Searches for Heavy Higgs bosons A/H/H^{+}/H^{++} with the ATLAS detector

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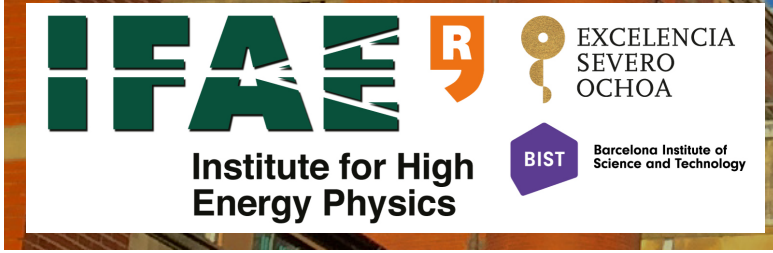
on behalf of the ATLAS Collaboration

DIS 2017, 5 Apr 2017
University of Birmingham, UK

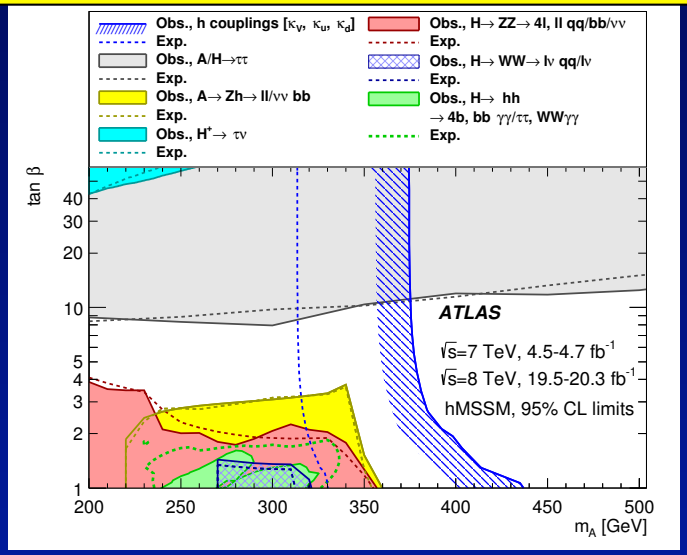


Introduction

- Motivation to extend the SM:
  - Solve the hierarchy problem, gauge coupling unification, stabilize the weak scale
- Reported in this talk:
  - Limits on various MSSM benchmark scenarios: m_h^{max}, $m_h^{mod\pm}$, hMSSM...
  - Limits on σ x BR for various processes

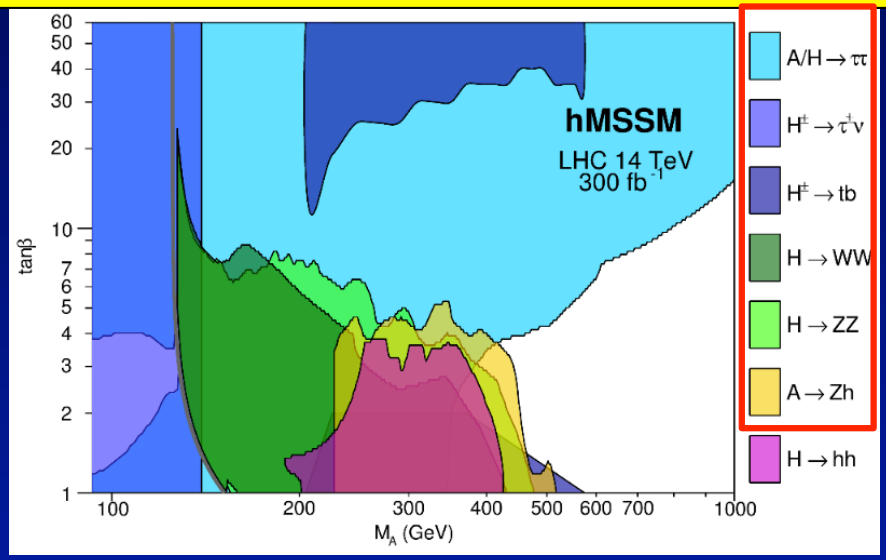
- Heavy Higgs bosons predicted in many Beyond Standard Model models, e.g.:
  - Two Higgs Doublet Model (2HDM):
    - h, H, A, H^+, H^-
  - Electroweak Singlet Model: h, H
  - Left-right symmetric models, Higgs Triplets Model: H^{++}

Excluded regions in (m_A, tan(β)) plane with Run 1



ATLAS Coll. Phys. Rev. D 92 (2015) 092004

LHC sensitivity in (m_A, tan(β)) plane with 300 fb^{-1}



A. Djouadi et al. JHEP06 (2015) 168

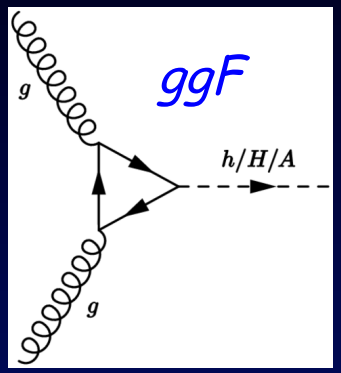
ATLAS-CONF-2016-085

13.3 fb^{-1}

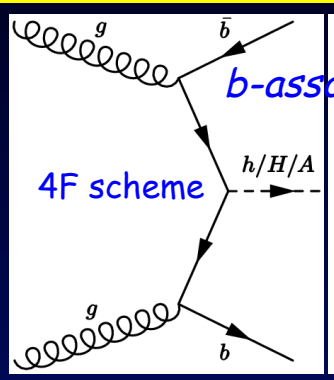
A/H $\rightarrow \tau^+\tau^-$ analysis search

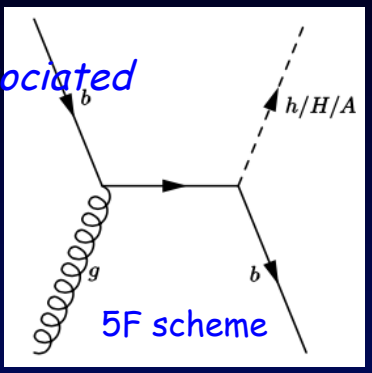
- Analysis introduction:
  - A/H produced through ggF or b-association
  - The couplings of the MSSM heavy Higgs bosons to τ, b-quark are enhanced w.r.t. the SM for large tan(β)
- Event categorization to exploit the two production mechanisms:
  - $\tau_{lep}\tau_{had}$: 0 b-tag / ≥1 b-tag / MET > 150 GeV
  - $\tau_{had}\tau_{had}$: 0 b-tag / ≥1 b-tag
- Selection:
  - 1(0) lepton, 1(2) τ_{had} opposite charge and Z veto
  - Reconstructed m_T^{tot} in both channels
- Main backgrounds:
  - $\tau_{lep}\tau_{had}$
    - Jets misidentified as leptons or τ from $t\bar{t}$, W+jets or multi-jets: estimated using CRs
    - $Z\rightarrow\tau\tau$ (0 b-tag) or $t\bar{t}$ (other)
  - $\tau_{had}\tau_{had}$
    - Multi-jet process faking taus: using CR

Production modes of neutral MSSM Higgs



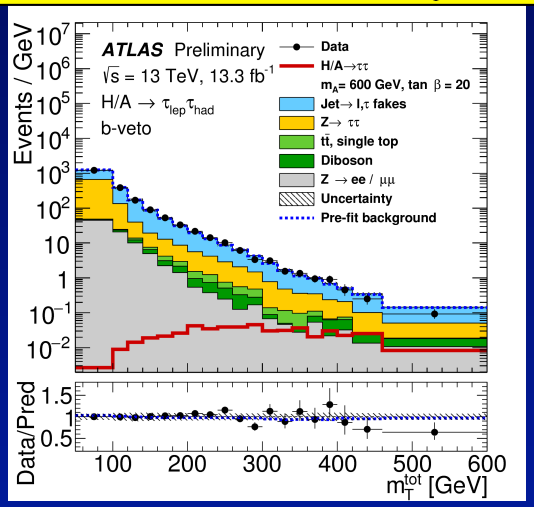
dominant at small tan(β)

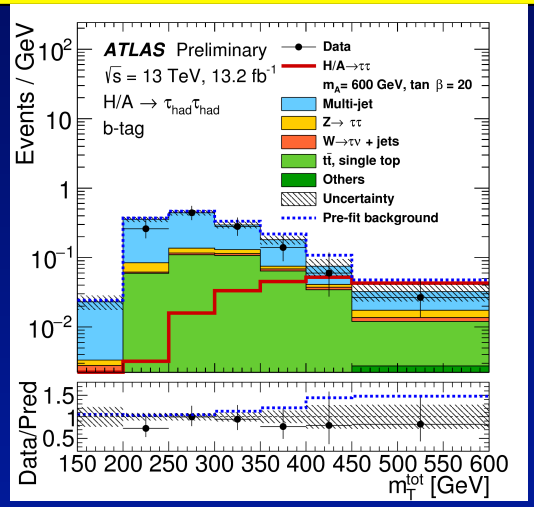




dominant at large tan(β)

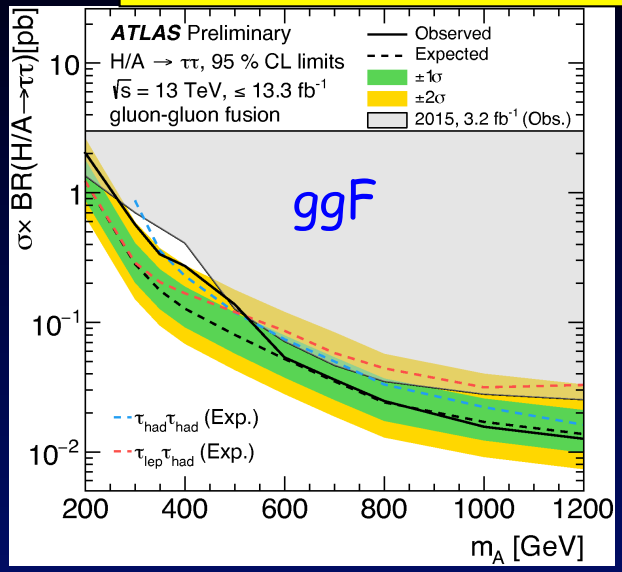
Total transverse mass for $\tau_{lep}\tau_{had}$ 0 b-tag and $\tau_{had}\tau_{had}$ b-tag categories

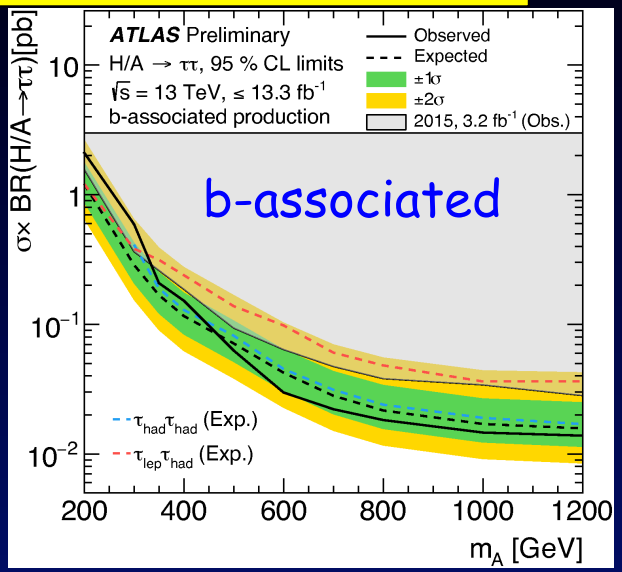




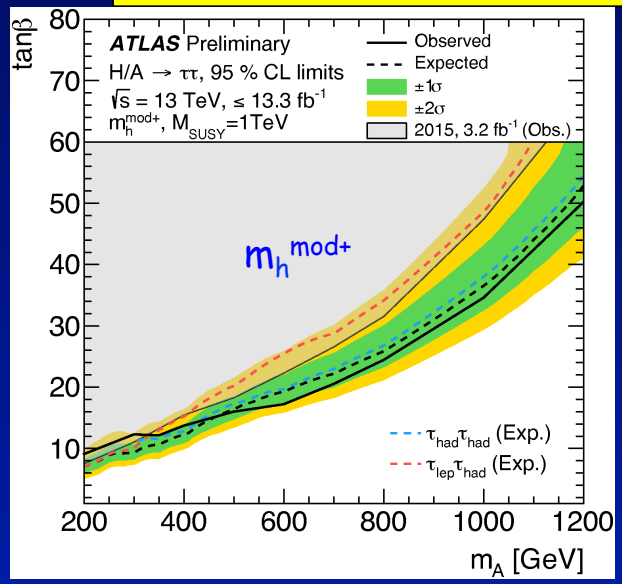
A/H → $\tau^+\tau^-$ analysis search results

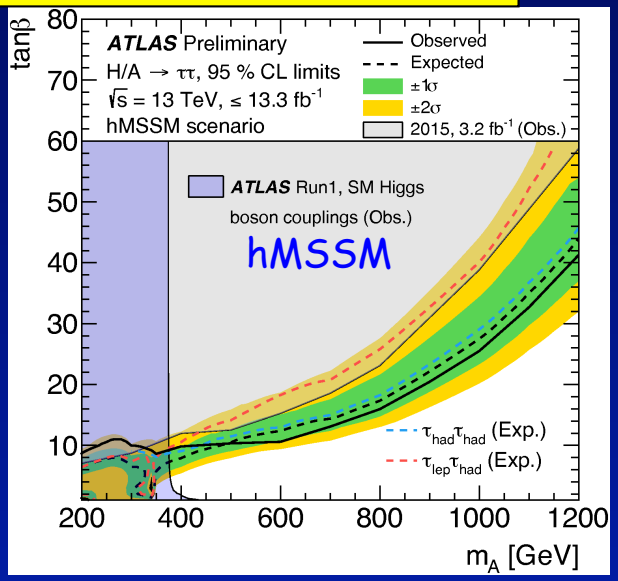
Observed and expected 95%CL limits on σ x BR as a function of m_A





Observed and expected 95%CL limits on tan(β) as a function of m_A



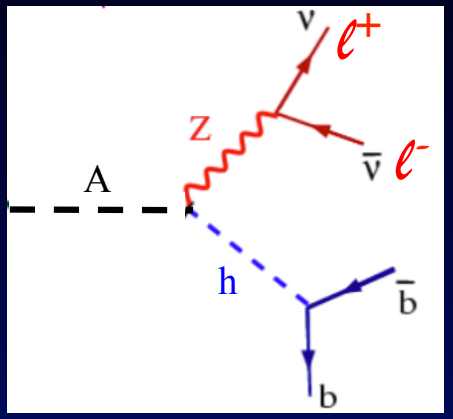


ATLAS-CONF-2016-015

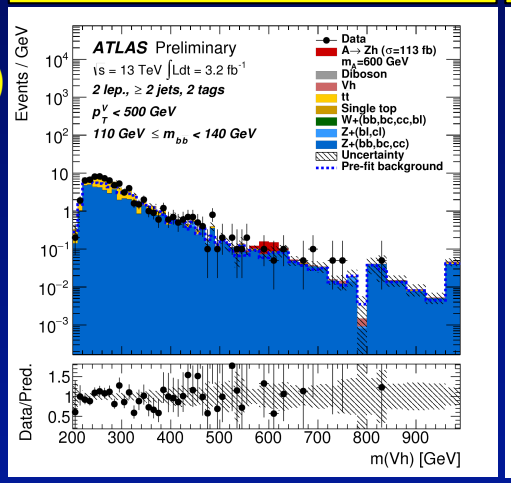
3.2 fb^{-1}

$A \rightarrow hZ \rightarrow b\bar{b}(l^+l^-$ or $\nu\bar{\nu})$ search

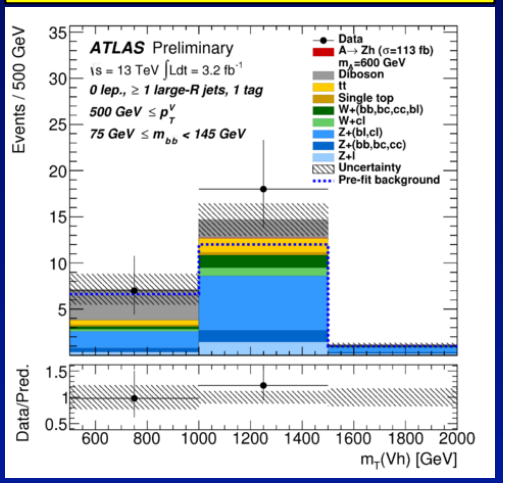
- Analysis introduction:
  - CP-odd A narrow width decay to hZ with clear signature and large Branching Ratio
- Event categorization:
  - # leptons [0,2] (MET or single lepton trigger)
  - p_T^Z [<, ≥] 500 GeV (≥2 small / ≥1 large R-jets)
  - # b-tagged jets [1,2]
- Selection:
  - m_{jj} compatible with m_h (125 GeV)
  - Discriminant: m_{inv}^{Zh} (2 lepton) or m_T^{Zh} (0 lepton)
- Main backgrounds:
  - $Z(l^+l^-$ or $\nu\bar{\nu})$ + b,c,light jets
    - Use CRs outside m_{jj} or m_J window
  - $t\bar{t}$ background
    - Use 2 CR (for 1/2 b-tags) with diff. lepton flavour (eμ) final state (in 2l low p_T^Z)



Zh invariant mass for the 2 lepton and $p_T^Z < 500$ GeV

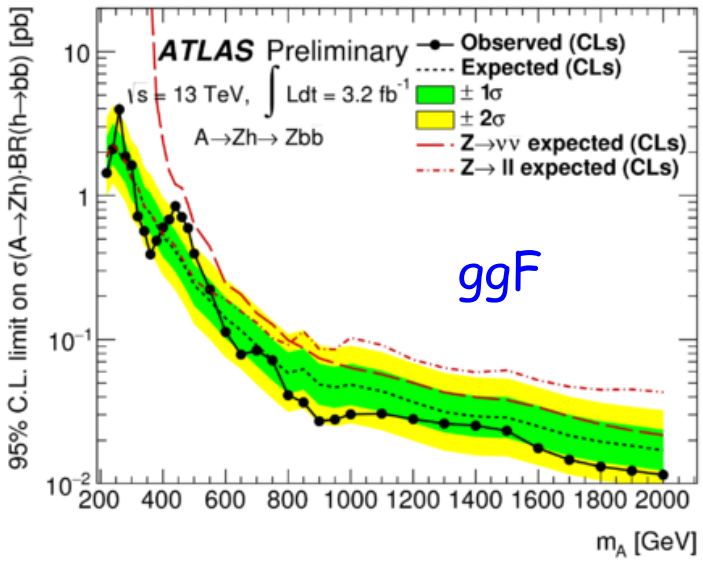


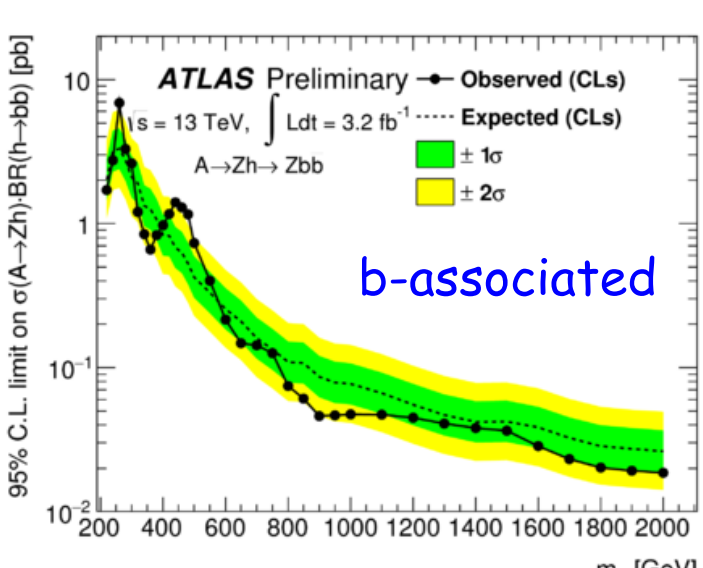
Zh transverse mass for the 0 lepton and $p_T^Z \geq 500$ GeV



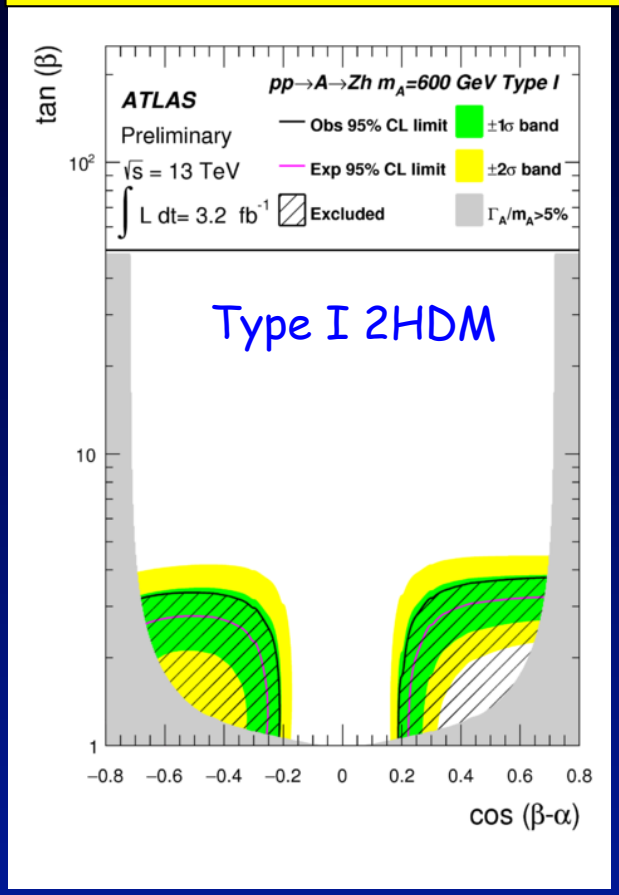
$A \rightarrow hZ \rightarrow b\bar{b}(l^+l^-$ or $\nu\bar{\nu})$ search results

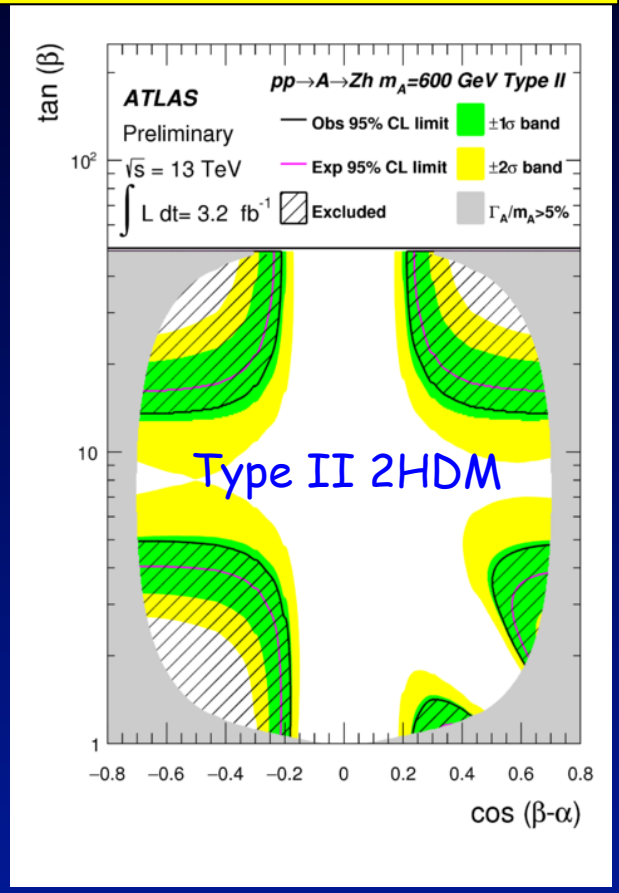
95%CL limits on σ x BR as a function of m_A





Limits on tan(β) versus cos (β-α) for Type I and II 2HDM with m_A= 600 GeV



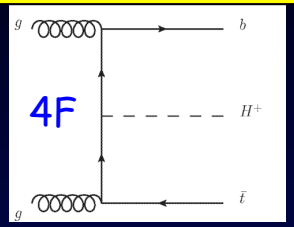


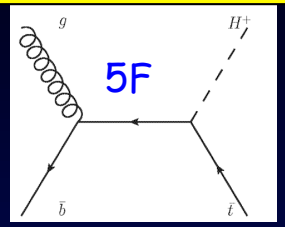
ATLAS-CONF-2016-088

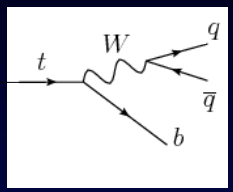
14.7 fb^{-1}

Charged Higgs search: $H^+ \rightarrow \tau_{had}\nu$

Production of H^+ ($m_{H+} > m_t$) in association with a top in 4F/5F schemes

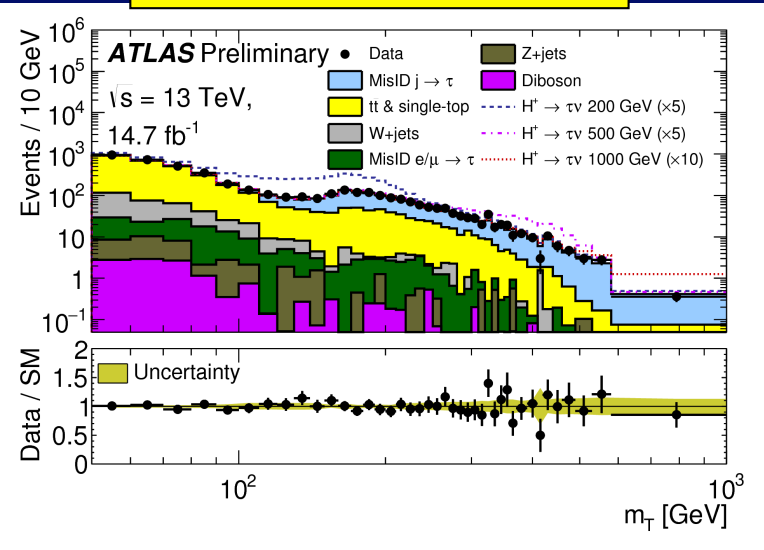




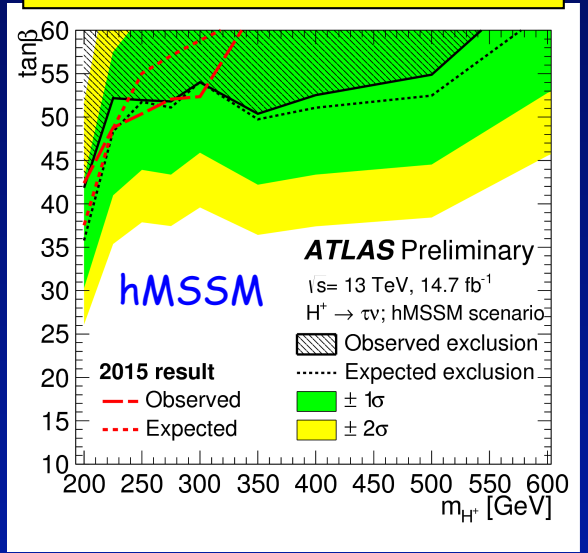


- Analysis introduction:
  - H^+ produced in association with a top (4F/5F)
  - Study channel where top decays hadronically
- Selection:
  - $E_T^{miss} > 150$ GeV
  - 1 hadronic tau and ≥ 3 jets w/ ≥ 1 b-tag
  - m_T used as discriminant
- Main backgrounds:
  - $t\bar{t}$ & single top w/ true τ_{had} & $W(\rightarrow\tau_{had}\nu)$ +jets
  - Misidentified jet as τ_{had} (mainly from multi-jet, estimated using CR)

Transverse mass distribution



Exclusion limits on tan(β) vs m_{H+}



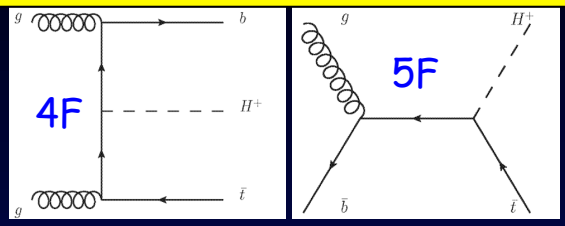
ATLAS-CONF-2016-089

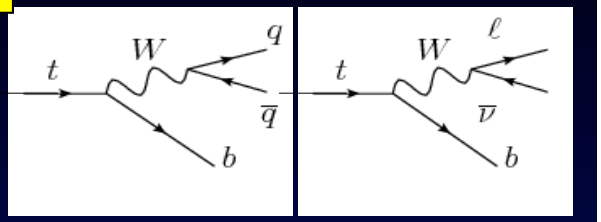
13.2 fb^{-1}

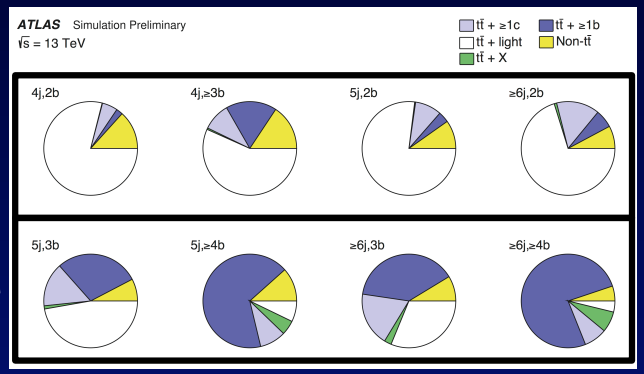
Charged Higgs search: $H^{\pm} \rightarrow tb$

- Analysis introduction:
  - Channel similar to ttH
  - pp → [b]tH$^{\pm}$ → [b](bjj)(bb $\nu\ell$) topologies
- Selection:
  - 1 lepton, ≥4 jets (≥2 b-tags)
  - Split SRs and CRs based on #jets and #b-jets
  - In the SRs: use BDT output to separate signal and background
  - In the CRs: use H_T^{had}
- Main backgrounds:
  - $t\bar{t}$+jets dominated by $t\bar{t}$ + ≥1b
    - Normalizations $t\bar{t}$ +≥1b/c free
  - Single top and $t\bar{t}H$

H$^+$ production in association with a top







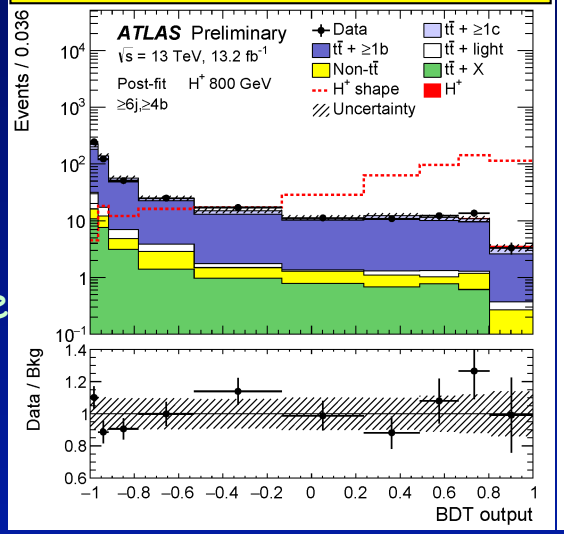
CRs

SRs

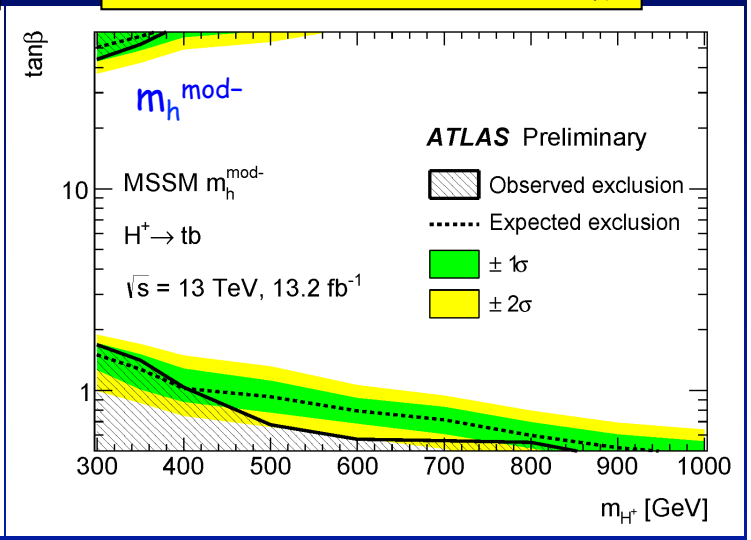
$H_T^{had} = \Sigma p_T^{jets}$

BDT output

BDT output for the ≥6j ≥4b SR



Exclusion limits on tan(β) vs m_{H^+}

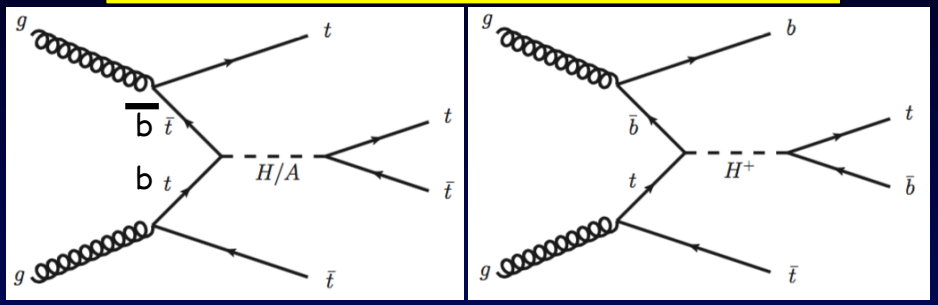


ATLAS-CONF-2016-104 | 13.2 fb^{-1}

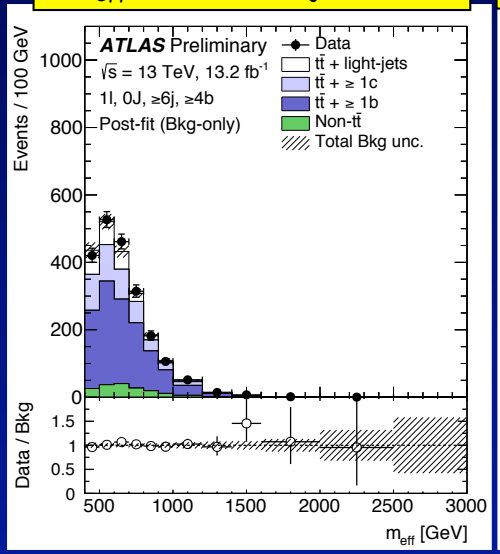
$t\bar{t}$+heavy flavour final states interpretation

- Analysis introduction:
  - Analysis designed to search for $T\bar{T}$ production
  - Result reinterpreted in the Higgs sector:
    - $b\bar{b}H/A(\rightarrow t\bar{t})$ or $t\bar{t}H/A(\rightarrow t\bar{t})$ (complementary to $H/A\rightarrow\tau\tau$)
    - $tbH^{\pm}(\rightarrow tb)$
- Selection:
  - 1 lepton, E_T^{miss}>20 GeV, ≥6 jets, 3/≥4 b-jets, 0/1/≥2 R-jets, $m_{bb}^{min\Delta R}$ < or > 100 GeV
  - m_{eff}: scalar sum $p_T^{lepton} + p_T^{jets} + E_T^{miss}$
- Events categorization:
  - 8 SR and 6 VR
- Backgrounds:
  - Use categories with low S/B & normalize bkgrs.
  - $t\bar{t}$ + ≥1b, left free in the fit
  - multi-jet estimated w/ data-driven method

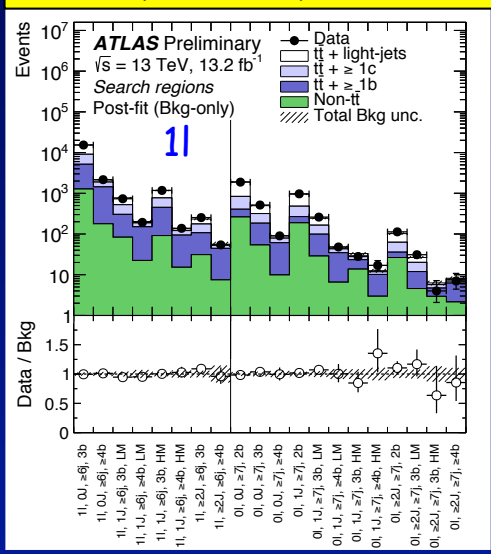
Example leading-order production of H/A or H$^+$



m_{eff} for 1l 0J ≥6j ≥4b SR

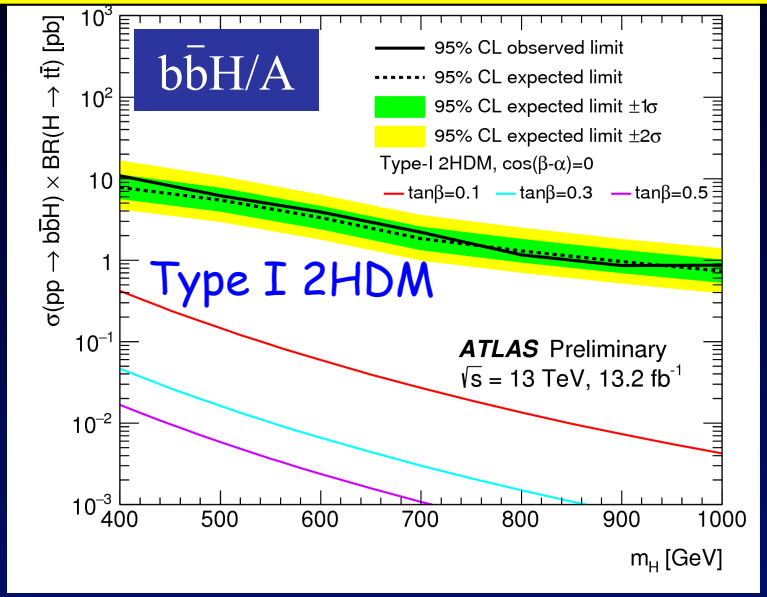


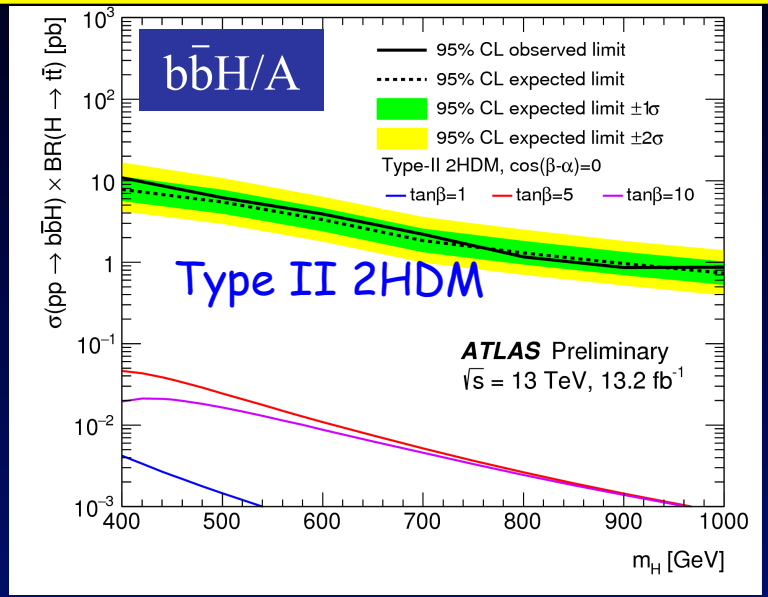
Data vs prediction yields in SRs



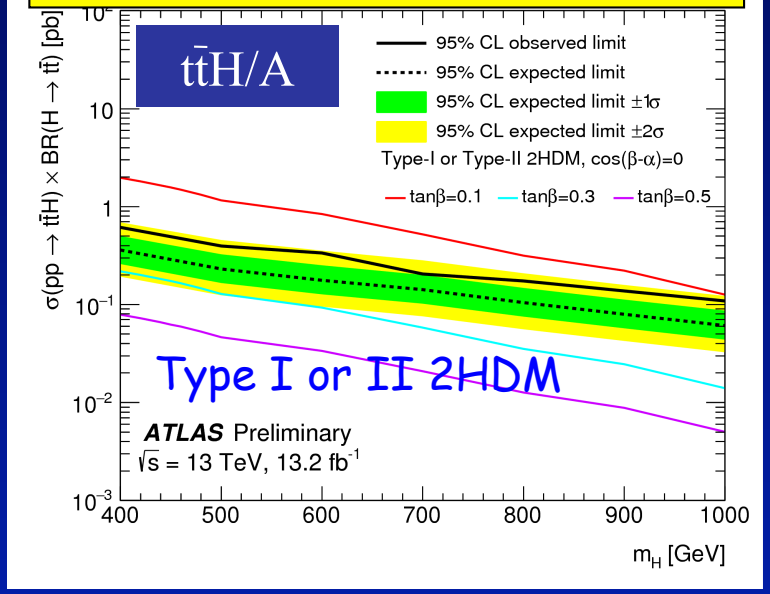
$t\bar{t}$+HF Higgs interpretation

Observed and expected 95%CL upper limits on $\sigma(pp \to b\bar{b}H) \times BR(H \to t\bar{t})$ as a function of the heavy Higgs boson mass

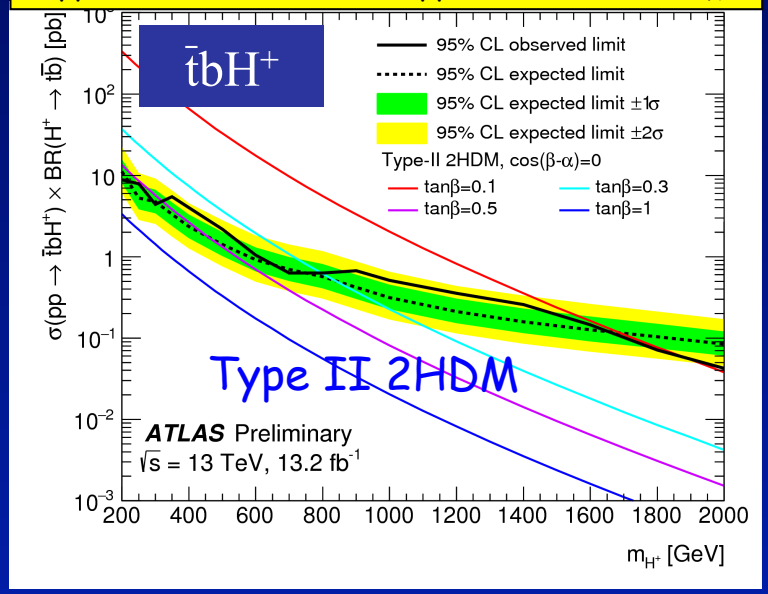




$\sigma(pp \to t\bar{t}H) \times BR(H \to t\bar{t})$ upper limits versus m_H



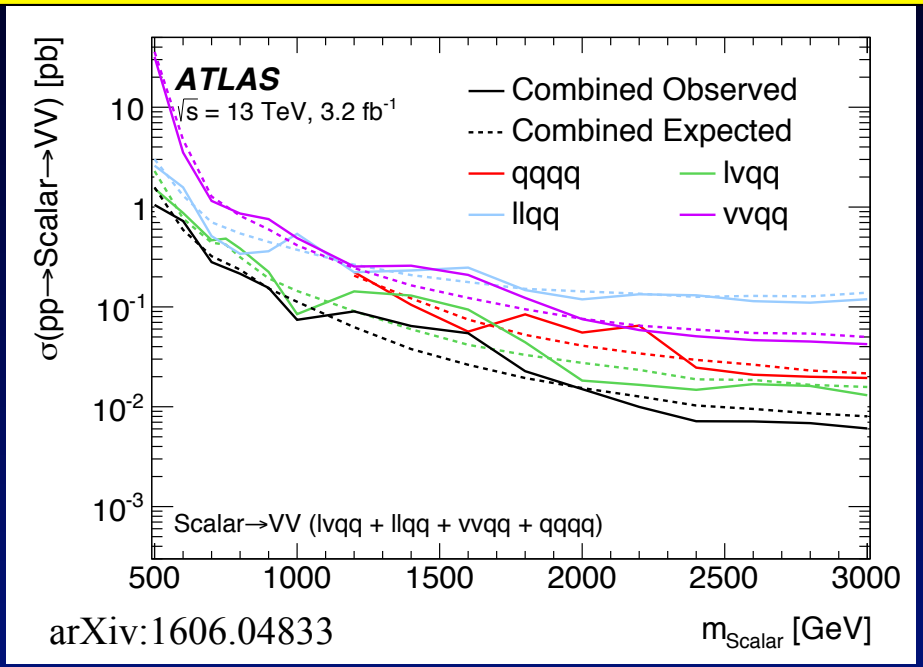
$\sigma(pp \to \bar{t}bH^+) \times BR(H^+ \to t\bar{b})$ upper limits versus m_{H^+}



Heavy Higgs searches in di-boson final states

- Di-boson final states searches performed in many different channels:
  - Narrow Width Approximation (NWA): 4 MeV, width << detector resolution
  - Large Width Assumption (LWA): with widths up to 15% of the m_H
- Covered in this talk:
  - ZZ → 4l
  - ZZ → ll νν
  - WW → lνlν

Limits on σ x BR(pp→Scalar→VV) as a function of the scalar mass



- Some other channels are covered in other talks at this conference:
  - Nicolò Vladi: "ATLAS Searches for VH, HH, VV, V+γ/γγ Resonances" (earlier today, WG3)
  - Yanlin Liu: "Searches for new phenomena in final states involving 'leptons and jets' or involving leptons using the ATLAS detector" (later today, WG3)

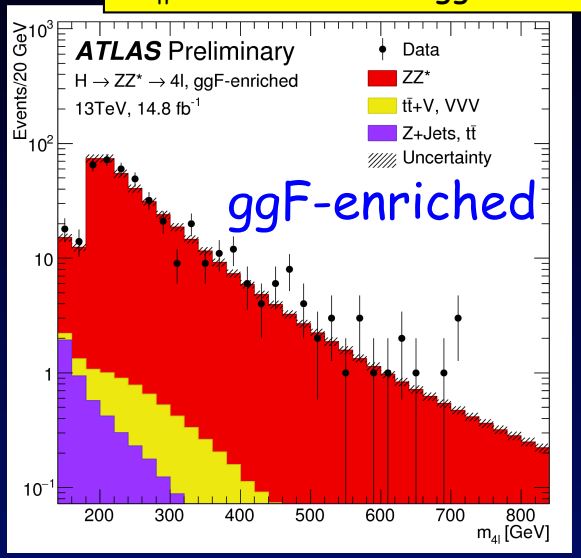
ATLAS-CONF-2016-079

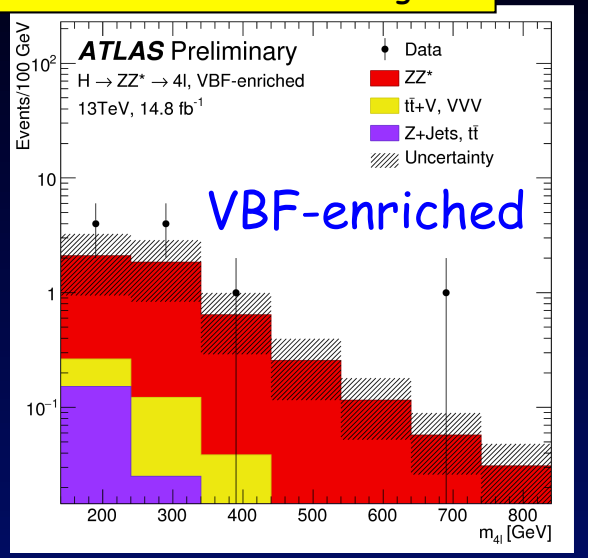
14.8 fb^{-1}

H → ZZ* → 4l analysis search

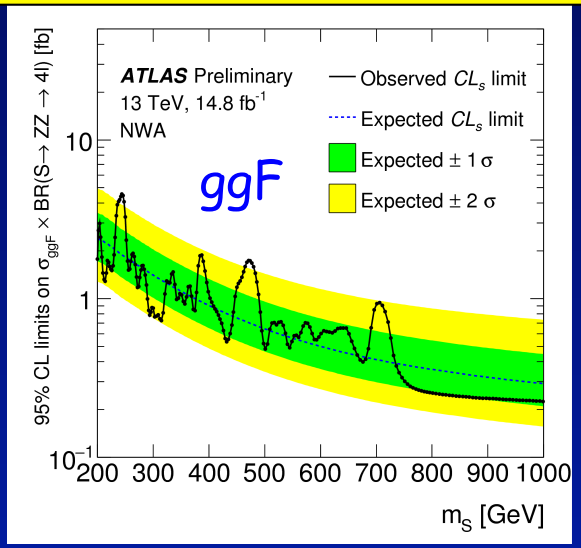
- Analysis introduction:
  - Production through ggF and VBF
  - Full reconstruction of final states:
    - 4e, 2e2mu, 4mu
    - m_{4l} (applying Z mass constraints)
      - Excellent mass resolution
- Signal region divided in 4 categories:
  - ggF: 4e, 2e2μ, 4μ
  - VBF: m_{jj}>400 GeV & $|\Delta\eta_{jj}| > 3.3$
- Dominant background:
  - non-resonant ZZ*
- Results:
  - Limits are given for heavy scalars assuming narrow or large width of 1, 5 or 10%

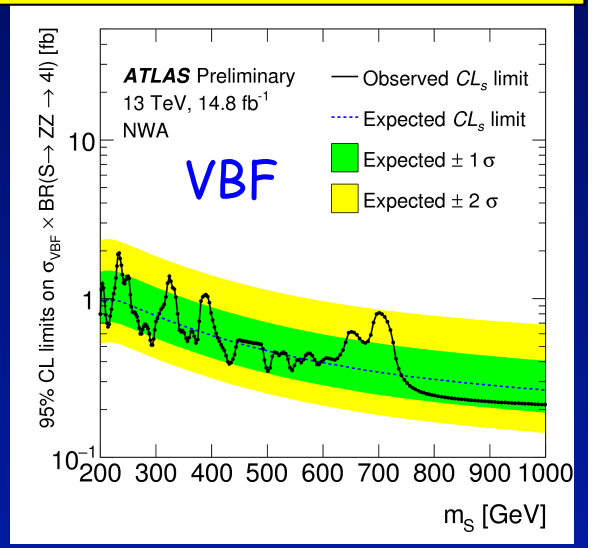
m_{4l} distribution for ggF-enriched and VBF-enriched regions





95%CL limits on σ x BR(H→ZZ→4l) as a function of a narrow heavy scalar mass





ATLAS-CONF-2016-056

13.3 fb^{-1}

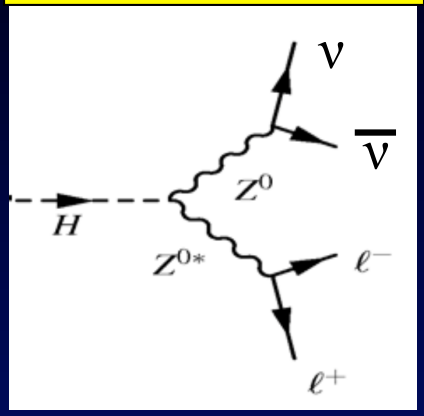
H → ZZ* → 2l 2ν analysis search

- Analysis introduction:
  - ggF production
  - NWA assumed
  - Channels analysed: e^+e^- and $\mu^+\mu^-$
- Selection:
  - 2 OS leptons w/ m_{ll} around Z mass
  - $E_T^{miss} > 120$ GeV
  - Discriminant: m_T^{ZZ}

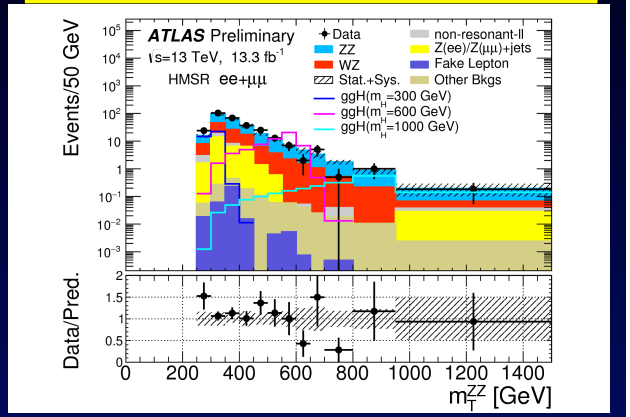
$$m_T^{ZZ} = \sqrt{\left(\sqrt{m_Z^2 + |p_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |E_T^{\text{miss}}|^2}\right)^2 - |\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}|^2}$$

- Main backgrounds:
  - ZZ interactions (from MC)
  - WZ from data using a 3 lepton CR
  - Z+jets (from data)

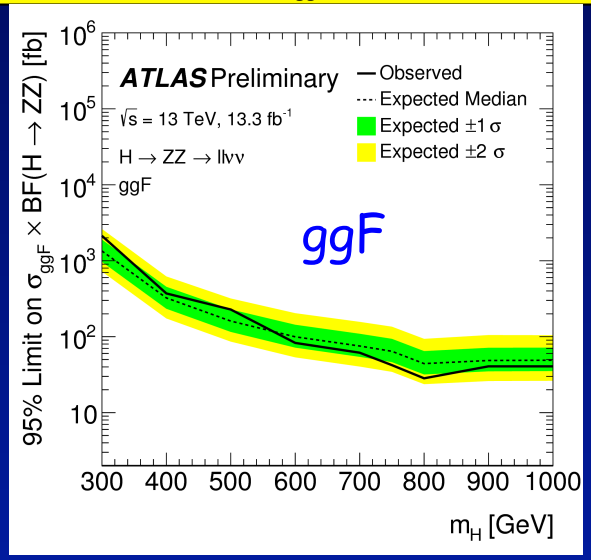
H → ZZ* → 2l 2ν decay



m_T^{ZZ} distribution for e^+e^- and $\mu^+\mu^-$



95% CL limits vs m_H of σ_{ggF} x BR(H→ZZ*→2l2ν)



ATLAS-CONF-2016-074

13.2 fb^{-1}

H → WW* → lν lν analysis search

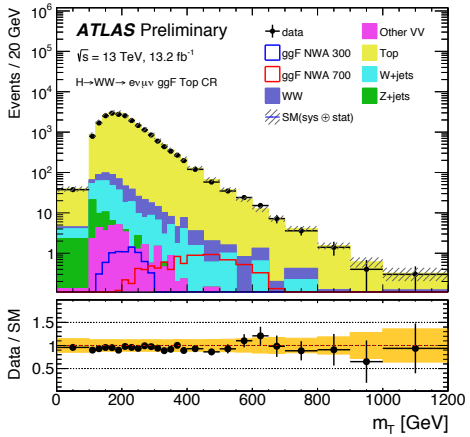
- Analysis introduction:
  - Studied ggF and VBF production modes
  - Only eν μν final states analysed
  - Used m_T as discriminating variable

$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - |\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|^2}$$

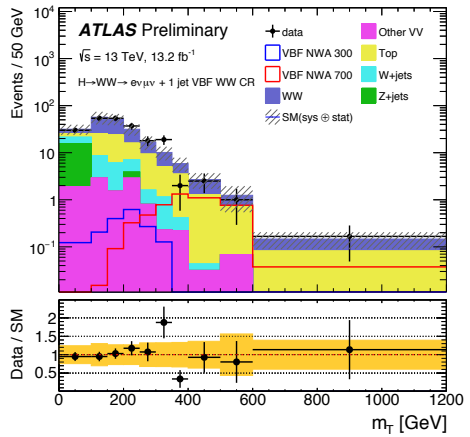
- Event categorization:
  - 3 SRs: ggF, VBF 1J, VBF ≥2J with m_{jj} > 500 GeV
  - 2 Top background CRs: ggF, VBF
  - 2 WW background CRs: ggF, VBF1J

- Main backgrounds:
  - $t\bar{t}$ and single-top, WW
    - Normalizations determined in the fit
  - Smaller bkgrs. from W/Z+jets

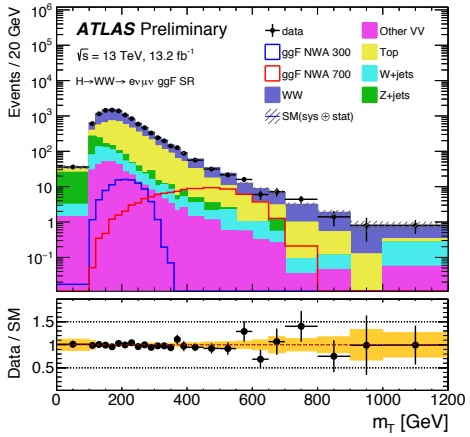
m_T distr. for ggF top CR



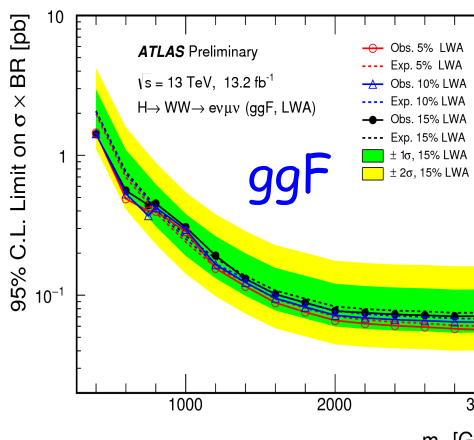
m_T distr. for VBF1J WW CR



m_T distr. for ggF SR



95% CL limits vs m_H of σ_{ggF} x BR



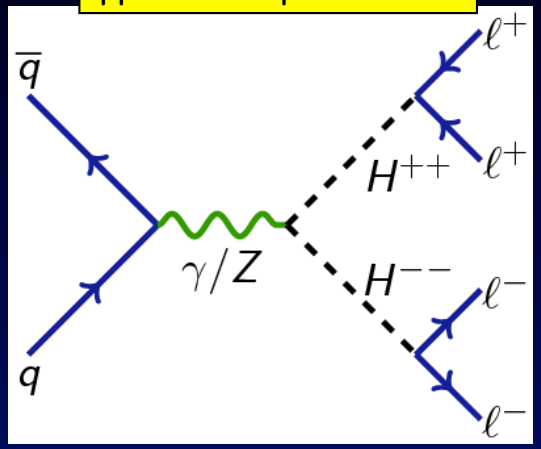
ATLAS-CONF-2016-051

13.9 fb^{-1}

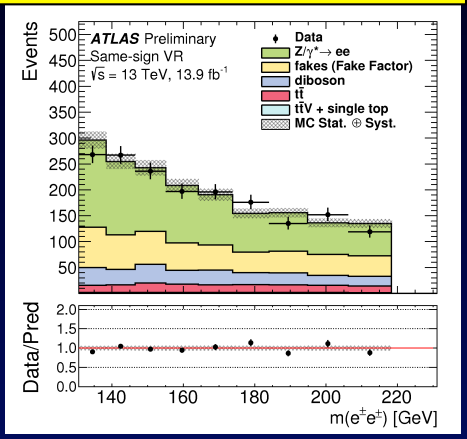
$H^{\pm\pm} \rightarrow e^{\pm}e^{\pm}$ analysis search

- Analysis introduction:
  - Doubly-charged Higgs can arise e.g. in left-right symmetric models, Higgs triplet model, etc.
  - Mainly pair-produced in Drell-Yan process
  - Studied events with ≥1 Same-Sign (SS) ee pair
- Event categorization:
  - 1 SR: ≥1 SS pair w/ $m_{ee} > 300$ GeV
  - 1 VR: ≥1 SS pair w/ $m_{ee} < 300$ GeV
  - 2 CRs: 1 OS pair and 0/1 SS pair to get scaling factors to correct bkgr.
- Main backgrounds:
  - SS electrons due to charge mis-ID: Drell-Yan, $t\bar{t}$ and di-boson
  - Multi-jet, W+jets events (data-driven)

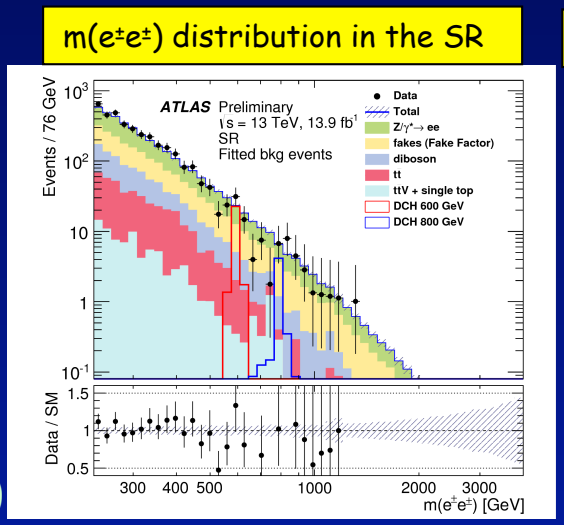
pp →$H^{++}H^{--}$ production



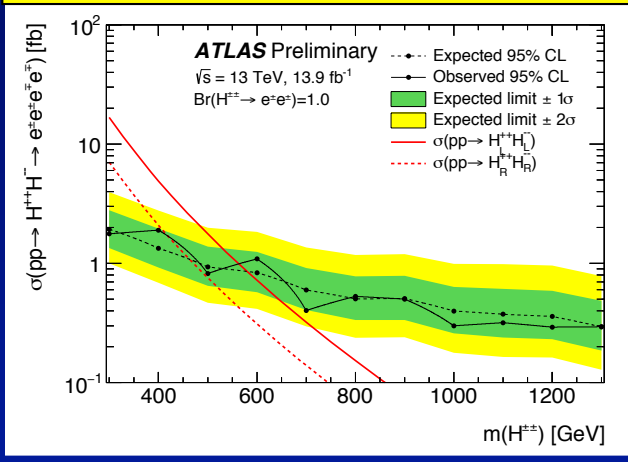
m($e^{\pm}e^{\pm}$) distribution in the VR



m($e^{\pm}e^{\pm}$) distribution in the SR



Limits vs m($H^{\pm\pm}$) of σ(pp→$H^{++}H^{--}$→$e^{\pm}e^{\pm}e^{\mp}e^{\mp}$)

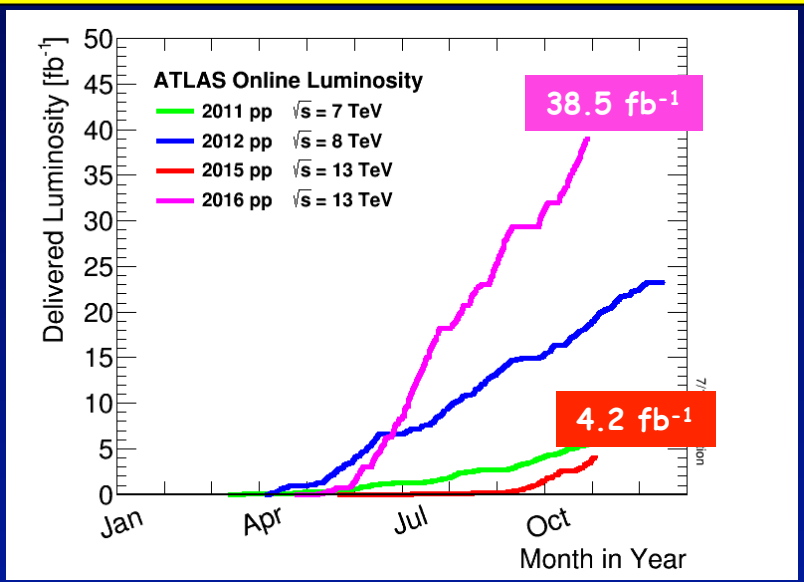


Summary and conclusions

- Many searches for heavy Higgs bosons have been performed in many different final states with no significant signal observed
- New limits have been placed in the tan(β) vs m_A phase space as well as in many cross-sections times branching ratios for various ranges of Higgs masses
- Analyses with the full 2016 data statistics are being finalized
- Time for getting new data this year approaches !

Stay tuned !

Cumulative delivered luminosity per day/year



THANK YOU !