VH and VBF Higgs production
ATLAS and CMS

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On behalf of the ATLAS and CMS collaborations

Higgs Couplings 2018
Tokyo, Japan
November 26th, 2018

New results since last year

ATLAS

- H→ $\gamma\gamma$ with 80 fb^{-1}, ***Preliminary*** (LINK)
- H → ZZ with 80 fb^{-1}, ***Preliminary*** (LINK)
- H → WW with 36 fb^{-1}, Submitted to ***Phys. Lett. B*** (LINK)
- H (125 GeV) combination with up to 80 fb^{-1}, ***Preliminary*** (LINK)

CMS

- H → $\gamma\gamma$ with 36 fb^{-1}, Accepted for publication in ***J. High Energy Phys.*** (LINK)
- H → ZZ with 80 fb^{-1}, ***Preliminary*** (LINK)
- H → WW with 36 fb^{-1}, Submitted to ***Phys. Lett. B*** (LINK)
- H (125 GeV) combination with 36 fb^{-1}, Submitted to ***Eur. Phys. J. C*** (LINK)

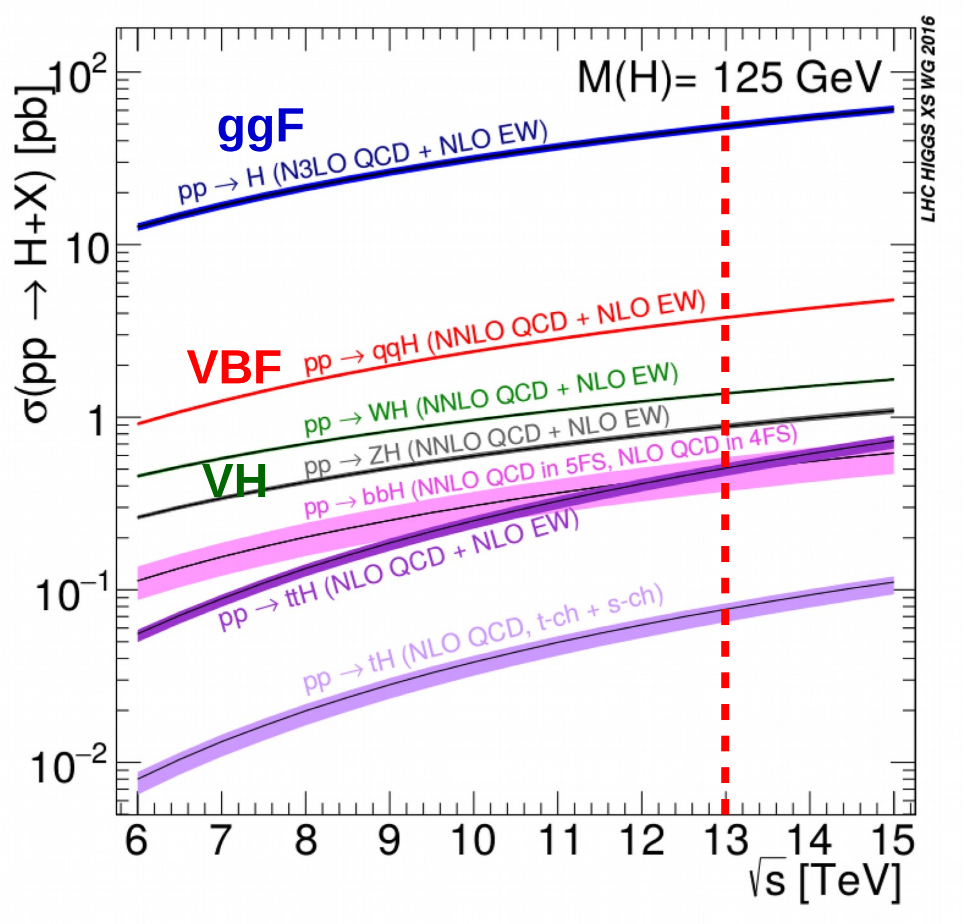
Covered in other talks:

- ATLAS H → $\tau\tau$ with 36 fb^{-1}, Submitted to ***Phys. Rev. D*** (LINK)
- CMS H → $\tau\tau$ with 36 fb^{-1}, Submitted to ***J. High Energy Phys.*** (LINK)
- V(H → bb) observation with 80 fb^{-1} by both ATLAS and CMS (ATLAS PUBLICATION, CMS PUBLICATION)

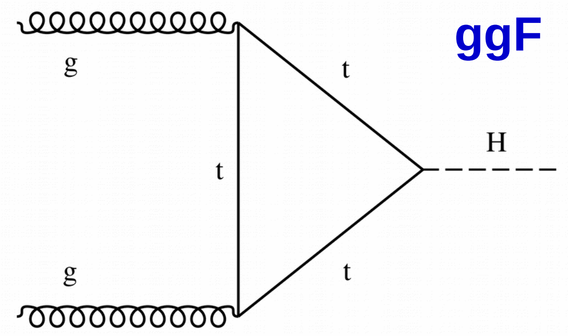
Outline

- Higgs production/decays - VH/VBF
- Simplified Template Cross-Sections (STXS)
- VH/VBF results in H → ZZ from ATLAS / CMS
- VH/VBF results in H → yy from ATLAS / CMS
- VH/VBF results in H → WW from ATLAS / CMS

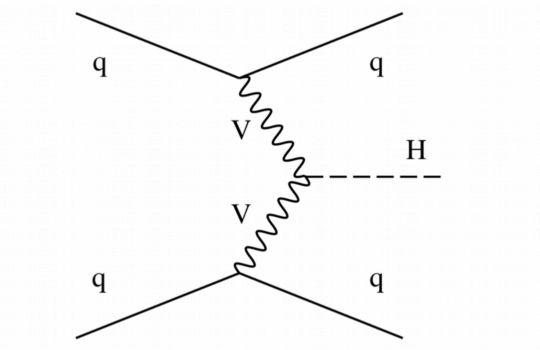
Higgs production modes



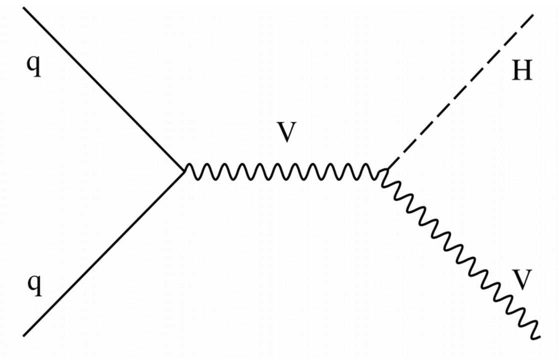
ggF



VBF



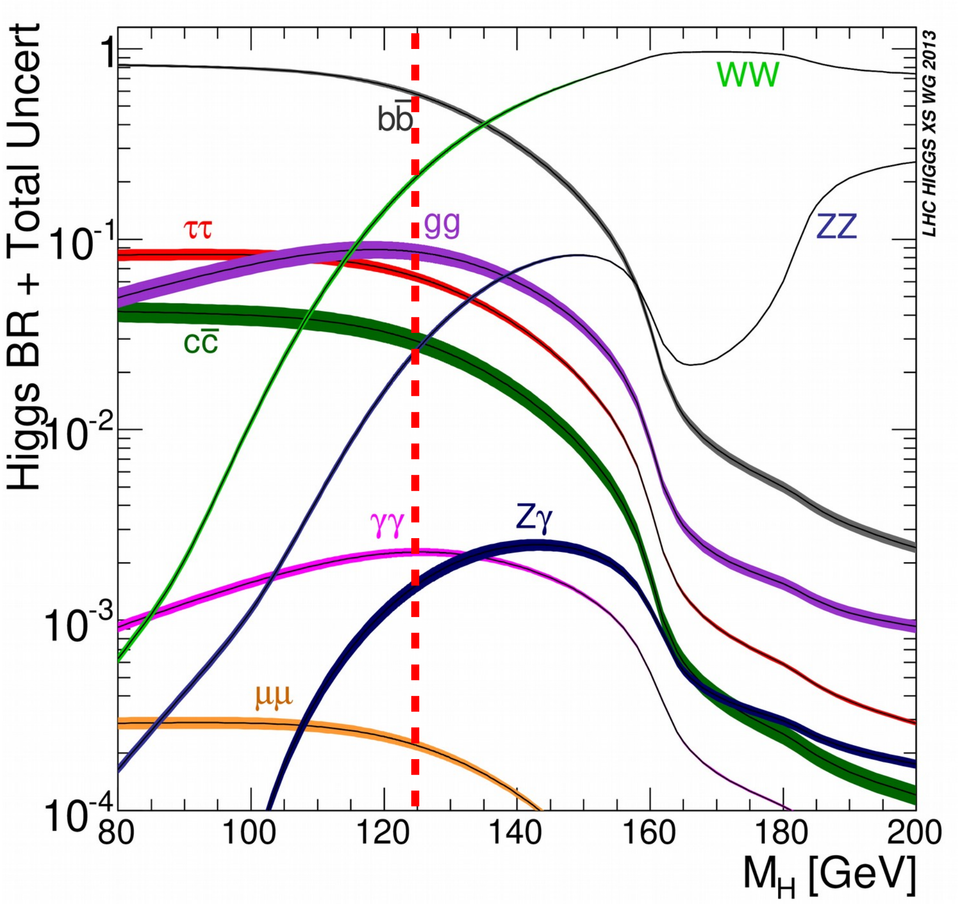
VH



VBF cross-section around 1 order of magnitude less than **ggF**, **VH** cross-section around ½ that of **VBF**

Direct **HVV** coupling in LO **VBF**/**VH** production, while **ggF** has a fermion loop

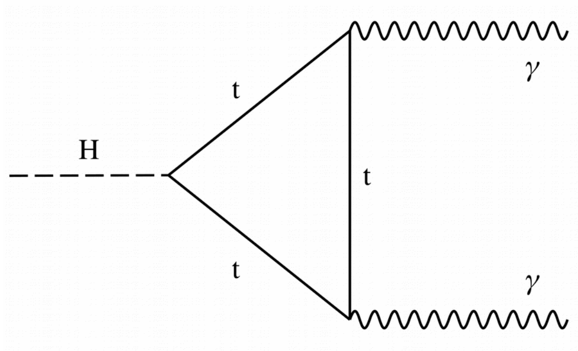
Higgs decay modes



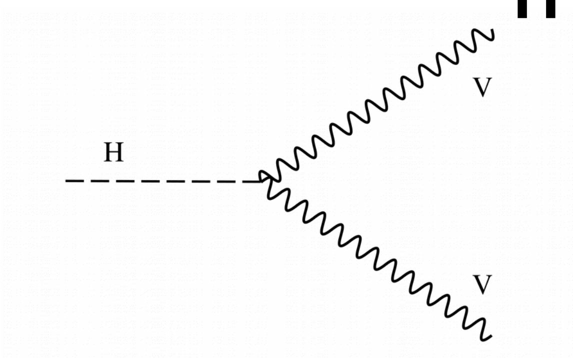
Highest BRs for 125 GeV Higgs are bb, WW, gg

Can’t ignore detector signature! e.g.
H → ZZ → 4l is much cleaner than H → bb → jetjet!

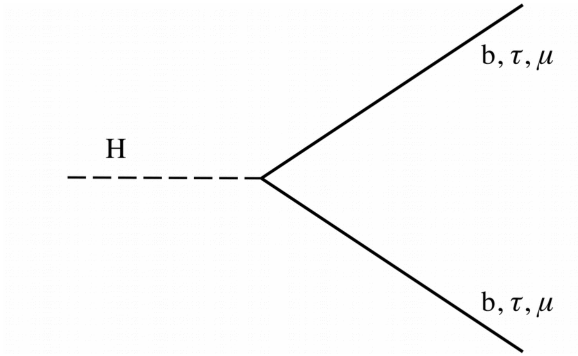
H → γγ



H → VV



H → ff



Simplified **T**emplate **X**-**S**ections
STXS

Goals:

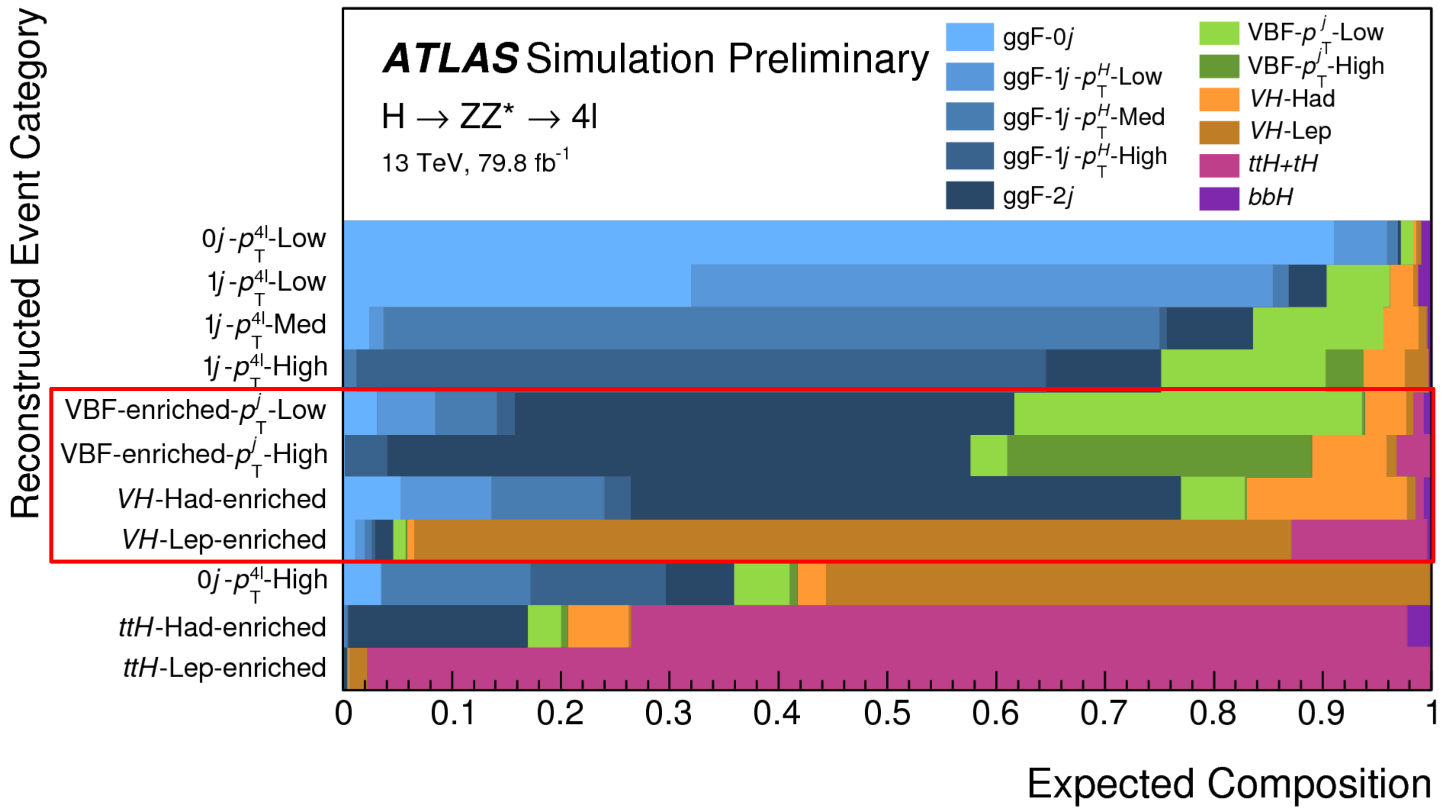
- More finely grained measurements than production mode measurements
- Reduce theoretical uncertainties folded into measurements
  → Shift dominant theory uncertainties to the interpretation level
- Isolate possible BSM effects into STXS bins designed for BSM sensitivity

Stages:
(increasing granularity)

- Stage 0 → Higgs production mode cross-section measurements in $|y_H| < 2.5$
  ggF, VBF, VH, ttH
- Stage 1 → 31 particle level categories (bins)
  Current data lacks sensitivity to resolve all Stage 1 categories
  → Reduced stage 1 measurements merge stage 1 bins where necessary

VH/VBF H → ZZ – ATLAS

Event categorization and reconstruction level signal composition



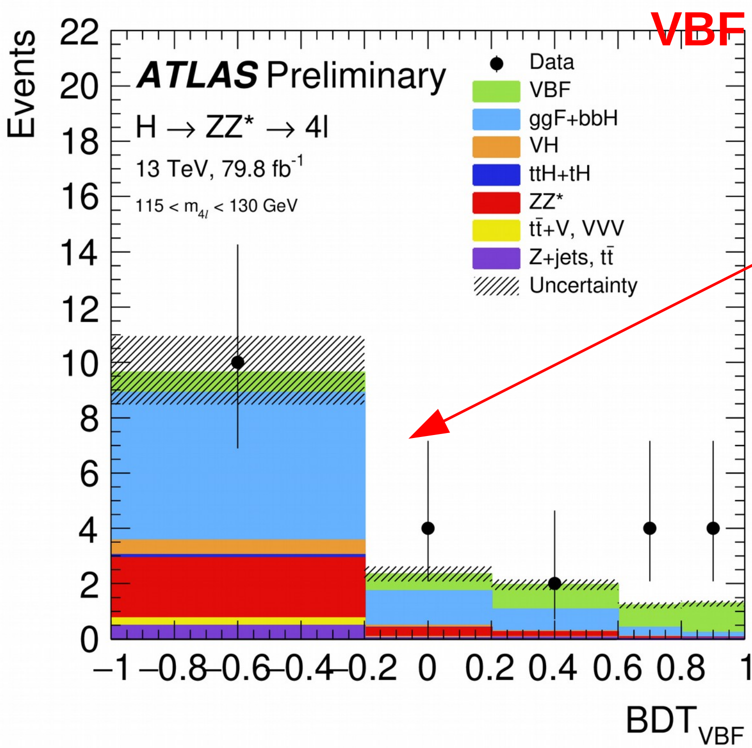
- Reconstructed event categories aimed at reduced stage 1 STXS measurement
- ggF production dominant even in VBF enriched VH hadronic categories (60-80% ggF)
- BDTs are used to improve the discrimination between production modes in each category

VH/VBF H → ZZ – ATLAS

BDT Discriminants

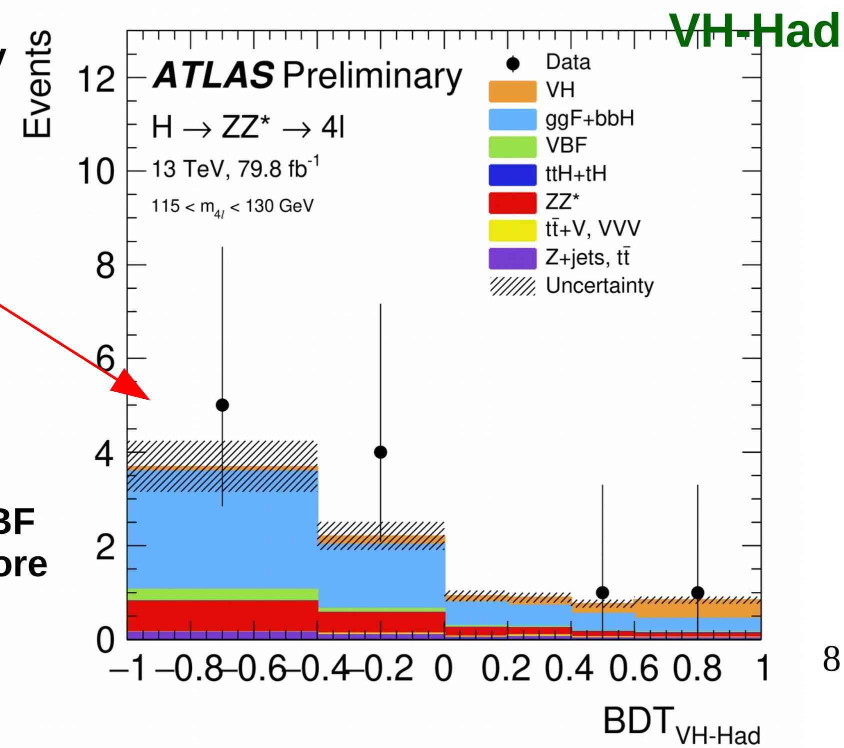
Reconstructed event category	BDT discriminant	Input variables
$0j$	$\mathrm{BDT}_{\mathrm{ggF}}$	$p_{\mathrm{T}}^{4\ell}$, $\eta_{4\ell}$, D_{ZZ^*}
$1j$-$p_{\mathrm{T}}^{4\ell}$-Low	$\mathrm{BDT}_{\mathrm{VBF}}^{1j\text{-}p_{\mathrm{T}}^{4\ell}\text{-Low}}$	p_{T}^{j}, η_j, $\Delta R(j, 4\ell)$
$1j$-$p_{\mathrm{T}}^{4\ell}$-Med	$\mathrm{BDT}_{\mathrm{VBF}}^{1j\text{-}p_{\mathrm{T}}^{4\ell}\text{-Med}}$	p_{T}^{j}, η_j, $\Delta R(j, 4\ell)$
$1j$-$p_{\mathrm{T}}^{4\ell}$-High	-	-
VBF-enriched-p_{T}^{j}-Low	$\mathrm{BDT}_{\mathrm{VBF}}$	m_{jj}, $\Delta\eta_{jj}$, p_{T}^{j1}, p_{T}^{j2}, $\eta_{4\ell}^{*}$, $\Delta R_{jZ}^{\mathrm{min}}$, $(p_{\mathrm{T}}^{4\ell jj})_{\mathrm{constrained}}$
VBF-enriched-p_{T}^{j}-High	-	-
VH-Had-enriched	$\mathrm{BDT}_{VH\text{-Had}}$	m_{jj}, $\Delta\eta_{jj}$, p_{T}^{j1}, p_{T}^{j2}, $\eta_{4\ell}^{*}$, $\Delta R_{jZ}^{\mathrm{min}}$, η_{j1}
VH-Lep-enriched	-	-
ttH-enriched	-	-

Discriminants in the 1-jet VBF categories are designed to disentangle VBF and ggF production



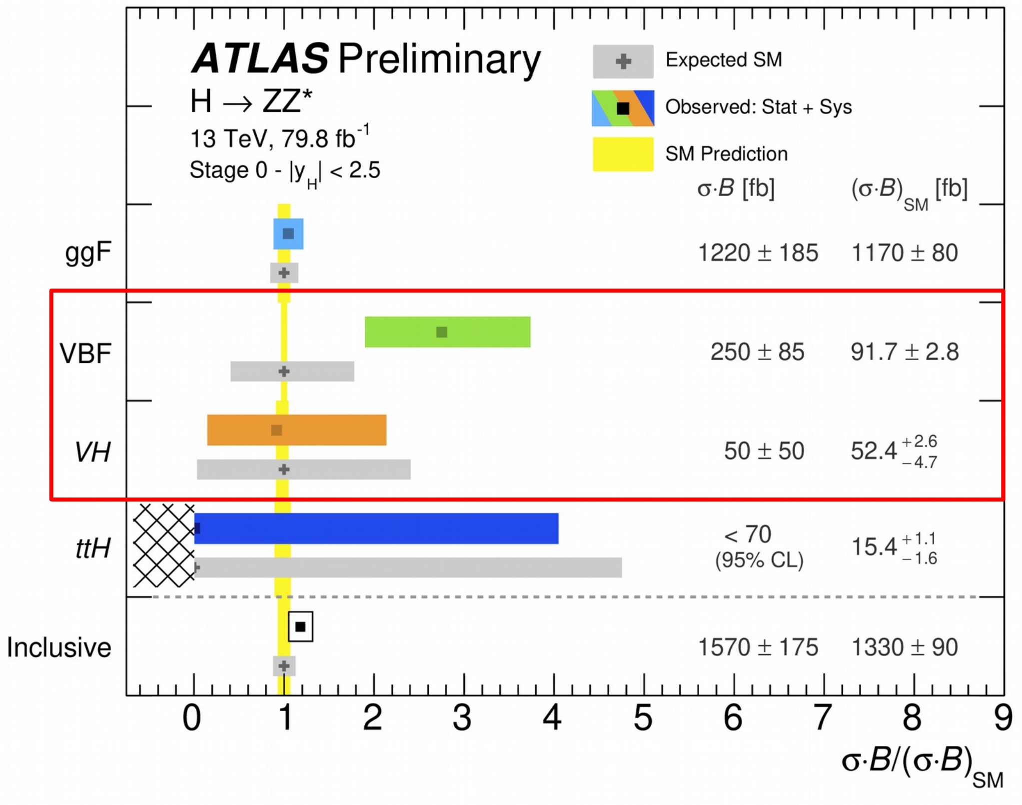
ggF production a very large "background" to both VBF and VH.

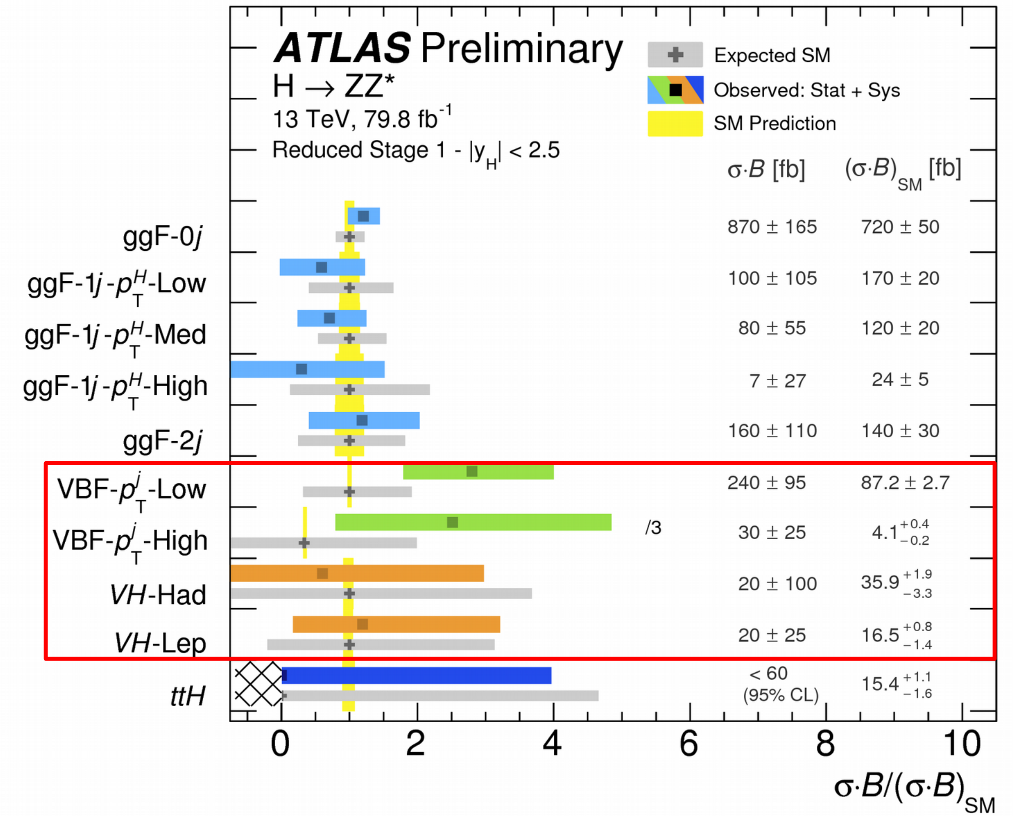
More data than expected for VBF at high BDT score



VH/VBF H → ZZ – ATLAS

Cross-sections





STXS Stage 0 Cross-sections:

- VBF observed cross-section 3x larger than SM prediction
- VH observed cross-section consistent with SM prediction

Reduced STXS stage 1 cross-sections

- VBF observed cross-sections: Larger deviation from SM prediction in the low leading jet p_T category
- VH observed cross-sections are consistent with the SM predictions

VH/VBF H → ZZ – CMS

Event categorization and kinematic discriminant definitions

Full kinematic information from each event is used
→ Higgs decays and associated particles extracted using ME calculations
→ Used to form kinematic discriminants, e.g.

$$\mathcal{D}_{\mathrm{bkg}}^{\mathrm{VBF+dec}} = \frac{\mathcal{P}_{\mathrm{sig}}^{\mathrm{VBF+VH+dec}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{sig}}^{\mathrm{VBF+VH+dec}}(\vec{\Omega}) + c^{\mathrm{VBF2jet}}(m_{4\ell}) \times (\mathcal{P}_{\mathrm{bkg}}^{\mathrm{VBS+VVV}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{bkg}}^{\mathrm{QCD+dec}}(\vec{\Omega}))}$$

$$\mathcal{D}_{\mathrm{bkg}}^{\mathrm{VH+dec}} = \frac{\mathcal{P}_{\mathrm{sig}}^{\mathrm{VBF+VH+dec}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{sig}}^{\mathrm{VBF+VH+dec}}(\vec{\Omega}) + c^{\mathrm{had.VH}}(m_{4\ell}) \times (\mathcal{P}_{\mathrm{bkg}}^{\mathrm{VBS+VVV}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{bkg}}^{\mathrm{QCD+dec}}(\vec{\Omega}))},$$

Category	Leptons	Jets	Discriminant
VBF-2jet	4	2-3 (< 1 b-tag) 4 (0 b-tags)	$D_{2jet} > 0.5$
VH-hadronic	4	2-3 (< 1 b-tag) 4 (0 b-tags)	$\max(D_{WH}, D_{ZH}) > 0.5$
VH-leptonic	4 + 1 (WH) 4 + 2 (ZH)	< 3 jets (0 b-tags)	-
VBF-1jet	4	1	$D_{1jet} > 0.5$
Untagged			

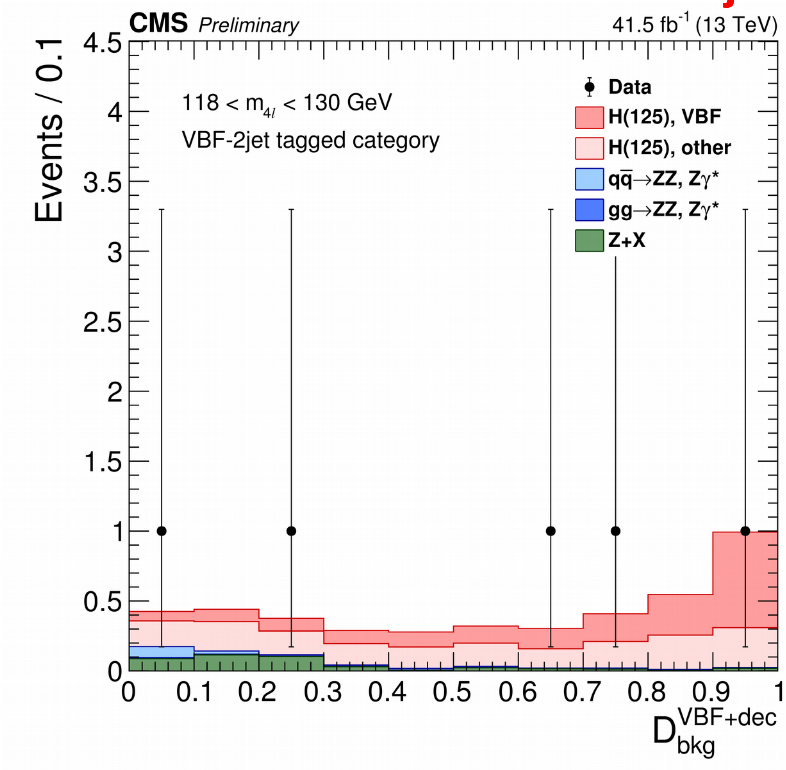
Categorization order ↓

Note: ttH not shown

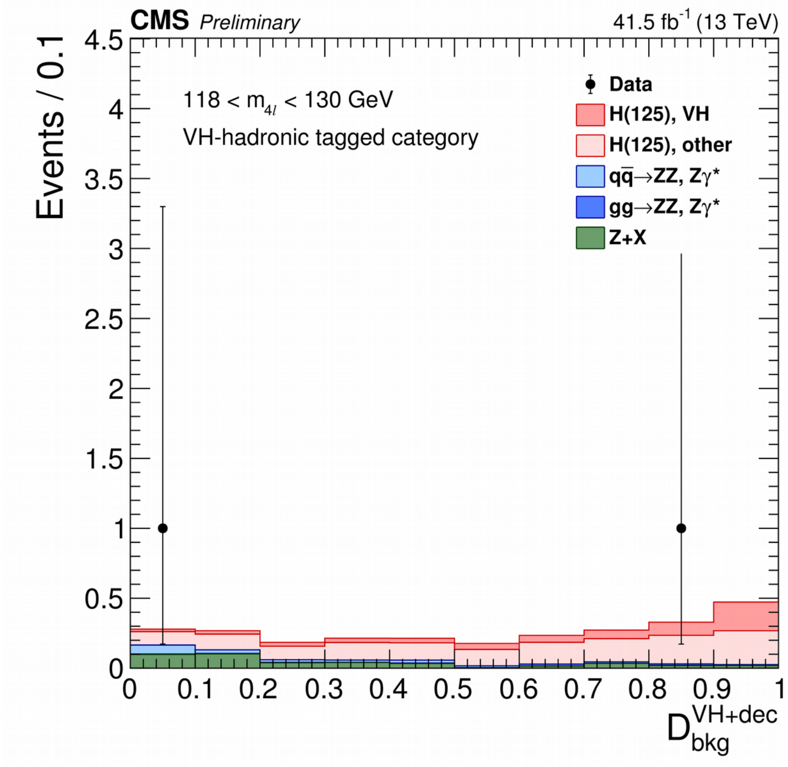
VH/VBF H → ZZ – CMS

Kinematic discriminant distributions (2017 dataset)

VBF-2jet



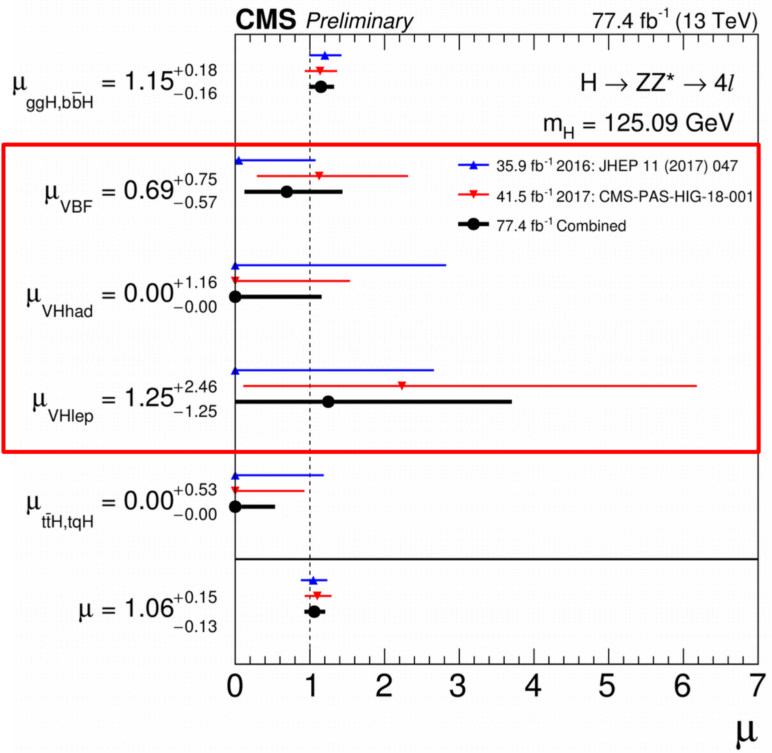
VH hadronic

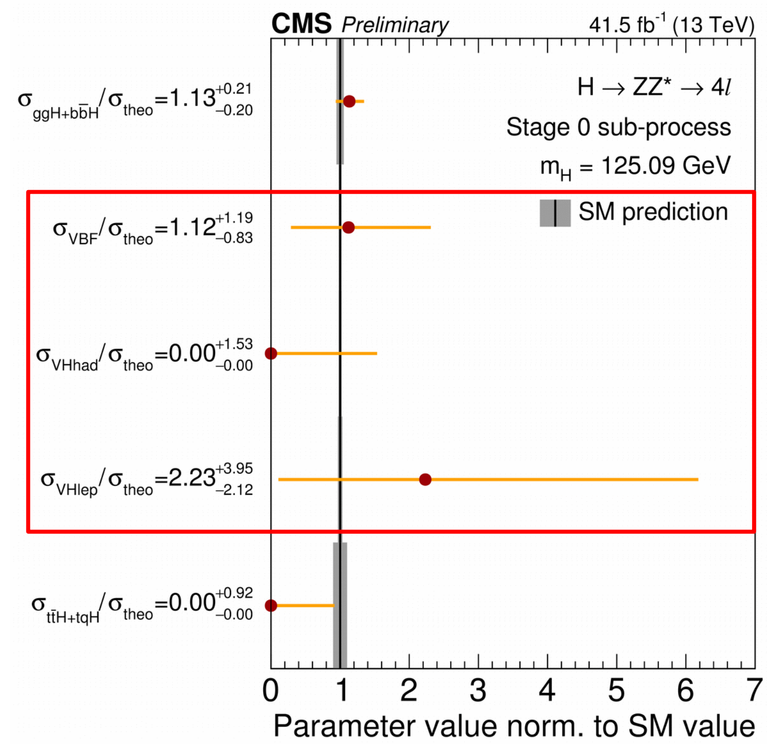


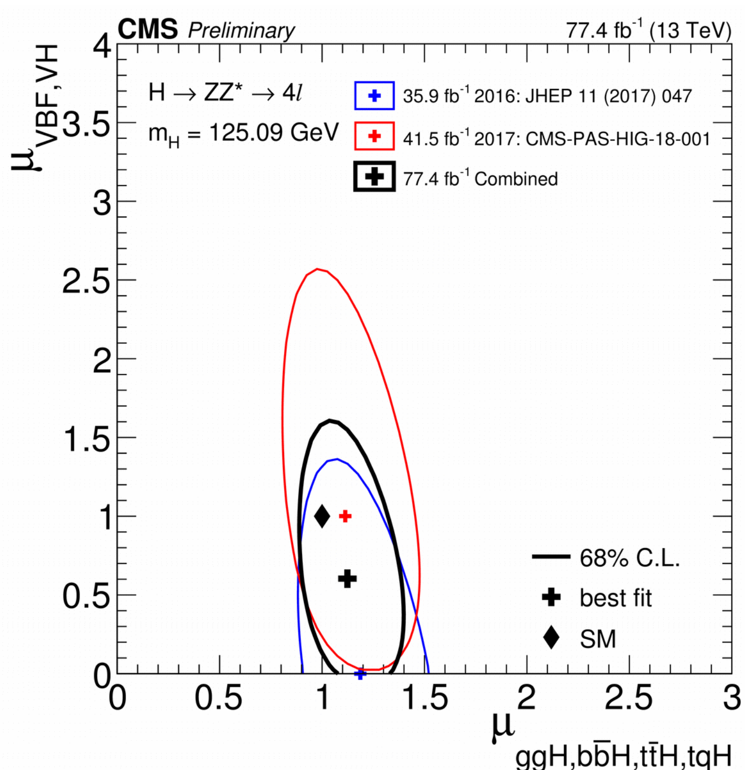
Good separation between VBF/VH and other Higgs production modes
→ Working as designed

VH/VBF H → ZZ – CMS

Cross-sections and signal strengths





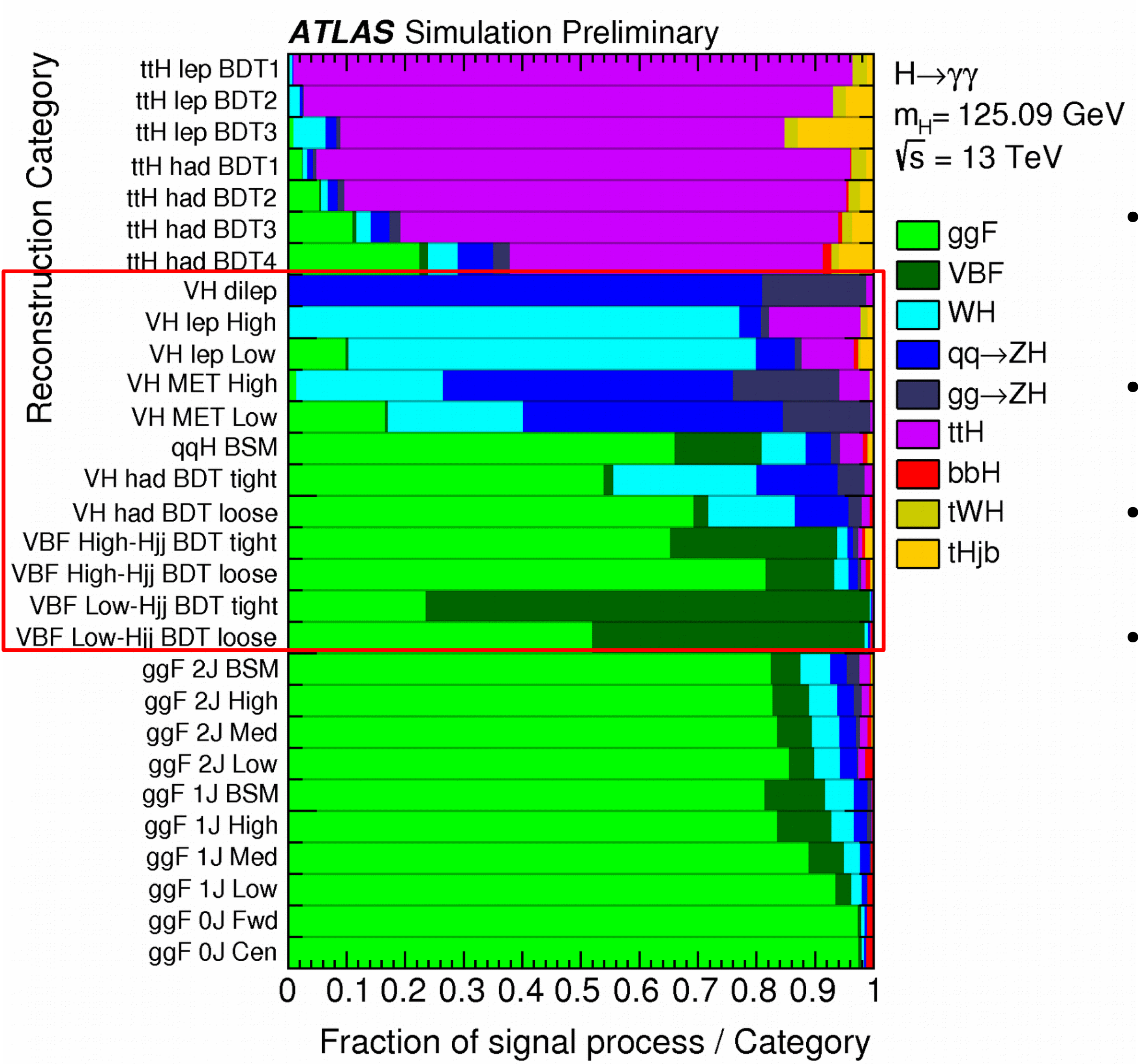


Combination of 2016 and 2017 datasets

Cross-sections and signal strengths are generally consistent with the SM

VH/VBF H → $\gamma\gamma$ – ATLAS

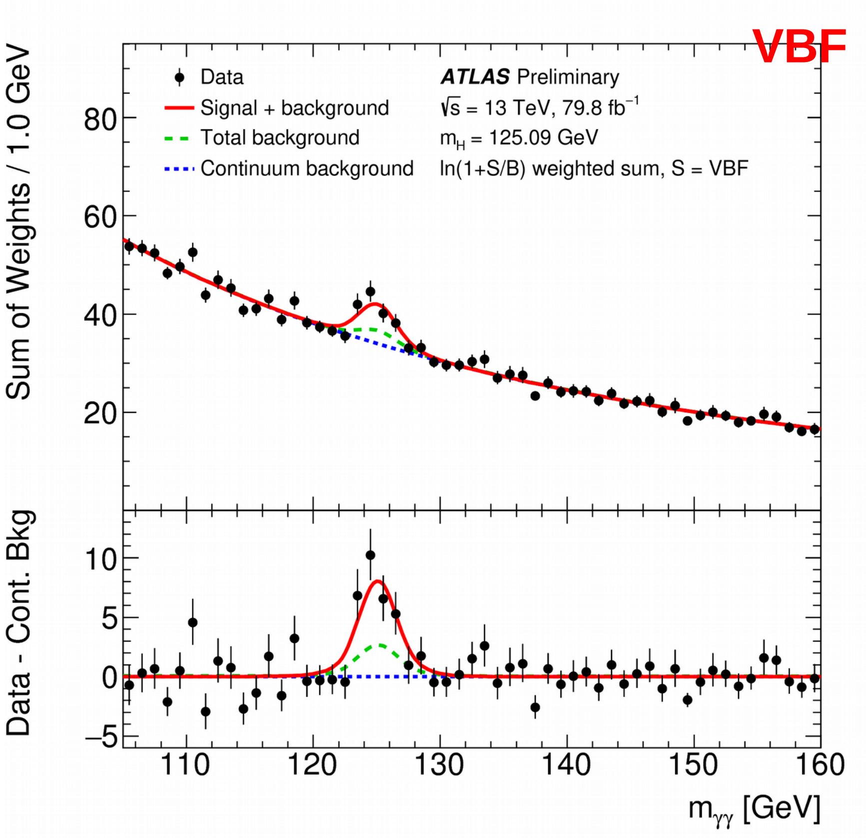
Event categorization and reconstruction level signal composition

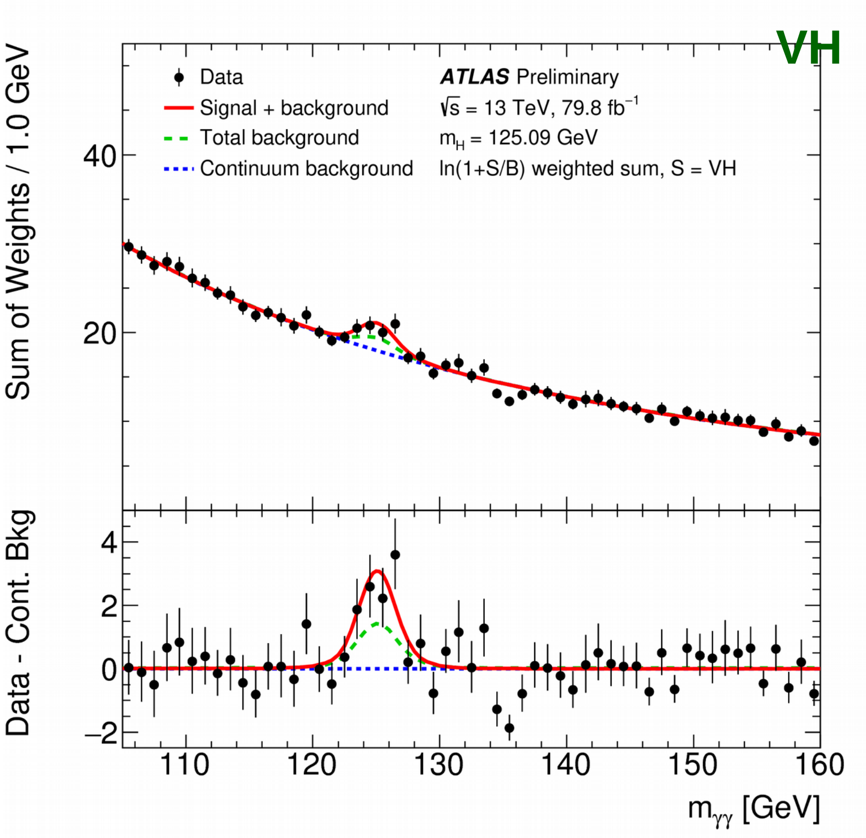


- Reconstructed event categories aimed at stage 1 STXS measurement
  →29 categories in total!
- VH leptonic categories signal composition ~70-80% VH
- Hadronic VH 25-40% of signal is VH
  →Large ggF contamination
- VBF categories signal composition varies from 25-90% VBF
  → Large ggF contamination

VH/VBF H $\rightarrow \gamma\gamma$ – ATLAS

Mass Spectra



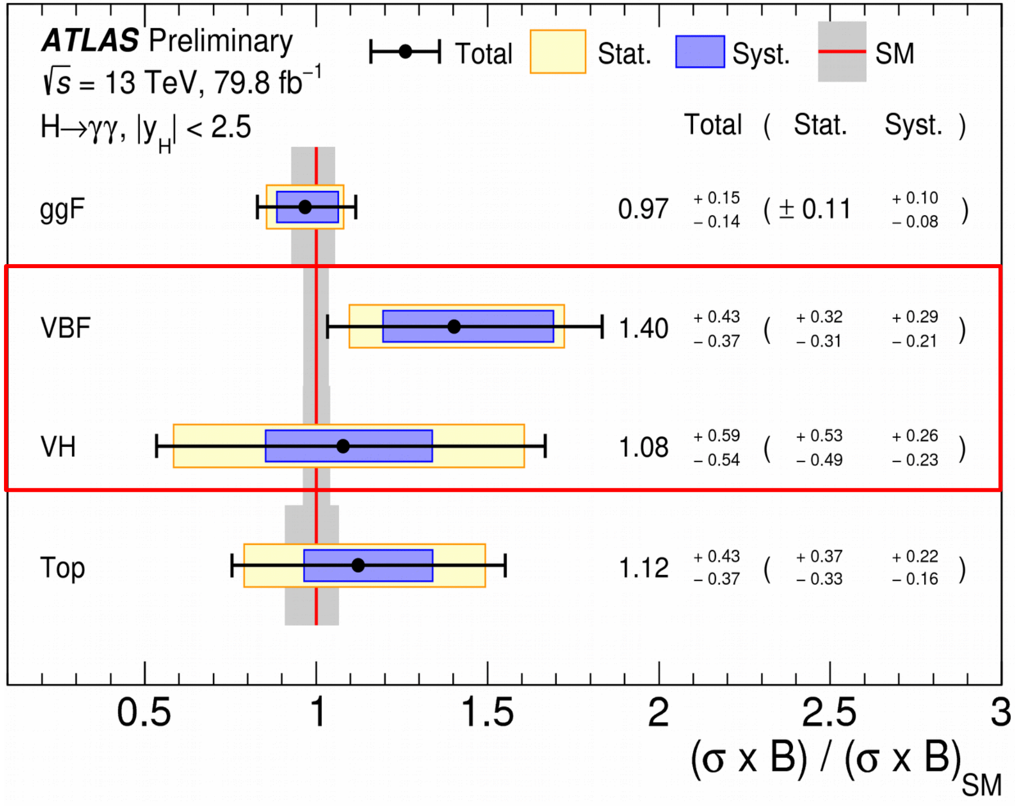


- Signal modeled by a double-sided Crystal Ball function
- Continuum background modeled by a function that depends on the region
  → background fits are performed in $m_{\gamma\gamma}$ sidebands
- Other backgrounds (e.g. $V\gamma\gamma$ for VH) are obtained from simulation
  → Other Higgs production modes are included in the “Total background” line in the above plots

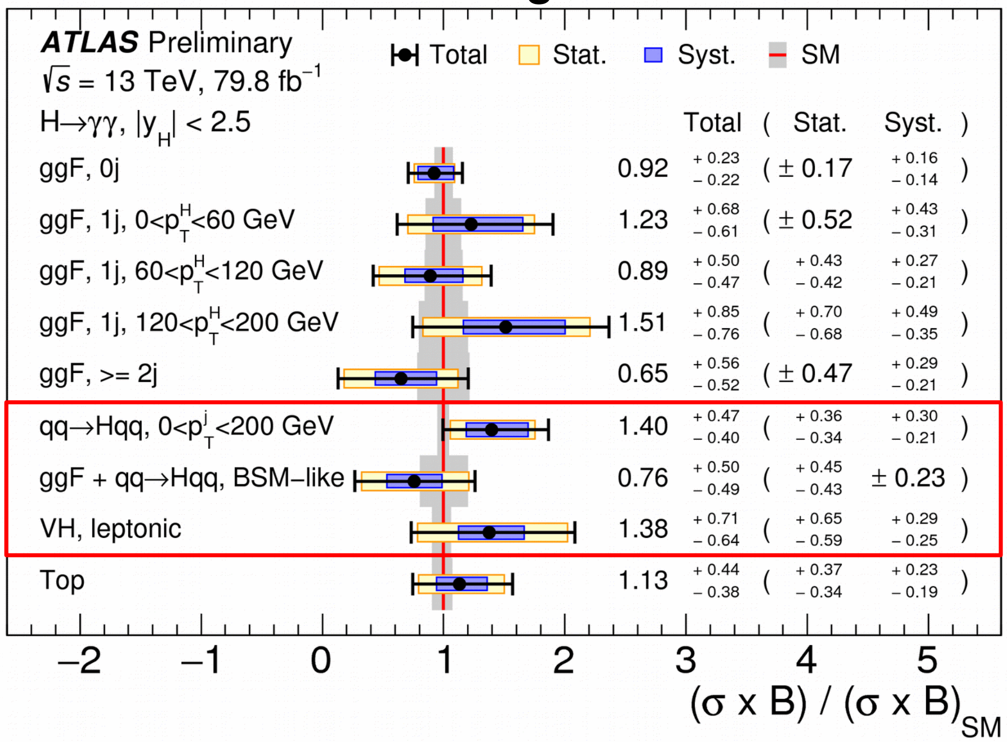
VH/VBF H → $\gamma\gamma$ – ATLAS

Cross-sections

STXS Stage 0 Cross-sections



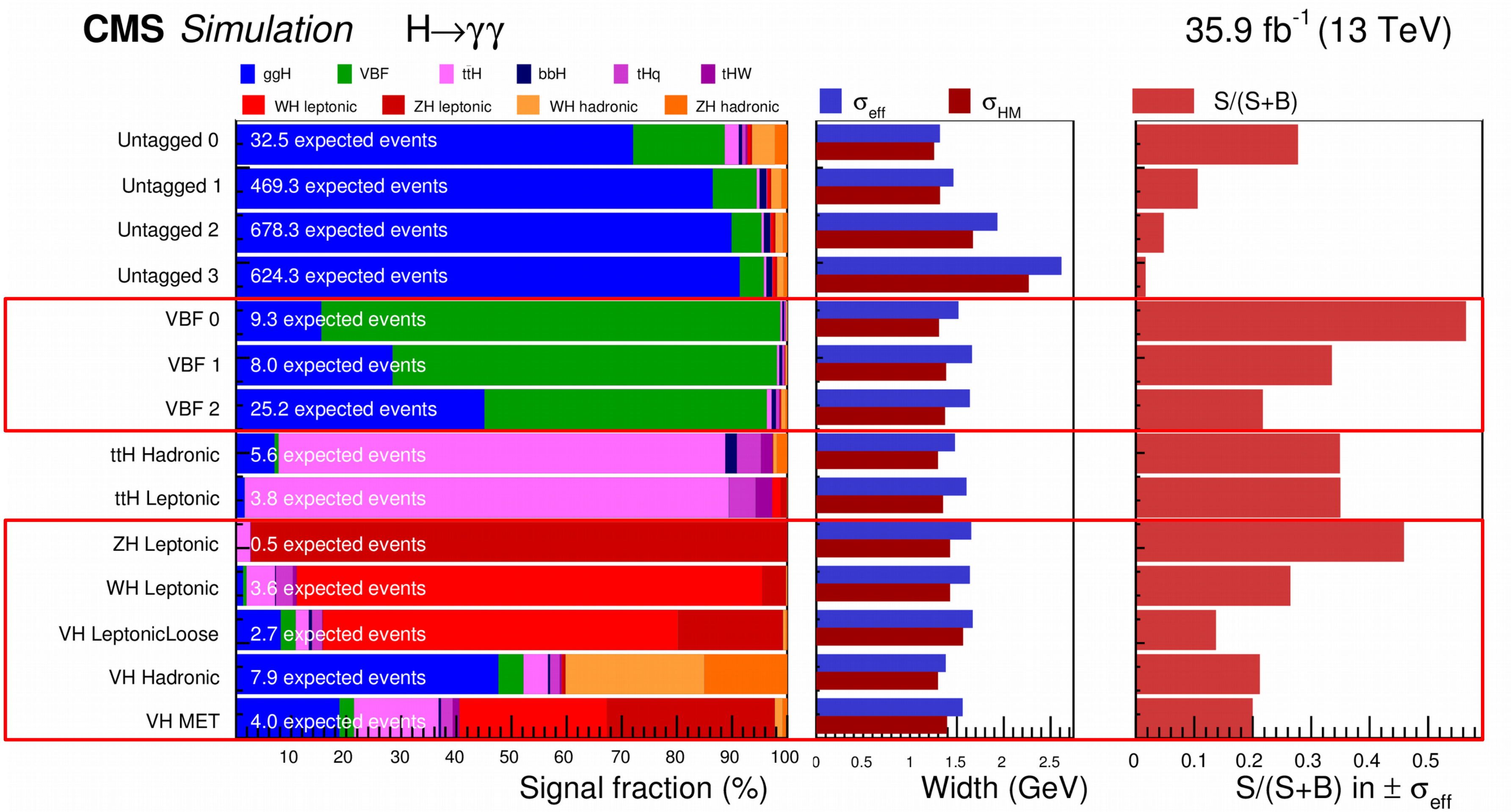
Reduced STXS stage 1 cross-sections



VBF and VH observed cross-sections are compatible with the SM prediction

VH/VBF H → $\gamma\gamma$ – CMS

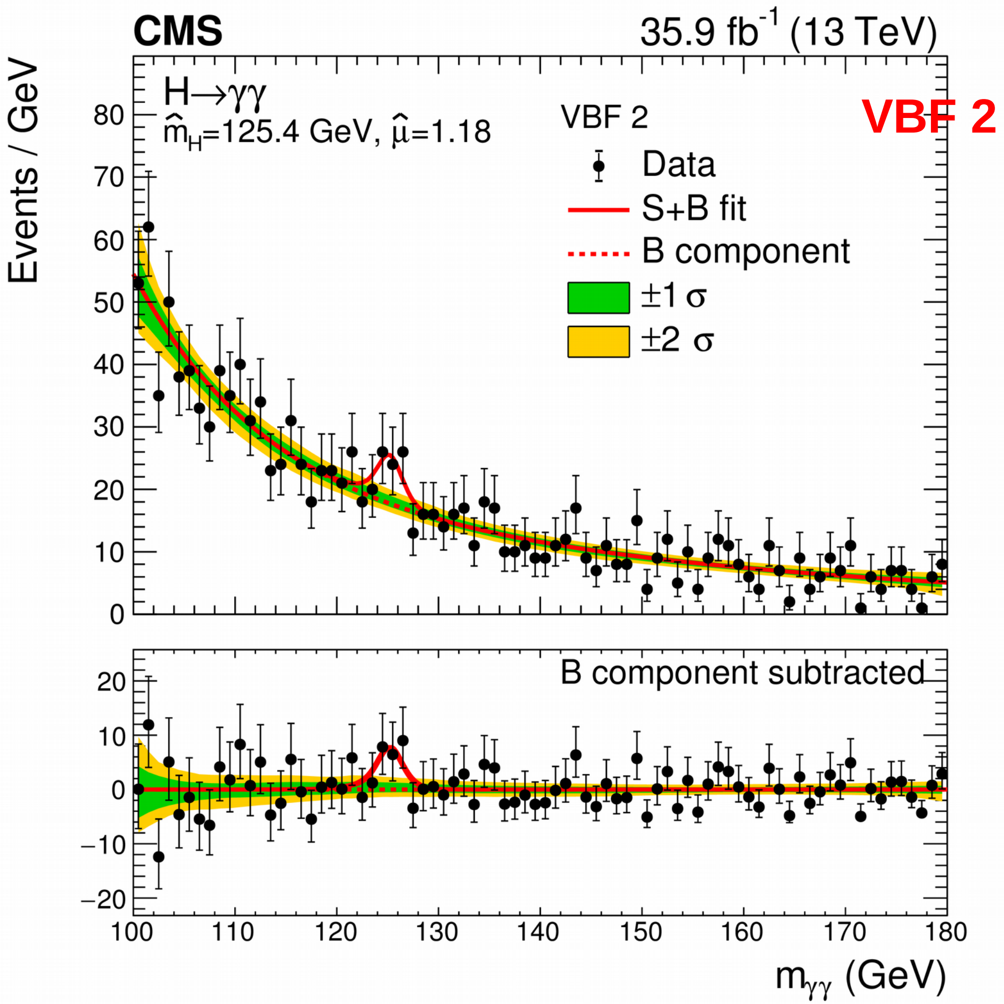
Event categorization and reconstruction level signal composition

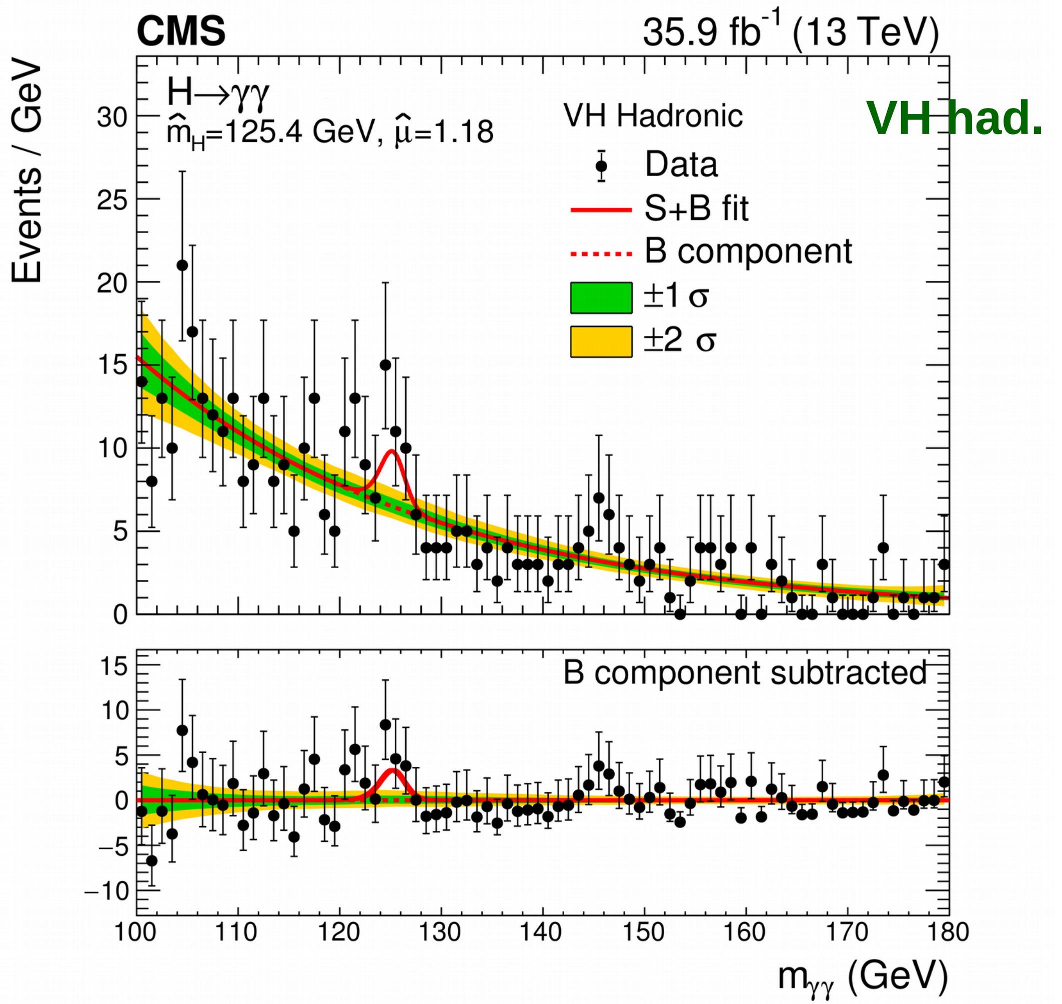


10-25% ggF contamination in VBF and VH hadronic categories

VH/VBF H $\rightarrow \gamma\gamma$ – CMS

Mass Spectra



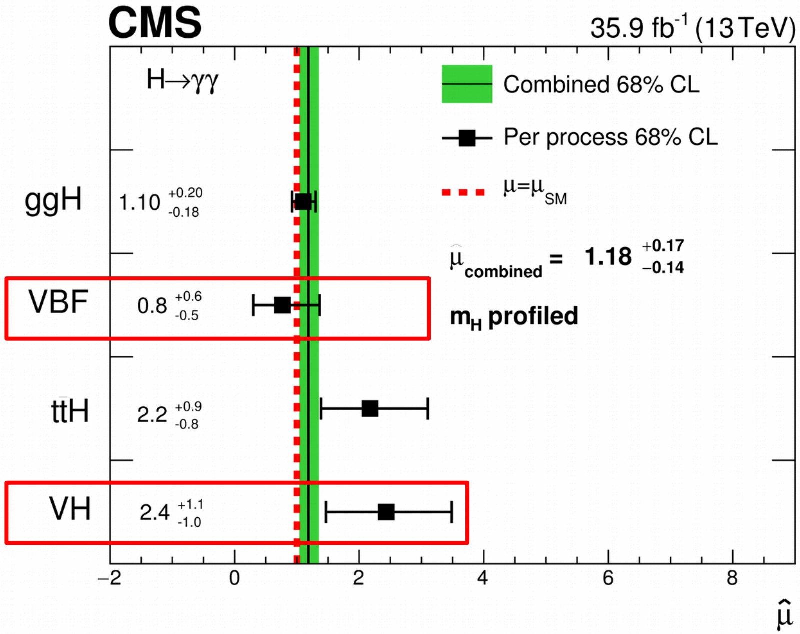


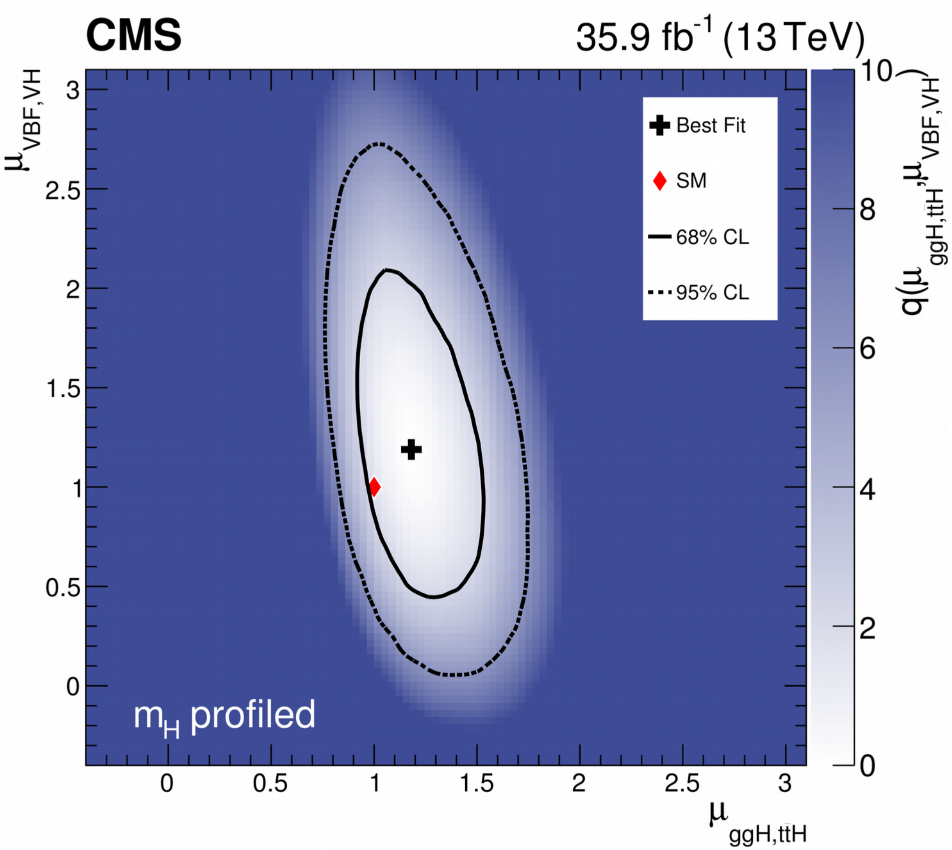
- Signal model for each production process: sum of up to 5 Gaussians
  → Final fit function in each category: sum of normalized function for each production process

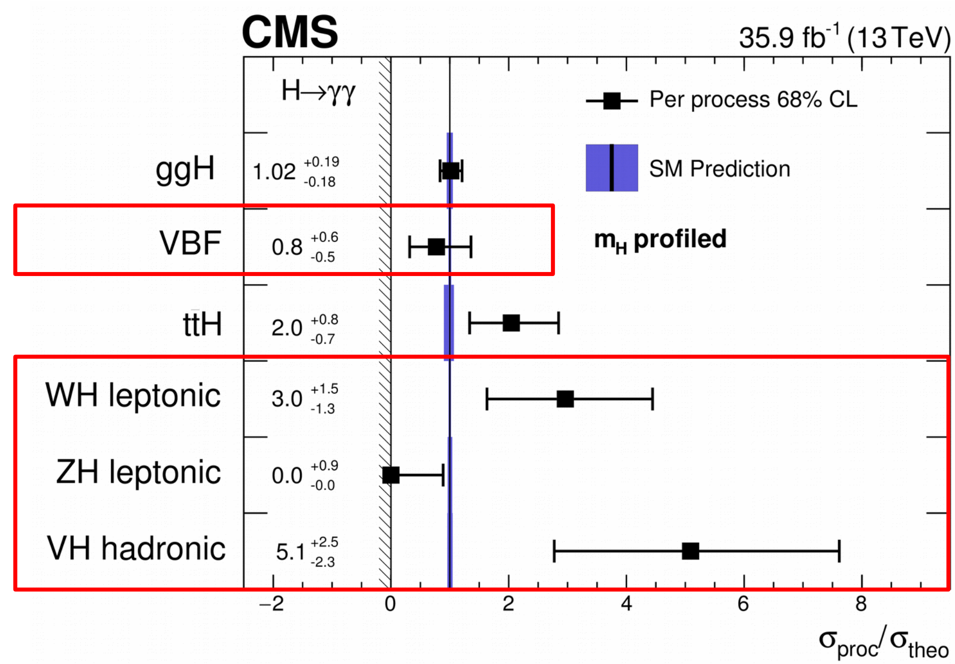
- Background model: Fit function included as a discrete nuisance parameter
  → Exponential, power law, polynomial functions (and more!) are all tried
  → Statistical fit penalized for N degrees of freedom in fit function

VH/VBF H $\rightarrow \gamma\gamma$ – CMS

cross-sections and signal strengths





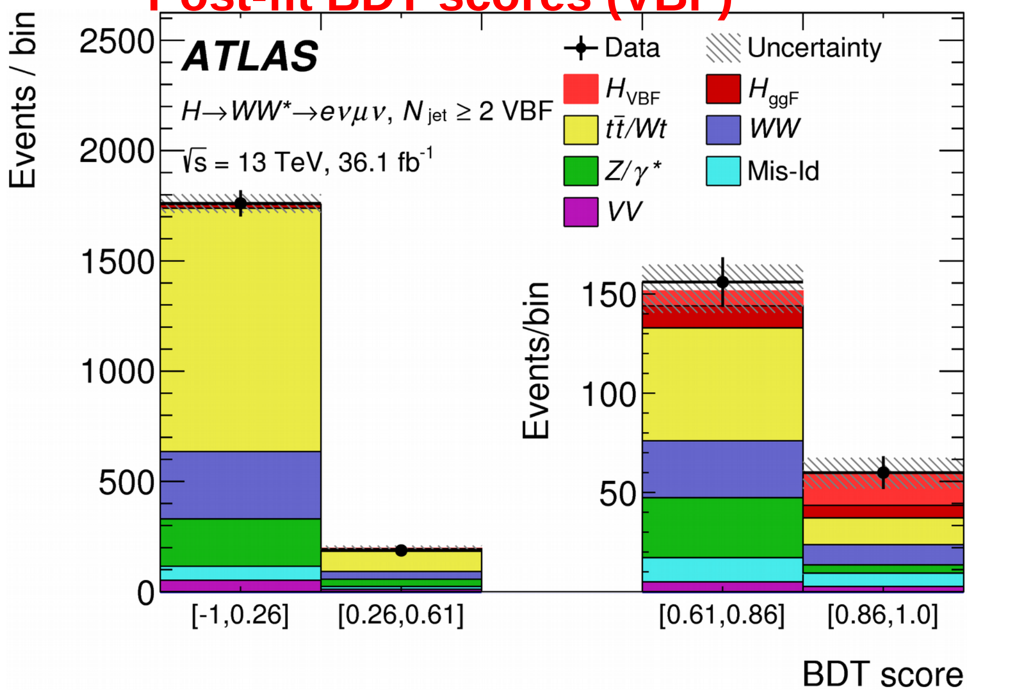


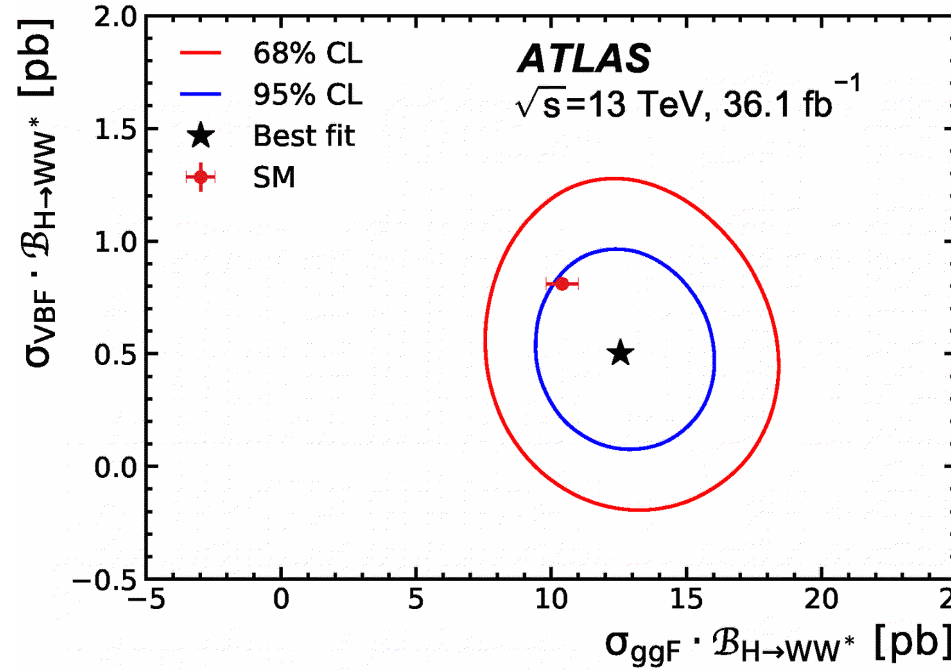
VBF cross-section and signal strength measurements are consistent with the SM

VH cross-sections and signal strengths slightly larger Than the SM prediction.

VBF H → WW – ATLAS

Post-fit BDT scores (VBF)





Discriminant variable	BDT
BDT input variables	m_{jj}, Δy_{jj}, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_{T}, $\sum_\ell C_\ell$, $\sum_{\ell,j} m_{\ell j}$, $p_{\mathrm{T}}^{\mathrm{tot}}$

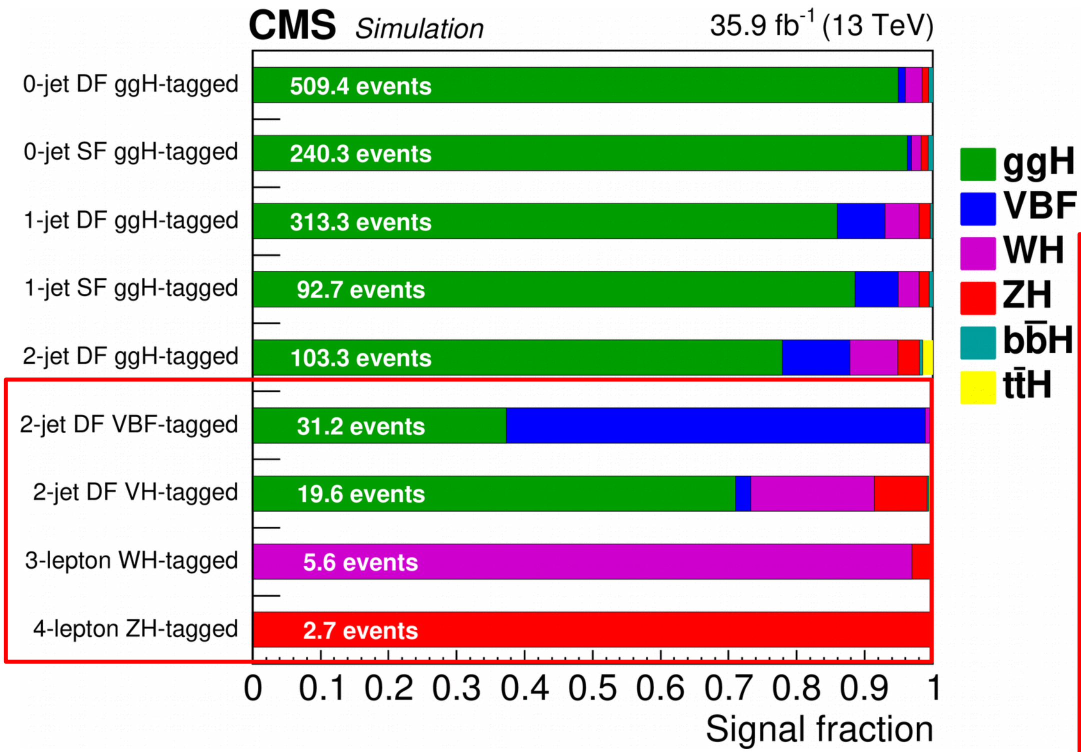
Best fit of two dimensional likelihood for $\sigma_{\mathbf{VBF}}$*$BR_{H\to WW}$ and $\sigma_{\mathbf{ggF}}$*$BR_{H\to WW}$ is consistent with the SM prediction

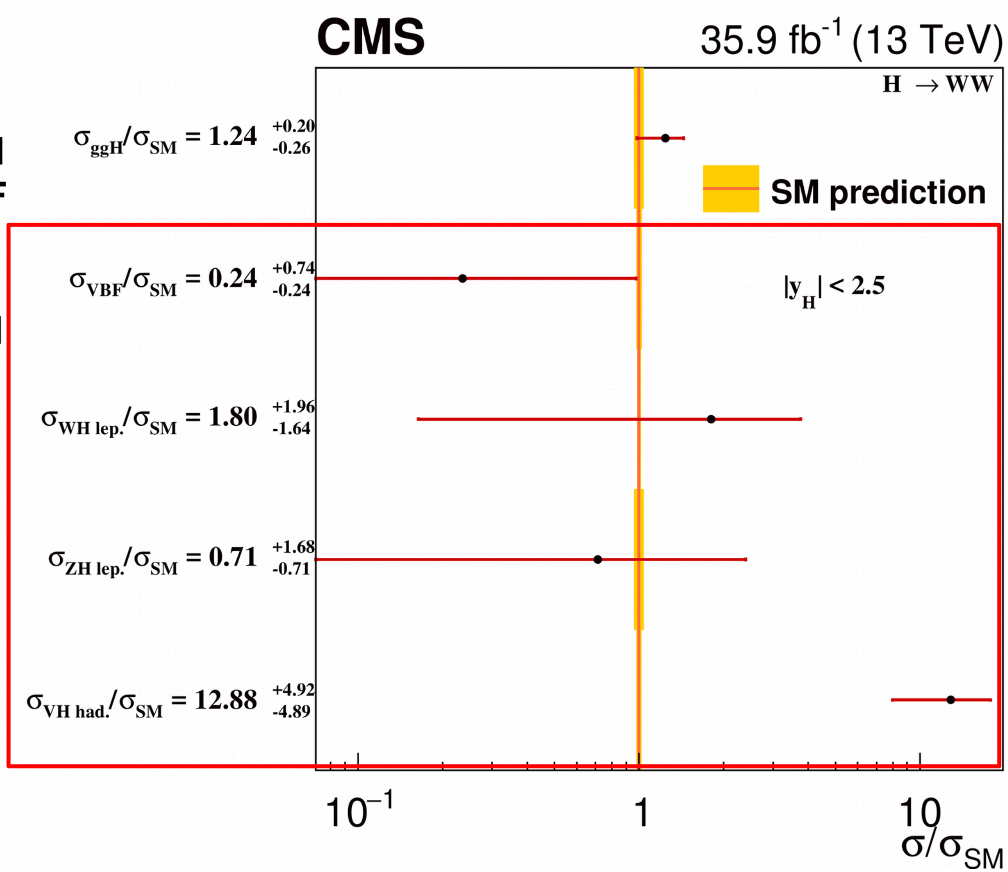
BDT used to enhance discriminating power between signal (VBF) and backgrounds, **including ggF!**

Signal strength

$$\mu_{\mathrm{VBF}} = 0.62^{+0.30}_{-0.28}(\mathrm{stat.}) \pm 0.13(\mathrm{theo\ syst.}) \pm 0.16(\mathrm{exp\ syst.}) = 0.62^{+0.37}_{-0.36}$$

VH/VBF H → WW – CMS





Signicant ggF contamination in **VBF-tagged** and **VH-tagged** categories.

WH-tagged (3 lepton) and **ZH-tagged** (4 lepton) very pure in WH/ZH

VH leptonic and **VBF** cross-sections are consistent with SM, **VH hadronic** cross-section is larger than the SM prediction

Summary

ATLAS

- Stage 0 and reduced Stage 1 STXS measurements from H → ZZ and H → $\gamma\gamma$
  → Both preliminary results used 80fb^{-1} of integrated luminosity
  → Generally consistent with SM predictions

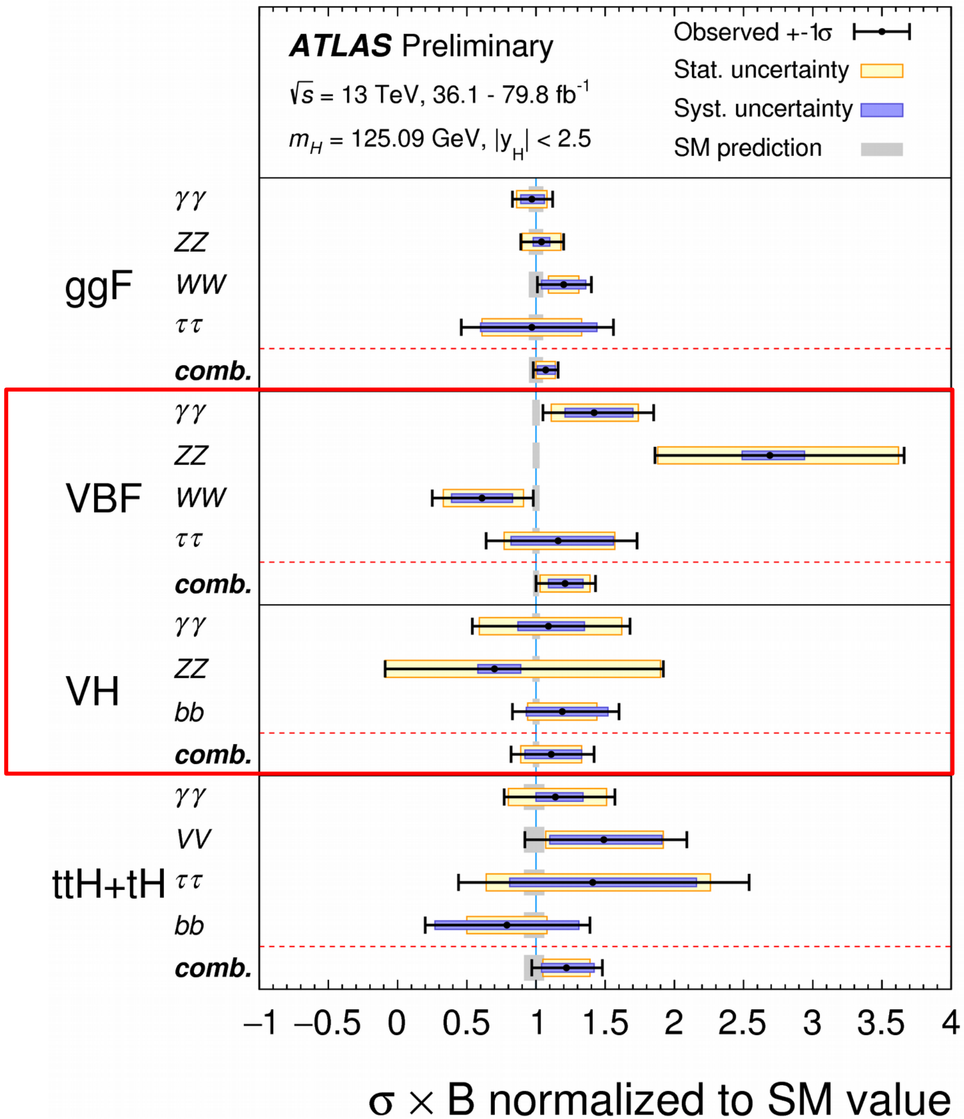
- VBF H → WW Stage 0 cross-section and signal strength measurement with 36 fb^{-1}
  → Consistent with SM prediction

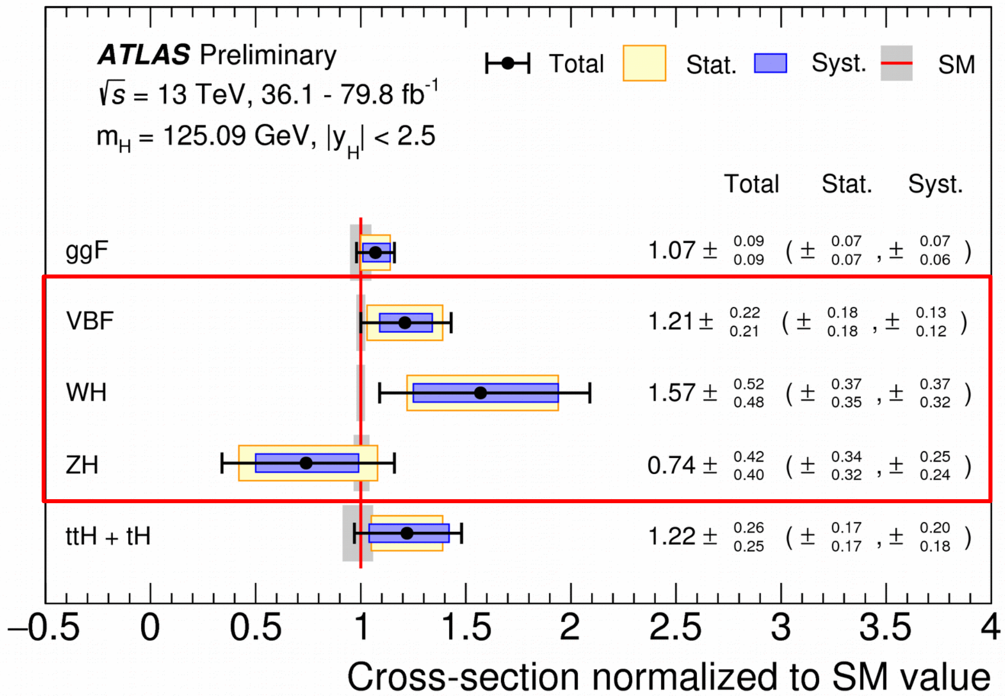
CMS

- Stage 0 STXS measurements from H → ZZ, H → $\gamma\gamma$, *H → WW*
  → H → ZZ result used 80fb^{-1} of integrated luminosity, H → $\gamma\gamma$ and H→ WW used 36fb^{-1}
  → Generally consistent with SM predictions

BACKUP SLIDES

H(125GeV) Combination ATLAS



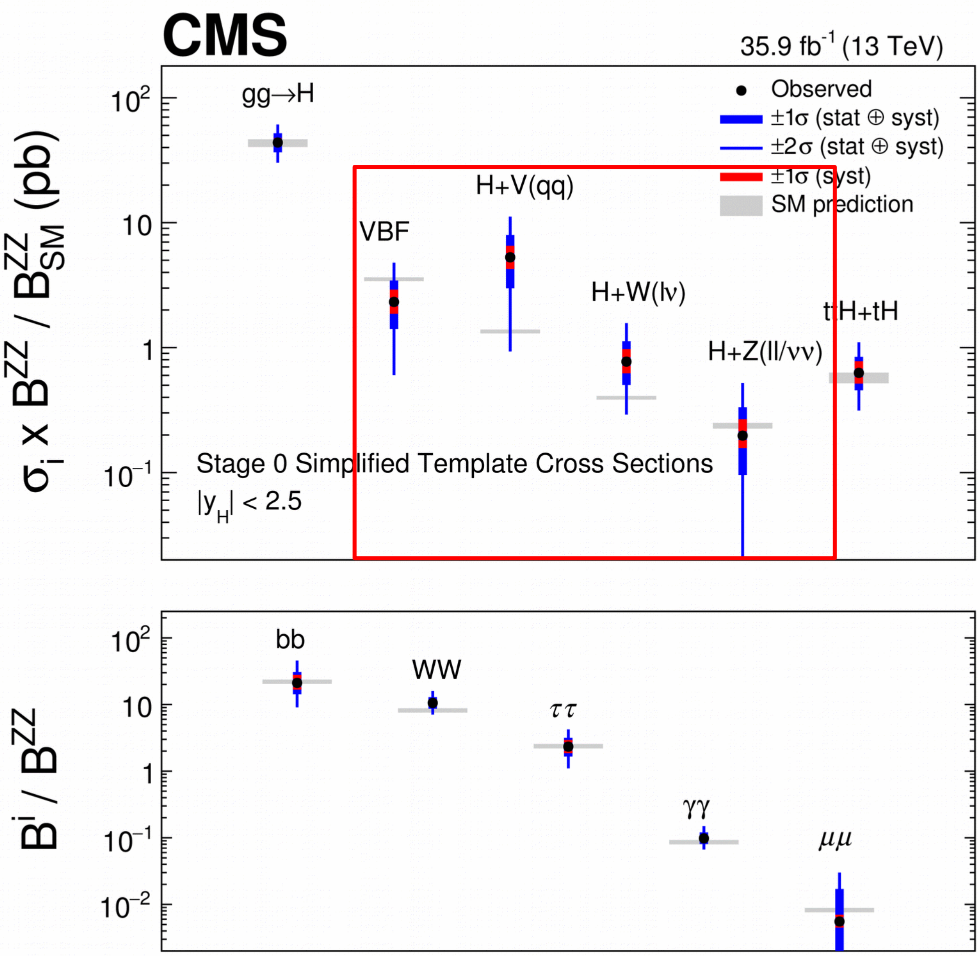


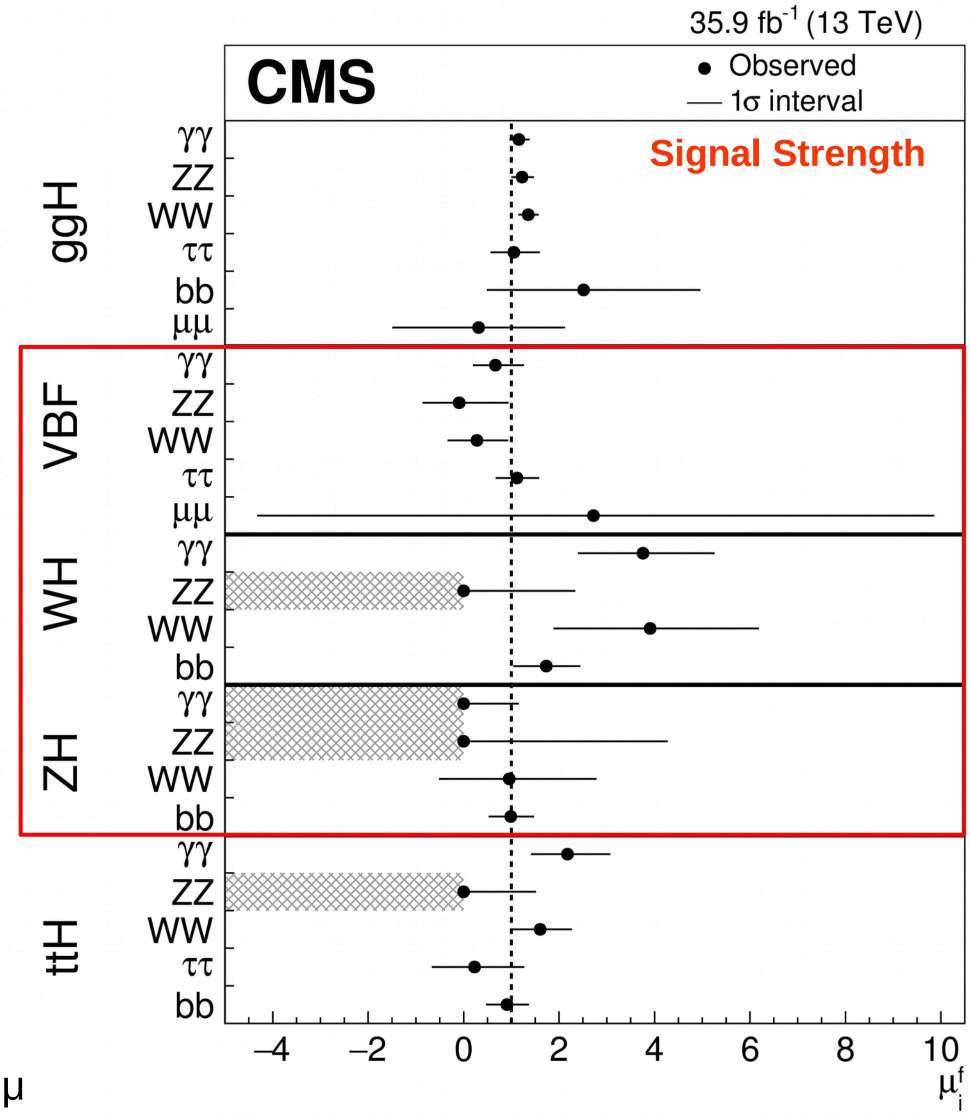
- Combined measurements of Higgs production cross-sections in the ZZ, γγ, WW, bb, ττ,and μμ decay modes

- Not all analyses were performed with the same integrated luminosity:
  → ZZ, γγ, and μμ => 80 fb^{-1}
  → WW and ττ => 36 fb^{-1}
  → tt(H→bb), ttH multi lep => 36 fb^{-1}

- Generally consistent with the SM prediction(s)!

H(125GeV) Combination CMS

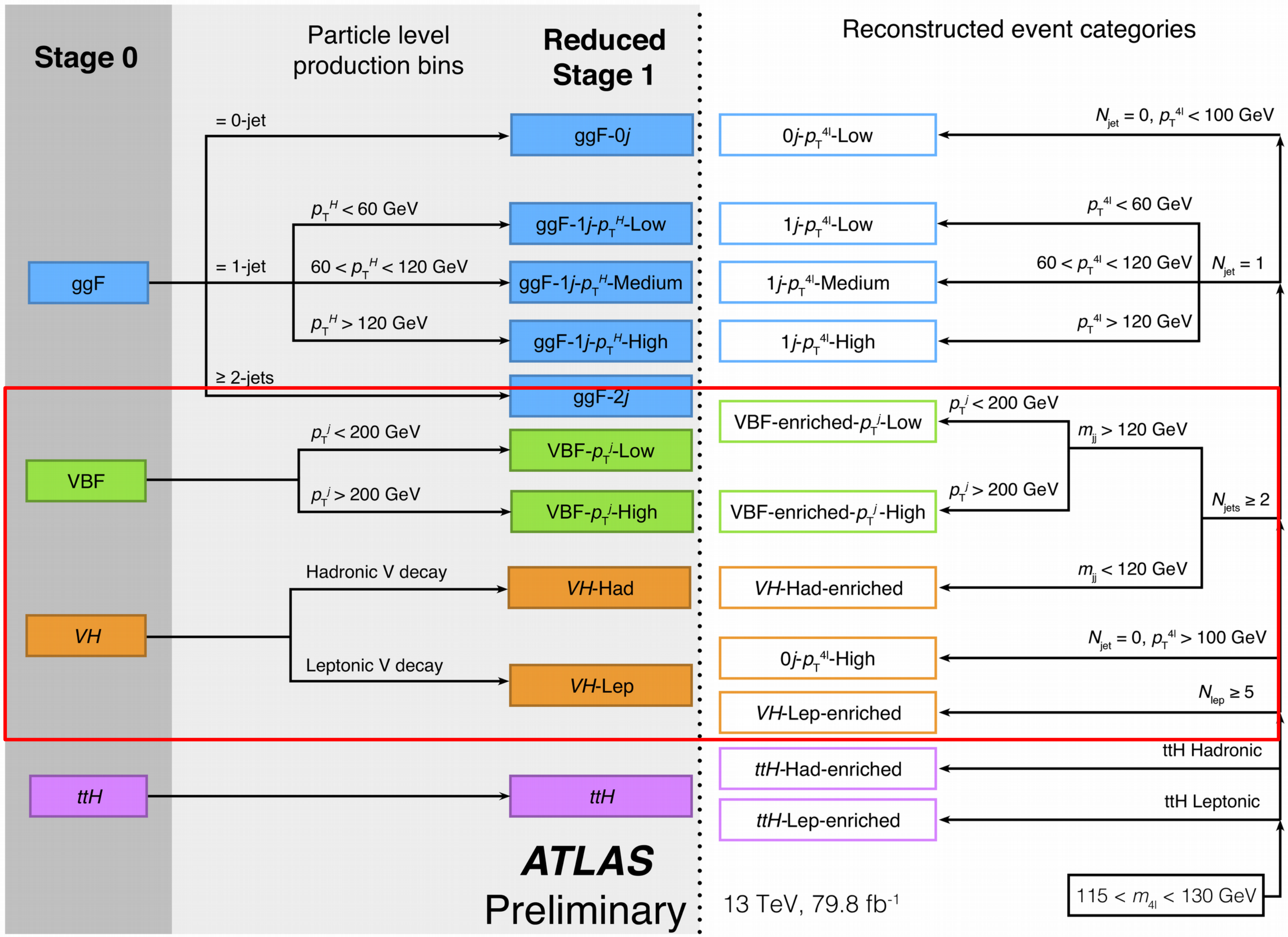




- Combined measurements of Higgs production cross-sections in the ZZ, γγ, WW, bb, ττ, and μμ decay modes
- Integrated luminosity of 35.9 fb-1 for all analyses
- Generally consistent with SM predictions

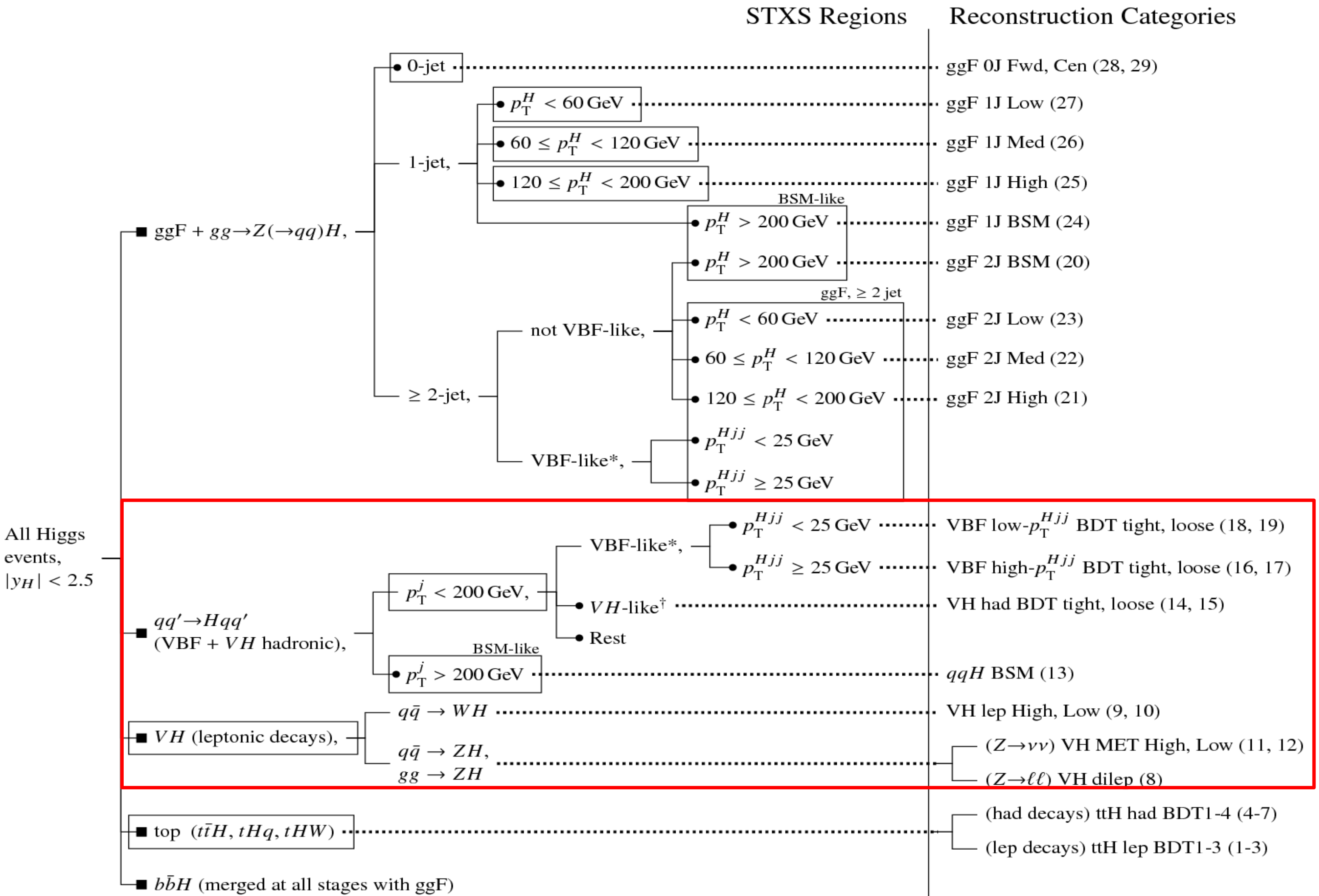
VH/VBF H → ZZ – ATLAS

Event categorization for STXS stage 0 and reduced stage 1



VH/VBF H → γγ – ATLAS

Event categorization for STXS



*VBF-like: m_{jj} > 400 GeV, $|\Delta y_{jj}|$ > 2.8

†VH-like: 60 < m_{jj} < 120 GeV

VH → tautau – CMS

Event Selection

WH selection

$p_T^{\tau_h} > 20\,\text{GeV}$, $|\eta^{\tau_h}| < 2.3$, $I^e < 0.1$, $I^\mu < 0.15$, b veto

Channel	Trigger ($p_T/|\eta|$)	Lepton selection: p_T (GeV)	τ_h selection: isolation
$e\mu\tau_h$	$\mu(22/2.1)$ or $e(25/2.1)$	$p_T^e > 15$ or 26, $p_T^\mu > 23$ or 15	MVA τ_h (60% eff.)
$\mu\mu\tau_h$	$\mu(22/2.1)$	$p_T^\mu > 23$, $p_T^\mu > 15$	MVA τ_h (60% eff.)
$e\tau_h\tau_h$	$e(25/2.1)$	$p_T^e > 26$	MVA τ_h (55 or 65% eff.)
$\mu\tau_h\tau_h$	$\mu(22/2.1)$	$p_T^\mu > 23$	MVA τ_h (55 or 65% eff.)

ZH selection

Z boson reconstructed from opposite charge, same-flavor light leptons, $60 < m_{\ell\ell} < 120\,\text{GeV}$, b veto

τ_h baseline requirements: $p_T^{\tau_h} > 20$, $|\eta^{\tau_h}| < 2.3$, MVA τ_h (65% efficiency)

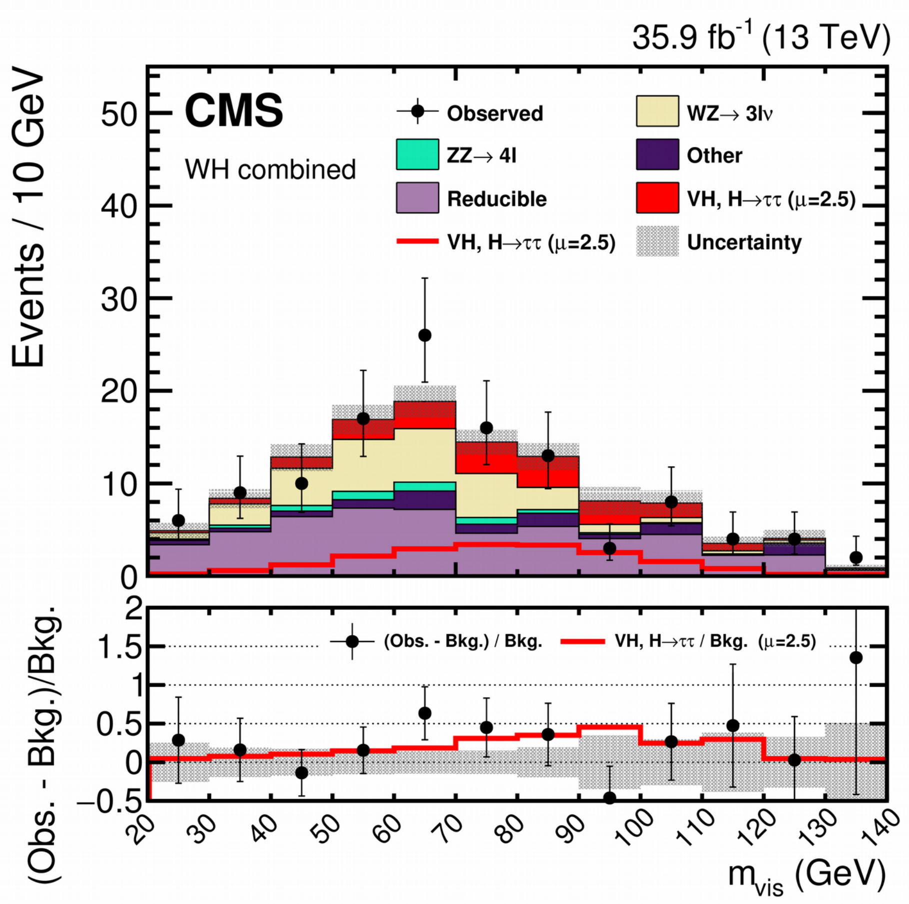
e baseline requirements: $p_T^e > 10$, $|\eta^e| < 2.5$, MVA ID (90% efficiency)

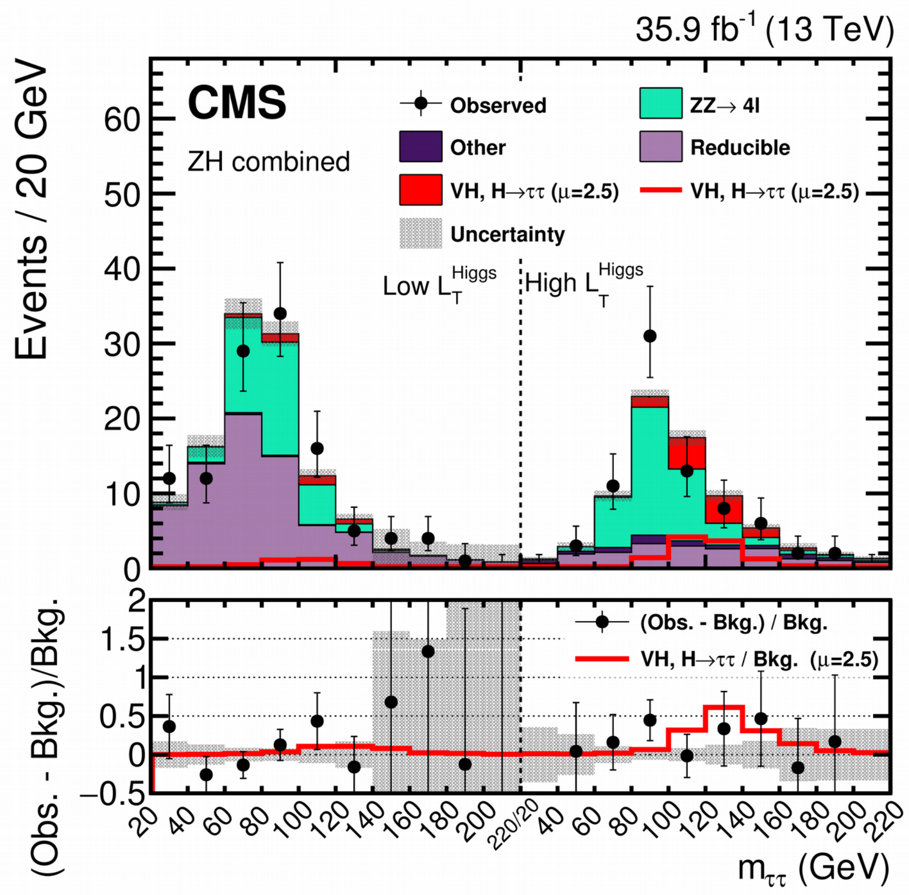
μ baseline requirements: $p_T^\mu > 10$, $|\eta^\mu| < 2.4$, μ ID ($>$ 99% efficiency) , $I^\mu < 0.25$

Channel	Trigger ($p_T/|\eta|$)	Lepton selection: p_T (GeV)	Lepton selection: isolation
$ee\mu\tau_h$			$I^\mu < 0.15$
$eee\tau_h$	$[e_1(23/2.5)\,\&\,e_2(12/2.5)]$	$[p_T^{e_1} > 24\,\&\,p_T^{e_2} > 13]$	e ID (80% eff.), $I^e < 0.15$
$ee\tau_h\tau_h$	or $e_1(27/2.5)$	or $p_T^{e_1} > 28$	baseline selection listed above
$eee\mu$			e ID (80% eff.), $I^e < 0.15$, $I^\mu < 0.15$
$\mu\mu\mu\tau_h$			$I^\mu < 0.15$
$\mu\mu e\tau_h$	$[\mu_1(17/2.4)\,\&\,\mu_2(8/2.4)]$	$[p_T^{\mu_1} > 18\,\&\,p_T^{\mu_2} > 10]$	e ID (80% eff.), $I^e < 0.15$
$\mu\mu\tau_h\tau_h$	or $\mu_1(24/2.4)$	or $p_T^{\mu_1} > 25$	baseline selection listed above
$\mu\mu e\mu$			e ID (80% eff.), $I^e < 0.15$, $I^\mu < 0.15$

VH → tautau – CMS

Mtautau





VH → tautau – CMS

Cross-section measurement