Search for a high mass neutral Higgs boson in fermion final states with the ATLAS detector

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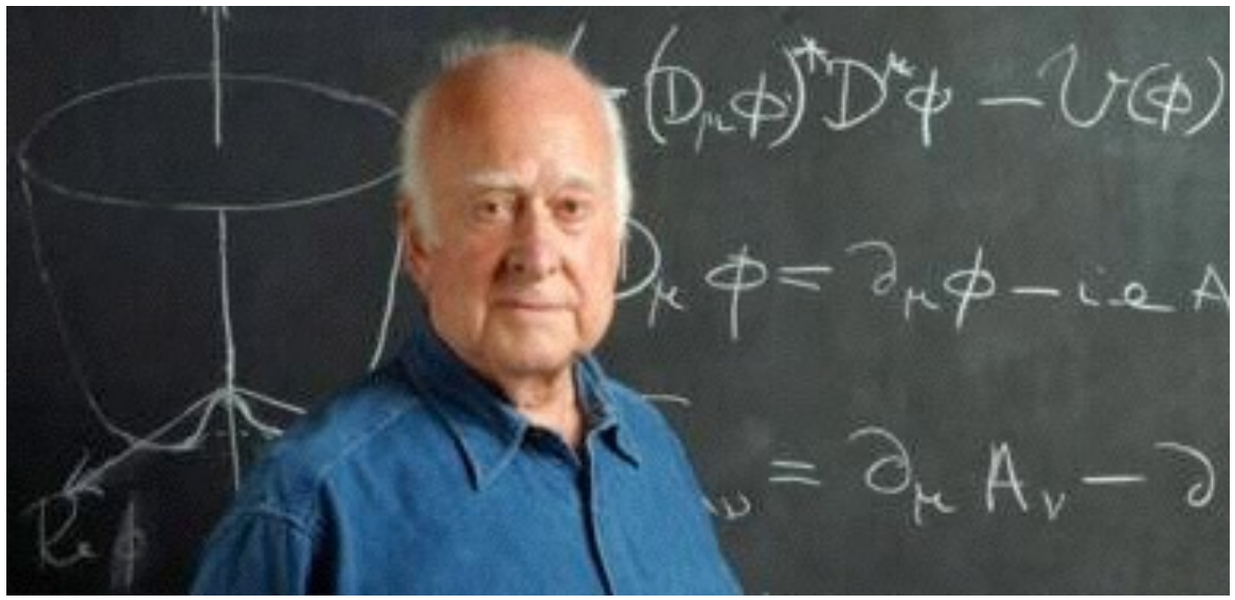
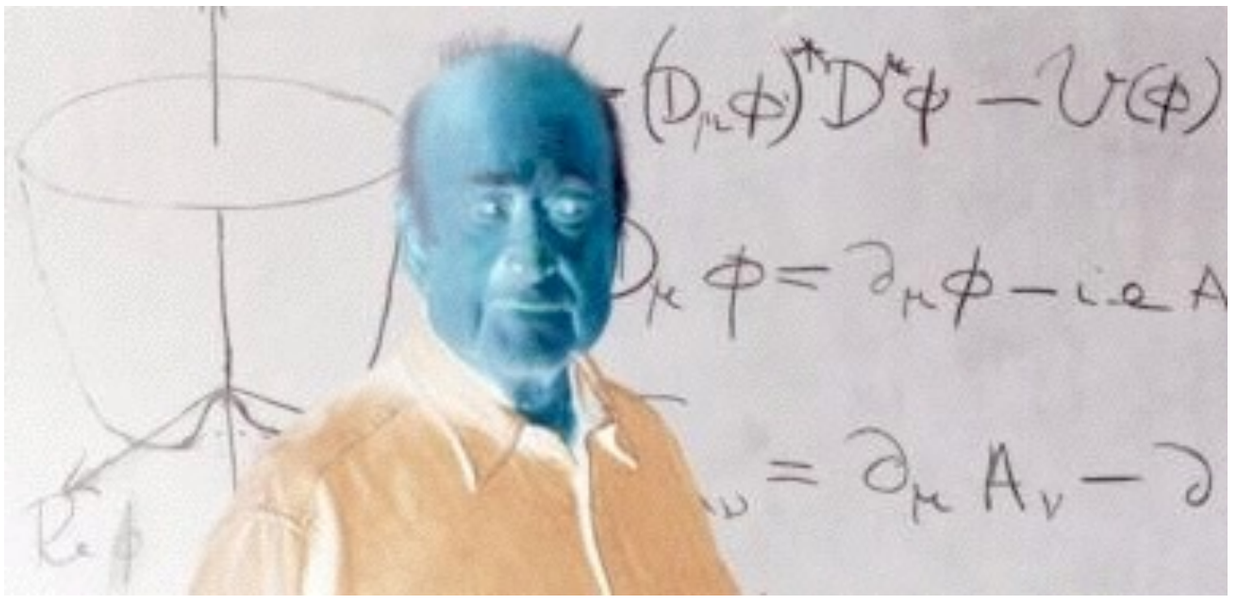
August 5, 2016

ICHEP-2016 — Chicago, USA

If the (light) Higgs mass is ~125 GeV, what next?



Standard Model Higgs



Beyond the SM Higgs

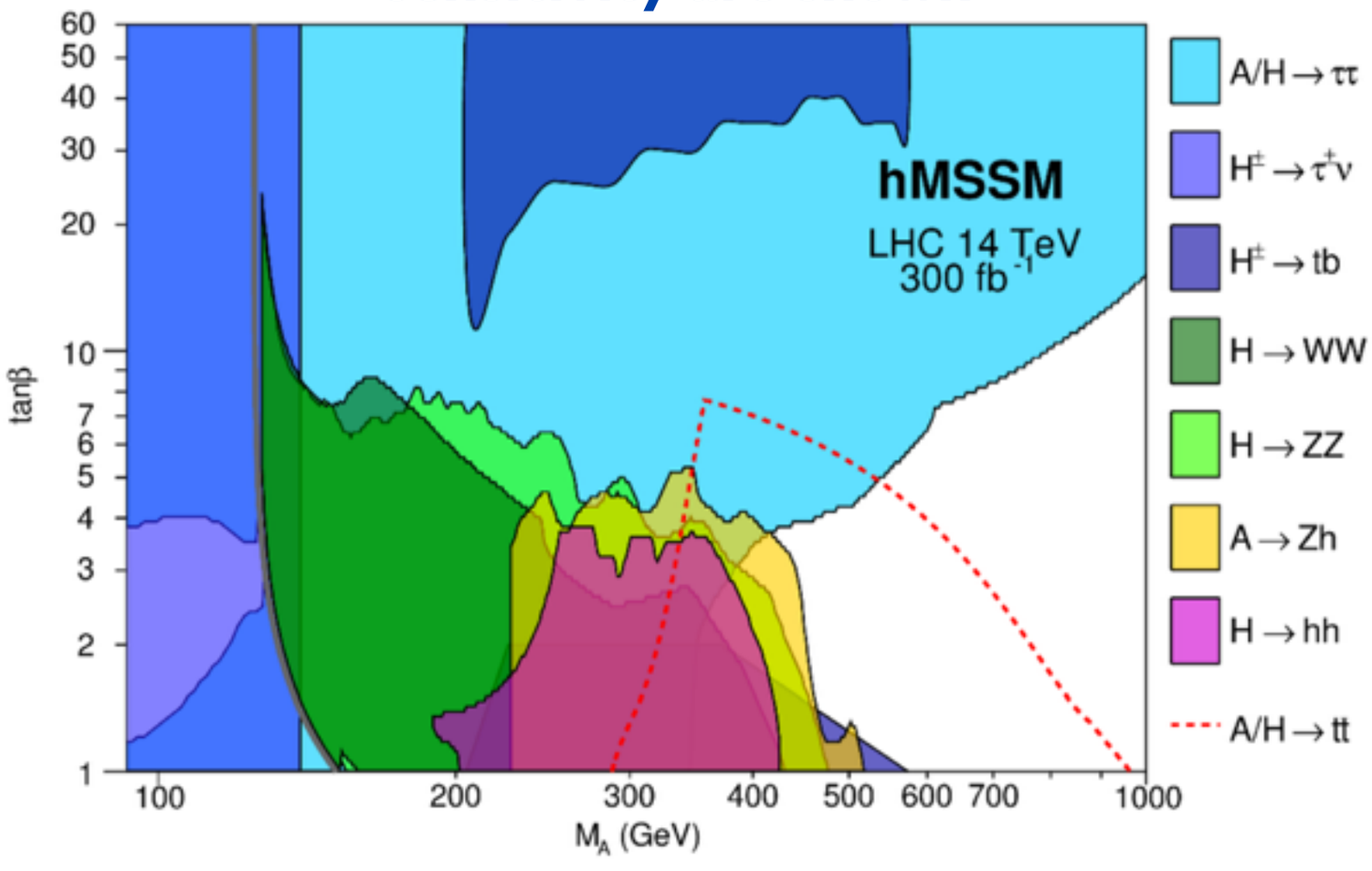
- Suppose that this is not the Standard Model Higgs… just one of several Higgs bosons?
  - More complicated Higgs sector? ⇒ 2HDM, MSSM, Doubly-charged Higgs, Composite
  - Light scalar Higgs? ⇒ NMSSM
- Searching for additional Higgs bosons at a higher mass (using fermions) is the focus of this talk
- Please see the other low- and high-mass Higgs search talks from ATLAS at ICHEP-2016:
  - Search for a high mass diphoton resonance (Bruno Lenzi; "Joint BSM & Higgs", Friday at 09:00)
  - Search for di-Higgs production (Tulin Varol; "Higgs Physics: 4", Friday at 11:50)
  - Search for high mass Higgs bosons (Karsten Koeneke; "Higgs Physics: 4", Friday at 13:10)
  - Search for the decay of the Higgs boson into two nMSSM pseudo-scalar particles (Lidija Zivkovic; "Higgs Physics: 5", Friday at 15:45)
  - Search for a high mass $Z\gamma$ resonance (Giovanni Marchiori; "Higgs Physics: 6", Friday at 17:50)
  - Charged Higgs boson searches (Carl Gwilliam; "Higgs Physics: 7", Saturday at 09:15)

MSSM Higgs Sector and a 125 GeV Higgs

- The MSSM ($h, A, H, H^{\pm}$) is compatible with a 125 GeV Higgs… for example:
  - hMSSM scenario: the measured value of 125 GeV can be used to predict masses and decay branching ratios of the other Higgs bosons
  - m_h^{mod+} scenario: the lightest CP-even Higgs is assigned to be the 125 GeV boson

- We have two new ATLAS high-mass neutral Higgs searches using fermions to show you…
  - A/H to ττ using 13.3 fb^{-1} of 13 TeV pp collision data ATLAS-CONF-2016-085
  - A/H to ttbar using 20.3 fb^{-1} of 8 TeV pp collision data ATLAS-CONF-2016-073

Theory projections for 2σ sensitivity are shown

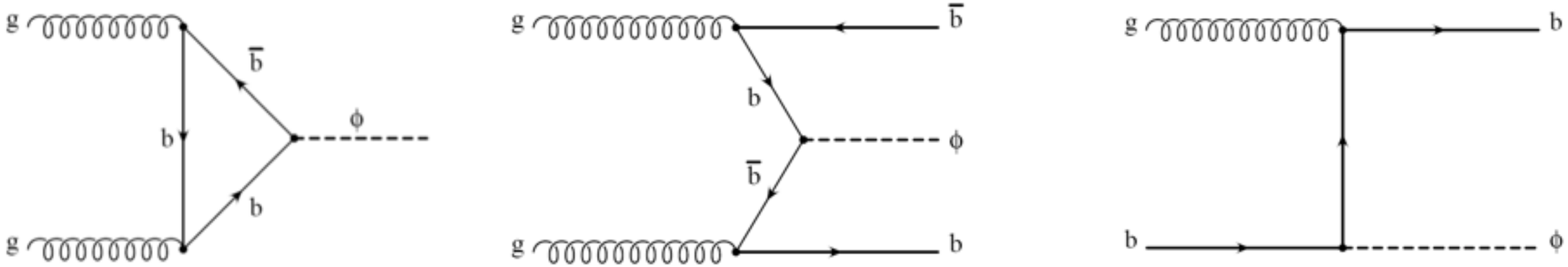


A/H to ττ and A/H to ttbar are each very important channels at mid- to high-m_A

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

MSSM Higgs Search ($A/H \to \tau^+\tau^-$)

- New ATLAS MSSM neutral Higgs search for ICHEP uses 13.3 fb^{-1} of 13 TeV data
  - 3.2 fb^{-1} from 2015 and 10.1 fb^{-1} from 2016
  - Improvement on the limits from the 2015 result submitted to EPJC: arXiv:1608.00890
- Can use different categories to target main production mechanisms
  - "no b-tag" targets gluon-fusion (dominant mode at small tanβ)
  - "b-tag" targets b-associated production (dominant mode at large tanβ)



- Can also separate based on the τ lepton decay mode (here lepton-hadron or hadron-hadron)
  - The addition of a high-MET trigger category in lep-had is new for the 2016 analysis
  - So in total, there are 5 categories considered by the analysis
- Monte Carlo samples used:
  - A/H to ττ signal: Powheg+Pythia8 (ggH) and aMC@NLO + Pythia8 (bbH)
  - Backgrounds:
    - Powheg+Pythia8 (W+jets in lep-had, Z+jets and top)
    - Sherpa (W+jets in had-had and dibosons)

Event Selection for the 5 Categories ($A/H \to \tau^+\tau^-$)

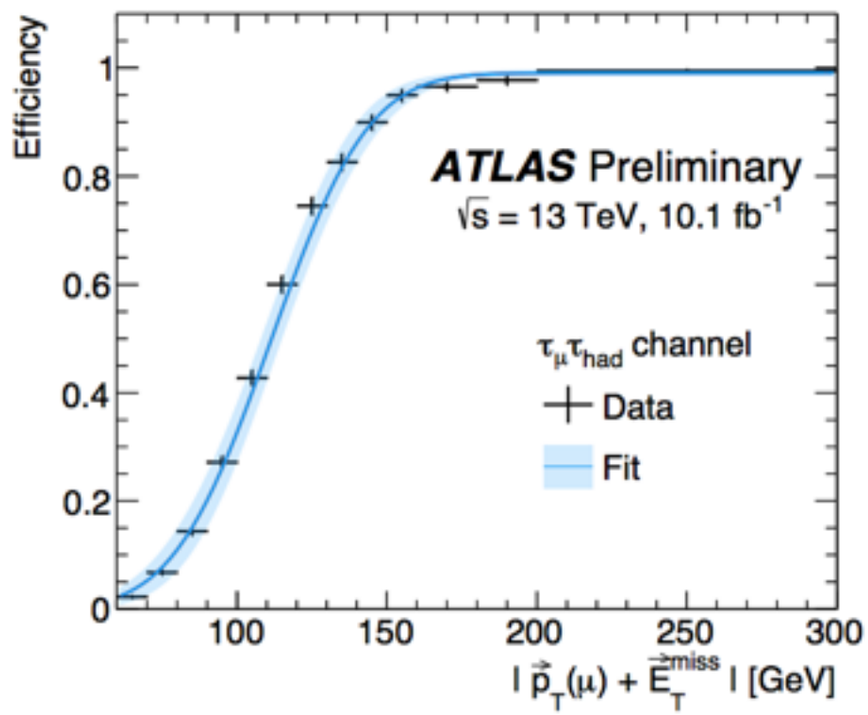
lep-had b-veto	lep-had b-tagged	lep-had high-MET

- For the lep-had analysis:
  - Single lepton triggers
  - Single hadronic tau (55%) with p_T >25 GeV
  - Single isolated electron or muon with p_T >30 GeV
  - Opposite charge
  - Veto events with an additional lepton
  - $\Delta\phi$(tau, e/mu) > 2.4
  - M_T(e/mu, MET) < 40 GeV $m_T(a,b) = \sqrt{2p_T(a)p_T(b)[1-\cos\Delta\phi(a,b)]}$
  - The e-had channel has an m_{vis} < 80 GeV and >110 GeV requirement
  - $N_{b\text{-jets}} = 0$ (b-veto)
  - $N_{b\text{-jets}} \geq 1$ (b-tag; 77%)

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

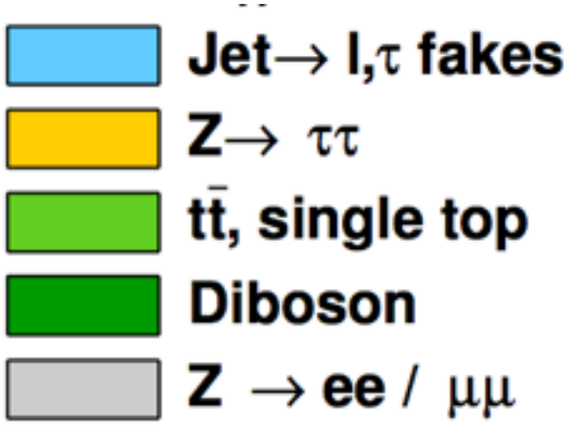
had-had b-veto	had-had b-tagged

- For the had-had analysis:
  - Single tau trigger with threshold of 80 GeV (or 125 GeV; depends on run period)
  - Leading tau (55%) with p_T >110 GeV (or p_T > 140 GeV with the 125 GeV trigger)
  - Second tau (60%) with p_T > 55 GeV (or 65 GeV for b-tagged category)
  - Opposite charge requirement
  - Veto events with a lepton
  - $\Delta\phi(\text{tau}_1, \text{tau}_2) > 2.7$
  - $N_{b\text{-jets}} = 0$ (b-veto)
  - $N_{b\text{-jets}} \geq 1$ (b-tag; 70%)



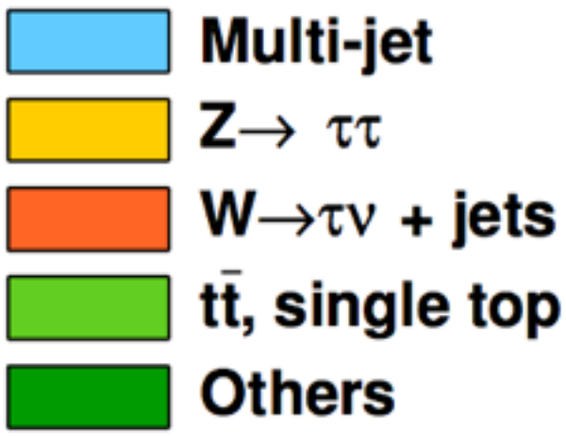
Background Estimation ($A/H \rightarrow \tau^+\tau^-$)

lepton-hadron final state



- Jets faking leptons (e,μ) and taus are not well modeled in Monte Carlo
  - Separate fake factors are derived from data control regions for W+jets/top and QCD
  - These fake factors are parameterized by tau p_T and number of tracks
  - The fake factors are combined by using a data-driven estimate for the multi-jets fraction taken from the anti-tau ID region (otherwise same as signal region)
  - The combined fake factors are obtained as a function of e/μ, category and hadronic tau p_T

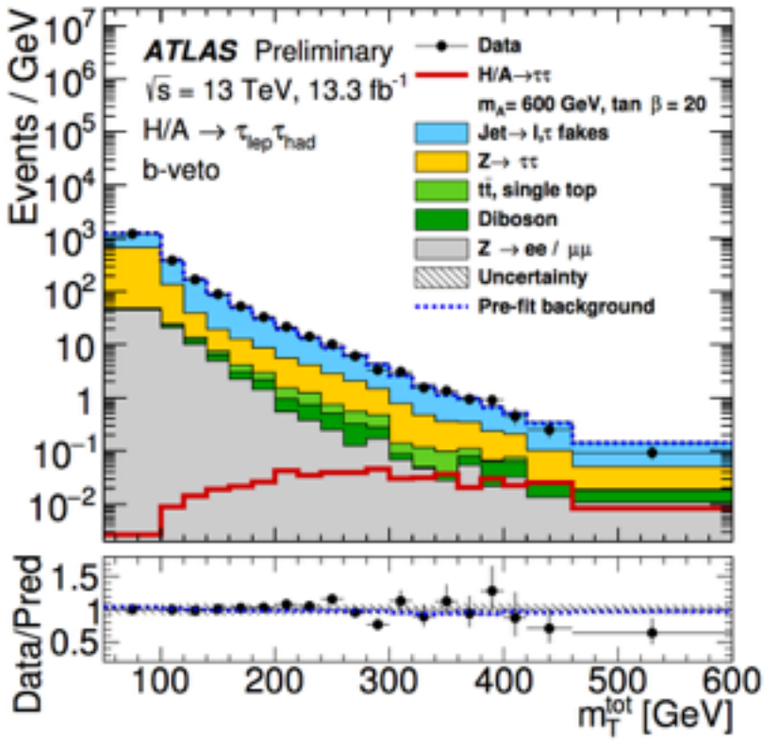
hadron-hadron final state

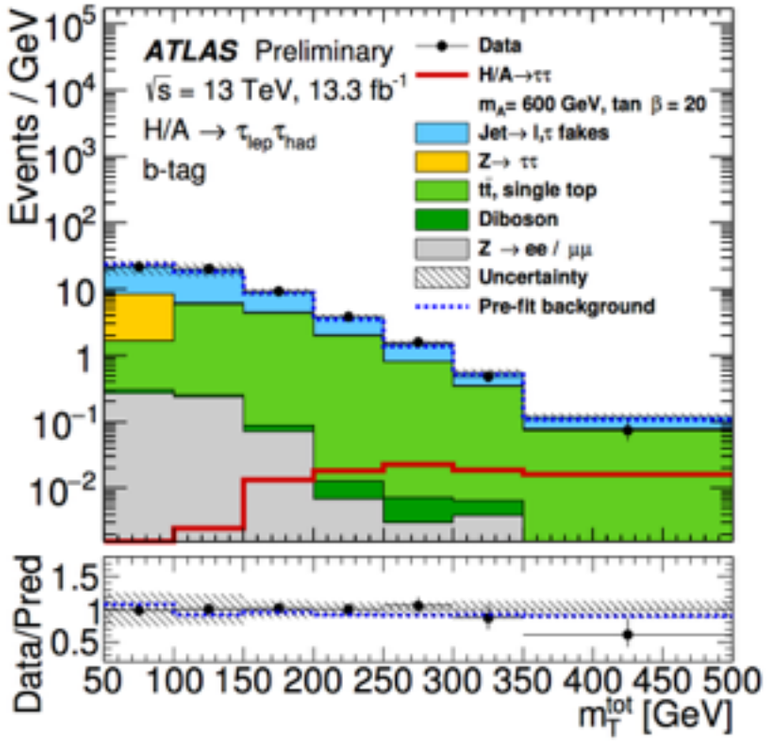


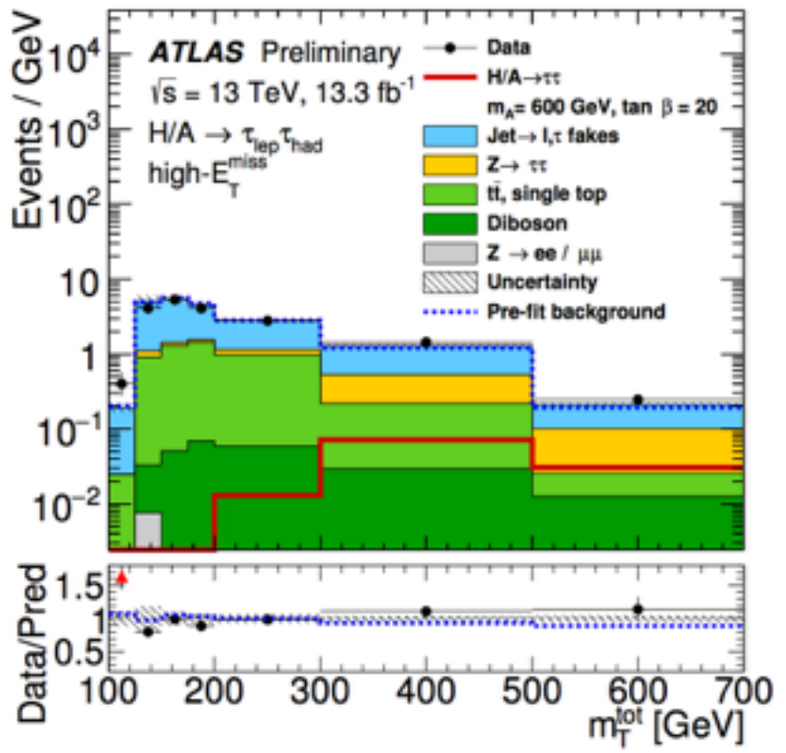
- Multi-jet backgrounds faking taus are not well modeled in Monte Carlo
  - A fake factor is derived from data control regions, and then applied to the anti-ID regions to obtain estimates for the signal regions
  - This fake factor is parameterized by tau p_T and number of tracks
- For W-jets and top backgrounds, different dedicated fake-rate corrections to MC are used
  - These corrections to MC are estimated from data

Post-fit Plots for the 5 Categories ($A/H \to \tau^+\tau^-$)

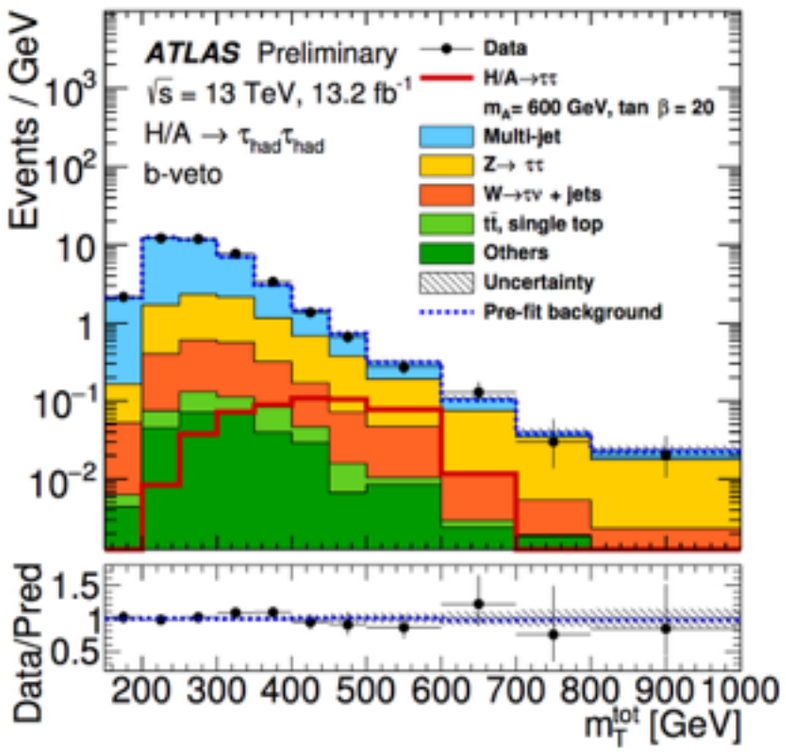
lep-had b-veto	lep-had b-tagged	lep-had high-MET

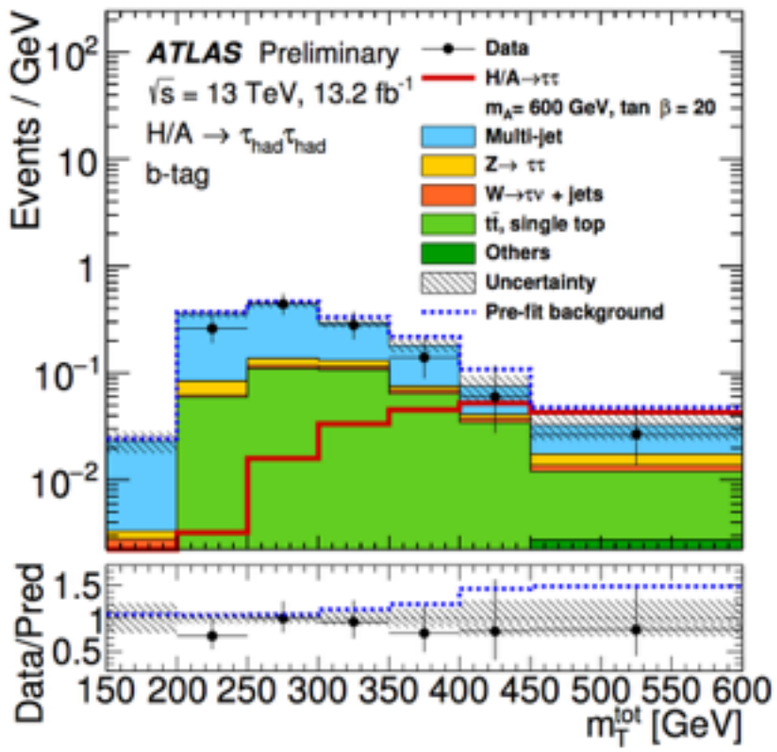






had-had b-veto	had-had b-tagged





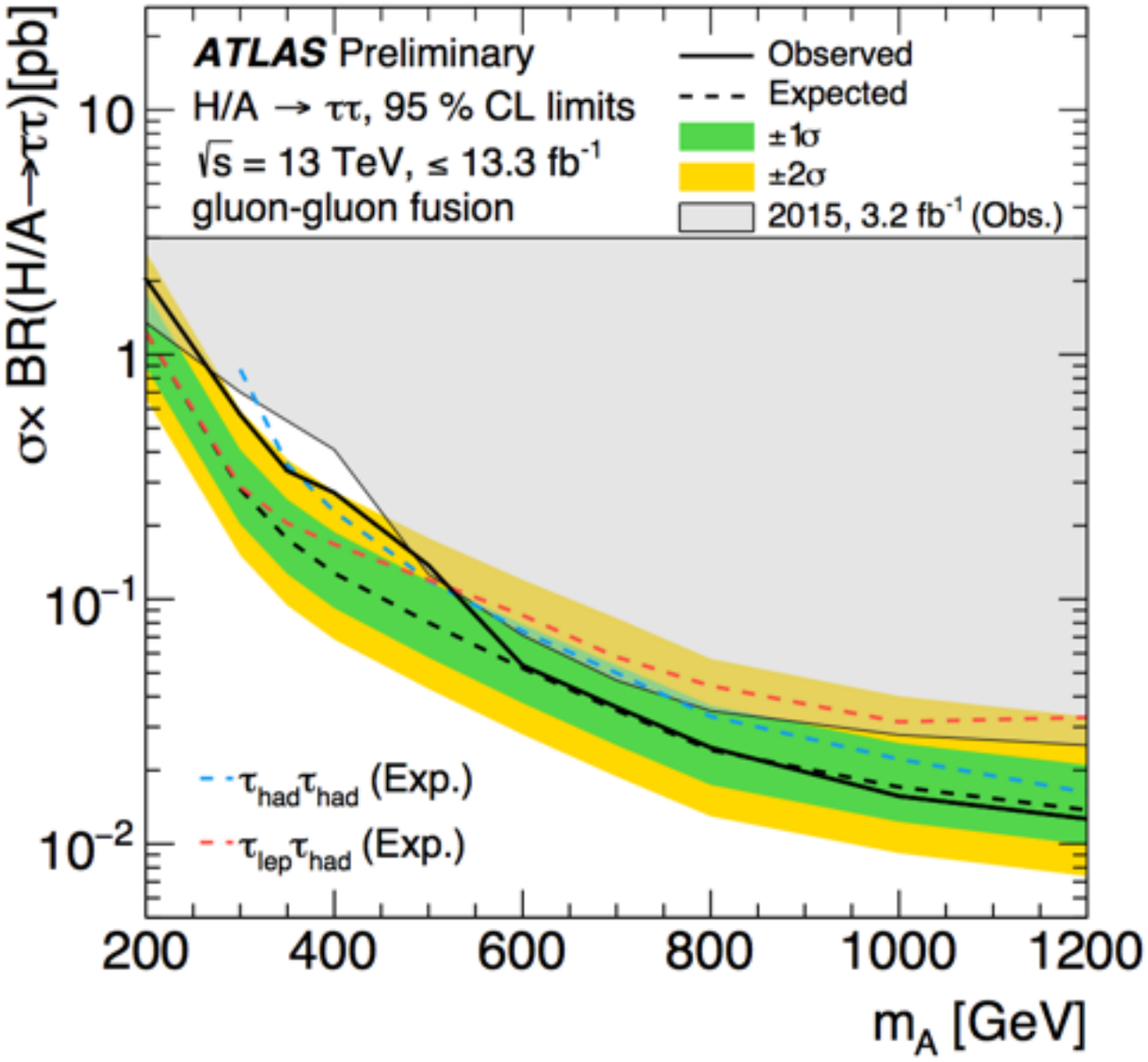
- Discriminant used is the m_T^{tot} variable, as it offers good separation of signal from backgrounds due to fake τs

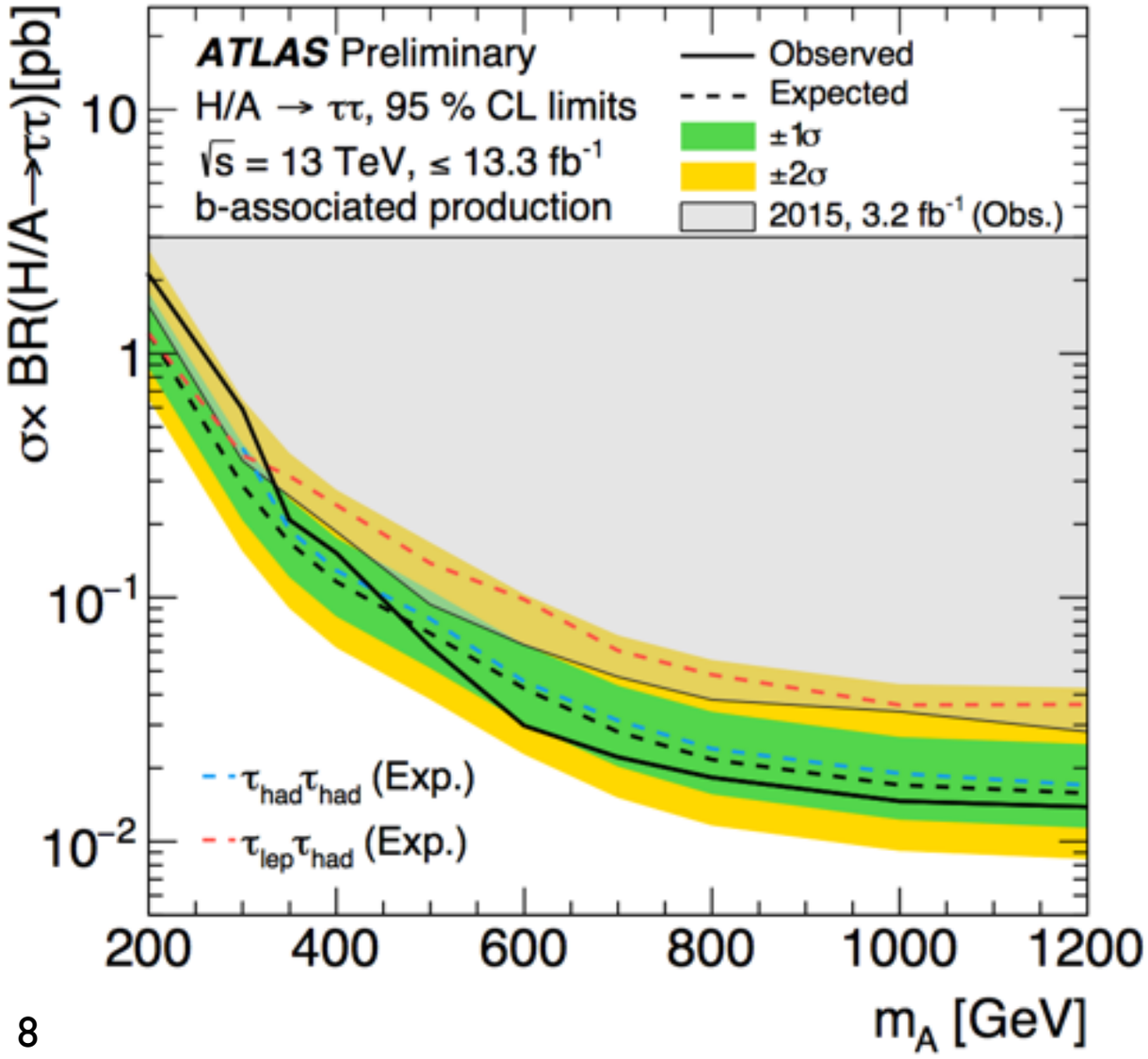
$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_{\mathrm{T}}^2(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_1) + m_{\mathrm{T}}^2(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_2) + m_{\mathrm{T}}^2(\tau_1, \tau_2)}$$

$$m_{\mathrm{T}}(a, b) = \sqrt{2 p_{\mathrm{T}}(a) p_{\mathrm{T}}(b)[1 - \cos \Delta\phi(a, b)]}$$

MSSM Neutral Higgs Search ($A/H \to \tau^+\tau^-$)

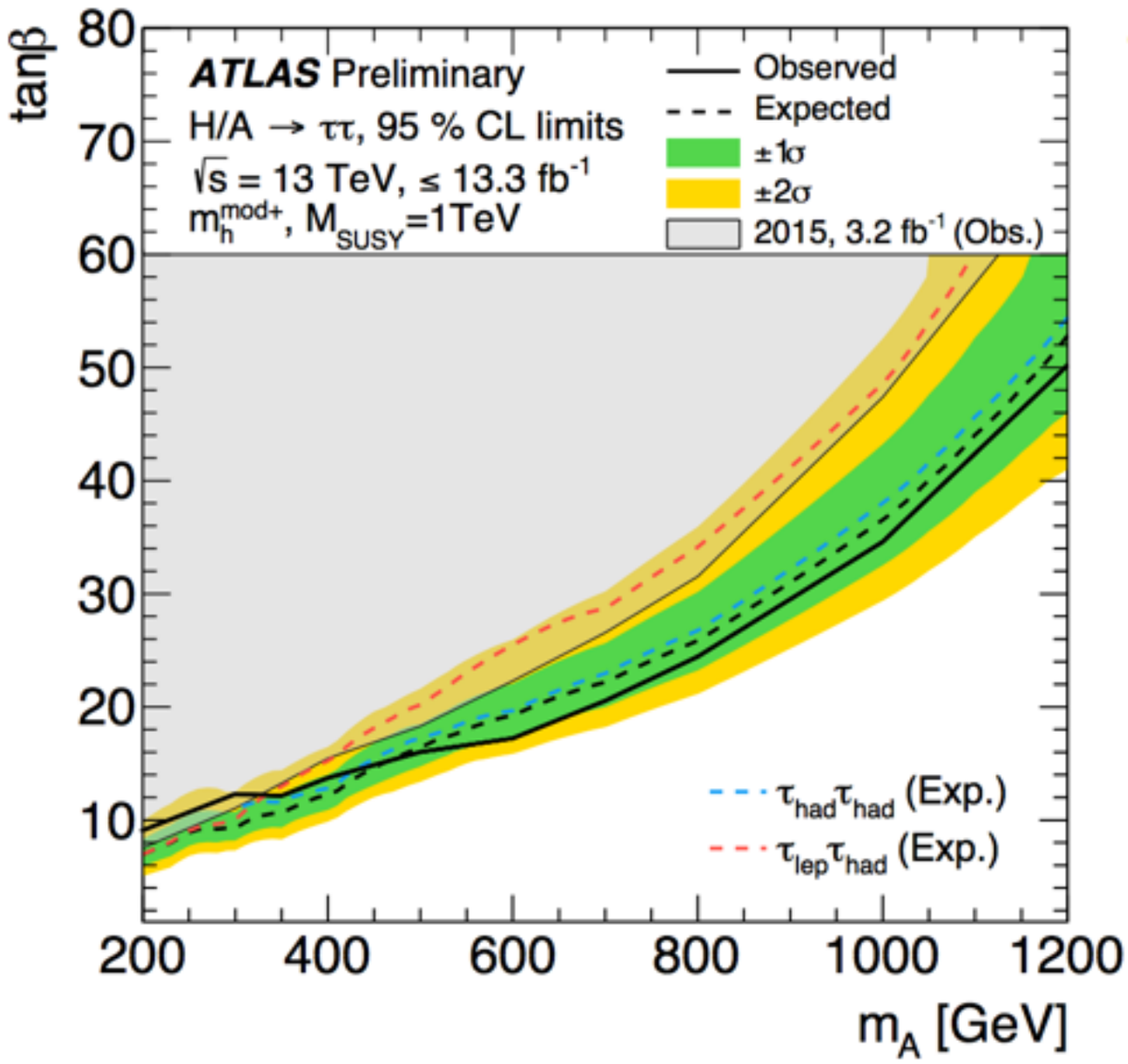
- Dominant systematics: τ energy scale, τ trigger, jet fake-related (lep-had), top modeling (had-had)
- Statistically combine the τ_{lep}-τ_{had} and τ_{had}-τ_{had} channels for one exclusion limit
  - NB: Limit from had-had starts at a higher m_A due to limited acceptance below 300 GeV
- We determine a σ x BR limit ($A/H \to \tau\tau$) for gluon-fusion and b-associated production separately; exclusions range from ~2.0 pb to 13-14 fb, depending on the Higgs mass and production mechanism

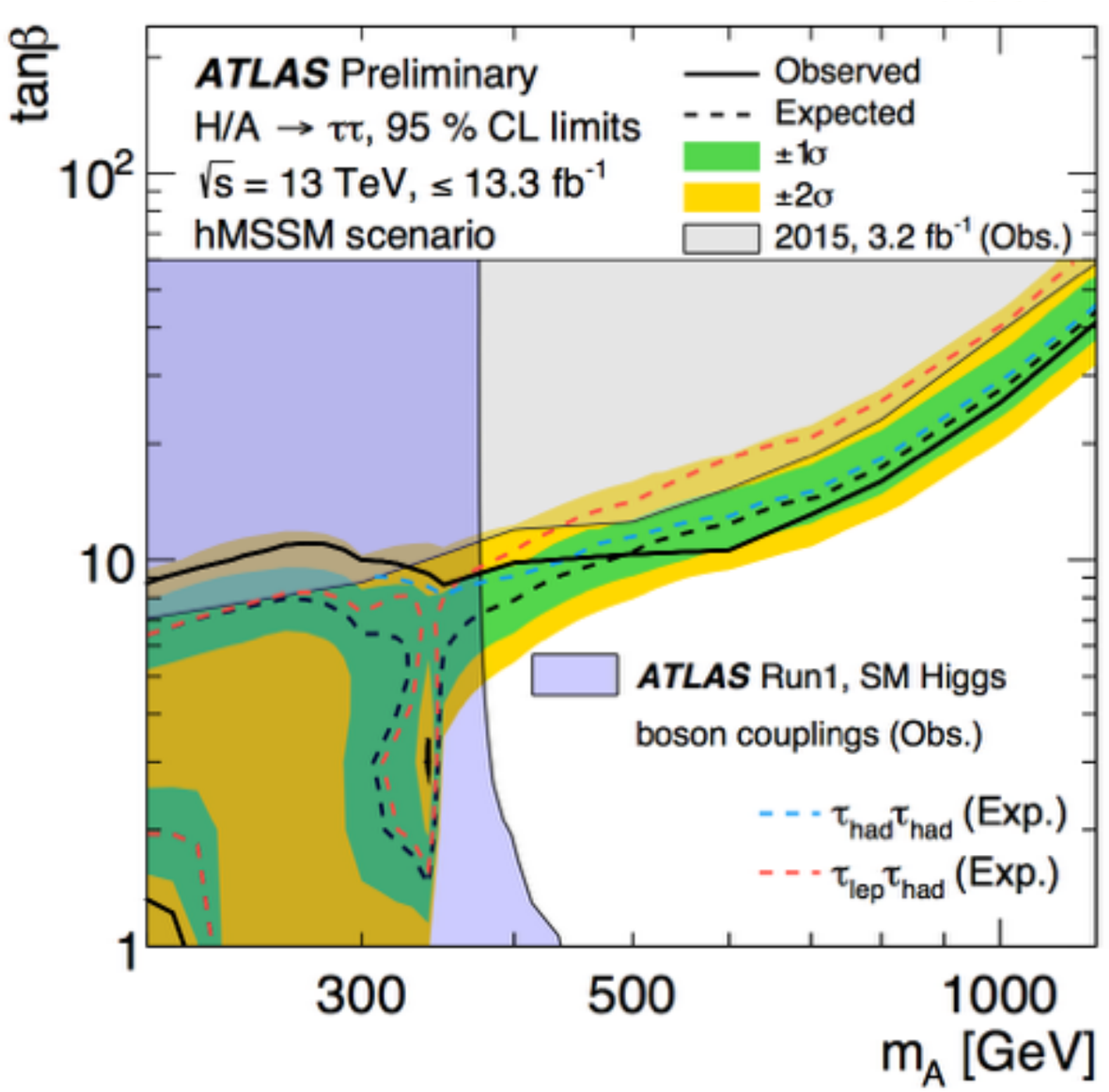




MSSM Neutral Higgs Search ($A/H \to \tau^+\tau^-$)

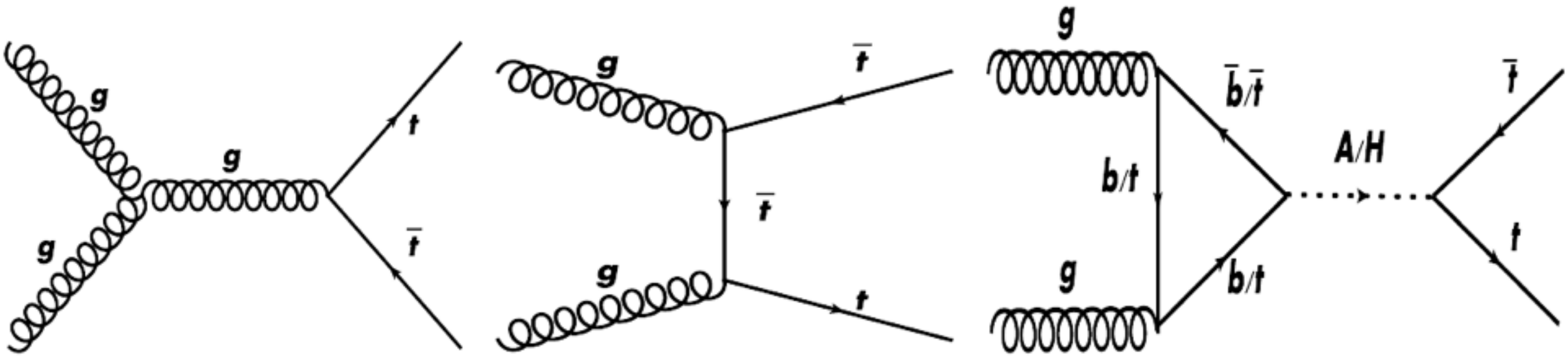
- We also show limits in the m_h^{mod+} and hMSSM benchmark scenarios
- In the m_h^{mod+} scenario, we exclude $\tan\beta > 16$ for $m_A = 600$ GeV and $\tan\beta > 35$ for $m_A = 1$ TeV
- In the hMSSM, we have sensitivity to exclude the low m_A-low $\tan\beta$ corner and the island around 350 GeV. Note: the features around 350 GeV are related to the $\sigma \times BR$ evolution near the $A/H \to t\bar{t}$ threshold
- hMSSM plot shows Run-1 couplings exclusion (κ_V, κ_u and κ_d)





High-mass Higgs Search (A/H→ttbar)

- We revisit a Run-1 ttbar resonance search that used 20.3 fb^{-1} of 8 TeV proton-proton collision data: ATLAS collaboration, JHEP 08 (2015) 148
- This analysis uses the ttbar lepton+jets channel, and takes the interference between the signal and ttbar background production modes into account for the first time

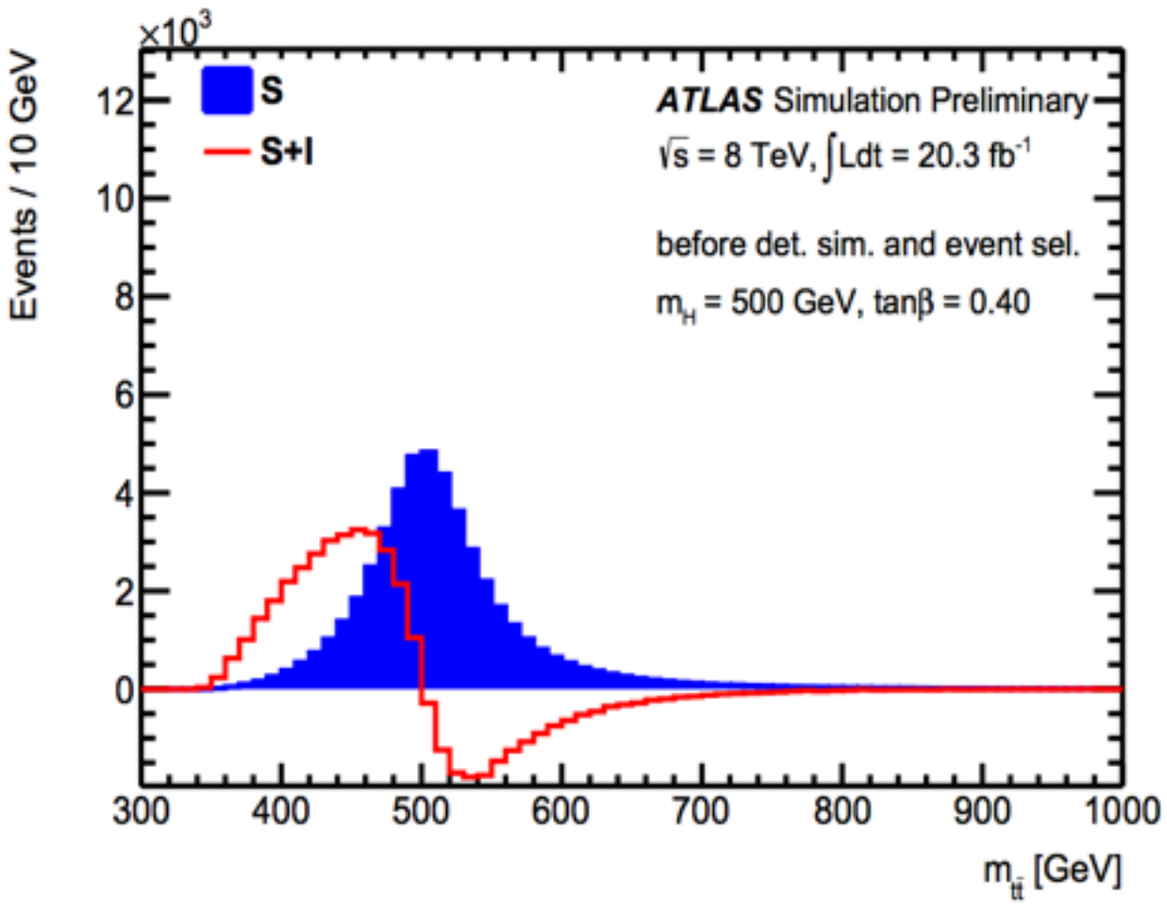


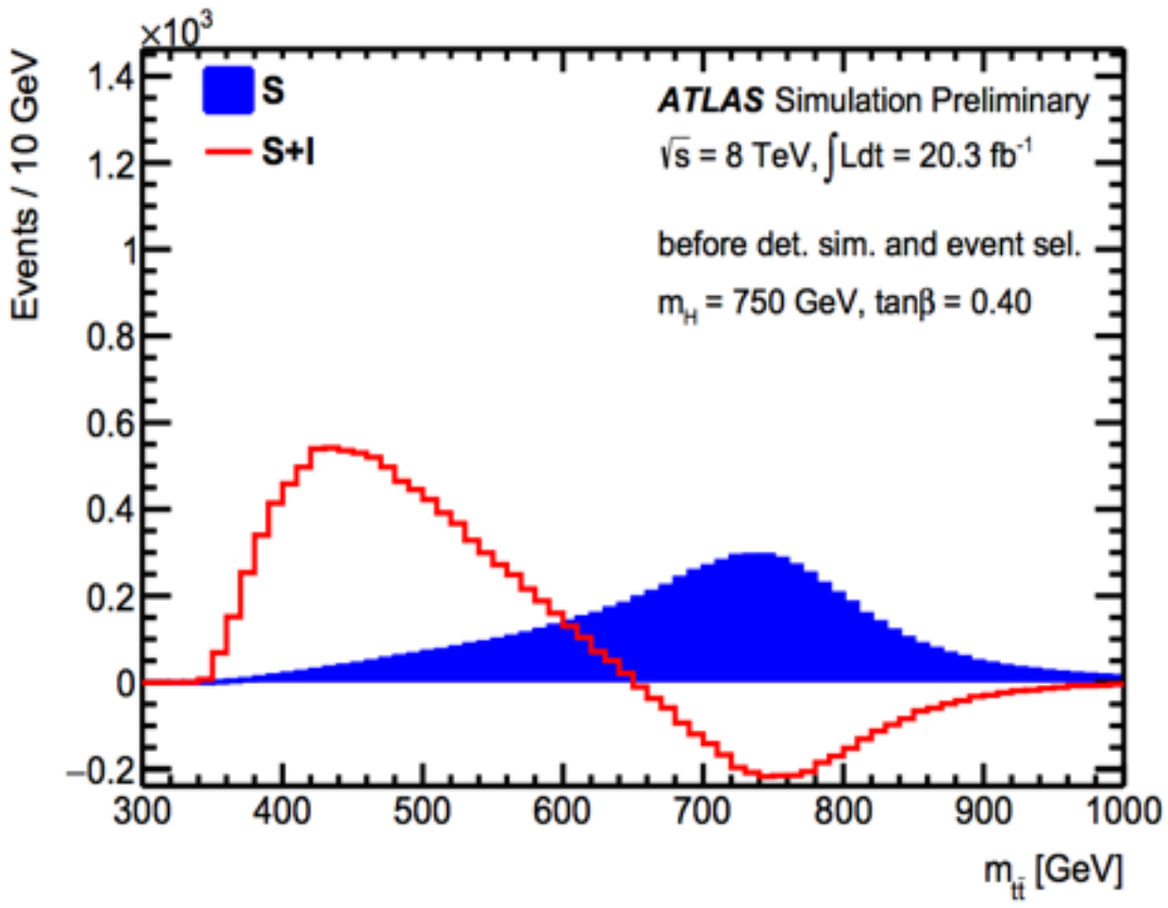
- Monte Carlo samples used:
  - A/H to ttbar signal: MadGraph5+Pythia6
  - Backgrounds:
    - ttbar: Powheg-Box+Pythia6
    - ttbar + V: Madgraph5+Pythia6
    - single top: Powheg+Pythia6
    - W+jets and Z+jets: Alpgen+Pythia6
    - Diboson: Sherpa

MadGraph5 used for both Direct and Indirect A/H signal generation (Direct used; difference taken as a modeling systematic)

Signal Modeling (A/H→ttbar)

- The signal process is simulated using the generator MadGraph5 v2.0.1 with the Higgs Effective Couplings Form Factor model (implements the production of scalar and pseudoscalar particles through loop-induced gluon fusion)
  - Loop contributions from both bottom and top quarks are taken into account
  - Signal shape is distorted from a simple Breit-Wigner peak, to a peak-dip structure
  - Statistical interpretation of measured event rates in data are compared to the total sum of Signal + Interference + Background (S + I + B)
  - The mass of the SM-like Higgs boson, h, is chosen to be 125 GeV and sin(β-α) is set to 1



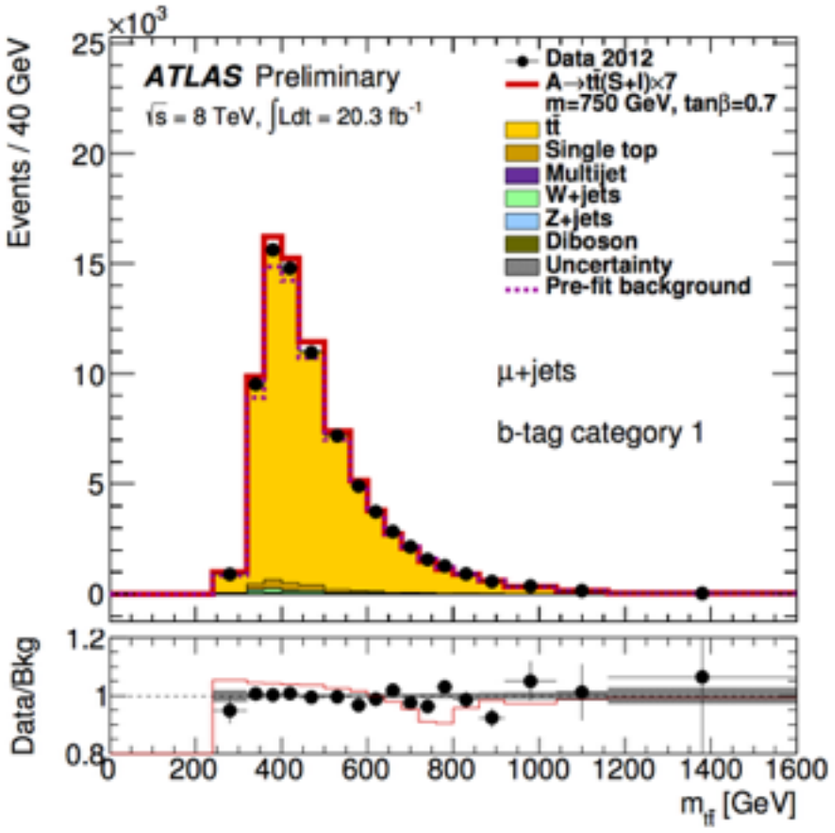


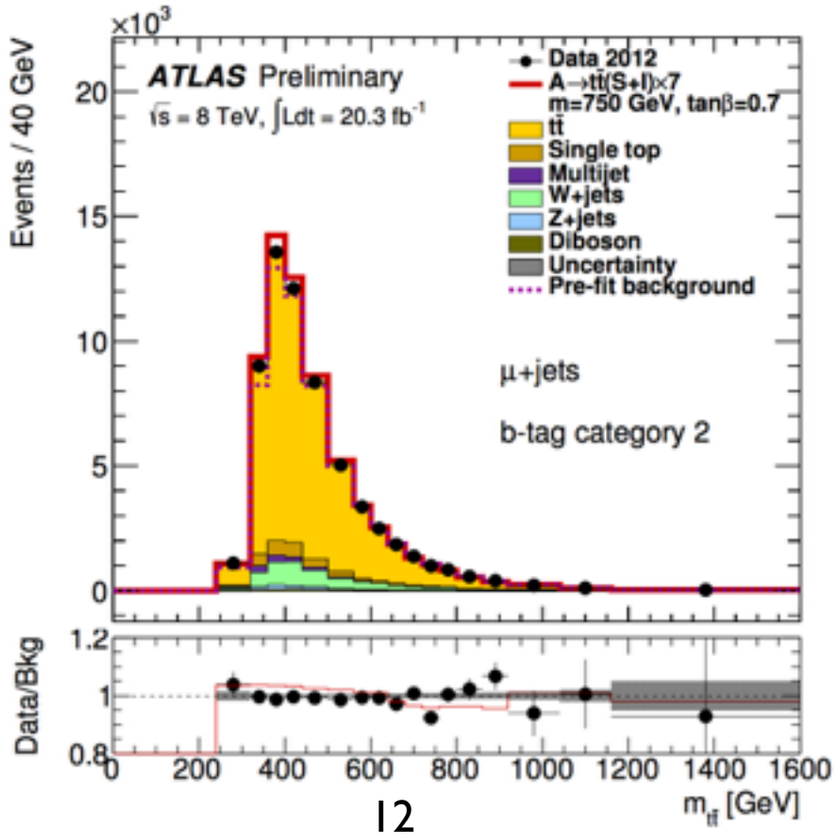
Event Selection / Mass Reconstruction (A/H→ttbar)

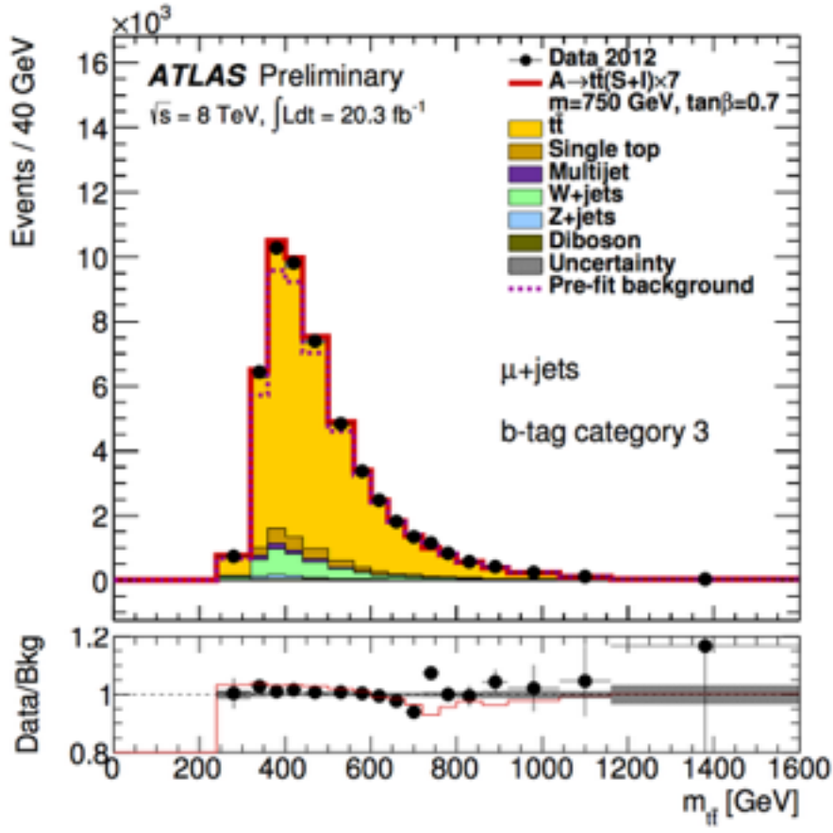
- Analysis targets the ttbar lepton+jets channel (one W to hadrons one to leptons)
  - Single electron or single muon triggers are used—2 categories (one for e; one for μ)
  - One high p_T electron or muon; high MET from the escaping neutrino; presence of at least 4 high p_T jets in the event; at least one jet originating from b quarks must be tagged (70%); Sum of MET and m_T > 60 GeV (multi-jets suppression) $m_{\mathrm{T}}^{W} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos\phi_{\ell\nu})}$
- A chi-squared fit is used for assignment of the decay products, then m_{tt} is reconstructed
  - Events further classified depending on the b-tagged jet(s) assignment—3 categories

$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{t_h - W}}{\sigma_{t_h - W}}\right]^2 + \left[\frac{m_{j\ell\nu} - m_{t_\ell}}{\sigma_{t_\ell}}\right]^2 + \left[\frac{(p_{\mathrm{T},jjb} - p_{\mathrm{T},j\ell\nu}) - (p_{\mathrm{T},t_h} - p_{\mathrm{T},t_\ell})}{\sigma_{\mathrm{diff}\,p_{\mathrm{T}}}}\right]^2$$

6 categories in total (2 lepton types) x (3 b-tagging classifications)



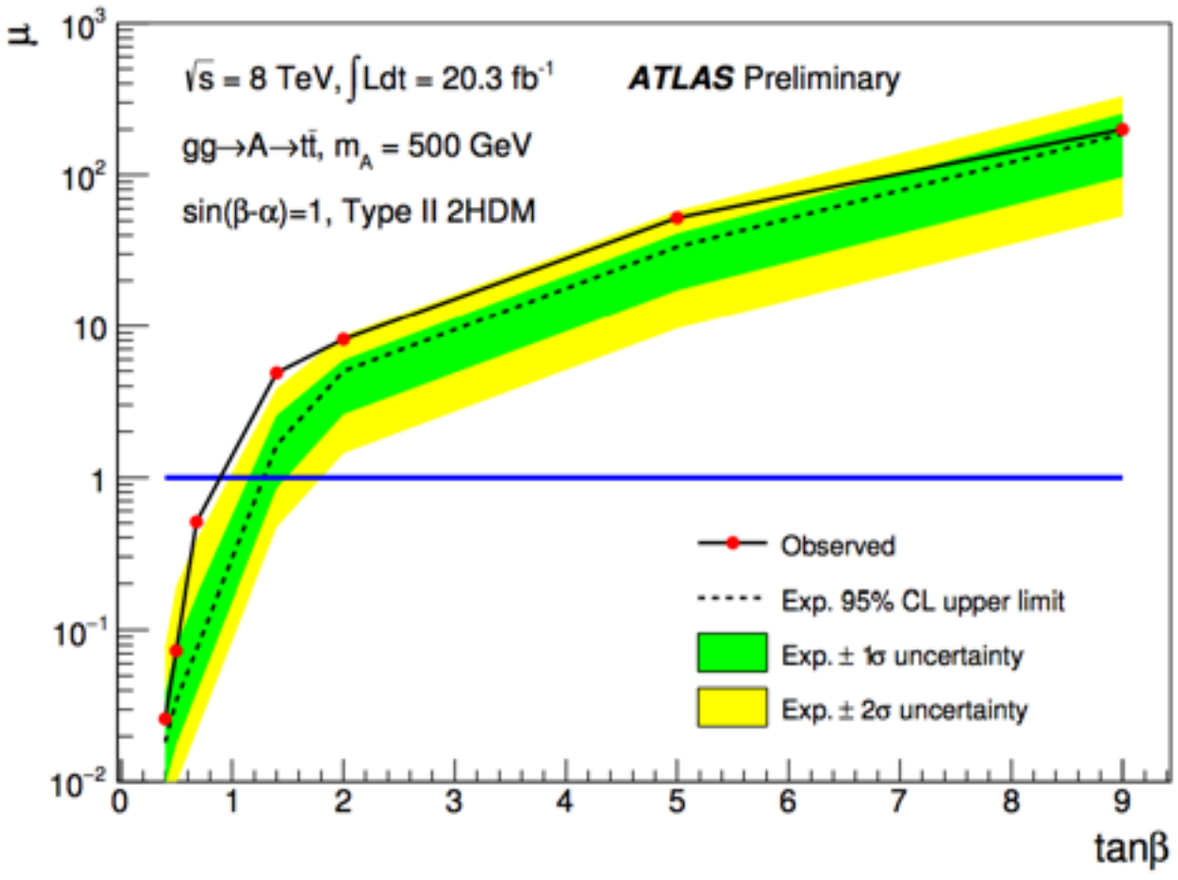


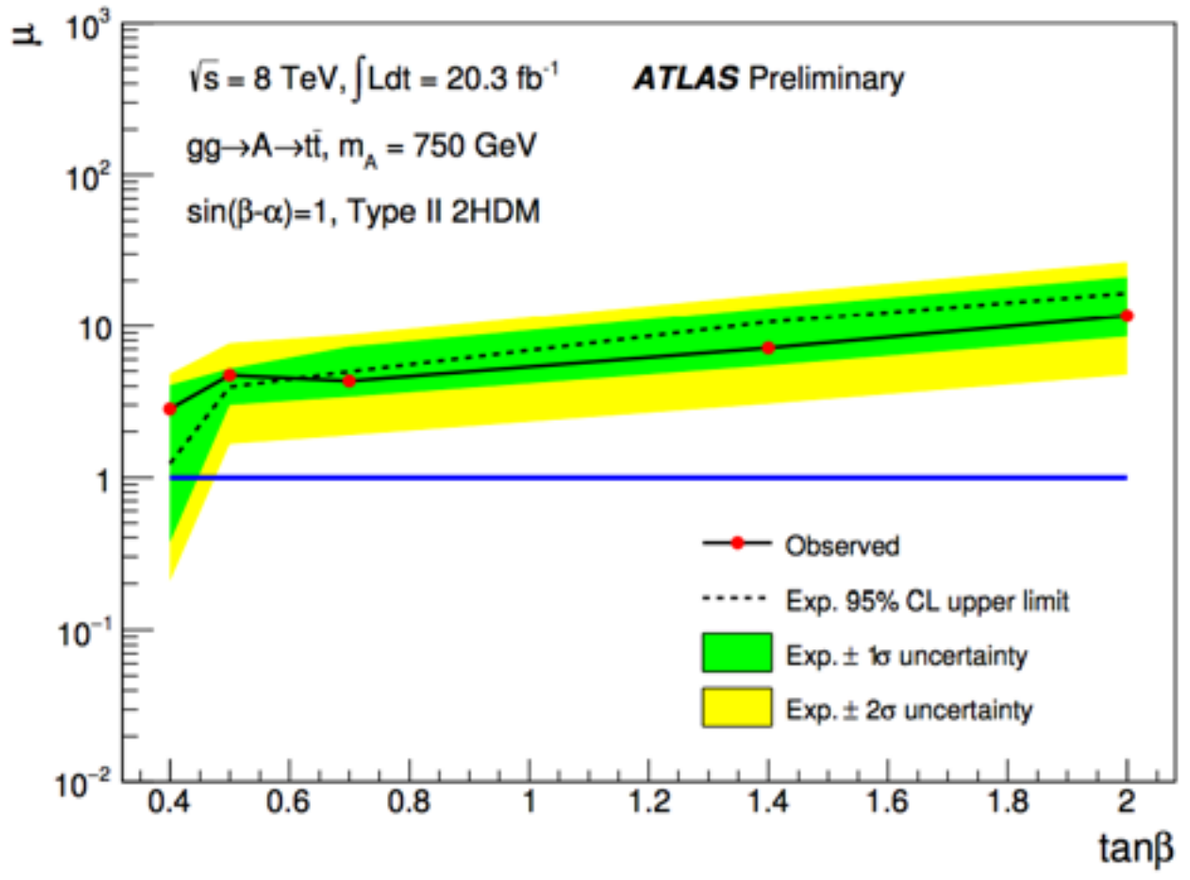


High-mass Higgs Search Results (A/H→ttbar)

- No significant excess over Standard Model background expectations is observed
- We set upper limits on the signal strength parameter μ as a function of the parameter tanβ for a neutral pseudoscalar A with a mass of 500 GeV and 750 GeV
- NB: The blue line at μ=1 corresponds to the signal strength in the Type-II 2HDM

NEW!

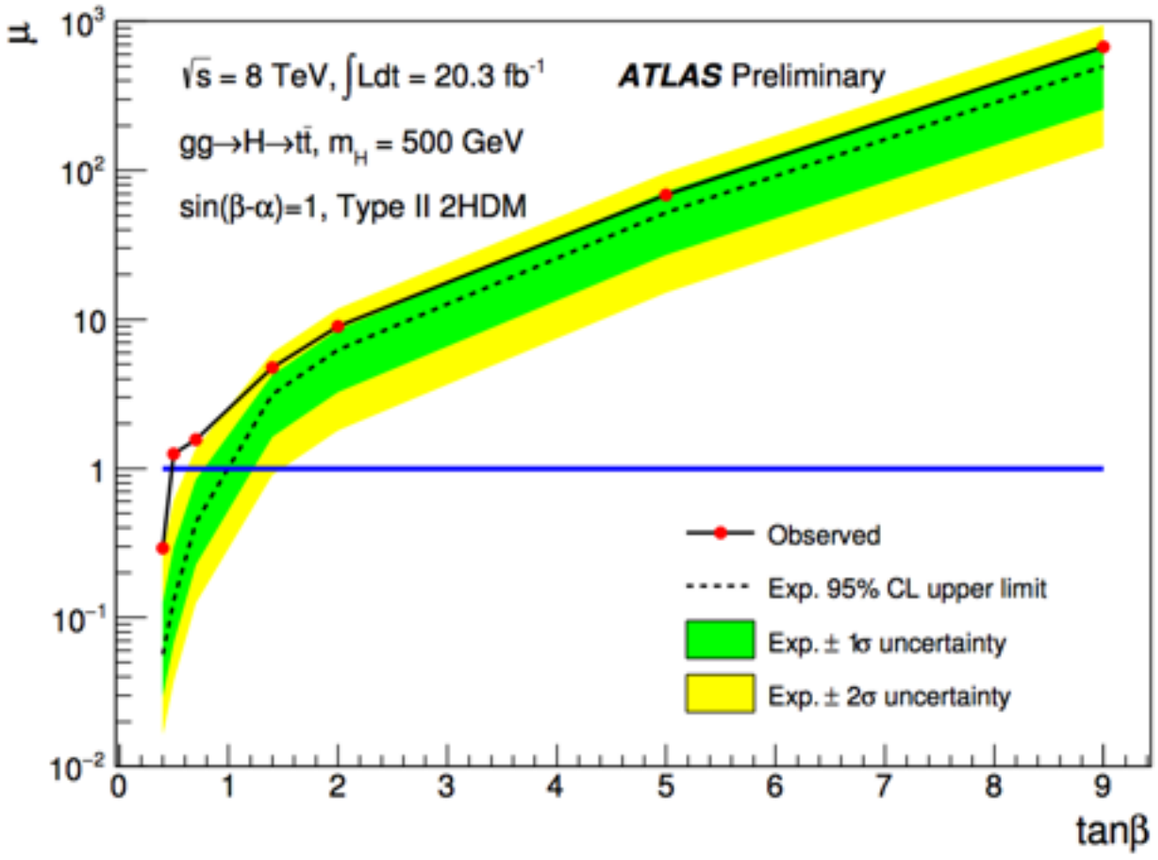


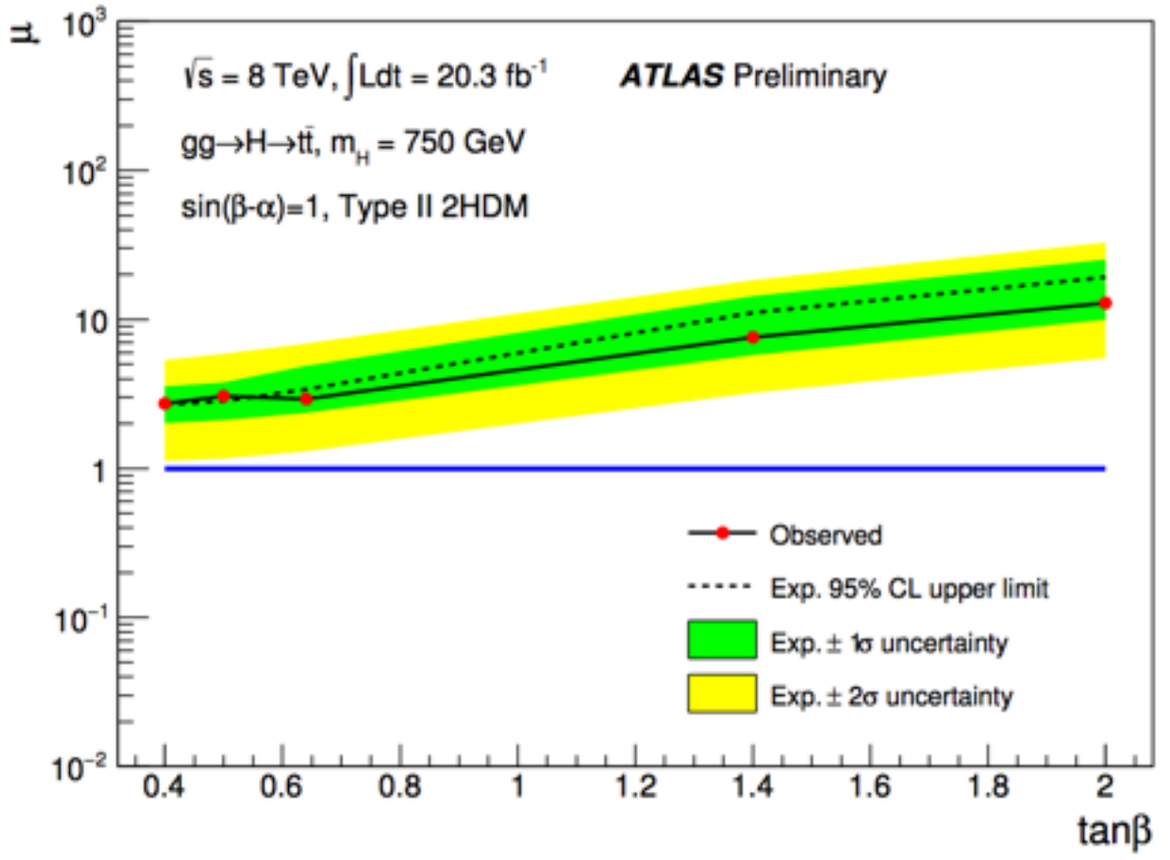


- For a neutral pseudoscalar A, with a mass of m_A=500 GeV, parameter values of tanβ < 0.85 in the Type-II 2HDM are excluded at the 95% CL. No tanβ values can be excluded for the higher mass point at 750 GeV.

High-mass Higgs Search Results (A/H→ttbar)

- No significant excess over Standard Model background expectations is observed
- We set upper limits on the signal strength parameter μ as a function of the parameter tanβ for a neutral scalar H with a mass of 500 GeV and 750 GeV
- NB: The blue line at μ=1 corresponds to the signal strength in the Type-II 2HDM





- For a neutral scalar H, with a mass of m_H=500 GeV, parameter values of tanβ < 0.45 in the Type-II 2HDM are excluded at the 95% CL. No tanβ values can be excluded for the higher mass point at 750 GeV.

Conclusions and Outlook

- ATLAS has performed new searches for high-mass neutral Higgs bosons decaying to fermions
  - The new A/H→ττ analysis uses up to 13.3 fb^{-1} of 13 TeV collision data recorded in 2015 and 2016; this result improves on a recent ATLAS paper submitted to EPJC
  - The A/H→ttbar analysis is an extension of a Run-1 search in 20.3 fb^{-1} of 8 TeV data and takes the interference between A/H signal and ggF ttbar into account for the first time

- No significant excess is observed in the data from either search, and 95% CL limits are set
  - **A/H→ττ:** We determine a σ x BR limit for gluon-fusion and b-associated production separately; exclusions range from ~2.0 pb at m_A=200 GeV to 13-14 fb for m_A between 600 GeV and 1 TeV
  - **A/H→ττ:** We also show limits in the m_h^{mod+} and hMSSM benchmark scenarios; e.g., in the m_h^{mod+} scenario, lowest tanβ constraint excludes tanβ > 9 for m_A = 200 GeV
  - **A/H→ttbar:** For a neutral pseudoscalar A, with a mass of m_A=500 GeV, parameter values of tanβ < 0.85 in the Type-II 2HDM are excluded at the 95% CL.
  - **A/H→ttbar:** For a neutral scalar H, with a mass of m_H=500 GeV, parameter values of tanβ < 0.45 in the Type-II 2HDM are excluded at the 95% CL.

- Stay tuned for more results from Run-II of the LHC; these are very exciting times!