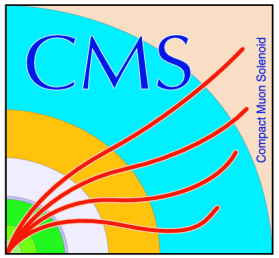

Heavy neutral and charged Higgs boson searches in the MSSM and the 2HDM at ATLAS and CMS

Gerrit Van Onsem (DESY)

QCD@LHC 2016
Zürich, Switzerland
25 August 2016

HELMHOLTZ ASSOCIATION

DESY

Observed Higgs boson may be part of extended sector

- Highlight of LHC Run 1: SM-like Higgs boson observed at 125 GeV by ATLAS and CMS

  Maybe part of larger Higgs sector?

- Many models beyond the SM predict **new (pseudo)scalar bosons**
  - Two-Higgs-Doublet models (2HDM)
  - Supersymmetry (MSSM)
  - Models with new electroweak Higgs singlets
  - Models with Higgs triplets
- 2HDM (and MSSM) predict two SU(2) doublets resulting in 5 physical Higgs bosons
  - **Charged H^+ and H^-**
  - **Neutral CP-even H and h**
  - **Neutral CP-odd A**

h often assumed to be observed Higgs boson at 125 GeV
→ leads to stringent constraints on allowed model parameter space

Explored parameter space depends on model assumptions

- 2HDM benchmark models
  - ***type-I*** both doublets couple to both up-type and down-type fermions equally
  - ***type-II*** one doublet couples to up-type, other to down-type fermions

  14 free parameters but can be reduced by assumptions
  - tan(ß) ratio of the VEV of the two SU(2) doublets
  - α mixing angle of mixing matrix
  - m_h, m_H, m_A, $m_{H\pm}$ physical masses of Higgs bosons
  - …
- MSSM example of a 2HDM of *type-II*
  - Usually scanning 2D plane of tan(ß) vs mass parameter
- New bosons could couple to fermions (τ, μ, t, b), SM bosons (H, W, Z) and each other

  → **rich phenomenology** at the LHC!

Charged $H^{\pm}$

- $H^{\pm} \rightarrow \tau\nu, tb$
- $H^{\pm} \rightarrow W^{\pm}Z$

H/A → fermions

- H/A → ττ
- H/A → bb
- H/A → tt

H → ZA, H/A → Zh

H/A → boson pair

- H → hh
- H → ZZ, WW

Disclaimers:
personal selection of searches, many results not covered in this talk!

Main focus on newer results, with CMS and ATLAS balance

Will not emphasize comparison of results between experiments
(note: sometimes requires careful evaluation of signal model assumptions)

Charged $H^{\pm}$

$H^{\pm} \rightarrow \tau\nu$, tb

$H^{\pm} \rightarrow W^{\pm}Z$

H/A → fermions

H/A → ττ

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H → ZA, H/A → Zh

H/A → boson pair

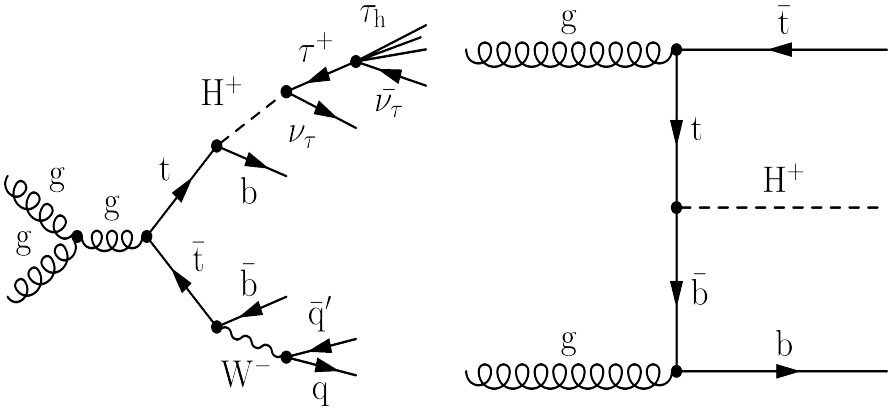
H → hh

H → ZZ, WW

$H^{\pm} \rightarrow \tau\nu$, tb

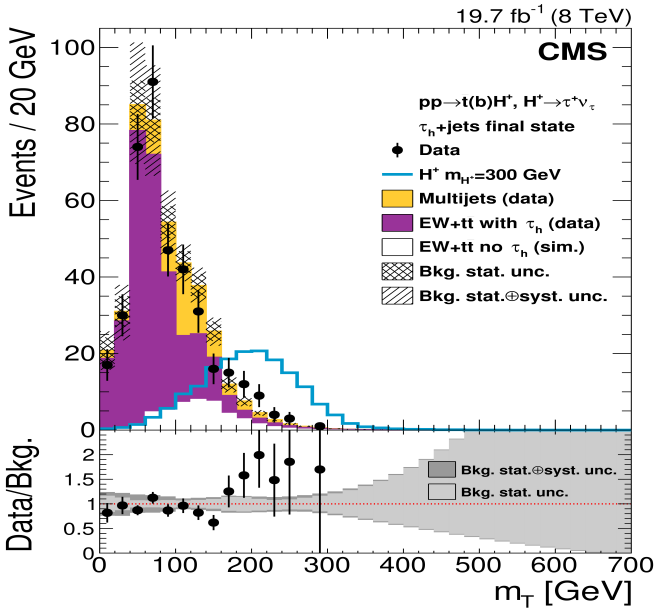
1508.07774
CMS, 8 TeV

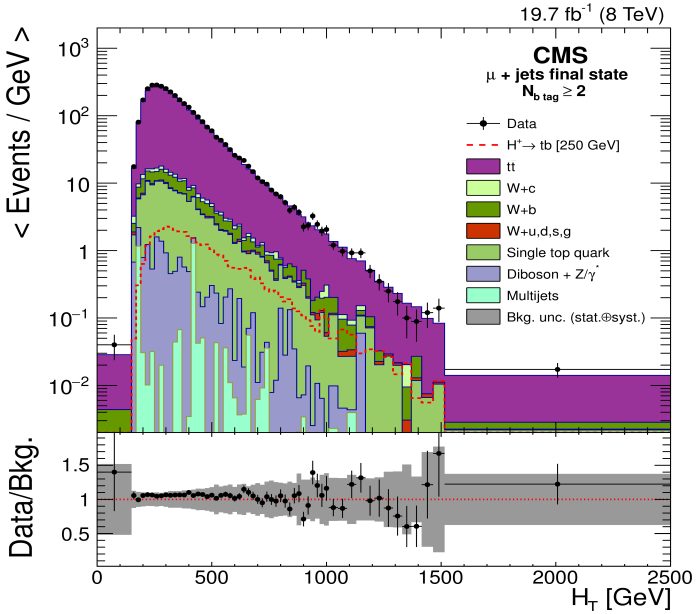
> Production/decay dependency on mass hierarchy of $H^{\pm}$ and top



Decay mode	Signatures for $m_{H^+} < m_t - m_b$	Signatures for $m_{H^+} > m_t - m_b$
	$pp \rightarrow t\bar{t} \rightarrow bH^+\bar{b}H^-/bH^+\bar{b}W^-$	$pp \rightarrow \bar{t}(b)H^+$
$H^+ \rightarrow \tau^+\nu_\tau$	τ_h+jets$^{(5)}$	τ_h+jets$^{(5)}$, $\mu\tau_h^{(6)}$, $\ell\ell'^{(7)}$
$H^+ \rightarrow t\bar{b}$	—	$\mu\tau_h^{(6)}$, $\ell\ell'^{(7)}$, ℓ+jets$^{(8)}$

> Discriminating variables: transverse mass m_T of τ_{had} and MET system, b-tagged jet multiplicity, and H_T (scalar sum of p_T of jets)

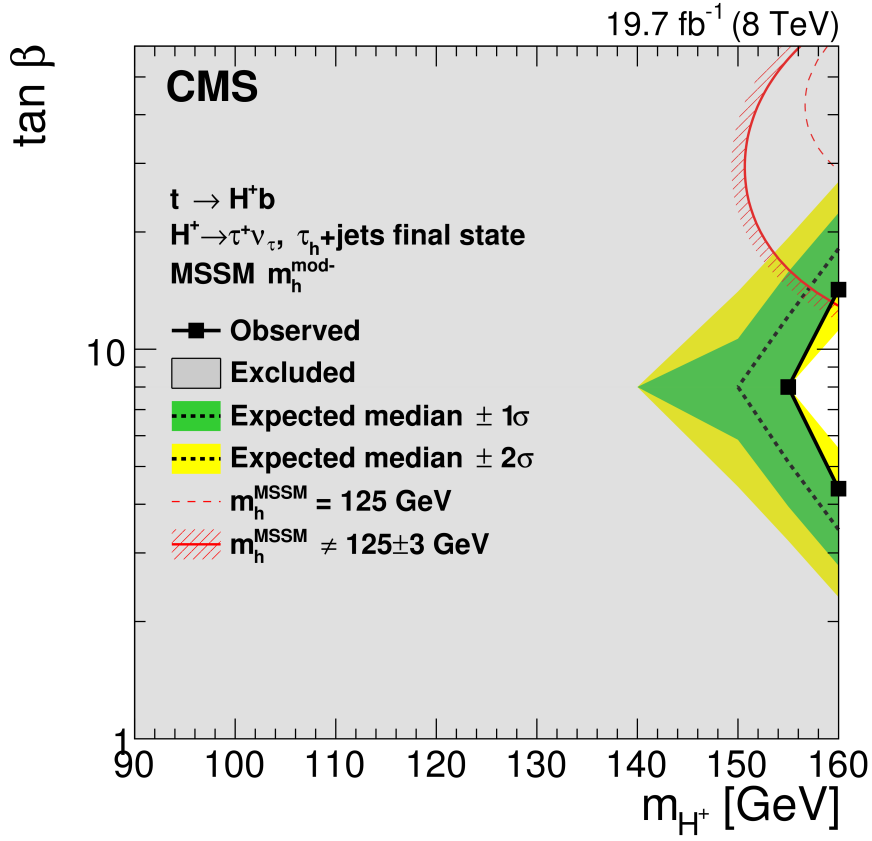




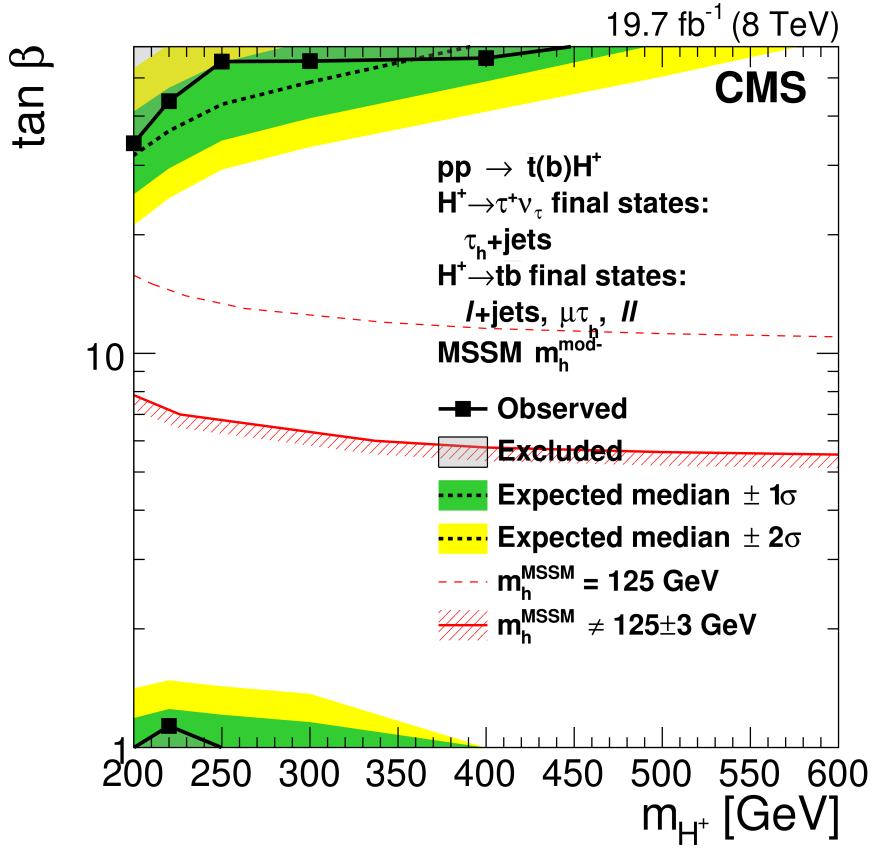
$H^{\pm} \rightarrow \tau\nu$, tb

1508.07774
CMS, 8 TeV

- Systematic uncertainties: τ identification, b-tagging, tt modelling, ...
- 95% CL limits can be derived on cross section (x branching ratios) or in specific MSSM scenarios



Low mass

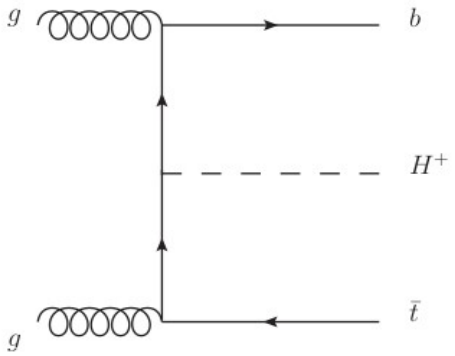


High mass

$H^{\pm} \rightarrow \tau\nu$

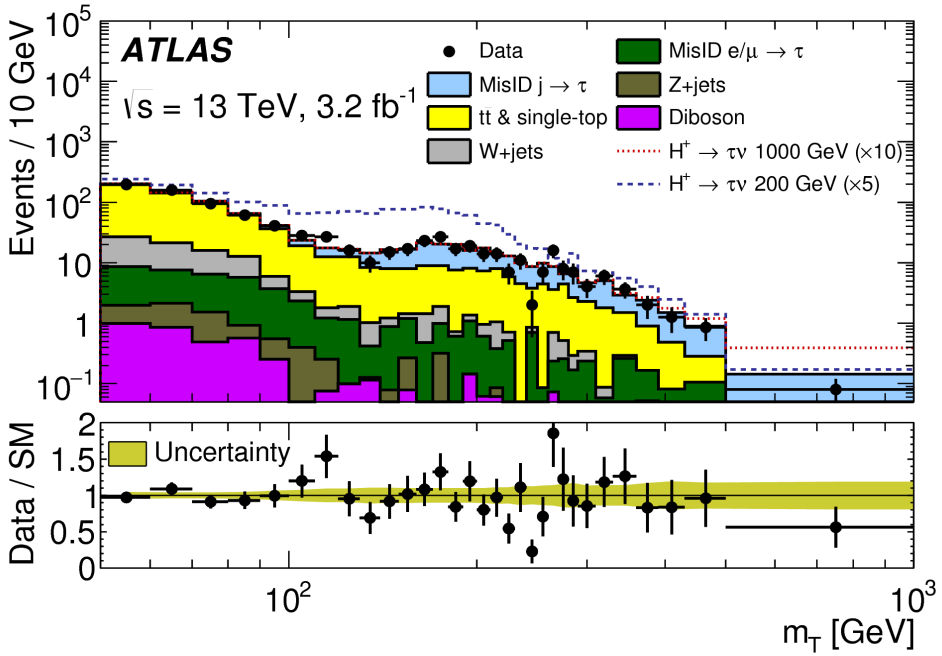
1603.09203
ATLAS, 13 TeV

> Production of $H^{\pm} \rightarrow \tau\nu$ in association with top



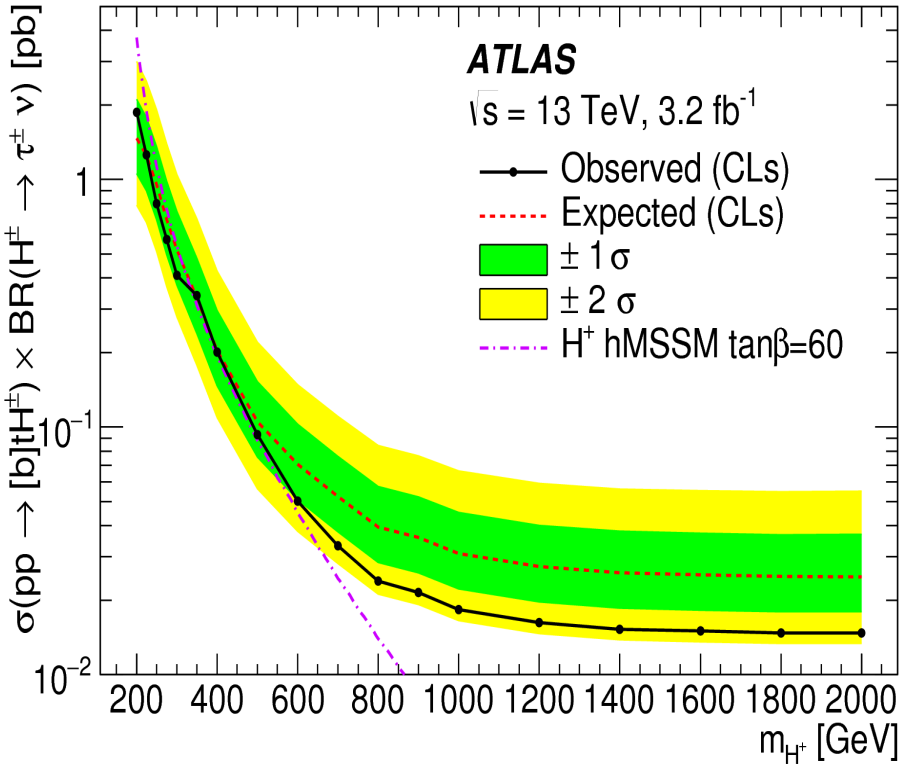
1 hadronically decaying $\tau_{\text{had-vis}}$
≥3 jets with ≥1 b-tag
MET > 150 GeV

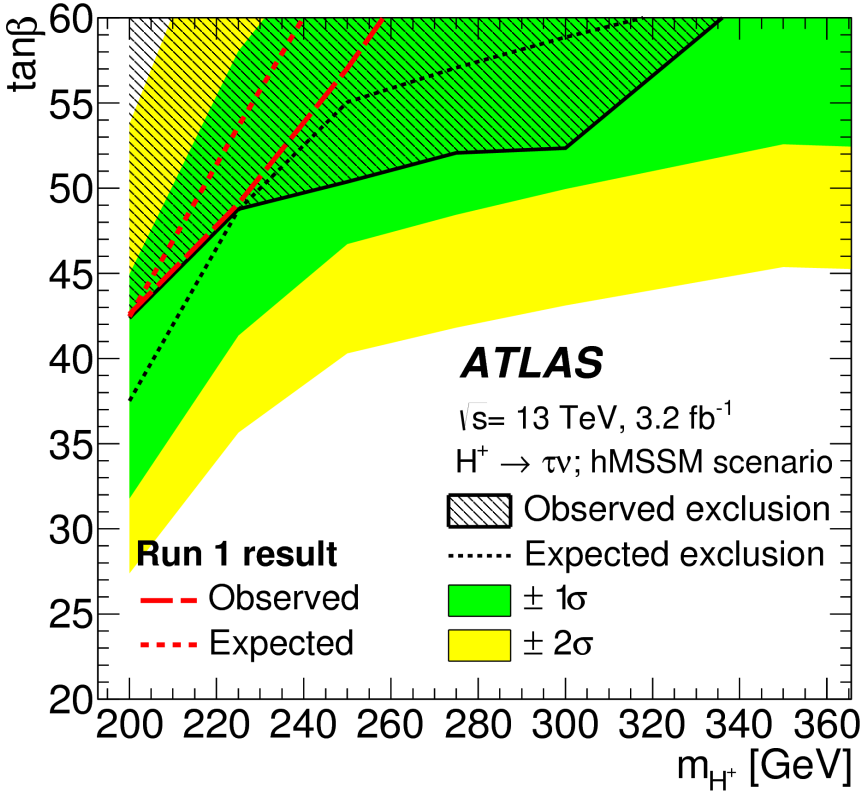
> Discriminating variable: m_T of $\tau_{\text{had-vis}}$ and MET system



Data-driven background estimation for jets and e/μ identified as τ
by applying fake factors derived from control regions

- Systematic uncertainties: τ identification, b-tagging, energy scale of jets and τ, ...
- Limits on cross section x branching ratio, and interpretation in MSSM context

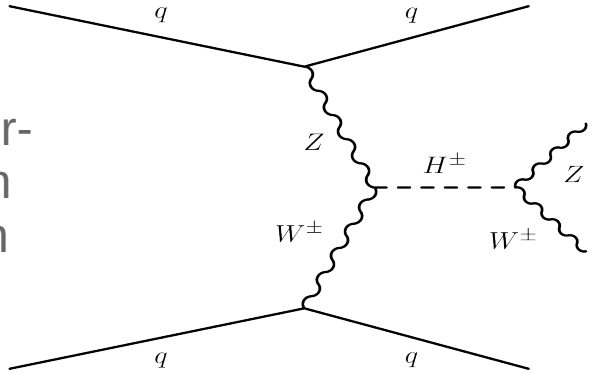




$H^{\pm} \rightarrow W^{\pm}Z$

> Coupling in 2HDM only at higher order, in Higgs Triplet models at tree level

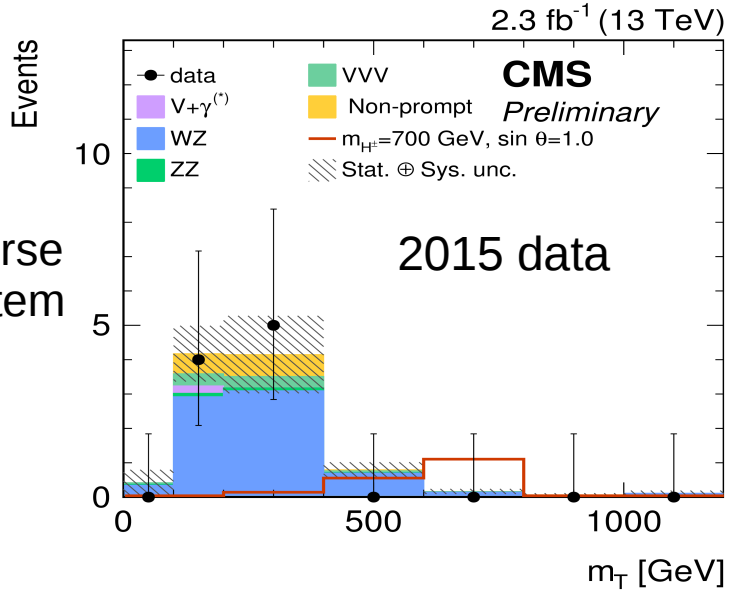
Vector-boson fusion

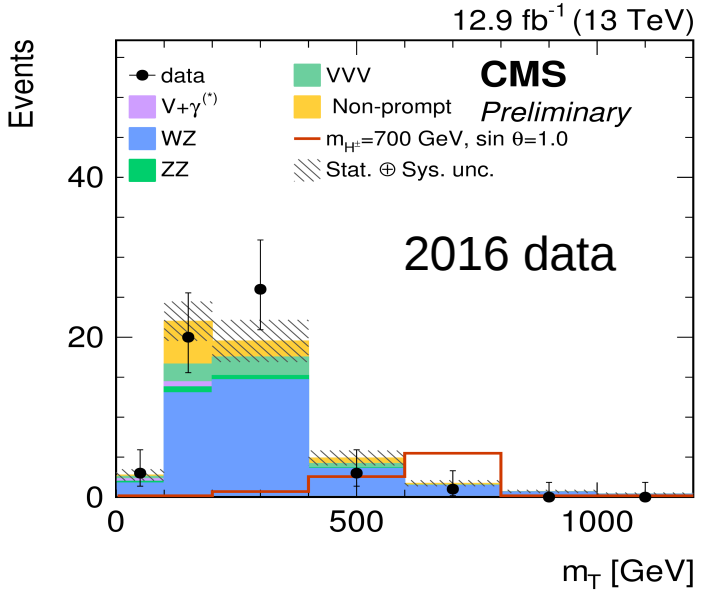


3 leptons (muon or electron)
2 jets, $|\Delta\eta_{jj}| > 2.5$, dijet mass > 500 GeV
MET > 30 GeV

> Dominating background WZ, followed by non-prompt leptons (latter estimated from data using fake rate method)

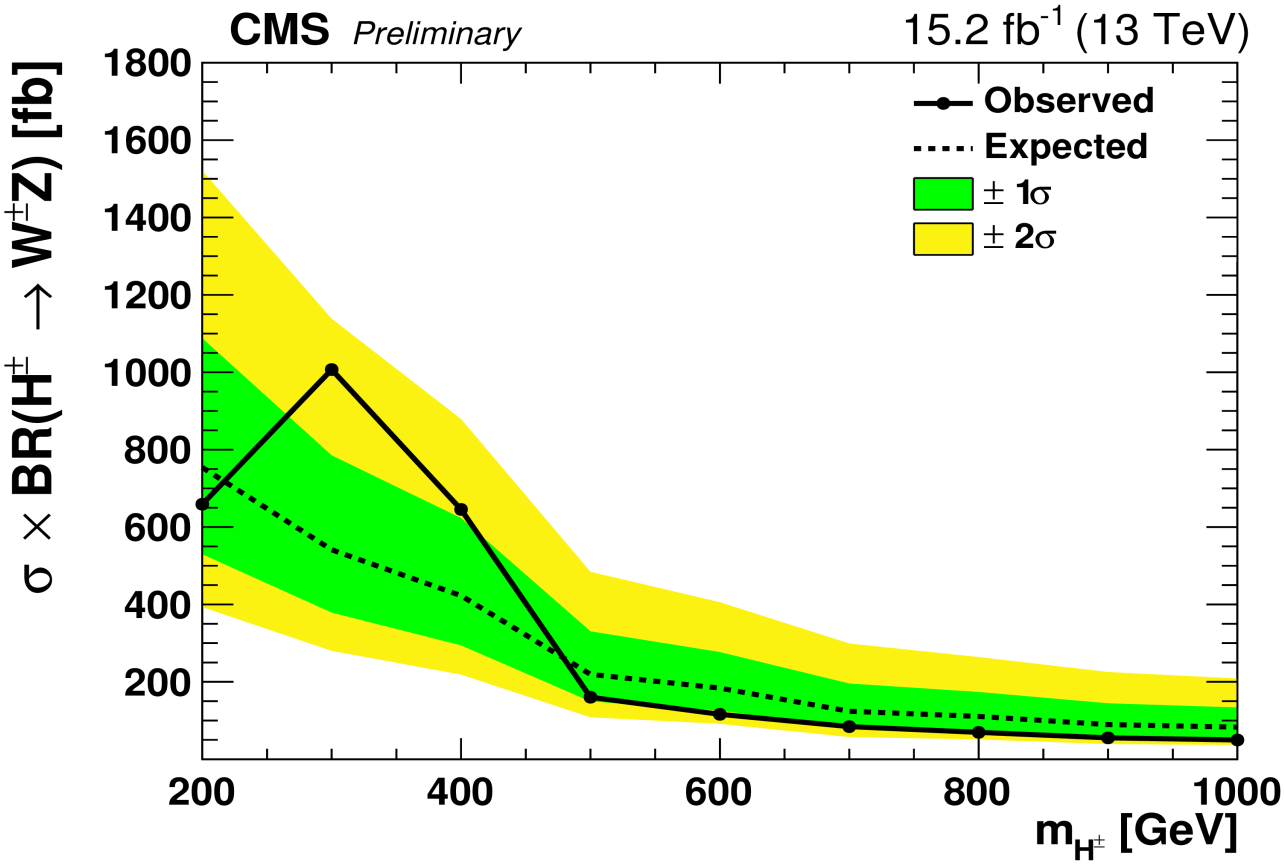
Discriminating variable: transverse mass of WZ system





$H^{\pm} \rightarrow W^{\pm}Z$

- Systematic uncertainties: WZ normalization, non-prompt background, jet energy scale, ...
- Limits on cross section x branching ratio



Charged $H^{\pm}$

- $H^{\pm} \rightarrow \tau\nu, tb$
- $H^{\pm} \rightarrow W^{\pm}Z$

H/A → fermions

- **H/A → ττ**
- **H/A → bb**
- **H/A → tt**

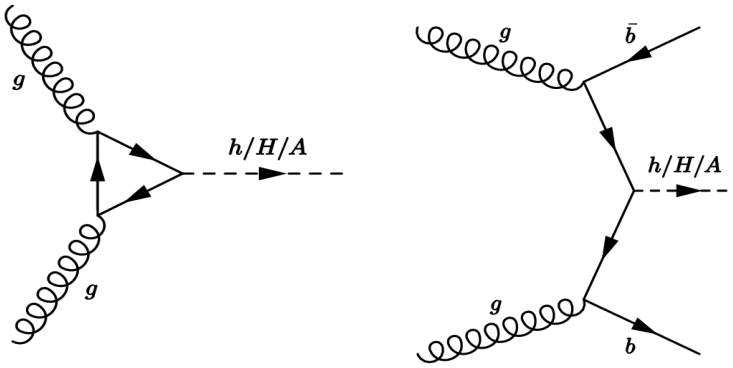
H → ZA, H/A → Zh

H/A → boson pair

- H → hh
- H → ZZ, WW

1608.00890
ATLAS, 13 TeV

> Gluon fusion and b-associated production

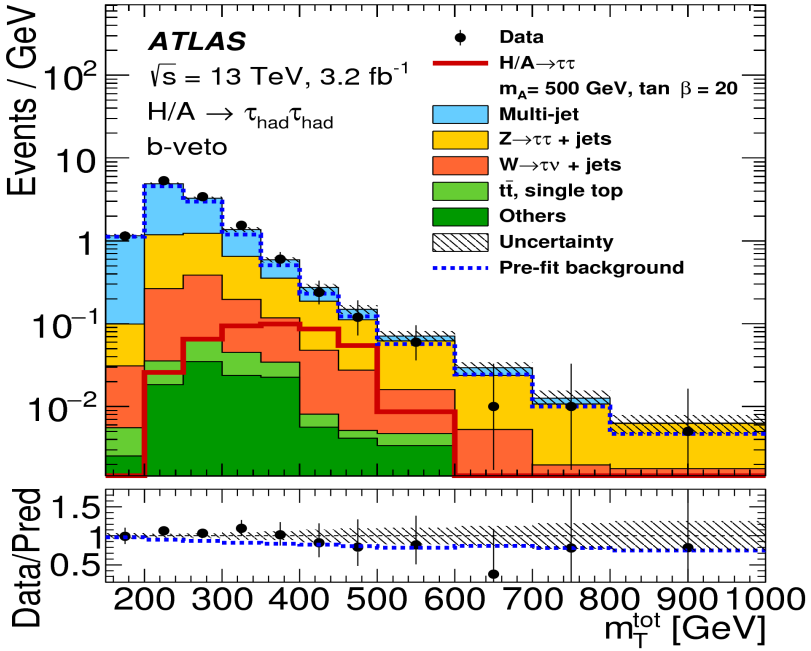


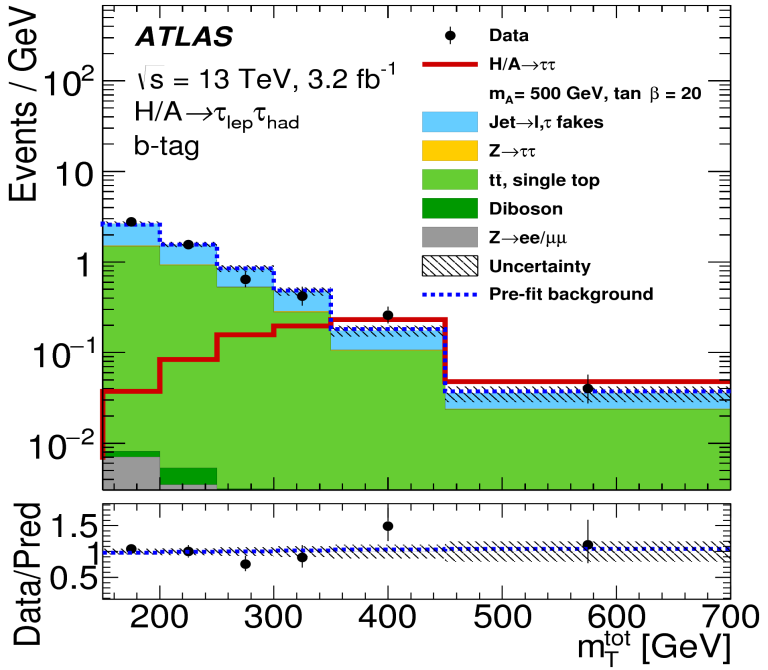
$\tau_{lep}\tau_{had}$ channel: 1 $\tau_{had\text{-}vis}$ and 1 lepton

$\tau_{had}\tau_{had}$ channel: 2 $\tau_{had\text{-}vis}$

- angular and mass cuts for W/Z background removal
- event categories according to presence of b-tagged jets

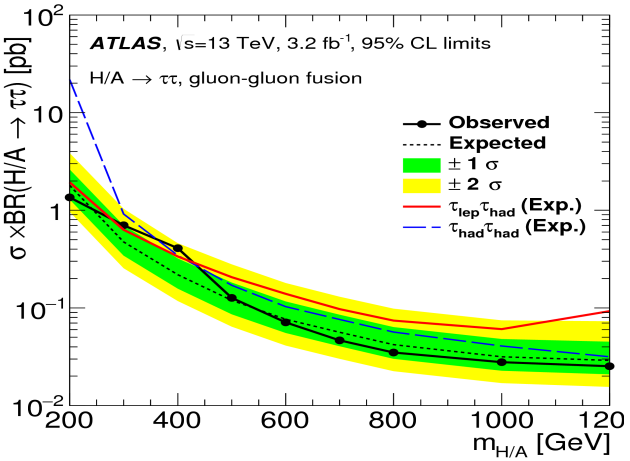
> Discriminating variable: **transverse mass of di-tau system**



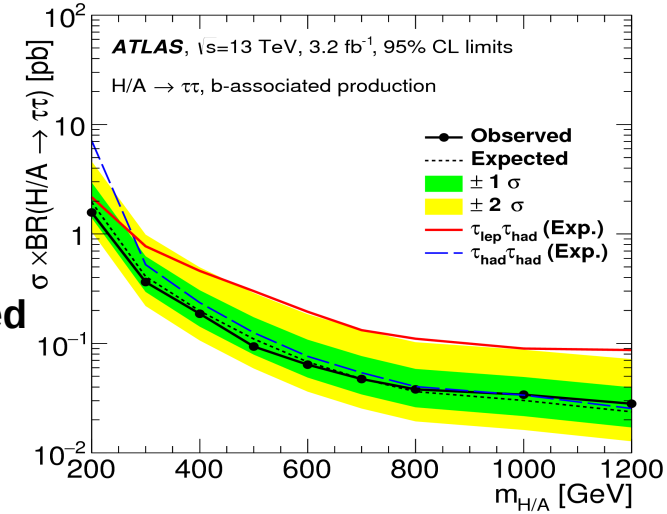


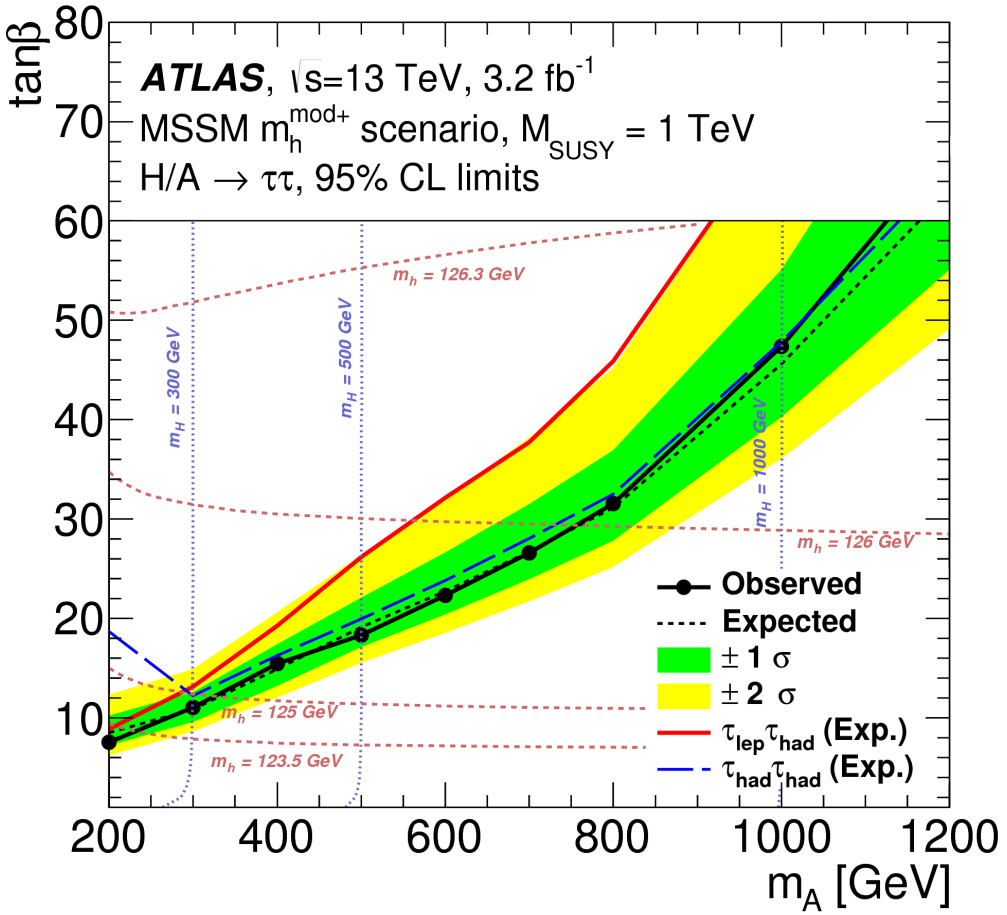
> Systematic uncertainties: top background normalizations, τ_{had} energy scale and trigger, ...

b-veto categories mainly sensitive to **gluon fusion**

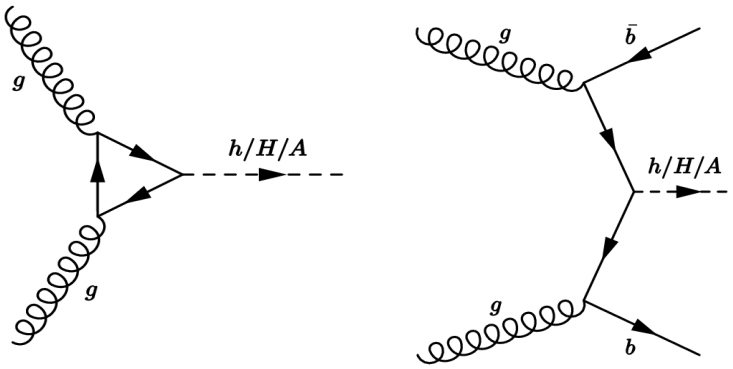


b-tag categories mainly sensitive to **b-associated production**





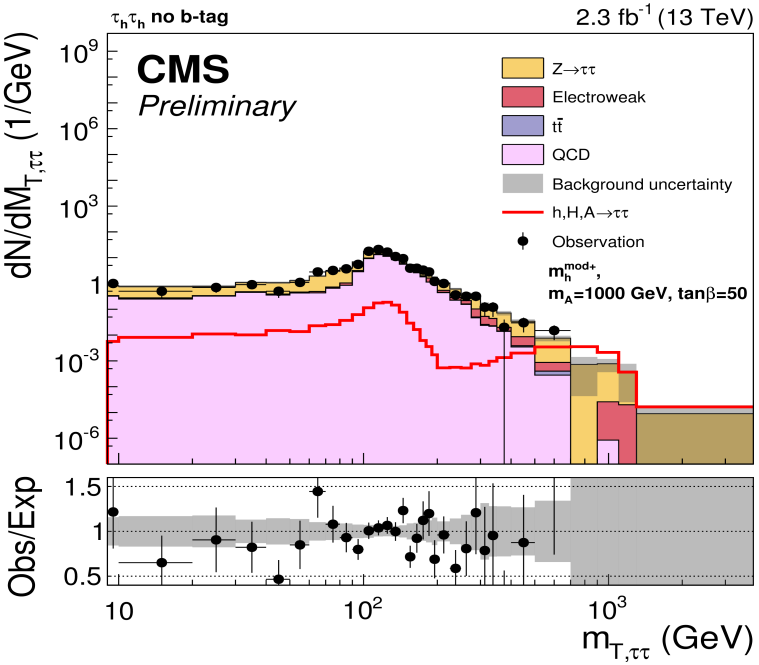
- Gluon fusion and b-associated production

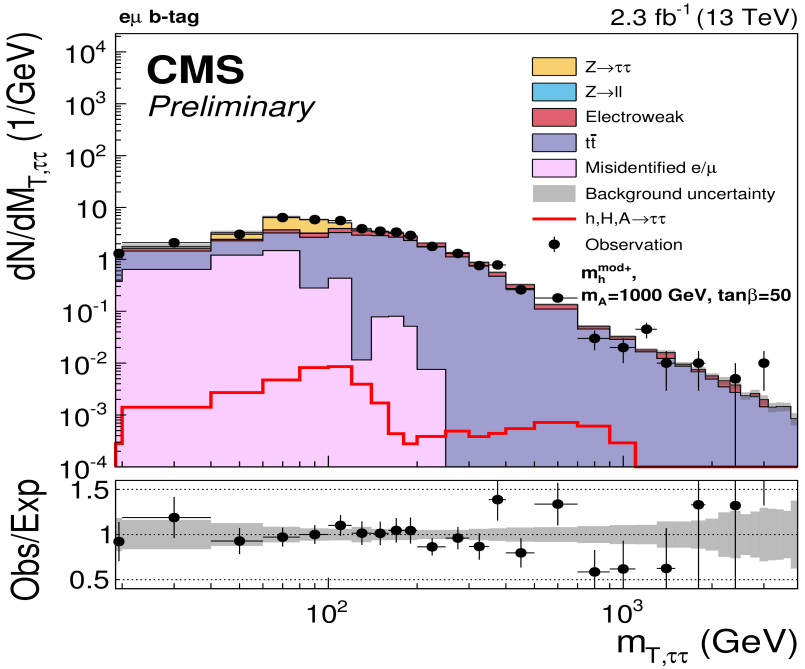


channels: $e\tau_{had}$, $e\tau_{had}$, $\mu\tau_{had}$, $\tau_{had}\tau_{had}$

- transverse mass cuts for W background removal
- topological discriminator cut for tt rejection
- event categories according to presence of b-tagged jets

- Discriminating variable: transverse mass of di-tau system



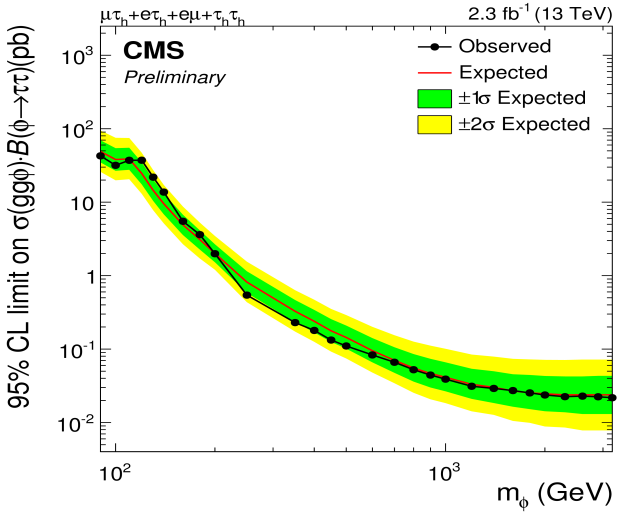


H/A → ττ

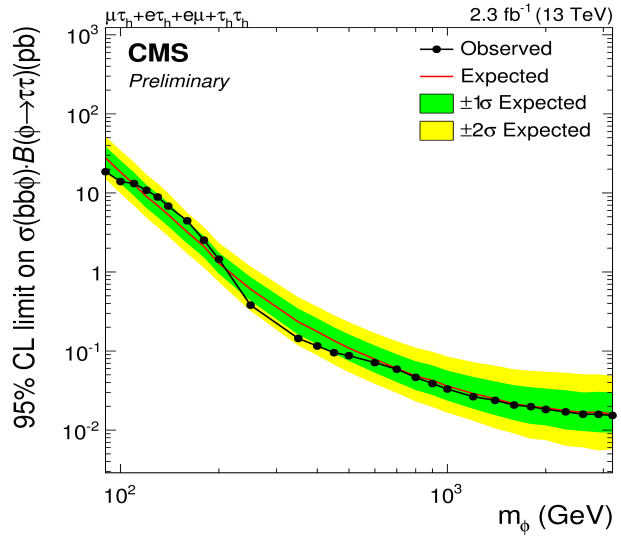
1608.00890
ATLAS, 13 TeV

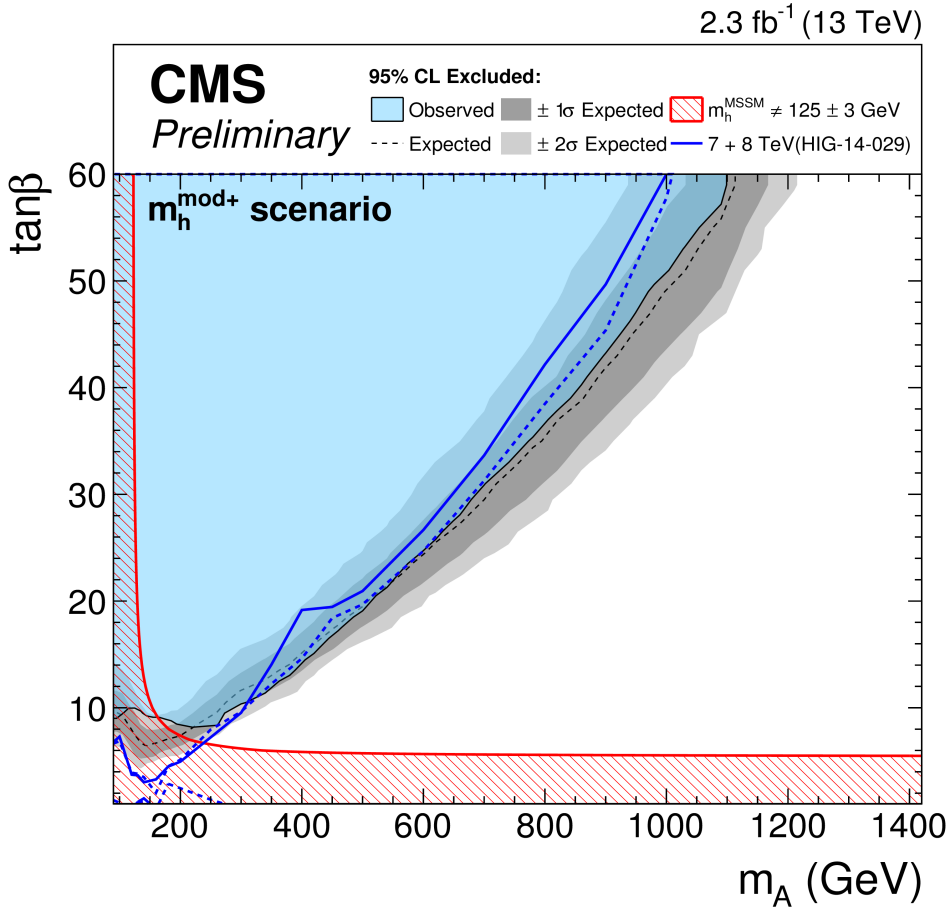
> Systematic uncertainties: top background normalizations, τ_{had} mis-identification rate, τ trigger, ...

b-veto categories mainly sensitive to **gluon fusion**



b-tag categories mainly sensitive to **b-associated production**





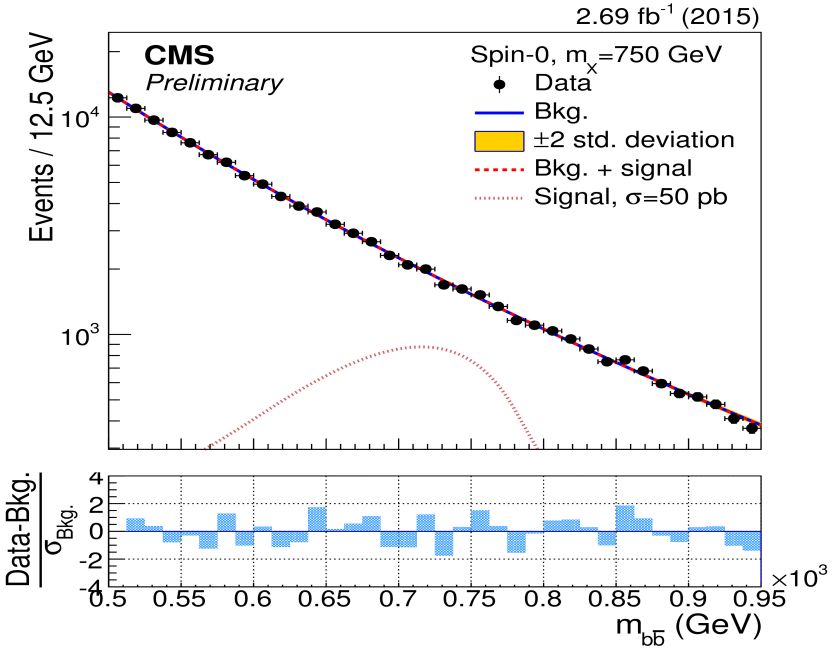
H/A → bb

- Narrow spin-0 resonance, can be interpreted as a heavy Higgs boson

  ≥2 medium b-tagged jets with ≥1 also tight b-tagged
  2 jets with highest b-tag output: p_T > 100 GeV and $\Delta\eta_{bb}$ < 1.6
  veto on leptons

- Discriminating variable: mass m_{bb} of bb system

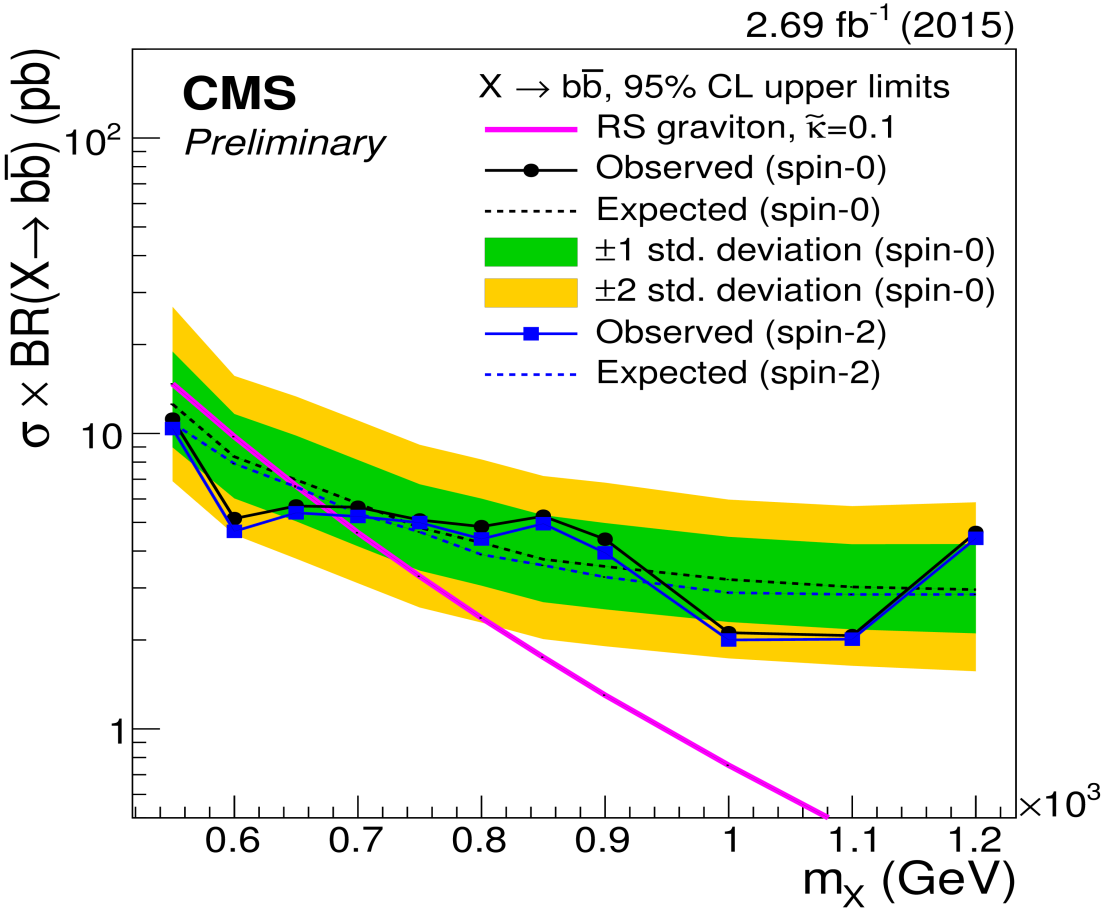
- Background prediction from smooth data-derived function



Signal parametrized as convolution of gaussian with exponential

H/A → bb

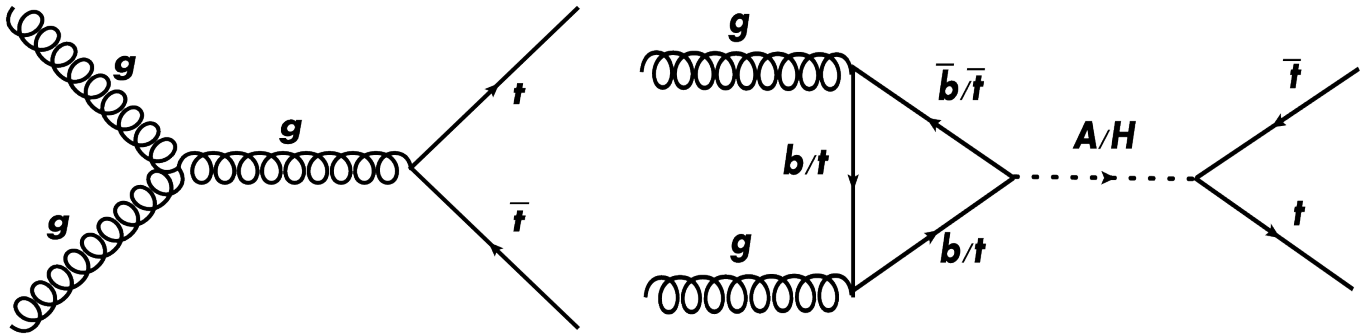
- Systematic uncertainties: jet energy resolution, b-tagging (signal) choice of PDF (background), ...
- Limits on cross section of bb resonance x branching ratio



H/A → tt

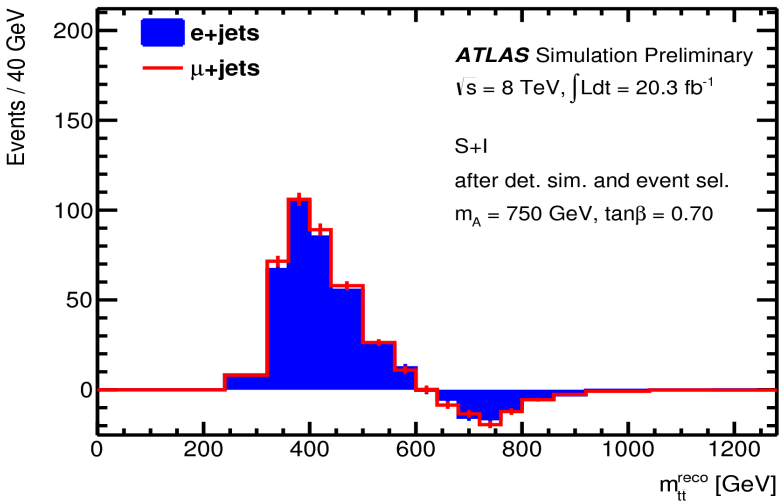
CONF-2016-073
ATLAS, 8 TeV

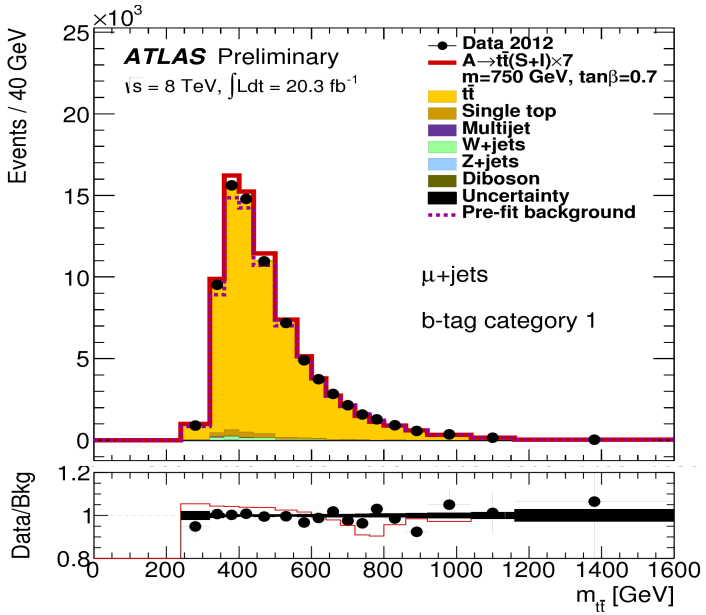
- If new Higgs boson mass above $2m_t$ threshold, decay to top pair allowed



1 muon or electron
≥ 4 jets
≥ 1 b-tagged jets

- Semileptonic top pair system reconstruction via kinematic fit
- Interference effects between SM tt and H/A → tt create 'peak-dip' structure in m_{tt} distribution



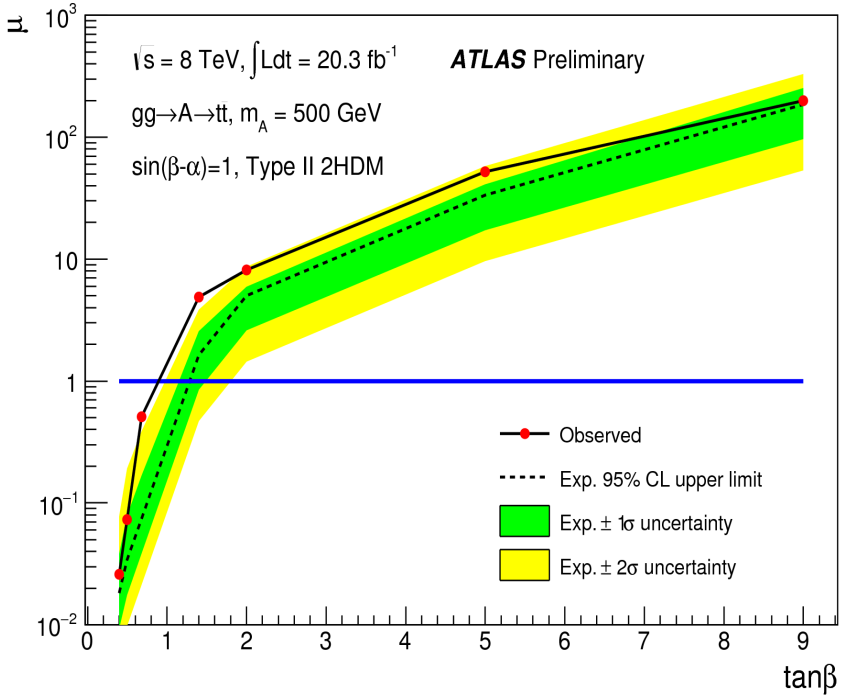


H/A → tt

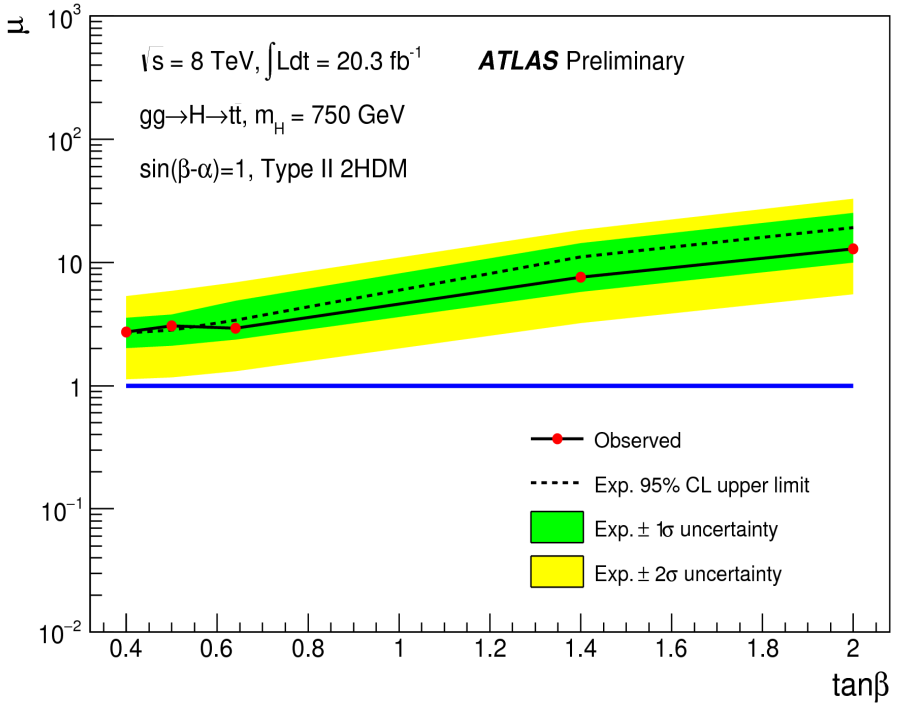
CONF-2016-073
ATLAS, 8 TeV

- Systematic uncertainties: jet energy scale and resolution, tt cross section, parton density functions, ...
- Upper limits on signal strength (non-trivial scaling of resonance and interference parts) vs tanβ

pseudoscalar mass 500 GeV



scalar mass 750 GeV



Charged $H^{\pm}$

- $H^{\pm} \rightarrow \tau\nu, tb$
- $H^{\pm} \rightarrow W^{\pm}Z$

H/A → fermions

- $H/A \rightarrow \tau\tau$
- $H/A \rightarrow bb$
- $H/A \rightarrow tt$

H → ZA, H/A → Zh

H/A → boson pair

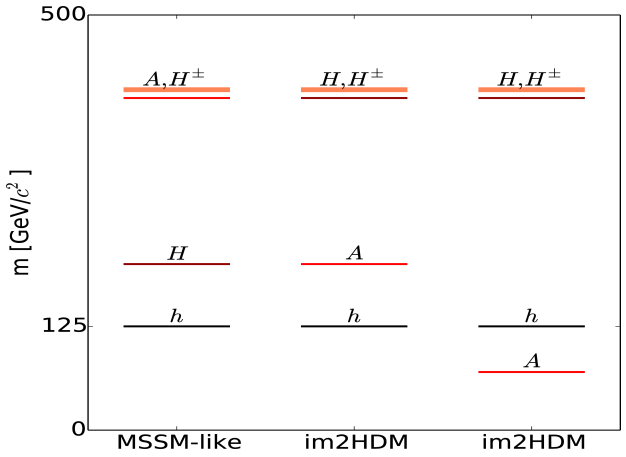
- $H \rightarrow hh$
- $H \rightarrow ZZ, WW$

H → ZA

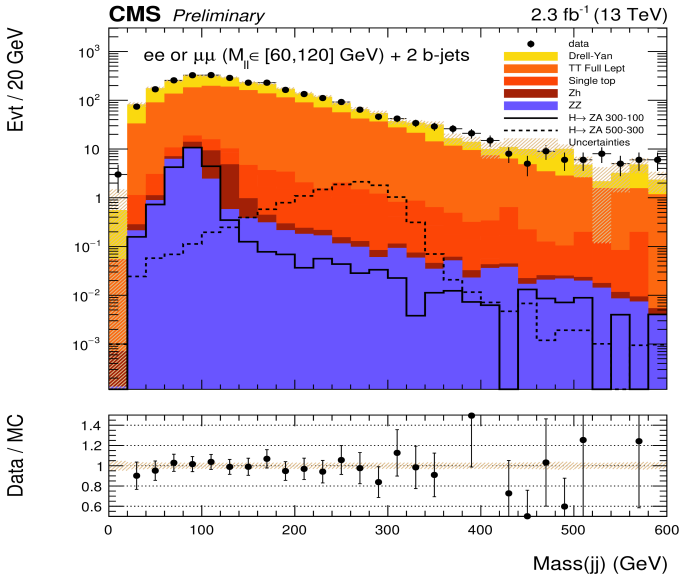
HIG-16-010
CMS, 13 TeV

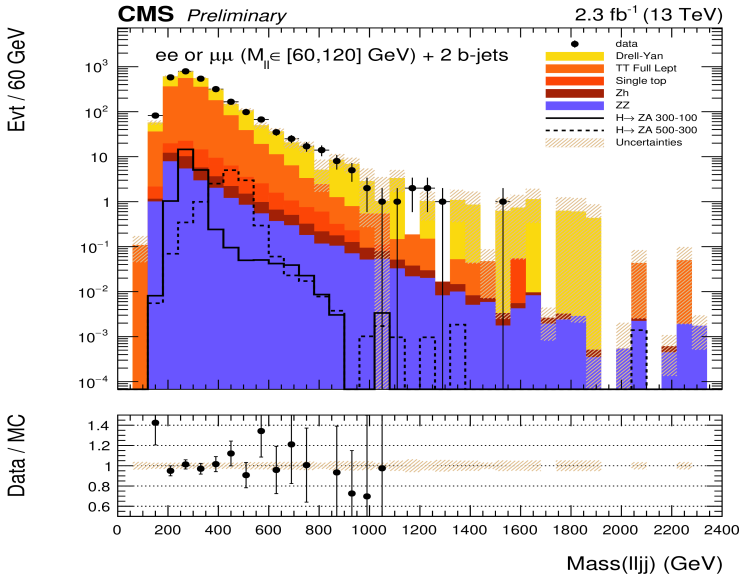
- Mass hierarchy might allow decay of one new Higgs boson to another
- Consider decay of H to Z (decaying to 2 leptons) and A (decaying to 2 b quarks)

  2 OSSF leptons
  ≥ 2 b-tagged jets



- Depending on (m_H, m_A) hypothesis, consider rectangular signal region in (m_{llbb}, m_{ll}) plane and use inverse as control region

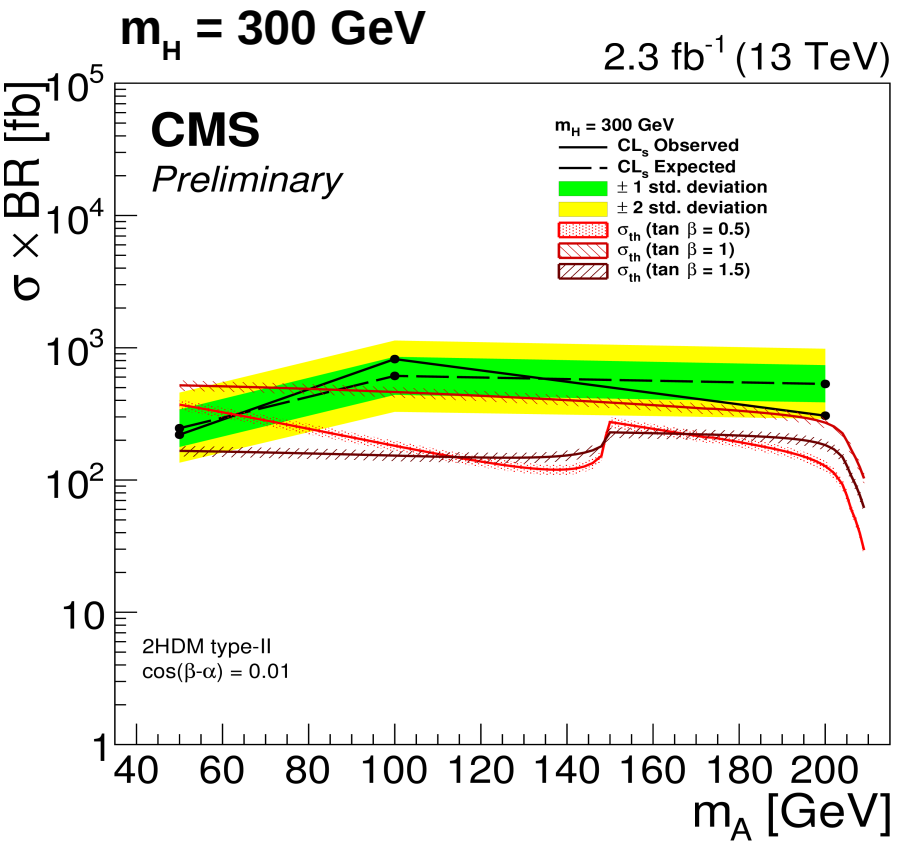


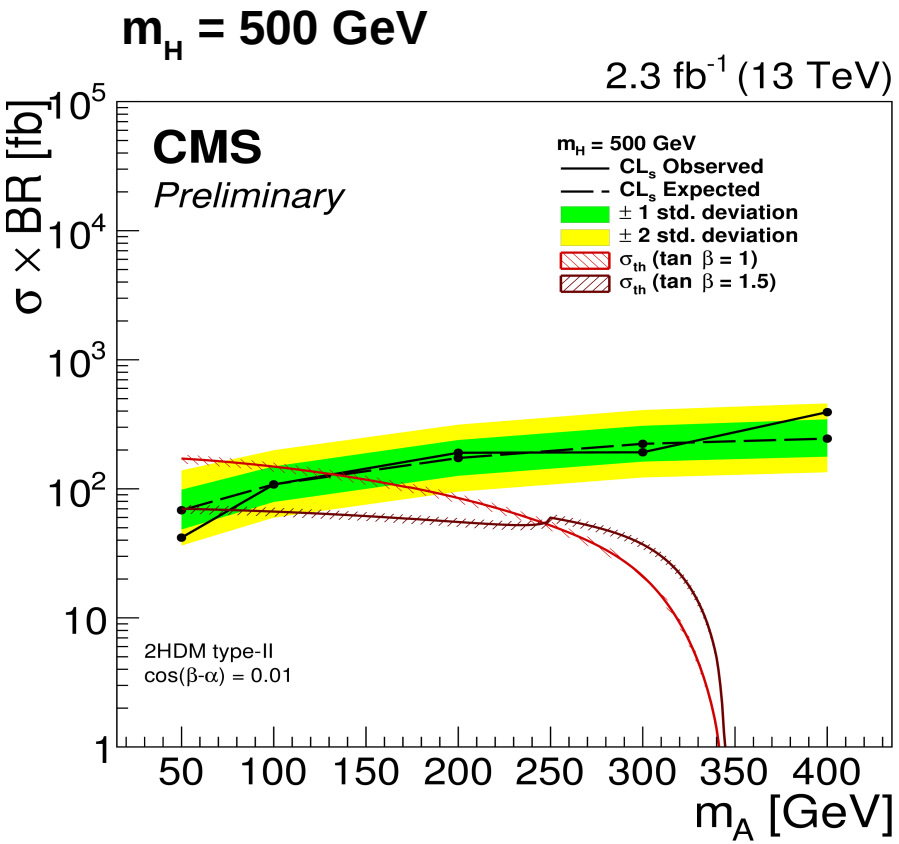


H → ZA

HIG-16-010
CMS, 13 TeV

- Systematic uncertainties: jet energy scale, b-tagging, background theory uncertainties, ...
- Limits on cross section x branching ratio





A → Zh

CONF-2016-015
ATLAS, 13 TeV

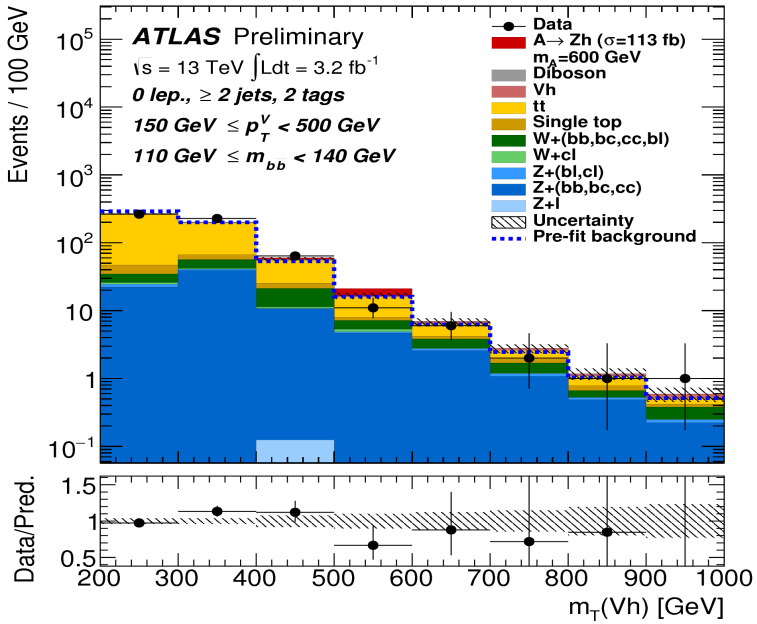
- Assumed decay of pseudoscalar A to Z boson and SM Higgs boson h
- Channels targeted: Z → ee, μμ, νν and H → bb

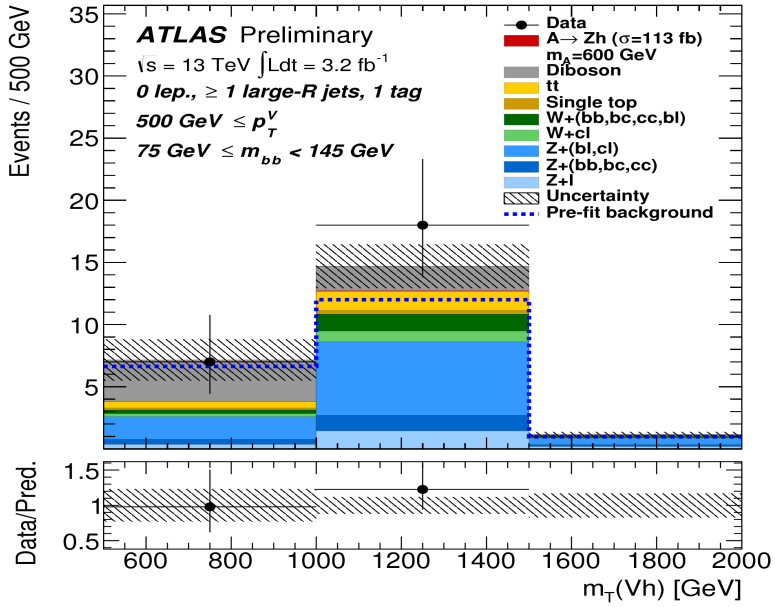
  Categories according to
  - #charged leptons (0 or 2)
  - p_T of Z candidate (low < 500 GeV, high ≥ 500 GeV)
  - #b-tagged jets (1 or 2)

  Requiring ≥1 *large-R* jet in high-p_T Z categories

  Requirements of dilepton mass and (di)jet mass: compatibility with Z and h

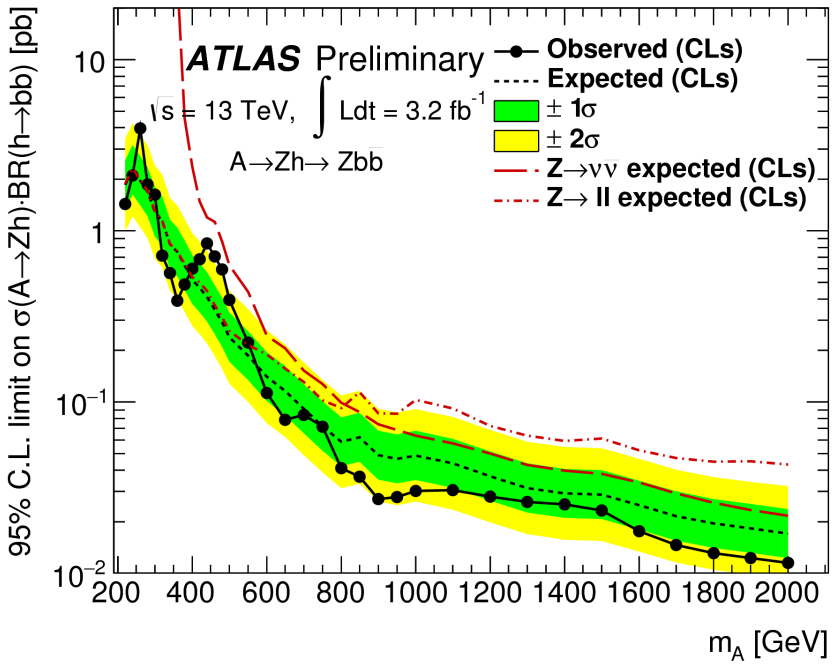
- Discriminating variable depending on category: (transverse) mass

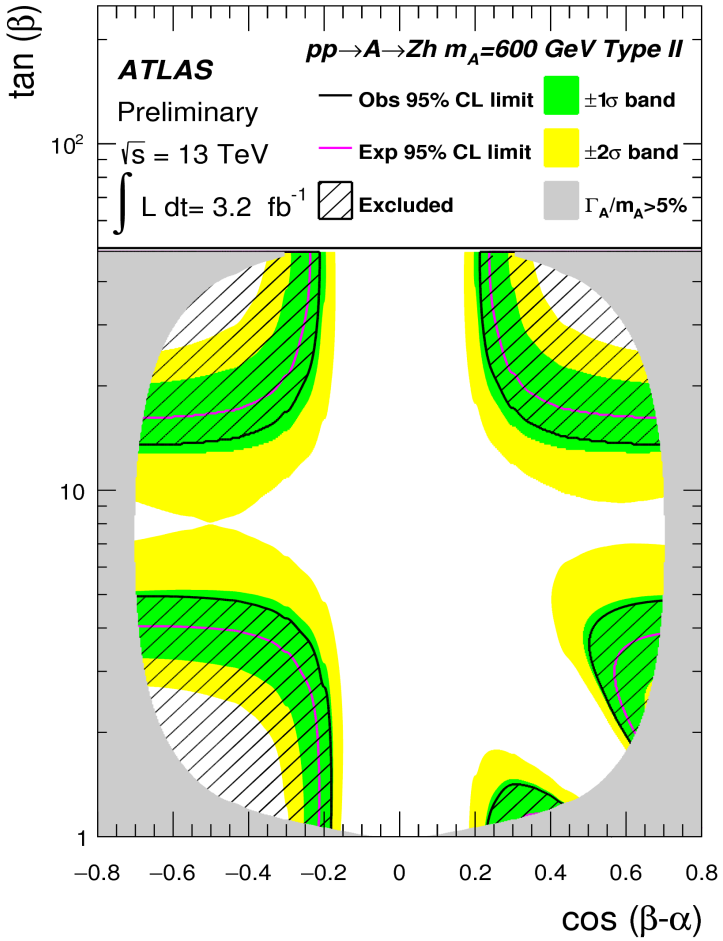




A → Zh

- Systematic uncertainties: jet energy scale and resolution, large-R jet mass, b-tagging, ...
- Limits on gluon fusion or b-associated production cross sections x BR, or interpretation in 2HDM parameter space





Charged $H^{\pm}$

- $H^{\pm} \rightarrow \tau\nu, tb$
- $H^{\pm} \rightarrow W^{\pm}Z$

H/A → fermions

- H/A → ττ
- H/A → bb
- H/A → tt

H → ZA, H/A → Zh

H/A → boson pair

- **H → hh**
- **H → ZZ, WW**

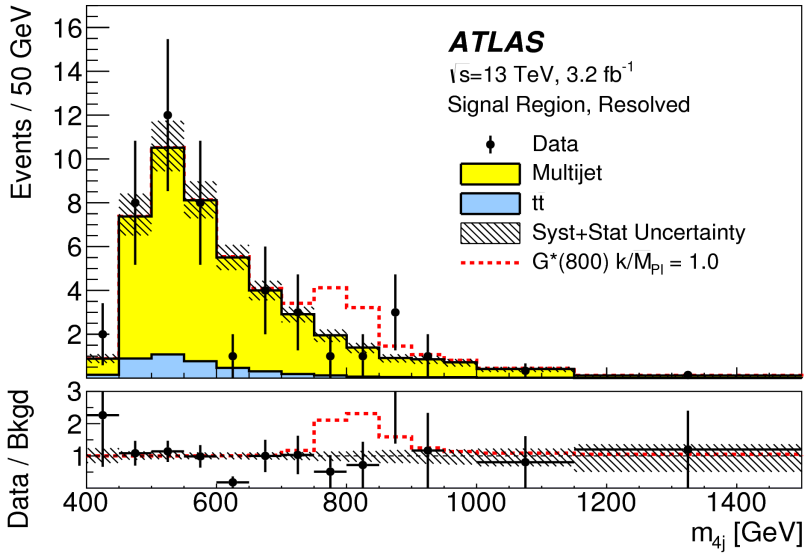
H→hh

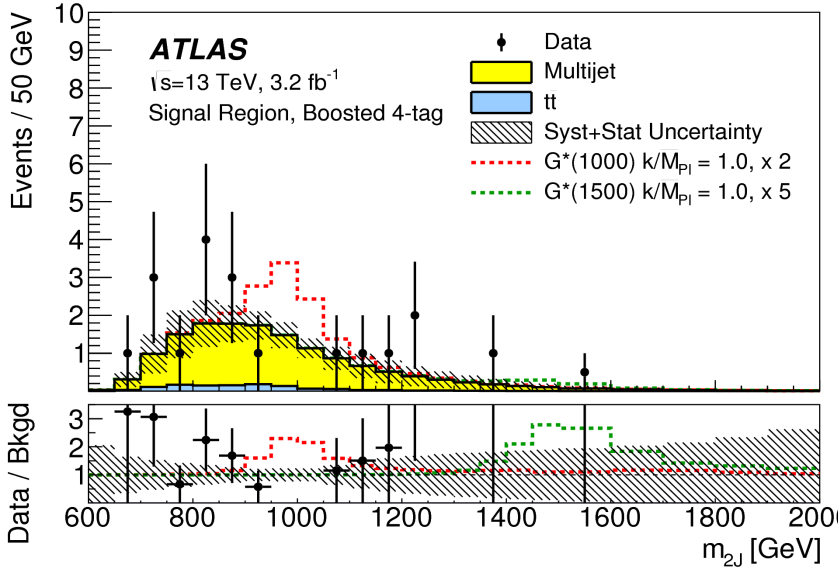
1606.04782
ATLAS, 13 TeV

- Search for resonant production of two SM-like h bosons
  - **“Resolved” regime** up to resonance mass 1.1 TeV

    ≥ 4 b-tagged jets
    forming 2 dijet systems with small ΔR
    m_{4jet} dependent p_T requirements on dijets
  - **“Boosted” regime** above 1.1 TeV

    3 or 4 b-tagged jets
    ≥ 2 large-R jets with ≥ 2 smaller-R track jets associated to each
- Discriminating variables: reconstructed resonance mass

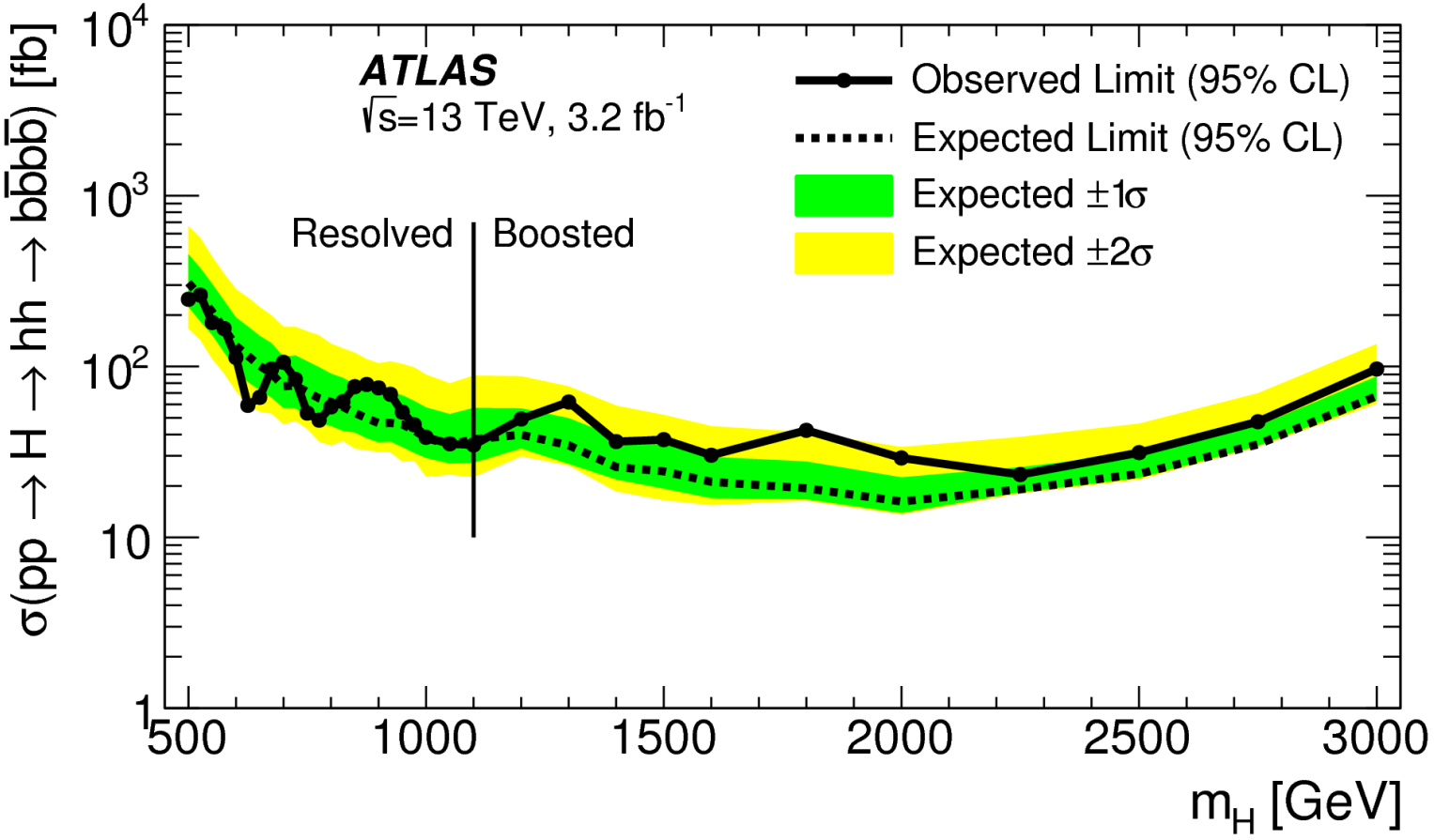




H → hh

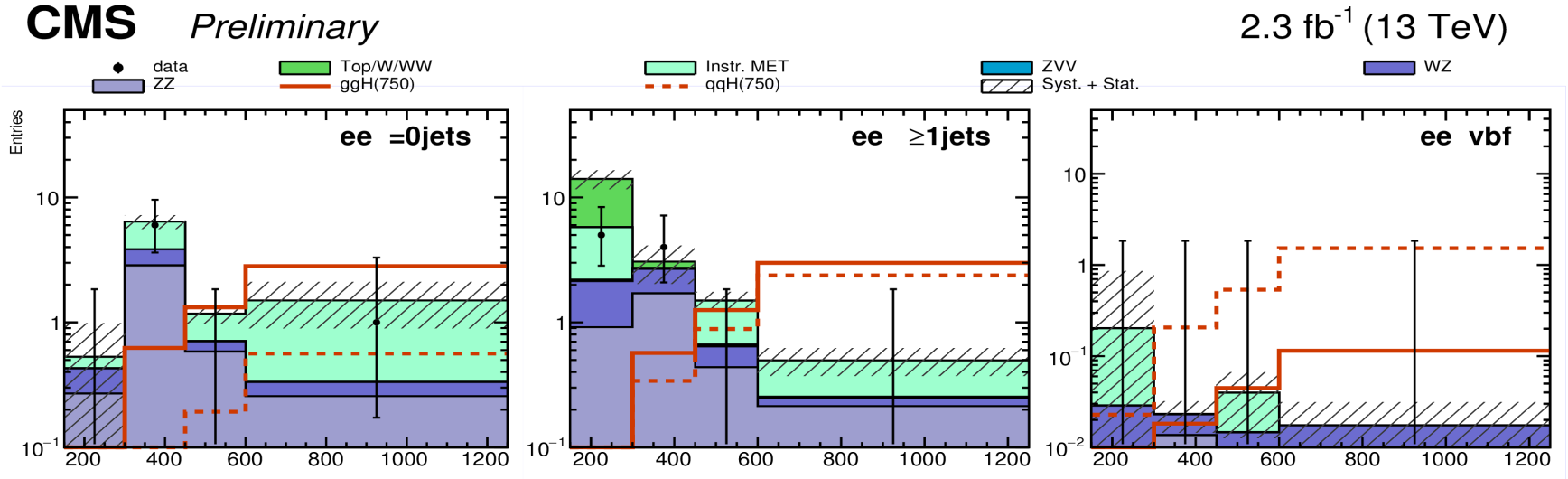
1606.04782
ATLAS, 13 TeV

- Systematic uncertainties: b-tagging, multijet background, large-R jet-mass scale and resolution, …
- Interpretation as new narrow-width Higgs resonance

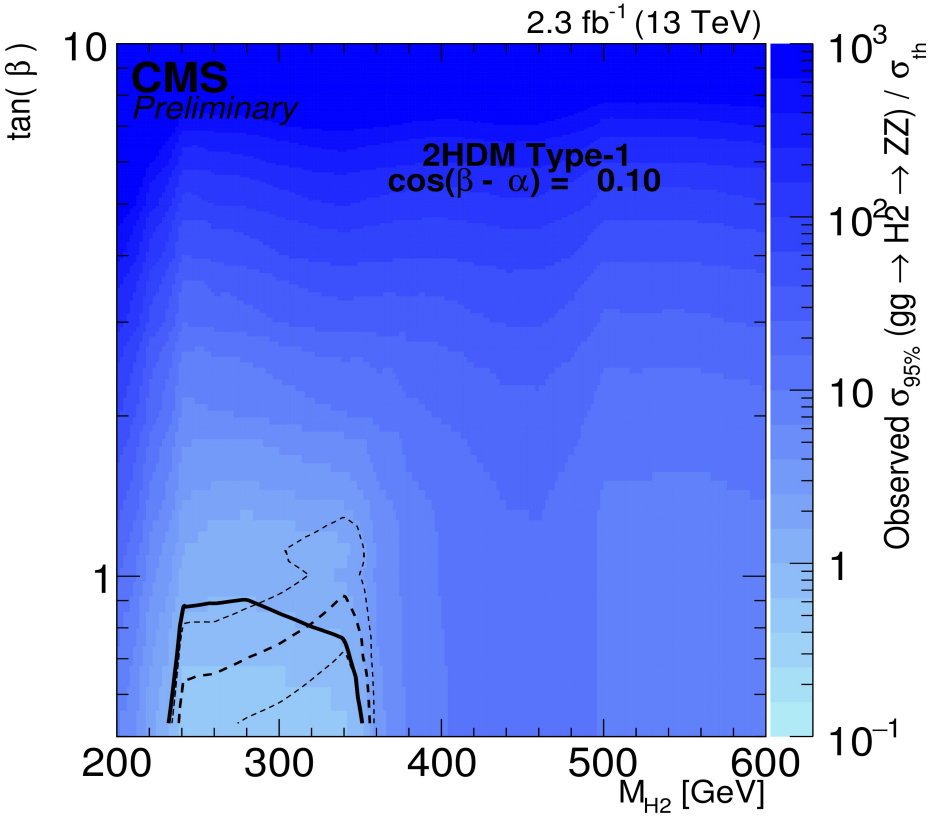


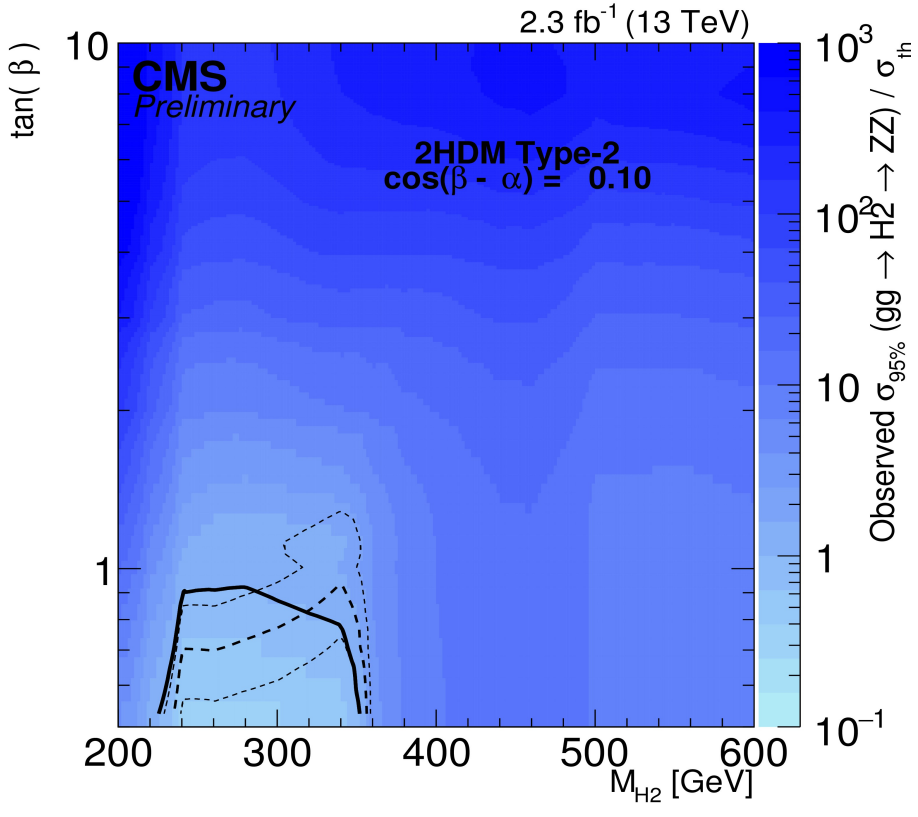
$H \rightarrow ZZ$

- Search for heavy scalar boson decaying to ZZ → 2l2v
  - 2 OSSF leptons (muons or electrons)
  - p_T dilepton > 55 GeV
  - MET ≥ 125 GeV
- Jet multiplicity categories
  - VBF category: ≥ 2 jets with large pseudorapidity gap and high mass
  - ≥ 1 jets failing VBF
  - 0 jets
- Discriminating variable: m_T of dilepton and MET system



- Systematic uncertainties: QCD scale in simulation, jet energy scale, background estimation, ...
- Interpretation in *type-I* and *type-II* 2HDM models





H→WW/ZZ

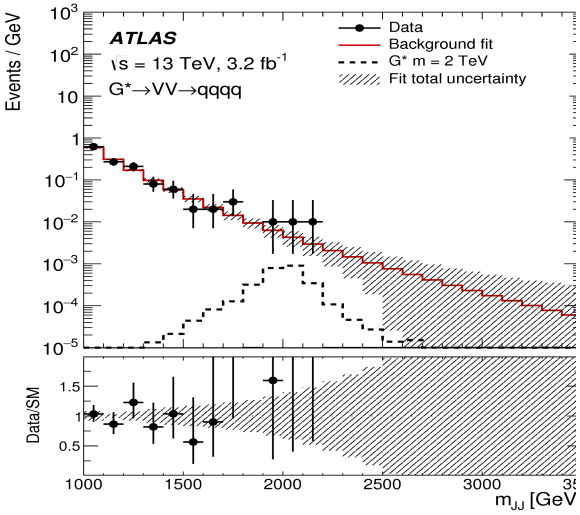
1606.04883
ATLAS, 13 TeV

- Relevant channels: qqqq, ννqq, llqq

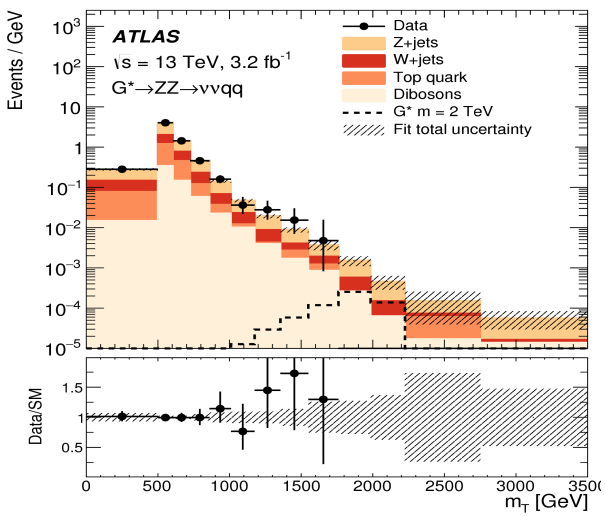
  ≥1 large-R jet, p_T > 200 GeV, mass > 50 GeV

  no leptons, MET > 250 GeV → ννqq
  no leptons, MET < 250 GeV, additional large-R jet → qqqq
  2 (OS)SF leptons in Z window → llqq

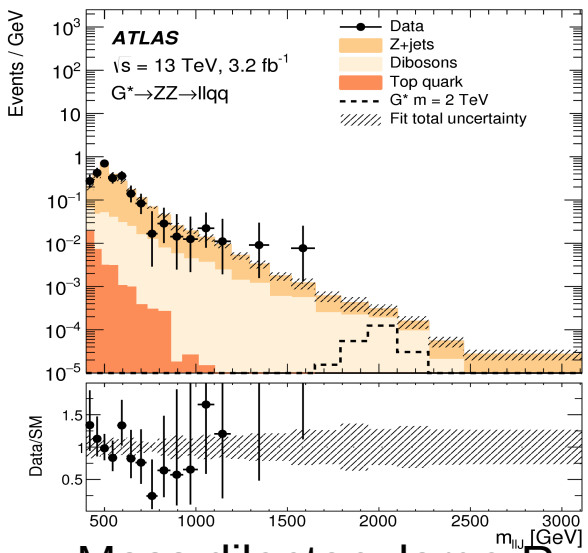
- Dominant backgrounds: multijet (qqqq) modelled as smoothly falling m_{JJ} spectrum, Z+jets (ννqq and llqq) from control region



Mass large-R jets system (qqqq)



Transverse mass (ννqq)

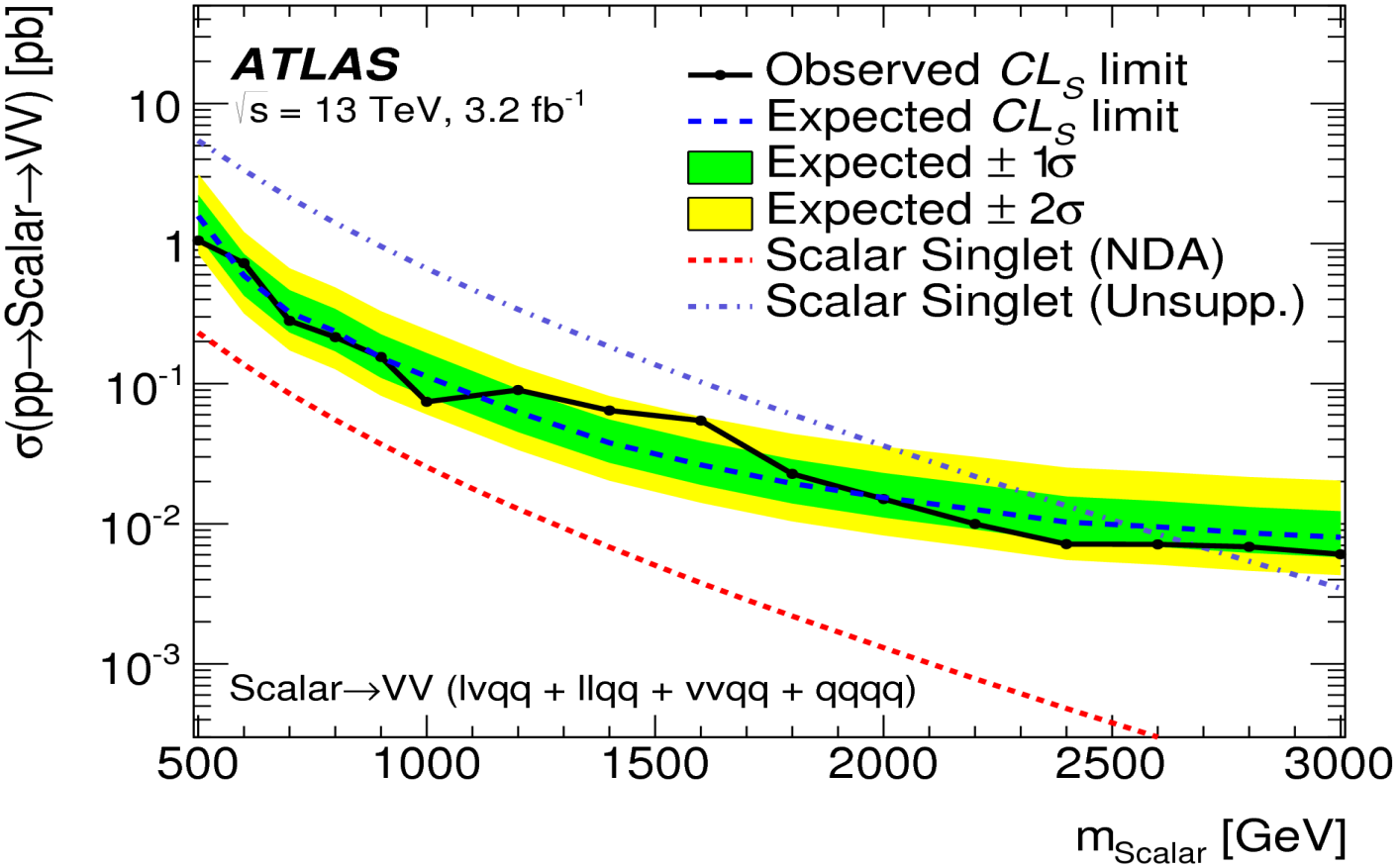


Mass dilepton, large-R jet system (llqq)

H→WW/ZZ

1606.04883
ATLAS, 13 TeV

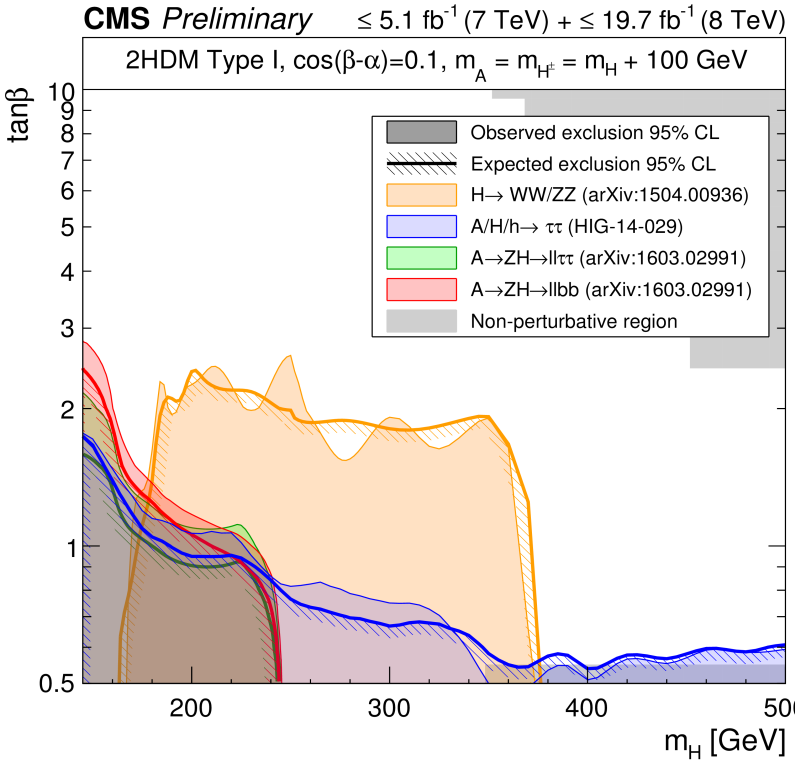
- Systematic uncertainties: large-R jet energy/mass scale and resolution, lepton energy scale, theoretical uncertainties of tt and diboson, …
- Interpretation as narrow-width scalar singlet

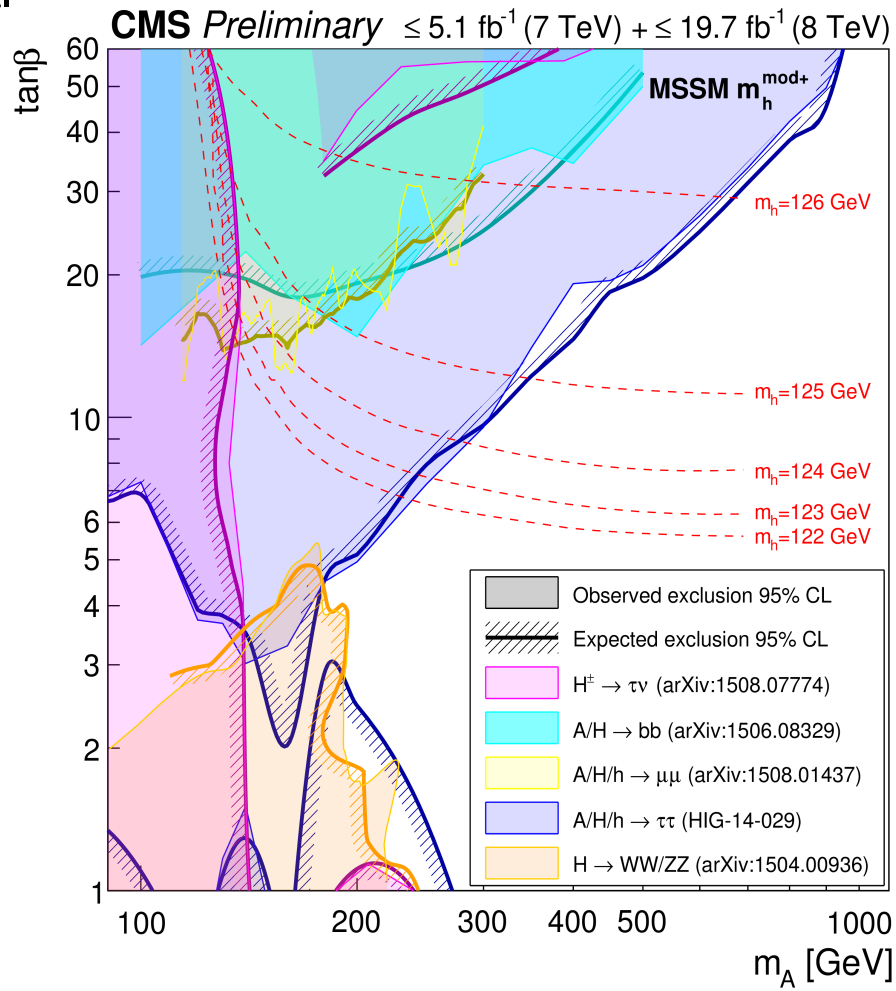


BSM Higgs summary of CMS Run-1

HIG-16-007
CMS, 7+8 TeV

- (Re)interpretation of 8 CMS Run-1 analyses in 2HDM and MSSM models
- Choice of fixed parameters motivated from theory + experimental constraints
- complementarity of experimental BSM searches explores large part of parameter space





Summary

- Observed Higgs boson at mass 125 GeV may be part of an **extended Higgs sector**

- Many BSM models predict **new scalar, pseudoscalar and charged or neutral Higgs bosons** (2HDM, MSSM, …)

- **Rich phenomenology**, extensive experimental program in ATLAS/CMS

  Many searches at 7 TeV, 8 TeV and now 13 TeV

- **Many exciting results expected** in the near future!

BACKUP

List of BSM Higgs searches at ATLAS and CMS

- References to be added