.13	0.90 ± 0.15	1.07 ± 0.11	0.93 ± 0.16	0.99 ± 0.18

Back Up

Data yields and fitted predictions for H-> inv.

Process	Fake-e CR	$W^{\gamma}_{e\nu}$ CR	$W^{\gamma}_{\mu\nu}$ CR	$Z^{\gamma}_{\text{Rev.Cen.}}$ CR	SR - DNN output score 0-0.25	0.25-0.6	0.6-0.8	0.8-1.0
Strong $Z\gamma$ + jets	7 ± 4	0.3 ± 0.1	3 ± 1	55 ± 6	31 ± 6	53 ± 10	10 ± 2	0.9 ± 0.2
EW $Z\gamma$ + jets	0.6 ± 0.1	0.3 ± 0.1	0.4 ± 0.2	7 ± 1	14 ± 2	39 ± 5	29 ± 4	10 ± 2
Strong $W\gamma$ + jets	44 ± 7	46 ± 6.1	127 ± 13	20 ± 2	29 ± 6	31 ± 9	8 ± 2	0.1 ± 0.2
EW $W\gamma$ + jets	21 ± 3	35 ± 4	66 ± 7	1.5 ± 0.2	5 ± 1	8 ± 1	5 ± 1	1.2 ± 0.3
jet$\rightarrow \gamma$	1 ± 1	2 ± 1	2 ± 2	2 ± 1	2 ± 2	2 ± 2	0.7 ± 0.8	–
jet$\rightarrow e$	32 ± 15	4 ± 2	–	–	–	–	–	–
$e \rightarrow \gamma$	–	2.6 ± 0.2	2.9 ± 0.2	13 ± 1	9 ± 1	9 ± 1	1.9 ± 0.2	0.3 ± 0.1
γ + jet	–	–	–	1.4 ± 0.5	0.7 ± 0.5	0.6 ± 0.4	0.04 ± 0.03	–
$t\bar{t}\gamma/V\gamma\gamma$	3 ± 1	8 ± 1	12 ± 2	3 ± 1	4 ± 1	2.4 ± 0.4	0.9 ± 0.2	0.01 ± 0.01
Fitted Bkg	108 ± 10	97 ± 7	214 ± 14	101 ± 7	93 ± 8	145 ± 11	55 ± 5	13 ± 2
H ($\mathcal{B}_{\text{inv}} = 0.37$)	–	–	–	3.3 ± 0.4	2.6 ± 0.3	15 ± 2	14 ± 2	7 ± 1
Data	108	95	216	100	94	146	51	16
Data/Fit	1.01 ± 0.14	0.97 ± 0.12	1.01 ± 0.09	0.98 ± 0.12	1.01 ± 0.13	1.01 ± 0.11	0.92 ± 0.15	1.25 ± 0.35

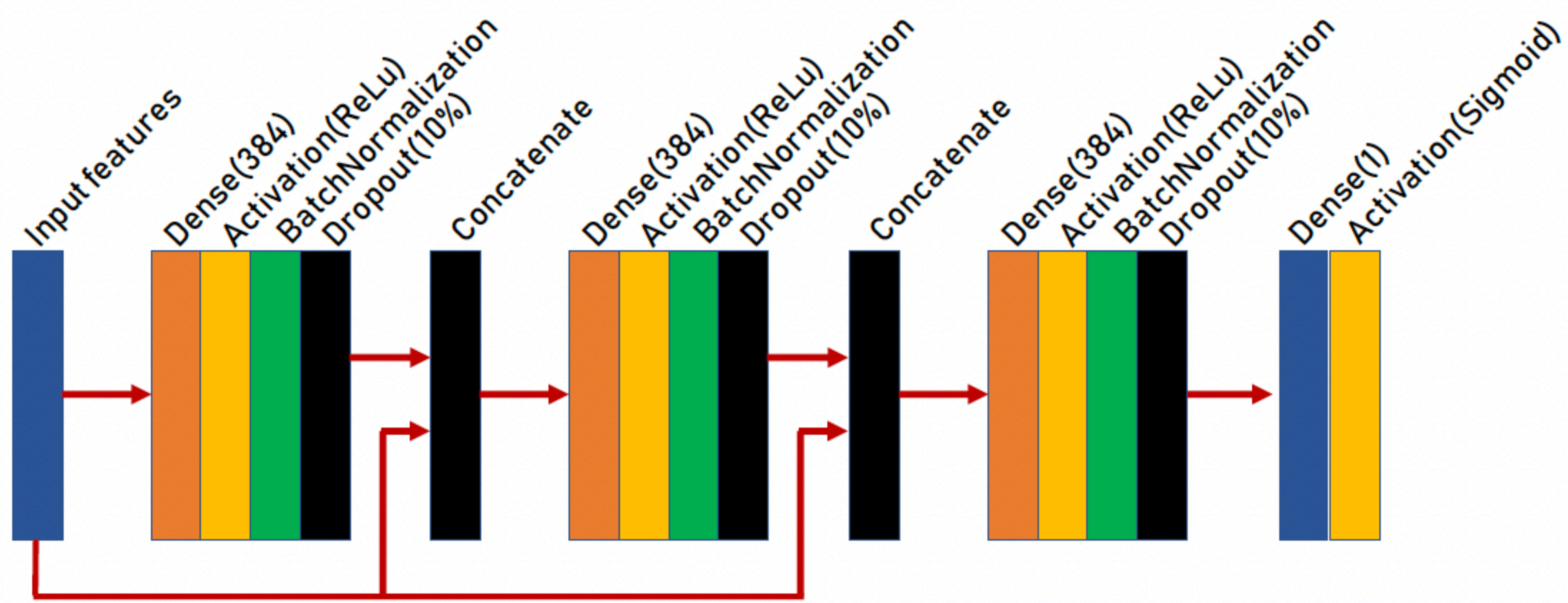
Back Up

The contributions from different groups of systematic uncertainties to the 1 sigma uncertainty bands .The evaluation is performed by fixing a given group of systematic uncertainties to their best-fit values and subtracting the new variance (σ2) of the best-fit value or the limit from the nominal variance including all systematic uncertainties.

Source	1σ Uncertainty on $\mu_{Z\gamma\text{EW}}$	1σ Uncertainty on $\mathcal{B}_{\text{inv}}$	1σ Uncertainty on $\mathcal{B}(H \to \gamma\gamma_{\text{d}})$
Jet scale and resolution	0.076	0.045	0.0011
$V\gamma +$jets theory	0.067	0.044	0.0018
pile-up	0.040	0.021	0.0004
Photon	0.035	0.031	0.0011
$e \to \gamma$, jet$\to e, \gamma$ Bkg.	0.035	0.034	0.0028
Lepton	0.027	0.003	0.0008
$E_{\text{T}}^{\text{miss}}$	0.023	0.018	0.0003
Signal theory shape	0.020	–	–
Signal theory acceptance	0.12	–	–
Data stats.	0.16	0.11	0.0056
$W\gamma +$jets/$Z\gamma +$jets Norm.	0.073	0.013	0.0004
MC stats.	0.063	0.046	0.0026
Total	0.25	0.15	0.0073

DNN event classification

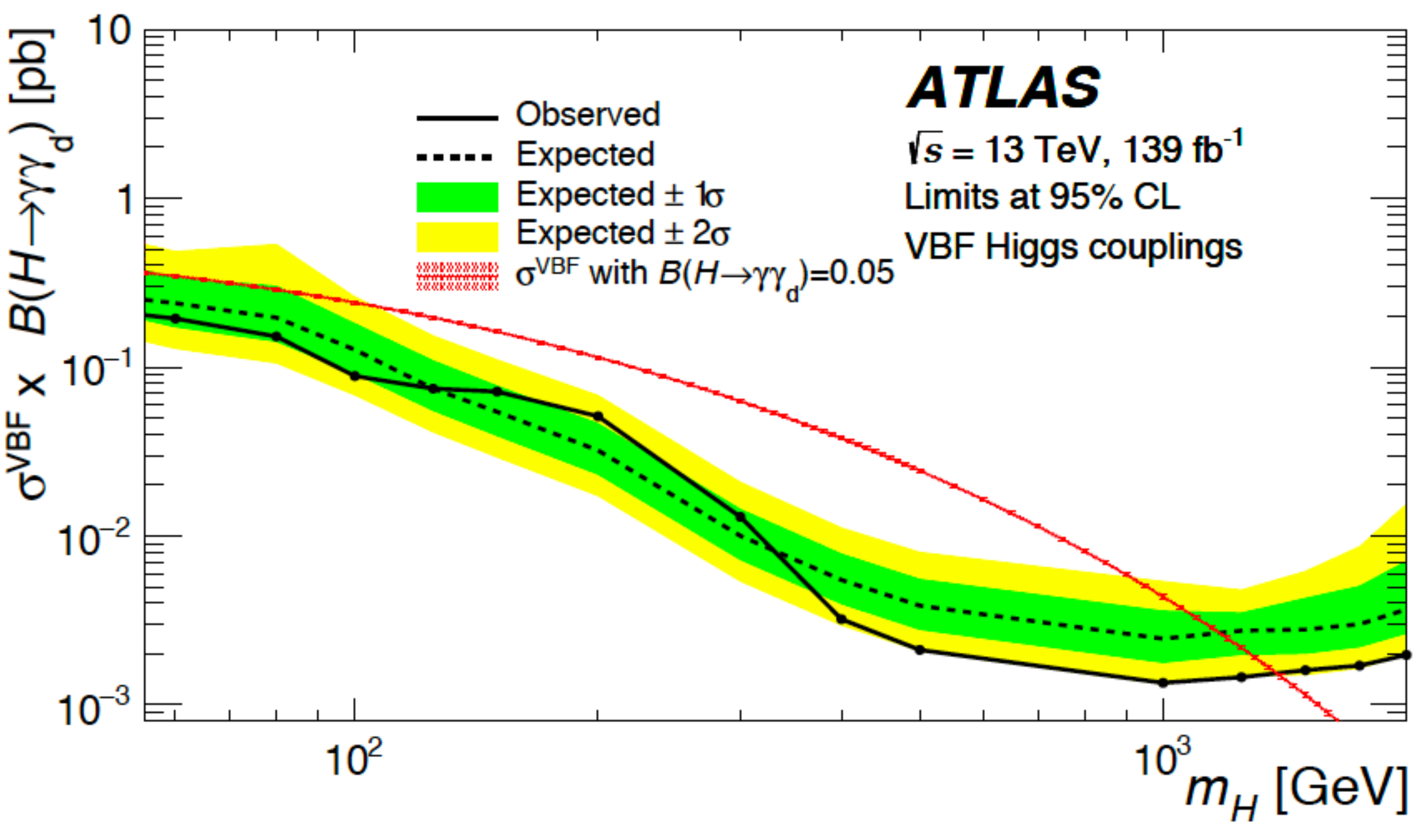
- A Dense Neutral Network (DNN) is used to discriminate between signal and background for the $H \to$ inv. search
- DNN architecture: 3 blocks, each composed of: 1.dense layer, 2. ReLU activation function, 3. Batch Normalization, and 4. Droupout rate.
  - Each block receives output of previous block concatenated with input features
  - Dropout and Batch Normalization layers are included to avoid over-training
  - Weights are updated by minimizing binary cross-entropy loss

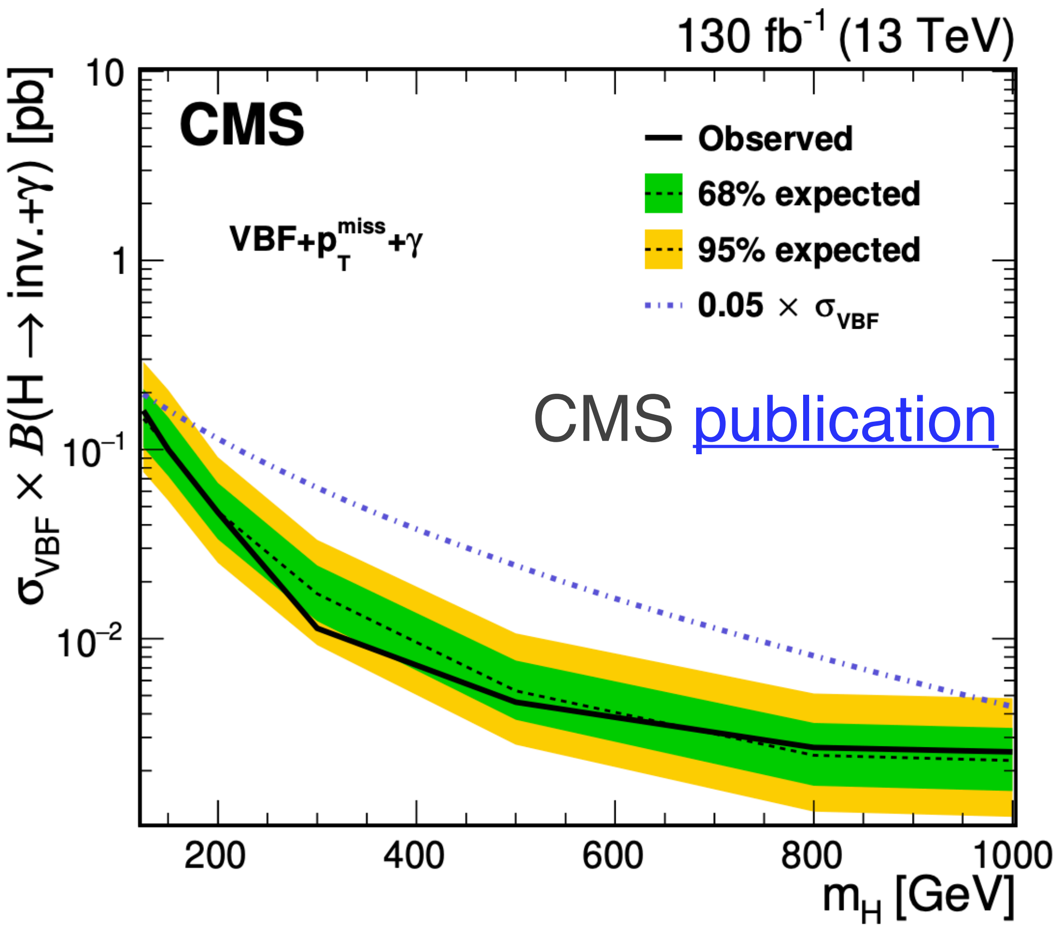


DNN architecture

Back Up

H->$\gamma\gamma_d$





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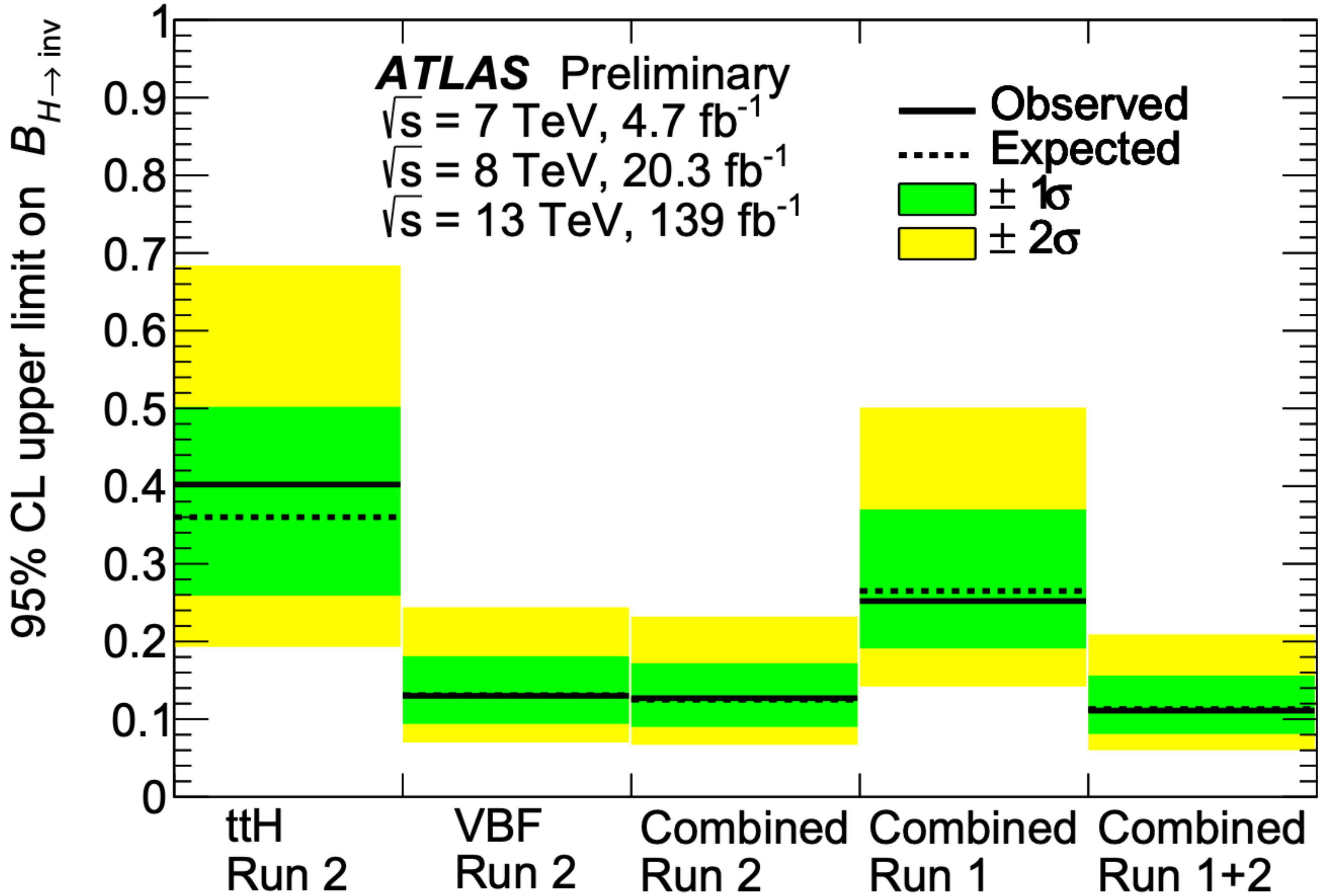
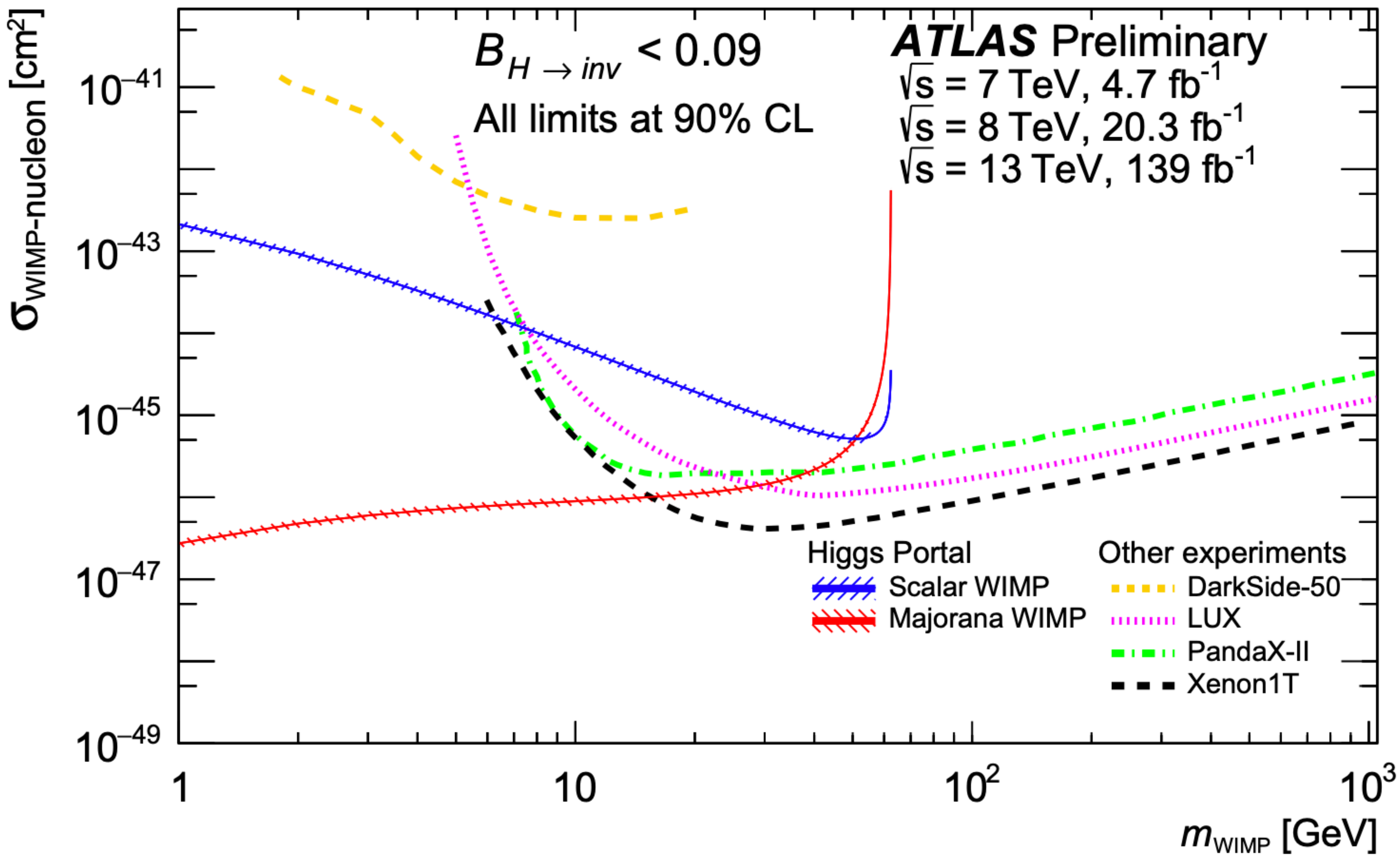


ATLAS-CONF-2020-052

H -> inv.

Analysis	$\sqrt{s}$ [TeV]	Int. luminosity [fb^{-1}]	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit	Reference
Run 2 VBF	13	139	$0.00^{+0.07}_{-0.07}$	0.13	$0.13^{+0.05}_{-0.04}$	[42]
Run 2 $t\bar{t}H$	13	139	$0.04^{+0.20}_{-0.20}$	0.40	$0.36^{+0.15}_{-0.10}$	This document
Run 2 Comb.	13	139	$0.00^{+0.06}_{-0.07}$	0.13	$0.12^{+0.05}_{-0.04}$	This document
Run 1 Comb.	7, 8	4.7, 20.3	$-0.02^{+0.14}_{-0.13}$	0.25	$0.27^{+0.10}_{-0.08}$	[36]
Run 1+2 Comb.	7, 8, 13	4.7, 20.3, 139	$0.00^{+0.06}_{-0.06}$	0.11	$0.11^{+0.04}_{-0.03}$	This document

Back Up



The interpretation of ATLAS results assumes Higgs portal scenarios where the 125 GeV Higgs boson decays to a pair of DM particles that are either scalars or Majorana fermions.