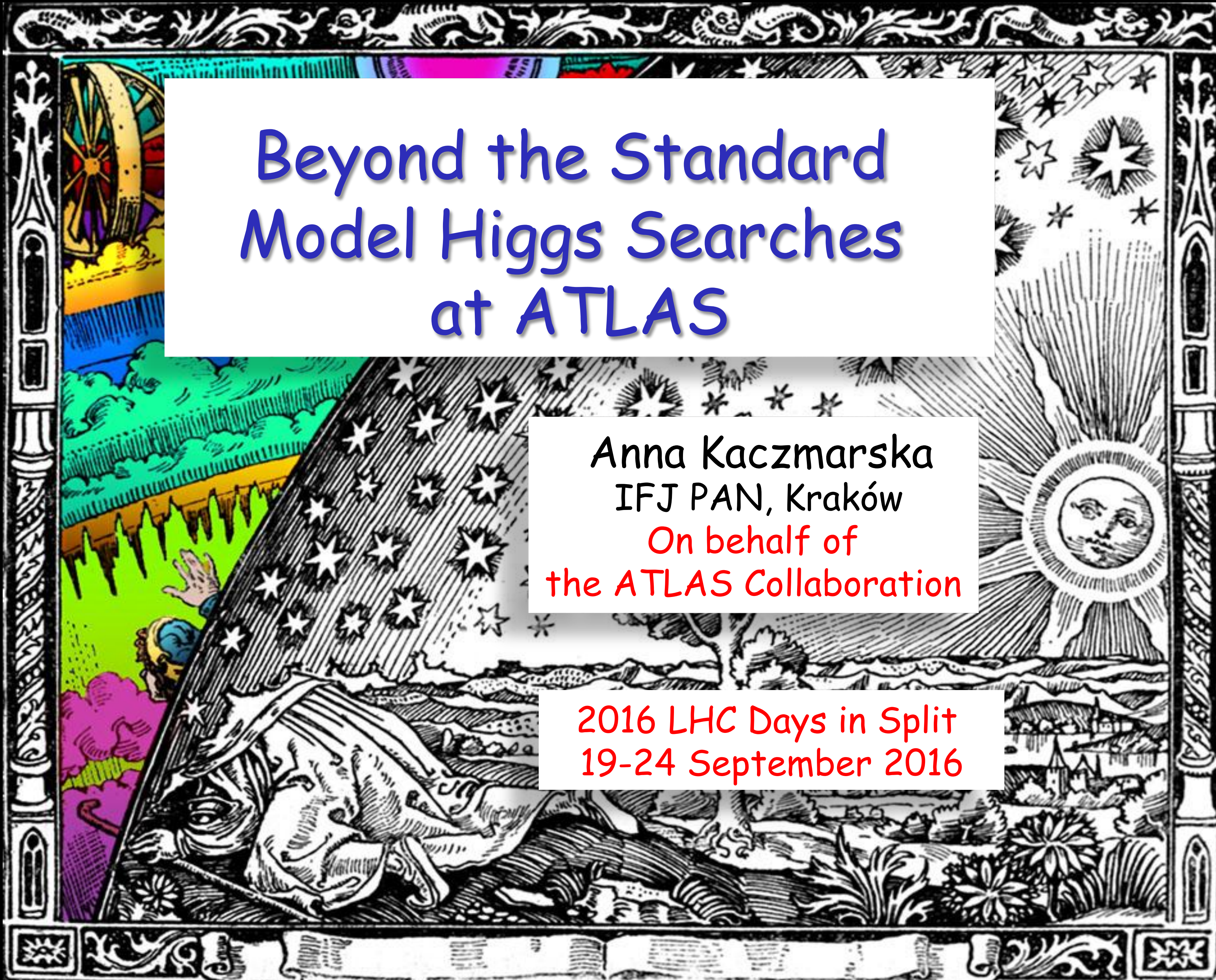


Beyond the Standard Model Higgs Searches at ATLAS

Anna Kaczmarska
IFJ PAN, Kraków
On behalf of
the ATLAS Collaboration

2016 LHC Days in Split
19-24 September 2016

Higgs Beyond the Standard Model (BSM)

- Discovery of a neutral scalar particle of mass ~125 GeV at the LHC confirmed the predicted electroweak symmetry breaking mechanism of the SM
- Experimental results show consistency with the SM Higgs boson

see talk by Dominik Duda *SM Higgs boson results ATLAS*

- **The question is if there is only one Higgs doublet (SM) or the Higgs sector is more complex?**

Various BSM models predict more than 1 Higgs boson:

Additional EW singlet

- The simplest extension to the SM Higgs sector involving the addition of one scalar EW singlet field to the doublet Higgs field of the SM
- Two CP-even Higgs bosons, where h (H) is the lighter 125 GeV (heavier) of the pair

Two Higgs doublet Model - 2HDM

- Five Higgs particles : h, H (neutral, CP-even), A (neutral, CP-odd), $H^{\pm}$
- MSSM Higgs sector with numerous benchmark models: hMSSM, m_h^{mod+}, etc.

Two Higgs doublet + singlet Model

- Next-to-Minimal Supersymmetric Standard Model – NMSSM

Higgs triplet models (SM doublet + triplet)

Topics in this talk

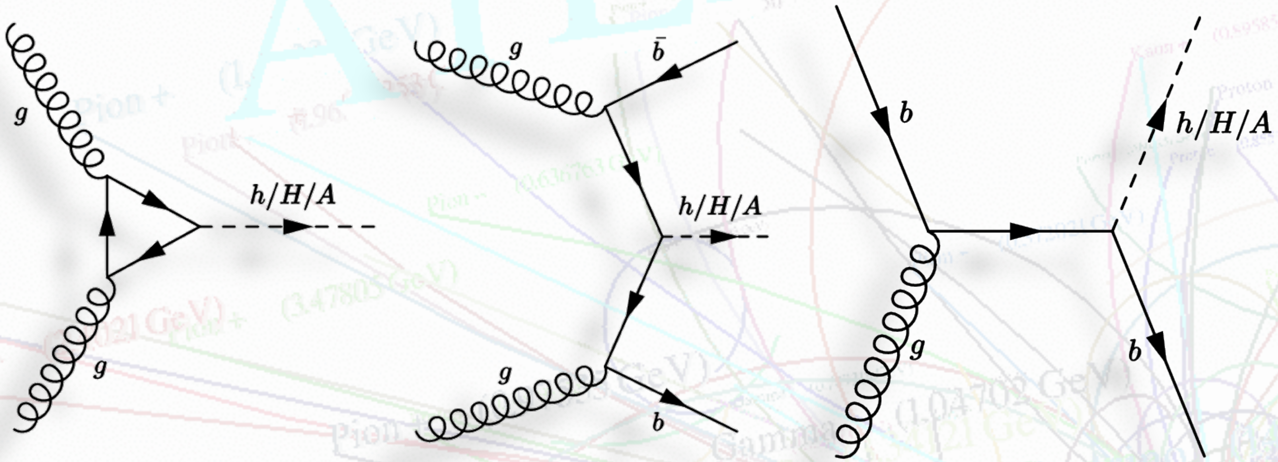
Strategies that use Higgs to find new physics:

- Indirectly, by looking for non-standard properties of light Higgs (spin, CP, couplings, LFV decays etc.)
- Directly, by explicit search for BSM objects
  - Additional Higgs bosons (neutral and charged, decays to SM particles or to Higgs bosons)
  - Higgs decays to BSM states (light scalar resonances, invisible decays, long lived particles etc.)

- **Charged Higgs**
  - $H^{\pm} \to \tau\nu$ (ATLAS-CONF-2016-088)
  - $H^{\pm} \to tb$ (ATLAS-CONF-2016-089)
- **Neutral Higgs**
  - $H \to \tau\tau$ (ATLAS-CONF-2016-085)
  - $H \to tt$ (ATLAS-CONF-2016-073)
- **Higgs to Higgs**
  - $hh \to 4b$ (ATLAS-CONF-2016-049)
  - $hh \to WW+2\gamma$ (ATLAS-CONF-2016-071)
- **Higgs to di-boson**
  - see talks by
    - Zhiqing Zhang *Heavy Higgs searches in diboson final states in ATLAS*
    - Yee Chinn Yap *Search for new physics through gamma gamma channel in ATLAS*

Disclaimer:
This is not full list of analyzed channels. Only the most recent results made public with the first portion of the Run2 2016 dataset shown.

Neutral Higgs searches (high mass)



Neutral MSSM Higgs boson at the LHC: gluon-gluon fusion and b-associated production

- In the MSSM, the heavy Higgs boson couplings to down-type fermions (τ,b) are strongly enhanced for a large part of the parameter space for large tanβ
- H/A → ttbar is enhanced at low tanβ and masses > 2*m_t

- **H/A→ττ** (ATLAS-CONF-2016-085)
- **H/A→ ttbar** (ATLAS-CONF-2016-073)

Neutral Higgs searches: H/A→ττ

ATLAS-CONF-2016-085

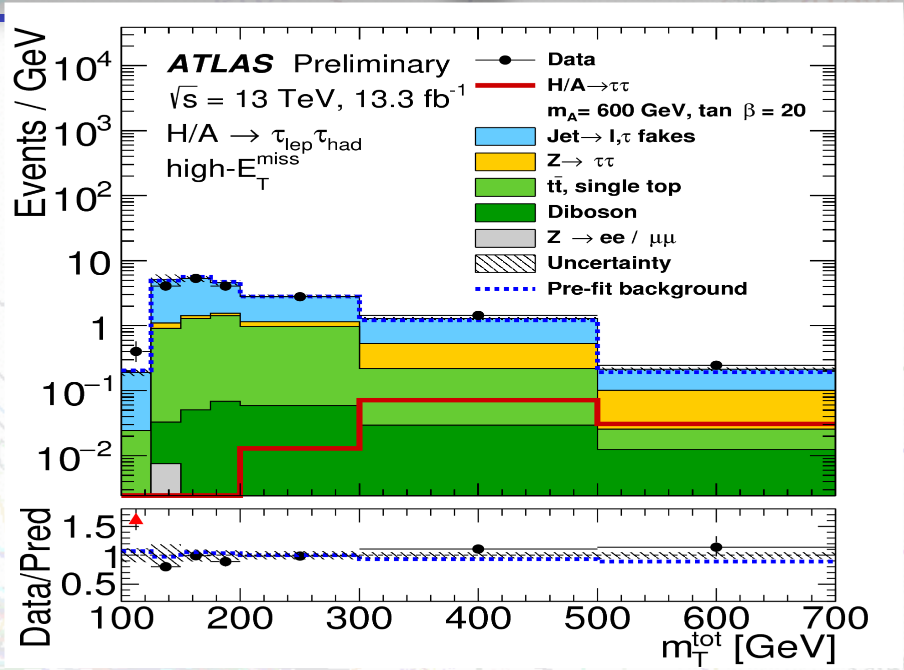
Require at least one hadronic τ decay:

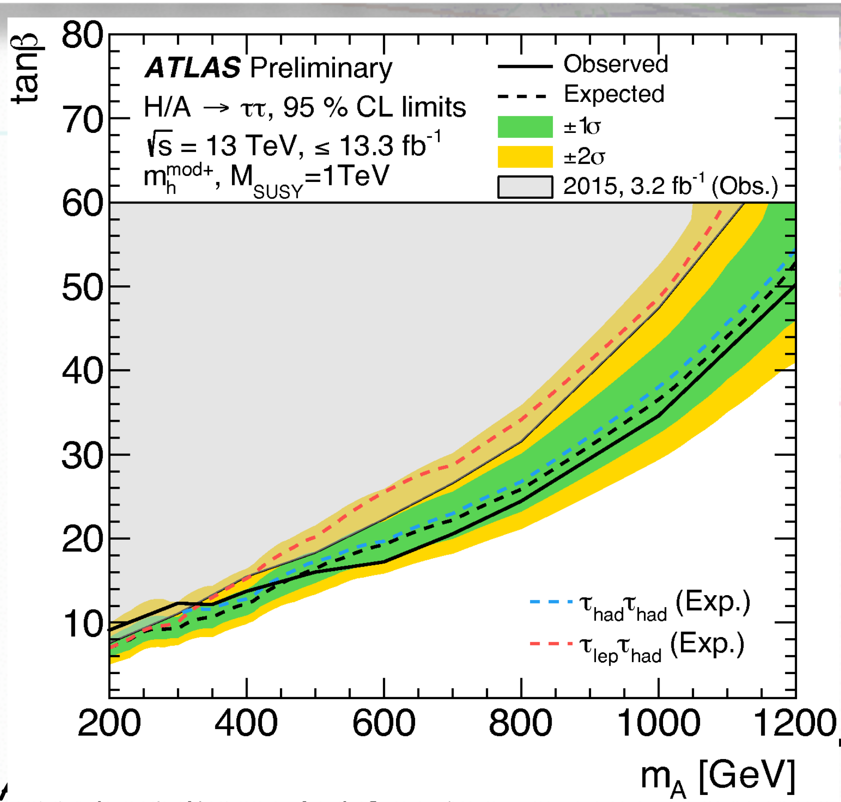
$\tau_{lep}\tau_{had}$ channel

- b-veto and b-tag categories (lepton trigger)
- High E_T^{miss} category (E_T^{miss} trigger) - new in 2016 analysis

$\tau_{had}\tau_{had}$ channel

- b-veto and b-tag categories (τ_{had} trigger)





$$m_T^{tot} = \sqrt{m_T^2(E_T^{miss},\tau_1) + m_T^2(E_T^{miss},\tau_2) + m_T^2(\tau_1,\tau_2)},$$

$m_T(a,b)=[2p_T(a)p_T(b)(1-\cos\Delta\varphi(a,b)]^{1/2}$

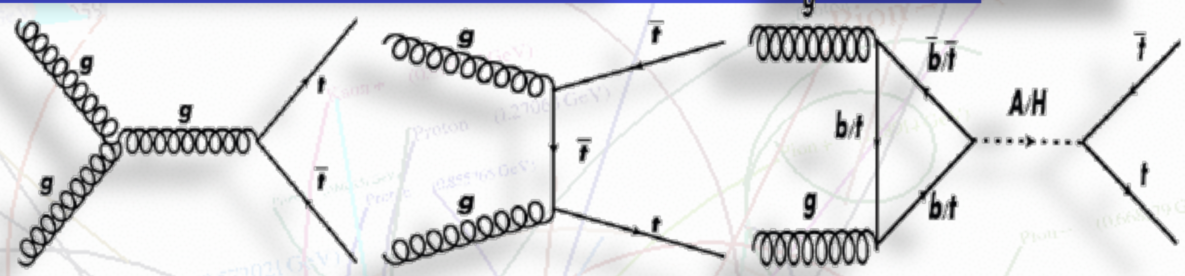
- σ×BR=2.0 (2.1) pb at $m_{H/A}$=200 GeV to 0.013 (0.014) pb at $m_{H/A}$=1.2 TeV for gluon-gluon fusion (b-associated production)
- Limits in the context of the MSSM m_h^{mod+} : tanβ<9 for m_A=200 GeV and tanβ<50 for m_A=1200 GeV
- Extends previous results for m_A > 350 GeV

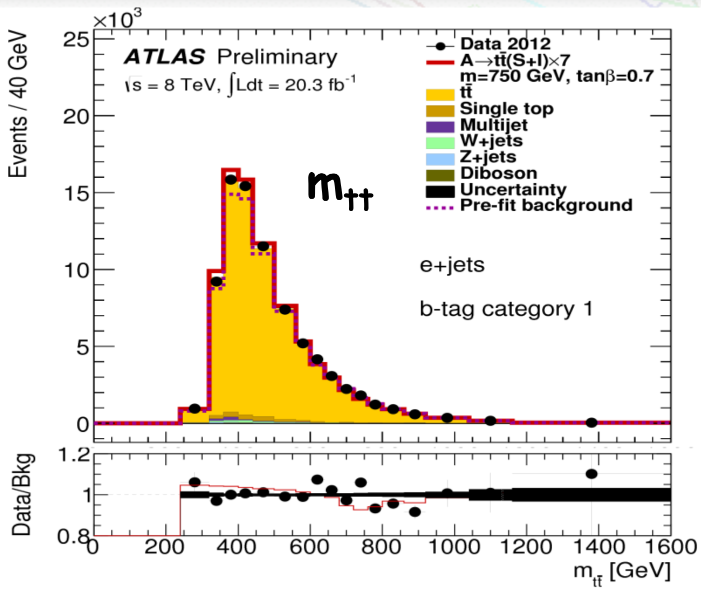
Neutral Higgs searches: H/A→ttbar

ATLAS-CONF-2016-073

8 TeV results

- ttbar lepton+jets channel (one W to hadrons, one to leptons)
- re-interpretation for the ttbar resonance search (JHEP 08 (2015) 148)

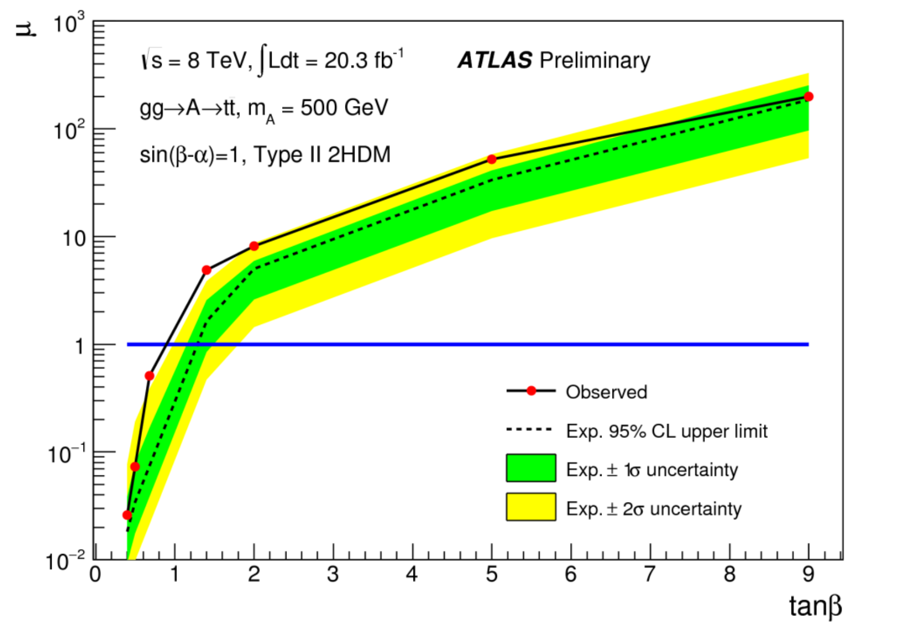




- interference between the signal and ttbar background production modes taken into account for the first time
  - the MadGraph code is modified to remove the SM ttbar matrix element to yield the pure signal + interference contribution on an event-by-event basis.

- For a neutral pseudoscalar A (scalar H) with a mass of 500 GeV, the parameter values tanβ < 0.85 (< 0.45) are excluded in the type-II 2HDM at 95% confidence level

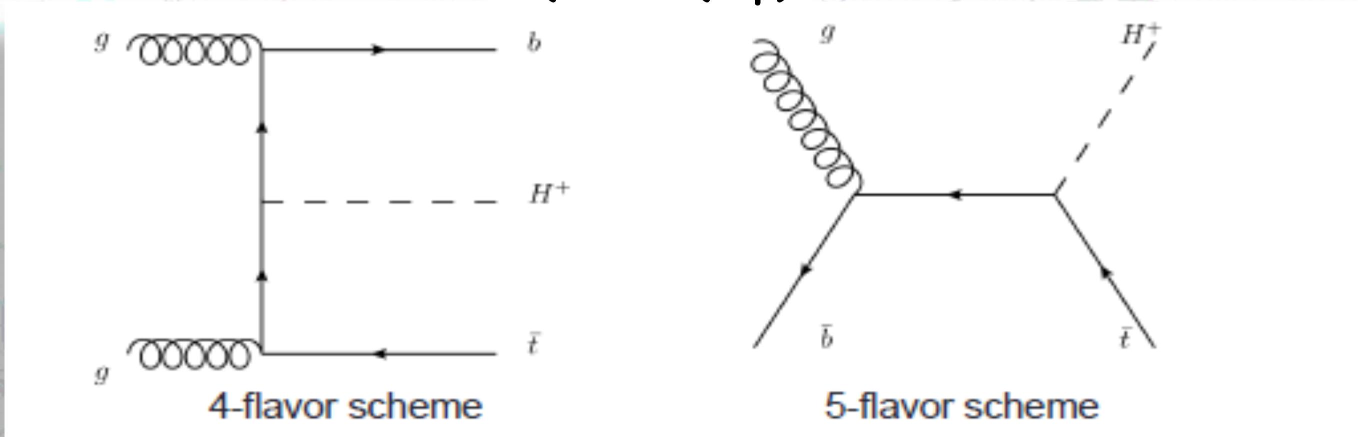
- No tanβ values can be excluded for the higher mass point at 750 GeV

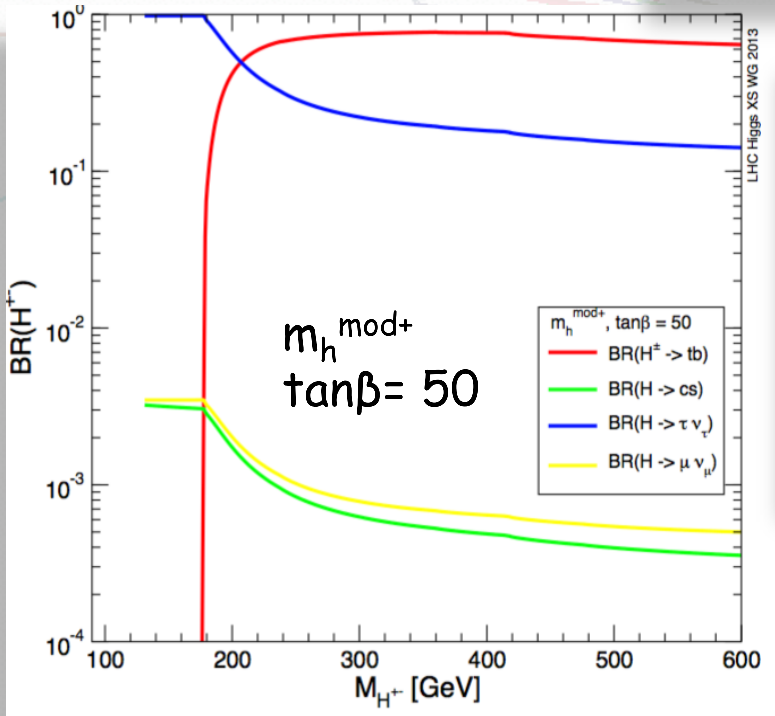


Charged Higgs searches (high mass)

m(H±)> m(top)

The main production mode of heavy charged Higgs boson at the LHC is in association with a top quark





arXiv:1307.1347

- Many BSM models predict extended Higgs sectors containing H± e.g. 2HDM, Higgs triplets
- At high mass H± → tb is the dominant decay mode
- BR(H± → τν) remains significant for a large range of masses for high tanβ
- Searches for heavy H± bosons :

- **H±→τ ν** (ATLAS-CONF-2016-088)
- **H±→ tb** (ATLAS-CONF-2016-089)

Charged Higgs searches: $H^{\pm} \rightarrow \tau\nu$

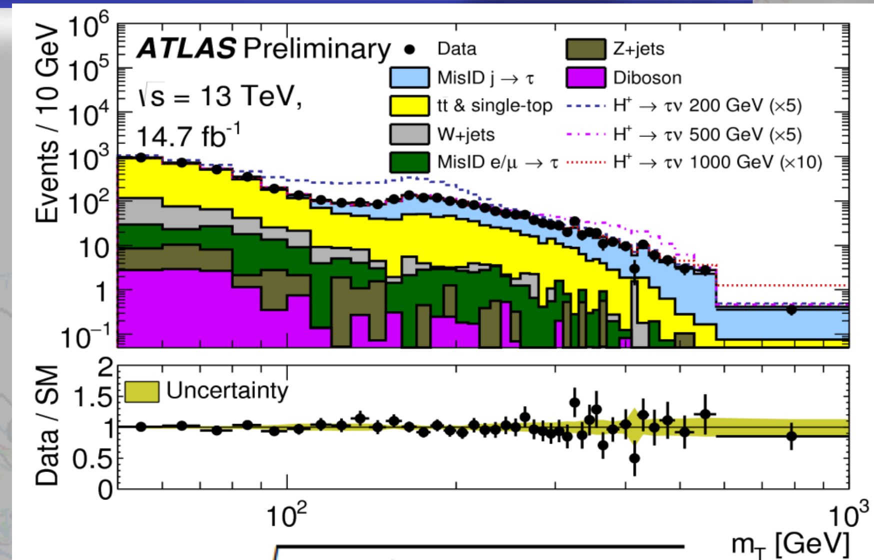
ATLAS-CONF-2016-088

Search in topology:

$pp \rightarrow [b]t\, H^{\pm} \rightarrow [b](j\, jb)(\tau_{had}\, \nu)$

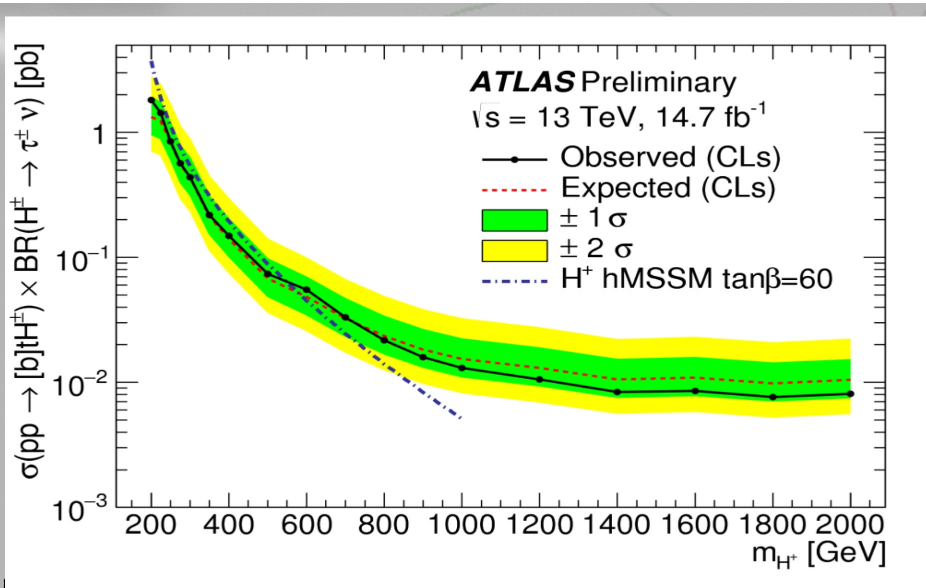
Event selection:

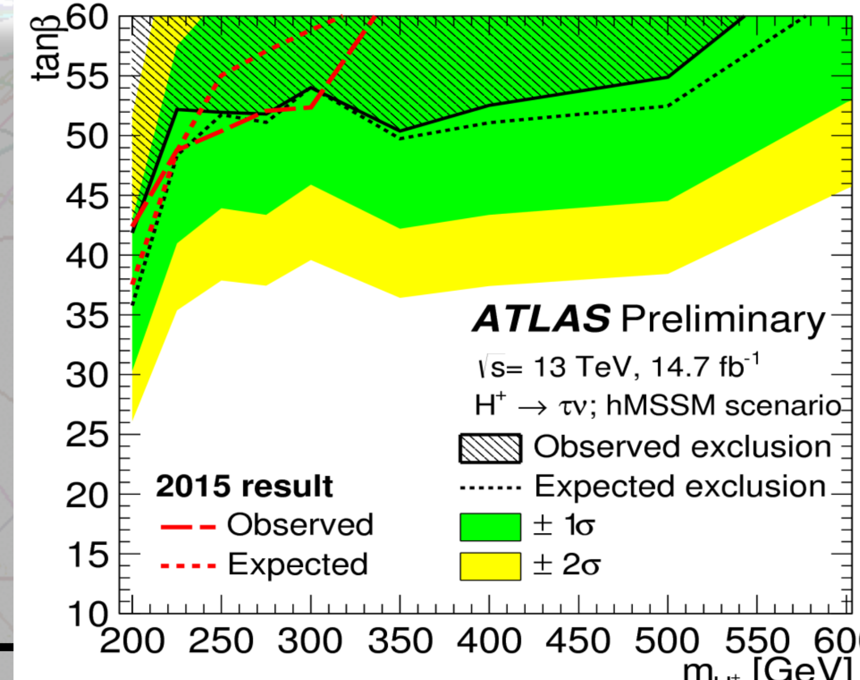
- E_T^{miss} trigger, $E_T^{miss} > 150$ GeV
- Hadronically decaying τ, no high-p_T e, μ
- N(jets) ≥ 3, N(b-tag) ≥ 1



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

- Upper limit on σ×BR between 2 pb and 8 fb for m_{H+} range of 200 GeV – 2 TeV
- In hMSSM, values of tanβ in the range 42–60 are excluded for a m_{H+} = 200 GeV
- At tanβ = 60 m_{H+} range from 200 to 540 GeV is excluded

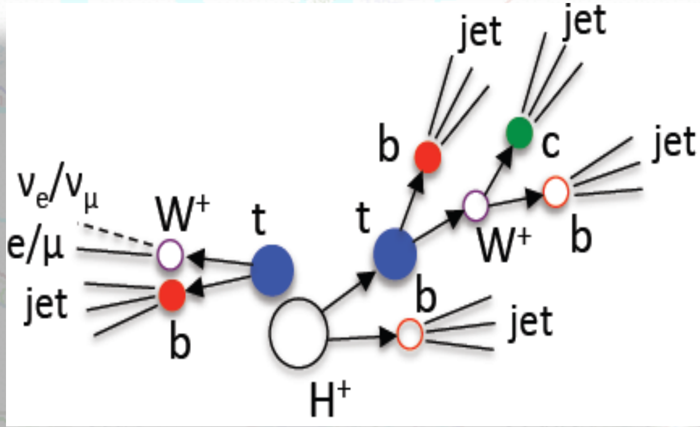


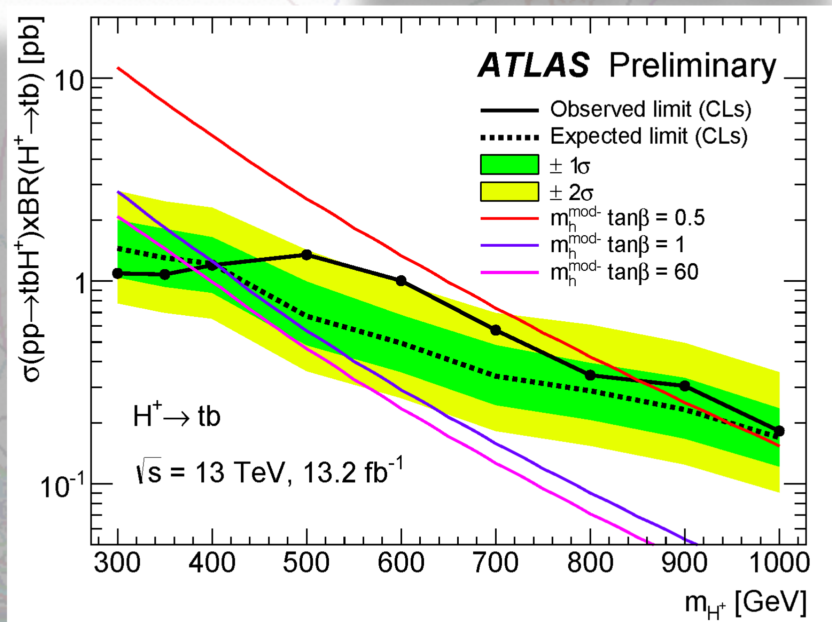


Charged Higgs searches: $H^{\pm} \rightarrow tb$

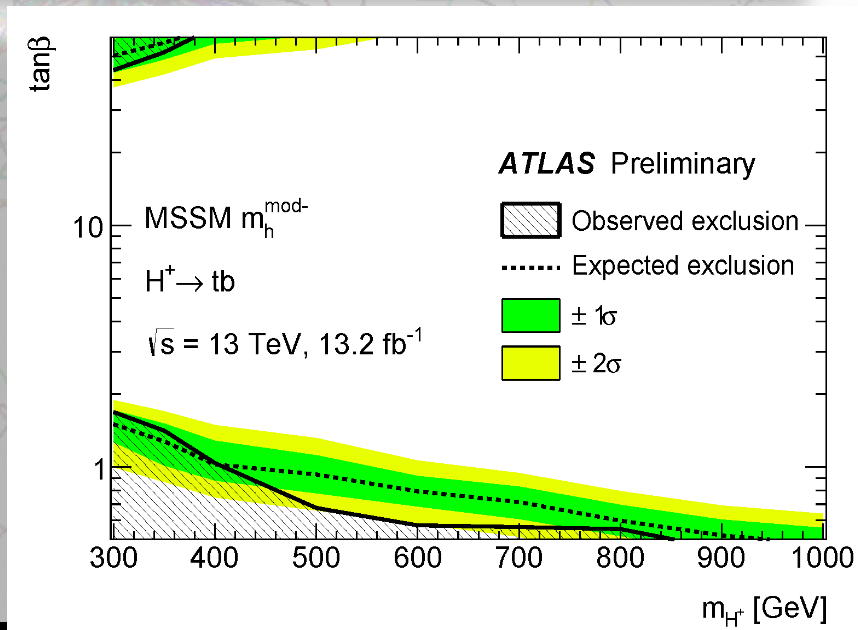
ATLAS-CONF-2016-089

Search using multi-jet final states with one e or μ from a top-quark decay





- Single lepton trigger, 1 lepton, ≥ 4 jets (≥ 2 b-tag)
- Signal/control regions based on N(jets) and N(b-tag)
- Maximum Likelihood fit to all regions based on:
  - BDT in the signal region
  - scalar sum of the p_T of the selected jets in CRs

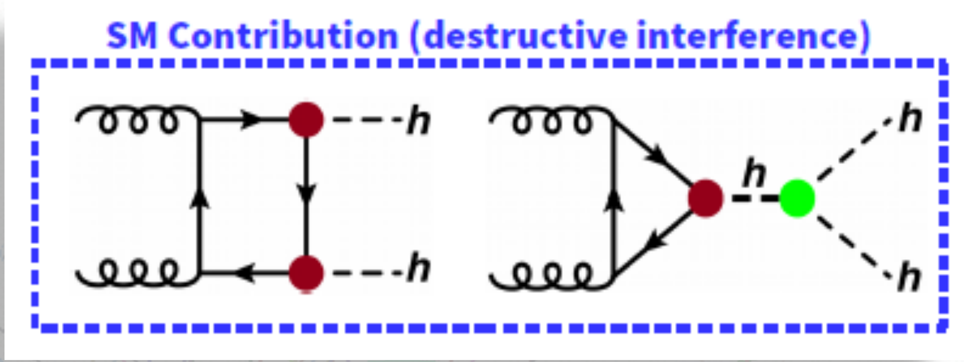


- Observed σ x BR limit: 1.1 pb -0.18 pb for mH+ range of 300 GeV –1 TeV
  - Unlike run 1, no broad excess
- In the context of the m_h^{mod-} scenario
  - some values of tan β in the range 0.5-1.7 are excluded for m_{H+} of 300-855 GeV
  - For m_{H+} between 300-366 GeV high values of tanβ are excluded

Di-Higgs searches

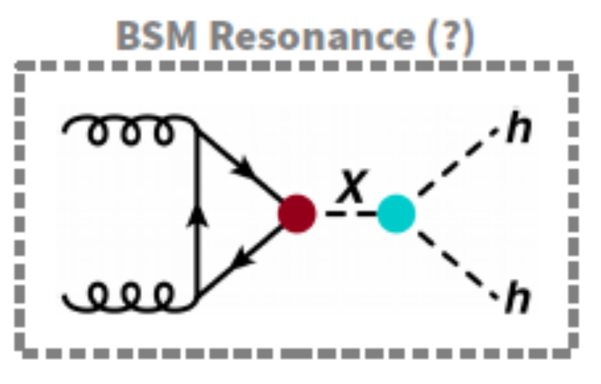
The SM cross section of the Higgs boson pair production is several orders of magnitude smaller than the single-Higgs production rate

- additional on-shell Higgs boson reduces production phase space and the two LO diagrams have destructive interference



BSM hh production significantly enhanced in many BSM models

- Resonant enhancements:
  - KK-graviton G* predicted in the bulk Randall-Sundrum model
  - 2HDM (i.e: heavy neutral scalar H of two-Higgs-doublet models)
- Non-resonant enhancement
  - predicted by models featuring light coloured scalars or direct ttbarhh vertices etc..



- **hh→ 4b** (ATLAS-CONF-2016-049)
- **hh → WW+2γ** (ATLAS-CONF-2016-071)

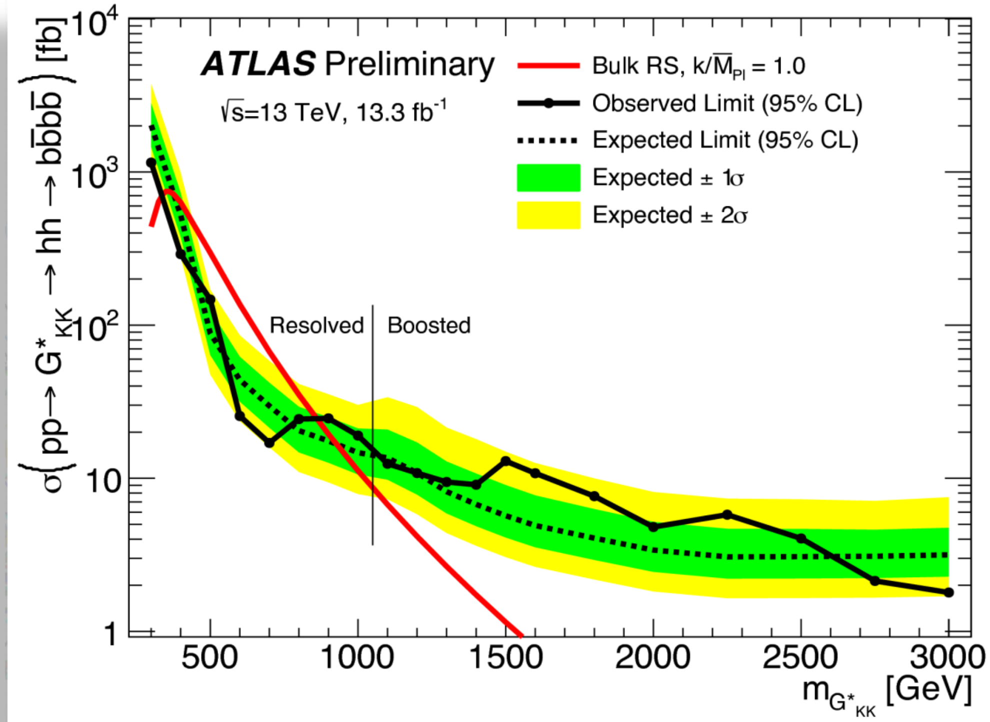
Di-Higgs searches: hh→4b

ATLAS-CONF-2016-049

- Large h→bb branching fraction
- Suffers from large multi-jet background

Resolved analysis:
- Optimized for non-resonant or low-mass hh systems
- Resolve all decay products
- 4 anti-kT jets (R=0.4), b-tagged
- Pair of b-jets to form Higgs candidate
- Invariant mass of two Higgs candidates

Boosted analysis:
- Optimized for higher mass resonant hh systems
- Two b-jets cannot be resolved due to the high boost -> apply substructure techniques
- ≥2 anti-kT jet (R=1.0)
- 2, 3 or 4 b-tagged track jets
- Invariant mass of the two large-R jets



Limit on spin-2 resonance
- σ =1000 – 2 fb in the mass range of 300 – 3000 GeV

Limit on non-resonant production
- < 330 fb (95% C.L.) (SM prediction = 11.3 fb)

Di-Higgs searches: hh → WW+2γ

ATLAS-CONF-2016-071

- Searches for the non-resonant and resonant production of pairs of Higgs bosons in the semi-leptonic WW+2γ final state, i.e. with two photons, two jets and one charged lepton
- Clean signal from h→ $\gamma\gamma$
- Large branching ratio of h → WW

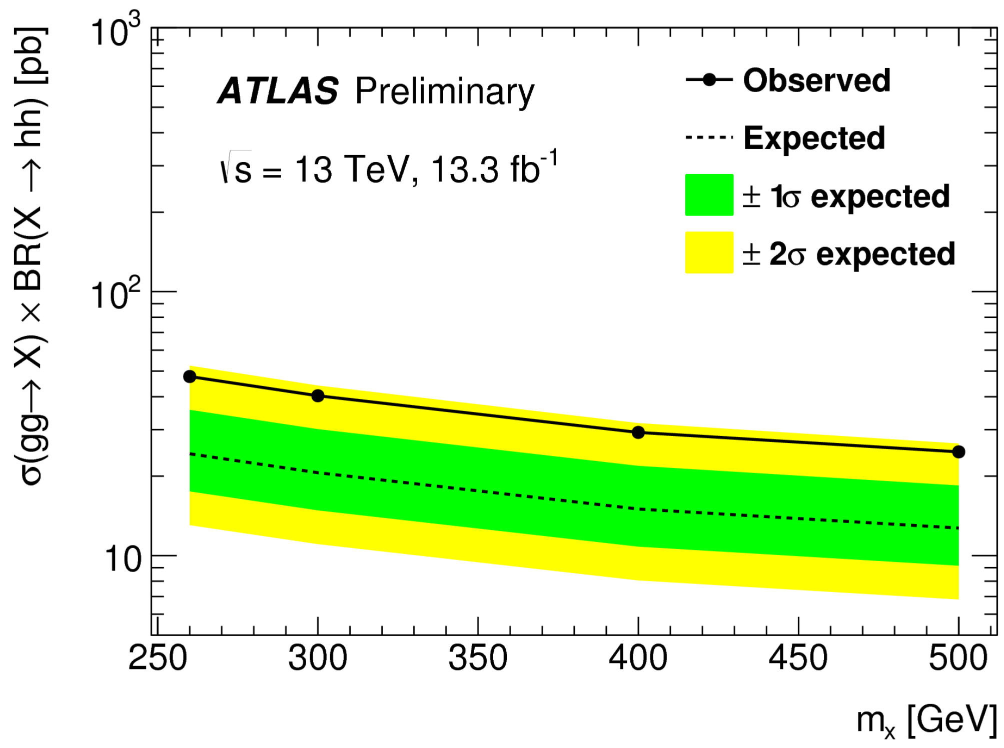
Event selection

- Diphoton triggers
- Two photons (p_T^γ > 35, 25 GeV)
- ≥ 2 jets and no b-jets, 1 charged lepton
- 105 < $m_{\gamma\gamma}$ < 160 GeV

Process	Number of events	
Continuum background	7.26	± 1.23
SM single-Higgs	0.616	± 0.115
SM di-Higgs	0.0187	± 0.002 24
Observed		15

Limits

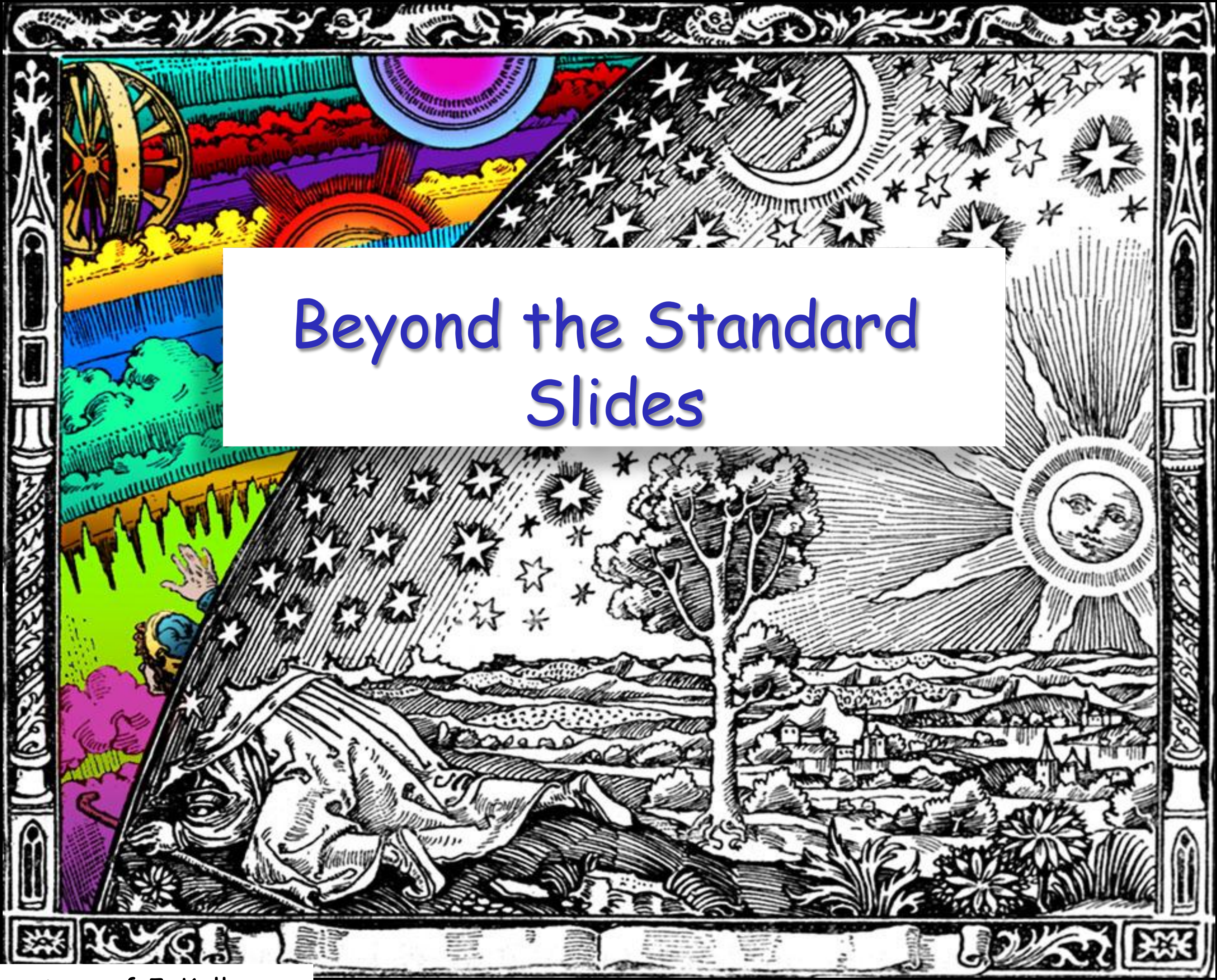
- **Non-resonant production**
  - σ(pp->hh) < 25 pb (95% C.L.)
  - expected: 12.9 pb
- **Resonant search**
  - In the range between 47.7 pb and 24.7 pb for a resonance mass of 260 – 500 GeV



Summary

- BSM Higgs probed via decays to SM states
- Wide variety of models considered...
- ... as well as model-independent interpretations
- No significant excess found however stringent limits set in multiple BSM models
- But we have not yet finished Run2, much more data to come!
  - So far in 2016, ATLAS has collected ~25 fb^{-1} of data at 13 TeV
  - By the end of year, 32-40 fb^{-1} is expected
- Do stay tuned!

Beyond the Standard Slides



Courtesy of J. Keller

Neutral Higgs searches: H/A→ττ

ATLAS-CONF-2016-085

Event selection

- lep-had analysis: b-veto and b-tag categories
  - Single lepton triggers
  - Single hadronic tau (55%) with pT >25 GeV
  - Single isolated ele or muon with pT >30 GeV
  - Opposite charge, di-lepton veto
  - $\Delta\phi$(tau, e/mu) > 2.4
  - MT(e/mu, MET) < 40 GeV
  - e-had channel: mvis < 80 GeV and >110 GeV

Background estimation

lep-had analysis

- Jets faking e,μ and taus are not well modeled in MC. Fake factors are derived from data.

had-had analysis

- Multi-jet backgrounds faking taus are not well modeled in MC. Fake factors derived from data.
- For W-jets and top backgrounds, different dedicated fake-rate corrections to MC (estimated from data) are used

---

- lep-had analysis: high-MET category
  - MET trigger for high-MET category (events with MET > 150 GeV)
  - This category introduced due to loss of efficiency for single lepton triggers

- had-had analysis: b-veto and b-tag categories
  - Single tau trigger
  - Leading tau with pT >110/140 GeV
  - Second tau with pT > 55 GeV (65 GeV for b-tagged category)
  - Opposite charge requirement
  - Veto events with a leptons
  - $\Delta\phi$(tau1, tau2) > 2.7

Dominant systematics: τ energy scale, τ trigger, jet fake-related (lep-had), top modeling (had-had)

Charged Higgs searches: $H^{\pm} \to tb$

ATLAS-CONF-2016-089

Semi-leptonic selection:

- Single lepton triggers
- 1 lepton with pT > 25 GeV
- ≥4 jets with pT >25GeV
- ≥ 2 b-tagged
- Split into SRs and CRs based on number of jets (Nj) & b-jets (Nb)

To separate signal from the SM background, different discriminants are used depending on the event category, and are then combined in a binned maximum-likelihood fit

- discriminating variable in the CR is the scalar sum of the pT of the selected jets
- BDT is used in the SR (trained against ttbar+≥1b for m(H±) ≤ 500 GeV, and all ttbar background for m(H±) ≥ 500 GeV)

Background dominated by ttbar + jets production

- Split into light/heavy flavour based on extra jets: ttbar + light, ttbar + ≥1c, ttbar + ≥1b

The variables entering the BDT training are :

- The highest jet p_T.
- The mass of the bb pair with minimum ΔR.
- The p_T of the fifth jet, ordered by b-tagged jets and then non–b-tagged jet
- The second Fox-Wolfram moment calculated using all jets and leptons.
- The average ΔR of all bb pairs.
- The ΔR of the lepton and the bb pair with smallest ΔR.
- The mass of the untagged jet-pair with minimum ΔR.
- The scalar sum of E_T calculated using all jets.
- The mass of the bb pair with maximum p_T.
- The mass of the bb pair with maximum mass.
- The mass of the jet triplet with maximum p_T.
- The centrality calculated using all jets and leptons.

Systematic uncertainties dominated by ttbar modeling, especially heavy flavour, b-tagging and jet energy scale/ resolution

Di-Higgs searches: hh→4b

ATLAS-CONF-2016-049

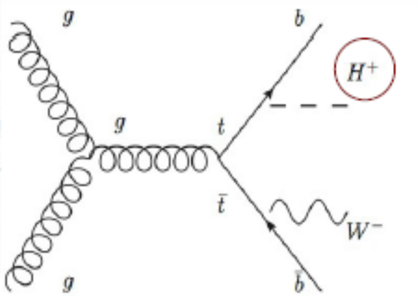
Resolved analysis:

- **Selection:**
  - 4 anti-kt jets with R=0.4 selected, each b-tagged (70% working point), with pT > 30 GeV and |η| < 2.5
- The mass of the two Higgs boson candidate system (m4j) is used as the final discriminant between Higgs boson pair production and the background
- **Vetoing events with ΔR(h,h) < 1.5**
- **Backgrounds:**
  - 98% QCD multijet (data-driven), 2% ttbar (taken from MC simulation)

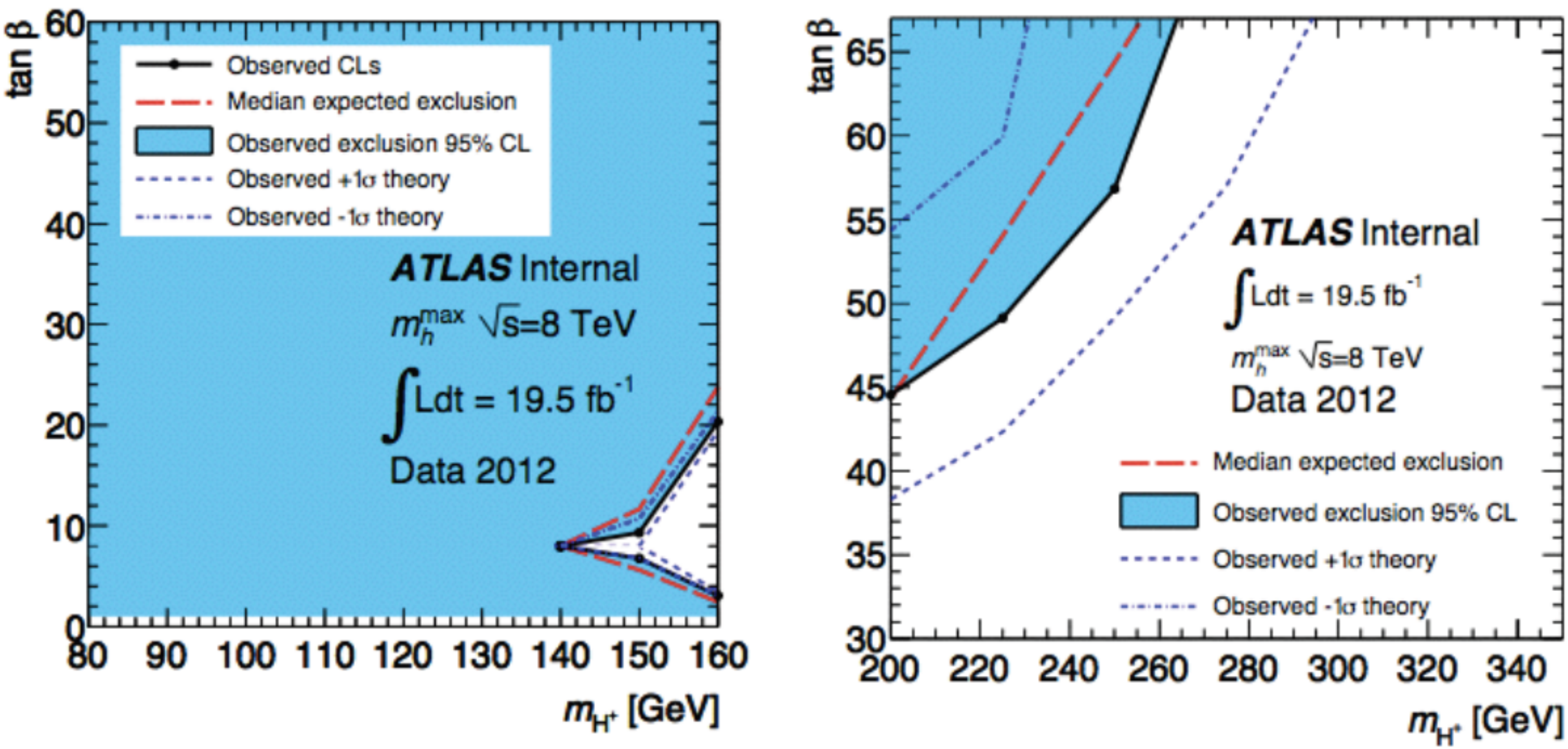
Boosted analysis:

- **Selection:**
  - At least two anti-kt jets with R=1.0 with pT > 250 GeV, |η|< 2.0 and mass mJ > 50 GeV
  - pT(lead_J) > 450 GeV
  - |Δη(J, J)| < 1.7
  - To be considered as a Higgs boson candidate, each large-R jet must have at least one b-tagged R=0.2 track-jet associated to it.
- **Backgrounds:**
  - 83-87% QCD multijet (data-driven), remainder from ttbar (data-driven)

Charged Higgs searches: $H^{\pm} \to \tau^{\pm}\nu$ (low mass)



JHEP03(2015)088

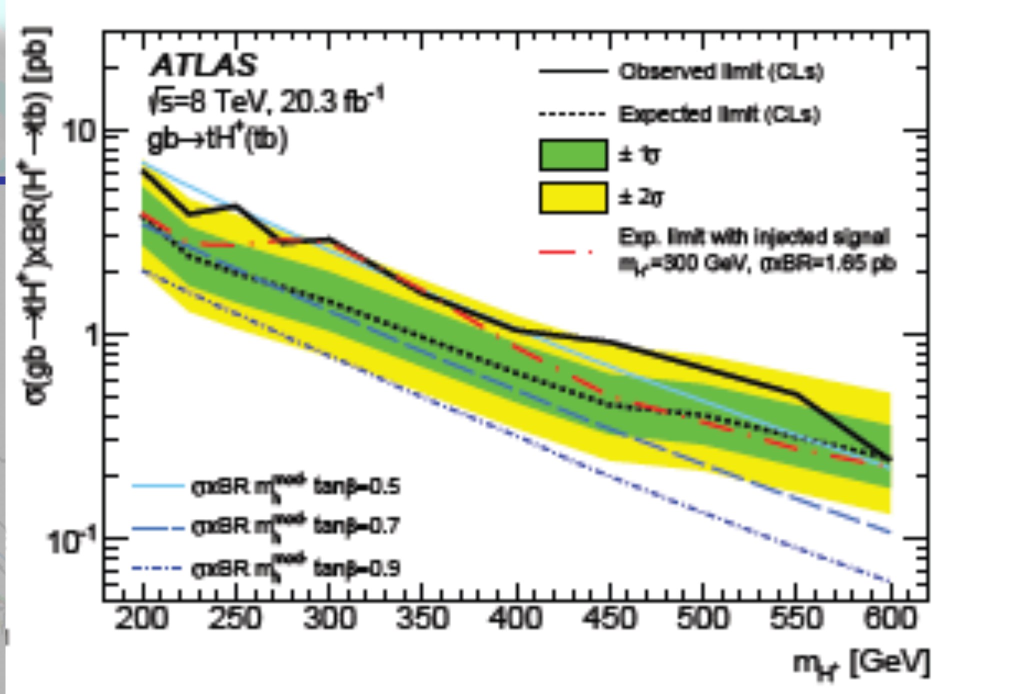


(a) Low mass H^+ (b) High mass H^+

$H^{\pm} \rightarrow tb$ @ 8 TeV

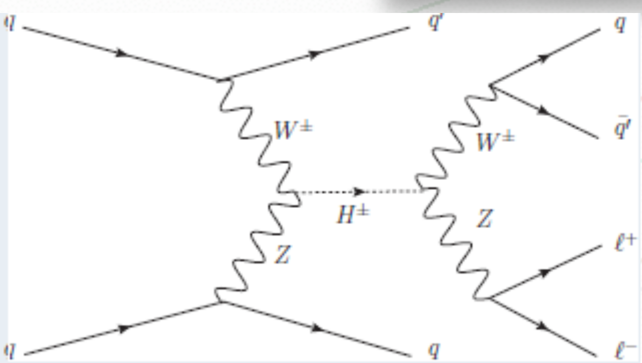
arXiv:1512.03704

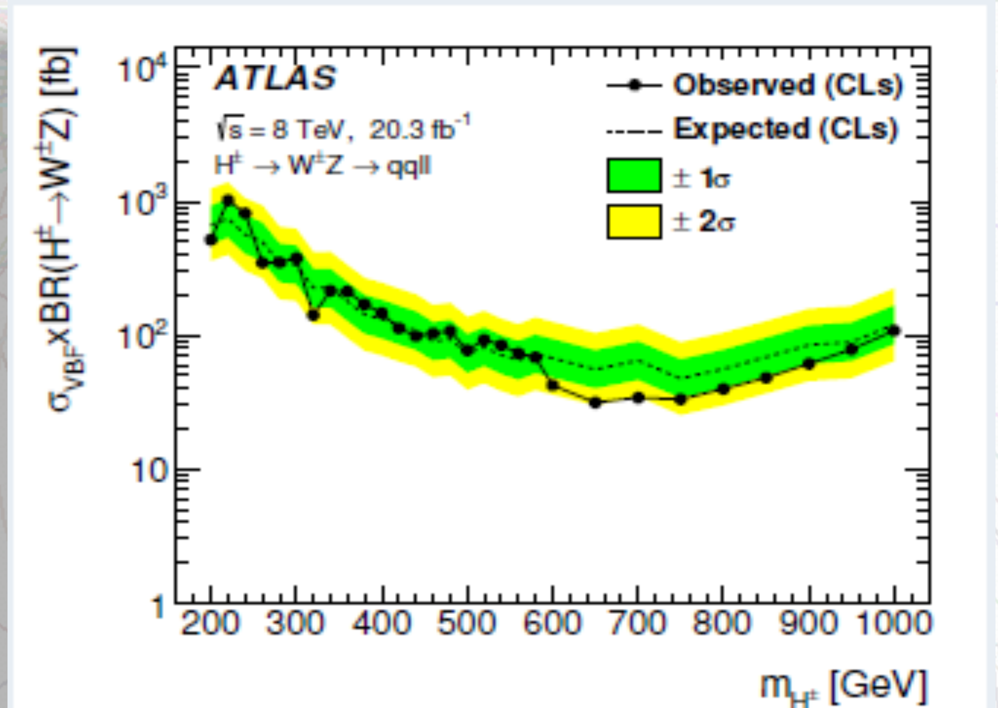
broad excess not compatible with signal hypothesis



VBF $H^{\pm} \rightarrow WZ$ @ 8 TeV

arXiv:1503.04233





Higgs triplet model (not MSSM).

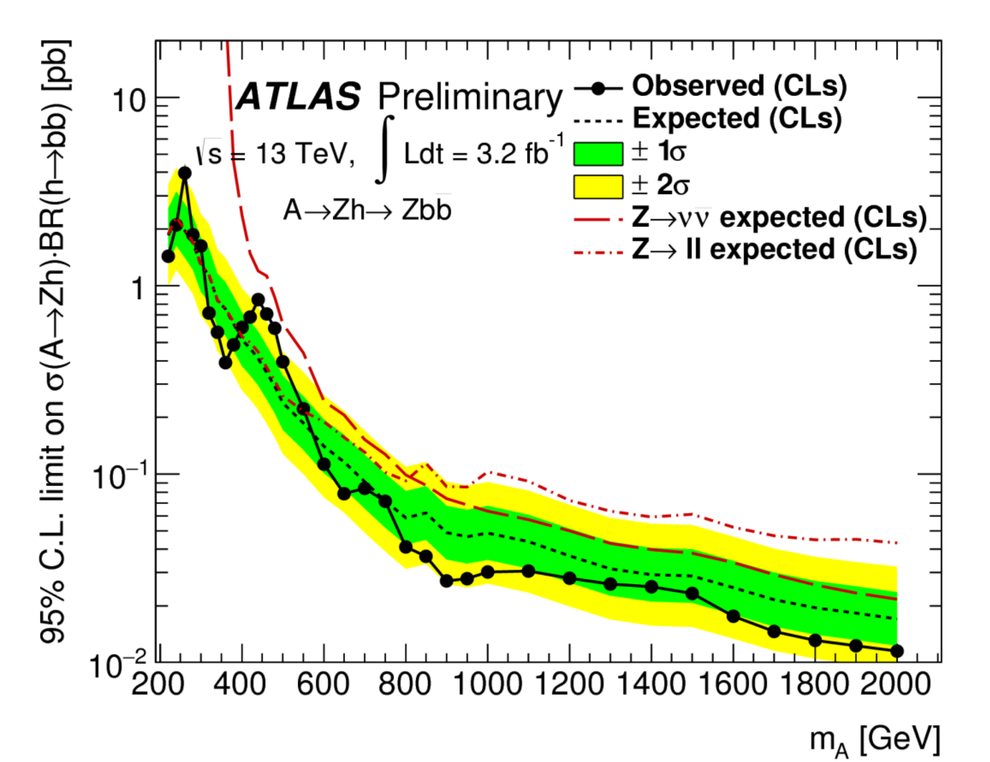
- **Require two forward separated jets in η with large dijet mass**

A -> Zh @ 13 TeV,

ATLAS-CONF-2016-015

A: CP-odd higgs boson of 2HDM
Z decay: (νν), (l+l-); h -> bb
(h->tautau in 8 TeV analysis: arXiv:1502.04478

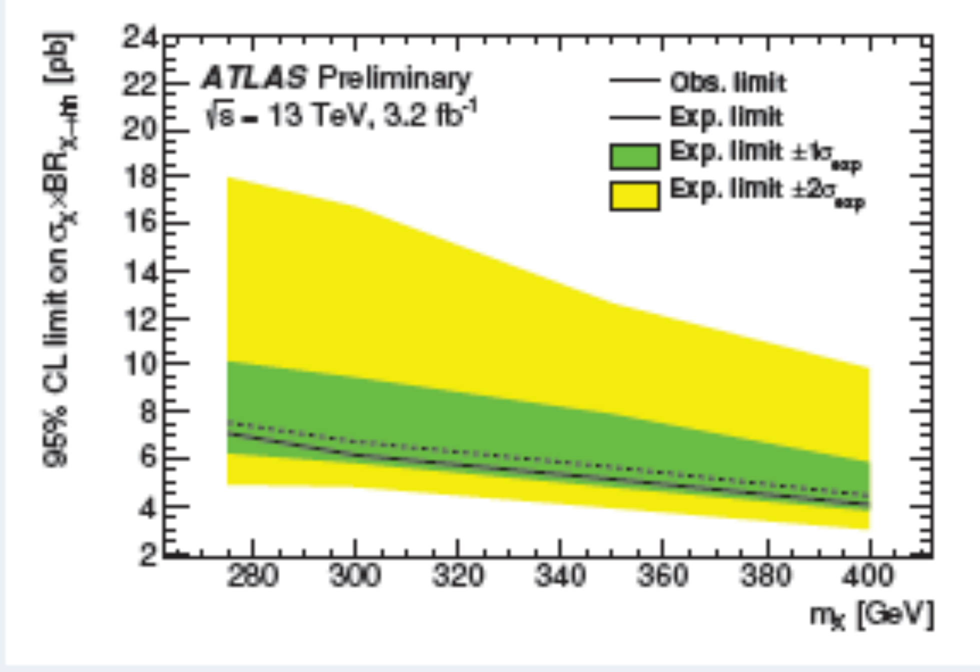
Best sensitivity from ggF production mode
Z → νν channel dominates sensitivity at high mass



H->bbγγ @ 13 TeV,

ATLAS-CONF-2016-004

2.4 sigma excess visible in Run 1
not observed

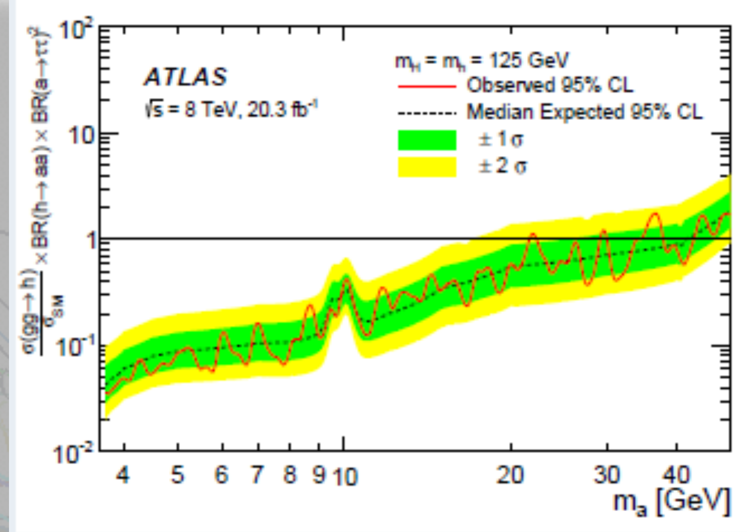


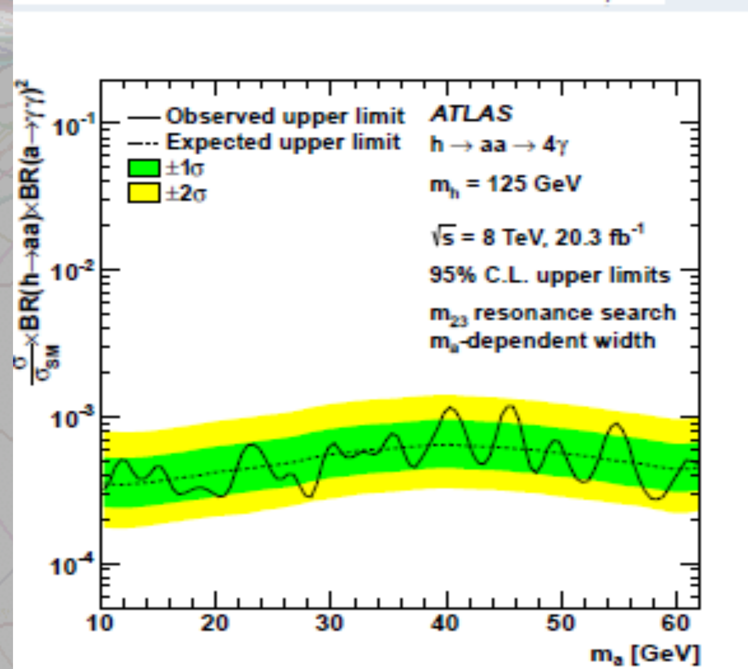
BSM light Higgs $H\to aa\to \mu\mu\tau\tau/\gamma\gamma\gamma\gamma$

arXiv:1505.01609
arXiv:1509.05051

- Additional (pseudo)scalars lighther than 125 GeV predicted in several models, e.g. 2HDM+S, NMSSM
- searching for BSM h(125) decays

assuming no coupling of *a*-boson to quarks:

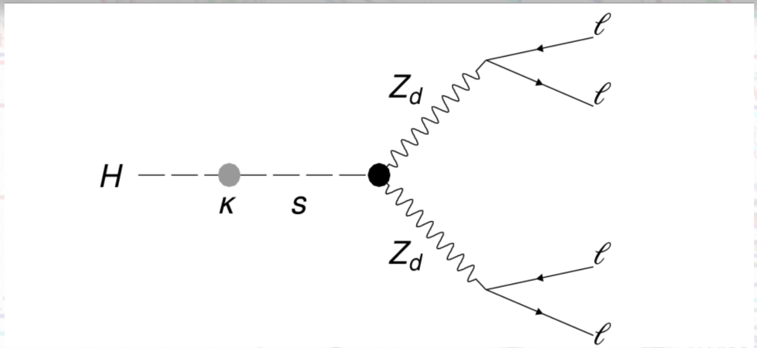


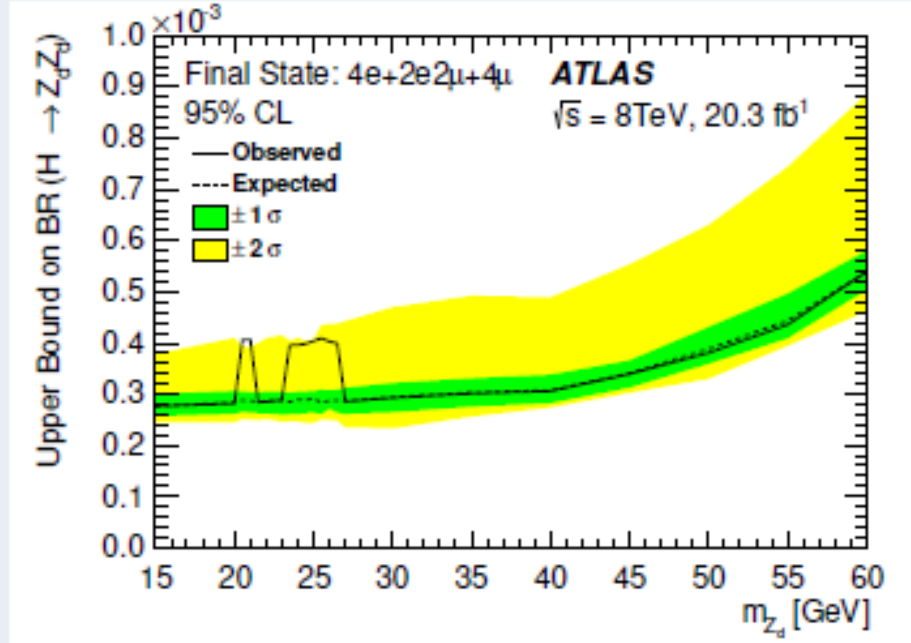


h -> ZZd ->4l and h -> ZdZd ->4l

arXiv:1505.07645

Dark Higgs Sector
• in dark sector, an additional Ud (1) symmetry could be broken by dark Higgs
• dark Higgs mixes with SM Higgs and decays to dark photons Zd



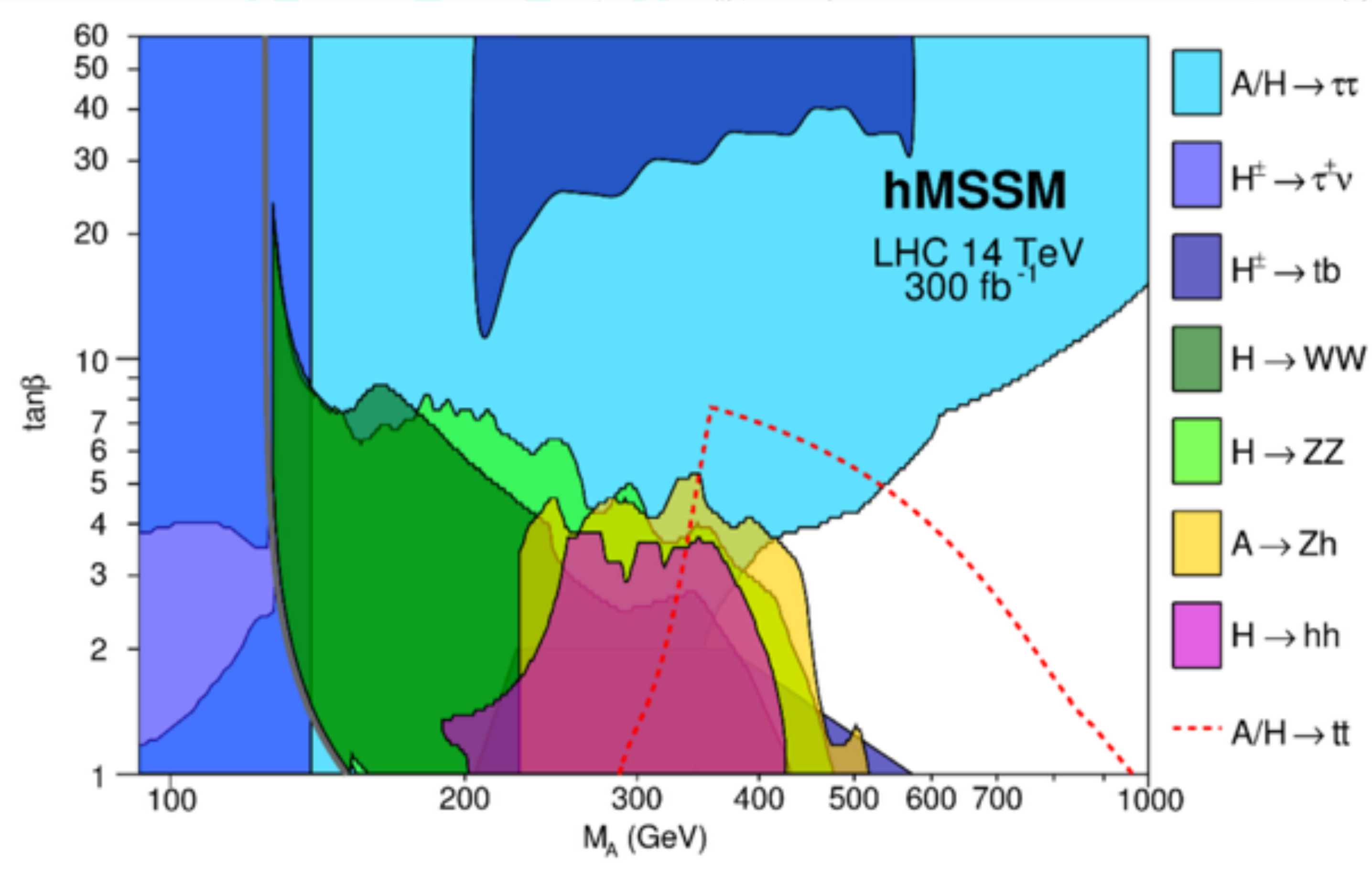


LFV Higgs decays

arXiv:1604.07730

• lepton flavour violating decays predicted by models with additional Higgs doublets, composite Higgs, ...
• looking for oppposite sign *e and* μ final states

Theory projections for 2σ sensitivity are shown



Djouadi, A., Maiani, L., Polosa, A. et al.
JHEP 06 (2015) 168