High mass dibosons and the (neutral, scalar) Higgs sector

- **High mass WW and ZZ distribution**
  - **h(125) contribution**
  - **H: new neutral, scalar, resonance**
- ATLAS and CMS results from run-1
- Which models to explore?
- Non-zero width, interferences

Many thanks to my ATLAS colleagues: M Duehrssen, Carl Gwilliam, Liron Barak and the HBSM group

BSM high mass neutral scalar: models

- SM h(125)
  - **Offshell analysis**, limit on width from offshell/onshell ratio

- SM-like: just the usual SM Higgs at another mass.
  - Production cross-sections, decays, total width well known
  - **Not realistic!** The h(125) already does the job for WW unitarization etc…

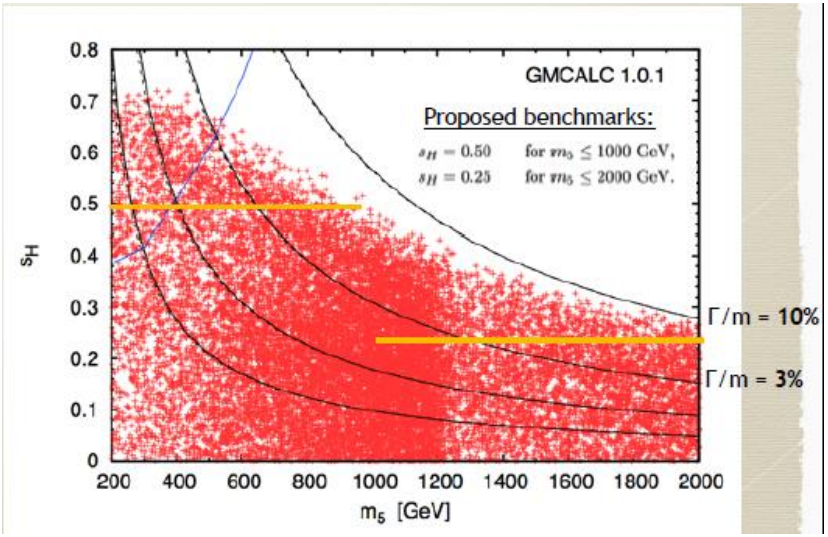
    => how much room is left? needs a model.

- EWS Electroweak Singlet
  - add a singlet to Higgs sector => states: h(125) + H(M)
  - couplings : C [h(125)], C' [H(M)], $C^2 + C'^2 = 1$
  - possible 'other' decays of H(M) parametrized by B_{new}
  - production and decays easily scaled from SM case
  - total width $\Gamma = \Gamma_{SM}\, C'^2/(1-B_{new})$

    not attractive, but a good "workhorse" for Higgs searches: ggF, VBF…

- 2HDM
  - add a doublet => states: h(125), H, A, H^+, H^-
  - parameters: tan(β) (ratio of vev's), α (h-H mixing) , masses (h, H, A, $H^{+/-}$), m_{12}^2(doublet mix)
  - 4 different types: I, II (includes MSSM), lepton-specific, flipped.
  - **production and decays predicted**
  - **width can be large** for some parts of parameter space
  - *ATLAS HZZ search: m(h)=125, m(H)=m(A)=m($H^{+/-}$), m_{12}^2=m(A)tan(β)/(1+tan(β)²)*
    => results in cos(β−α), tan(β) space for chosen m(H)

- Higgs Triplet : Georgi-Machacek model *LHCHXSWG-2015-001*
  - add doublet and triplet. parameter s^2_H fraction of m(W) and m(Z) due to triplet
  - H_5^0 fermiophobic, coupled only to VV: **VBF only**, and **Γ(ZZ) ~ 2x Γ(WW) (!)**
  - proposed benchmarks:
    - m(H) = 1 TeV, s_H = 0.5
      - σ(H) = s^2_H*σ(H)$_{SM}$ = 12.8 fb
      - Γ(H) = s^2_H*Γ(H)$_{SM}$ = 8%m(H).
    - m(H) = 2 TeV, s_H = 0.25
      - σ(H) = s^2_H*σ(H)$_{SM}$ = 0.255 fb
      - Γ(H) = s^2_H*Γ(H)$_{SM}$ = 8%m(H).



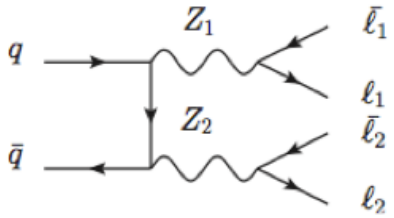
h(125) and VV production

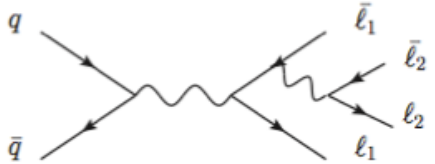
VV only (non – VBF: qqVV…)

- Non-Higgs VV
  - q q continuum

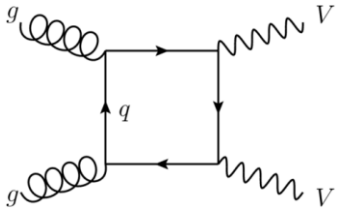
    NLO Generators

    NNLO cross-section





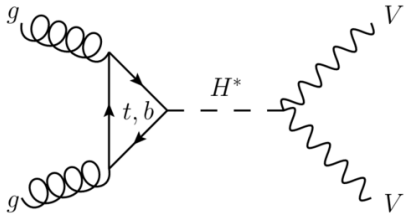
  - gg-ZZ continuum
    - **only known at LO!**



- h(125) VV
  - gg fusion

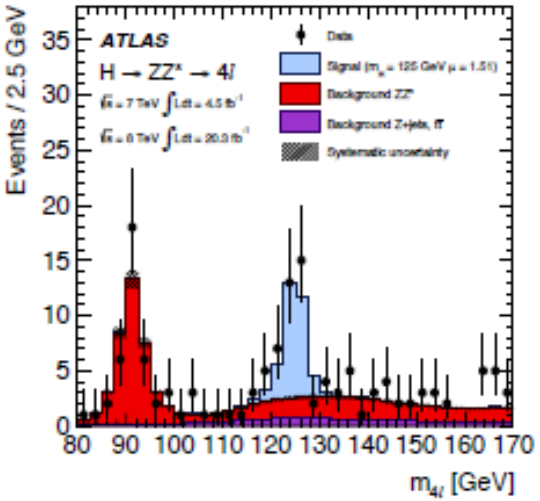
    NLO Generators

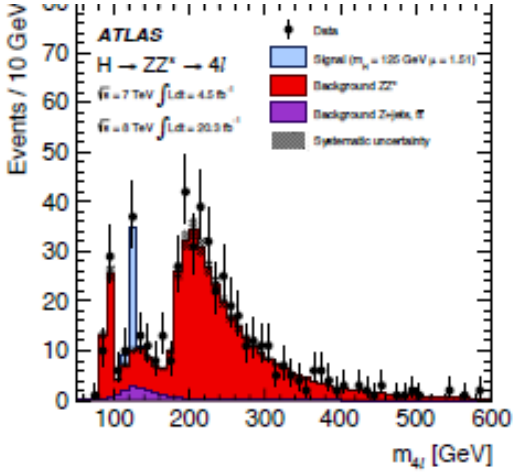
    N3LO cross-section

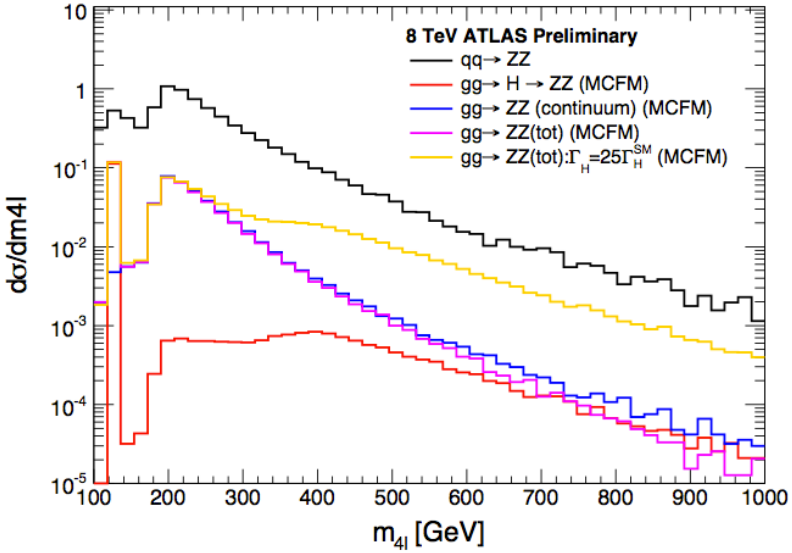


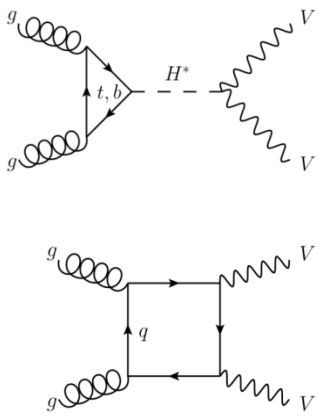
SM- h(125)

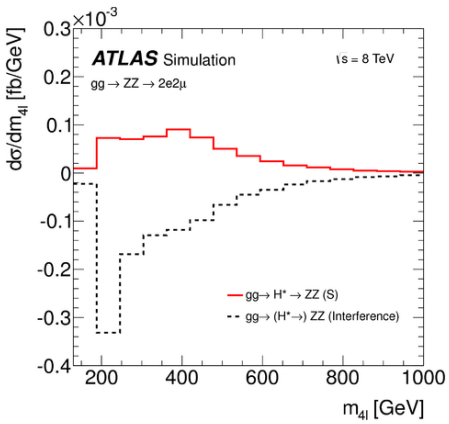
- VV: ZZ and WW modes central for the discovery (with $\gamma\gamma$, but $\gamma\gamma$ not very promising for high mass…)











SM-h(125) offshell/width analysis

- Goal (Caola, Melnikov): compare offshell/onshell h(125) -> VV and set limit on Γ_h:

$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma^{\text{SM}}_H}, \qquad \mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

$\mu_{offshell}$ is interesting in itself; assuming $\kappa_{offshell} = \kappa_{onshell}$, limit on $\mu_{offshell}$ => limit on Γ_h

- qq-ZZ continuum
  - ZZ- 4 leptons: minimize qq by Matrix Element analyses which favor gg
  - ZZ- llvv : request large Etmiss, large mT(ZZ); same for WW(evμv)
  - modelling: NLO QCD + NLO EW corrections

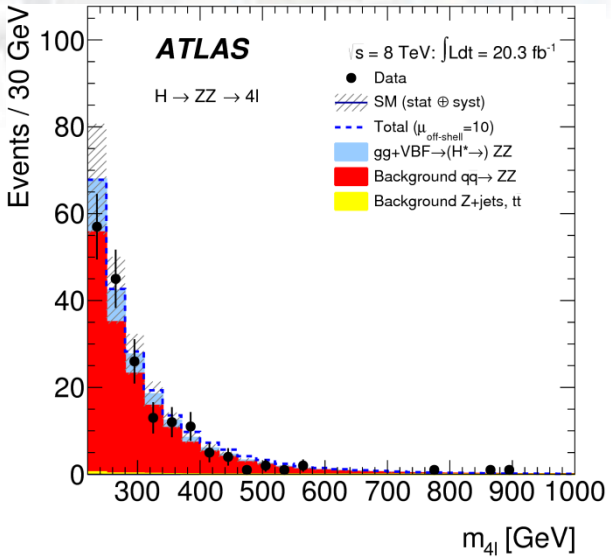
- gg-ZZ: treatment of interference: h125[S] – ggZZ continuum [B]
  - compute SM: $S_{SM}(Mzz)$, $B(Mzz)$, $SBI_{SM}(Mzz)$; extract $I_{SM} = SBI_{SM} - S_{SM} - B$
  - For any different coupling $S_k = kS_{SM}$, scale I by √k => $SBI_k = kS_{SM} + \sqrt{k}\, I_{SM} + B$

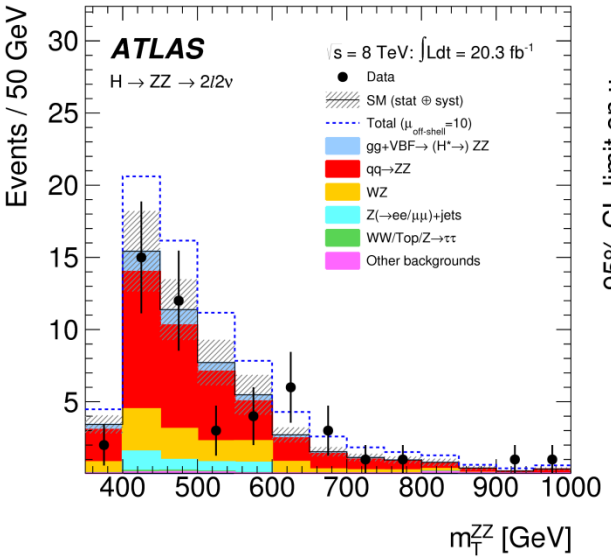
    $SBI_k = (k- \sqrt{k})S_{SM} + \sqrt{k}\, SBI_{SM} + (k- \sqrt{k})B$

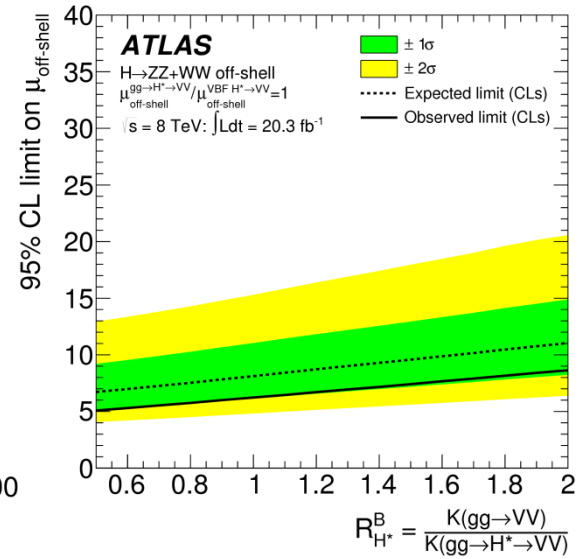
- Fit k such that $SBI_k(M)$ match the data M(ZZ) spectrum.

- gg-ZZ continuum only known at LO (box)
  - how to predict signal (gg-H-ZZ)?
    - generate LO (***gg2VV, MCFM***), multiply by NNLO/LO K_{QCD}-factor [mass-dependent] (Passarino)
    - interference: YR: choice of x 1, x √ K_{QCD}, x K_{QCD} ? => K_{QCD} (Bonvini et al.)
    - ATLAS gives results as a function of K_{QCD} (bkd)/K_{QCD} (signal)
    - CMS adopts K_{QCD} (bkd) = K_{QCD} (signal)
  - How to treat acceptance?
    - ZZ-4 lepton analysis not dependent on p_T(ZZ), but ZZ-llvv analysis does depend on p_T(ZZ) (m_T cut!)
  - ATLAS recipe: use ***SHERPA/OpenLoops*** to generate gg -> (H) -> VV+0 jet +1jet merged (*not real NLO!*),
    reweight S(M), B(M), SBI(M) each separately.
- VBF: VV + 2 jets: similar treatment, replacing $\kappa_g^2 \kappa_V^2$ by κ_V^4
  - VBF-h(offshell), VBF-like t-channel h : independent of Γ_H
  - Vh, h-> V*+2jets : scales like κ_V^4 / Γ_H (!)

h(125) offshell/width: results







- ATLAS

$R^B_{H^*}$	Observed 0.5	**1.0**	2.0	Median expected 0.5	**1.0**	2.0	Assumption
$\Gamma_H/\Gamma_H^{\rm SM}$	4.5	**5.5**	7.5	6.5	**8.0**	11.2	$\kappa_{i,\text{on-shell}} = \kappa_{i,\text{off-shell}}$
$R_{gg} = \kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}$	4.7	**6.6**	8.6	7.1	**9.0**	13.4	$\kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}$, $\Gamma_H/\Gamma_H^{\rm SM}$=1

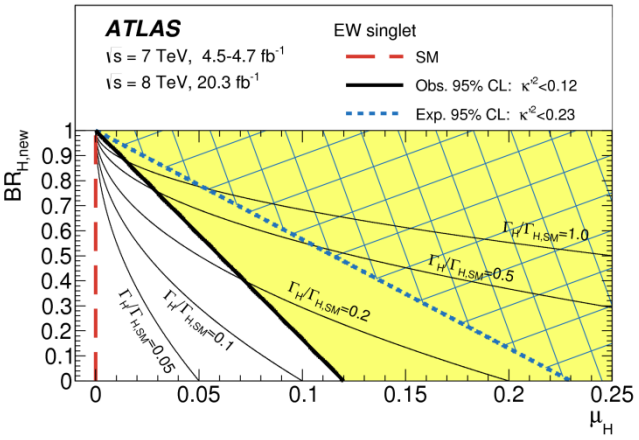
- CMS: similar analysis: $\Gamma_H/\Gamma_H^{SM} < 5.4$

- Conversely, in h(125) couplings analysis, offshell limit can be used to limit BR_{inv}

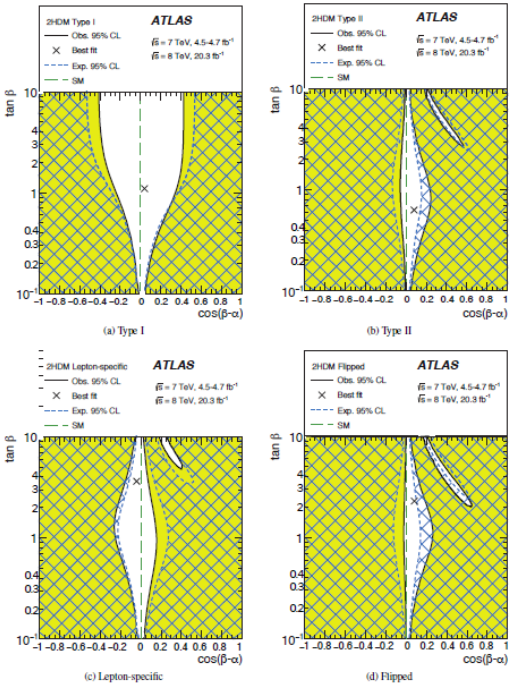
High mass H: indirect constraints

- In any realistic model the h(125) couplings set constraints on a possible H

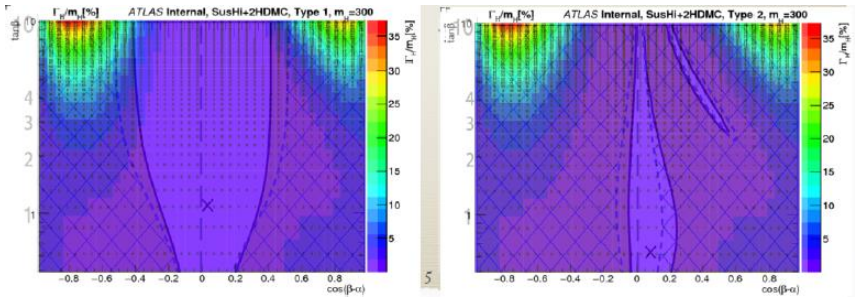
- EWS
  - **$C'^2 < 0.12$**(0.23 exp) for B_{new}= 0. (ATLAS)
    For **m(H) = 1 TeV => Γ< 80** (150) GeV



- 2HDM
  - constrains to be close to alignment limit



Γ(H)/m(H) < ~10-15%
in allowed area



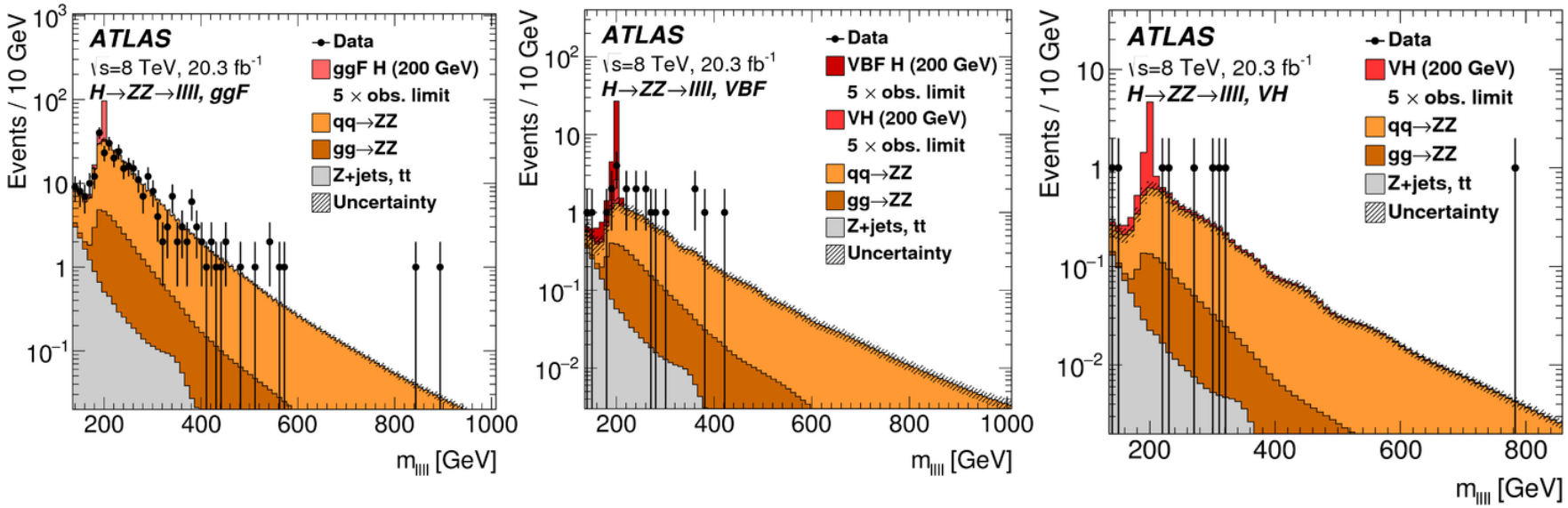
High mass, direct searches: the question of the width

- Narrow width approximation
  - simple for generation: neglect interference
  - simple for analysis: "bump search", bump width = experimental resolution
  - not realistic! High mass Higgs: strongly coupled at least to VV = > non-zero width

- Non-zero width
  - which generator?
  - how to treat interferences?
    - H - continuum, H - h
  - Is this model-dependent? What are the limits?
    - available : SM-like Higgs: CPS scheme at NLO (Powheg), full interference at LO
  - How to analyse?
    - limit the search to "not-too-large width"10-15% m(H)?
      - bump, small interference effects
  - How to present the results?
    - model-independent? Signal+Bkd+Interference? only Signal?

High mass search : ATLAS ZZ (4 leptons)

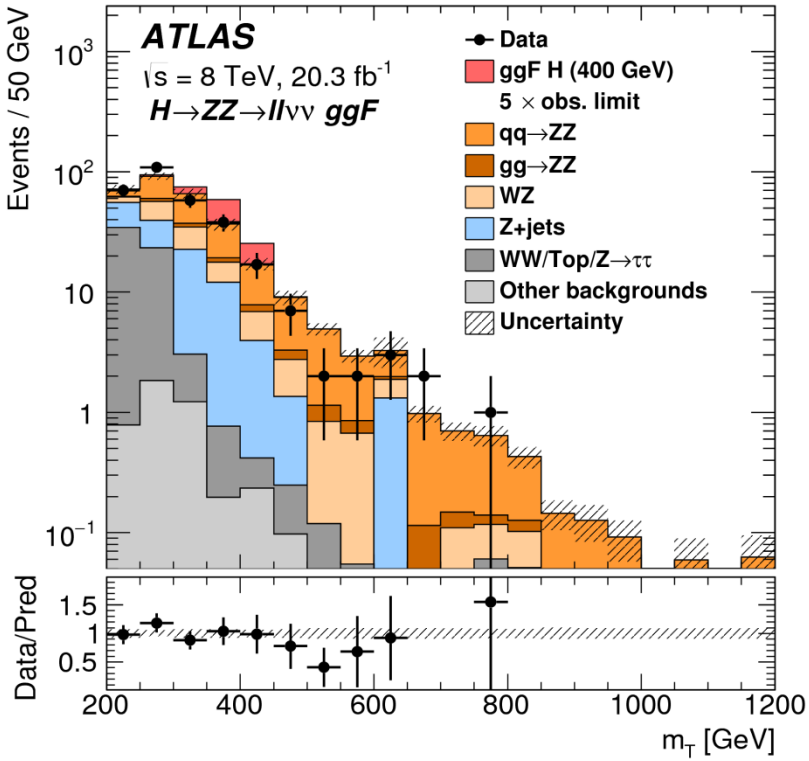
- Mostly real ZZ, some Z+ jets and ttbar at low mass



- Dominated by qq -> ZZ
- ZZ mass spectrum per production mode (tag VBF, VH)

ZZ (ll νν)

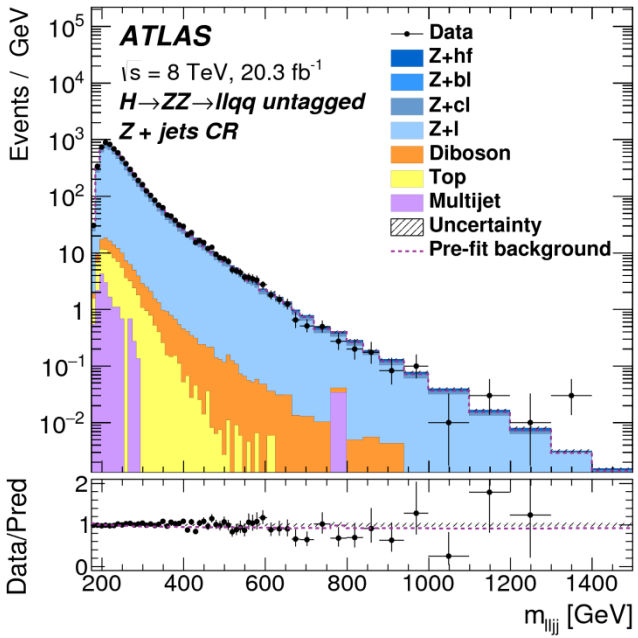
- Similar analysis, but 2 leptons + Missing E_T(> 70 GeV) [and $\Delta\phi$ (Etmiss,ll)> 2.8 and…]

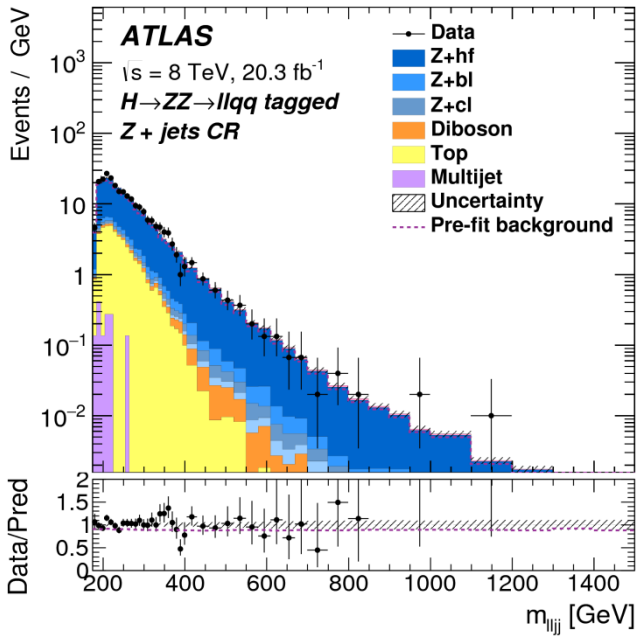


- Low statistics but good sensitivity

ATLAS ZZ llqq

- llqq complete final state, but a lot more background
  - Can use two b-tag to favour Z(ll) Z(bb)
  - Also: the qq jets merge: ‘ merged regime’

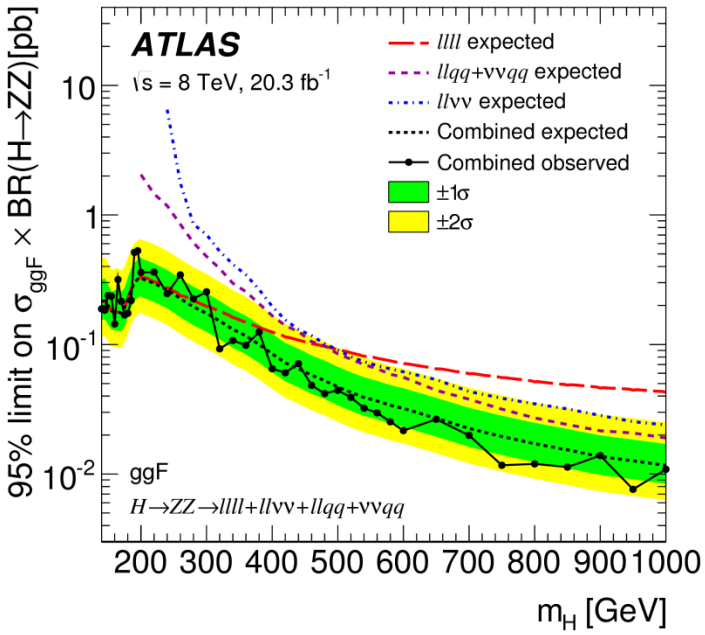


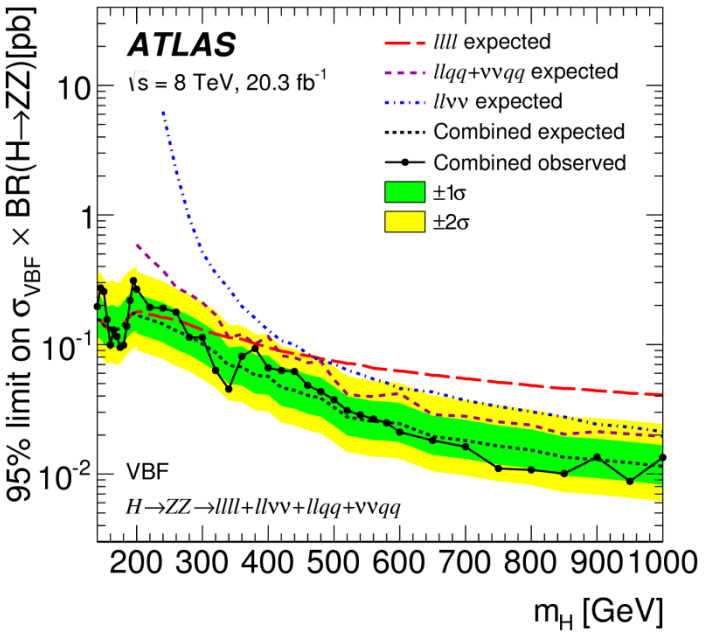


  - Dominated by Z+jets background
    - diboson far below, and gg->ZZ even lower!

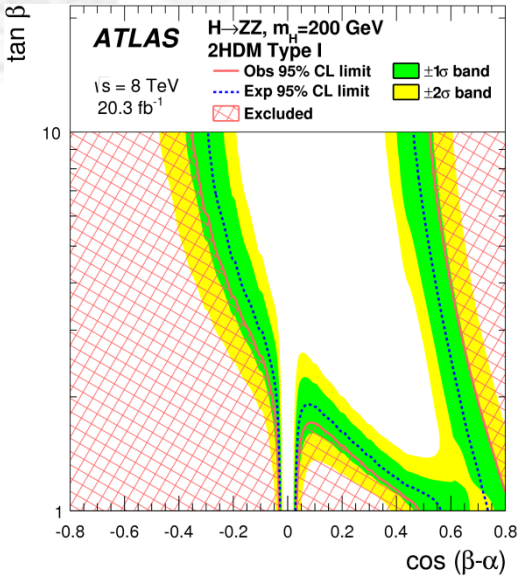
Extracted limits

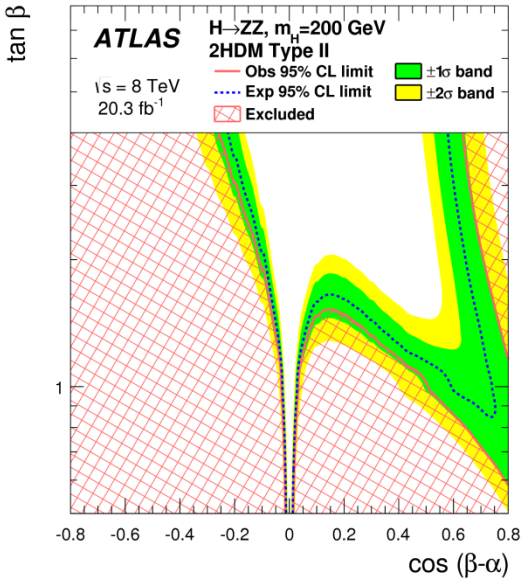
- ATLAS ZZ: limits are extracted in the Narrow Width Approximation: (NWA)
  - "Model independent" : ggF and VBF separately



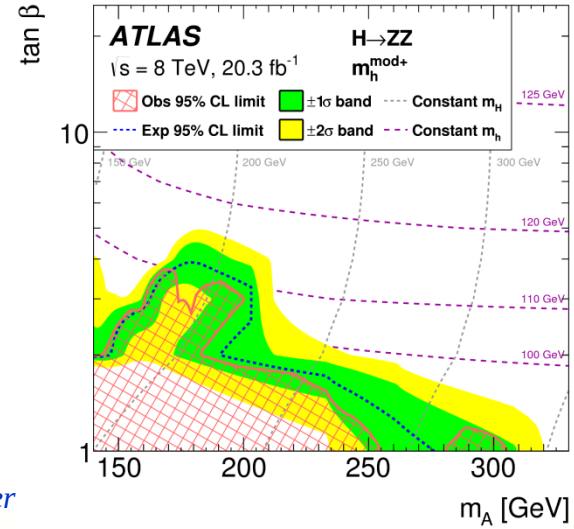


- In turn can be interpreted in 2HDM scenarios, [fixes the cross-sections including VBF/ggF ratio, etc.] ***in a region of parameters where the width is narrow (< 0.5% x m(H))***

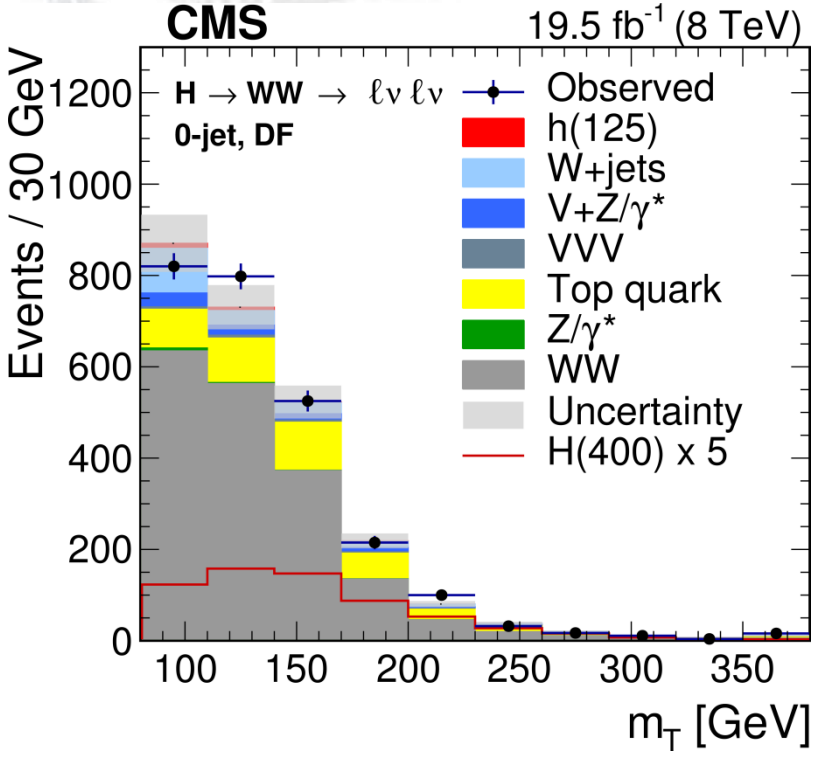


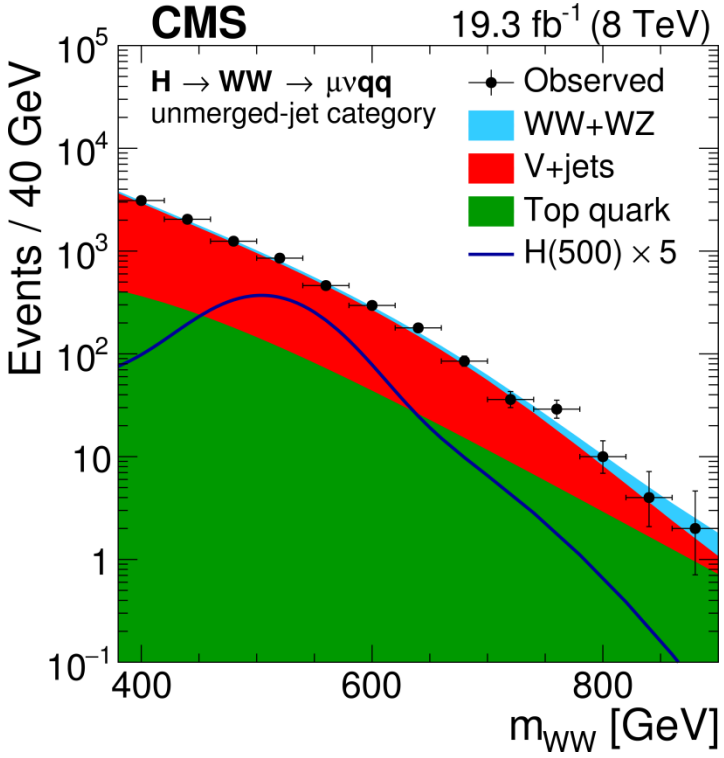


- … and as a MSSM (different scenarios)
  here m_h^{mod+}



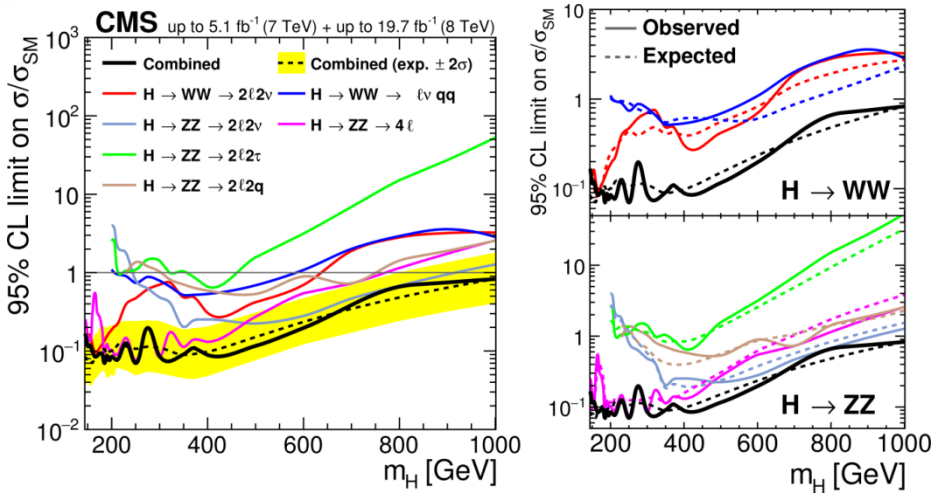
- Example 2: CMS high mass WW analysis





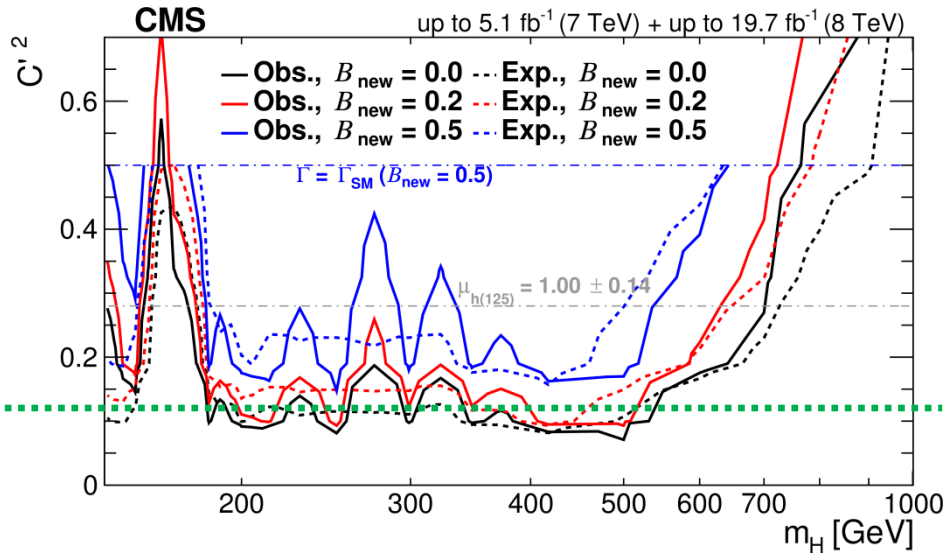
- **CMS High mass VV results:** ***includes non-zero width***

- SM-like



- EWS

ATLAS indirect (observed)



Summary of experimental results

- ATLAS:
  - ZZ: **only NWA** : by production mode (ggF, VBF), 2HDM , MSSM
  - WW: **NWA, SM-like** (CPS), 'intermediate' (CPS, **EWS-inspired** with B_new = 0)

- CMS:
  - ZZ and WW: **SM-like Higgs** (CPS) , **EWS** (CPS, C' and B_new, with $\Gamma < \Gamma_{SM}$)
  - By production mode (ggF, VBF)
  - Interference H-background taken into account (with some approximation)

    Interference h-H neglected ("covered by syst uncertainty")
  - **no 2HDM**

- ***not very consistent!***
- main reason: high mass analyses derived from run-1 "Higgs searches", not really planned in advance for high-mass, additional Higgs: width, interferences added later…

Preparing for run-2

- Analyze in a more coherent way: non-zero width, interferences for all channels.
  - only publish VV spectrum ? (with correlations between bins) , fine but:
    - signal and background have different acceptances
      - ***(we even design the analysis for that!)***
    - not completely unfolded (complicated, long…)
  - Signal search
    - MC samples:
      - bump search: signal + background without interference?
        - » signal = cross-section + width
    - Full signal + bkd models, taking into account interference(s)
    - Signal model + bkd model: can we calculate the interference in a universal way?

ggF High mass: modelling

- NWA: "standard" generators are fine: Powheg (+ Pythia8: ggF, VBF at NLO
  (does not include interference)

- Non-zero width
  - without interference: "adapted" MC, like MG5_aMC@NLO
    generate H with width, scale ds/dM (M) by "propagator"
    depending on M (H virtuality)

$$\frac{1}{\pi}\frac{\sqrt{\hat{s}}\hat{\Gamma}_H \widehat{\mathrm{BR}}\left(H^0 \to d_1 d_2\right)}{(\hat{s}-M_H^2)^2+M_H^2\Gamma_H^2},$$

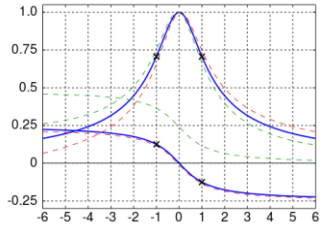
    (several choices in MG5_aMC@NLO, this one recommended (YR) to reproduce full calculation; other choices may lead to a spurious peak at low mass…)

  - with interference: we only have SM, or close-to-SM generators
    - ***GG2VV*** : LO. **SM**: h, interference h + B; **EWS**: h, H, interferences: h-B, H-B, h-h
      (or MG5 ?, GOSAM?)
    - Other models (2HDM, THM…): no generator? Anyway we cannot generate one MC sample for each point in parameter space of BSM models!

    => can we play the same game as in the "offshell" analysis?
    keep B, scale S by k(M), scale I by √k

- H scalar => H-bkd interference only depends on H virtuality M
  - *sign of I ? Flips sign below/above H peak…*

    more generally phase of k? Is there a universal formula?



$tan(\phi) = (m_0\text{-}m)/\Gamma$

- Can we move from LO to NLO? *(p_T/ n_jets is a large correction in several analyses…)*
  - use GG2VV for interference
  - reweight to Powheg . Reweight only as a function of H virtuality m(VV) ?

  this should work for NLO QCD *(?). What about NLO EWK?*

- VBF
  - t-channel h and H-exchange is a background, but it is model dependent!

    predictions for BSM models?
  - EWK corrections: large for SM (as large as QCD!) : -20% at 500 GeV ; *BSM?*
  - interference effects expected to be strong (they unitarize the SM!)

Questions

- Which models should we investigate for high mass neutral, scalar Higgs?
  - NWA
  - ~~SM-like~~
  - EWS
  - 2HDM
  - Higgs-Triplet
  - Other?

- Which parameter range?
  - which range of mass, of width?
  - only allowed by h(125) coupling constraints, or are there possibilities to evade them?
  - EWS: which B_{new}?

More questions…

- How to present our results in a consistent way?
  - only the VV mass spectrum, with correlation between bins?
  - same, with qqVV subtracted?
  - same, with interference unfolded => “signal only”?
  - integrated with off-shell analysis?
- NLO:
  - When is ggVV going to be available?
  - What is the “best strategy” while we wait?
- VBF: all of the above?

Thank You!