General review of Higgs properties

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(On behalf of ATLAS experiment)

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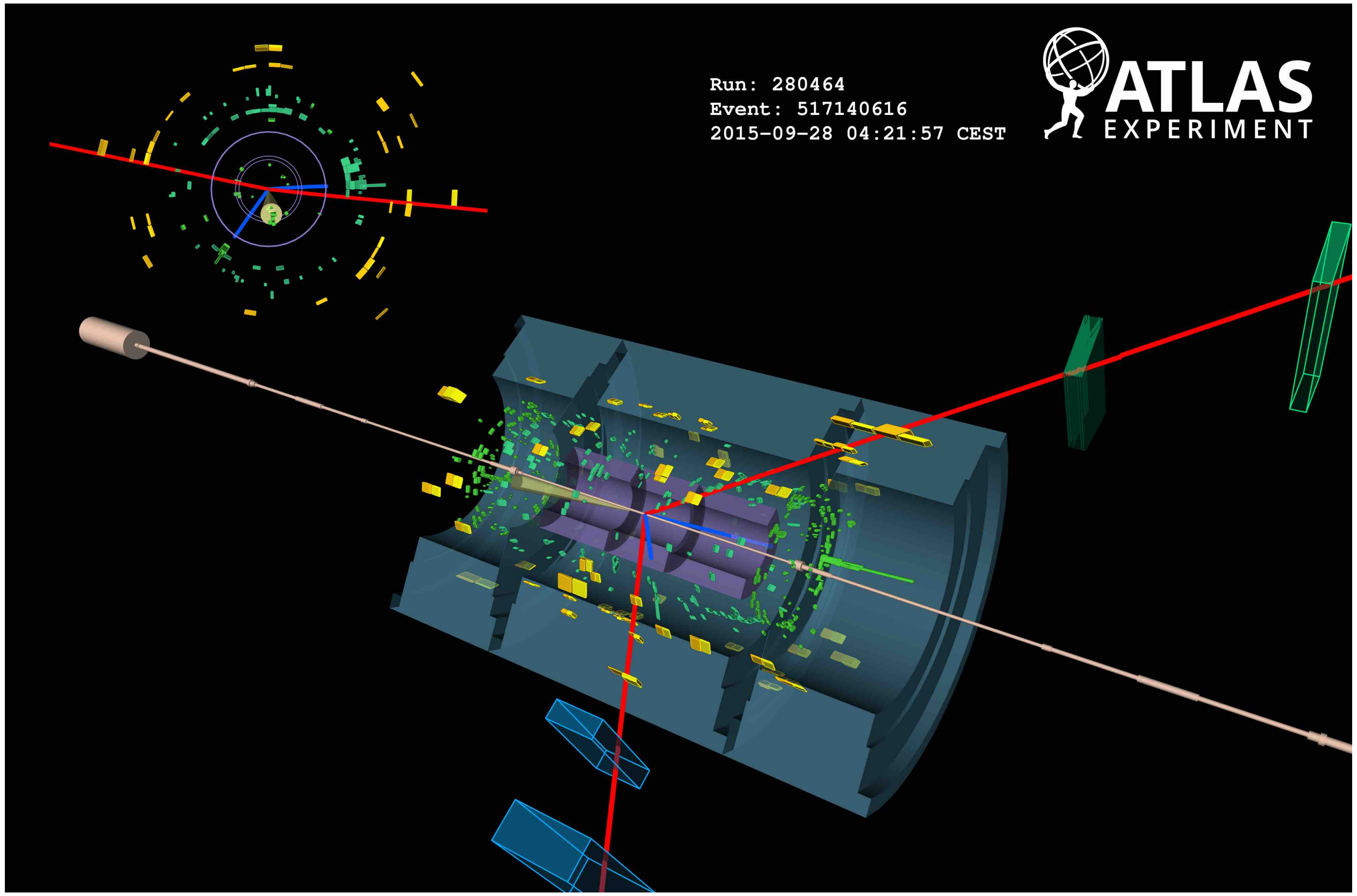
How well do we know the 10 years old

$$\mathcal{L} = -g_{Hf\bar{f}}\bar{f}fH + \frac{g_{HHH}}{6}H^3 + \frac{g_{HHHH}}{24}H^4 + \delta_V V_\mu V^\mu \left(g_{HVV}H + \frac{g_{HHVV}}{2}H^2\right)$$

$$g_{Hf\bar{f}} \equiv y_f = \frac{m_f}{v},\ g_{HVV} = \frac{2m_V^2}{v},\ g_{HHVV} = \frac{2m_V^2}{v^2},\ g_{HHH} = \frac{3m_H^2}{v},\ g_{HHHH} = \frac{3m_H^2}{v^2};$$

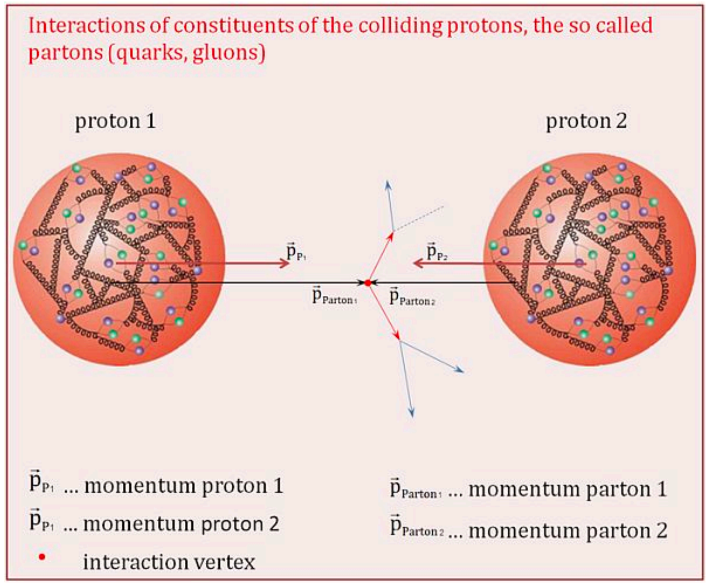
<u>Outline</u>

- **Introduction**
- **H → $\gamma\gamma$ STXS measurement**
- **H width from off-shell ZZ***
- **Higgs CP from H → ZZ * → 4l**
- **Search for HH in 4b final state**
- **Charm Yukawa in VH mode**
- **Summary**



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayRun2Physics

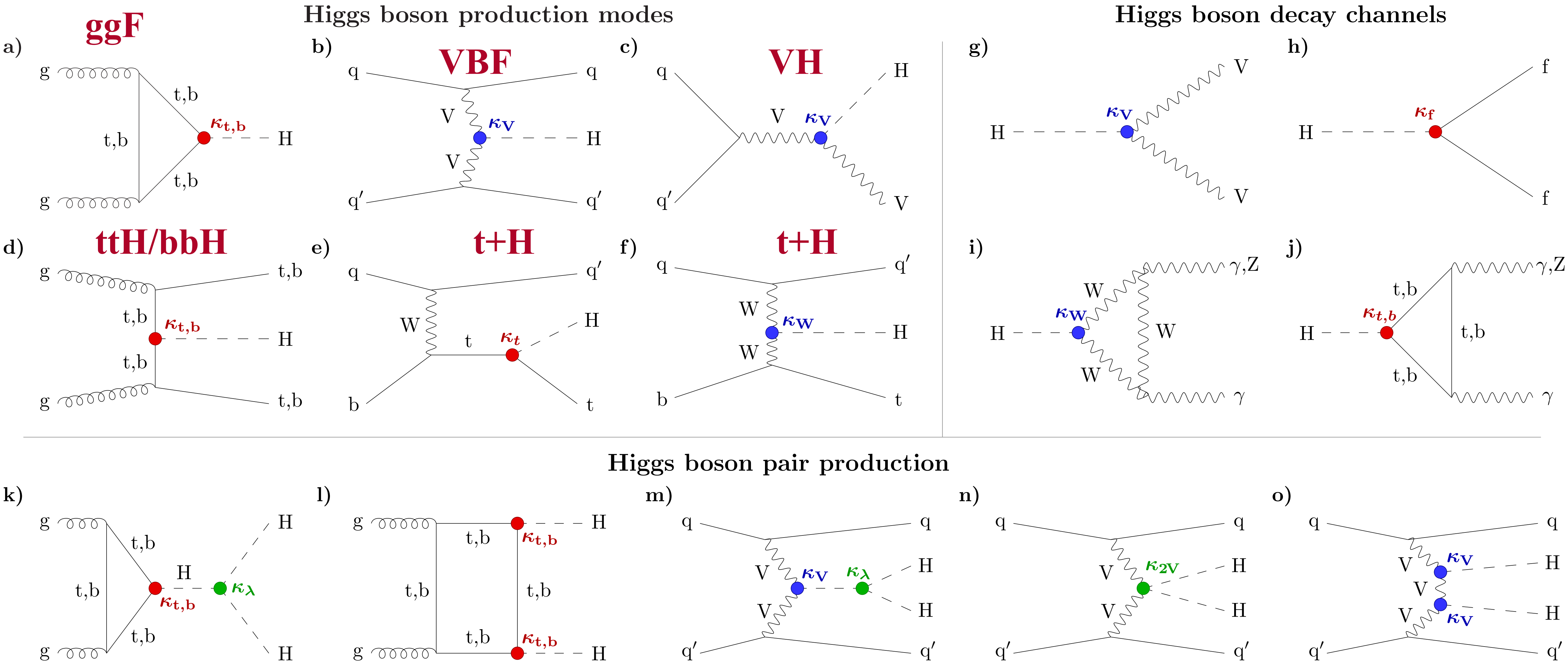
We need to produce some H to detect



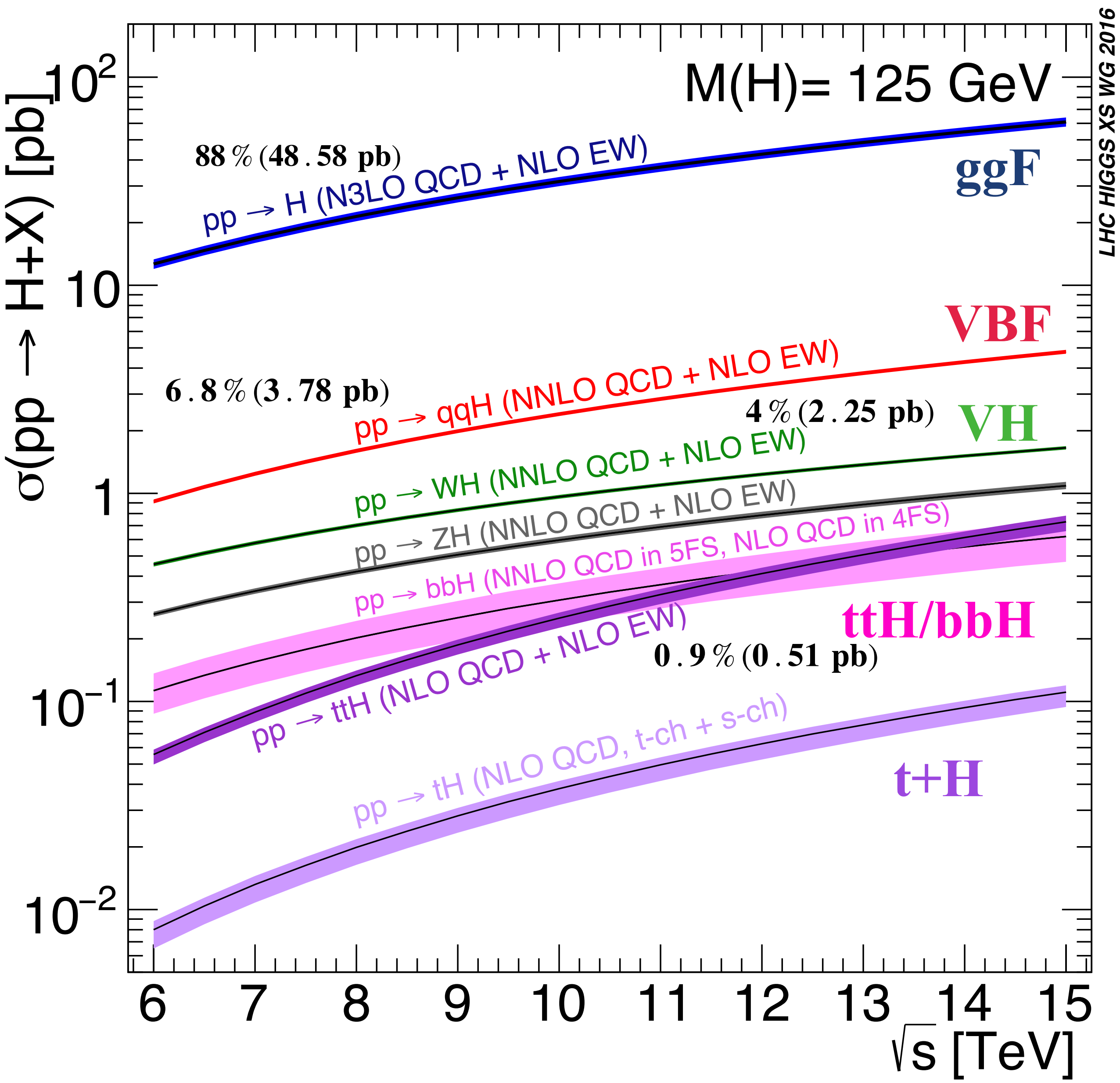
$$\mathbf{C = \kappa_C\ C_{SM}}$$

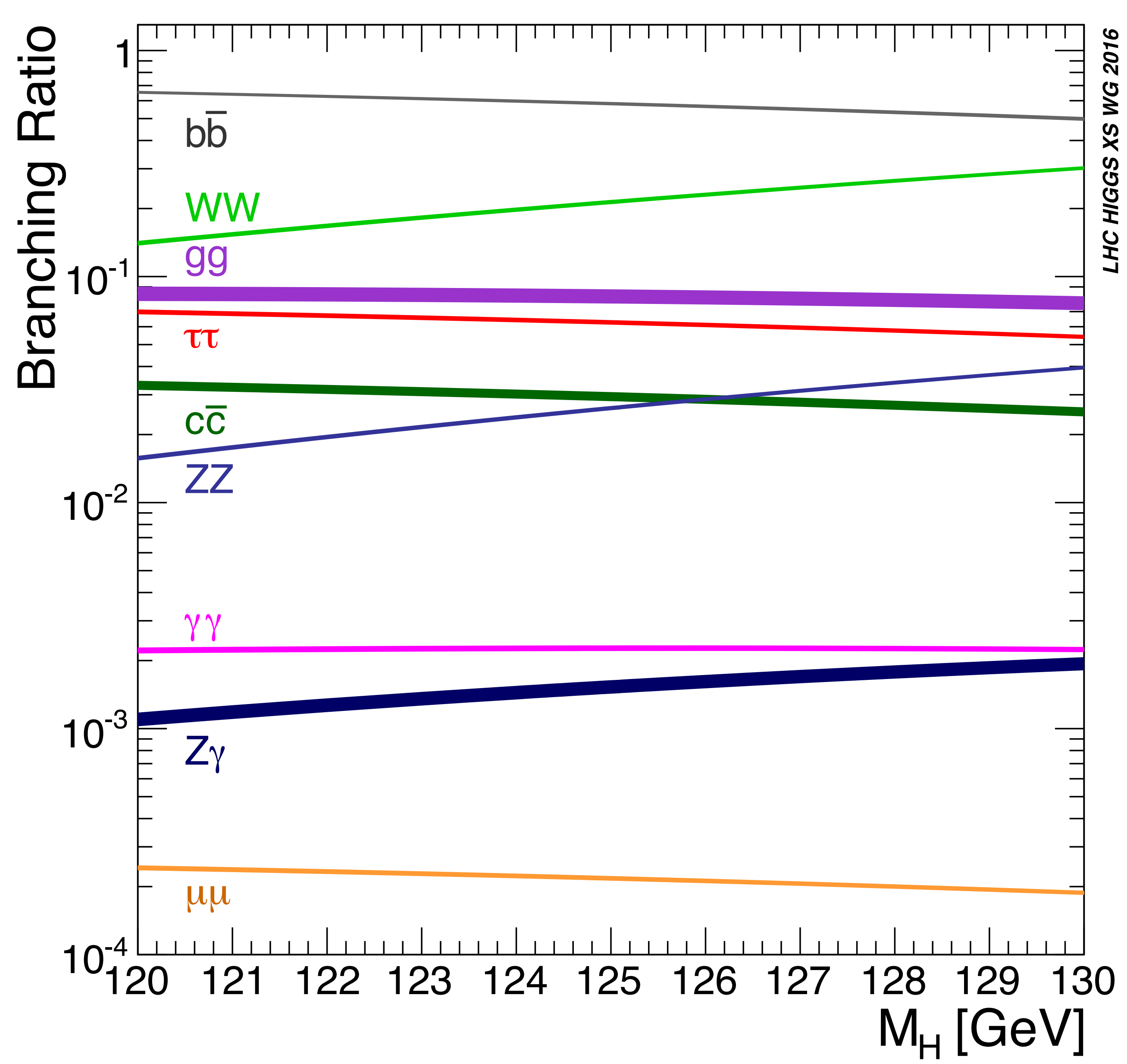
$$\bar{N}(pp \to H \to ab) \sim \int dx_1 dx_2 \sum_{ij} f_i(x_1) f_j(x_2) \hat{\sigma}(i+j \to H) \times \mathscr{BR}(H \to a+b)$$

Nature volume 607, pages 60–68 (2022)



We measure a combination

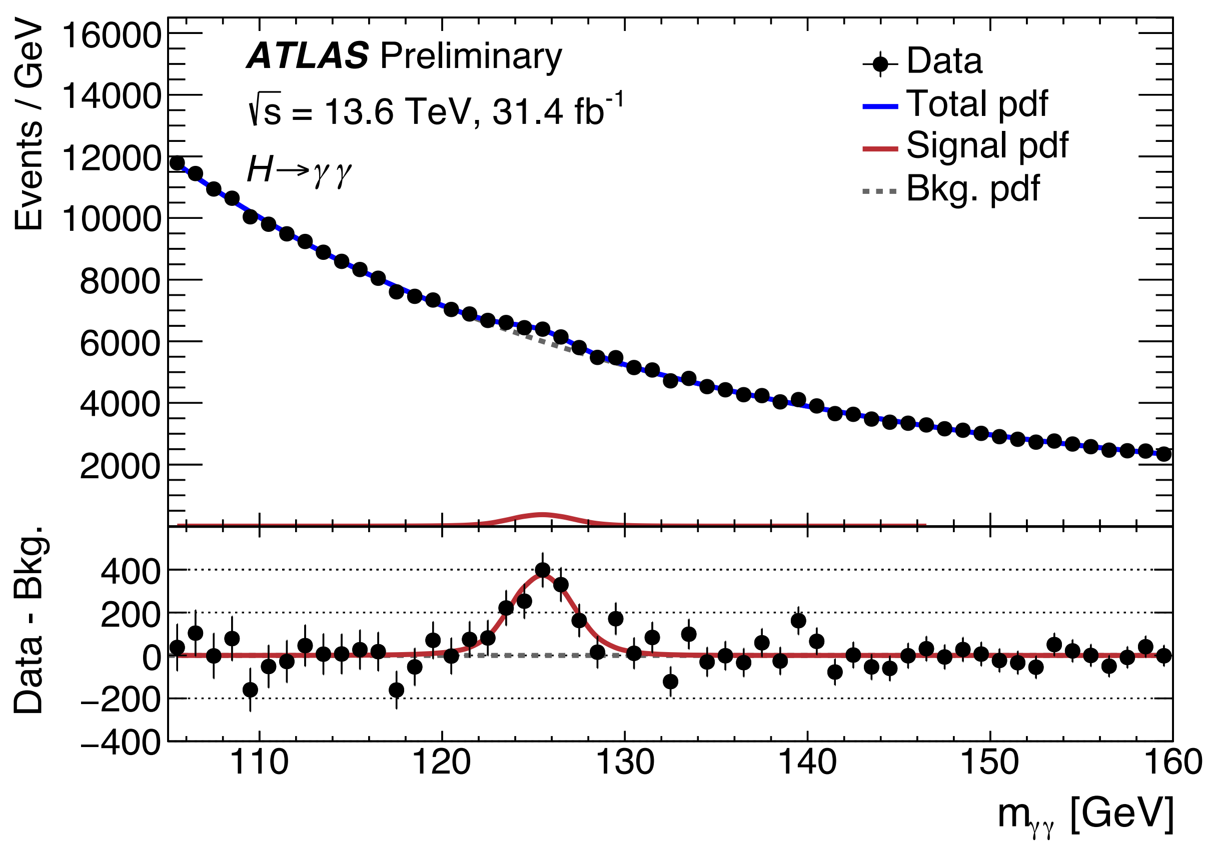


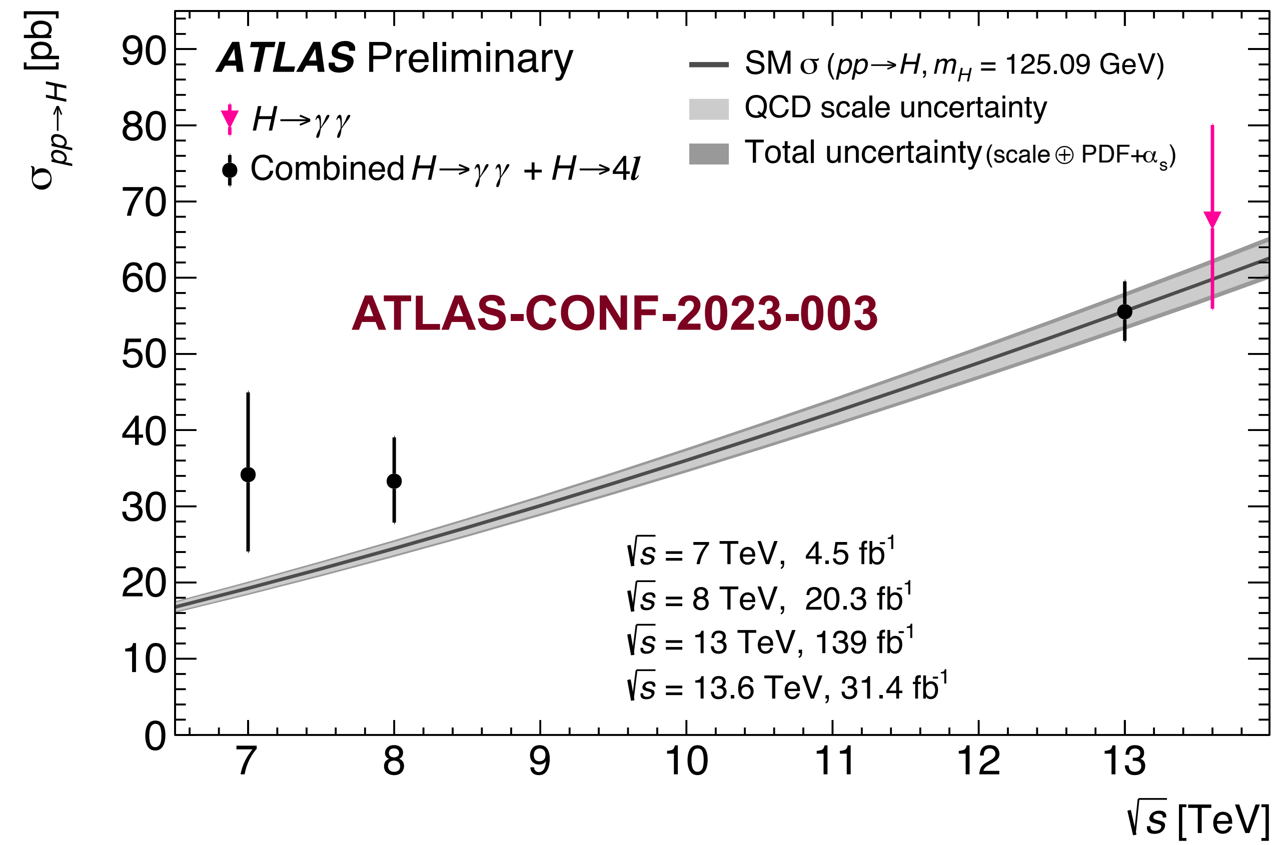


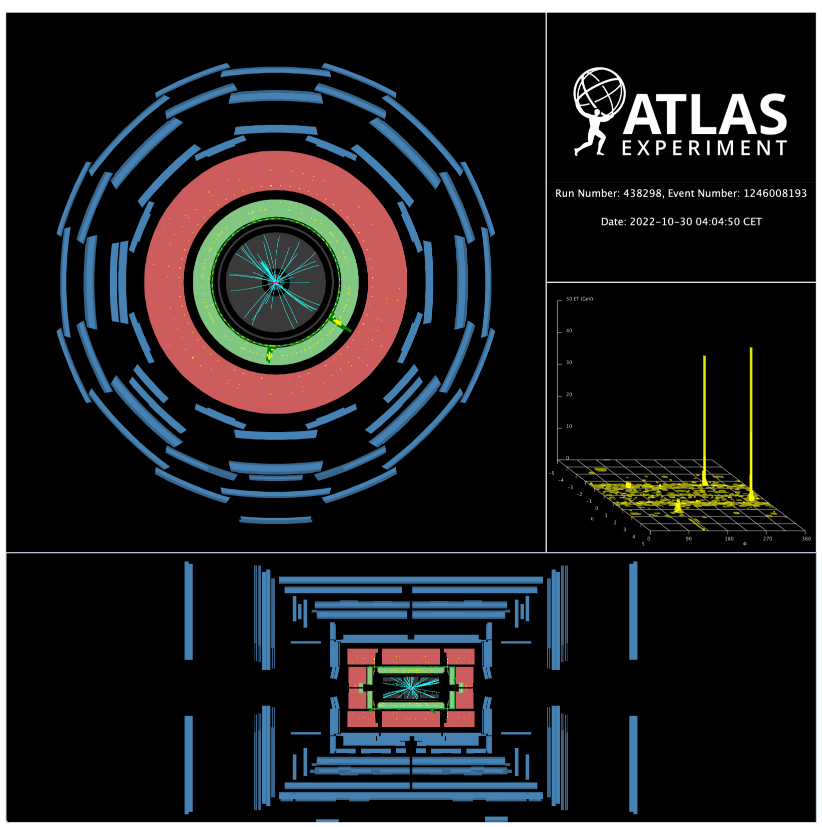
The major production and decay modes of Higgs boson

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG

First Higgs measurement at 13.6 TeV







Di-photon trigger with E_T > 25, 35 GeV with medium selection criteria.
Trigger efficiency > 99.4%.
The NN based PV reconstruction efficiency is 71.4%

Di-photon fiducial region : $|\eta| < 2.37$, **modulo** $1.37 < |\eta| < 1.52$
105 GeV $< m_{\gamma\gamma} < 160$ GeV **for isolated photons.**
This fiducial region is 50% of the total phase space.

$$\sigma_{\text{fid}}(pp \to H \to \gamma\gamma) = 76^{+14}_{-13}\ \text{fb} = 76 \pm 11(\text{stat})\ ^{+9}_{-7}(\text{syst})\ \text{fb}$$

67.5 ± 3.4 fb. **SM prediction**

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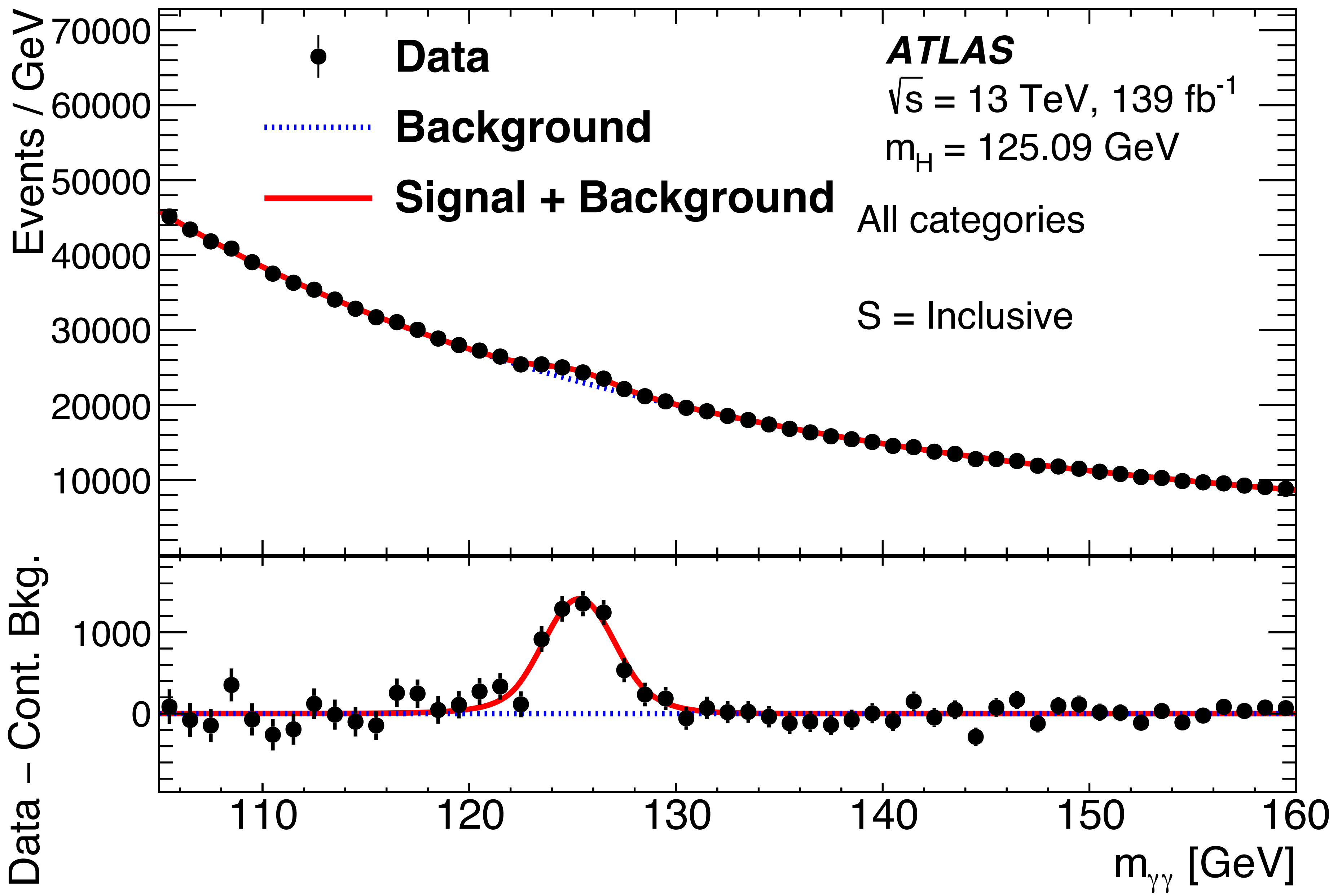
H properties from H → $\gamma\gamma$: STXS

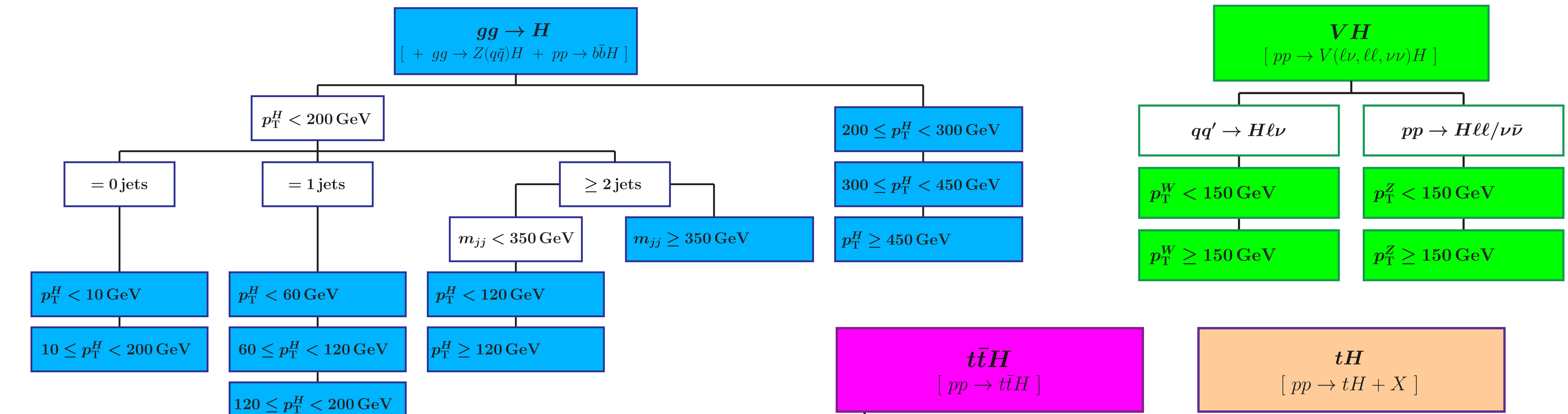


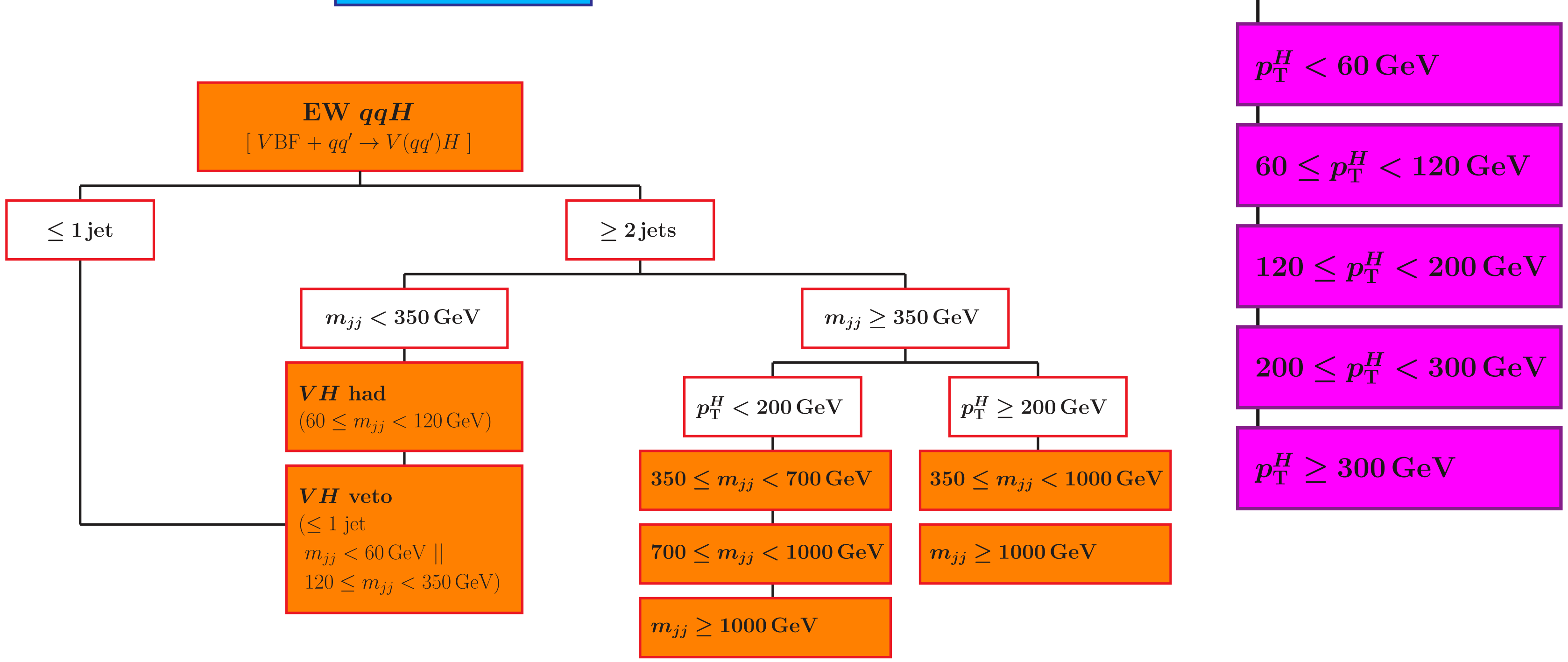
The strategy of this analysis is to divide the Higgs productions measurements into different categories, emulating different physics process.

H properties from H → $\gamma\gamma$: STXS

arXiv 2207.00348

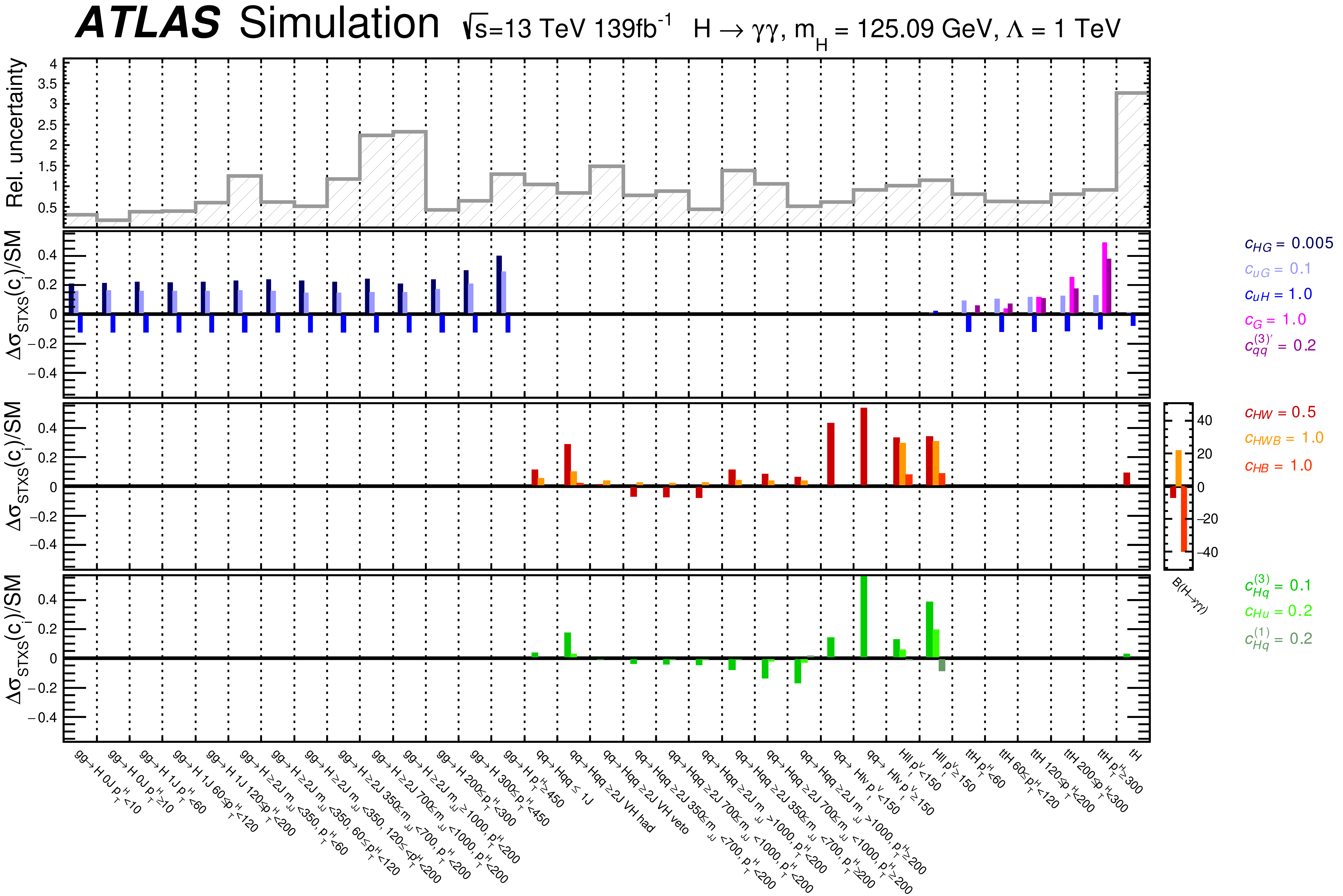
H → $\gamma\gamma$ production x-section is measured in 48 different STXS regions.



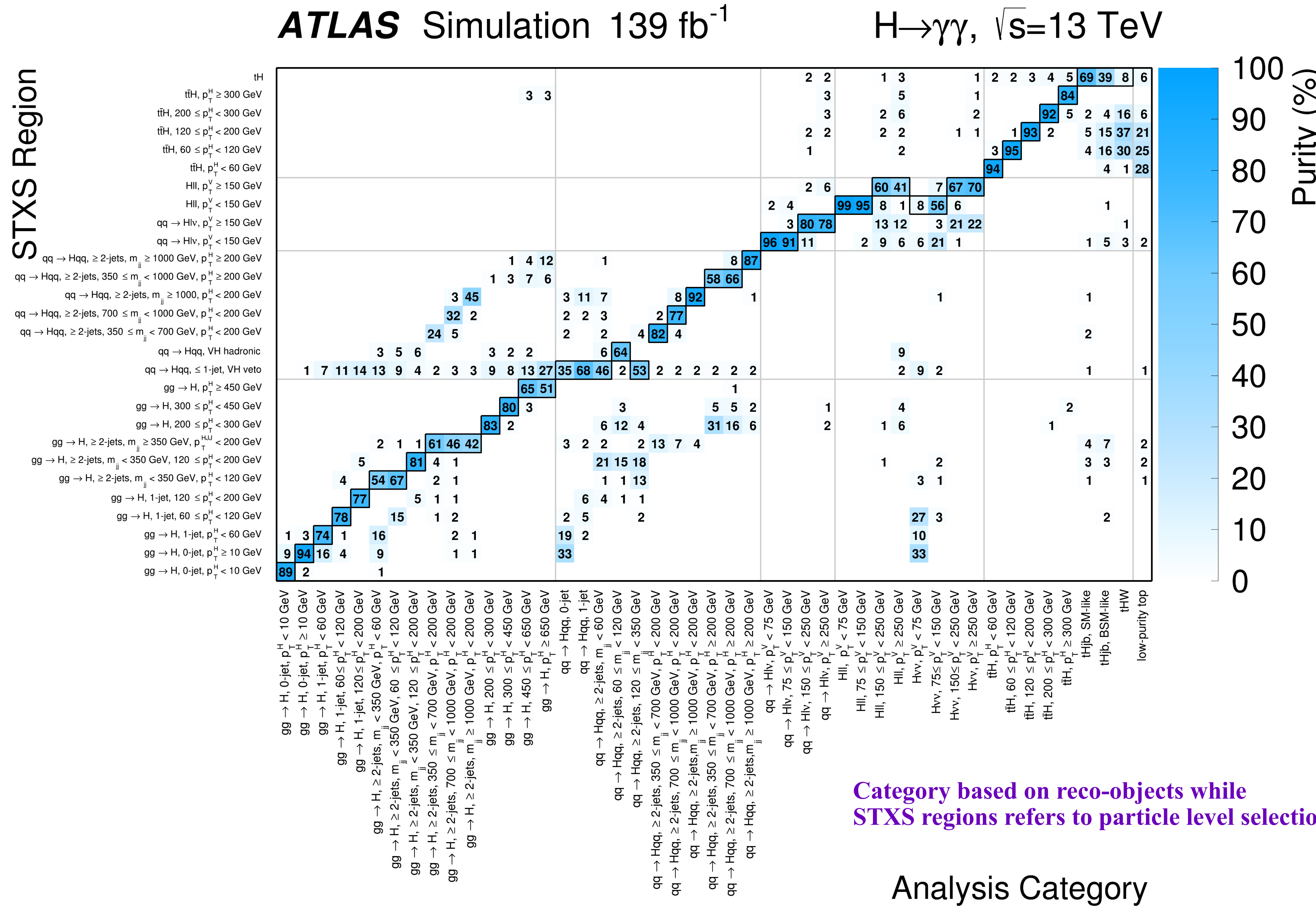


- Cross sections per production mode in different regions of phase space
  - ✓ Reduce dependency on theory
  - ✓ Allow MVA analysis
  - ✓ Exploit sensitivity of each channel specific region of phase space (designed for combination)
  - ✓ Inclusive in decays (for now)
  - ✓ Binning defined to allow better estimate of theoretical uncertainties, and easier merging when insufficient experimental sensitivity
  - ✓ Largely model-independent approach to test for BSM deviations in kinematic distributions

Impact on SMEFT parameters

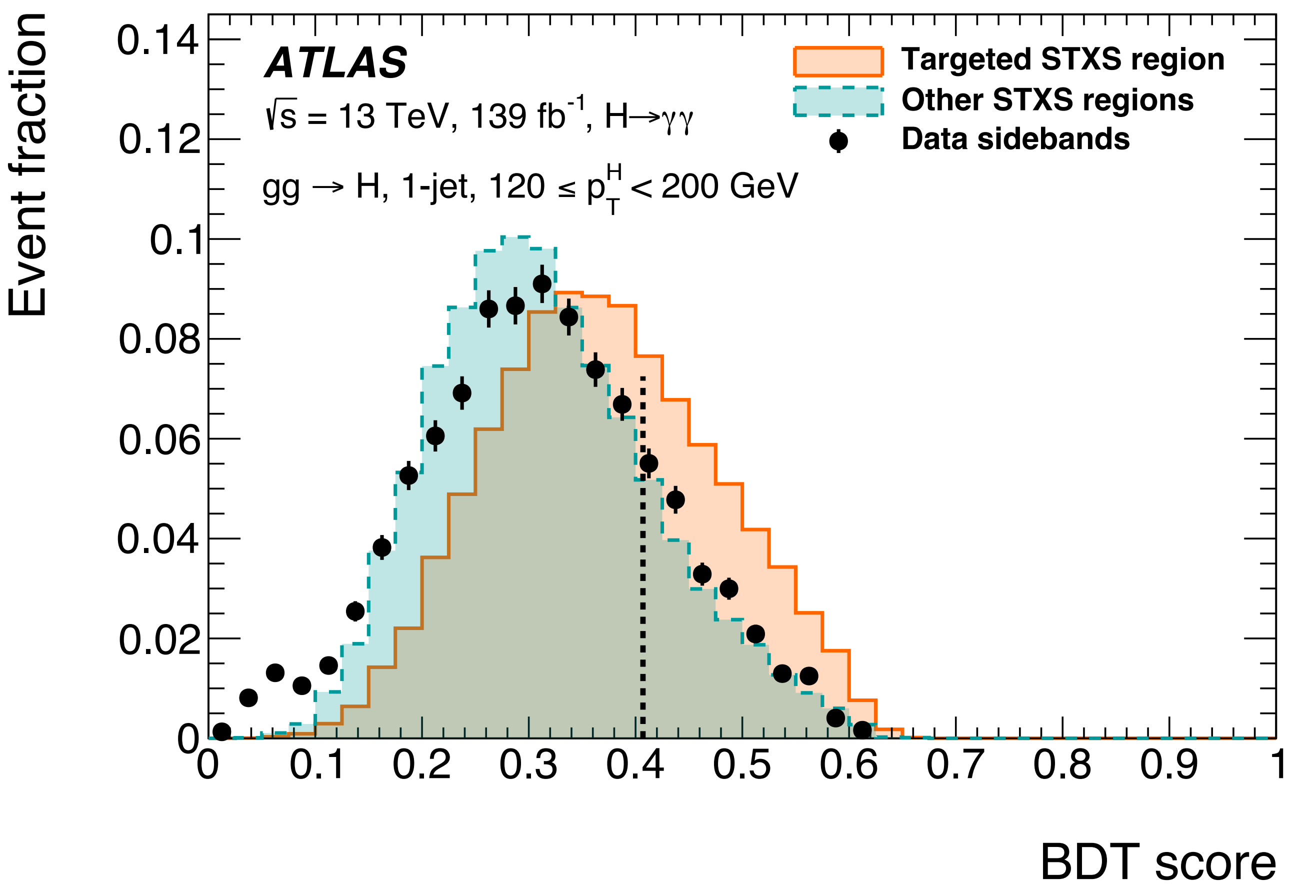


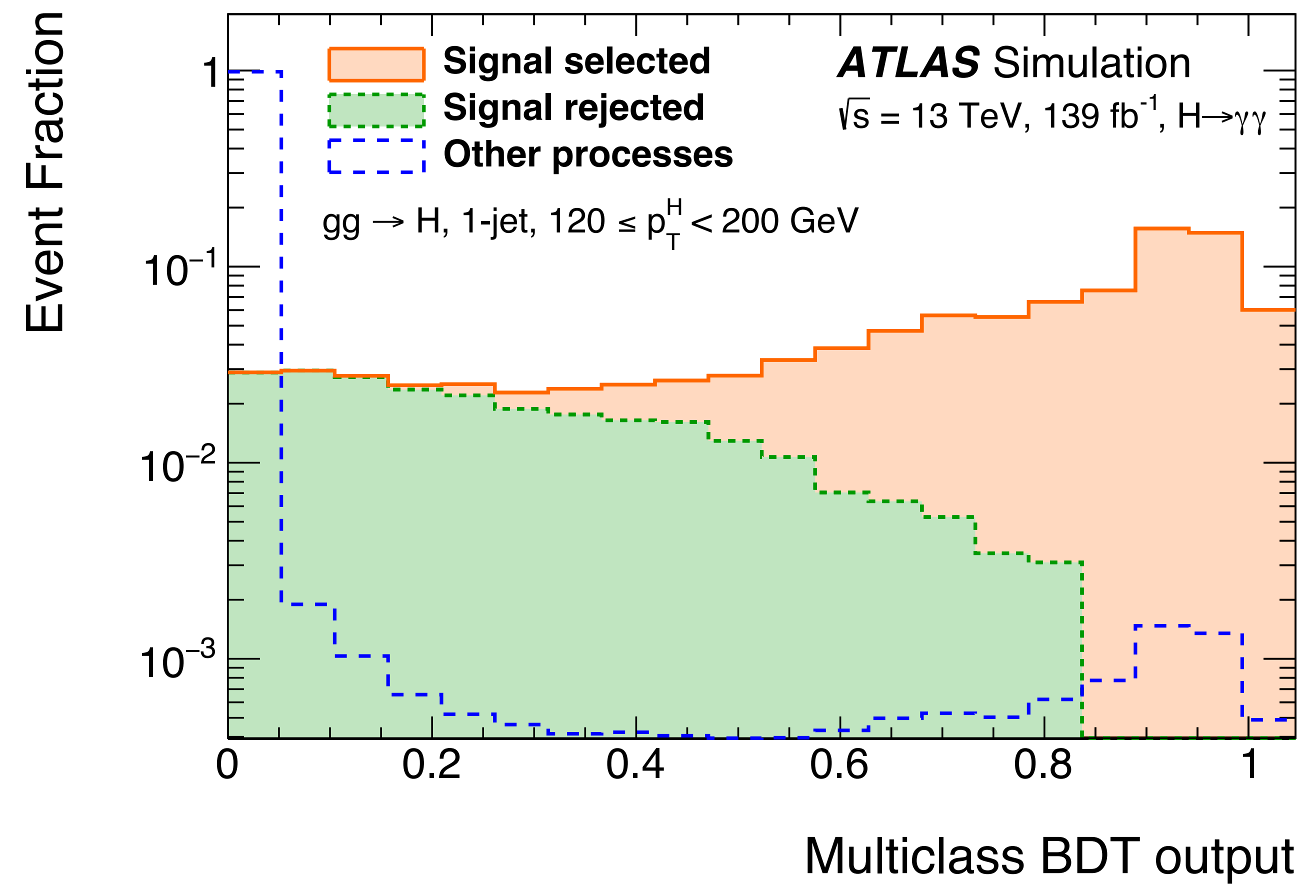
Contribution of STXS regions to categories



Category based on reco-objects while STXS regions refers to particle level selections.

BDT based region assignment

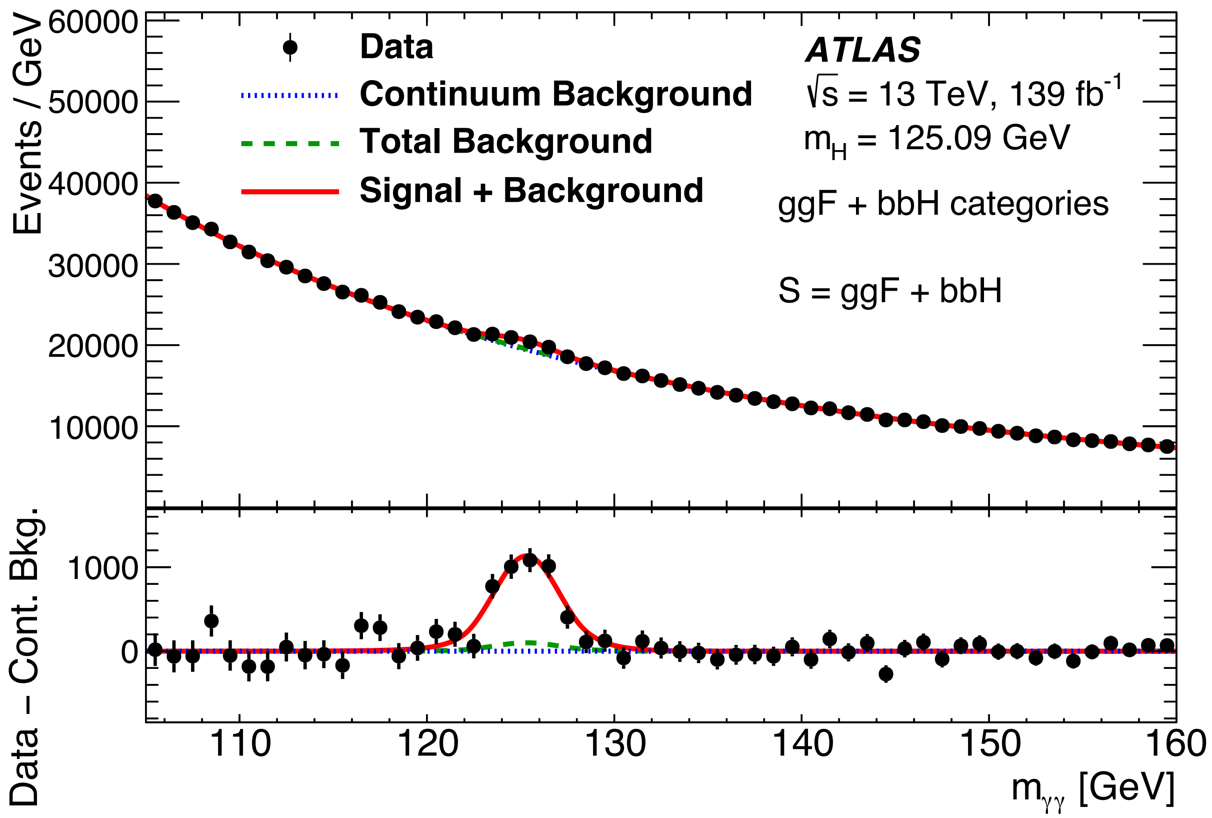


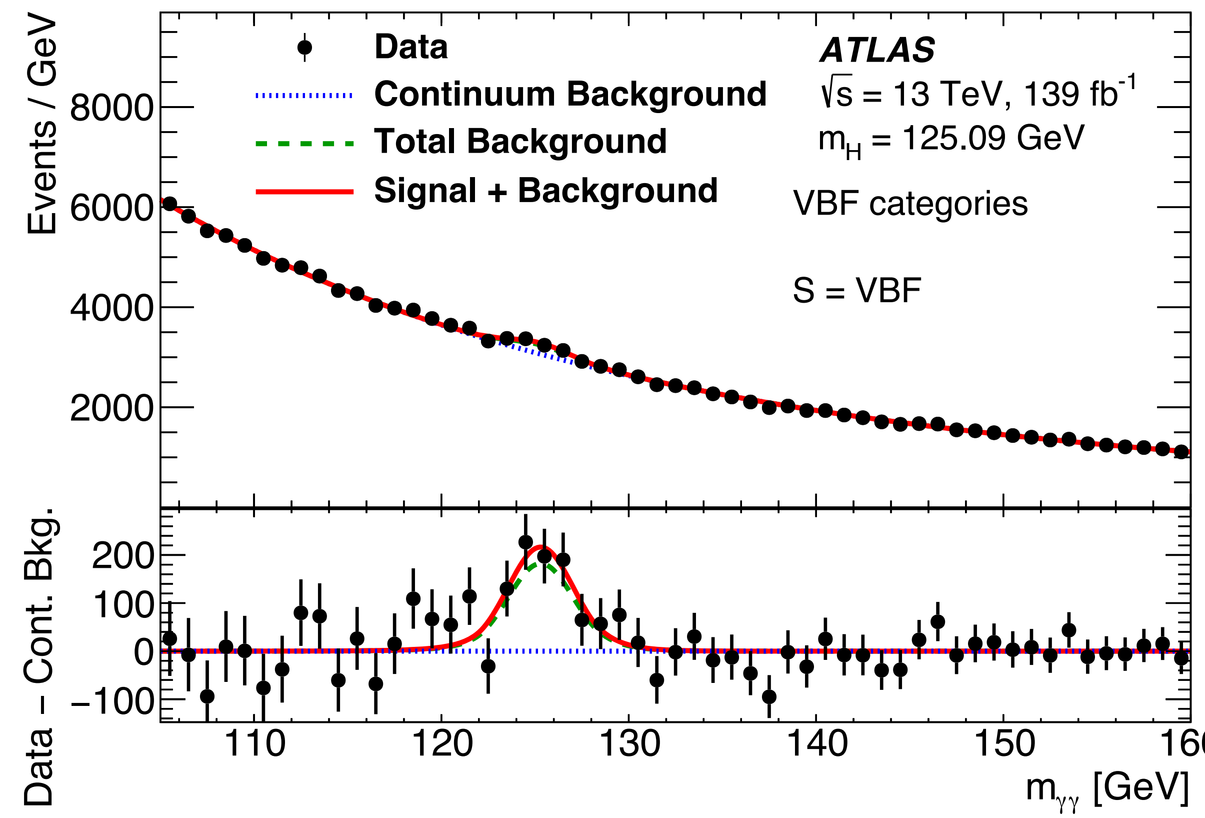


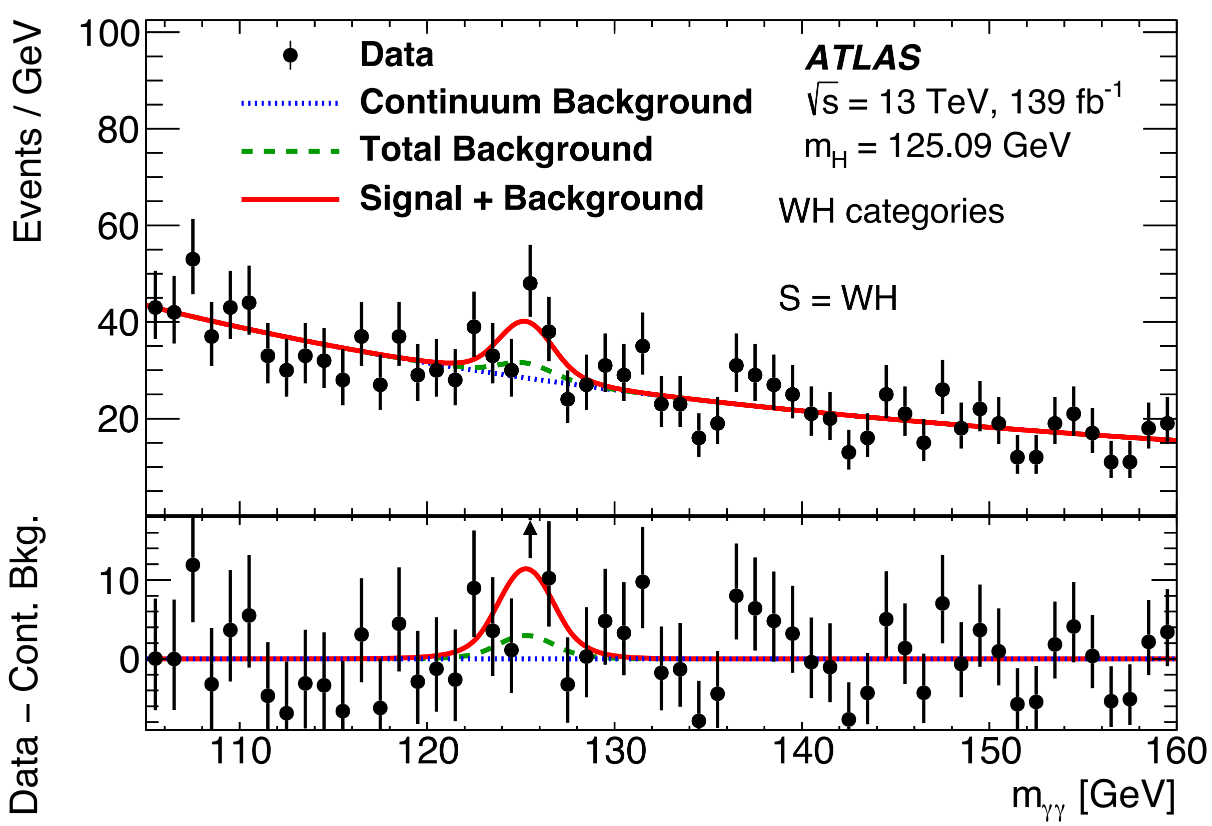
STXS classes	Variables
Individual STXS classes from $gg \to H$ $qq' \to Hqq'$ $qq \to H\ell\nu$ $pp \to H\ell\ell$ $pp \to H\nu\bar{\nu}$	All multiclass BDT variables, $\boldsymbol{p}_{\mathrm{T}}^{\gamma\gamma}$ projected to the thrust axis of the $\gamma\gamma$ system ($p_{\mathrm{Tt}}^{\gamma\gamma}$), $\Delta\eta_{\gamma\gamma}$, $\eta^{\mathrm{Zepp}} = \frac{\eta_{\gamma\gamma}-\eta_{jj}}{2}$, $\phi^*_{\gamma\gamma} = \tan\left(\frac{\pi-\lvert\Delta\phi_{\gamma\gamma}\rvert}{2}\right)\sqrt{1-\tanh^2\left(\frac{\Delta\eta_{\gamma\gamma}}{2}\right)}$, $\cos\theta^*_{\gamma\gamma} = \left\lvert\frac{(E^{\gamma_1}+p_z^{\gamma_1})\cdot(E^{\gamma_2}-p_z^{\gamma_2})-(E^{\gamma_1}-p_z^{\gamma_1})\cdot(E^{\gamma_2}+p_z^{\gamma_2})}{m_{\gamma\gamma}+\sqrt{m^2_{\gamma\gamma}+(p_{\mathrm{T}}^{\gamma\gamma})^2}}\right\rvert$ Number of electrons and muons.
all $t\bar{t}H$ and tHW STXS classes combined	p_{T}, η, ϕ of γ_1 and γ_2, p_{T}, η, ϕ and b-tagging scores of the six highest-p_{T} jets, $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$ significance, $E_{\mathrm{T}}^{\mathrm{miss}}$ azimuthal angle, Top reconstruction BDT scores of the top-quark candidates, p_{T}, η, ϕ of the two highest-p_{T} leptons.
$tHqb$	$p_{\mathrm{T}}^{\gamma\gamma}/m_{\gamma\gamma}$, $\eta_{\gamma\gamma}$, p_{T}, invariant mass, BDT score and $\Delta R(W,b)$ of t_1, p_{T}, η of t_2, p_{T}, η of j_F, Angular variables: $\Delta\eta_{\gamma\gamma t_1}$, $\Delta\theta_{\gamma\gamma t_2}$, $\Delta\theta_{t_1 j_F}$, $\Delta\theta_{t_2 j_F}$, $\Delta\theta_{\gamma\gamma j_F}$ Invariant mass variables: $m_{\gamma\gamma j_F}$, $m_{t_1 j_F}$, $m_{t_2 j_F}$, $m_{\gamma\gamma t_1}$ Number of jets with $p_{\mathrm{T}} > 25$ GeV, Number of b-jets with $p_{\mathrm{T}} > 25$ GeV*; Number of leptons*, $E_{\mathrm{T}}^{\mathrm{miss}}$ significance*

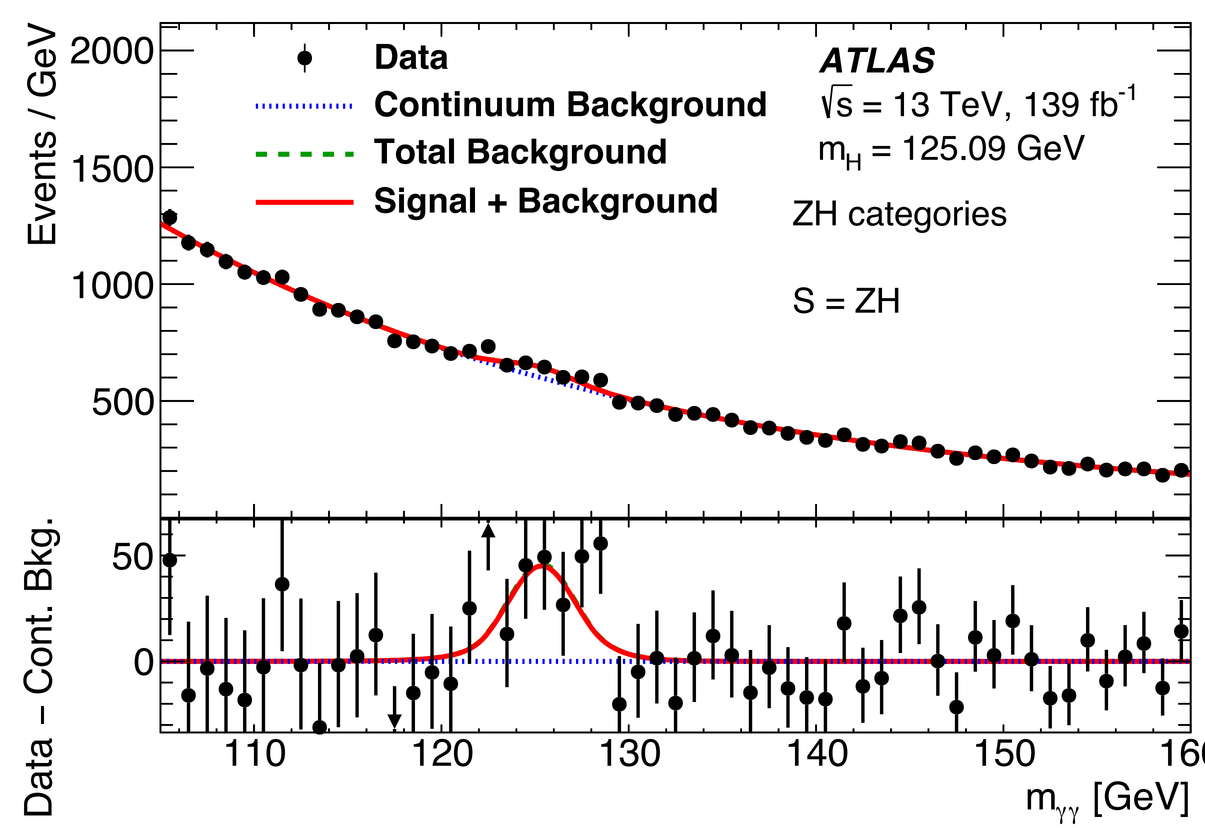
η_{γ_1}, η_{γ_2}, $p_{\mathrm{T}}^{\gamma\gamma}$, $y_{\gamma\gamma}$,
$p^{\dagger}_{\mathrm{T},jj}$, m_{jj}, and Δy, $\Delta\phi$, $\Delta\eta$ between j_1 and j_2,
$p_{\mathrm{T},\gamma\gamma j_1}$, $m_{\gamma\gamma j_1}$, $p_{\mathrm{T},\gamma\gamma jj}$†, $m_{\gamma\gamma jj}$
Δy, $\Delta\phi$ between the $\gamma\gamma$ and jj systems,
minimum ΔR between jets and photons,
invariant mass of the system comprising all jets in the event,
dilepton p_{T}, di-e or di-μ invariant mass (leptons are required to be oppositely charged),
$E_{\mathrm{T}}^{\mathrm{miss}}$, p_{T} and transverse mass of the lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ system,
p_{T}, η, ϕ of top-quark candidates, $m_{t_1 t_2}$
Number of jets†, of central jets ($|\eta| < 2.5$)†, of b-jets† and of leptons,
p_{T} of the highest-p_{T} jet, scalar sum of the p_{T} of all jets,
scalar sum of the transverse energies of all particles ($\sum E_{\mathrm{T}}$), $E_{\mathrm{T}}^{\mathrm{miss}}$ significance,
$\left|E_{\mathrm{T}}^{\mathrm{miss}} - E_{\mathrm{T}}^{\mathrm{miss}}(\text{primary vertex with the highest } \sum p^2_{\mathrm{T,track}})\right| > 30$ GeV
Top reconstruction BDT of the top-quark candidates,
$\Delta R(W,b)$ of t_2,
η_{j_F}, $m_{\gamma\gamma j_F}$
Average number of interactions per bunch crossing.

Obtained results : diphoton mass

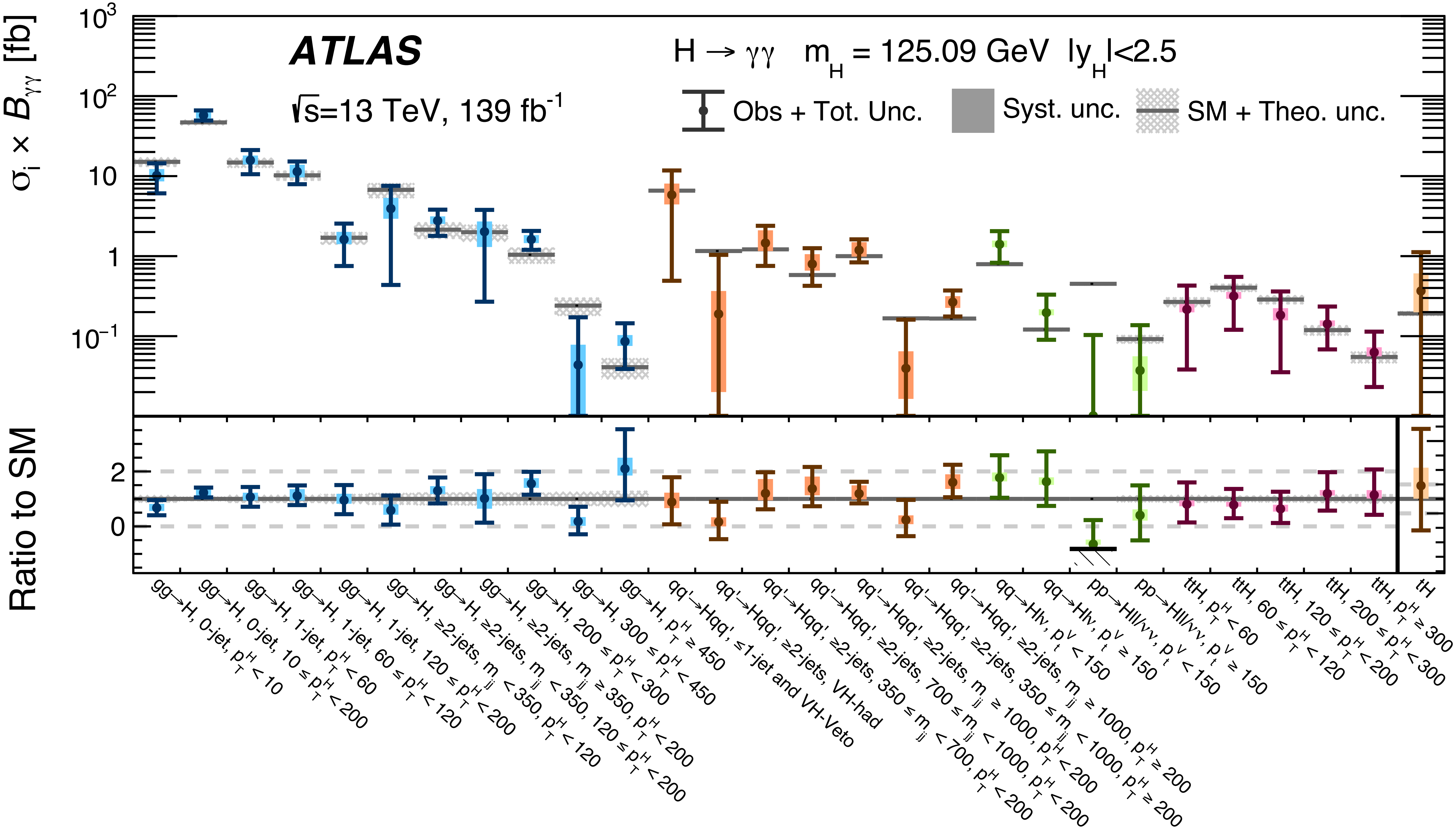






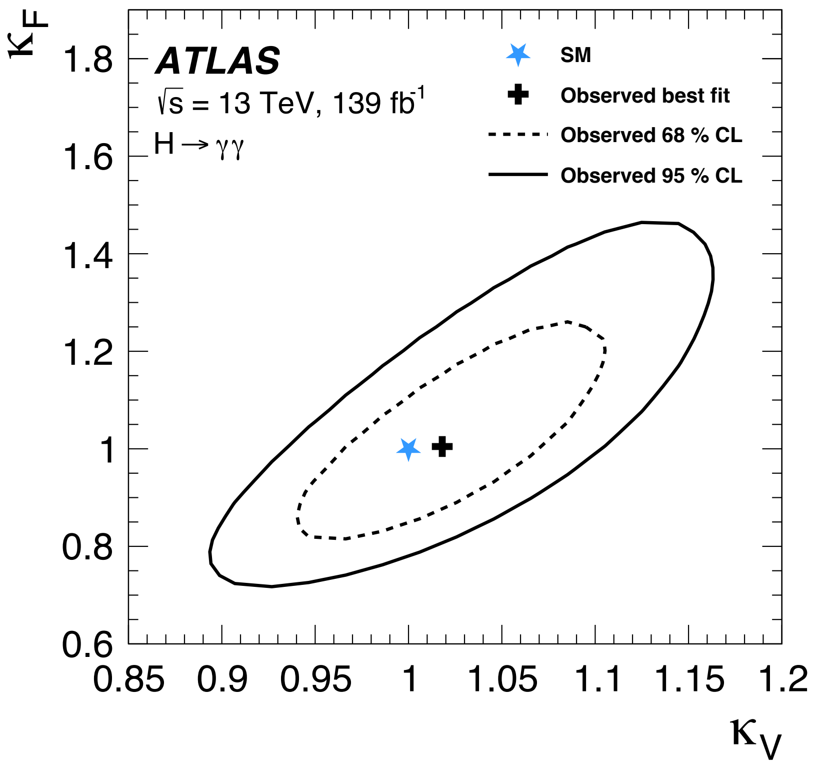


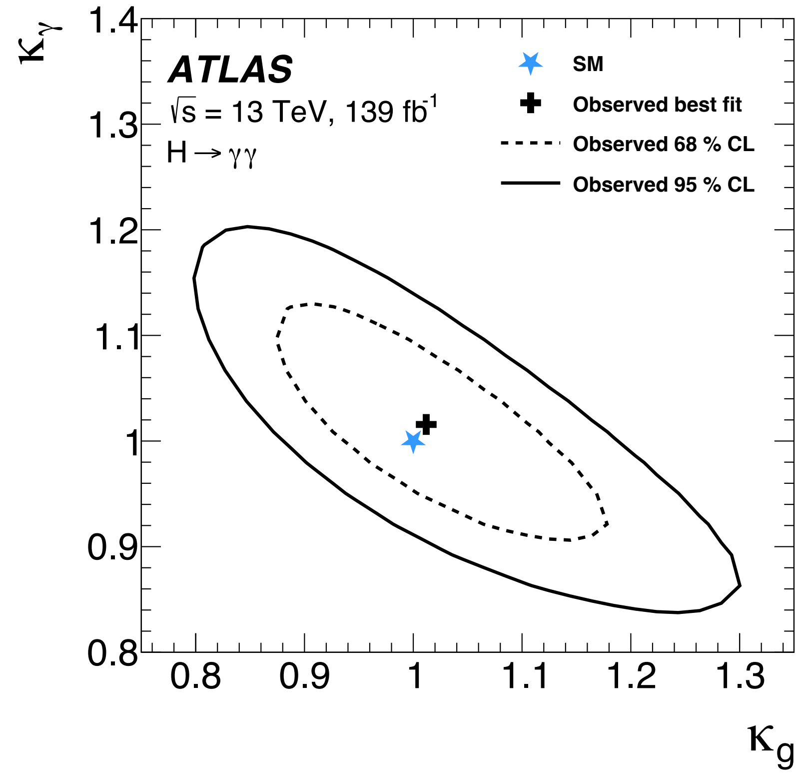
Obtained results : signal strengths

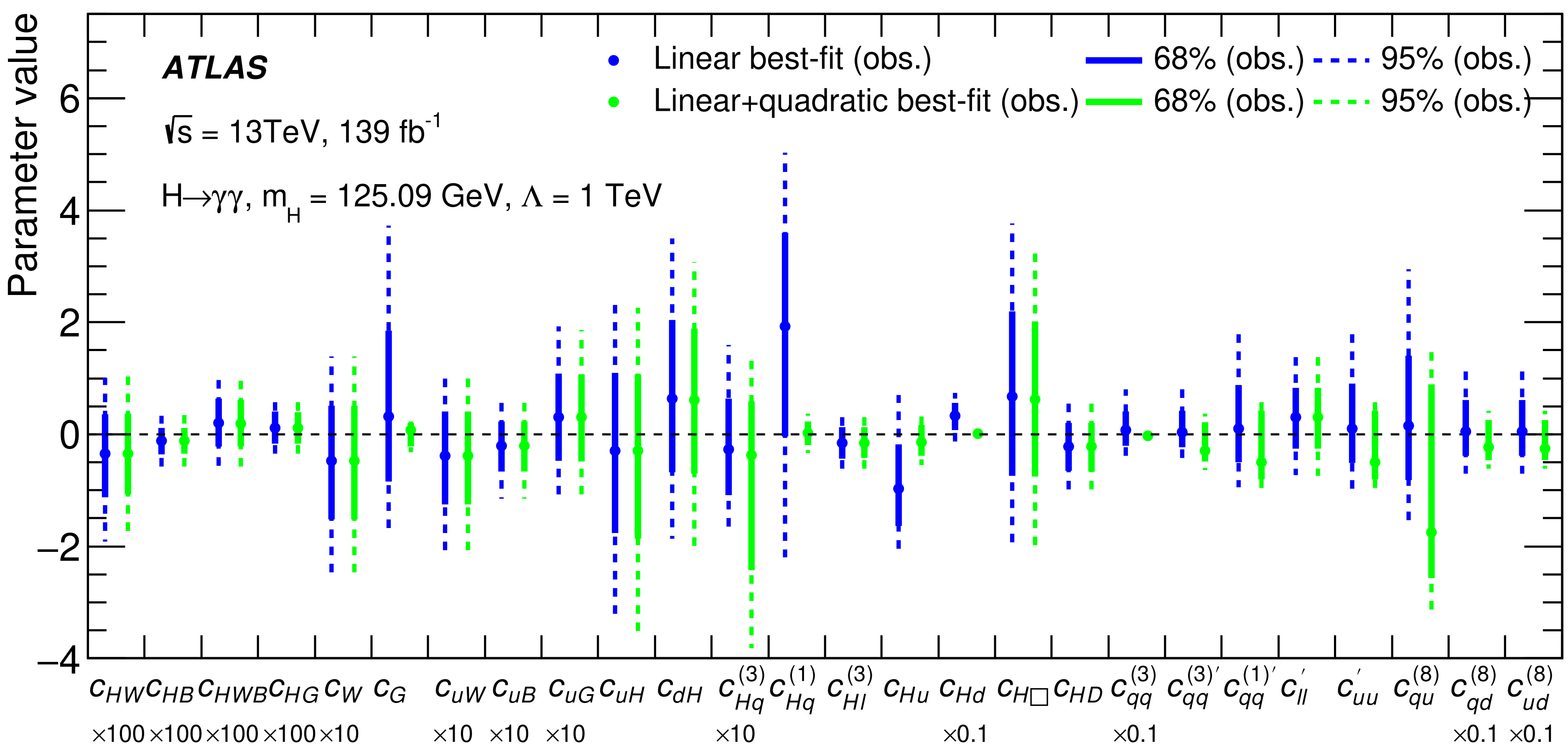


$$\mu = 1.04^{+0.10}_{-0.09} = 1.04 \pm 0.06\ (\text{stat.})^{+0.06}_{-0.05}\ (\text{theory syst.})\ ^{+0.05}_{-0.04}\ (\text{exp. syst.}).$$

Obtained results : SMEFT & κ parameters







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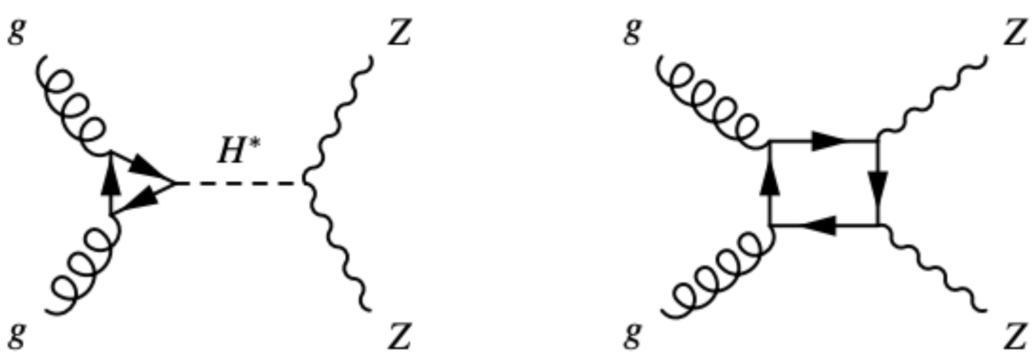
H width from off shell HZZ

arXiv 2304.01532

Higgs width can be measured by taking the ratio of off-shell to on-shell production x-section

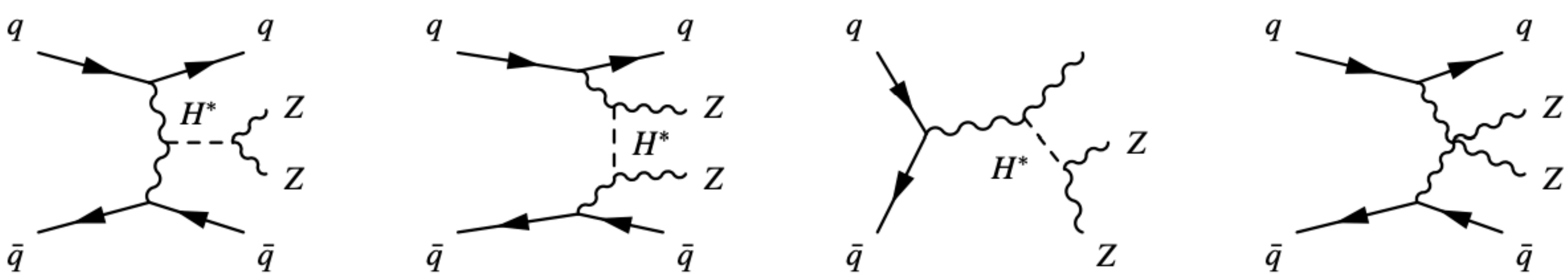
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m^2_{ZZ}}$$

Off shell regime $\sqrt{s} >> M_Z, m_t$



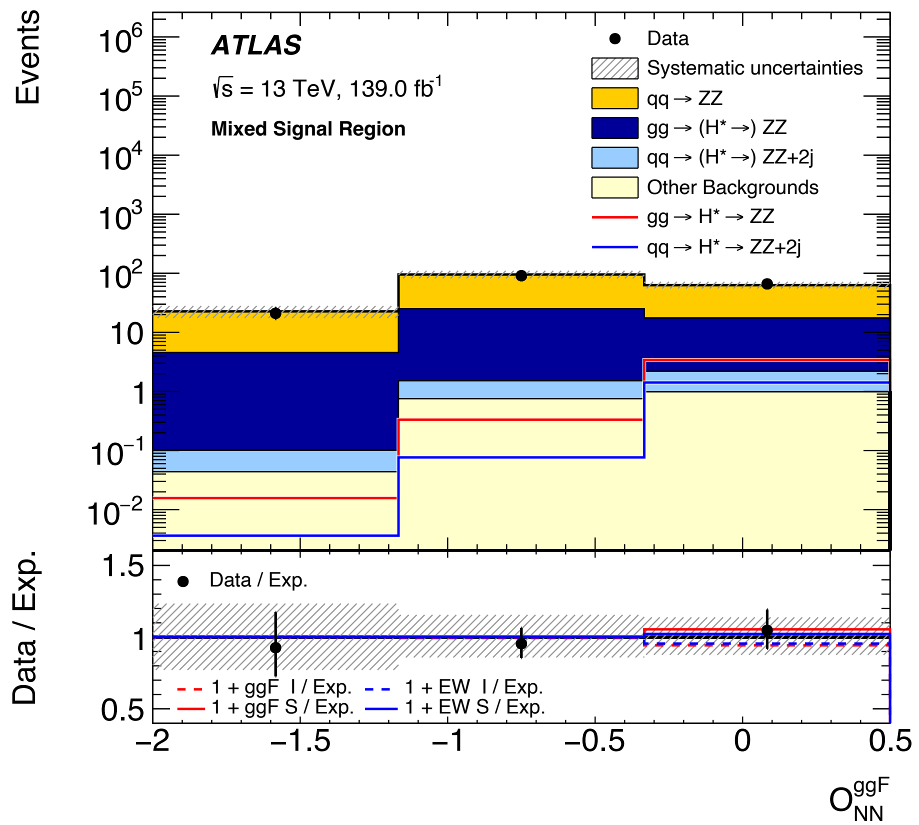
ggF signal & bkg.

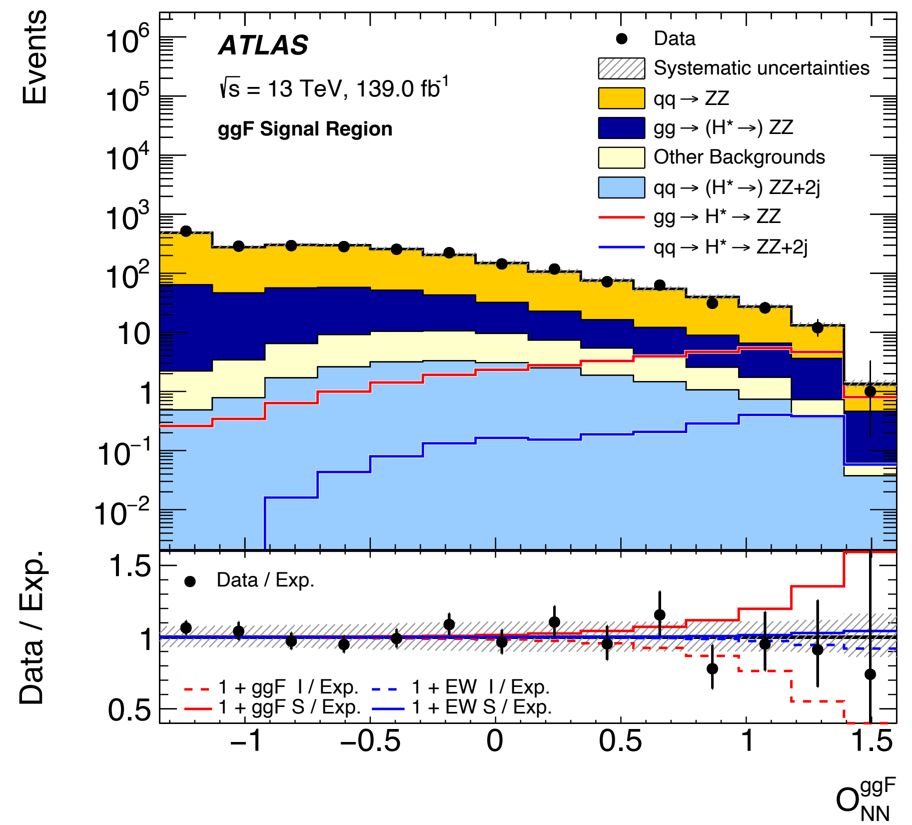
VBF signal & bkg.

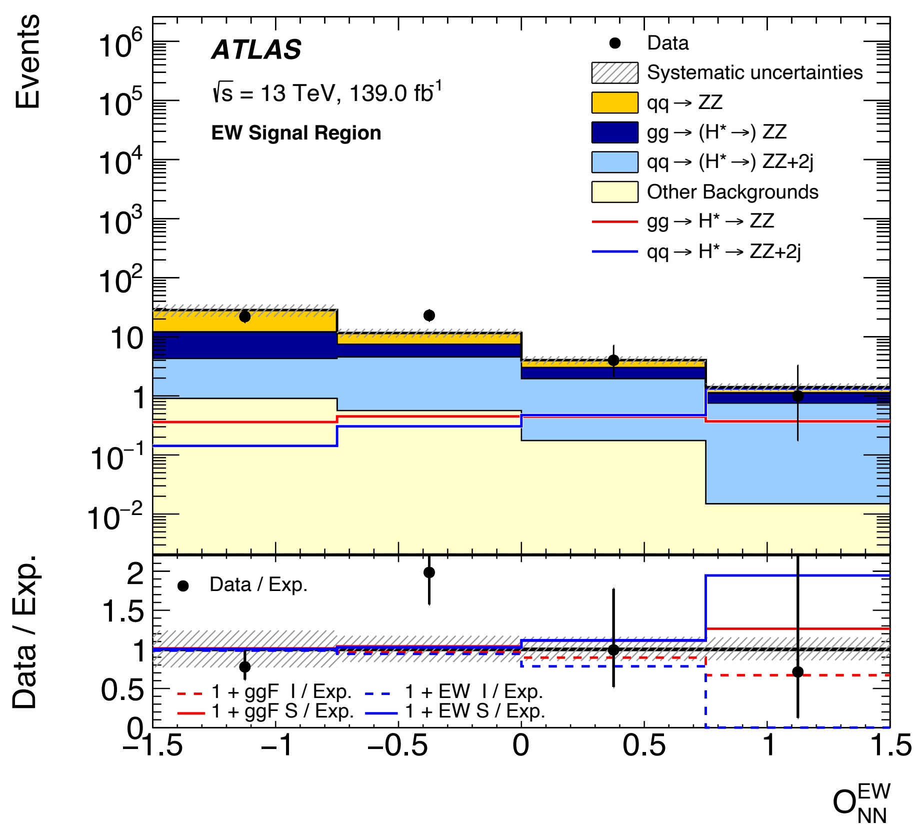


ZZ to 4l analysis

arXiv 2304.01532







$$m_{4l} > 220 \text{ GeV}$$

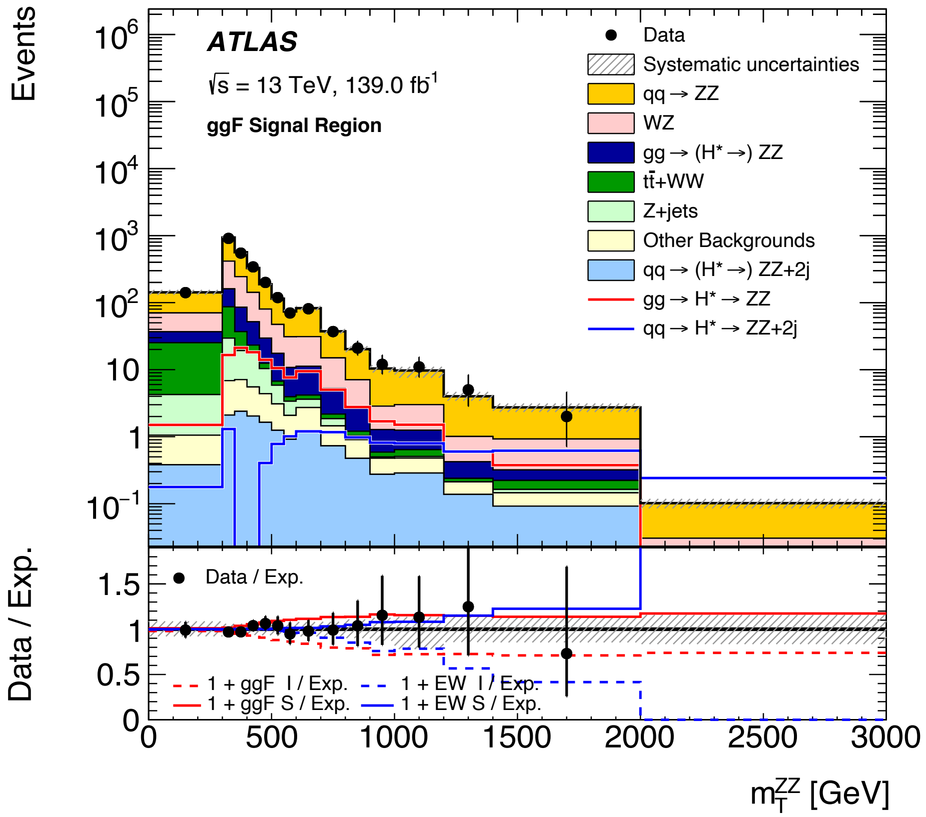
Main bkg : $q\bar{q} \rightarrow ZZ$; $180 < m_{4l} < 220$ GeV **0, 1, > 2J**

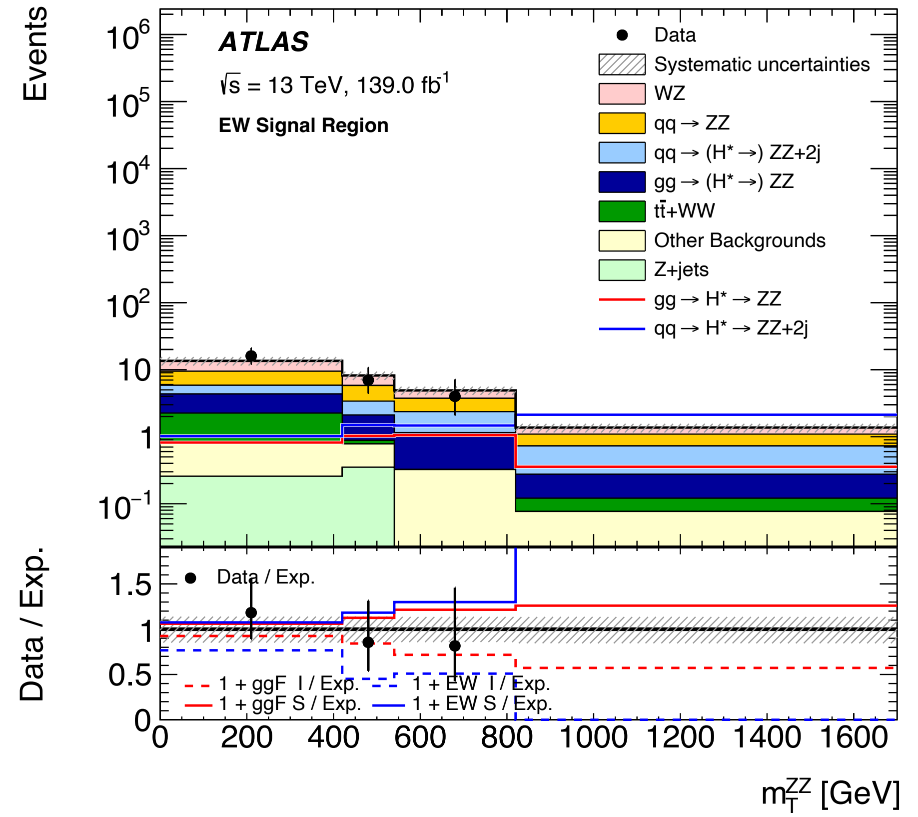
$$O_{NN} = \log_{10}\left(\frac{P_S}{P_B + P_{NI}}\right)$$

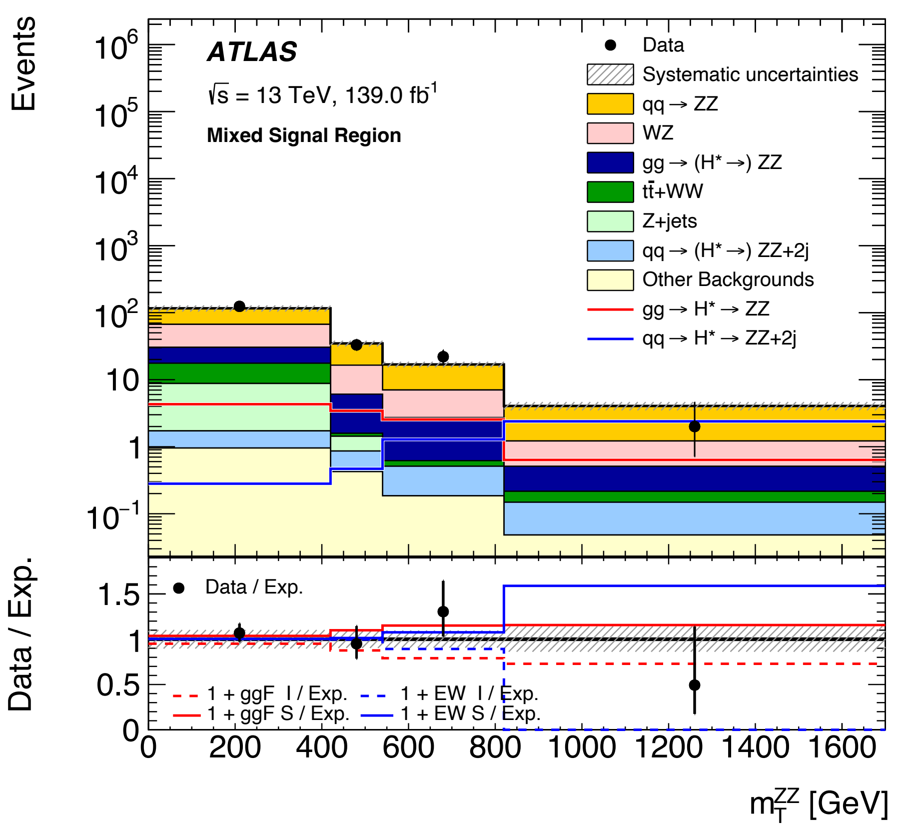
Two different NN for ggF & EW SR

H to ZZ to 2l + 2 nu

arXiv 2304.01532







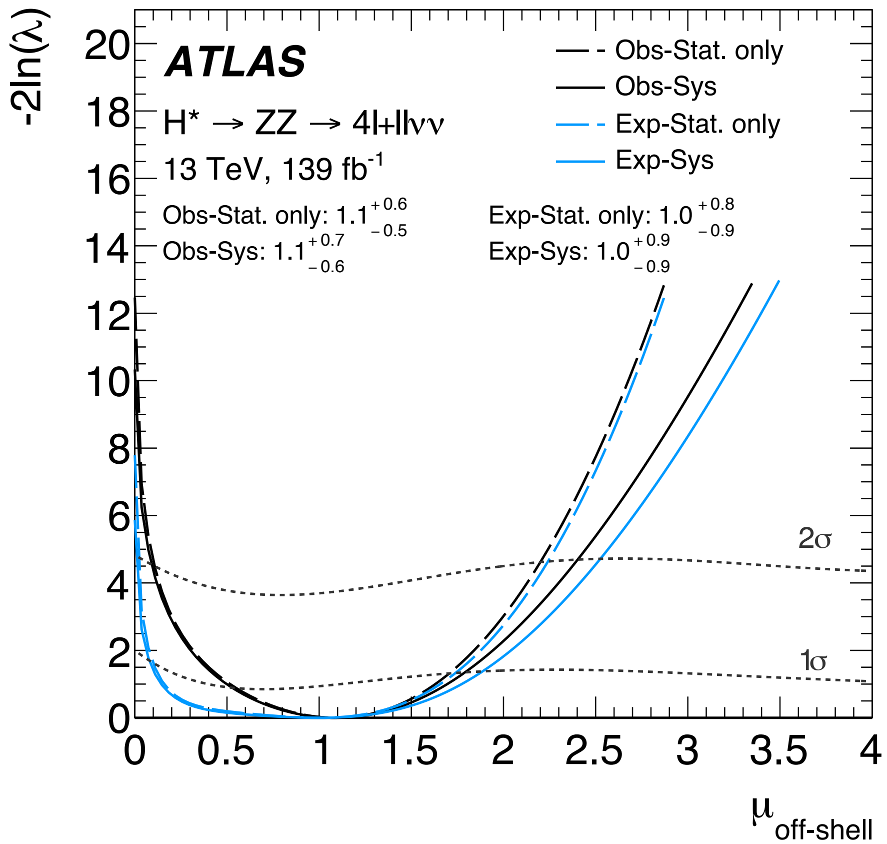
$$m_{\mathrm{T}}^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_{\mathrm{T}}^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_{\mathrm{T}}^{\mathrm{miss}}\right)^2}\right]^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$

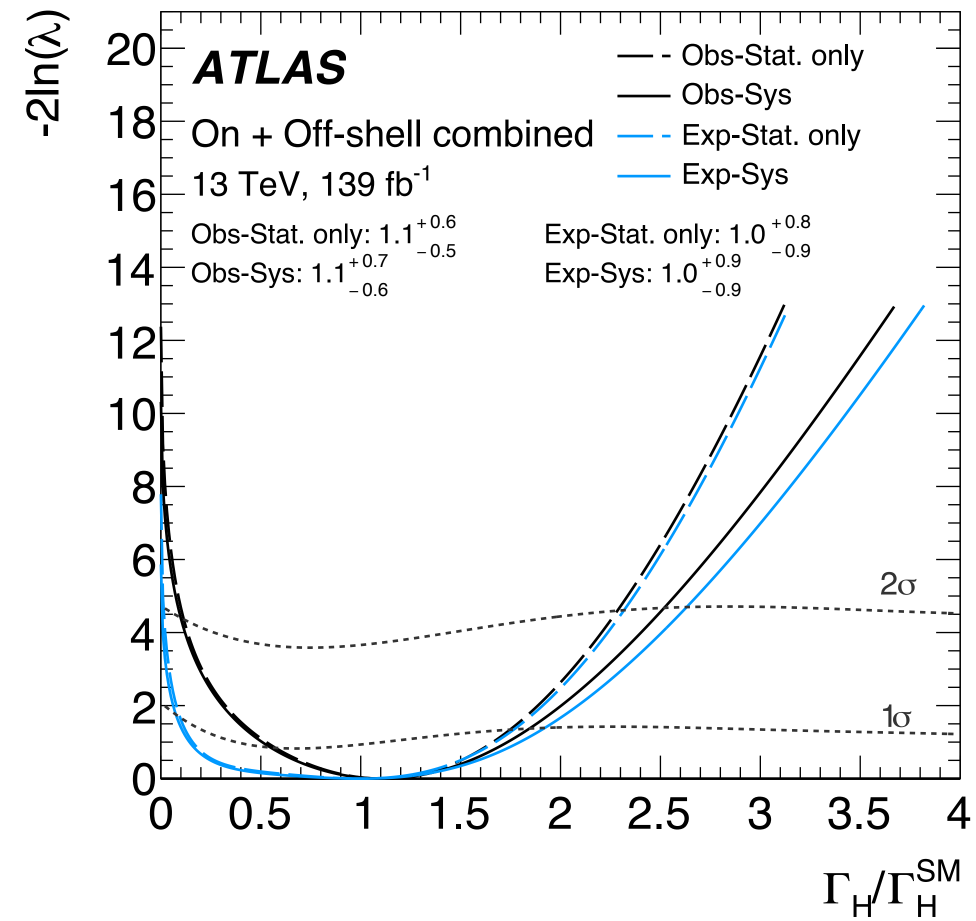
Reducible bkg's (ttbar, s-top, qq to WW) are killed by $76 < m_{ll} < 106$ GeV.

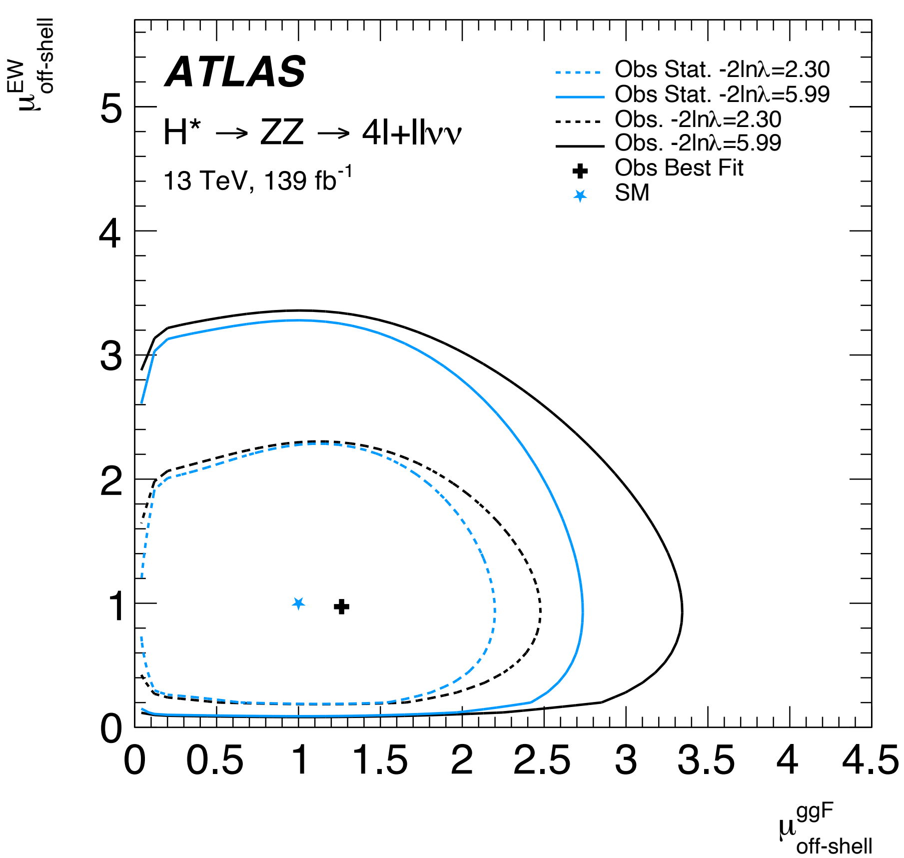
Scale uncertainty associated with $q\bar{q} \to ZZ$ is one of the largest sources of uncertainty, can be upto 40%.

H width from off shell HZZ

arXiv 2304.01532







$$\mu^{\mathrm{ggF}}_{\mathrm{off-shell}} = \kappa^2_{\mathrm{g\,,off-shell}}\ \kappa^2_{\mathrm{V\,,off-shell}}$$

$$\mu^{\mathrm{EW}}_{\mathrm{off-shell}} = \kappa^4_{\mathrm{V\,,off-shell}}$$

Combination of 4l and 2l+2mu channels are presented.

Width found to be $4.5^{+3.3}_{-2.5}$ MeV.

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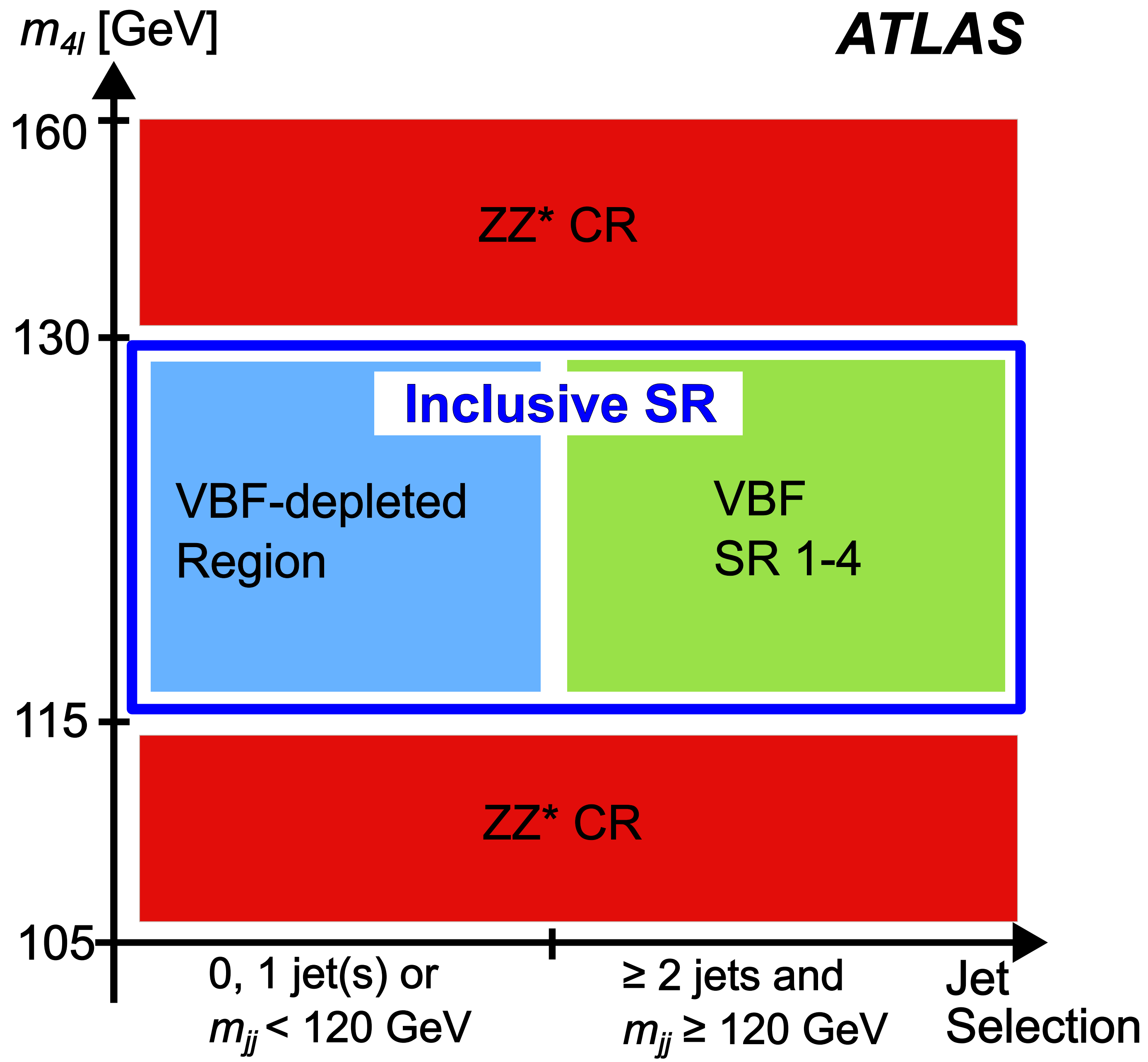
Test of CP invariance from H → ZZ* → 4 lep

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
	Higgs Basis	
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\widetilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\widetilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\widetilde{c}_{\gamma\gamma}$

SMEFT CP-odd dim-6 operators relevant for H → ZZ → 4l channel



Regions used for direct BSM coupling measurement

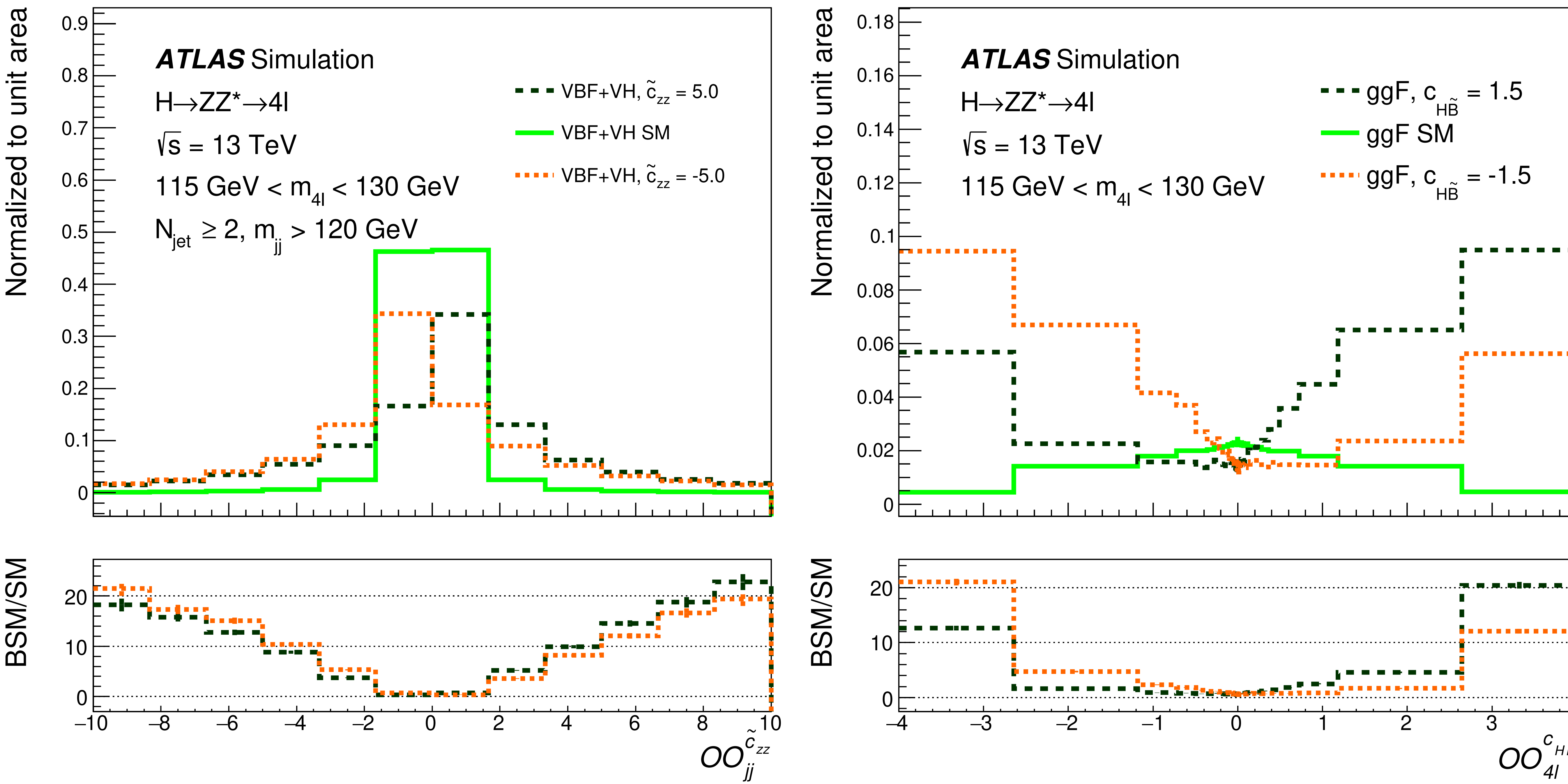
arXiv 2304.09612

Matrix element based optimal observables are used to constrain CP-odd couplings in SMEFT

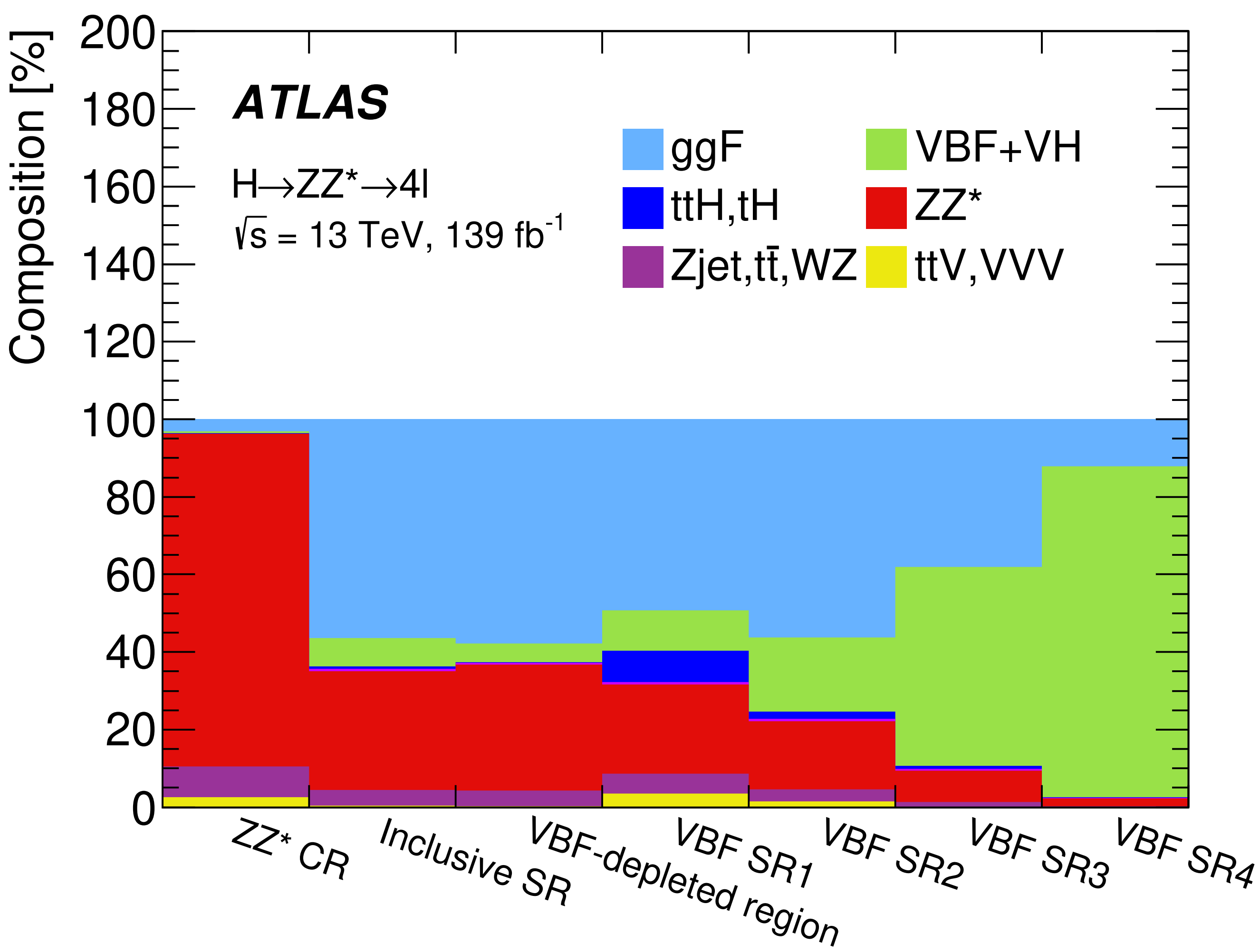
Test of CP invariance from H → ZZ * → 4 lep

$$|\mathcal{M}|^2 = \left|\mathcal{M}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_{\mathrm{BSM},i}\right|^2$$
$$= |\mathcal{M}_{\mathrm{SM}}|^2 + 2\sum_i \frac{c_i}{\Lambda^2}\Re\left(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM},i}\right) + \sum_i\sum_j \frac{c_i c_j}{\Lambda^4}\Re\left(\mathcal{M}^*_{\mathrm{BSM},i}\mathcal{M}_{\mathrm{BSM},j}\right)$$

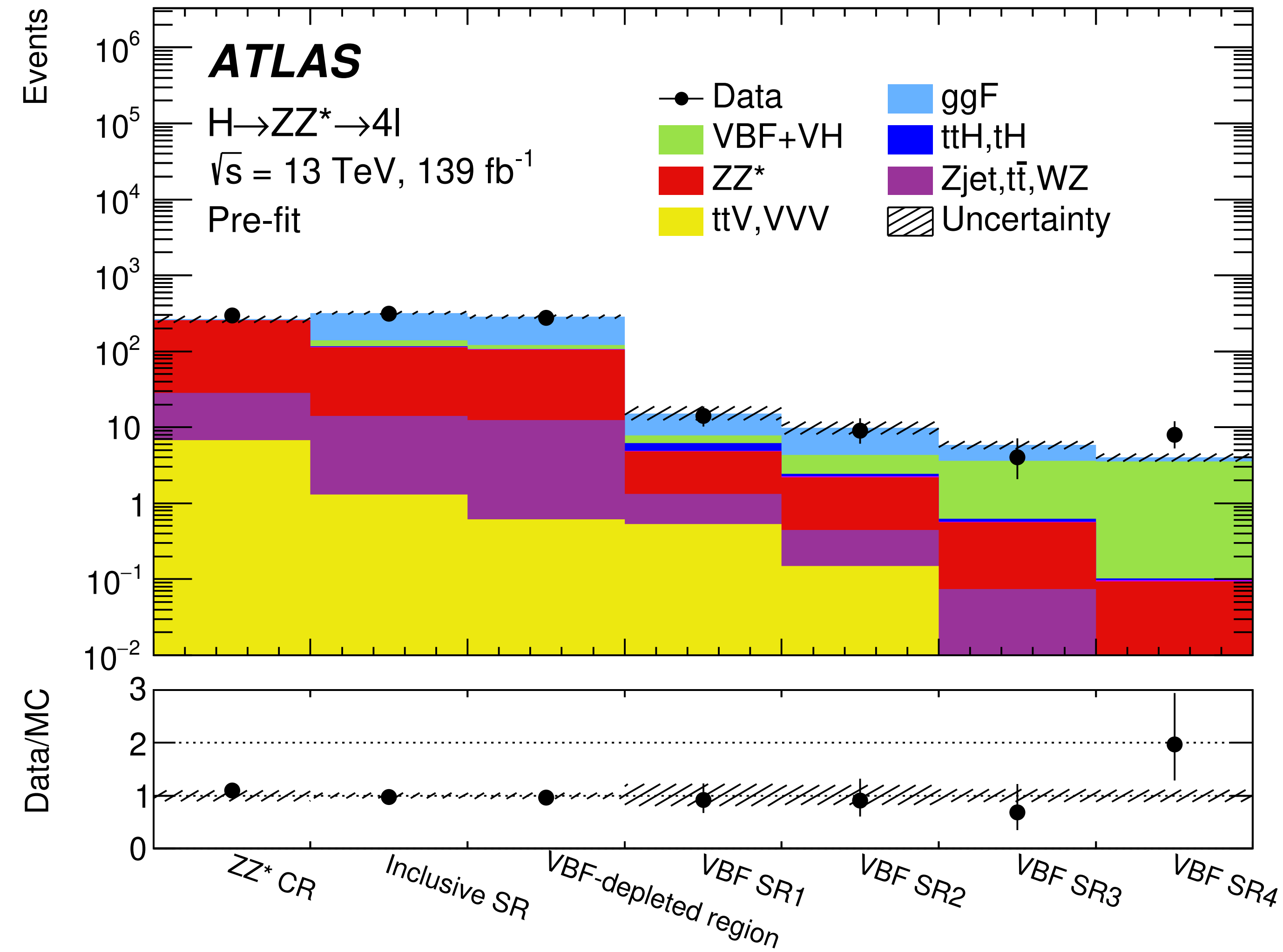
$$OO = \frac{2\Re\left(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM}}\right)}{|\mathcal{M}_{\mathrm{SM}}|^2}$$



The expected & observed event yields



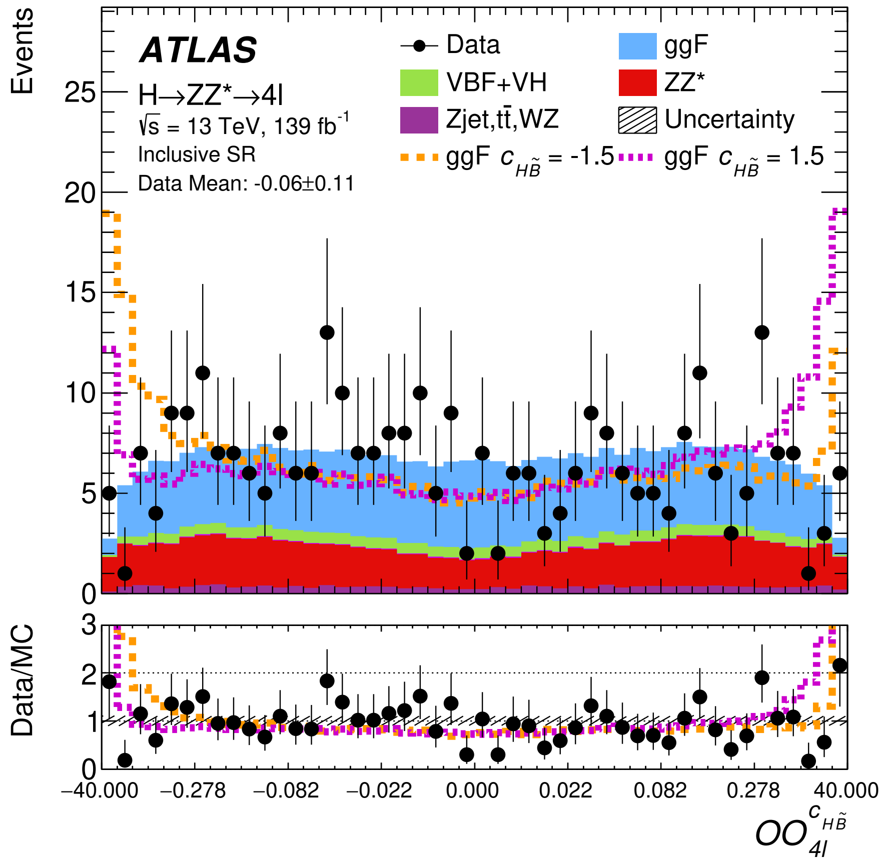
Rel. composition of the predicted event yields

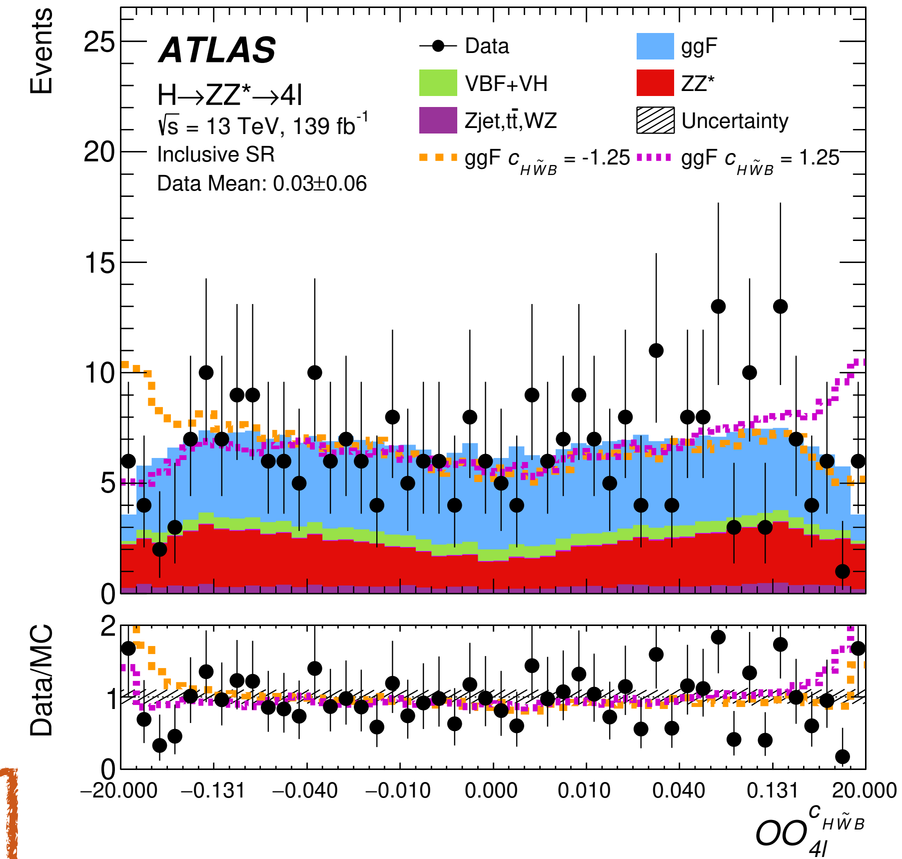


The number of observed events and expected contributions in each event category.

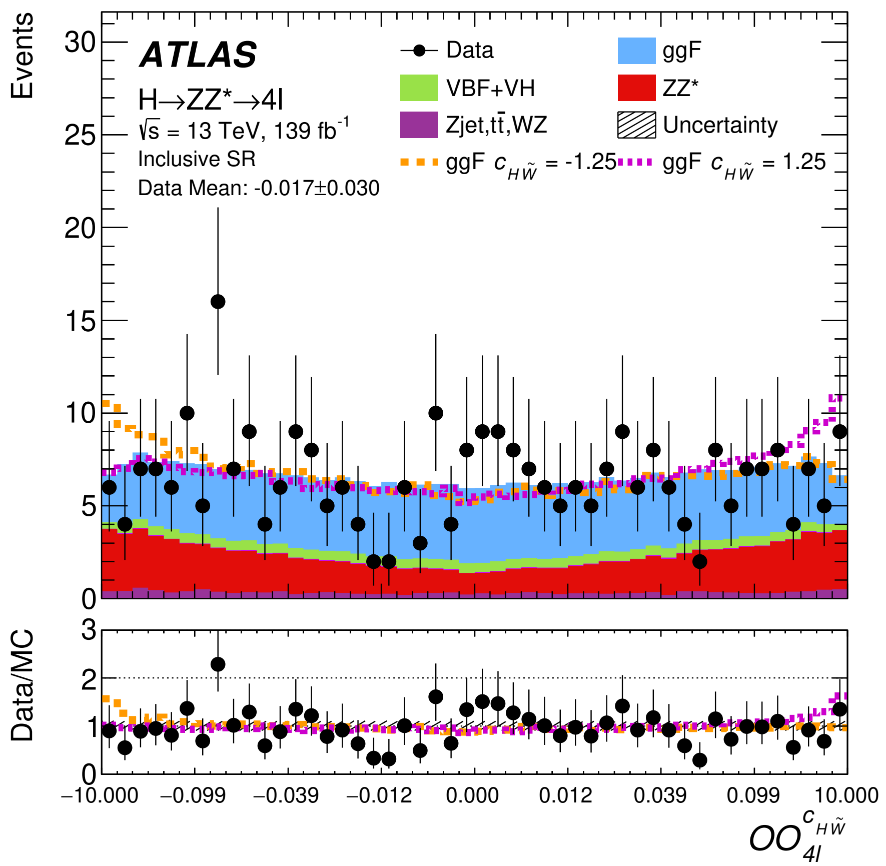
- ☑ **The dominant background is non-resonant ZZ* production ~ 30% : MC based estimation + data-driven normalization.**
- ☑ **Z+jets, t-tbar, WZ are reducible backgrounds : estimated in data-driven way.**
- ☑ **The tri-boson big (WWZ, WZZ and ZZZ) and ttX are estimated from simulation.**

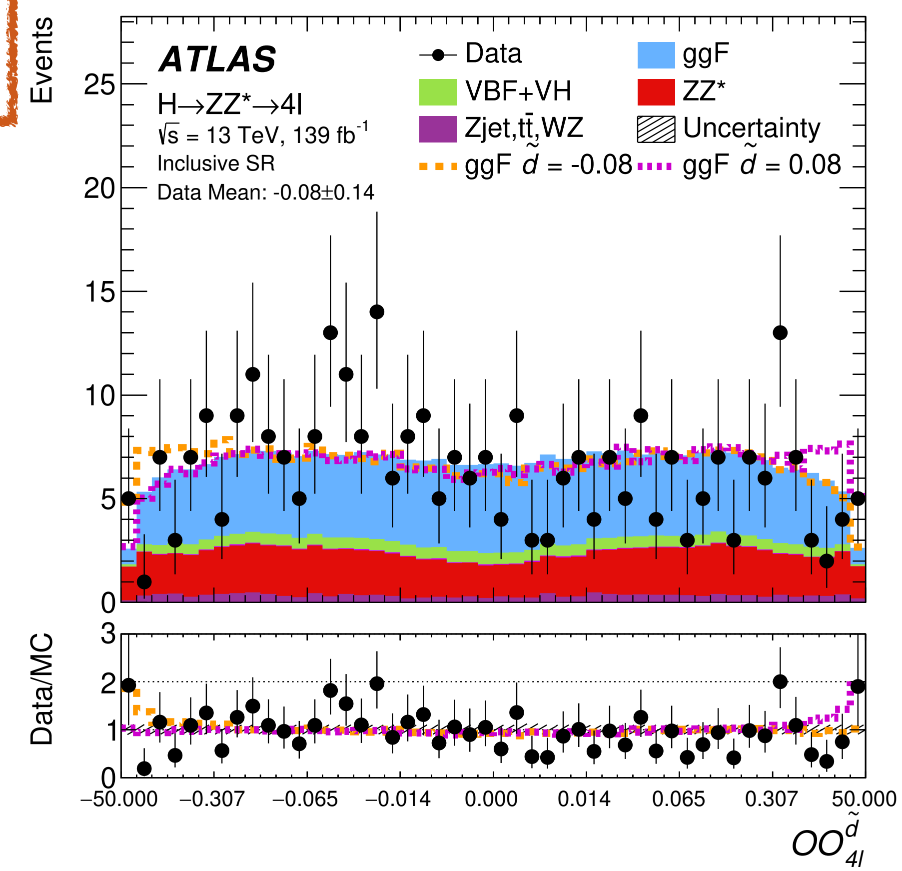
The expected & observed event yields



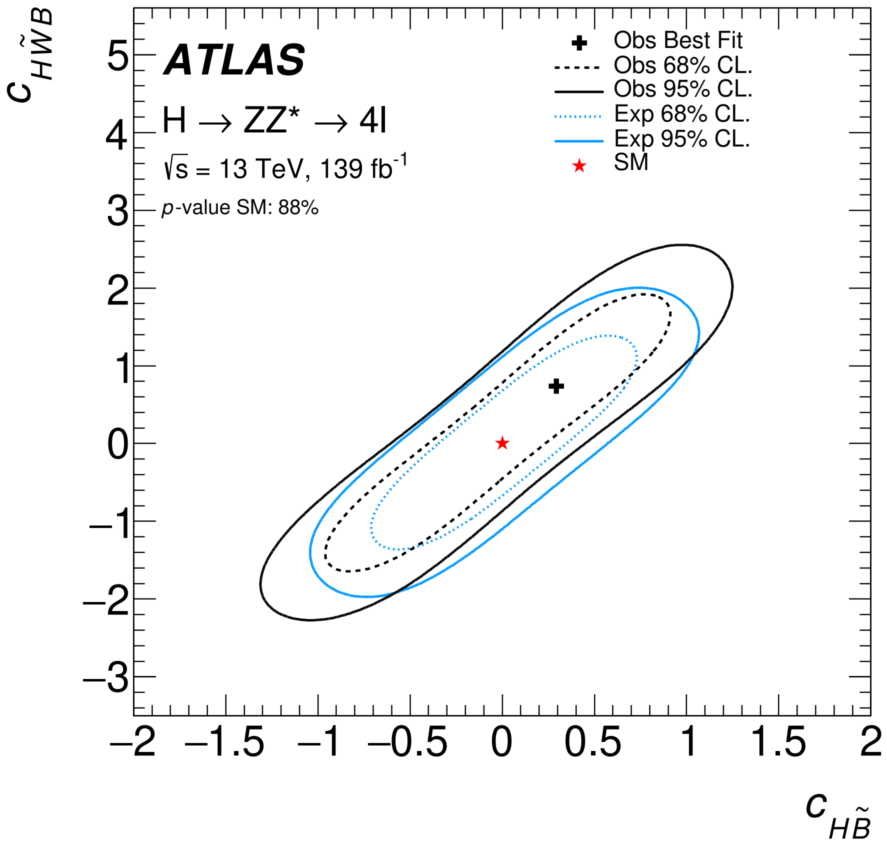


No statistically significant deviation from 0 is observed in any of the distributions

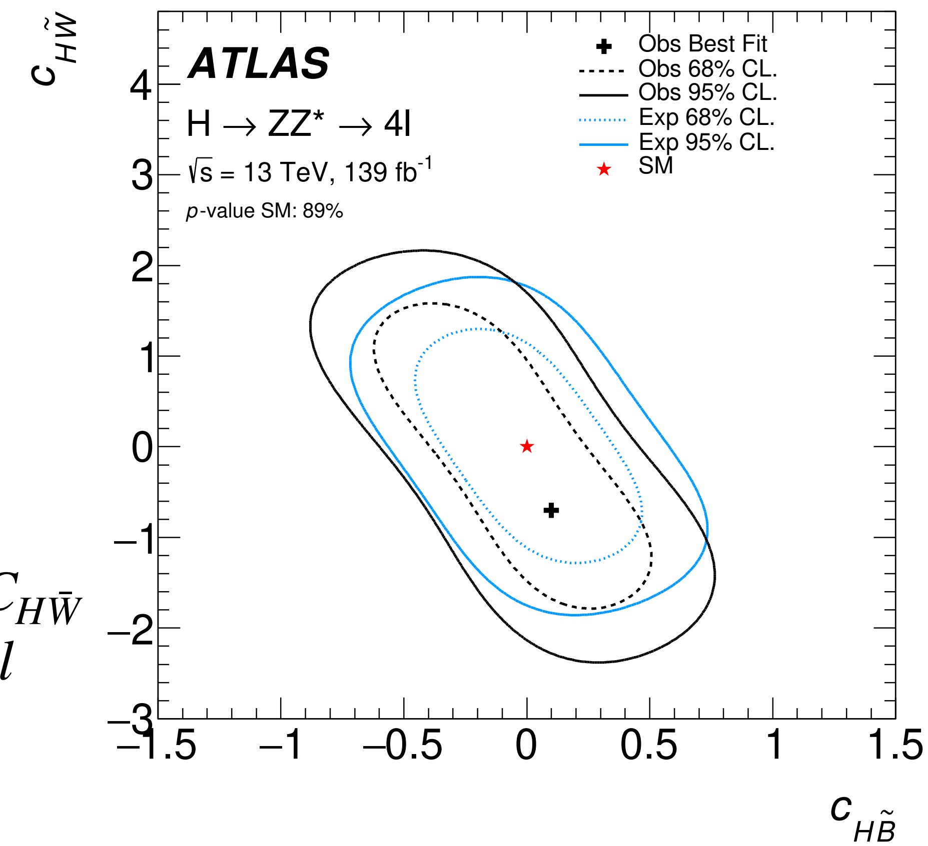


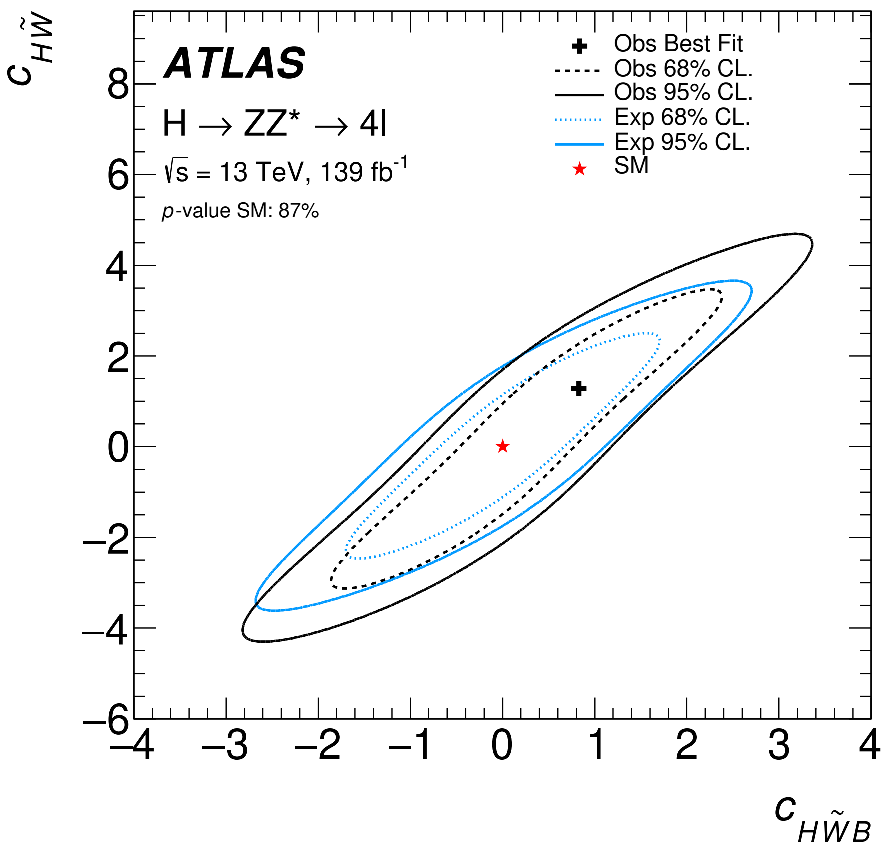


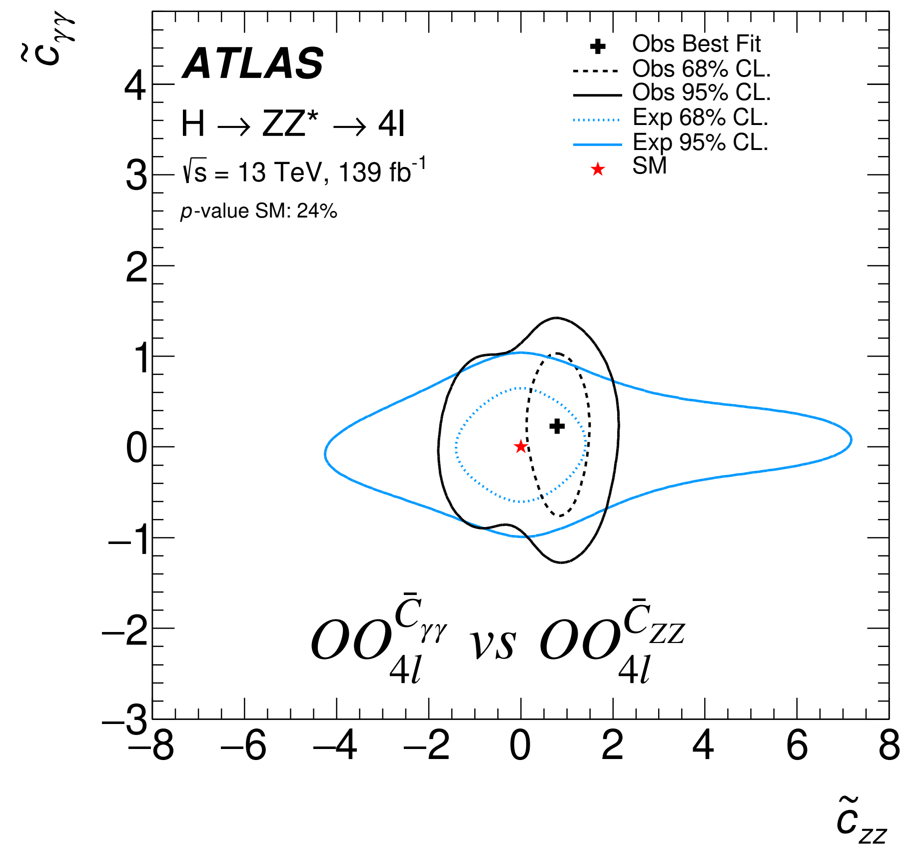
CL contours



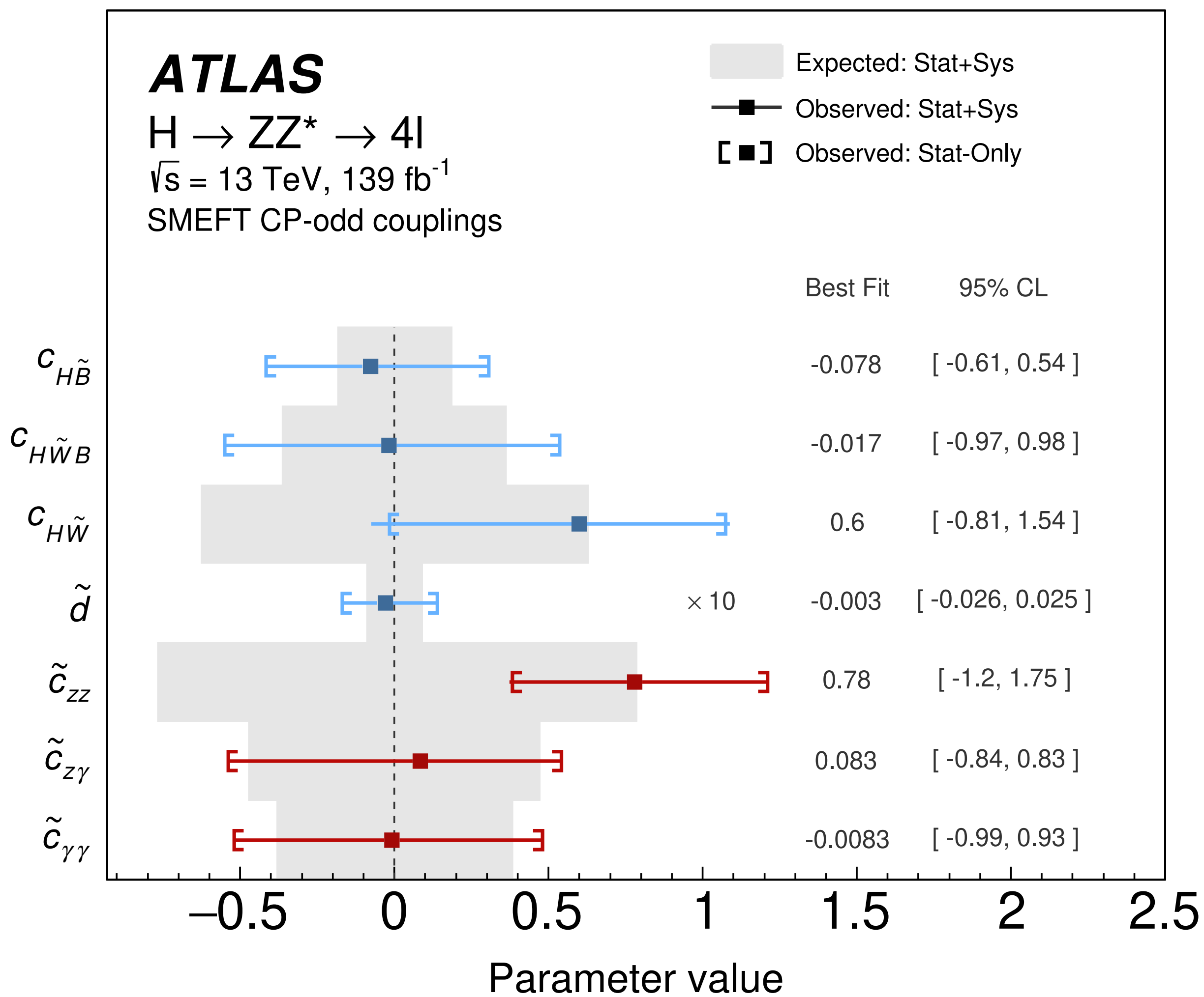
$OO_{4l}^{C_{H\bar{B}}}$ vs $OO_{4l}^{C_{H\bar{W}}}$

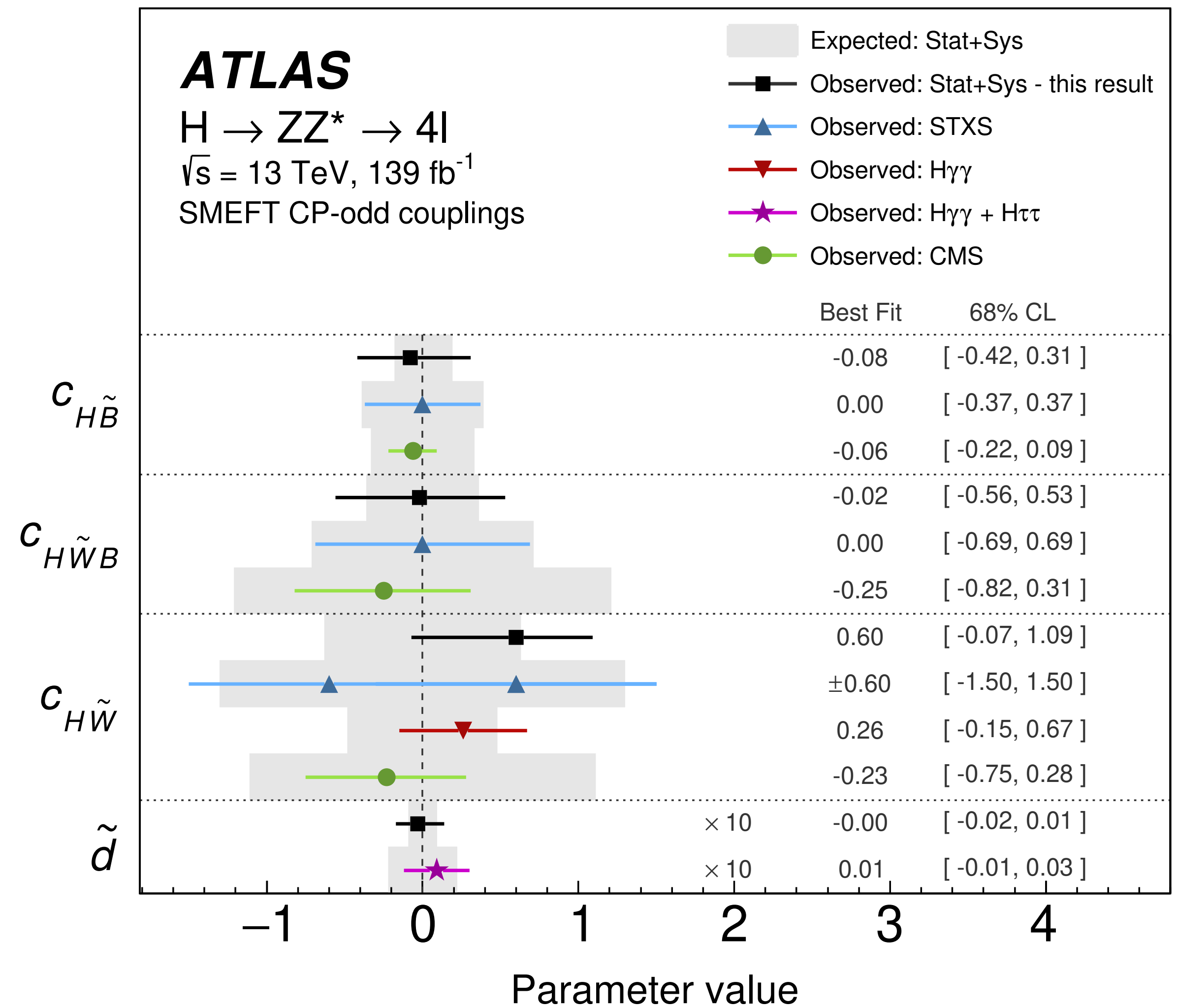






Extracted effective couplings





Warsaw basis couplings and $\tilde{d}$ are in blue.
Higgs basis couplings are in red.

$C_{H\tilde{W}}$ is from prod + decay fit.
$\tilde{C}_{ZZ}$ is from production only fit.

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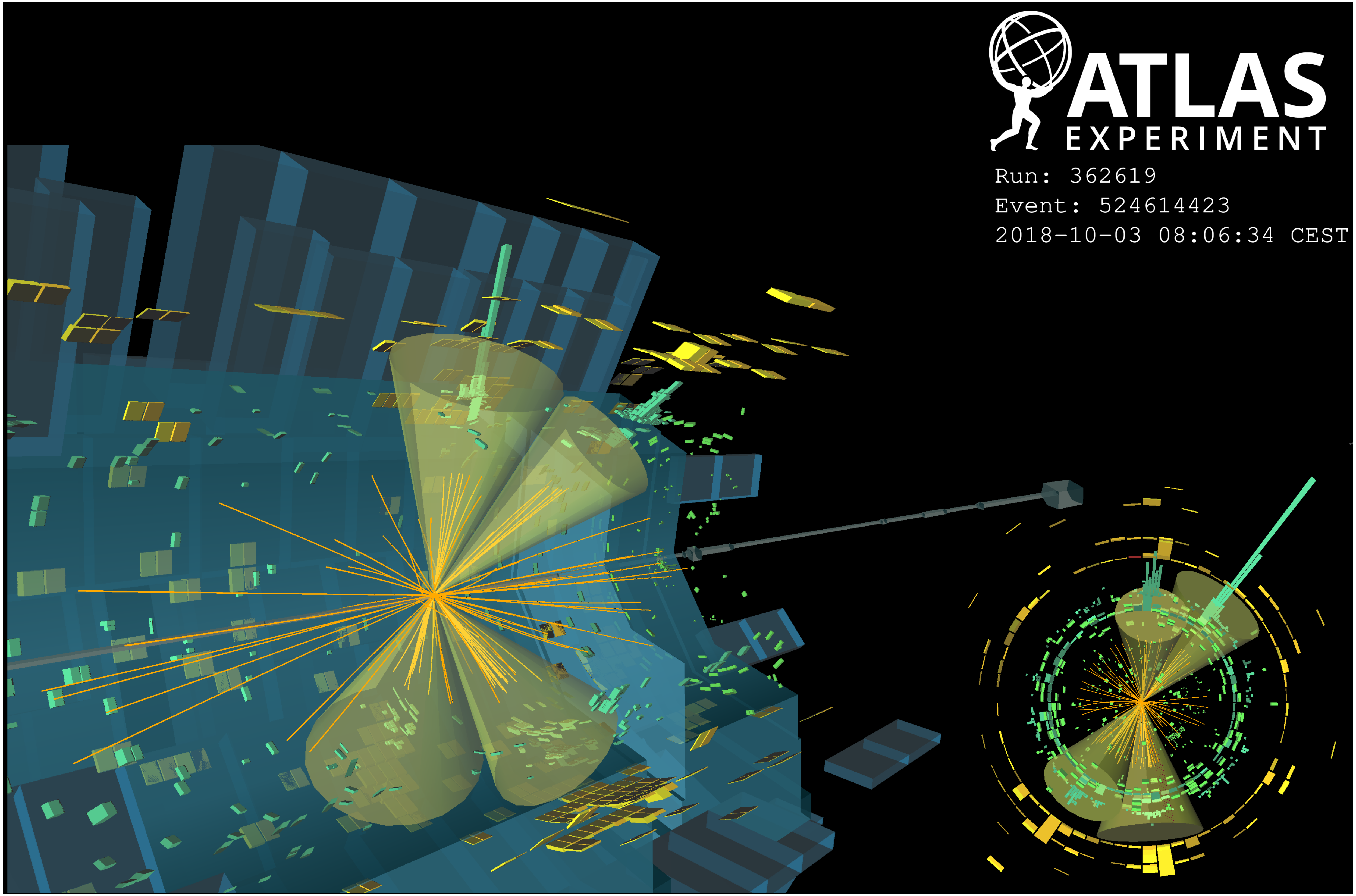
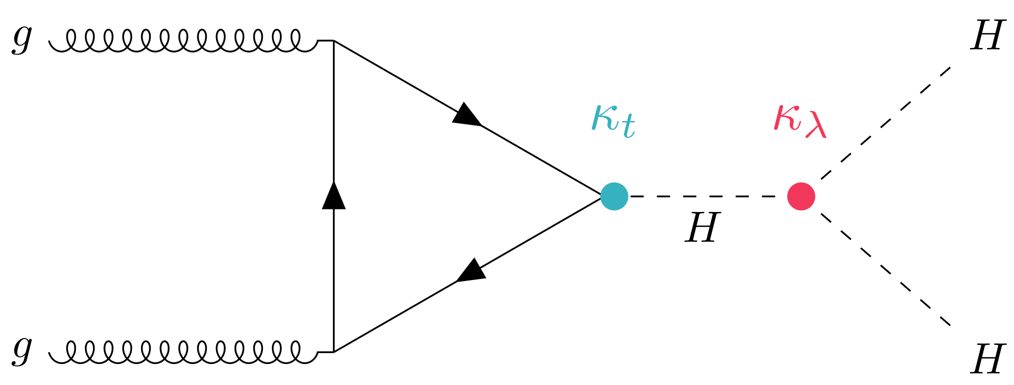
- ☐ Charm Yukawa in VH mode
- ☐ Summary

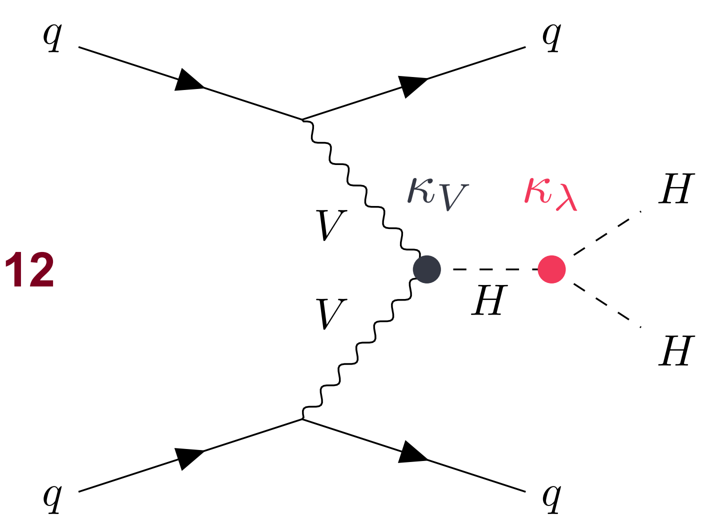
Search for HH production in 4b final state

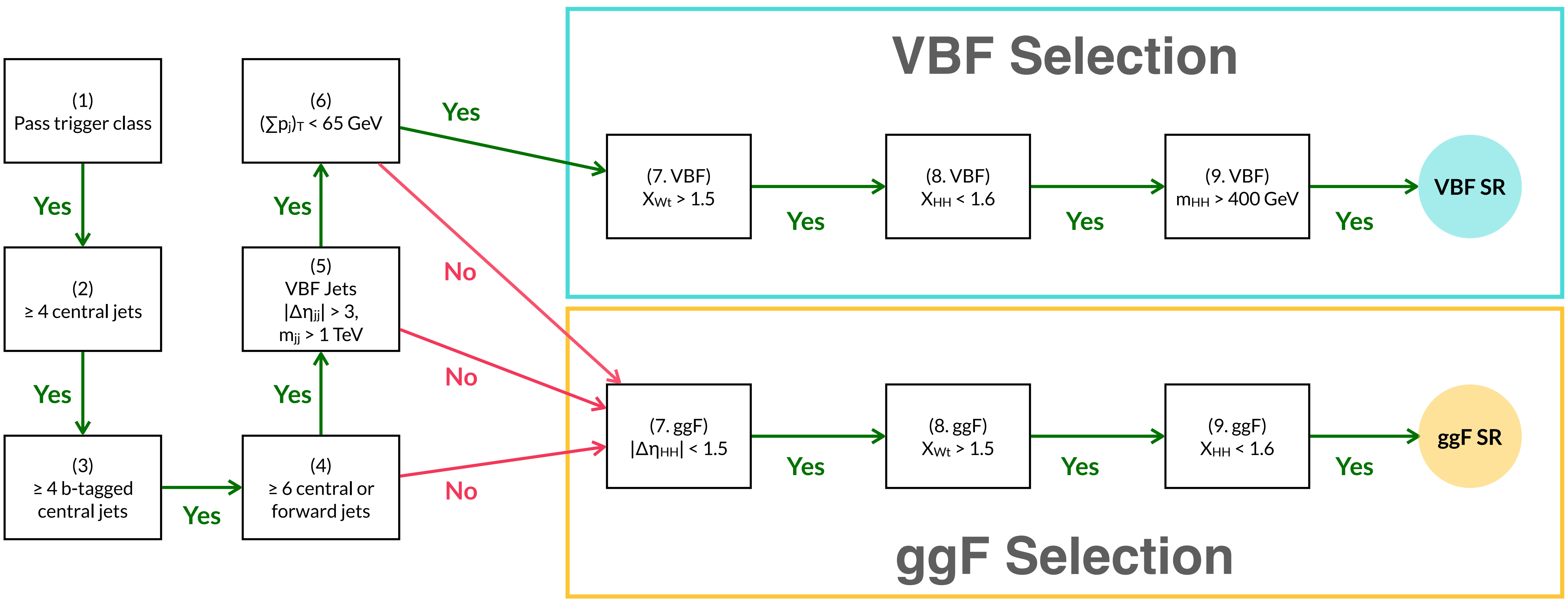


Search for HH production in 4b final state

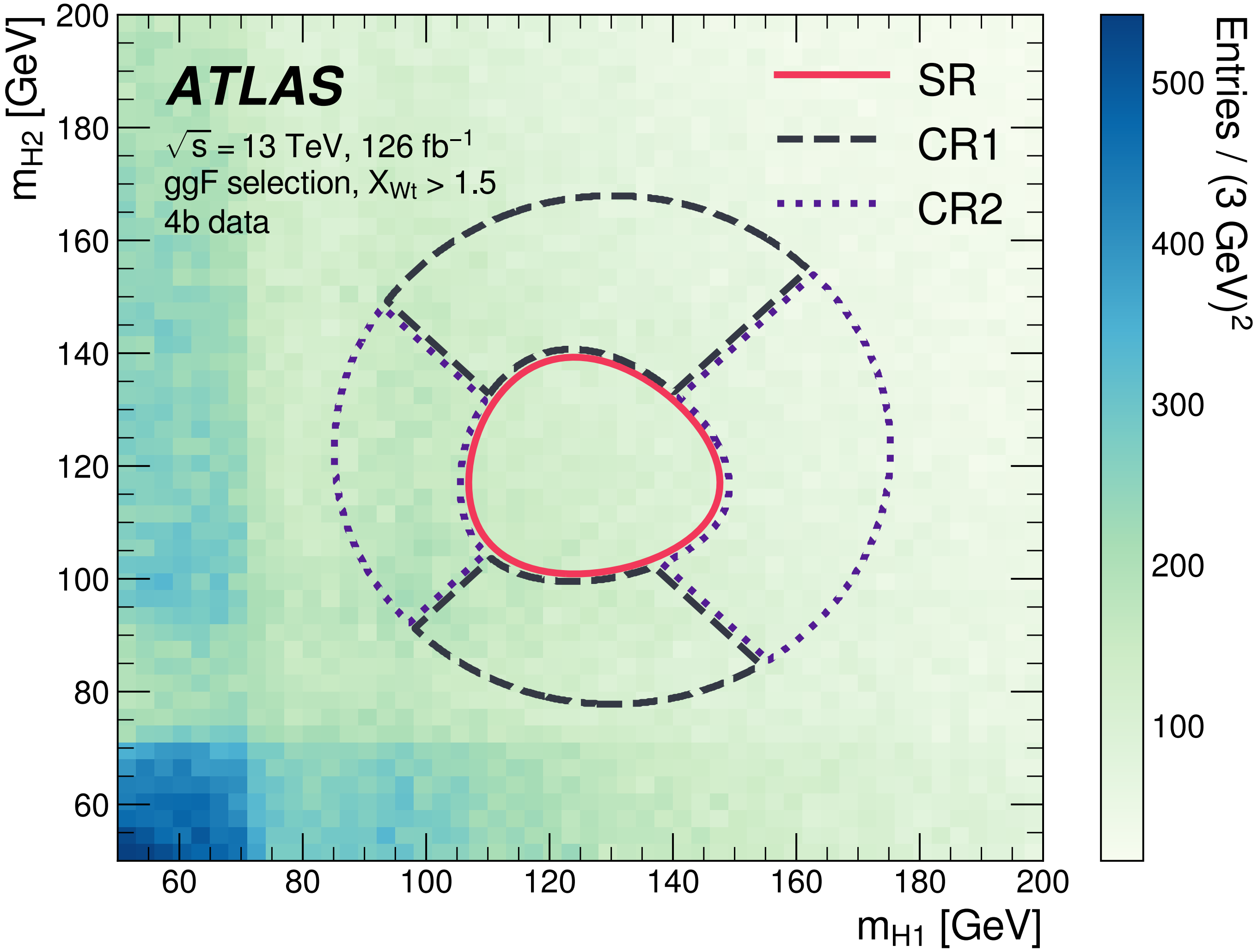


arXiv 2301.03212

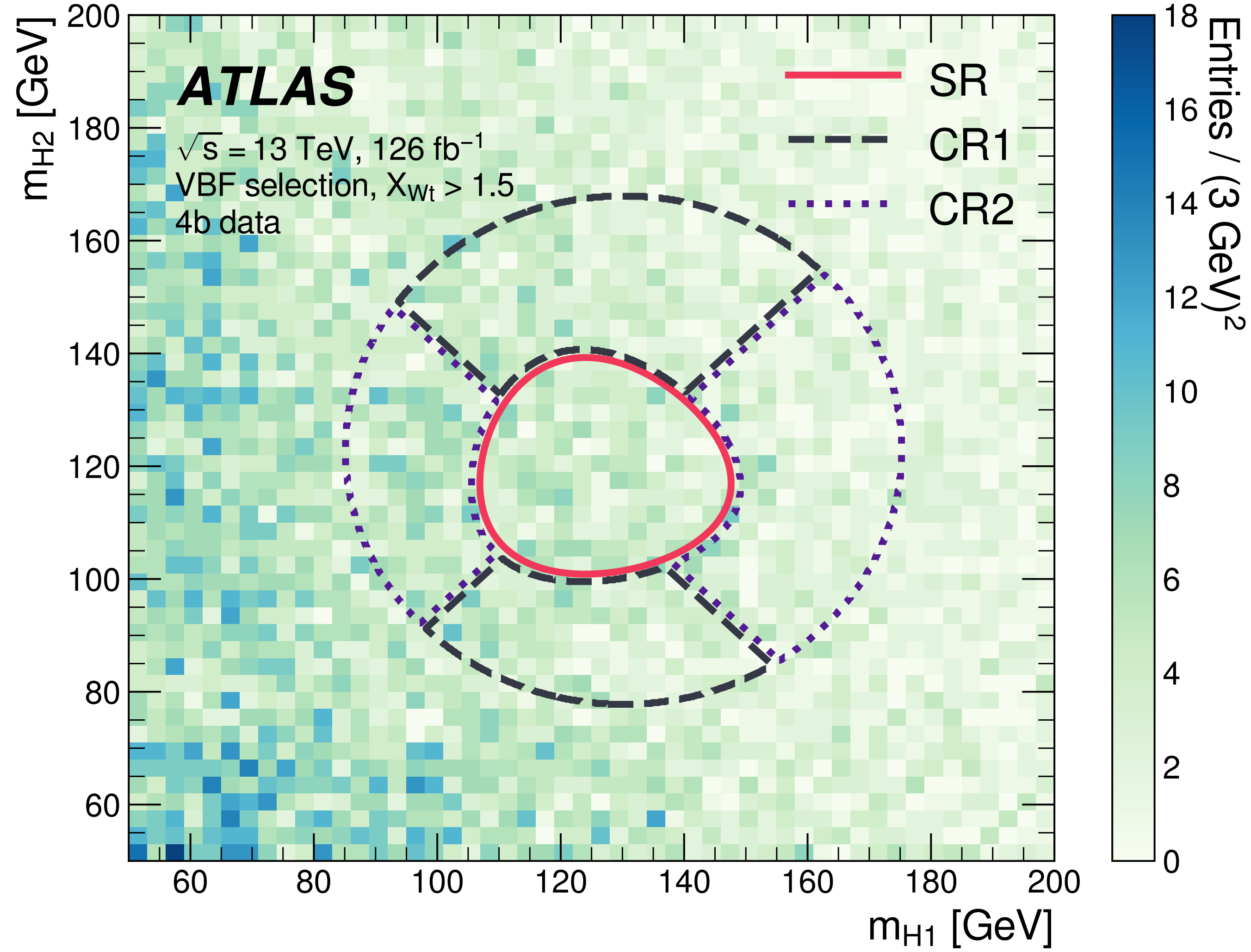




Definition of the analysis region



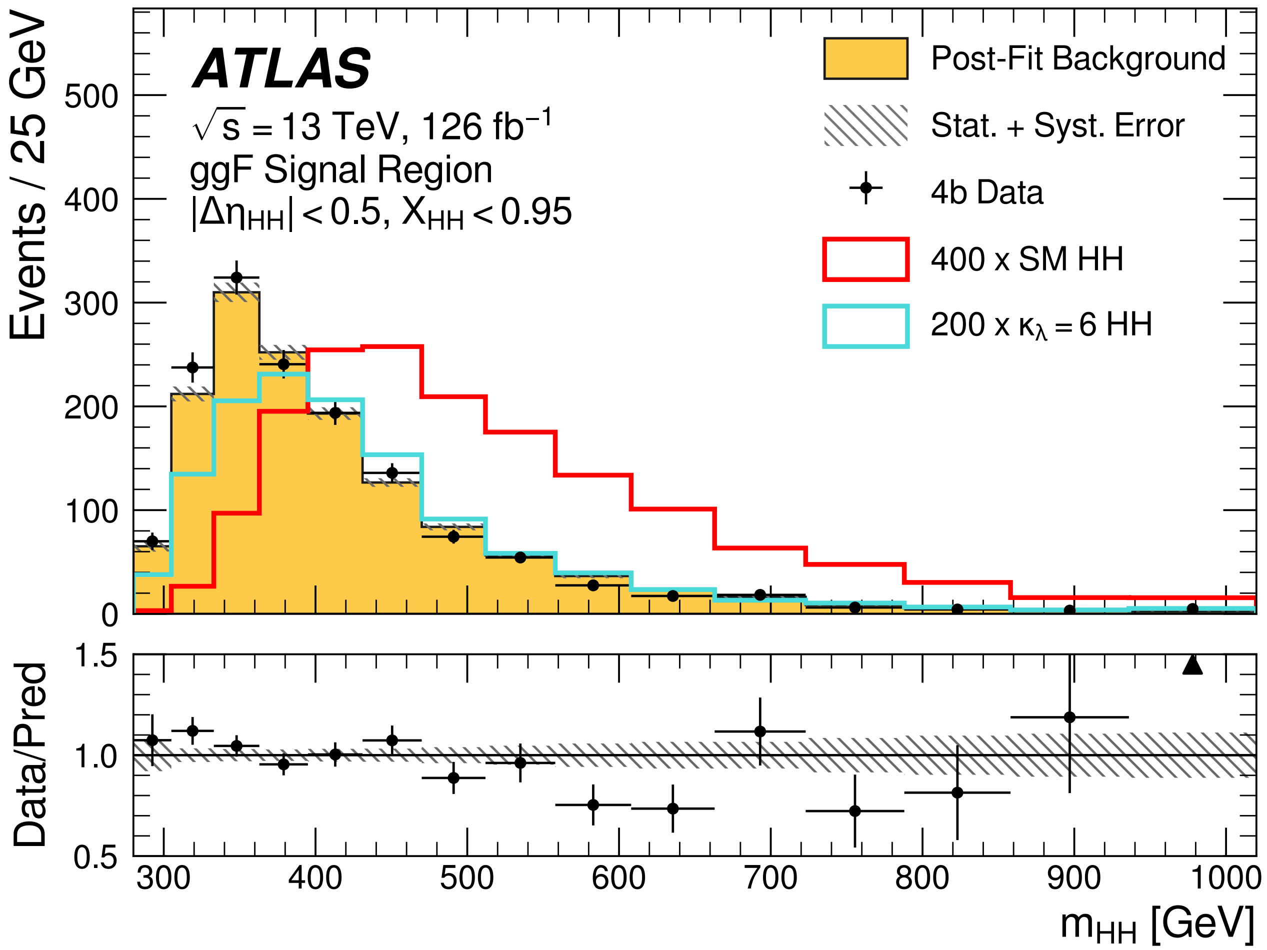
ggF signal region

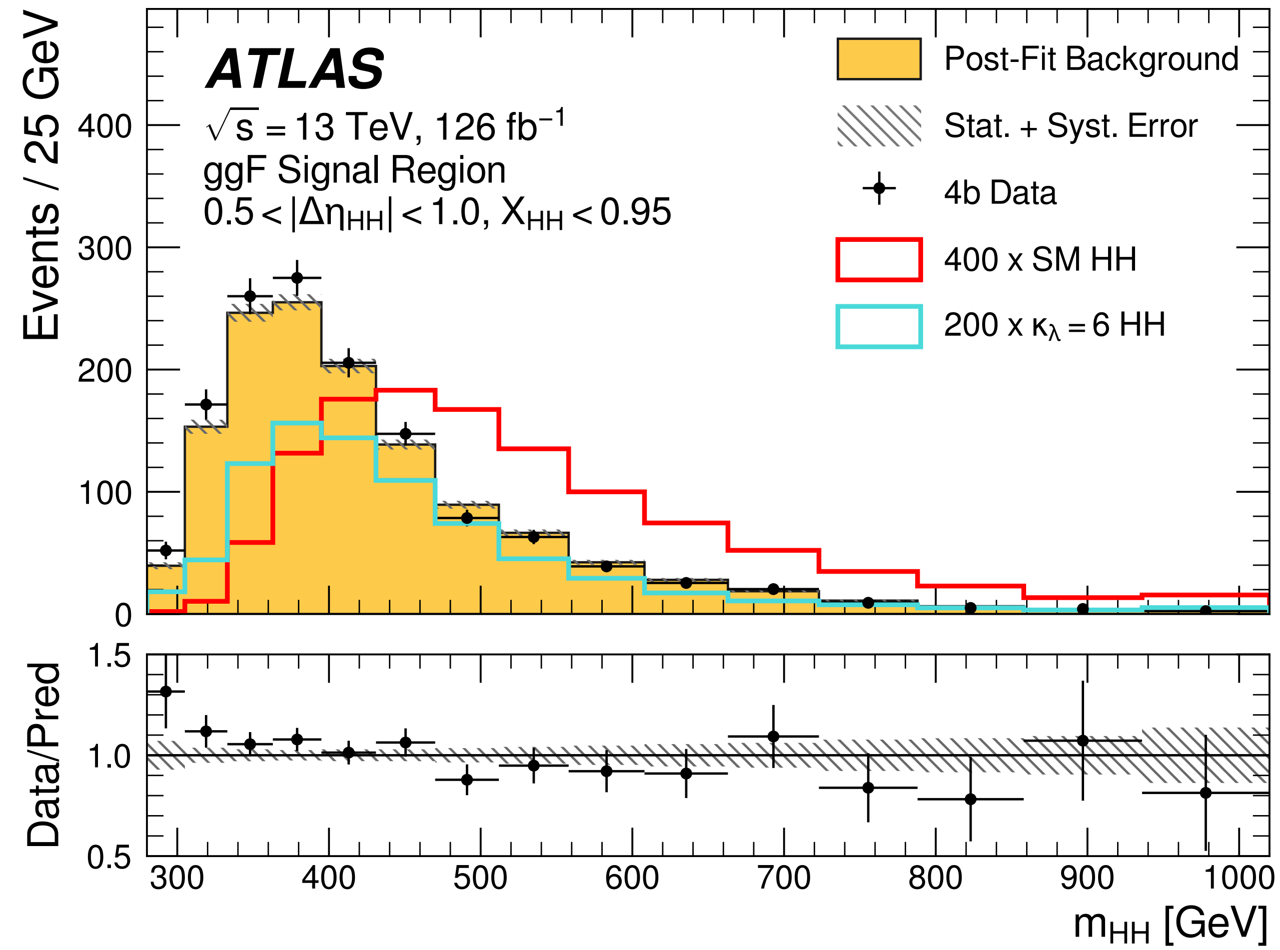


VBF signal region

The mass planes of the reconstructed Higgs boson candidates.

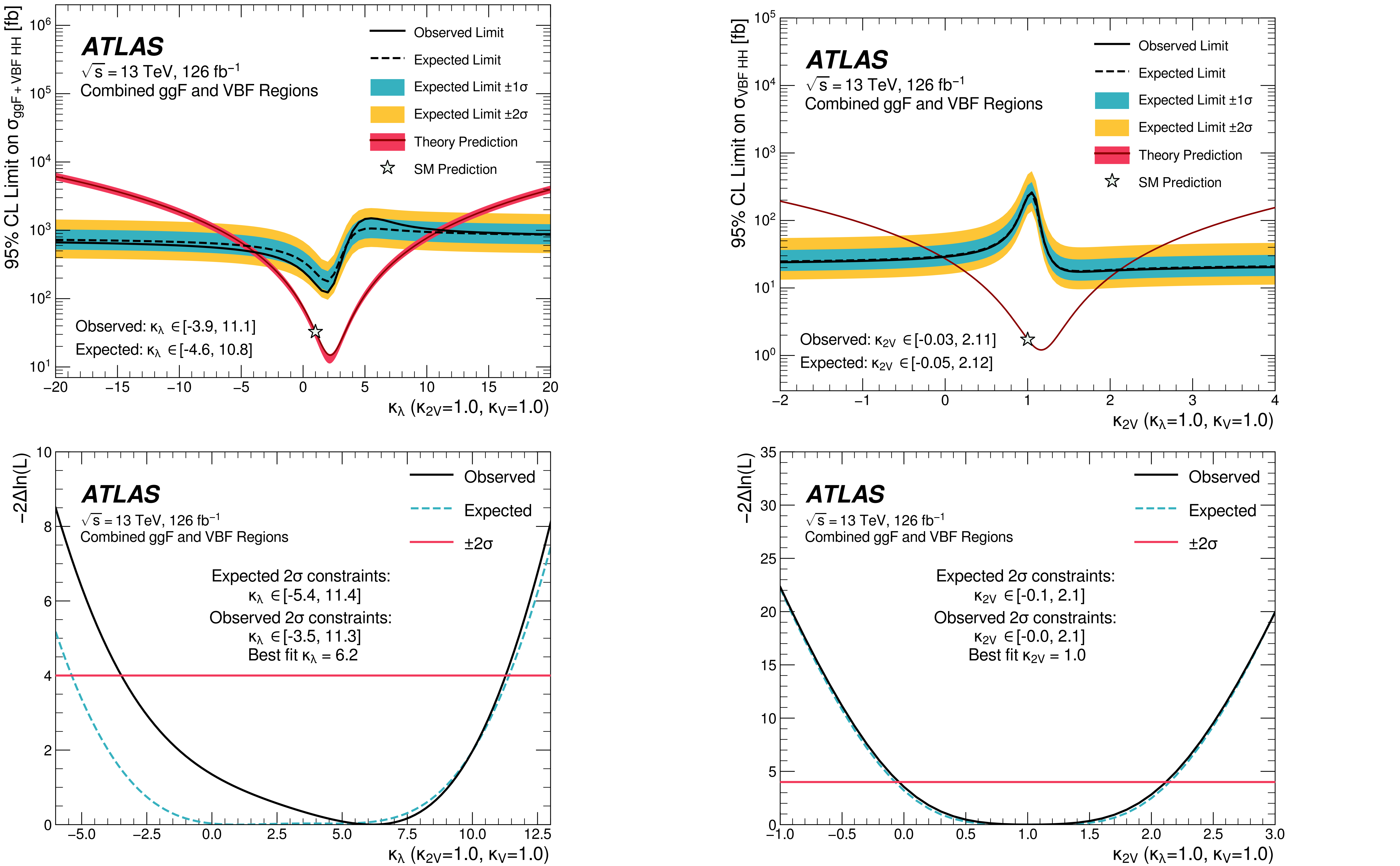
Search for HH production in 4b final state





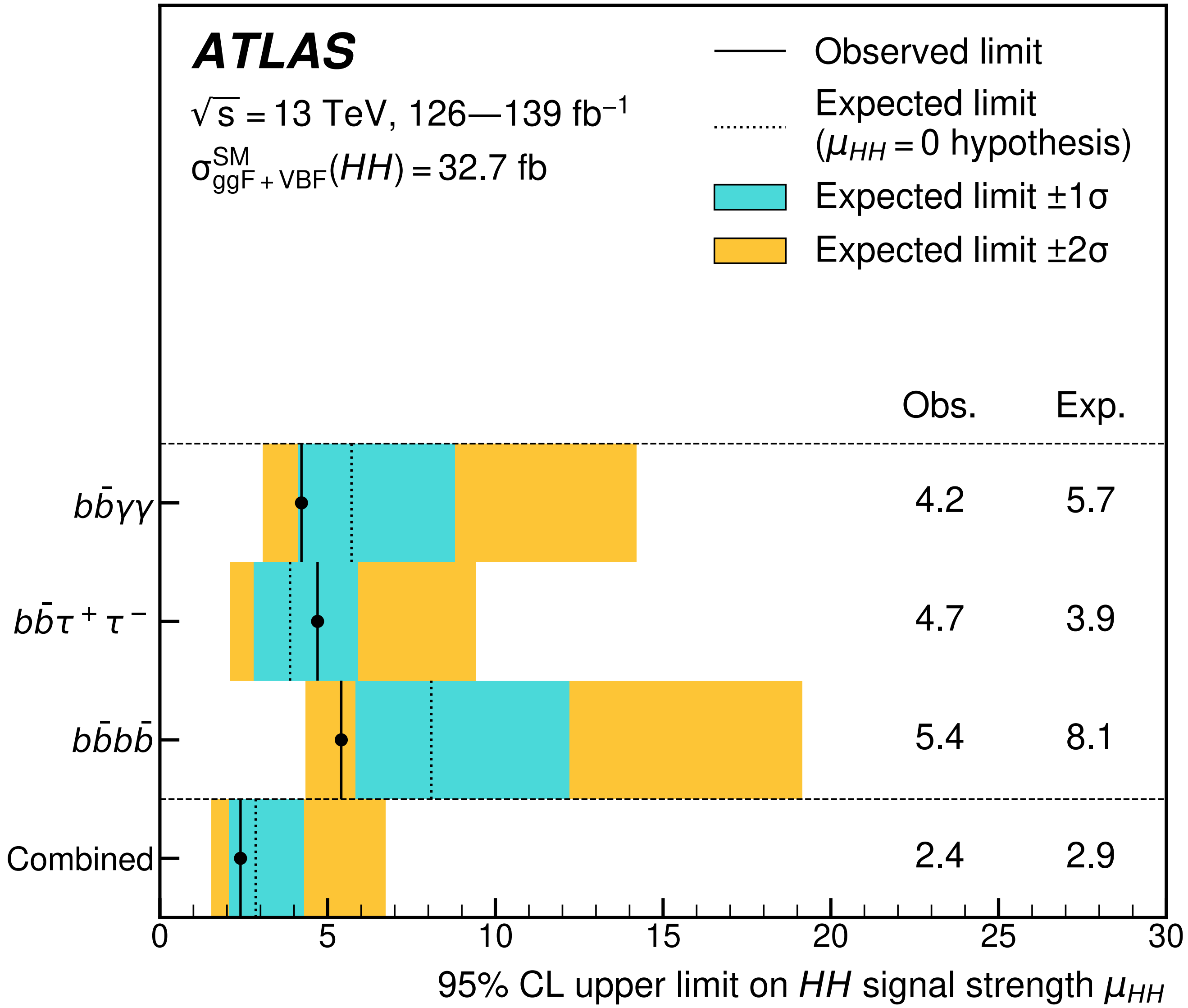
$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\,\text{GeV}}{0.1\, m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\,\text{GeV}}{0.1\, m_{H2}}\right)^2}$$

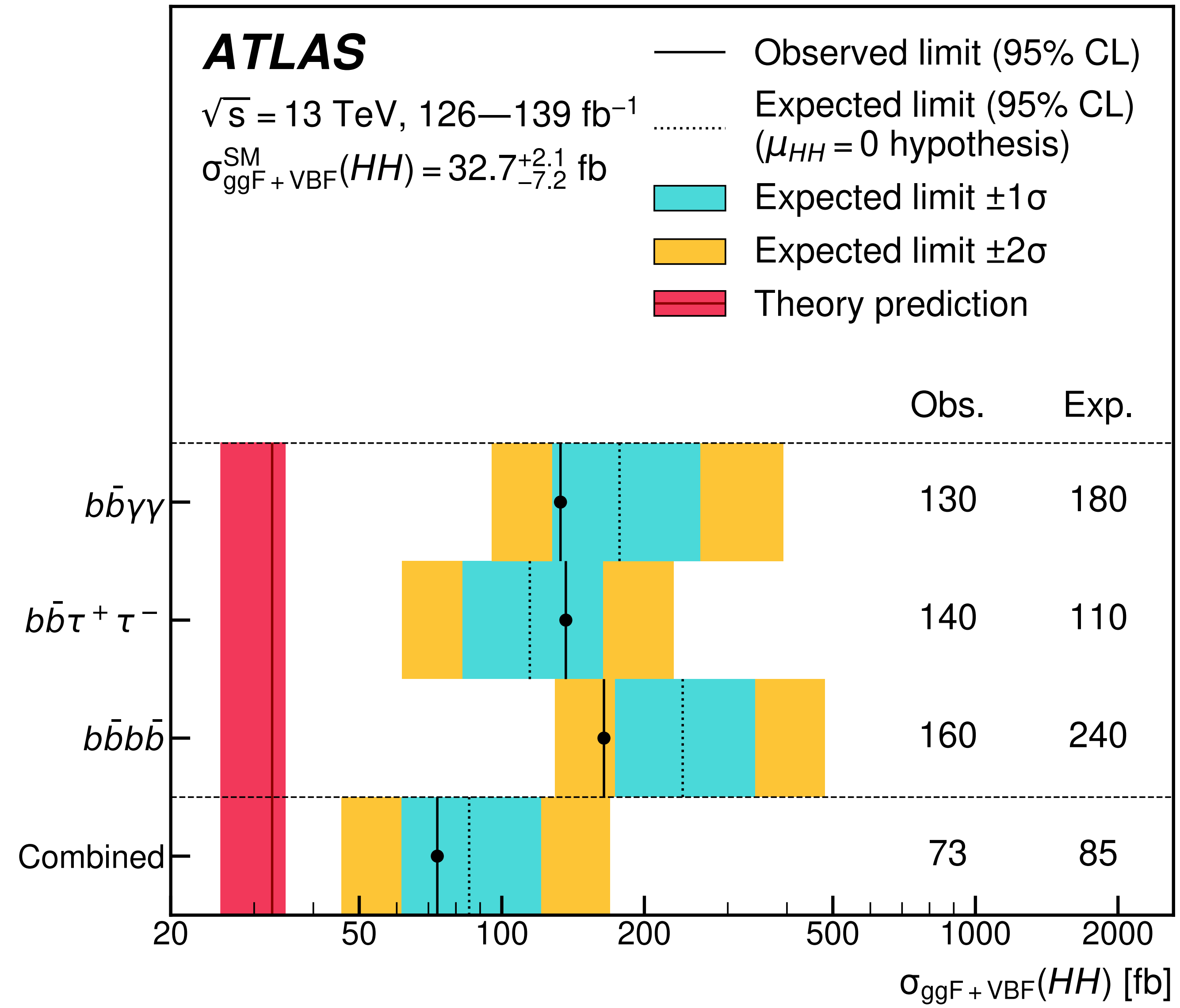
Search for HH production in 4b final state



Double & Single Higgs combination

arXiv 2211.01216

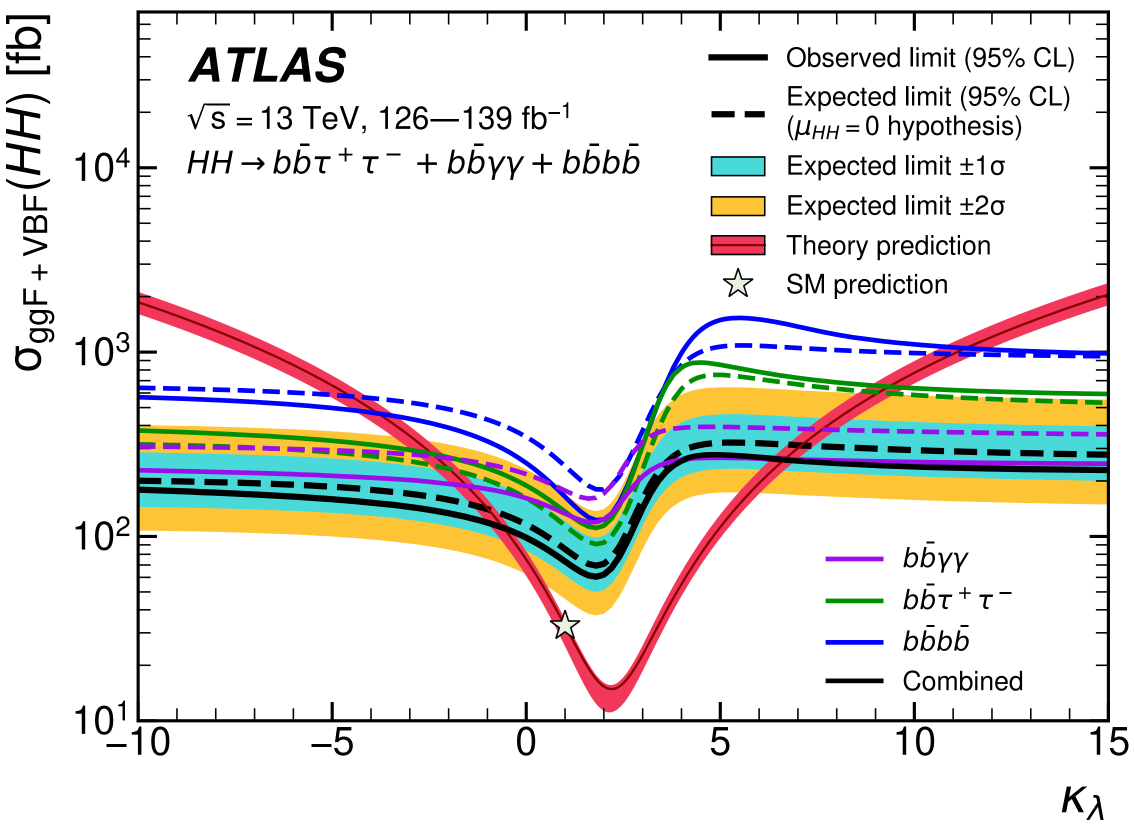


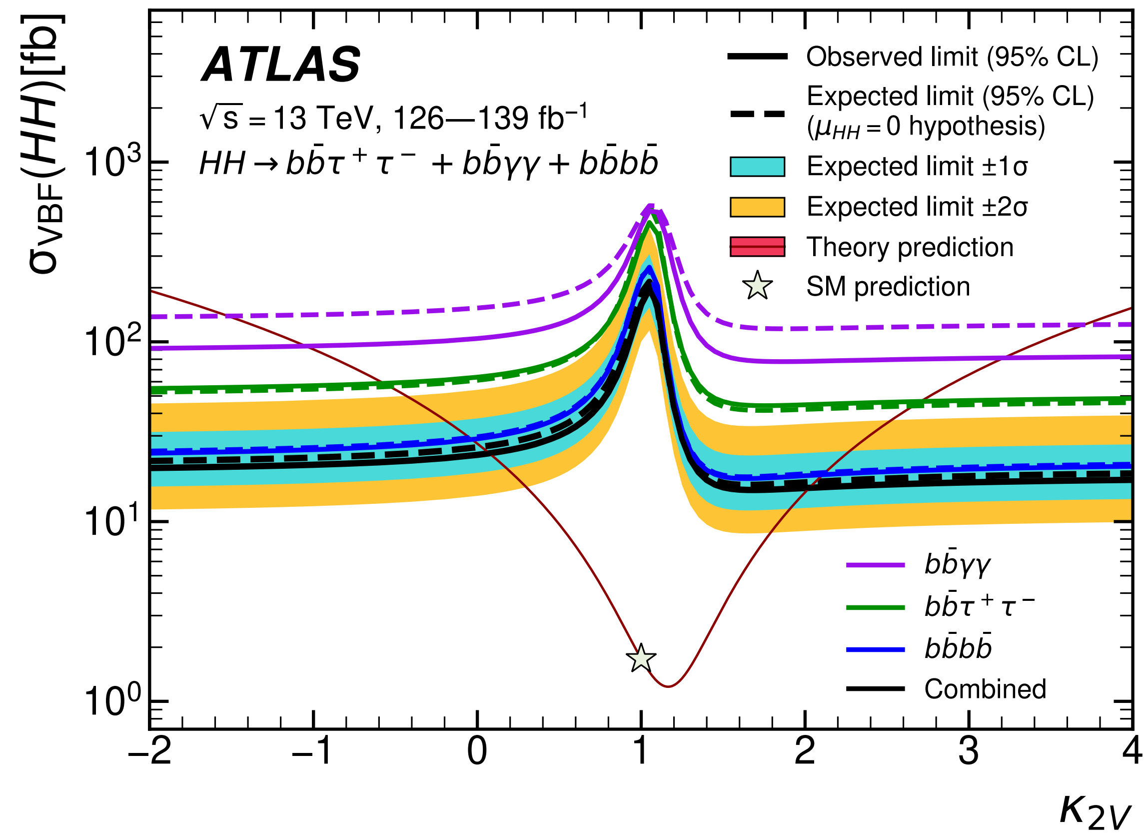


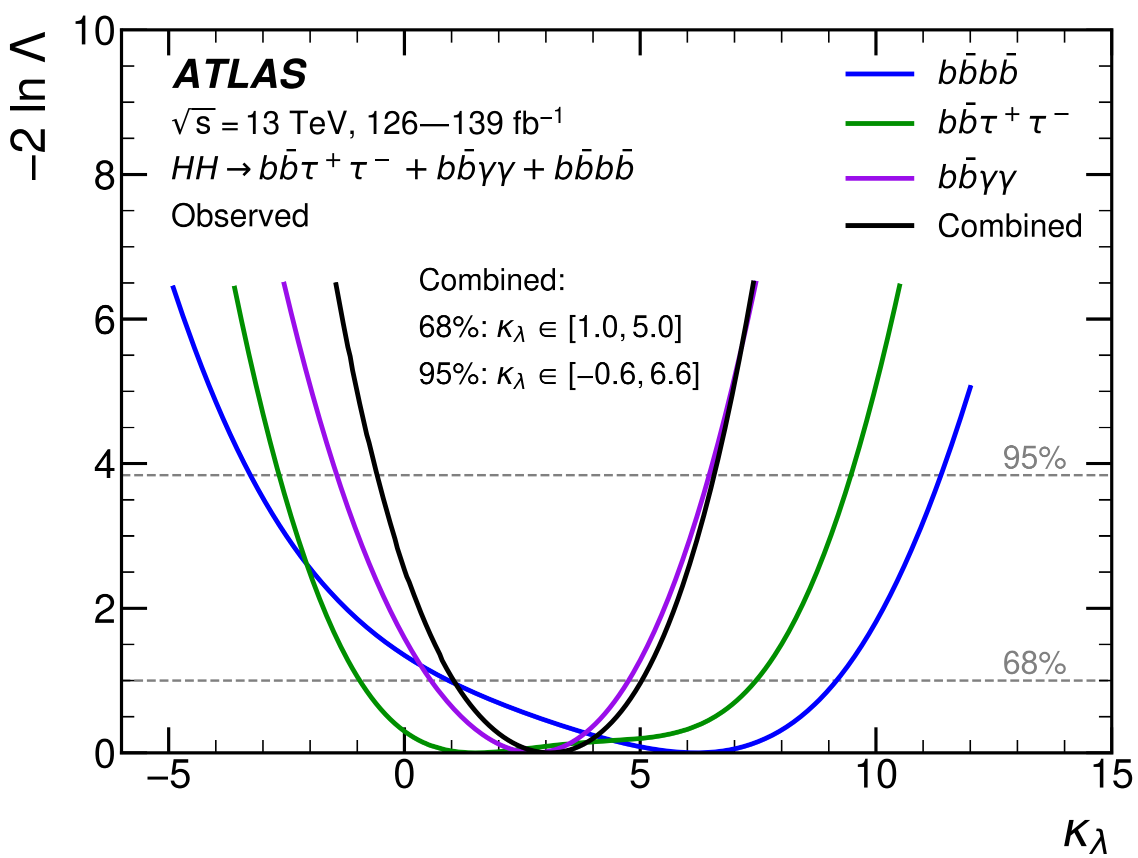
Observed and expected 95% CL upper limits on the signal strength. The SM prediction is with Higgs mass m_H = 125.09 GeV.

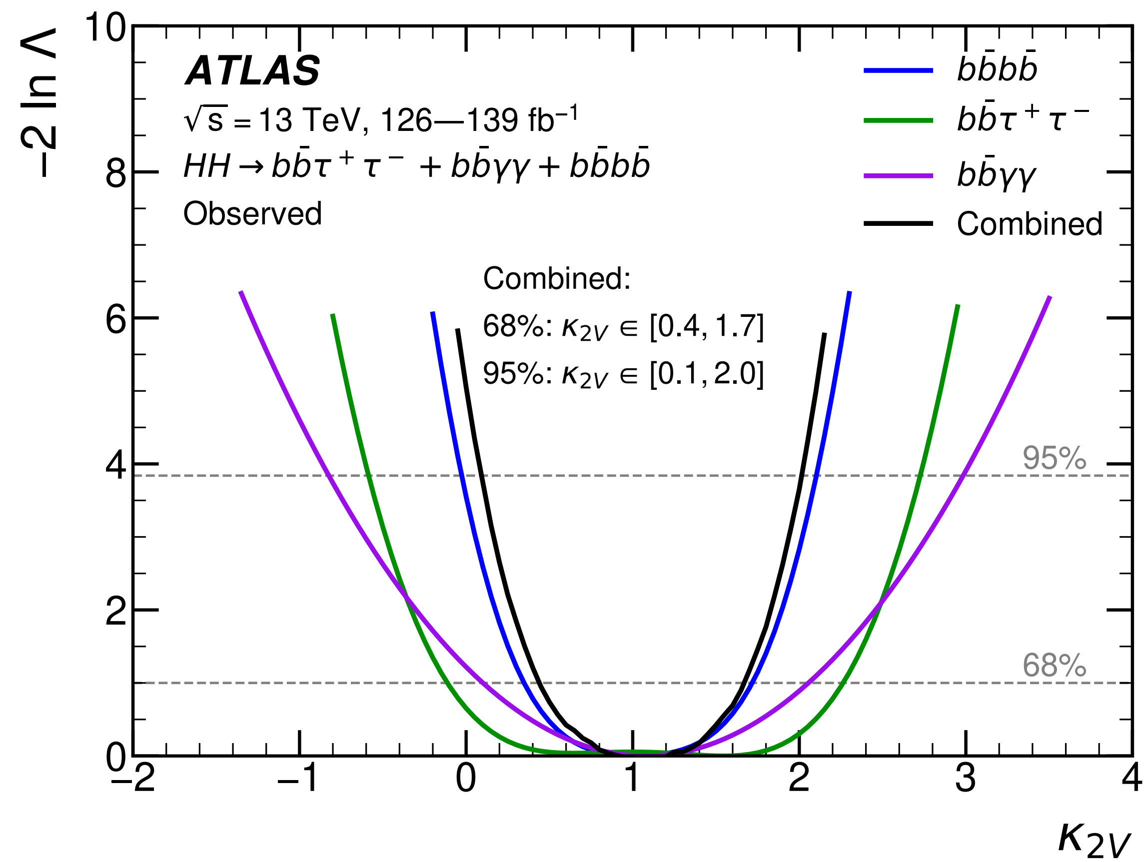
Observed and expected 95% CL upper limits on HH x-section. The SM prediction is with Higgs mass m_H = 125.09 GeV.

Double & Single Higgs combination









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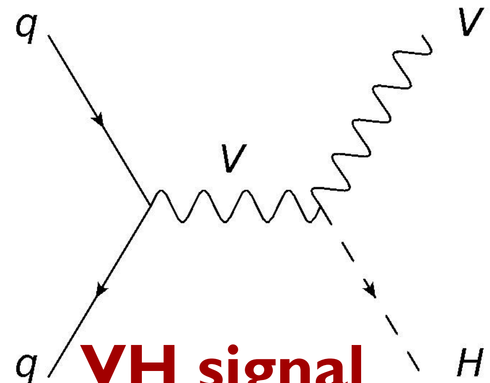
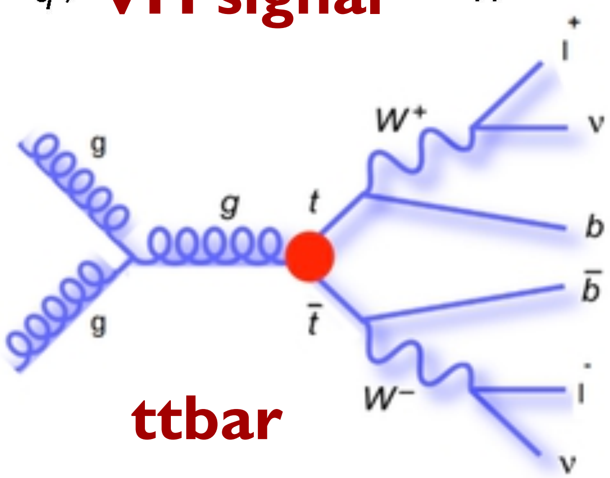
V + H to cc : Charm Yukawa probe

Signal : pp → V + H ; H → $c\bar{c}$



VH signal



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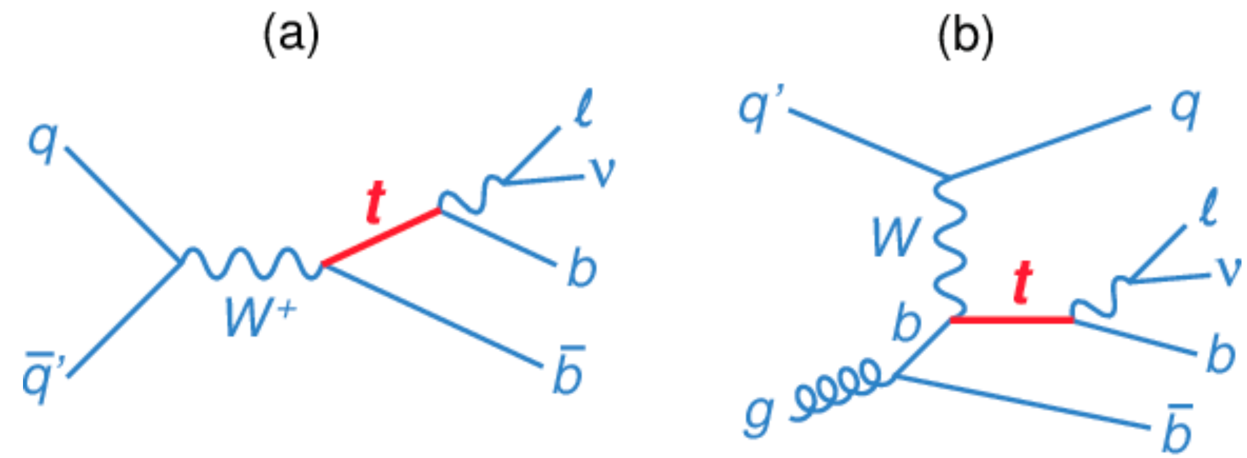
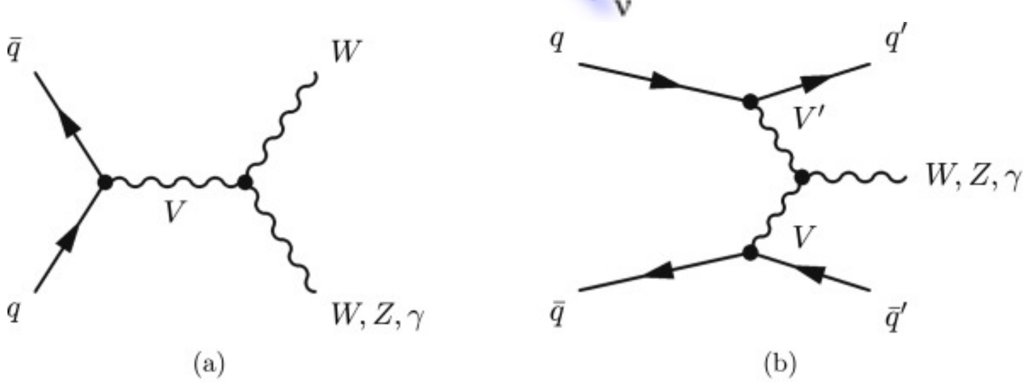
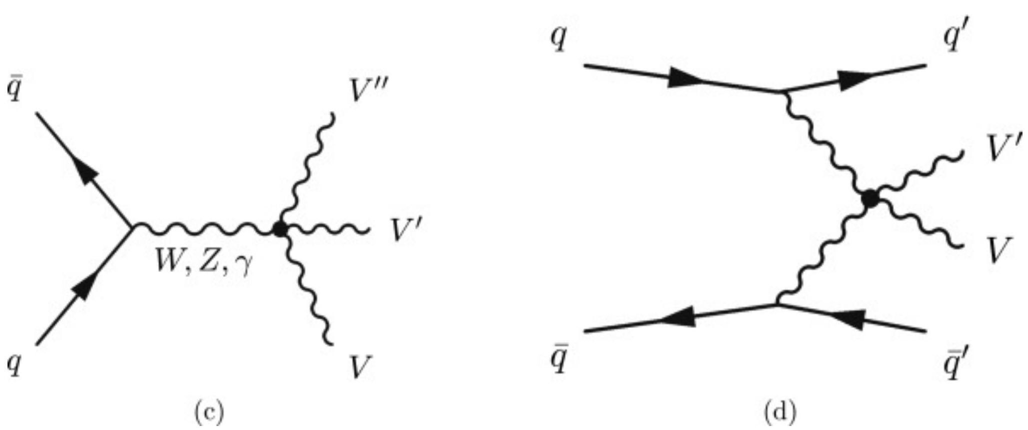
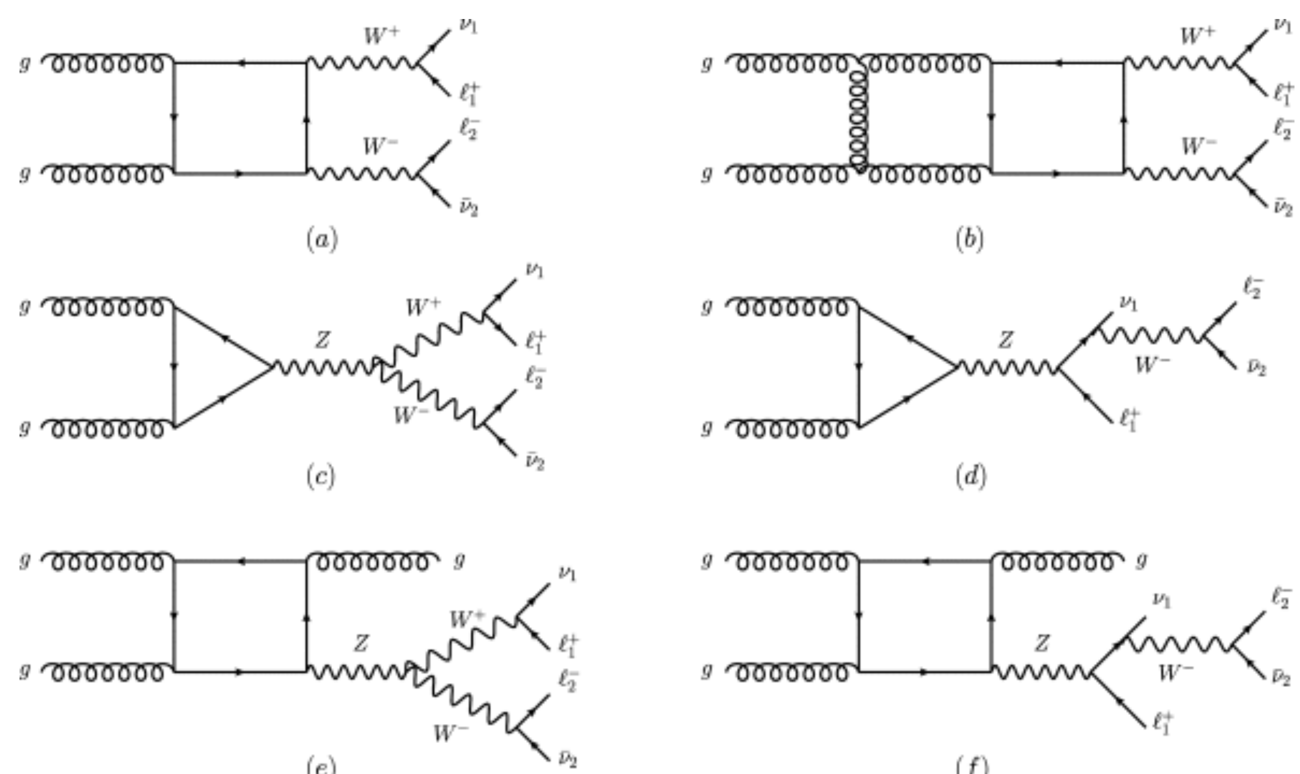




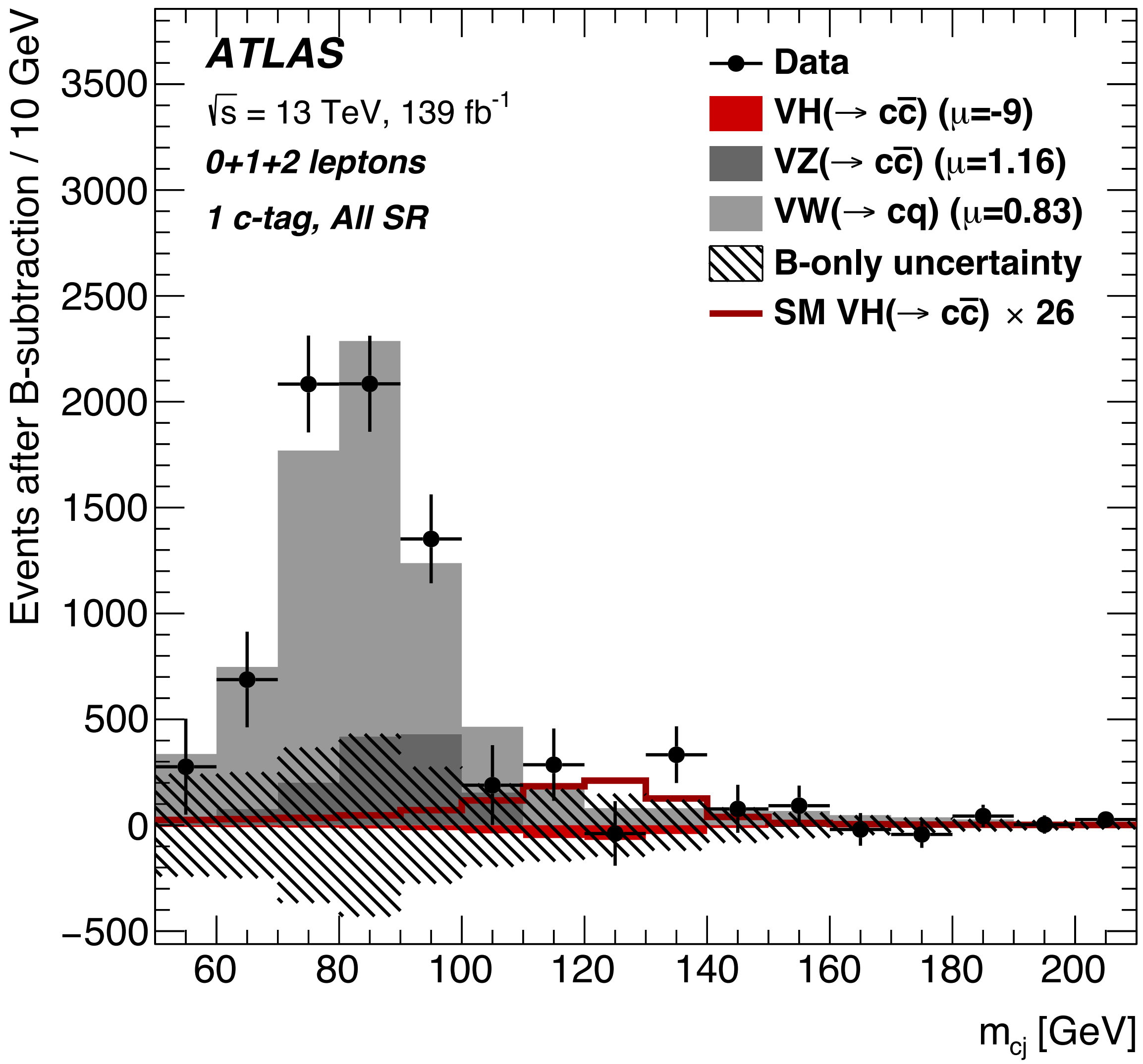
quark initiated multi-boson/V+jets

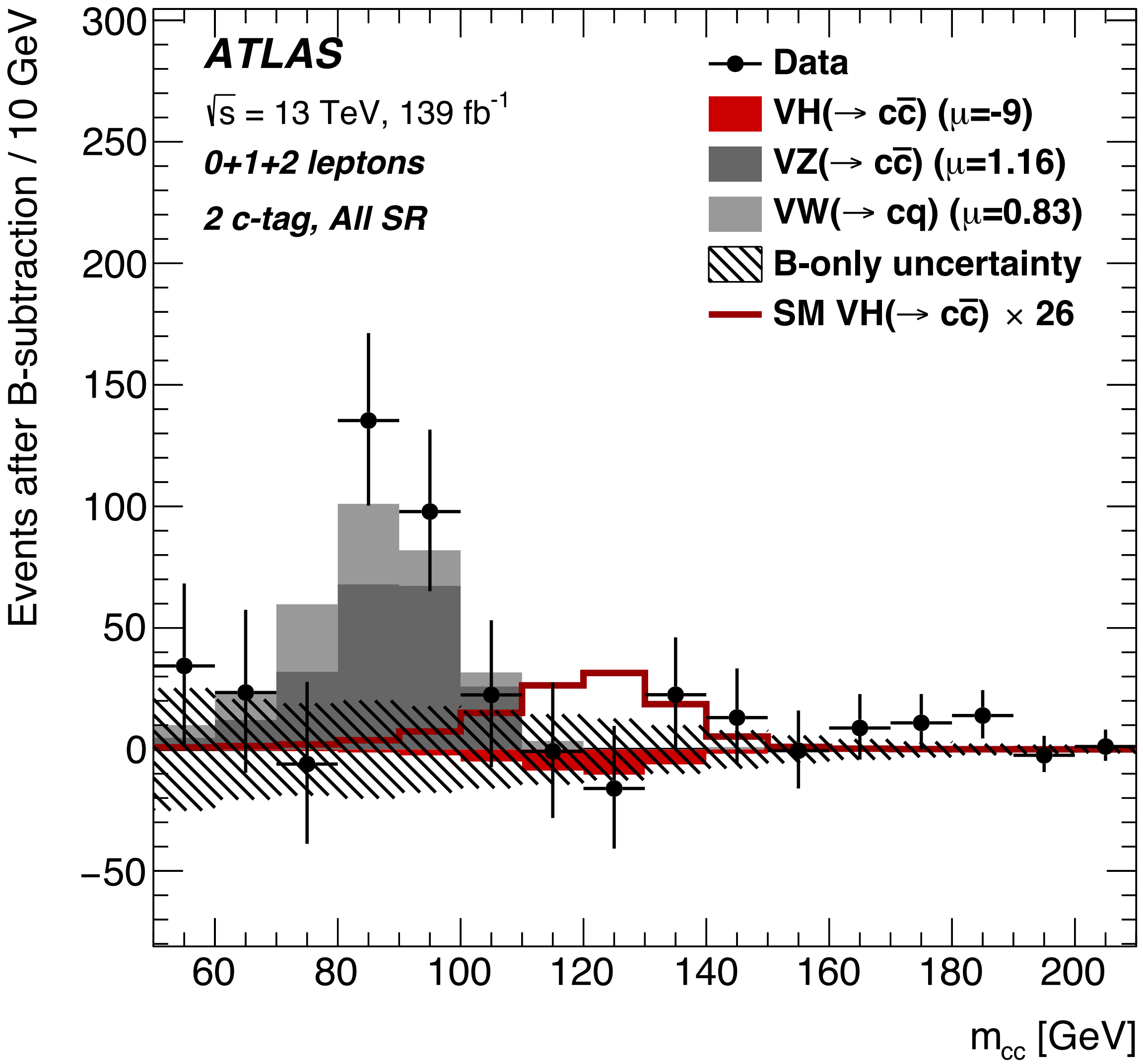




gluon initiated multi-boson/V + jets

Extraction of 3 POI



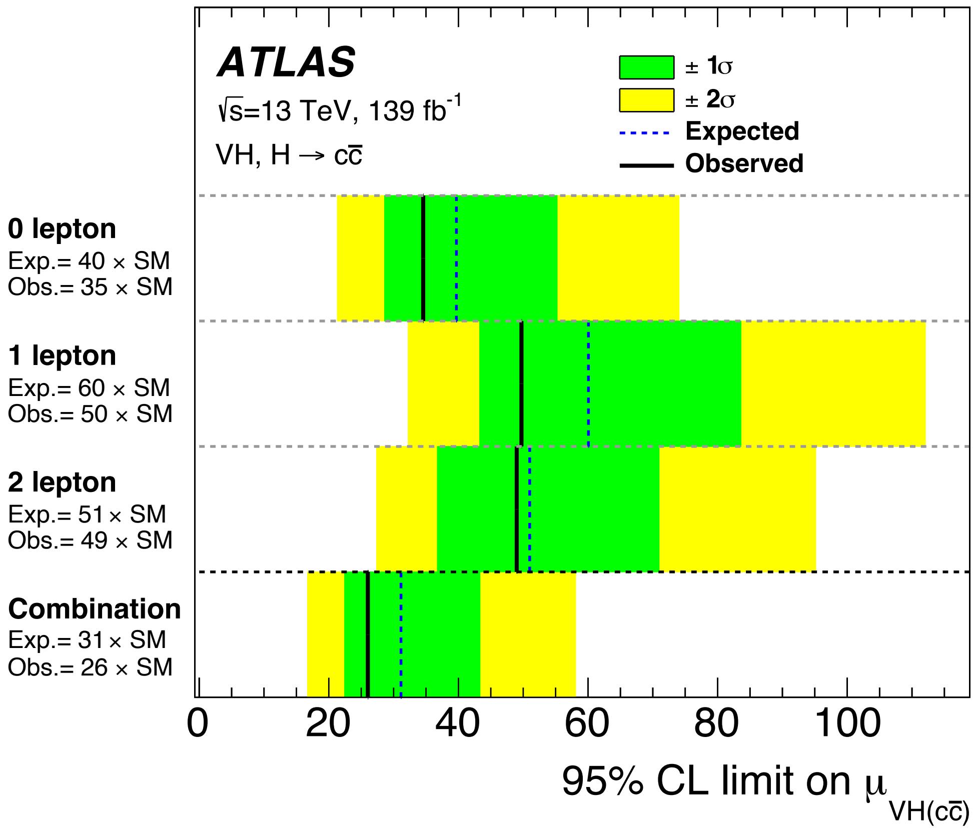


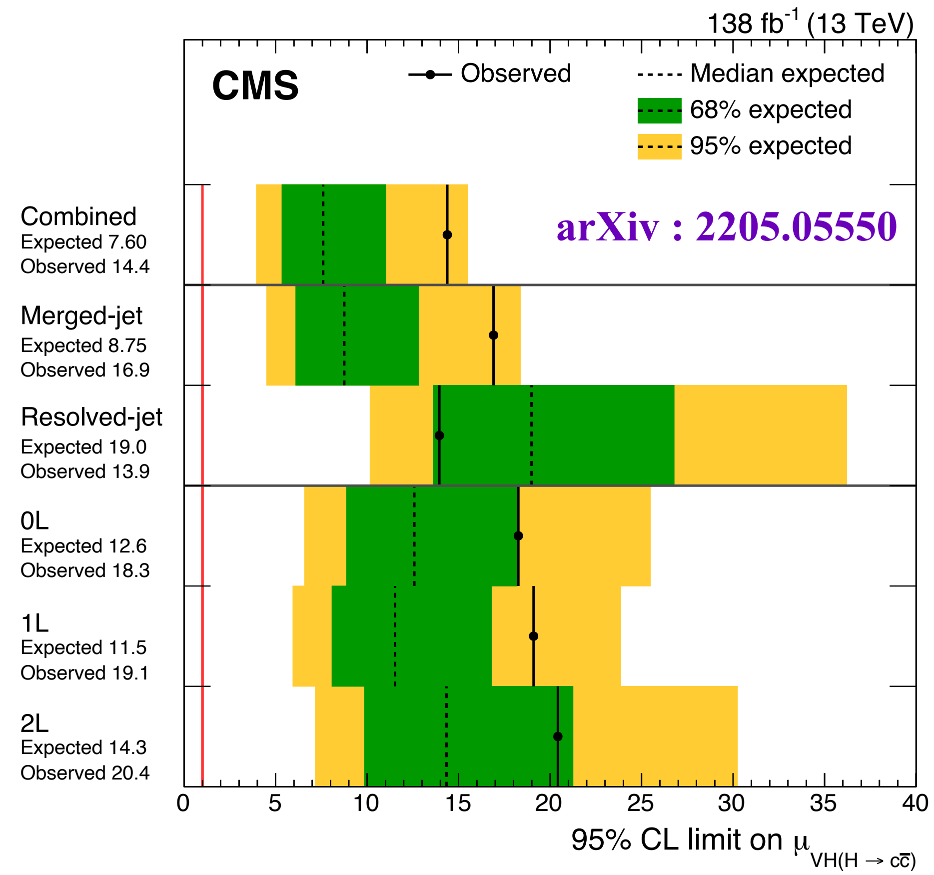
The 3 POI fit after background subtraction combining the three channels

Establishing the consistency of nuisance parameter pull across different regions and understanding the correlation across regions is a key part of this search strategy in order to reliably extract the POI from likelihood fit.

Where do we stand compared to CMS

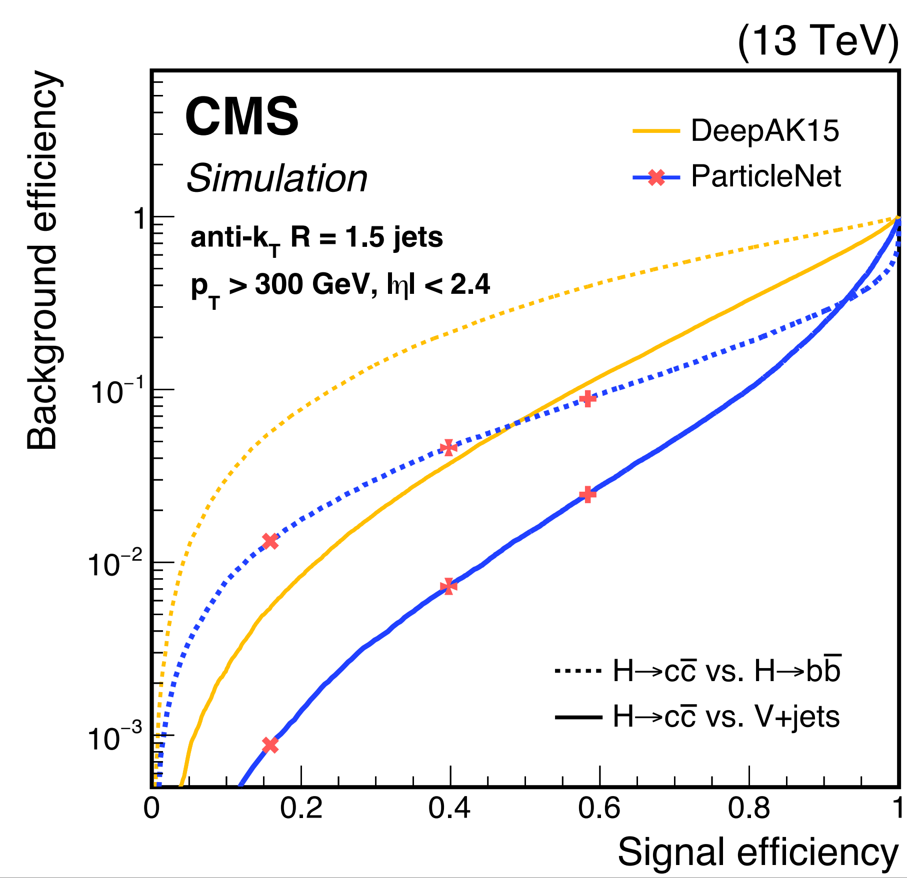
Eur. Phys. J. C (2022) 82:717





ATLAS bound : $|\kappa_c| < 8.5$

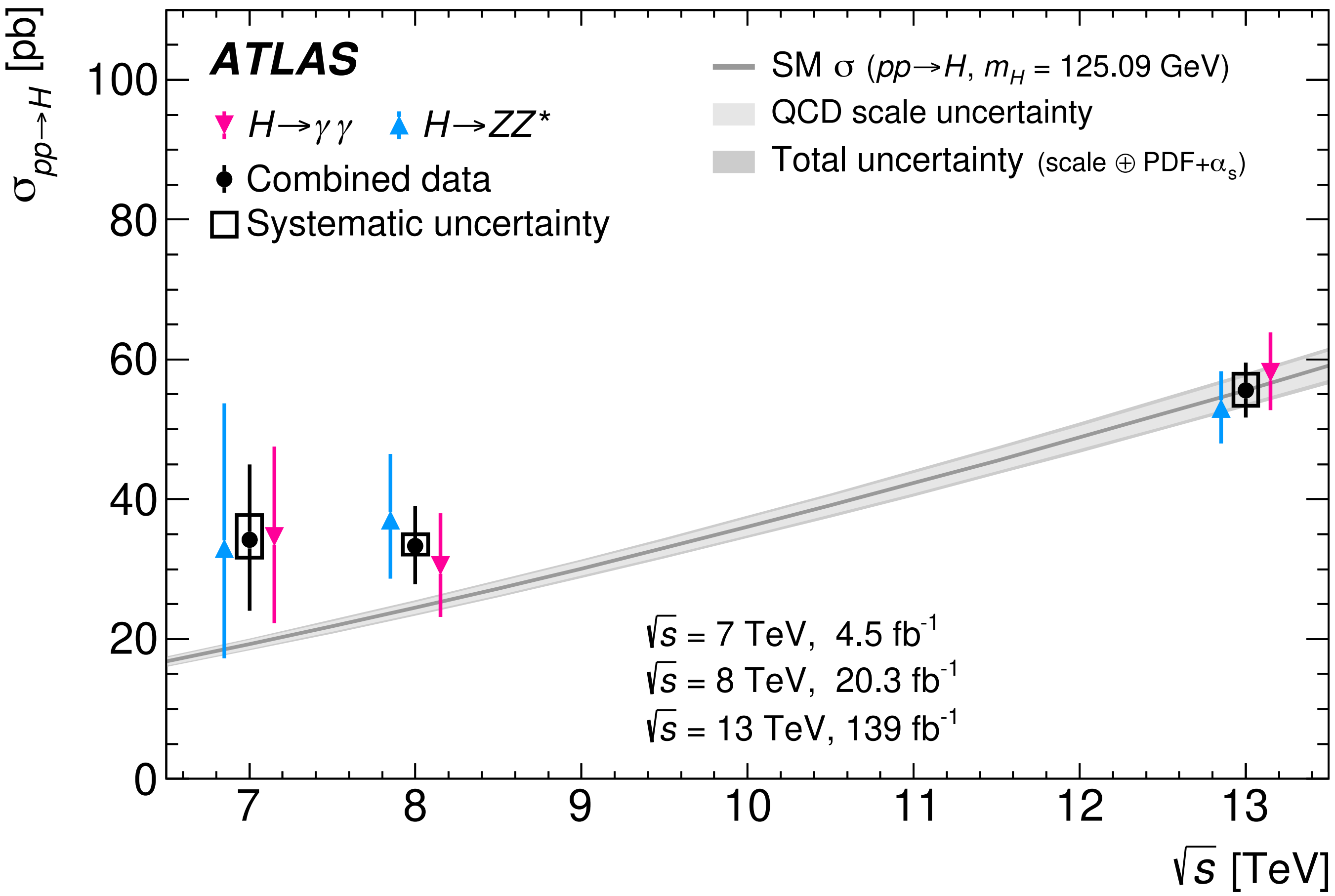
CMS bound : $1.1 < |\kappa_c| < 5.5$

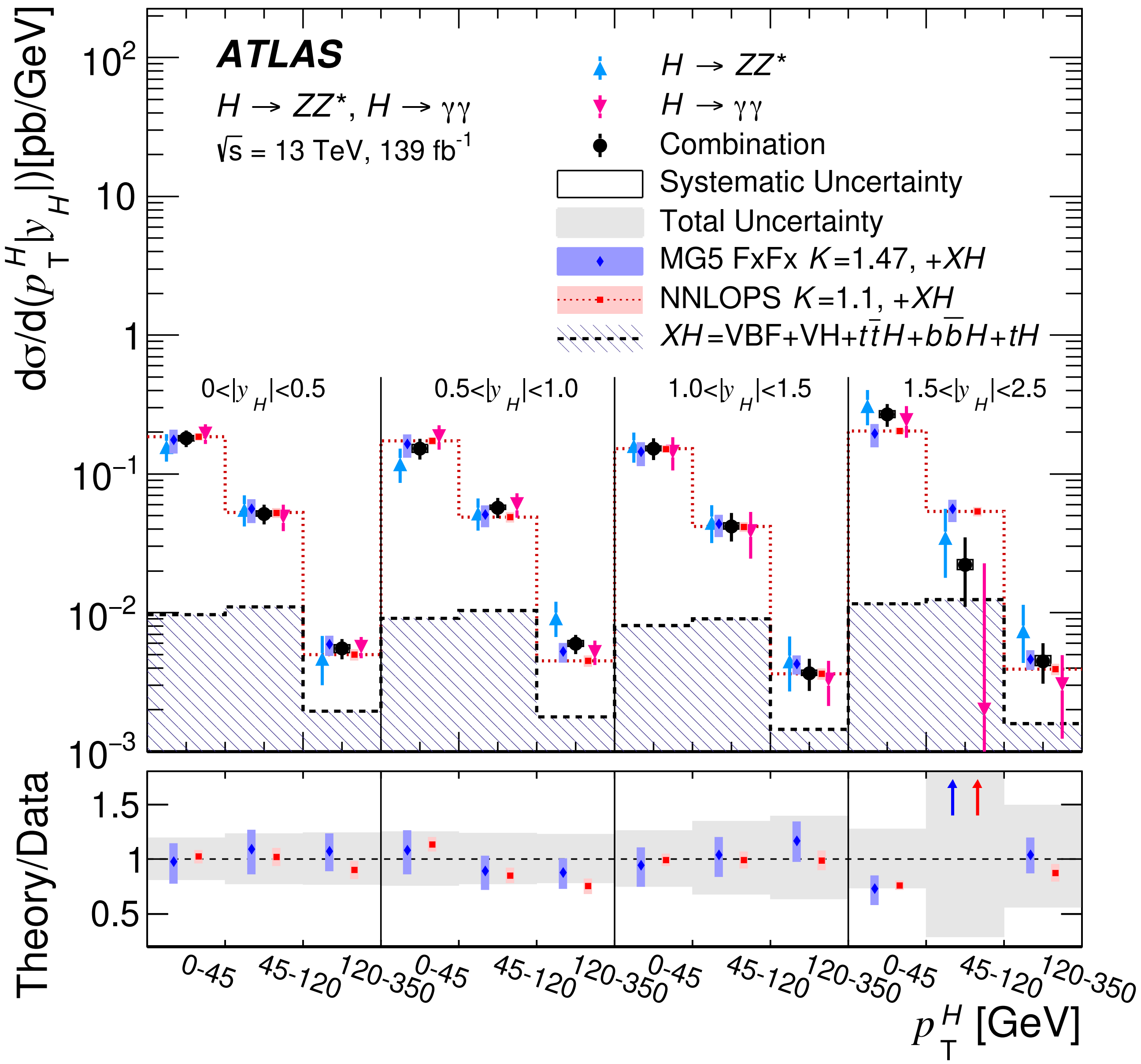


Probable reasons for CMS got better limit :

1. They merged the boosted channel
2. They don't anti-tag the b-jet : higher statistical significance.
3. Have a dedicated GNN based Xcc tagger

Extraction of κ_b & κ_c from $\mathbf{p_T^H}$ $(\gamma\gamma + \mathbf{ZZ})$



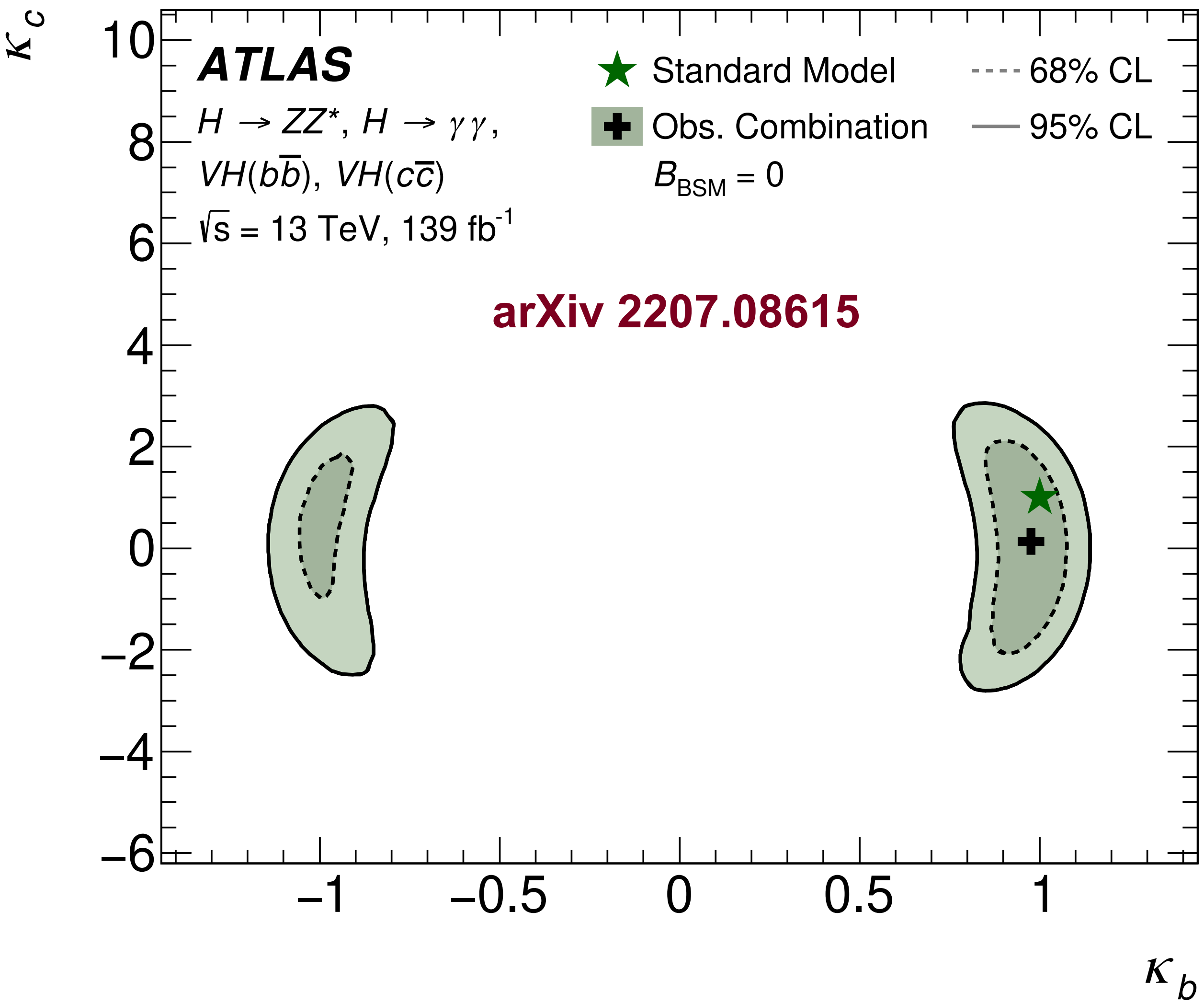


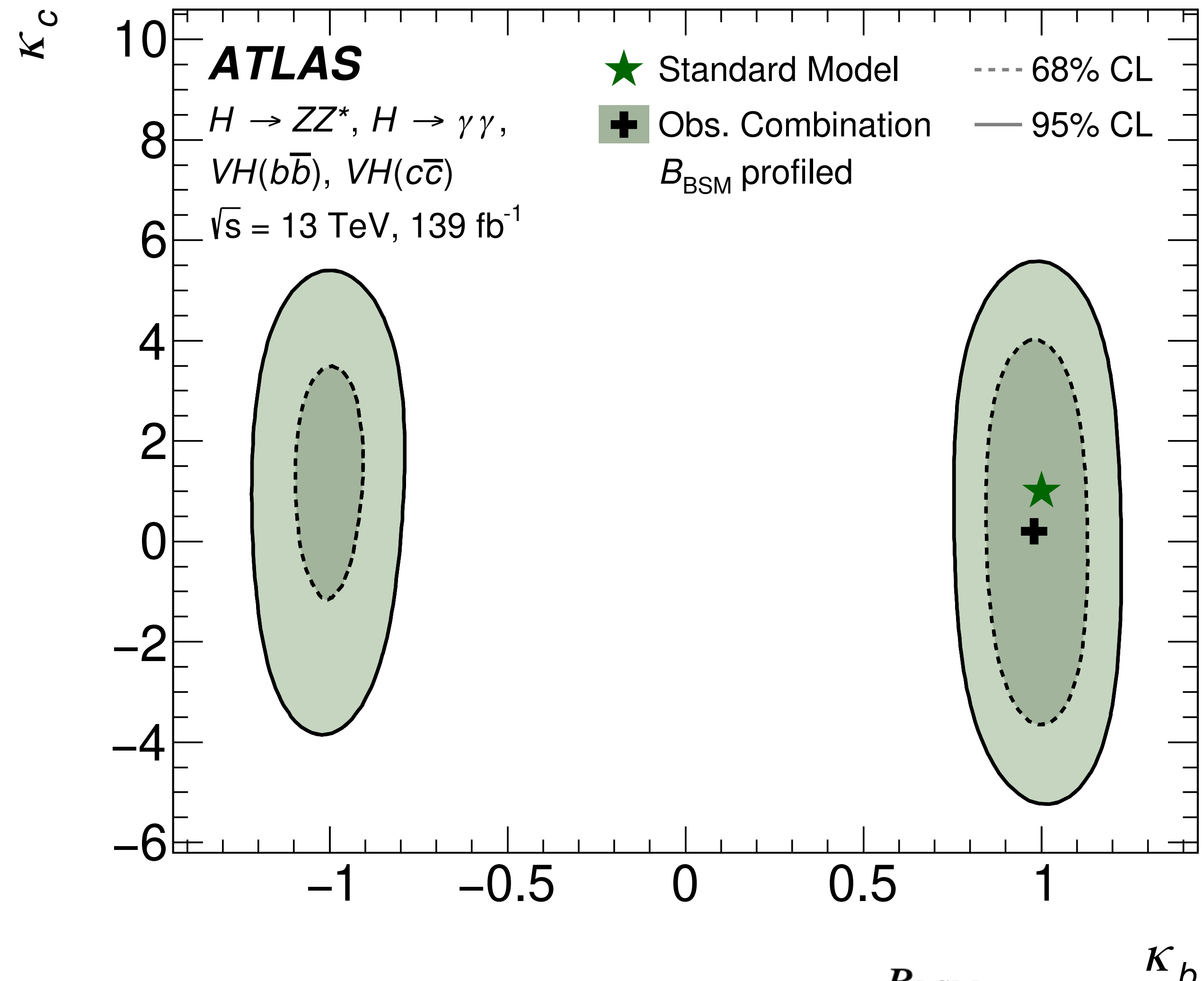
arXiv 2207.08615

The combined measurement of H pT from H → ZZ* → 4l and H → $\gamma\gamma$ is made.

Measured inclusive x-section : $55.5^{+4.0}_{-3.8}$ pb, predicted 55.6 ± 2.8 pb.

Extraction of κ_b & κ_c from p_T^H





$$\Gamma_{\mathrm{BSM}} = \Gamma \times B_{\mathrm{BSM}} = \Gamma_{\mathrm{SM}} \frac{B_{\mathrm{BSM}}}{1-B_{\mathrm{BSM}}}$$

Channel	Parameter	Observed 95% confidence interval	Expected 95% confidence interval
$H \to ZZ^* \to 4\ell$	κ_b	$[-1.14, -0.88] \cup [0.80, 1.17]$	$[-1.23, -0.87] \cup [0.82, 1.20]$
	κ_c	$[-2.94,\ 2.99]$	$[-3.33, 3.14]$
$H \to \gamma\gamma$	κ_b	$[-1.12, -0.78] \cup [0.78, 1.07]$	$[-1.18, -0.87] \cup [0.83, 1.19]$
	κ_c	$[-2.46,\ 2.32]$	$[-3.03,\ 3.09]$
Combined	κ_b	$[-1.09, -0.86] \cup [0.81, 1.09]$	$[-1.14, -0.92] \cup [0.86, 1.15]$
	κ_c	$[-2.27,\ 2.27]$	$[-2.77,\ 2.75]$

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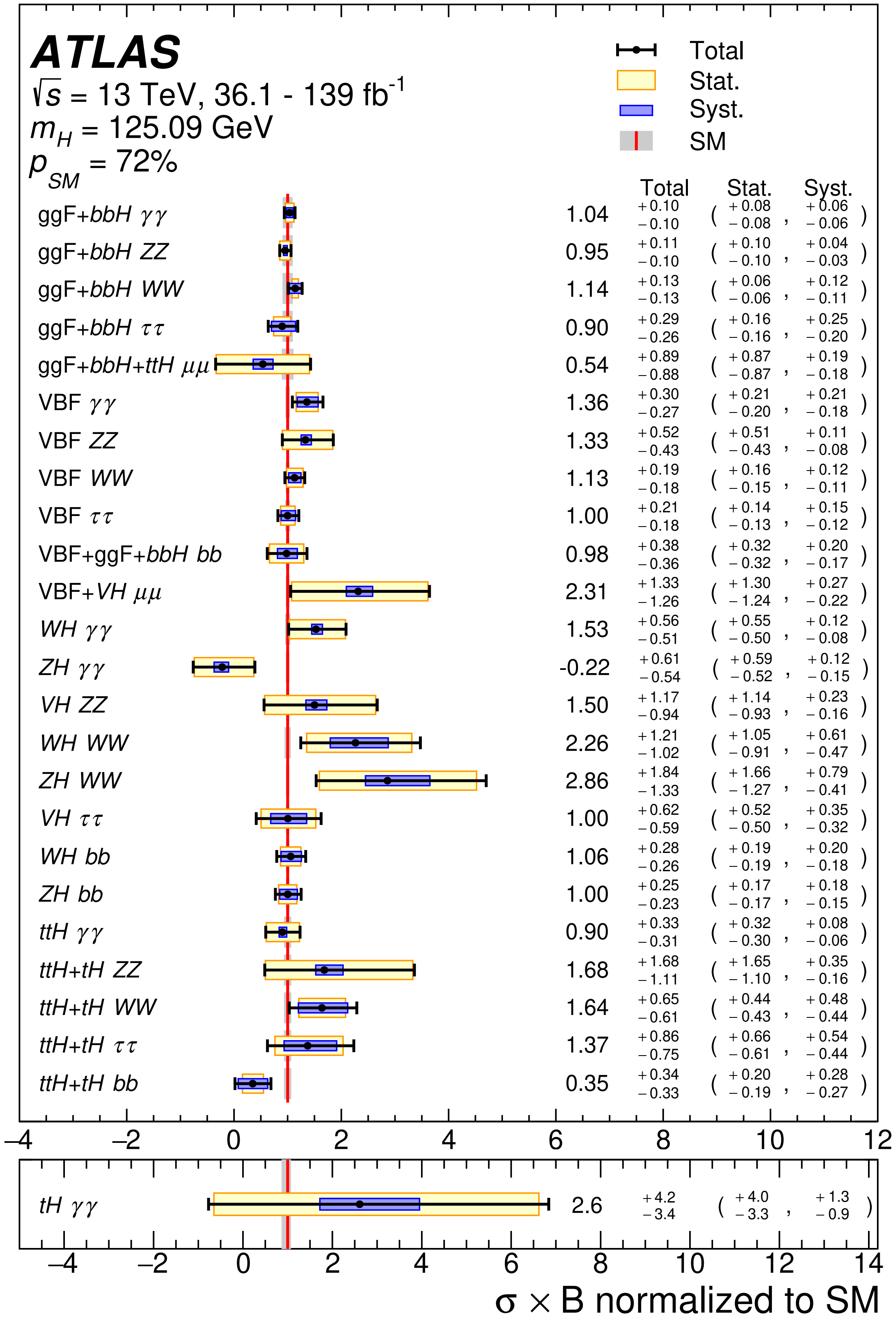
Take away

Nature volume 607, pages 52–59 (2022)



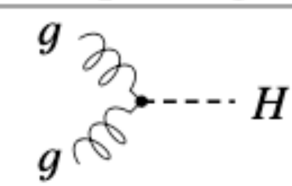
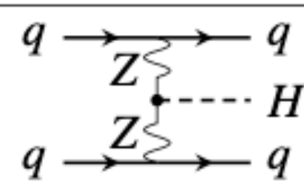
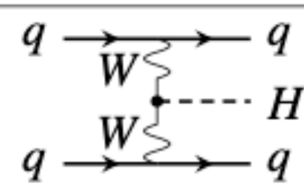
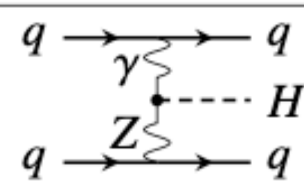
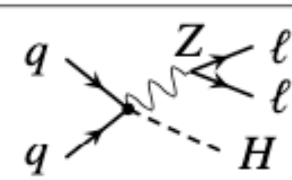
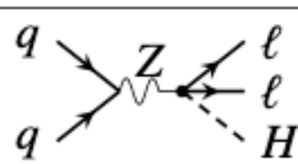
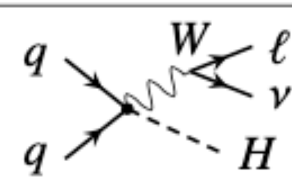
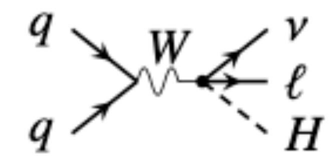
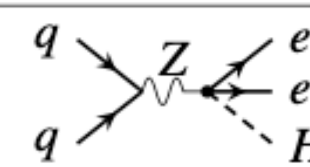
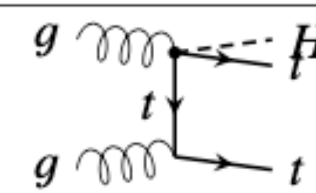
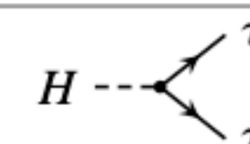
- ☑ Higgs precision measurement is must in order to understand dynamics of SM and probe beyond standard model physics.
- ☑ The Run-3 and HL-LHC will give us golden opportunity to do Higgs physics and it's worth exploiting it.
- ☑ There are still plenty of room to innovate new techniques : a few % improvement of H width measurement has large implications on physics understanding.
- ☑ The up-to-date Higgs Mass, CP measurements & width are presented.
- ☑ The SMEFT & kappa framework fits are yet to show any hints of BSM models.

THANK YOU!!

Take away

Backup

EFT couplings

Wilson coefficient	Operator definition	Example diagram
c_{HG}	$\Phi^\dagger\Phi G^a_{\mu\nu}G^{a\mu\nu}$	
c_{HB}	$\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu}$	
c_{HW}	$\Phi^\dagger\Phi W^I_{\mu\nu}W^{I\mu\nu}$	
c_{HWB}	$\Phi^\dagger\Phi W^I_{\mu\nu}B^{I\mu\nu}$	
c_{Hq1}	$(i\Phi^\dagger \overleftrightarrow{D}_\mu\Phi)(\bar q\gamma^\mu q)$	
c_{Hl1}	$(i\Phi^\dagger \overleftrightarrow{D}_\mu\Phi)(\bar\ell\gamma^\mu\ell)$	
c_{Hq3}	$(i\Phi^\dagger \overleftrightarrow{D}^I_\mu\Phi)(\bar q\sigma^I\gamma^\mu q)$	
c_{Hl3}	$(i\Phi^\dagger \overleftrightarrow{D}^I_\mu\Phi)(\bar\ell\sigma^I\gamma^\mu\ell)$	
c_{Hu}	$(i\Phi^\dagger \overleftrightarrow{D}^I_\mu\Phi)(\bar u\gamma^\mu u)$	
c_{Hd}	$(i\Phi^\dagger \overleftrightarrow{D}^I_\mu\Phi)(\bar d\gamma^\mu d)$	
c_{He}	$(i\Phi^\dagger \overleftrightarrow{D}_\mu\Phi)(\bar e\gamma^\mu e)$	
$\lvert c_{uG}\rvert$	$(\bar q\sigma^{\mu\nu}T^a\tilde\Phi u)G^a_{\mu\nu}$	
$\lvert c_{eH}\rvert$	$(\Phi^\dagger\Phi)(\bar\ell e\Phi)$	
$\lvert c_{dH}\rvert$	$(\Phi^\dagger\Phi)(\bar q d\Phi)$