Searches for additional Higgs bosons in the MSSM with the ATLAS detector

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On behalf of the ATLAS collaboration

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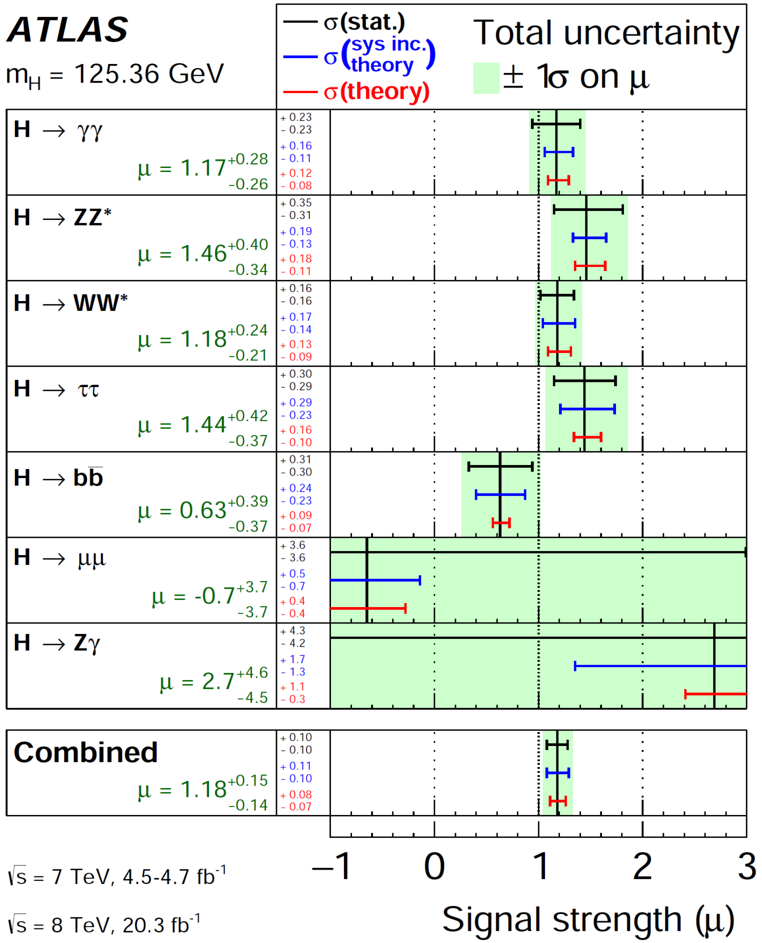
Introduction

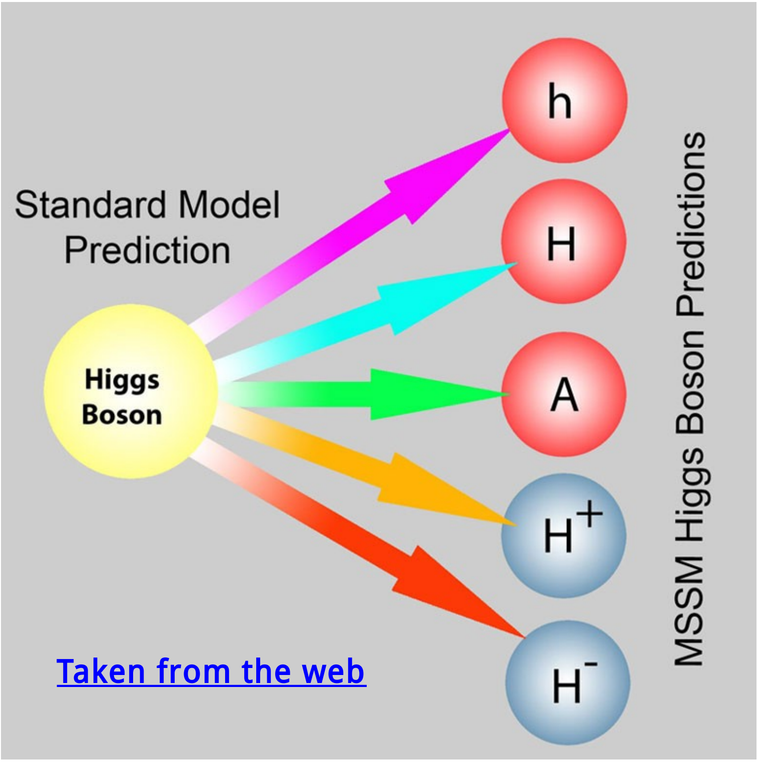
Discovery of a new scalar in 2012 at the LHC at m_h= 125 GeV.

- Masses, spin/parity and couplings compatible with the SM Higgs boson.

Possibility that there are more Higgs bosons → Still not ruled out by measurements.

In the MSSM, two Higgs doublets $\Phi_u = (\Phi^+_u, \Phi^0_u)$ and $\Phi_d = (\Phi^0_d, \Phi^-_d)$ → 5 mass eigenstates: h (SM Higgs), H, A, H^+,H^-



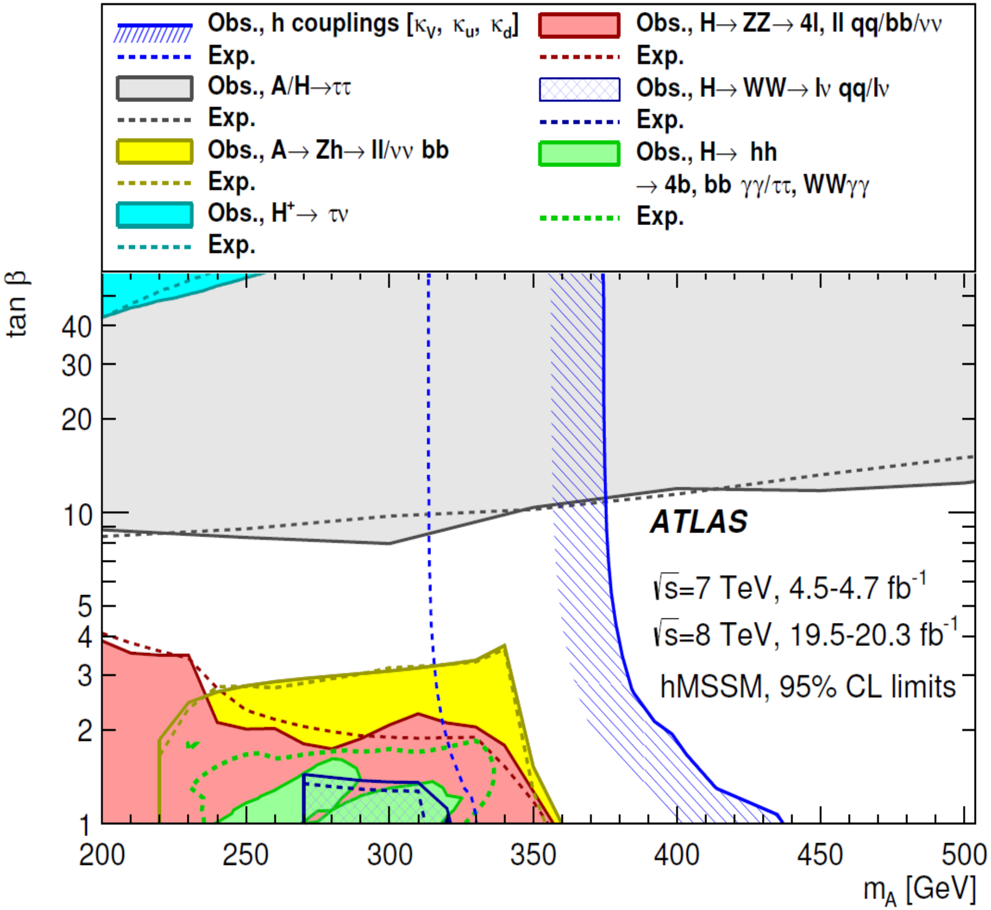


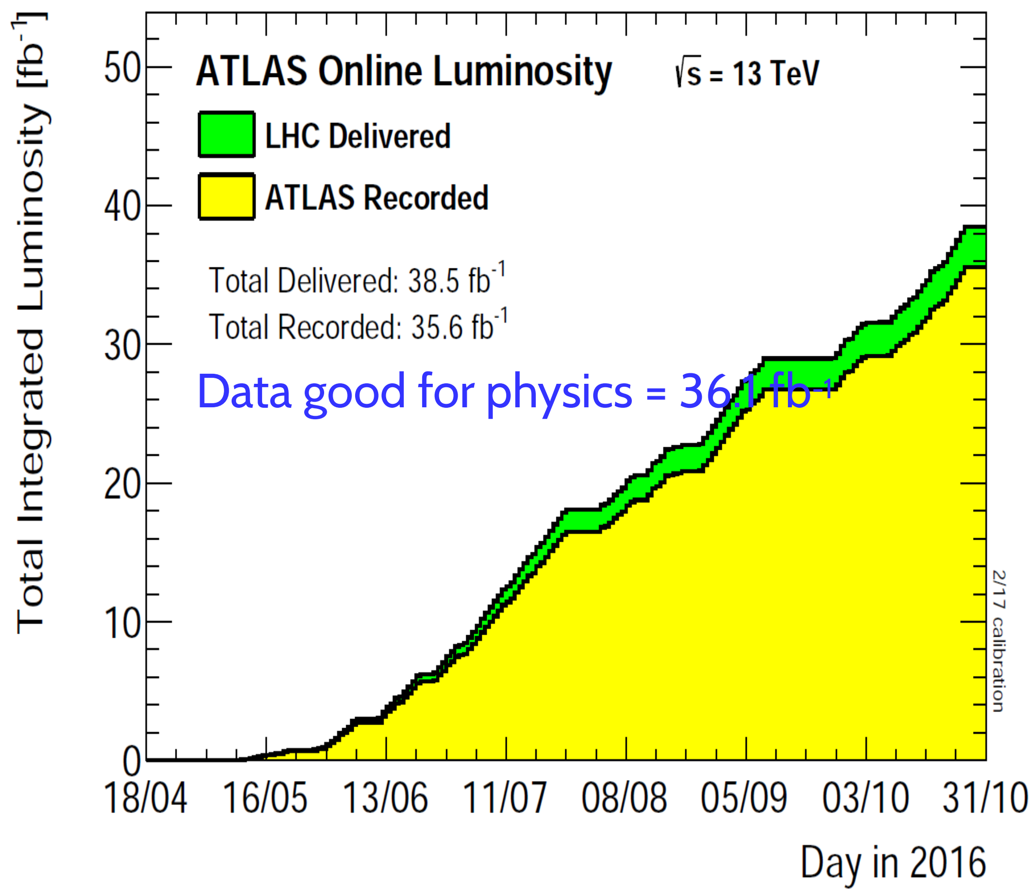
Run I legacy

No new resonances were found during Run I. Main interpretation using hMSSM → Phenomenology approximately described by tanβ and m_A .

In Run II, results are public with partial 2015+2016 dataset or full 2015+2016 luminosity (36.1 fb^{-1})

Focusing on charged Higgs and A/H searches → High-mass searches/di-Higgs/Higgs couplings talks during the workshop.





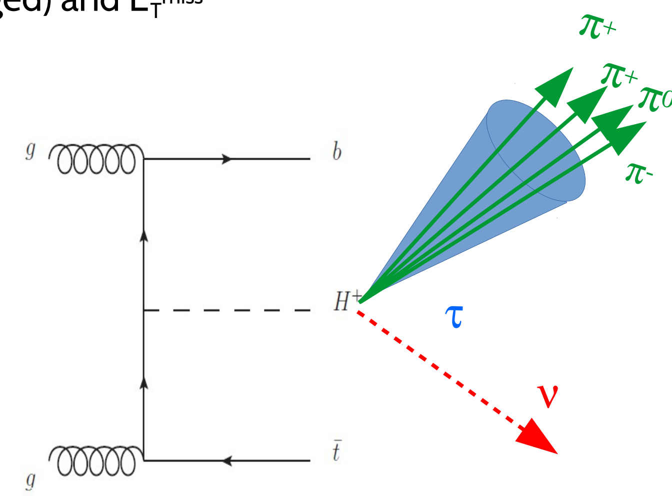
Charged Higgs searches : $H^{+,-} \rightarrow \tau \nu$

ATLAS-CONF-2016-088

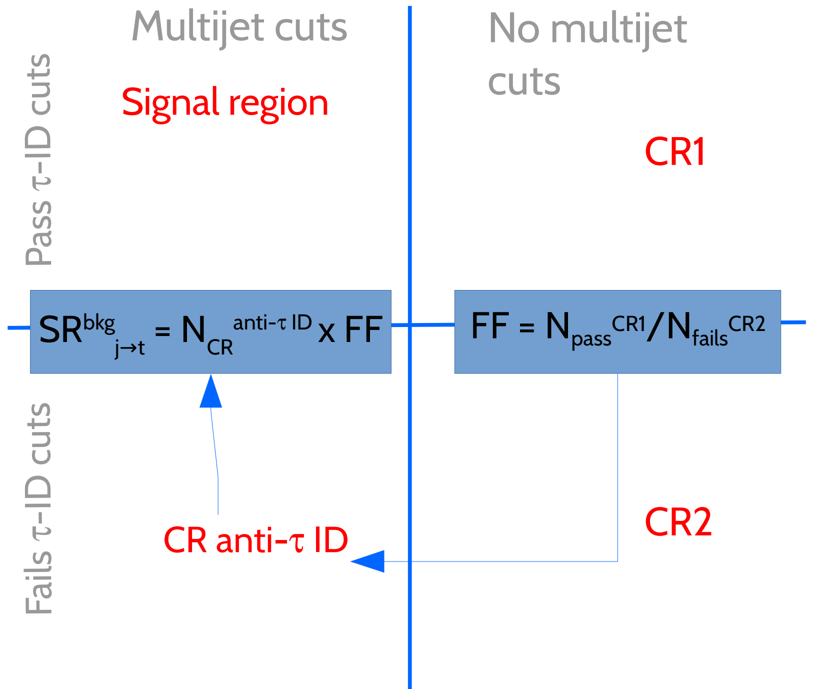
$\mathcal{L}$ = 14.7 fb^{-1}

Final state with hadronic τ's and at least 3 jets from tbH+ production (at least 1b-tagged) and E_T^{miss}

- Main backgrounds are the $t\bar{t}$, jet → τ, W → τν and Z → ττ.
  - Data-driven jet → τ fake factors estimated on multijet enriched CRs.
  - e/μ misidentification rate estimated on Z → ee events.
  - Other backgrounds: shape from simulation and validated in data control regions.
- Main uncertainties related to jet → τ fake factors, jet energy scale and tt parton shower model.



Sample	Event yield	Syst.	Stat.
True τ_{had}			
$t\bar{t}$ & single-top-quark	2880	± 770	± 25
$W \rightarrow \tau\nu$	265	± 51	± 18
$Z \rightarrow \tau\tau$	43	± 6.8	± 7.6
diboson (WW, WZ, ZZ)	13.8	± 2.2	± 1.7
Misidentified e, $\mu \rightarrow \tau_{\text{had-vis}}$	126	± 24	± 6.5
Misidentified jet $\rightarrow \tau_{\text{had-vis}}$	1170	± 110	± 16
All backgrounds	4500	± 800	± 36
H^+ (200 GeV), hMSSM $\tan\beta = 60$	523	± 86	± 4
H^+ (1000 GeV), hMSSM $\tan\beta = 60$	7.5	± 0.6	± 0.05
Data	4645		



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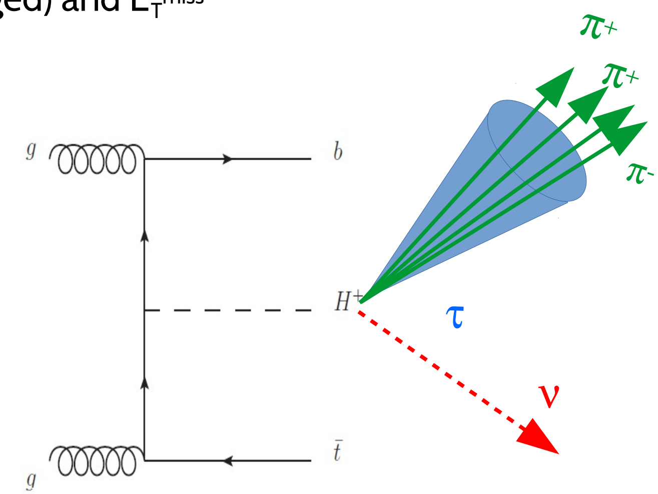

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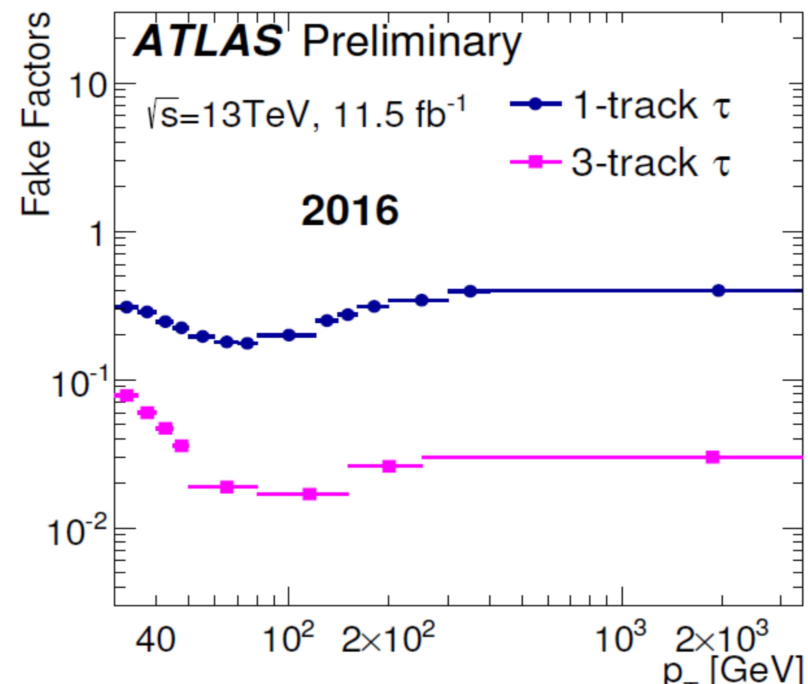
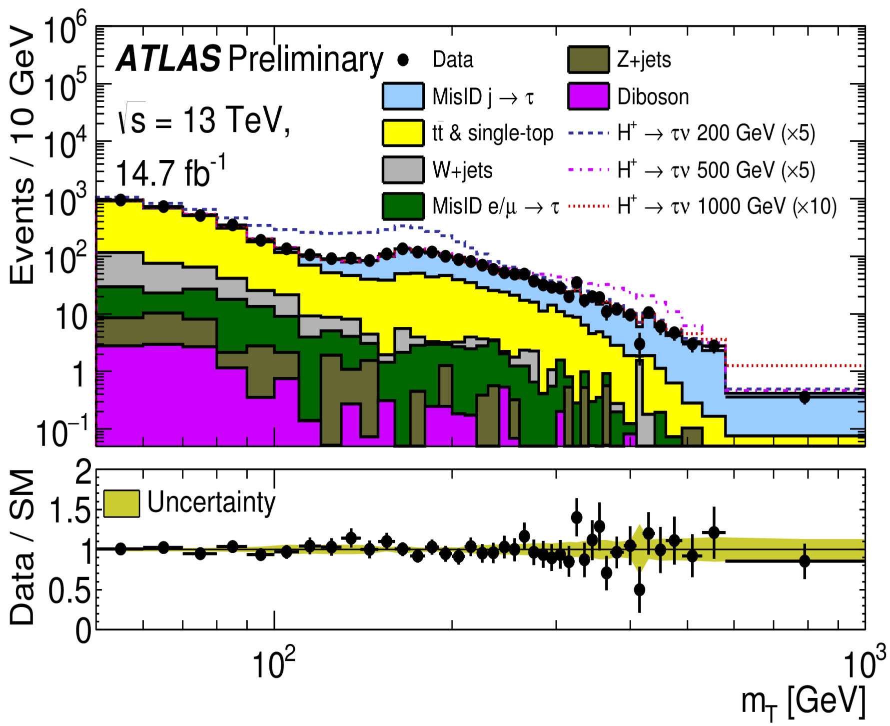
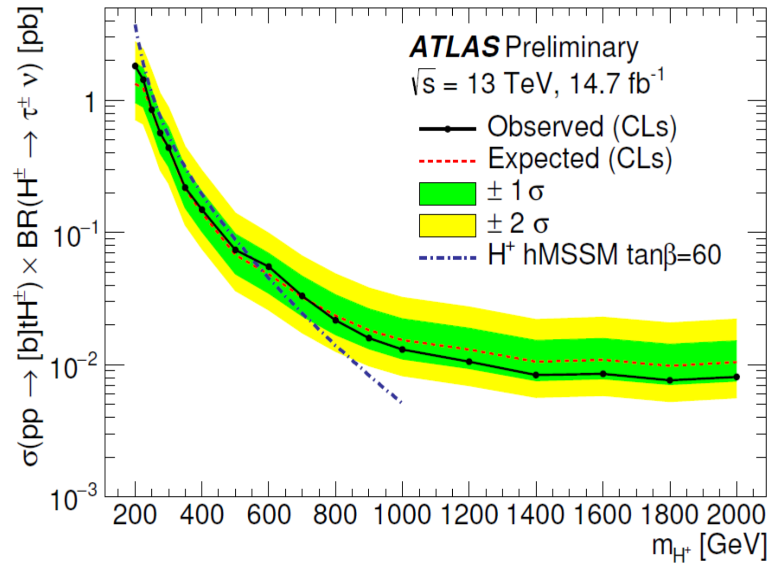


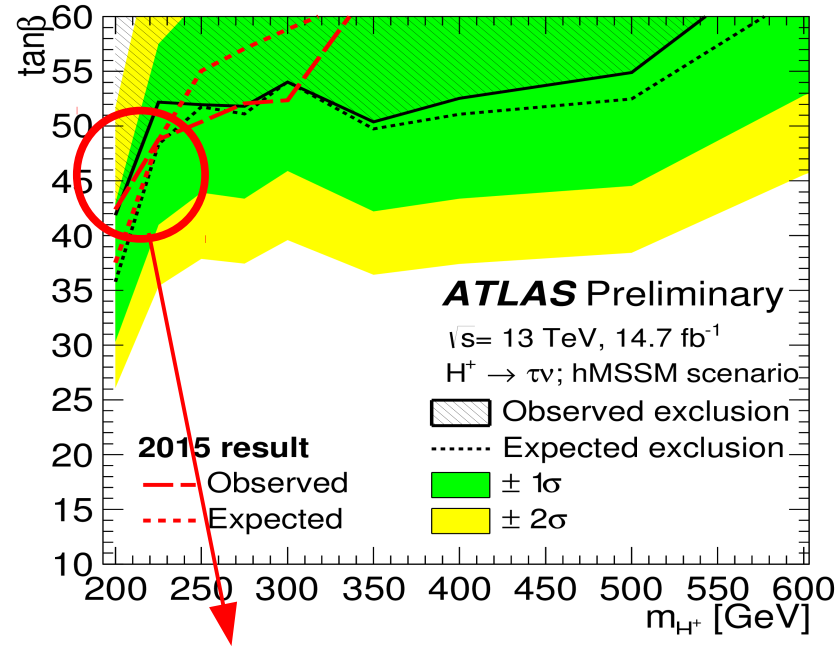
Charged Higgs searches : $H^{+,-} \rightarrow \tau\nu$ ATLAS-CONF-2016-088

- Fits on SR m_T distribution defined to get one medium ID hadronic τ plus E_T^{miss} and b-jets.
- No BSM is observed → Limits on cross-section



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





Due to different μ_R and μ_F in simulated samples

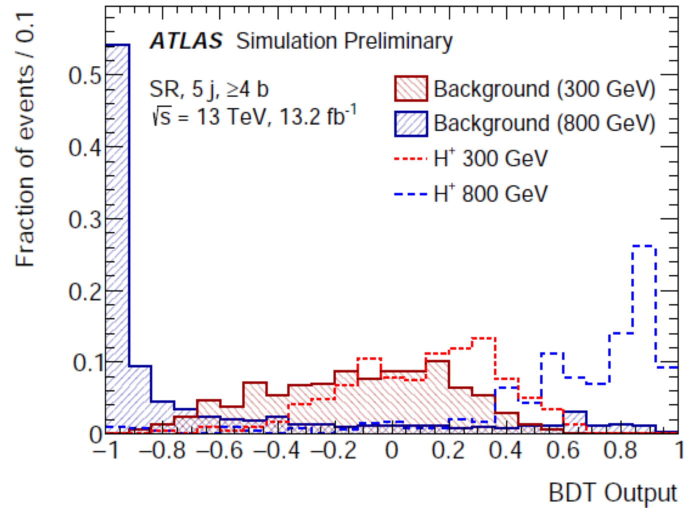
Charged Higgs searches : $H^{+,-} \rightarrow tb$

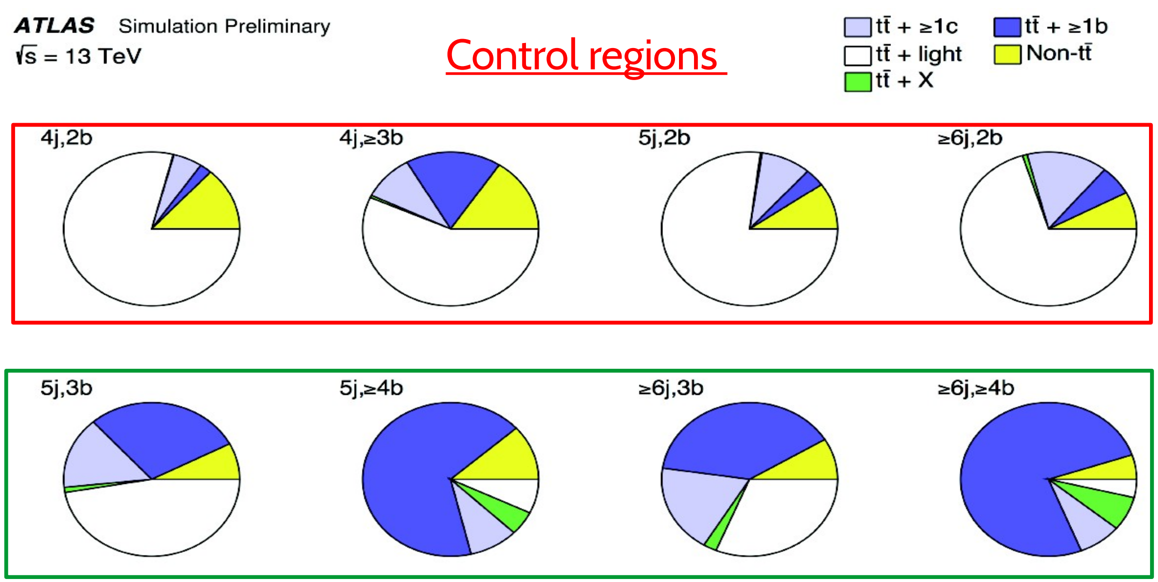
ATLAS-CONF-2016-089

$\mathcal{L}$ = 13.2 fb^{-1}

Similar production than $H^{+} \rightarrow \tau\nu$ → Final state: 2 top-quark and 2-b-quarks

- At least 4 jets, at least two b-jets and 1 lepton.
- Main background is $t\bar{t}$: divided according to additional jet flavour.
- Profit of the high number of jets and b-jets in the signal.
  - Define SRs and CRs depending of the N_{bjet} and N_{jet}
  - Trained BDTs for each simulated signal
- Dominated by tt+1b modeling, normalization and b-tagging efficiency





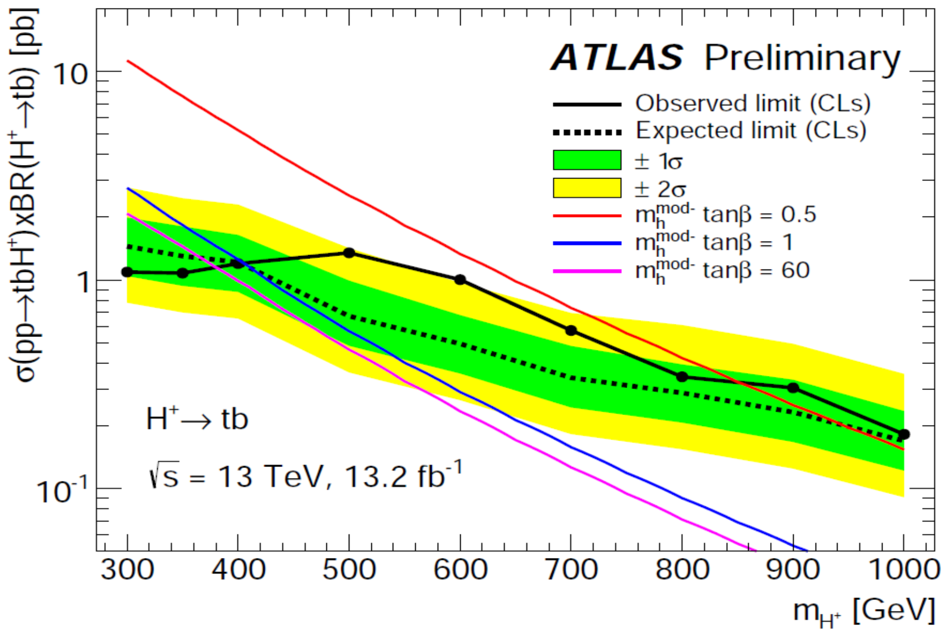
Signal regions

Uncertainty Source	$\Delta\mu(H^{+}_{300})$		$\Delta\mu(H^{+}_{800})$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53	+0.07	−0.07
Jet flavour tagging	+0.30	−0.29	+0.07	−0.07
$t\bar{t}+\geq 1c$ modelling	+0.23	−0.22	+0.03	−0.03
Background model statistics	+0.19	−0.19	+0.05	−0.05
Jet energy scale and resolution	+0.18	−0.17	+0.03	−0.03
$t\bar{t}$+light modelling	+0.16	−0.16	+0.03	−0.03
Other background modelling	+0.15	−0.14	+0.03	−0.03
Jet-vertex association, pileup modelling	+0.12	−0.11	+0.01	−0.01
Luminosity	+0.12	−0.12	+0.01	−0.01
Light lepton (e, μ) ID, isolation, trigger	+0.01	−0.01	< +0.01	< −0.01
Total systematic uncertainty	+0.72	−0.79	+0.13	−0.11
$t\bar{t}+\geq 1b$ normalisation	+0.36	−0.36	+0.03	−0.03
$t\bar{t}+\geq 1c$ normalisation	+0.15	−0.14	+0.02	−0.02
Total statistical uncertainty	+0.44	−0.43	+0.08	−0.08
Total	+0.84	−0.90	+0.15	−0.13

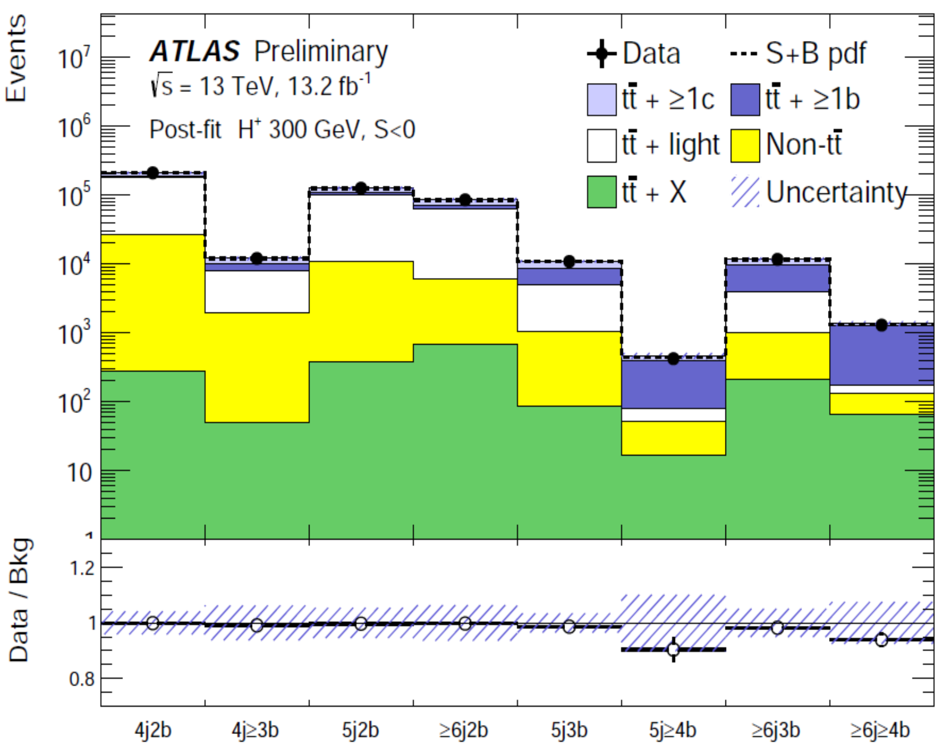
Charged Higgs searches : $H^{+,-} \rightarrow tb$

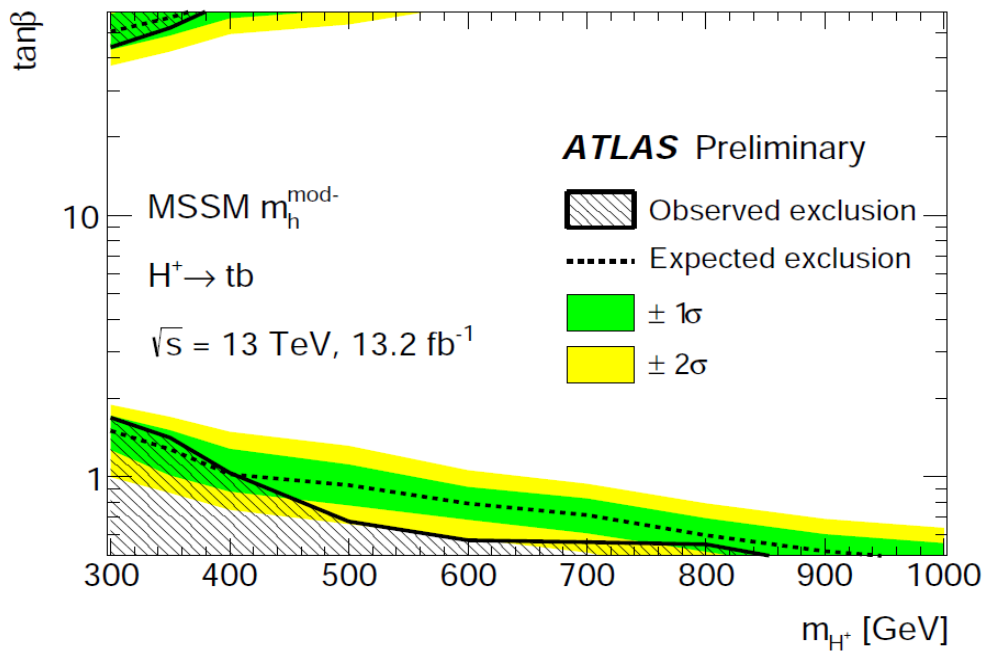
[ATLAS-CONF-2016-089]

- Simultaneous fit to all SRs and CRs distributions
  - Discriminant variable in SRs: BDTs
  - Discriminant variables in CRs: H_T^{had}



Post-fit N_{events} for CRs and SRs





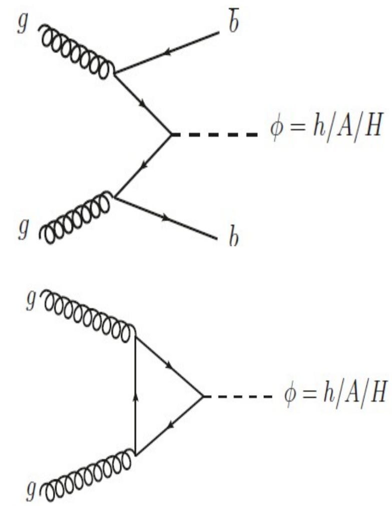
Neutral Higgs searches: H/A → ττ

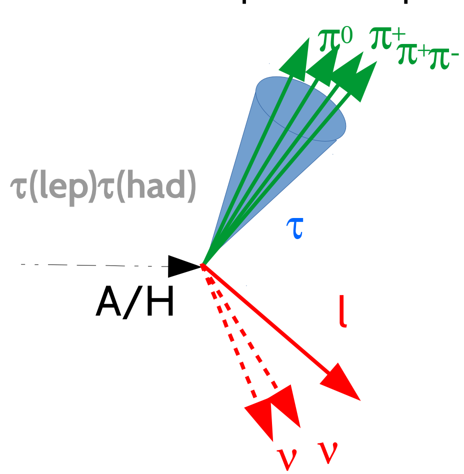
JHEP 1801 (2018) 055

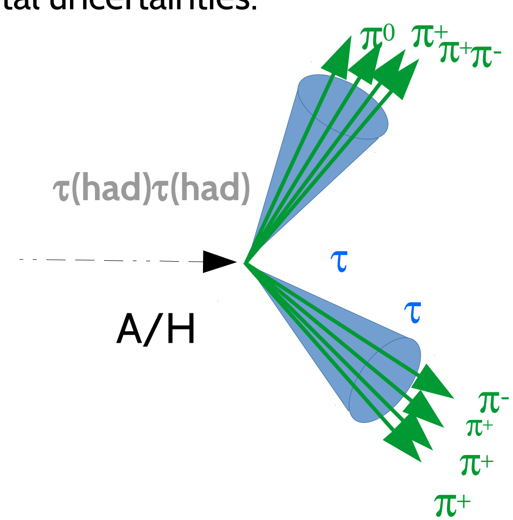
$\mathcal{L}$ = 36.1 fb^{-1}

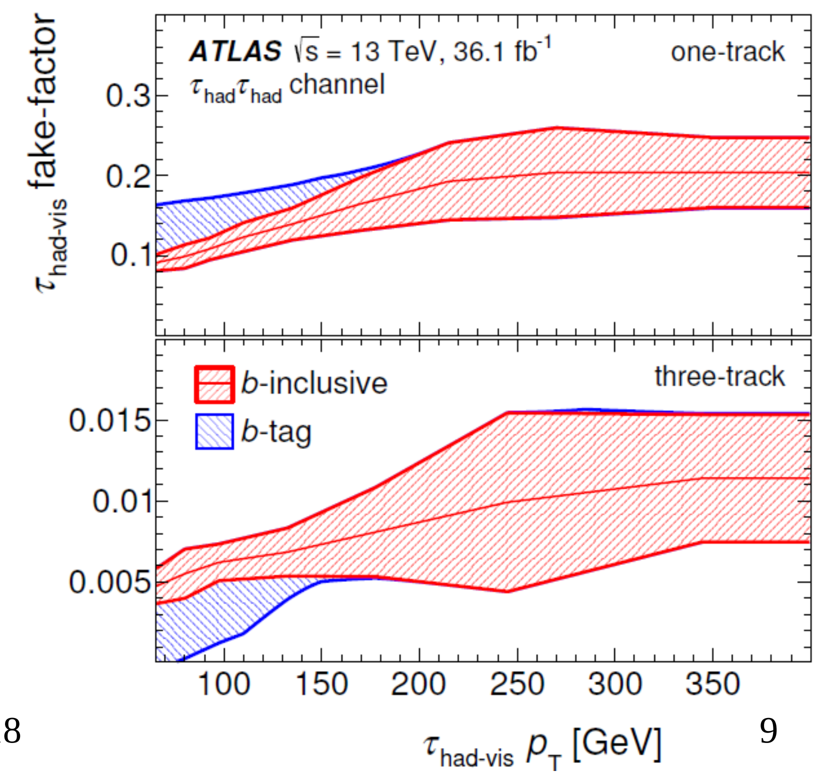
Searching for two τ's in the final state. Two τ decays are triggered: τ(lep)τ(had) and τ(had)τ(had)

- τ(had)τ(had) selecting two jets passing τ-ID criteria
- τ(lep)τ(had), 1 lepton +1 τ-jet candidate back-to-back.
- b-veto and b-tag to enhance significant for each production mode.
- Main backgrounds come from misidentification of τ and Z → ττ
  - Jet → τ : fake factors depending on jet p_T estimated on data CRs enriched with multijet events.
  - τ(lep): e/μ → τ fakes coming mainly from W+jets, tt and lepton+jets events.
  - Important experimental uncertainties.





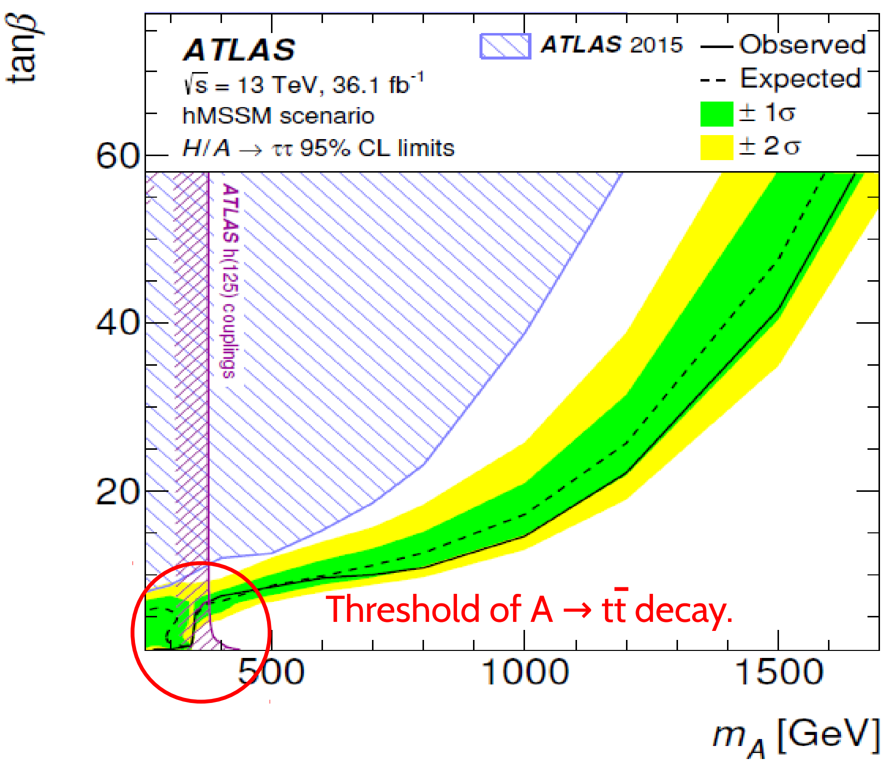


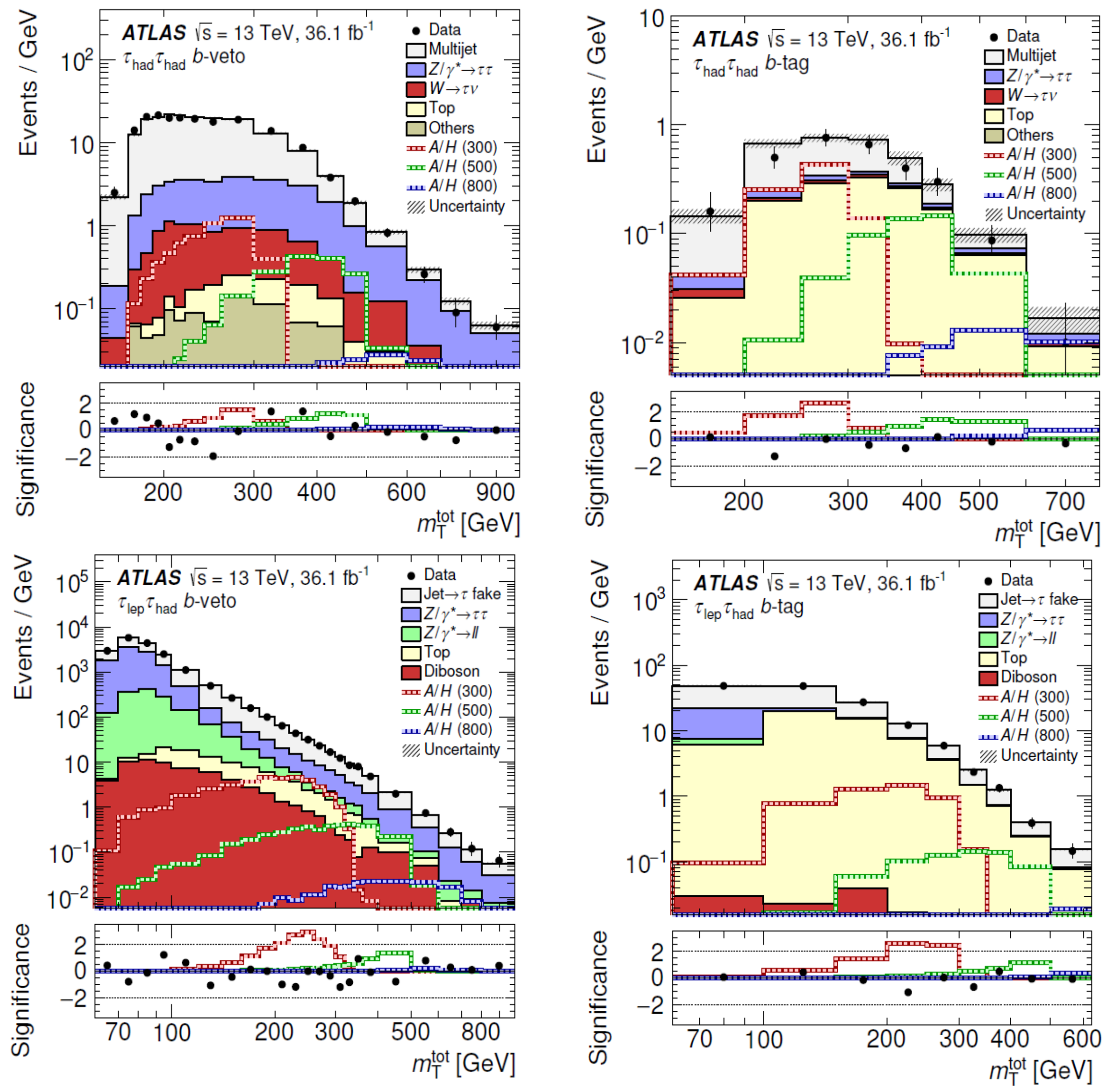


Neutral Higgs searches: H/A → ττ

JHEP 1801 (2018) 055

- Considering ggF and b-associated production: categories with no b-jet or with b-jet.
- No BSM excess is found
    - Discriminant variable is m_T^{tot}





$$m_{\mathrm{T}}^{\mathrm{tot}} \equiv \sqrt{(p_{\mathrm{T}}^{\tau 1} + p_{\mathrm{T}}^{\tau 2} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{p}_{\mathrm{T}}^{\tau 1} + \mathbf{p}_{\mathrm{T}}^{\tau 2} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

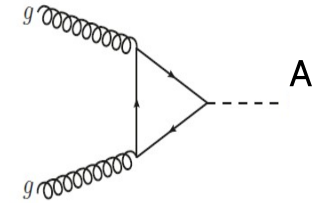
Neutral Higgs searches: A → Zh

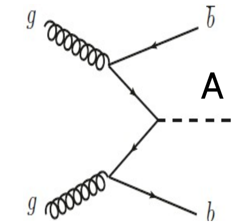
CERN-EP-2017-250

$\mathcal{L}$ = 36.1 fb^{-1}

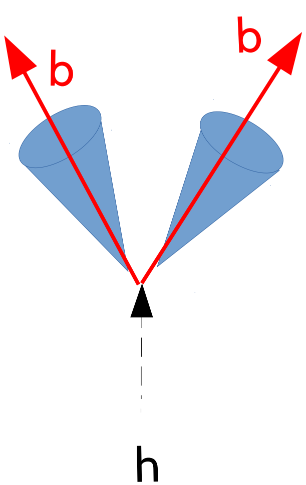
Production via gluon-fusion or bbA. Considering the Z → νν,ll decays and h → bb.

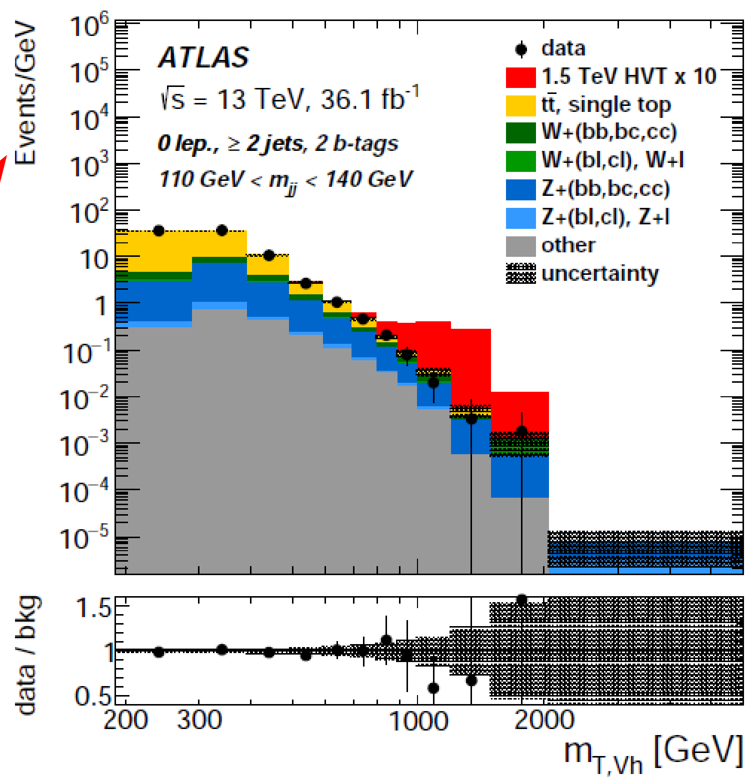
- The range of m_A could provide boosted Higgs bosons → Both b-jets merged in a large one.
  - Merged: searching for a large-R (1.0) b-jet. Resolved: searching for two R=0.4 b-jets.
- Z → ll, νν : 2-leptons and 0-lepton categories.
- bbA search: requiring one more small b-jet (merged and resolved categories + >=1 b-jet)
- Main uncertainties from jet energy estimation, large-R jet mass calibration and b-tagging efficiency.



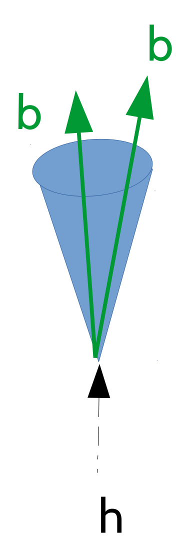


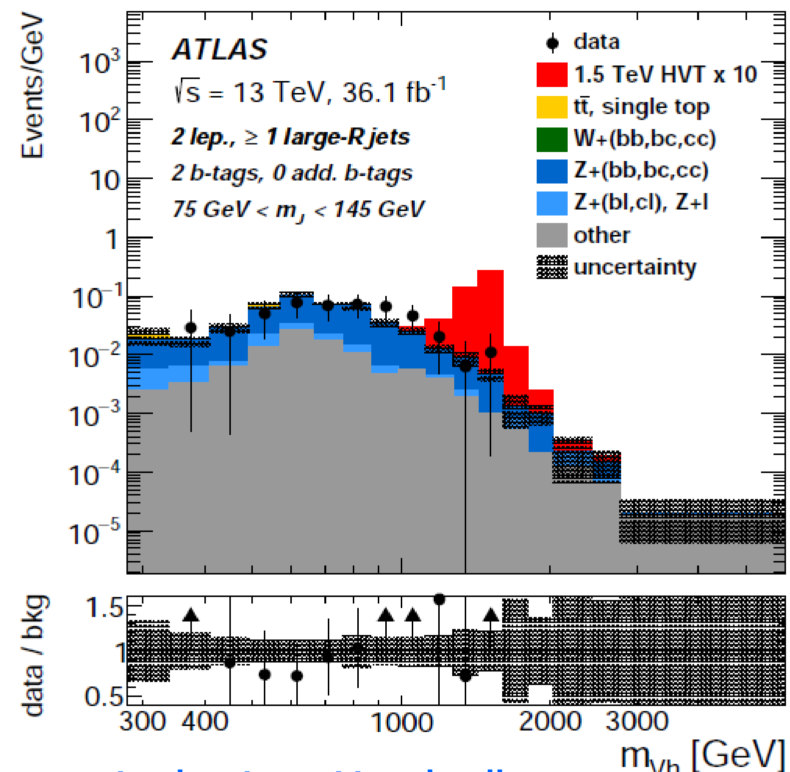
Resolved





Merged





Look at Jason Veatch talk for large-R jet details.

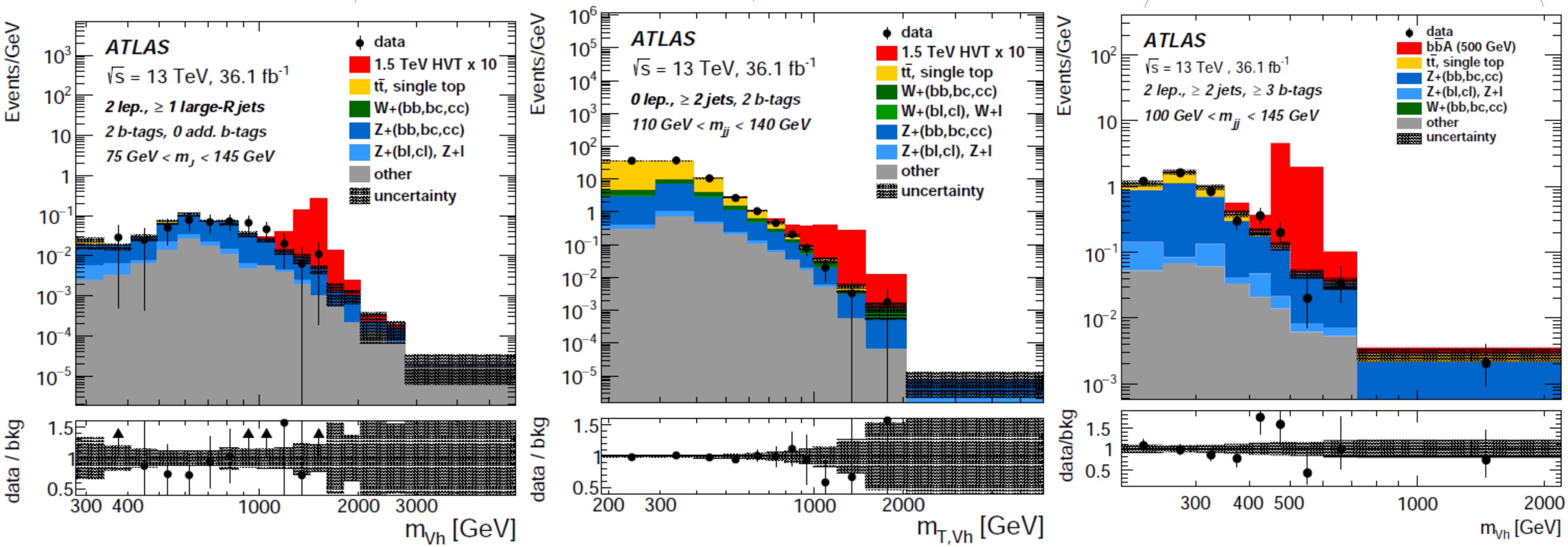
Neutral Higgs searches: A → Zh

CERN-EP-2017-250

- Discriminant variables are m_{TZh} (0L) and m_{Zh} (2L)
- Combined fits on all categories with 2 small b-jets (1 large-R b-jet) for ggF production
- Fit on additional categories for bbA production

Fitted regions for ggF production

Fitted regions for bbA production

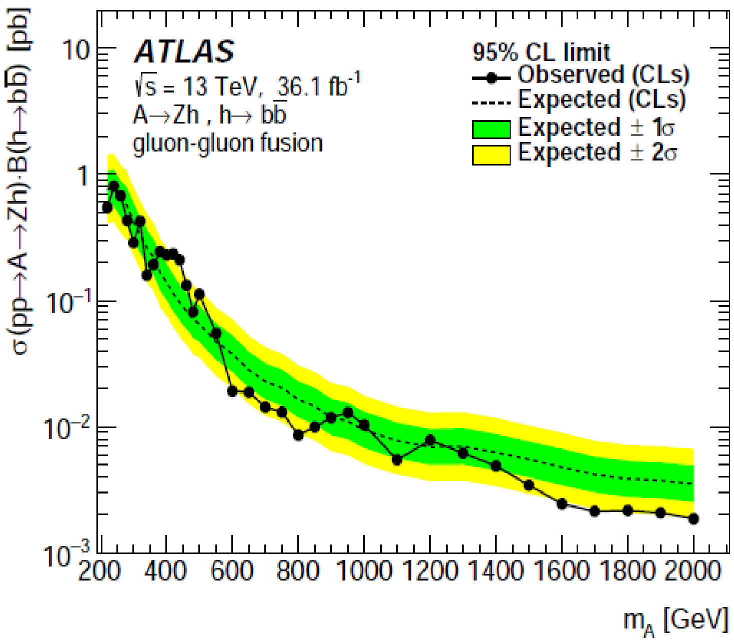


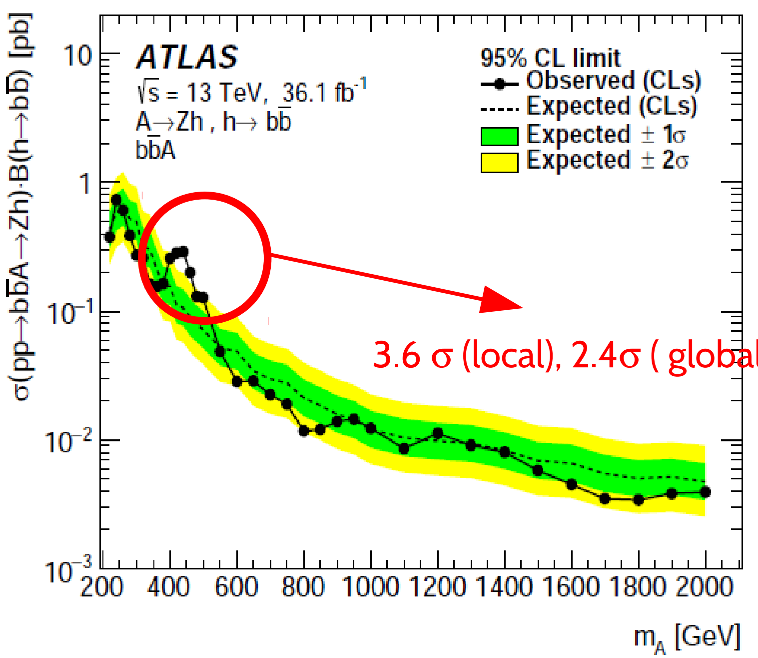
$$m_{\mathrm{T},Vh} = \sqrt{(E_{\mathrm{T}}^{h} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{\mathrm{T}}^{\,h} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}})^2},$$

$$m_{Vh} = \sqrt{\left(E_h + E_{\ell^+\ell^-}\right)^2 - \left(\vec{p}_h + \vec{p}_{\ell^+\ell^-}\right)^2}$$

Neutral Higgs searches: A → Zh

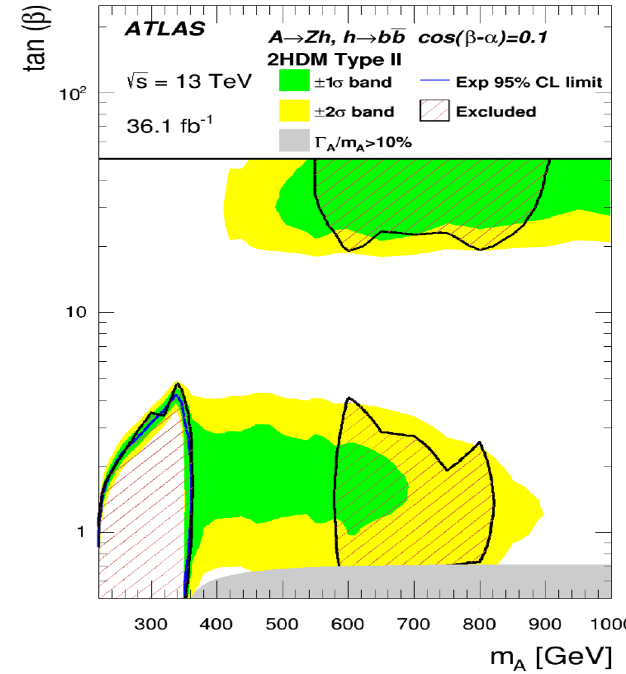
CERN-EP-2017-250

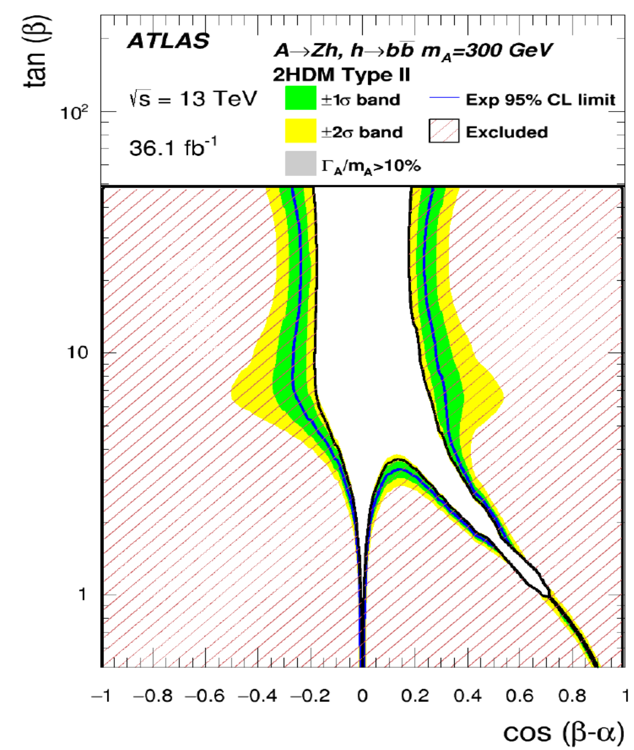




3.6 σ (local), 2.4σ (global) in dimuon category.

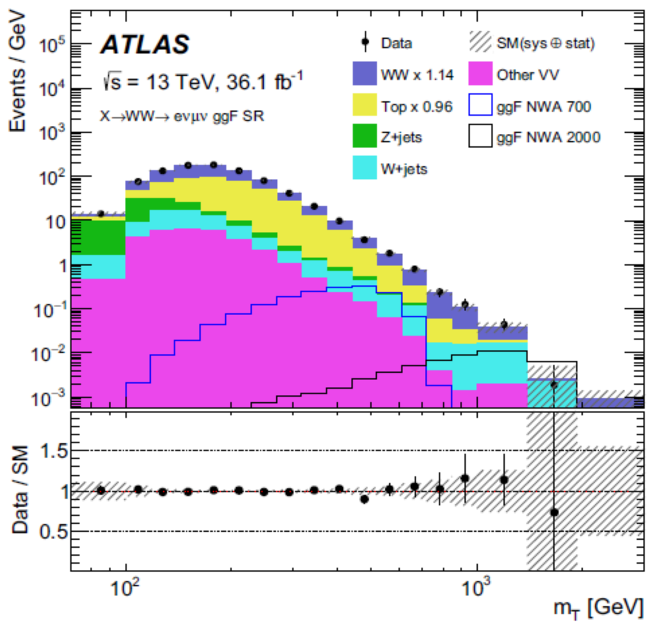
2HDM limits derived by combining bbA and ggF production

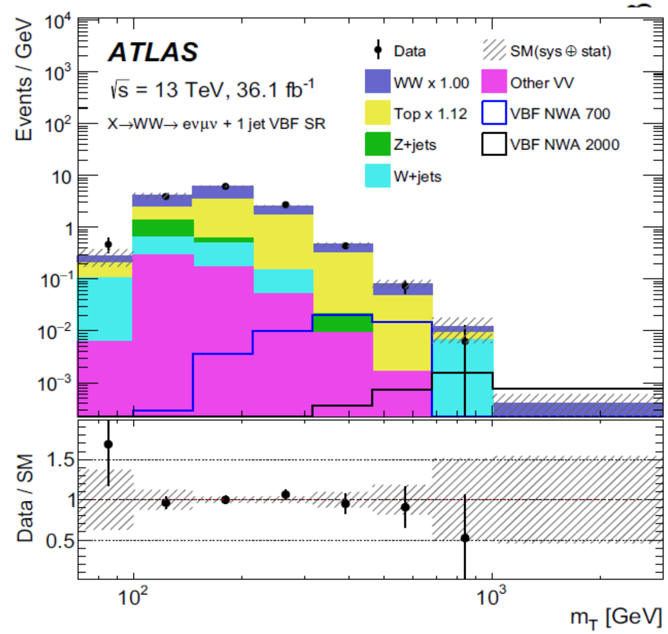


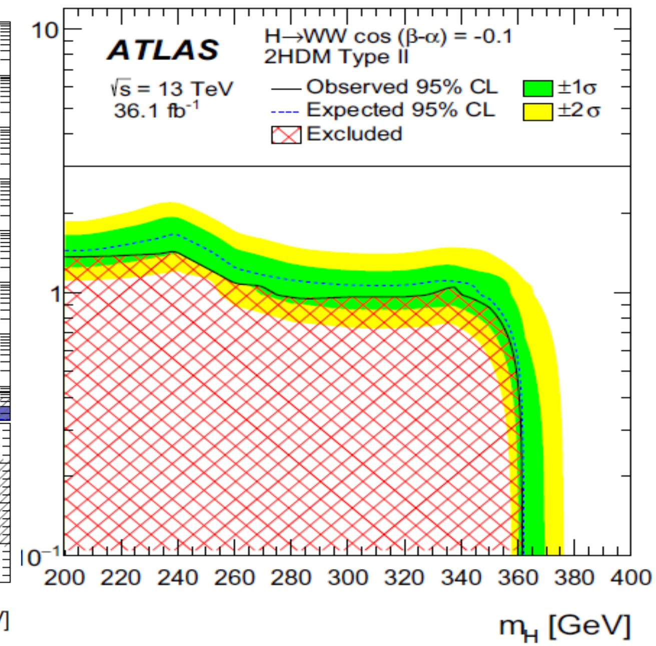


Additional searches: high-mass searches

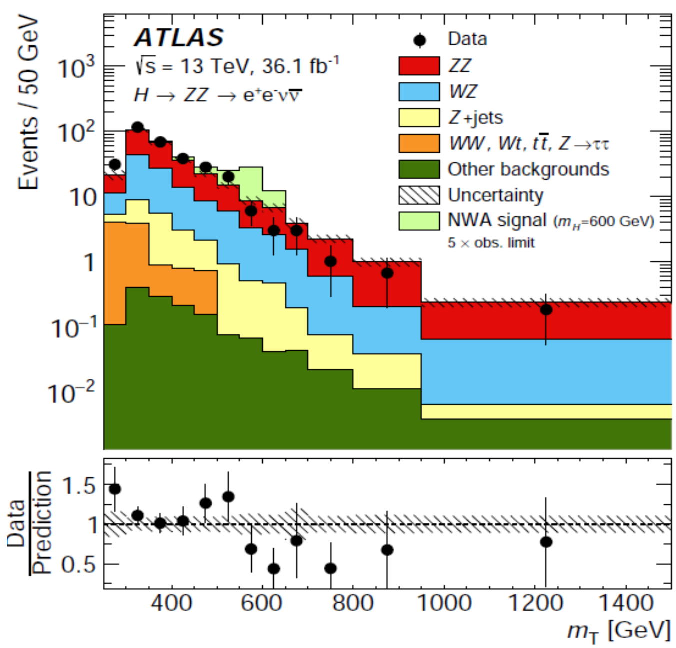
High mass: X → WW → llνν   Eur.Phys.J. C78 (2018) no.1, 24 $\mathcal{L}$ = 36.1 fb^{-1}

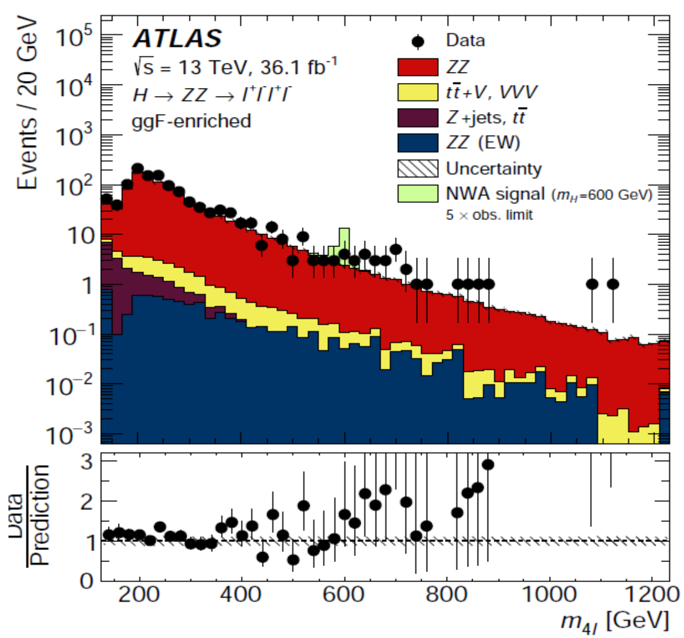


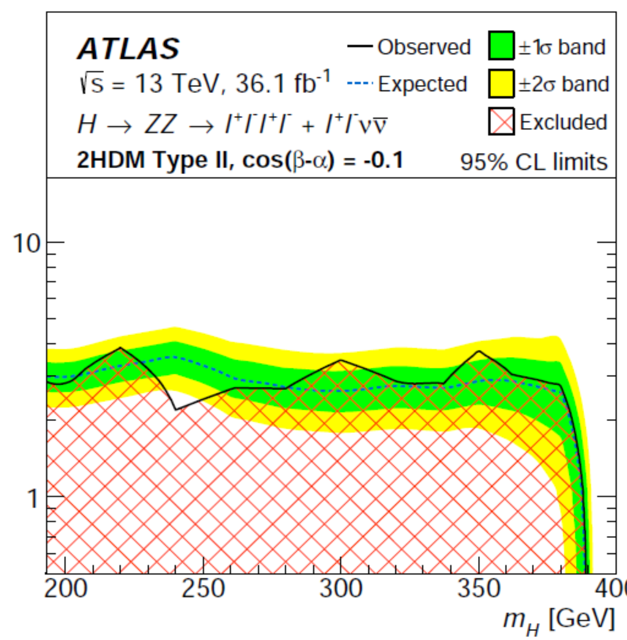




High mass: X → ZZ → 4l , 2l2ν   CERN-EP-2017-251 $\mathcal{L}$ = 36.1 fb^{-1}

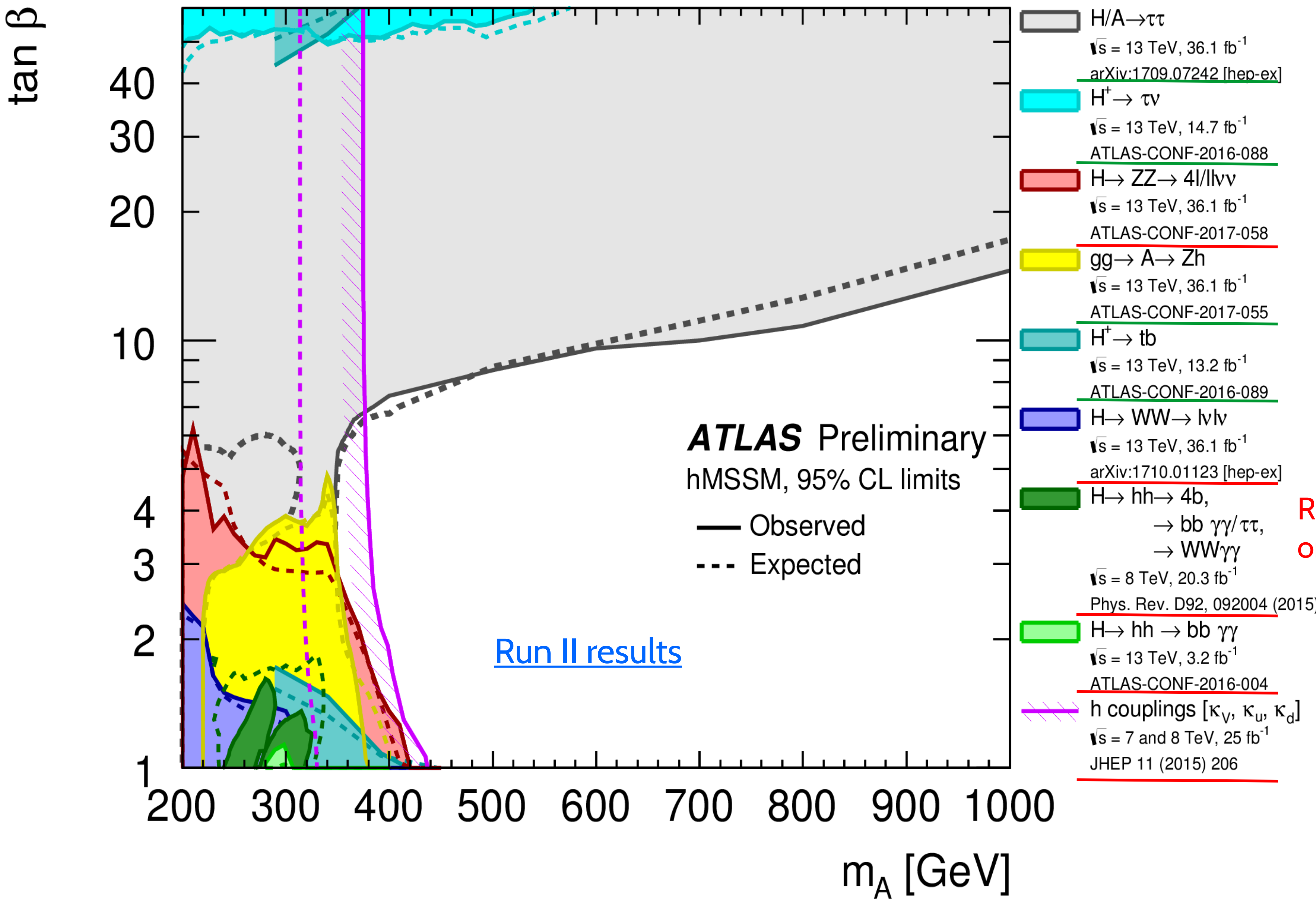






Summary plot of Run II results

Limits and reinterpretation of limits of the searches into the plane [m_A,tanβ] in the hMSSM framework.



Presented in this talk

Reinterpretable on MSSM

See presentations from Yaquan Fang, Monica Trovatelli and Flavia de Almeida Dias

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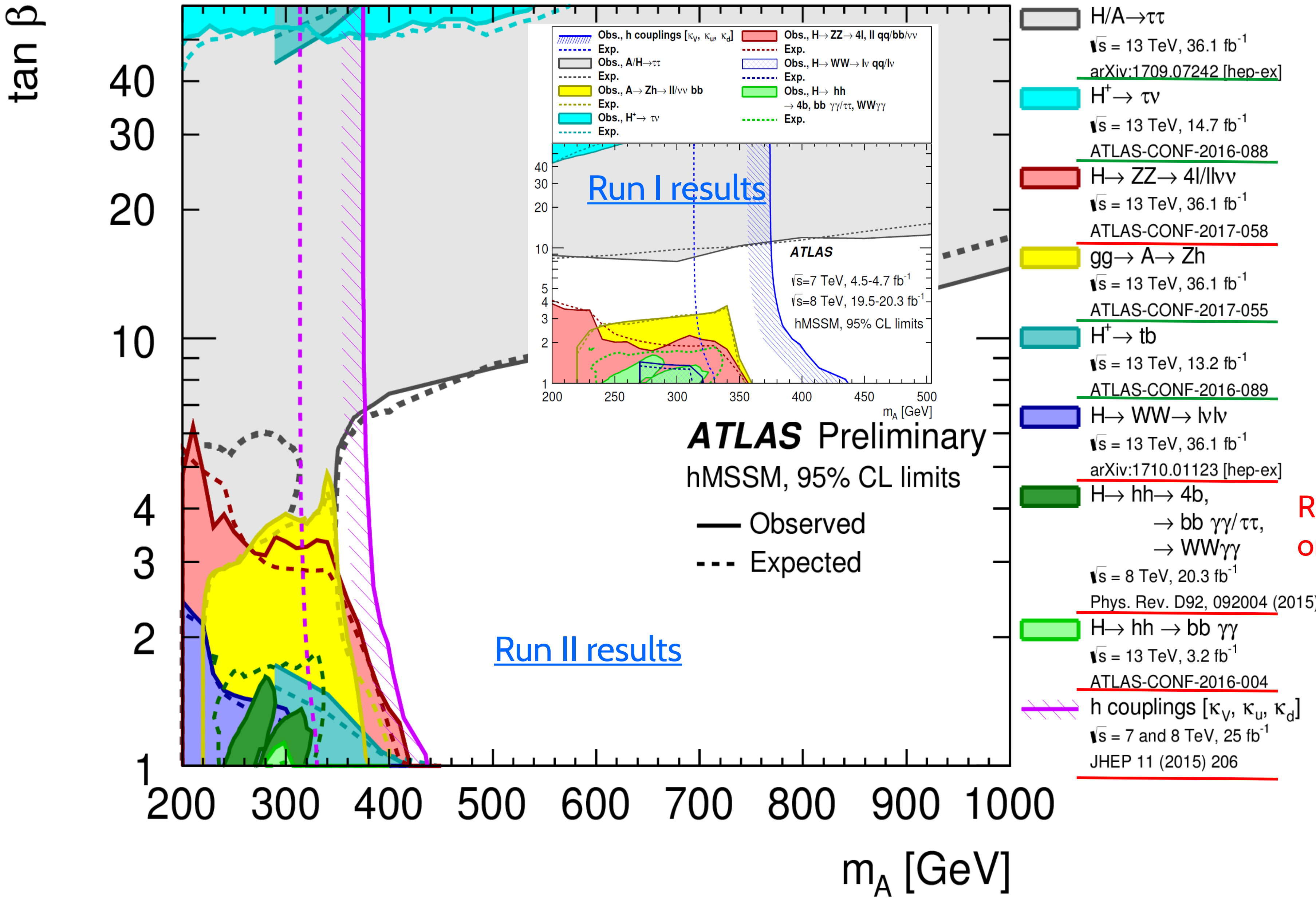

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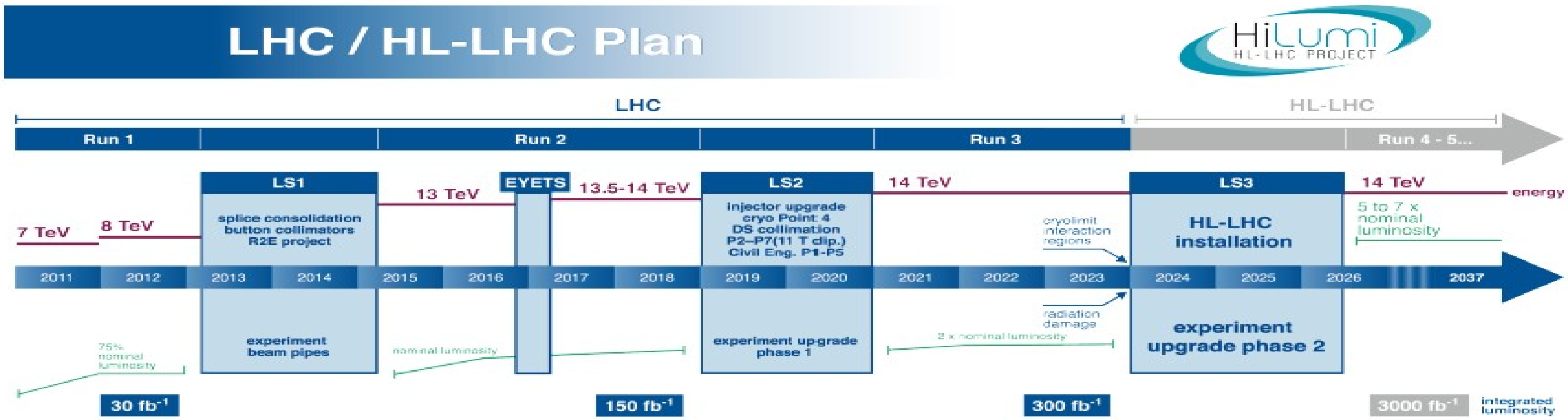
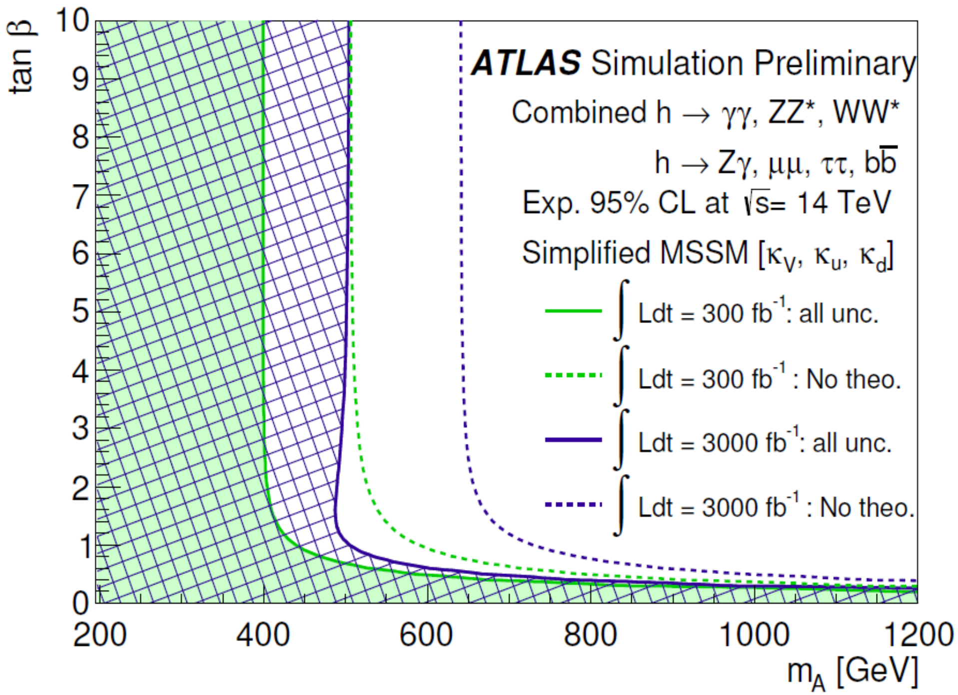
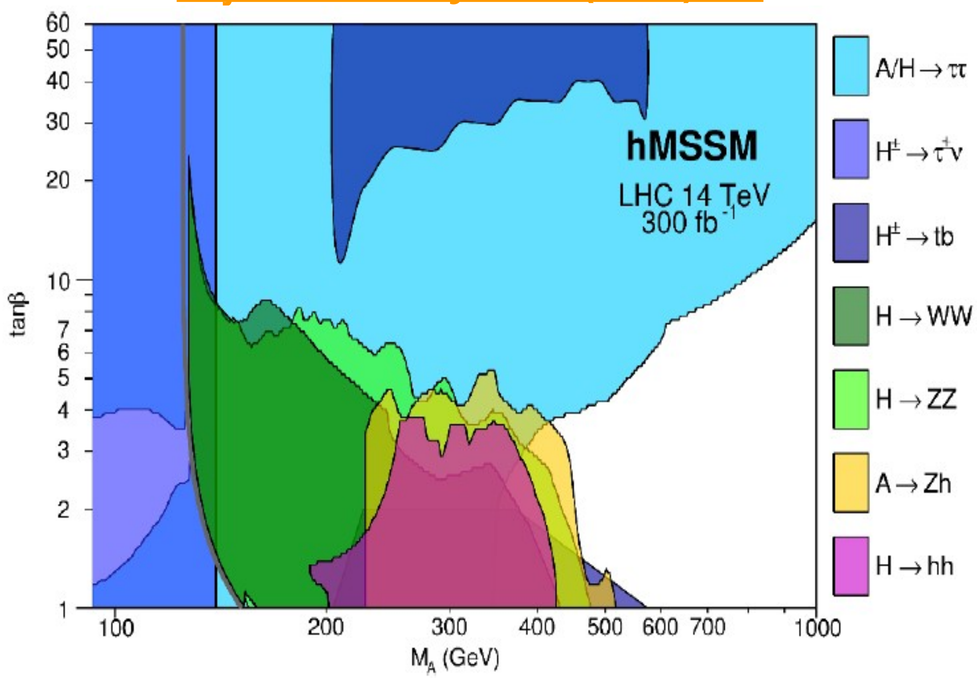
Prospects for next LHC upgrades



ATL-PHYS-PUB-2014-017



Adjouadi et al. JHEP06(2015)168

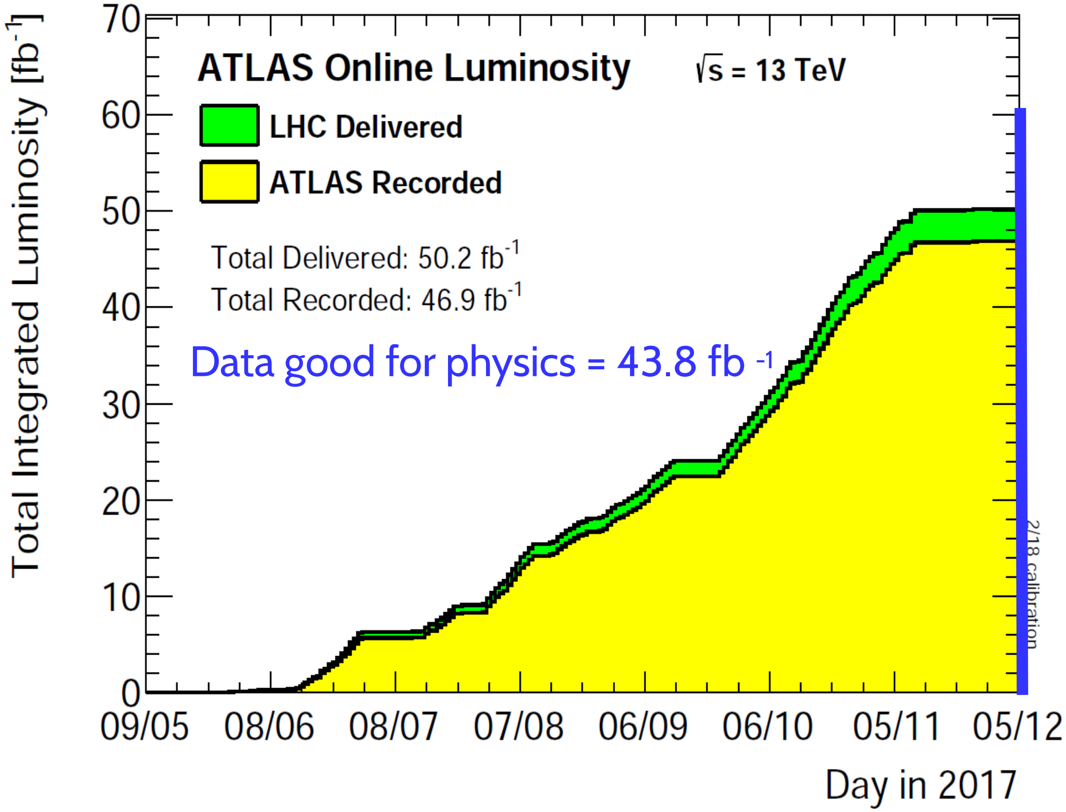


Still a large region of the parameter space can be explored

Conclusions

- Presented a small selection of additional Higgs boson searches in ATLAS at 13 TeV.
  - Many other searches also have results interpretable in terms of an additional Higgs production
- By now, there are no significant excesses from additional Higgs bosons in ATLAS data.
- Results presented here correspond to an integrated luminosity of 36.1 fb^{-1} collected during 2015+2016
- New techniques are being developed: jet color-flow, neural networks ...

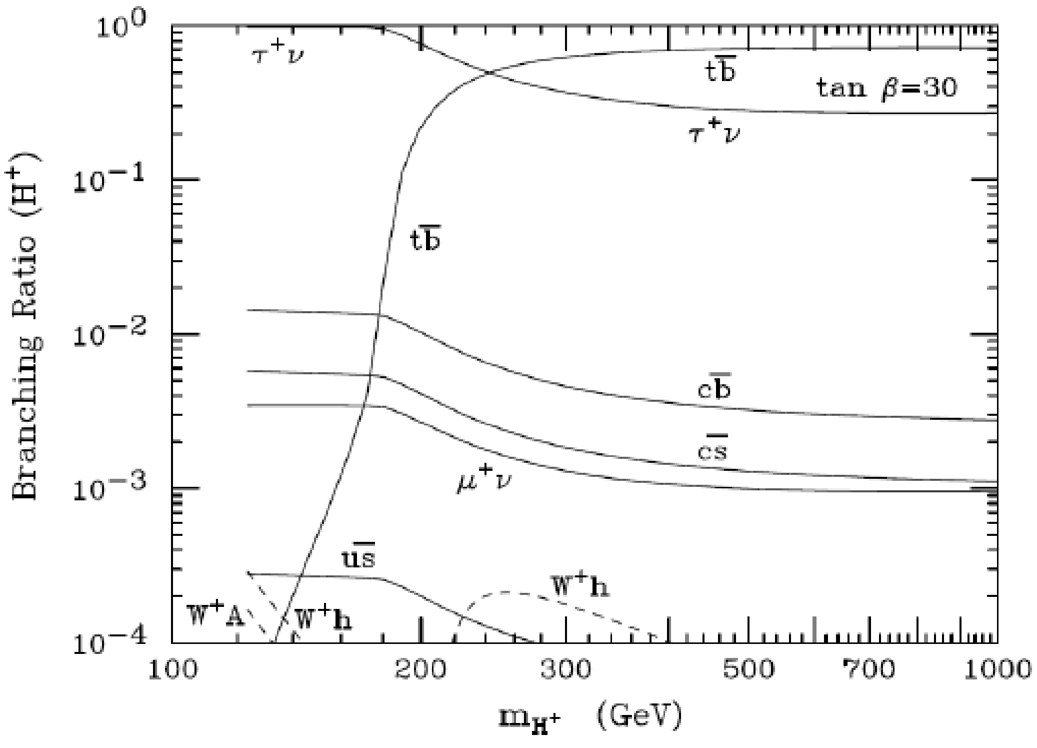
Stay tuned for the 2017 results !!

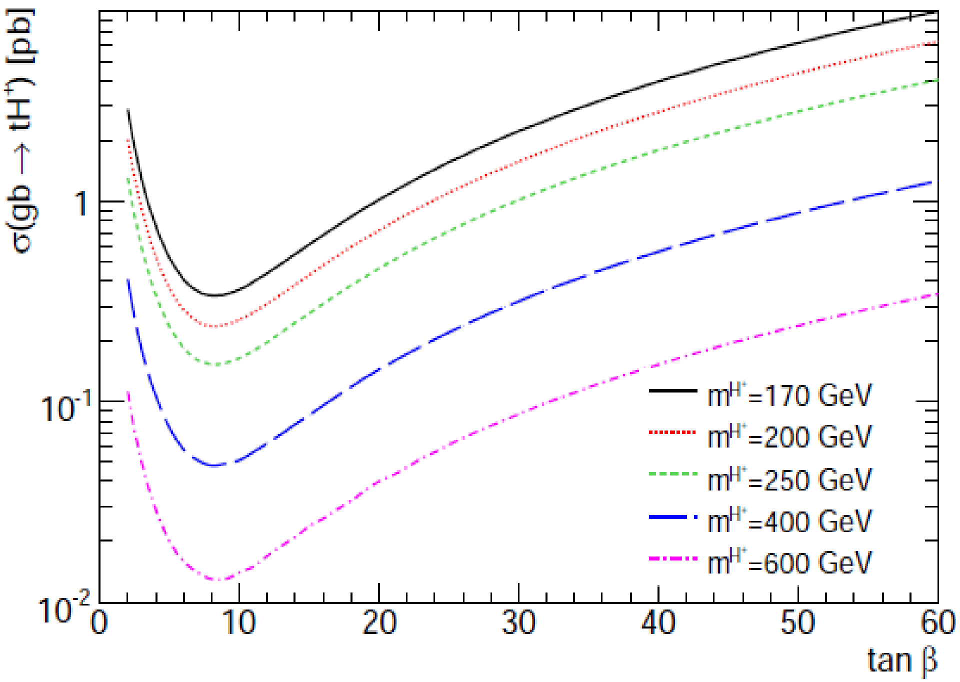


Additional material

Charged Higgs phenomenology

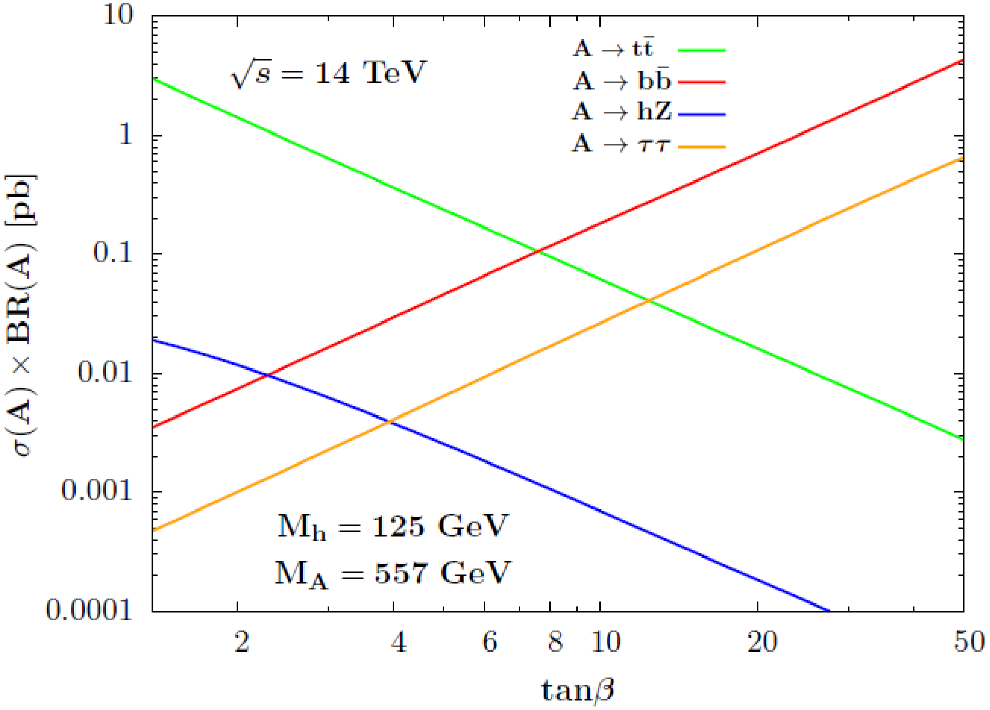
https://arxiv.org/pdf/0710.1761.pdf

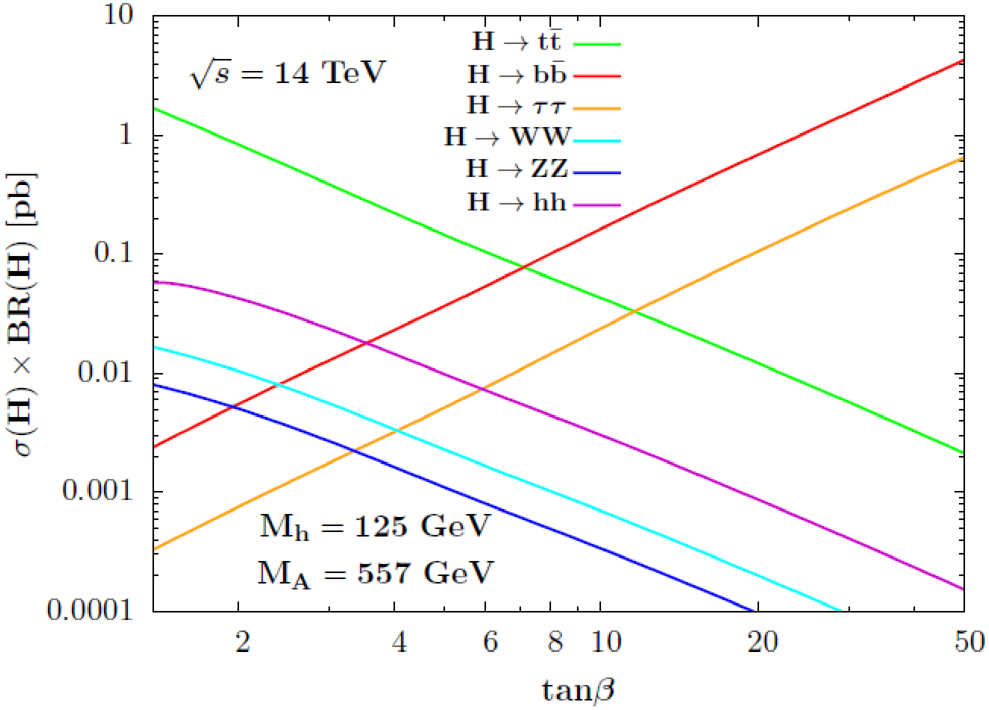




Neutral heavy Higgses phenomenology

A.Djouadi et al. (arXiv:1307.5205)





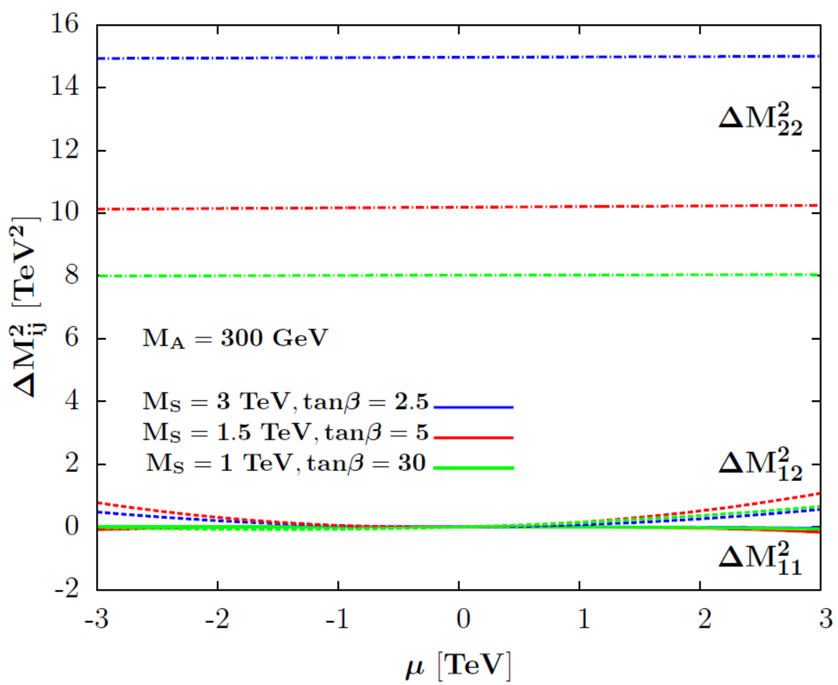
The Higgs sector and the MSSM

A.Djouadi et al. (arXiv:1307.5205)

A.Djouadi et al. (arXiv:1307.5205)

- Assuming that:
  - Observed Higgs is the lightest one (h)
  - Only radiative corrections from top and stop are not negligible
  - All other SUSY heavy particles are heavy enough to neglect contributions on couplings

$$M_S^2 = M_Z^2 \begin{pmatrix} c_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & s_\beta^2 \end{pmatrix} + M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + \begin{pmatrix} \Delta\mathcal{M}_{11}^2 & \Delta\mathcal{M}_{12}^2 \\ \Delta\mathcal{M}_{12}^2 & \Delta\mathcal{M}_{22}^2 \end{pmatrix}$$



Radiative corrections

$$M_H^2 = \frac{(M_A^2+M_Z^2-M_h^2)(M_Z^2 c_\beta^2+M_A^2 s_\beta^2)-M_A^2 M_Z^2 c_{2\beta}^2}{M_Z^2 c_\beta^2+M_A^2 s_\beta^2-M_h^2}$$

$$\alpha = -\arctan\left(\frac{(M_Z^2+M_A^2)c_\beta s_\beta}{M_Z^2 c_\beta^2+M_A^2 s_\beta^2-M_h^2}\right)$$

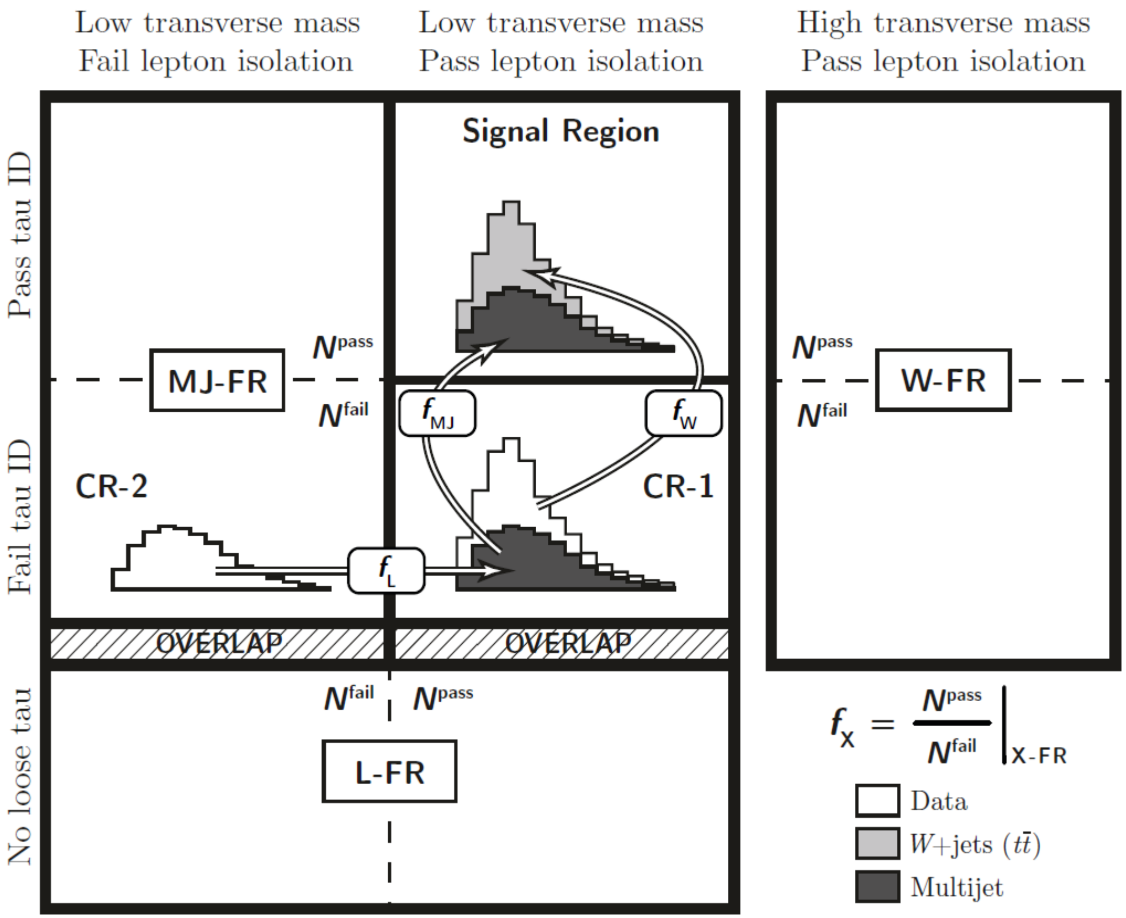
	g_{VV}	g_{uu}	$g_{dd,\ell\ell}$
A	0	$\cot\beta$	$\tan\beta$
H	$\cos(\beta-\alpha)$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
h	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$

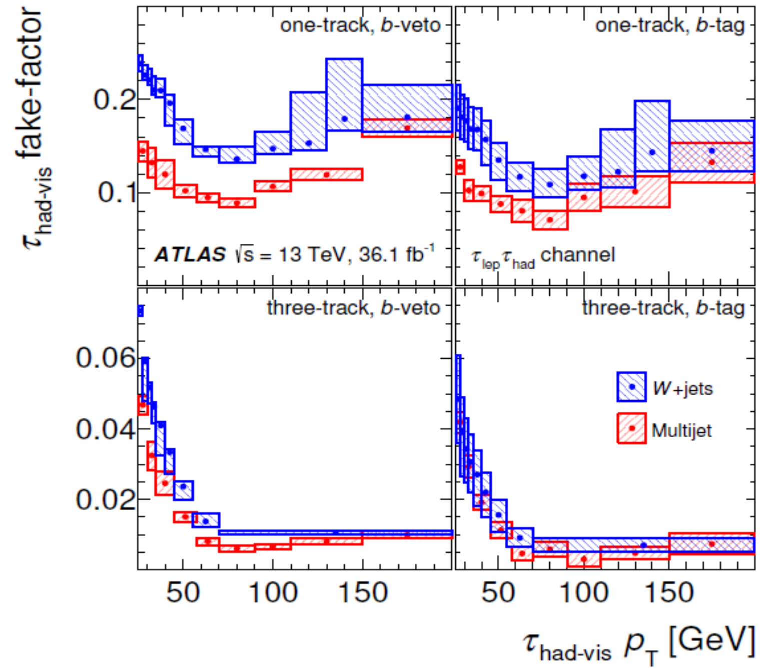
With these assumptions, the MSSM Higgs sector can be approximately well-described by tanβ and mA

JHEP 1801 (2018) 055

H/A → τ(lep)τ(had) : jet bkg estimation

Region	Selection
SR	ℓ (trigger, isolated), τ_1 (medium), $q(\ell)\times q(\tau_1)<0$, $\lvert\Delta\phi(\mathbf{p}_\mathrm{T}^{\ell},\mathbf{p}_\mathrm{T}^{\tau_1})\rvert>2.4$, $m_\mathrm{T}(\mathbf{p}_\mathrm{T}^{\ell},\mathbf{E}_\mathrm{T}^\mathrm{miss})<40$ GeV, veto $80<m(\mathbf{p}^{\ell},\mathbf{p}^{\tau_1})<110$ GeV ($\tau_e\tau_\mathrm{had}$ channel only)
CR-1	Pass SR except: τ_1 (very-loose, fail medium)
CR-2	Pass SR except: τ_1 (very-loose, fail medium), ℓ (fail isolation)
MJ-FR	Pass SR except: τ_1 (very-loose), ℓ (fail isolation)
W-FR	Pass SR except: $70\,(60)<m_\mathrm{T}(\mathbf{p}_\mathrm{T}^{\ell},\mathbf{E}_\mathrm{T}^\mathrm{miss})<150$ GeV in $\tau_e\tau_\mathrm{had}$ ($\tau_\mu\tau_\mathrm{had}$) channel
CR-T	Pass SR except: $m_\mathrm{T}(\mathbf{p}_\mathrm{T}^{\ell},\mathbf{E}_\mathrm{T}^\mathrm{miss})>110\,(100)$ GeV in the $\tau_e\tau_\mathrm{had}$ ($\tau_\mu\tau_\mathrm{had}$) channel, b-tag category only
L-FR	ℓ (trigger, selected), jet (selected), no loose $\tau_\mathrm{had\text{-}vis}$, $m_\mathrm{T}(\mathbf{p}_\mathrm{T}^{\ell},\mathbf{E}_\mathrm{T}^\mathrm{miss})<30$ GeV





JHEP 1801 (2018) 055

H/A → τ(had)τ(had) : jet → τ fake estimation

Region	Selection
SR	τ_1 (trigger, medium), τ_2 (loose), $q(\tau_1) \times q(\tau_2) < 0$, $\lvert\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\tau_1}, \mathbf{p}_{\mathrm{T}}^{\tau_2})\rvert > 2.7$
CR-1	Pass SR except: τ_2 (fail loose)
DJ-FR	jet trigger, τ_1+τ_2 (no identification), $q(\tau_1) \times q(\tau_2) < 0$, $\lvert\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\tau_1}, \mathbf{p}_{\mathrm{T}}^{\tau_2})\rvert > 2.7$, $p_{\mathrm{T}}^{\tau_2}/p_{\mathrm{T}}^{\tau_1} > 0.3$
W-FR	μ (trigger, isolated), τ_1 (no identification), $\lvert\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\mu}, \mathbf{p}_{\mathrm{T}}^{\tau_1})\rvert > 2.4$, $m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\mu}, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}) > 40\,\mathrm{GeV}$ b-veto category only
T-FR	Pass W-FR except: b-tag category only