# Search for neutral and charged BSM Higgs Bosons with the ATLAS detector

**ICNFP 2017**

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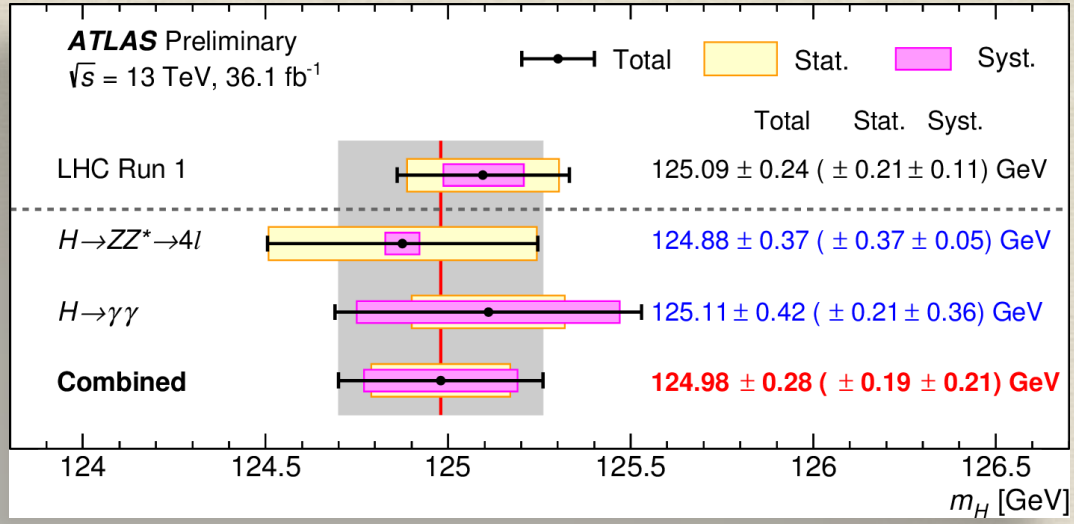
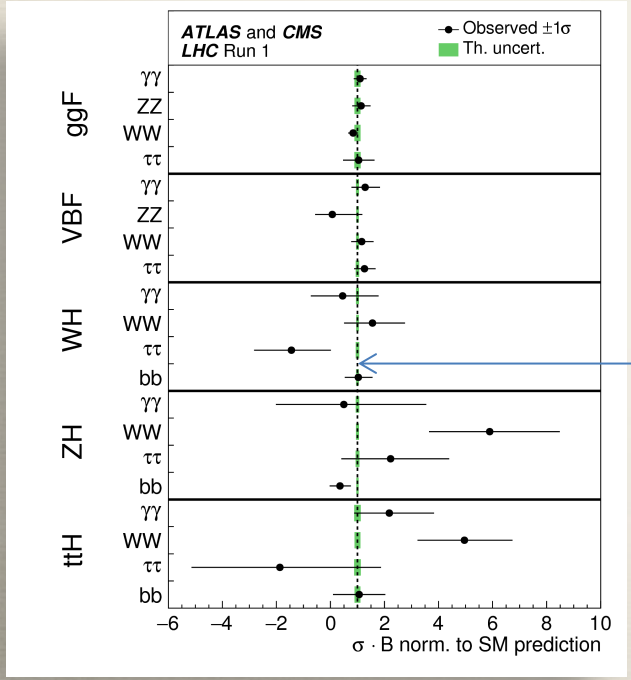
**on behalf of the ATLAS Collaboration**
**( Institute of Nuclear Physics P.A.N., Cracow PL )**

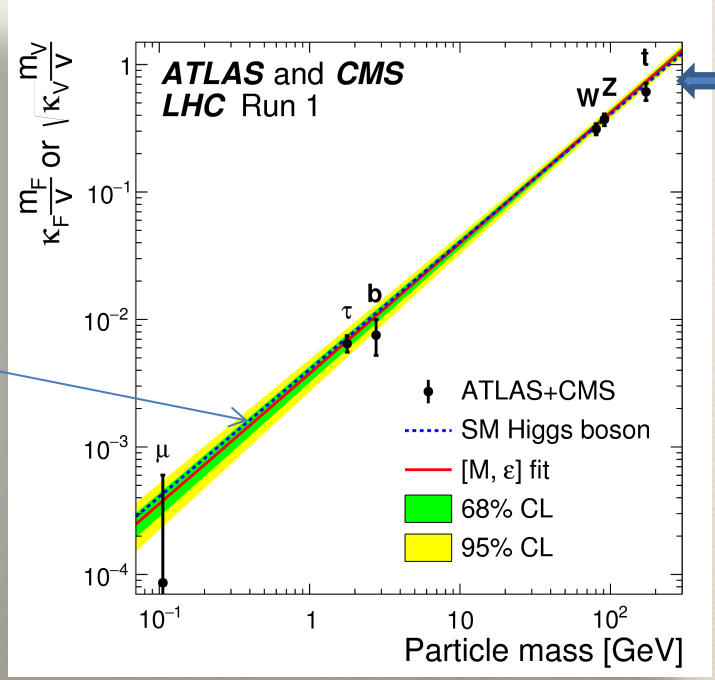
# The big picture (Run 1->Run 2)

ATLAS & CMS combined mass:
**PRL 114, 191803 (2015)**
ATLAS Run 2: **ATLAS-CONF-2017-047**
ATLAS & CMS combined couplings:
**JHEP 08 (2016) 045**




SM




top from ggH production x-section

So far the Higgs…
looks like SM,
sounds like SM,
smells like SM.

T.Kibble G.Guralnik R.C.Hagen F.Englert R.Brout & P.Higgs

But:
CONSISTENT with SM ≠ INCOMPATIBLE with BSM

- Essential questions:
  - Is the 125 GeV Higgs the only one (extended sector)?
  - Is it responsible for all the particle mass?
  - Is it fundamental?
- Need to define models of interest. Most popular are additional EW singlet, 2HDM, NMSSM, additional Higgs Triplet, Georgi-Machacek, Composite Higgs, etc.
- All allow for SM-like light Higgs phenomenology with smaller or larger coupling modifications.

# ROADMAP

**Explore the 125 GeV Higgs**

- Production rates (ggH, WH,ZH, VBF, ttH, HH, tH, bbH)
- Decay widths ($\gamma\gamma$, ZZ, WW, bb, $\tau\tau$, $\mu\mu$, $Z\gamma$, $\phi\gamma$, $\rho\gamma$, etc.)
- Couplings to SM particles
- Spin and parity
- LFV, H->$\alpha\alpha$, H->inv, $\gamma+\not{E}$, etc.

**Explicit search for BSM scalars**

- Heavy neutral CP-even and CP-odd states ($\gamma\gamma$, ZZ, WW, bb, $\tau\tau$, HH, HZ, tt)
- Charged Higgs ($\tau\nu$, tb, WZ, cs, etc.)
- Doubly-charged Higgs
- Any deviations from SM backgrounds?

**How much of the BSM scenarios can current data exclude?**

# THIS TALK

- Focuses on the explicit searches for heavier members of the scalar sector.
- Shows results based on full 2015+2016 data ~36 $fb^{-1}$ @13 TeV (with a couple of exceptions)
- Only results targeting heavy scalars discussed.
- Couplings, rare decays, pair production, etc. of the 125 Higgs boson not covered.

- Outline:
  - Heavy neutral Higgs decaying to bosons
  - Heavy neutral Higgs decaying to fermions
  - Heavy charged and doubly-charged Higgs

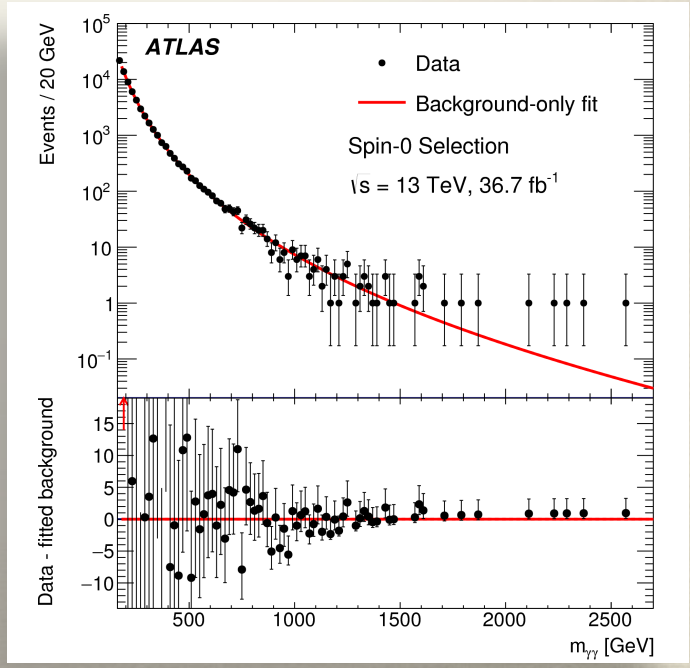
# BSM Higgs -> bosons

# Heavy neutral Higgs->γγ

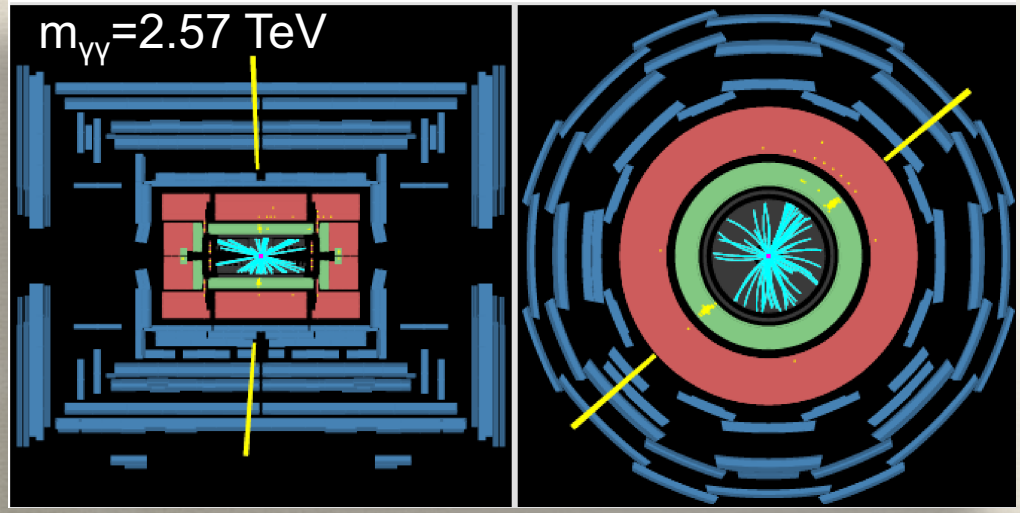
arXiv:1707.04147
2015+2016, 36.7 $fb^{-1}$

- Generic search for γγ resonance across a wide range of masses: 200 GeV<$m_{\gamma\gamma}$<2700 GeV and $\Gamma_H/m_H$ =[0% - 10%] using 36.7 $fb^{-1}$
- Analysis optimised for two hypotheses: spin 0 and spin 2 (Landau-Yang)
- Two isolated (calo & tracks) photons in central rapidity region (spin 0)
- 90% background irreducible di-photon QCD (+ γj, jj)
- Background modeled from simultaneous functional fit to $m_{\gamma\gamma}$ for sig+bkg

Spin 0 hypothesis
(very similar for spin 2 selection )



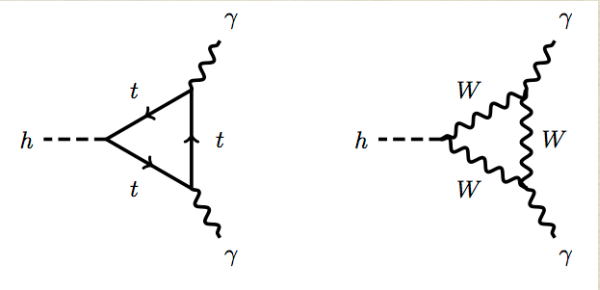

The highest mass γγ candidate

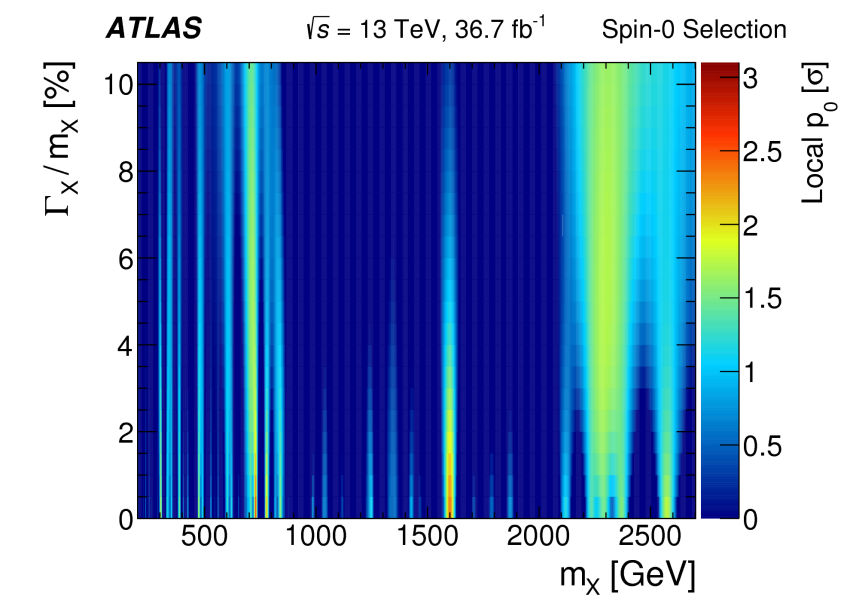


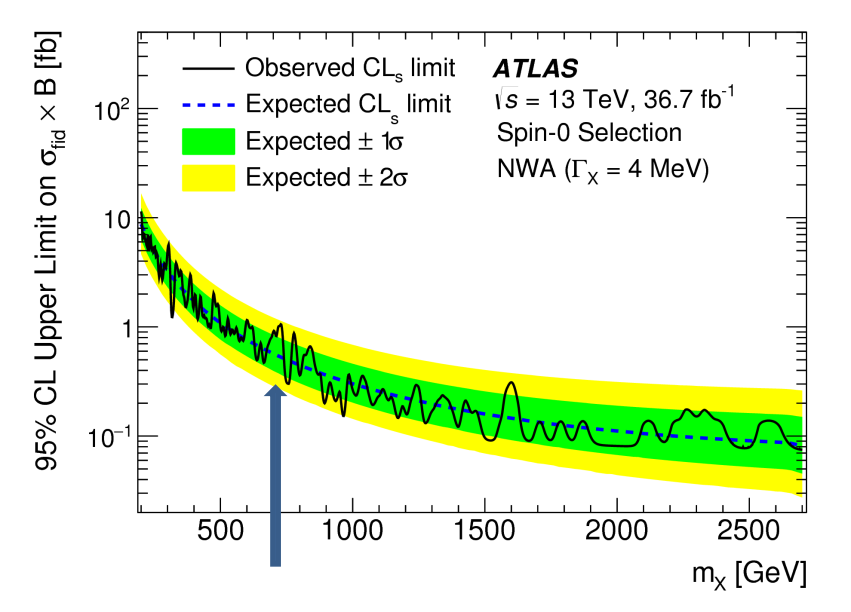
# Heavy neutral Higgs->γγ

arXiv:1707.04147
2015+2016, 36.7 fb$^{-1}$

- Fit results:



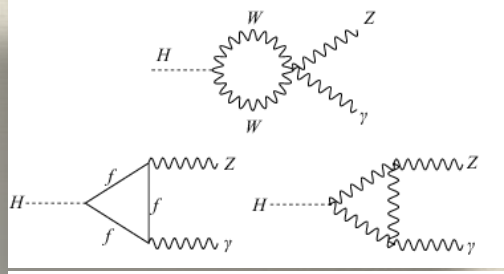



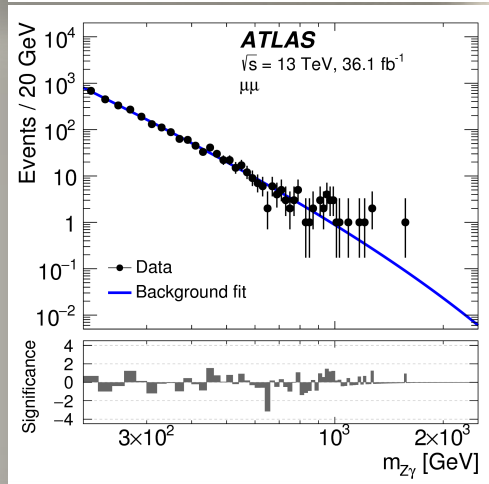

Largest excess: 2.6 σ local around 730 GeV for narrow width driven by 2015 data and corresponding to null global significance (less than the median largest deviation in background-only pseudo-experiments)

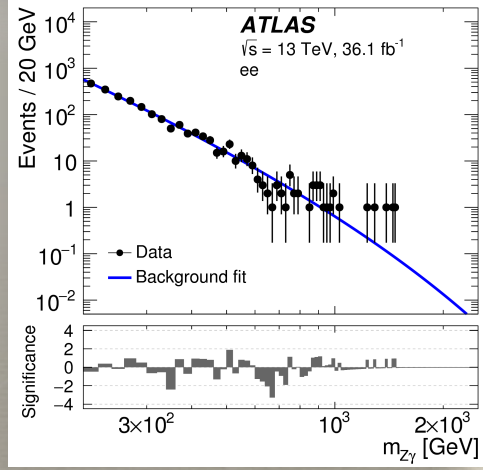
# Heavy neutral Higgs->Zγ->llγ

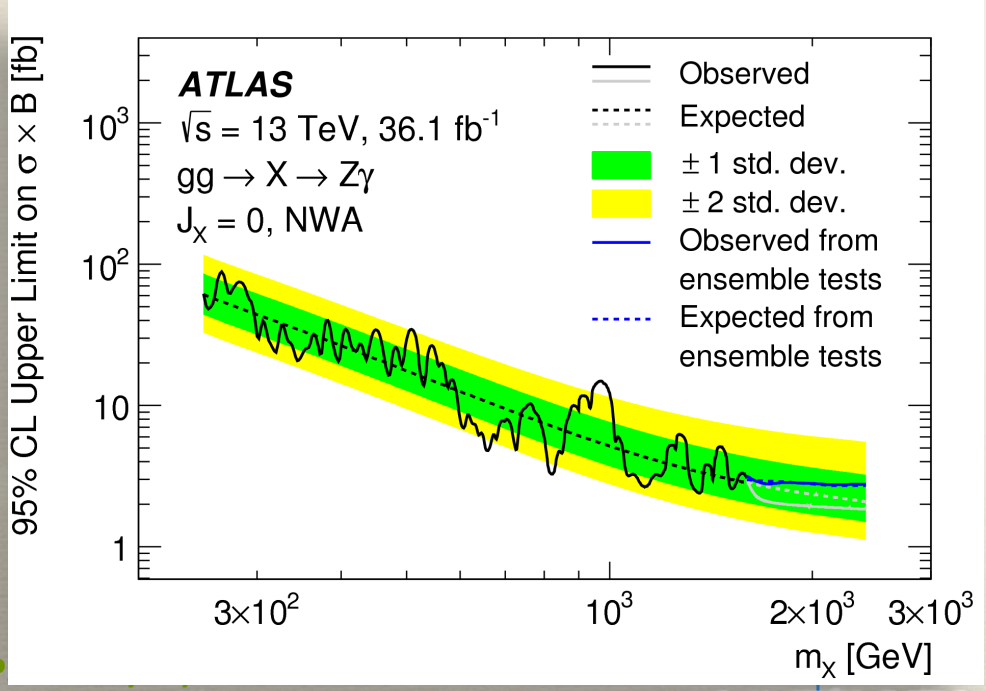
**ATLAS-HIGG-2016-14**
2015+2016, 36.1 fb$^{-1}$

- A same-flavour opposite sign isolated (track) lepton pair + photon
- Two categories: **ee** and **μμ**.
- Trigger-matched e(μ) $p_T$>18(24) GeV
- Isolated (calo+track) photon, $p_T(\gamma)$>15 GeV
- Main background non-resonant Zγ (irreducible) and Z+jets (reducible), analytical model from fit to data in CR
- 2.7(0.8)σ local(global [200-2500]) @ $m_H$=960 GeV



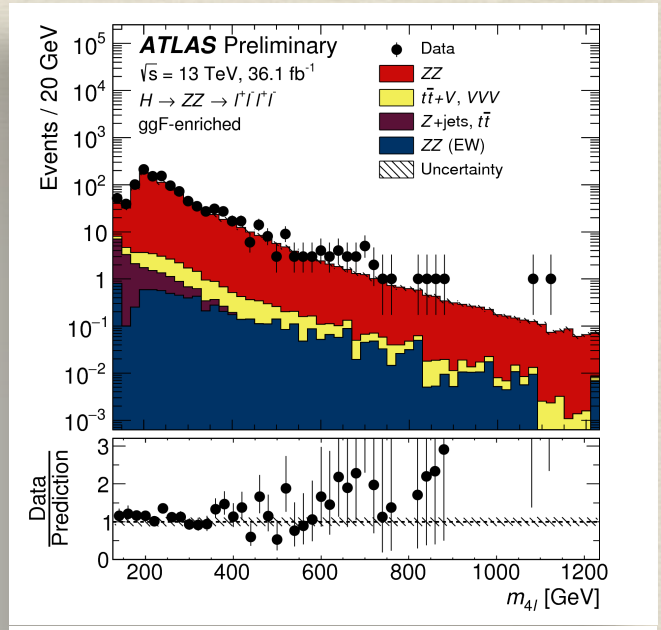
# Heavy neutral Higgs->ZZ->llll/ννll

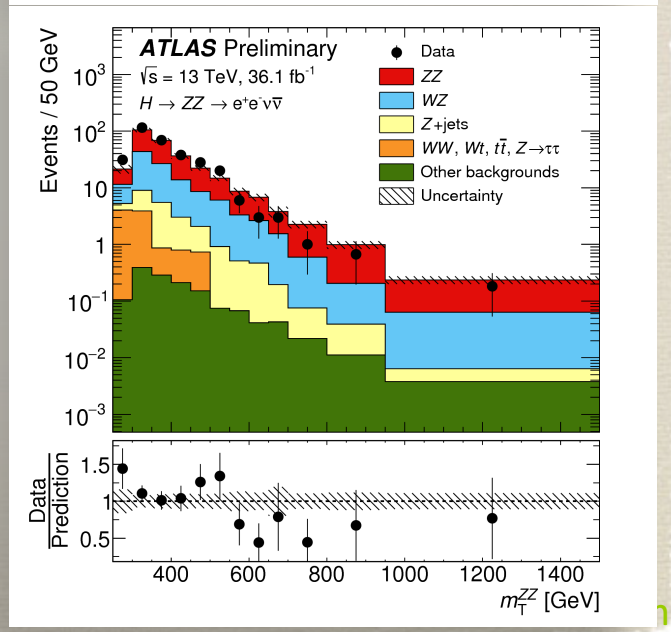
ATLAS-CONF-2017-058
2015+2016, 36.1 fb$^{-1}$

- **Z->llll:** two same-flavour opposite sign isolated (calo+track) lepton pairs
- **ggF** and **VBF:** ≥2jets $p_T$>30 GeV $\Delta\eta_{jj} > 3.3, mjj > 400$ GeV
- 4 categories: VBF, ggF (4e, 2eμ, 4μ)
- Main background (~97%) non-resonant ZZ (from MC) - interference accounted for!

- **Z->ννll:** same-flavour opposite sign isolated (calo+track) lepton pair + missing transverse energy
- **ggF** and **VBF:** ≥2jets $p_T$>30 GeV $\Delta\eta_{jj} > 4.4, mjj > 550$ GeV
- $E_T^{miss}$>120 GeV, Δϕ(ll, $E_T^{miss}$)>2.7
- 3 categories: VBF, ggF (ee, μμ)
- Main background (~60%) non-resonant ZZ and ZW (~30%) estimated from MC.

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

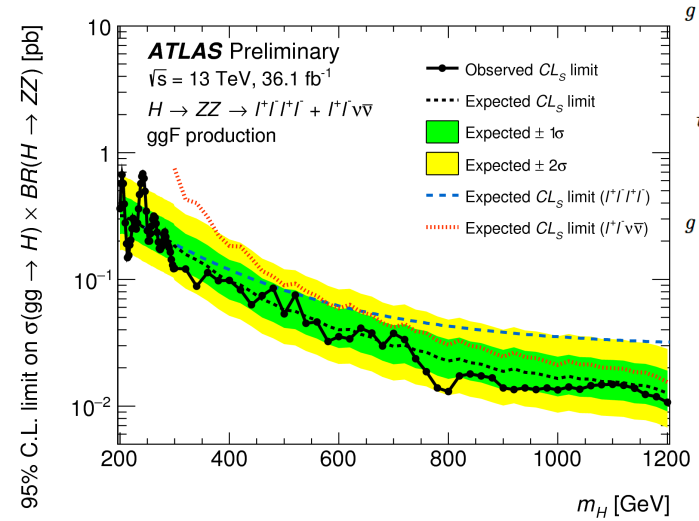


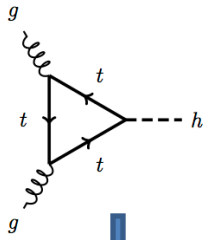



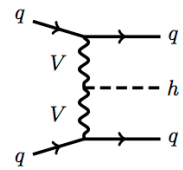
# Heavy neutral Higgs->ZZ->llll/ννll

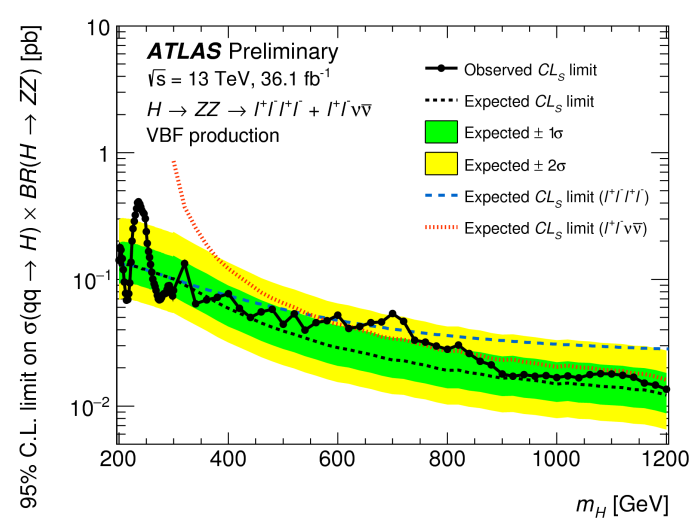
ATLAS-CONF-2017-058
2015+2016, 36.1 fb$^{-1}$

**Fit results:** Narrow (ggF and VBF) and large width (1-10% of $m_H$, ggF only) signal hypotheses tested



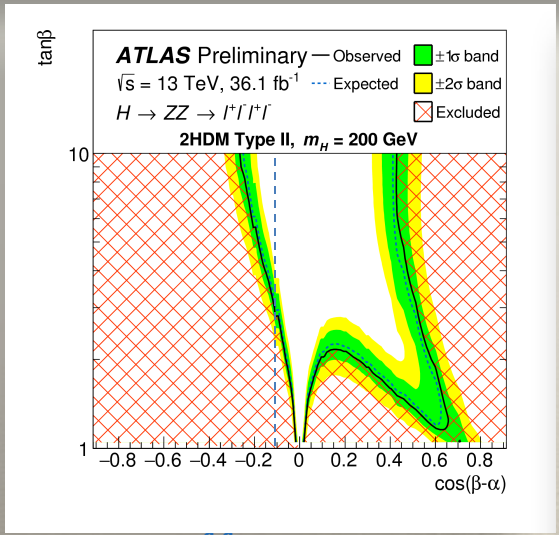



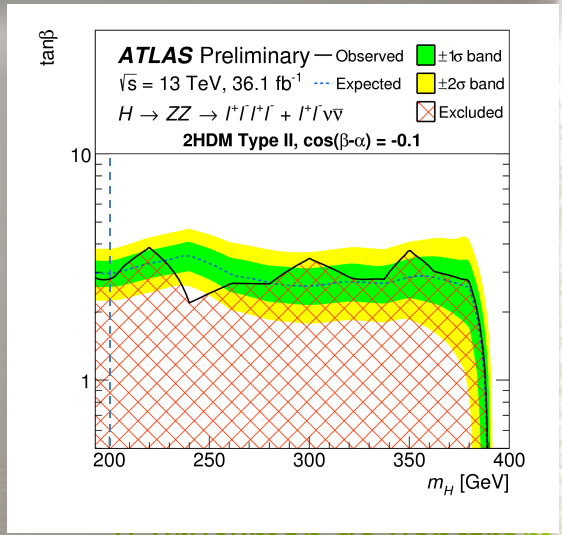




llll shows 3.6(2.2) σ local (global) excess at ~240 GeV and 700 GeV. When combined with ννll, the 700 GeV one reduces to 2.0(1.0) σ local (global).

**2HDM type2 interpretation:** (example)

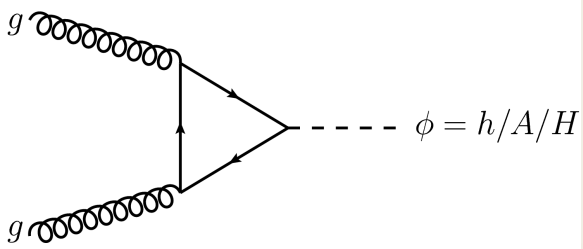


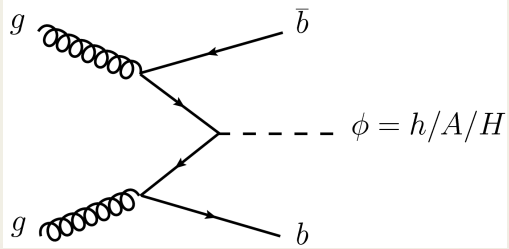



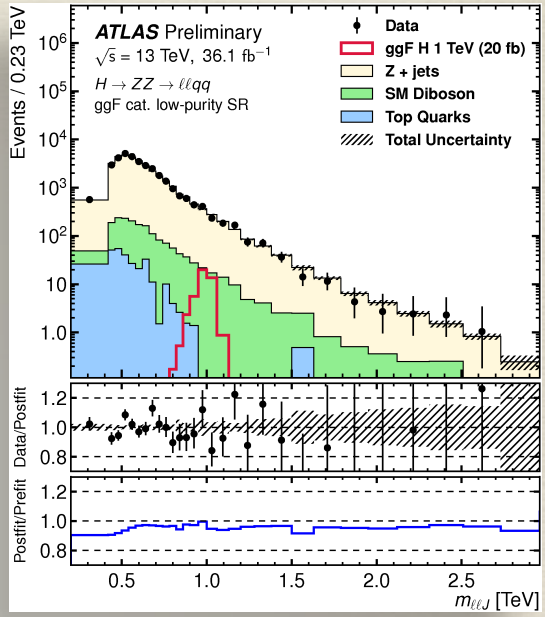
# Heavy H->ZZ->llqq/ννqq
# CP-odd A->Zh->llbb/ννbb

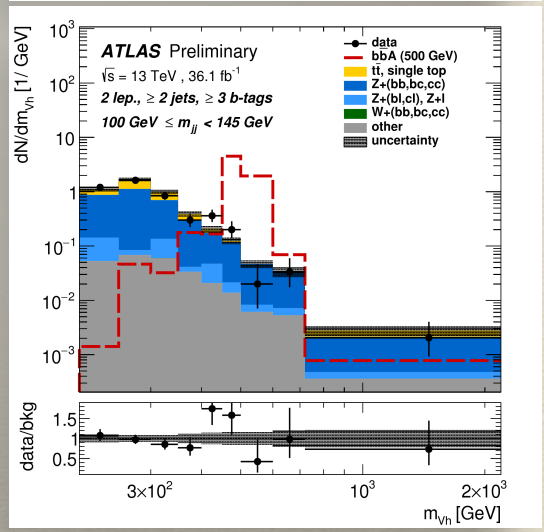
ATLAS-EXOT-2016-29
ATLAS-CONF-2017-055
2015+2016, 36.1 fb$^{-1}$

- **llqq/bb:** same-flavour opposite sign (μ only) isolated (calo+track) lepton pair + jet(s) (b-tag)
- **ννqq/bb:** missing transverse energy + jet(s) (b-tag)
- Merged (*llJ*) or resolved (*llJJ*) selection (sequential)
- Improved jj mass resolution using both calo & track information
- **H->ZZ: ggF** and **VBF:** two forward jets with high $\Delta\eta_{jj}$ & $m_{jj}$
- **A->Zh: ggF** and **bbA:** through >2 b-tag category.



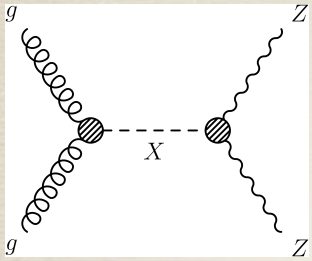




- Main backgrounds: Z+jets, ttbar, W+jets (shape from MC, normalisation from CR)
- Maximum likelihood fit to m or $m_T$ separately for ggF and VBF (H->ZZ) or b-associated A production (A->Zh)

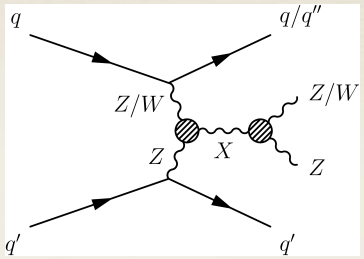
# Heavy neutral H->ZZ->llqq/ννqq

ATLAS-EXOT-2016-29
2015+2016, 36.1 fb$^{-1}$

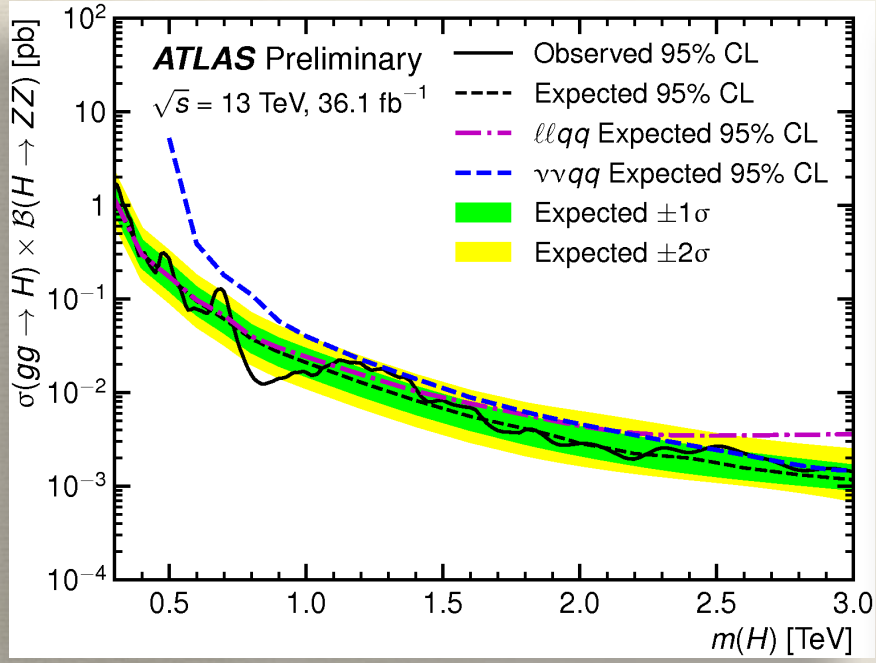
**Fit results:** Narrow width ggF and VBF signal hypotheses tested

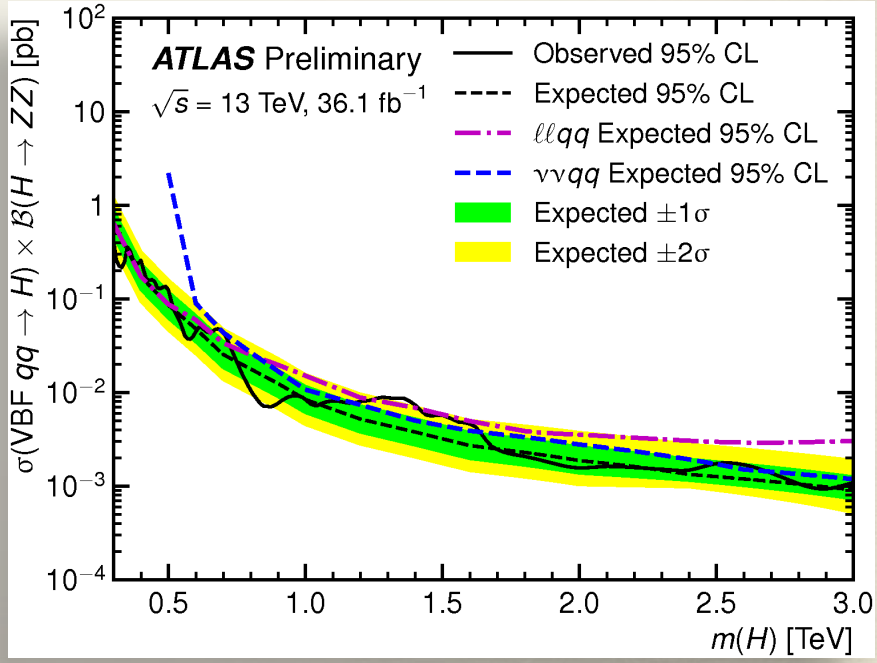



ggF




VBF



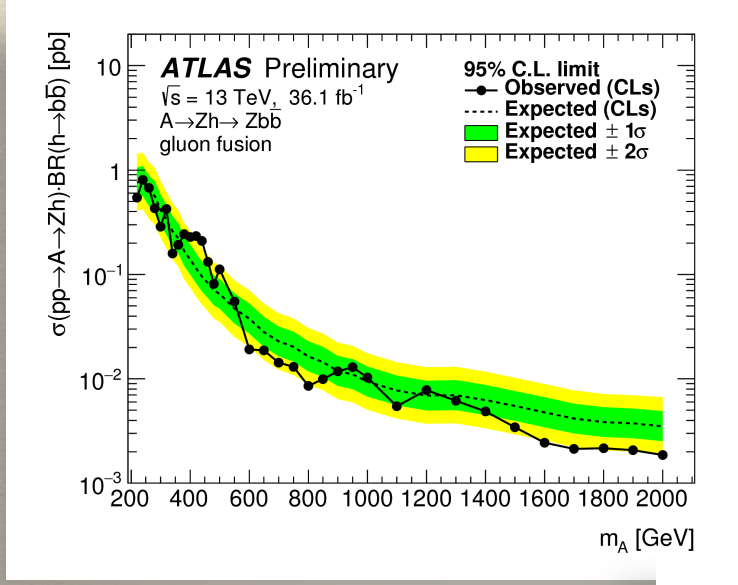




A 3.0 σ local deficit observed ~800 GeV, corresponding to 1.9 σ global (look elsewhere).

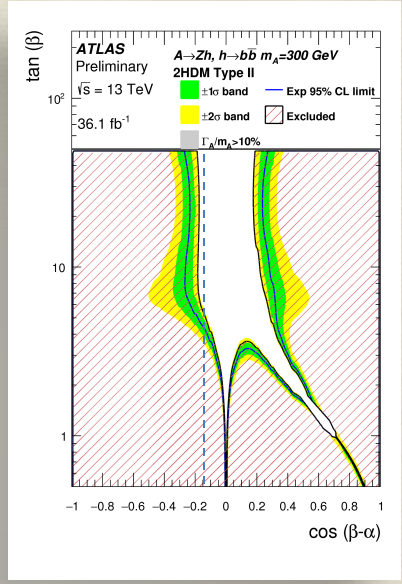
# CP-odd A->ZH->llbb/ννbb

ATLAS-CONF-2017-055
2015+2016, 36.1 fb$^{-1}$

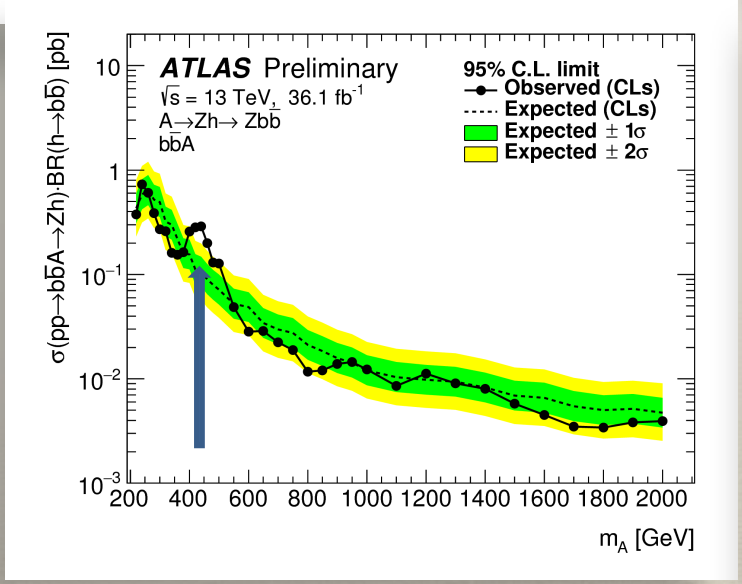
## Fit results:

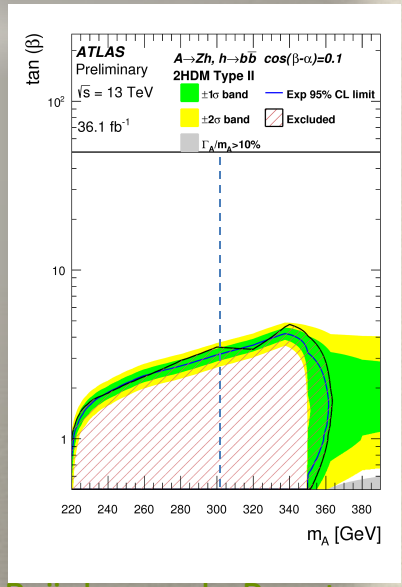



- The σxBR limits combine both the 0-lepton and 2-lepton channels.
- The 2HDM exclusions based on combination of ggF and bb-associated production.




Mild excess around 440 GeV, mainly driven by the 2-lepton di-muon channel in the resolved category with 3+ *b*-tags, with the local (global) significance of 3.6 σ (2.4 σ).

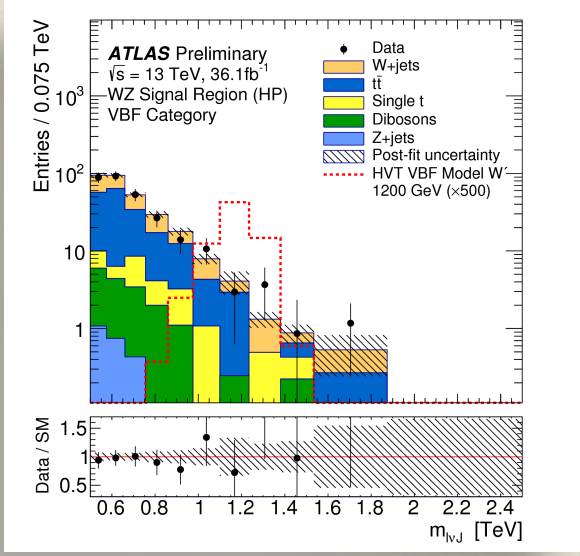


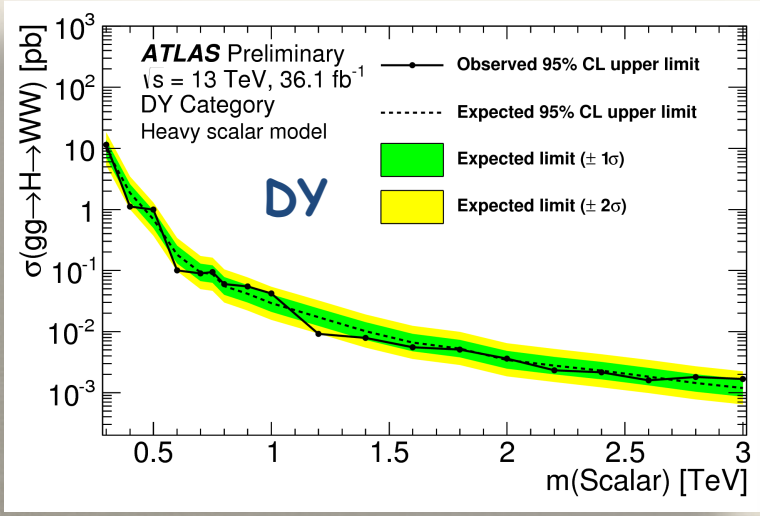
# Heavy neutral H->WW->lνqq

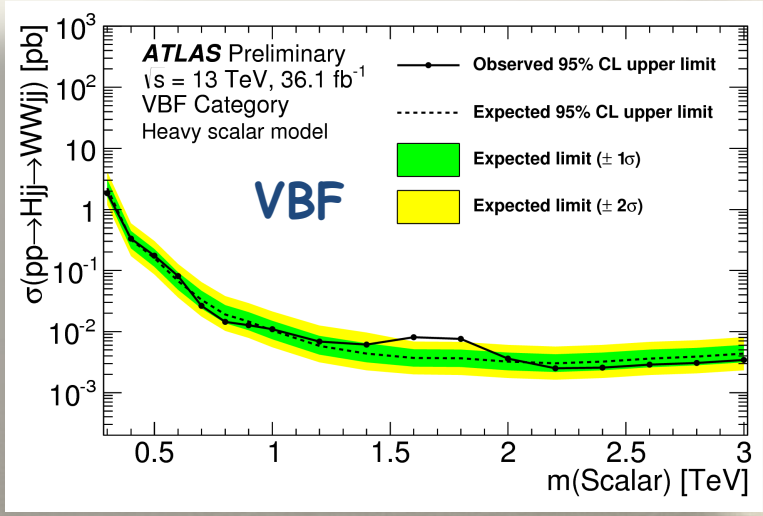
ATLAS-CONF-2017-051
2015+2016, 36.1 fb$^{-1}$

- Isolated lepton + MET + jj/J (Resolved/Boosted)
- Improved jj mass resolution using both calo & track information
- **DY(ggF&qq)** and **VBF:** two forward jets with high $\Delta\eta_{jj}$ & $m_{jj}$
- Main background W+jets (>50%) then ttbar. MC normalized from simultaneous fit to $m_{WW}$ in SR and CR (W+jets, ttbar)
- CR orthogonal in $m_{jj}$ or $m_J$/D2
- $m_{WW}$ from $m_W$ constraint on lν system.
- Narrow width 300< $m_H$ <3000 GeV Drell-Yan and VBF signal hypotheses tested with profile-likelihood-ratio fit:




No significant deviation from the SM background observed.



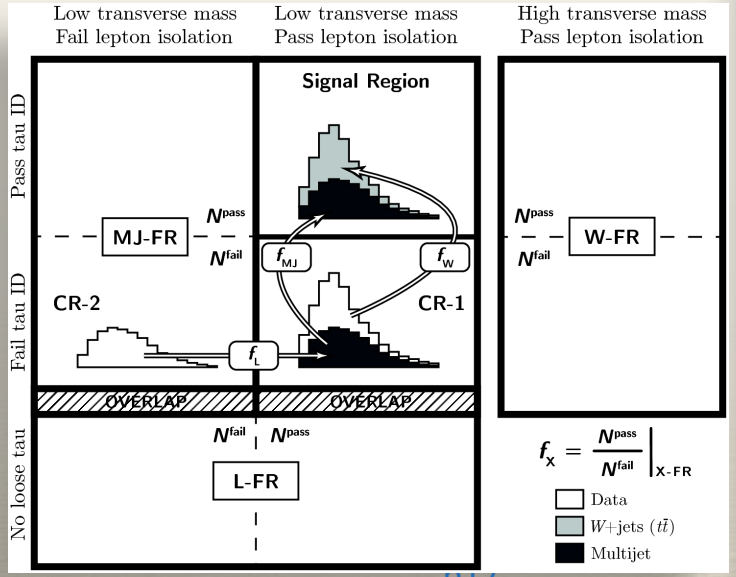

(compl. **H->WW->lνlν** out soon!)

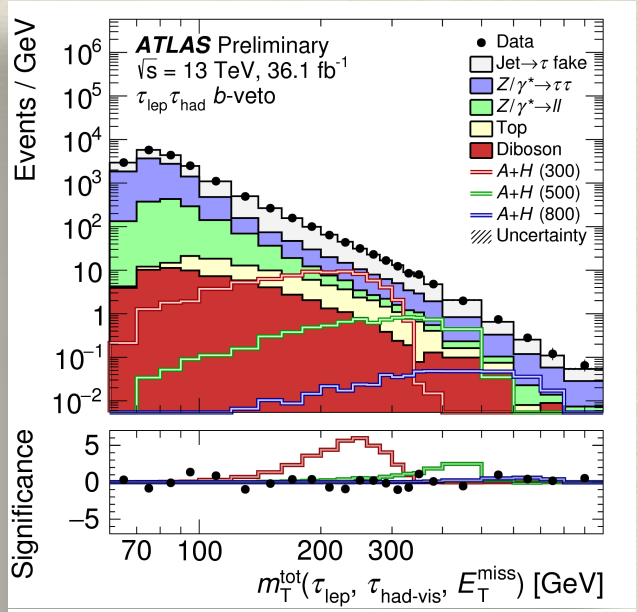
# BSM Higgs -> fermions

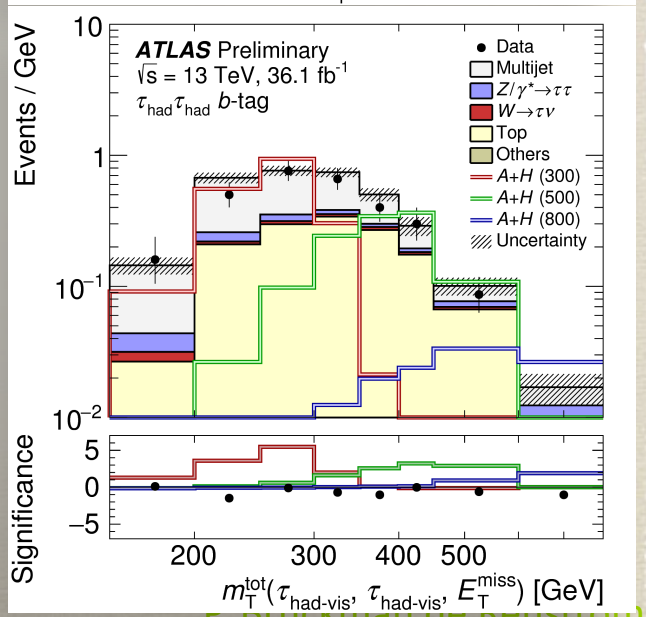
# Heavy neutral Higgs->ττ

ATLAS-CONF-2017-050
2015+2016, 36.1 fb$^{-1}$

- Generic search for ττ resonance across a wide range of masses: 200 GeV<$m_{\tau\tau}$<2250 GeV
- Analysis optimised for two hypotheses: spin 0 (H/A) and spin 1 (Z')
- $\tau_{lep}\tau_{had}$ search channel:
  - Trigger-matched lepton and a $\tau_{had}$,
- $\tau_{had}\tau_{had}$ search channel:
  - Trigger-matched tau, pt(τ)>65 GeV
- **B-tag** and **B-veto** categories
- Background dominated by jet->τ in W+jets and ttbar (QCD) for $\tau_{lep}\tau_{had}$ ($\tau_{had}\tau_{had}$) searches and is estimated using the fake-factor method:



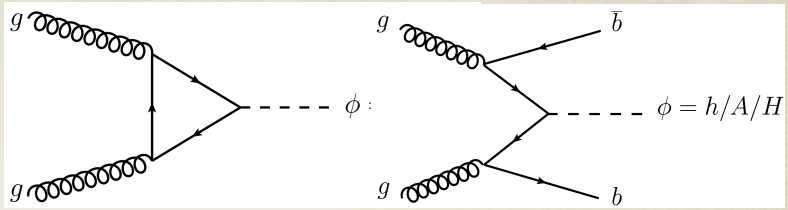



# Heavy neutral Higgs->ττ

ATLAS-CONF-2017-050
2015+2016, 36.1 fb$^{-1}$

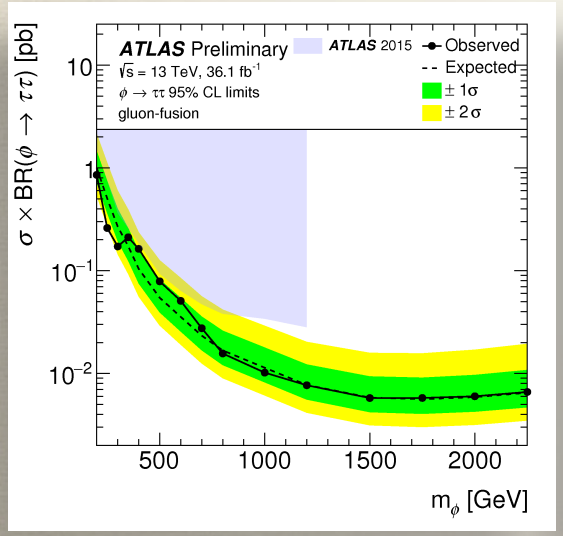
**Fit results**:

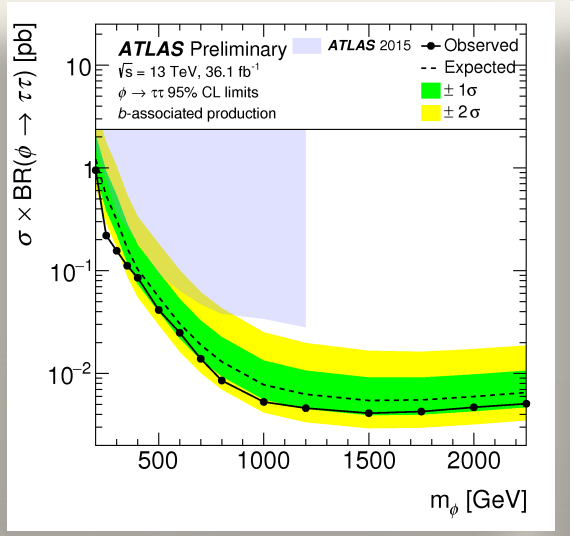
- Likelihood fits separately for b-veto and b-tag categories to enhance sensitivity to ggF and b-associated production.

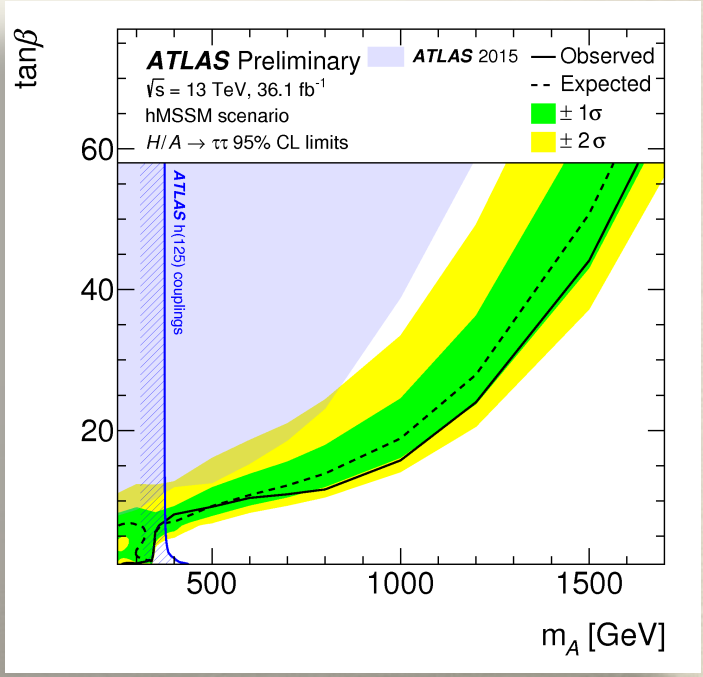



- The 2HDM exclusion based on combination of ggF and b-associated limits.
- Both $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels use $m_T$ as the discriminant variable:

$$m_T^{tot} \equiv \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{miss})^2 - (\mathbf{p}_T^{\tau_1} + \mathbf{p}_T^{\tau_2} + \mathbf{E}_T^{miss})^2}$$



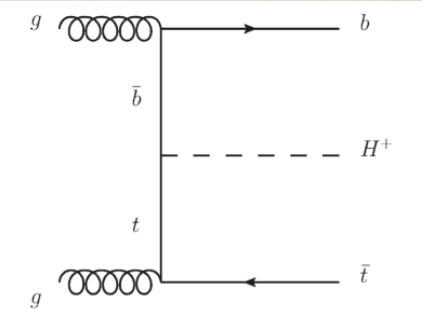




- Exclusion limits much improved w.r.t. 2015 results.

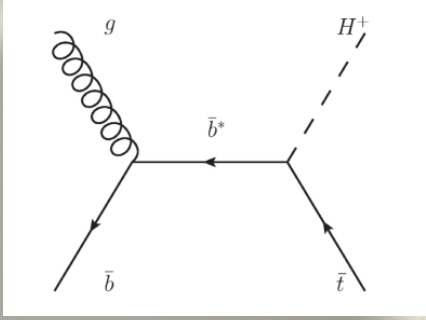
# Search for $H^+/H^{++}$

# Charged Higgs

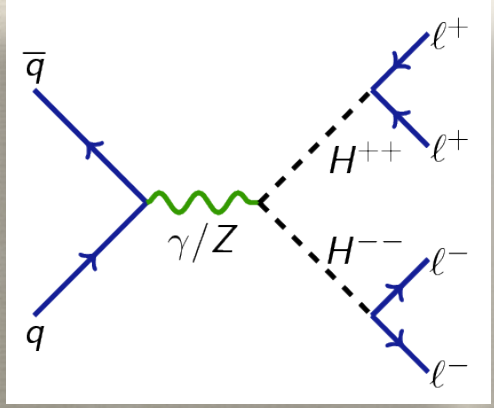
- A charged scalar of the EWSB sector would spectacularly sign BSM. Needed with more than one HD (notably SUSY).

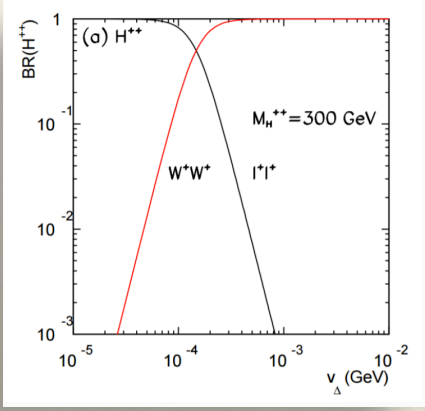


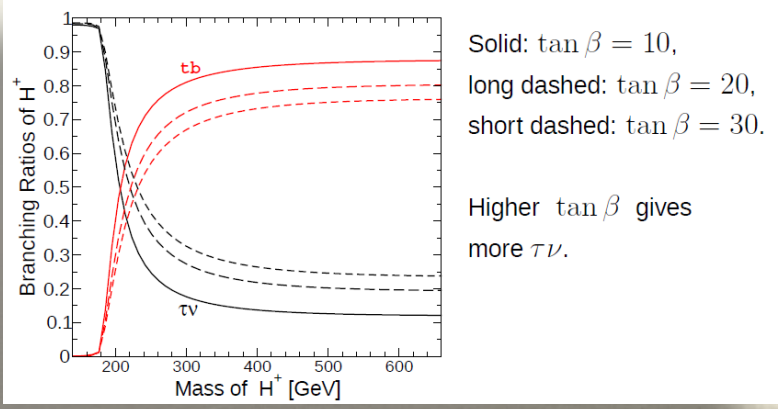

- $H^+$ tagged together with the accompanying top.
- Within MSSM BR($H^+ \to \tau\nu$) saturates the decay for $m_H < m_t$ and remains significant in large range of masses for high tan(β).
- For low tan(β) $H^+ \to tb$ dominates for $m_H > m_t$




- $H^{++}$ assumed to be pair-produced (Triplet models).
- $H^{++} \to l^+l^+$ ($W^+W^+$) probes the low(high) $\nu_\Delta$ range (LRSM)



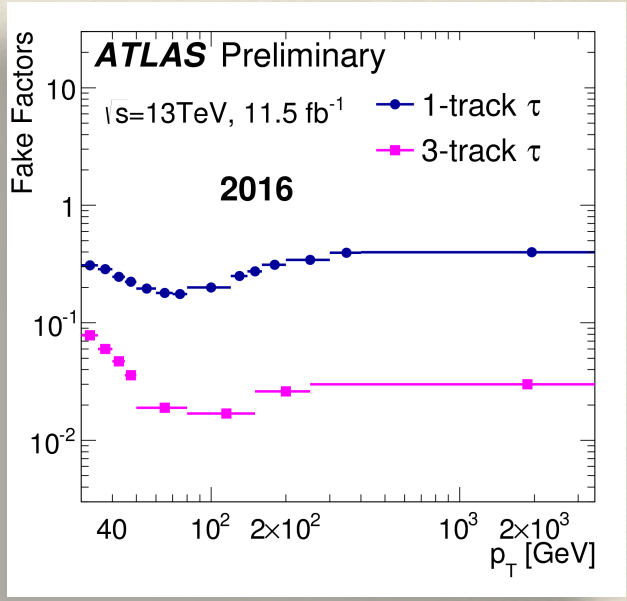

Solid: $\tan\beta = 10$,
long dashed: $\tan\beta = 20$,
short dashed: $\tan\beta = 30$.

Higher $\tan\beta$ gives more $\tau\nu$.

# Charged $H^+ \to \tau\nu \to \tau_{had}$+jets

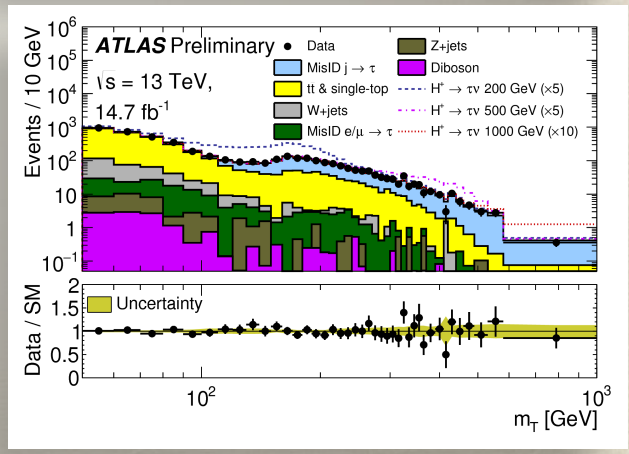
ATLAS-CONF-2016-088
2015+2016, 14.7 $fb^{-1}$

- Search in the high $m_{H+}$ mass region (200-2000 GeV) assuming the top-associate $H^+$ production and fully hadronic top decays.
  - MET trigger, hadronic $\tau$ with $p_T$>40 GeV, $\geq$ 3jets with $p_T$>25 GeV (+b-tag), MET>150 GeV
- Main backgrounds ttbar, W+jets and jet->$\tau$ from multi-jet. All but jet->$\tau$ from MC and validated in CR's. jet->$\tau$ from data using fake-factor method. FF's extracted in the QCD CR (b-veto, MET<80 GeV)




- Limit based on profile likelihood fit to the $m_T(\tau, \text{MET})$ distribution:

$$m_T = \sqrt{2 p_T^{\tau} E_T^{miss} (1 - \cos \Delta\phi_{\tau, E_T^{miss}})},$$

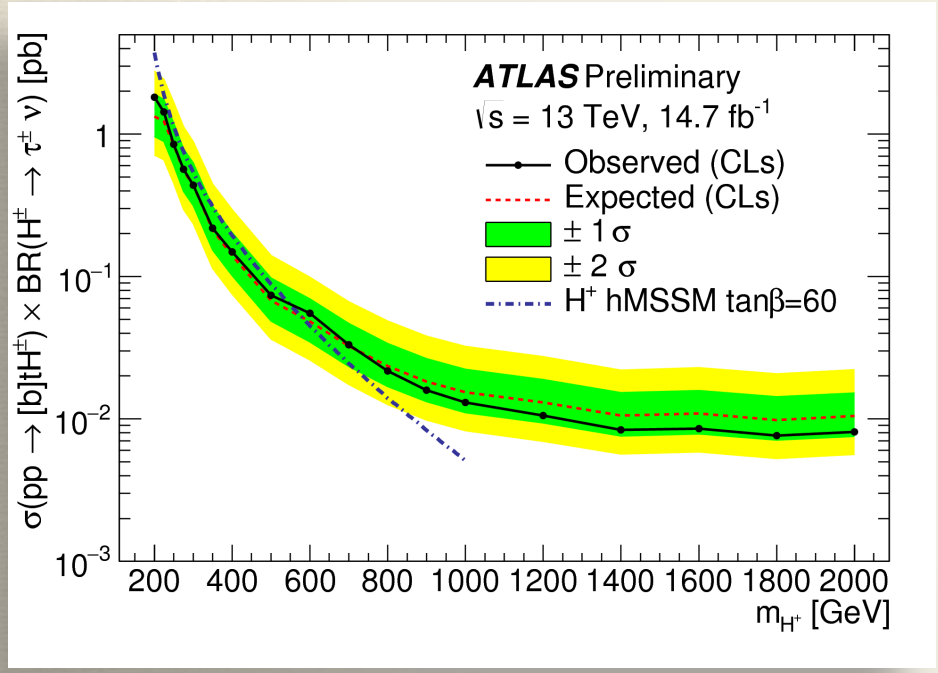


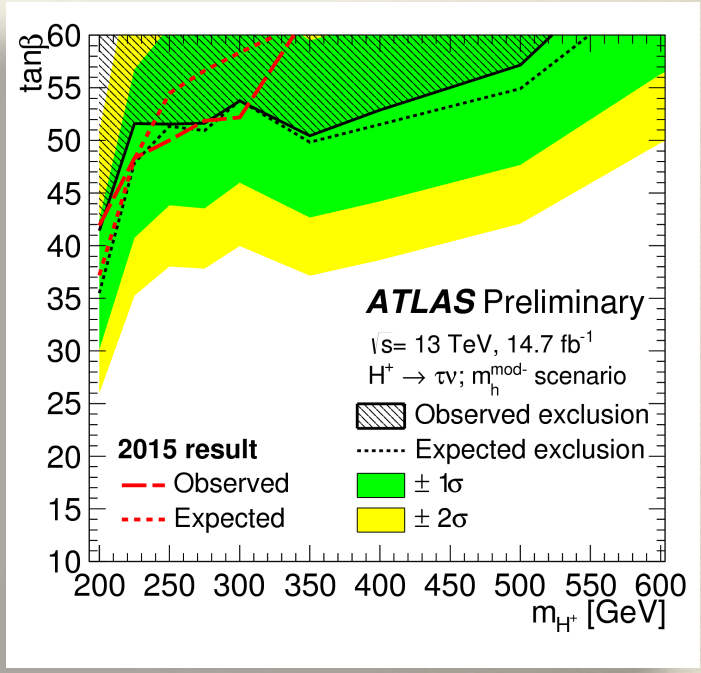
# Charged $H^+ \to \tau\nu \to \tau_{had}$+jets

ATLAS-CONF-2016-088
2015+2016, 14.7 $fb^{-1}$

## Fit results:

- Exclusion limits given in various flavours of MSSM models.
- Here $m_h^{mod-}$ scenario exmpl.:



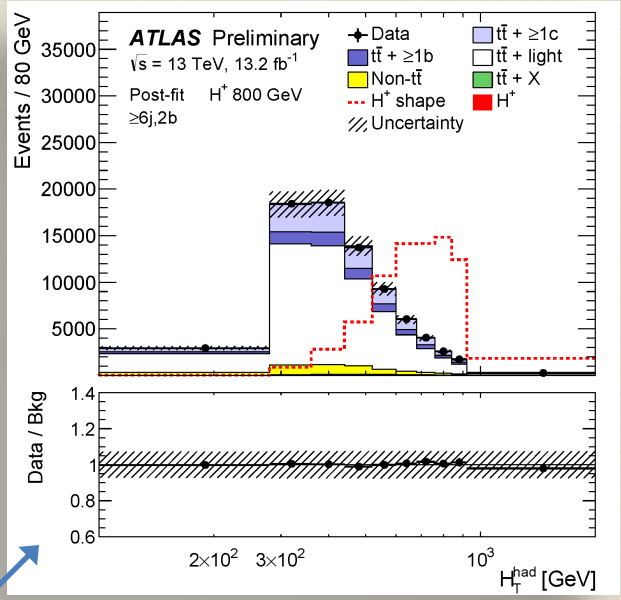



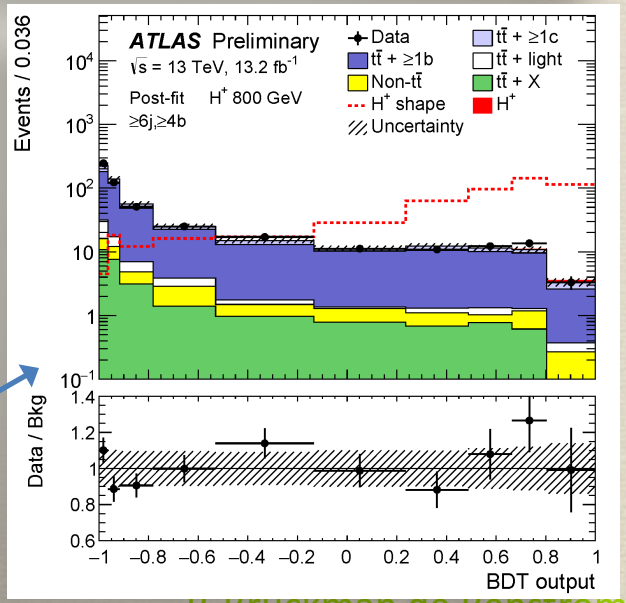

The result is based on 14.7 $fb^{-1}$ data (ICHEP 2016). Update to the full 2015+2016 data set with substantial improvements is now imminent.

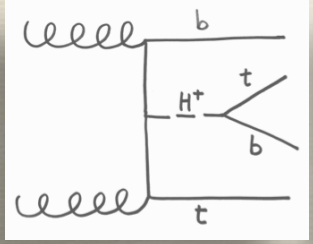
# Charged $H^+ \to tb \to l$+jets

ATLAS-CONF-2016-089
2015+2016, 14.7 $fb^{-1}$

- Search in the high $m_{H+}$ mass region (300-1000 GeV) assuming the top-associate $H^+$ production.
- Trigger-matched lepton + 6 jets (4 b-jets!)
  - Isolated lepton (e or m) with $p_T$>25 GeV, ≥ 4jets with $p_T$>25 GeV, ≥ 2 b-tagged (70% eff.), τ veto
- Main background ttbar+b-jets. Modelled from MC (Powheg+Pythia) with normalization free in the fit.
- Simultaneous profile likelihood fit to SR (BDT) and CR $H_T^{had}$. ttbar+c/b free in the fit.



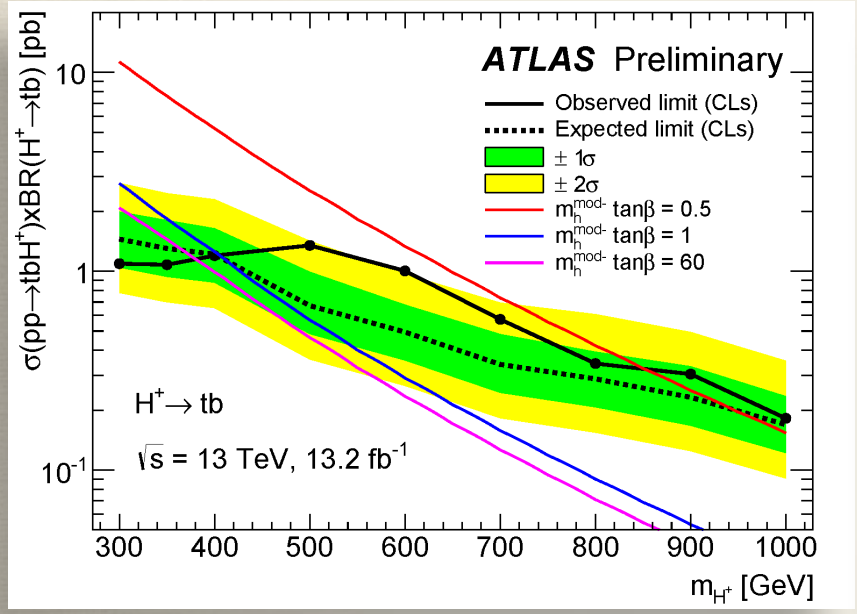

| | 2b | 3b | ≥4b |
|---|---|---|---|
| 4j | CR | CR | |
| 5j | CR | SR | SR |
| ≥6j | CR | SR | SR |

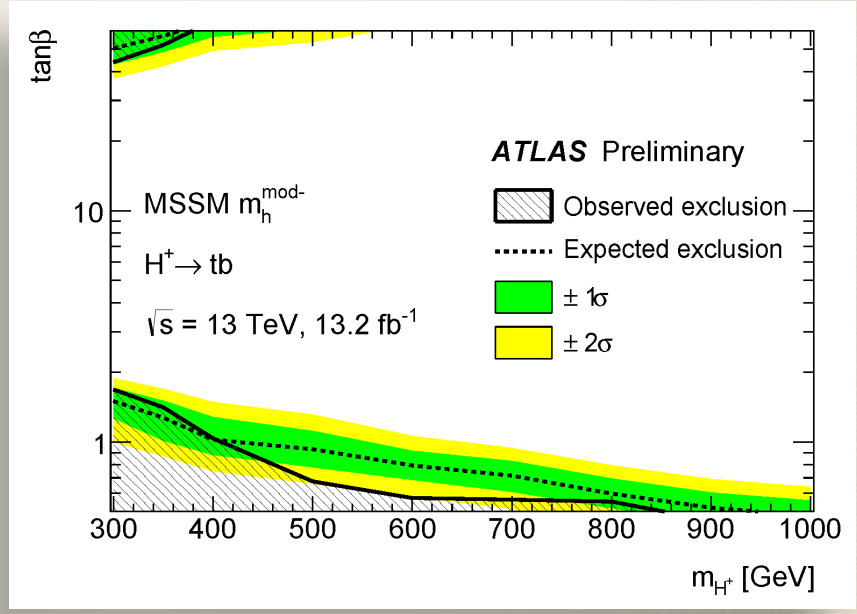
# Charged $H^+ \to tb \to l+jets$

ATLAS-CONF-2016-089
2015+2016, 14.7 $fb^{-1}$

## Fit results:

- Exclusion limits given in various flavours of MSSM models.
- Here $m_h^{mod-}$ scenario exmpl.:



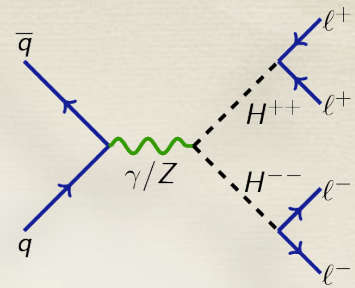



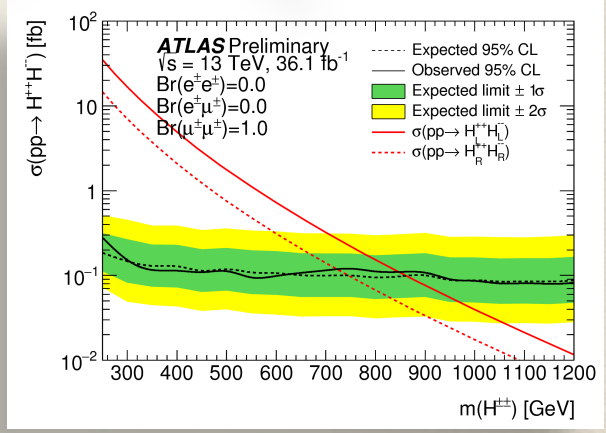

The result is based on 14.7 $fb^{-1}$ data (ICHEP 2016). Update to the full 2015+2016 data set with substantial improvements is now imminent.

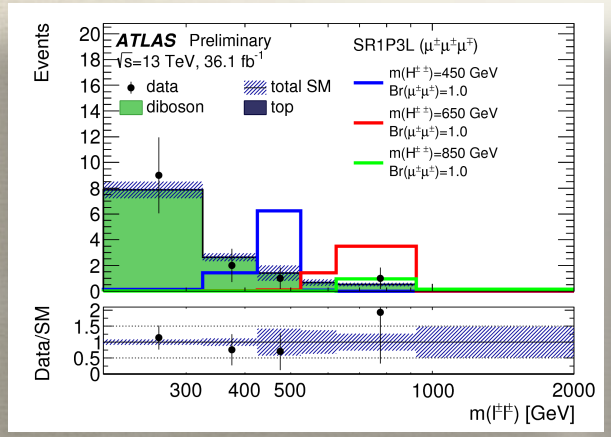
# Doubly charged $H^{++}$->$l^+l^+$

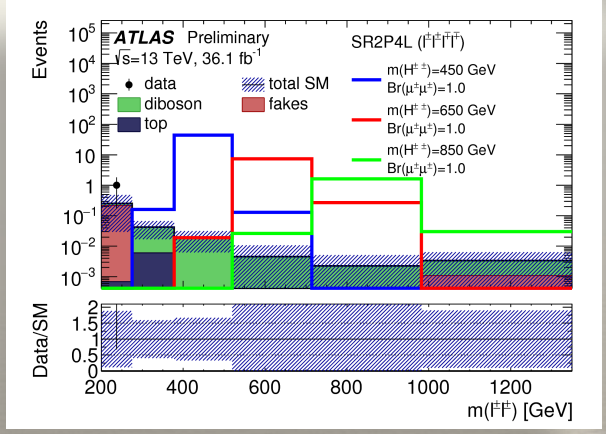
**ATLAS-CONF-2017-053**
2015+2016, 36.1 $fb^{-1}$

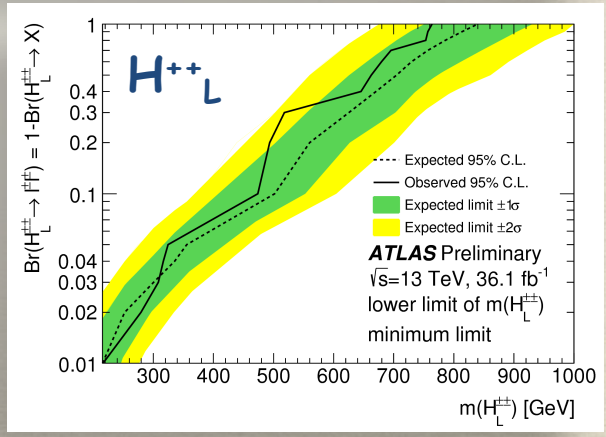
- Assumed D-Y pair-produced Higgses and targets low $\nu_\Delta$ LRSM when H++ decays quasi-exclusively to leptons (compl. **$H^{++}$->$W^+W^+$** out soon!)
- A search for same-charge isolated lepton pairs in the range: 250 GeV<$m_{ll}$<1200 GeV (ee, eμ, μμ)
- 2,3-lepton: m($l^+l^+$), 4-lepton: mean $m^{1,2}$($l^+l^+$)
- Background: di-boson (MC with charge mis-id. from data) and fake lepton from 'fake factor'.



# CONCLUSIONS

- ATLAS conducted a wide variety of searches for BSM scalar particles (CP-even and CP-odd H, singly and doubly charged Higgses)
- Most results based on the full 2015+2016 dataset (remaining are being updated as we speak)
- No evidence for BSM phenomena in the scalar sector.
- Analyses managed to place exclusion limits on various BSM scenarios (notably 2HDM, MSSM).
- By the end of Run 2, we will be looking into x4 larger dataset, so should double our statistical sensitivity.

**2017 data is being collected. Stay tuned!**

**THANK YOU.**

# BONUS MATERIAL

# 2HDM Models

- ❖ Generic class implementing a second Higgs doublet.
- ❖ Variants depend on specific coupling scheme:

**Type I**: One doublet couples to vector bosons, the other couples to fermions.
**Type II**: one doublet couples to up-type quarks, the other to down-type quarks and leptons: „MSSM -like"
**Lepton-specific**: couplings to quarks as in the Type I model and to leptons as in Type II.
**Flipped**: couplings to quarks as in the Type II model and to leptons as in Type I.

$$\tan\beta \equiv v_2/v_1 \qquad g_{hVV}^{2HDM}/g_{hVV}^{SM} = \sin(\beta-\alpha)$$

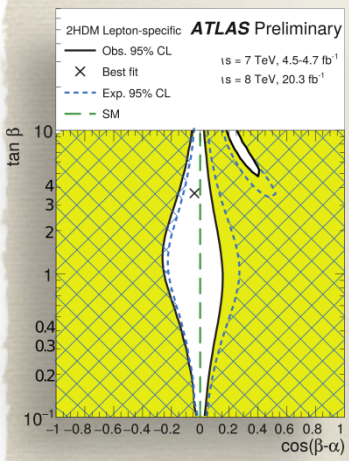
$$v_1^2 + v_2^2 = \bar{v}^2 \approx (246\ \mathrm{GeV})^2 \qquad g_{HVV}^{2HDM}/g_{HVV}^{SM} = \cos(\beta-\alpha)$$

| Coupling scale factor | Type I | Type II | Type III | Type IV |
|---|---|---|---|---|
| $\kappa_V$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ |
| $\kappa_u$ | $\cos(\alpha)/\sin(\beta)$ | $\cos(\alpha)/\sin(\beta)$ | $\cos(\alpha)/\sin(\beta)$ | $\cos(\alpha)/\sin(\beta)$ |
| $\kappa_d$ | $\cos(\alpha)/\sin(\beta)$ | $-\sin(\alpha)/\cos(\beta)$ | $\cos(\alpha)/\sin(\beta)$ | $-\sin(\alpha)/\cos(\beta)$ |
| $\kappa_l$ | $\cos(\alpha)/\sin(\beta)$ | $-\sin(\alpha)/\cos(\beta)$ | $-\sin(\alpha)/\cos(\beta)$ | $\cos(\alpha)/\sin(\beta)$ |

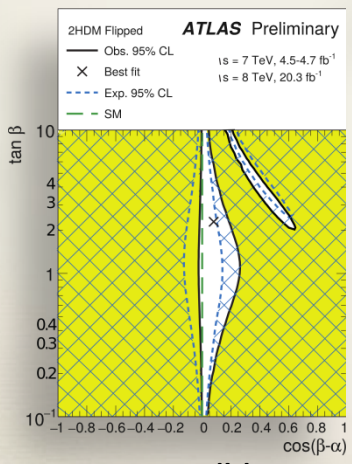
# 2HDM Models

- „Decoupling": A, $H^0$, $H^\pm$ much heavier than the light h.
- h looks pretty much like a SM Higgs („Alignment")
- Decoupling is not necessary.
- $\cos(\beta-\alpha)\rightarrow 0$ realizes Alignment.

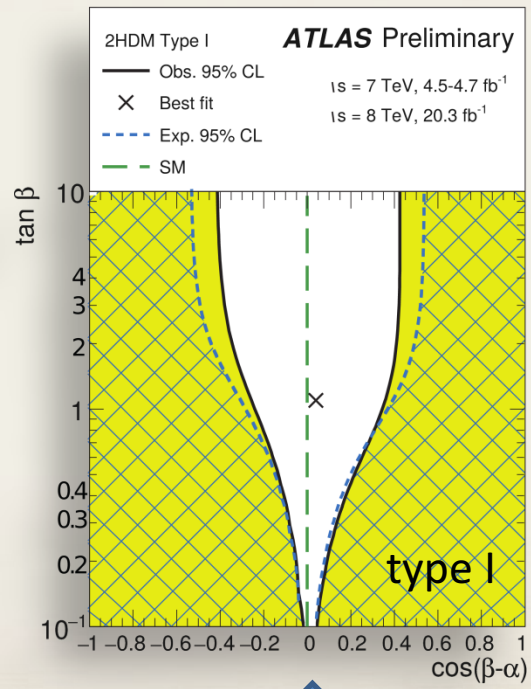
Inverted coupling to down-type fermions ($\tau$,*b*)

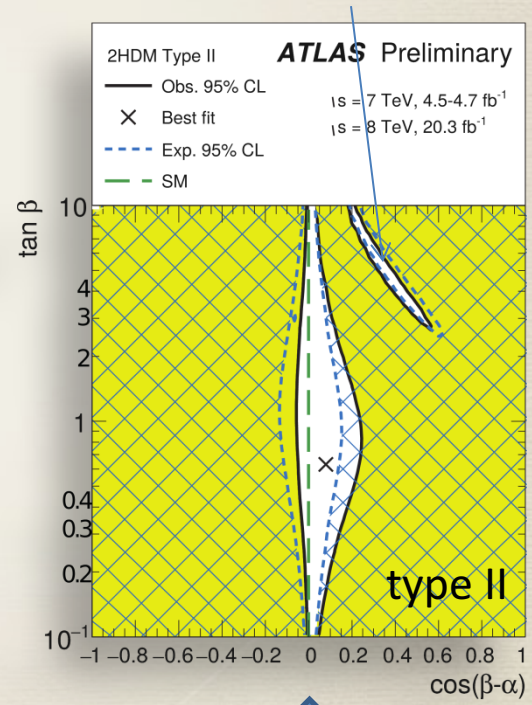



type III
(lepton specific)




type IV
(flipped)




„Alignment"
h recovers properties of the SM Higgs