Search for a high mass neutral Higgs boson using the ATLAS detector

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on behalf of the ATLAS Collaboration

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After the 125GeV Higgs boson discovery, an important question remains:

Is this the only Higgs boson?

➡ Extensions to the SM predict additional heavy Higgs boson(s) we could observe in proton-proton collisions at the LHC

In this presentation: The latest search limits from ATLAS of heavy neutral Higgs decaying in the diboson channels, using $20.3/fb$ at $\sqrt{s} = 8\,TeV$

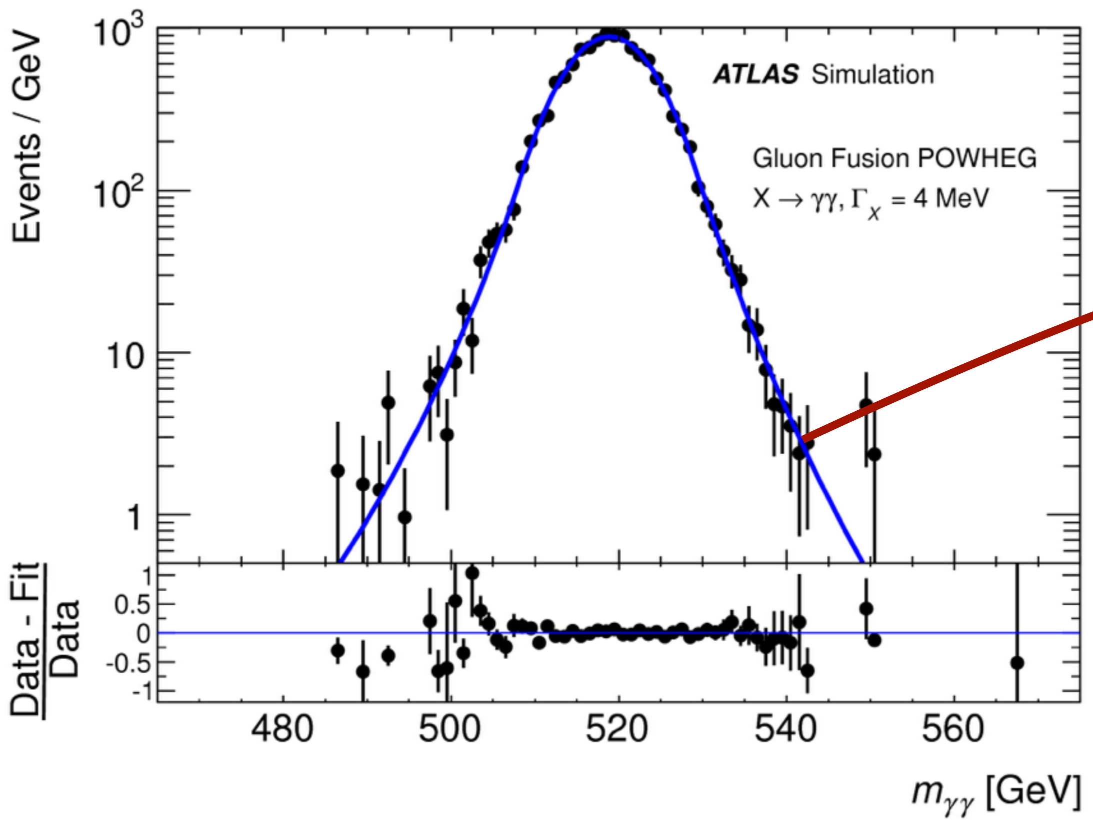
- $H \rightarrow \gamma\gamma$ (July 2014: Phys. Rev. Lett. 113, 171801)
- $H \rightarrow ZZ$ (July 2015: arXiv:1507.05930)
- $H \rightarrow WW$ (August 2015: Preliminary results to be submitted)

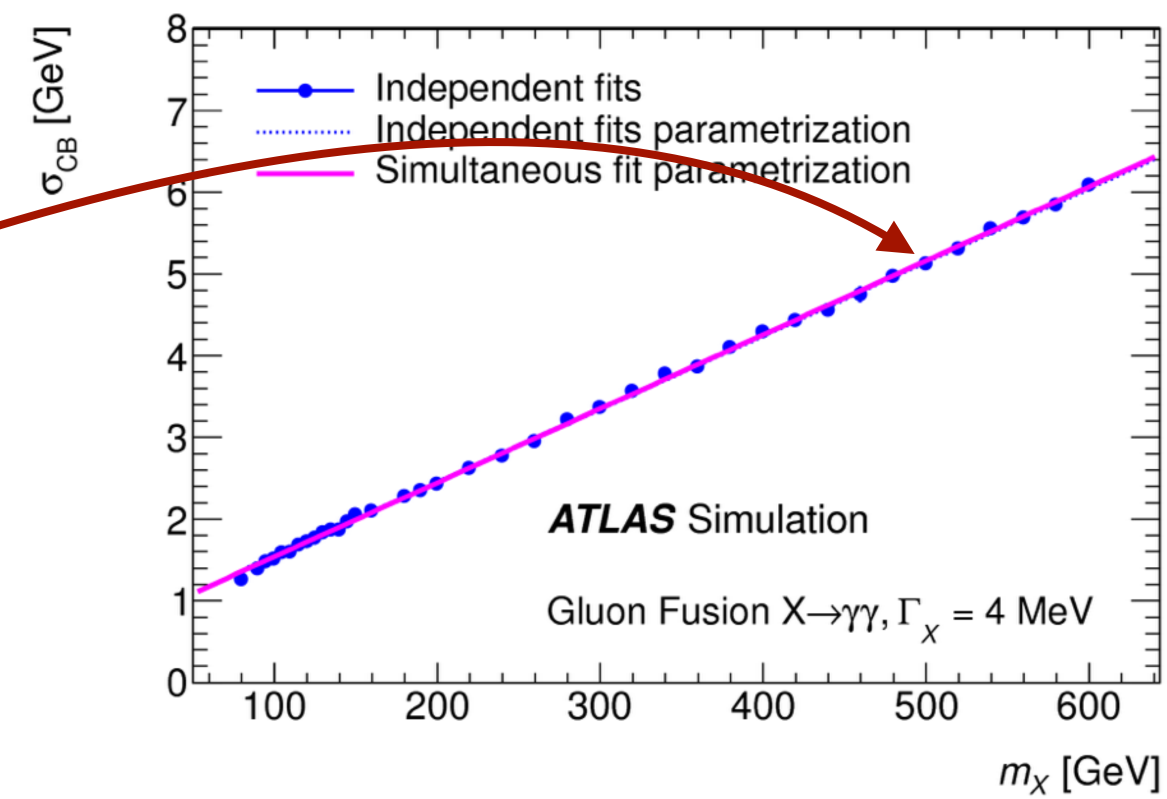
As one discovery channel for the 125GeV Higgs, $H \rightarrow \gamma\gamma$ has additional importance in high mass searches (Phys. Rev. Lett. 113, 171801)

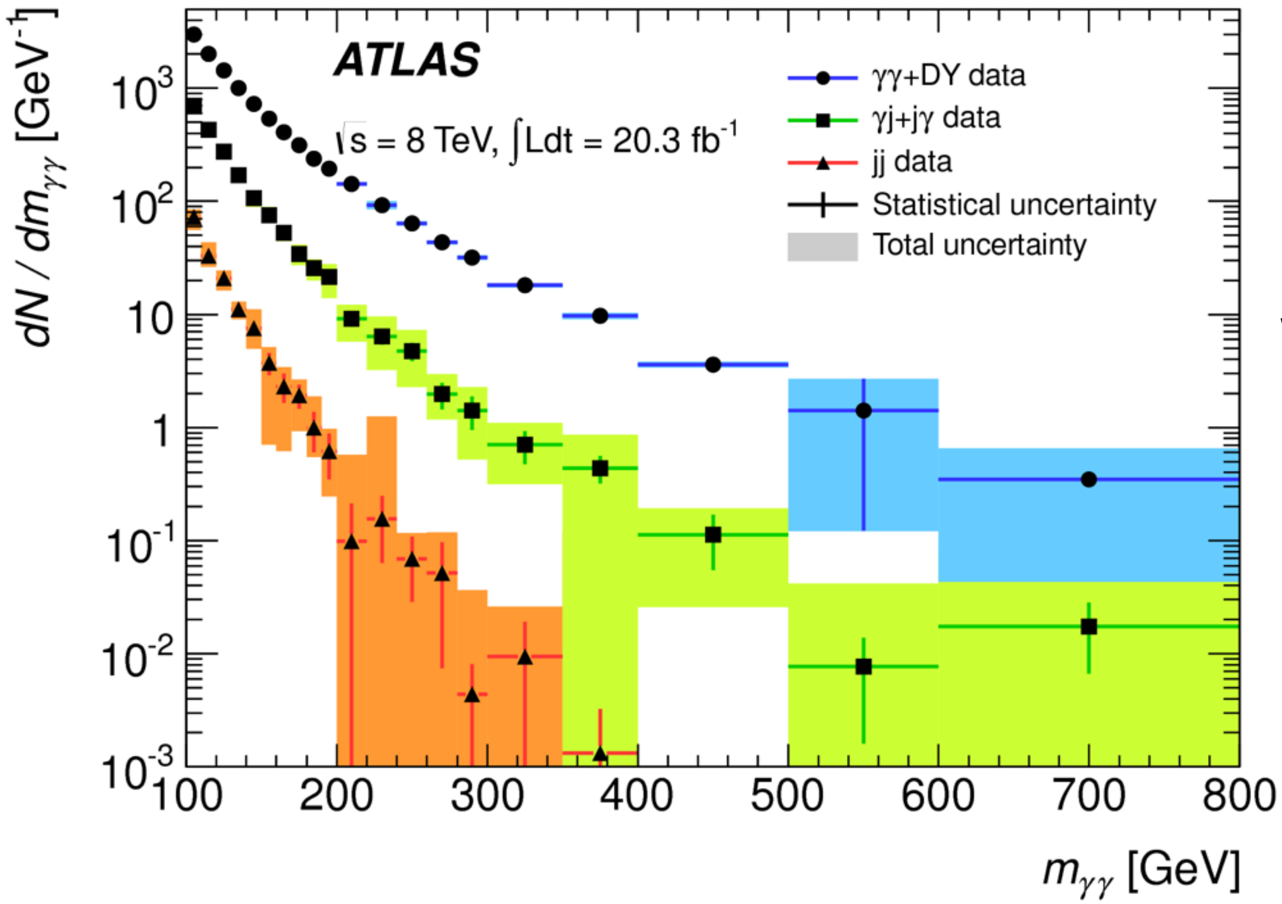
➡ resonant signal on smooth background: clean search!

Signal Model:

- double-sided Crystal Ball with parameters fit on different simulated mass points
- All production modes use same PDF







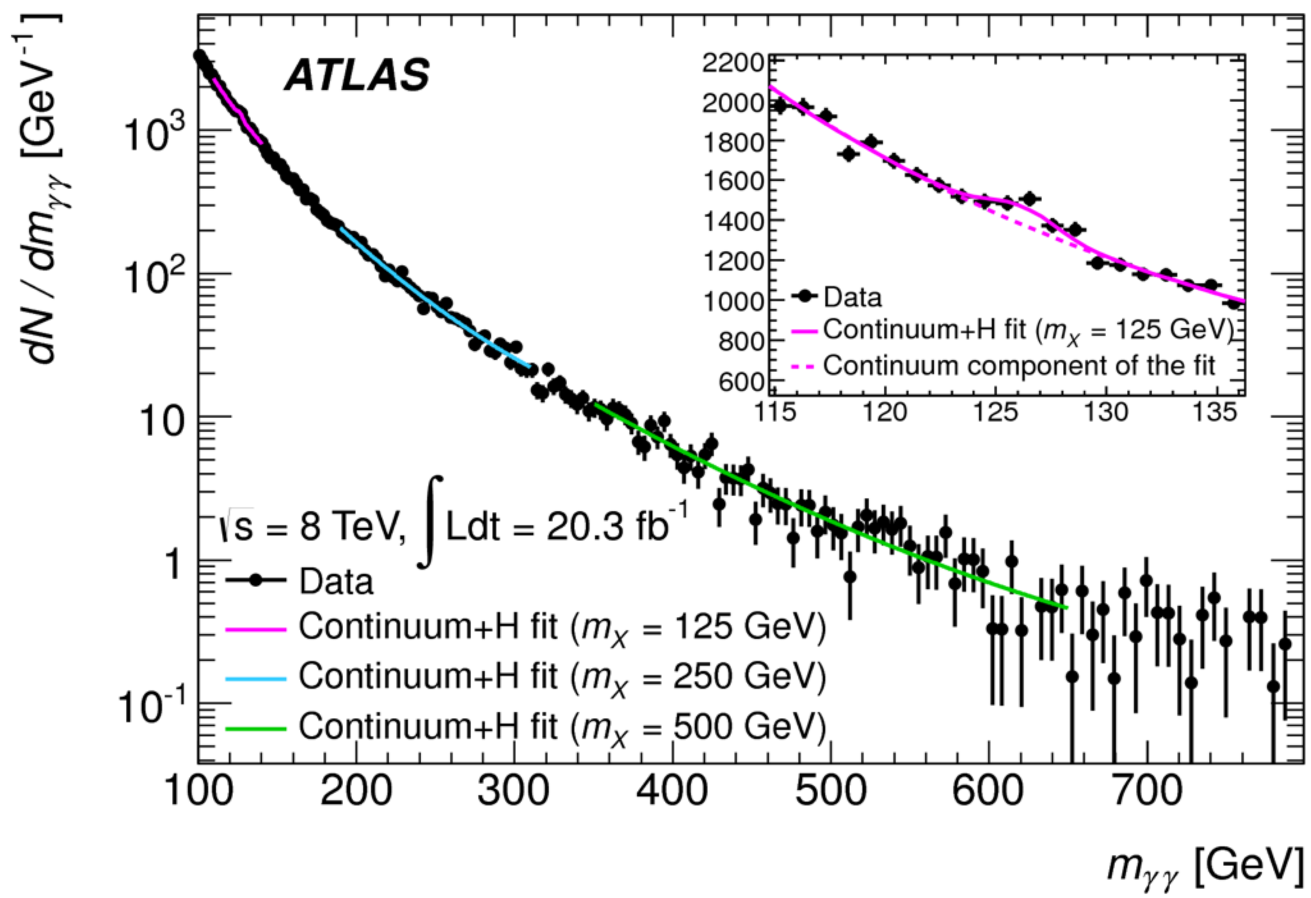
Backgrounds:

Composition in data:

$$\gamma\gamma(83.7\%),\ \gamma\ jet(15.1\%),\ jet\ jet(1.2\%)$$

Where $\gamma\gamma$ includes doubly-converted DY $Z \to ee$

Composition derived using a 2Dx2D sideband method in isolation vs identification for both photons [arXiv:1107.0581]



- Parameterized by pol-2 in sliding window
- Shape/window choice:
    - Fit S+B on background only spectrum
    - signal yield bias < 20% stat. error

Statistical Interpretation

- Limits are $95\% CL_s$ using the q_μ test statistic

Narrow-width approximation

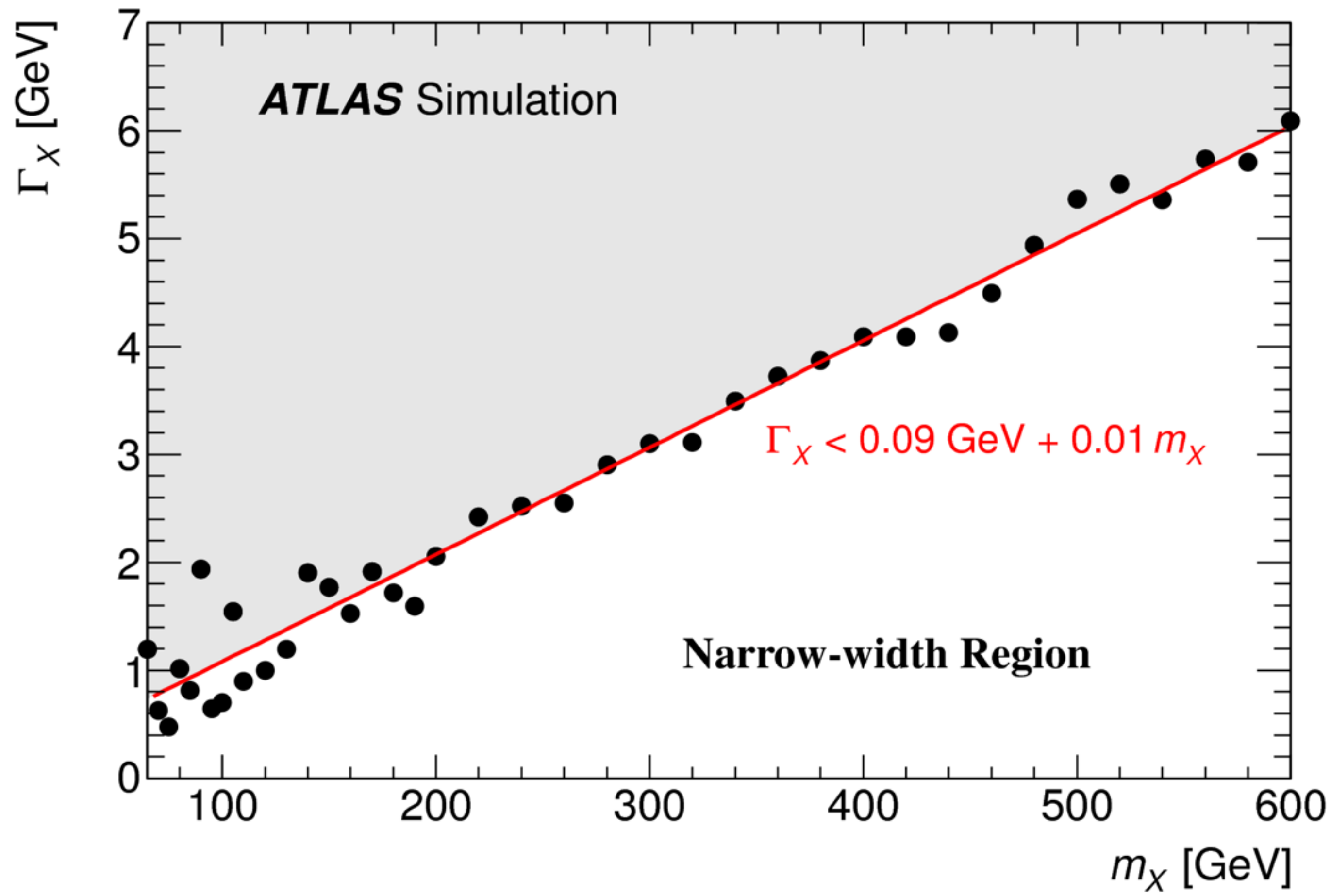
For different mass hypotheses find limits on:

$$\sigma_{fid} \cdot BR(X \to \gamma\gamma) = \frac{N_{data}}{C_X \mathcal{L}}$$

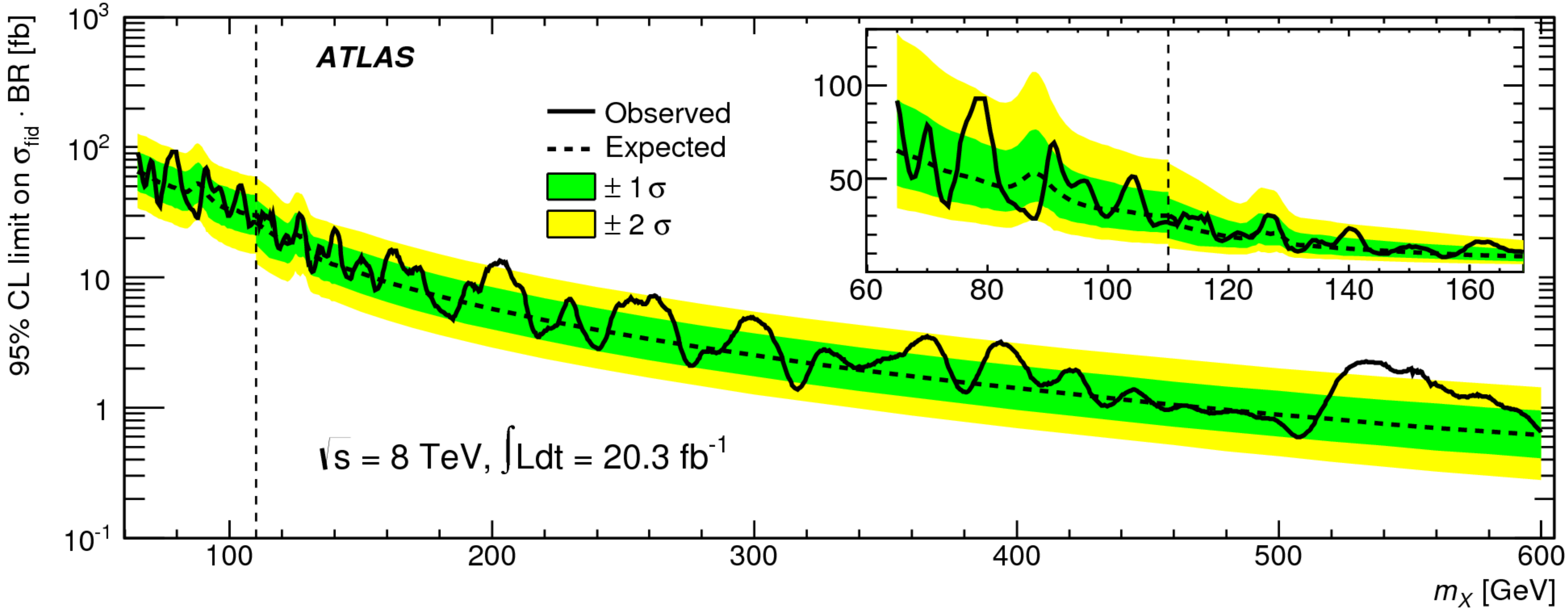
Efficiency factor derived from MC ggF samples $C_X = \frac{N^{reco}_{MC}}{N^{fid}_{MC}}$

MC samples have $\Gamma_H = 4\, MeV$

→ ***Narrow-width limit: bias < 10% signal yield***



Limits in Narrow Width Approximation



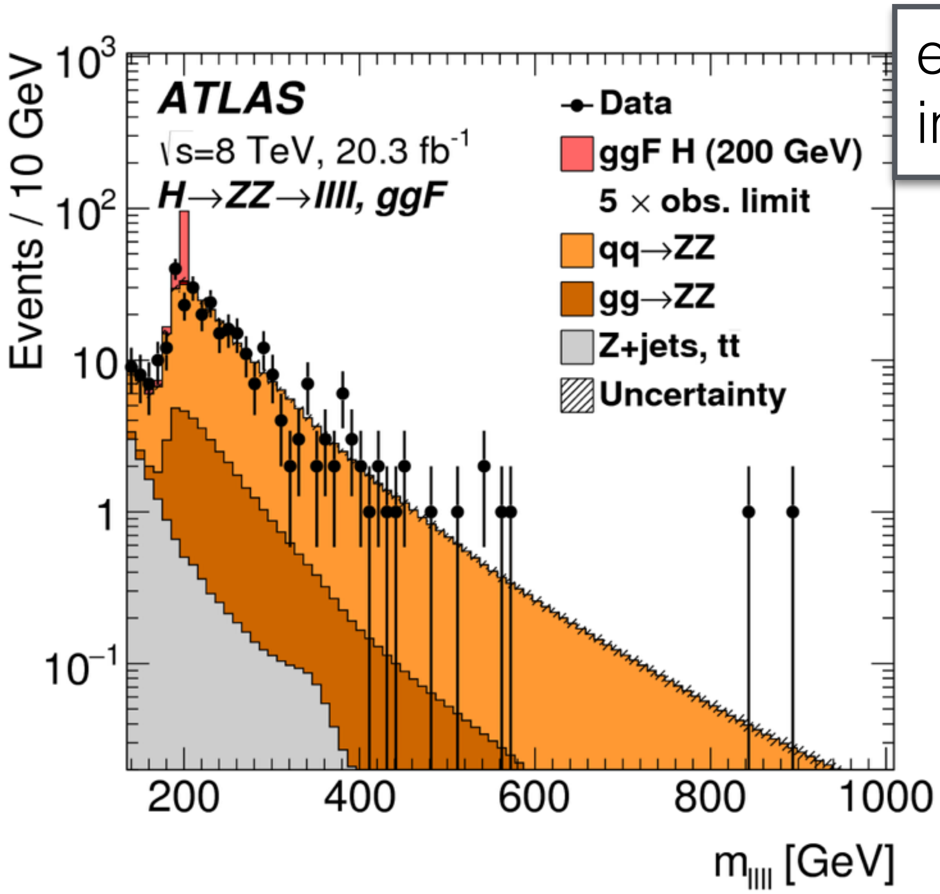
Largest excess corresponds to $z_0 = 2.2$ at $m_X = 530\,GeV$

The other discovery channel for the 125 GeV Higgs, $H \to ZZ$, is a powerful probe to search for additional heavy Higgs

Four decay channels enter ATLAS' search (arXiv:1507.05930)

$$H \to ZZ \to \ell\ell\ell\ell,\ \ell\ell qq,\ \ell\ell\nu\nu,\ \nu\nu qq$$

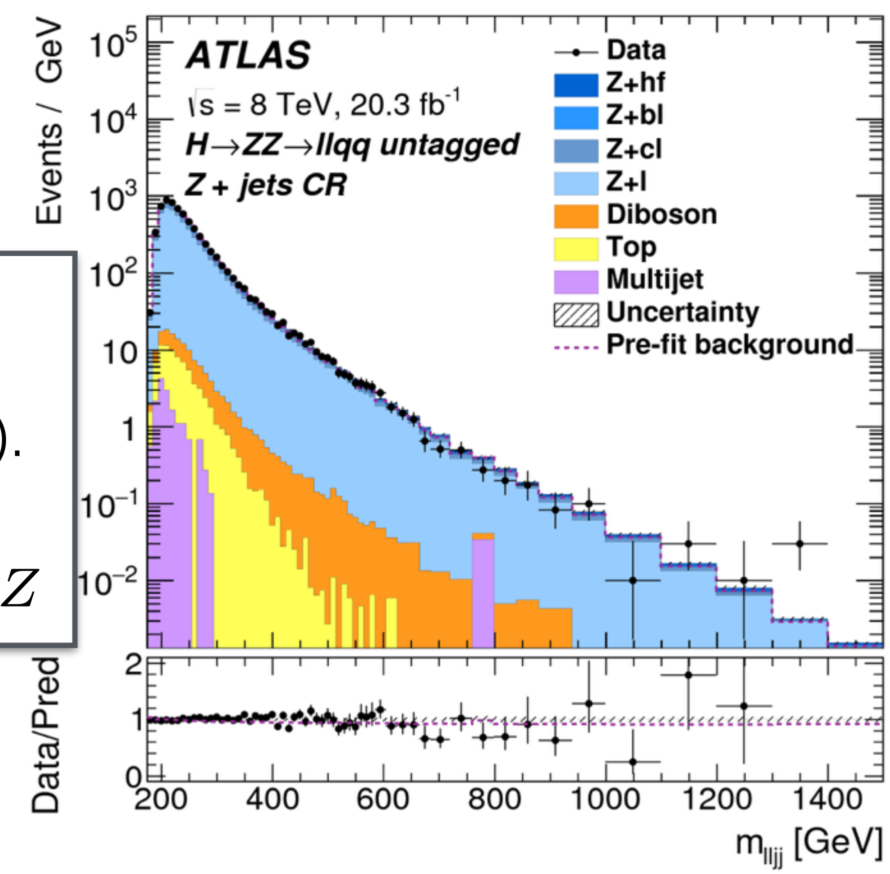
Some background processes modelled using MC simulation:



eg. $qq \to ZZ$ in $\ell\ell\ell\ell,\ \ell\ell\nu\nu,\ \nu\nu qq$

Others use **data-driven** estimates, often fit simultaneously between channels:

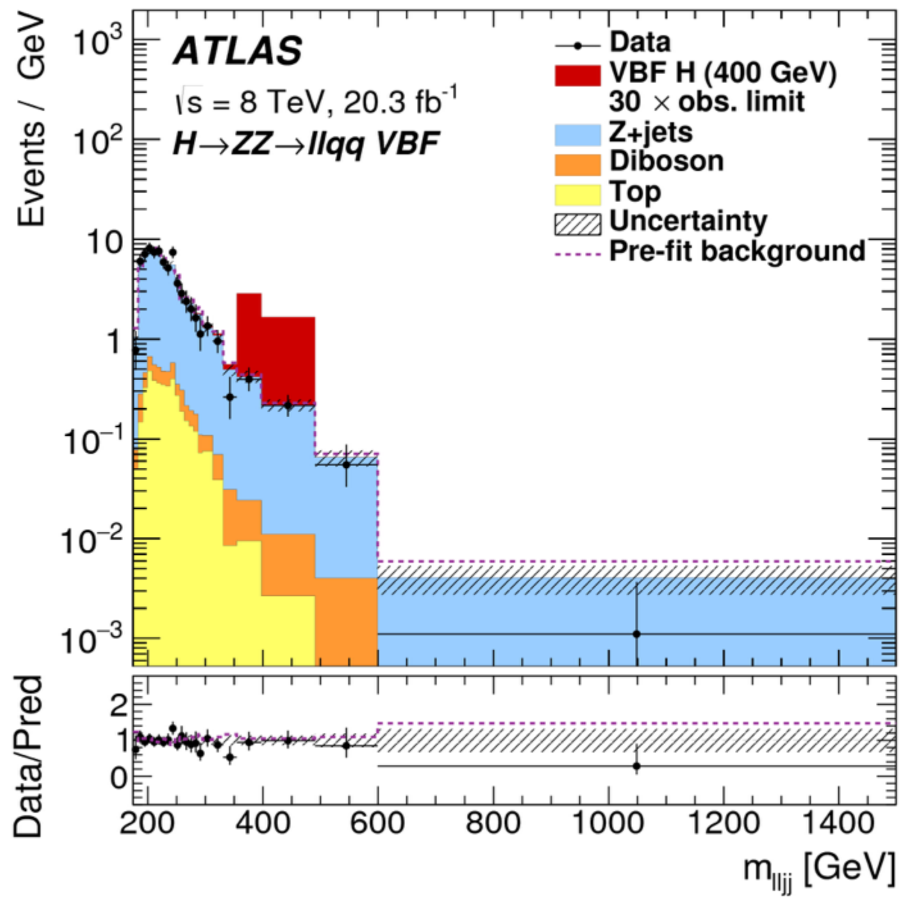
eg. $Z + Jets$ here in a sub-channel of $\ell\ell qq$ (important in all channels). Control region built by requiring m_{jj} far from m_Z



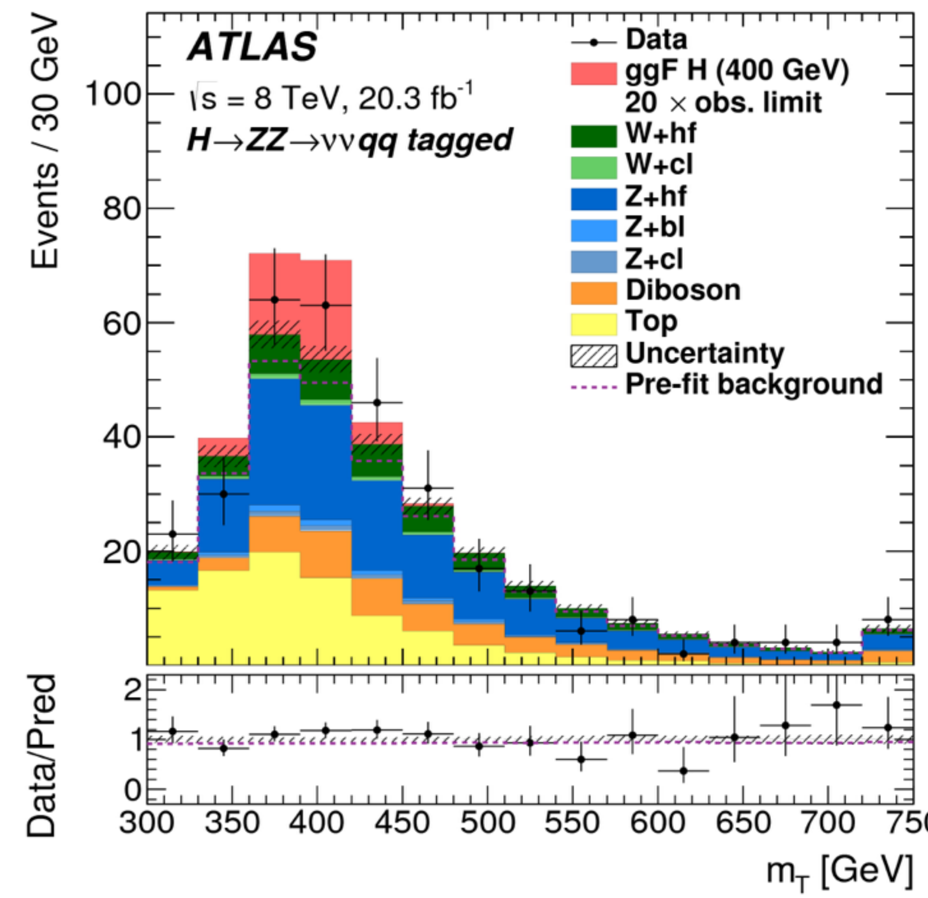
Analysis outline:

- Each channel ($\ell\ell\ell\ell, \ell\ell qq, \ell\ell\nu\nu, \nu\nu qq$) has a discriminating variable sensitive to m_H

eg:



fully reconstructed channels: invariant mass



channels with neutrinos: transverse mass

- Distributions are made for signal & background in each channel
- Channels separate categories for ggF and VBF production based on additional jets in the event (except: $\nu\nu qq$ does not model VBF)
- Additional sub-channels designed to improve sensitivity based on lepton flavour, jet categorization

Statistical Interpretation

- The four channels enter a simultaneous fit
- Limits are $95\% CL_s$ using the $\tilde{q}_{\mu}$ test statistic
- Both interpretations derived using MC samples with $\Gamma_H = 4\,MeV$

Model-independent (narrow width) interpretation

No assumption is made on relative contribution of ggF and VBF to production

For different mass hypotheses find limits on parameters of interest:

$$\sigma_{ggF} * BR(H \to ZZ)$$
$$\sigma_{VBF} * BR(H \to ZZ)$$

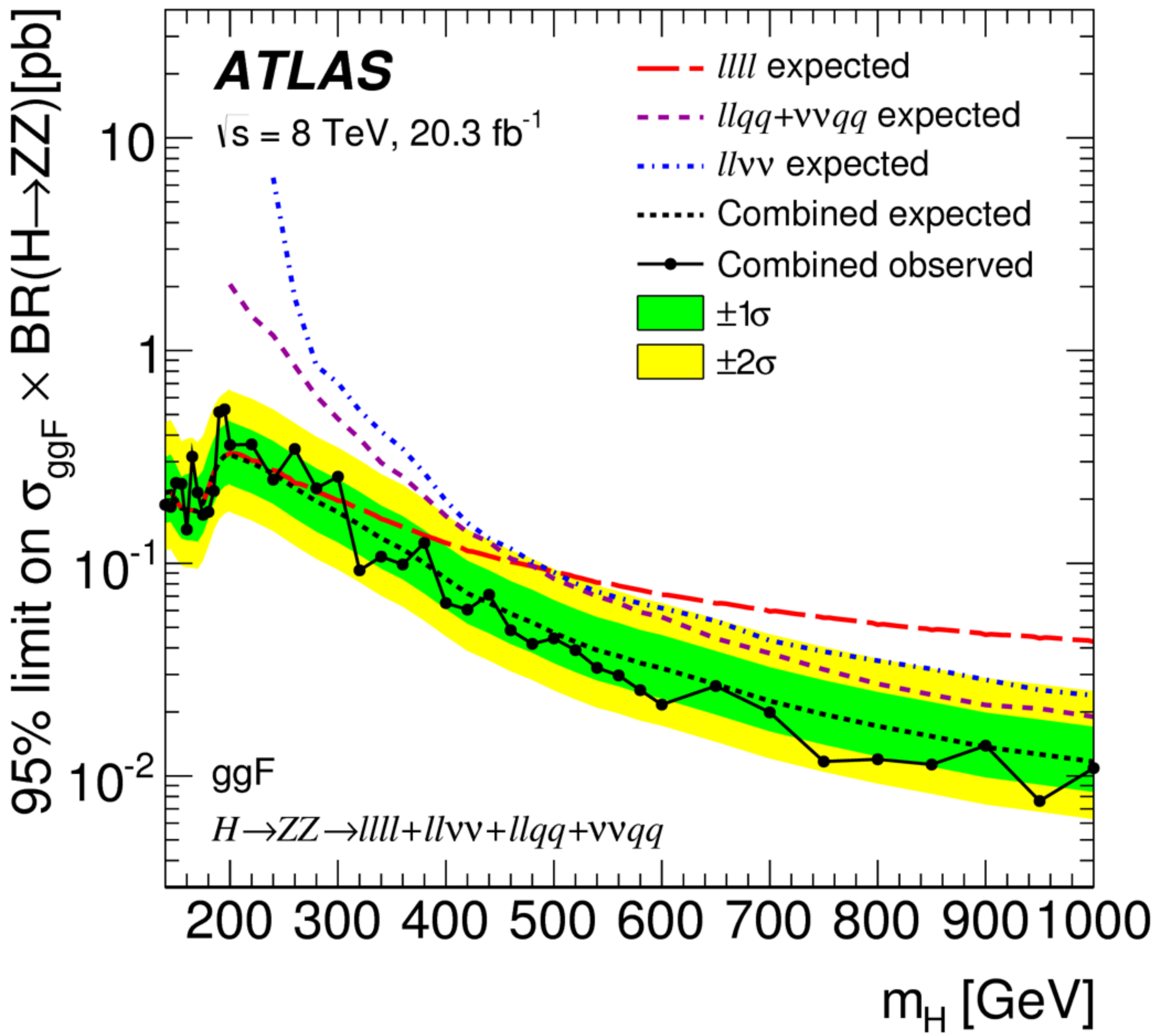
2HDM interpretation

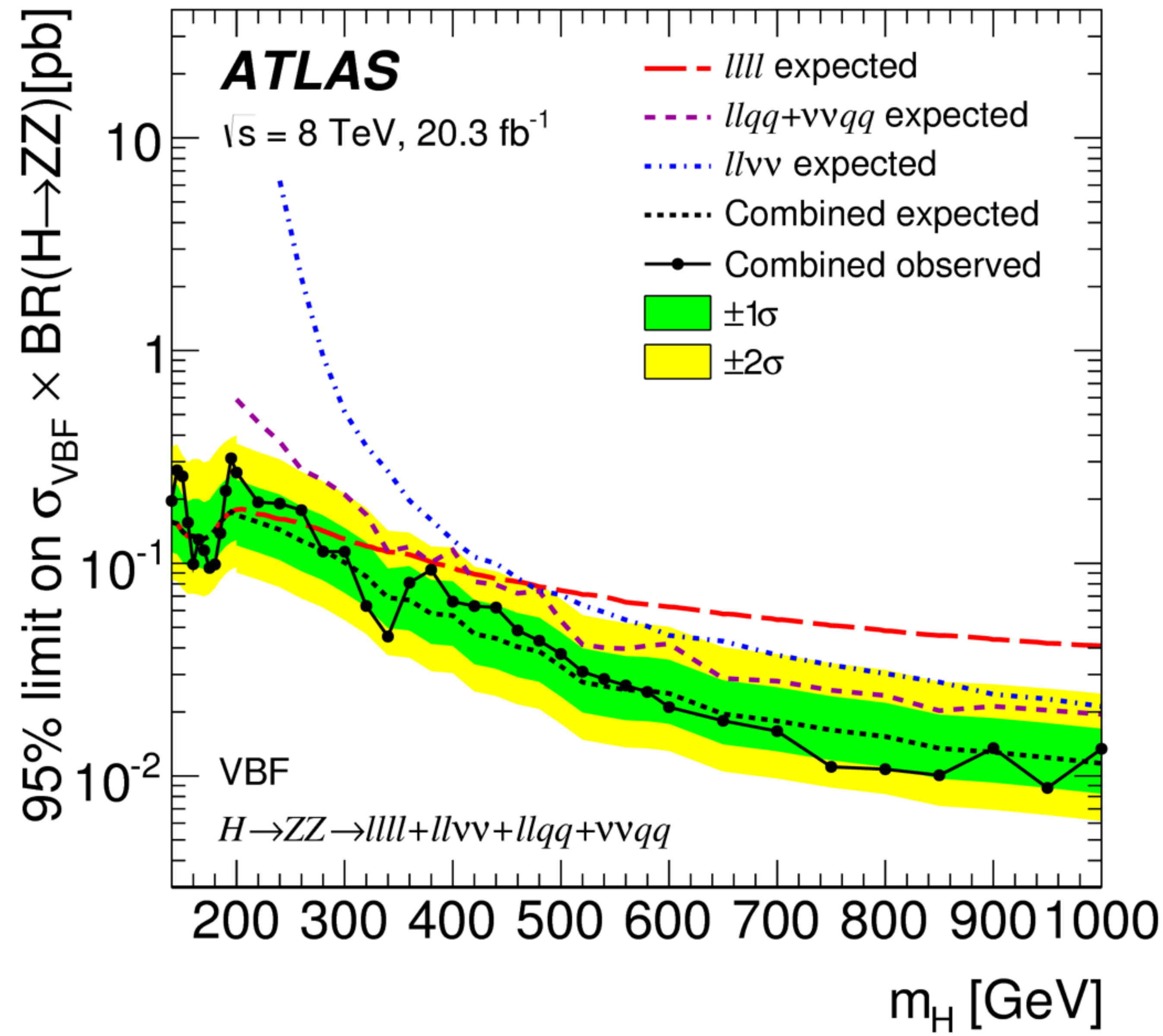
Type-I and *Type-II* considered

Relative contribution of ggF and VBF, and branching ratios are fixed by 2HDM

Limits set in parameter space of $m_H,\ tan\beta,\ cos(\beta - \alpha)$

Parameter ranges are set such that $\Gamma_H < 0.5\% m_H$ and the light Higgs couplings are not enhanced by more than 3 times the Standard Model





ggF limits

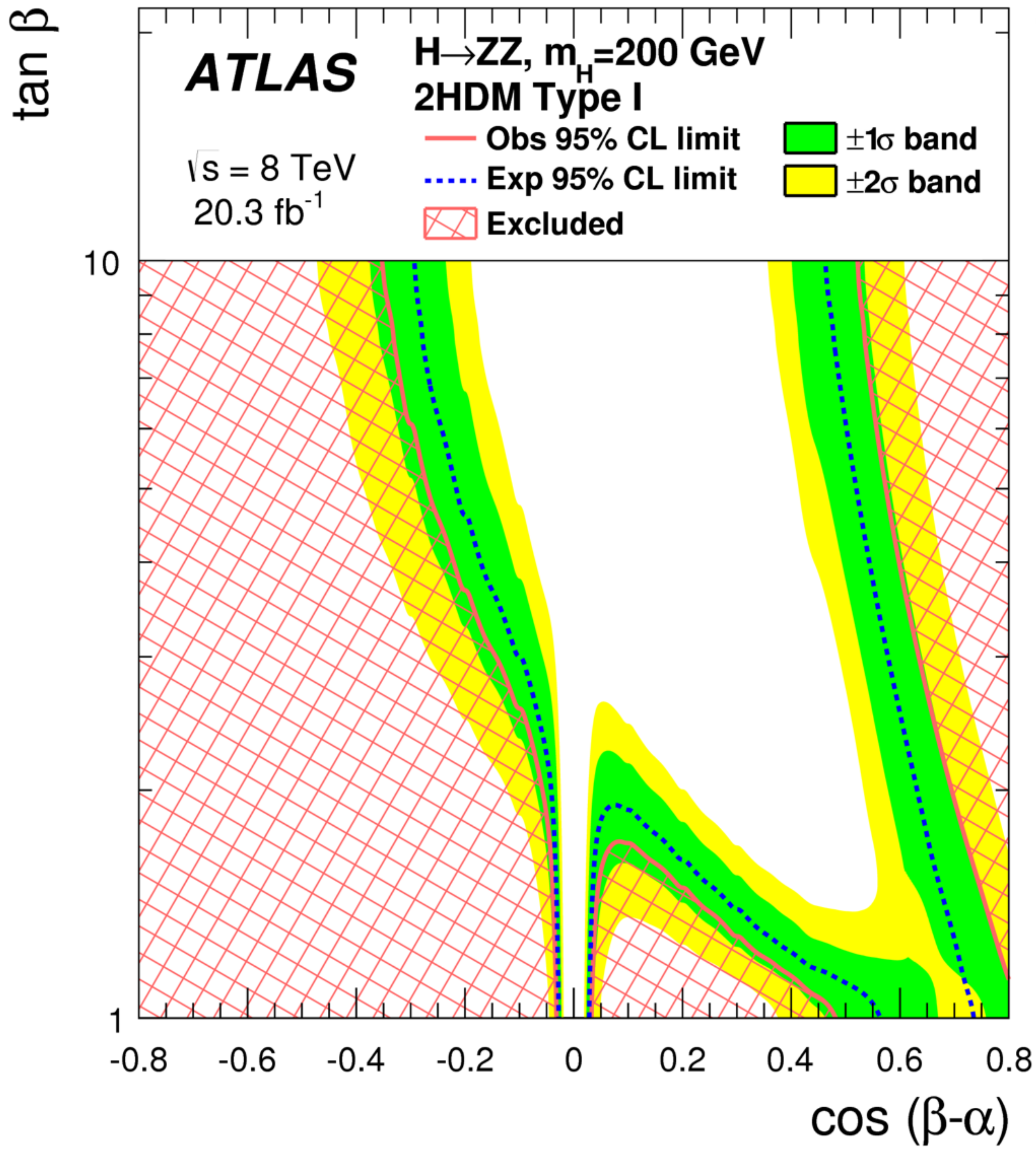
530 fb @ 195 GeV

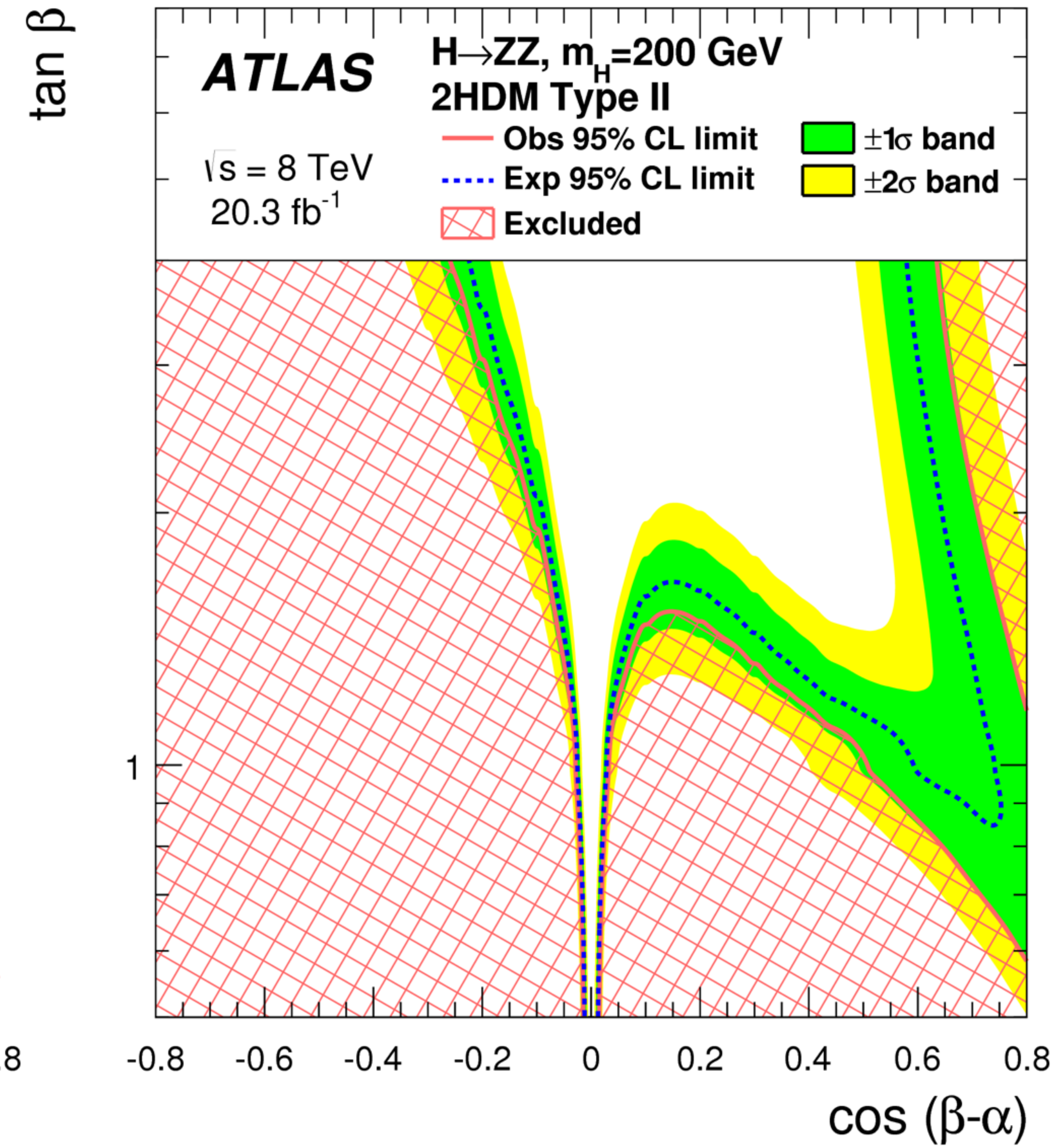
8 fb @ 950 GeV

VBF limits

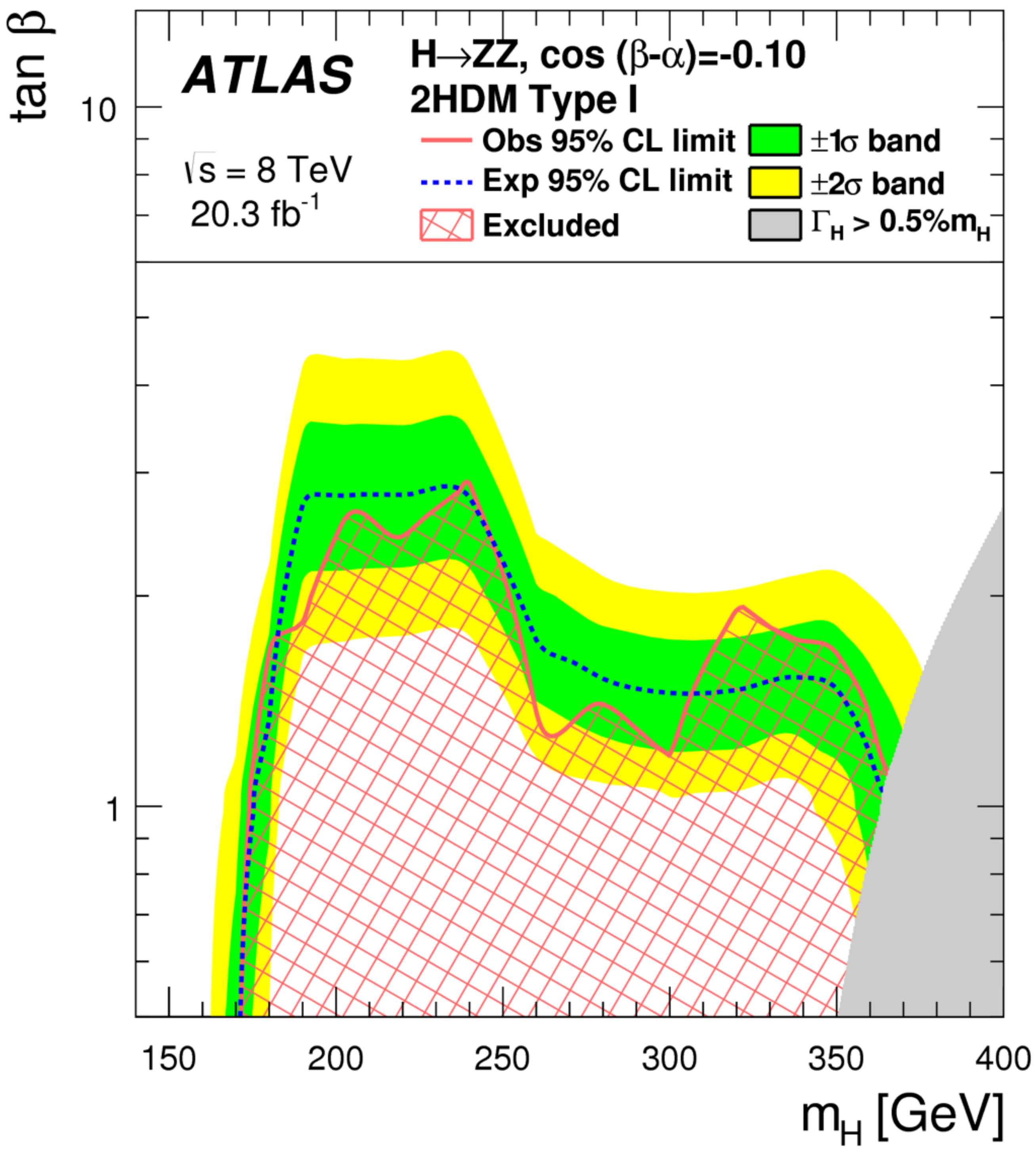
310 fb @ 195 GeV

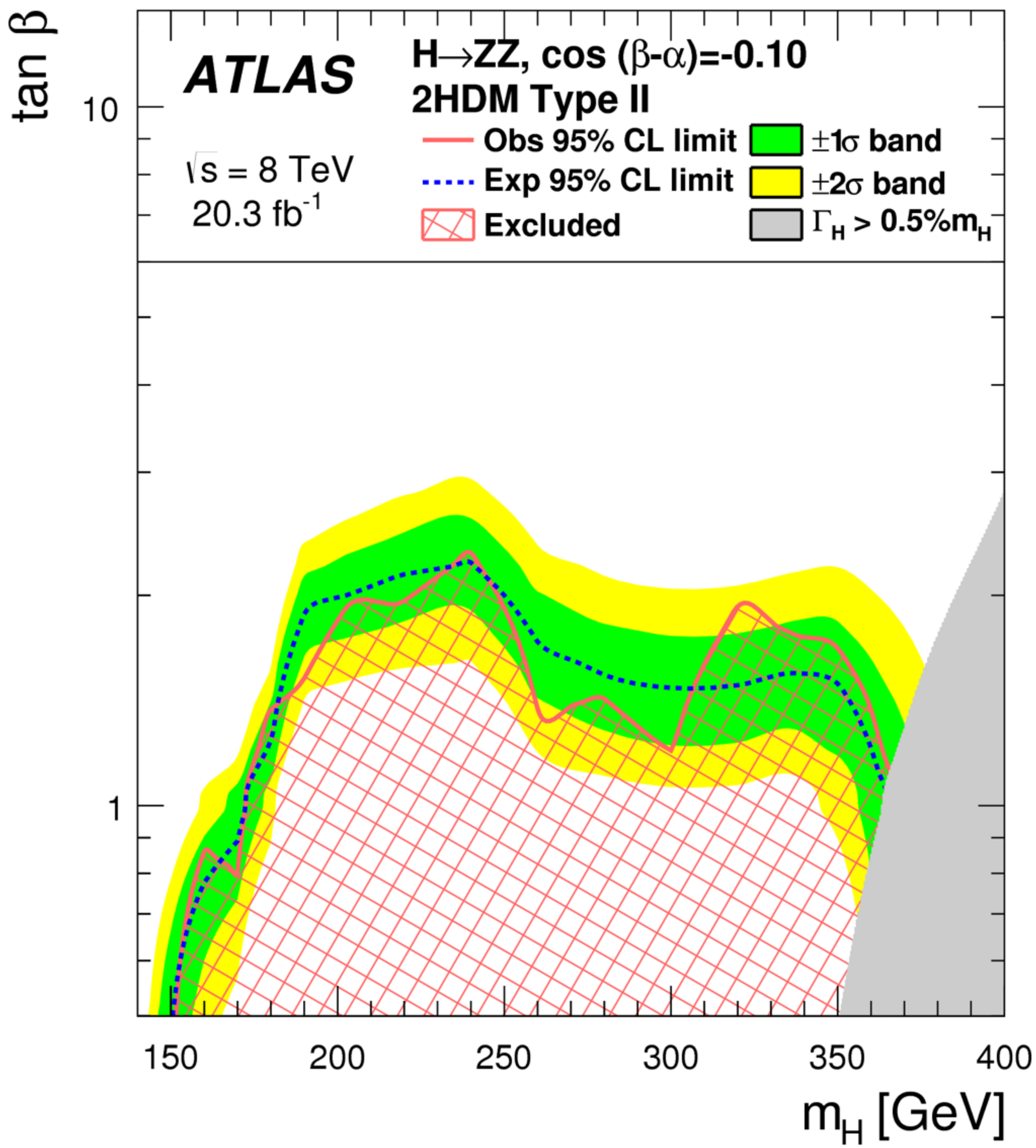
9 fb @ 950 GeV





2HDM Type-I **2HDM Type-II**





2HDM Type-I **2HDM Type-II**

$H \rightarrow WW$ also very powerful due to high branching ratio (~60% for masses probed)

Two decay channels enter ATLAS' search:

$$H \rightarrow WW \rightarrow \ell\nu\ell\nu,\ \ell\nu qq$$

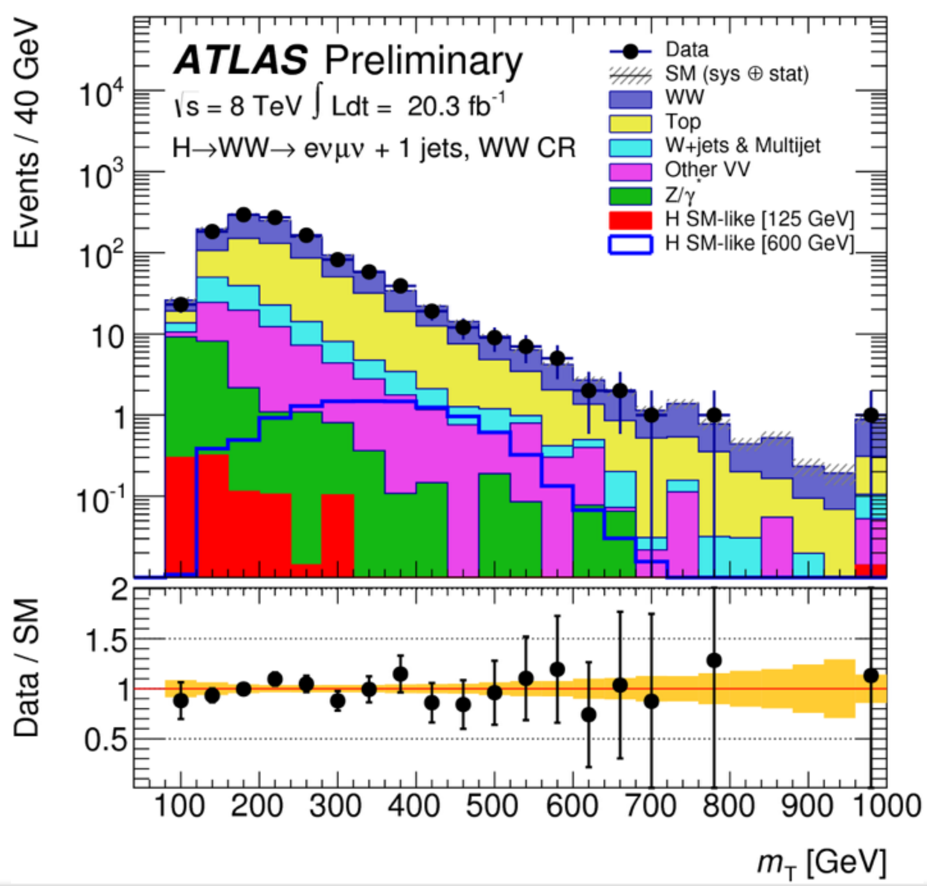
Different backgrounds dominate different channels: $WW,\ Top,\ W + jets,\ multijet$

Where possible, estimations are **data-driven.** General approach:

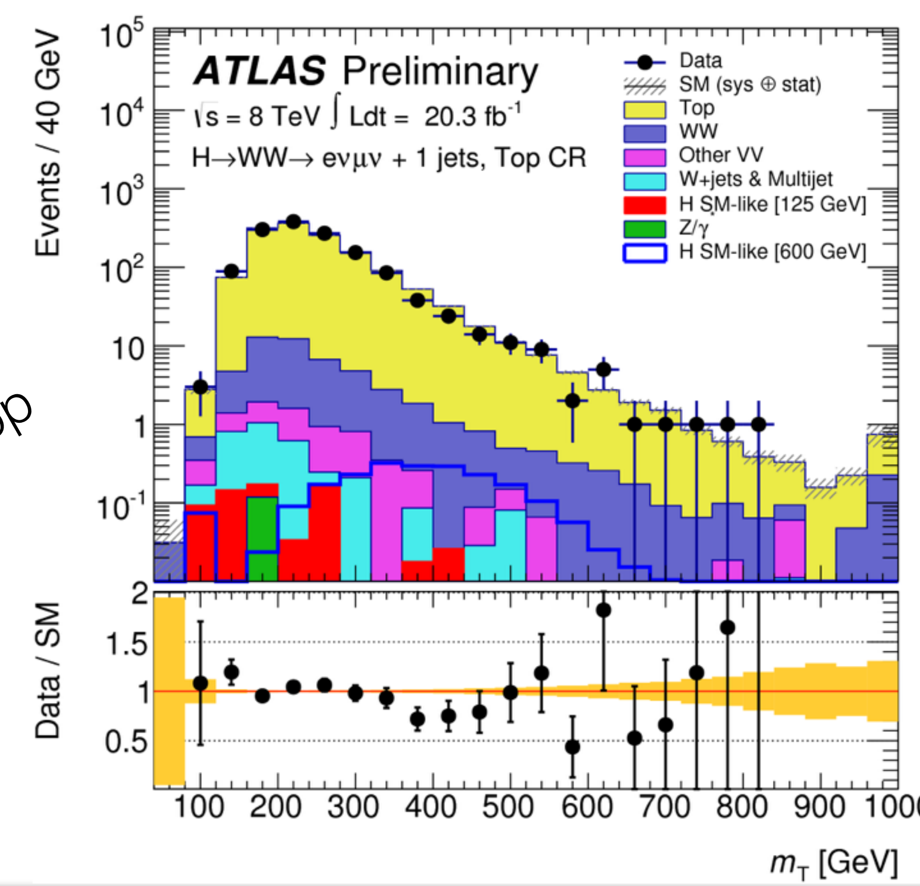
- build control regions to enrich each background
- extrapolation factors bring the fit result from the CR to the yield in the SR

e.g.

Control region enriched in WW



Control region enriched in Top



- Analyses split into categories designed to increase sensitivity
- Signal production modes and background sources vary by category

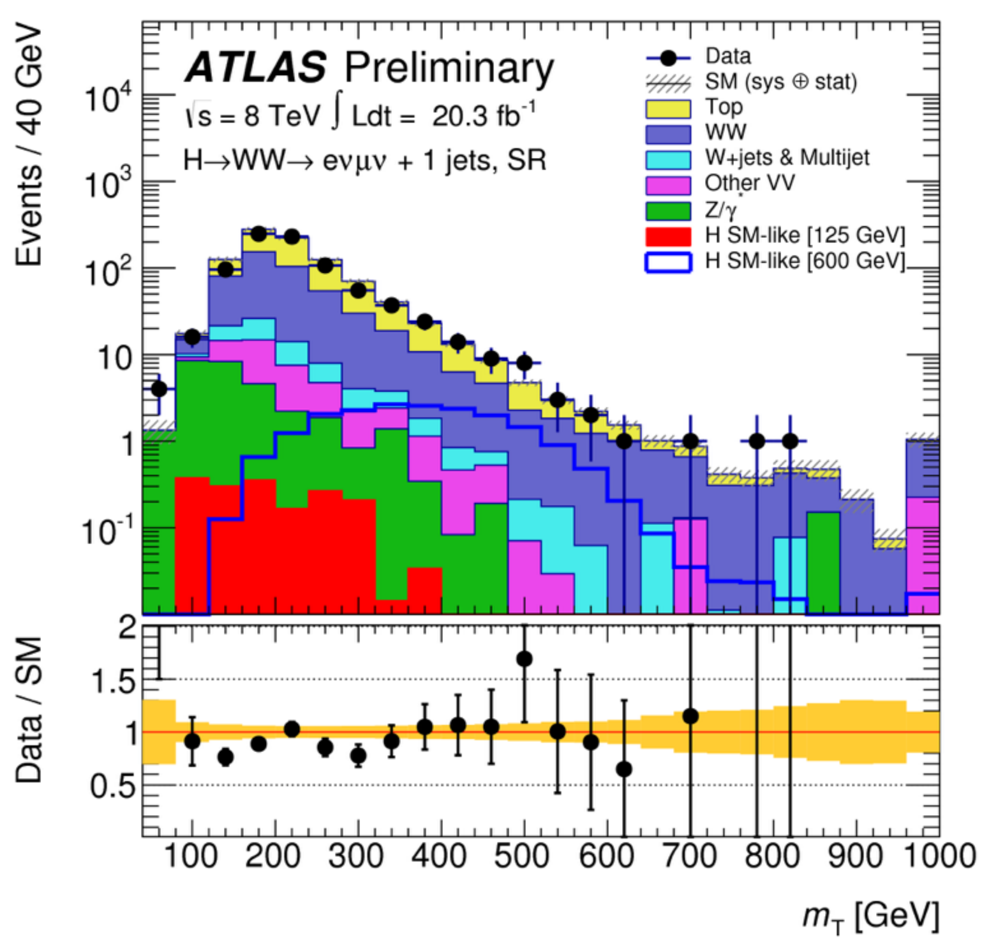
$\ell\nu\ell\nu$ is split by

- same/different flavour leptons
- $N_{jets} \; = \; 0, \; 1, \; \geq 2$

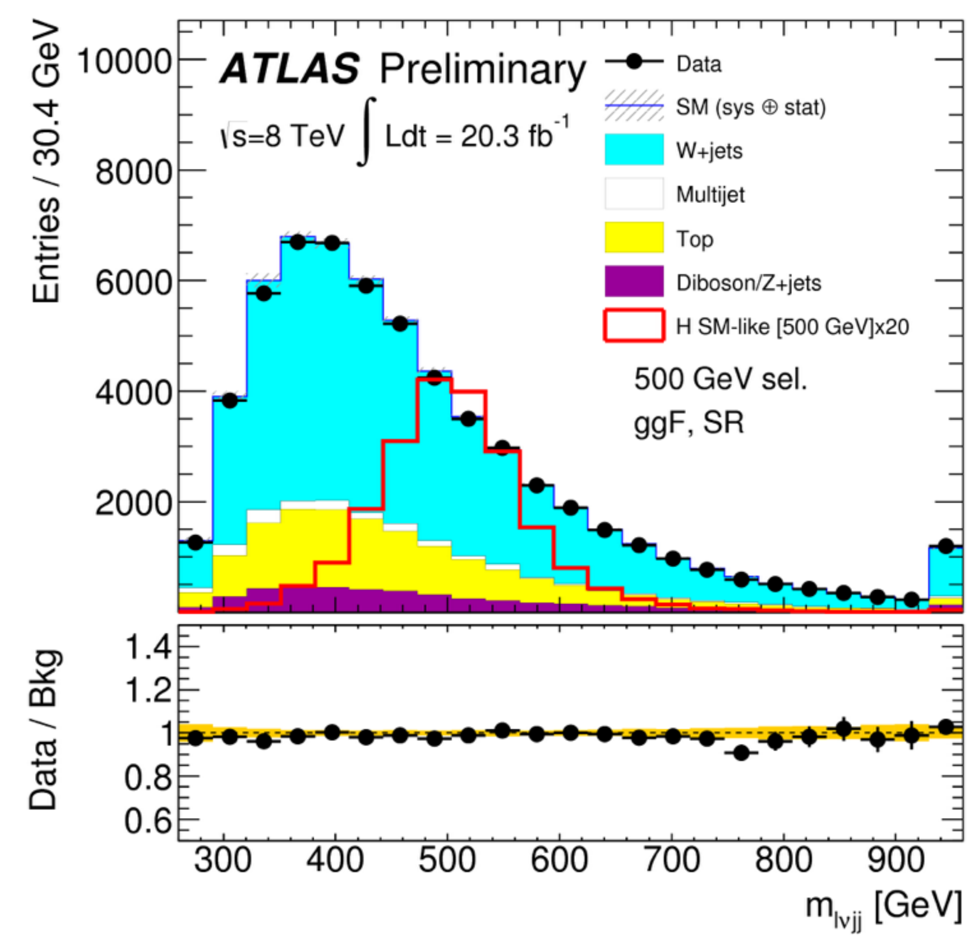
$\ell\nu qq$ is split by

- flavour/charge of lepton

Each channel calculates a mass discriminant on which the final fit is done:



Example of two of the signal regions post-fit:



$\ell\nu\ell\nu \rightarrow m_T$

transverse mass of ℓ, ℓ, E_T^{miss}

$\ell\nu qq \rightarrow m_{\ell\nu jj}$

invariant mass where $m_W, \; E_T^{miss}$ are used to constrain $\vec{p}_\nu$

Statistical Interpretation

- Both channels $\ell\nu\ell\nu,\ \ell\nu qq$ enter combined limit setting

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Narrow-Width Approximation

Width of resonance is fixed for all mass at $\Gamma_H = 4.07 MeV$

No assumption is made on relative contribution of ggF and VBF to production

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Standard Model Width Scenario

Width of resonance is the SM Higgs boson width for that mass $\Gamma_H = \Gamma_H^{SM}$

No assumption is made on relative contribution of ggF and VBF to production

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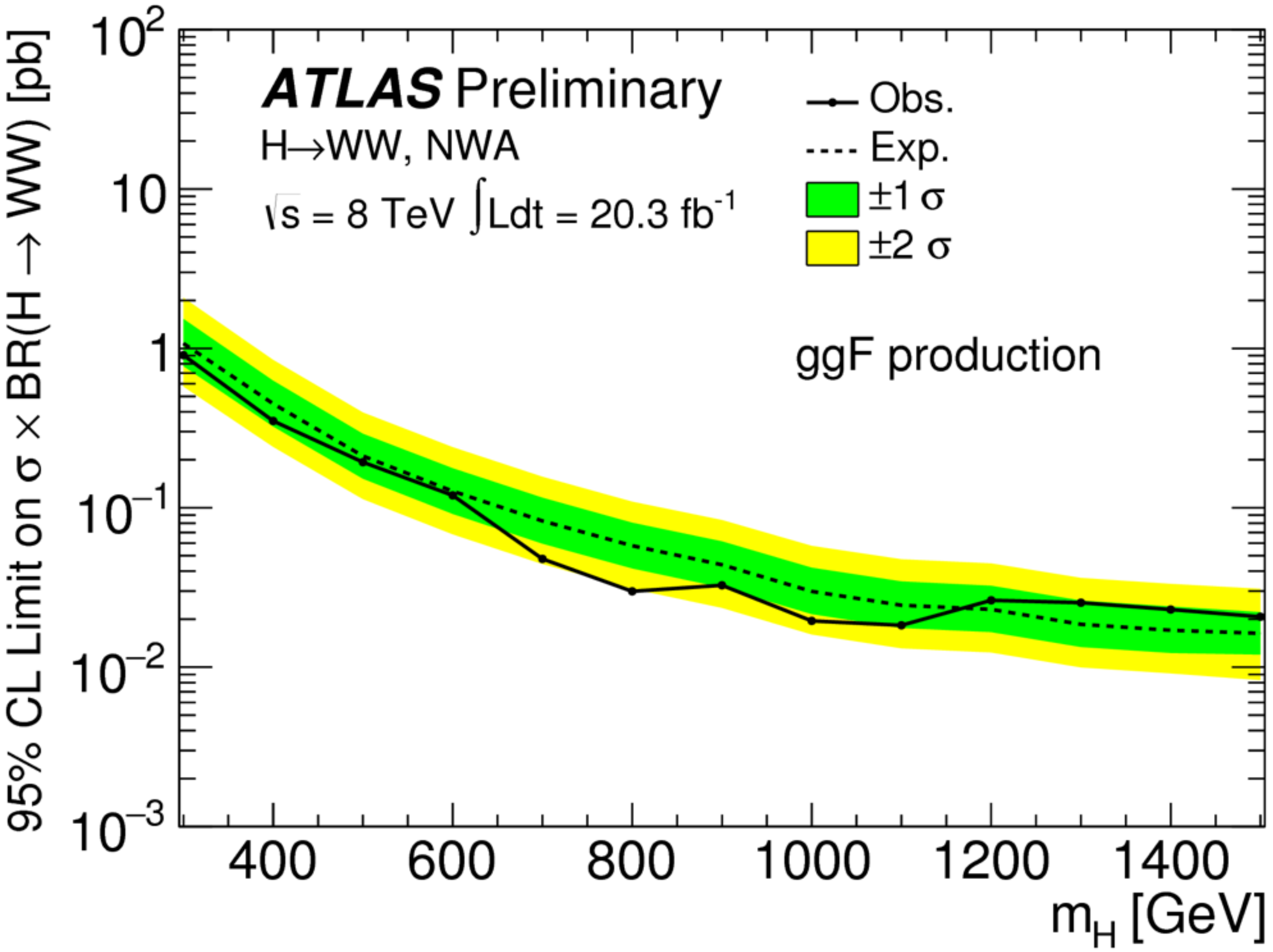
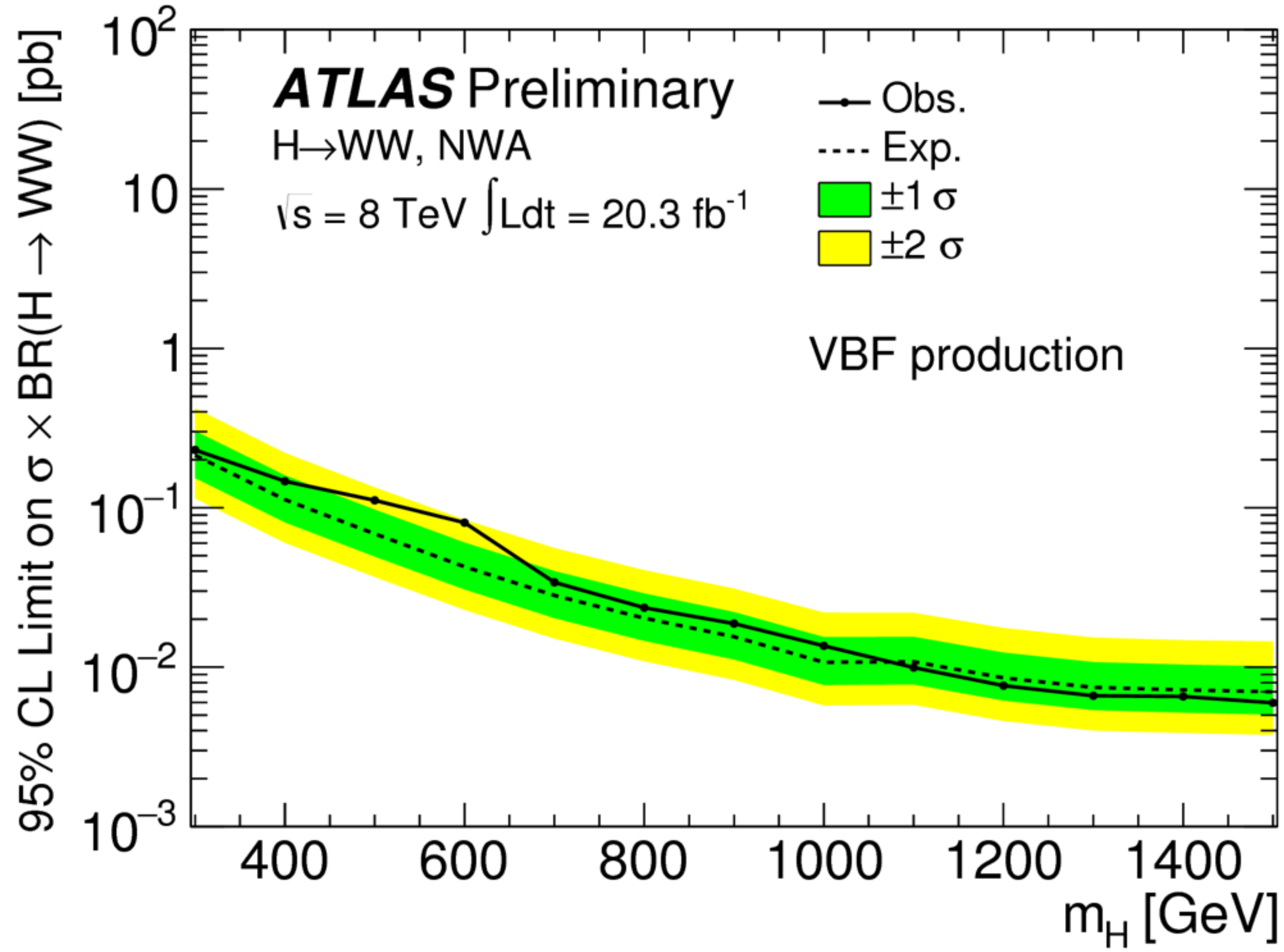
Intermediate-Width Scenario

Width of resonance intermediate to above - parameterized as $\Gamma_H = \kappa'^2 \cdot \Gamma_{H,SM}$

Limits in Narrow Width Approximation $\Gamma_H = 4.07 MeV$





ggF limits

~900 fb @ 300 GeV

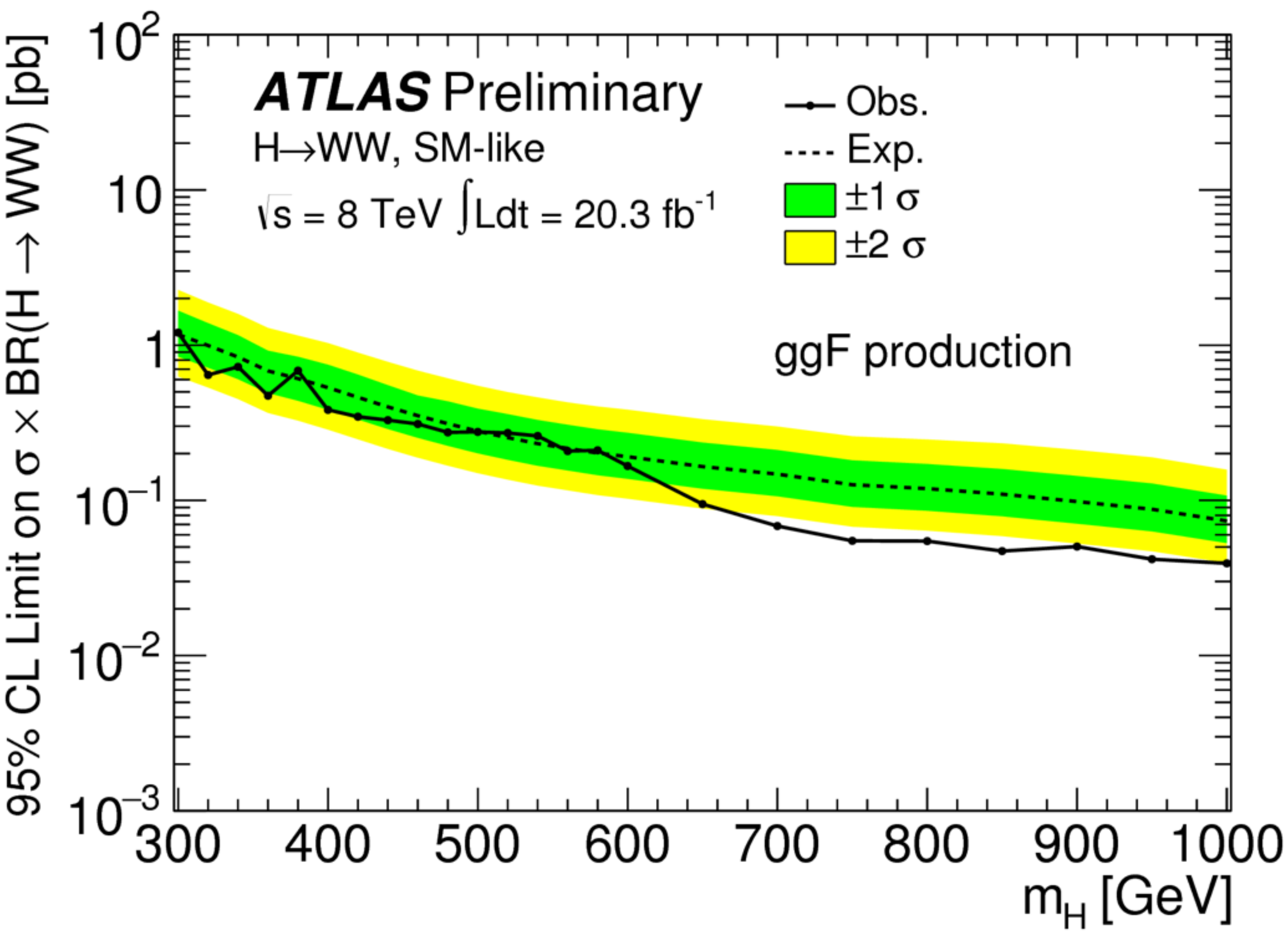
~20 fb @ 1500 GeV

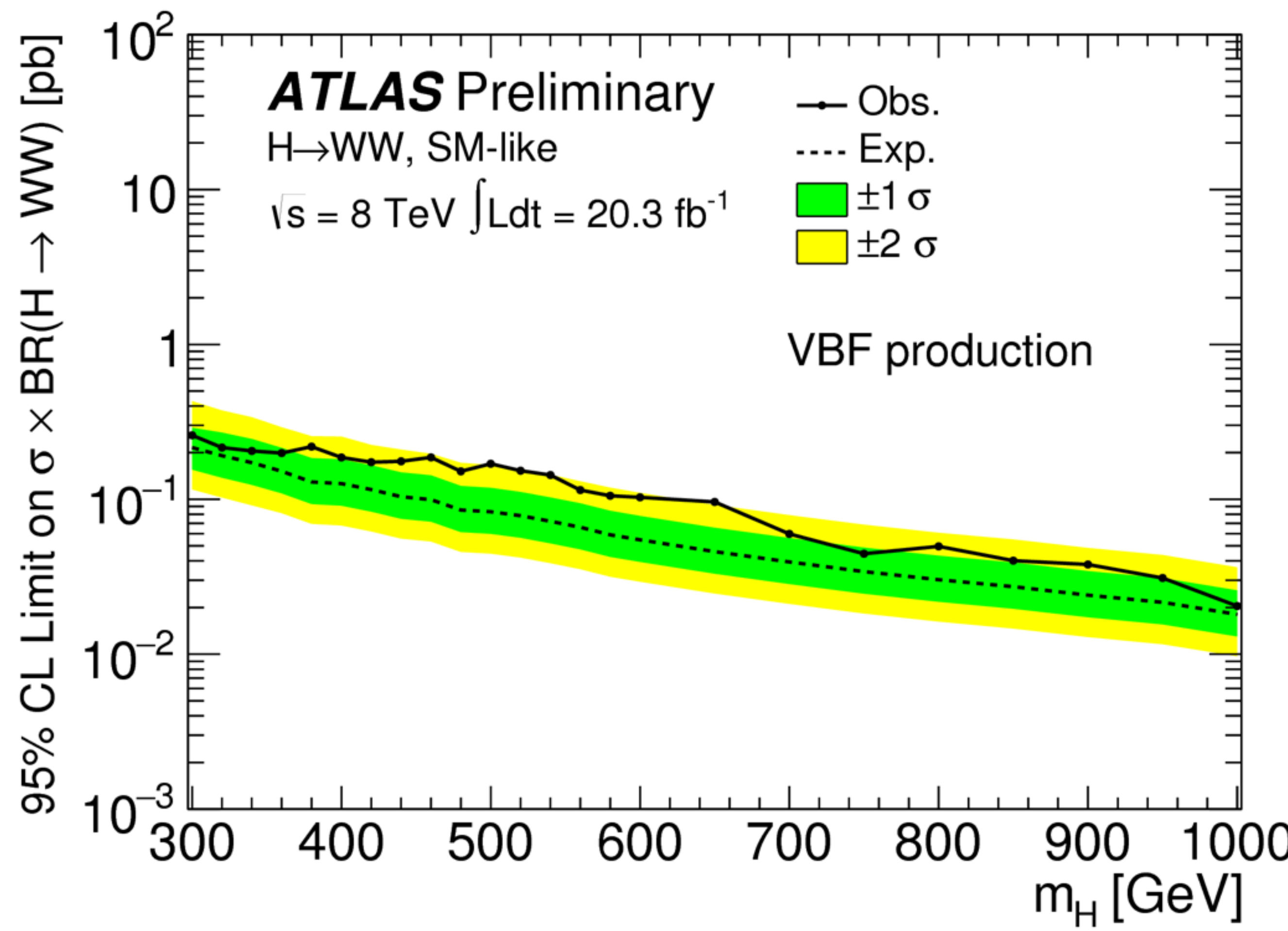
VBF limits

~230 fb @ 300 GeV

~6 fb @ 1500 GeV

Limits in Standard Model-like scenario with $\Gamma_H = \Gamma_H^{SM}$





ggF limits

~1100 fb @ 300 GeV

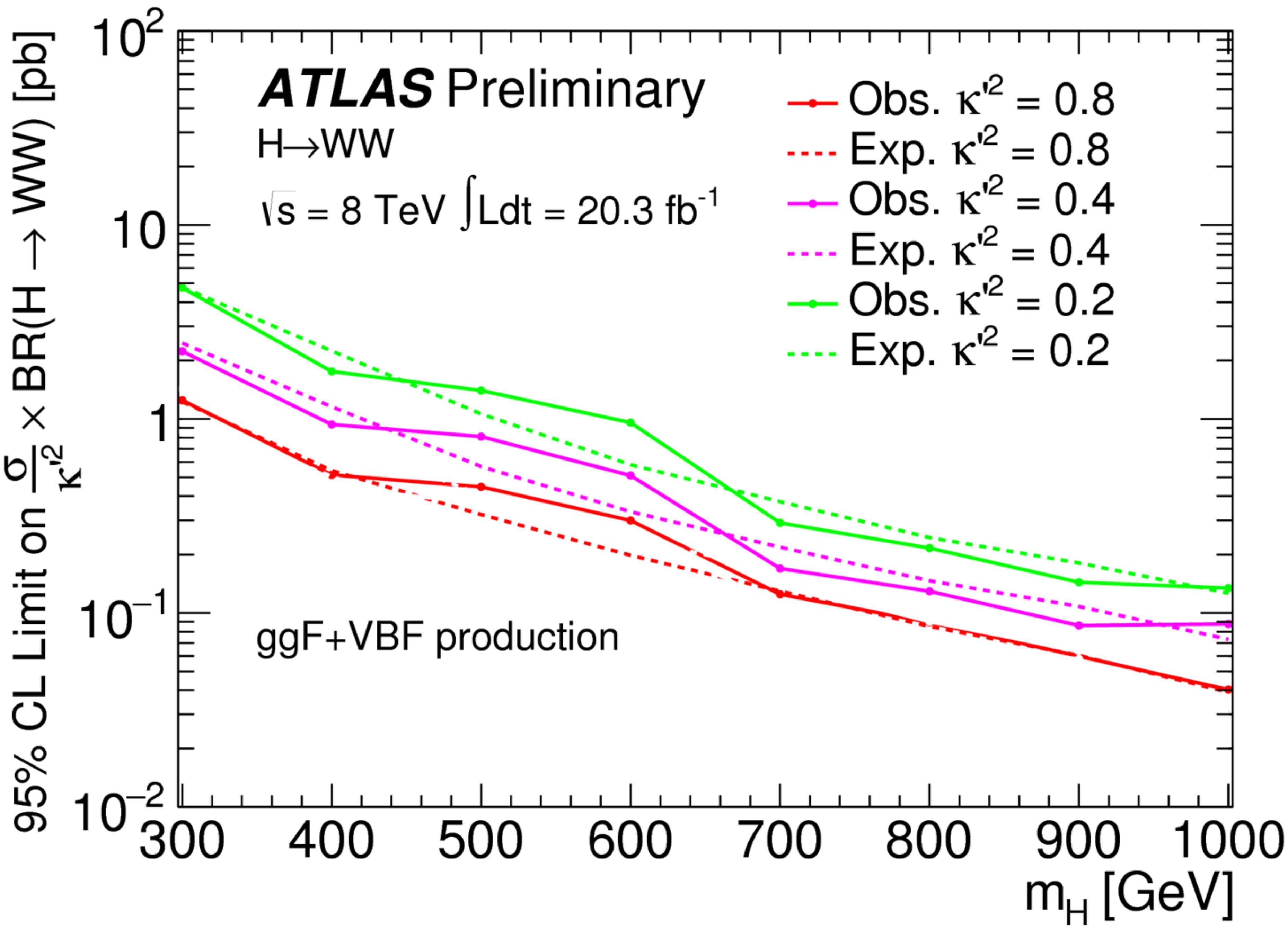
~40 fb @ 1000 GeV

VBF limits

~250 fb @ 300 GeV

~20 fb @ 1000 GeV

Limits in Intermediate-Width Scenario with $\Gamma_H = (20\%, 40\%, 80\%) \cdot \Gamma_H^{SM}$



n.b. limit on $\frac{\sigma}{\kappa'^2} BR$ to separate otherwise overlapping results

Summary

Shown here were searches for high-mass neutral Higgs bosons decaying in the diboson channels using the full $20.3/fb$ of ATLAS data at $\sqrt{s} = 8\,TeV$

- $H \to \gamma\gamma$: limits set on $\sigma_{fid} \cdot BR(X \to \gamma\gamma)$ for narrow resonances up to 600GeV.
- $H \to ZZ$: limits set on $\sigma_{ggF(VBF)} \cdot BR(X \to ZZ)$ for narrow resonances up to 1 TeV. Limits are also set in the 2HDM context providing the strongest ever exclusions in some of the parameter space probed. [See backup for MSSM interpretations]
- $H \to WW$: limits set on $\sigma_{ggF(VBF)} \cdot BR(X \to WW)$ for narrow resonances up to 1.5 TeV, and SM-width resonances up to 1 TeV. Limits are also set for intermediate widths for masses up to 1 TeV.

$H \rightarrow \gamma\gamma$

The following slides all come from Phys. Rev. Lett. 113, 171801 + auxiliary figures unless otherwise noted

Systematics

TABLE II. Summary of the systematic uncertainties

Signal and Higgs boson yield		*Z component of Drell–Yan*	
Luminosity	2.8%	Normalization[b]	9–25%
Trigger	0.5%	Peak position[b]	1.5–3.5%
γ identification[a]	1.6–2.7%	Template shape[b]	1.5–3%
γ isolation[a]	1–6%	*Higgs boson background*	
Energy resolution[a b]	10–40%	Cross-section[c]	9.6%
Signal and Higgs boson peak position		Branching ratio	4.8%
Energy scale	0.6%	C_X *factor*	
Continuum $\gamma\gamma$, γj, jj, *DY*		Topology[a]	3–15%
Signal bias[a]	1–67 events	Pile-up & U. E.[a]	1.4–3.2%

[a] mass-dependent.
[b] category-dependent.
[c] factorization scale + PDF uncertainties [1307.1347]

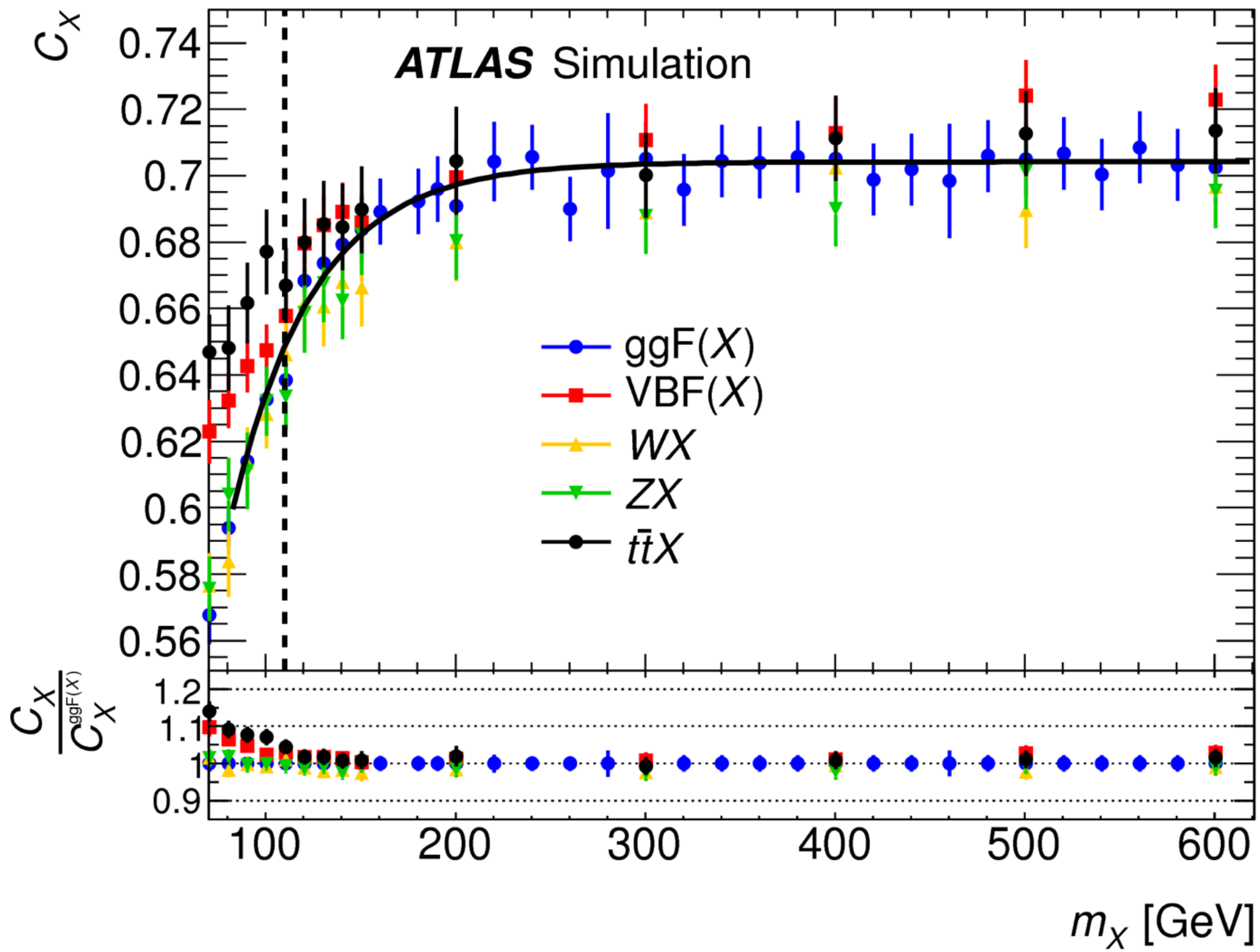
$H \rightarrow \gamma\gamma$ Event Selection

- Primary Vertex with at least 2 tracks with pT>0.4GeV
- Two photons with $E_T > 22GeV$, $|\eta| < 2.37$ excluding barrel/endcap transition region with poor efficiency $1.37 < |\eta| < 1.56$
- ID: Shower shape criteria used to achieve efficiencies ranging from 70 - 99%
- Calorimeter isolation: $E_T^{iso} < 6\,GeV$ using a cone of $\Delta R = 0.4$
- Track Isolation: $p_T^{iso} < 2.6\,GeV$ using a cone of $\Delta R = 0.2$
- Invariant mass: $E_T^{\gamma_{1(2)}}/m_{\gamma\gamma} > 0.4(0.3)$

The Fiducial Cuts (used to calculate C_X) are identical except the following:

- Transition region $1.37 < |\eta| < 1.56$ is included
- Both isolation requirements replaced by requiring $p_T^{iso(no\ \nu)} < 12\,GeV$ in a cone of $\Delta R = 0.4$

$$C_X = \frac{N_{MC}^{reco}}{N_{MC}^{fid}}$$



- C_X from ggF is used in final fit
- Systematic uncertainty covers largest spread per bin in this plot

$H \rightarrow ZZ$

The following slides all come from arXiv:1507.05930 + auxiliary figures unless otherwise noted

Systematics

ggF mode: Systematic source	Effect [%]	VBF mode: Systematic source	Effect [%]
$m_H = 200$ GeV			
$gg \rightarrow ZZ$ K-factor uncertainty	27	$gg \rightarrow ZZ$ acceptance	13
Z+hf $\Delta\phi$ reweighting	5.3	Jet vertex fraction ($\ell\ell qq/\nu\nu qq$)	13
Luminosity	5.2	$gg \rightarrow ZZ$ K-factor uncertainty	13
Jet energy resolution ($\ell\ell qq/\nu\nu qq$)	3.9	$Z+$jets $\Delta\phi$ reweighting	7.9
QCD scale $gg \rightarrow ZZ$	3.7	Jet energy scale η modelling ($\ell\ell qq/\nu\nu qq$)	5.3
$m_H = 400$ GeV			
$qq \rightarrow ZZ$ PDF	21	$Z+$jets estimate ($\ell\ell\nu\nu$)	34
QCD scale $qq \rightarrow ZZ$	13	Jet energy resolution ($\ell\ell\ell\ell/\ell\ell\nu\nu$)	6.5
$Z+$jets estimate ($\ell\ell\nu\nu$)	13	VBF $Z+$jets $m_{\ell\ell jj}$	5.5
Signal acceptance ISR/FSR ($\ell\ell\ell\ell/\ell\ell\nu\nu$)	7.8	Jet flavour composition ($\ell\ell\ell\ell/\ell\ell\nu\nu$)	5.3
$Z+b\bar{b}$, $Z+c\bar{c}$, $p_{\mathrm{T}}^{\ell\ell}$	5.6	Jet vertex fraction ($\ell\ell qq/\nu\nu qq$)	4.8
$m_H = 900$ GeV			
Jet mass scale ($\ell\ell qq$)	7	$Z+$jets estimate ($\ell\ell\nu\nu$)	19
$Z+jj$ p_{T}^{Z} shape ($\nu\nu qq$)	5.6	Jet mass scale ($\ell\ell qq$)	8.7
$qq \rightarrow ZZ$ PDF	4.3	$Z+jj$ $p_{\mathrm{T}}^{\ell\ell}$ shape	7.3
QCD scale $qq \rightarrow ZZ$	3.5	Jet energy resolution ($\ell\ell\ell\ell/\ell\ell\nu\nu$)	4.4
Luminosity	2.6	Jet flavour composition (VV/Signal)	2.6

Monte Carlos used in analysis

Physics process	$H \to ZZ$ search final state	Generator	Cross-section normalization	PDF set	Tune
		W/Z boson + jets			
$Z/\gamma^* \to \ell^+\ell^-/\nu\bar{\nu}$	$\ell\ell\ell\ell/\ell\ell\nu\nu$	ALPGEN 2.14	NNLO	CTEQ6L1	AUET2
	$\ell\ell qq^\dagger/\nu\nu qq$	SHERPA 1.4.1	NNLO	NLO CT10	SHERPA default
$W \to \ell\nu$	$\ell\ell\nu\nu$	ALPGEN 2.14	NNLO	CTEQ6L1	AUET2
	$\nu\nu qq$	SHERPA 1.4.1	NNLO	NLO CT10	SHERPA default
		Top quark			
$t\bar{t}$	$\ell\ell\ell\ell/\ell\ell qq/\nu\nu qq$	POWHEG-BOX r2129	NNLO+NNLL	NLO CT10	PERUGIA2011C
	$\ell\ell\nu\nu$	MC@NLO 4.03			AUET2
s-channel and Wt	$\ell\ell\ell\ell/\ell\ell qq/\nu\nu qq$	POWHEG-BOX r1556	NNLO+NNLL	NLO CT10	PERUGIA2011C
	$\ell\ell\nu\nu$	MC@NLO 4.03			AUET2
t-channel	all	ACERMC 3.8	NNLO+NNLL	CTEQ6L1	AUET2
		Dibosons			
$q\bar{q} \to ZZ(*)$	$\ell\ell qq/\nu\nu qq$	POWHEG-BOX r1508	NLO	NLO CT10	AUET2
	$\ell\ell\ell\ell/\ell\ell\nu\nu$	POWHEG-BOX r1508	NNLO QCD NLO EW	NLO CT10	AUET2
EW $q\bar{q}$ ($\to h$) $\to$ $ZZ(*) + 2j$	$\ell\ell\ell\ell$	MADGRAPH 5 1.3.28		CTEQ6L1	AUET2
gg ($\to h^*$) $\to ZZ$	$\ell\ell\ell\ell$	MCFM 6.1	NNLO	NLO CT10	AU2
	$\ell\ell\nu\nu$	GG2VV 3.1.3	(for $h \to ZZ$)	NLO CT10	AU2
$q\bar{q} \to WZ$	$\ell\ell\nu\nu/\ell\ell qq/\nu\nu qq$	POWHEG-BOX r1508	NLO	NLO CT10	AUET2
	$\ell\ell\ell\ell$	SHERPA 1.4.1			SHERPA default
$q\bar{q} \to WW$	all	POWHEG-BOX r1508	NLO	NLO CT10	AUET2
		$m_h = 125$ GeV SM Higgs boson (background)‡			
$q\bar{q} \to Zh \to$ $\ell^+\ell^- b\bar{b}/\nu\bar{\nu}b\bar{b}$	$\ell\ell qq/\nu\nu qq$	PYTHIA 8.165	NNLO	CTEQ6L	AU2
$gg \to Zh \to$ $\ell^+\ell^- b\bar{b}/\nu\bar{\nu}b\bar{b}$	$\ell\ell qq/\nu\nu qq$	POWHEG-BOX r1508	NLO	CT10	AU2
		Signal			
$gg \to H \to ZZ(*)$	all	POWHEG-BOX r1508	—	NLO CT10	AU2
$q\bar{q} \to H + 2j$; $H \to ZZ(*)$	all	POWHEG-BOX r1508	—	NLO CT10	AU2
$q\bar{q} \to (W/Z)H$; $H \to ZZ(*)$	$\ell\ell\ell\ell$	PYTHIA 8.163	—	CTEQ6L1	AU2

$H \to ZZ \to \ell\ell\ell\ell$

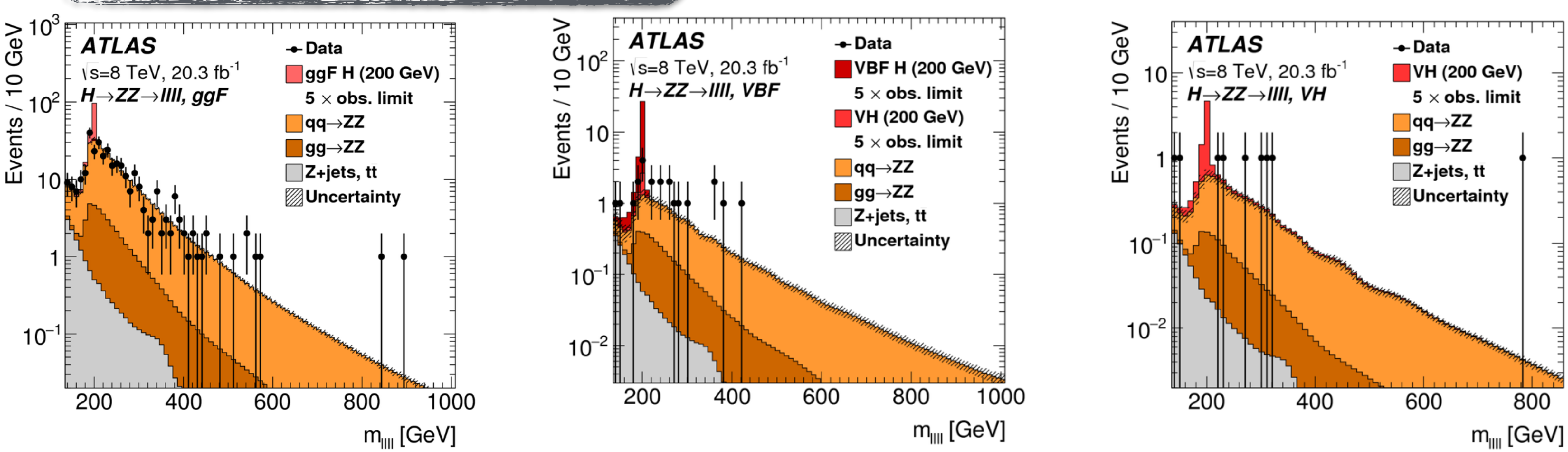
- Only channel which includes search for VH production: included for $m_H < 200\,GeV$
- Due to high resolution, only channel using unbinned likelihood fit

- Split in 3 production categories based on jets in event
- ggF split further into 4 channels to improve resolution $(4e, 4\mu, 2e2\mu, 2\mu2e)$
- Dominant background $qq \to ZZ$ estimated using MC corrected to NNLO
- Other backgrounds:

  $gg \to ZZ$ estimated using MC corrected to NNLO

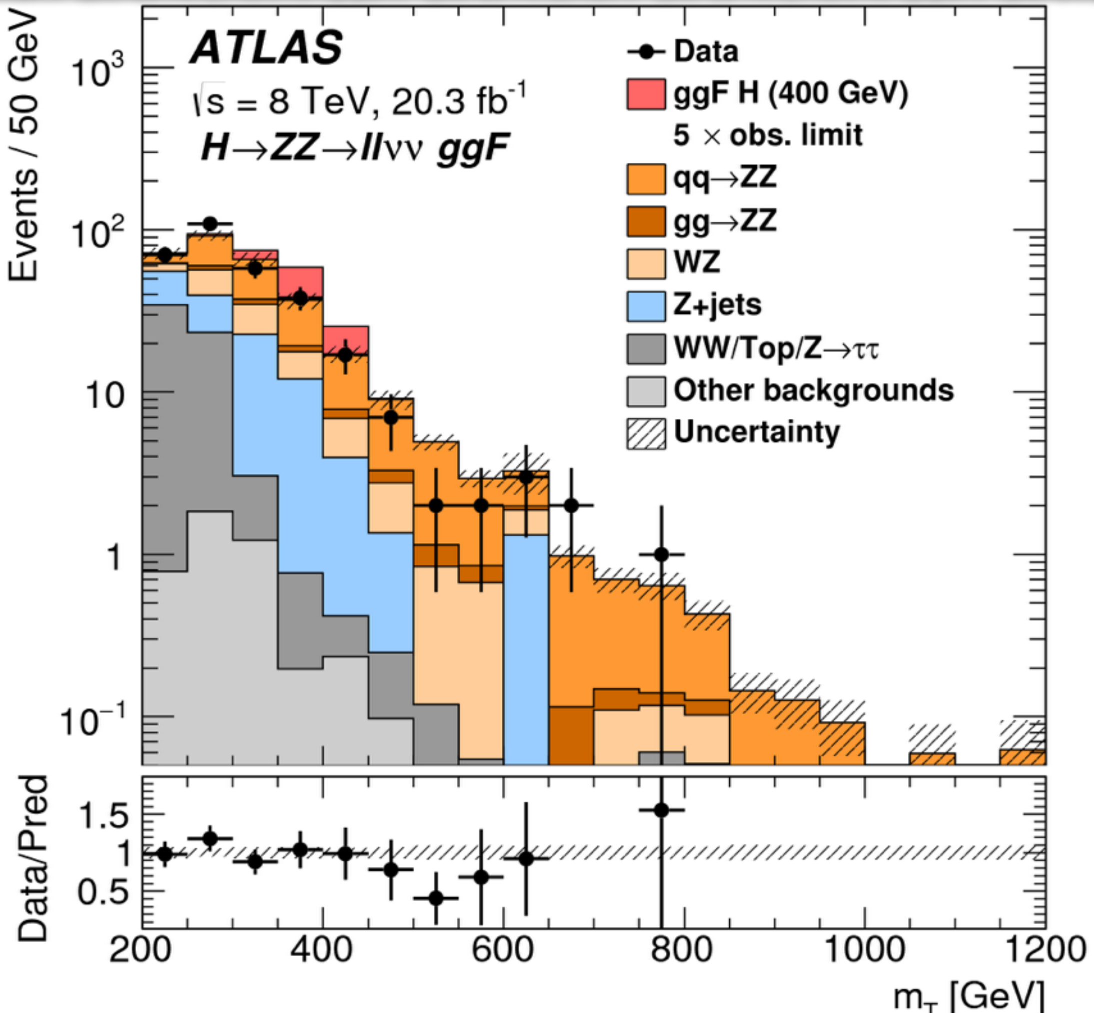
  $Z + Jets, t\bar{t}$ estimated using fits to $m_{\ell\ell}$ distributions in control regions with inverted cuts for $\ell\ell\mu\mu$ or fits on inner detector variables in relaxed control regions for $\ell\ell ee$ which are then extrapolated to the signal region

observable: invariant mass $m_{\ell\ell\ell\ell}$



$H \to ZZ \to \ell\ell\nu\nu$

- Events contain exactly 2 very high quality leptons with $76 < m_{\ell\ell}/GeV < 106$, and no additional high p_T leptons
- Events categorized as ggF or VBF based on additional jets
  - VBF: $m_{jj} > 550\,GeV$
  - ggF: maximum 1 jet $p_T > 30\,GeV,\ \eta_j < 2.5$
- Drell-Yan Z production suppressed by cut on $\Delta\phi\left(\vec{p}^{\ell\ell}, \vec{E}_T^{miss}\right)$
- Boosed Z's enriched by requiring $\Delta\phi_{\ell\ell} < 1.4$



observable: transverse mass m_T^{ZZ} $$\left(m_T^{ZZ}\right)^2 = \left(\sqrt{m_Z^2 + \left|p_T^{\ell\ell}\right|^2} + \sqrt{m_Z^2 + \left|E_T^{miss}\right|^2}\right)^2 - \left|\vec{p}_T^{\ell\ell} + \vec{E}_T^{miss}\right|^2$$

- Backgrounds
  - $gg/qq \to ZZ$ estimated as in $\ell\ell\ell\ell$
  - WZ estimated using MC (Powheg), validated on data containing additional leptons
  - $WW,\ t\bar{t},\ Wt,\ Z \to \tau\tau$ estimated from data using $e^{\pm}\mu^{\mp}$ pairs
  - $Z + Jets$ is estimated from data using an ABCD method on $\Delta\phi\left(\vec{p}^{\ell\ell}, \vec{E}_T^{miss}\right)$ and $\Delta\phi_{\ell\ell}$

$H \to ZZ \to \ell\ell qq$

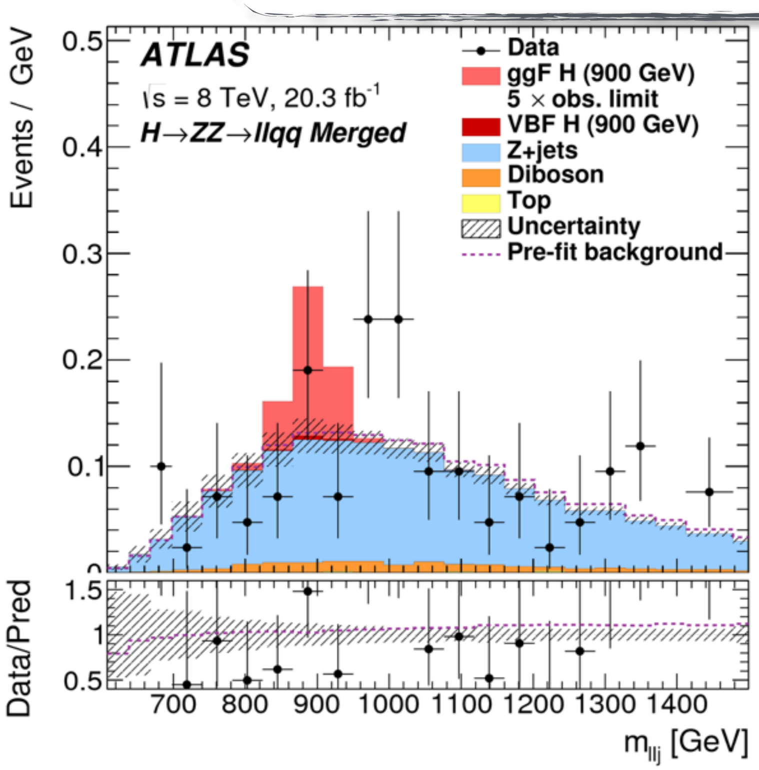
- Events contain exactly 2 very high quality leptons with $83 < m_{\ell\ell}/GeV < 99$, and no additional high p_T leptons
- ggF events are sub-categorized as *resolved* or *merged* to account that at high m_H, the jets from $Z \to q\bar{q}$ decay will overlap and not be resolved
- In the resolved channel, events are sub-categorized based on number of b-tagged jets
- Backgrounds:

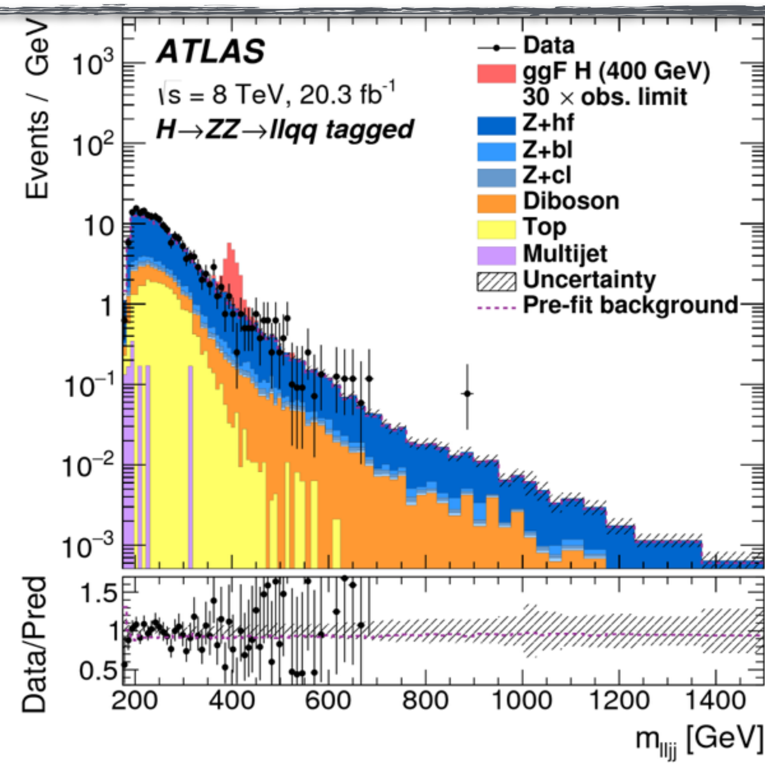
$Z + Jets$ shape from MC, normalizations (in each category above) are nuisance params in final fit. Control regions are built by inverting cuts on m_{jj} and building pdfs in the b-tagging category.

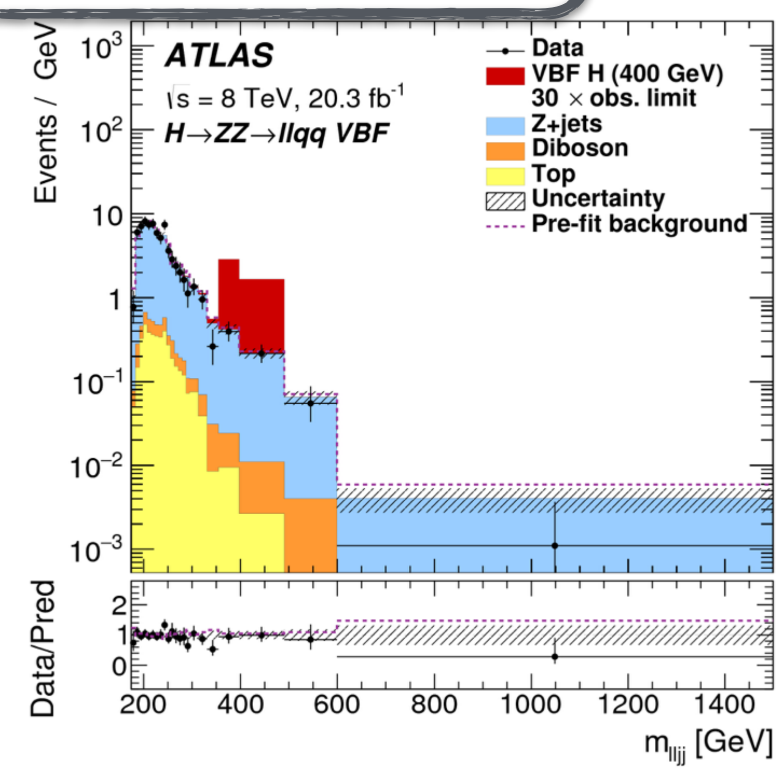
ZZ/WZ taken from MC simulation; differences between generators treated as systematic uncertainty.

Top estimated using $e^{\pm}\mu^{\mp}$ pairs; top scaling fit simultaneously during final combination.

observable: transverse mass $m_{\ell\ell j(j)}$ in the merged (resolved) channel







$H \to ZZ \to \nu\nu qq$

- Events contain no leptons (as defined in $\ell\ell qq$ search)
- Require $E_T^{miss} > 160\,GeV$, $70 < m_{jj}/GeV < 105$
- To suppress multijet backgrounds, require

$$\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{miss}) < \pi/2\ ,\ \Delta\phi(\vec{E}_T^{miss}, j_{nearest}) > 0.6$$

- Search divided into categories from number of b-tagged jets
- Sensitivity improved by a floating cut on p_T^j increasing linearly with the test mass m_H
- Jet momenta are scaled to bring $m_{jj} \to m_Z$

observable: transverse mass m_T^{ZZ}

$$(m_T^{ZZ})^2 = \left(\sqrt{m_Z^2 + \left|p_T^{jj}\right|^2} + \sqrt{m_Z^2 + \left|E_T^{miss}\right|^2}\right)^2 - \left|\vec{p}_T^{jj} + \vec{E}_T^{miss}\right|^2$$

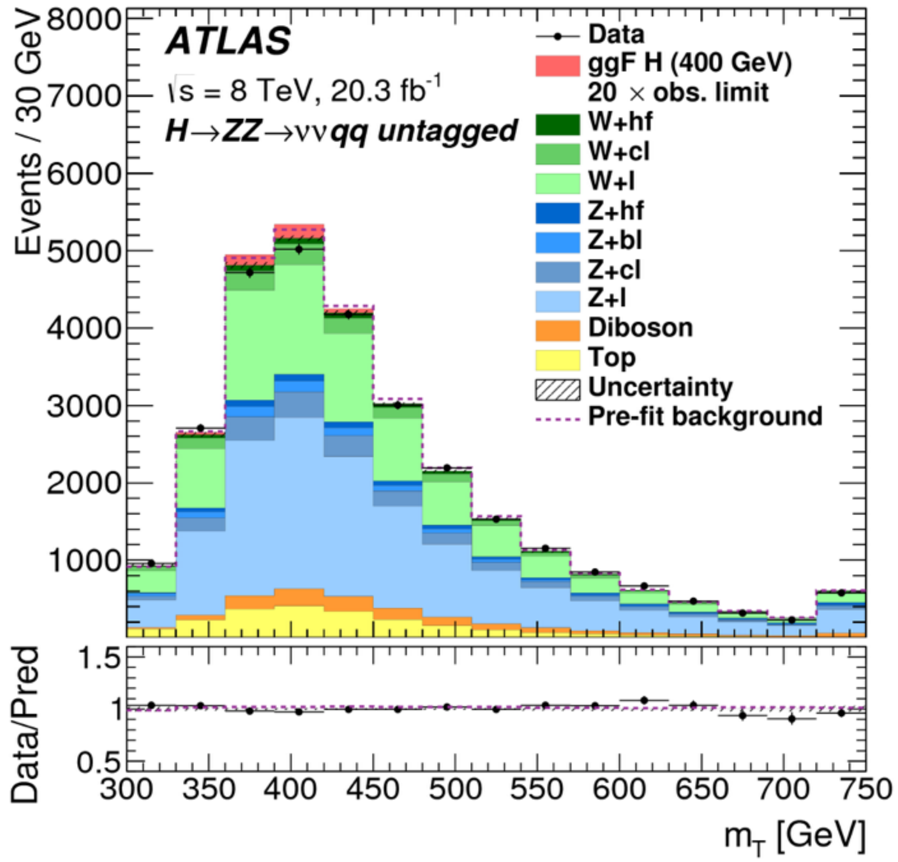
the range of m_T^{ZZ} used in fit depends on m_H

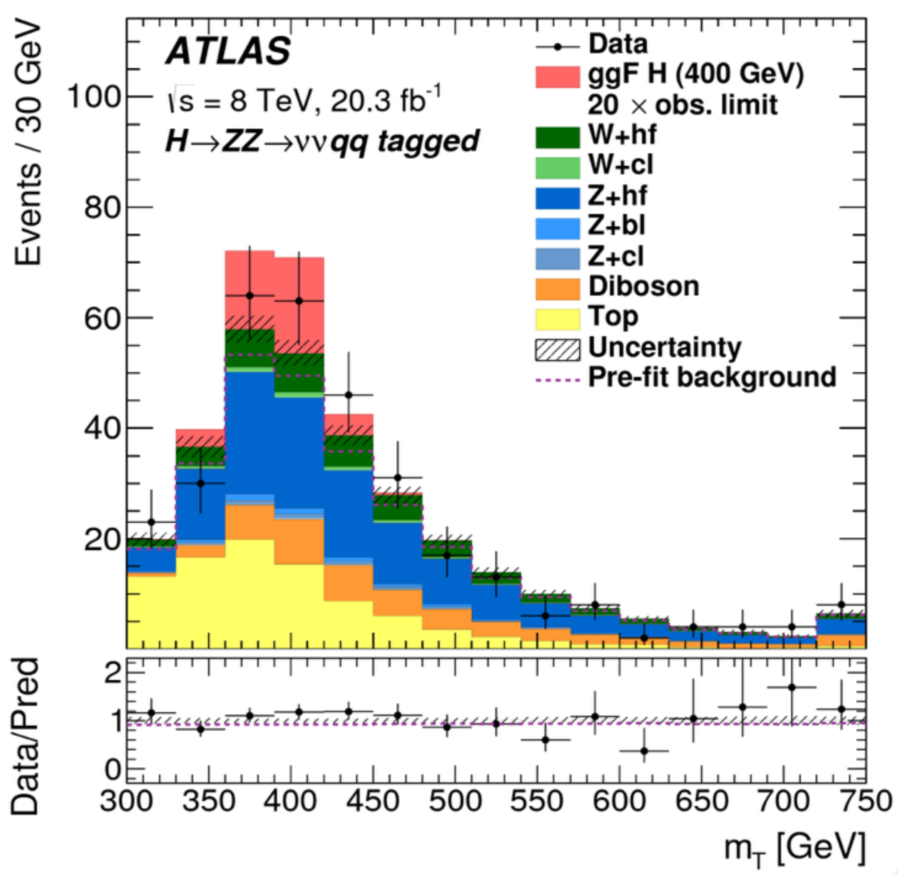
Backgrounds:

$W + Jets$ estimated from data using CR with exactly 1 loose muon, in each of several b-tagging categories of the jets

$Z + Jets$ same as with $\ell\ell qq$ with an additional CR containing exactly 2 loose muons
A further E_T^{miss}- dependant function corrects the MC shape

$WW/WZ, Top$ same as other channels





2HDM Overview [arXiv:1106.0034]

Two doublets Φ_1, Φ_2 couple to fermions as:

	Φ_1	Φ_2
$Type\, I:$		u, d, ℓ
$Type\, II:$	d, ℓ	u

5 physical Higgs bosons: CP-even h, H, one CP-odd A, two charged $H^{\pm}$

assumed to be the 125GeV Higgs (→ h)

high-mass Higgs under search (→ H)

Additional parameters:

- $tan\,\beta$ ratio between vacuum expectation value of two doublets
- α mixing angle of doublets

➡ HZZ coupling proportional to $cos(\beta - \alpha)$

➡ *Alignment Limit* $cos(\beta - \alpha) \rightarrow 0$ leaves the h indistinguishable from a SM Higgs

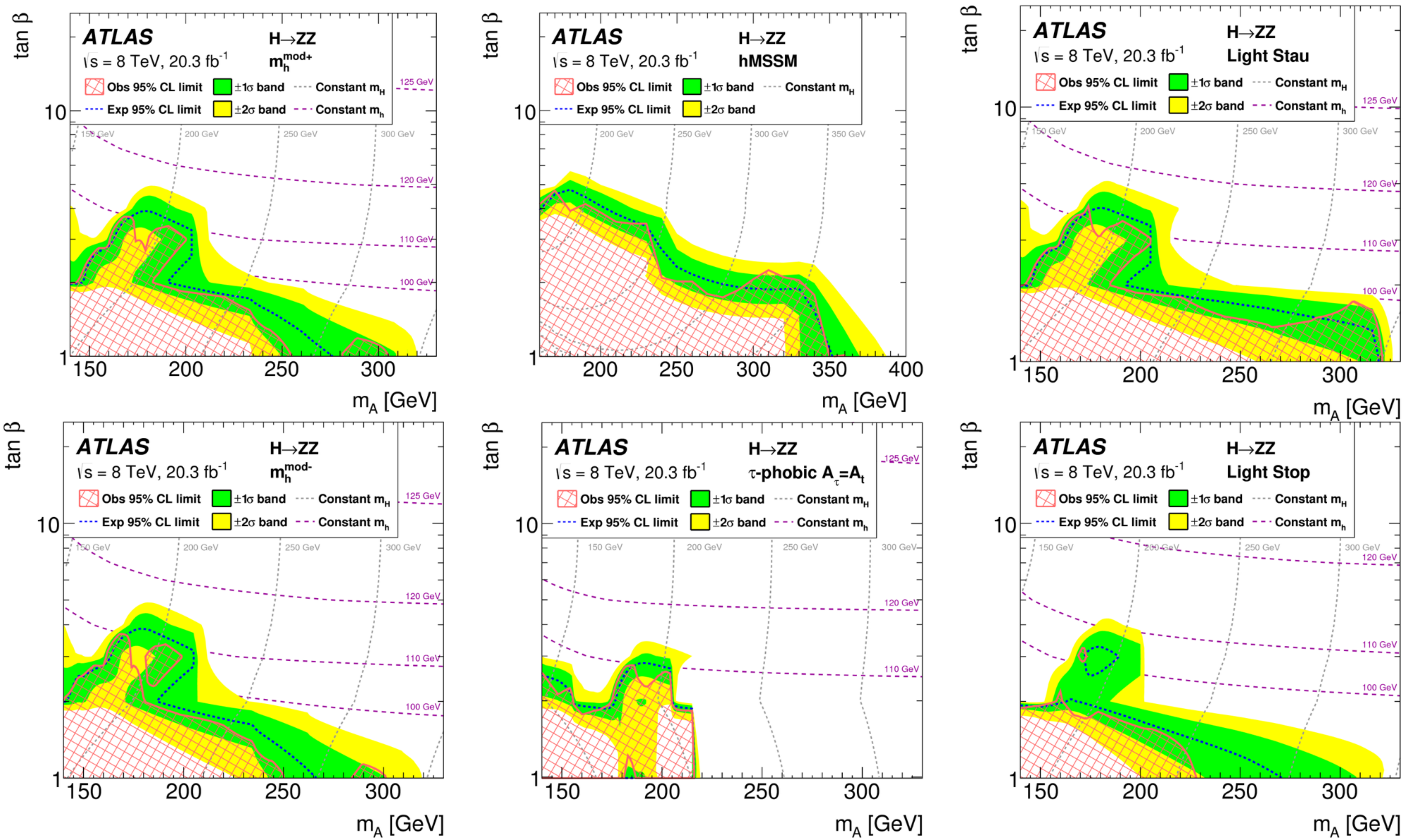
2HDM considered in presented limits:

$$m_h = 125\, GeV, \quad m_A = m_H = m_{H^{\pm}}, \quad m_{12}^2 = m_A^2\, tan\beta/(1 + tan\beta^2)$$

MSSM Interpretations

as defined in 1307.1347, 1302.7033, 1101.0593

The value of m_A fully determines the value of m_H. For the lightstau model the trilinear coupling was set to $A_T = A_t$. The vertical dashed grey lines indicate contours of constant m_H, while the horizontal dashed purple lines indicate contours of constant m_h (for the hMSSM model m_h = 125 GeV for the entire phase space shown, so the constant m_h contours are not shown).



$H \to WW$

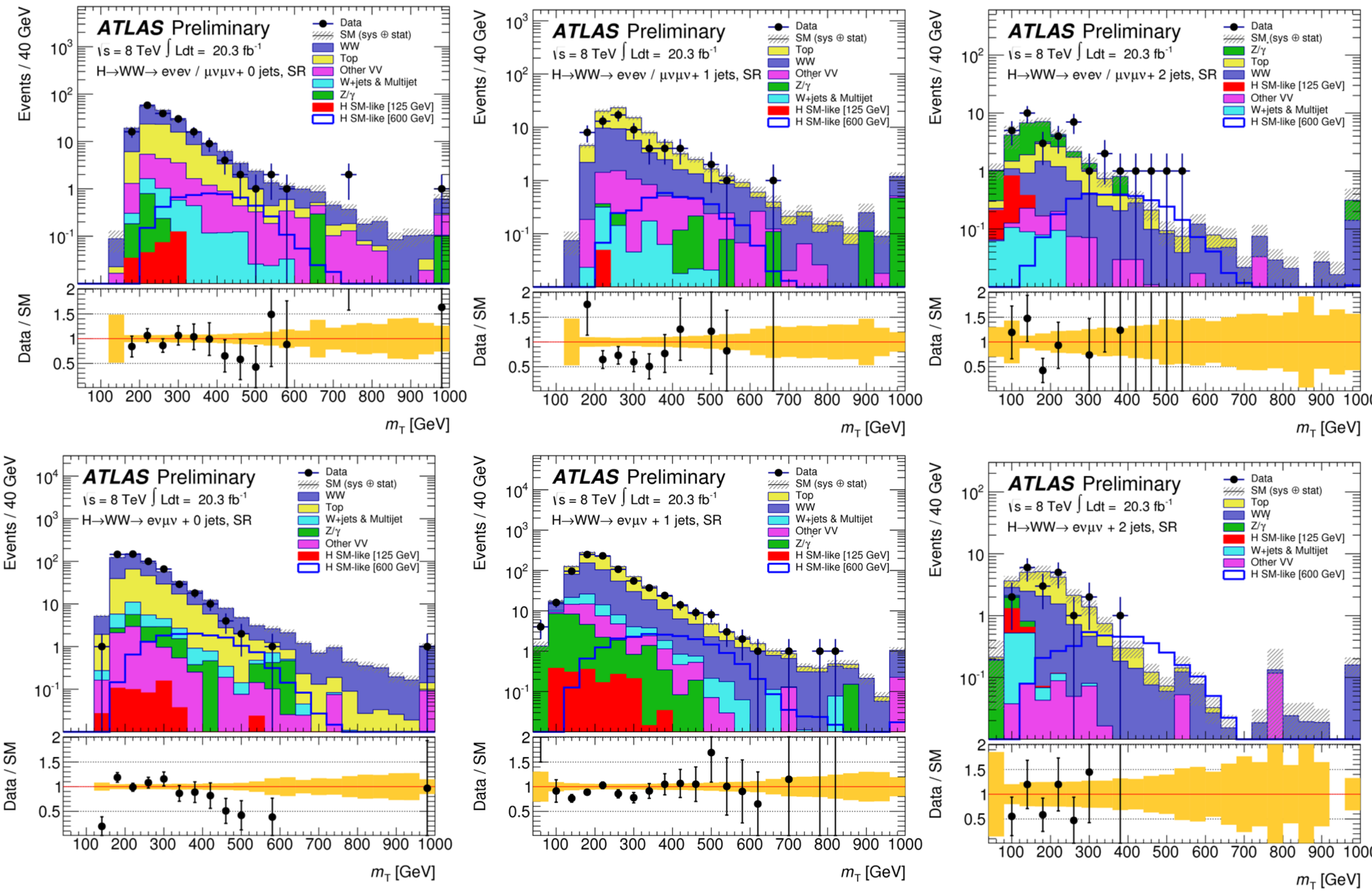
The following slides all represent ATLAS Preliminary results: to be submitted

$H \to WW \to \ell\nu\ell\nu$ Signal Regions

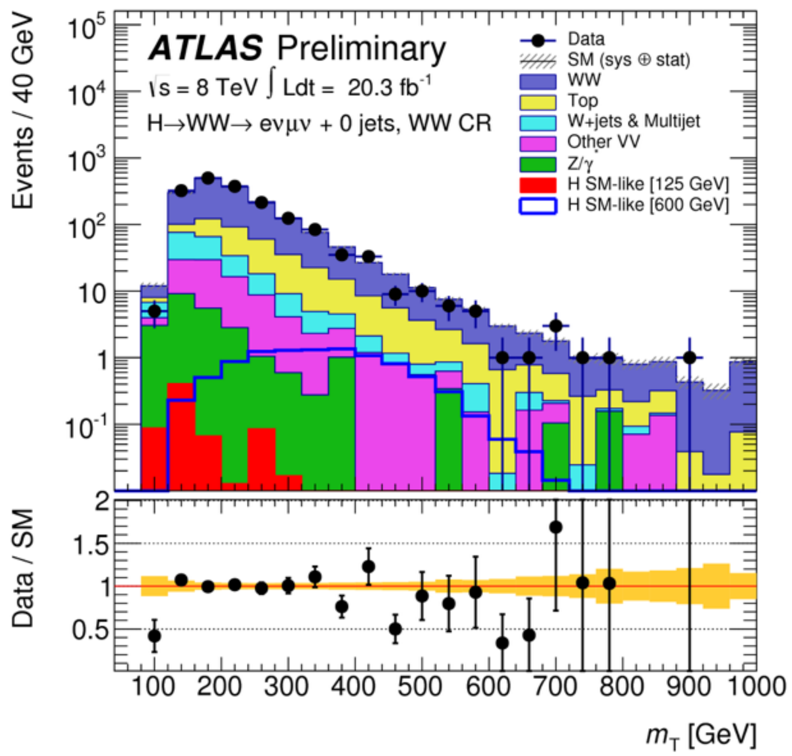
0 jets | 1 jet | 2+ jets

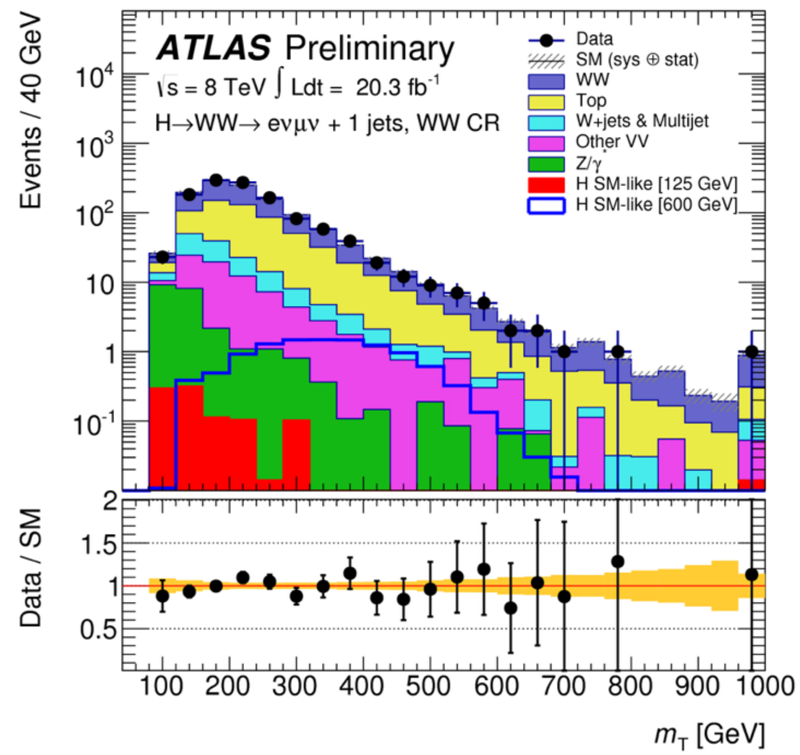
same flavour

different flavour



$H \to WW \to \ell\nu\ell\nu$ Control Regions





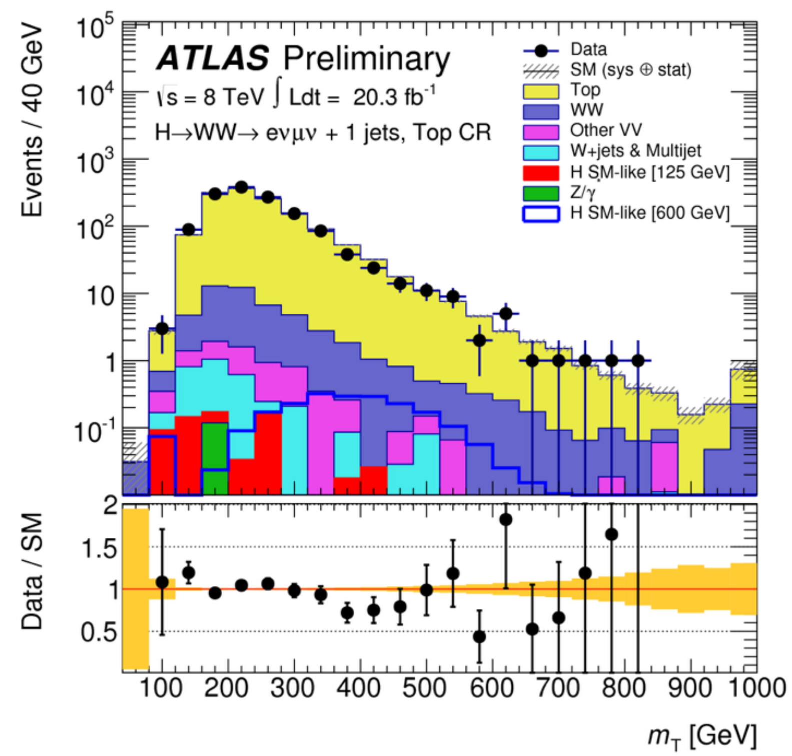
WW Control Regions

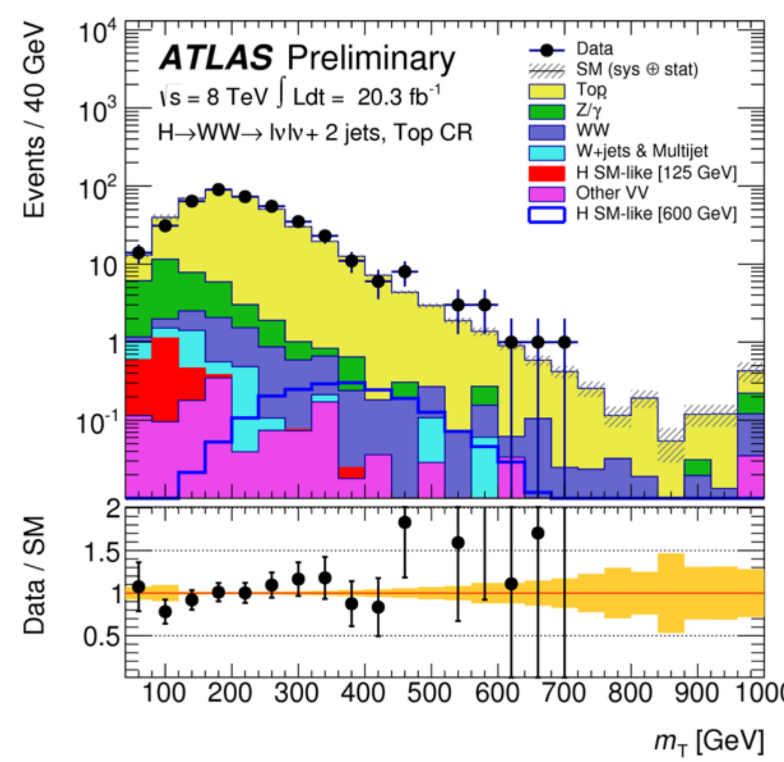
only different flavour final state is used

Top Control Regions

in 1-jet category, only different-flavour final state is used

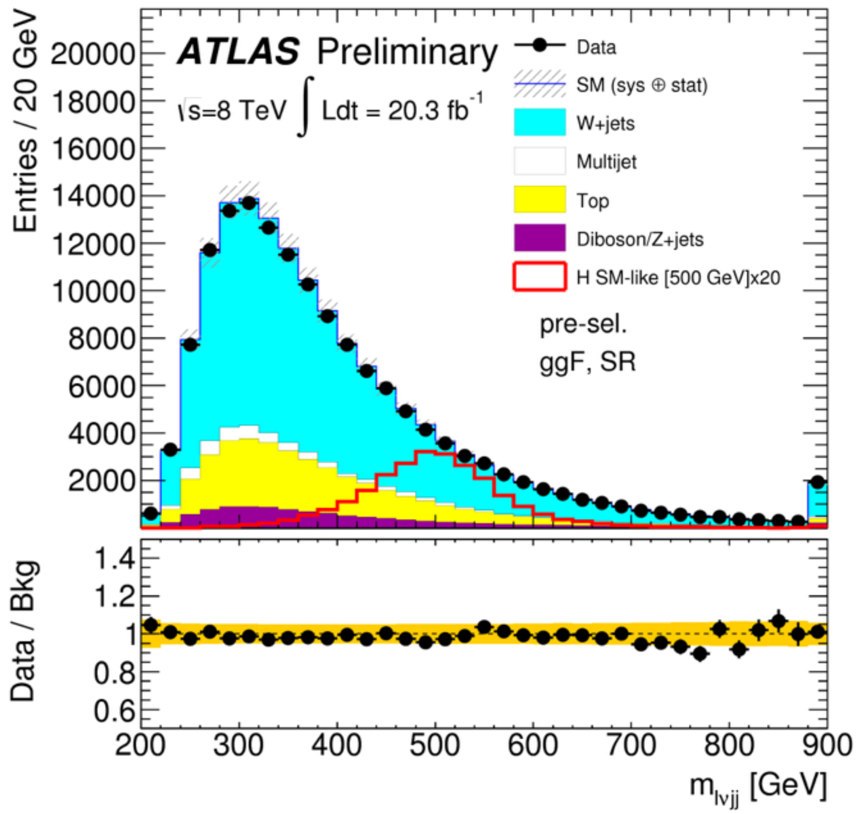
in 2+jet category, both different/same-flavour finals states are used



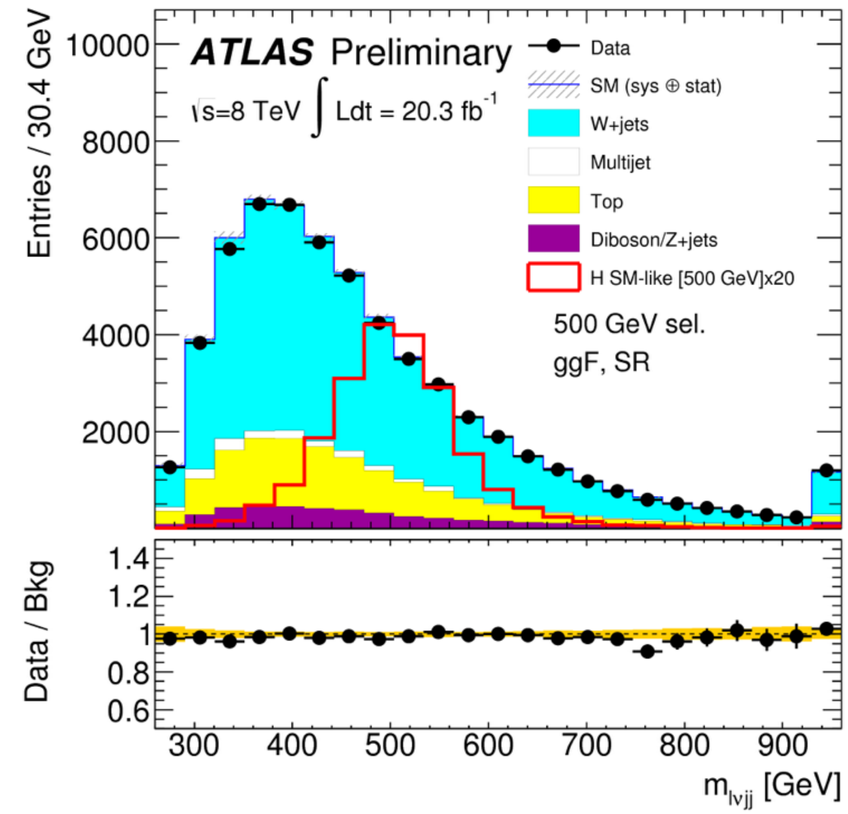


$H \to WW \to \ell\nu qq$ Signal Regions

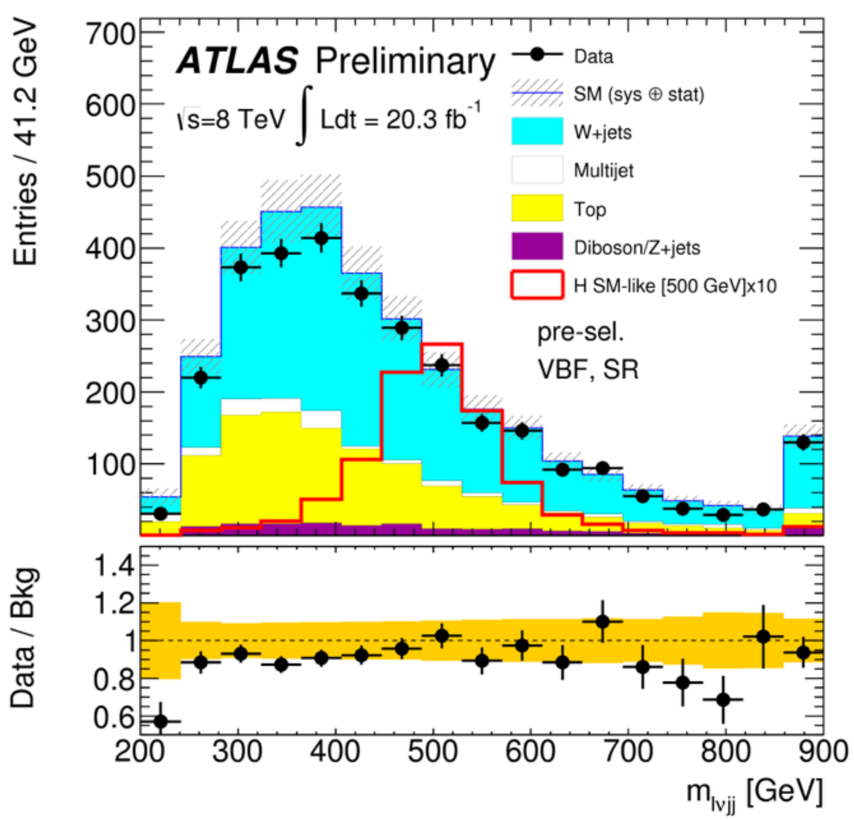
ggF category



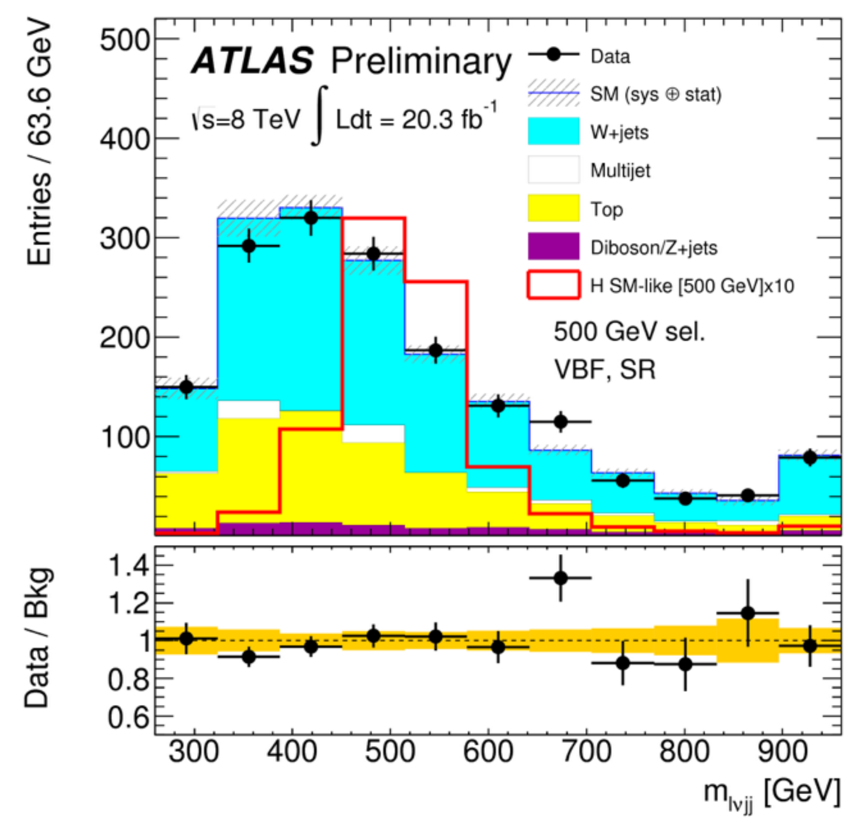
Signal regions have a mass hypothesis-specific selection to enhance sensitivity



VBF category

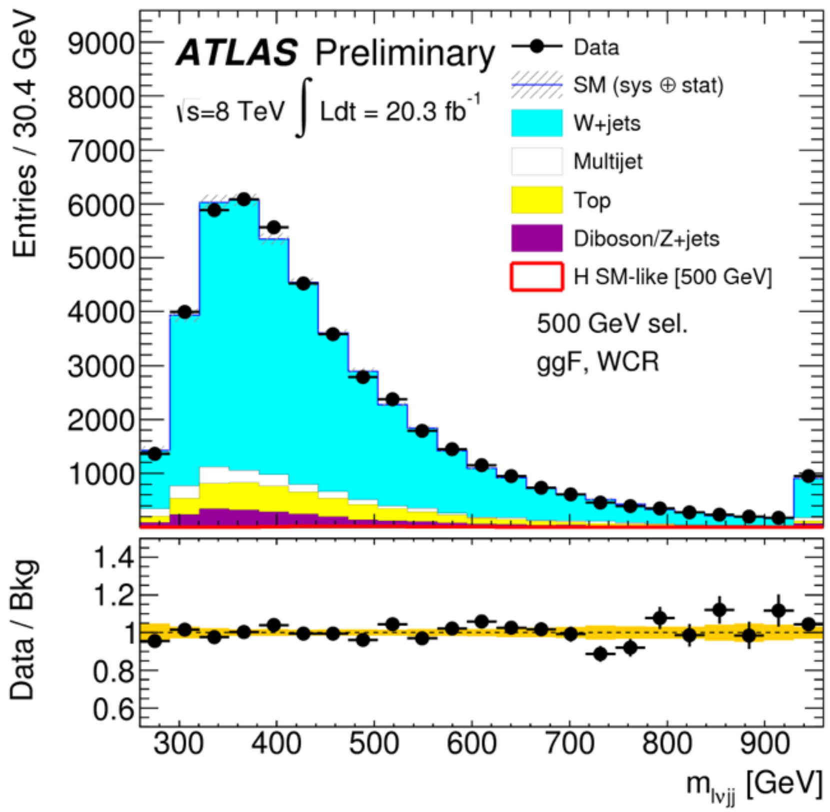


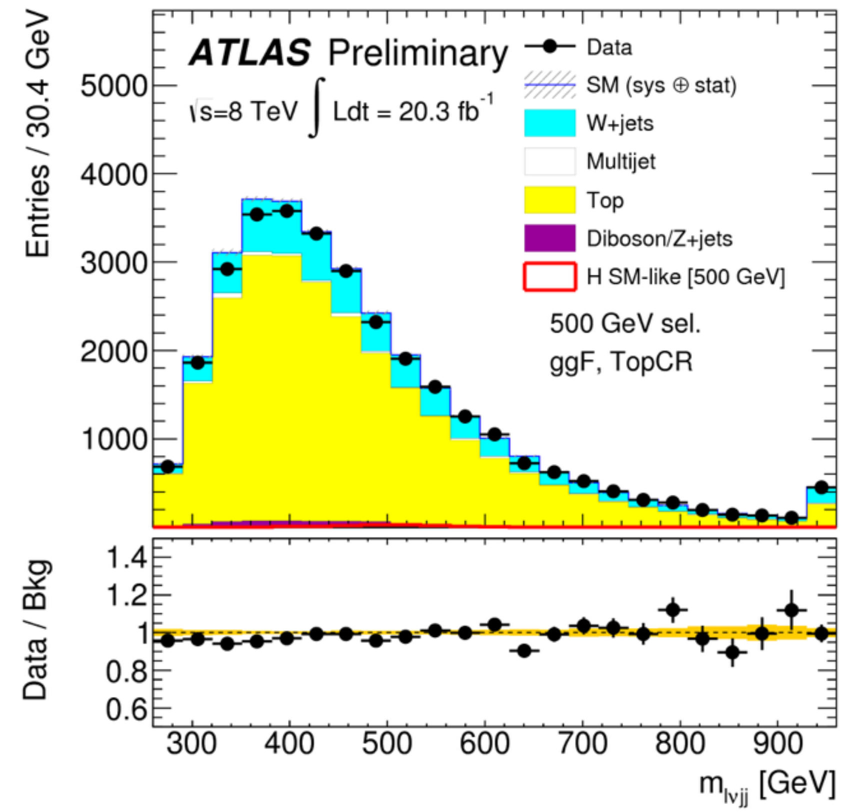
applying 500 GeV selection



$H \to WW \to \ell\nu qq$ Control Regions

ggF category

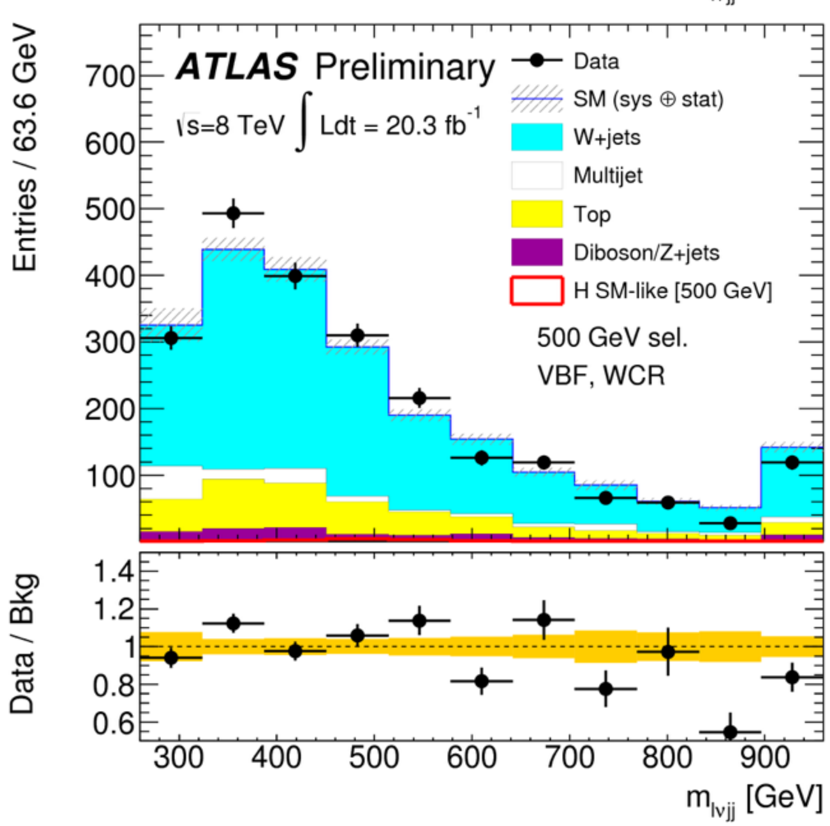


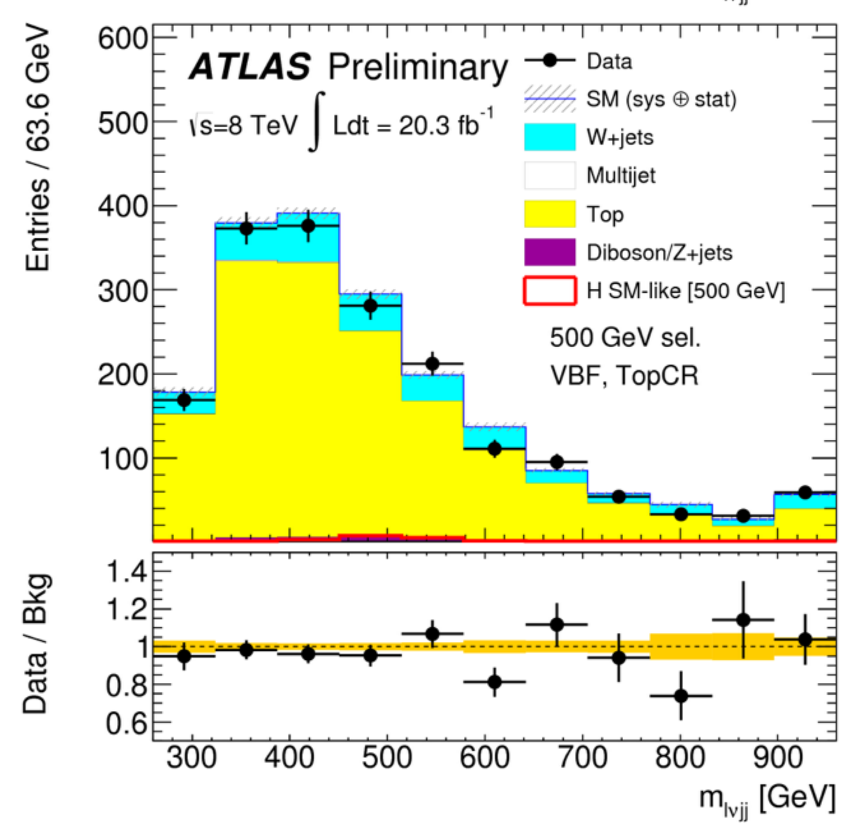


WW-enriched CRs

Top-enriched CRs

VBF category





Statistics used

(summarized from arXiv:1503.07622, arXiv:1007.1727)

$$CL_s$$

$$\frac{\int_{q_{obs}}^{\infty} f(q|\mu, \hat{\hat{\theta}}(\mu, obs))dq}{\int_{q_{obs}}^{\infty} f(0|\mu, \hat{\hat{\theta}}(0, obs))dq} = 5\%$$

➡ modified confidence interval (not actually a confidence interval) which protects against downwards fluctuations excluding arbitrarily small signal strengths

$$q_\mu \begin{cases} -2\,ln\,\lambda(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases}$$

$$\tilde{q}_\mu \begin{cases} -2\,ln\,\tilde{\lambda}(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases}$$

➡ test statistics for upper limit setting. Defined around physical limitation $\mu > 0$, and common sense limitations - observing $\hat{\mu} > \mu$ should be treated as signal-like

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}})}{L(\hat{\mu}, \hat{\theta})}$$

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