Search for additional Higgs Bosons in $t\bar{t}$ Final States
including interference effects

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[1]DESY

1. Why look for additional Higgs Bosons?

- The Standard Model is incomplete.
  - No candidate for Dark Matter, hierarchy problem, ...
- Introduce a second scalar complex doublet field ⇒ Two-Higgs-Doublet Models (2HDMs)
  - Simplest (not-strongly-constrained) extension of the SM Higgs sector
  - Motivated by e.g. SUSY (hMSSM) or axion models
- Consider CP conserving potential with softly broken Z_2 symmetry

Higgs Bosons in a 2HDM

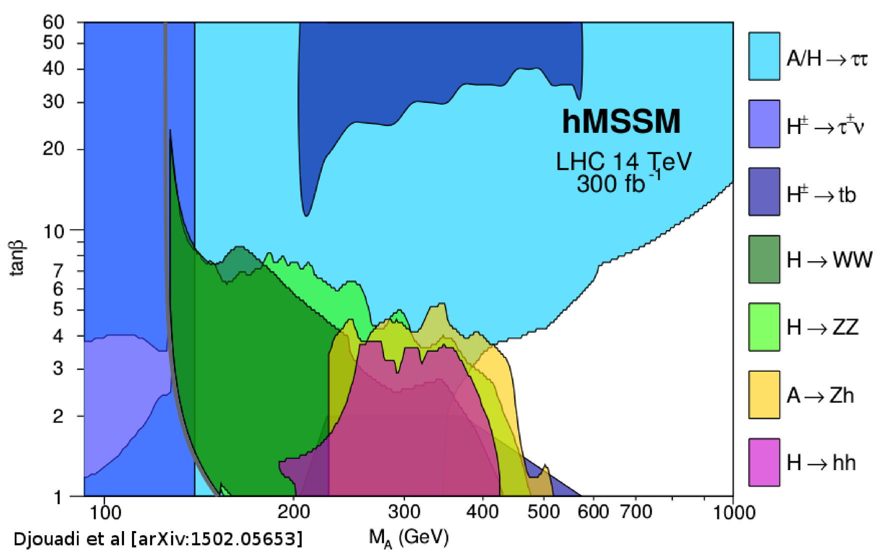
- CP-even: h^0, H^0
- CP-odd: A^0
- Charged: $H^{\pm}$

Free parameters

- Higgs boson masses
- $\tan\beta$: ratio of Higgs VEVs
- α: mass mixing between h and H
- Alignment limit: $\cos(\beta - \alpha) = 0$
  - h: 125 GeV boson with SM couplings

2. Exploring the last Blind Spot

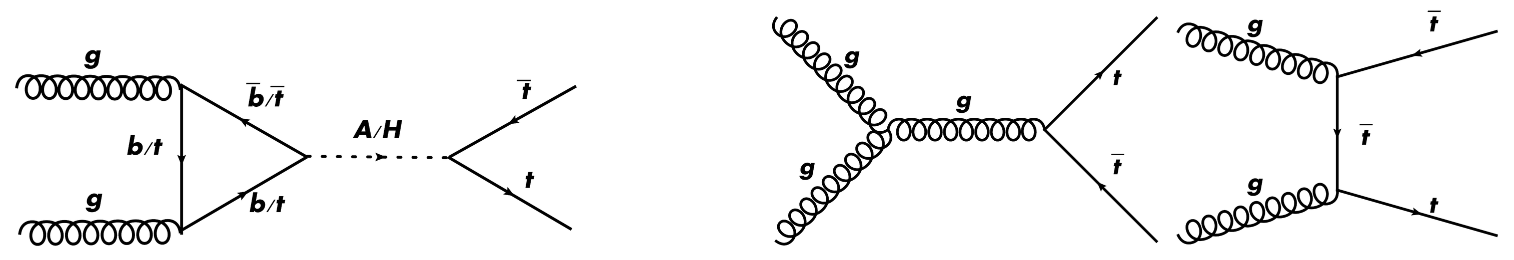
- Probe the 2D parameter space in $m_{A/H}$ and $\tan\beta$
- Type-II 2HDM (e.g. hMSSM)
- Small $\tan\beta$ ⇒ large couplings to up-type fermions (and vice versa)



- Unique sensitivity of $A/H \to t\bar{t}$ for $m_{A/H} > 2m_{\mathrm{top}}$, $\tan\beta \approx O(1)$

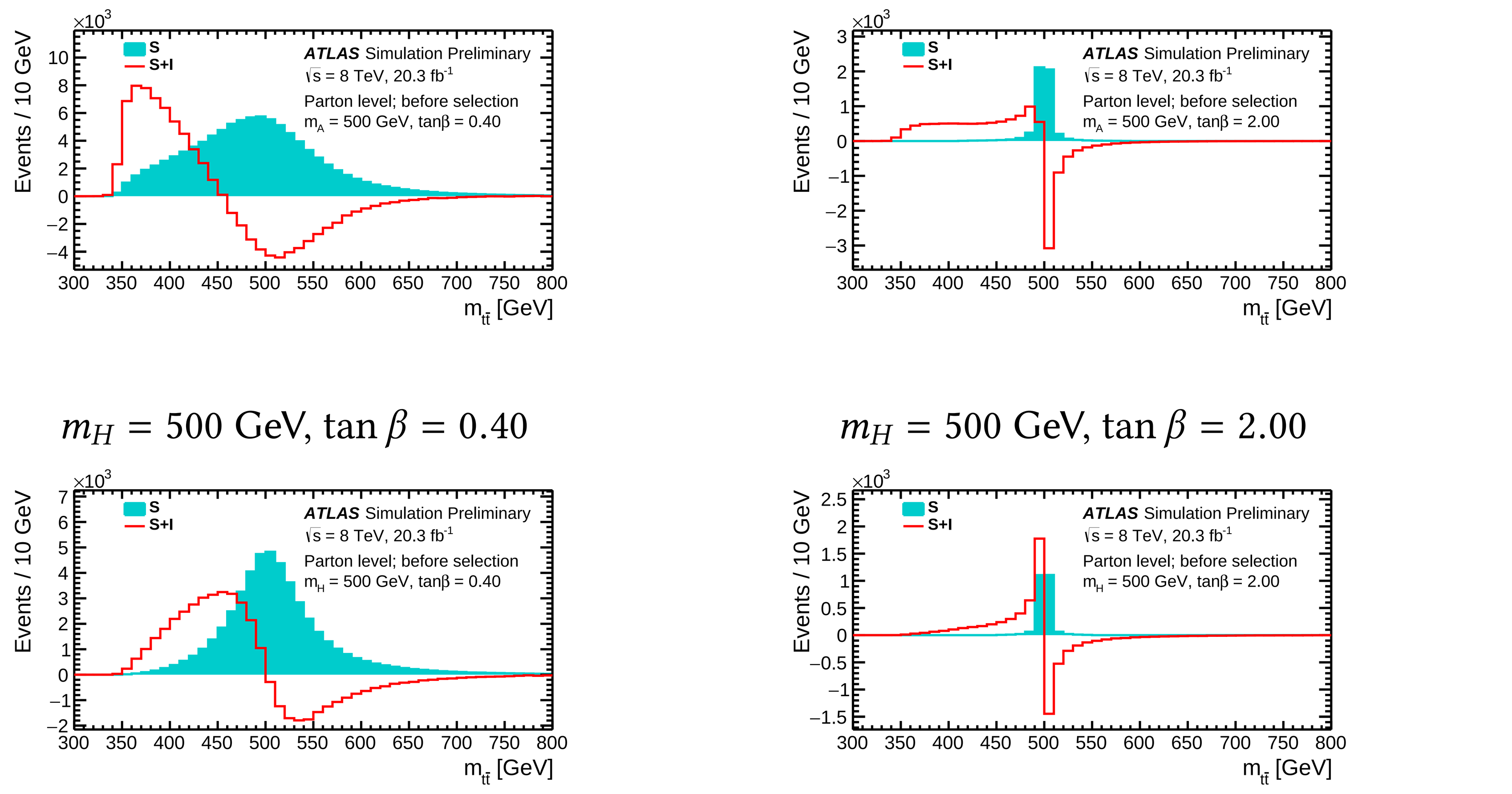
3. The Challenge: Interference

- Large irreducible background from SM $t\bar{t}$ (> 85% post selection)
- Dominated by $gg \to t\bar{t}$
- **Strong interference** with $gg \to A/H \to t\bar{t}$



$gg \to A/H \to t\bar{t}$ SM $gg \to t\bar{t}$

4. Non-trivial Signal Shape!



- Significant off-shell peak from imaginary phase in production loop
- Width of S and $S + I$ decreases with increasing $m_{A/H}$ and increasing $\tan\beta$

5. Modelling Interference

a) Signal process $gg \to A/H \to t\bar{t}$

- Model MadGraph_aMCatNLO v2.4.3
- Leading order in QCD
- Loop contributions from top and bottom quarks

b) Disentangle interference from SM $t\bar{t}$ background

- Most reliable background prediction from Powheg+Pythia6
- Pure $S + I$ component obtained by removing matrix element for SM $t\bar{t}$ background in MadGraph

c) Signal parameter range

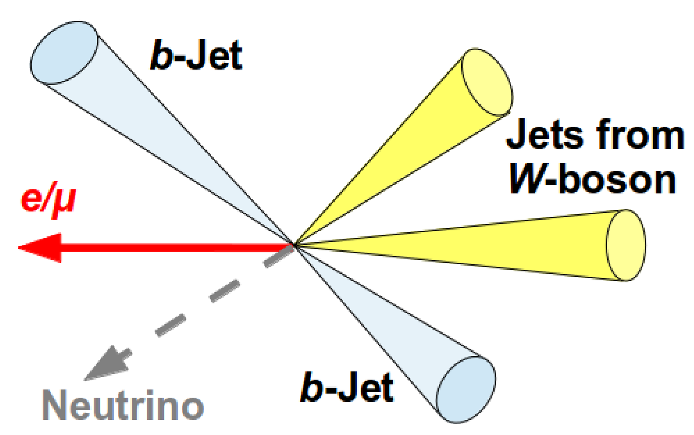
- $m_{A/H} \geq 500$ GeV
  Smaller masses require an accurate modelling of Higgs boson decays into virtual top quarks and the implementation of higher-order corrections not available in the MadGraph model.
- $\tan\beta \geq 0.4$
  To ensure perturbativity of Higgs couplings.
- S and $S + I$ samples for varying values of $(mA/H, \tan\beta)$ obtained from a few pure signal samples after the detector simulation via an **event-by-event reweighting**.

d) Higher-order corrections

- Pure signal S:
$$k_S = \sigma_S^{\mathrm{2HDMC+SusHi}} / \sigma_S^{\mathrm{MG,LO}}$$
- Interference term I
$$k_I = \sqrt{k_B \cdot k_S} \text{ with } k_B = \sigma_{t\bar{t}}^{\mathrm{NNLO+NNLL}} / \sigma_{t\bar{t}}^{\mathrm{MG,LO}} = 1.87$$
- Signal-plus-interference $S + I$
$$(S + I) = [(S + I) - S] \cdot k_I + S \cdot k_S.$$

6. Signal Regions [Based on "resolved" selection in JHEP 08 (2015) 148]

- Exactly one electron or muon
  - $p_T > 25$ GeV, $|\eta| < 2.5$
  - tight, mini-isolated
- $E_T^{\mathrm{miss}} > 20$ GeV
- $E_T^{\mathrm{miss}} + m_T^W > 60$ GeV
- ≥ 4 anti-k_t $R = 0.4$ jets
  - $p_T > 25$ GeV, $|\eta| < 2.5$
- $\geq 1b$-tagged jets
  - MV1 70% operating point

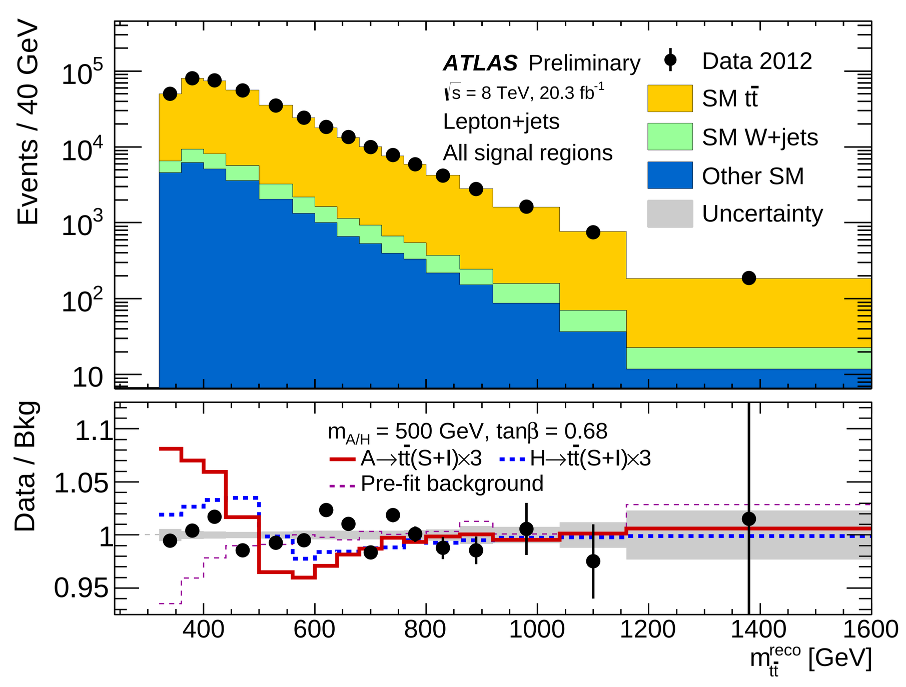


Six mutually exclusive signal regions

- e+jets and μ+jets channels
- Three b-tagging categories:
  - Both top-quark candidates have matching b jet
  - Only hadronic/leptonic top-quark candidate has matching b jet

7. Reconstruction

- Neutrino four vector from E_T^{miss} and W-boson mass requirement for p_z^ν
- Kinematic χ^2 fit to reconstruct $t\bar{t}$ system
- Experimental resolution for $t\bar{t}$ invariant mass: 8% for resonance mass of 500 GeV



8. Dominant Systematic Uncertainties

Signal

- Top-quark mass: $\Delta m_{\mathrm{top}} = \pm 1$ GeV
- PDF
- Jet energy scale (JES)
- Factorisation/renormalisation scale
- Reweighting ($S + I$ only)

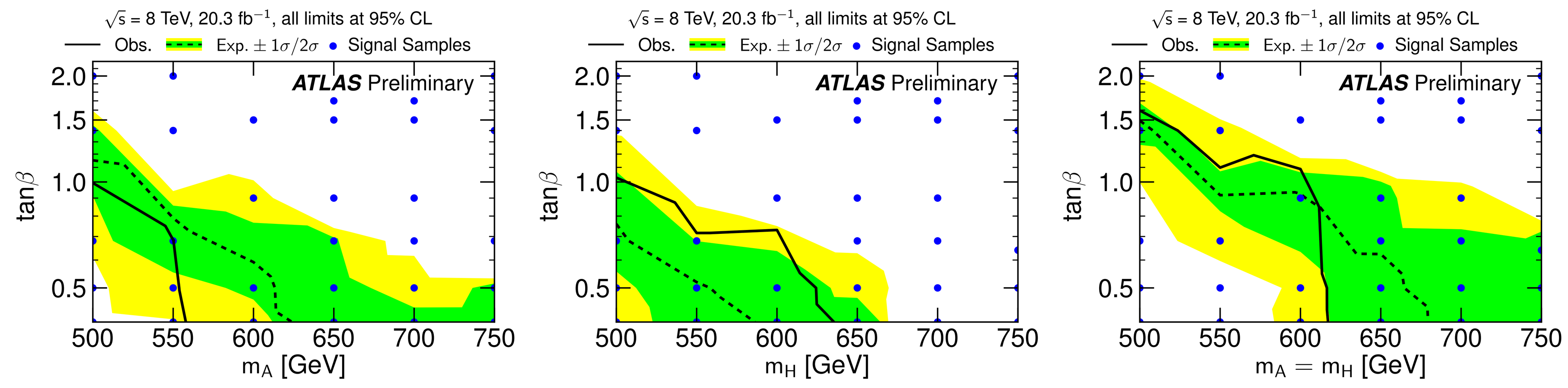
Background

- $t\bar{t}$ production cross-section (± 6.5%)
- $t\bar{t}$ ISR/FSR modelling
- $t\bar{t}$ PS + fragmentation
- JES

Impact on both shape and normalisation of $t\bar{t}$ invariant mass spectra taken into account.

9. Exclusion Limits

- Profile likelihood fit with uncertainties taken into account as nuisance parameters
- Shape of binned $m_{t\bar{t}}^{\mathrm{reco}}$ distributions parameterised in terms of signal strength μ
$$\mu \cdot S + \sqrt{\mu} \cdot I + B = \sqrt{\mu} \cdot (S + I) + (\mu - \sqrt{\mu}) \cdot S + B.$$
- Only bins with $m_{t\bar{t}}^{\mathrm{reco}} > 320$ GeV considered to avoid threshold effects not perfectly described by the simulation.
- Limits are CL_s asymptotic limits at 95% confidence level
- Benchmark: 2HDM in the alignment limit ($\mu = 1$)
- Three mass hierarchies:
  - $m_A << m_H$: Only A contribution in $t\bar{t}$ invariant mass spectrum
  - $m_H << m_A$: Only H contribution in $t\bar{t}$ invariant mass spectrum
  - $m_A = m_H$: Spectra add up. Motivated by the MSSM and EW precision constraints.



ATLAS EXPERIMENT

References:
[1] ATLAS, CERN-EP-2017-134, to be submitted to PRL

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