Search for high mass bosonic resonances with the ATLAS detector

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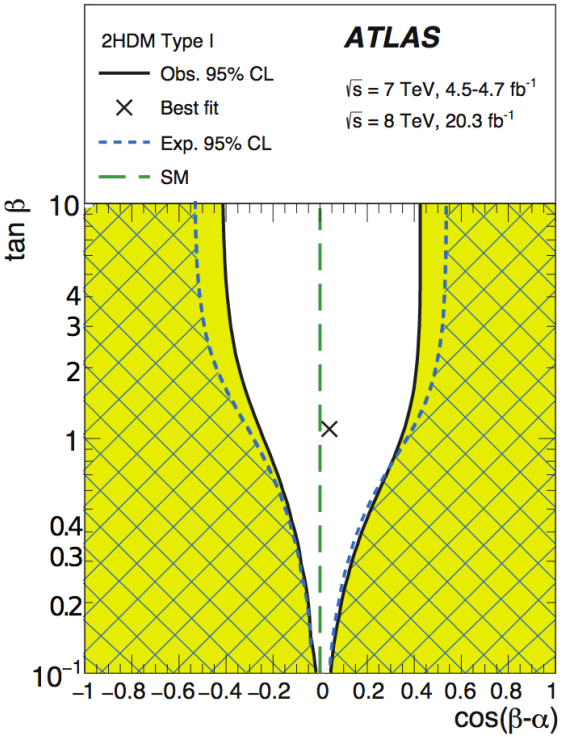
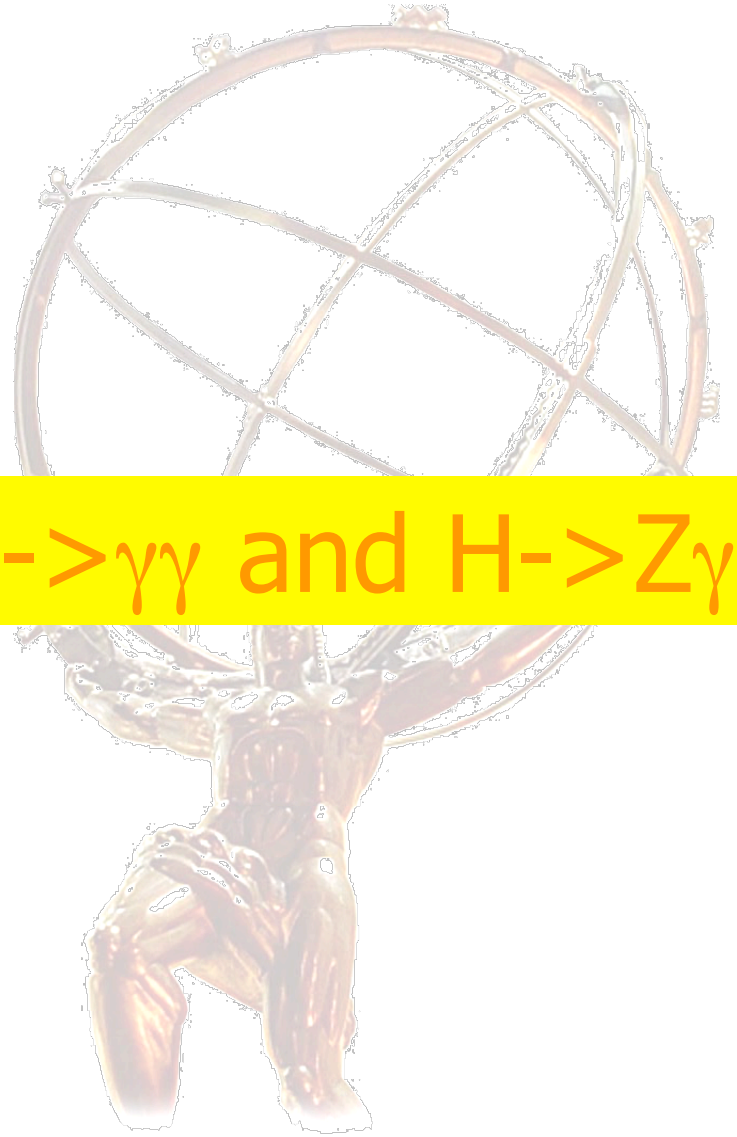
Search for extended Higgs sectors

- The 125 GeV Higgs boson discovery in 2012 was a major breakthrough in particle physics
  - A long campaing of measurements of its properties indicates that it's consistent with the expectations of the SM Higgs boson

https://arxiv.org/abs/1509.00672

- Current experimental data can't rule out the posibility that it is part of an extended Higgs sector
- Typical benchmark model is 2HDM (two Higgs-doublets models) :
  - 5 Higgs bosons in total : two neutral CP-even h and H, one neutral CP-odd A, and two charged H±
  - 6 parameters : 4 masses (m_h, m_H, m_A and $m_{H^{+/-}}$) tanβ (ratio of the vev of the 2 doublets) and α (mixing angle between the 2 CP-even scalars)
  - Several channels considered : diphoton, Zγ, 4l, llvv, llqq,vvqq





H->γγ and H->Zγ

Search for a high mass Higgs in the di-photon channel

Updated to 36.7 fb^{-1} : two selections optimized separately for the search for a heavy Higgs-like scalar or spin-2 (graviton in the Randall-Sundrum model)

- Pre-selection :
  - $E_T^{\gamma 1} > 40$ GeV, $E_T^{\gamma 2} > 30$ GeV in $|\eta_\gamma| < 2.37$, excluding 1.37-1.52
  - Tight photon identification
  - Photon isolation (calorimetric + track isolation)

Higgs like (spin-0) selection

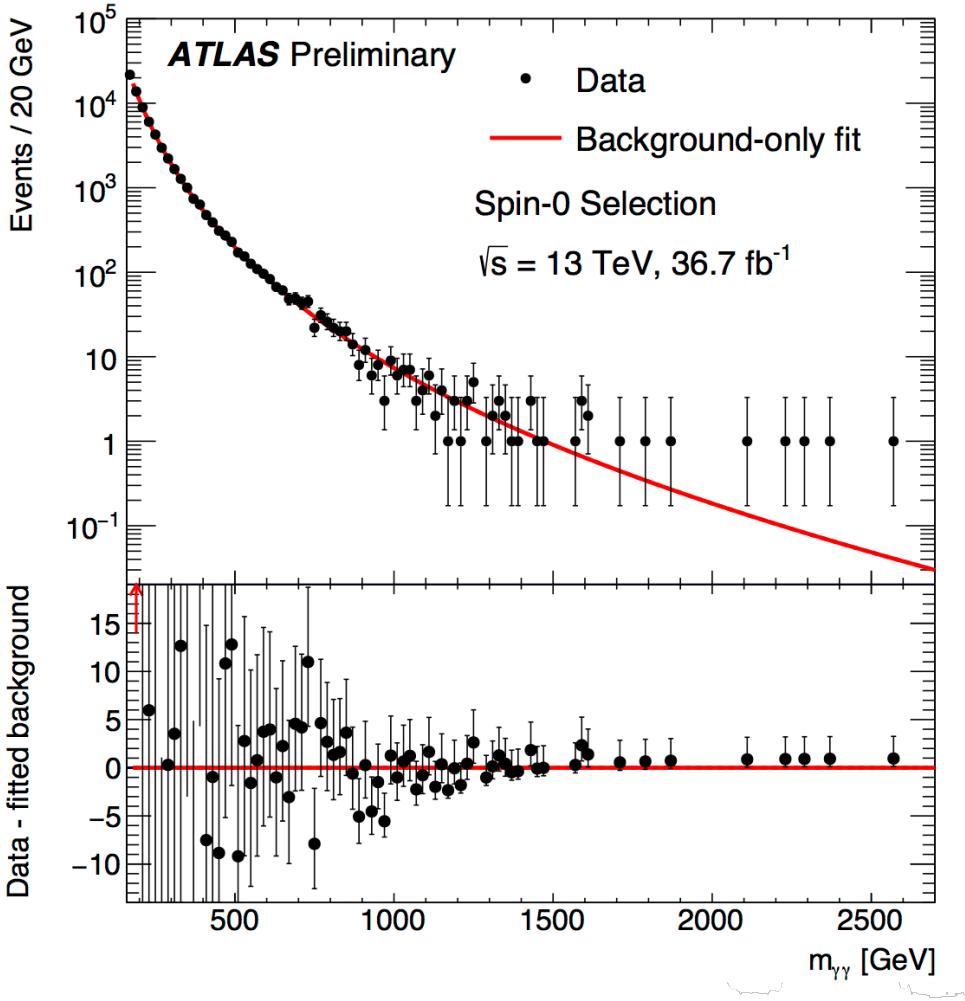
- $E_T^{\gamma 1} > 0.4\ m_{\gamma\gamma}$, $E_T^{\gamma 2} > 0.3\ m_{\gamma\gamma}$ (+20% significance for $m_X > 600$ GeV)
- Effectively deplete forward regions
- Model-independent: limits on the fiducial cross section
- Search range m_X= [200 GeV – 2.7 TeV] and Γ_X/m_X =[0% - 10%]

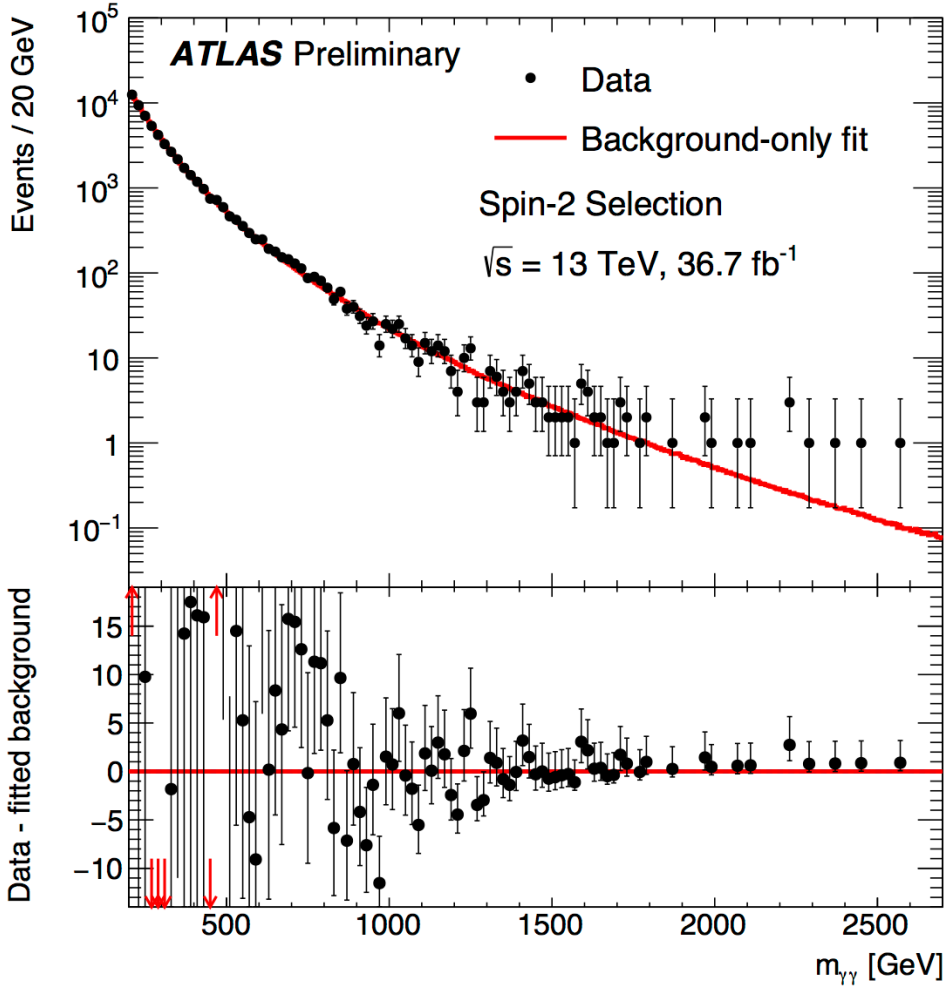
Graviton like (spin-2) selection

- Kinematics of the RS graviton used as banchmark
- $E_T^{\gamma 1} > 55$ GeV, $E_T^{\gamma 2} > 55$ GeV : simple and general selection
- Search range m_G=[500 GeV–2.7TeV] κ/M_Pl = [0.01-0.3] (Γ_G/m_G ~ [0.01% - 11%])

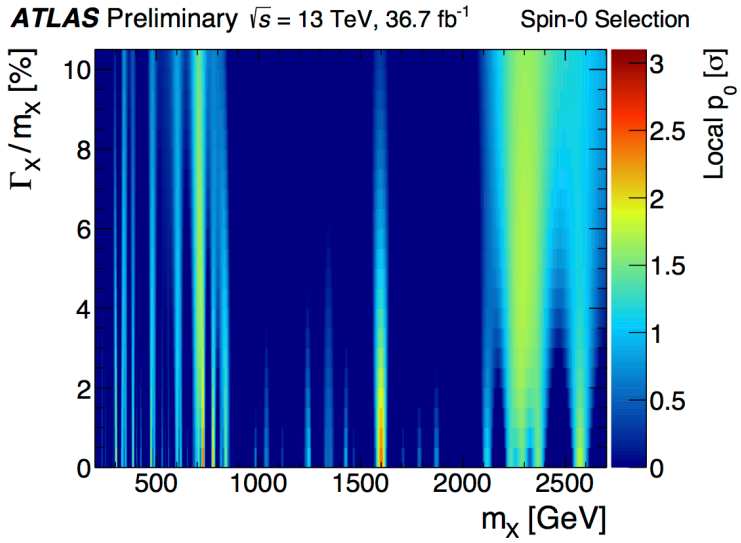
- Background: irreducible from QCD di-photon events (90%) + reducible γj and jj.
- Background modeling from sidebands in spin-0 search or MC template for spin-2 search

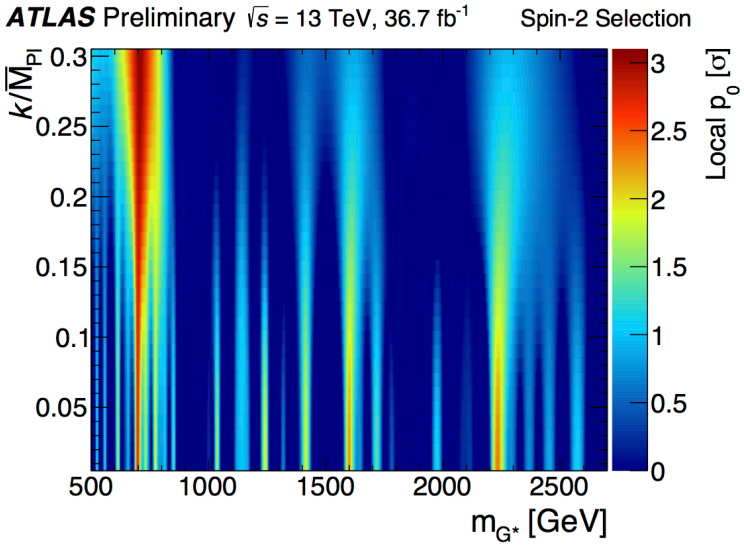
Search for a high mass Higgs in the di-photon channel

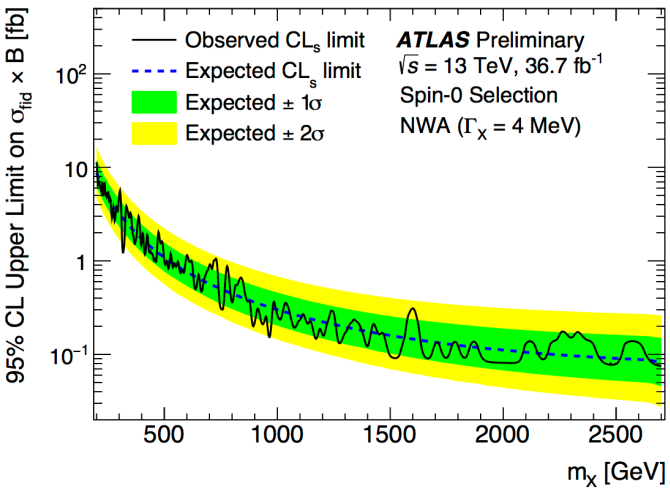


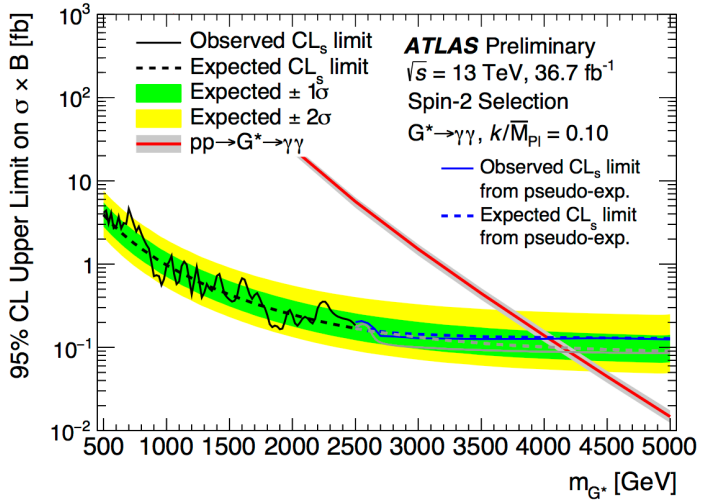


Search for a high mass Higgs in the di-photon channel







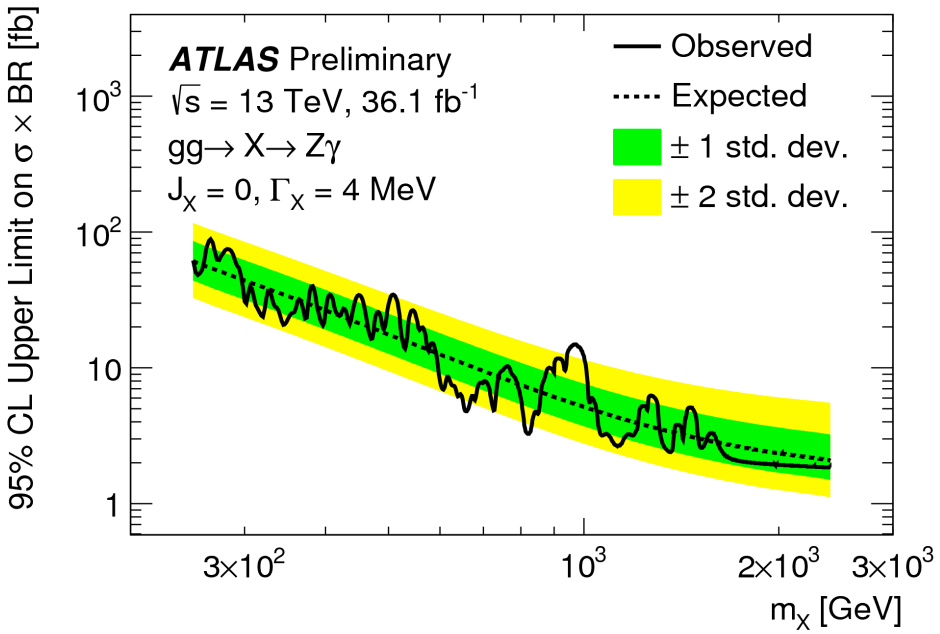


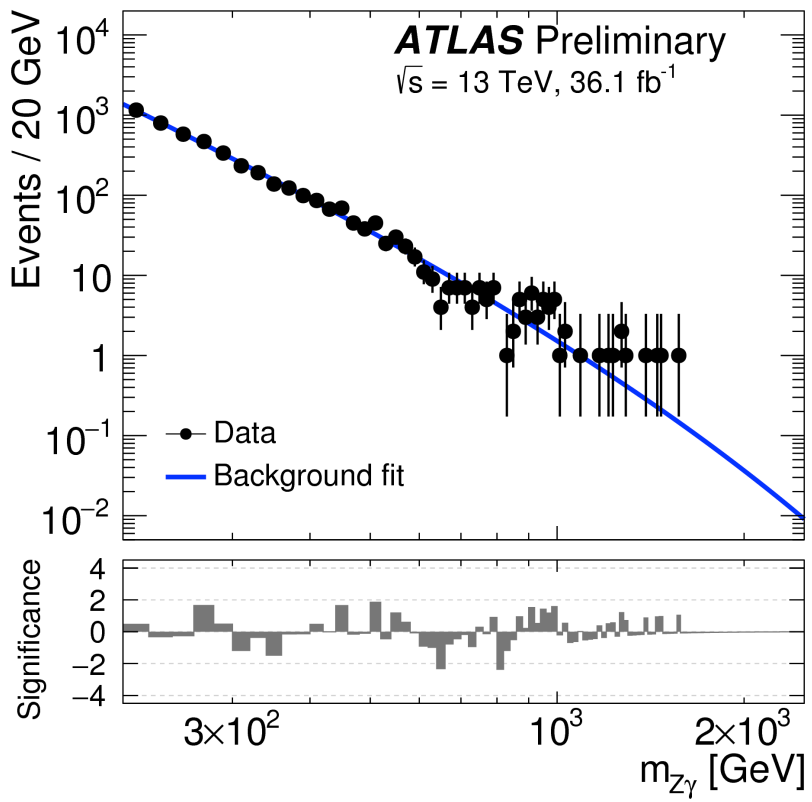
Largest excess :

- spin-0 : 2.6 σ local around 730 GeV for narrow width
- spin-2 : 3.0 σ local around 710 GeV and large width (k/M_{Pl}=0.30).
- Global signif. <1 σ
- m_G > 4.1 @ 95% CL
- limits 5.7-8.6 TeV on the ultraviolet cutoff scale M_S depending on the number of extra dim and the formalisms

Search for a high mass Higgs in the Z-photon channel

- Two same-flavour opposite-charge leptons (l = *e*, μ) to form a *Z* boson candidate and at least one photon candidate.
- Two categories (for the high mass search) for e^+e^- and $\mu^+\mu^-$ events



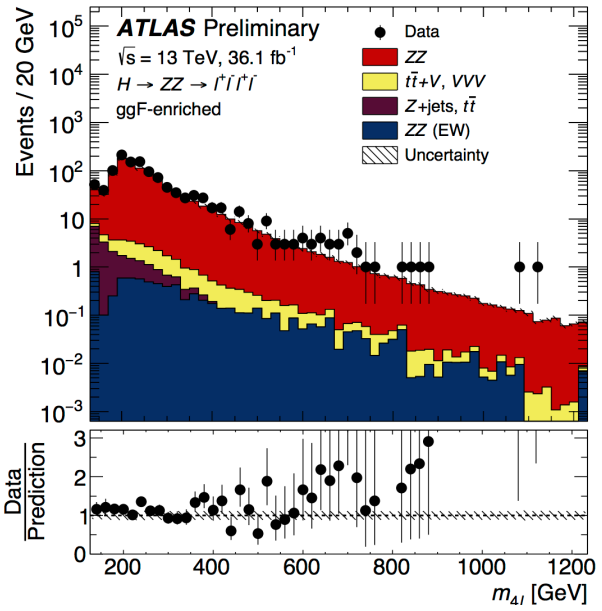


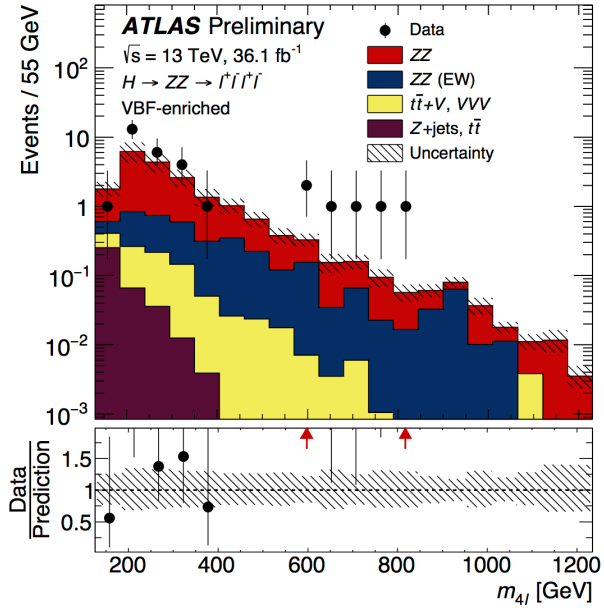
- Main background (irreducible) non resonant Zγ and (reducible) Z+j fitted both on data
- No significant excesses: 2.7σ local at m_H=960 GeV, 0.8 σ global in [200–2500]

H->ZZ->llll / llνν / llqq / ννqq

High mass higgs in ZZ->llll: analysis strategy

- Two same-flavour opposite sign isolated lepton pairs
- Events are classified into a VBF enriched category and 3 ggF enriched categories (exclusive)
  - VBF enriched category : two (or more) separated jets ($\Delta\eta$>3.3) and m_{jj}>400 GeV
  - ggF enriched categories : 4e, 4μ and 2e2μ
- Main background
  - $ZZ^{(*)}$ non resonant production (~95 %) and EW vector boson scattering (15% for VBF and 1% for ggF) : modelled through MC; typical uncertainties 13% (ggF)and 50 % (VBF)
  - Z+jet and tt from control regions in data
- Look for excesses in the 4l invariant mass spectrum
- Narrow (ggF and VBF) and large width (1-10% of m_H, ggF only) signal hypotheses tested



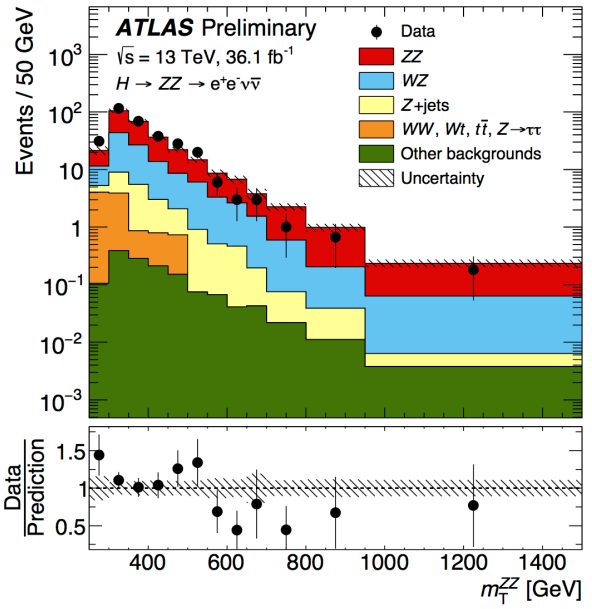


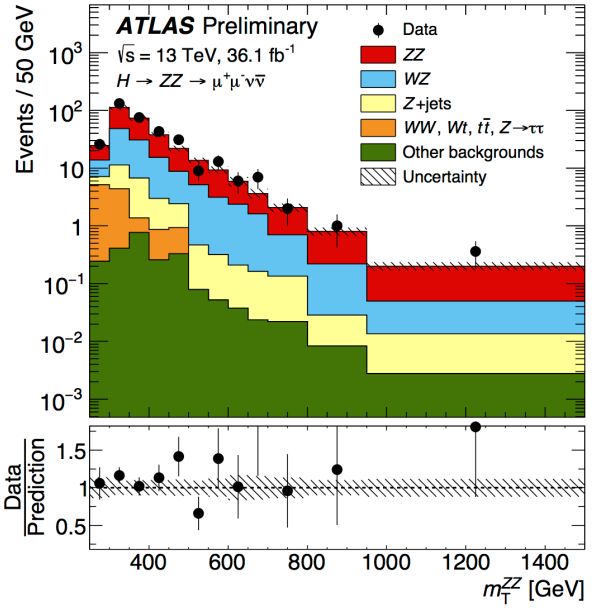
High mass Higgs in ZZ->llνν: analysis strategy

- Two isolated leptons consistent with originating from a Z
- Large missing transverse momentum E_T^{miss} > 120 GeV
- Events are classified into a VBF enriched category and 2 ggF enriched categories (exclusive)
  - two well separated jets (deta >4.3) and m_{jj} > 550 GeV
  - ggF enriched categories : ee, μμ
- Main background
  - ZZ* non resonant production (60 %) from MC
  - WZ (30%) from MC normalised in 3l control region
  - non resonant ll from e-μ control region(WW, tt)
  - Z+jet and W+jets from control regions in data
- Look for excesses in the transverse mass

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

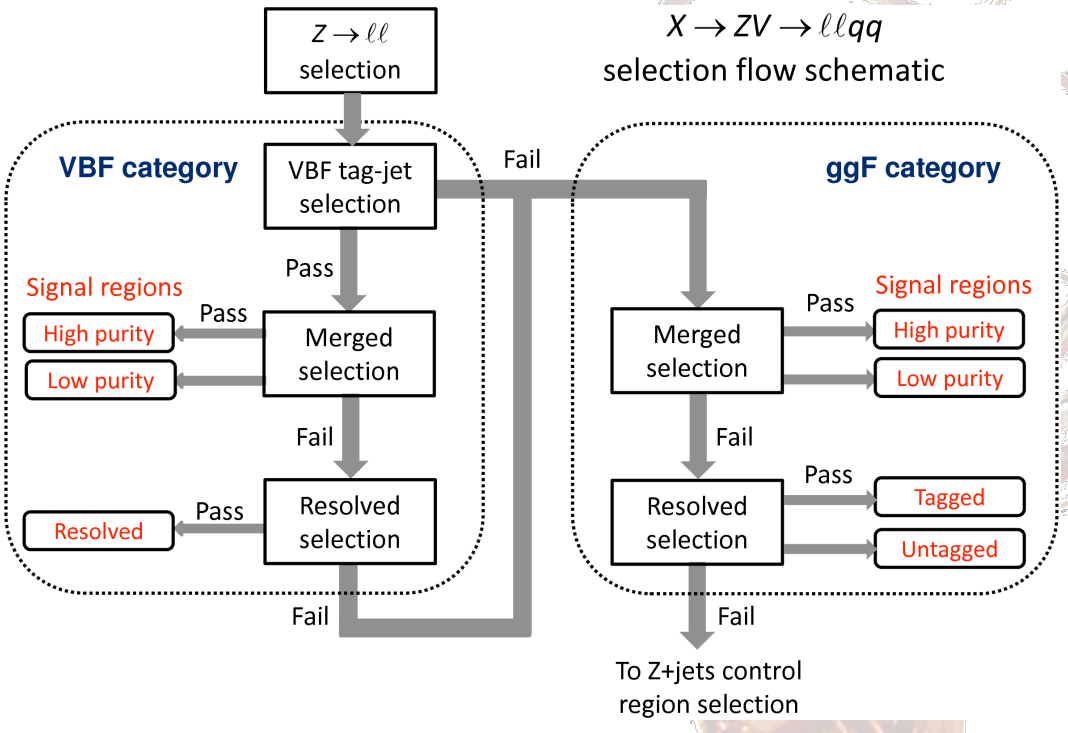
- Narrow (ggF and VBF) and large width (1-10% of m_H, ggF only) signal hypotheses tested





High mass Higgs in ZZ-> llqq final: analysis strategy

- Typically look for ZV events in which V goes into two jets and one Z in the ll or νν
- ggF and VBF searched separately: events are classified into VBF/ggF enriched categories



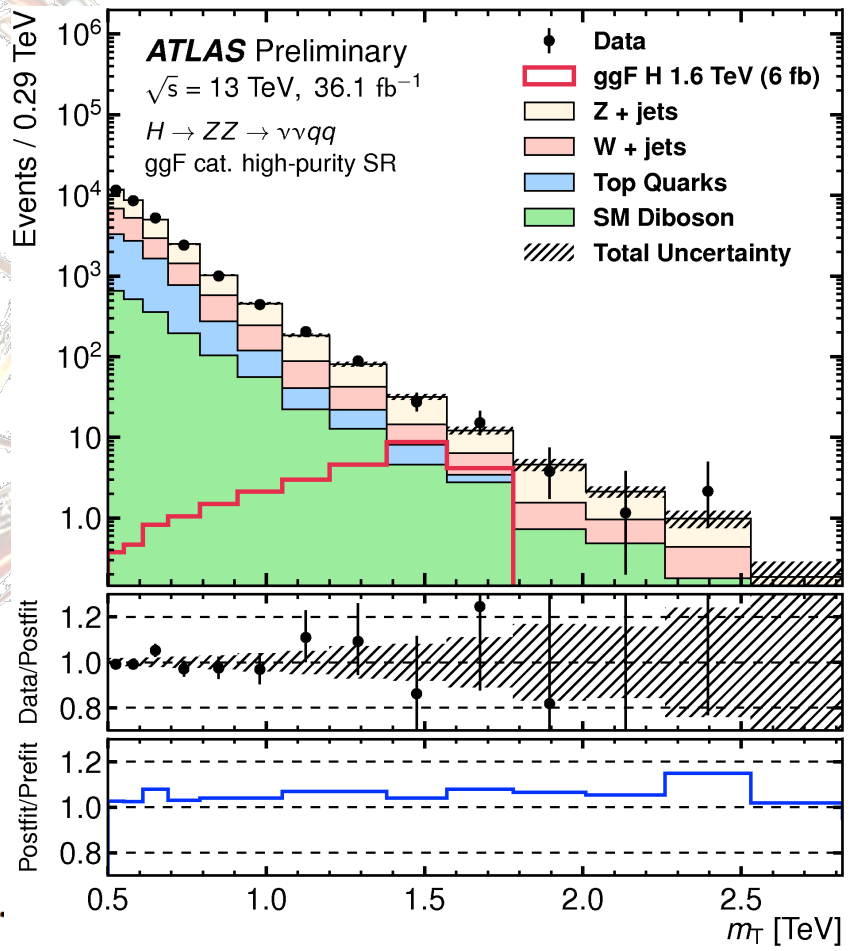
- Z boson reconstruction : two same flavour leptons with an invariant mass compatible with the Z
- Separation of the ggF/VBF : two jets in the opposite hemisphere, $\Delta\eta > 4.7$ and $m_{jj} > 770$ GeV
- Merged : one large-R jet, boson tagger with 2 different efficiency wp
- Resolved : two categories, 2 b-tag jets, <2 b-tag jets
- Discriminant variable m_{llJ} or m_{lljj}

- Z+jets main background : shape from MC normalised in a control region in data
- Top-quark production : from MC normalised in a controld region in data
- Diboson (ZZ and ZW) completely from MC simulation

High mass Higgs in ZZ -> vvqq: analysis strategy

- Hadronically decaying V boson recoiling against a large missing transverse momentum
- Only merged analysis
- Look for narrow width Higgs bosons
- Event selection :
  - E^{T}_{miss} > 250 GeV and veto on loose electrons and muons
  - 1 large-R jet with p_T>200 GeV
- VBF category: $\Delta\eta$ > 4.7 and m_{jj} > 630 GeV
- Two categories based on the boson tagger wp
- Final discriminant is the transverse mass

$$m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T},J} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left(\vec{p}_{\mathrm{T},J} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right)^2} \qquad E_{\mathrm{T},J} = \sqrt{m_J^2 + p_{\mathrm{T},J}^2}.$$

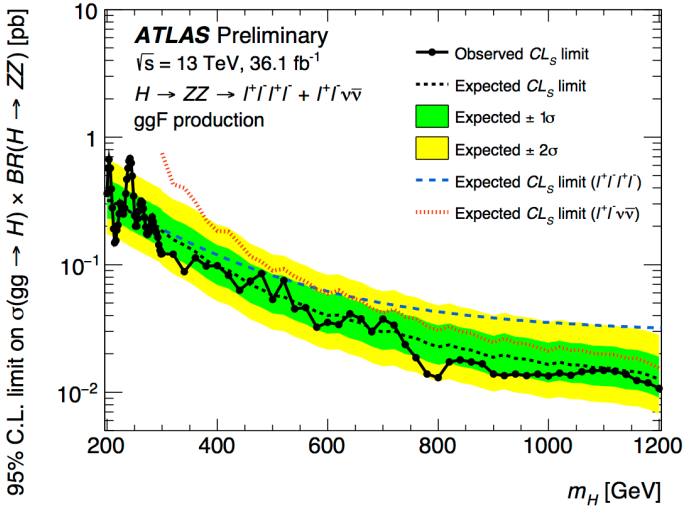


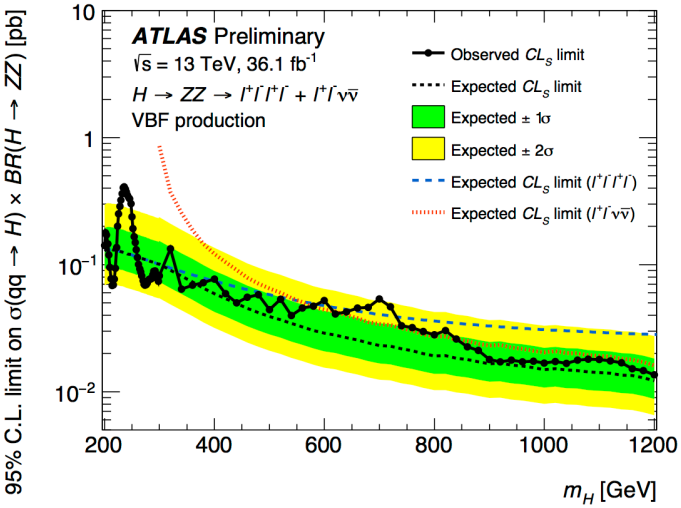
- All background shapes from MC normalised to data in appropriate control regions
  - Z+jets ; W+jets and ttbar

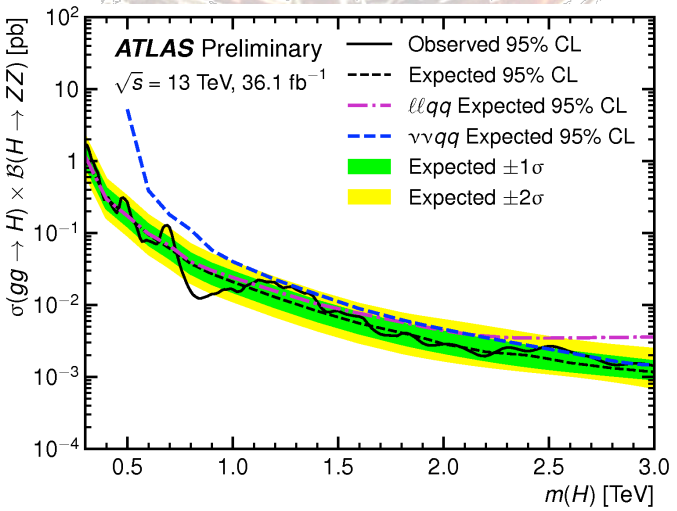
High mass Higgs in ZZ : results

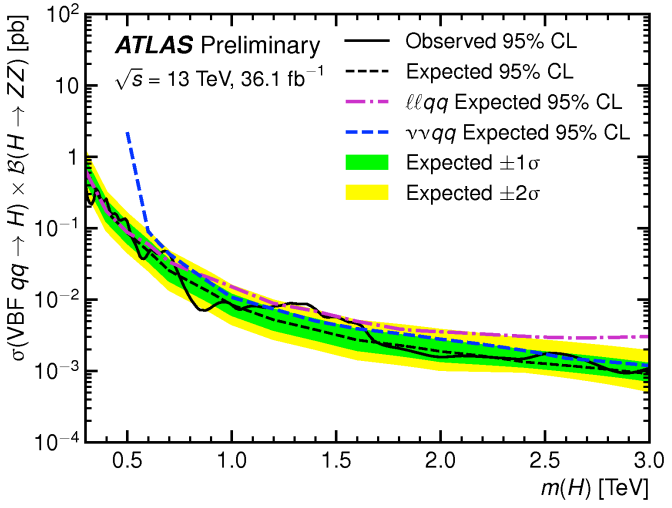
Data consistent with the background only expectation

- No excesses in llνν
- A 3.6 (2.2) σ local(global) excess at 240 GeV (mostl 4e)
- A 3.6 (2.2) σ local(global) excess at 700 GeV in 4l (excluded by llνν)
- Simultaneous fit in 4l and llνν: largest combined excess at 700 GeV is 2σ local (< 1 σ global)
- 3.0 (1.9) σ global (global) deficit at m_{llJ} ~ 800 GeV in the llqq ggF high purity category.

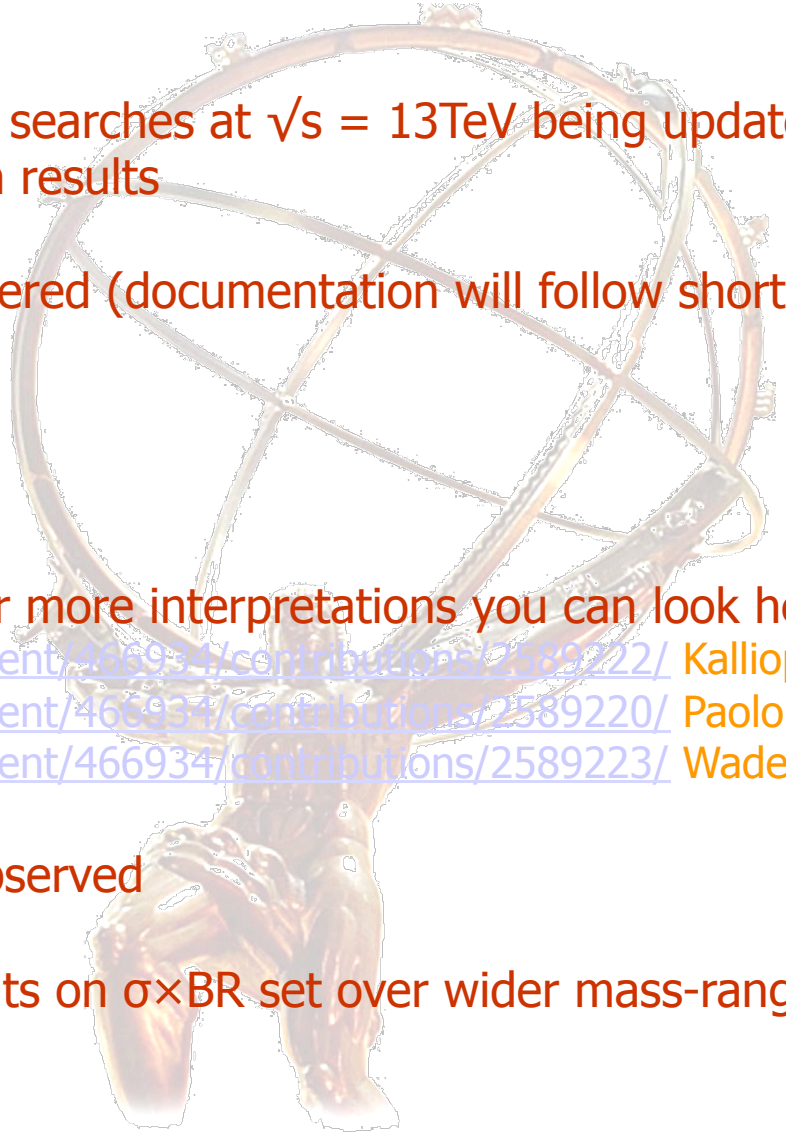








Conclusion



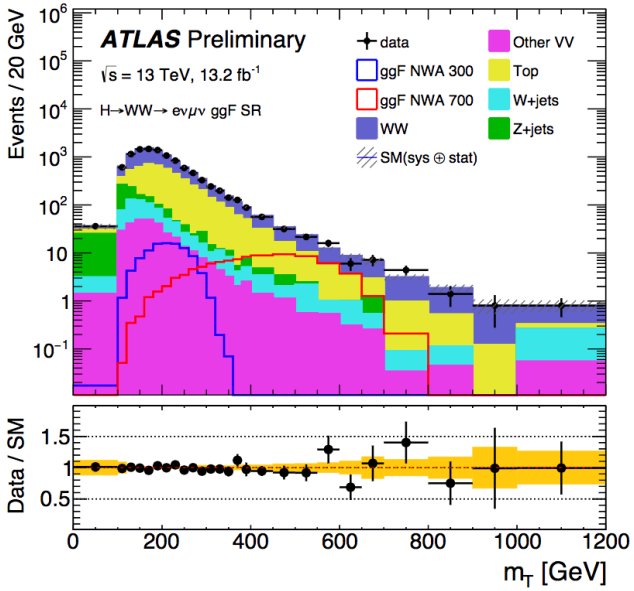
- Heavy scalar Higgs-boson searches at $\sqrt{s}$ = 13TeV being updated to ~ 36 fb^{-1} for many channels, many new fresh results
- Several final states considered (documentation will follow shortly) :
  - Di-photon
  - $Z\gamma$
  - $ZZ \rightarrow llll/ll\nu\nu$)
  - ZZ-> $llqq/\nu\nu qq$
- Panorama is very rich : for more interpretations you can look here
  - https://indico.cern.ch/event/466934/contributions/2589222/ Kalliopi Iordanidou
  - https://indico.cern.ch/event/466934/contributions/2589220/ Paolo Mastrandrea
  - https://indico.cern.ch/event/466934/contributions/2589223/ Wade Cameron Fisher
- No significant excesses observed
- Significantly improved limits on $\sigma \times BR$ set over wider mass-ranges. Already collecting new data !

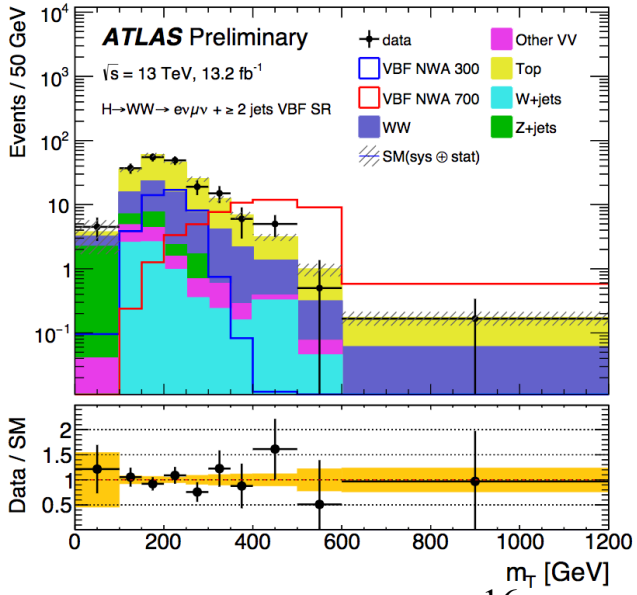
Backup

High mass Higgs in WW->lvlv: analysis strategy

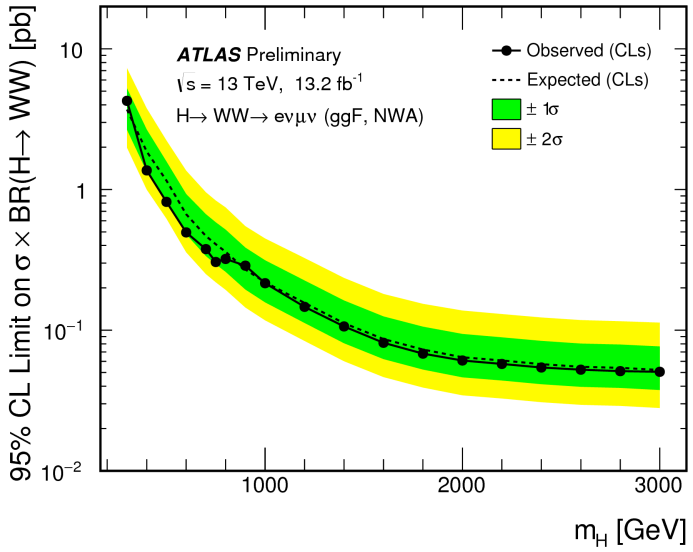
- Fully-leptonic, different-flavor
- one- and at least two-jets optimised for a (VBF)-like signal and the remaining category is quasi-inclusive for a (ggF)-like signal
  - ≥2 jets with mjj > 500 GeV and |Δyjj| > 4 1 jet with |ηj| > 2.4 and min(|Δηjl|) > 1.75
  - Rest is ggF
- Two different hypotheses are tested:
  - a narrow width approximation (NWA), width of the heavy Higgs boson is smaller than the experimental resolution
  - large width assumption (LWA), widths of 5%, 10%, 15%
- Main background : top-quark and WW additional contributions from W/Z+ jets and the diboson processes WZ, Wγ,Wγ*, and ZZ
  - Ttbar and WW shapes from MC normalized to data, W+jet from data
- Look for excesses in the transverse mass

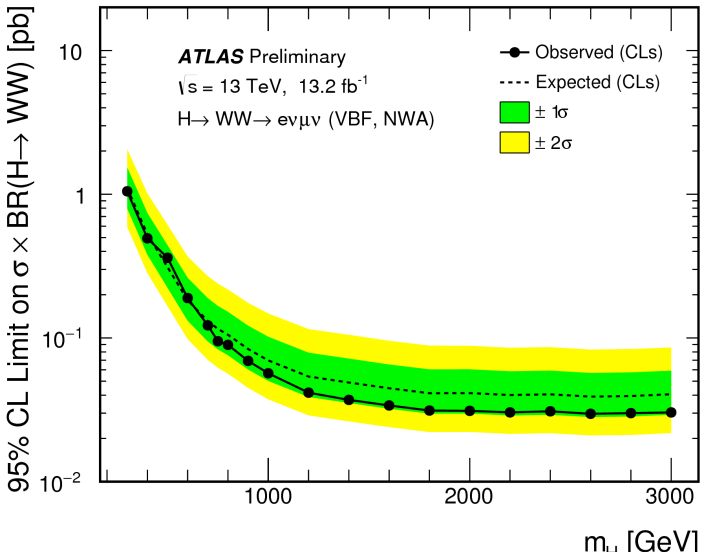
$$m_T \equiv \sqrt{\left[\sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_T^{\text{miss}})^2}\right]^2 - |\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}|^2}$$



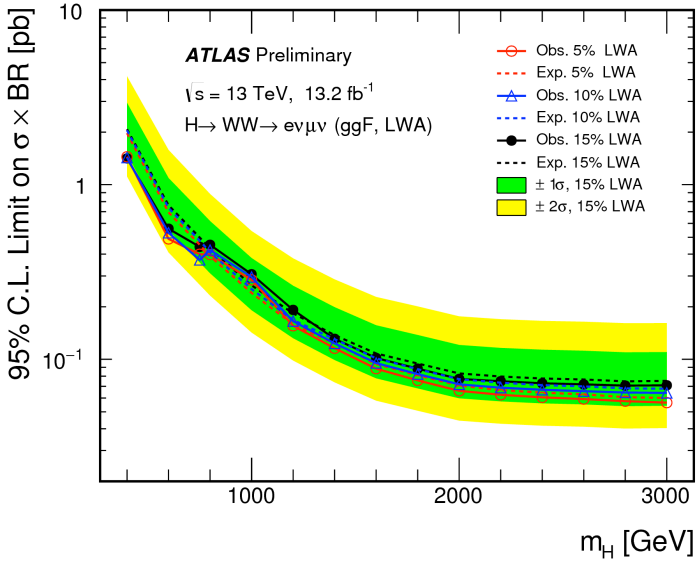


High mass Higgs bosons in the WW->lvlv channel : results

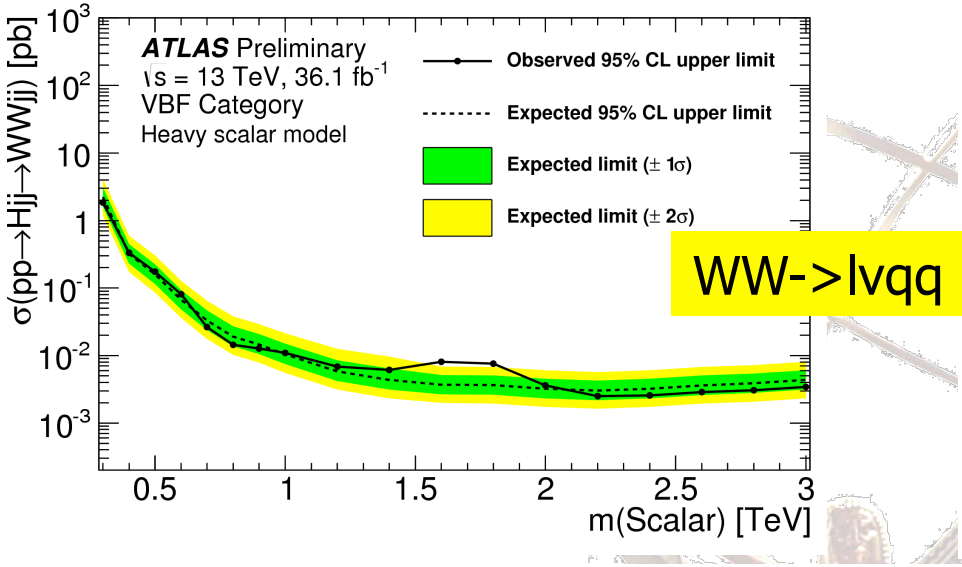




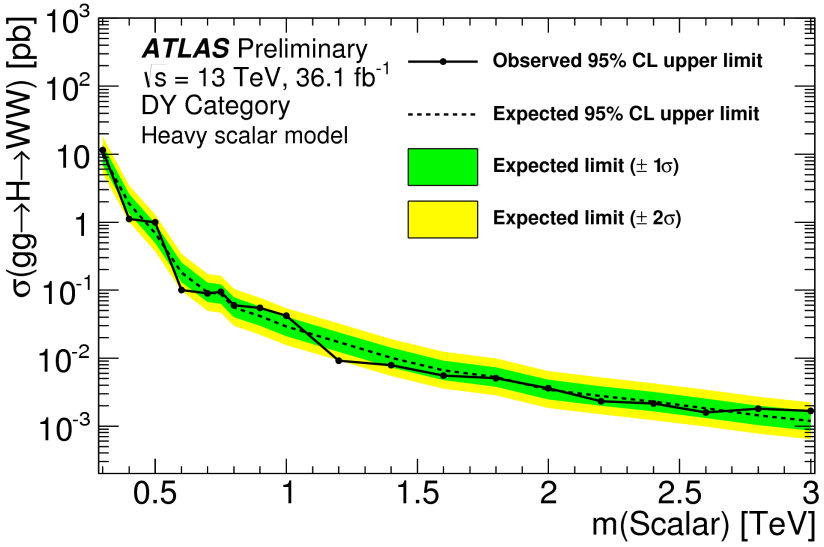
- No significant excess in the mass range between 300 GeV and 3 TeV.
- Upper limits on the product of the production cross section and the H→WW branching ratio for narrow width and intermediate widths (of 5,10,15% of the heavy Higgs boson mass).

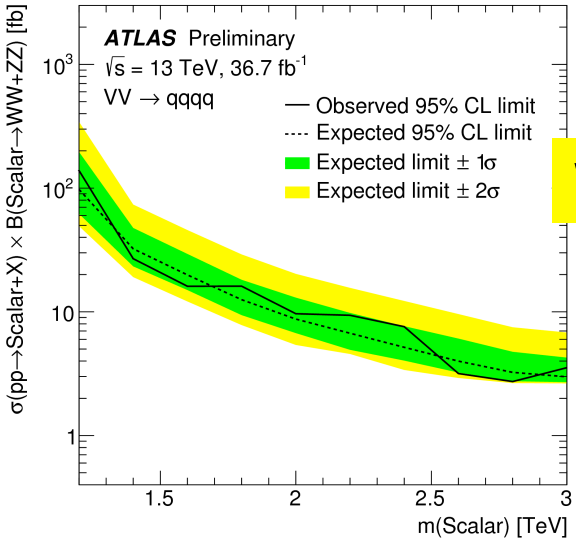


High mass Higgs in the WW/ZZ->qqqq/WW->lvqq channels: results



WW->lvqq



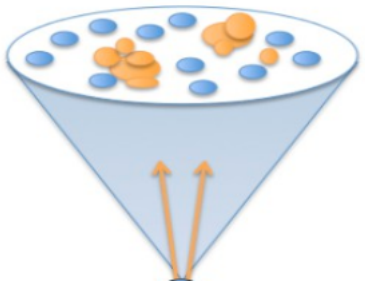


WW/ZZ->qqqq

Boson tagger

FAT JET

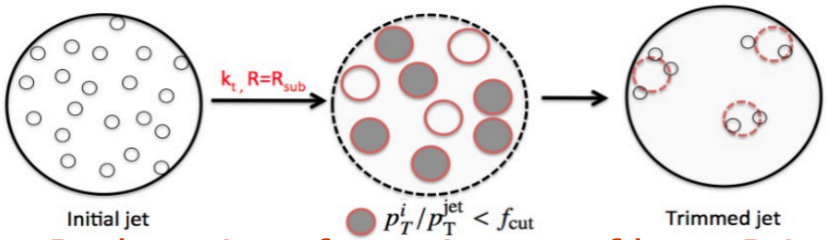
Large radius parameter to collect all radiation From the original decay



Build large radius jets, typically R = 1 using antiK_T algorithm

GROOMING

- ❑ remove PU+UE
- ❑ Increase signal/ background separation
- ❑ Improve resolution of the signal mass peak



- ❑ Reclustering of constituents of large-R jet into small-R jets of size R_{sub}
- ❑ Remove subjet i if $p_T^i < f_{cut} \times p_T^{jet}$

TAGGER

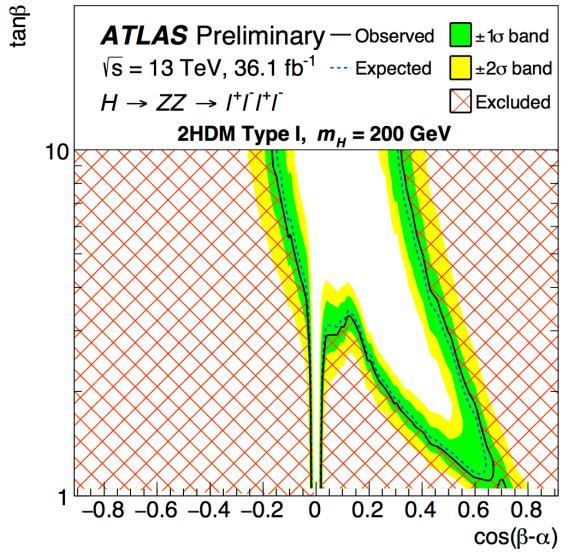
Observables to characterize the underlying jet substructure

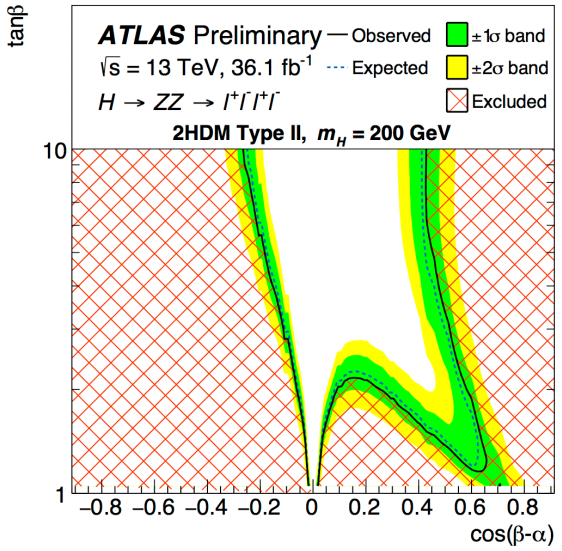
$$D_2^{\beta=1} = E_{CF3}\left(\frac{E_{CF1}}{E_{CF2}}\right)^3$$

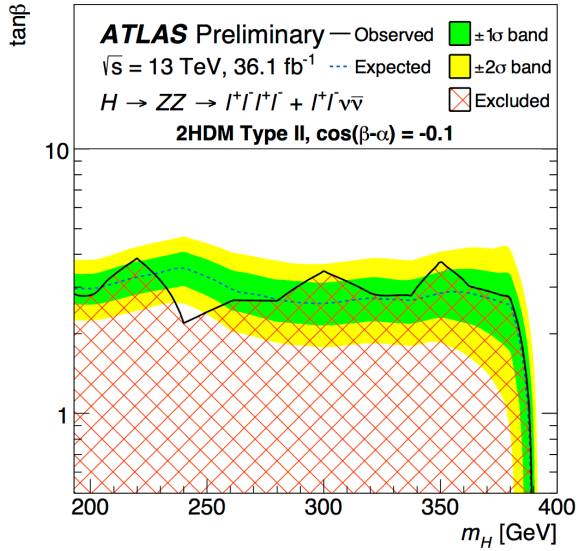
(JHEP 1306 (2013) 108)

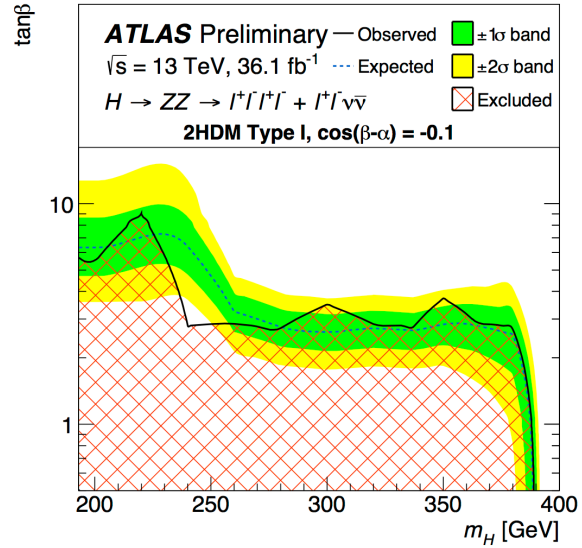
- ❑ Energy correlations functions (ECFs): combine the p_T and angular separation of all jet constituents (ECF1), all pairs of jet constituents (ECF2) and triplets (ECF3)
- ❑ Cut on $D^{\beta=1}_2$ to reject QCD jets

2HDM interpretation of the ZZ->4l+llνν results



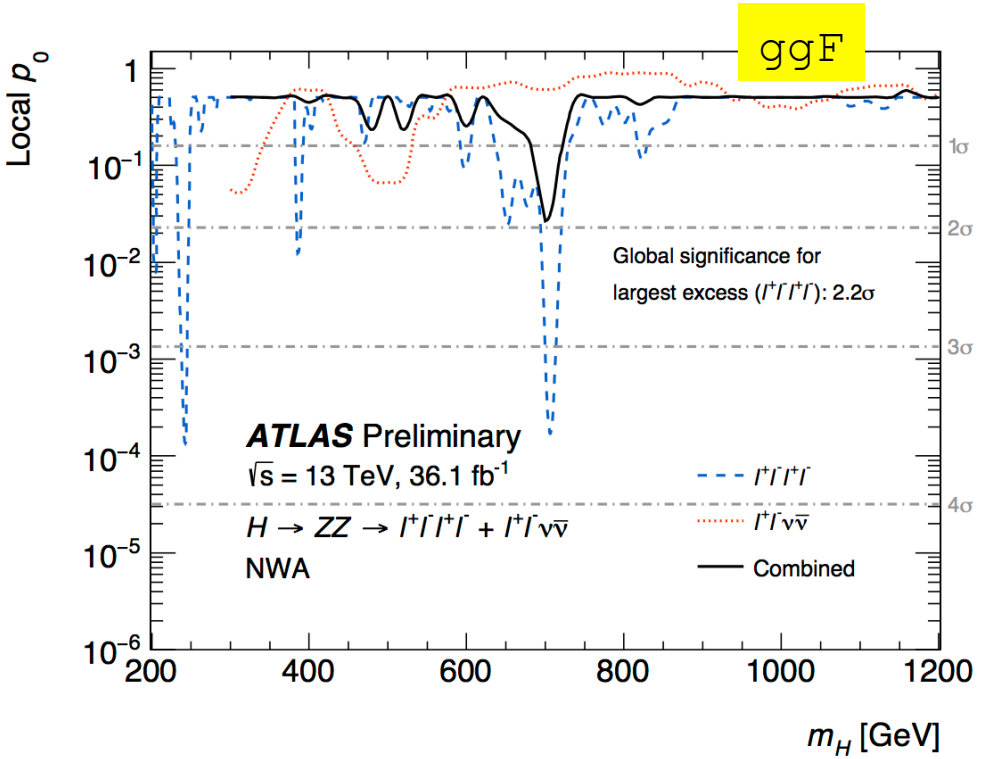






More on H->4l results

Process	ggF-enriched categories e^+e^- channel	ggF-enriched categories $\mu^+\mu^-$ channel	VBF-enriched category
ZZ	$177 \pm 3 \pm 21$	$180 \pm 3 \pm 21$	$2.1 \pm 0.2 \pm 0.7$
WZ	$93 \pm 2 \pm 4$	$99.5 \pm 2.3 \pm 3.2$	$1.29 \pm 0.04 \pm 0.27$
$WW/t\bar{t}/Wt/Z \to \tau\tau$	$9.2 \pm 2.2 \pm 1.4$	$10.7 \pm 2.5 \pm 0.9$	$0.39 \pm 0.24 \pm 0.26$
Z + jets	$17 \pm 1 \pm 11$	$19 \pm 1 \pm 17$	$0.8 \pm 0.1 \pm 0.5$
Other backgrounds	$1.12 \pm 0.04 \pm 0.08$	$1.03 \pm 0.04 \pm 0.08$	$0.03 \pm 0.01 \pm 0.01$
Total background	$297 \pm 4 \pm 24$	$311 \pm 5 \pm 27$	$4.6 \pm 0.4 \pm 0.9$
Observed	320	352	9



Process	ggF-enriched categories 4μ channel	ggF-enriched categories $2e2\mu$ channel	ggF-enriched categories $4e$ channel	VBF-enriched category
ZZ	$297 \pm 1 \pm 40$	$480 \pm 1 \pm 60$	$193 \pm 1 \pm 25$	$15 \pm 0.1 \pm 6.0$
ZZ (EW)	$1.92 \pm 0.11 \pm 0.19$	$3.36 \pm 0.14 \pm 0.33$	$1.88 \pm 0.12 \pm 0.20$	$3.0 \pm 0.1 \pm 2.2$
Z + jets/$t\bar{t}/WZ$	$3.7 \pm 0.1 \pm 0.8$	$7.8 \pm 0.1 \pm 1.1$	$4.4 \pm 0.1 \pm 0.8$	$0.37 \pm 0.01 \pm 0.05$
Other backgrounds	$5.1 \pm 0.1 \pm 0.6$	$8.7 \pm 0.1 \pm 1.0$	$4.0 \pm 0.1 \pm 0.5$	$0.80 \pm 0.02 \pm 0.30$
Total background	$308 \pm 1 \pm 40$	$500 \pm 1 \pm 60$	$203 \pm 1 \pm 25$	$19.5 \pm 0.2 \pm 8.0$
Observed	357	545	256	31

More on ZZ->llqq